Current and future neutrino experiments

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Plan

- short introduction
- non-oscillation experiments
  - neutrino mass measurements
  - search for neutrinoless double beta decay
- oscillation experiments
  - reactor neutrinos
  - solar neutrinos
  - atmospheric neutrinos
  - long baseline experiments
  - search for sterile neutrinos
- summary

Neutrino mixing

- mixing matrix for 3 active flavours

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

2 additional phases if neutrinos are Majorana particles

- 3 mixing angles θ_{12}, θ_{13}, θ_{23}, CP violation phase δ_{CP}

$$P_{\nu_\alpha\to\nu_\beta}=\delta_{\alpha\beta}-4\sum_{i>j}\Re\left(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\right)\sin^2\Delta m^2_{ij}\frac{L}{4E}\pm2\sum_{i>j}\Im\left(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\right)\sin^2\Delta m^2_{ij}\frac{L}{4E}$$

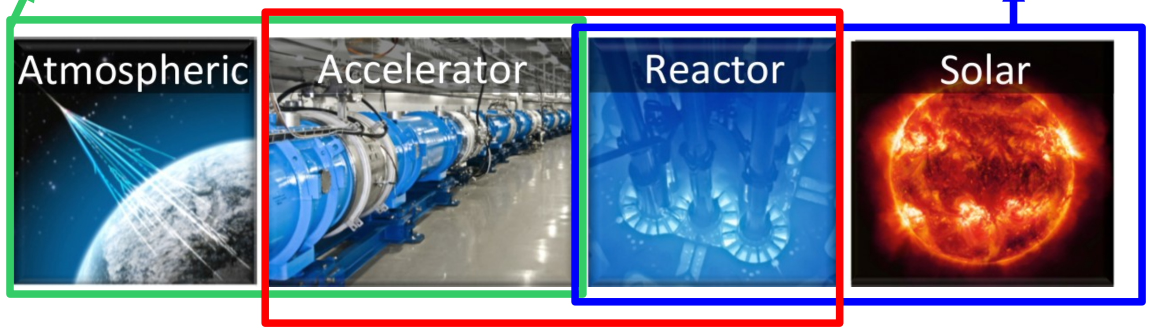
- 2 independent mass splittings: $\Delta m^2_{21} = m^2_2 - m^2_1$, $\Delta m^2_{32} = m^2_3 - m^2_2$,
- 2 “controlled” parameters: baseline **L** and neutrino energy **E**
- the presence of matter (electrons) modifies the mixing
  - energy levels of propagating eigenstates are altered for **ν_e component** (different interaction potentials in kinetic part of the hamiltonian)
  - matter effects are sensitive to ordering of mass eigenstates

Known and unknown

- neutrino properties are measured using neutrinos from various sources in various processes and detection techniques

mixing parameters: oscillation experiments

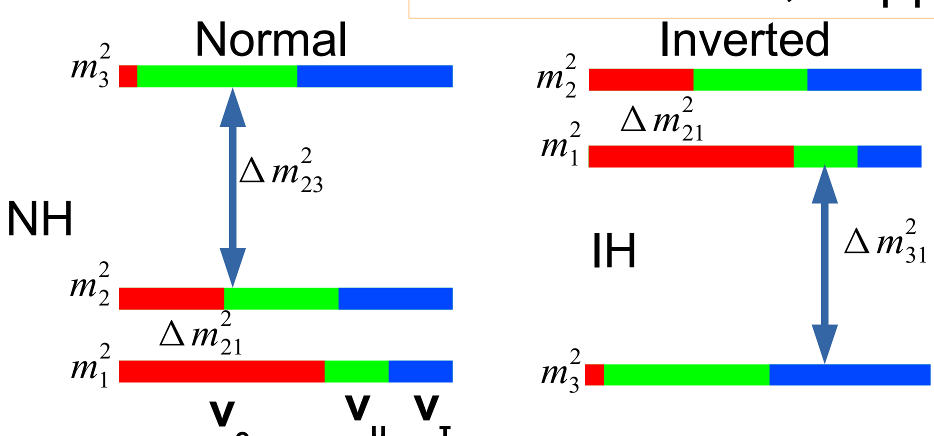
$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



Majorana neutrinos? 0νββ decay

$\sin^2(\theta_{12}) = 0.304 \pm 0.014$
$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}$ eV^2
$\sin^2(\theta_{23}) = 0.51 \pm 0.05$ NH
$\sin^2(\theta_{23}) = 0.50 \pm 0.05$ IH
$\Delta m^2_{32} = (2.44 \pm 0.06) \times 10^{-3}$ eV^2
$\Delta m^2_{32} = (2.51 \pm 0.06) \times 10^{-3}$ eV^2
$\sin^2(\theta_{13}) = (2.19 \pm 0.12) \times 10^{-2}$
δ_{CP} = some hints

mass hierarchy: matter effects, 0νββ



absolute mass scale: β and 0νββ decay, cosmology

sterile neutrinos? oscillation experiments, cosmology

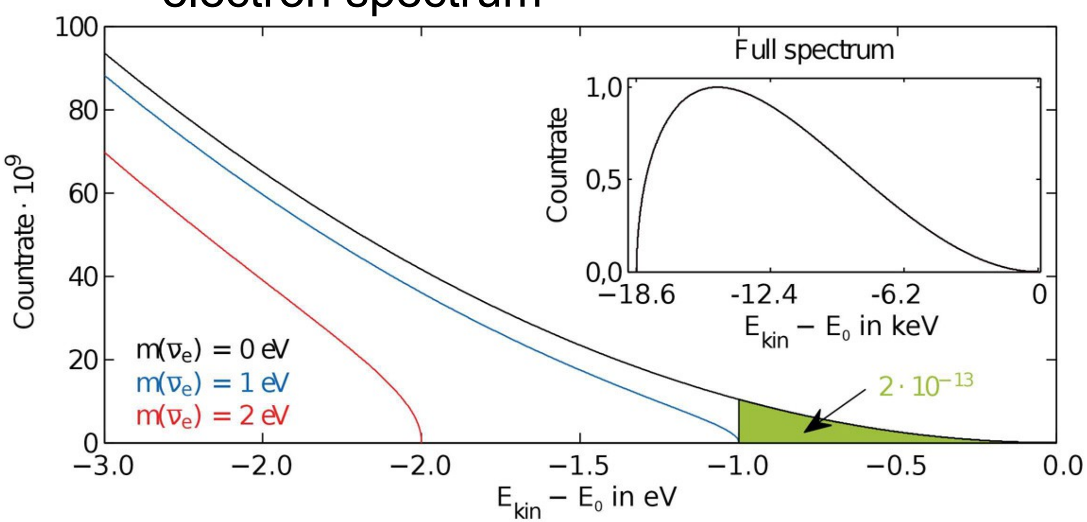
Measurements of neutrino mass

- absolute scale of neutrino mass can be obtained from:

	current upper limit	sensitivity (long-term)	observable
cosmology	0.2-0.6 eV	15 meV	Σm_i
neutrinoless double β decay	0.1-0.4 eV	20-40 meV	$m^2_{\beta\beta} = \lvert\Sigma U_{ei}\, m_i\rvert^2$
β decay and electron capture	2 eV	40-100 meV	$m^2_{\beta} = \Sigma\lvert U_{ei}\rvert^2\, m_i^2$

strong model dependence:
- cosmological model
- nuclear matrix elements+Majorana phases

electron spectrum



E_0 = 18.6 eV for tritium

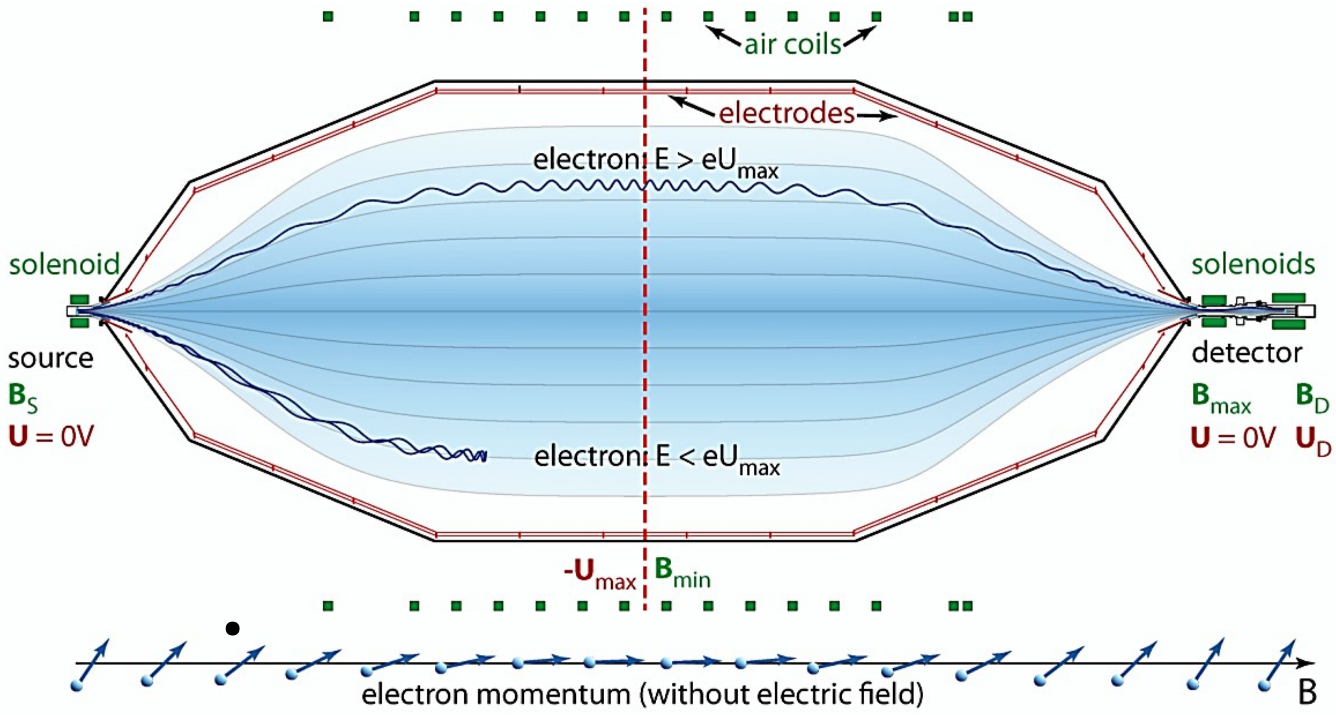
Requirements
- high activity source
- excellent energy resolution:
huge spectrometer needed→ **KATRIN**

Other possible methods:
- cyclotron radiation emission spectroscopy (PROJECT 8)
- calorimetric measurement for holmium-163
(ECHO, HOLMES, NuMECS)

KATRIN

KArlsuhe TRItium Neutrino experiment

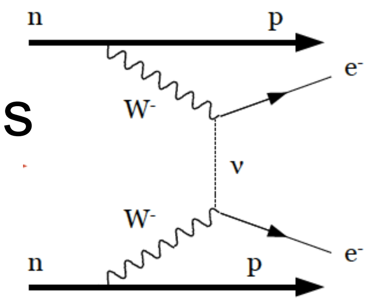
- gaseous molecular tritium source, activity 170 GBq
- lossless electron transport in magnetic field (5.6 T), huge main spectrometer (70 m total beamline)
- 200 meV sensitivity (design, 90% CL)
  - $\sigma_{stat} \approx 0.018\ eV^2$, $\sigma_{sys,tot} \approx 0.017\ eV^2$
  - m = 0.35 eV observable with 5σ



- status:
  - June 2017: tests and calibration with Kr source
  - June 2018 - start of data taking with tritium

also: sensitive to eV- and keV-sterile neutrinos

Dirac or Majorana neutrinos?



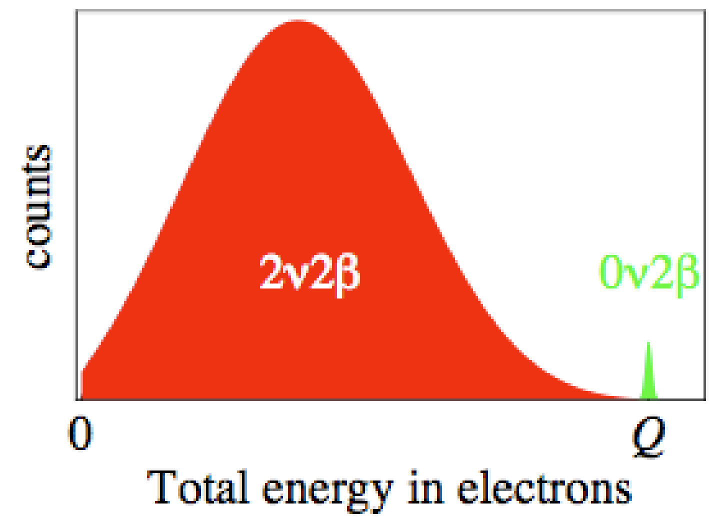
- neutrinoless double β decay - only for Majorana neutrinos
  - lepton number not conserved
  - lifetime > ~10^{26} years implies mass < 0.1 eV

$$(T_{1/2})^{-1} = G(Q_{\beta\beta}, Z)\, g_A^4 |M^{0\nu}|^2 \langle m_{\beta\beta} \rangle^2$$

phase space factor (good accuracy)

nuclear matrix elements (large uncertainties)

- signature:
  - good energy energy resolution
  - and low background needed



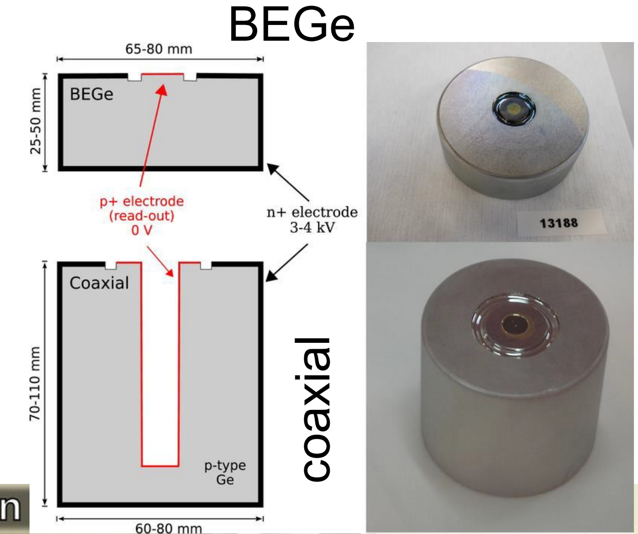
- isotopes: ^{76}Ge, ^{82}Se, ^{100}Mo, ^{130}Te, ^{136}Xe

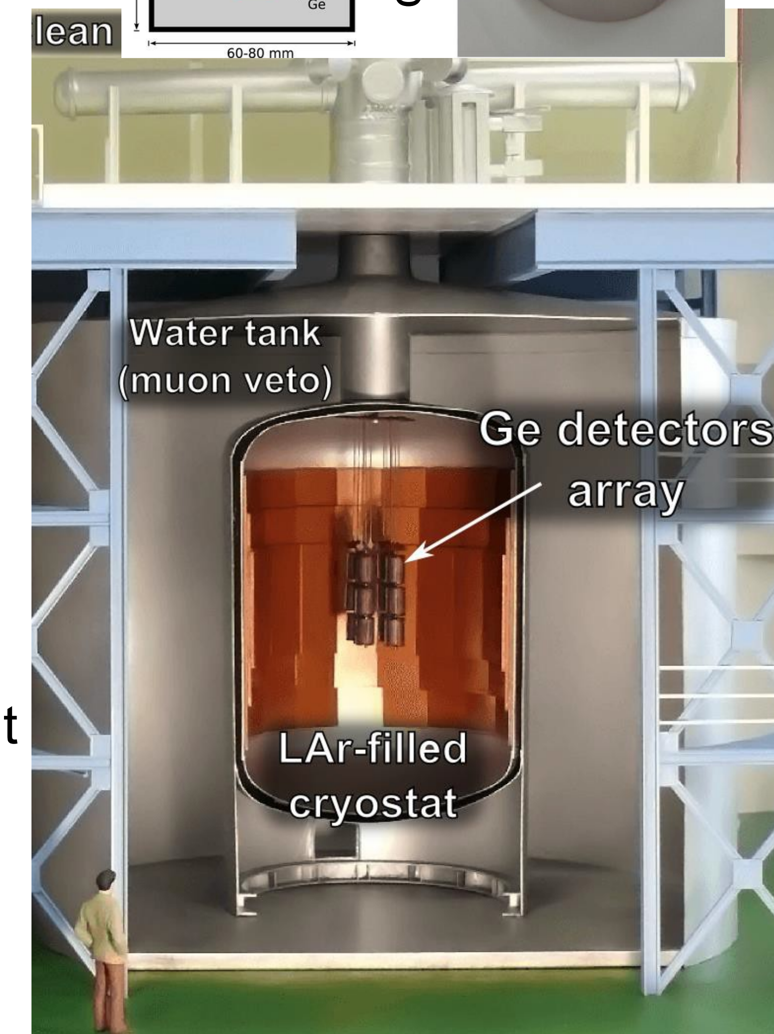
^{76}Ge	^{82}Se	^{100}Mo	^{130}Te	^{136}Xe
Majorana **GERDA** (LEGEND)	NEMO-3 (SuperNEMO, CUPID)	AmoRE (CUPID)	CUORE (SNO+)	**EXO-200** KamLAND-Zen (NEXO, NEXT, PANDA-X III)

semiconductor
bolometer
scintillator
liquid TPC
gas TPC
tracking calorimeter

GERDA

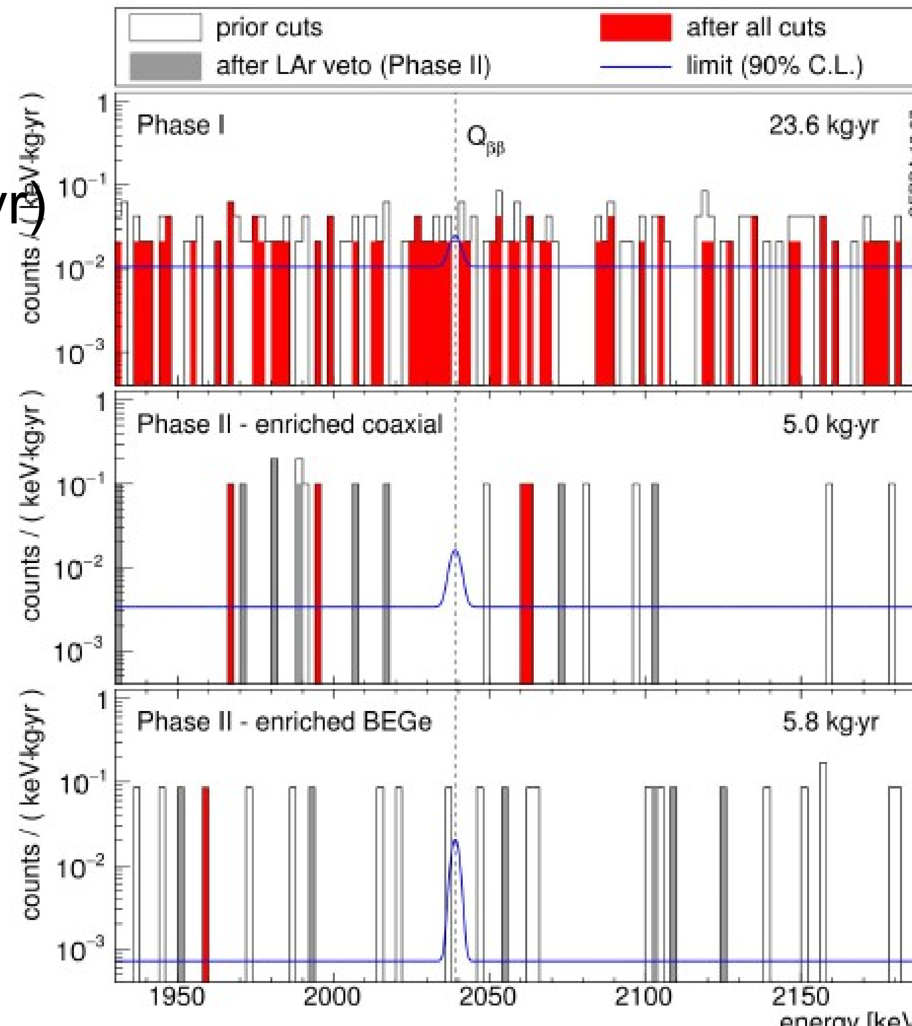
- GERmanium Detector Array immersed in an active liquid argon shield
  - germanium mono-crystals enriched in ^{76}Ge (86%), currently ~36 kg
  - source = detector
- region of interest $Q_{\beta\beta}$ = 2039 keV
- excellent energy resolution at ROI:
  - coaxial 4.0 ± 0.2 keV, BEGe 3.0 ± 0.2 keV
- lowest background in ROI
  - LAr: cooling, passive shield and veto
    - PMT and SiPM readout of scintillation light
  - water Cherenkov and plastic scintillator muon veto
  - located in underground LNGS laboratory





Results from GERDA

- phase I+IIa published data
  - background at ROI for BEGe detectors: $(0.7^{+1.1}_{-0.5})\cdot 10^{-3}$cts/(keV·kg·yr)
  - limit: $\mathbf{T_{1/2} > 5.3\cdot 10^{25}}$ **yr** (90% CL)
    (sensitivity: $T_{1/2} > 4.0\cdot 10^{25}$ yr)
  - $\mathbf{m_{\beta\beta} < 0.15\text{-}0.33}$ **eV**
    (for nuclear matrix elements range 2.8-6.1)



