T2K and other long baseline experiments

(bonus: reactor experiments)

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Neutrino mixing and oscillations

mixing of flavor and mass eigenstates → PMNS matrix parametrized as

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}1&0&0\\0&c_{23}&s_{23}\\0&-s_{23}&c_{23}\end{pmatrix}\cdot\begin{pmatrix}c_{13}&0&s_{13}e^{-i\delta_{CP}}\\0&1&0\\-s_{13}e^{i\delta_{CP}}&0&c_{13}\end{pmatrix}\cdot\begin{pmatrix}c_{12}&s_{12}&0\\-s_{12}&c_{12}&0\\0&0&1\end{pmatrix}\cdot\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$c_{xy} = \cos\theta_{xy}$
$s_{xy} = \sin\theta_{xy}$

$$P_{\nu_\alpha\to\nu_\beta}=\delta_{\alpha\beta}-4\sum_{i>j}\Re\left(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\right)\sin^2\Delta m^2_{ij}\frac{L}{4E}\pm 2\sum_{i>j}\Im\left(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\right)\sin^2\Delta m^2_{ij}\frac{L}{4E}$$

(in vacuum)

oscillation probabilities depend on:

- 6 parameters – constants of nature
  - 3 mixing angles: θ_{12}, θ_{13}, θ_{23}
  - 2 independent mass splittings: $\Delta m^2_{21} = m^2_2 - m^2_1$, $\Delta m^2_{32} = m^2_3 - m^2_2$,
  - CP violating phase: δ_{CP}
- and 2 which can be controlled: baseline **L** and neutrino energy **E**

Known and unknown

PDG 2016

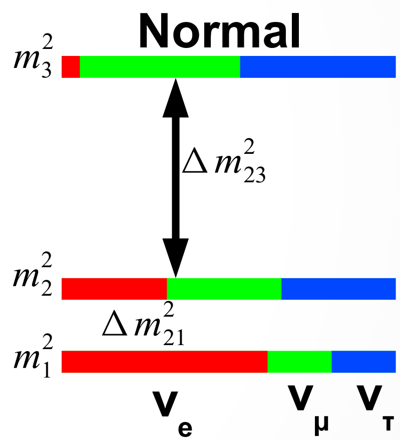
$\sin^2\theta_{23} = 0.51 \pm 0.05$ (NH)
$\sin^2\theta_{23} = 0.50 \pm 0.05$ (IH)
$\sin^2\theta_{12} = 0.304 \pm 0.014$
$\sin^2\theta_{13} = 0.0219 \pm 0.0012$

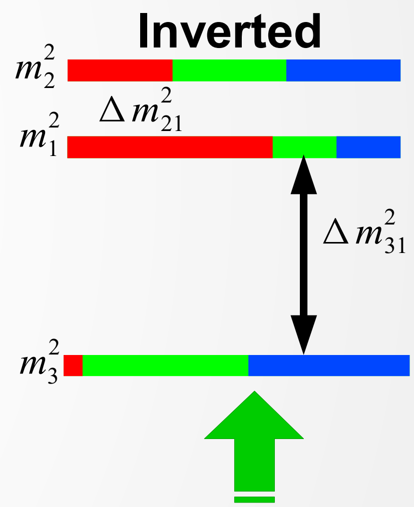
$\Delta m^2_{21} = (7.53 \pm 0.18)\cdot 10^{-5}$ eV^2
$|\Delta m^2_{32}| = (2.44 \pm 0.06)\cdot 10^{-3}$ eV^2 (NH)
$|\Delta m^2_{32}| = (2.51 \pm 0.06)\cdot 10^{-3}$ eV^2 (IH)
δ_{CP} = some hints

- **mass hierarchy**: sign of the mass splitting Δm^2_{32}
  - from solar experiments we know that $m_2 > m_1$
- **mixing angle θ_{23}**: maximal? If not, which octant?
- **CP violation in leptonic sector**: value of the δ phase
- existence of sterile neutrinos
- mass of neutrinos
- nature of neutrinos: Dirac or Majorana?

separate talk

separate talk





only in appearance experiments (accelerators)

reactors atmosphere accelerators

not in oscillation experiments

Oscillation experiments

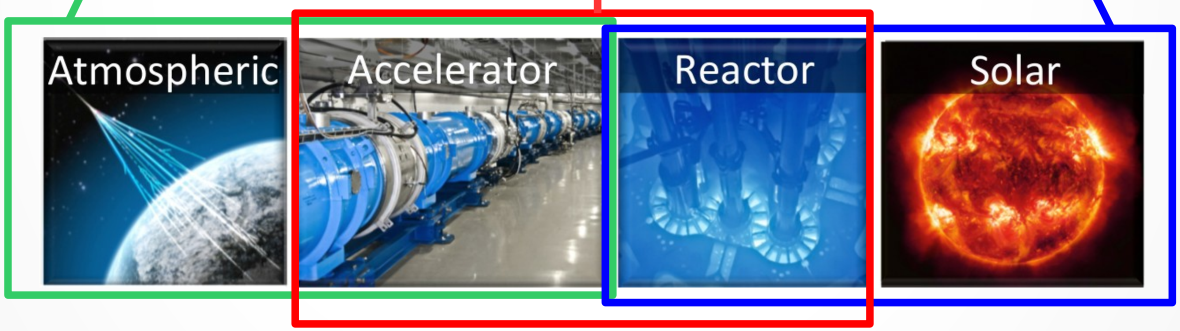
mixing of flavor and mass eigenstates → PMNS matrix parametrized as

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}1&0&0\\0&c_{23}&s_{23}\\0&-s_{23}&c_{23}\end{pmatrix}\cdot\begin{pmatrix}c_{13}&0&s_{13}e^{-i\delta_{CP}}\\0&1&0\\-s_{13}e^{i\delta_{CP}}&0&c_{13}\end{pmatrix}\cdot\begin{pmatrix}c_{12}&s_{12}&0\\-s_{12}&c_{12}&0\\0&0&1\end{pmatrix}\cdot\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

"atmospheric sector"

atmosphere: ν_μ disappearance

accelerators: ν_μ disappearance and ν_τ appearance



accelerators: ν_e appearance

reactors: $\bar{\nu}_e$ disappearance

"solar sector"

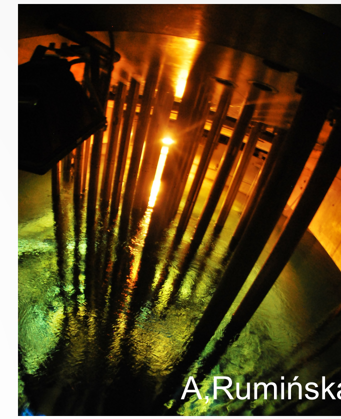
separate talk

Sun: ν_e disappearance

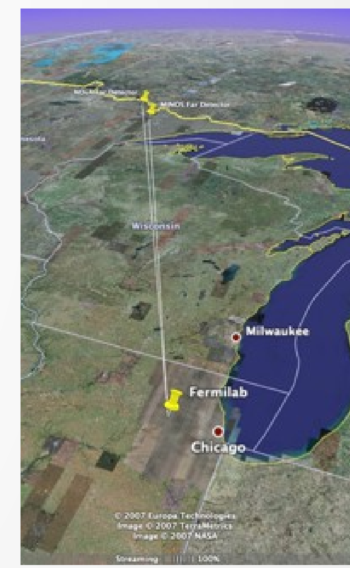
reactors: $\bar{\nu}_e$ disappearance

Outline

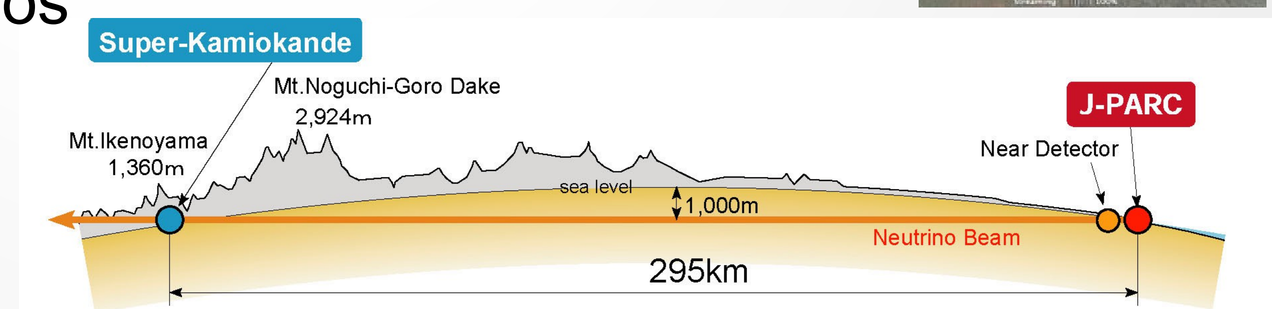
- reactor neutrinos
  - now: θ_{13} measurements
  - in the future: mass hierarchy



- accelerator neutrinos
  - now: θ_{23} measurements and CPT conservation
    θ_{13} measurements and search for CP violation
  - plans for the future:
    discovery of CP violation and
    determination of mass hierarchy

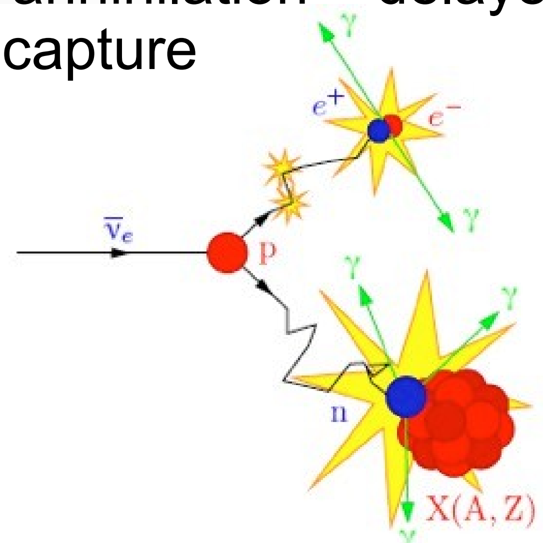


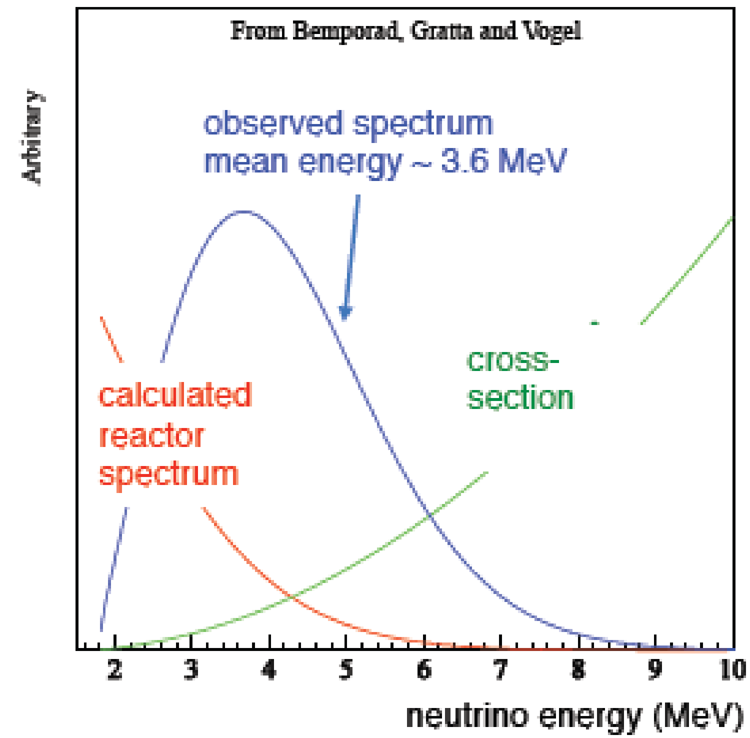
- long-baseline experiments
  with atmospheric neutrinos



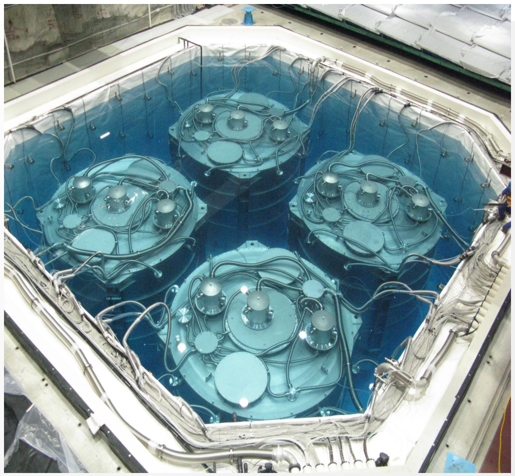
Reactor neutrinos

- **electrons antineutrinos** from decays of uranium and thorium fission products
  - ~10^{20} ν/GW s, 6/fission,
  - energies ~few MeV
- detection by **inverse beta decay**
  - positron annihilation + delayed signal from neutron capture





- Daya Bay, RENO, Double CHOOZ
  - liquid scintillator detectors
  - near and far stations



