HQL2012
Summary of the Neutrino Physics session

Gianpaolo Bellini, Rupert Leitner, Adam Para
Charles University,
Prague

14:30 Recent Results on Solar Neutrinos

Recent Results on Solar Neutrinos
Presenter(s): RANUCCI, Gioacchino *(Istituto Nazionale di Fisica Nucleare)*
Location: Prague

SUN

14:55 Observation of nonzero theta13 at reactor antineutrino experiments

The Daya Bay Reactor Neutrino Experiment has measured a non-zero value for the neutrino mixing angle Î¸13 with a significance of 5.2 standard deviations in 55 days of data. Six antineutrino detectors deployed in two near (flux-weighted baseline 470... ***Show full description***
Presenter(s): BAND, Henry *(University of Wisconsin)*
Location: Prague

REACTORS

15:25 Long baseline neutrino disappearance

Long baseline neutrino disappearance
Presenter(s): NICHOL, Ryan James
Location: Prague

ACCELERATORS

15:55 Status of the geoneutrino study

Status of the geoneutrino study
Presenter(s): ZAVATARELLI, sandra *(INFN Genova Italy)*
Location: Prague

EARTH

16:40 Developments on double beta decay search

Developments on double beta decay search
Presenter(s): CREMONESI, Oliviero *(INFN)*

Location: Prague

DIRAC or MAJORANA?

17:05 Searches for high energy neutrinos

Searches for high energy neutrinos
Presenter(s): BRUNNER, Juergen *(CPPM)*
Location: Prague

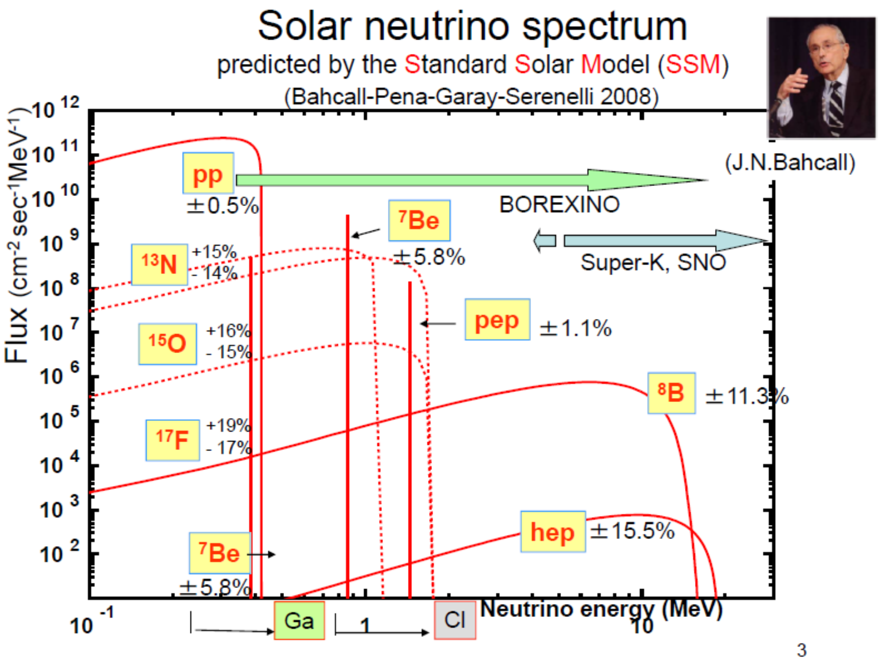
COSMOS

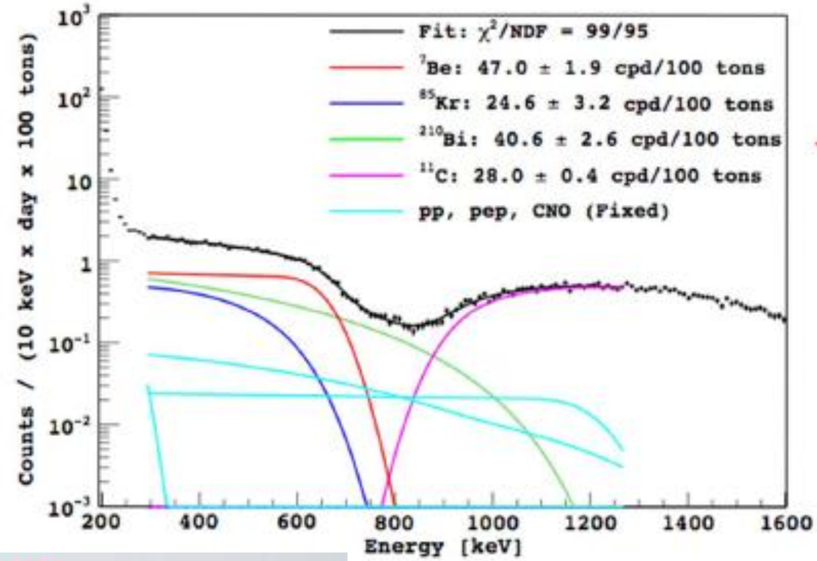
17:30 Possible existence of sterile neutrinos

Possible existence of sterile neutrinos
Presenter(s): LINK, Jonathan *(Virginia Tech)*
Location: Prague

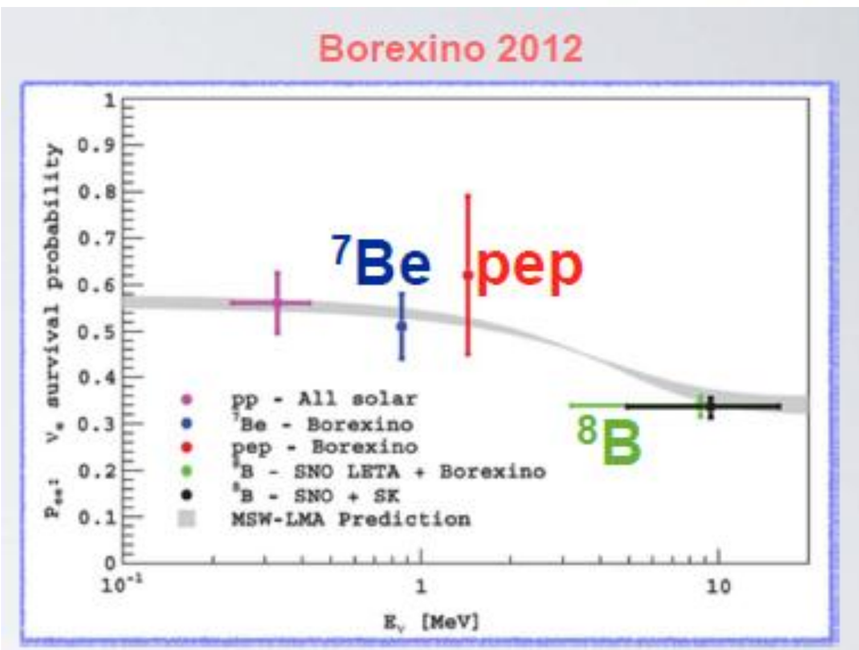
MORE THAN 3 NEUTRINOS?