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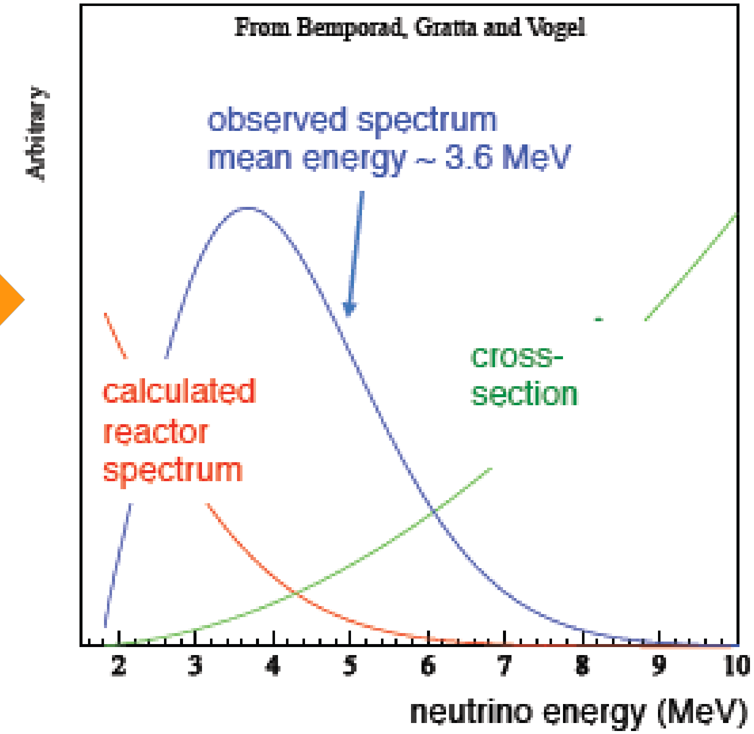
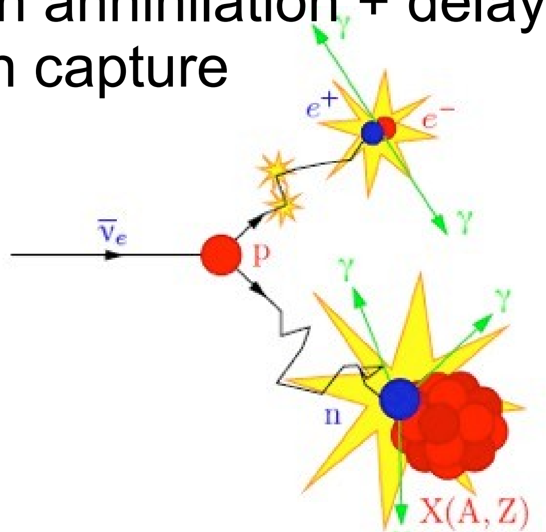
- new preliminary results for total exposure of 46.7 kg·yr (TAUP 2017):
  - $\mathbf{T_{1/2} > 8.0\cdot 10^{25}}$ **yr** (90% CL)
  - $\mathbf{m_{\beta\beta} < 0.12\text{-}0.27}$ **eV**
- mid 2018: 10^{26} yr – if no signal observed
- final exposure 100 kg·yr with sensitivity $1.3\cdot 10^{26}$ yr (limit) or $\sim 8\cdot 10^{25}$ yr (50% for 3σ discovery)
- plans for ton-scale ^{76}Ge experiment (LEGEND)

Reactor neutrinos

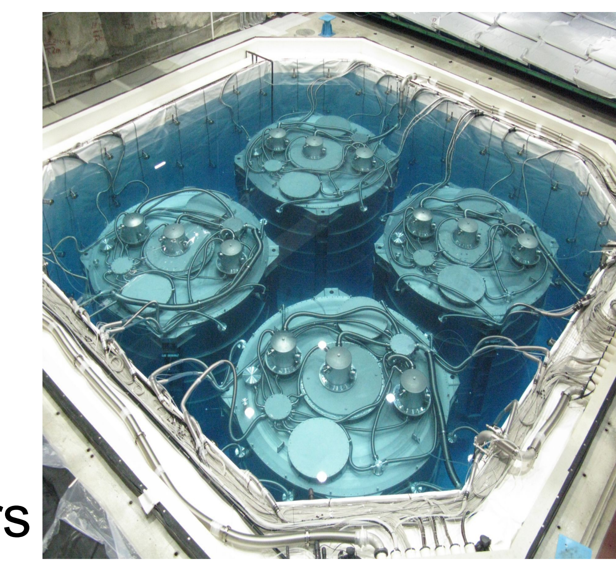
- **electrons antineutrinos** from decays of uranium and thorium fission products
  - ~10^{20} ν/GW s, 6/fission,
  - energies ~few MeV



- detection by **inverse beta decay**
  - positron annihilation + delayed signal from neutron capture



- **Daya Bay**, RENO, Double CHOOZ
  - liquid scintillator detectors, doped with Gd
  - near and far stations to reduce systematic errors



Daya Bay

Oscillations of reactor neutrinos

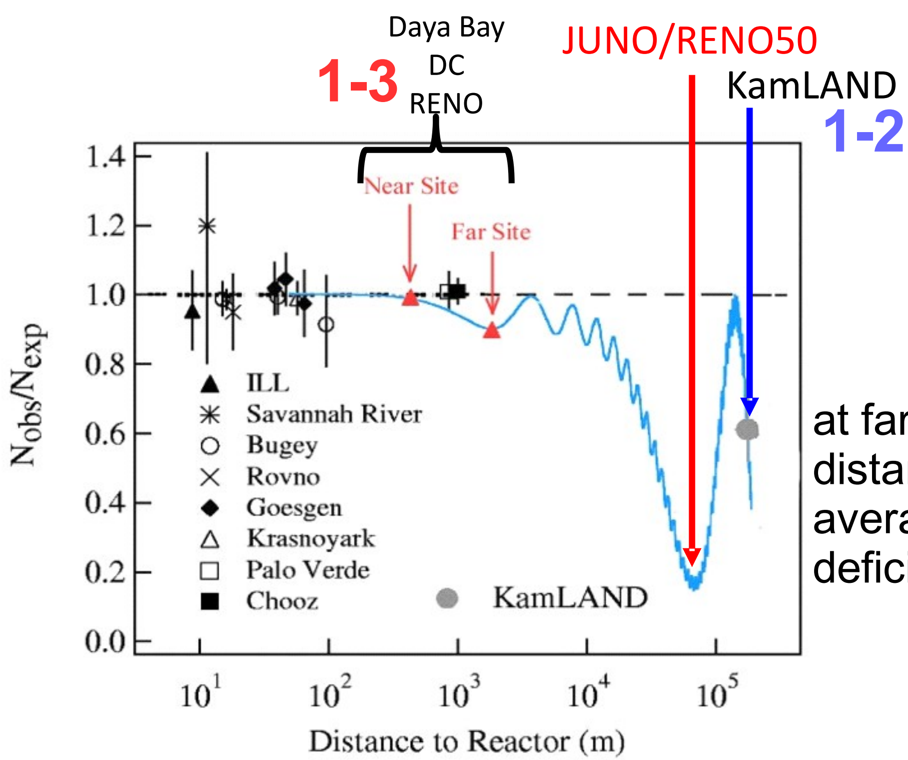
- sectors 1-2 and 1-3 available, depending on the **baseline**

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

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

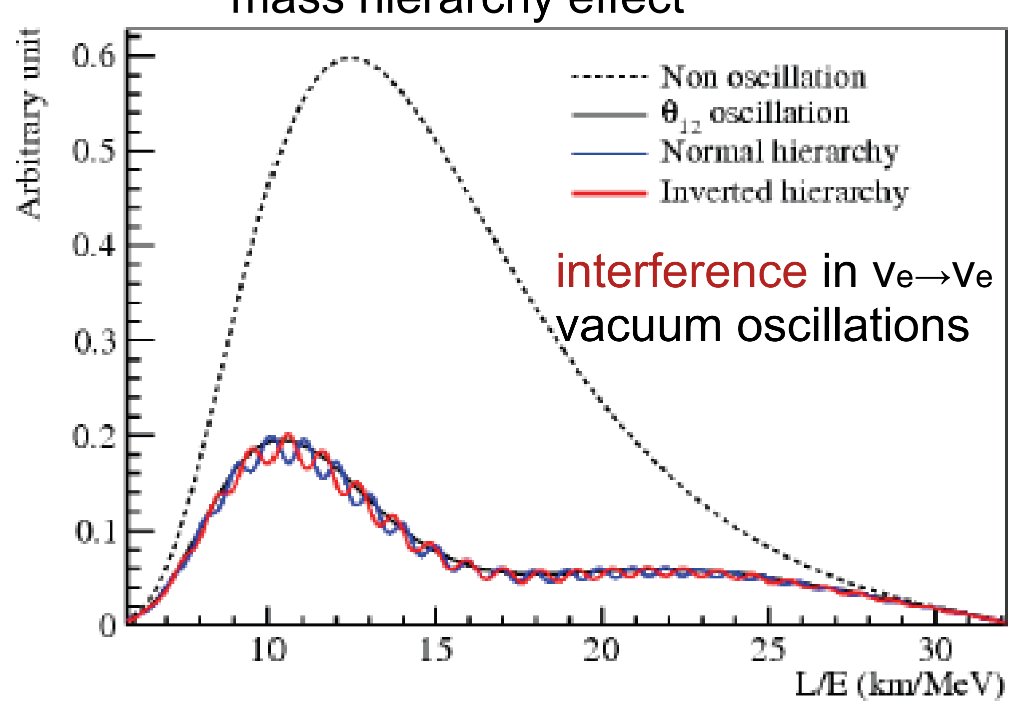
$$- \sin^2 2\theta_{13} \left[c_{12}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} + s_{12}^2 \sin^2 \frac{\Delta m_{32}^2 L}{4E} \right]$$

sector 1-3



at far distance: average deficit

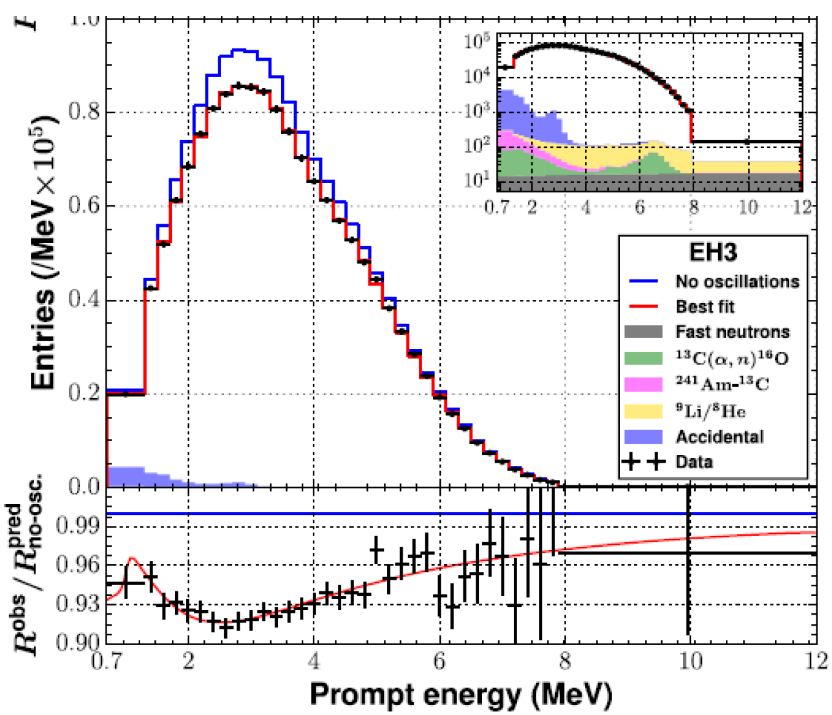
mass hierarchy effect



Reactor neutrinos: sector 1-3

- Daya Bay: most precise measurement of θ_{13}

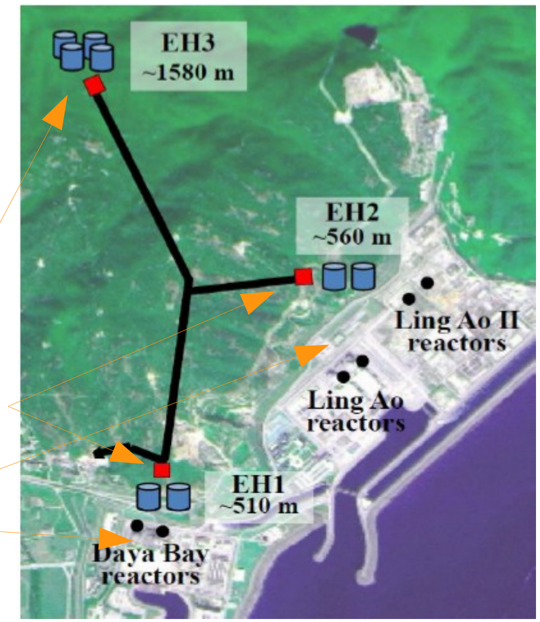
$\sin^2 2\theta_{13} = 0.0841 \pm 0.0027$ (stat.) ± 0.0019 (syst.)



Far Detector

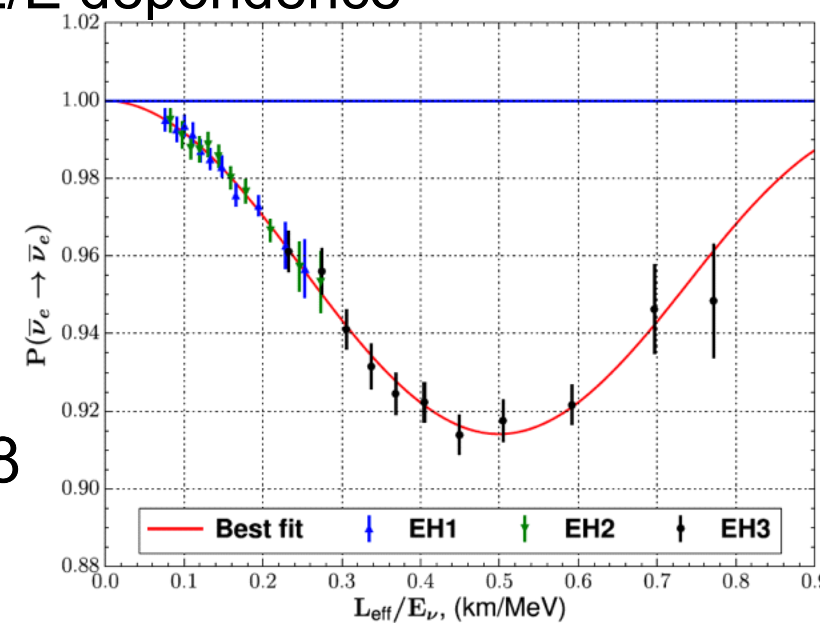
Near Detectors

reators



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

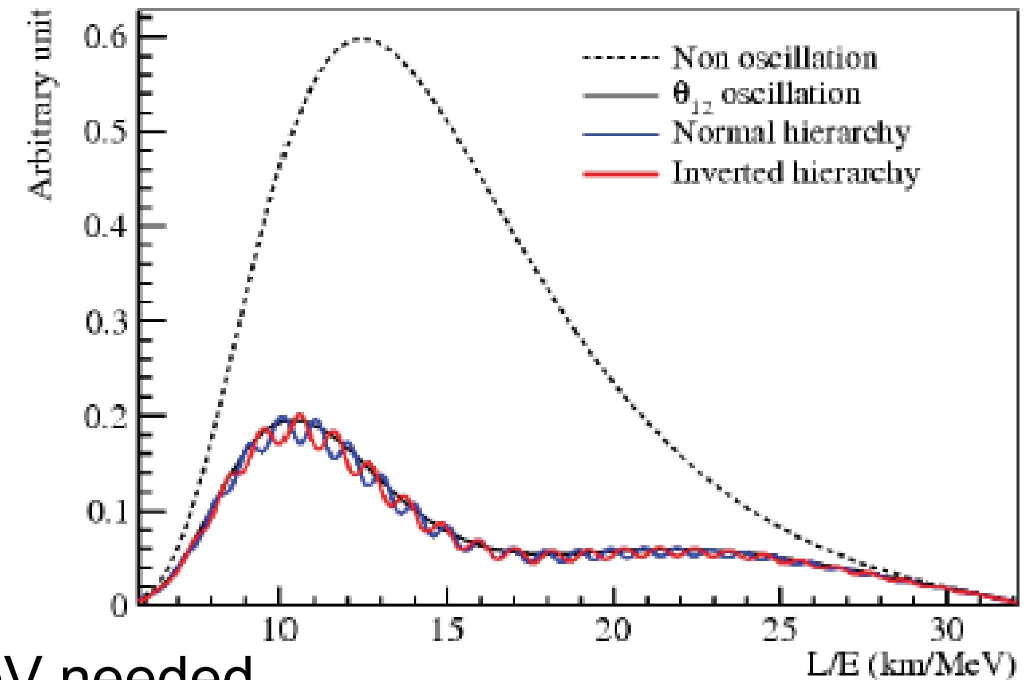
survival probability:
clear L/E dependence

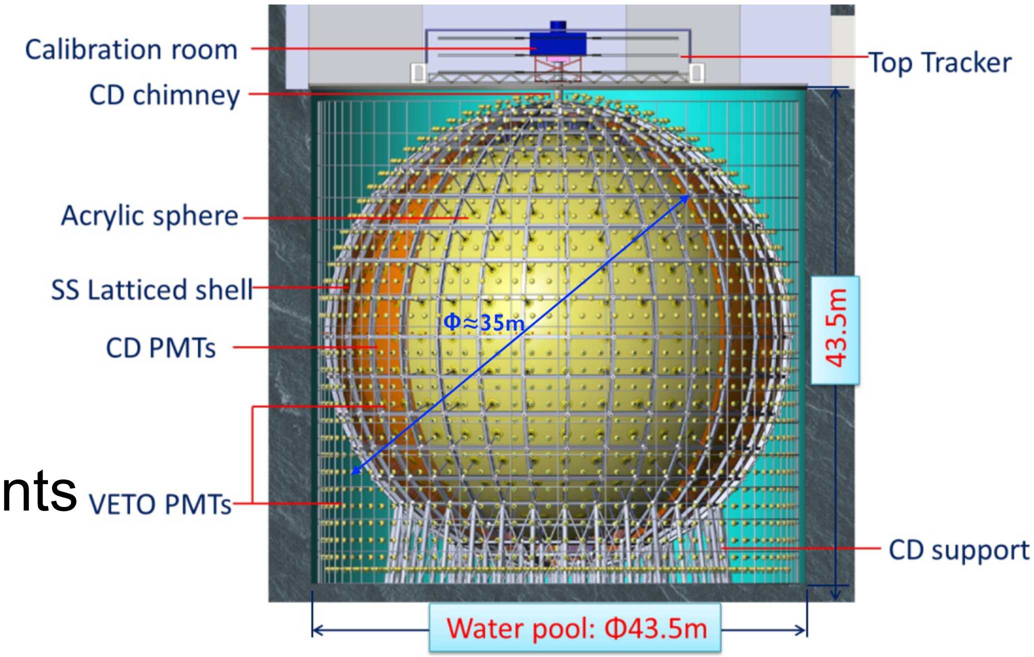


- measurement from RENO: 0.086±0.008 and Double Chooz: 0.119±0.016

Reactor neutrinos: mass hierarchy

- plans for medium baseline
- **JUNO** (~2020) in China
  - active mass: 20 kton liquid scintillator
  - 2 independent PMT systems:
    - 18000 20" PMTs
    - 25000 3" PMTs
  - **3% energy resolution** at 1 MeV needed
  - 2 nuclear power plants (6+4 cores) at 53 km
  - expected event rate 83/day
  - start in 2020, 3σ sensitivity to mass hierarchy after 6 years
  - also precise (<1%) measurements of Δm^2_{21}, $\sin^2\theta_{12}$,





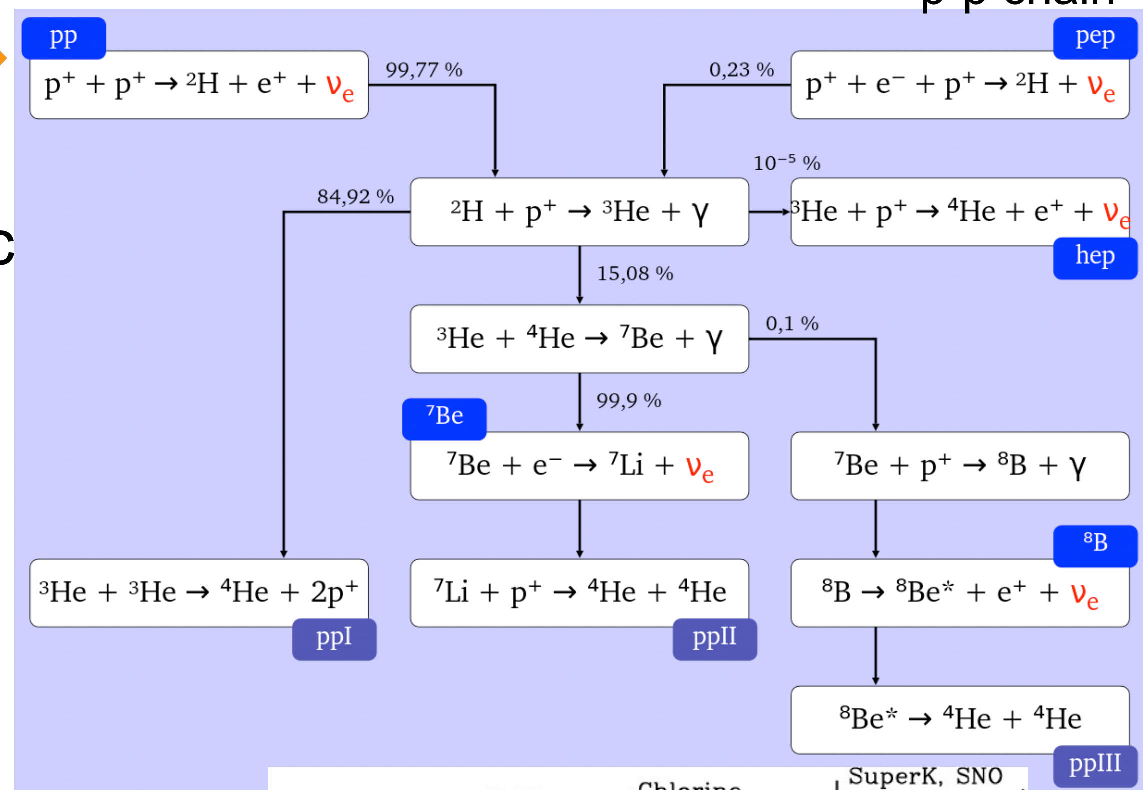
Solar neutrinos

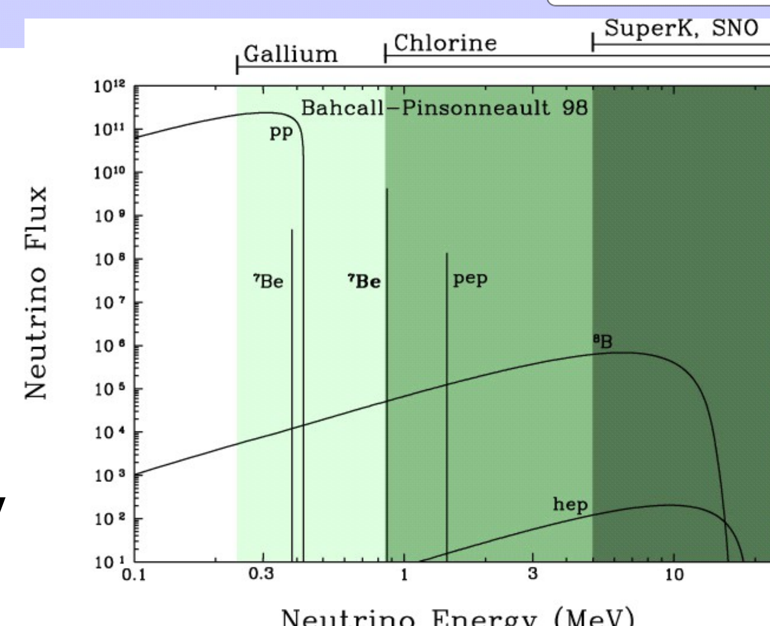
- electron neutrinos from fusion reactions in the Sun
- continuous or monoenergetic spectrum, depending on the production process
  - energies ~few MeV
- deficit of ν_e observed since 60ties (Davis, Nobel 2002)
- mystery solved by SNO

  → presence of neutrinos **other than ν_e** proved by the measurement of total flux in NC and ES interactions (McDonald, Nobel 2015)