Daya Bay

Oscillations of reactor neutrinos

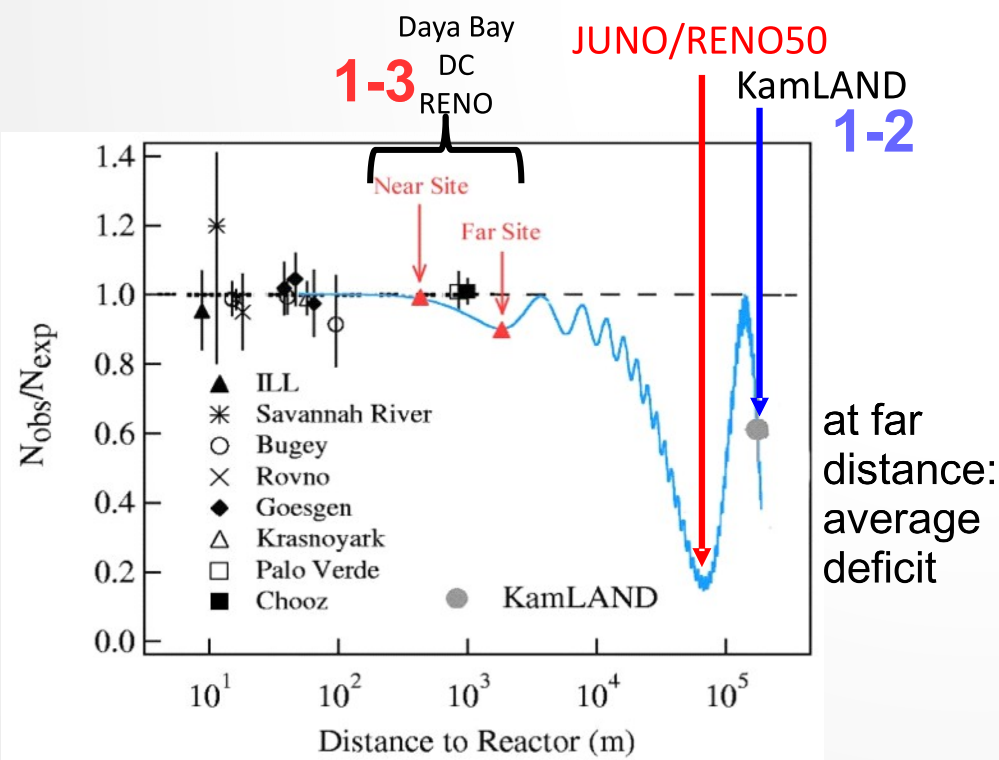
$$P\left(\overline{\nu_e} \to \overline{\nu_e}\right) \simeq 1 - \sin^2 2\theta_{12} c_{13}^4 \sin^2 \frac{\Delta m_{21}^2 L}{4E}$$

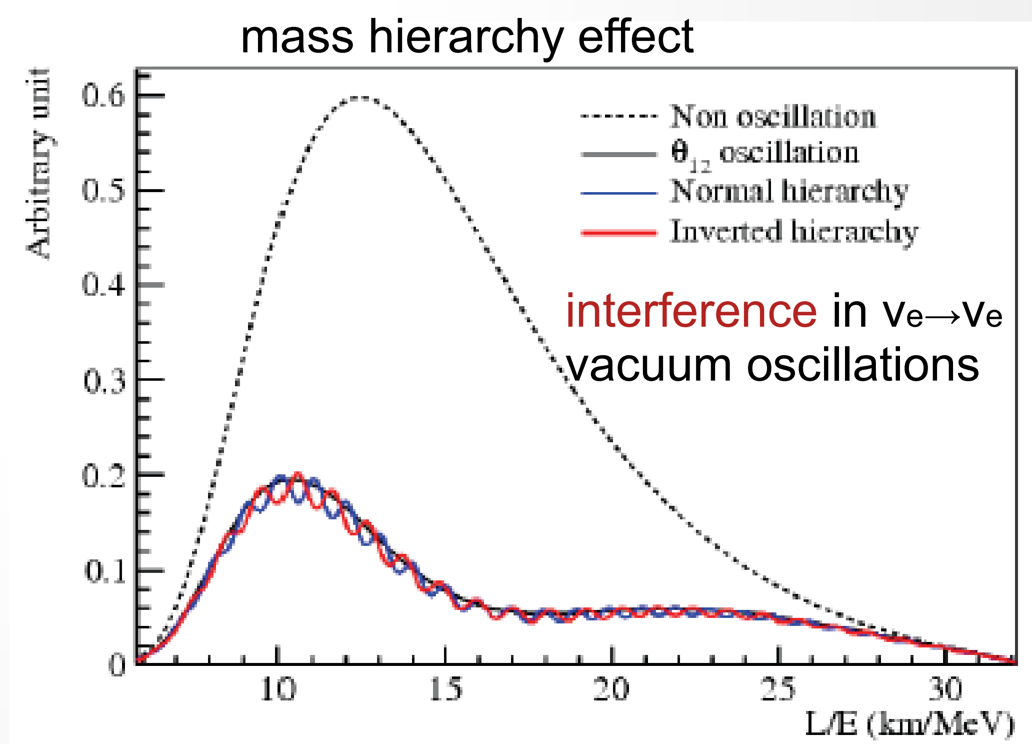
sector 1-2: KamLAND, most precise determination of Δm^2_{21}

$$- \sin^2 2\theta_{13} \left[c_{12}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} + s_{12}^2 \sin^2 \frac{\Delta m_{32}^2 L}{4E} \right]$$

sector 1-3

- sectors 1-2 and 1-3 available, depending on the **baseline**

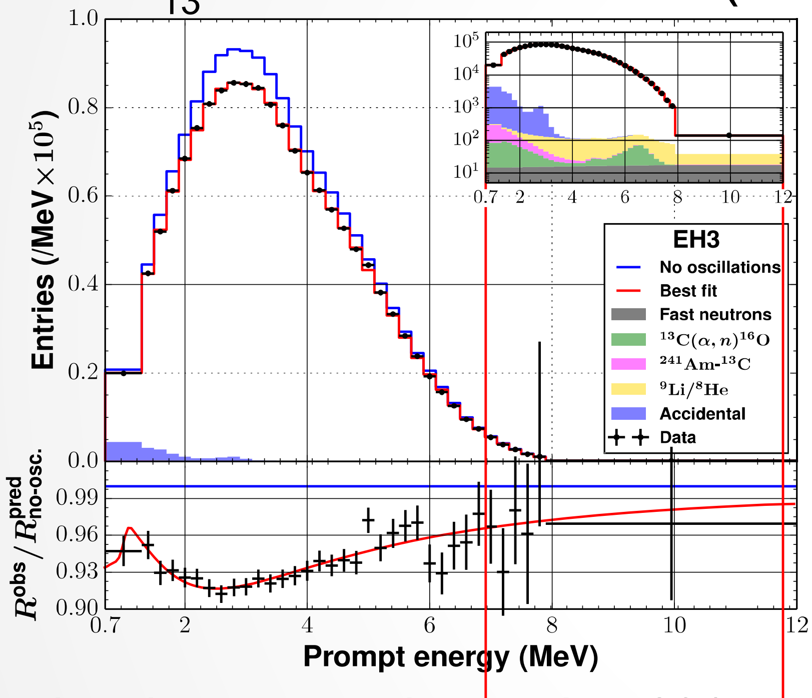


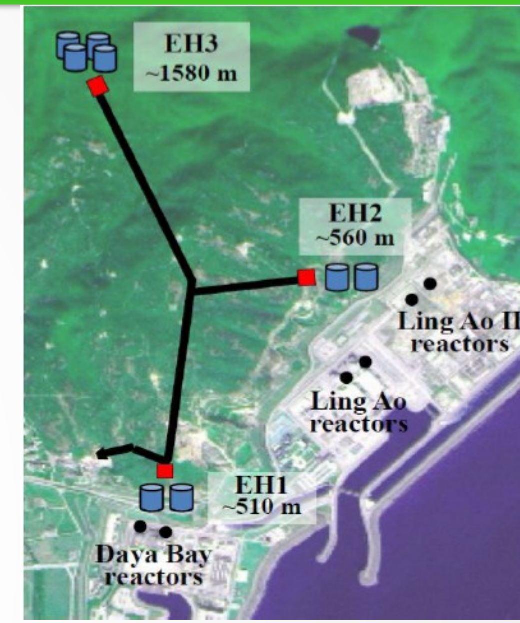


Short baseline → sector 1-3

- Daya Bay: most precise measurement of $\boldsymbol{\theta_{13}}$

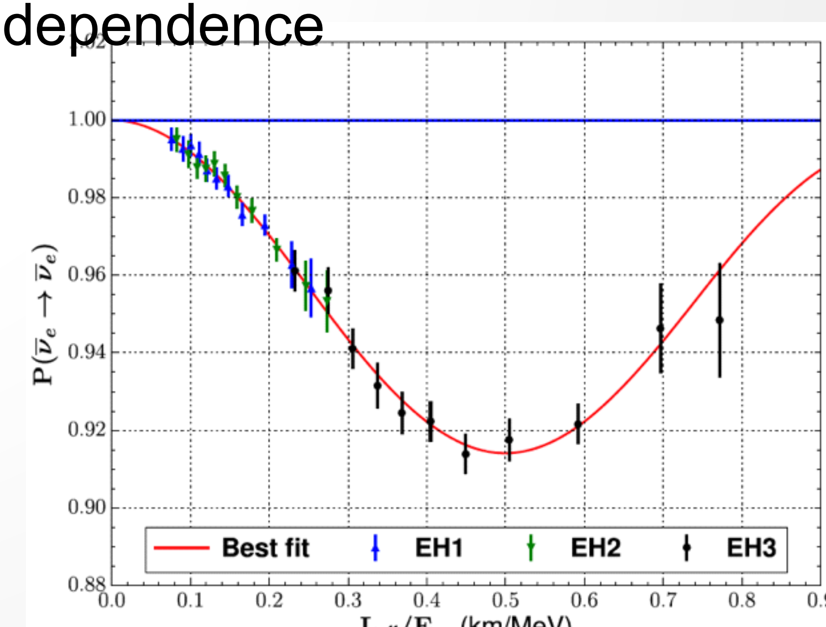
  $\sin^2 2\theta_{13} = 0.0841 \pm 0.0027$ (stat.) ± 0.0019 (syst.)





using data colected up to July 2015
– 1230 days
– >2.5 million events
(Phys.Rev.D 95, 072006 (2017))

survival probability:
clear L/E dependence

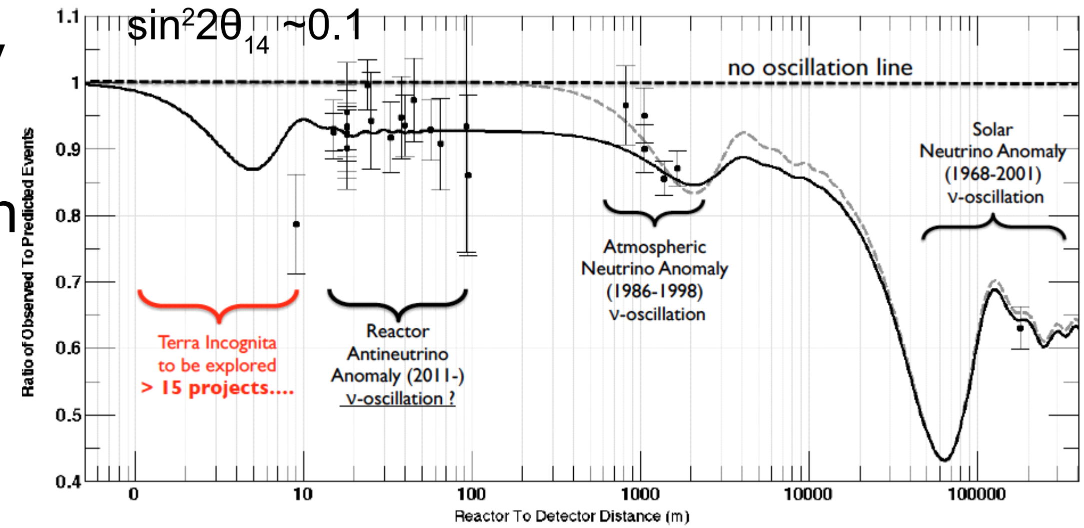


- new measurement also from RENO:
  0.086±0.006 (stat.)±0.005 (syst.)

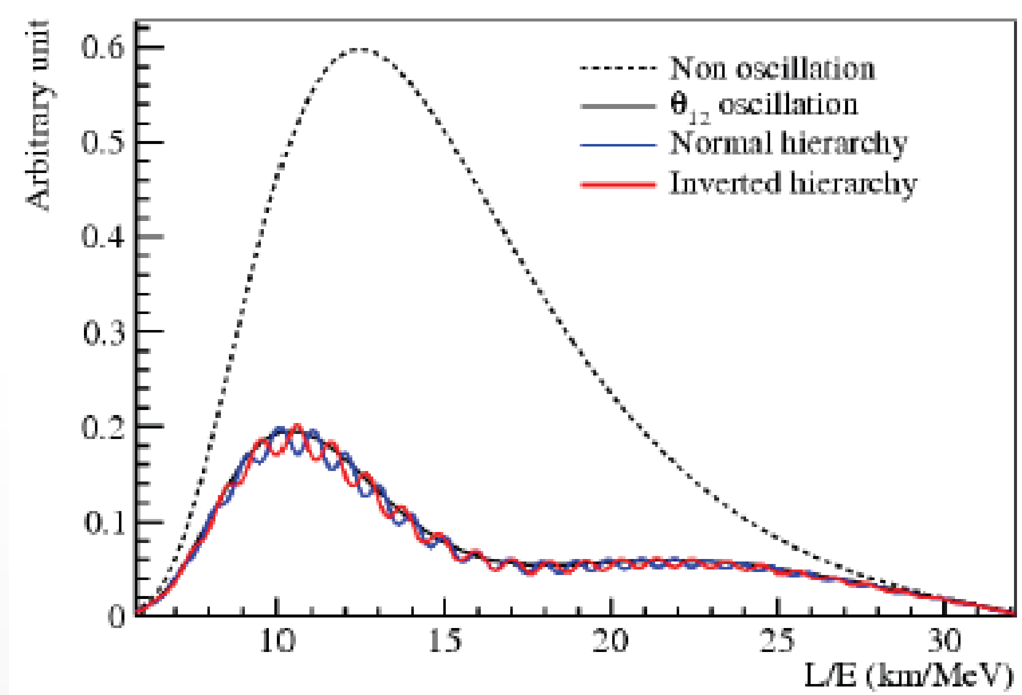
Reactor neutrinos in the future

- questions to be answered
  - an excess of events at 5 MeV in near detector
  - total neutrino flux smaller than expected
    - sterile neutrinos?

