Neutrino Experiment
Summary

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MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

W⁻IN 2015

June 8-13, 2015
MPIK, Heidelberg

MAX-PLANCK-GESELLSCHAFT

- Thank you very much for LOC !

  venue, shuttle bus, lunch, excursion, banquet etc…

- Many thanks to all the speakers !

  excellent talks, some new results, good questions etc…

Photo: C. Föhr

Session Overview

- ❑ Neutrino 1: Reactor ν
- ❑ Neutrino 2: Solar/Low E/Atmos ν
- ❑ Neutrino 3: Sterile ν
- ❑ Neutrino 4: ν meets astroparticle phys
- ❑ Neutrino 5: Longbaseline ν & theory
- ❑ Neutrino 6: Double beta decay
- ❑ Neutrino 7: ν theory
- ❑ Neutrino 8: Theory & future R&D

Total 8 sessions:
~30 experimental
talks

2 New results

Q1.
Why neutrinos are so attractive ?

They are standard model (SM) particles BUT behaves like BSM particles !

Neutrino masses & oscillations

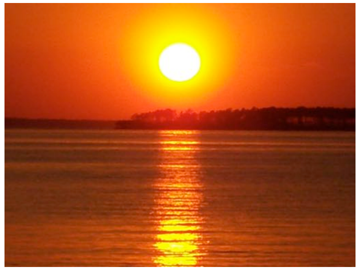
Still mysterious !

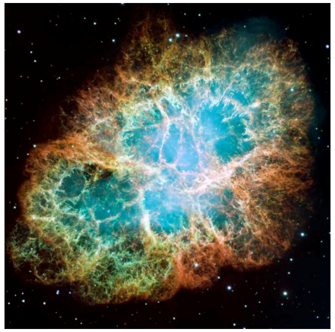
Mass ordering, CP violation ?,
Dirac vs. Majorana, absolute mass,
Sterile neutrinos ?

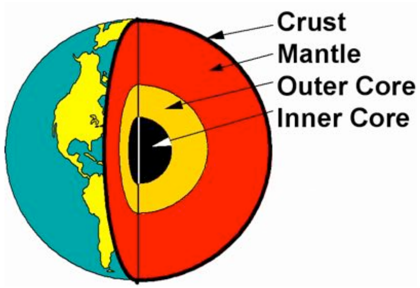
Q2.
How can we approach to unveil the mysteries ?

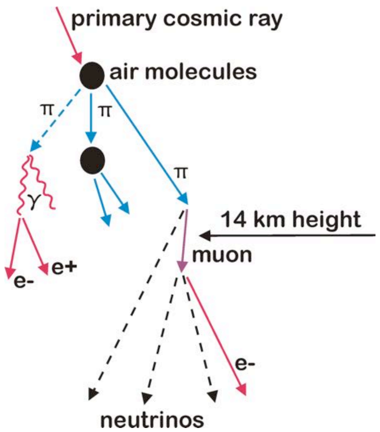
Use all possibilities !

- Use natural resources
- Use artificial resources









Use all possibilities !

- Use natural resources
- Use artificial resources

- Use different techniques
- Use similar techniques also

Use all possibilities !

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- Do collaboration:
  exp & exp
  theory & exp
  theory & theory

Use all possibilities !

- Use natural resources
- Use artificial resources

- Use different techniques
- Use similar techniques also

- Do collaboration:
  exp & exp
  theory & exp
  theory & theory

- Think wise & Work hard !

PMNS matrix (1962)

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \boxed{\begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

Most ν_e content

least ν_e content

- **P**ontecorvo
- **M**aki
- **N**akagawa
- **S**akaga

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmos. (ν_μ, $\overline{\nu}_\mu$ deficit)
Long baseline (ν_μ deficit)

Reactor ($\overline{\nu}_e$ deficit)
Long baseline ($\nu_\mu \rightarrow \nu_e$)

Solar (ν_e deficit)
Reactor ($\overline{\nu}_e$ deficit)

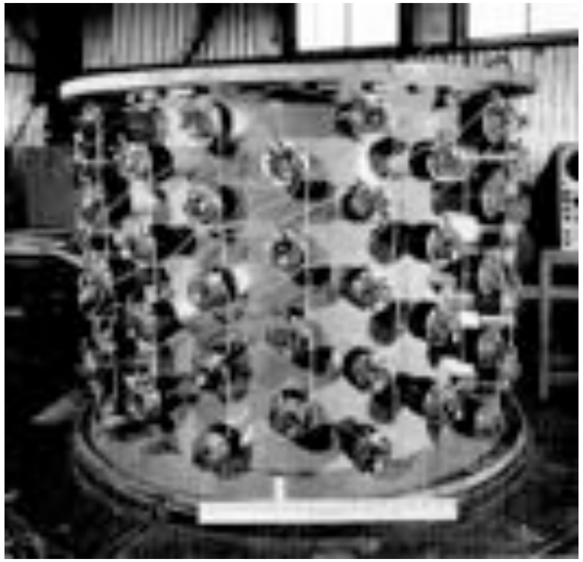
Neutrino Oscillation Milestones

Atmos. Neutrino Oscillation	θ_{23}	**~45°** **(1998)** **Super-K;** K2K
↓		↓ 3 years
Solar Neutrino Oscillation	θ_{12}	**34°** **(2001)** **SNO**, **Super-K;** KamLAND
↓		↓ 11 years
Reactor Neutrino Oscillation	θ_{13}	**9°** **(2012)** **Daya Bay, RENO** Double Chooz

Nature was very kind to us !

First discovery of neutrino is from reactor neutrinos !

In **1956** @Savannah river, S. Carolina
By Reines and Cowan



So it is fair for me to start with reactor neutrinos !