- measured spectrum and rate strongly depends on the detection technique

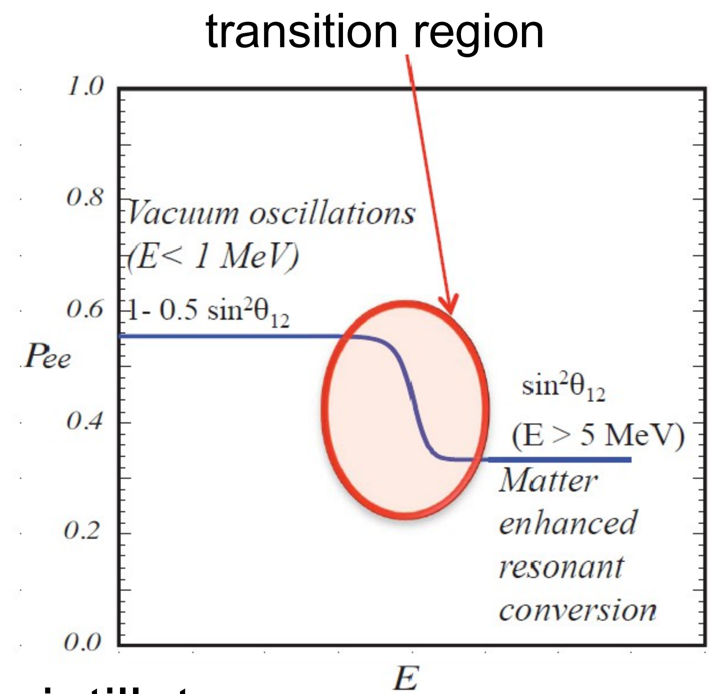
p-p chain





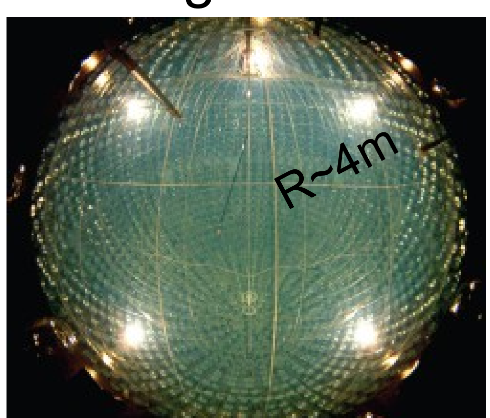
Solar neutrinos: MSW effect

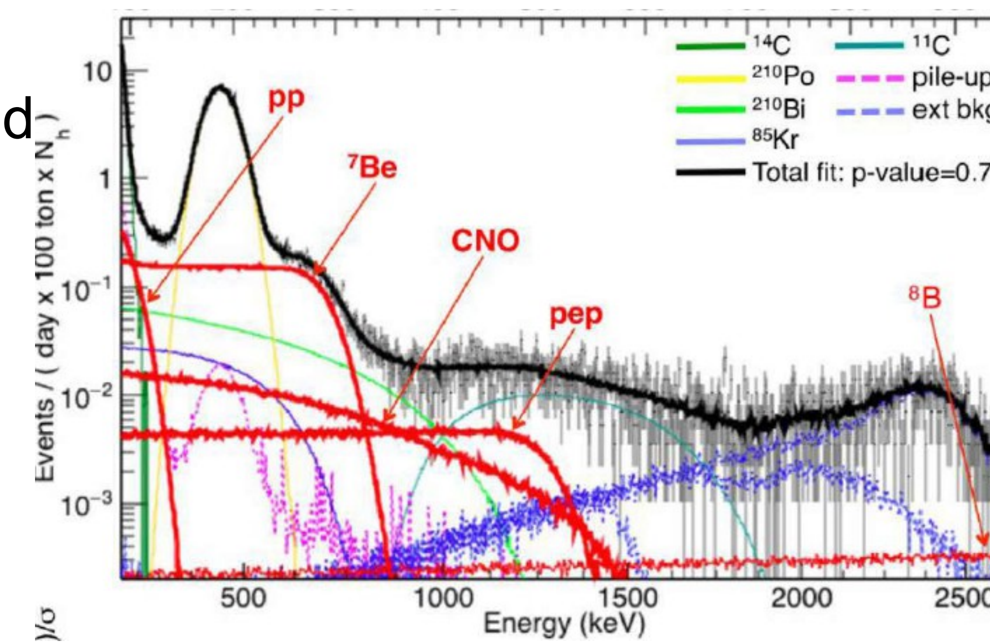
- expected behaviour for solar neutrinos
  - resonant enhancement of neutrino mixing in matter occurs for particular energies, depending on electron density and Δm^2
  - vacuum oscillations below 1 MeV
  - resonant conversion above 5 MeV
- **Borexino** measurements
  - elastic scattering: $\nu + e^- \rightarrow \nu + e^-$ in liquid scintillator
  - low threshold (~70 keV), ultra-low radioactive background + excellent background control



270t of liquid organic scintillator (100t fiducial)

1000t of liquid buffer

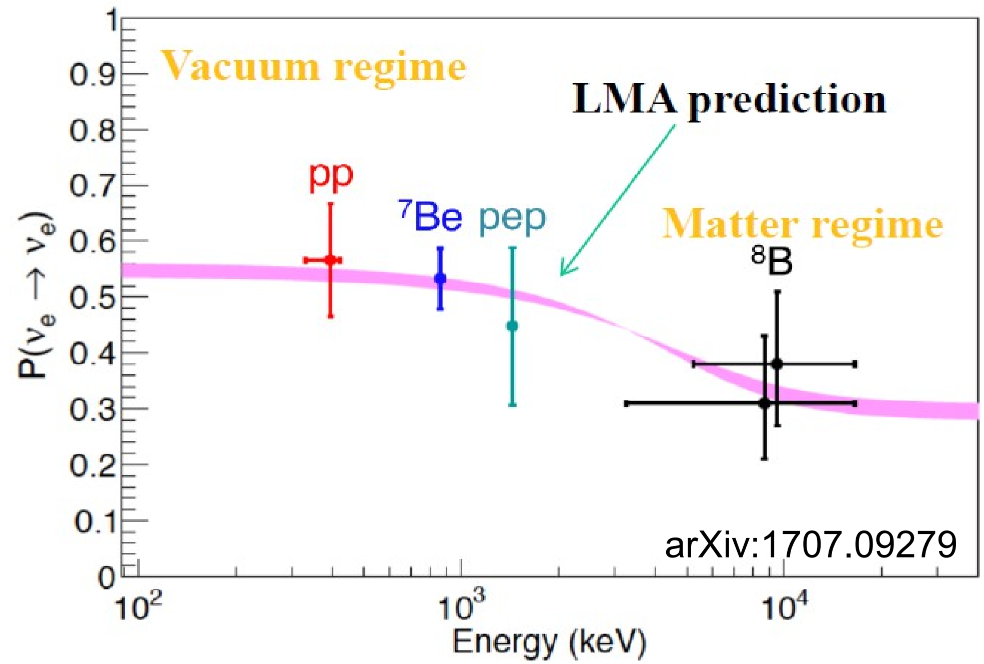




arXiv:1707.09279

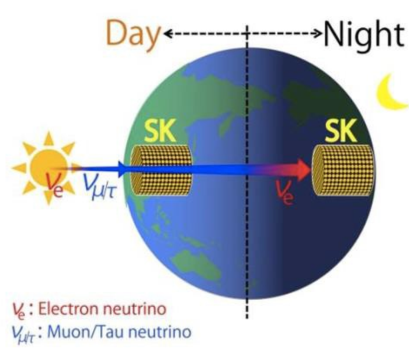
Measurements of solar neutrinos

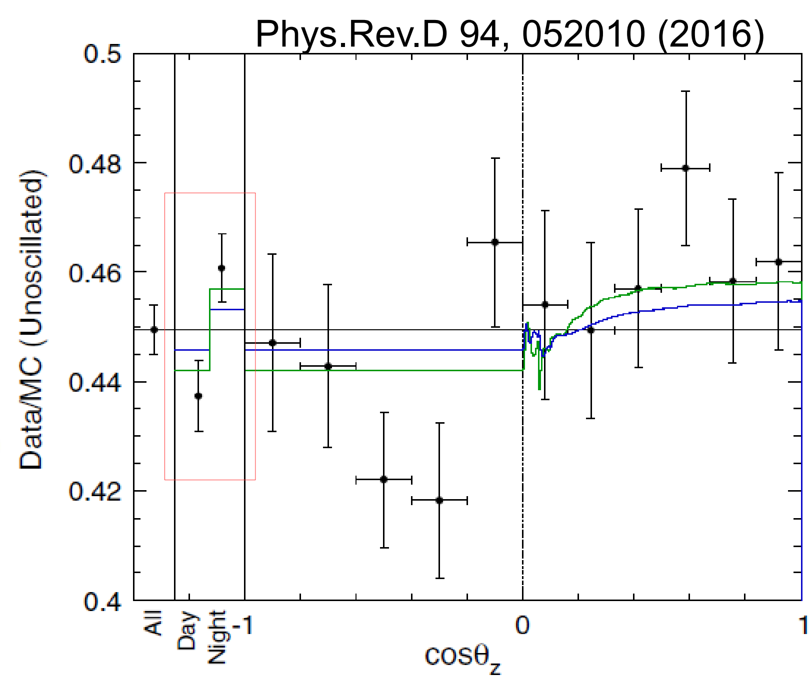
- Borexino measurements:
  - first detection of ^{7}Be and pep neutrinos
  - almost full solar neutrino spectroscopy
    - hunt for CNO neutrinos
- what about matter effects in Earth?
  - above 7MeV: ν_e regeneration expected
  - can be studied by day/night asymmetry



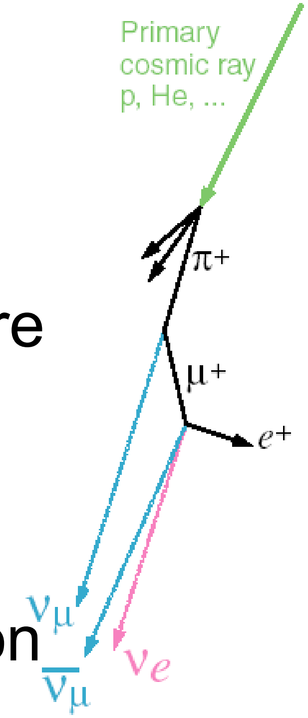
● ~3.3% for ^{8}B neutrinos (Super-Kamiokande) 2.9σ significance

● consistent with 0 for ^{7}Be neutrinos (Borexino)

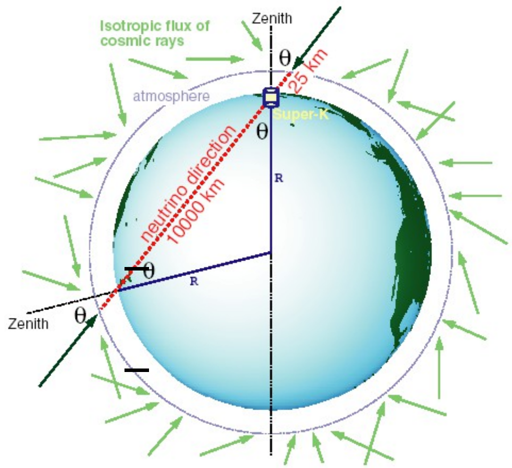




Atmospheric neutrinos



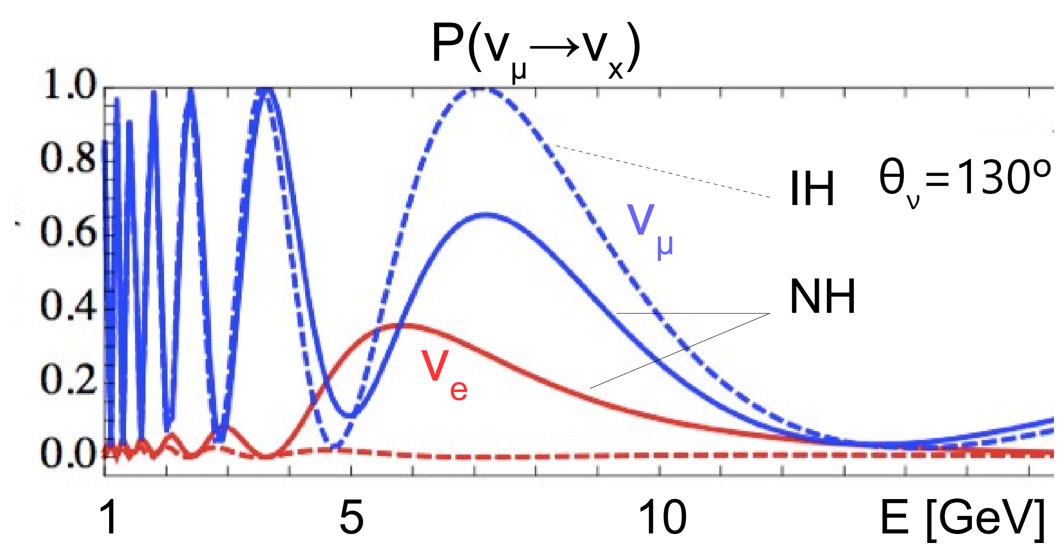
- produced in the decays of the particles emerging from the interactions of the primary cosmic rays with the atmosphere



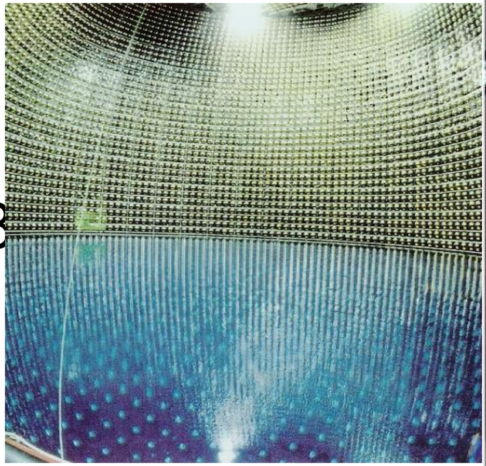
$$\pi^+ \rightarrow \mu^+ \nu_\mu \,,\ \mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$
$$\pi^- \rightarrow \mu^- \bar{\nu}_\mu \,,\ \mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

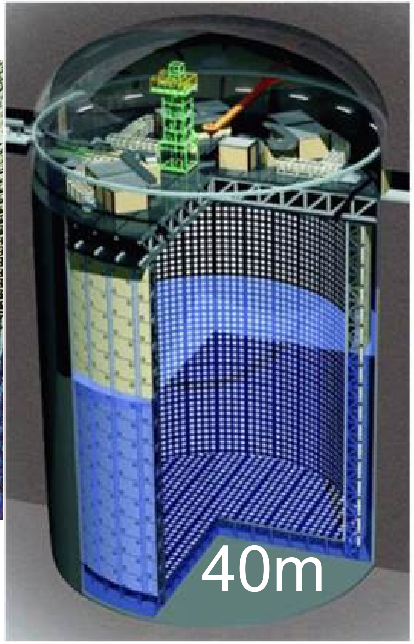
  – baseline determined by ν arrival direction
  – energies ~sub-GeV-TeV

- oscillation parameters in sector 2-3 can be measured (results will be shown later)
- mass hierarchy can be determined using 6-12 GeV neutrinos thanks to matter effect in the Earth
  - for normal (inverted) hierarchy oscillations enhanced for (anti)neutrinos

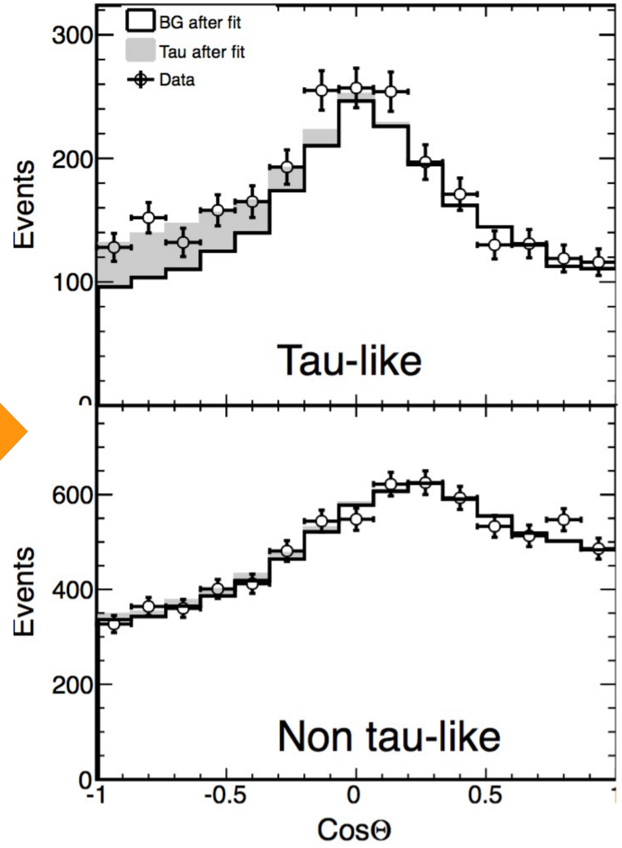


Super-Kamiokande





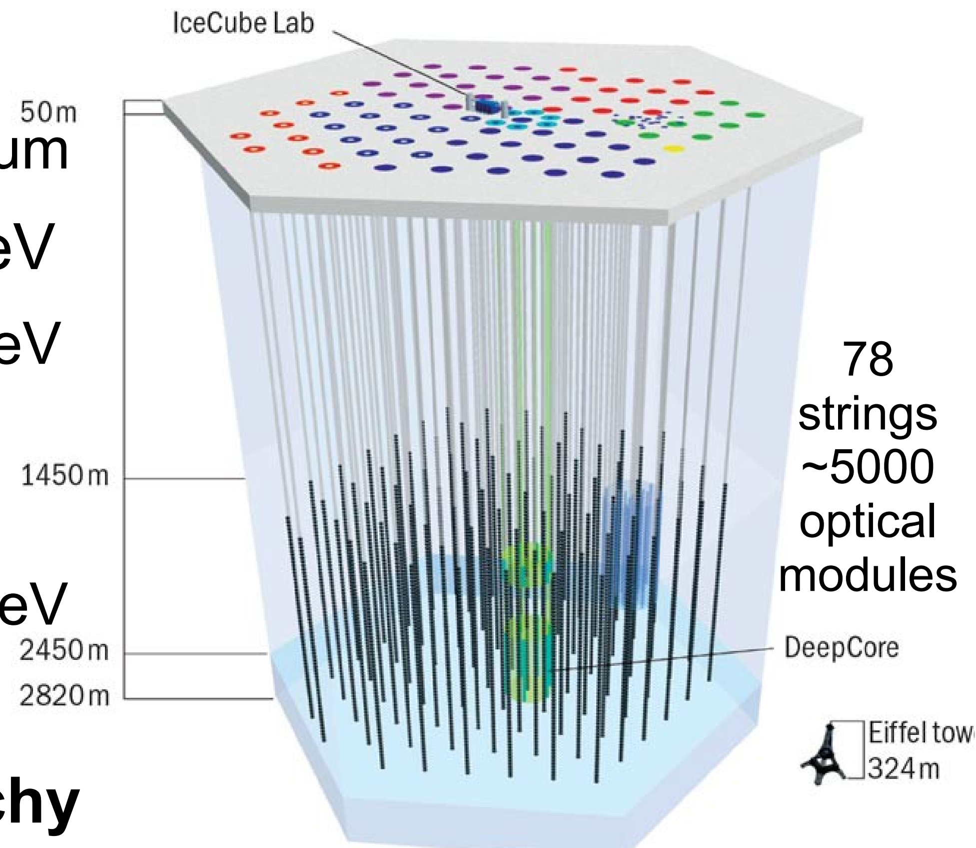
- oscillations of atmospheric neutrinos (ν_μ disappearance) discovered in 1998 (Kajita, Nobel 2015)
- water Cherenkov detector
  - total mass 50 kt, fiducial mass 22.5 kt
  - >11 000 PMTs in inner detector
  - ΔE/E ~10% for 2-body kinematics
  - very good μ/e separation
    - muons misidentified as electrons: <1%
- still producing results: ν_τ appearance search (hadronic τ decay modes)
  - neural network, for upward direction events
  - no tau appearance hypothesis excluded with 4.6 σ
  - dominated by statistical uncertainty

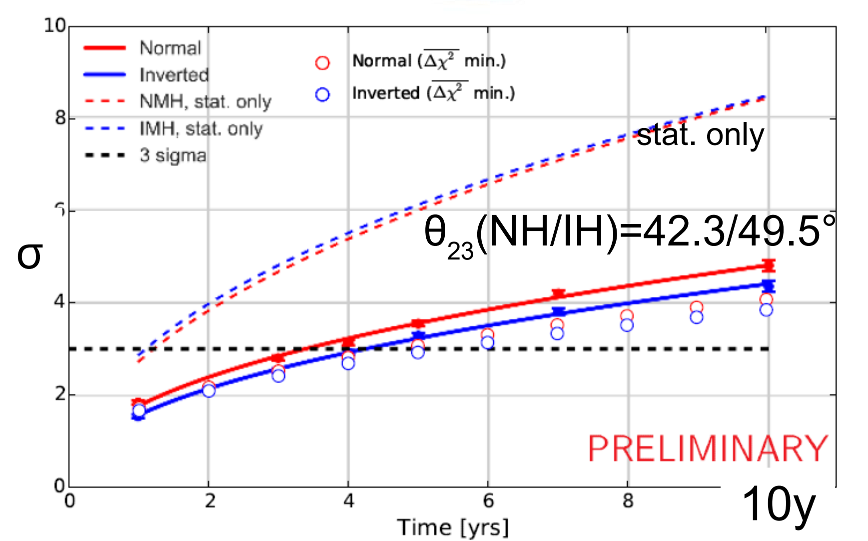


arXiv:1711.09436

"Natural" detector: IceCube

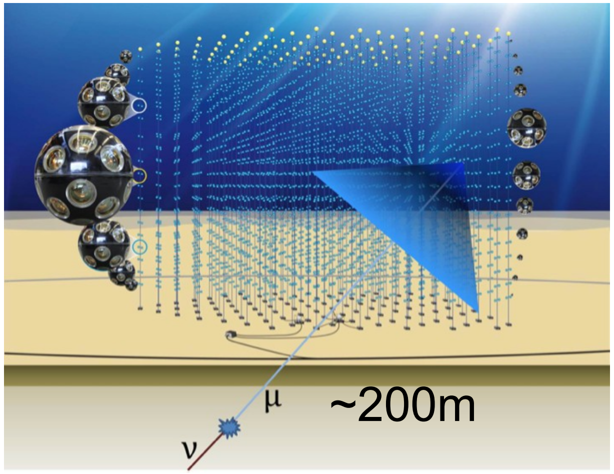
- located at the South Pole
  - 1km^3 of ice used as detector medium
- energy range: ~100 GeV to ~10 PeV
  - first oscillation maximum at ~25 GeV
- → DeepCore
  - 8 short distance strings (~500 modules) optimized for ~10-100 GeV
  - expected 60k atm. neutrinos/year
- PINGU to determine **mass hierarchy**
  - neutrinos energies below 12 GeV
  - 40 additional strings, spacing 22m, 50 modules per string
  - energy resolution ~20% above 10GeV, zenith angle resolution 5° at 20GeV
  - start in 2018, 4 years to be completed