Δm^2_{14} ~1eV^2
$\sin^2 2\theta_{14}$ ~0.1

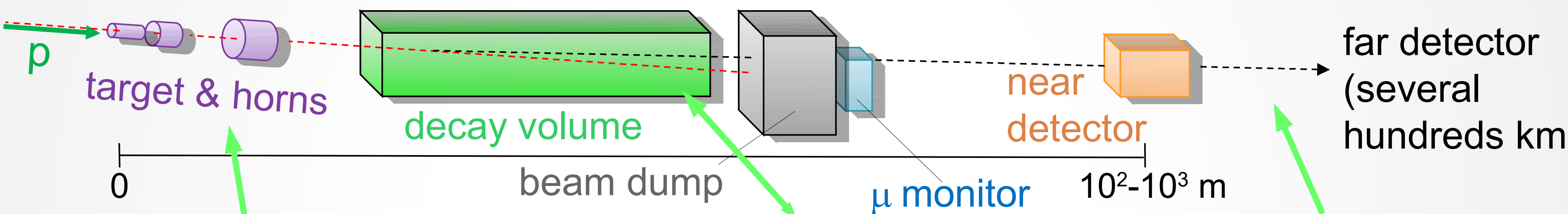


- plans for medium baseline → **mass hierarchy**
  - **JUNO** (~2020) 20kton liquid scintillator detector in China
  - **3%** energy resolution at 1 MeV needed



Accelerator neutrinos

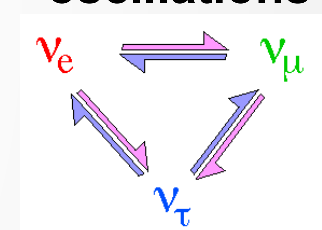
- relatively well controlled beam of neutrinos
  - energy, direction, intensity, type (ν_μ or $\bar{\nu}_\mu$)



focussing of positive or negative pions

$\pi \rightarrow \mu\, \boldsymbol{\nu}_\mu$	~100% BR
$K \rightarrow \mu\, \boldsymbol{\nu}_\mu$	~63.5% BR
$K_L \rightarrow \pi\, \mu\, \boldsymbol{\nu}_\mu$	~27.0% BR
+ electron neutrinos	

oscillations

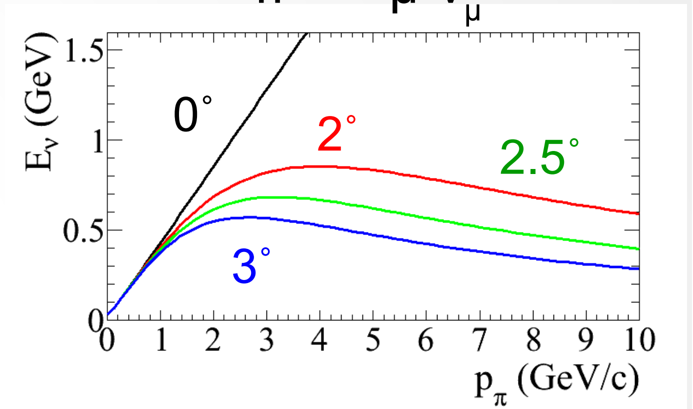


- **ν_μ disappearance and ν_e appearance**
- two currently running experiments:
  - T2K in Japan: peak energy **600 MeV**, baseline **295 km**
  - NOvA in US: **2 GeV**, **810 km**
- two more planned in the future

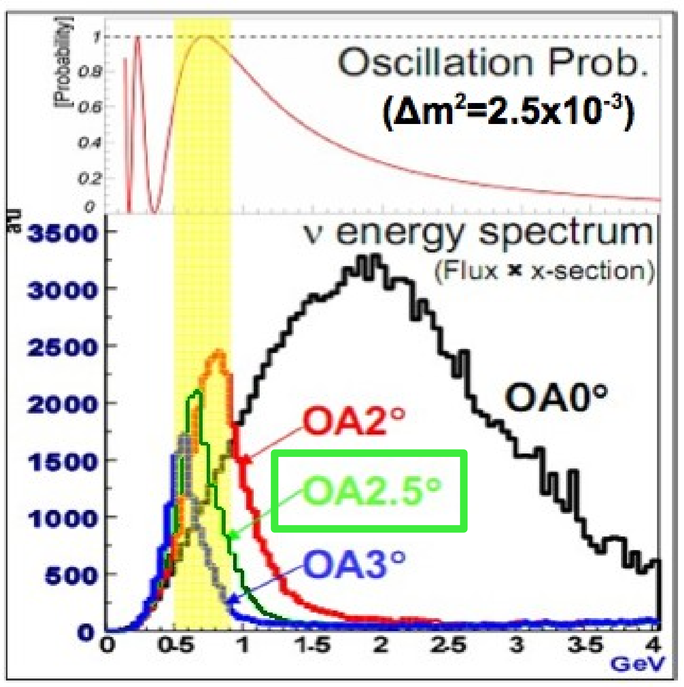
Off-axis beam

- kinematics of pion decay → threshold energy for neutrinos emitted at a given angle
- **narrow spectrum** peaked at oscillation maximum
- lower mean energy
  - CC quasi-elastic sample enhanced – neutrino energy reconstruction from lepton momentum and emission angle (important for T2K)
  - reduced background from higher energy interactions (mostly pion production) and contamination of intrinsic ν_e
- direction must be precisely controlled
  - δOA~1mrad (0.057°) → δE/E ~2% at far detector

$\pi^+ \to \mu^+\nu_\mu$

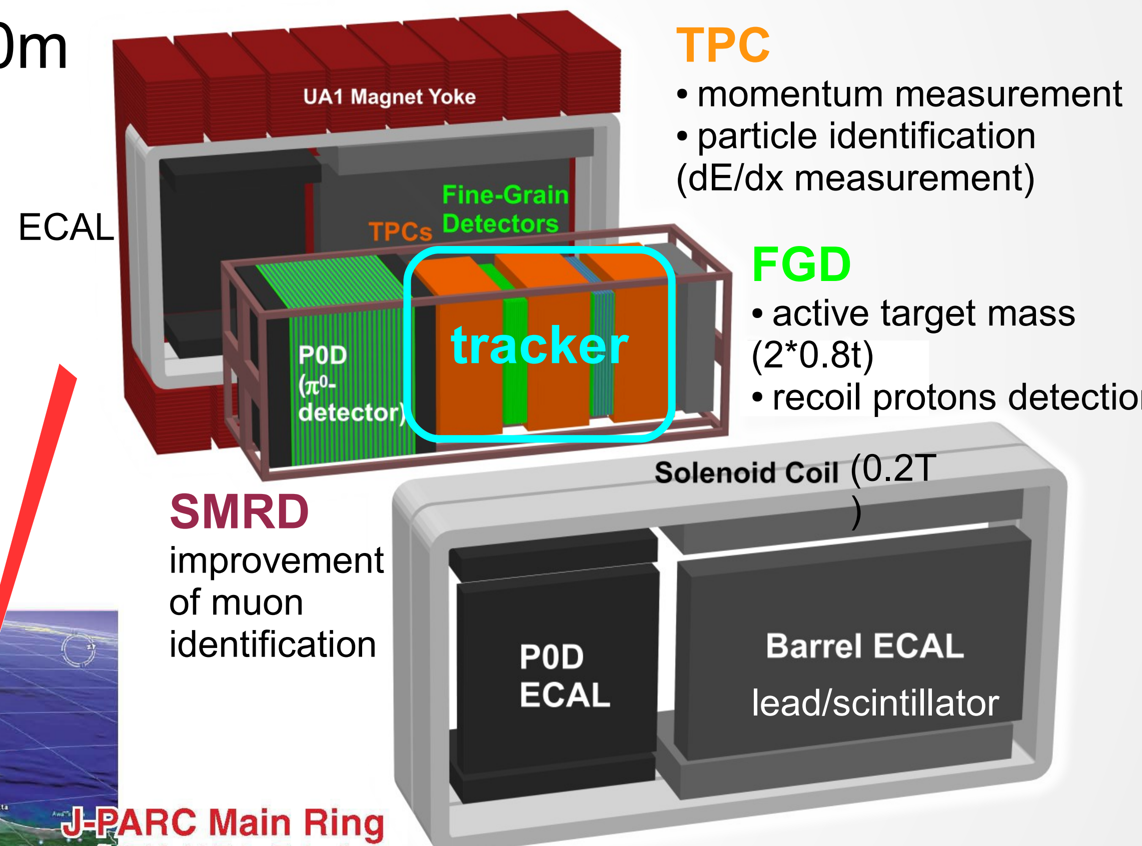


T2K



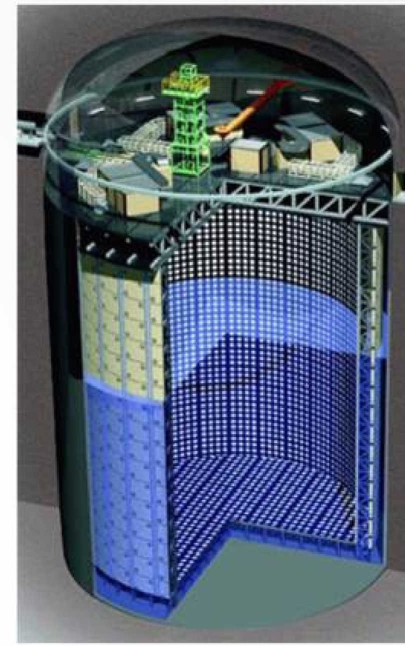
T2K

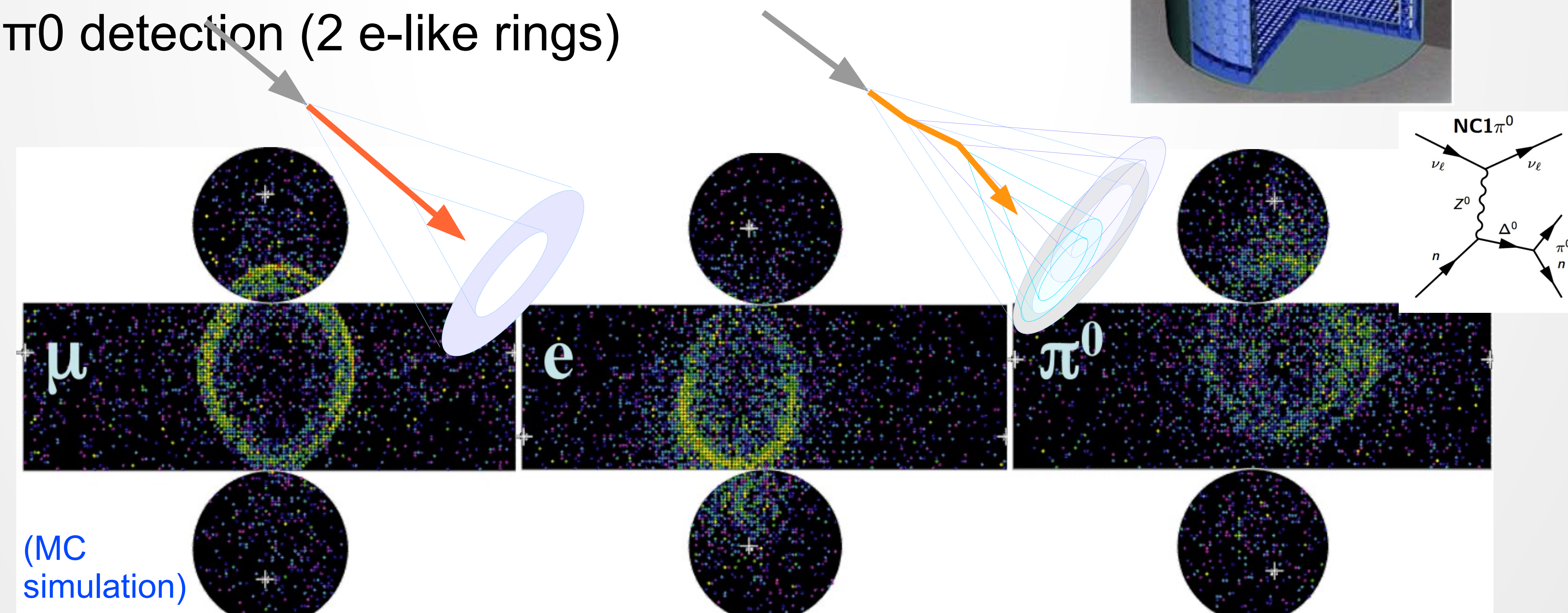
- started to take data in 2010, antineutrino beam mode 2014-2016
- located in **Japan**, beam from J-PARC (Tokai) to **Super-Kamiokande**
- set of **near detectors** at 280m from target
  - multi-purpose magnetized off-axis ND280
  - cross-shaped on-axis detector (INGRID)



Super-Kamiokande = T2K Far Detector

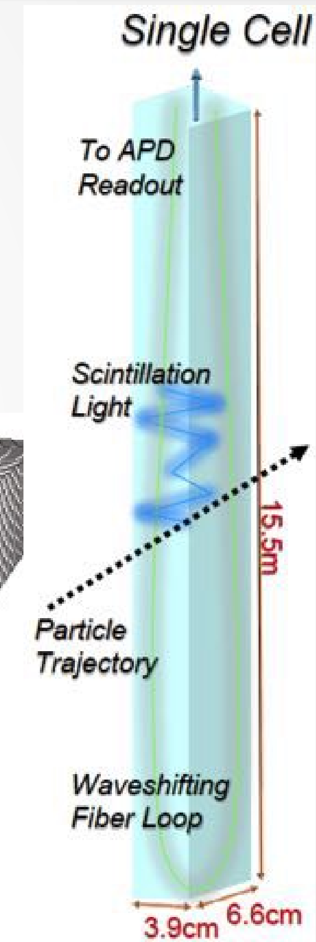
- water Cherenkov detector
  - total mass 50 kt, fiducial mass 22.5kt
  - >11 000 PMTs in inner detector
- ΔE/E ~10% for 2-body kinematics
- very good μ/e separation
  - muons misidentified as electrons: <1%
- π0 detection (2 e-like rings)