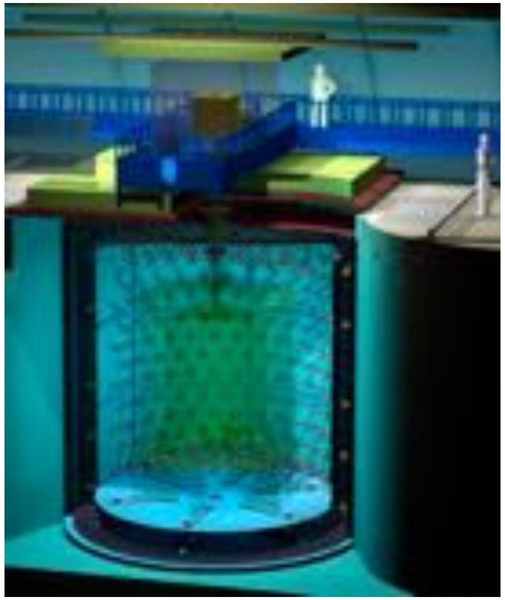
Reactor θ_{13} Experiments

Double Chooz

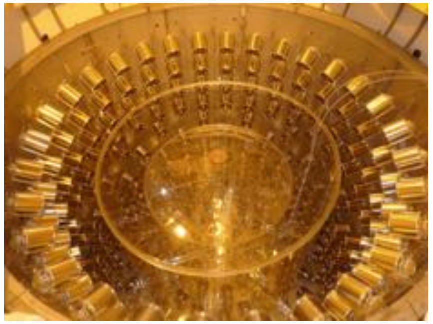
RENO

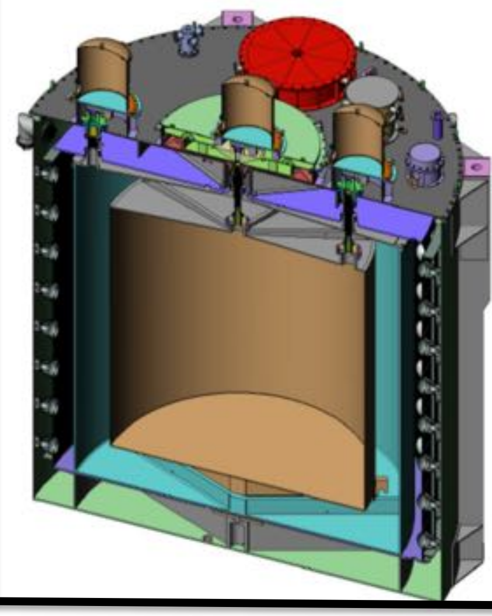
Daya Bay

θ_{13} Reactor Neutrino Detectors

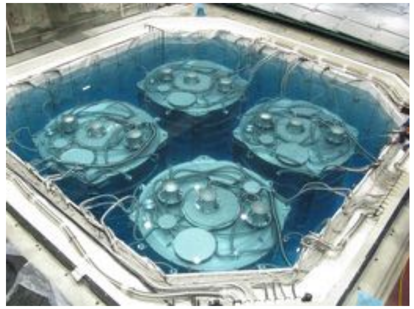


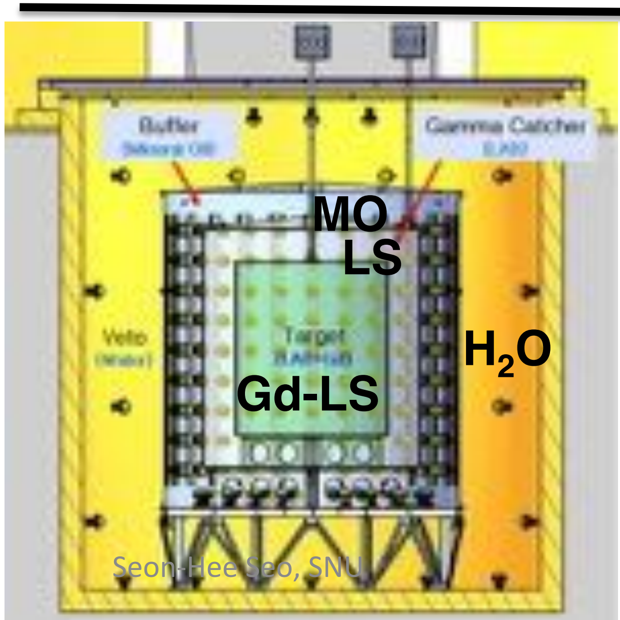
DOUBLE Chooz





Daya Bay θ_{13}

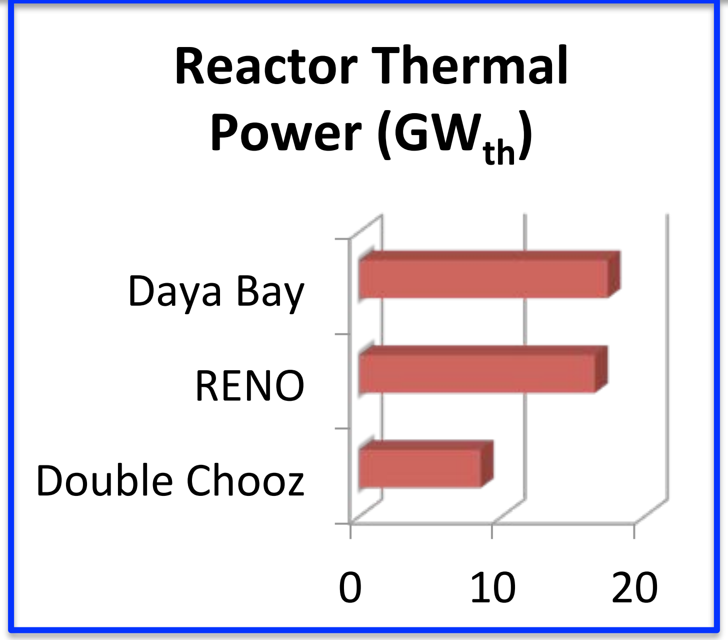


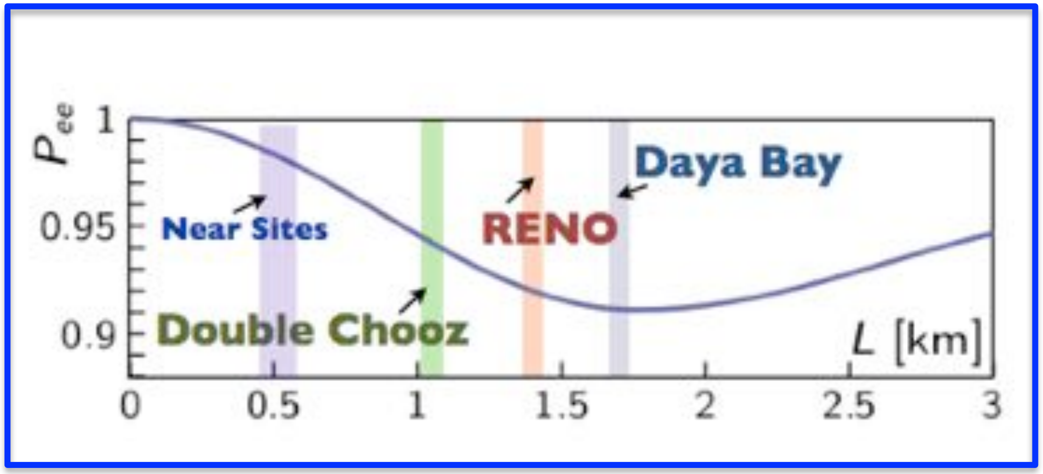


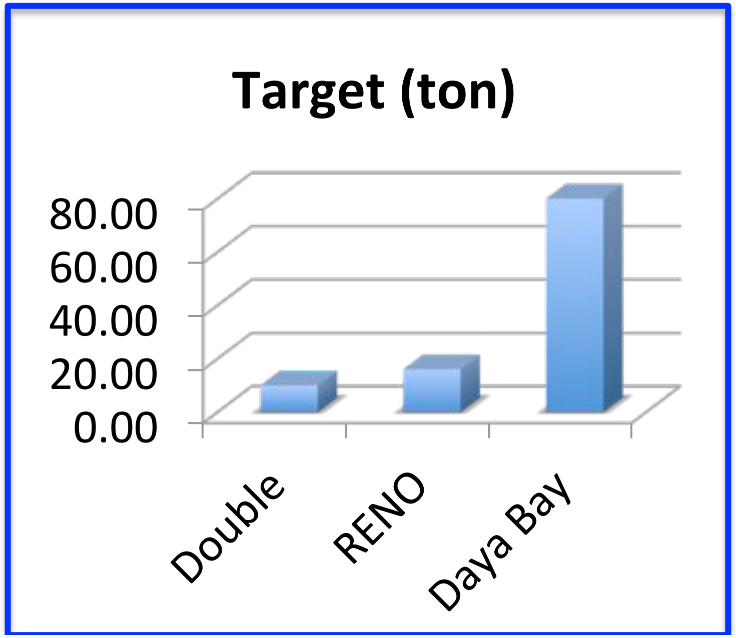
RENO ν θ_{13}

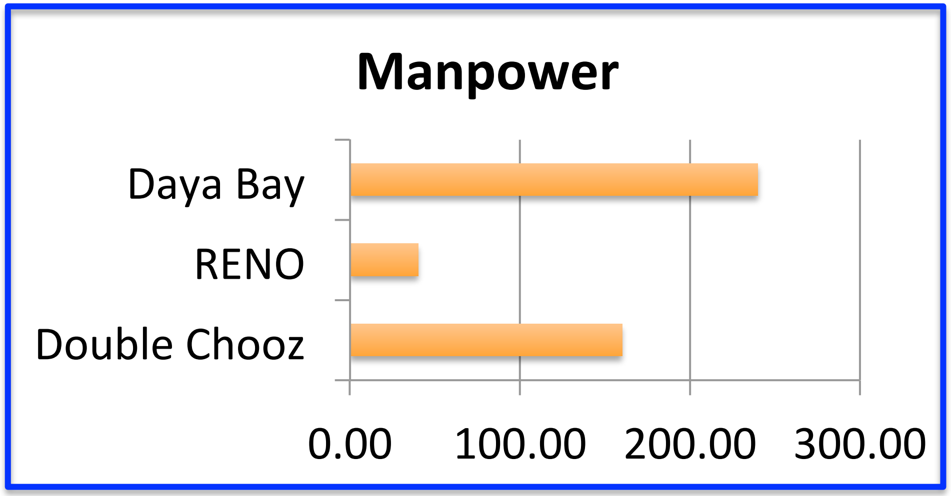
1. Cylindrical structure (four layers)
2. Neutrino Target: liquid scintillator with 0.1 % Gd doping

Comparisons









Double Chooz

$\Delta m^2_{31} = 2.44 \times 10^{-3} eV^2$
(MINOS)

2 reactor off data
(7 events in 7.24 days)

2 methods:
RATE + SHAPE

Prompt spectrum fit

JHEP 1410 (2014) 86

n-Gd: Rate+shape

$$\sin^2(2\theta_{13}) = 0.090^{+0.032}_{-0.029}$$

$\chi^2/n_{dof} = 52.2/40$

n-Gd: Rate-only

$$\sin^2(2\theta_{13}) = 0.090^{+0.034}_{-0.035}$$

n-H: Rate-only

$$\sin^2(2\theta_{13}) = 0.097 \pm 0.053$$

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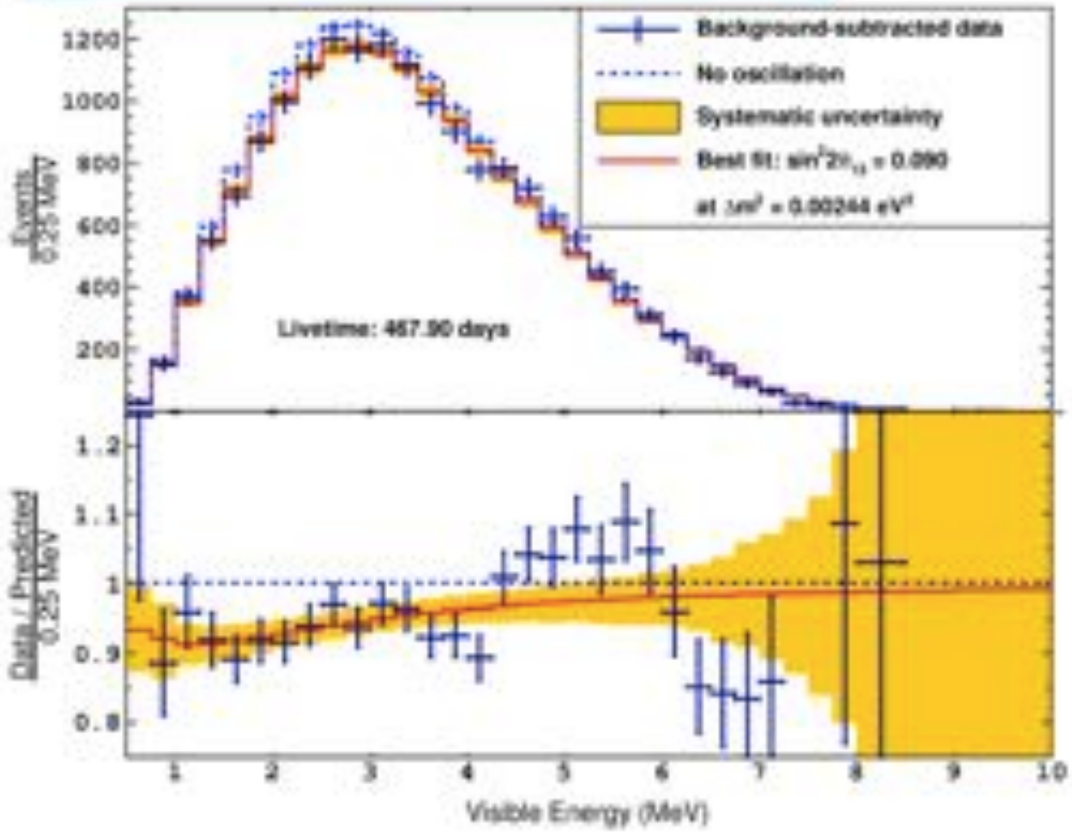
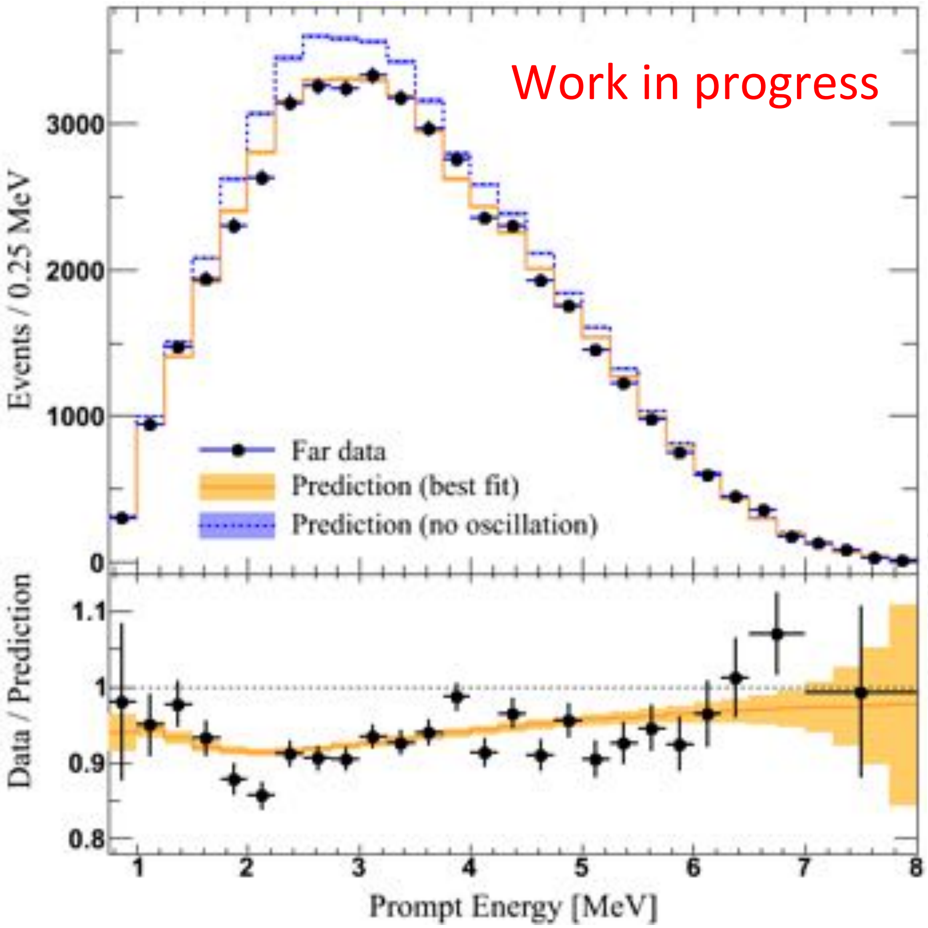