Recent results on solar neutrinos





$$1-\frac{1}{2}\sin^2(2\vartheta_{12})$$

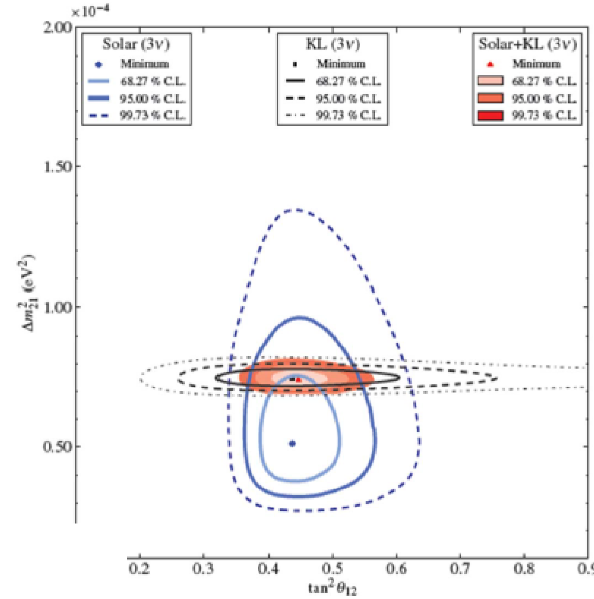


$$\sin^2(\vartheta_{12})$$

Joint oscillation analysis of solar and KamLAND anti-ν data

Epilogue: precise determination of the oscillation parameters

arXiv:1109.0763



Analysis	$\tan^2\theta_{12}$	Δm^2_{21}[eV^2]	$\sin^2\theta_{13}(\times 10^{-2})$
Solar	$0.436^{+0.048}_{-0.036}$	$5.13^{+1.49}_{-0.98} \times 10^{-5}$	< 5.8 (95% C.L.)
Solar+KL	$0.446^{+0.030}_{-0.029}$	$7.41^{+0.21}_{-0.19} \times 10^{-5}$	$2.5^{+1.8}_{-1.5}$ < 5.3 (95% C.L.)

→ In agreement with DayaBay and Reno

Solar neutrino investigation has been of paramount importance in assessing the phenomenon of neutrino oscillation

The plenty of data stemming form radiochemical, water Cerenkov and scintillation experiments have pinpointed with high accuracy the values of the oscillation parameters

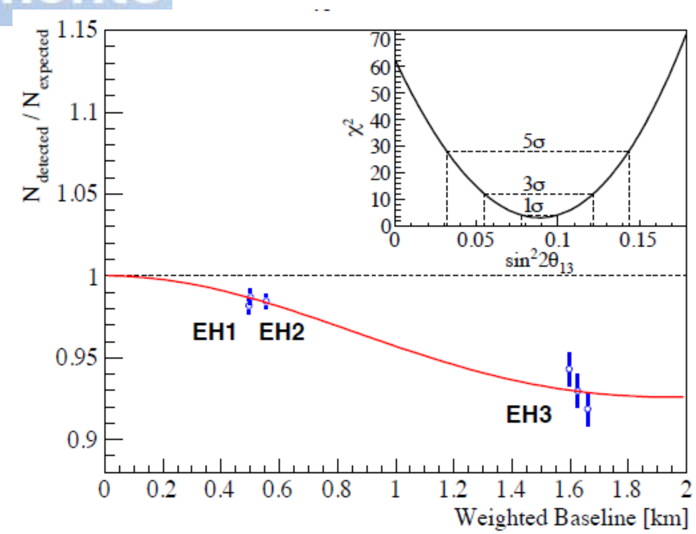
The recent Borexino data allowed to studied ν oscillations in the previously untested low energy vacuum-like regime, further validating the currently favored MSW-LMA oscillation paradigm

The study of neutrino oscillation through solar neutrinos is surely one of the more successful chapters of contemporary particle physics

Observation of Nonzero θ_{13} at Reactor Antineutrino Experiments

	Reactor power	Det masses NEAR	FAR
Daya Bay	17.4 GW	60 t	60 t
Double Chooz	9.4 GW	-	10 t
RENO	16.2 GW	16 t	16 t

Daya Bay



Uses standard χ^2 approach.

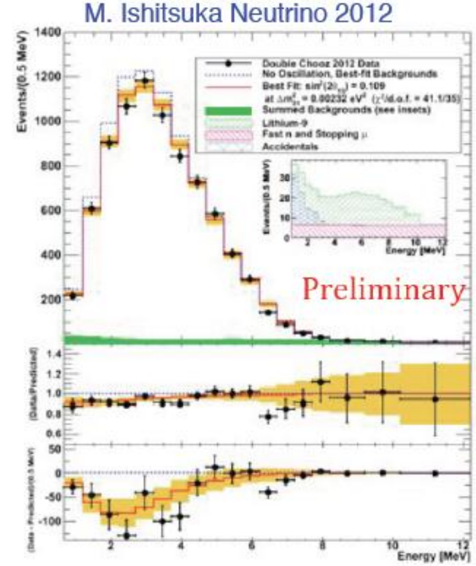
Far vs. near relative measurement. [Absolute rate is not constrained.]

Most precise measurement of $\sin^2 2\theta_{13}$ to date.

$\sin^2 2\theta_{13} = 0.089 \pm 0.010$ (stat) ± 0.005 (syst)