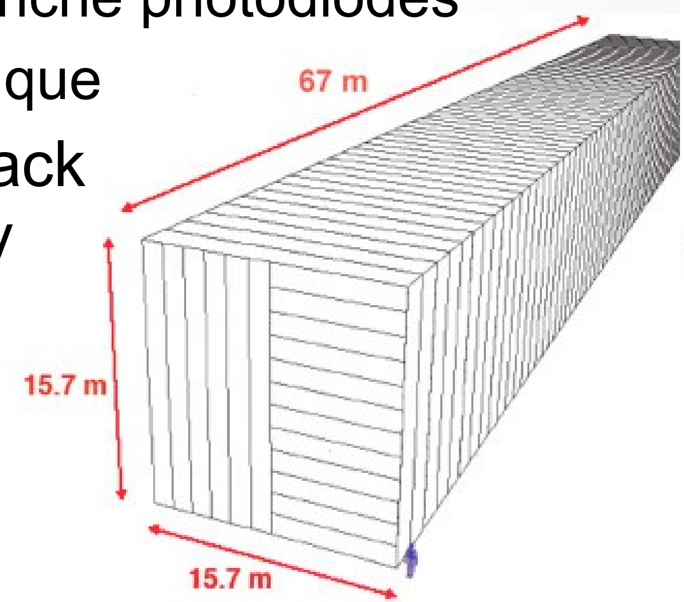


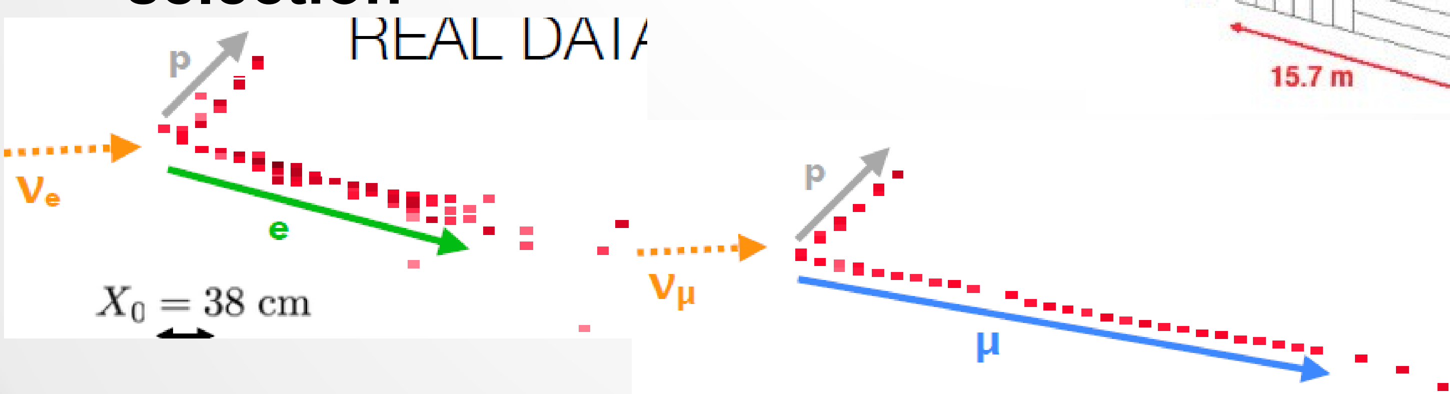


NOvA

- started in 2013, last oscillation results shown in 2016
  - beam from Fermilab, 14 mrad (0.84°) off-axis
- 14 kton (**10.3** kton FV) 65% active Far Detector
  - 15.6m plastic cells filled with liquid scintillator
  - wavelenght-shifting fibers + avalanche photodiodes
  - **Near Detector** in the same technique
- **energy estimation** from lepton track length and visible hadronic energy
- image transformation and neural networks used in ν_e **event selection**

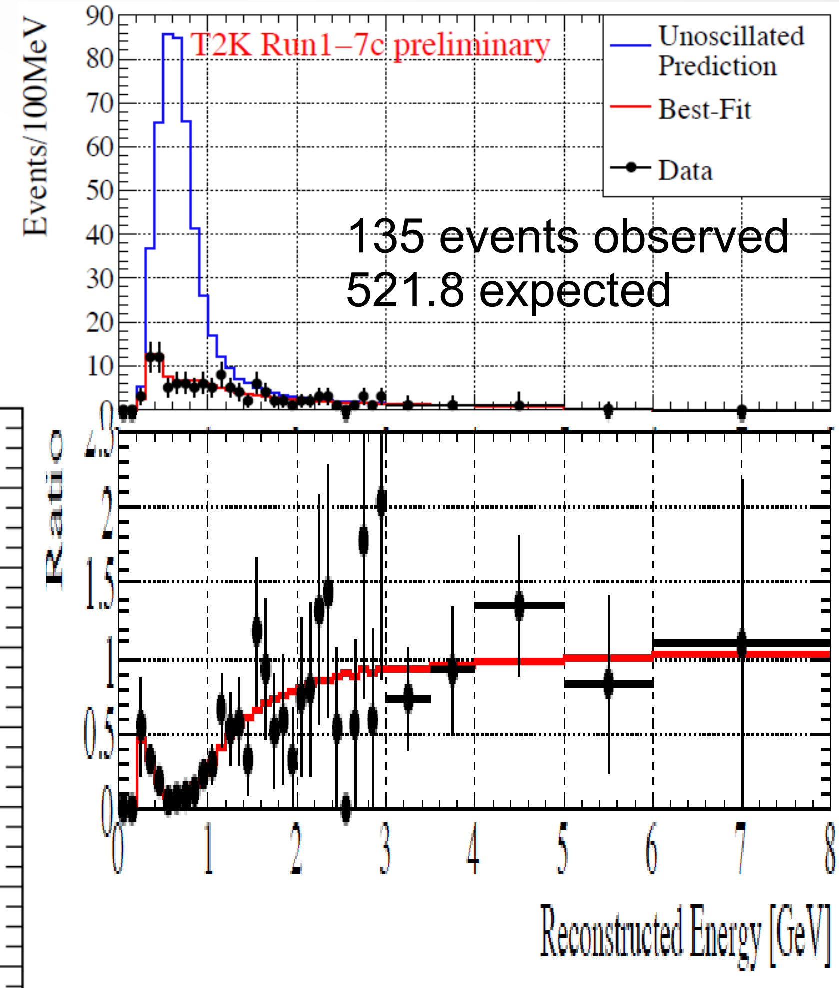


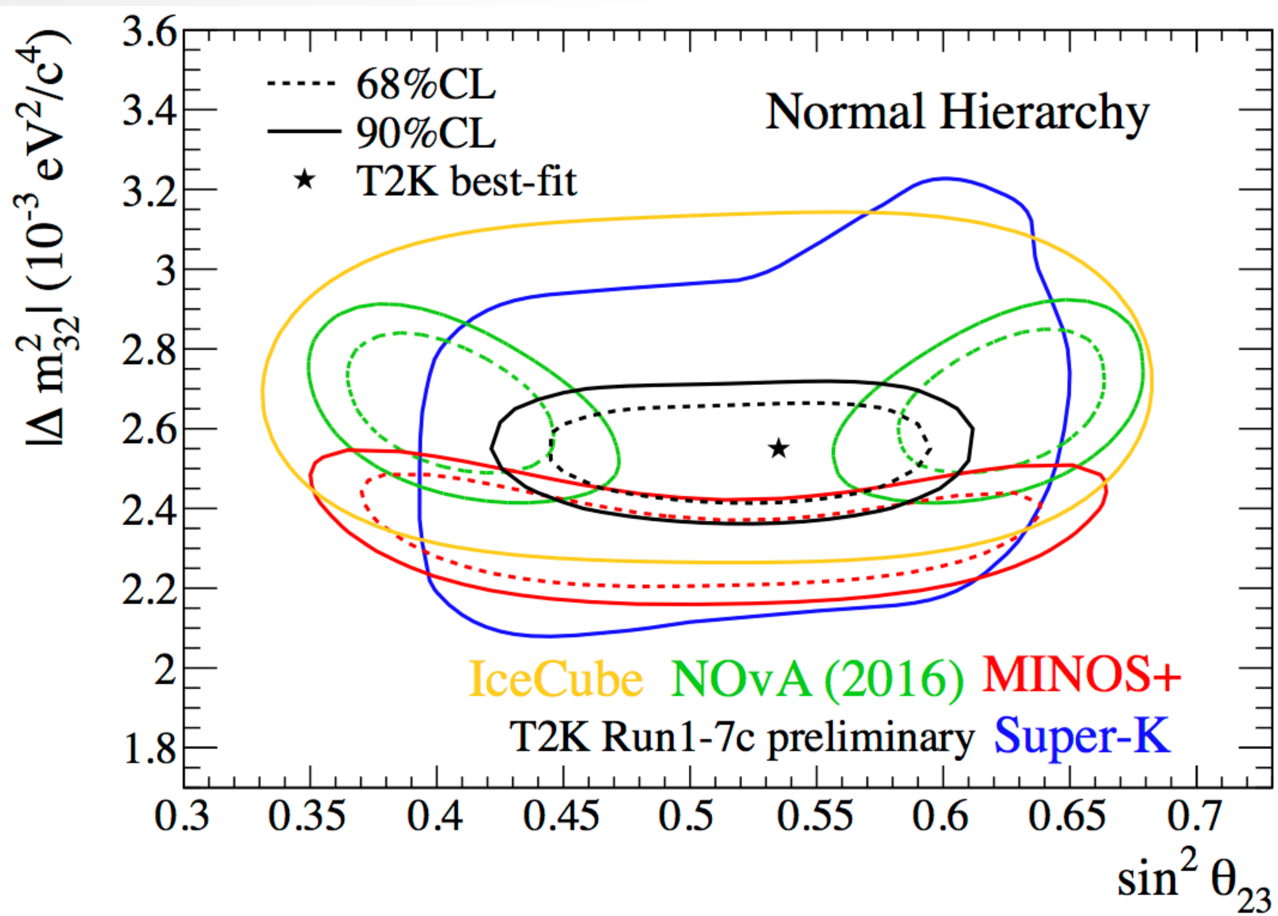




ν_μ disappearance

- oscillation pattern in T2K:
  - **preference** for maximal mixing
- but NOvA **excludes** maximal mixing at 2.6σ

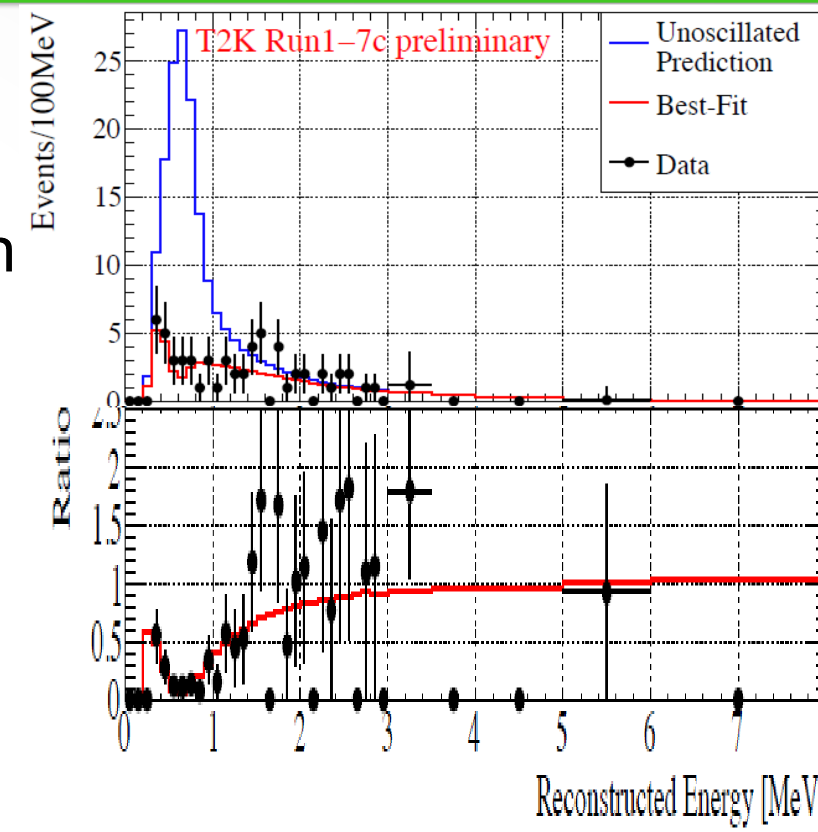


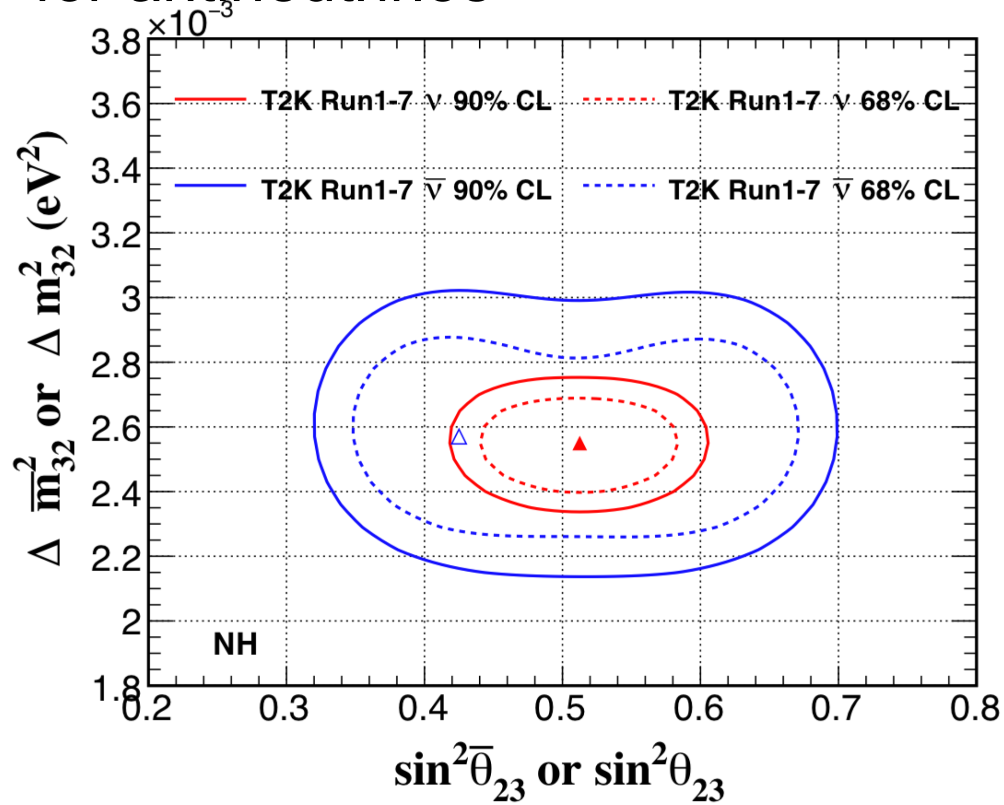


to be investigated...
(new T2K results soon)

$\bar{\nu}_\mu$ disappearance in T2K

- **CPT test** by comparing $\nu_\mu \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ modes
- 184.8 events expected without oscillation
- 66 events observed
- independent oscillation parameters for antineutrinos





results consistent with **no difference** between disappearance of neutrinos and antineutrinos

→ CPT conserved

What so special about $\nu_\mu \to \nu_e$ channel?

