Co nowego w fizyce neutrin ?

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Seminarium Fizyki Wysokich Energii
14.11.2014

Introduction

Neutrino physics after summer/autumn conferences

- Part 1: this seminar
- Part 2: Paweł Przewłocki, seminar in December

Based on:

- Neutrino 2014, Boston, 2-7.07.2014
- TMEX 2014, Warsaw, 3-5.09.2014 (organizers: NCBJ and UW)
- NNN 2014, Paris,4-6.11.2014
- Updated fit to three neutrino mixing, M.C.Gonzalez-Garcia, M.Maltoni, T.Schwetz, September 2014
- Sterile neutrino oscillations: the global picture, J.Kopp,M.Maltoni,T.Schwetz, March 2014

Outline

1. Status of Neutrino Oscillations
2. High-Energy Neutrinos
3. Recent Results from Reactor Experiments
4. Sterile Neutrinos

STATUS OF NEUTRINO OSCILLATIONS

3 flavor neutrino mixing

mixing matrix $\boldsymbol{U_{PMNS}}$: 3 mixing angles θ_{ij}, CP phase δ

+ 2 mass differences Δm^2_{21}, Δm^2_{32}

$s_{13} = \sin\theta_{13}$
$c_{13} = \cos\theta_{13}$

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

atmospheric ν
+ K2K, MINOS
$\sin^2 2\theta_{23} = 0.999 \pm 0.018$
$\theta_{23} \approx 45°$
$\Delta m^2_{32} = (2.44 \pm 0.06) \cdot 10^{-3} eV^2$

reactor ν
+ LBL
$\sin^2 2\theta_{13} = 0.093 \pm 0.008$
$\theta_{13} \approx 9°$

solar ν
+ KamLAND
$\sin^2 2\theta_{12} = 0.846 \pm 0.021$
$\theta_{12} \approx 33°$
$\Delta m^2_{21} = (7.53 \pm 0.18) \cdot 10^{-5} eV^2$

PDG 2014

Open questions:

Dirac or Majorana?

$\theta_{23} \gtreqless 45°$?

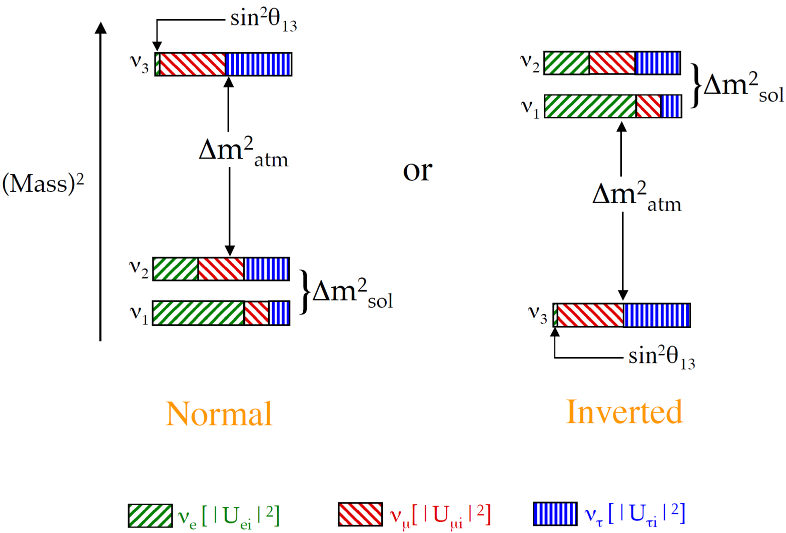
$\delta = ?$

absolute mass scale?

$\Delta m^2_{31} \gtrless \Delta m^2_{32}$?

Marianne Göger-Neff, NNN2014

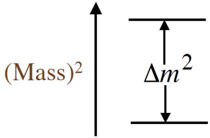
3 flavour neutrino mixing



B.Kayser

Neutrino oscillations

- Before θ_{13} were measured, oscillation probability were often approximated by two-flavour formula:



$$P(\nu_\alpha \to \nu_\beta) \simeq \sin^2 2\theta_{\alpha\beta} \sin^2 \left[1.27\Delta m^2 (eV^2) \frac{L(km)}{E_\nu(GeV)}\right]$$

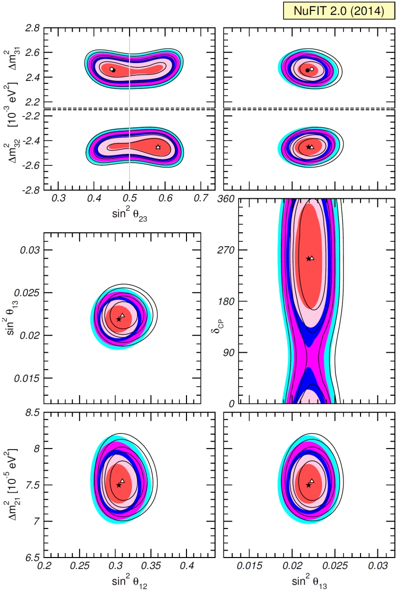
Neutrino oscillations

- Currently:
  In long-baseline experiments:

$$P(\nu_\mu \to \nu_\mu) \approx 1 - (\cos^4\theta_{13}\sin^2 2\theta_{23} + \sin^2 2\theta_{13}\sin^2\theta_{23})\sin^2\left(\frac{\Delta m^2_{13}L}{4E}\right) + (\text{matter terms})$$

$$\begin{aligned} P(\nu_\mu \to \nu_e) \simeq\ & \sin^2 2\theta_{13}\sin^2\theta_{23}\sin^2\frac{\Delta m^2_{31}L}{4E_\nu} \\ & - \frac{\sin 2\theta_{12}\sin 2\theta_{23}}{2\sin\theta_{13}}\sin\frac{\Delta m^2_{21}L}{4E_\nu}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{31}L}{4E_\nu}\sin\delta_{CP} \\ & + (\text{CP even term, solar term, matter effect term}) \end{aligned}$$

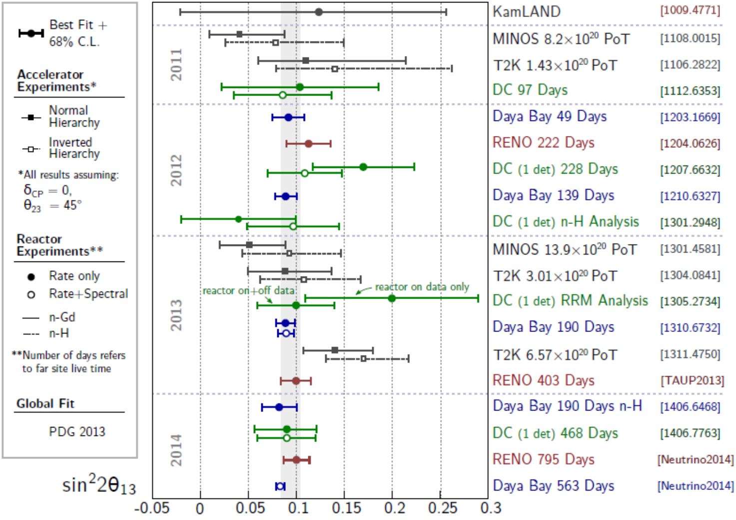
Results from global fit



Global 3ν fit

- Two-dimensional projections after minimization with respect to the undisplayed parameters.
- 1 σ, 2 σ, 3 σ contours
- full regions: free normalization of reactor fluxes + reactor SBL data
- void regions: predicted reactor fluxes, no reactor SBL data
- Δm^2_{31} for NO (Normal ordering/hierarchy)
- Δm^2_{32} for IO