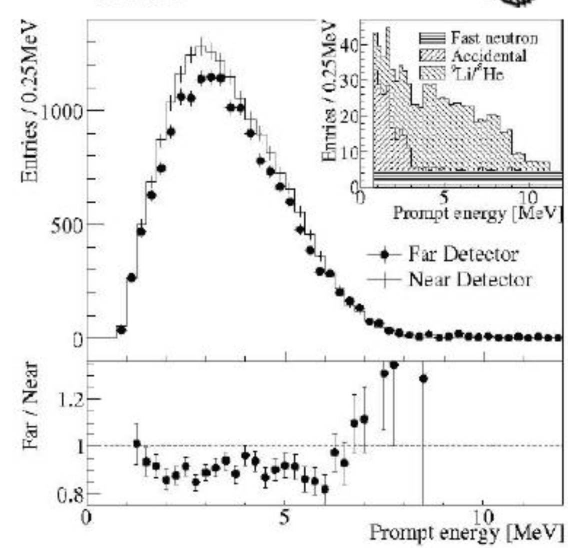
Double Chooz update

M. Ishitsuka Neutrino 2012

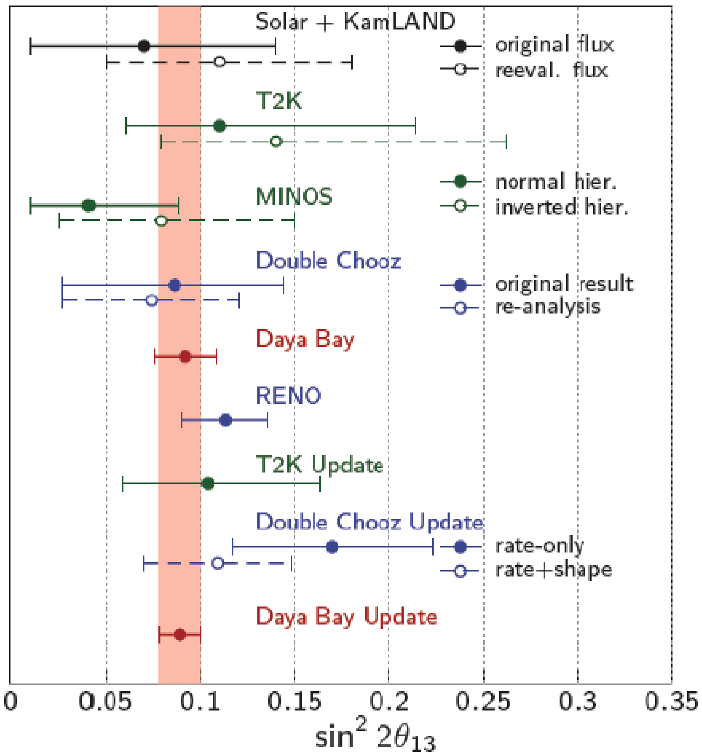


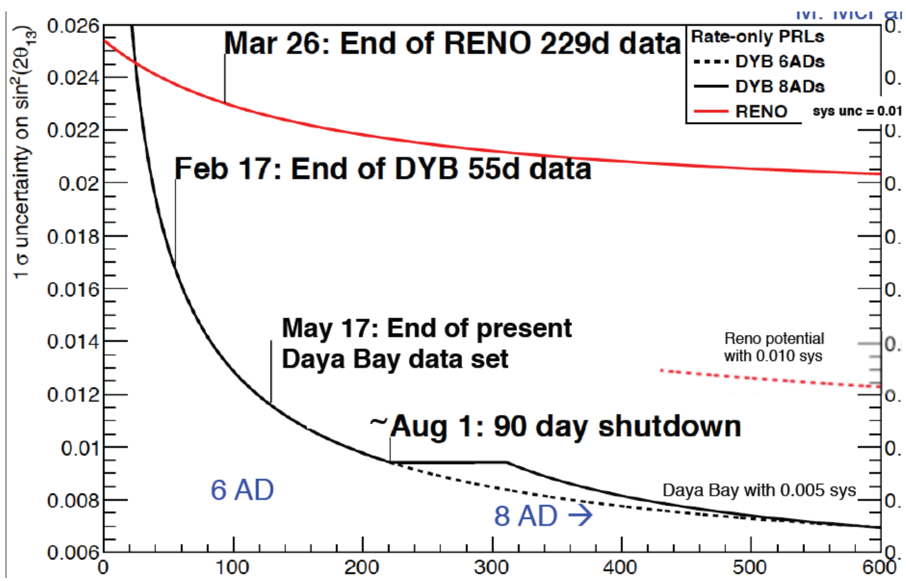
Rate only: $\sin^2 2\theta_{13} = 0.170 \pm 0.035$(stat) ± 0.040(syst)
Rate+Shape: $\sin^2 2\theta_{13} = 0.109 \pm 0.030$(stat) ± 0.025(syst)

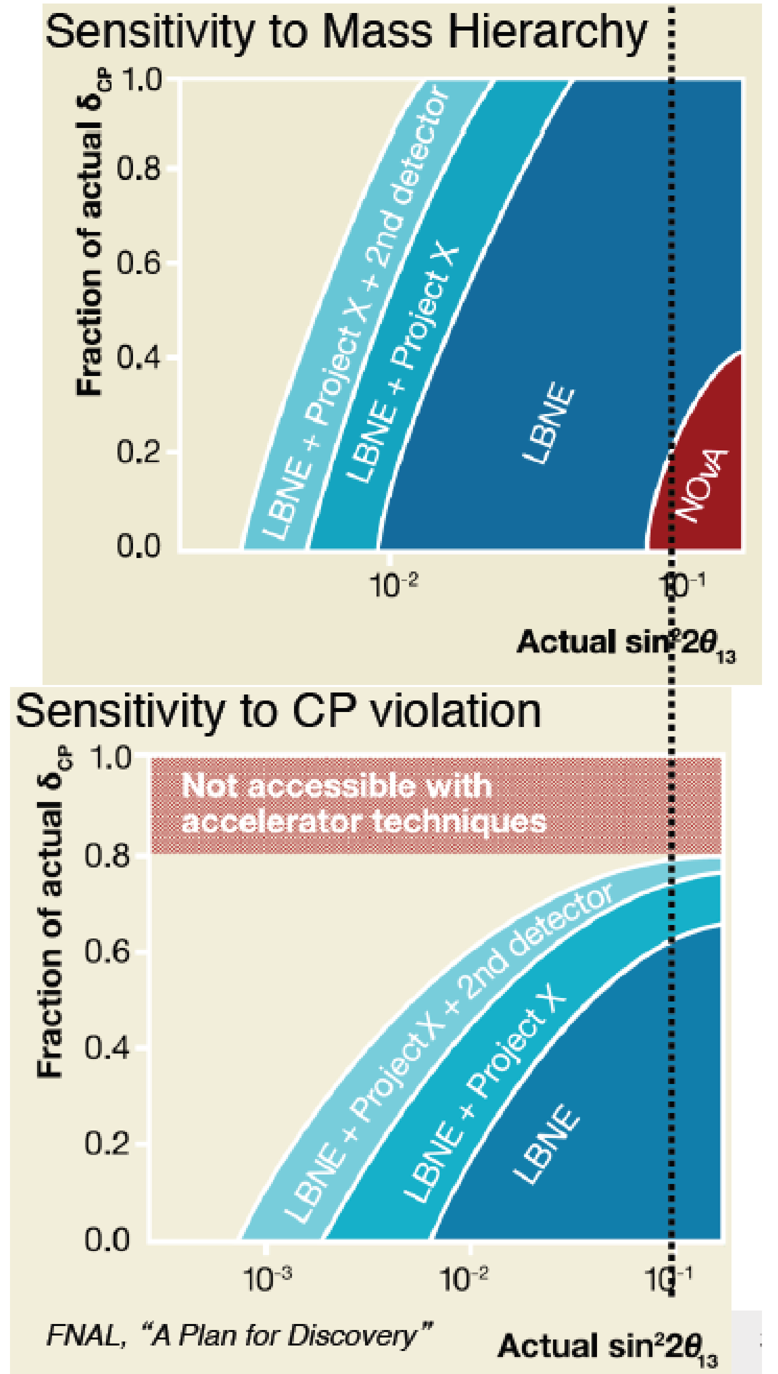
Reno



$$\sin^2 2\theta_{13} = 0.113 \pm 0.013(stat.) \pm 0.019(syst.)$$

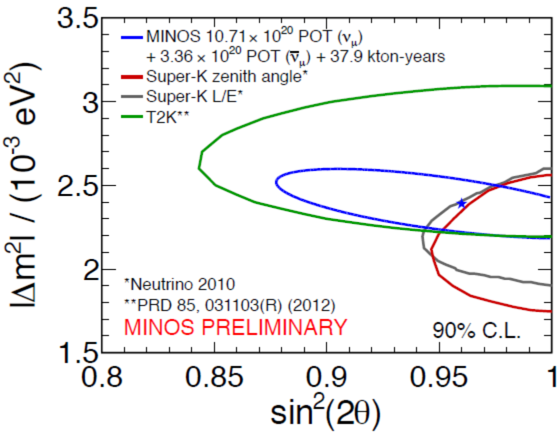

Solar + KamLAND
original flux
reeval. flux
T2K
MINOS
normal hier.
inverted hier.
Double Chooz
original result
re-analysis
Daya Bay
RENO
T2K Update
Double Chooz Update
rate-only
rate+shape
Daya Bay Update
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
$\sin^2 2\theta_{13}$


Mar 26: End of RENO 229d data
Rate-only PRLs
DYB 6ADs
DYB 8ADs
RENO
sys unc = 0.01
Feb 17: End of DYB 55d data
May 17: End of present
Daya Bay data set
Reno potential
with 0.010 sys
~Aug 1: 90 day shutdown
6 AD
8 AD →
Daya Bay with 0.005 sys
1 σ uncertainty on $\sin^2(2\theta_{13})$
0.026
0.024
0.022
0.02
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0
100
200
300
400
500
600