- allows for CP violation studies

$$P(\nu_\mu \to \nu_e) = 4 c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \Delta_{31}$$ **dominant term**

$$+8 c_{13}^2 s_{12} s_{13} s_{23} (c_{12} c_{23} \cos \delta_{CP} - s_{12} s_{13} s_{23}) \cos \Delta_{32} \sin \Delta_{31} \sin \Delta_{21}$$

$$-8 c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin \delta_{CP} \sin \Delta_{32} \sin \Delta_{31} \sin \Delta_{21}$$ **CP violation**

$$+4 s_{12}^2 c_{13}^2 (c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2 c_{12} c_{23} s_{12} s_{23} s_{13} \cos \delta_{CP}) \sin^2 \Delta_{21}$$

matter

$$-8 c_{13}^2 s_{13}^2 s_{23}^2 \frac{aL}{4E_\nu} (1 - 2 s_{13}^2) \cos \Delta_{32} \sin \Delta_{31} + 8 c_{13}^2 s_{13}^2 s_{23}^2 \frac{a}{\Delta m_{31}^2} (1 - 2 s_{13}^2) \sin^2 \Delta_{31}$$

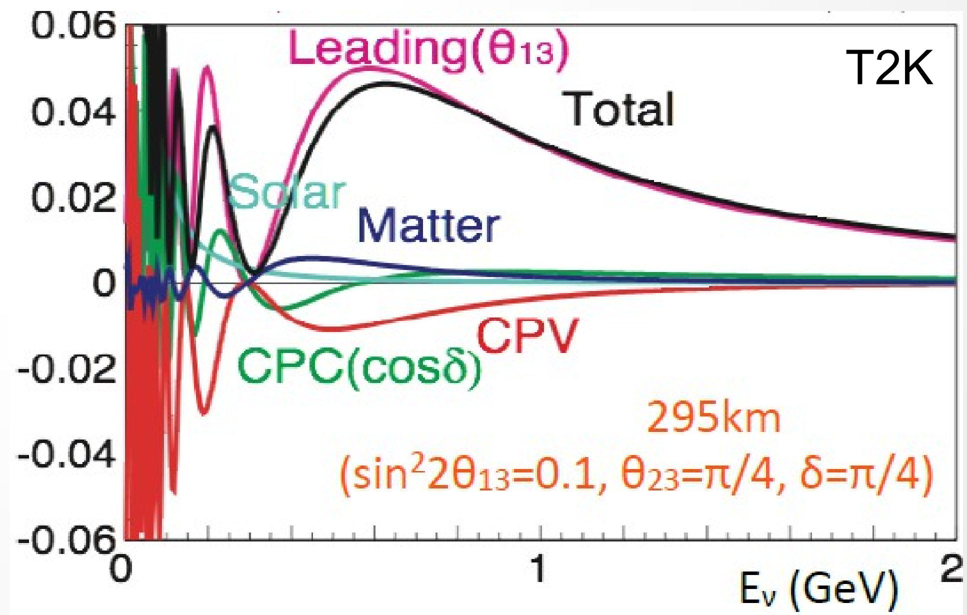
for $\bar{\nu}$

$$\delta_{CP} \to -\delta_{CP}$$

$$a \to -a \qquad a = 2\sqrt{2} G_F n_e E_\nu$$

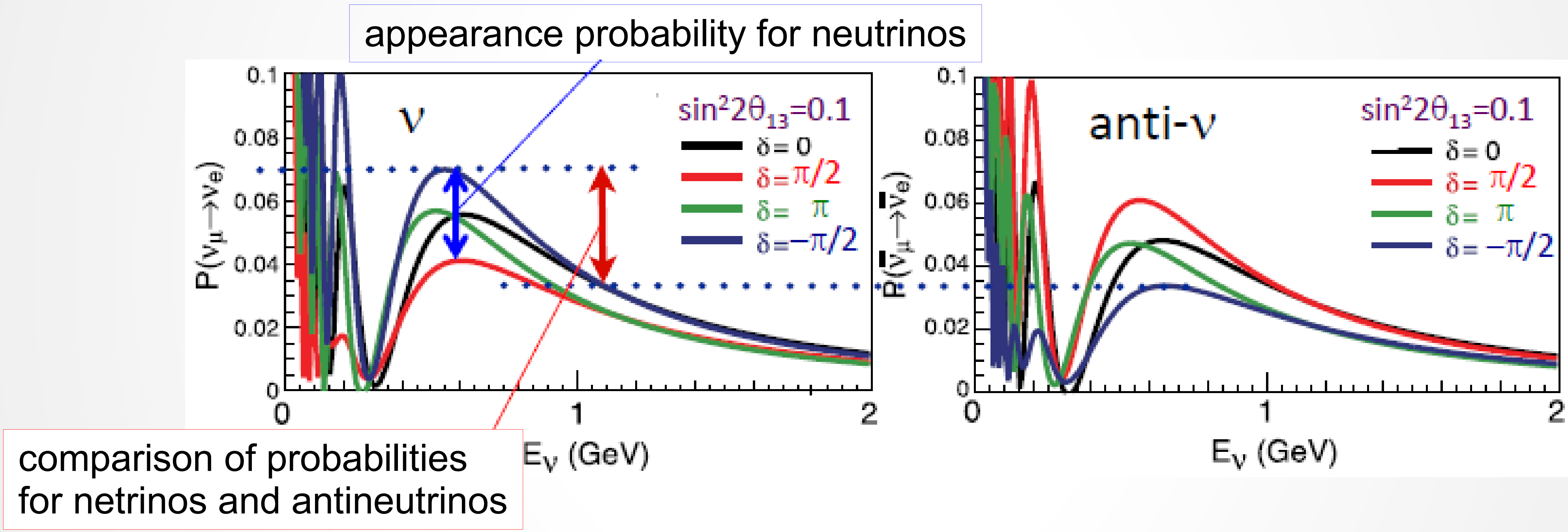
n_e related to matter density

subleading effect,
can be as large as 30%
of dominant



ν_e appearance and search for ~~CP~~

- method 1: use θ_{13} from reactor experiments for predictions and compare to neutrino data



- method 2: compare measured $P(\nu_\mu \to \nu_e)$ with $P(\bar{\nu}_\mu \to \bar{\nu}_e)$
- method 3: use wide band beam to cover the 2[nd] maximum

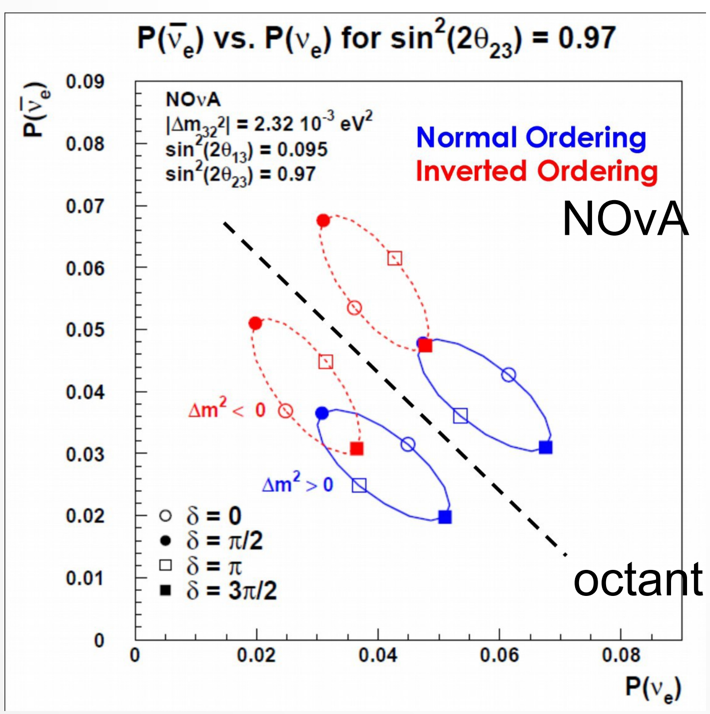
ν_e vs. $\bar{\nu}_e$ appearance

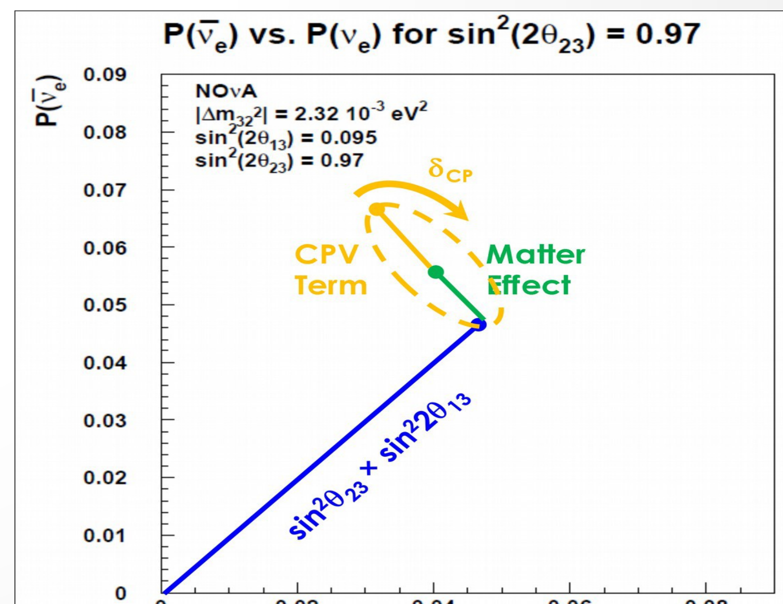
- problems and opportunities:
  - different probabilities for ν and $\bar{\nu}$ even if CP is not violated – due to **matter effects**
  - **parameter degeneracies** to disentagle: effects from mass hierarchy, CP violation, octant of θ_{23} – more effects to study
  - combination of experiment with different baseline increase sensitivity

$P(\bar{\nu}_\mu \to \bar{\nu}_e)$

biprobability plot

excellent resolution needed





Joao Coelho (Tufts)

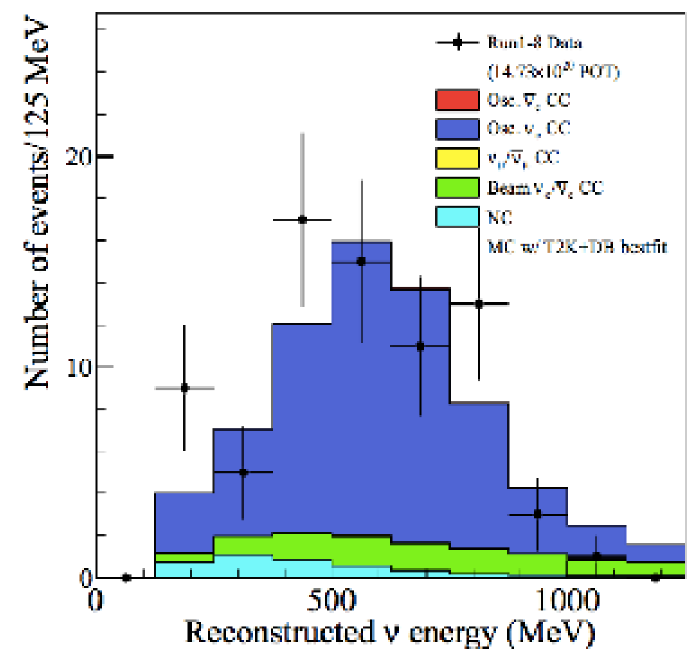
$P(\nu_\mu \to \nu_e)$

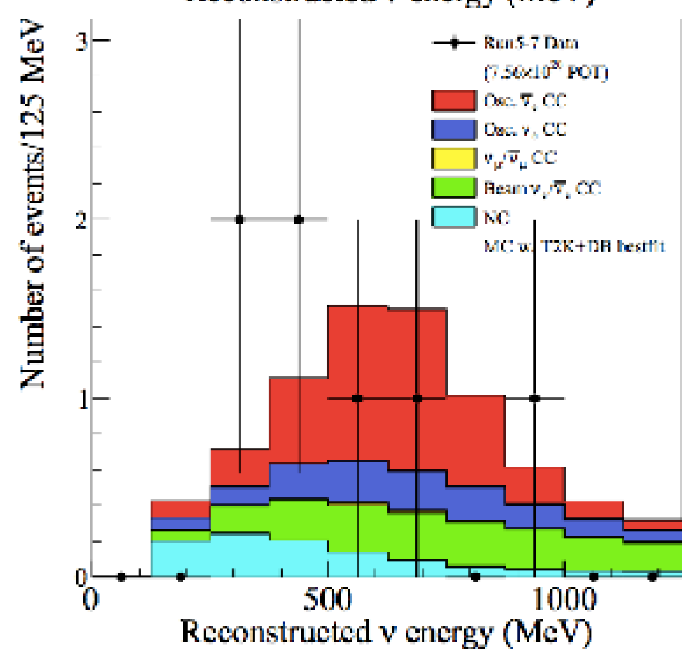
T2K analysis

- ν / $\bar{\nu}$ datasets ~ 2:1
- ν_e appearance
  - observed: **74** CC QE + **15** 1π events
- $\bar{\nu}_e$ appearance
  - observed: **7** events

δ_{CP}	-0.5π	0	0.5π	π	observed
ν_e CCQE	73.5	61.5	49.9	62	74
ν_e CC1π	6.92	6.01	4.87	5.78	15
$\bar{\nu}_e$ CCQE	7.93	9.04	10.04	8.93	7