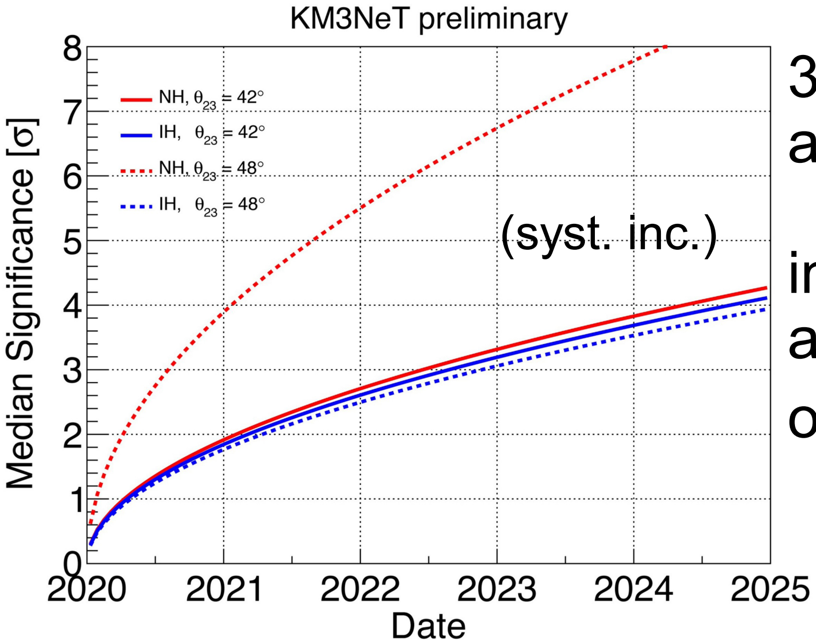




“Natural” detector: KM3NeT

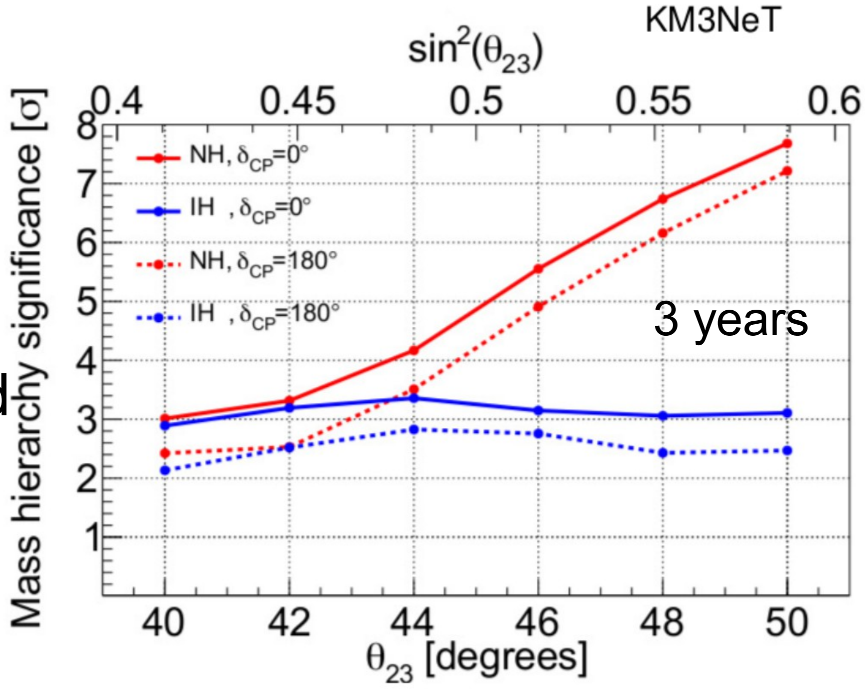
- KM3NeT in Mediterannean Sea
- ORCA - Oscillation Research from Cosmics in the Abyss
  - dense array (spacing 20m) of multi-PMT digital modules (115 strings) at depth of 2475m
  - expected ~50 000 events/year
  - at 10GeV: energy resolution ~25%, zenith angle resolution 5°
  - completion expected in 2020





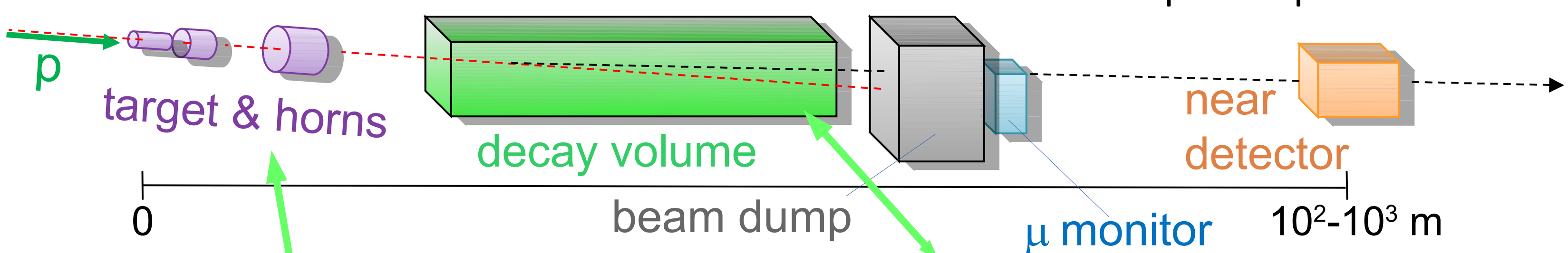
3σ significance: after 3-4 years

in case of NH and θ_{23} in second octant → 5σ!



Long baseline experiments

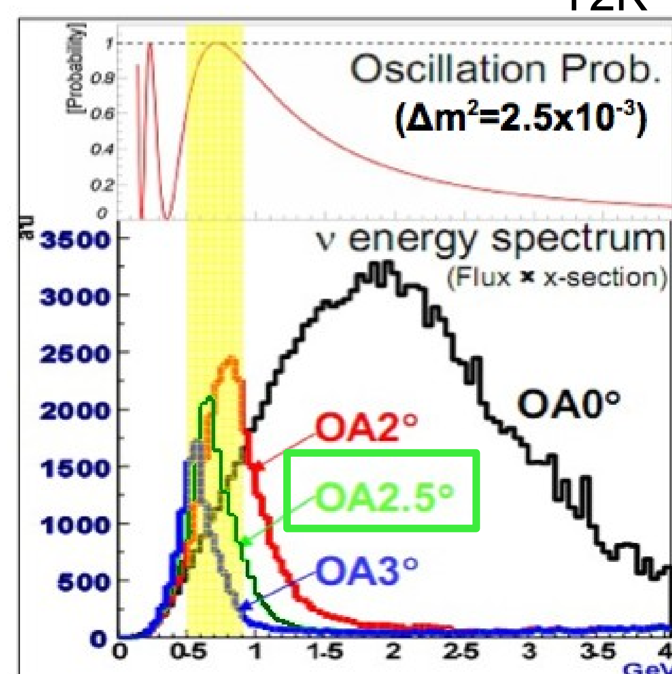
- relatively well controlled beam of neutrinos
  - energy (~GeV), direction, intensity, type (ν_μ or $\bar{\nu}_\mu$)



$\pi \rightarrow \mu\, \nu_\mu$ ~100% BR
$K \rightarrow \mu\, \nu_\mu$ ~63.5% BR
$K_L \rightarrow \pi\, \mu\, \nu_\mu$ ~27.0% BR
+ electron neutrinos

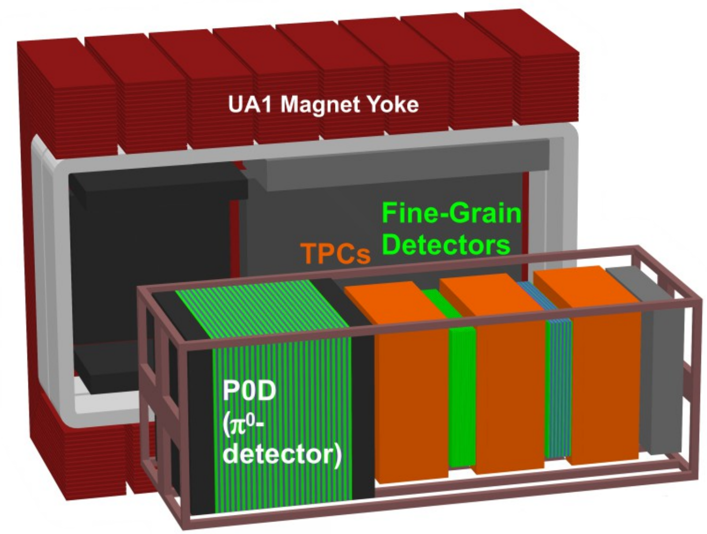
- ν_μ disappearance and ν_e appearance
- two currently running experiments with **off-axis** beam
  - kinematics of pion decay → threshold energy for neutrinos emitted at a given angle
  - **narrow spectrum** peaked at oscillation maximum

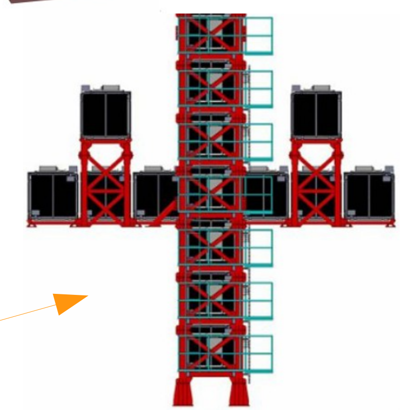
T2K



T2K

- started to take data in 2010, antineutrino beam mode 2014-2016
- located in Japan, beam 2.5° off-axis from J-PARC (Tokai) to Super-Kamiokande (FD)

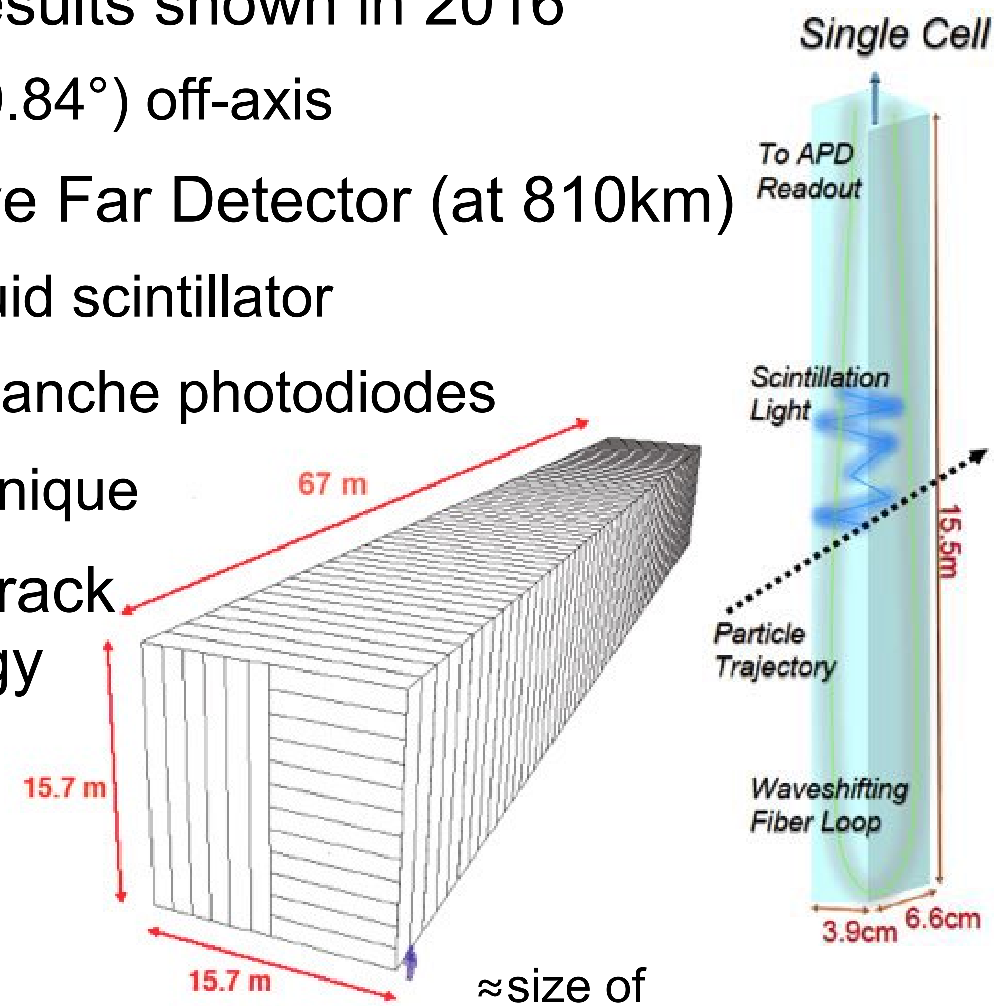


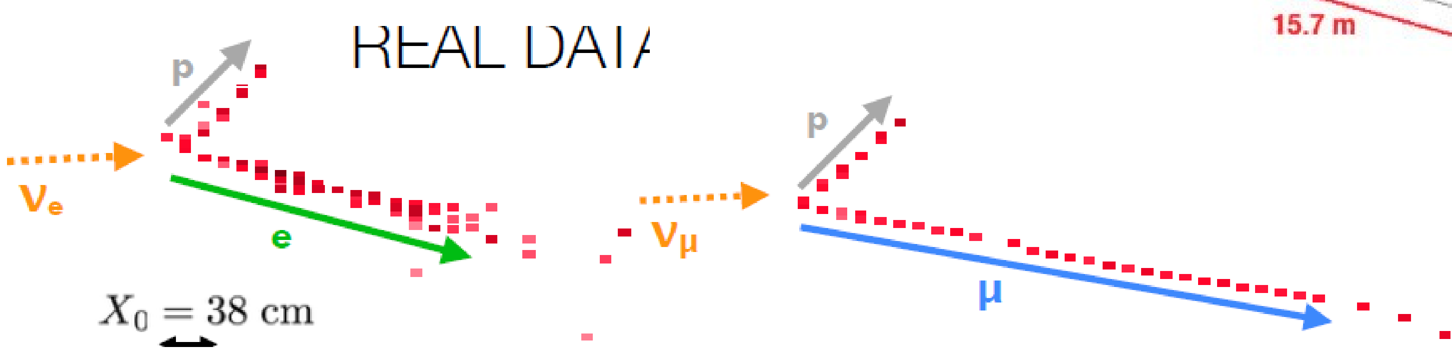


- set of **near detectors** at 280 m from target
  - multi-purpose magnetized off-axis ND280
  - cross-shaped on-axis detector (INGRID)
- samples of ND280 events used to correct event predictions for FD
- in FD: FCFV one-ring $\nu_{\mu/e}$ events = CC QE candidates
  - recently CC1π ν_e sample added in analysis

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 (at 810km)
  - 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**



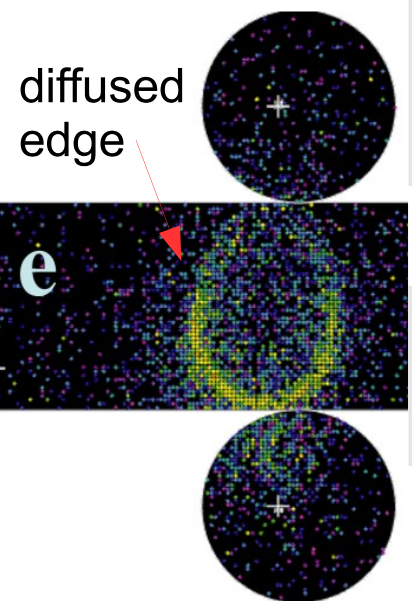


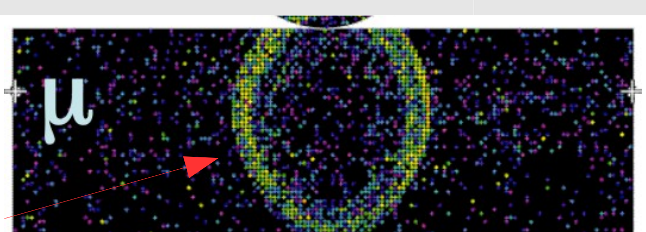
≈size of

T2K and NOvA

	T2K	NOvA
baseline	**295** km	**810** km
peak energy	**600** MeV	**2** GeV
Near Detector	multi-purpose (TPC, FGD, ECAL) magnetized	extruded plastic cells filled with liquid scintillator
Far Detector	50 kton Water Cherenkov	14 kton scintillator
data sets	neutrino and antineutrino	neutrino (antineutrino not published yet)
E_ν reconstruction	CC QE events	calorimetric
ν_e/ν_μ recognition	shape of Cherenkov rings	image transformation, neural network

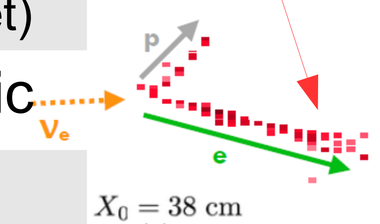
diffused edge

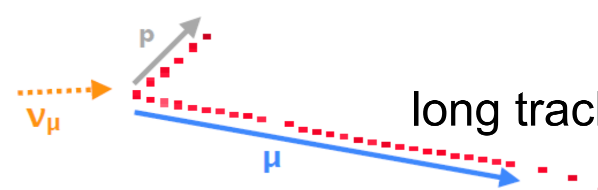




sharp edge

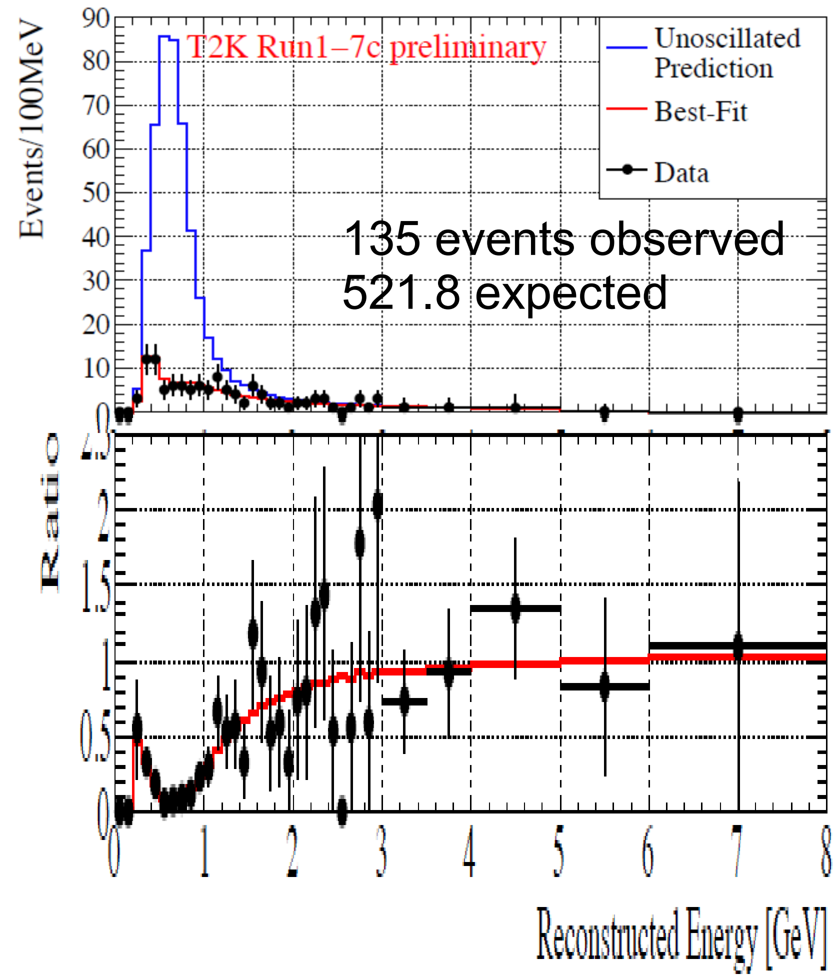
cascade



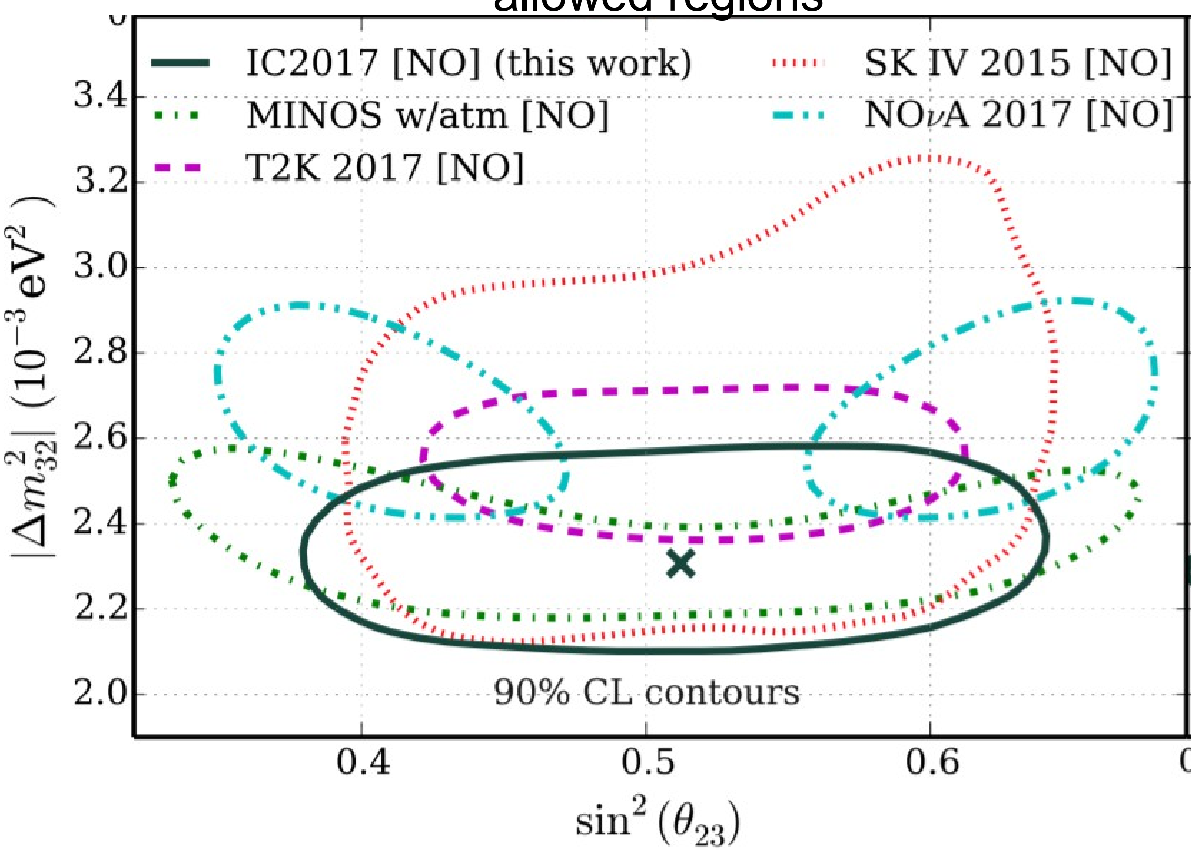


ν_μ disappearance

- oscillation pattern in T2K:
  - **preference** for maximal mixing
    (PRD 96, 092006 (2017))
- but NOvA **excludes** maximal mixing at 2.6σ (PRL 118, 151802 (2017))