New result on n-H analysis will come out soon.

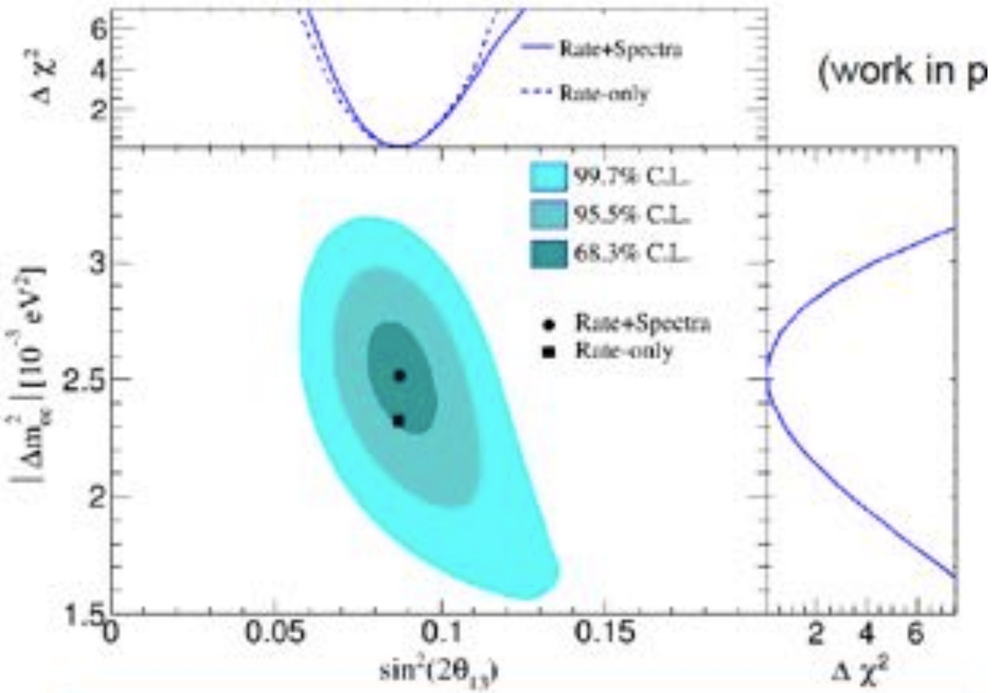
J. Mariano López Castaño

RENO

Won Qook Choi



New result: rate+shape
(n-Gd: ~800 days)



$\Delta m_{ee}^{2} = [2.52 \pm 0.19(\text{stat}) \pm 0.17(\text{syst})] \times 10^{-3}\ \text{eV}^2$

$\sin^2 2\theta_{13} = 0.087 \pm 0.008(\text{stat.}) \pm 0.008(\text{syst.})$

$\sin^2 2\theta_{13} = 0.088 \pm 0.008(\text{stat}) \pm 0.007(\text{syst})$

Rate-only: n-Gd ~800 days

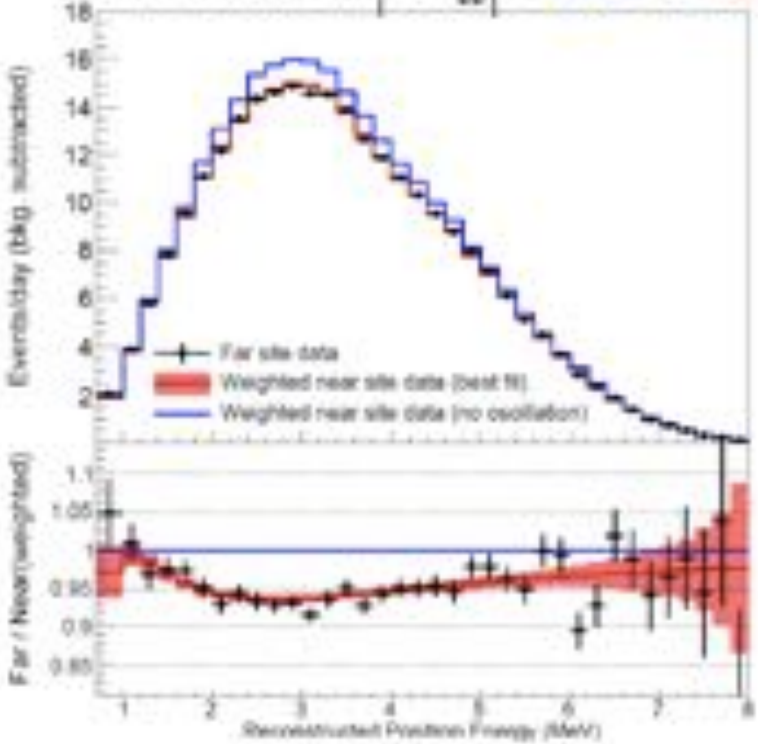
Work in progress

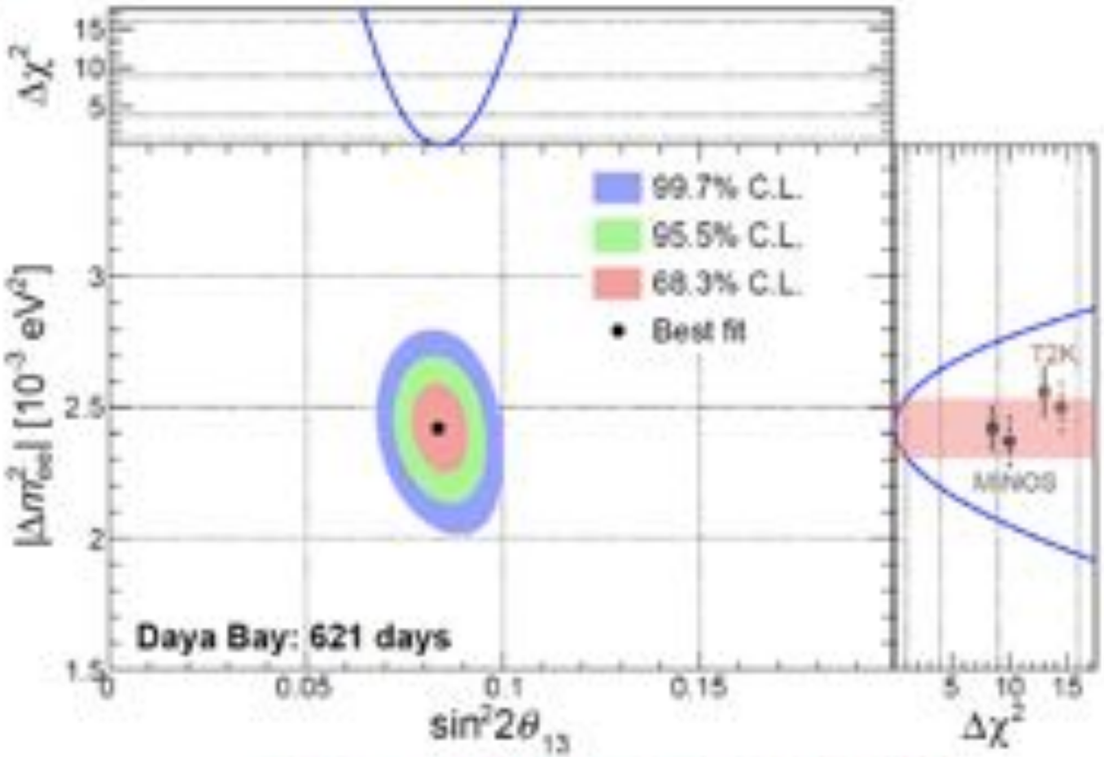
Daya Bay

Miao He

- Far/near relative measurement
- Observed data highly consistent with oscillation interpretation
- Precision of $\sin^2 2\theta_{13}$: 10% → 6%
- Precision of $|\Delta m^2_{ee}|$: 8% → 4%