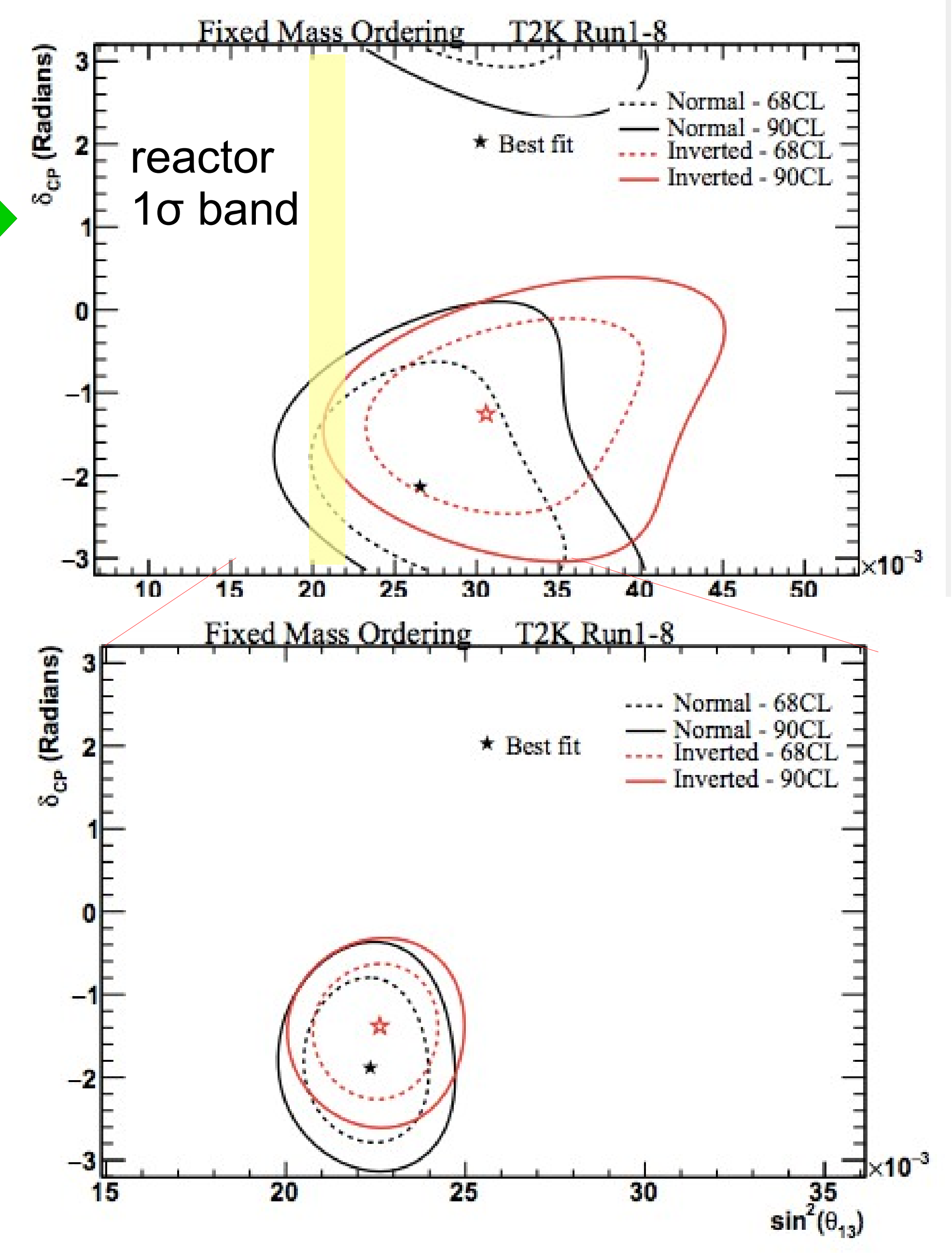
- more ν_e appearance and less $\bar{\nu}_e$ appearance than expected if CP is conserved





Hints on CP violation

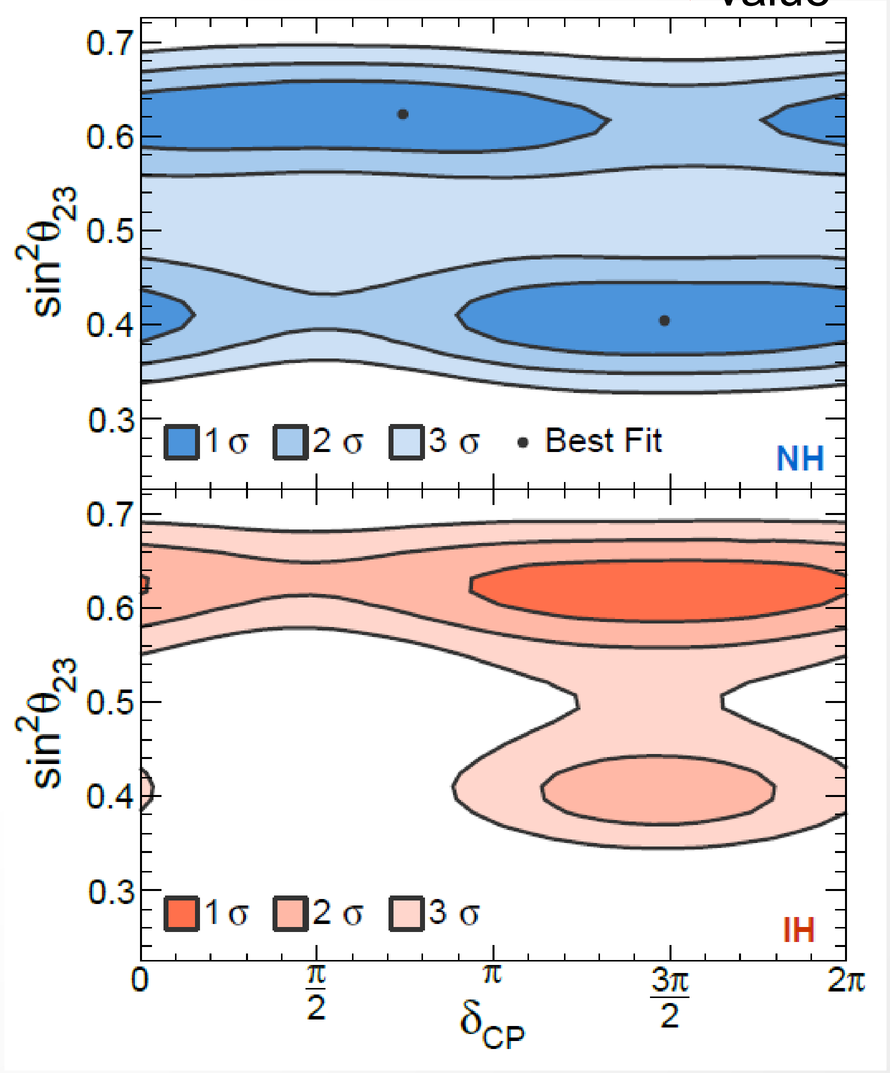
- T2K data only
  - θ_{13} =consistent with reactor measurement
  - closed δ_{CP} contours
- with reactor constraints
  - improved limits on δ_{CP}
  - 2σ confidence interval δ_{CP} = [-2.98, -0.60] (NH)
    [-1.54, -1.19] (IH)
  - **CP conserving values disfavoured at >2σ**
- T2K has up to 3σ sensitivity with proposed extended run (T2K phase II) and upgraded near detector



What about NOvA ?

- from February 2017 data taking with antineutrino beam
  - no results shown yet
- ν_e appearance shown at NEUTRINO 2016
- allowed regions for δ_{CP}
- 2 degenerated best fit points
- for all values of δ_{CP} and both octants the inverted hierarchy predicts fewer events than observed

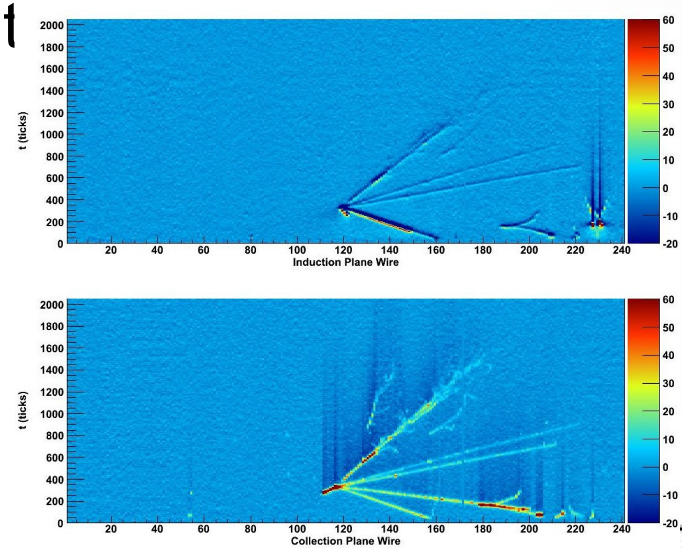
T2K preferred value



PRL 118, 231801 (2017)

Future ~2025

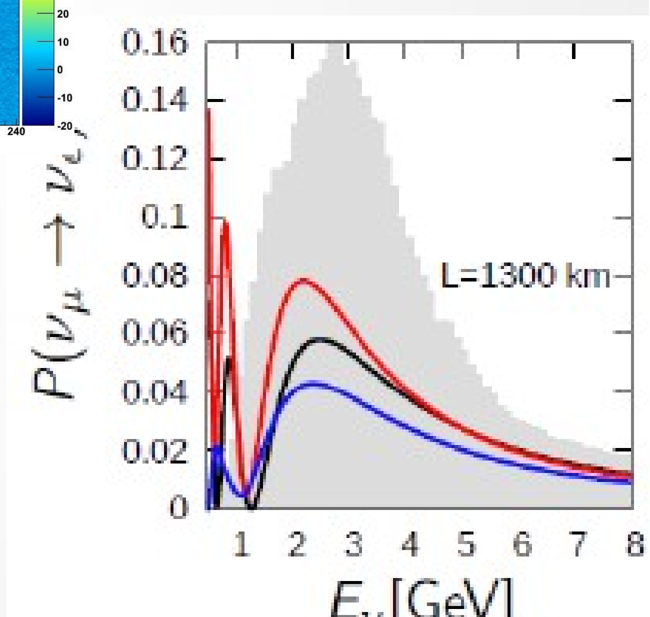
- T2K and NOvA will continue to run over next several years
  - upgrade of ND280 planned in near future, Gd added to Super-K
- next generation appearance experiment optimized for improved δ_{CP} and hierarchy sensitivit



DEEP UNDERGROUND NEUTRINO EXPERIMENT

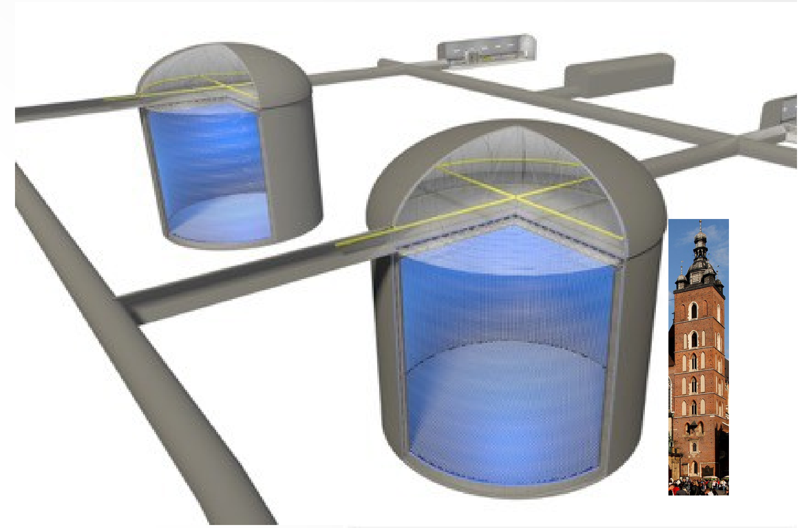
separate talk on LAr

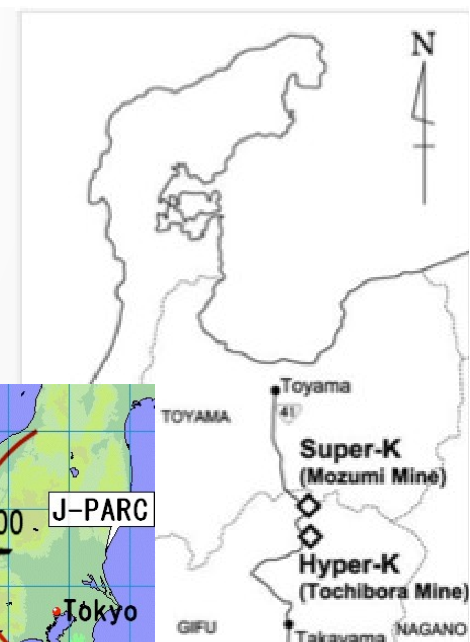
- liquid argon technique, 4x17 kton **LAr TPC** fiducial mass **>40kton**
  19.1m (16.9m) W
  x 18m(15.8m) H
  x 66m(63.8m) L
- very long baseline: **1300 km**
- megawatt class beam
- **wide spectrum** covering the 1st and 2nd oscillation maxima

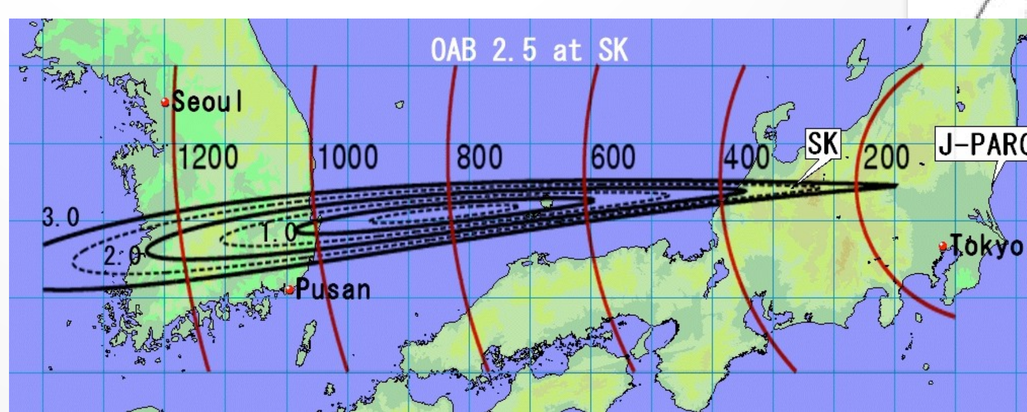


Hyper-Kamiokande

- 2 vertical tanks
  - building in stages possible
  - significant reduction of costs
  - one tank in Korea?
- 260kton per tank,
  fiducial volume: **190 kton** (= 10xSK)
- tank dimensions: 60m height x 74m diameter
- high PMT coverage (40%)
  - inner detector: 40 000 PMT of 50cm diameter
  - outer detector: 6 700 PMT of 20cm diameter
- 2x better photon efficiency and timing resolution (1ns) → enhanced physics potential