Sensitivity to Mass Hierarchy
Fraction of actual δ_{CP}
1.0
0.8
0.6
0.4
0.2
0.0
LBNE + Project X + 2nd detector
LBNE + Project X
LBNE
NOνA
10^{-2}
10^{-1}
Actual $\sin^2 2\theta_{13}$
Sensitivity to CP violation
Fraction of actual δ_{CP}
Not accessible with
accelerator techniques
1.0
0.8
0.6
0.4
0.2
0.0
LBNE + Project X + 2nd detector
LBNE + Project X
LBNE
10^{-3}
10^{-2}
10^{-1}
FNAL, "A Plan for Discovery"
Actual $\sin^2 2\theta_{13}$

Long Baseline Neutrino Oscillation Experiments

Muon (anti) neutrino disappearance:

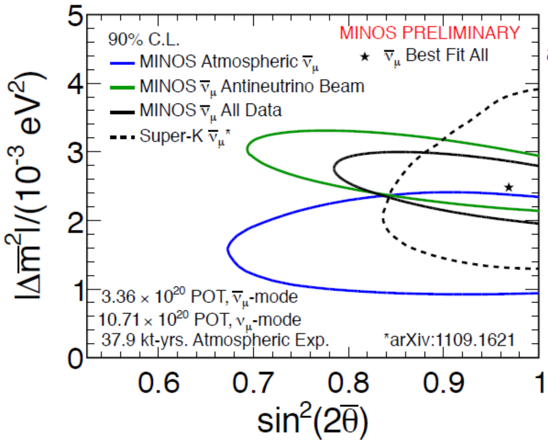


New MINOS neutrino oscillation parameters:

$$\Delta m^2 = 2.39^{+0.09}_{-0.10} \times 10^{-3} eV^2$$

$$\sin^2(2\theta) = 0.96^{+0.04}_{-0.04}$$

$$\sin^2(2\theta) > 0.90 \text{ at } 90\% \text{ C.L.}$$



New MINOS antineutrino oscillation parameters:

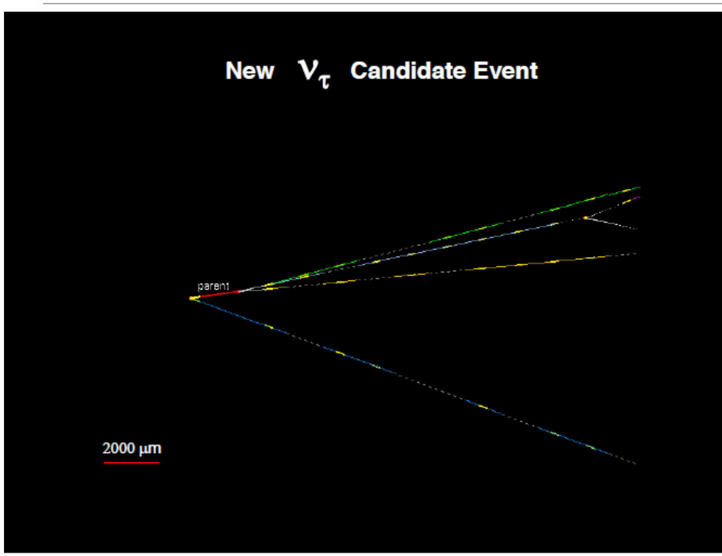
$$|\Delta \overline{m}^2| = 2.48^{+0.22}_{-0.27} \times 10^{-3} eV^2$$

$$\sin^2(2\overline{\theta}) = 0.97^{+0.03}_{-0.08}$$

$$\sin^2(2\overline{\theta}) > 0.83 \text{ at } 90\% \text{ C.L.}$$

Tau neutrino appearance:

New OPERA Tau Candidate Event



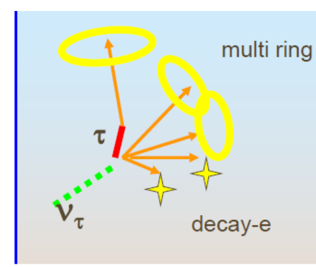
Observation of tau neutrino appearance is a missing piece in the standard oscillation picture.

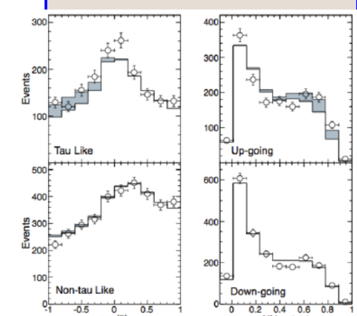
Out of 4126 events analysed OPERA expects:
0.2 background events
2.1 tau events

Observe:
2 tau candidates

Super-Kamiokande Tau Appearance

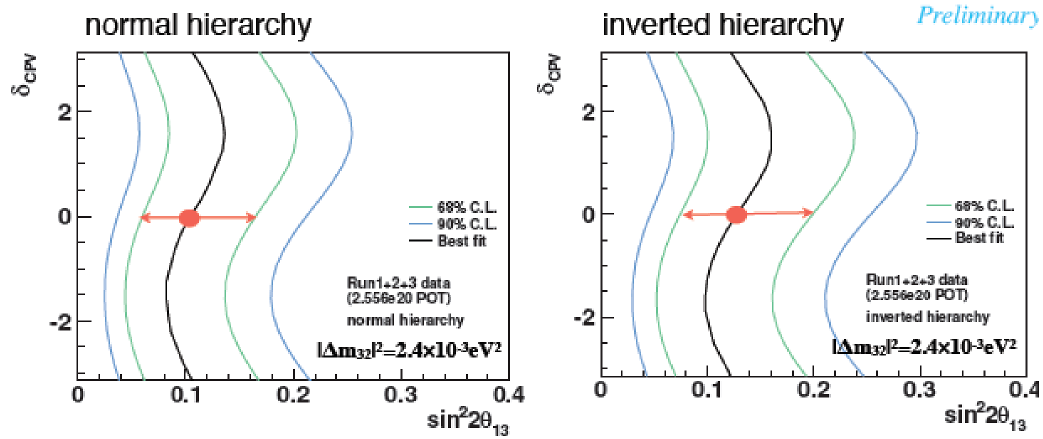
- Super-Kamiokande searched for tau neutrino appearance in the atmospheric sample
- No event-by-event identification, use statistical separation
- They observe excess of tau-like events
  - 3.8σ deviation from null hypothesis
  - 180 ± 44.3(stat.) +17.8/-15.2 (sys.)





arXiv:1206.0328v1

Measurement of Theta13 via electron neutrino appearance:

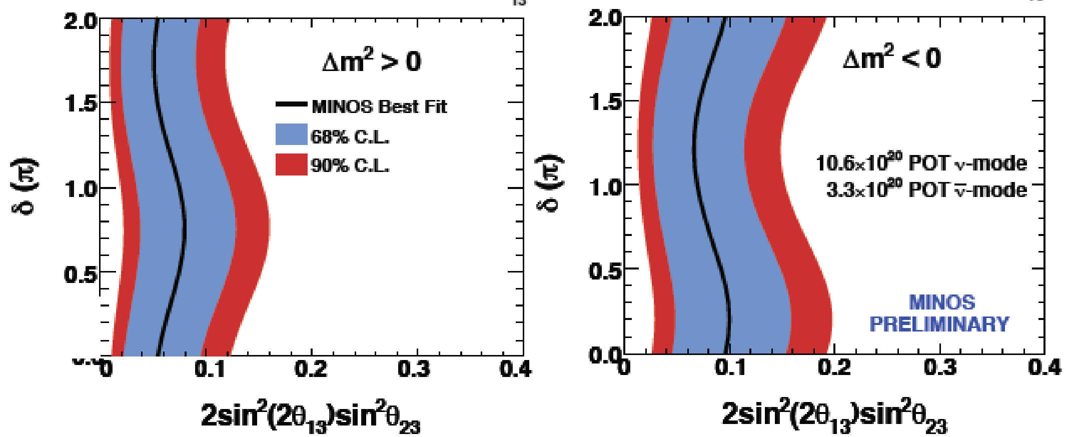


T2K:
Normal

$\sin^2 2\theta_{13} = 0.104^{+0.060}_{-0.045}$ @ δ_{CP}=(

Inverted

$\sin^2 2\theta_{13} = 0.128^{+0.070}_{-0.055}$ @ $\delta_{CP}=0$



MINOS:
Normal

$\sin^2(2\theta_{13}) = 0.053$

$0.01 < \sin^2(2\theta_{13}) < 0.12$

Inverted

$\sin^2(2\theta_{13}) = 0.094$

$0.03 < \sin^2(2\theta_{13}) < 0.19$

for $\delta_{cp}=0$, $\sin^2(2\theta_{23})=1$

- We have entered the age of precision neutrino physics

Fractional 1σ accuracy [defined as 1/6 of ±3σ range]

