Neutrino 2020 – Conference Report

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High Energy Physics Seminar
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Introduction

- Neutrino 2020: The XXIX International Conference on Neutrino Physics and Astrophysics,
- Fermilab conference entirely online, Zoom webinar
- On Monday through Thursday from June 22 - July 2, 2020
- All sessions plenary
- Communication on Slack
- Virtual poster sessions
- 3469 unique visitors attented the talks

Also: results from recent (end of July 2020) combined analysis of oscillation data (with included results from Neutrino 2020)

Sessions

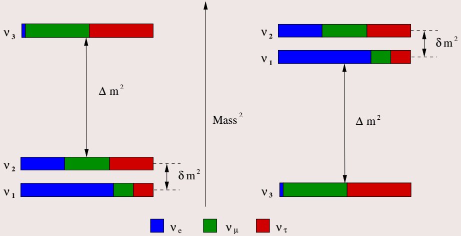
List of sessions

- Direct Neutrino Mass Measurements
- Neutrino Interactions
- Solar Neutrinos
- Theory of neutrino mass, mixing, leptogenesis, and BSM
- Neutrino Cosmology
- **Reactor and Geo Neutrinos**
- **Long baseline experiments and beams**
- **Probing the universe: neutrino astronomy**
- Neutrinoless double beta decay and underground facilities
- Accelerator sterile neutrino searches

Sessions

(Not complete) list of challenging problems

- Determination of the neutrino mass scale
  KATRIN: $m_\nu < 1.1$ eV $(90\% C.L.)$
- Determination of mass hierarchy (ordering)



  (NOvA+T2K, JUNO, PINGU, ORCA, DUNE)
- Quest to find CP violation in the leptonic sector
  (T2K, NOvA, DUNE, T2HK)

Sessions

(Not complete) list of challenging problems

- Are there sterile neutrinos ?
  (Reactor experiments, accelerator experiments, KATRIN, IceCube, cosmology . . .)
- Dirac or Majorana ?
  Neutrinoless double beta decay experiments.

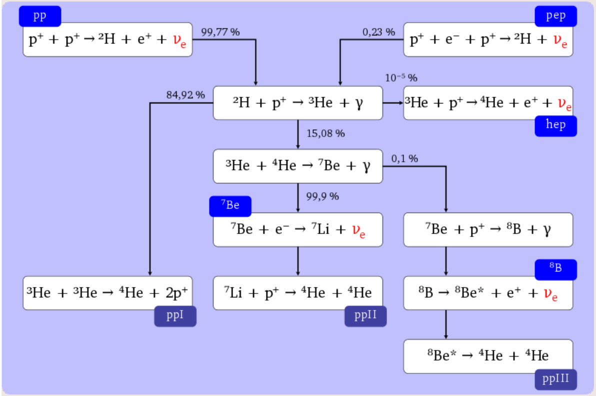
Sessions

New important results

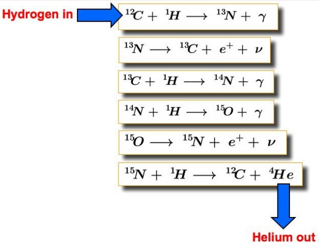
- Neutrino Interactions
  Great progress in understanding how neutrinos interact with matter (T2K, Minerva, NOvA, MicroBooNE . . .)
- Solar Neutrinos
  Borexino: First observation of neutrinos from CNO cycle
- Theory of neutrino mass, mixing, leptogenesis, and BSM
- Neutrino Cosmology
- Probing the universe: neutrino astronomy

Solar neutrinos

Borexino observes solar neutrinos from CNO cycle



pp chain, > 99% of the energy in the Sun



CNO cycle, remaining 1% of the energy ?

Borexino observes solar neutrinos from CNO cycle

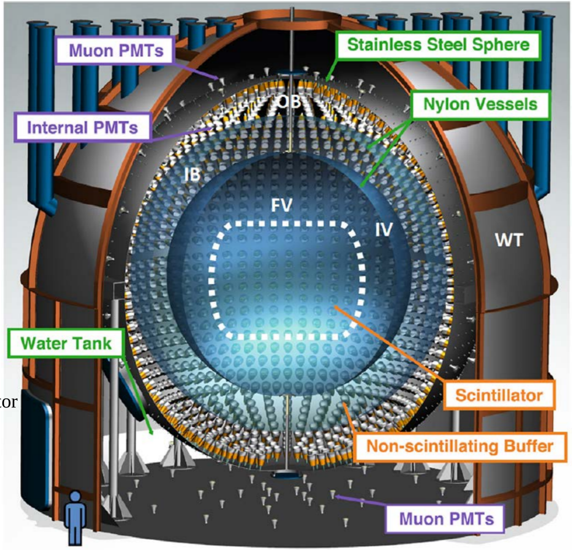
The Borexino detector @ Gran Sasso

Active volume 280 tons of liquid scintillator

Detection principle

$$\nu_x + e \to \nu_x + e$$

Elastic scattering off the electrons of the scintillator threshold at ~ 60 keV (electron energy)



2020 Jun 23

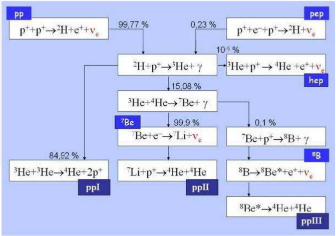
G. Ranucci - First detection of solar neutrinos from CNO cycle with Borexino

2

Borexino observes solar neutrinos from CNO cycle

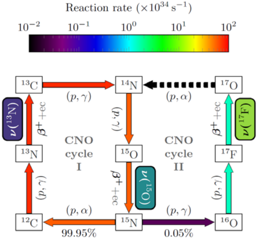
Standard Solar Model : “engine” of the Sun, solar neutrinos production and spectrum predictions

Developed by **John Bahcall** for more than 40 years



pp chain

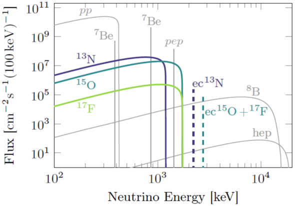
>99% of the energy in the Sun



Dominant in massive stars

the remaining <1% in the Sun ?