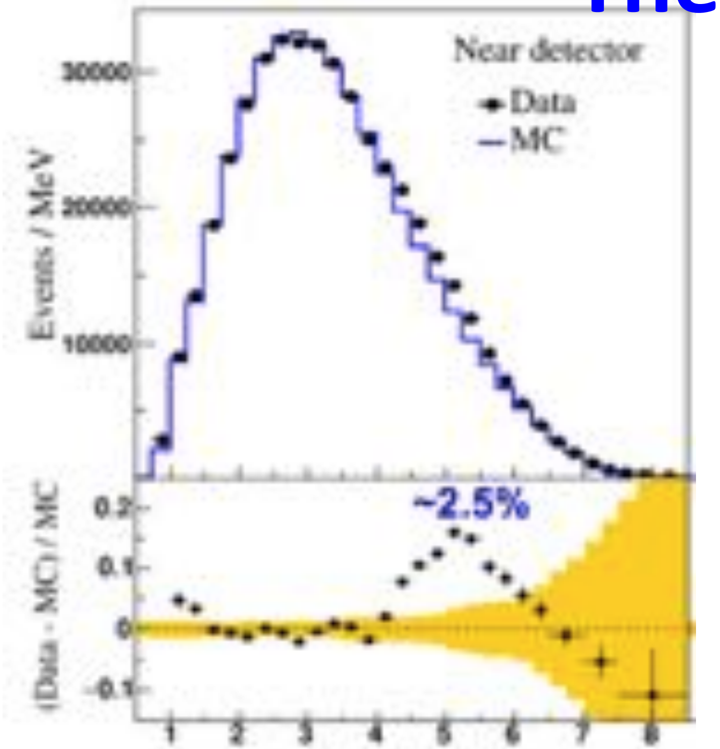
$$\sin^2 2\theta_{13} = 0.084 \pm 0.005$$
$$|\Delta m^2_{ee}| = (2.42 \pm 0.11) \times 10^{-3}\,\mathrm{eV}^2$$

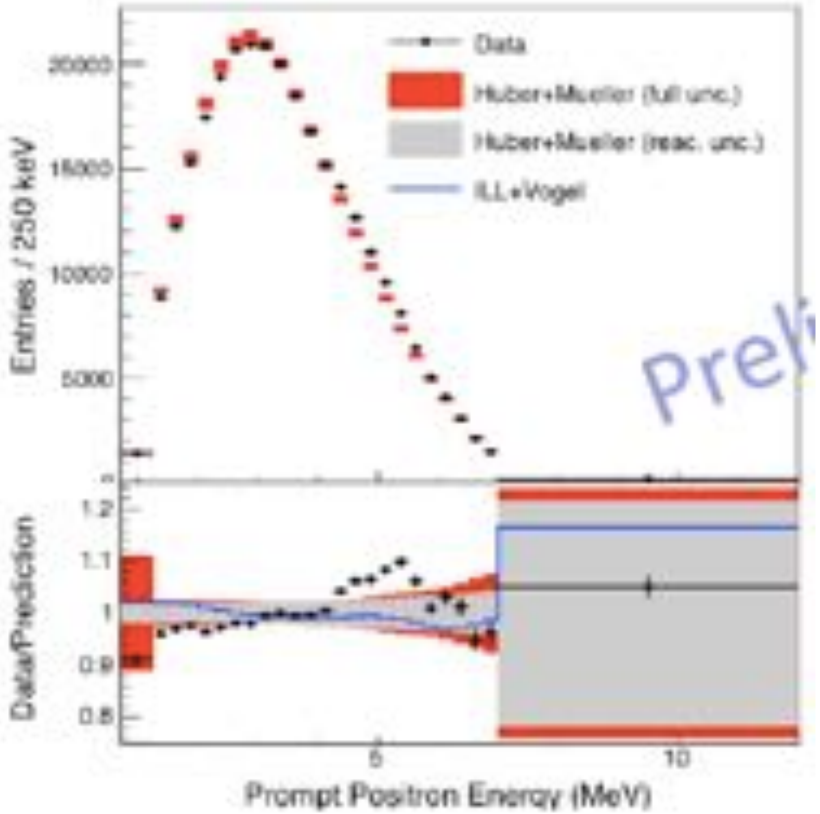


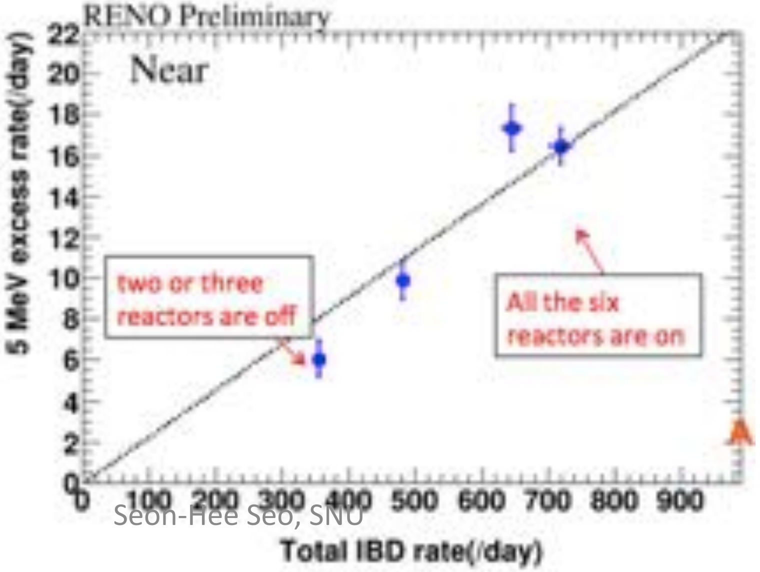


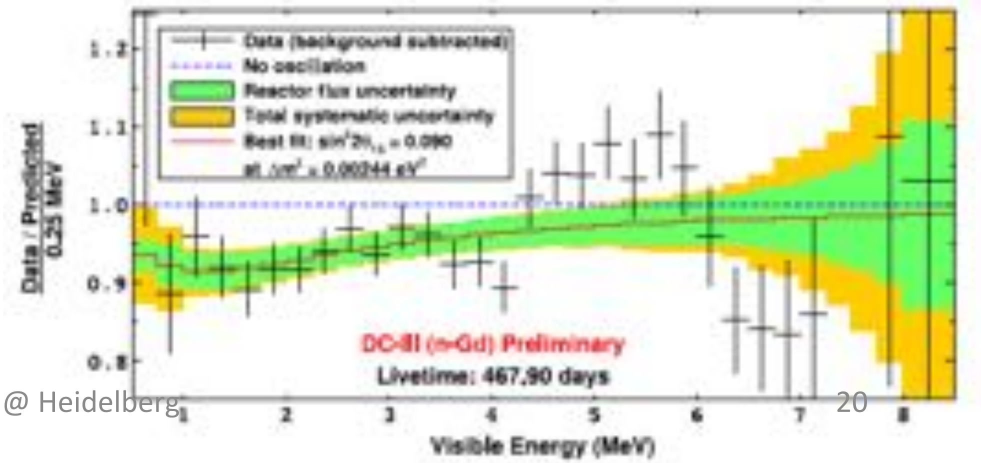
$\Delta m^2_{ee} \sim \Delta m^2_{32} \pm 5.2 \times 10^{-5}$ [eV^2]