Summary of Results on θ_{13}

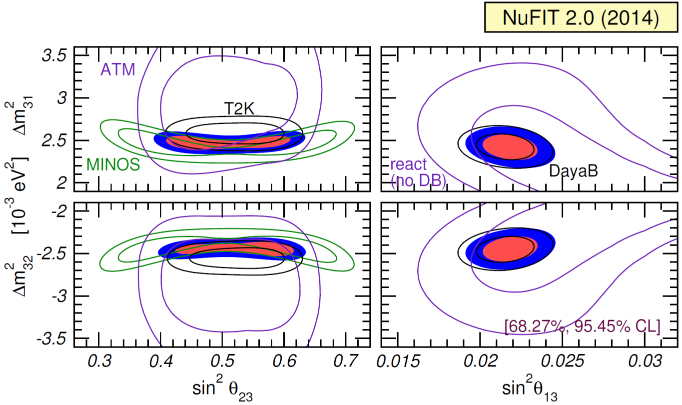


Marianne Göger-Neff, NNN2014

θ_{13} measurements $\rightarrow$ results from global fit

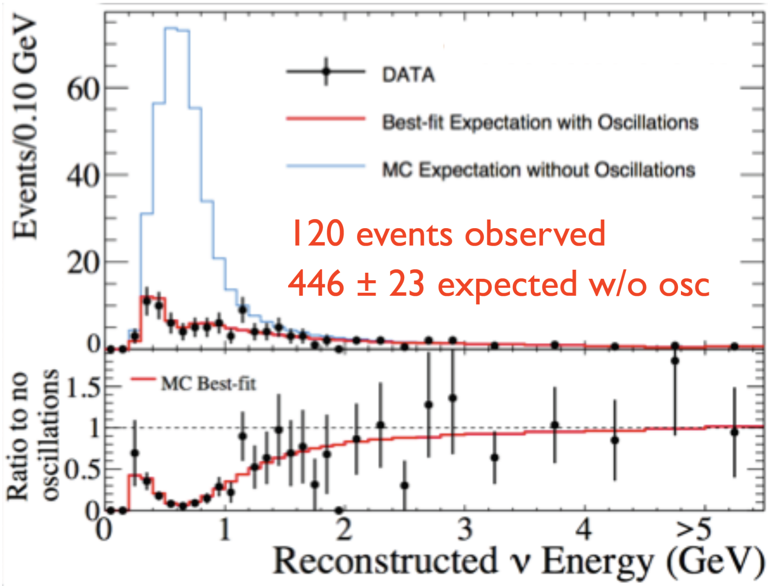
- difference between best fit θ_{13} from reactors and $\nu_\mu \rightarrow \nu_e$ at T2K leads to best global fit value close to $\delta_{CP} = \frac{3}{2}\pi$

Results from global fit

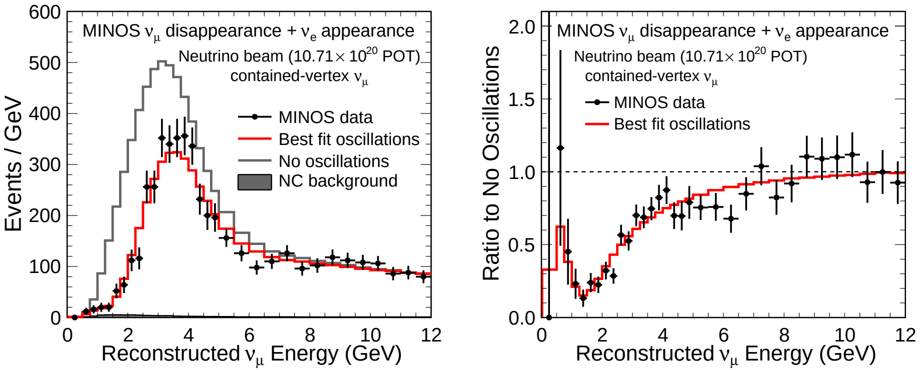


- Tendency (for IO) towards non-maximal mixing and second octant of δ_{23} driven by: MINOS ν_μ disappearance and difference between best fit θ_{13} from reactors and $\nu_\mu \to \nu_e$ at T2K.

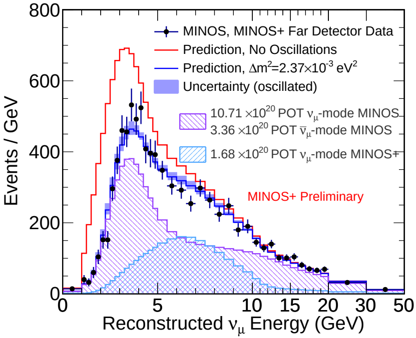
Inputs for global fits - ν_μ disappearance, T2K