Latest SSM spectral prediction
A. Serenelli
EPJA, volume 5, id 78 (2016)
N. Vinyoles et al.
The Astrophysical Journal, 835:202 (16pp), 2017

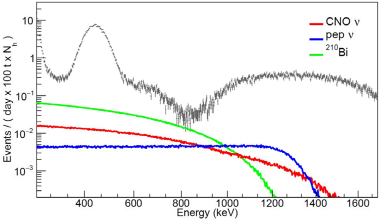


Controversy about the surface metallicity composition of the Sun: predictions differ up to 28% for the CNO ν flux using lower (LZ) or higher Z (HZ) models

Borexino observes solar neutrinos from CNO cycle

The Borexino quest for CNO neutrinos after the complete pp chain measurement

CNO ν – pep ν – ^{210}Bi correlations



- Borexino data
- CNO ν expected spectrum
- ^{210}Bi spectrum
- pep ν spectrum

The **spectral fit** returns only the sum of **CNO** and **^{210}Bi**, if both are left free

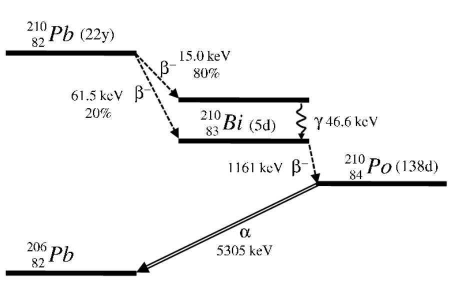
Note also the low rates:

- R(CNO ν)$_{expected}$ ~ 3-5 cpd/100ton
- R(^{210}Bi) ~ 10 cpd/100ton
- R(pep) ~ 2.5 cpd/100ton

Thanks to Borexino unprecedented purity @ 95% C.L ^{232}Th< 5.7 10^{-19} g/g ^{238}U < 9.4 10^{-20} g/g other backgrounds less relevant apart the cosmogenic ^{11}C

The pep flux can be constrained at the 1.4 % level through the solar luminosity constraint coupled to SSM predictions on the pp to pep rate ratio and the most recent oscillation parameters - J. Bergström et al., JHEP, 2016:132, 2016

Borexino observes solar neutrinos from CNO cycle



Two sources of ^{210}Po:

- $^{210}Po^S$ from ^{210}Pb in the liquid scintillator
- $^{210}Po^V$ from ^{210}Pb on the inner surfaces of the vessel

$^{210}Po^V$ may detach and move into the scintillator (diffusion or convective currents)

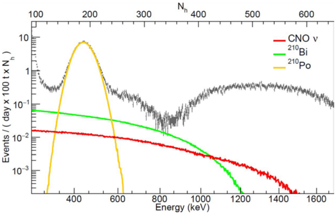
^{210}Bi independent determination from ^{210}Po

Degeneracy in the fit removable with a constraint on ^{210}Bi

Independent estimation of ^{210}Bi rate

^{210}Bi-^{210}Po analysis:
Extract the ^{210}Bi decay rate in Borexino through the study of the ^{210}Po decay rate

$$^{210}\mathrm{Pb} \xrightarrow[32\,\mathrm{y}]{\beta^-} {}^{210}\mathrm{Bi} \xrightarrow[7.23\,\mathrm{d}]{\beta^-} {}^{210}\mathrm{Po} \xrightarrow[199.1\,\mathrm{d}]{\alpha} {}^{206}\mathrm{Pb}$$



^{210}Po is "easier" to identify wrt ^{210}Bi:
- Monoenergetic decay → "gaussian" peak
- α decay → pulse shape discrimination

If the ^{210}Bi is in equilibrium with ^{210}Po, an independent measurement of the latter decay rate gives directly the ^{210}Bi one (secular equilibrium scenario)

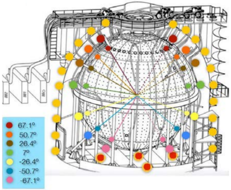
→ The quest for CNO is turned into the quest of ^{210}Bi through ^{210}Po !

Posters: "Strategy of detection of solar CNO neutrinos with Borexino Phase-III data" Xuefeng Ding #438 session 2
"Borexino Sensitivity Studies towards Detection of Solar Neutrinos from the CNO Fusion Cycle" Ömer Penek #235 session 3

Multiple approaches to monitor, understand, and suppress the temperature variations

Thermal insulation & Active Gradient Stabilization System

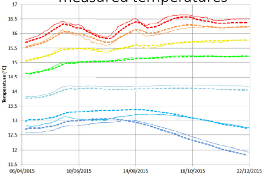
Temperature monitoring probes



54 temperature probes

Fluid dynamical simulation

Very good agreement with measured temperatures



time

6/04 2015 | 10/06 2015 | 14/08 2015 | 18/10 2015 | 22/12 2015

- Double layer of mineral wool (thermal conductivity down to 0.03 W/m/K) & Active Gradient Stabilization System (2014-2016)
- Temperature Probes (2014-2015)
- Fluid dynamical simulations
- Hall C Temperature Stabilization (2019)

V. di Marcello et al., NIM A 964, id. 163801

Enduring effort over the past six years

2020 Jun 23

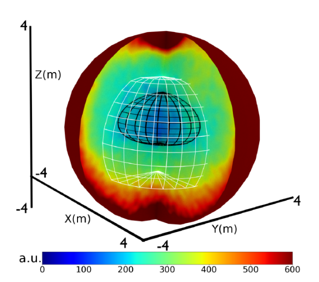
G. Ranucci - First detection of solar neutrinos from CNO cycle with Borexino

7

Borexino observes solar neutrinos from CNO cycle

^{210}Bi upper limit from ^{210}Po data

- LPoF (Low Polonium Field): region with minimum ^{210}Po rate
- $R(^{210}Po_{min}) = R(^{210}Bi) + R(^{210}Po^V)$



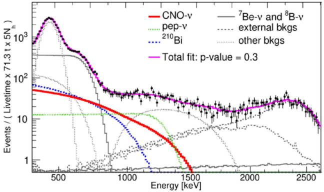
LPOF – black grid, FV – white grid

Borexino observes solar neutrinos from CNO cycle

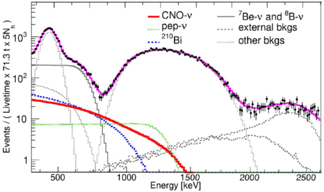
TFC = Three-Fold Coincidence (μ, n and β^+) to reduce background from ^{11}C isotope. ^{11}C from muon-initiated spallation on ^{12}C.