allowed regions



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

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

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

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

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

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

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

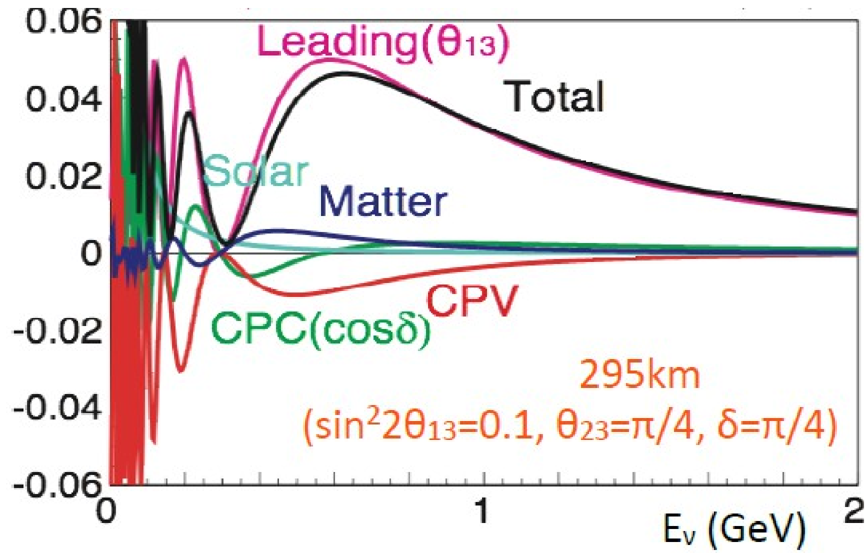
for $\bar{\nu}$

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

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

n_e related to matter density

subleading effect can be as large as 30% of dominant



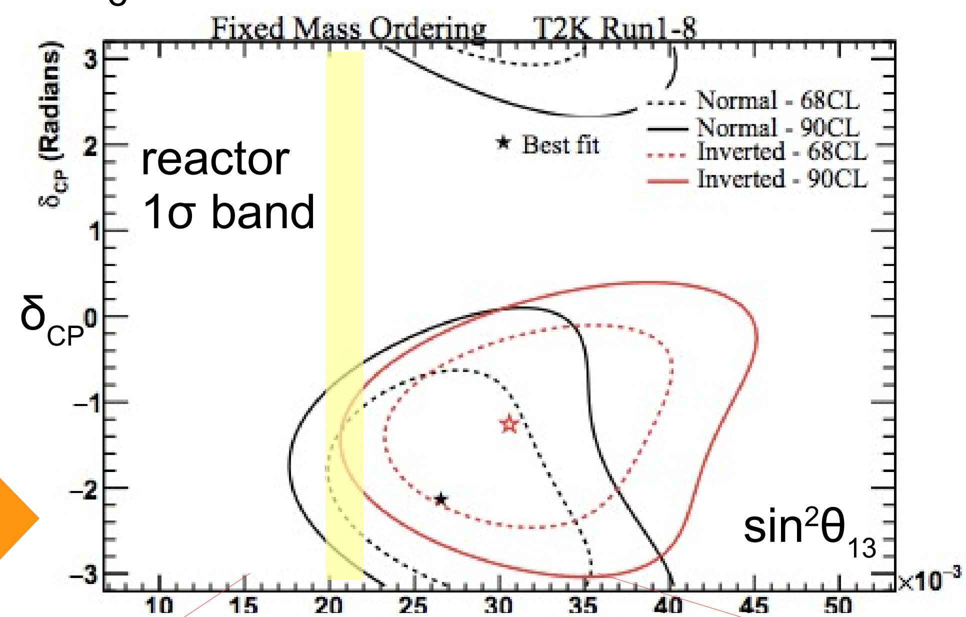
- **parameter degeneracies** to disentagle: effects from mass hierarchy, CP violation, octant of θ_{23} – more effects to study
- combination of experiment with different baseline increases sensitivity

Hints on CP violation

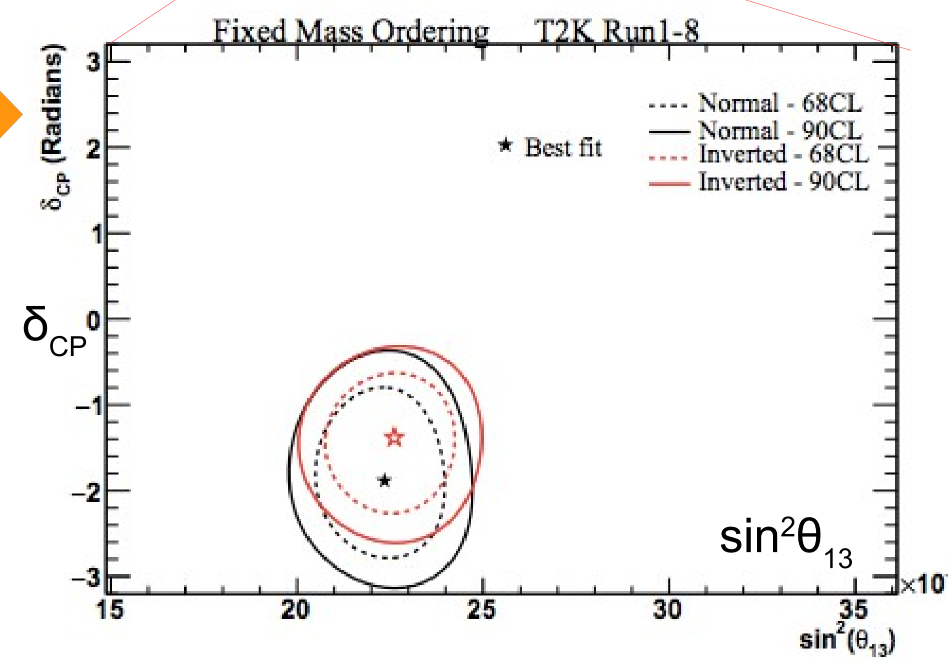
- T2K data, joint fit of (anti)ν_μ and (anti)ν_e samples

δ_{CP}	-0.5π	0	0.5π	π	data
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

  - allowed regions for δ_{CP} and $\sin^2\theta_{13}$
  - θ_{13} consistent with reactor, closed δ_{CP} contours



- with reactor constraints on θ_{13}
  - improved limits on δ_{CP}
  - 2σ confidence interval
    δ_{CP} = [-2.98, -0.60] (NH)
    [-1.54, -1.19] (IH)

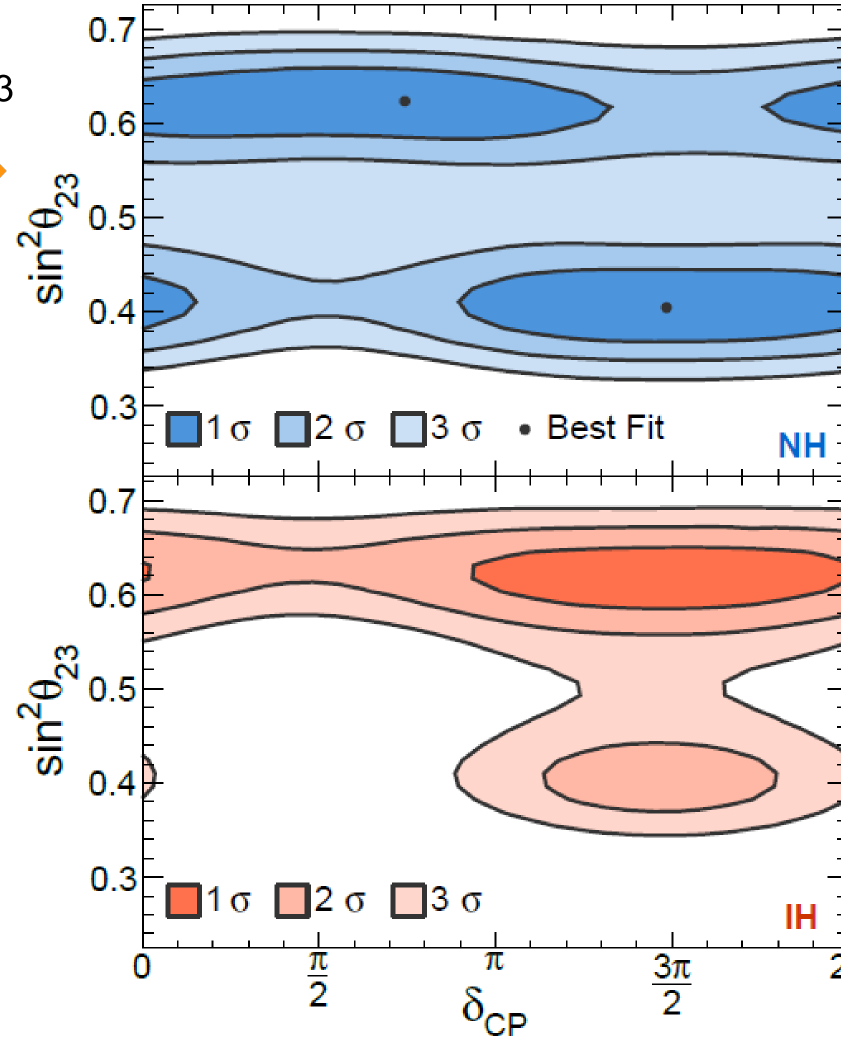


- **CP conserving values disfavoured at >2σ**

NOvA results

- ν_e appearance shown at NEUTRINO 2016 with 33 observed events
  - allowed regions for δ_{CP} and $\sin^2\theta_{23}$
- 2 degenerated best fit points
  3σ exclusion of inverted hierarchy and lower θ_{23} octant around $\delta_{CP} = \pi/2$
- for all values of δ_{CP} and both θ_{23} octants the inverted hierarchy predicts fewer events than observed → small preference for normal hierarchy
- new results will be announced today in Fermilab

T2K preferred value

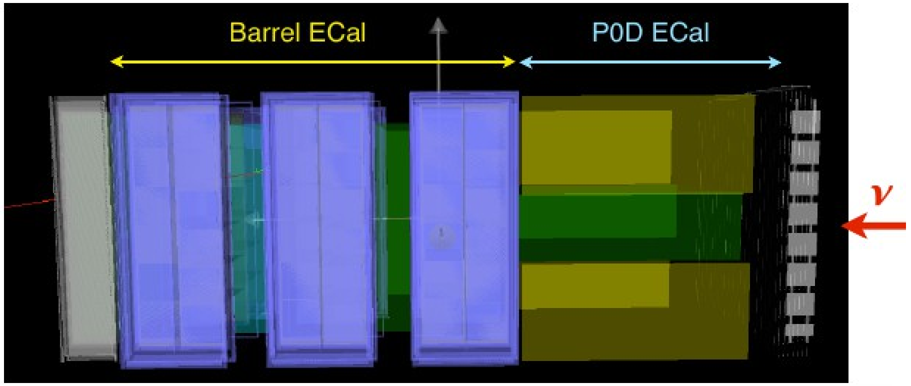


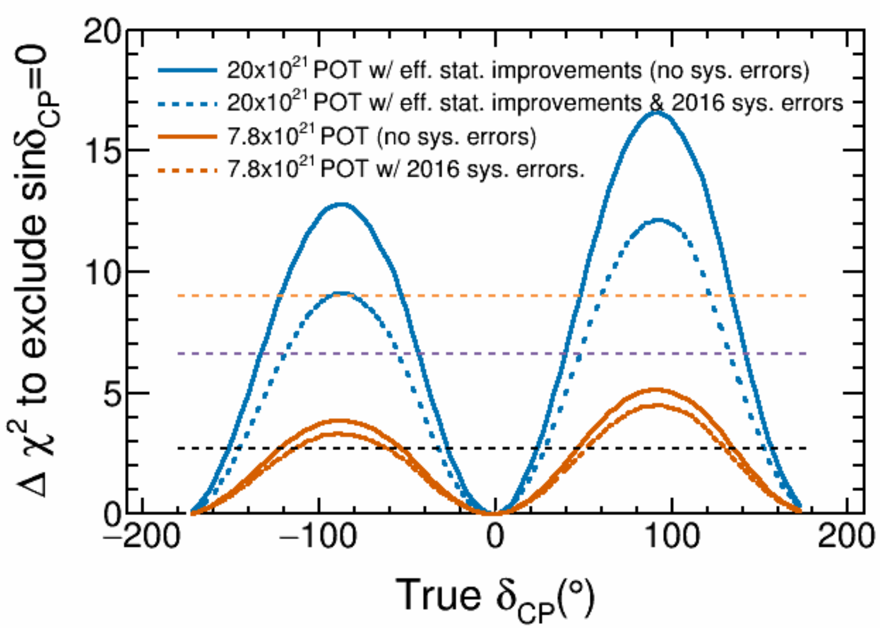
PRL 118, 231801 (2017)

Near future for LBL experiments

T2K and NOvA will continue to run over next several years

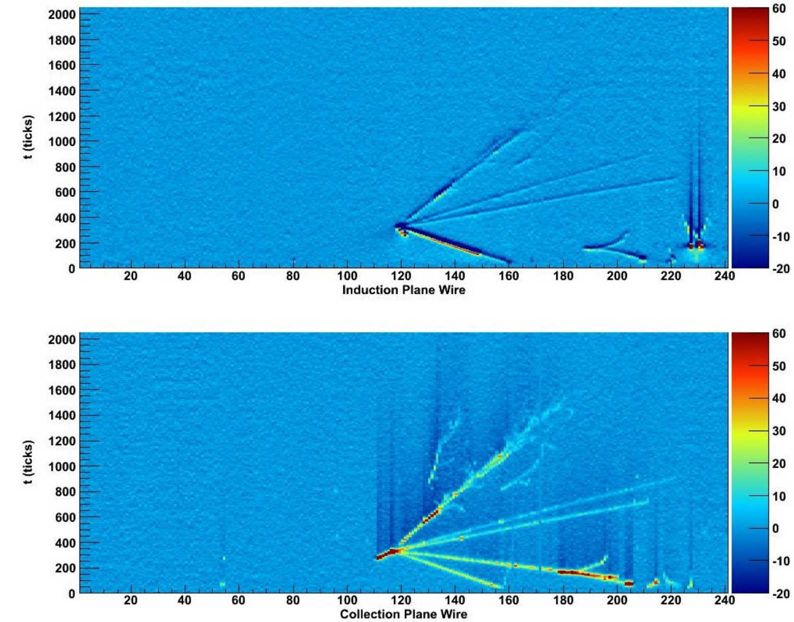
- T2K proposes phase 2 with upgrade of near detector and Gd added to Super-Kamiokande
  - expanded ND280 angular acceptance
  - reduction of flux and cross section uncertainties
  - antineutrino event tagging in SK
  - technical design soon, aim for installation 2020/2021 for T2K II
- up to 3σ sensitivity for rejecting the no-CPV hypothesis
- **next generation** of LBL already being planned, designed for **5σ** sensitivity for CP violation
  - but not only! Physics program is really wide

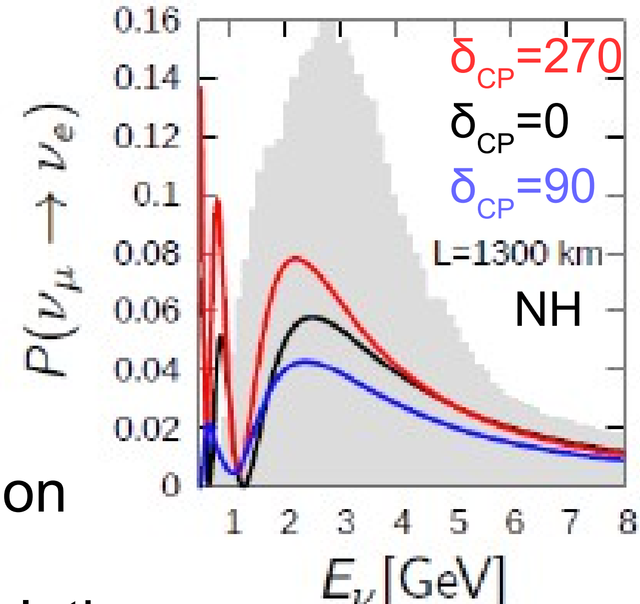




DUNE

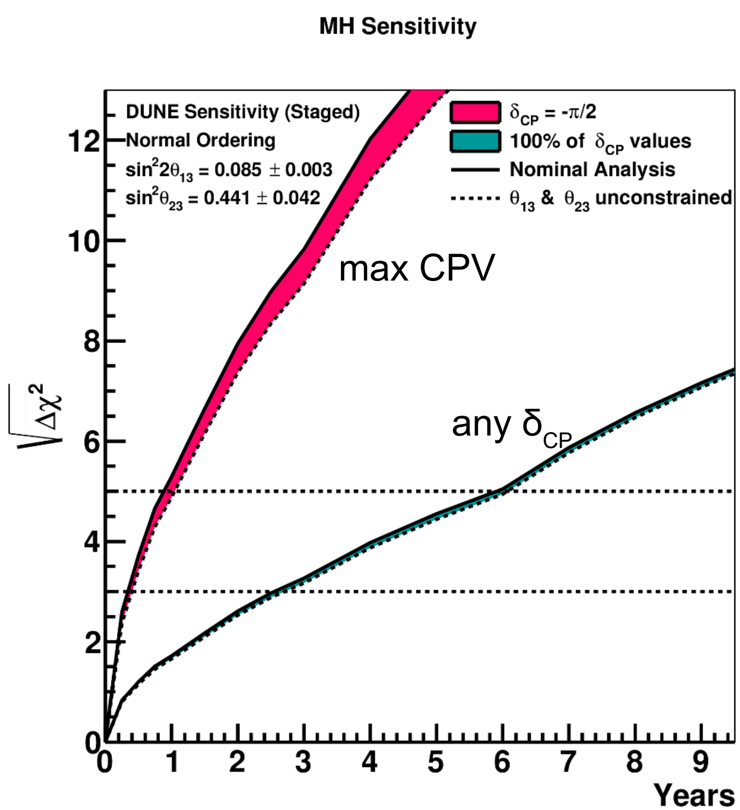
- liquid argon imaging technique
  - dense target, ionization and scintillation signal, close to full acceptance
  - PID based on dE/dx and range, excellent photon/electron separation
- very long baseline: **1300** km
- Far Detector: 4x17 kton LAr TPC (>40 kton fiducial mass), single or dual phase
  19.1m (16.9m) W x 18m(15.8m) H x 66m(63.8m) L
- design of Near Detector on-going
- megawatt class on-axis broadband beam (1.2→2.4 MW)
  - wide spectrum covering the 1st and 2nd oscillation maxima → together with distance breaks the degeneracy between matter effects and CP violation

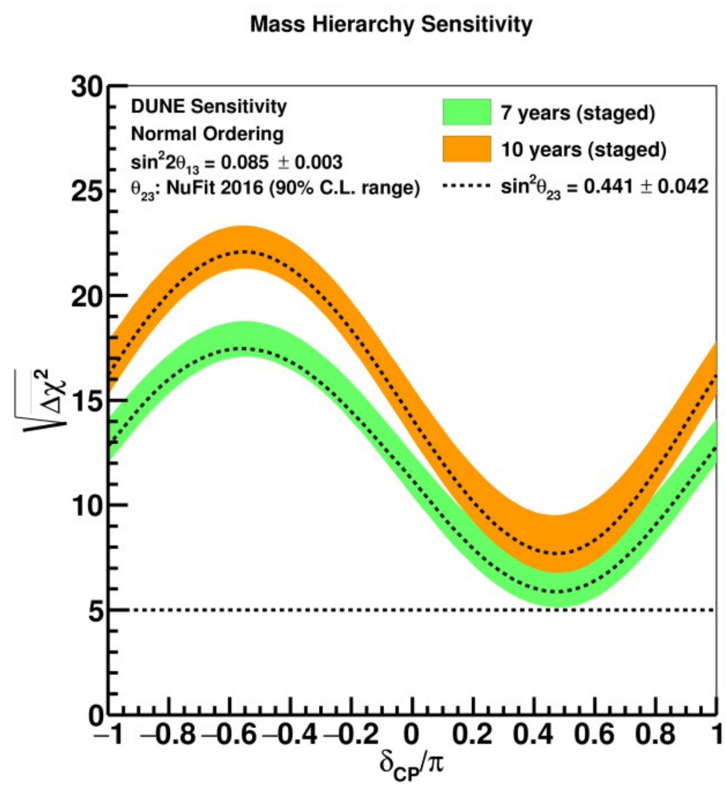




DUNE sensitivity: mass hierarchy

- assumptions: staging, 1.07 MW beam with 20 kton, after 7 years 2.14 MW with 40 kton, $\nu:\bar{\nu}$ data taking 1:1, θ_{23} non maximal
- mass hierarchy determination – relatively quick





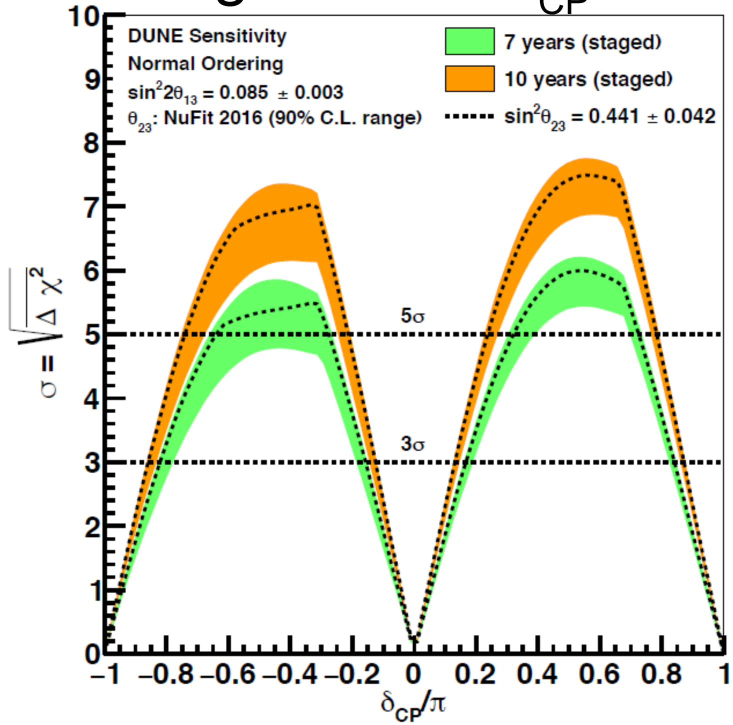
band corresponds to 90%CL width for θ_{23}