The 5 MeV Excess

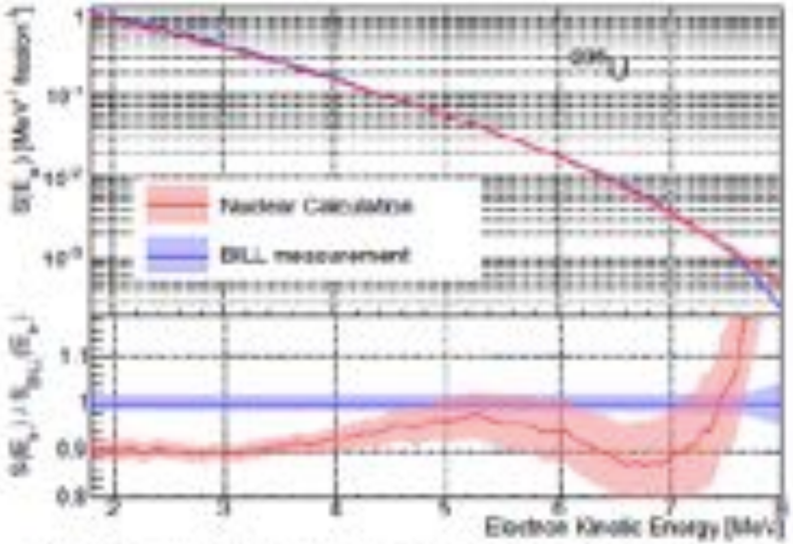




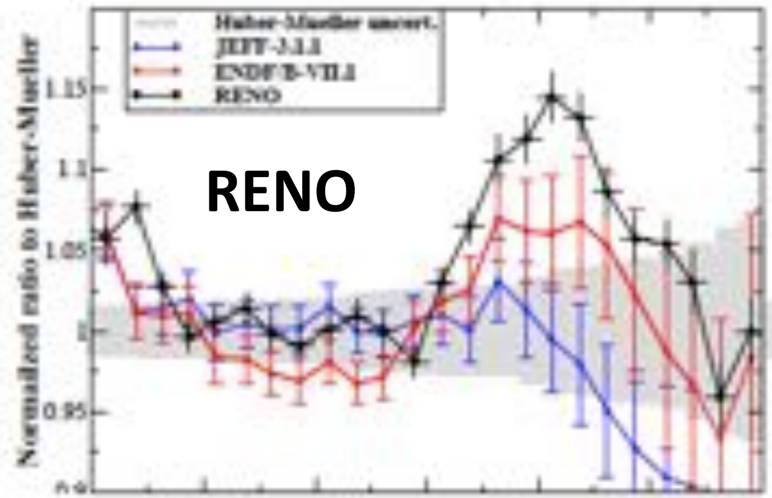


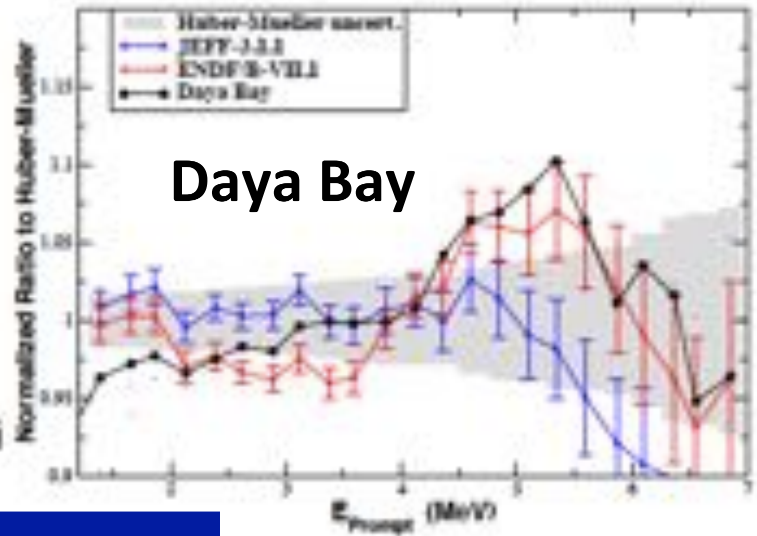


The different nuclear database do not agree on the origin of the Bump - the uncertainties in the databases are large



Dwyer & Langford, PRL, 114 012502 (2015)



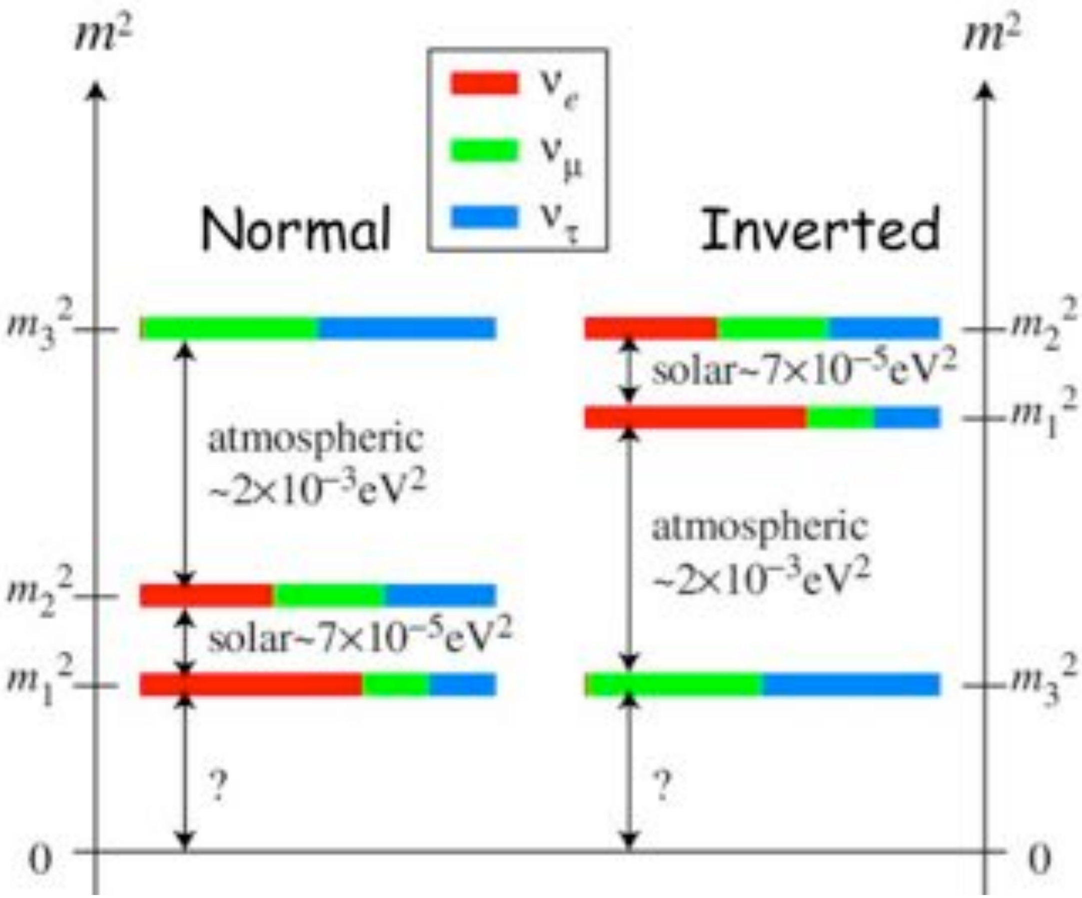


- ENDF/B-VII.1 predicts that it results from an analogous shoulder in the ILL ^{235}U β spectrum
  -Also predicts a large bump for ^{238}U
- JEFF-3.1.1 does not predict a bump for ^{235}U or ^{239}Pu
  - Agrees with Schreckenbach for both these nuclei
  - But predicts a significant bump for ^{238}U

Anna Hayes

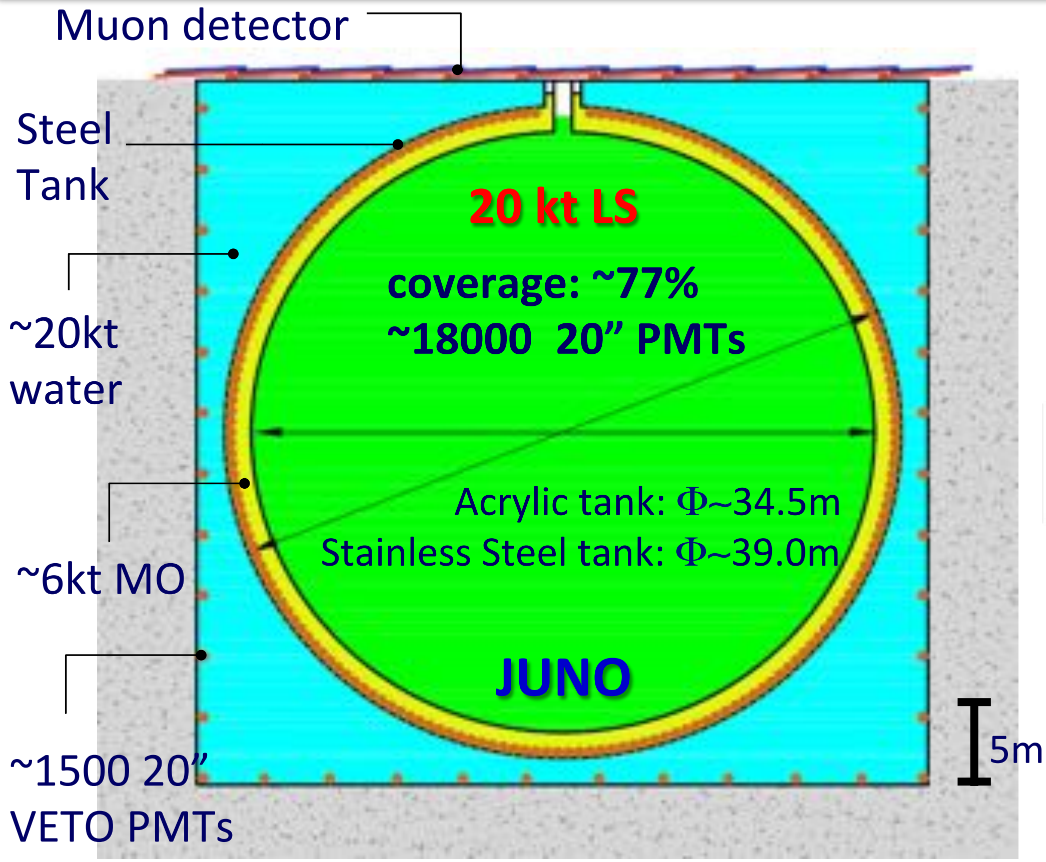
Neutrino Mass Ordering: JUNO & RENO-50

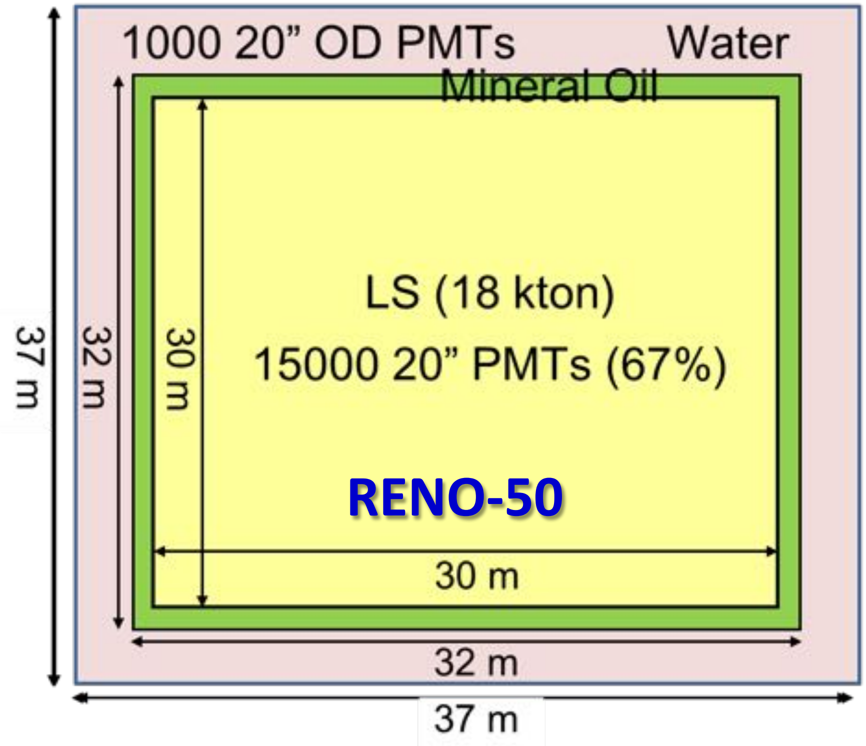
Which one ?