CNO-ν analysis: Phase-III MV fit

TFC-subtracted spectrum



TFC-tagged spectrum



Multivariate fit (0.32-2.64 MeV)
July '16 – February '20

Maximization of a binned likelihood **3 distributions simultaneously**:

- Reconstructed energy for TFC-tagged and TFC-subtracted datasets (^{11}C identification)
- Radial position

pep-ν rate constrained	→ solar luminosity constraint
^{210}**Bi rate** constrained	→ ^{210}**Bi-**^{210}**Po tagging**
CNO rate	→ free to vary
Other ν and bkg rates	→ free to vary

Result

CNO best fit 7.2 cpd/100t
asymmetric confidence interval -1.7 +2.9 cpd/100t
(stat only) asymmetry ↔ ^{210}Bi upper limit

Borexino observes solar neutrinos from CNO cycle

Results

- The CNO solar neutrino rate:
  $7.2^{+3.0}_{-1.7}$ counts per day (cpd)/100 tons, 60% C.L.
- Corresponding flux of ν on Earth:
  $7.0^{+3.0}_{-2.0} \times 10^8\ cm^{-2}s^{-1}$
- Absence of CNO signal disfavoured at 5.0σ

Neutrino oscillations (3ν and 4ν)

Probability of $\nu_\alpha \rightarrow \nu_\alpha$ disappearance in model with two neutrinos

$$\mathrm{P}_{\nu_\alpha \rightarrow \nu_\alpha} = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Neutrino oscillation matrix in the three-flavour model

$$|\nu_j\rangle = \sum_{\alpha=\mathrm{e},\mu,\tau} U_{\alpha j}|\nu_\alpha\rangle.$$

$$\mathrm{U} = \begin{pmatrix} U_{\mathrm{e}1} & U_{\mathrm{e}2} & U_{\mathrm{e}3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}.$$

$|U_{\alpha j}|^2$ describe the neutrino flavour-α fraction of ν_j

Neutrino oscillation matrix

Extended oscillation matrix:

$$\mathrm{U} = \begin{pmatrix} U_{\mathrm{e}1} & U_{\mathrm{e}2} & U_{\mathrm{e}3} & U_{\mathrm{e}4} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & \cdots \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & \cdots \\ U_{\mathrm{s}1} & U_{\mathrm{s}2} & U_{\mathrm{s}3} & U_{\mathrm{s}4} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix}.$$

Active-sterile mixing must be small:

$$|U_{\alpha i}|^2 \ll 1 \qquad (\alpha = \mathrm{e}, \mu, \tau; i = 4, \ldots, N).$$

Mixing angles in 3+1 model

Mixing matrix U can be parameterized by the mixing angles θ_{34}, θ_{24}, θ_{14}, phases δ_2 and δ_3 in addition to θ_{23}, θ_{13} and θ_{12} and δ_1,

$$
\begin{aligned}
|U_{e4}|^2 &= \sin^2\theta_{14}, \\
|U_{\mu 4}|^2 &= \cos^2\theta_{14}\sin^2\theta_{24}, \\
|U_{\tau 4}|^2 &= \cos^2\theta_{14}\cos^2\theta_{24}\sin^2\theta_{34}.
\end{aligned}
$$

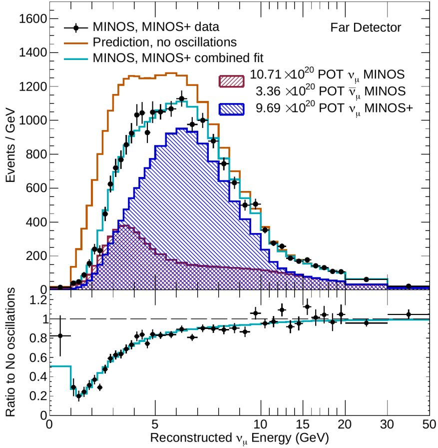
For small angles $|U_{e4}|^2 = \sin^2\theta_{14}$, $|U_{\mu 4}|^2 \simeq \sin^2\theta_{24}$ and $|U_{\tau 4}|^2 = \sin^2\theta_{34}$.

Potential of neutrino experiments to study U

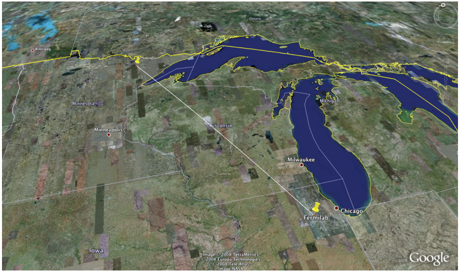
type of measurement	sensitive to
ν_{e} or $\overline{\nu}_{\mathrm{e}}$ disappearance	$\lvert U_{\mathrm{e}i} \rvert$
ν_{μ} or $\overline{\nu}_{\mu}$ disappearance	$\lvert U_{\mu i} \rvert$
$\nu_{\alpha} \to \nu_{\beta}$ appearance	$\lvert U_{\alpha i} \rvert$ and $\lvert U_{\beta i} \rvert$