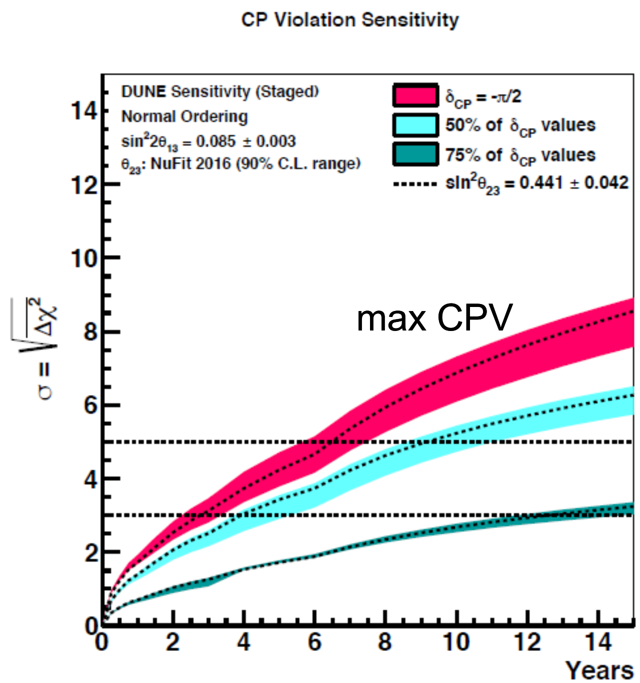
DUNE sensitivity: CP violation

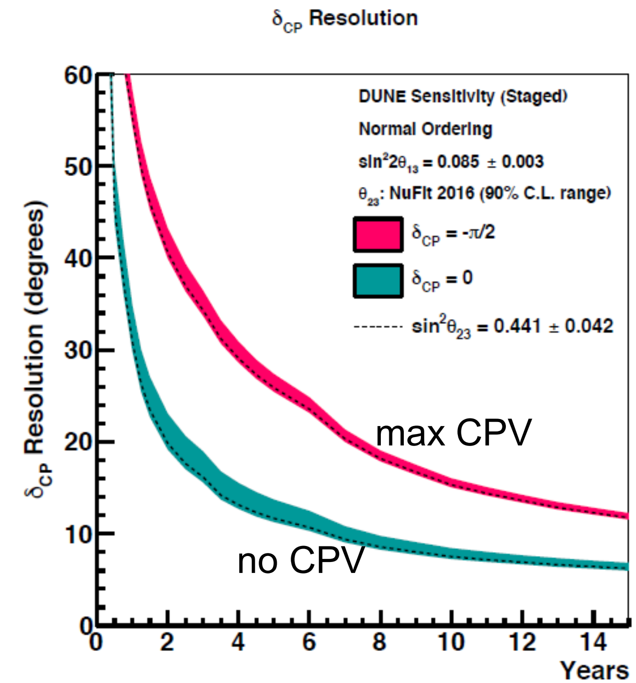
- rejection of $\sin\delta_{CP}=0$

  range of true δ_{CP}

δ_{CP} resolution

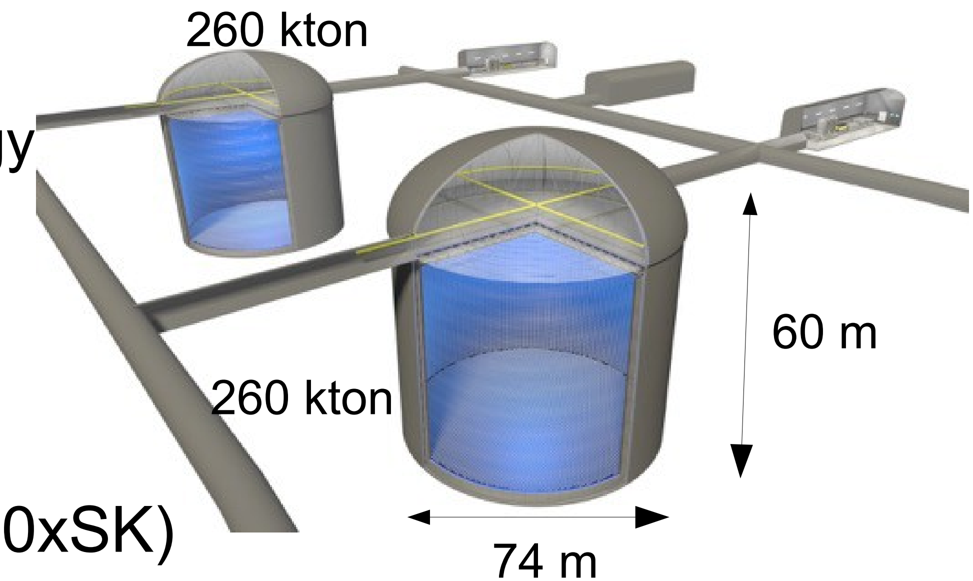




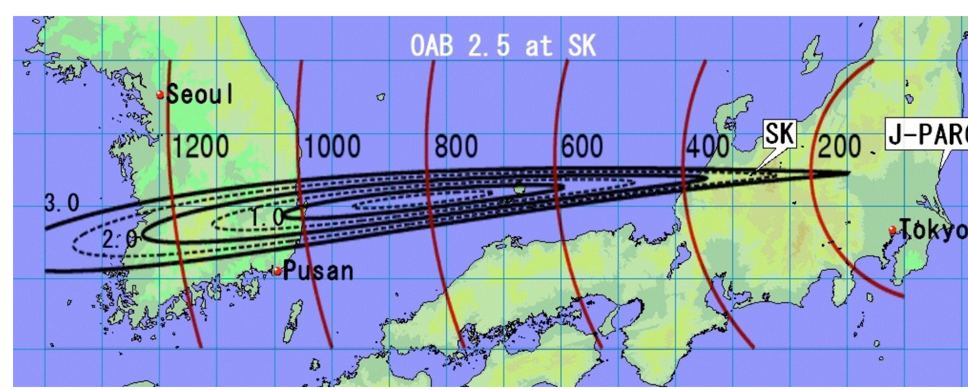


- far site construction started 2017
  - detector installation expected 2021, physics run 2024 (20 kton), beam 2026
  - 770 t LAr ProtoDUNE prototypes (single- and dual-phase) under construction at CERN, beam tests expected in 2018

Hyper-Kamiokande



- Water Cherenkov detector
  - mature, known, scalable technology
- 2 vertical tanks
  - building in stages possible
  - significant reduction of costs
- fiducial volume: 190 kton each (= 10xSK)
- new improved PMTs: 2x better photon efficiency and timing resolution (1ns) (other solutions under study)
- candidate site 8 km south of Super-Kamiokande
  - the same baseline (295 km) and off-axis angle (2.5°) as Super-K
  - second tank in Korea?



- continuous upgrade of J-PARC beam: 1.326 MW by 2026
- intermediate detector at 1-2km?

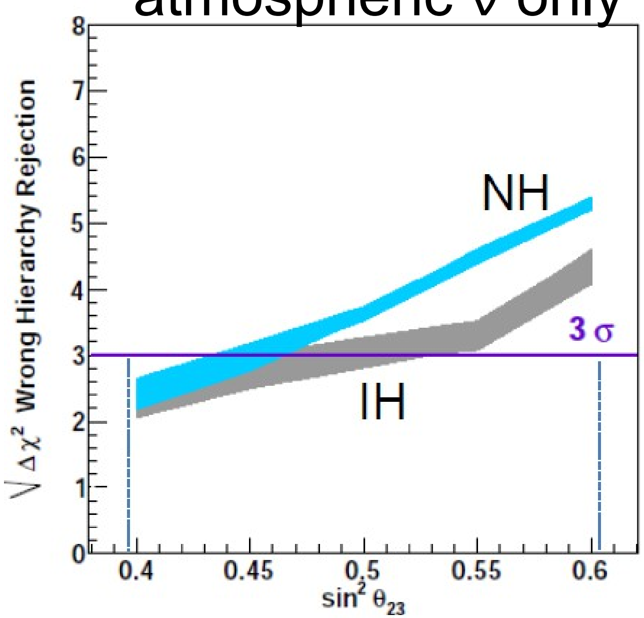
H-K sensitivity: mass hierarchy

- assumptions: 1st tank with 1.3 MW beam, 2nd tank 6 years later, ν:$\bar{\nu}$ data taking 1:3,
- sensitivity increased by combining beam and atmospheric neutrinos
  - 10 years exposure (2.6 Mton year) >5σ determination of mass hierarchy (if not known yet)
  - improved perfomance for θ_{23} octant determination

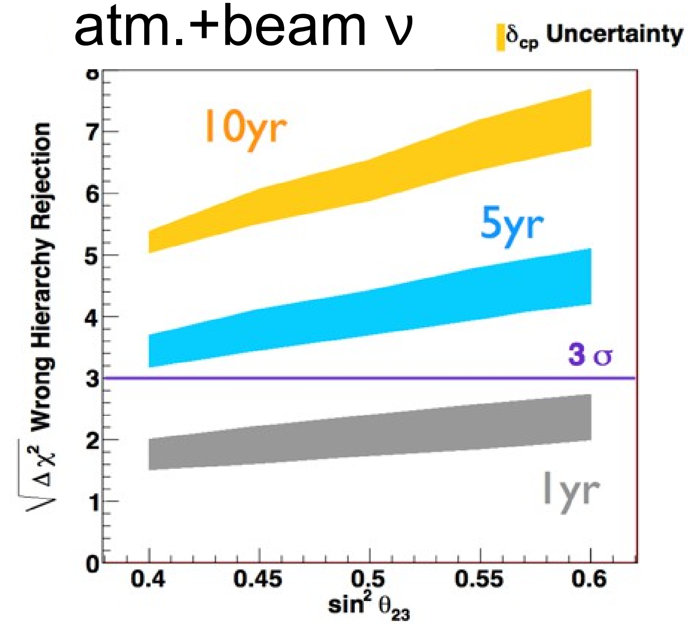
10 yrs NH		Mass Hierarchy (σ)	
		Atm	Atm+Beam
2Tanks	θ_{23}=0.4	2.2	5.3
	θ_{23}=0.6	5.2	6.9

10 yrs NH	Octant (σ)	
	Atm	Atm+Beam
θ_{23}=0.45	2.2	5.8
θ_{23}=0.55	1.7	3.7

atmospheric ν only

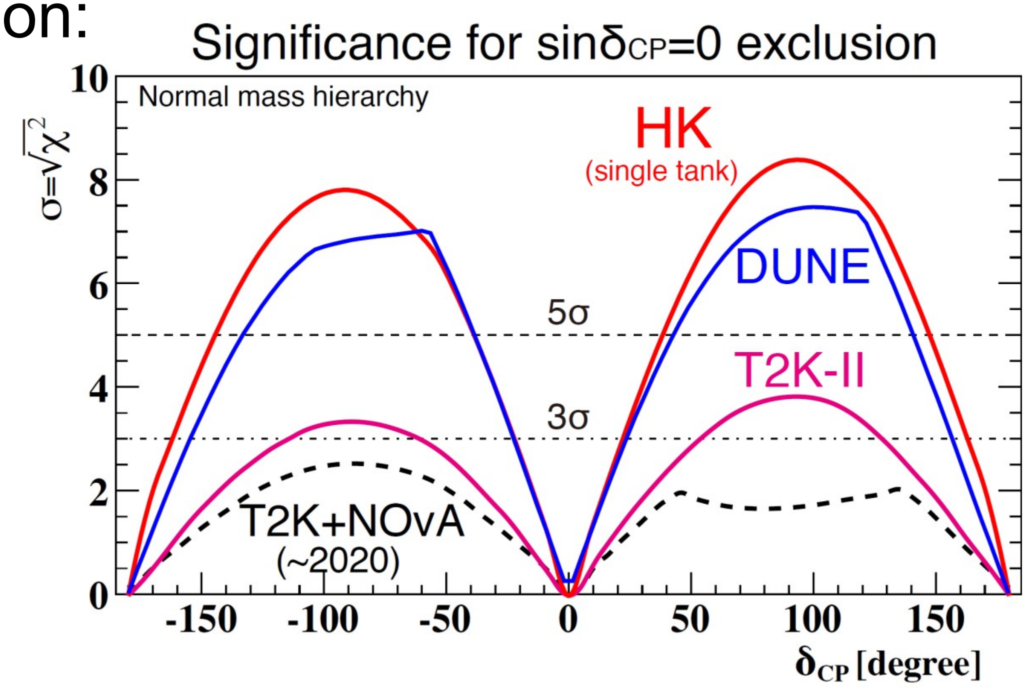


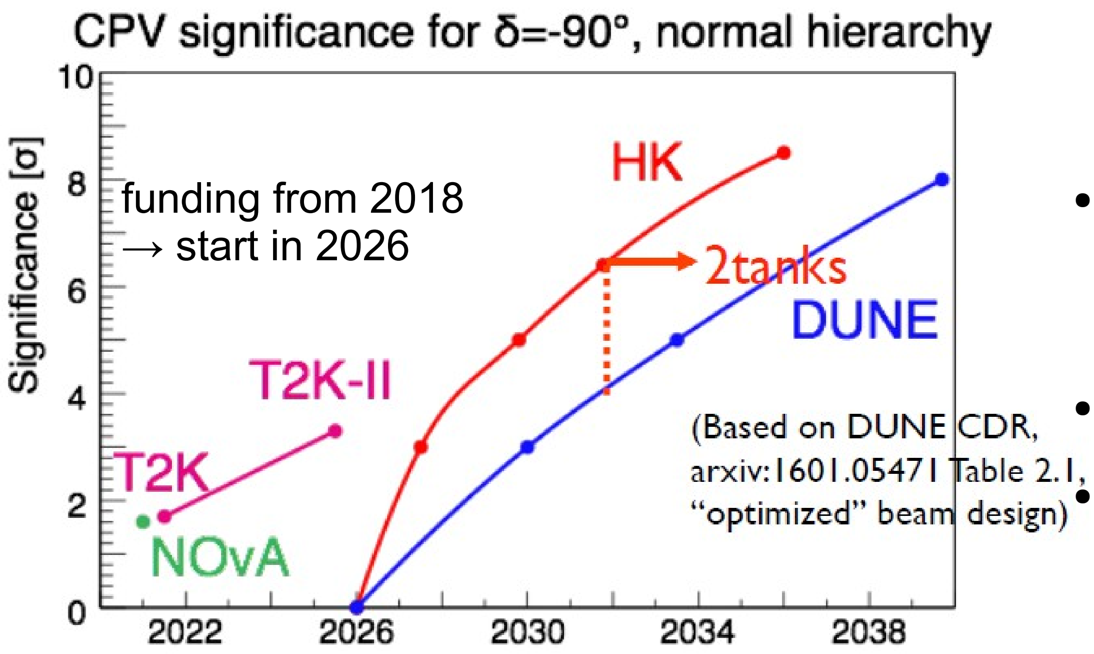
atm.+beam ν



H-K sensitivity: CP violation

- exclusion of $\sin\delta_{CP}=0$ with precision:
  - $> 8\sigma$ if true $\delta_{CP} = \pm 90°$
    $> 5\sigma$ for 57% of δ_{CP} values
    $> 3\sigma$ for 76% of δ_{CP} values
- δ_{CP} resolution
  - 21° precision at $\delta_{CP}=90°$
    7° precision at $\delta_{CP}=0°$





- selected as one of important large scale projects by Science Council of Japan
- listed on the ROADMAP2017 of MEXT
- upgrade of J-PARC is top priority in KEK Project Implementation Plan

Sterile neutrinos

- Experimental hints:
  - **LSND** anomaly: $\bar{\nu}_e$ appearance in $\bar{\nu}_\mu$ beam (3.8σ)
  - **MiniBooNE**: (anti)ν_e appearance in (anti)ν_μ beam (3.8σ)

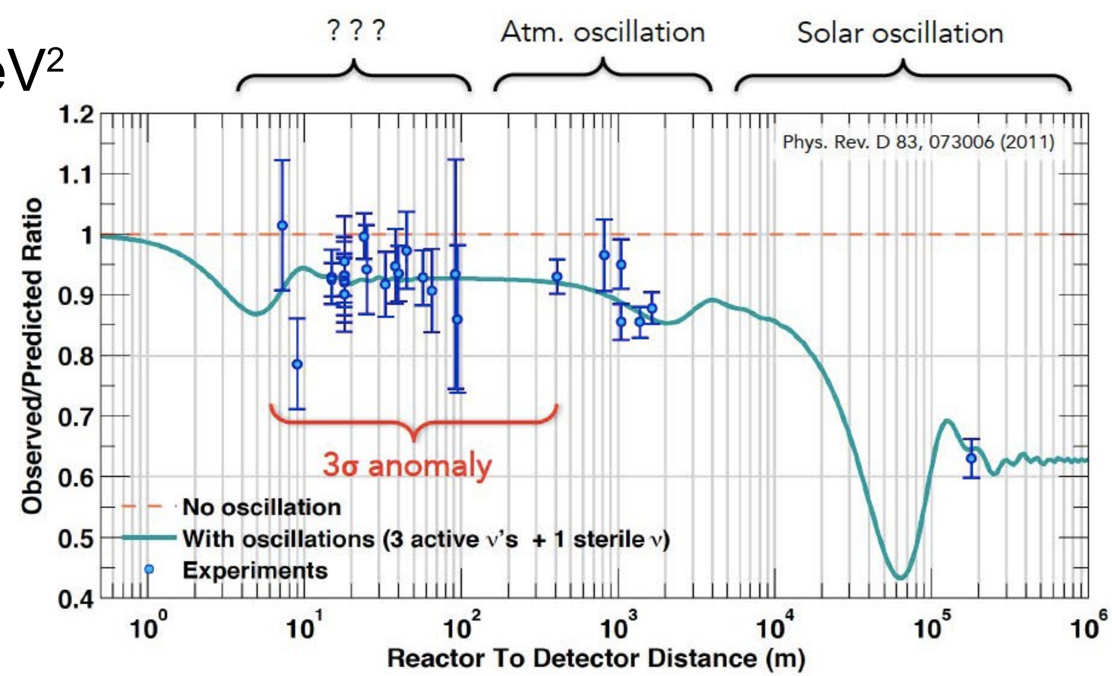
    } different short baseline different energy similar L/E

    - LSND effect expected at high energy, but excess seen at low energy
  - **gallium** anomaly: lower ν_e event rates for ^{51}Cr and ^{37}Ar sources used to calibrate solar neutrino detectors filled with gallium (2.9σ)
  - **reactor** anomaly: deficit of $\bar{\nu}_e$ compared to reactor flux prediction (2.8σ)
  - all anomalies point to $\Delta m^2 \sim 1 eV^2$
- sterile neutrinos can affect oscillations through mixing:

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

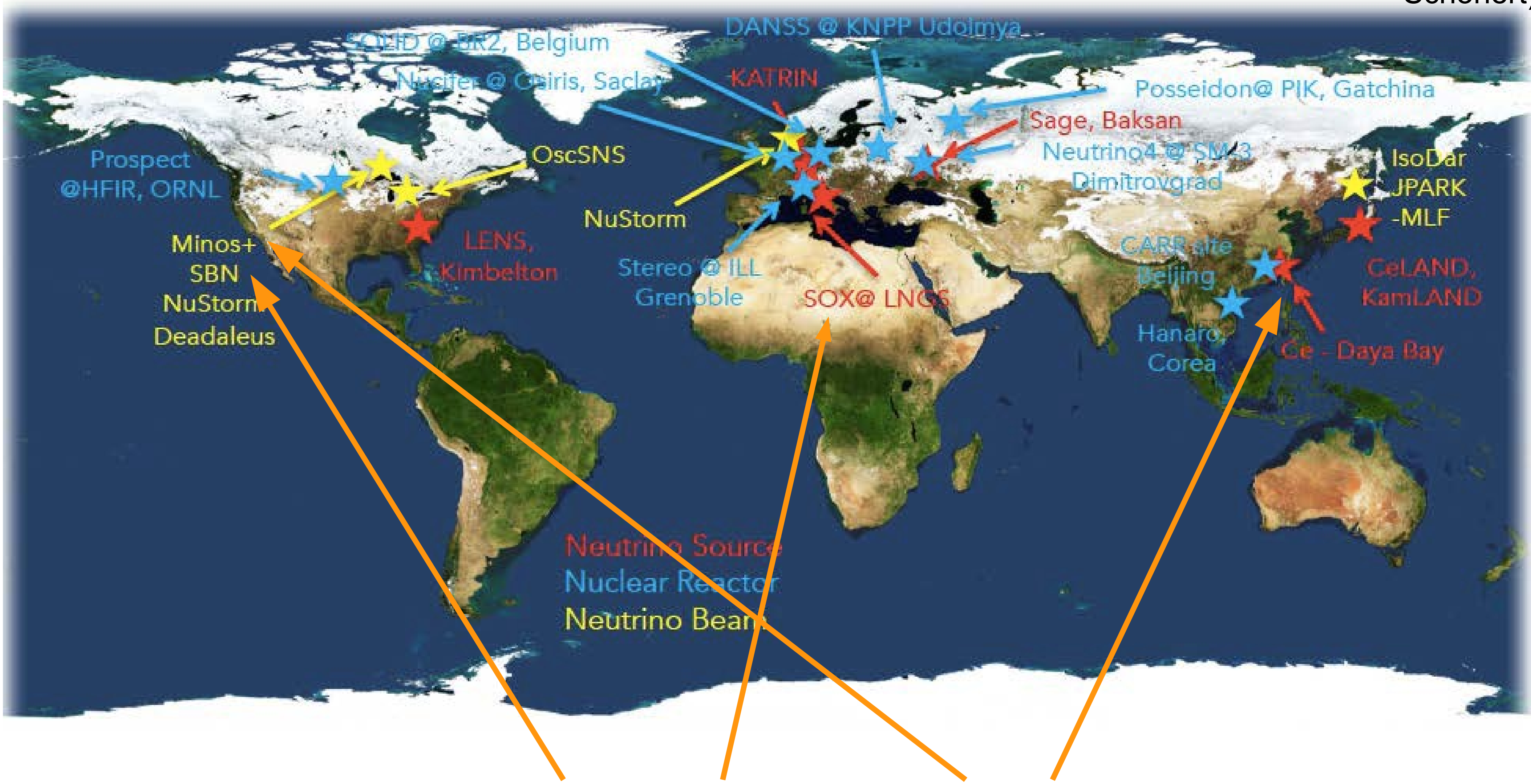
SBL

3+1 hypothesis



Searching for sterile neutrinos

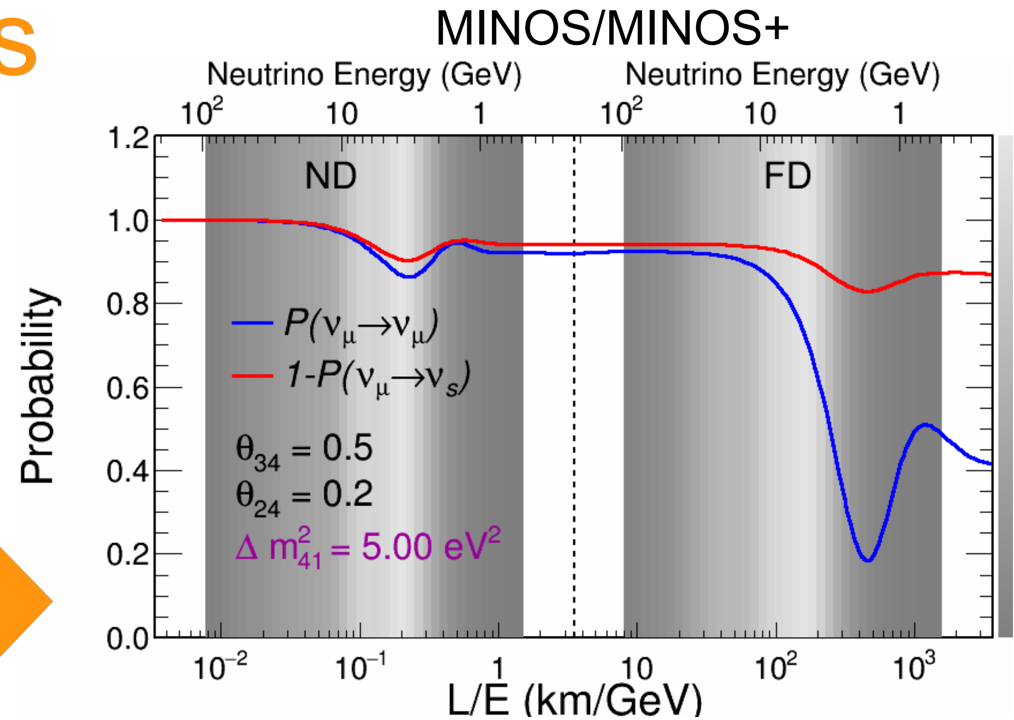
(Stefan Schönert)