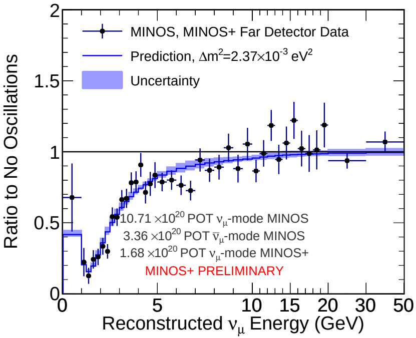


Inputs for global fits - ν_μ disappearance, MINOS



MINOS + ν_μ disappearance curve



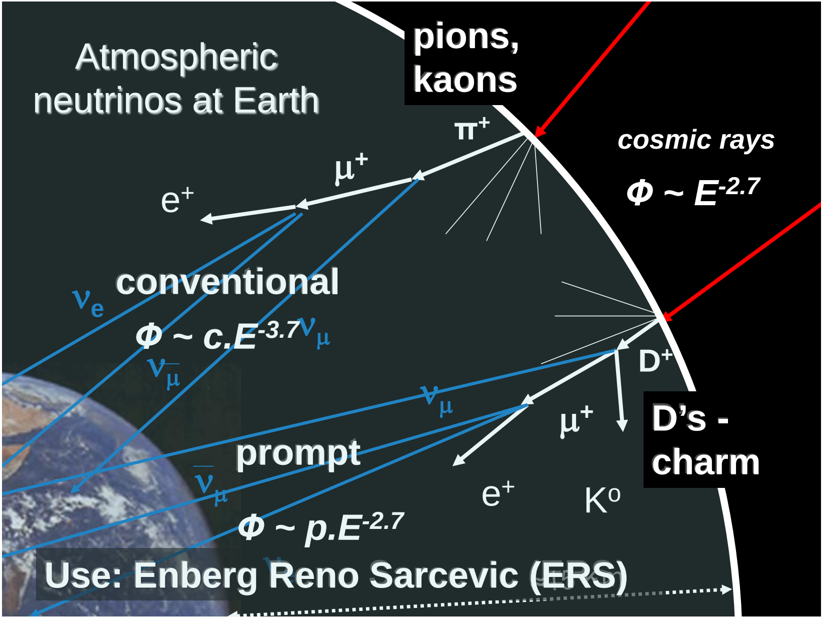


HIGH-ENERGY NEUTRINOS

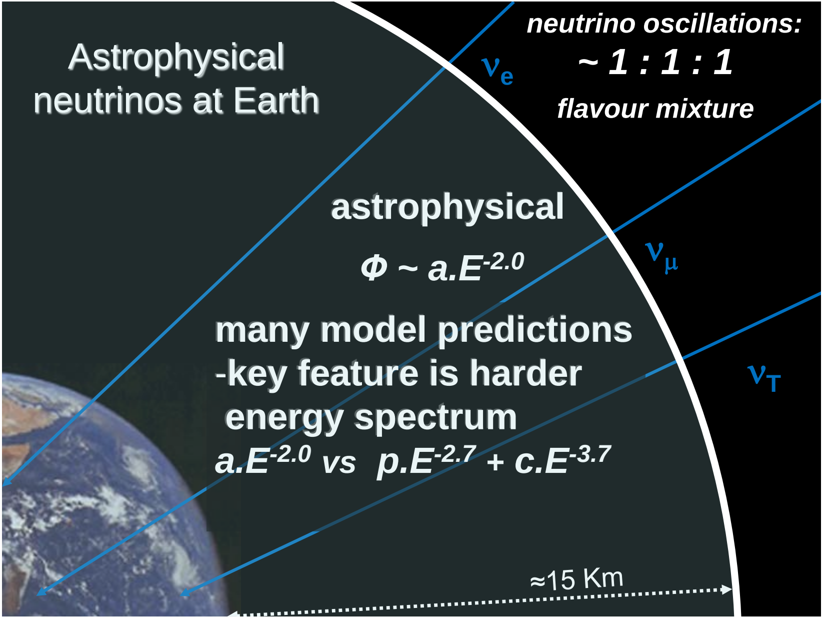
High Energy Neutrinos

New results from Ice Cube

- Astrophysical neutrinos
- Atmospheric neutrinos

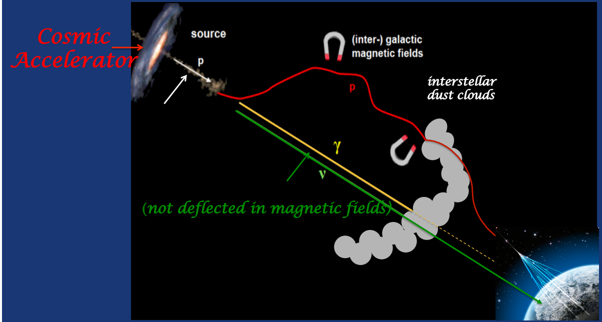


Gary C.Hill, Neutrino 2014



Gary C.Hill, Neutrino 2014

High Energy Neutrinos - Motivation



Neutrinos as probes of the high-energy Universe

J. Kiryluk (SBU), TMEX2014

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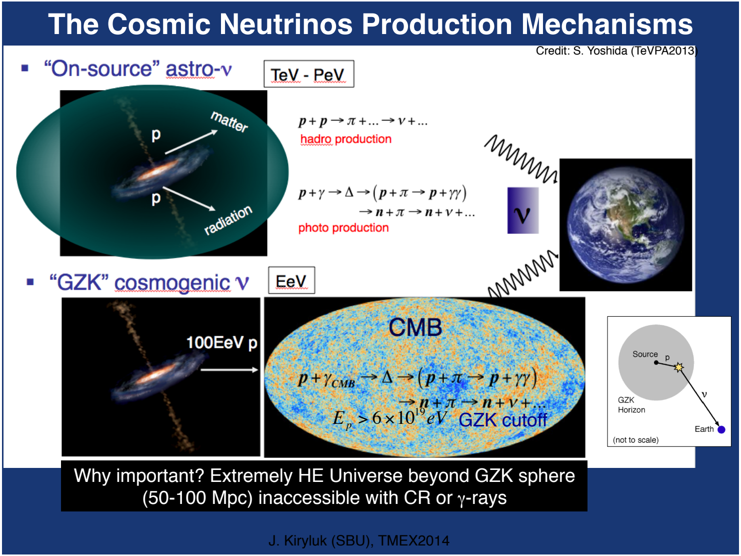

The Cosmic Neutrinos Production Mechanisms
Credit: S. Yoshida (TeVPA2013)
"On-source" astro-ν
TeV - PeV
matter
p
p
radiation
p + p → π + ... → ν + ...
hadro production
p + γ → Δ → (p + π → p + γγ)
→ n + π → n + ν + ...
photo production
ν
"GZK" cosmogenic ν
EeV
100EeV p
CMB
p + γ_CMB → Δ → (p + π → p + γγ)
→ n + π → n + ν + ...
E_p > 6×10^19 eV
GZK cutoff
Source
p
ν
GZK
Horizon
Earth
(not to scale)
Why important? Extremely HE Universe beyond GZK sphere
(50-100 Mpc) inaccessible with CR or γ-rays
J. Kiryluk (SBU), TMEX2014

IceCube

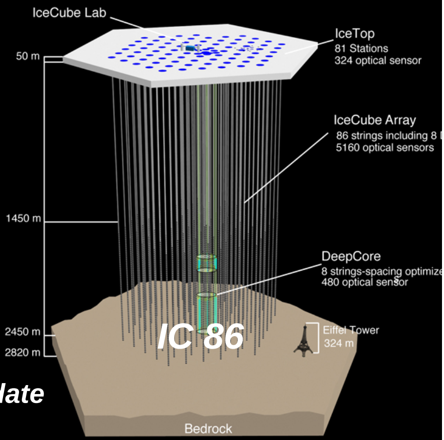
IceTop

Construction:
Dec 2004 – Dec 2010

86 strings x 60 DOM
IceTop air shower array

Partial detectors analysed:
IC40, IC59, IC79

Full detector:
IC86, 3 ½ years running to date
HESE: IC79/86-1
HESE-2: IC79/86-1/86-2



Gary C.Hill, Neutrino 2014

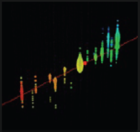
Ice Cube detector

Ice Cube - total volume $1km^3$
DOM = Digital Optical Module

- 78 strings spaced 125m apart on a hexagonal grid;
  DOMs placed every 17m
- 8 strings from Deep Core: distance between strings=30-60m;
  50 DOMs placed every 7m at depth 2100-2450 m
  and 10 DOMs placed every 10m at depth 1750-1850m

Neutrino event signatures

CC Muon Neutrino

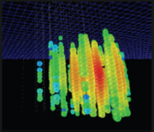


$$\nu_\mu + N \to \mu + X$$

track (data)

factor of ≈ 2 energy resolution
$< 1^\circ$ angular resolution

Neutral Current / Electron Neutrino



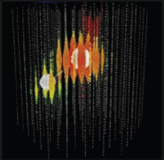
$$\nu_e + N \to e + X$$
$$\nu_x + N \to \nu_x + X$$

cascade (data)

$\approx \pm 15\%$ deposited energy resolution
$\approx 10^\circ$ angular resolution
(at energies $\gtrsim 100$ TeV)

CC Tau Neutrino

time



$$\nu_\tau + N \to \tau + X$$

"double-bang" and other signatures (simulation)

(not observed yet)

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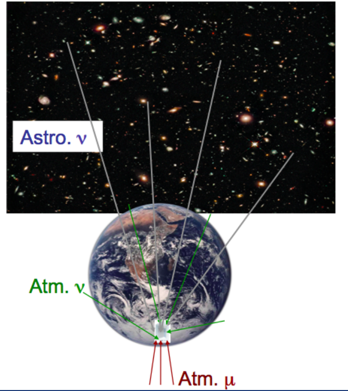
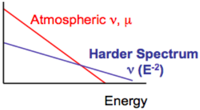
Neutrino Diffuse Flux Search: Method

Diffuse flux = effective sum from all (unresolved) extraterrestrial sources (e.g.AGNs)
Possibility to observe diffuse signal even if flux from an individual source is too small to be detected by point source techniques.