Long-baseline experiments, three-flavour oscillations

Final 3ν oscillation results from MINOS/MINOS+



$$P_{\nu_\mu \to \nu_\mu} \approx 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$



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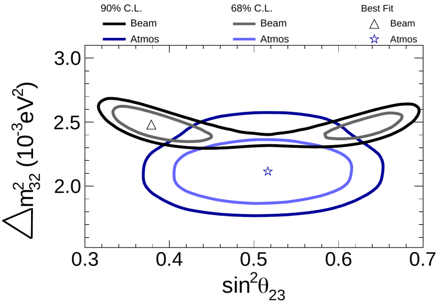
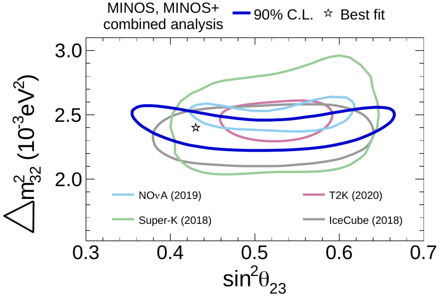


Beam and atmospheric data



Combined analysis

(Similar constraints on Δm^2_{32} from Daya Bay !)

Long baseline experiments

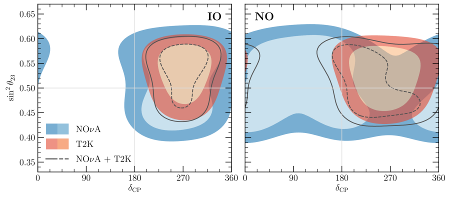
Mass ordering (hierarchy) and CP violation

- Study of $P(\nu_\mu \to \nu_e)$ vs $P(\overline{\nu}_\mu \to \overline{\nu}_e)$
- Before Neutrino 2020: hints for normal neutrino ordering and CP violation in neutrino sector

Status of hints for normal neutrino ordering and CP violation

After Neutrino 2020

Results from global analysis including new data from T2K and NOvA:



1σ and 2σ allowed regions

NuFit 5.0

`http://www.nu-fit.org/`

arXiv:2007.14792

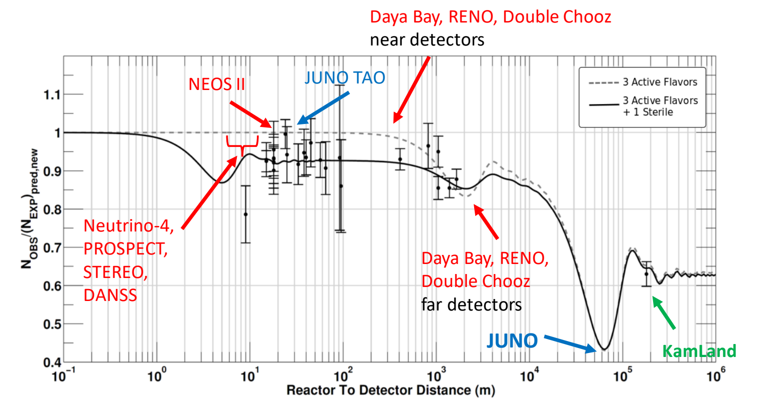
- hints for normal neutrino mass ordering decreased (currently at 2.7σ)
- CP conserving value $\delta_{CP} = \pi$ within 0.6σ of the global fit point.
- With inverted mass ordering CP violation is favoured at $\sim 3\sigma$ level.

Reactor experiments

Reactor antineutrino oscillations

$$P^{3\nu}_{(\overline{\nu_e}\to\overline{\nu_e})} \simeq 1 - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

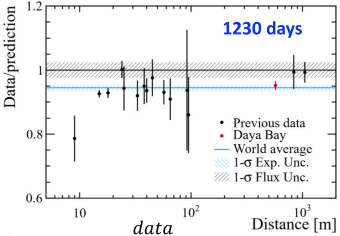
$$= 1 - \sin^2 2\theta_{13}\sin^2\Delta_{ee} - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} \qquad \Delta_{ij} = \frac{1.27\Delta m^2_{ij} L}{E_\nu}$$

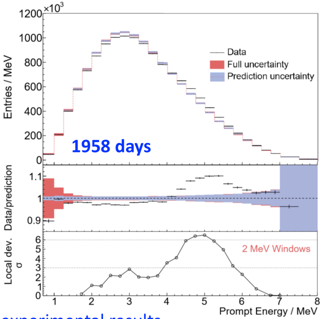


T.Lasserre

Reactor experiments – Daya Bay

PRD ***100*** *052004 (2019)* *PRL* ***123*** *111801 (2019)* ***R. Mandujano's Poster #426***





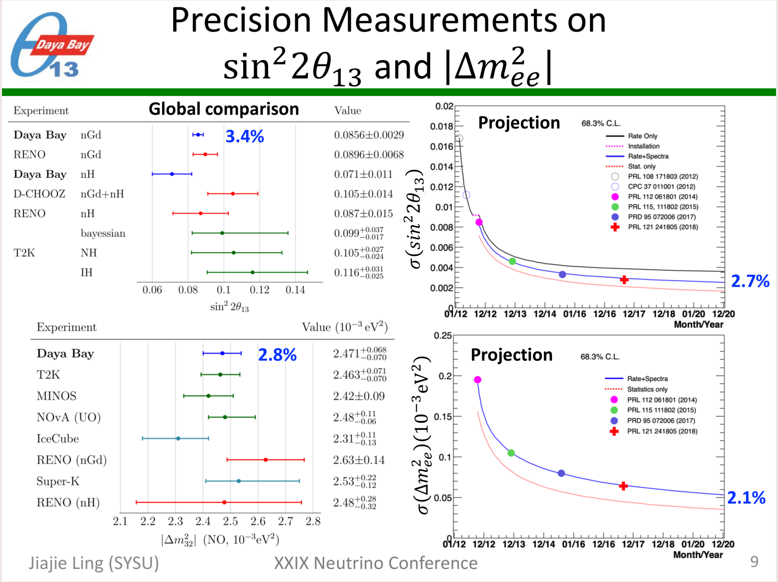
$$R = \frac{data}{Model\ (Huber + Mueller)}$$

$$= 0.952 \pm 0.014(exp) \pm 0.023(model)$$

- Daya Bay result is consistent with the previous experimental results
- Data/prediction spectrum shows a total >5σ deviation, especially significant deviation at 4-6 MeV region of the prompt energy (>6σ)
- No effect on far/near relative measurement for θ_{13} and Δm^2_{ee}