JUNO & RENO-50

Gioacchino Ranucci





	KamLAND	BOREXINO	JUNO	RENO-50
LS mass	~1 kt	~0.3 kt	20 kt	18 kt
Energy Resol	6%/	5%/	~3%/	~3%/
Light yield	250 p.e./MeV	500 p.e./	1300 p.e./MeV	>1000 p.e./MeV

Scientific Potential of JUNO/RENO-50

- Resolve the mass hierarchy
  - ~4 standard-deviation discrimination in 6 years
- Precision determination of neutrino-mixing parameters

	Current fractional precision	JUNO/ RENO-50
$\sin^2 2\theta_{12}$	5%	0.7%
$\sin^2 2\theta_{23}$	5%	NA
$\sin^2 2\theta_{13}$	10%	~15%
Δm^2_{21}	3%	0.6%
Δm^2_{31}	5%	0.6%

- Search for supernova neutrinos
  - ~5000 events for supernovae occur at 8 kpc
- Study geo-neutrinos
  - ~1000 events in a 5-year run

@Recontre du Vietnam 2013

Sterile Neutrino Searches

SOX
NEOS
NuLat

Why Sterile neutrinos ?

Experimental anomalies are seen:

Reactor ν anomaly

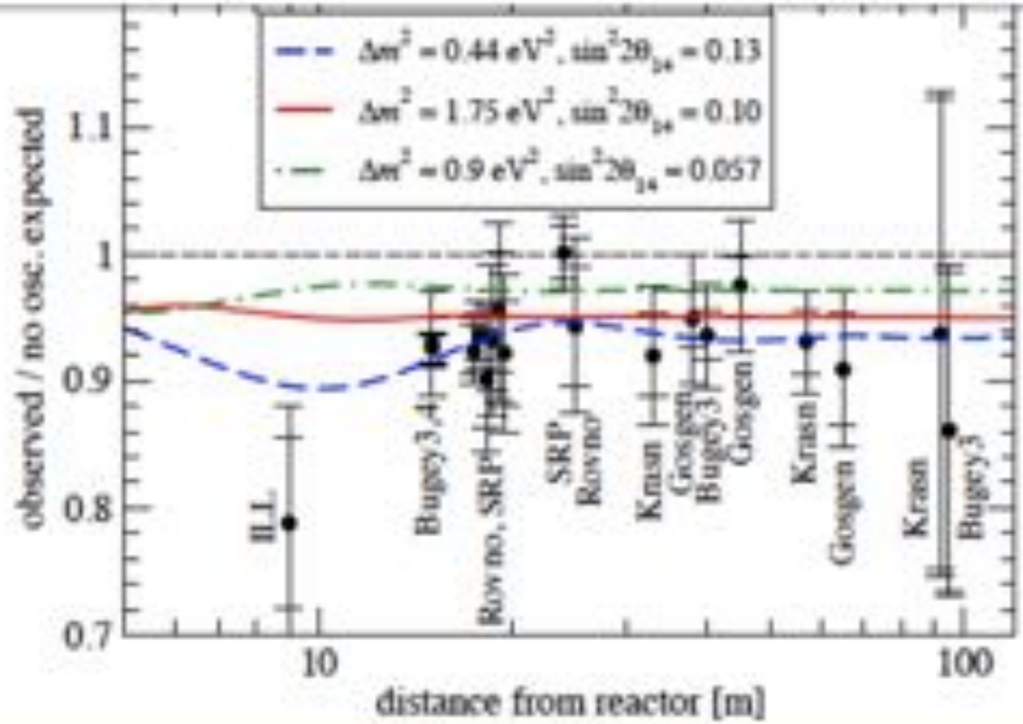
Source anomaly

Accelerator ν anomaly

The Reactor Antineutrino Anomaly

obs/expected=0.94 (~3σ) deficit in the detected antineutrinos from short baseline reactor experiments

G. Mention et al., Phys. Rev. D 83 073006 (2011)



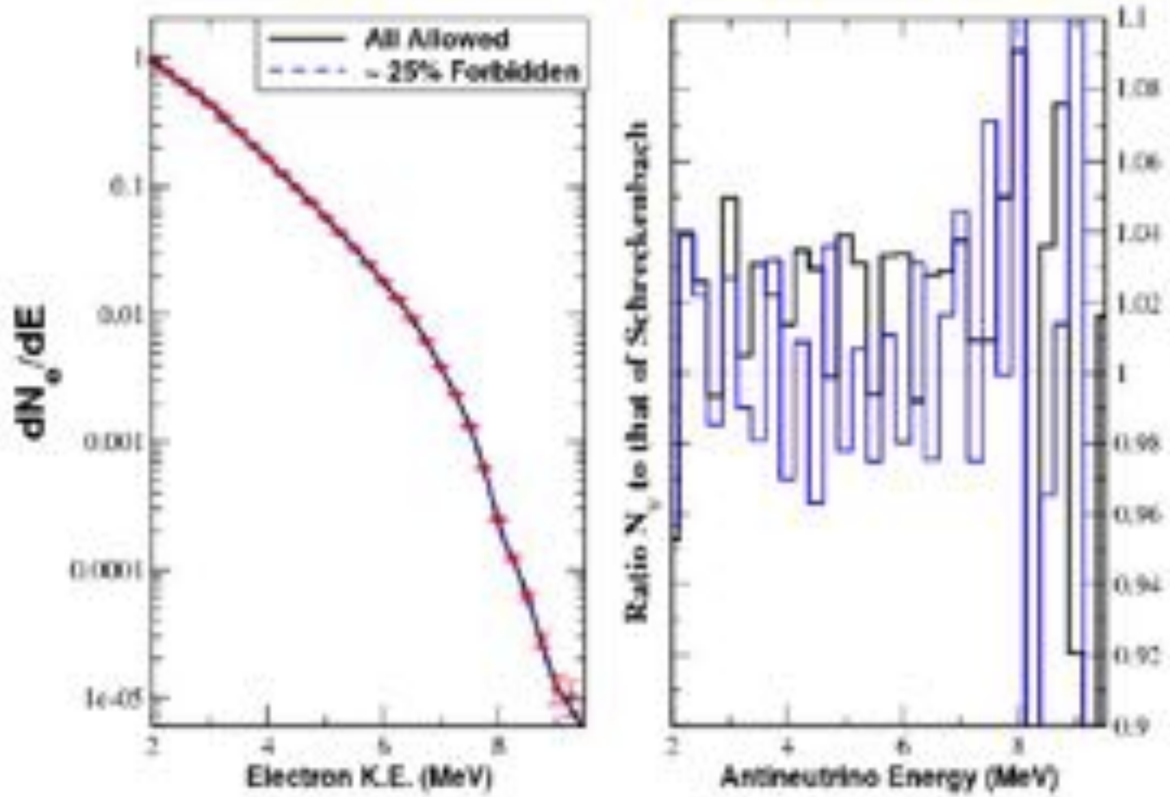
J. Kopp, et al. JHEP 05 (2013)050

The effect mostly comes from the detailed physics involved in the nuclear beta-decay of fission fragments in the reactor

Th. A. Mueller et al., Phys. Rev. C 83, 054615 (2011).

Additional contributions from (1) Off-equilibrium nuclei and (2)Increase in the detection cross section

Fit to Schreckenbach's beta spectrum



If all allowed:
⇒ +2.2% antineutrinos

If 25% forbidden transitions
=> +0.06% antineutrinos

Anna Hayes

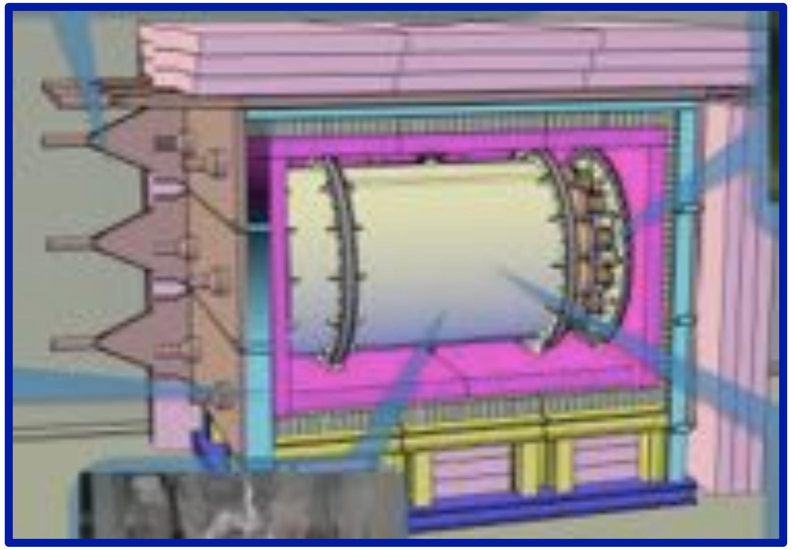
Different fitting procedures: (1) all allowed; (2)all branches either allowed or forbidden; (3) 30% forbidden equally spaced ;(4) 30% forbidden with a bias to higher energies + several different combinations of forbidden operators

Changes in the antineutrino spectrum range from 0-4%
Problem arises because of lack of knowledge on how to treat forbidden transitions