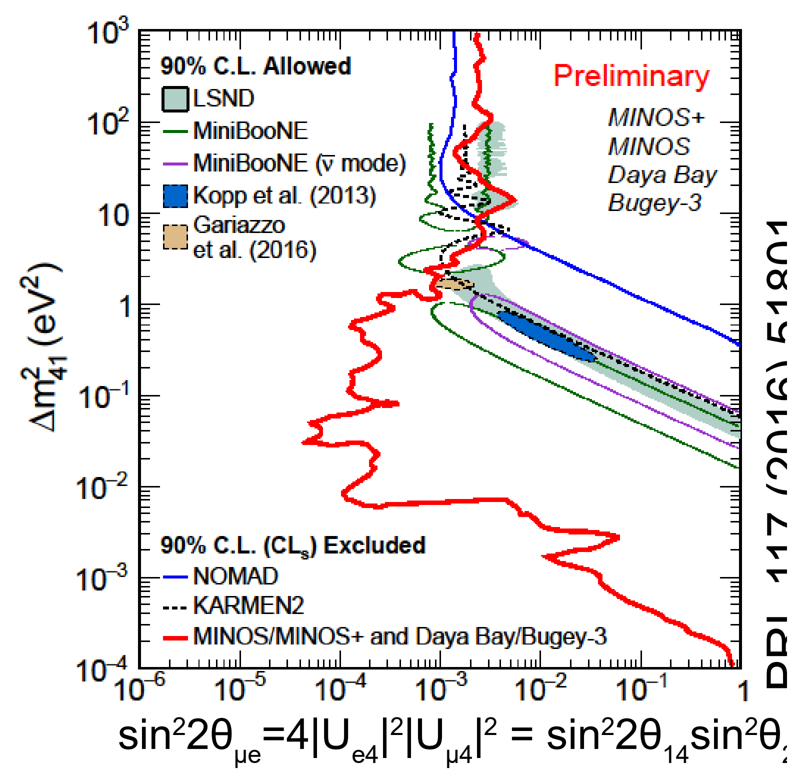


in this talk: future experiments current results

Current results

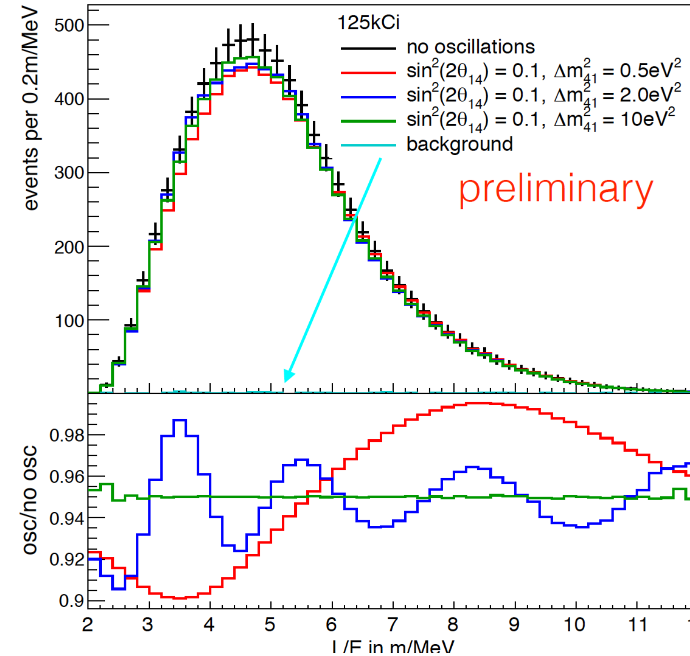
- Daya Bay: fuel evolution measurement explains the reactor anomaly?
  - oscillations disfavored at 2.6σ
    PRL 118 (2017) 251801
- ν_μ disappearance in MINOS/MINOS+
  - long baseline experiment (735 km)
  - sensitive to θ_{24}, θ_{34} and Δm^2_{41}
  - both CC and NC channels used
  - ratio of Near and Far detector spectra
- combined with Daya Bay
  (to have θ_{14} measurement for comparison in LSND phase space)
- tension between appearance and disappearance experiments

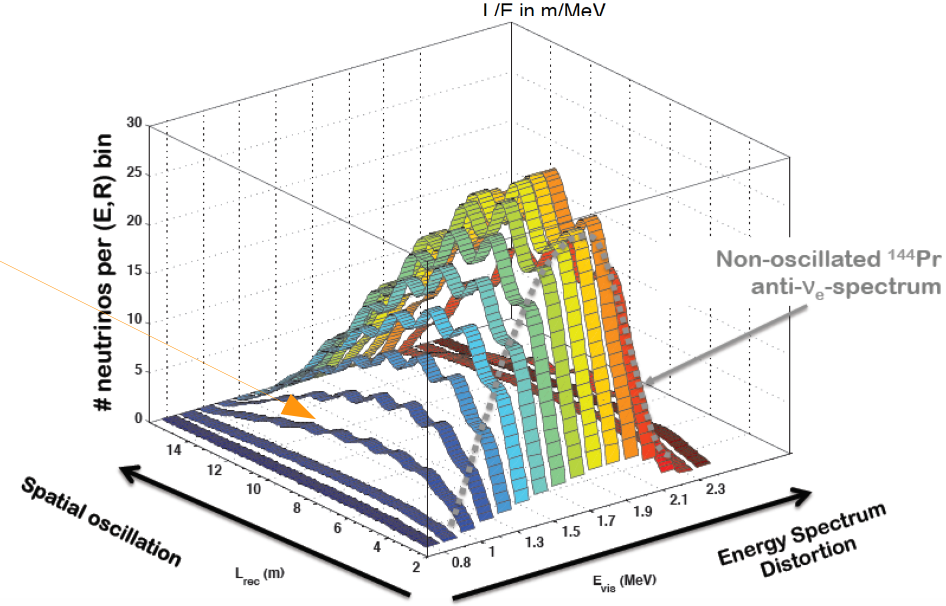


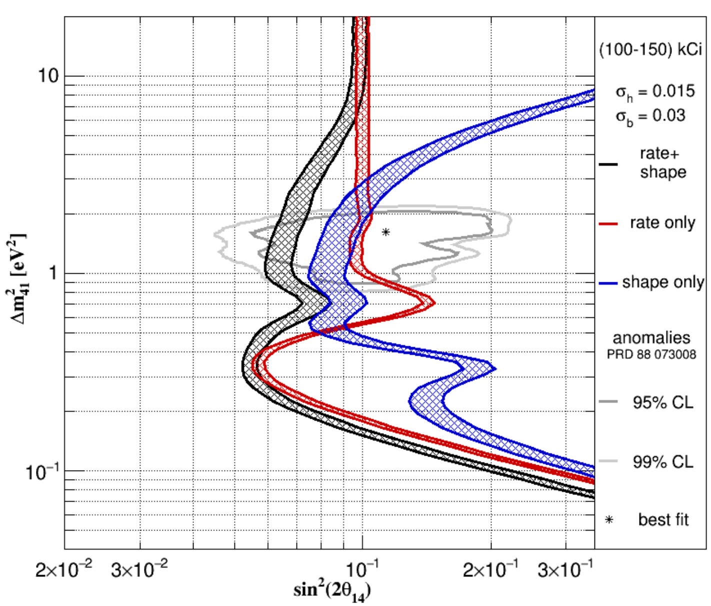


CeSOX

- Borexino detector and $\bar{\nu}_e$ from PBq ^{144}Ce-^{144}Pr source
  - γ radiation must be fully shielded
  - activity measured by heat
- two different techniques
  - distortion of the energy spectrum
  - dependence on the distance from the source (spatial waves)
    - vertex resolution ~15cm





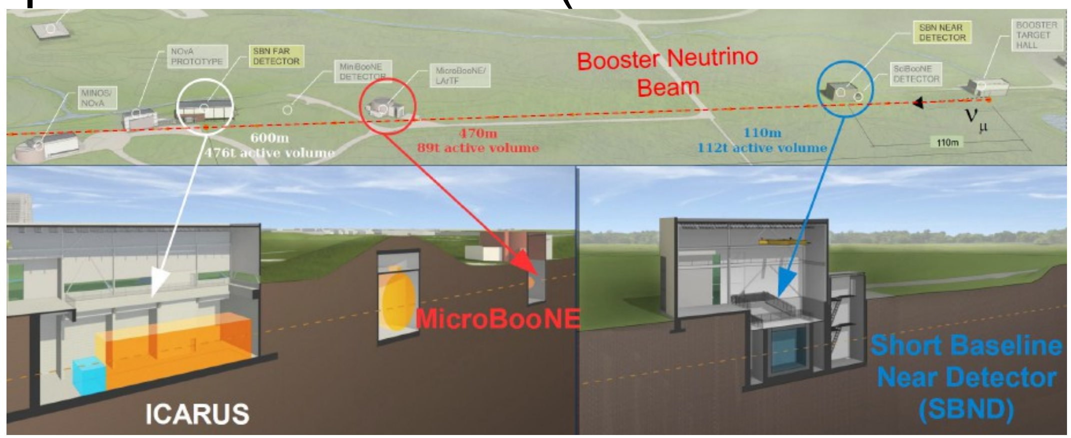


- source delivery to LNGS: April 2018
- physics run: 18 months (>10k events)

Liquid argon detectors in Fermilab

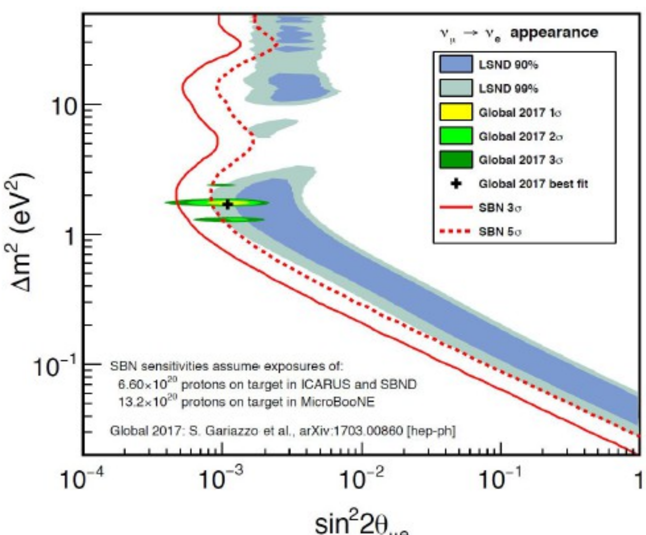
- is the excess in MiniBooNE coming from misidentified photons?
- liquid argon detectors can provide the answer
  - 3 detectors planned in Fermilab (Short Baseline Neutrino Program)

476 t active mass
at 600 m
during installation

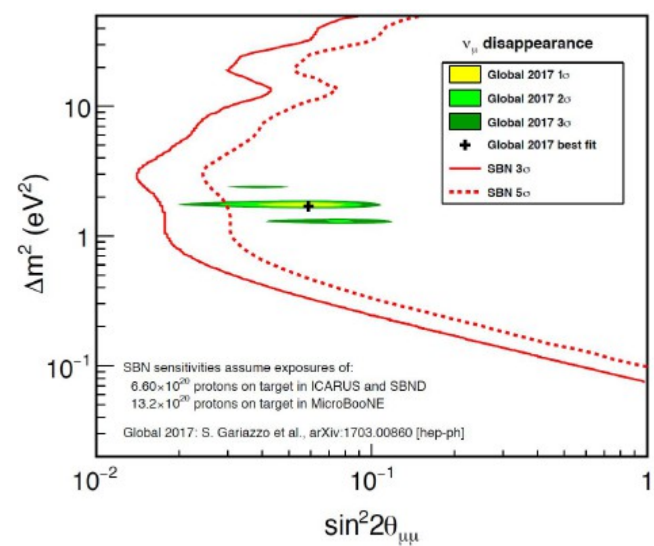


112 t active mass
at 110 m
in construction

85 t active mass
at 470 m, running

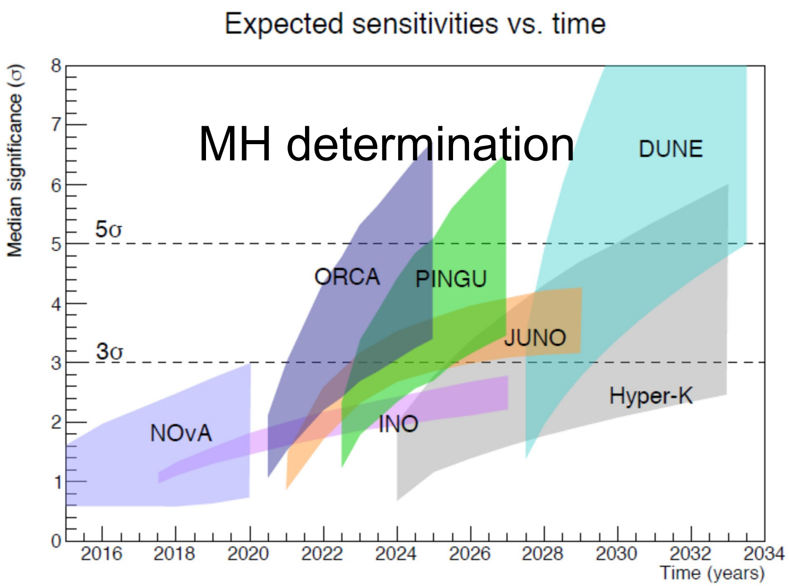


(anti)ν_e appearance and
(anti)ν_μ disappearance
can be studied



Summary

- era of precision measurements in neutrino oscillation physics
  - sensitivity and precision continuosly improved
- expected progress in next few years...
  - mass measurement in beta decay – KATRIN starting soon
  - 0γββ not observed, stronger limits expected in 2018
  - mixing angles – tension in θ_{23} measurements to be resolved
  - some hints on CP violation and mass hierarchy
    - 3σ for MH ~2020? for CPV ~2025?
  - no signal of sterile neutrinos yet – some answers within 3-5 years
- ...and in ~10years
  - 5σ sensitivity for mass hierarchy
  - 5σ sensitivity for CP violation

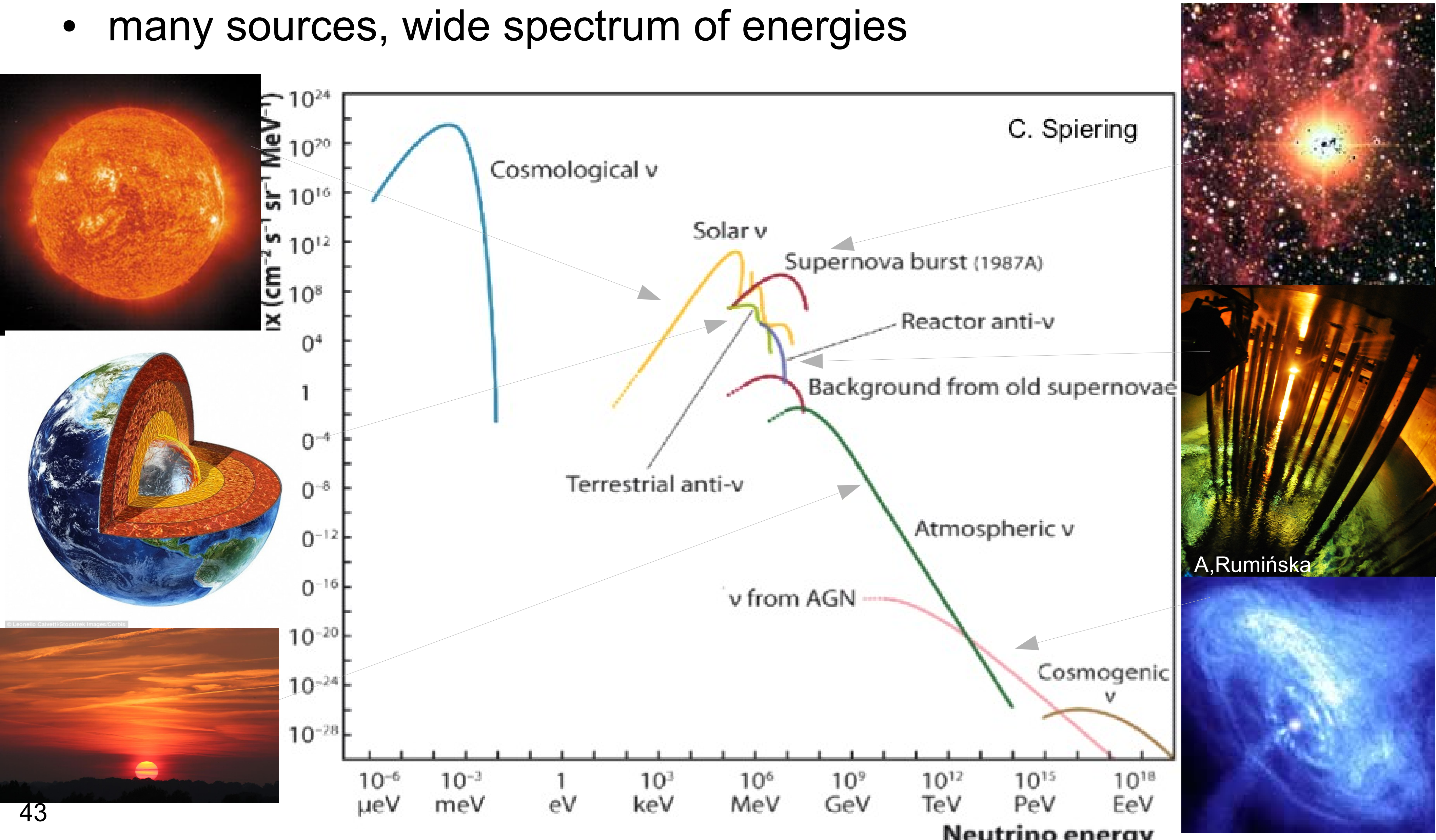


JHEP 1403 (2014) 028

Backup slides

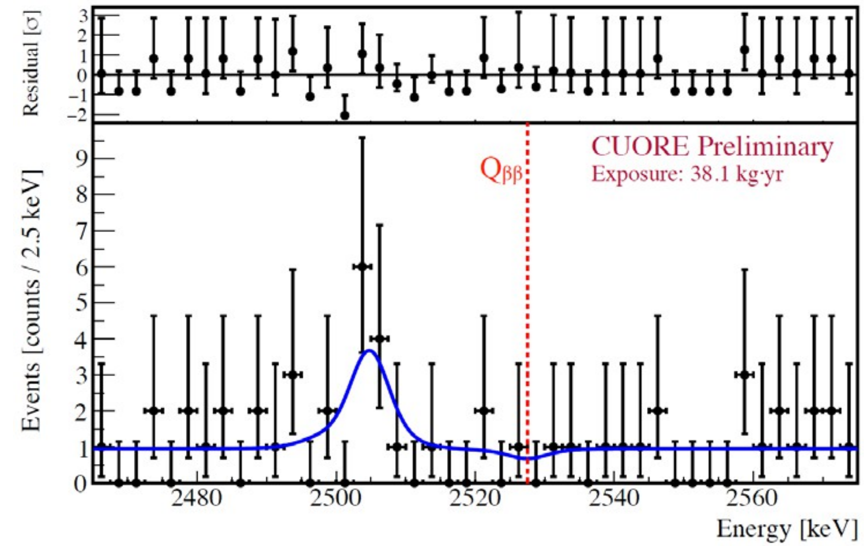
Sources of neutrinos

- second most abundant particles in the Universe
- many sources, wide spectrum of energies

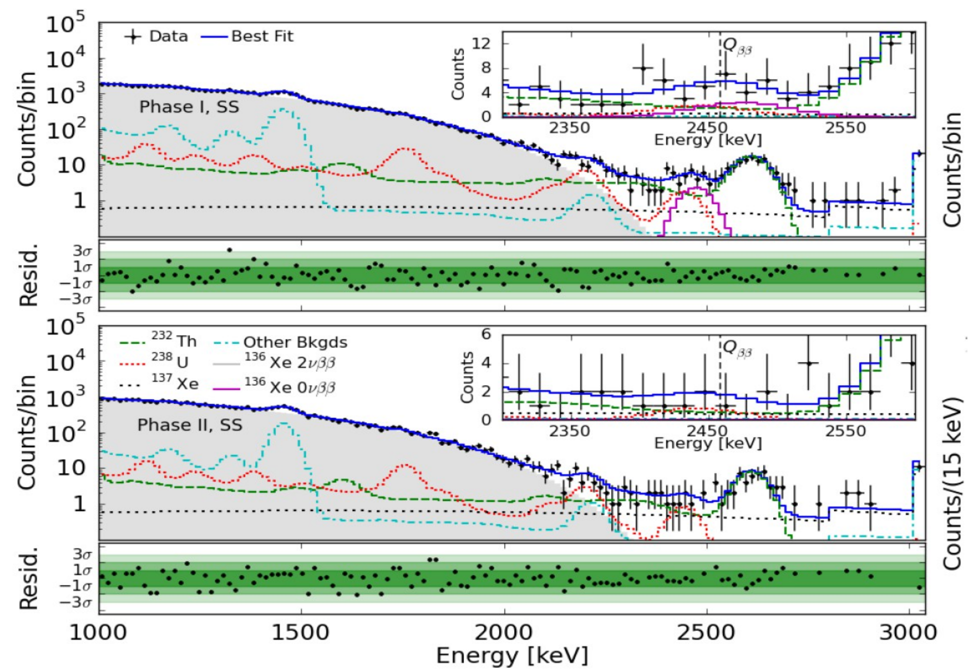


0νββ experiments

- CUORE: TeO_2 bolometers
  - 206kg of ^{130}Te
  - $T_{1/2} > 6.6 \cdot 10^{24}$ yr
  - $m_{\beta\beta} < 210\text{-}590$ meV