- Search for excess of astrophysical neutrinos with a harder spectrum than background atmospheric neutrinos using energy and direction (self-veto)



- Advantage over point source search: can detect weaker fluxes
- Sensitive to all three flavors of neutrinos
- Disadvantage: high background
  solution: containment cut / veto technique

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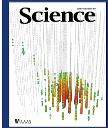


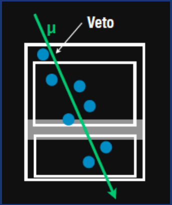
Discovery of Cosmic Neutrinos with IceCube

IC79+IC86 analysis of 2010-2013 data (3 years) to search for "High Energy Starting Events" (HESE) all-flavor neutrinos

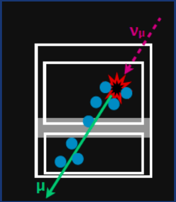
IceCube (2 years), Science 22 Vol. 342 no. 6161
IceCube (3 years), Phys. Rev. Lett.; arXiv:1405.5303

Method:

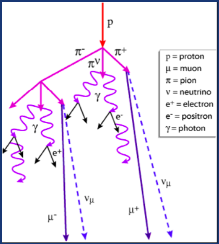
- Select high charge (Q > 6000 p.e.) events with vertices well contained in the detector volume
- No flavor tagging, combination of neutrino induced muons and cascades
- Use of the "veto" technique to reject bg (μ and atm. ν) and veto tagging to estimate remaining bg from data



Reject



Accept



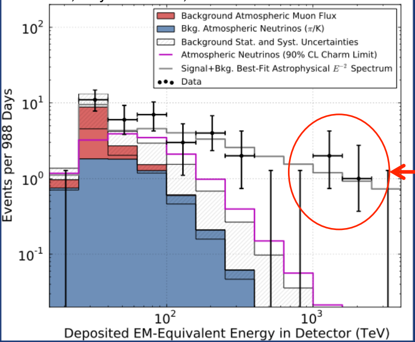
Schönert et al., arXiv:0812.4308

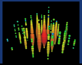
Discovery of Cosmic Neutrinos with IceCube

IC79+IC86 analysis of 2010-2013 data (3 years) to search for "High Energy Starting Events" (HESE) all-flavor neutrinos

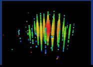
Observed 37 events (28 cascade-like, 9 track-like) in 30 TeV < E_ν < 3 PeV,
Expected 8.4 ± 4.2 number of background μ and $6.6^{+5.9}_{-1.6}$ atm. ν events.

IceCube , Phys.Rev.Lett.; arXiv:1405.5303

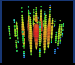




E = 1.0 PeV
θ = 62°



E = 2.0 PeV
θ = 34°



E = 1.1 PeV
θ = 23°

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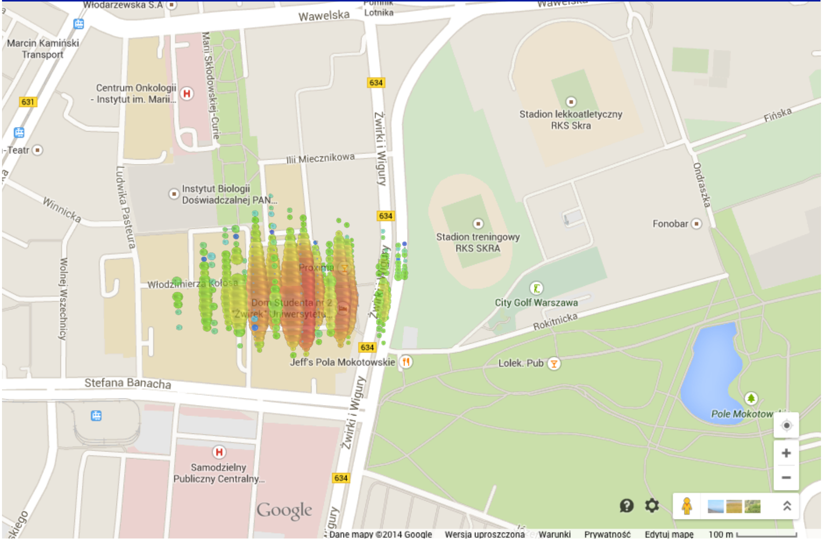
IceCube: One of the Highest Energy Neutrinos Ever Detected



Discovery of Cosmic Neutrinos with IceCube

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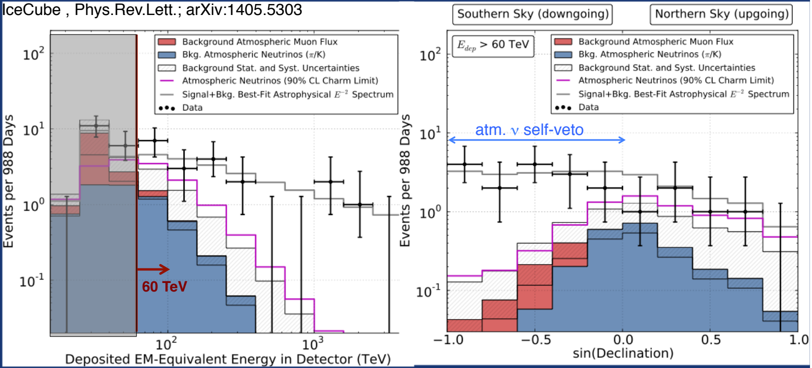
IceCube , Phys.Rev.Lett.; arXiv:1405.5303



Best-fit results: $E^2\Phi = (0.95 \pm 0.30) \times 10^{-8} \left[\mathrm{GeV\,s^{-1}sr^{-1}cm^{-2}}\right], \quad 60\,\mathrm{TeV} \le E_\nu \le 3\,\mathrm{PeV}$ (per ν flavor)

Alternative expanation: softer spectrum $\gamma = -2.3 \pm 0.3$

Background only hypothesis disfavored at 5.7σ

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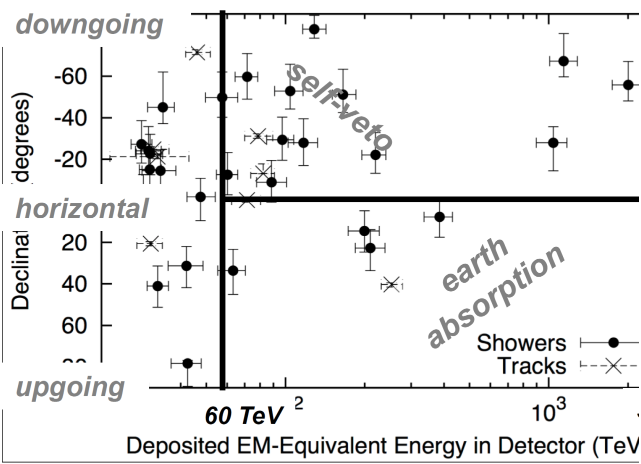
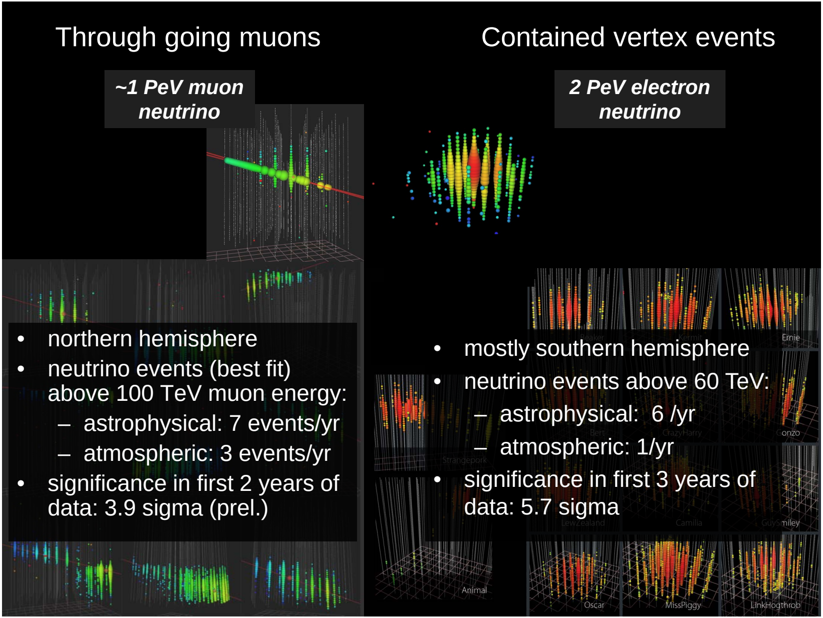
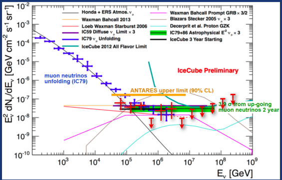
Arrival angles and deposited energies of the highest energy events.