δm^2	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$	Δm^2
2.6%	5.4%	13%	13%	3.5%

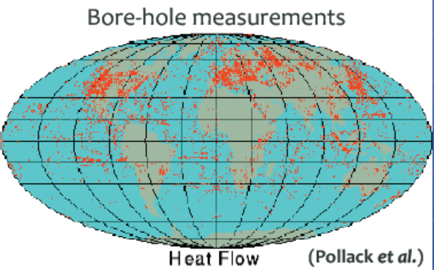
From G. Fogli @Neutrino2012

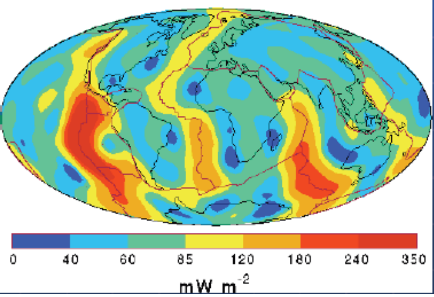
- Long baseline neutrino experiments have started to test the mass hierarchy and CP-violating phase

- Next generation of neutrino experiments will be CP vilation searches

The study of geo-neutrinos

Earth surface heat flux





Conductive heat flow : ~ 60 mW/m²

From bore-hole temperature gradients

Total surface heat flux:

- (31 ± 1) TW (Hofmeinster& Criss 2005)
- (46 ± 3) TW (Jaupart er all 2007)
- (47 ± 2) TW (Davies and Davies 2010)

(same data , different analysis)

Systematic errors:
Different assumption
of fluids in the zone

The Earth shines in anti-ν (Φ_ν~ 10^6 cm^{-2} s^{-1})

$^{238}U \rightarrow {}^{206}Pb + 8\alpha + 8e^- + 6\bar{\nu}_e + 51.7$ MeV

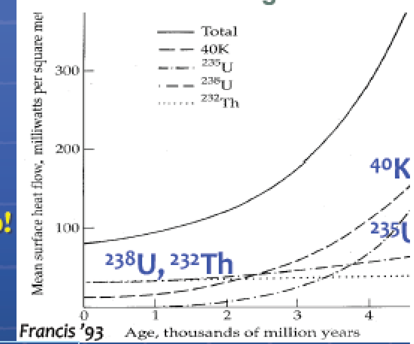
$^{232}Th \rightarrow {}^{208}Pb + 6\alpha + 4e^- + 4\bar{\nu}_e + 42.8$ MeV

$^{40}K \rightarrow {}^{40}Ca + e^- + 1\bar{\nu}_e + 1.32$ MeV

$^{235}U \rightarrow {}^{207}Pb + 7\alpha + 4e^- + 4\bar{\nu}_e + 46.4$ MeV

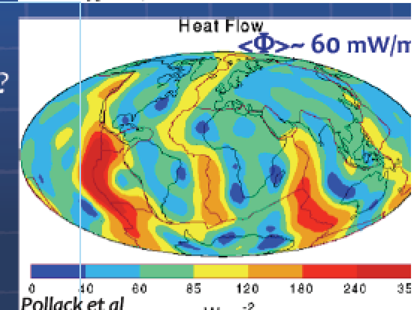
✓ **Released heat and anti-neutrinos flux in a well fixed ratio!**

Contribution changed in time!

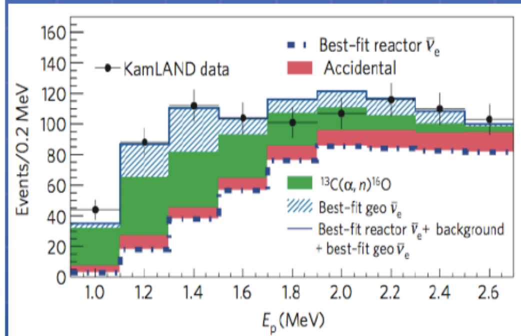


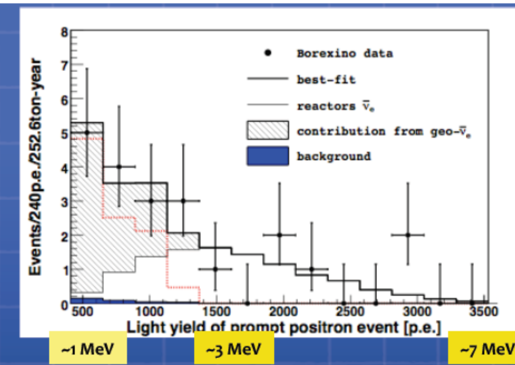
Open questions:

- *What is radiogenic contribution to the Earth energy budget?*
- *What is the distribution of the radiogenic elements?*
  - *How much in the crust and how much in the mantle?*
  - *Core composition: energy source driving the geo- dynamo? ^{40}K ? Geo-reactor (Herndon 2001)?*
- *Are the standard geochemical models (BSE) correct?*



KamLand (2002 – 2009) Borexino (2007 – 2009)





Period	Mar 02- Nov. 09
Tot. Ev. [gν e.w.]	841
Reactors ev.	485 ± 27
$^{13}C(\alpha,n)^{16}O$	165 ± 18
Geo-ν ev.	111_{-43}^{+45}
Accidental ev.	80 ± 0.1

Period	Dec.07 – Dec.09
Tot ev [full sp.]	21
Reactors ev.	$10.7_{-3.4}^{+4.3}$
Geo-n ev.	$9.9_{-3.4}^{+4.1}$
Background ev.	0.4 ±0.05

A. Gando *et al.*, Nature Geoscience **1205** (2011).

G. Bellini *et al.*, *PLB* **687** (2010) 299-304.

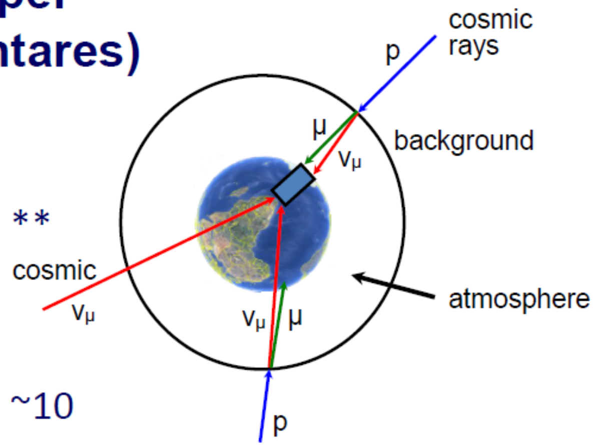
HQL 2012, Prague *Sandra Zavatarelli, INFN Genova Italy*

- ✓ A new interdisciplinary field is born;
- ✓ Collaboration among geologists and physicists is a must;
- ✓ The geo-neutrinos have already been successfully detected;
- ✓ The combined results from different experimental sites have stronger impact –> multi-site measurements are crucial!
- ✓ The first geologically significant results are starting to appear;
- ✓ New measurements (now in Japan the reactors are off!) and the new generation experiments are needed for geologically highly significant results… .