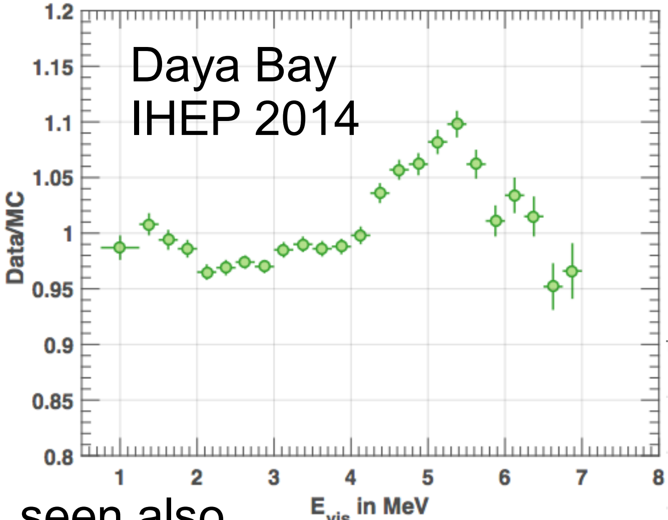
- EXO-200
  - 177.6 kg y
  - $T_{1/2} > 1.8 \cdot 10^{25}$yr (90% CL)
  - $\langle m_{\beta\beta} \rangle < 147\text{-}398$ meV

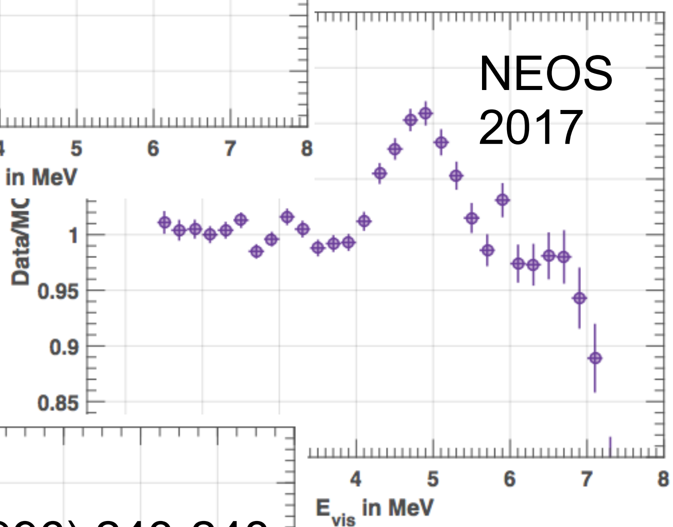


- No statistically significant excess: combined p-va

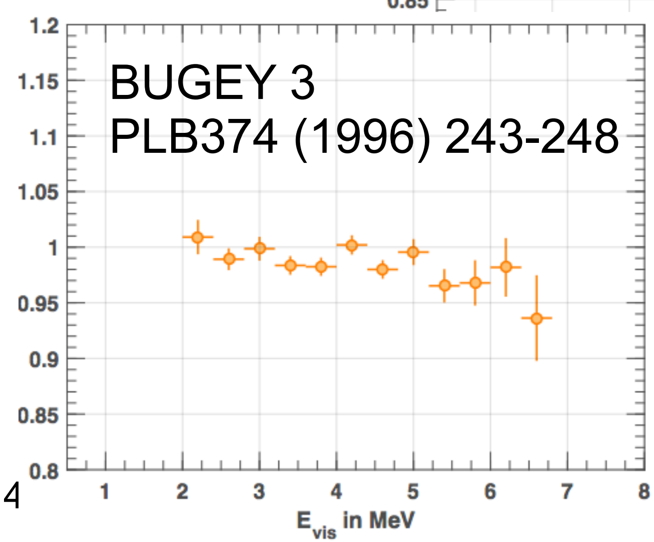
Reactor spectra measurements

- bump at 5 MeV



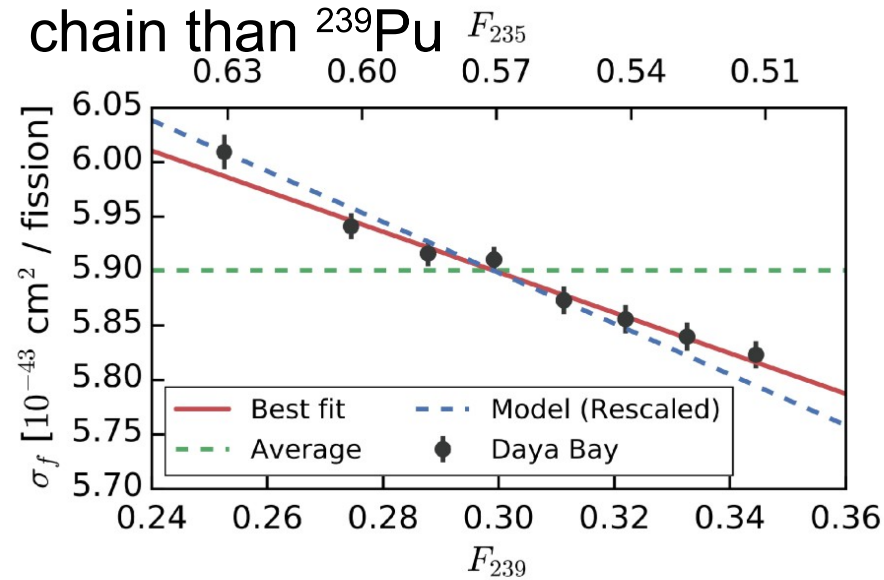


seen also by RENO and Double CHOOZ



RENO sees correlations with ^{235}U fraction (fresh fuel)

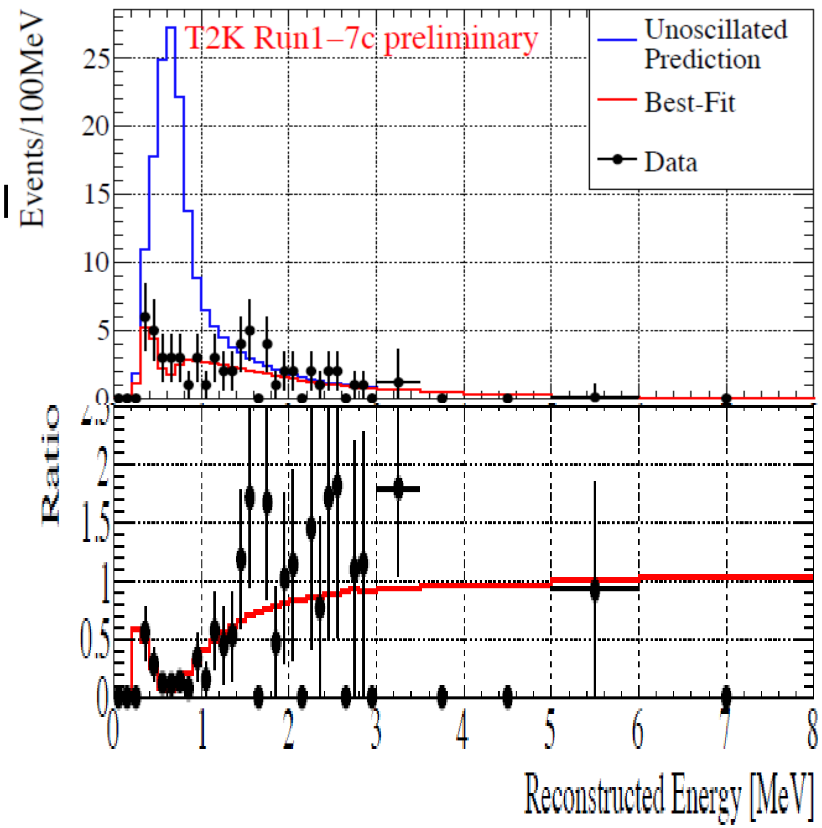
- evolution of flux and spectrum
(Daya Bay, PRL 118, 251801 (2017))
  - fuel composition evolves over time
  - expected more $\bar{\nu}_e$ from ^{235}U fission chain than ^{239}Pu

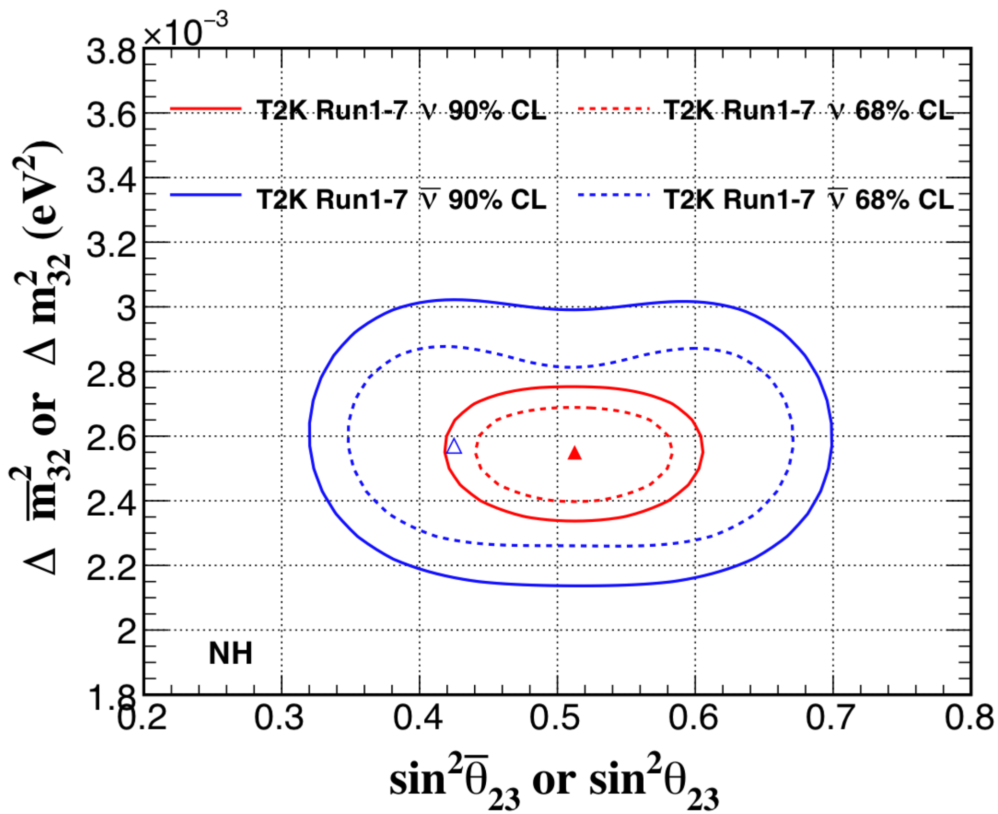


overestimated contribution from ^{235}U

$\bar{\nu}_\mu$ 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

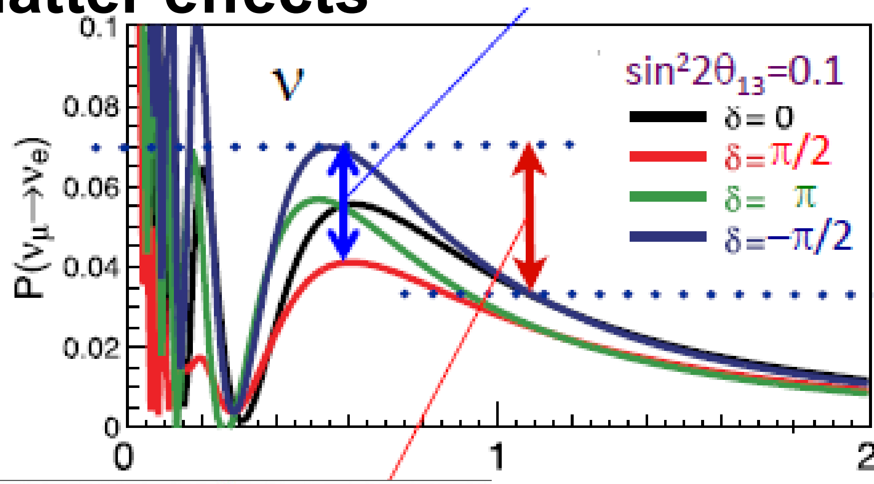


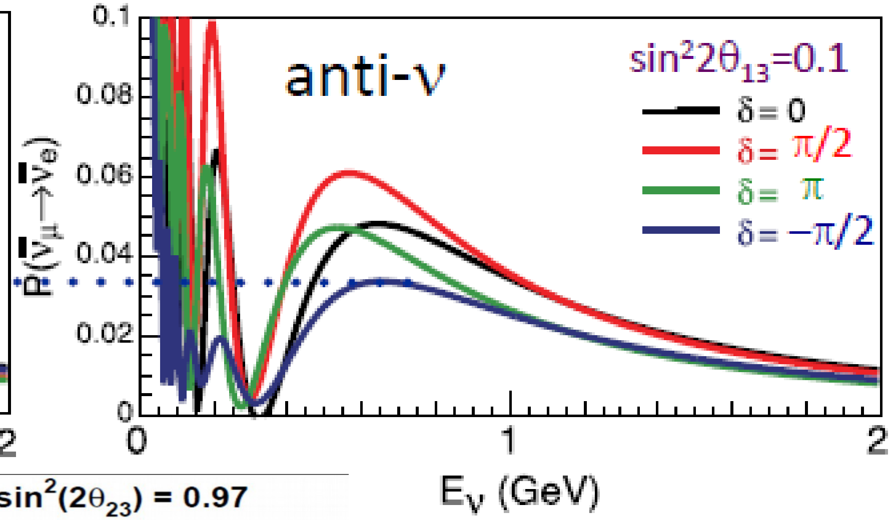


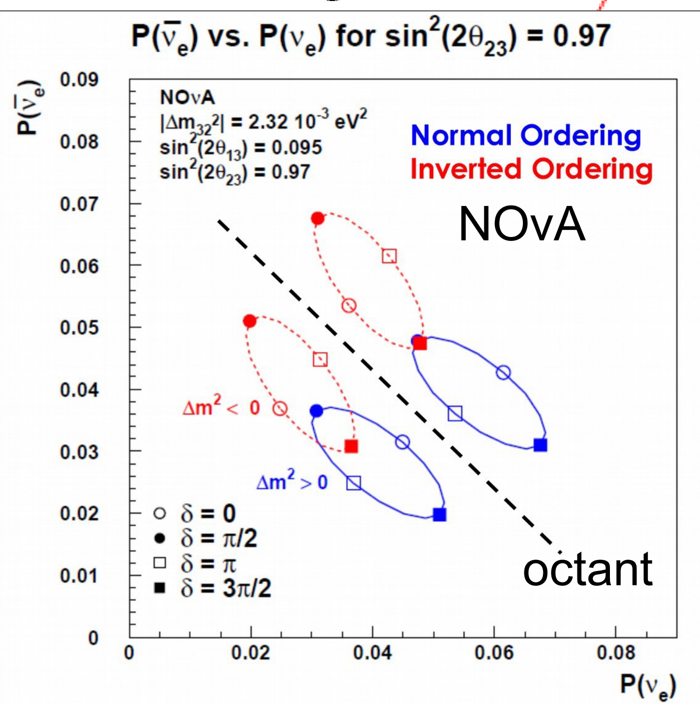
results consistent with **no difference** between disappearance of neutrinos and antineutrinos
→ CPT conserved

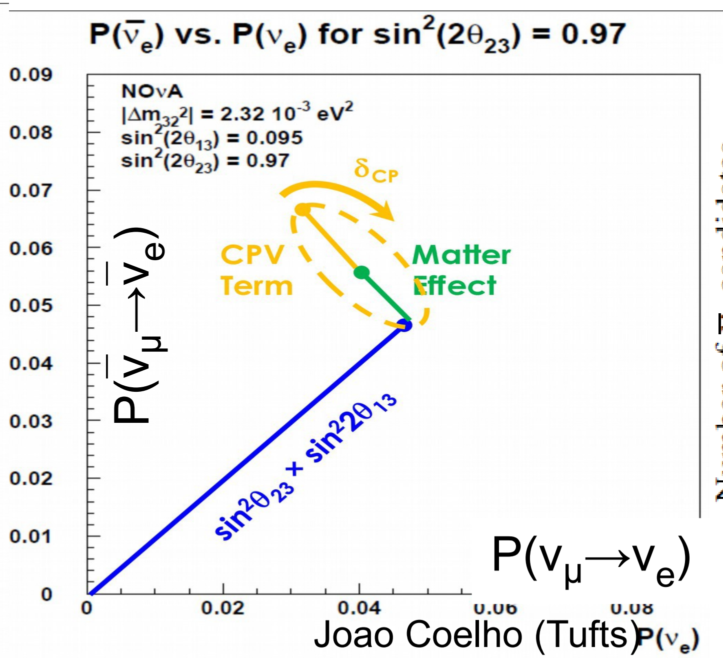
ν_e vs. $\bar{\nu}_e$ appearance

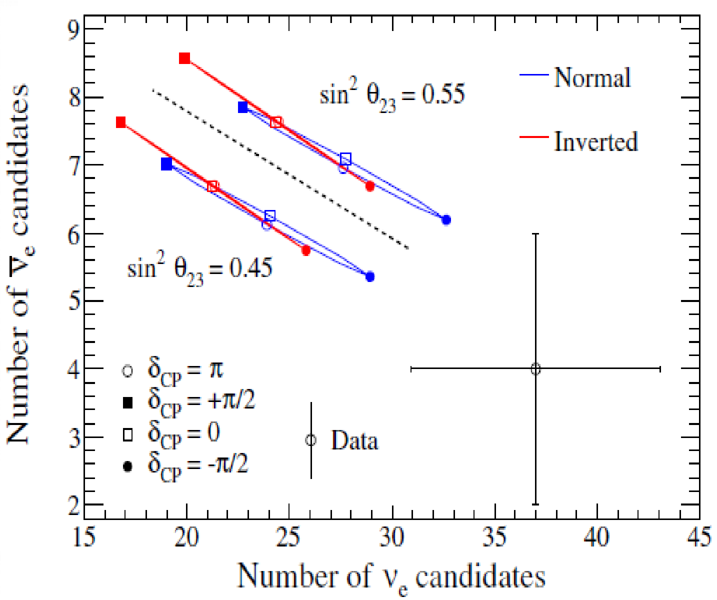
- different probabilities for ν and $\bar{\nu}$ even if CP is not violated – due to **matter effects**











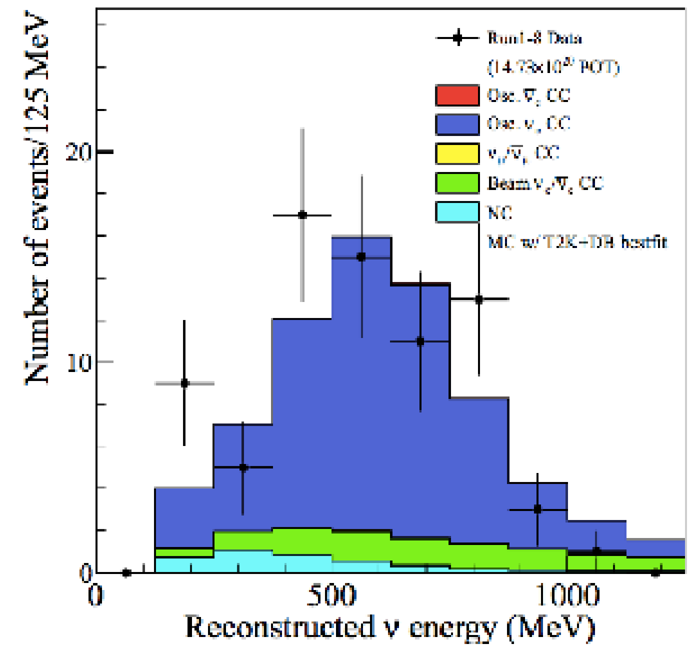
biprobability plots

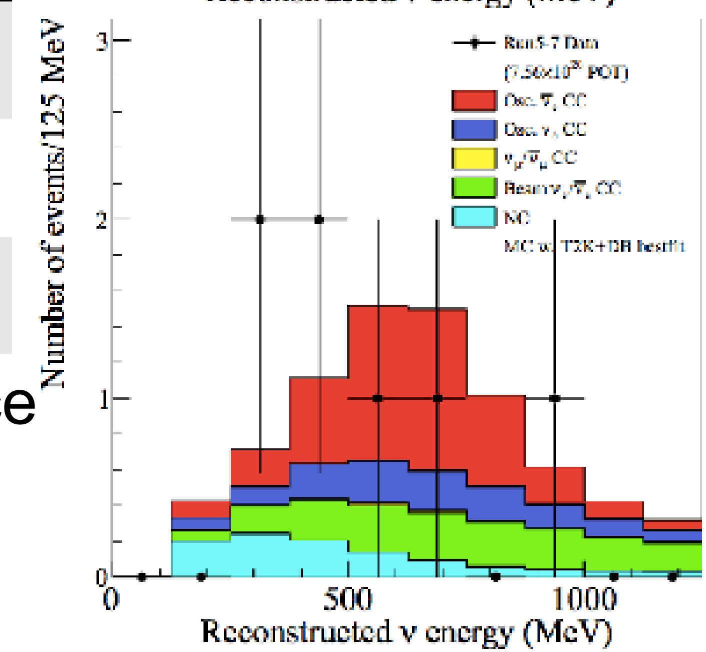
T2K results

- 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

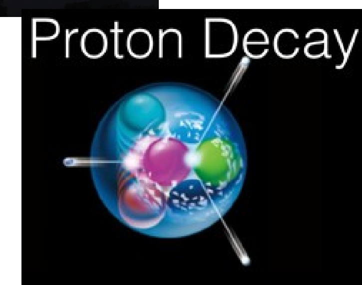
- more ν_e appearance and less $\bar{\nu}_e$ appearance than expected if CP is conserved



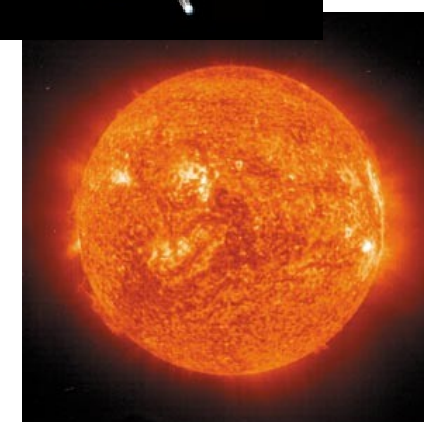


Other physics in future LBL experiments

- neutrino oscillations
  - with beam and atmospheric neutrinos
  - CP violation
  - precise measurement of θ23
  - mass hierarchy determination



- searching for nucleon decay
  - sensitivity 10x better than Super-K (10^{35} years)
  - HK: $p \to e^+\pi^0$, DUNE: $p \to \mu\pi^+K^+$, $p \to e^+\pi^+\pi^-$ and $p \to K^+\nu$, $p \to e^+K^0$ and $p \to \mu^+K^0$



- neutrino astrophysics
  - precise measurement of solar neutrinos, sensitivity to address solar and reactor neutrinos discrepancy
  - supernova burst and relic supernova neutrinos
  - geoneutrinos

- indirect Dark Matter search