Gary C.Hill, Neutrino 2014

Neutrino Diffuse Flux Search: Results (Status 2014)



- IceCube astrophysical flux results:

$$E^2\Phi = (2.85 \pm 0.90) \times 10^{-8}\,[\mathrm{GeV s^{-1} sr^{-1} cm^{-2}}] \quad E_\nu \geq 60\,\mathrm{TeV} \quad (IceCube, HESE\ 3y)$$

$$E^2 \cdot \Phi = (2.9 \pm 1.0) \times 10^{-8}\,[\mathrm{GeV cm^{-2} s^{-1} sr^{-1}}] \quad E_\nu \geq 100\,\mathrm{TeV}\ (IceCube, 3 \times \nu_\mu, 2y)$$

Consistent measurements!

consistent with isotropic flux (extra-Galactic origin?) and equal flavor ratio:

$$\nu_\mu : \nu_e : \nu_\tau = 1:1:1$$

- Consistency between IceCube results and the Waxman-Bahcall bound:

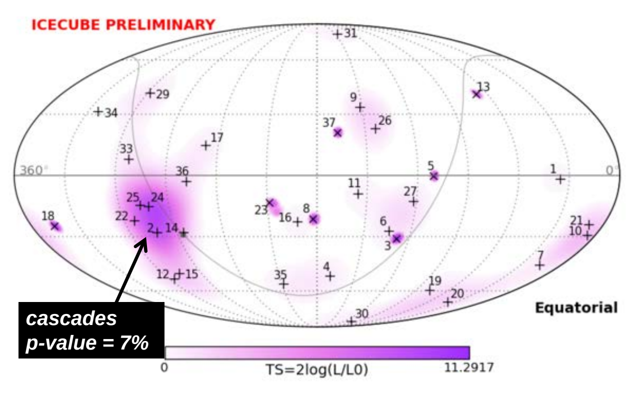
$$E^2\Phi \leq E^2\Phi_{WB} = 3.4 \times 10^{-8}\,[\mathrm{GeV s^{-1} sr^{-1} cm^{-2}}] \quad (derived\ for\ UHE\ CR,\ E_{CR} > 10^{19}\,eV)$$

A coincidence?

may imply ν and CR's produced by the same sources (?),
e.g. Starburst galaxies (?)

The beginning of extra-Galactic neutrino astrophysics

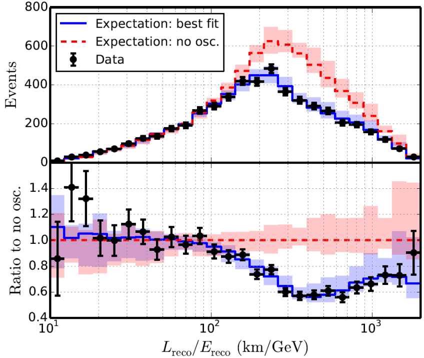
Do the HESE events cluster -
is there a brighter than average source?

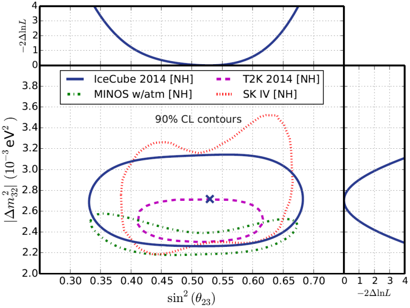


No evidence of spacial clustering. (Grey line = galactic plane)
Gary C.Hill, Neutrino 2014

Ice Cube - atmospheric neutrinos

Neutrino oscillations in Ice Cube Deep Core
Neutrino energies between 10 GeV and 100 GeV





Precision of measurement comparable to Super-K experiment !

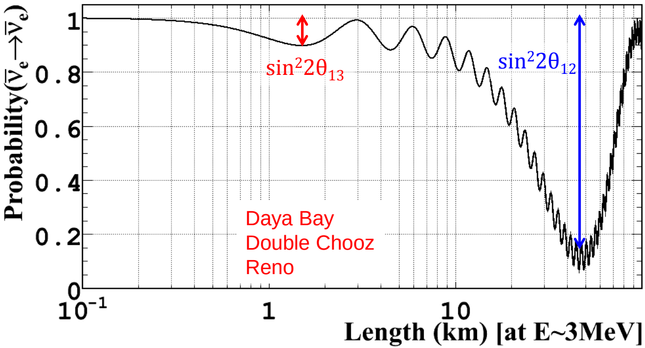
RECENT RESULTS FROM REACTOR EXPERIMENTS

Physics goals:

- precise measurement of θ_{13}
- determination of reactor neutrino flux and spectrum
- search for/limit on light sterile neutrinos
- determination of mass hierarchy (with future experiments)

Survival probability for $\overline{\nu}_e$

$$P(\overline{\nu}_e \to \overline{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}^2 L}{4E_\nu}\right)$$



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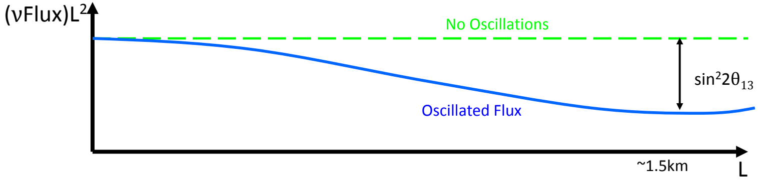
Oscillation experiments at nuclear reactors

nuclear reactor: intense, isotropic source of electron-antineutrinos, ‘for free’

- $E_\nu < 10$ MeV $\Rightarrow$ disappearance experiment
- look for rate deviation from $1/r^2$ and spectral distortions in 1-2 km
- clean measurement of θ_{13} , independent of δ-CP & matter effects

$$P(\overline{\nu}_e \to \overline{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E_{\overline{\nu}}}$$



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Antineutrino Detection

Inverse Beta Decay (IBD) in Gd-loaded scintillator

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

$Q_{thr} = m_e + M_n - M_p \approx 1.8$ MeV

prompt event:

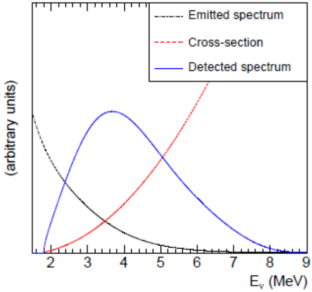
$$E_{vis} \cong E_\nu - E_n - 0.8\text{MeV}$$
$$\approx 1 - 10 \text{ MeV}$$

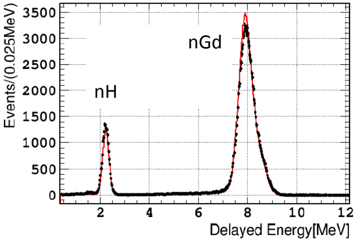
delayed event: $\tau \sim 30 - 200\ \mu s$