High Energy Neutrinos

Muon tracks in the detector

- **Muons detected per year (IceCube/Antares)**
  - Atmospheric μ *
    7×10^{10} / 7×10^{8}
  - Atmospheric ν→μ **
    8×10^{4} / 2×10^{3}
  - cosmic ν→μ ~10

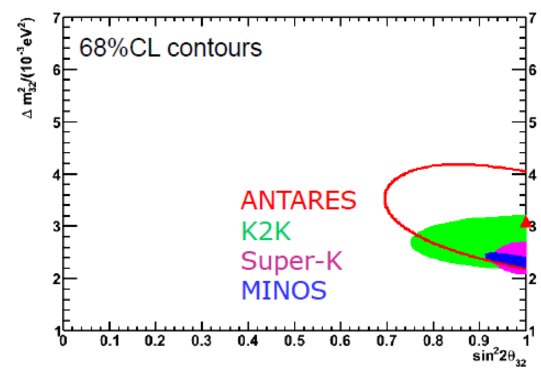


- * 2000/20 per second
- ** 1 every 6 min/5h

Neutrino Oscillations in ANTARES : Result

First measurement of oscillation parameters with high energy neutrino telescope

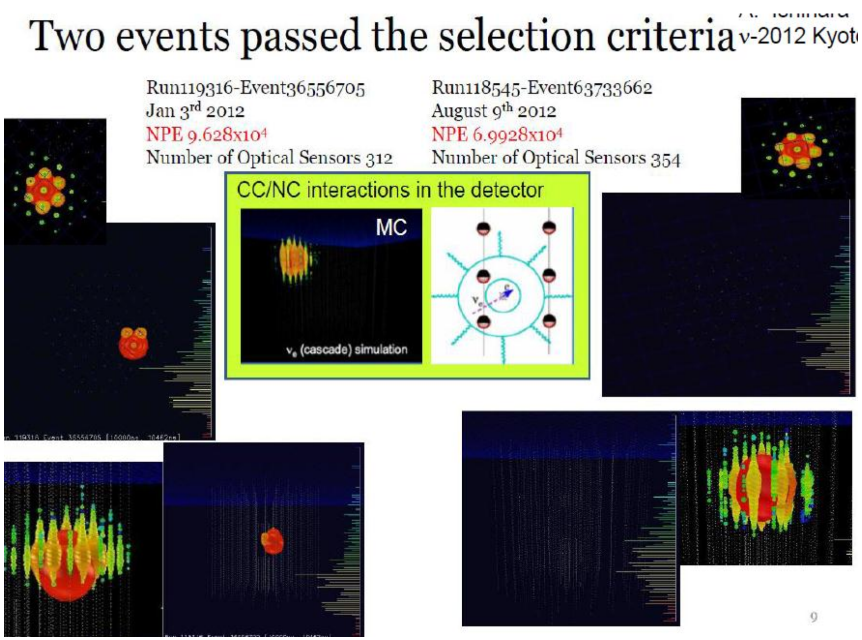
Refined measurement expected from DeepCore



Assuming maximal mixing: $\Delta m^2=(3.1\pm0.9)\ 10^{-3}\ eV^2$

Submitted to PLB (arXiv:1206.0645v1 [hep-ex])

Searches for cosmogenic neutrinos



- IceCube and Antares are producing lots of interesting results
  - Astrophysics
  - Particle physics
- IceCube is opening the era of km^3 physics
- ANTARES most sensitive for Galactic sources
- Realistic models start to be challenged
- First high energetic astrophysical neutrino observation might by around the corner

Searches for GRB neutrinos

GRB could be signes of CR production. If protons are accelerated and interacts they produce pi0 and charged pions, pi0 decays to gamma, charged pions to neutrions. Therefore neutrino are searched in coincidencies with GRB:

- Combined (IC40, IC59) search results
  - Expect 8.4 events, see 0 → *0.27 Guetta et al prediction*
- ***Where are the neutrinos?*** → *Nature Paper*
- ***Do we already rule out GRB as The CR source?***

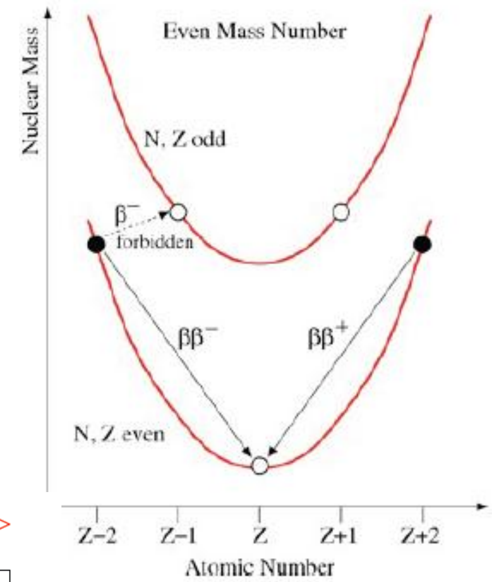
Developments on double beta decay search

$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}$

Neutrinoless double beta decay ($0\nu\beta\beta$)

$$(A,Z) \rightarrow (A,Z+2) + 2e^-$$

is particularly intriguing for its implications in particle Physics



- **Lepton Number** non conservation
- **Majorana nature** of ν
- Measurement of absolute ν **mass scale**
- Determination of neutrino **mass hierarchy**
- **CP** violation measure in the leptonic sector

$$\tau_{0\nu}^{-1} = G_{0\nu}(Q,Z)|M^{0\nu}|^2 < m_{ee} >$$

PHASE SPACE FACTOR — NME — EFFECTIVE MAJORANA MASS

$$< m_{ee} > = \sum_k U_{ek}^2 m_k$$

NEUTRINO MIXING MATRIX — NEUTRINO MASS EIGENVALUES

$$= c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 e^{i\alpha} m_2 + s_{13}^2 e^{i\beta} m_3$$

Heidelberg –Moscow (HM) (stopped in May 2003)

dominated DBD scenario over a decade. claim of evidence!!