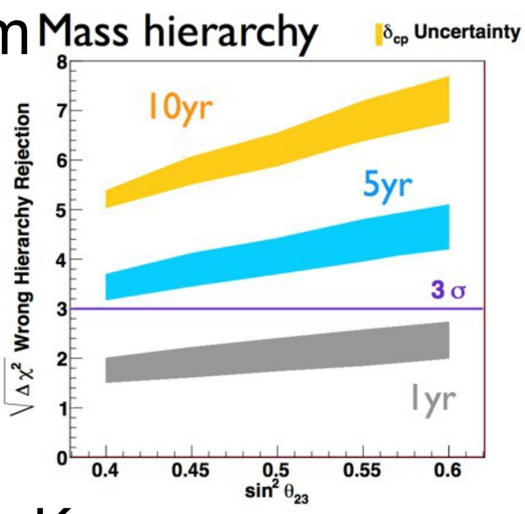


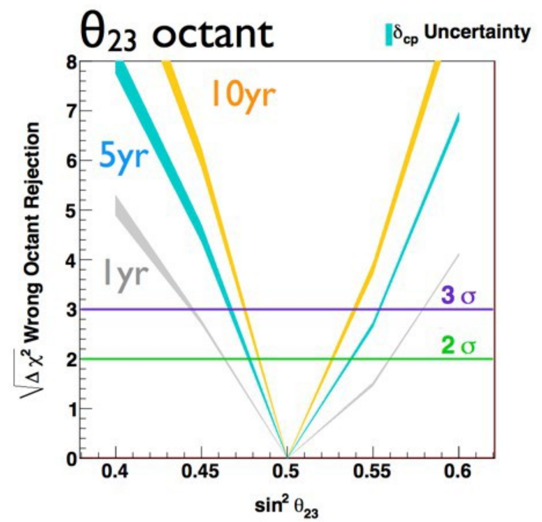


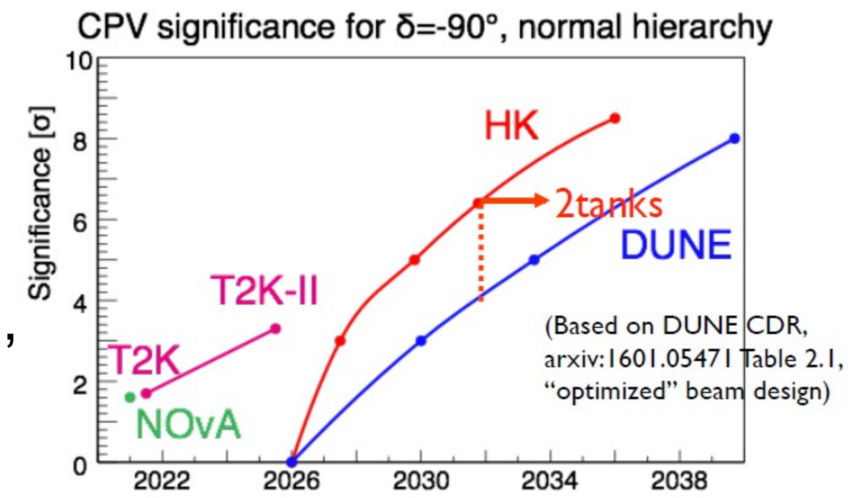


Hyper-K physics program

- **neutrino oscillations** with beam and atmospheric neutrinos
  - precise measurement of θ_{23}
  - mass hierarchy determination
  - CP violation
- searching for **nucleon decay**
  - sensitivity 10x better than Super-K (10^{35} years)
  - all visible modes can be advanced
- **neutrino astrophysics**
  - precise measurement of solar neutrinos, sensitivity to address solar and reactor neutrinos discrepancy.
  - supernova burst and relic supernova neutrinos
- indirect **Dark Matter** search

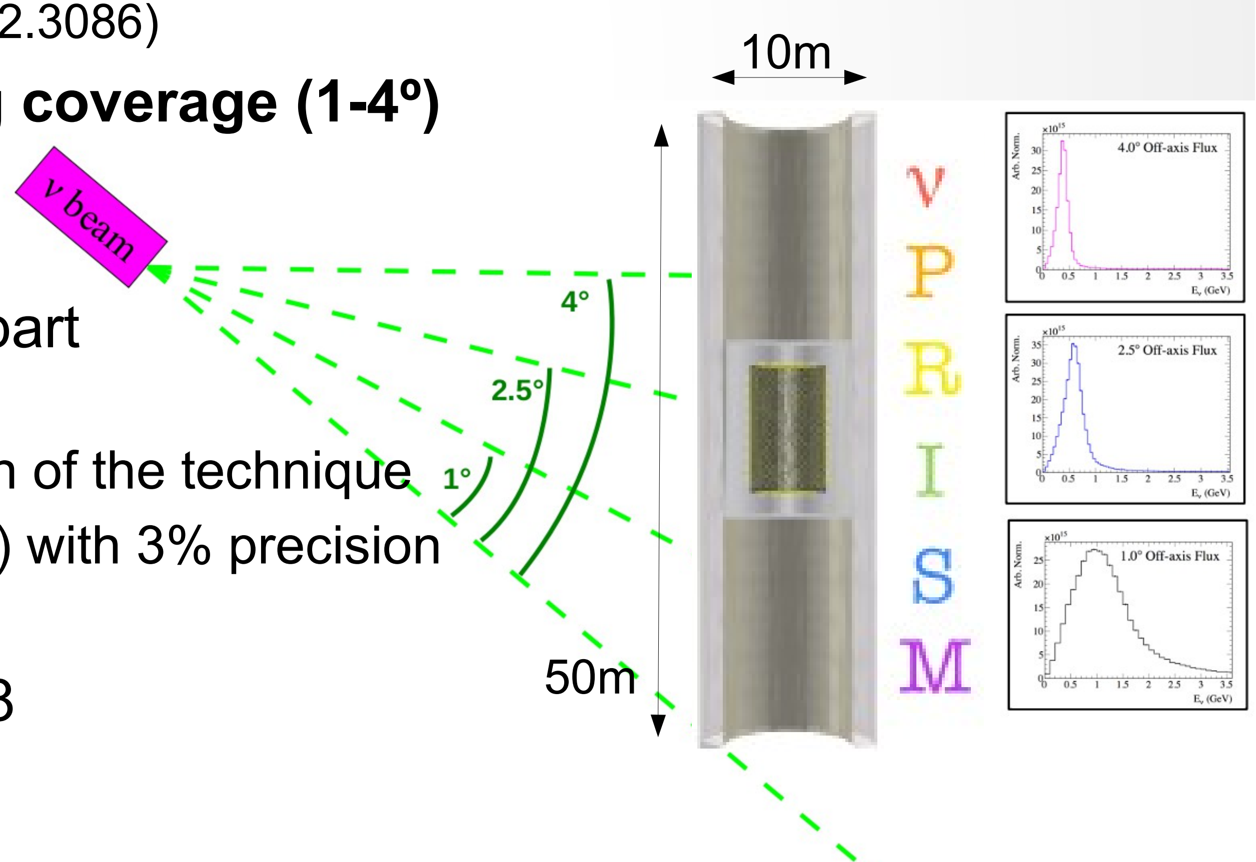






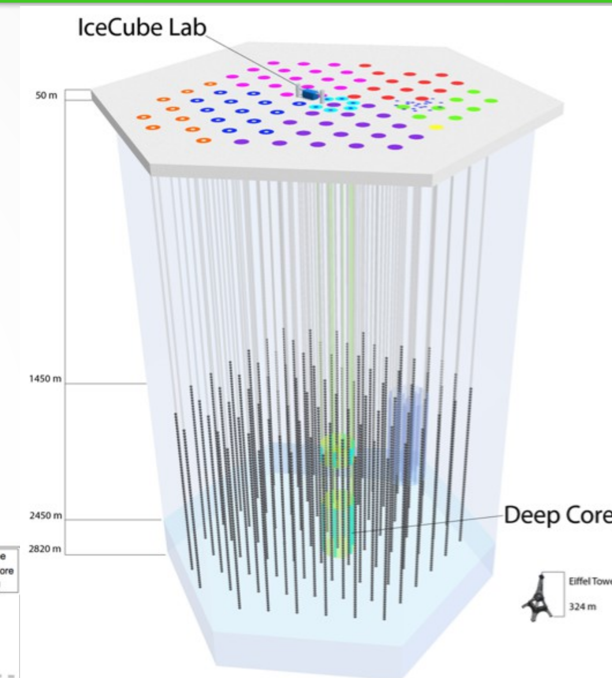
Intermediate detector

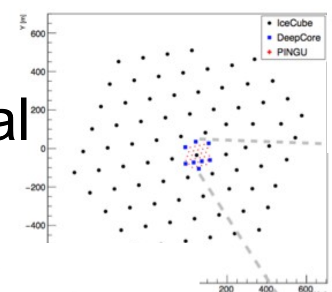
- at ~1-2 km the **ν flux** is much more similar to that at Far Detector
  - avoid significant pile-up of events
- **intermediate** water Cherenkov detector
  - further reduction of systematic uncertainties → same target and 4π acceptance as Far Detector
- NuPRISM project (arXiv:1412.3086)
  - **off-axis angle spanning coverage (1-4º)**
  - energy dependence of neutrino interactions
  - phase 0: non-moveable part placed near ND280
    - tests and demonstration of the technique
    - physics goal: $\sigma(\nu_e)/\sigma(\nu_\mu)$ with 3% precision
  - TDR to be ready in 2017, possible approval in 2018

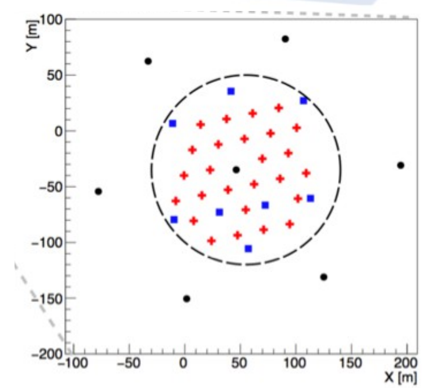


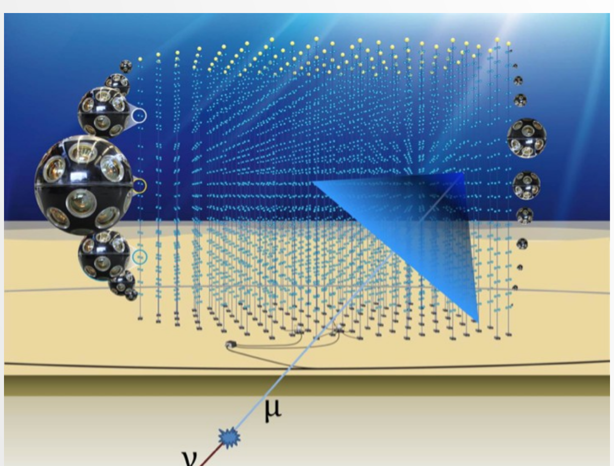
Atmospheric experiments

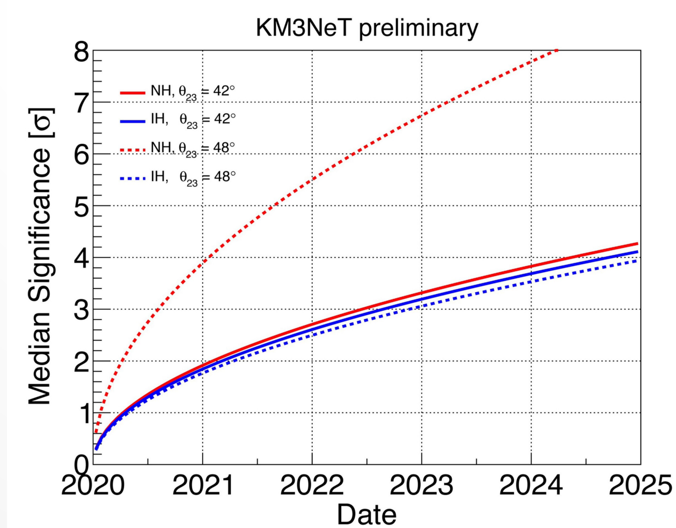
- **matter effect** in Earth → mass hierarchy (below 12 GeV), θ_{23} octant
- IceCube / PINGU
  - lower threshold (~GeV) with 22 m spacing of string
  - expected 60k atm. neutrinos/year
- KM3NeT / ORCA
  - dense array (20m) of multi-PMT digital modules (115 strings)











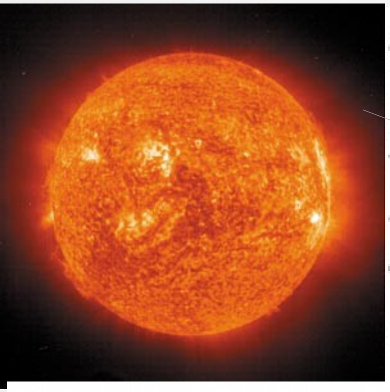
Summary

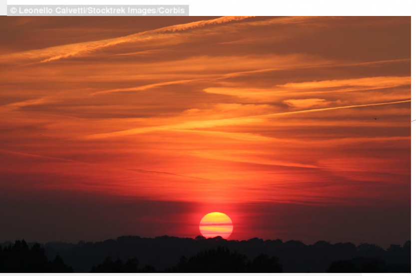
- era of precision measurements in neutrino oscillation physics
- some hints on the CP violation and mass hierarchy, but to have a definitive answer
  - more data needed (and new experiments?)
  - combination of results from different experiments gives better sensitivity
- other questions remain
  - 5 MeV “bump” and total flux for reactor neutrinos (and other anomalies) → sterile neutrinos?
  - discrepancy in Δm^2_{21} measurements from reactor and solar neutrinos
  - θ_{23} maximal or not?