$n + Gd \rightarrow Gd^* \rightarrow Gd + \gamma$'s (~ 8 MeV)

or

$n + H \rightarrow D + \gamma$ (2.2 MeV)





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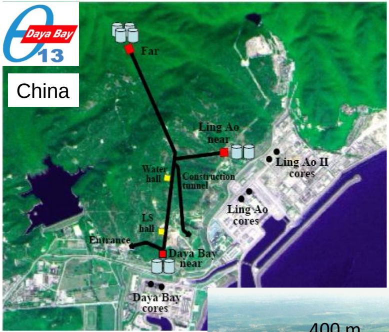
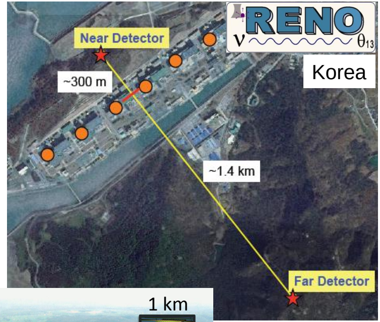
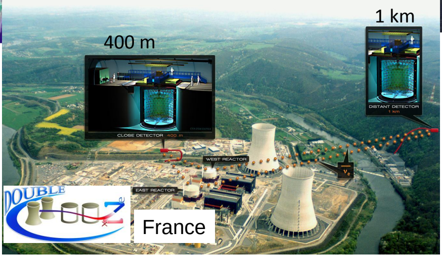
3 reactor experiments for θ_{13}



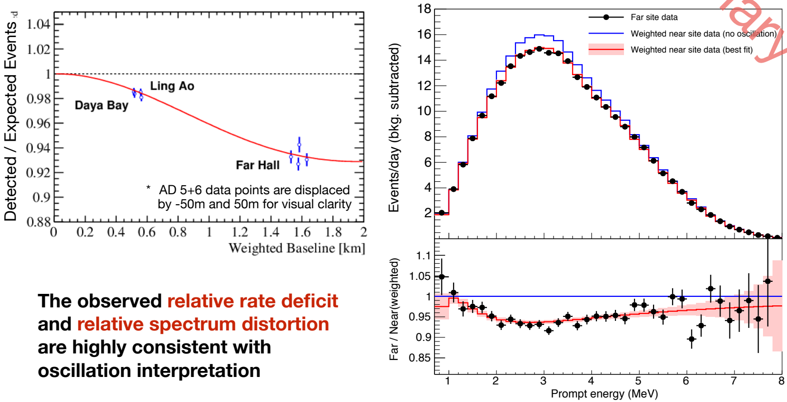




Marianne Göger-Neff, NNN2014

Far v.s. Near Comparison

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



The observed relative rate deficit and relative spectrum distortion are highly consistent with oscillation interpretation

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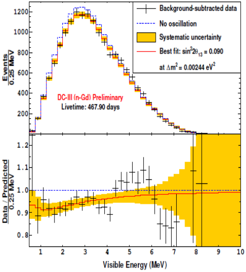
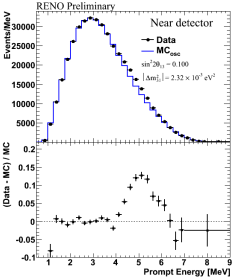
Chao Zhang, Neutrino 2014

Measurement of Reactor Spectrum

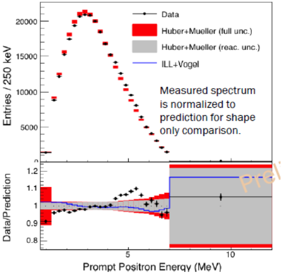
- spectral distortion observed from [4, 6] MeV by all 3 experiments
- 1-2 % excess



Double Chooz, arXiv:1406.7763



RENO, Neutrino2014



Daya Bay, ICHEP 2014

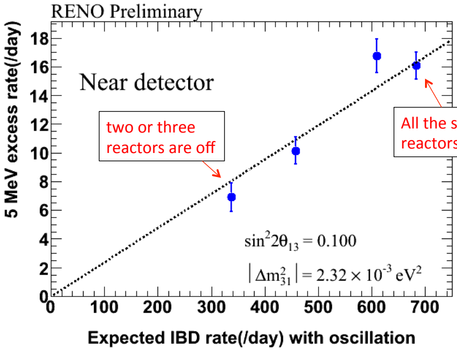
- correlated with reactor power
- no known background, no distortion of calibration spectra

$\Rightarrow$ possible explanation: beta decay branches of fission products

arXiv:1407.1281

Marianne Göger-Neff, NNN2014

Observation of new reactor ν component at 5 MeV



5 MeV excess has a clear correlation with reactor thermal power !

We take into account the excess at 5 MeV to the expected spectral shape.

Seon-Hee Seo (RENO experiment), Neutrino 2014

STERILE NEUTRINOS

Sterile neutrinos

- Sterile neutrino = neutrino that does not couple to the Standard Model W or Z boson
- In 1995 LSND reported an excess in the $\overline{\nu_\mu} \to \overline{\nu_e}$ channel that can be explained by existence of mixing between active and sterile neutrinos

The Current Situation

$$\text{Probability}(\text{Oscillation}) \propto \sin^2\left[1.27\Delta m^2(\text{eV}^2)\frac{L(\text{m})}{E(\text{MeV})}\right]$$

There are several hints of oscillation with $L(\text{m})/E(\text{MeV}) \sim 1$:

These ⇒ a $\Delta m^2 \sim 1$ eV^2, bigger than the two established splittings.

⇒ At least **4** mass eigenstates

⇒ At least **4** flavors

Then $$\frac{\Gamma(Z \to \nu\bar{\nu})\big|_{\text{Exp}}}{\Gamma(Z \to \text{One } \nu\bar{\nu} \text{ Flavor})\big|_{\text{SM}}} = 2.98$$

⇒ At least **1** sterile neutrino

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B.Kayser, TMEX 2014

The Hints

Experiment	Possible Oscillation	Comment
LSND	$\bar{\nu}_\mu \to \bar{\nu}_e$	Interesting
MiniBooNE	$\nu_\mu \to \nu_e$	Somewhat disfavored by ICARUS & OPERA
MiniBooNE	$\bar{\nu}_\mu \to \bar{\nu}_e$	NOT constrained by ICARUS & OPERA
Reactor Exps.	$\bar{\nu}_e \to$ Not $\bar{\nu}_e$	Flux uncertainty ~ 6% size of effect
^{51}Cr and ^{37}Ar Source Exps.	$\nu_e \to$ Not ν_e	Detector calibration?

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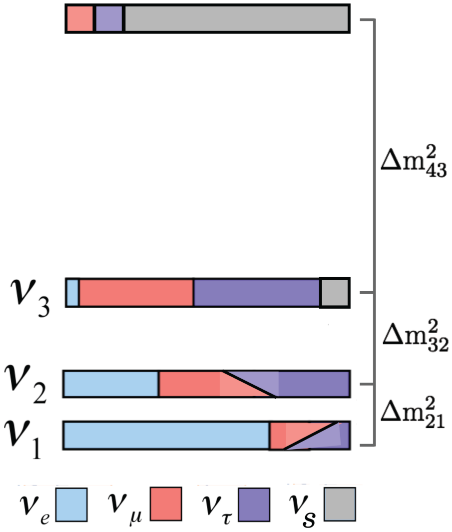
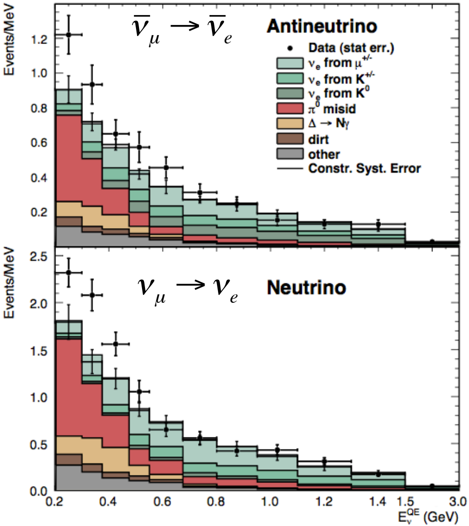
B.Kayser, TMEX 2014

3+1 model



- In 3+1 model additional parameters: Δm^2_{43}, θ_{14}, θ_{24}, θ_{34}, δ_{14}, δ_{24}
- Other discussed models: 3+2, 1+3+1, . . .