NEMO3

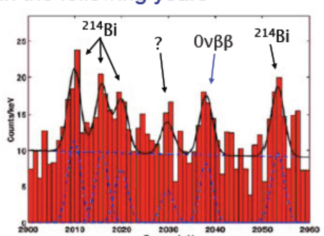
intermediate generation experiment capable to study different isotopes

CUORICINO (stopped in june 2008)

intermediate generation experiment based on the bolometric technique

Nucleus	Detector	EXP	Material	kg y	$\tau_{1/2}$ Limit (y) (90% CL)
^{76}Ge	Ge diode	IGEX/HDM*	Ge	~ 47.7	> 1.6-1.9 x 10^{25}
^{82}Se	Tracking	NEMO3	Se	4.5	> 3.2 x 10^{23}
^{100}Mo	Tracking	NEMO3	Mo	31.5	> 1.0 x 10^{24}
^{96}Zr	Tracking	NEMO3	Zr	0.03	> 9.2 x 10^{21}
^{150}Nd	Tracking	NEMO3	Nd	0.1	> 1.8 x 10^{21}
^{128}Te	Bolometer	Cuoricino	TeO_2		> 1.1 x 10^{23}
^{130}Te	Bolometer	Cuoricino	TeO_2	19.75	> 2.8 x 10^{24}
^{136}Xe	Xe scint	DAMA	L Xe	~ 4.5	> 1.2 x 10^{24}
^{116}Cd		Solotvina			> 1.7 x 10^{23}
^{48}Ca					> 1.4 x 10^{22}
^{160}Gd					> 1.3 x 10^{21}

First claim in January 2002 (**Klapdor-Kleingrothaus HV et al. hep-ph/0201231**) with a statistics of 55 kg y and a 2.2-3.1 statistical significance → strong criticism
Claim confirmed in 2004 with the addition of a significant (~1/4) new statistics and improved in the following years

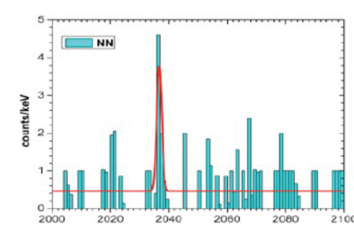


1990 - 2003 data, all 5 detectors
exposure = 71.7 kg×y
$T_{1/2}$ = 1.2×10^{25} years
⟨m⟩ = 0.44 eV

H.V.Klapdor-Kleingrothaus et al., Phys. Lett. B 586 (2004) 198

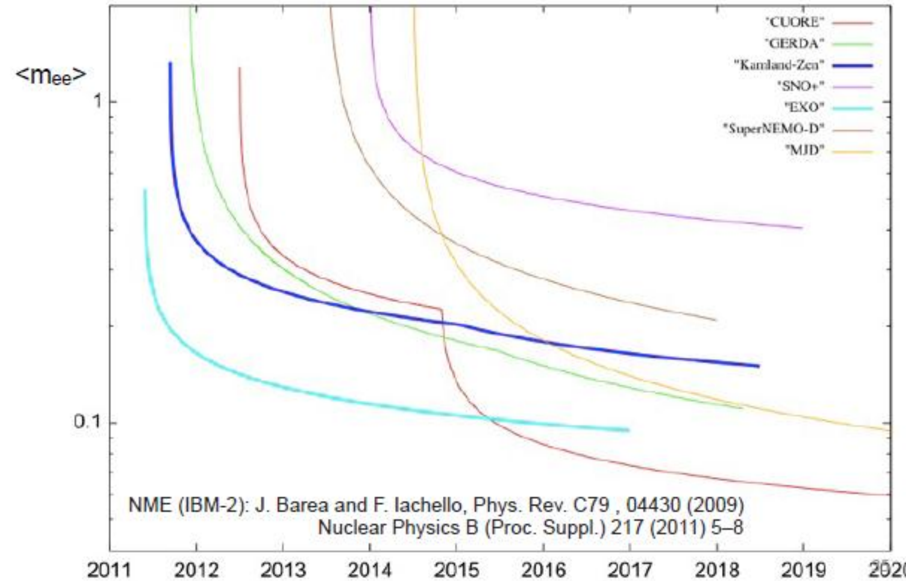
1995-2003 data new re-analysis: SSE selection by MC & ANN
6.4σ signal
7.05 ± 1.11 events
$2.23^{+0.44}_{-0.31}$ 10^{25} years / 0.32±0.03 eV

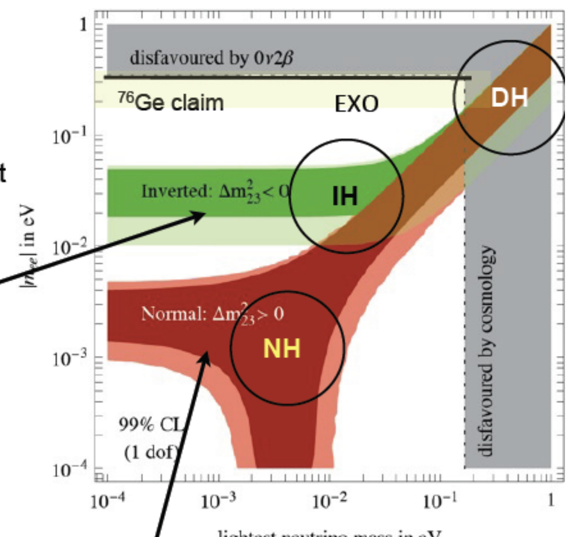
H.V.Klapdor-Kleingrothaus et al., Phys. Scr. T127 (2006) 40-42



all future experiment will certainly have to cope with this result

Experiment	Nucleus	Mass	Technique	Location	Date
Current experiments (funded, construction, running)					
GERDA I/II	^{76}Ge	15/35	ionization	LNGS	2011/13
Majorana	^{76}Ge	30	ionization	SUSEL	2014
EXO200	^{136}Xe	200	liquid TPC	WIPP	2011
Cuore0/Cuore	^{130}Te	10/200	bolometer	LNGS	2012/14
Kamland-Zen	^{136}Xe	400	liquid scintillator	Kamioka	2011
SNO+	^{150}Nd	44	liquid scintillator	Sudbury	2014
R&D (funding, prototyping)					
NEXT	^{136}Xe	100	gas TPC	Canfranc	2013+
Candles III	^{48}Ca	0.35	scintillating crystals	Oto Cosmo	2011
MOON	^{82}Se/^{150}Nd				
DCBA	^{150}Nd	32	tracking		
Cobra	^{116}Cd		solid TPC	LNGS	
SuperNEMO	^{82}Se	7/100-200	track/calorimeter	Modane	2014/?
XMASS	^{136}Xe		liquid scintillator	Kamioka	
Lucifer	^{82}Se	17.6	scintillating bolometer	LNGS	2014