NEOS

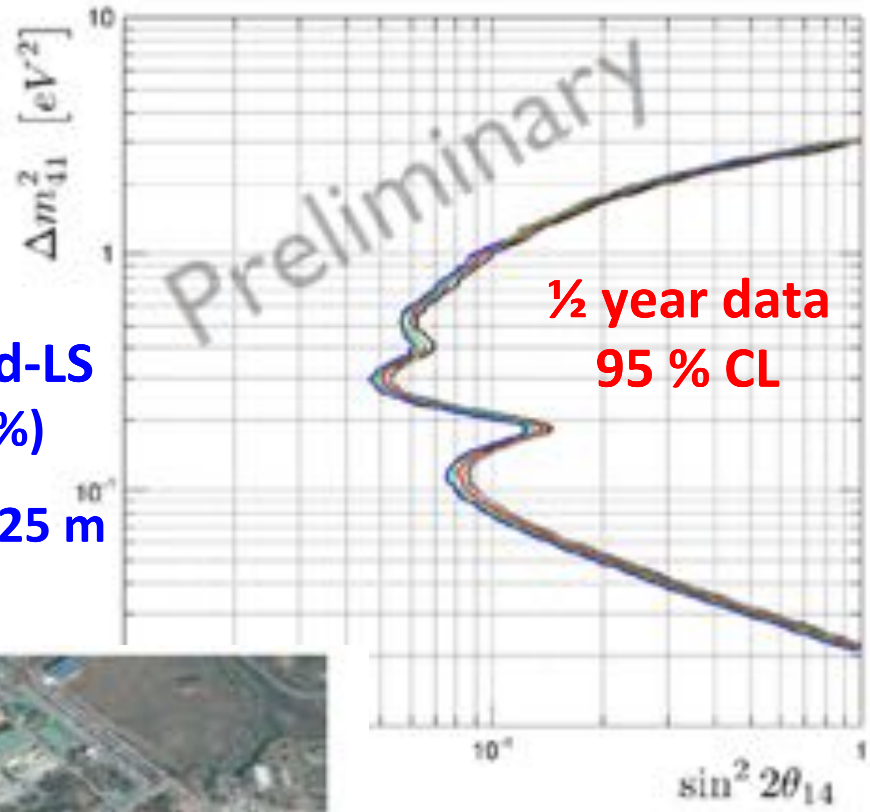
Yoomin Oh

Neutrino Experiment for Oscillation at Short baseline
(previously introduced as Hanaro)



1000 L Gd-LS (0.5%)

Baseline: 25 m



½ year data
95 % CL

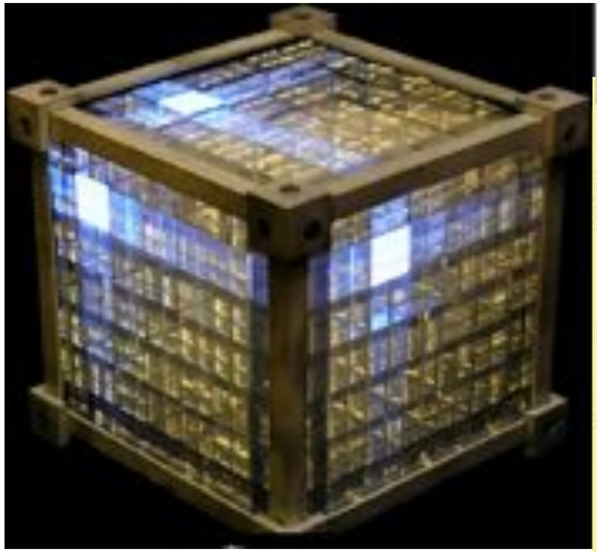
Data taking in 2 months

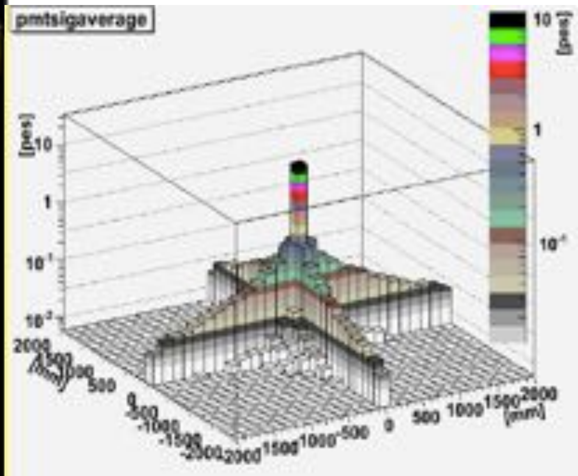
NuLat

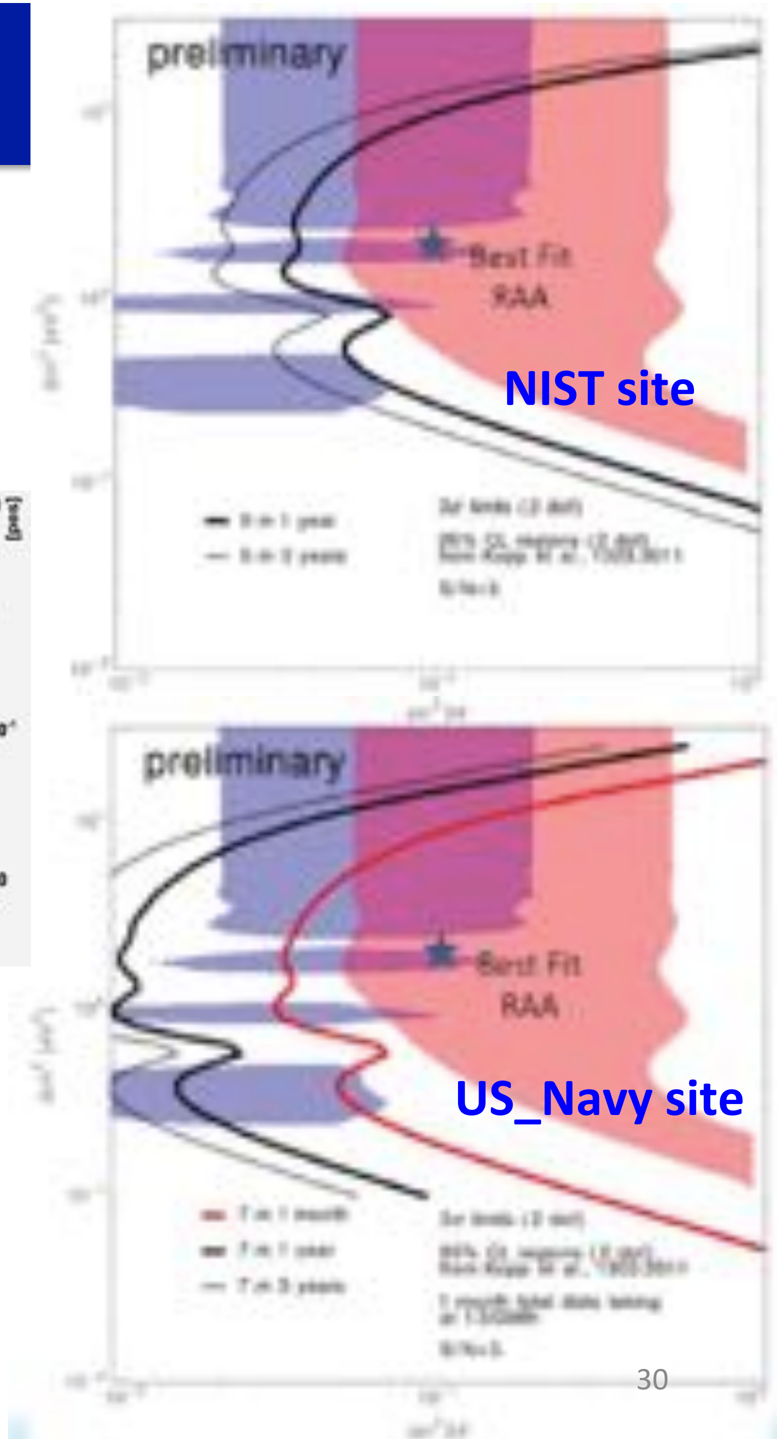
Jelena Maricici

Neutrino Lattice

NuLat – Novel Detector for Sterile Neutrino Search with Reactor Neutrinos







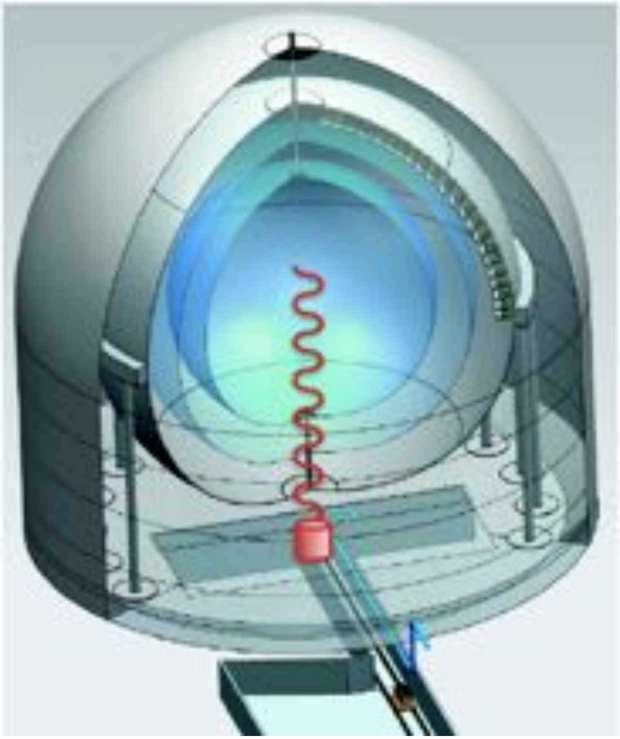
- ^{6}Li doped (0.5%) plastic scintillator
- 2.5 inch cube; 15X15X15
- Full 3D light collection