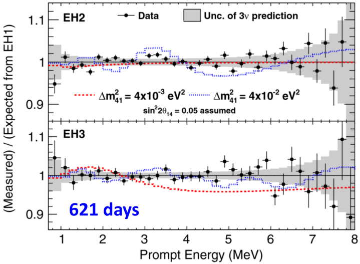
Jiajie Ling (SYSU) XXIX Neutrino Conference 13

Reactor experiments – Daya Bay

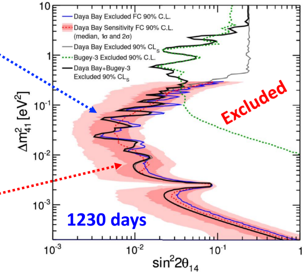


Sterile Neutrino Search

PRL ***117*** *151802 (2016)*



arXiv:2002.00301, accepted by PRL



$$P(\bar{\nu}_e \to \bar{\nu}_e) \cong 1 - cos^4\theta_{14} sin^2 2\theta_{13} sin^2\left(\frac{\Delta m^2_{31} L}{4E_\nu}\right) - sin^2 2\theta_{14} sin^2\left(\frac{\Delta m^2_{41} L}{4E_\nu}\right)$$

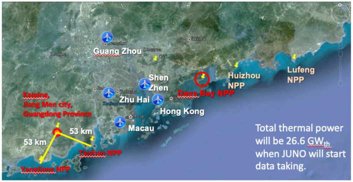
- Search for an additional oscillation frequency besides Δm^2_{31} and Δm^2_{32}
- Data is consistent with 3-ν model; No light sterile neutrino signal observed
- Consistent results from Feldman-Cousins and CLs methods

The most stringent upper limit for light sterile neutrinos ($\Delta m^2 < 0.2$ eV^2)

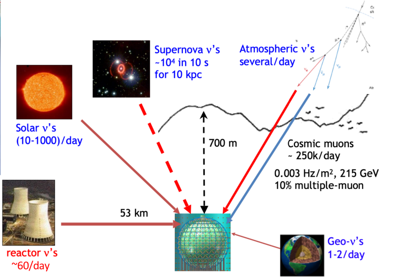
Future reactor experiment – JUNO

Jiangmen Underground Neutrino Observatory (JUNO)

- JUNO has a rich program in neutrino physics and astrophysics



Nuclear power plant	Status	Power
Daya Bay	Operational	17.4 GW
Huizhou	Planned	17.4 GW
Lufeng	Planned	17.4 GW
Yangjiang	Operational	17.4 GW
Taishan	Operational	9.2 GW (2 reactors online now)



From J. Pedro Ochoa-Ricoux's Nufact 2019

3

Future reactor experiment – JUNO

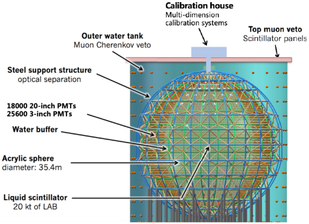
Keys for the JUNO detector

1. Optimal baseline for the detector
2. Large statistics
   - 26.6 GW_{th} power
   - ~60 IBD events per day
3. Energy resolution < 3%/√E between 1 MeV and 8 MeV

$$\frac{\sigma_{E_{\rm vis}}}{E_{\rm vis}} = \sqrt{\left(\frac{a}{\sqrt{E_{\rm vis}}}\right)^2 + b^2 + \left(\frac{c}{E_{\rm vis}}\right)^2}$$

a: the statistical term
b: a constant term independent of the energy, dominated by position non-uniformity
c: the contribution of a background noise term

4. Energy scale uncertainty < 1%
   - Comprehensive calibration strategy
5. Background control



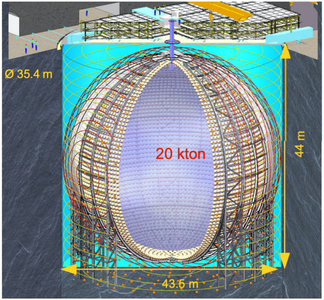
Experiment	Daya Bay	Borexino	KamLAND	JUNO
Target mass [tons]	8 x 20	~300	~1,000	20,000
Photo electron collection [p.e./MeV]	~160	~500	~250	~1200
Energy resolution	~8.5%	~5%	~6%	~3%
Photocathode coverage	12%	34%	34%	75%
Energy calibration uncertainty	0.5%	1%	2%	<1%

9

Future reactor experiment – JUNO

Central detector (CD)

- 35 m diameter acrylic sphere
- Stainless steel truss
- 20,000 tons purified liquid scintillator
- 18,000 20-inch PMTs
- 25,600 3-inch PMTs
- Filling/Overflow/Circulation (FOC) system



Yue Meng, Neutrino2020 10

Future reactor experiment – JUNO

Physics Prospects

$$
\begin{aligned}
P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\
P_{21} &= \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) \\
P_{31} &= \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) \\
P_{32} &= \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})
\end{aligned}
$$

$$\Delta_{ij} = 1.27\Delta m^2_{ij} L/E$$

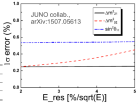
Neutrino mass ordering

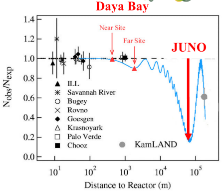
- 3σ neutrino mass ordering sensitivity within 6 years.
- 4σ with Δm^2_{32} input from accelerator experiments.
- $> 5\sigma$ combined analysis with IceCube within 3–7 years or PINGU in 2 years (arXiv: 1911.06745)