Sterile neutrinos - MiniBooNE data



The Hint From MiniBooNE

78.4 ± 28.5 excess events

162.0 ± 47.8 excess events

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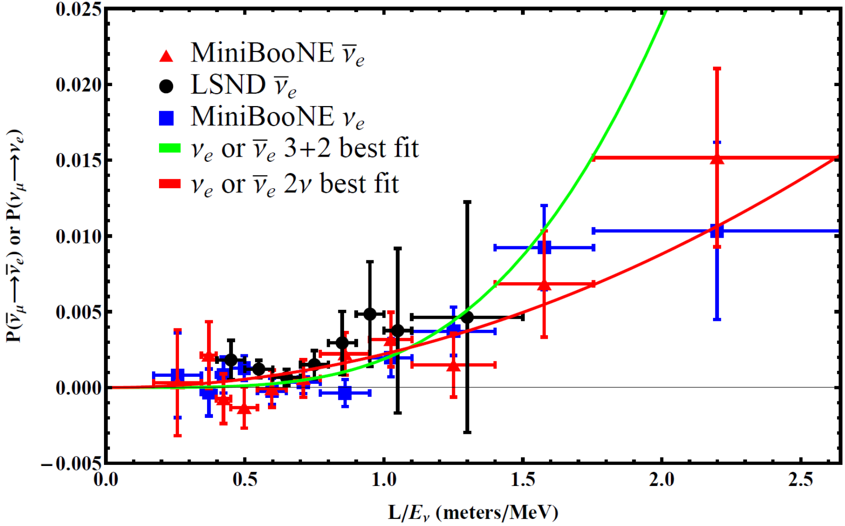
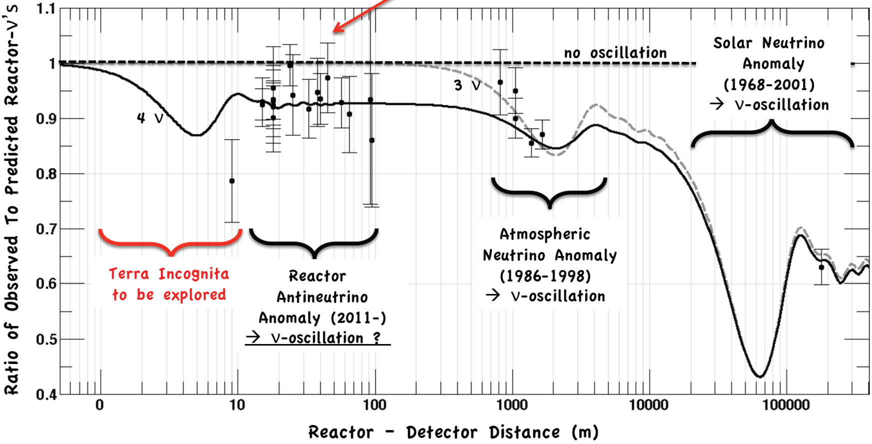

MiniBooNE $\overline{\nu}_e$
LSND $\overline{\nu}_e$
MiniBooNE ν_e
ν_e or $\overline{\nu}_e$ 3+2 best fit
ν_e or $\overline{\nu}_e$ 2ν best fit
$P(\overline{\nu}_\mu \to \overline{\nu}_e)$ or $P(\nu_\mu \to \nu_e)$
L/E_ν (meters/MeV)
0.025
0.020
0.015
0.010
0.005
0.000
−0.005
0.0
0.5
1.0
1.5
2.0
2.5

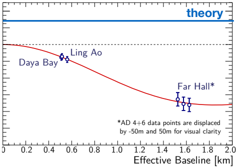
Sterile neutrinos - reactor anomaly

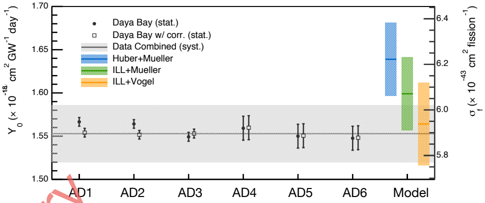
- Observed/predicted averaged event ratio: R=0.927±0.023 (3.0 σ)



Th. Lasserre - Neutrino 2012 8

Absolute Reactor Antineutrino Flux





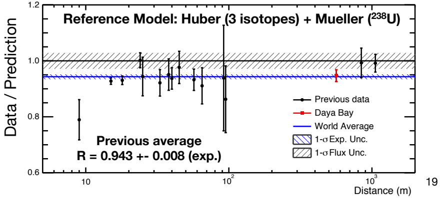
preliminary

Flux Measurement Uncertainty

	Uncertainty
statistics	0.2%
θ_{13}	0.2%
reactor	0.9%
detector efficiency	2.1%
Total	2.3%

^{235}U : ^{238}U : ^{239}Pu : ^{241}Pu	0.586 : 0.076 : 0.288 : 0.050
Y_0 (cm^2 GW^{-1} day^{-1})	1.553×10^{-18}
σ_f (cm^2 fission^{-1})	5.934×10^{-43}
Data / Prediction (Huber+Mueller)	0.947 ± 0.022
Data / Prediction (ILL+Vogel)	0.992 ± 0.023

Daya Bay's reactor flux measurement is consistent with previous short baseline experiments



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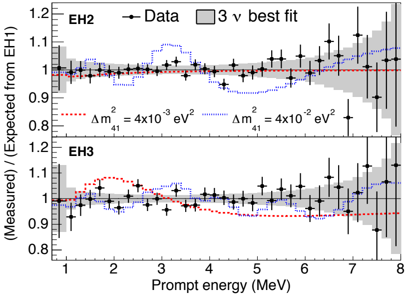
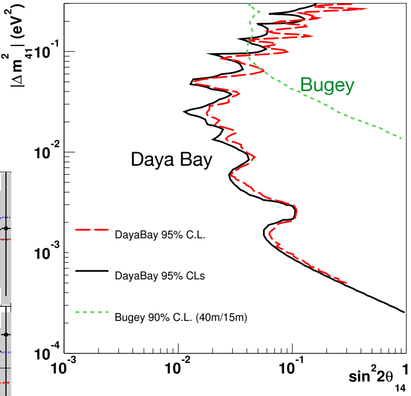
Chao Zhang (Daya Bay experiment), Neutrino 2014