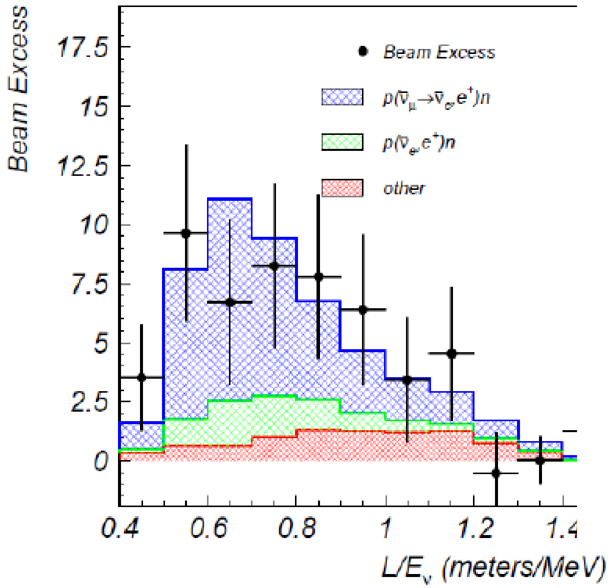




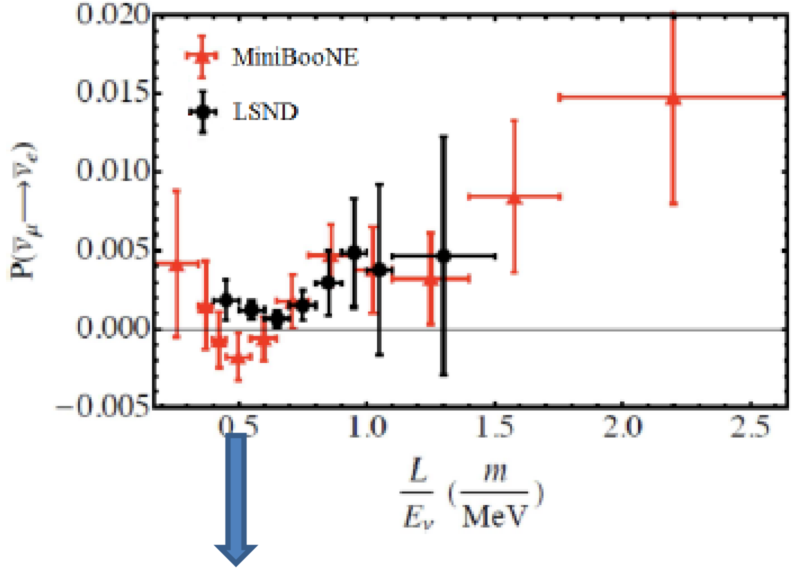
- $0\nu\beta\beta$ searches have still a very strong scientific motivation: lepton number violation, Majorana nature and properties (mass) of ν
- NME calculations: better understanding but still discrepancies ~2 in calculations
- Present generation experiments look for large masses (~100 kg) good energy resolutions and low background to sound the IH region in a variety of DBD nuclei
- Three of them (GERDA, EXO-200 and Kamland-Zen) have already started data taking and have just provided exciting results while CUORE is in an advanced phase of construction.
- Claim for evidence in ^{76}Ge with $\langle m_{ee} \rangle$ ~ 0.3 eV (DH) (6σ)will be soon scrutinized.
- A number of 10-50 kg projects aim at understanding backgrounds origin and demonstrating the feasibility of high sensitivity "zero background" next generation experiment to sound the NH region in the next 5-10 years.
- Their results will determine the best isotope and technique for future experiments

Light Sterile Neutrinos: The Evidence

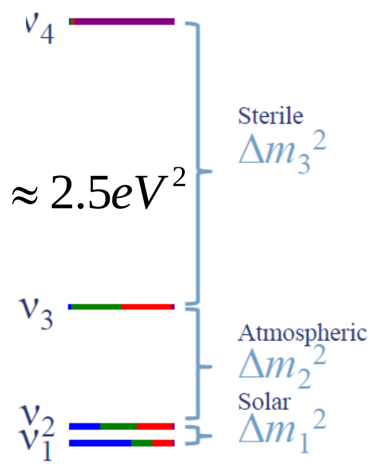
LSND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$



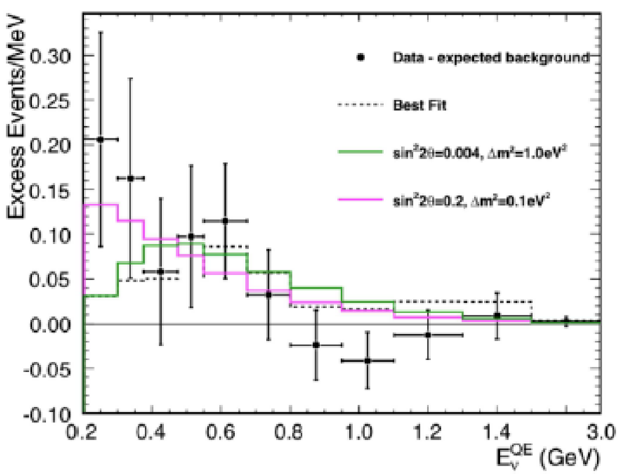
Event Excess: 32.2 ± 9.4 ± 2.3



$$1.267\Delta m^2 \frac{0.5m}{MeV} = \frac{\pi}{2} \Rightarrow \Delta m^2 = \frac{\pi}{2}\frac{1}{0.5 \cdot 1.267} \approx 2.5eV^2$$



MiniBooNE $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$



Event Excess: 54.9 ± 17.4 ± 16.3

Gallium Anomaly

The solar radiochemical detectors GALLEX and SAGE used intense EC sources (^{51}Cr and ^{37}Ar) to "calibrate" the $\nu_e Ga$ cross section.

The average ratio of measurement to theory is

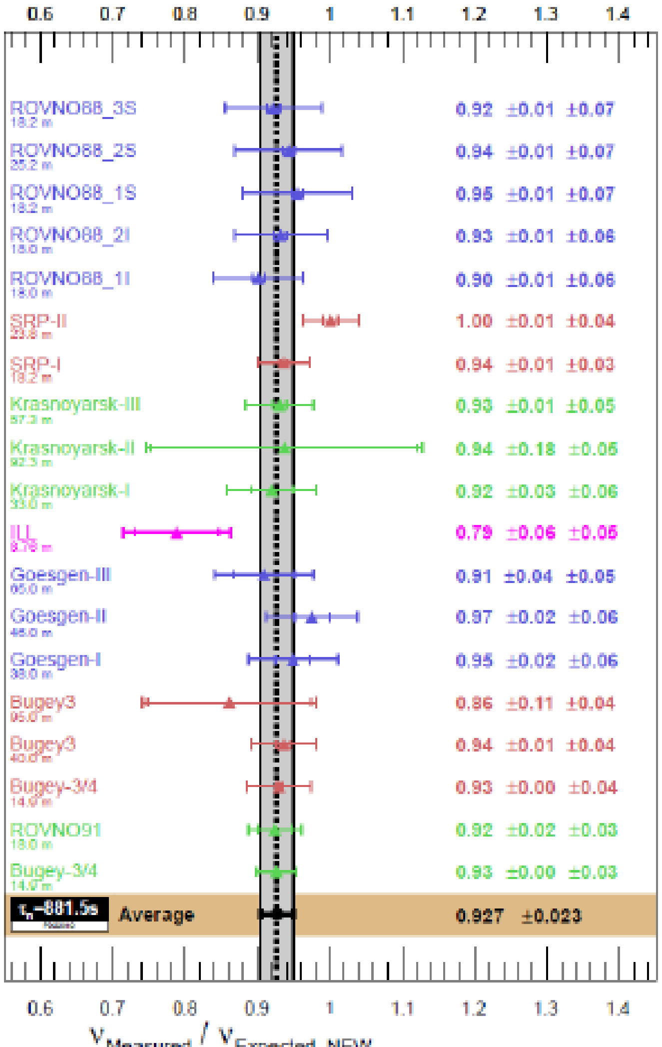
R=0.86±0.05 (Bahcall)

Or

$R=0.76^{+0.09}_{-0.08}$ (Haxton)

The deficit *may* be due to sterile neutrino oscillations.

Reactor Anomaly



Cosmology and the Number of Neutrinos

- The preferred 4 light neutrinos are actually light degrees of freedom: they don't have to be neutrinos, an axion would work as well.
- BBN disfavors 5 neutrinos, while fits to all of the particle data seem to require 5 neutrinos.

- There is a great deal of interest in sterile neutrinos lately
  - *Workshop on Beyond Three Family Neutrino Oscillations,* LNGS, April 2011
  - *Short-Baseline Neutrino Workshop,* Fermilab, May 2011
  - *Sterile Neutrinos at the Crossroads Workshop,* Virginia Tech, Sept. 2011
  - *Future Short Baseline Neutrino Experiments –Needs & Options,* Fermilab, March 2012
  - *Light Sterile Neutrinos: A White Paper,* arXiv:1204.5379, April 2012
- There are many hints of sterile neutrinos in particle physics:
  LSND, MiniBooNE $\bar{\nu}$, Gallium, Reactor Flux
- There are many null or ambiguous results as well:
  KARMEN, Bugey, MiniBooNE ν, Accelerator Disappearance
- There are several proposals/concepts for new, hopefully definitive tests of the $\Delta m \sim 1$ eV^2 sterile neutrino hypothesis.