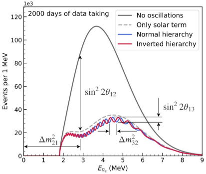
Neutrino oscillation parameters

- Sub-percent accuracy for θ_{12}, Δm^2_{21} and Δm^2_{31}
- Current precision

	Δm^2_{21}	$\lvert\Delta m^2_{31}\rvert$	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$	δ
Dominant Exps.	KamLAND	T2K	SNO+SK	Daya Bay	NOνA	T2K
Individual 1σ	2.4%	2.6%	4.5%	3.4%	5.2%	70%
Nu-FIT 4.0	2.4%	1.3%	4.0%	2.9%	3.8%	16%







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From CERN Courier

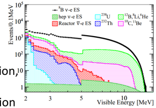
4

Future reactor experiment – JUNO

Physics Prospects

Solar neutrinos

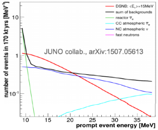
- ^{8}B solar neutrino detection via neutrino-electron elastic scattering in JUNO
- Large target mass, effective cosmogenic background rejection, background (10^{-17} g/g U/Th)
- Shed new light on current tension in Δm^2_{21} between solar and reactor neutrinos measurement with the same detector



Expected signal and background spectrum
arxiv: 2006.11760

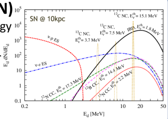
Diffuse Supernove Neutrino Background (DSNB)

- 3σ sensitivity in 10 years or strongest constraint
- Star formation rate and core collapse neutrino spectrum



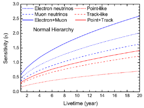
SuperNOVA neutrinos (SN)

- Sensitivity: flavor content, energy spectrum, time evolution
- 10000 events (5000 via IBD) for SN @ 10kpc
- Low threshold 0.2 MeV



Atmospheric neutrinos

- Measure θ_{23} with 6° precision
- Complimentary neutrino mass ordering sensitivity via matter effect



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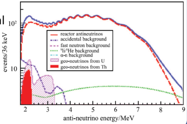
Future reactor experiment – JUNO

Physics Prospects

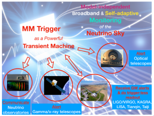
Geo-neutrinos

- Explore origin and thermal evolution of the Earth
- 400 – 500 neutrinos per year
- Precision 6% in 10 years



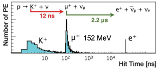
Multi-messager astrophysics

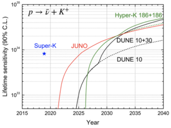
- lower the energy threshold of the detector down to O(10) keV
- Realtime monitoring of the MeV transient neutrino sky



Proton decay

- Competitive sensitivity to proton decay searches
- Triple coincidence signal





- Reactor flux shape precise measurement
- Sterile neutrinos
- Other exotic searches, etc

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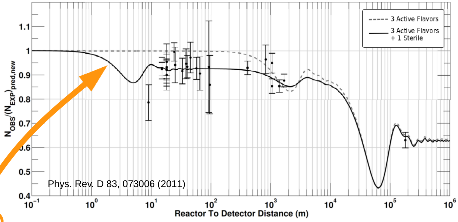
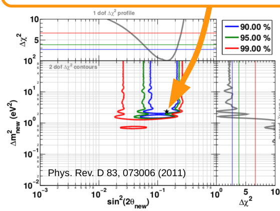
Very short baseline reactor experiments – Motivation

Motivation

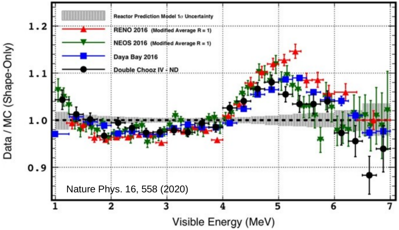
- Improved reactor neutrino flux predictions:
  → deficit in measured fluxes
- One possible explanation:
  → light sterile neutrinos
- Sterile neutrinos:
  → new oscillation channel visible at small L/E



Reactor Antineutrino Anomaly (RAA)
$\sin^2(2\theta_{new})=0.14$, $\Delta m^2_{new}=2.4\,eV^2$



- Energy spectral distortion w.r.t. model
  → up to ~10% between 4 and 6 MeV

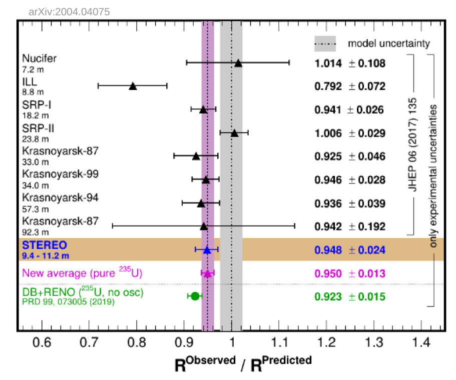


Very short baseline reactor experiments

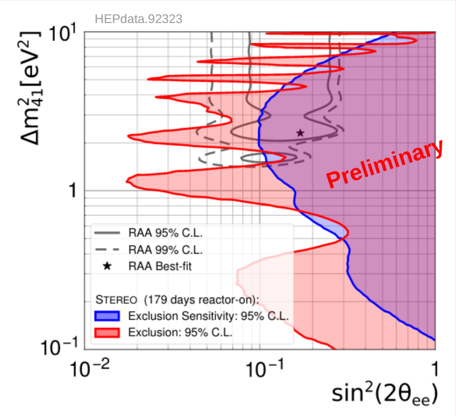
- PROSPECT - Oak Ridge, US, baseline 6.7-9.2 m
- STEREO - Grenoble, France, baseline 9-11 m
- Neutrino-4 - Dimitrovgrad, Russia, baseline 6-12 m
- Future: NEOS-II (Korea, 23.7 m), JUNO-TAO (Korea, 30-35 m)