Light Sterile Neutrino Search Results

- All 217 days of 6-AD period
- Consistent with standard 3-flavor neutrino oscillation model
- Able to set stringent limits in the region 10^{-3} eV^2 < Δm^2_{41} < 0.1 eV^2



dashed curves assumes $\sin^2 2\theta_{14} = 0.1$



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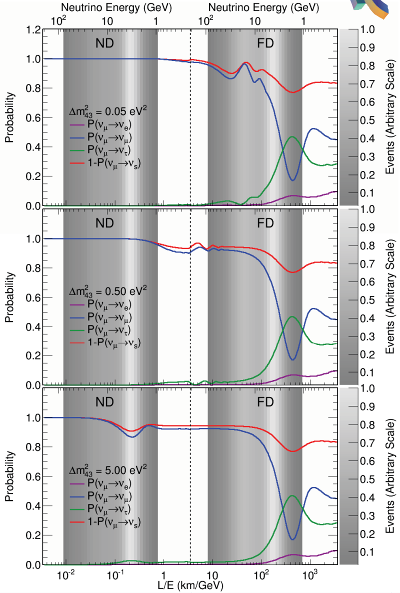
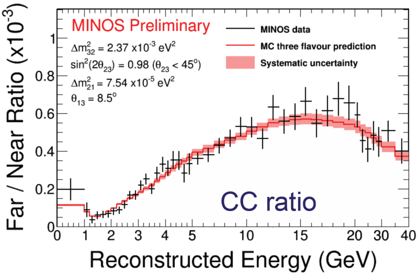
Chao Zhang (Daya Bay experiment), Neutrino 2014

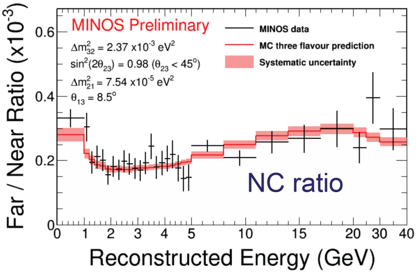
4-Flavor Oscillations

- $\nu_\mu \rightarrow \nu_s$ mixing causes energy-dependent depletion of NC and ν_μ-CC energy spectra w.r.t 3-flavor mixing
- Small Δm^2_{43} (> Δm^2_{32}):
  - FD spectral distortions at energies above 3-flavor oscillation maximum
  - No ND effects
- Medium Δm^2_{43}:
  - Rapid oscillations at FD average out
  - No ND effects
  - Counting experiment
- Large Δm^2_{43}:
  - Rapid oscillations at FD average out
  - ND spectral distortions affect extrapolation to FD



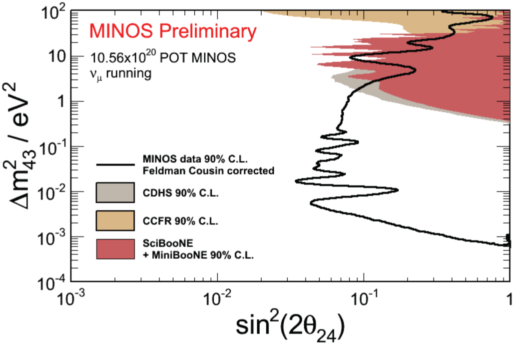
Limits on sterile neutrinos from MINOS



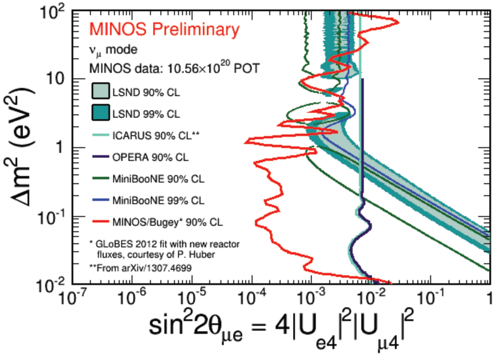


- Ratio of energy spectra at FD to ND, ν_μ
- Red/pink: predicted assuming no sterile neutrinos
- Fit the observed FD/ND ratios for CC and NC

Limits on sterile neutrinos from MINOS

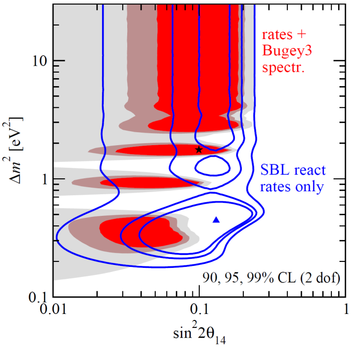


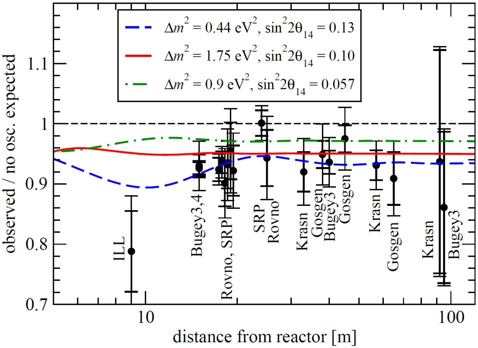
- Strongest constraints on $\nu_\mu \to \nu_s$ disappearance for $\Delta m^2_{43} < 1 eV^2$



- These results rule out much of $\Delta m^2_{43} < 1 eV^2$ for sterile neutrinos
- Collaborating with Daya Bay to use their results

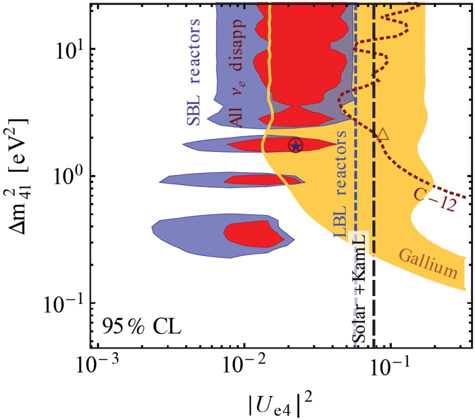
Sterile neutrinos - global analysis of available data





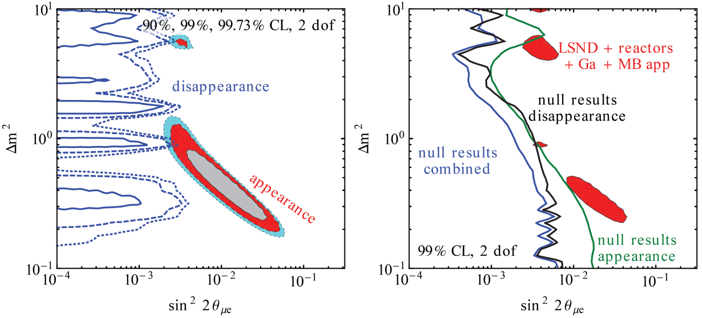
Allowed regions of oscillation parameters from SBL reactor data.
Rate only - contours; +Bugey spectral data - colored regions.

Sterile neutrinos - global analysis of available data



Allowed regions at 95% CL for 3+1 oscillations. Combined region from all ν_e and $\overline{\nu_e}$ data sets in red.

Sterile neutrinos - global analysis of available data



- Results of global fit in 3+1 scenario
- Exclusion limits from disappearance data
- Allowed regions from appearance data
- Right: Allowed regions from LSND,MiniBooNE,SBL reactors,Gallium exp. only

Compatibility of appearance and disappearance data is very low for 3+1,3+2 and 1+3+1 schemes

Summary

- Neutrino oscillations:
  - era of precision measurements
  - next goals: δ_{CP} and mass hierarchy
- High energy neutrinos in Ice Cube:
  - discovery of astrophysical neutrinos
  - first precision measurement of parameters of neutrino oscillations
- Reactor experiments:
  - θ_{13} - precision of $\sin^2 2\theta_{13}$ from Daya Bay $< 6\%$
  - absolute neutrino flux and spectrum was measured by Daya Bay
  - (4,6) MeV excess in energy spectrum of unknown origin
- Light sterile neutrinos: interesting anomalies but exclusion limits are more and more stringent