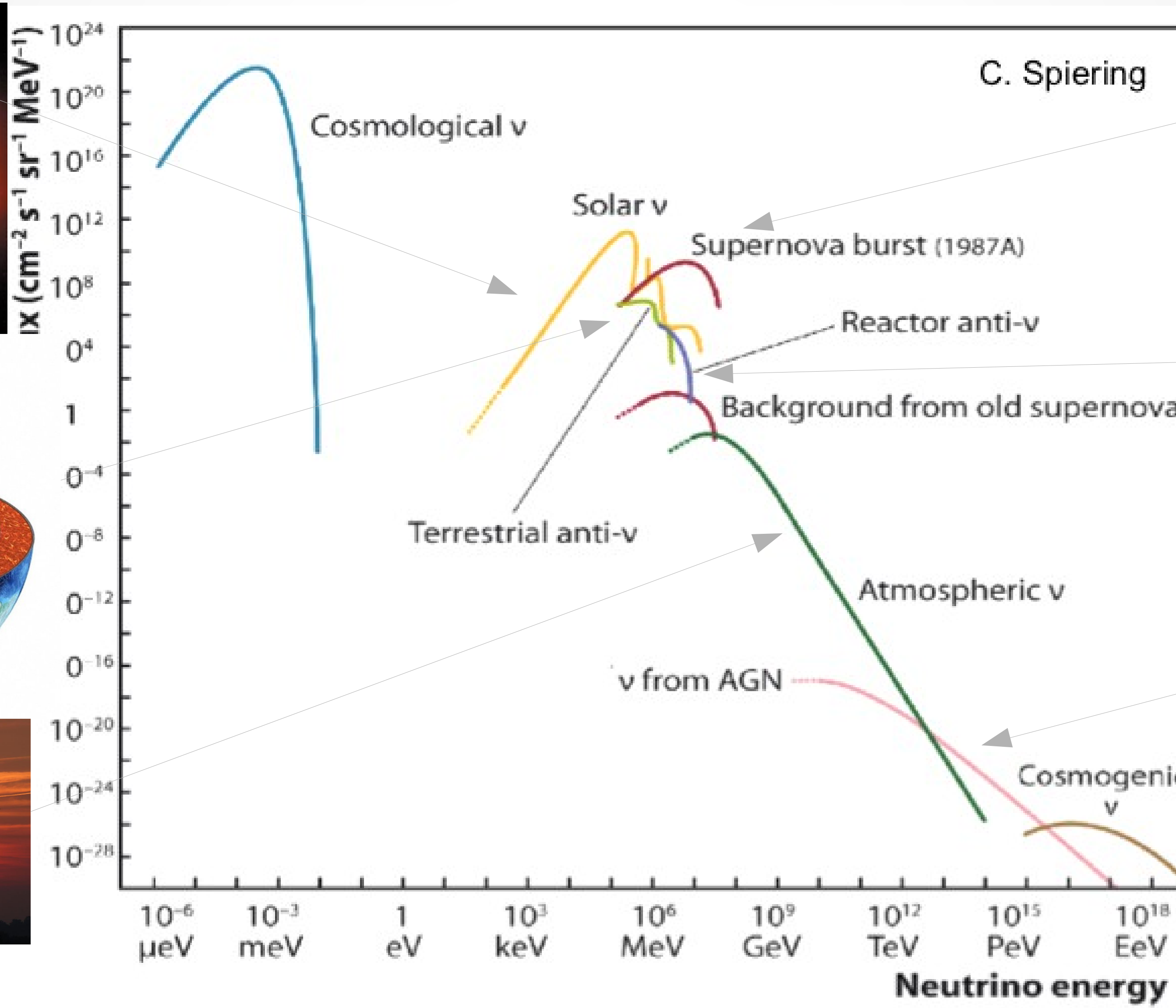
Backup

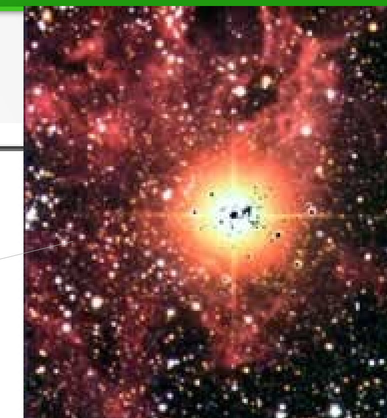
Sources of neutrinos

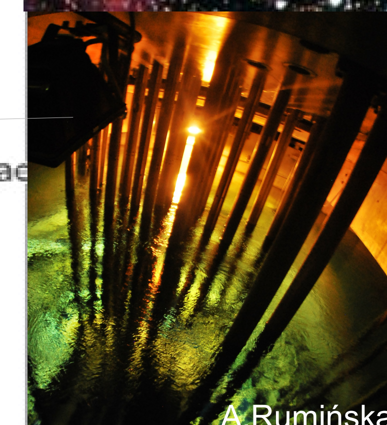
- many sources, wide spectrum of energies



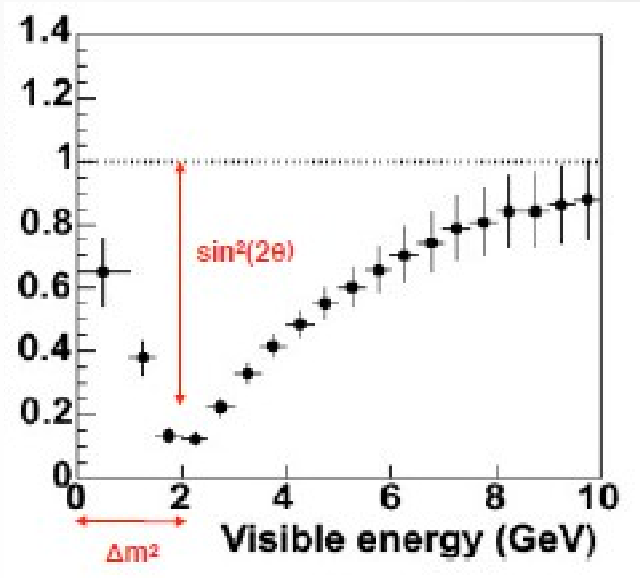








Disappearance vs. appearance

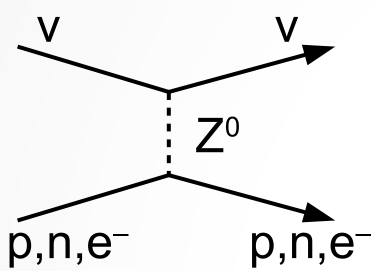


- **disappearance:**
  - looking for the same flavour of neutrinos at the production and detection point
  - dip in the **measured/expected ratio** → information on mixing angle and mass splitting
  - CPT conservation requires the same survival probability for neutrinos and antineutrinos
- **appearance**: direct observation of the flavour change
- possible appearance channels for 3 flavours:
  - $\nu_e \rightarrow \nu_{\mu,\tau}$: neutrino energy below threshold for charged lepton production (solar, reactor)
  - $\nu_\mu \rightarrow \nu_\tau$: challenging: large τ lepton mass, small *ct*, discovered 2015
  - $\nu_\mu \rightarrow \nu_e$: subdominant, discovered 2013
  - ν_τ: no good ν_τ sources

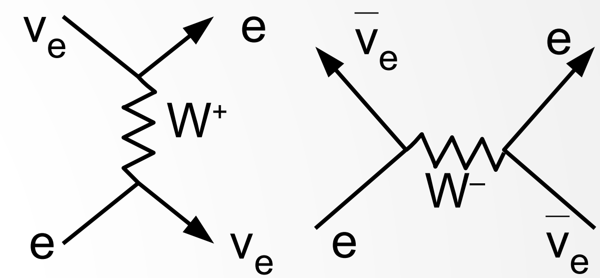
Matter effects

- solar neutrinos are produced in dense matter of the Sun and propagation in matter is affected by the presence of **electrons**

same for ν_e, ν_μ, ν_τ



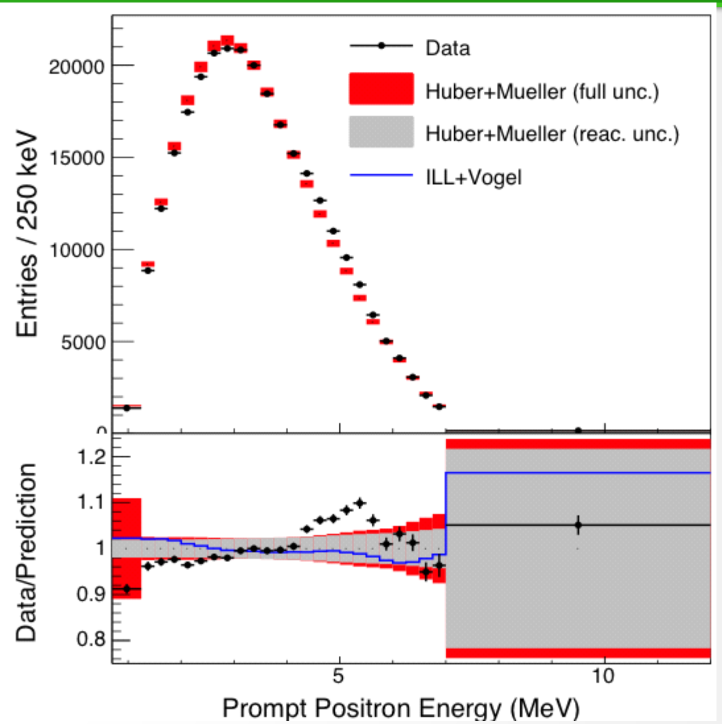
only for ν_e



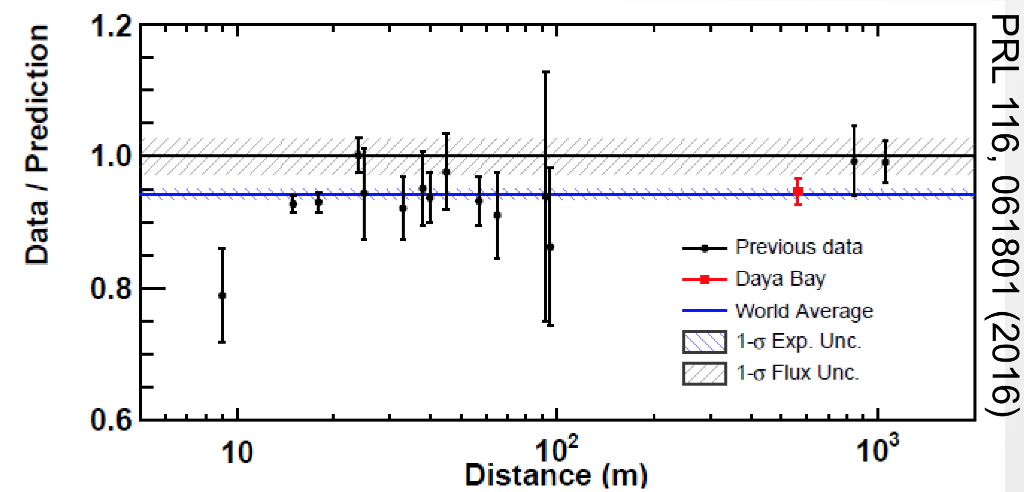
- energy levels of propagating eigenstates are altered for **ν_e component** (different interaction potentials in kinetic part of the hamiltonian)
  - effective mass changed: ν_e raised, $\bar{\nu}_e$ lowered
  - sensitivity to $\Delta m^2 \sim 10^{-5}$ eV^2, while oscillations in vacuum to 10^{-10} eV^2
- resonant enhancement occurs for particular energies
  - depending on electron density and Δm^2
  - for Sun we observe resonance transition around 10 MeV
- matter effects are sensitive to mass ordering

To be studied:

- measurements of the neutrino flux in Daya Bay, RENO and Double Chooz showed an excess of events at 5 MeV
- possible explanation: decays of prominent fission daughter isotopes
  - a single beta branch cannot simulate this excess



- in general, total measured flux is smaller than expected: so called **reactor anomaly**



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Medium baseline

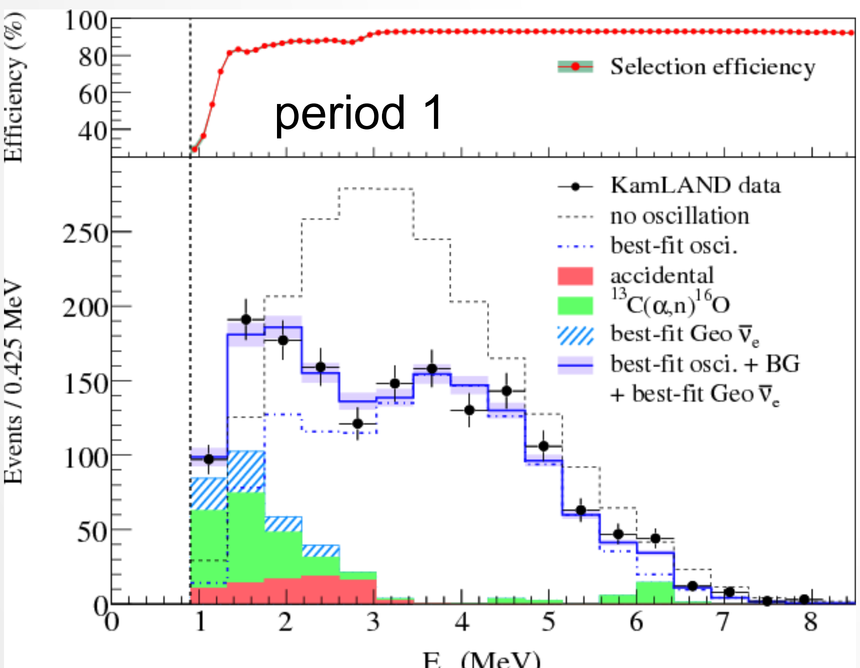
- KamLAND experiment
  - located in the same place as Super-K
  - 1kt liquid scintillator + gadolinium to capture neutrons

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$$+H \rightarrow D + \gamma \quad 2.2\ \text{MeV}, \ \sim 200\ \mu s$$

$$+Gd \rightarrow Gd^* \rightarrow \gamma's \quad \sim 8\ \text{MeV}, \ \sim 30\ \mu s$$

  - sources: Japanese and Korean reactors (~200km)



significant rate deficit found