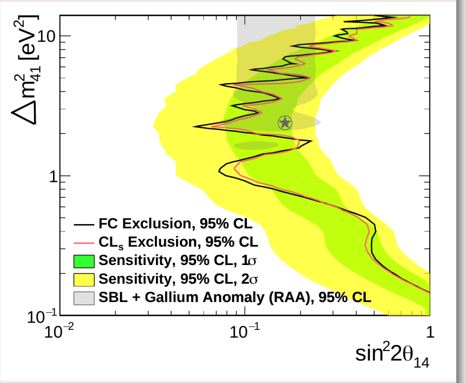
Very short baseline reactor experiments

Flux measurements

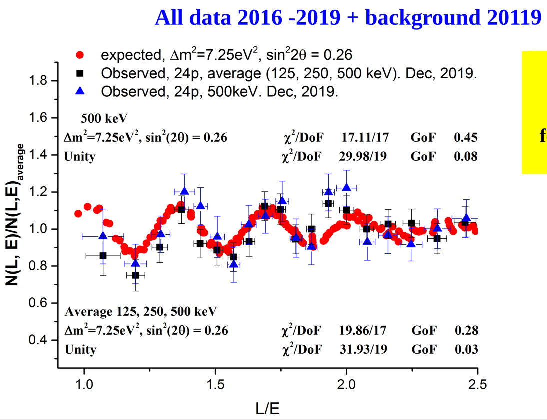


Limits from STEREO and PROSPECT





Very short baseline reactor experiment – Neutrino-4



The period of oscillation is 1.4 m for neutrino energy 4 MeV

A.P.Serebrov, et al.
JETP Letters,
Volume 109, (2019)
Issue 4, pp 213–221.

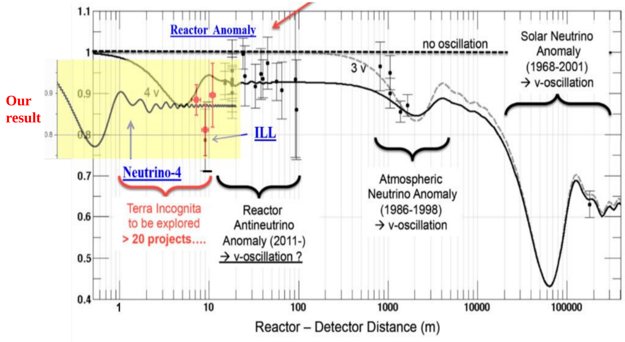
arxiv:1809.10561

arXiv:2005.05301

20

Very short baseline reactor experiment – Neutrino-4

Reactor antineutrino anomaly with oscillation curve obtained in experiment Neutrino-4



T. Mueller, D. Lhuillier, M. Fallot et al., Phys. Rev. C 83, 054615 (2011).

28

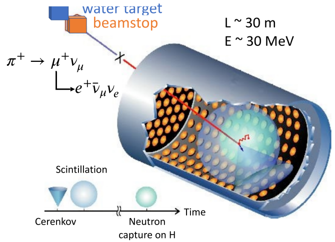
Accelerator experiments in sterile neutrino searches

Comparing MiniBooNE and LSND

LSND (1993-1998)

0.8 GeV proton beam

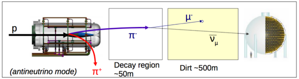
Decay At Rest neutrino flux

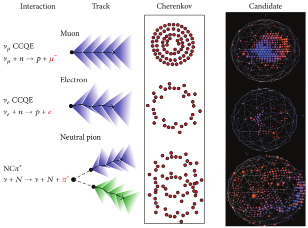


MiniBooNE (2002-2019)

8 GeV proton beam

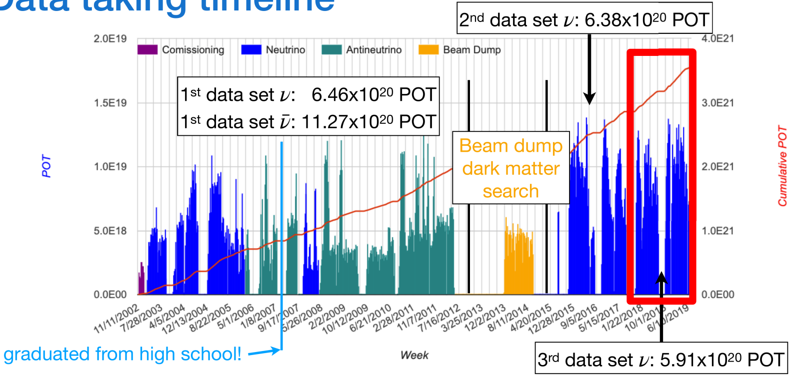
Decay In Flight beam





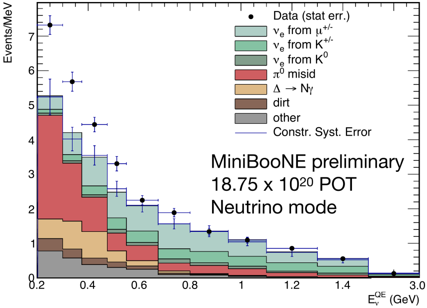
Different systematics. Same L/E baseline.

Data taking timeline



- We have added another ~6x10^{20} POT to the neutrino dataset since the previous data release.
- The detector was turned off at the end of summer 2019, mothballed and waiting for future use…
- Almost 17 years of running, or as much as 5 army ants worth of protons!

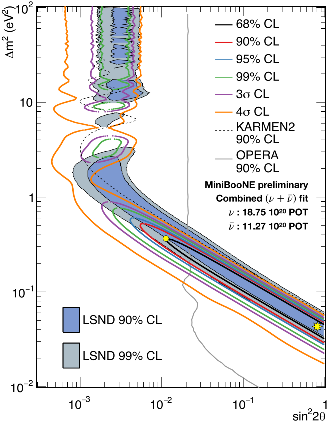
Neutrino energy and 3ν prediction



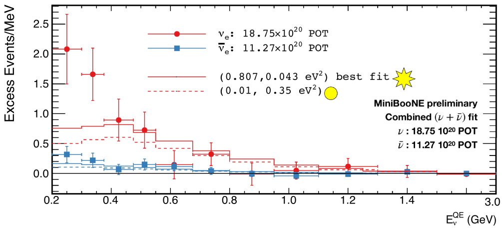
- Excess of data events with respect to our background prediction
- We report an excess of 560.6 ± 119.6 electron-like events (neutrino mode)

- **Significance : 4.7 σ in neutrino mode only**

Preferred regions in sterile neutrino hypothesis



- Neutrino mode excess 4.7σ,
- **Neutrino+Anti-neutrino modes excess : 4.8σ**



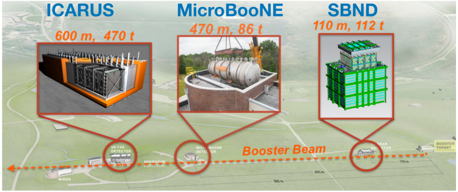
Neutrino + Anti-Neutrino Mode

$$(\Delta m^2, \sin^2 2\theta) = (0.043\ \text{eV}^2, 0.807)$$

$$\chi^2/ndf = 21.7/15.5\ (\text{prob} = 12.3\%)$$

Accelerator sterile neutrino searches – tests of LSND and MiniBooNE excess

- MiniBooNE stopped data-taking
- Waiting for results of MicroBooNE (LAr) tests of MiniBooNE low energy excess (photon vs electron)
- Fermilab Short Baseline Neutrino Program (SBN) (also *JSNS*^{2} in J-PARC in Materials and Life Science).



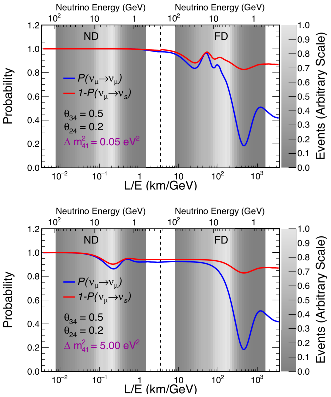
Accelerator sterile neutrino searches - MINOS/MINOS+

4-Flavor Oscillations at MINOS

Small

Δm^2_{41}

Large



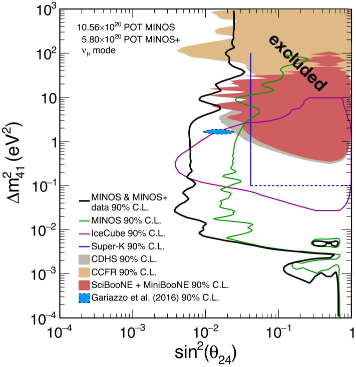
Small Δm^2_{41} : Oscillations at the FD

Large Δm^2_{41}: Large oscillations at the ND

Accelerator sterile neutrino searches - MINOS/MINOS+

MINOS+ Exclusion

P. Adamson *et al.* [MINOS Collaboration], Phys. Rev. Lett. **122**, 091803 (2019)



Fit θ_{23}, θ_{24}, Δm^2_{32}, and Δm^2_{41}

Fix δ_{13}, δ_{14}, δ_{24}, and θ_{14} to zero

(no sensitivity)

- Simultaneous 2 detector fit over long baseline
- Improvement over previous FD/ND ratio method
- Improvement with MINOS+ extra statistics

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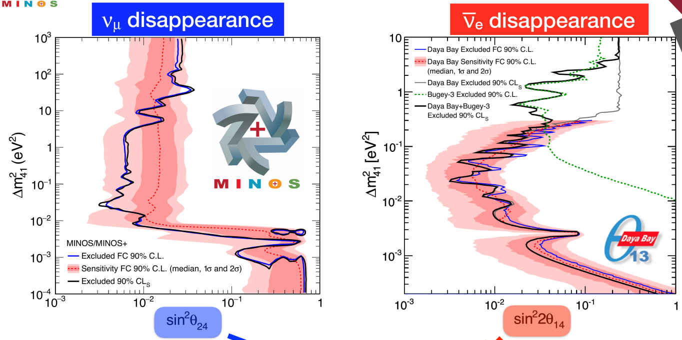
Accelerator sterile neutrino searches - MINOS/MINOS+

MINOS+/Daya Bay/Bugey-3 Exclusion

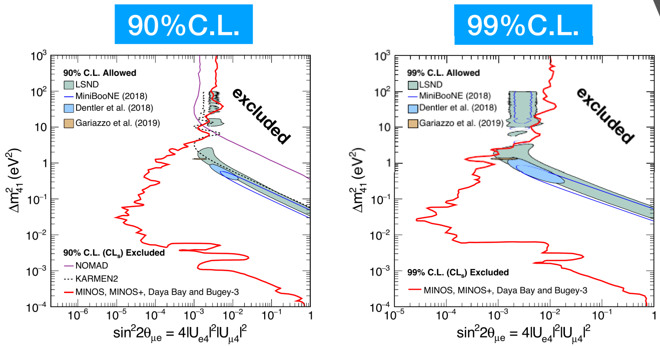


$$4|U_{e4}|^2|U_{\mu 4}|^2 = \sin^2\theta_{24}\sin^2 2\theta_{14} \equiv \sin^2 2\theta_{\mu e}$$

arXiv:2002.00301 (accepted by PRL)

Accelerator sterile neutrino searches - MINOS/MINOS+

MINOS+/Daya Bay/Bugey-3 Exclusion



arXiv:2002.00301 (accepted by PRL)

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Summary

- Neutrino 2020 virtual conference was a success
- Many interesting new results
- If you are interested in details: not only slides, but also video recordings are available on the conference web page: `https://conferences.fnal.gov/nu2020/`