5X5X5 demonstrator: deployment in 2016

SOX

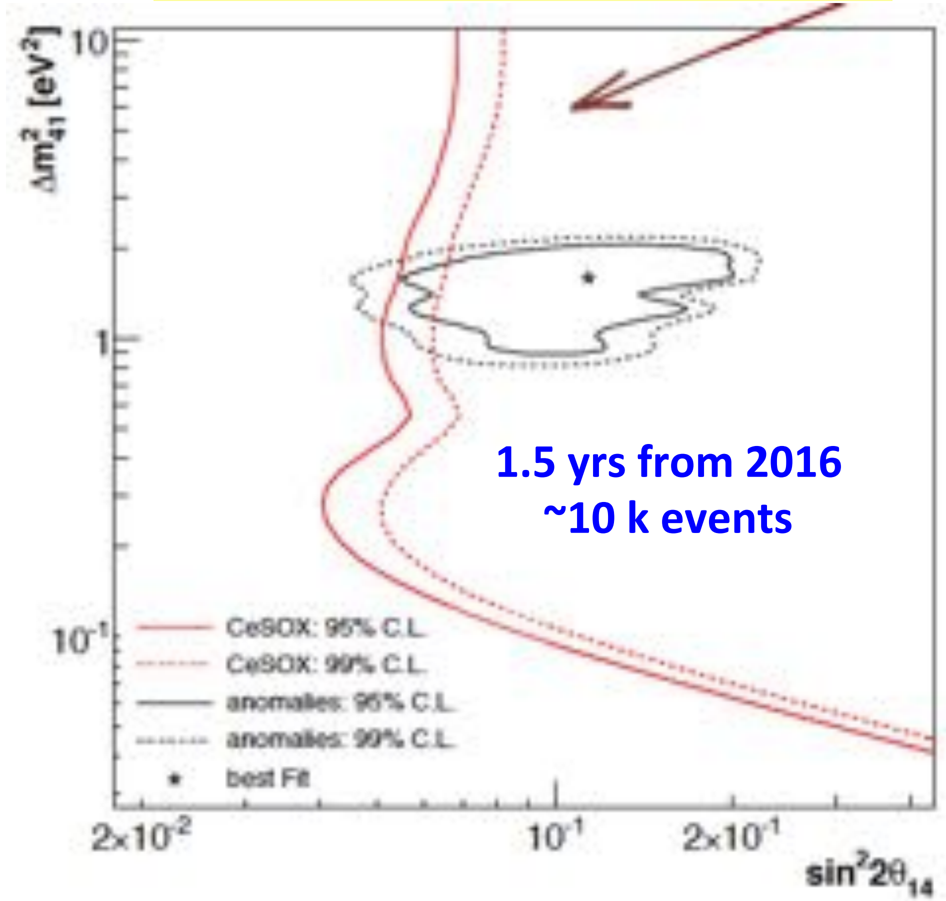
Michael Wurm

Short-baseline oscillations in Borexino



- 270 ton ultrapure scintillator
- Baseline: 8.5 m
- Fiducial radius: 4 m (~240 ton)

1st phase CeSOX sensitivity



- 1st phase: ^{144}Ce anti-ν_e source
- 2nd phase: ^{51}Cr ν_e source (similar sensitivity)

Reactor Proposals

Lhuiller @Neutrino 2014

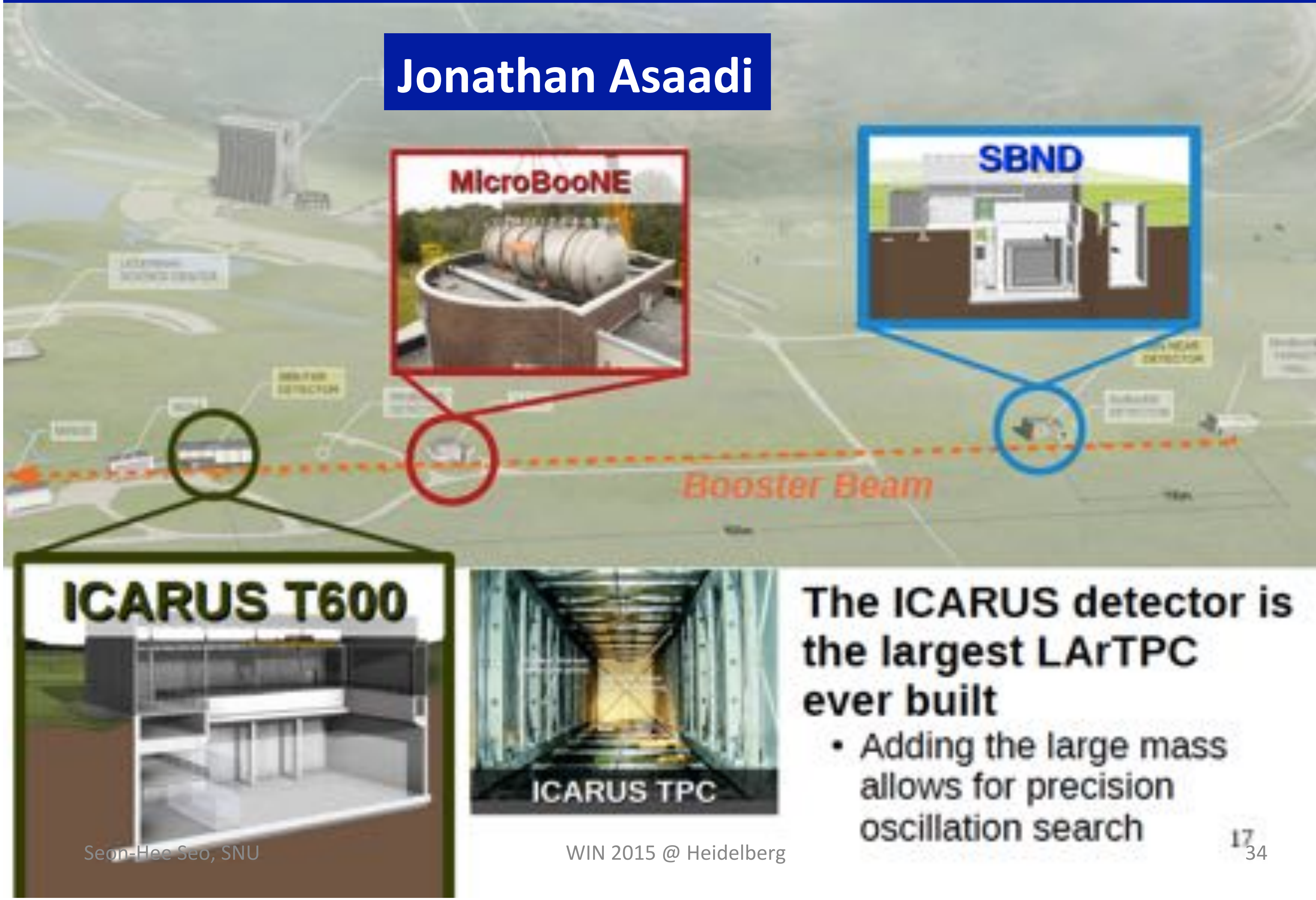
	P_{th} (MW)	M_{target} (tons)	L (m)	Depth (m.w.e.)	Expected Data Taking
Nucifer (FRA)	70	0.8	7	13	analyzing
Poseidon (RU)	100	~ 3	5-8	~ 15	?
Stéréo (FRA)	57	1.75	8.8-11.2	18	2015
Neutrino 4 (RU)	100	1.5	6-12	~ 10	2015
Hanaro (KO)	30-2800	~ 1	6	few	2015
DANSS (RU)	3000	0.9	9.7-12.2	50	2015
Prospect (USA)	85	1 & 10	7-18	few	?
SoLid (UK)	45-80	2.9	6-8	10	2016

Wish list:

It would be very good to have one sterile ν sensitivity plot for all experiments !

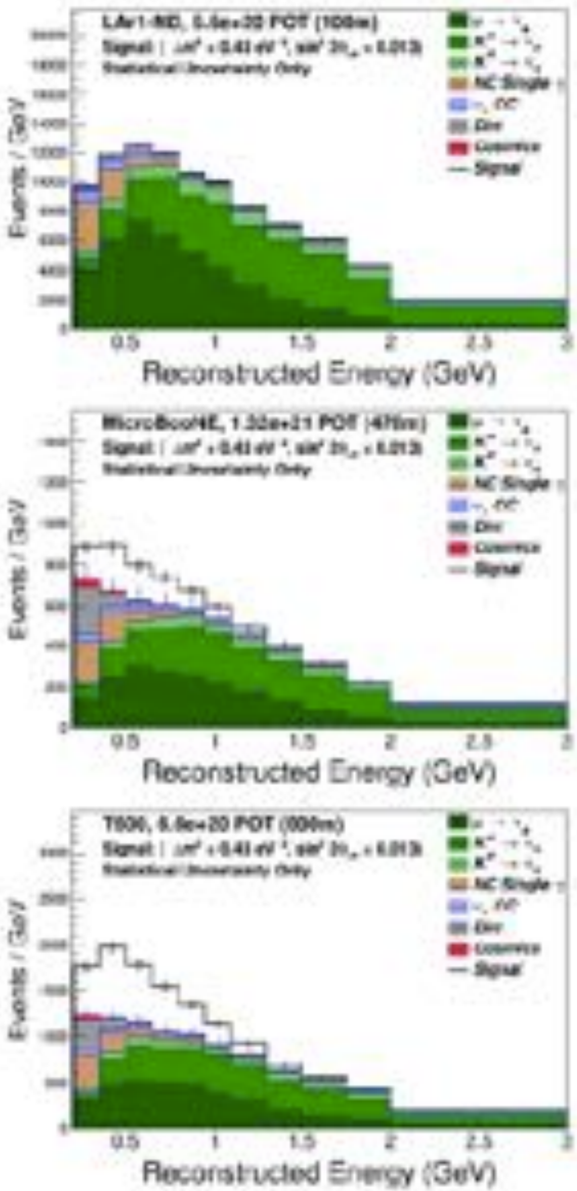
Shoart Baseline ν Program @Fermilab

Jonathan Asaadi

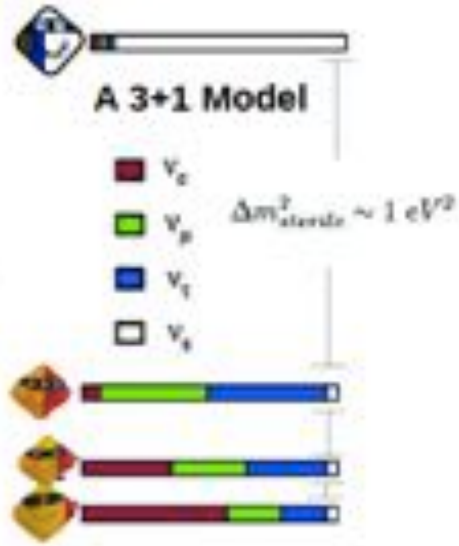


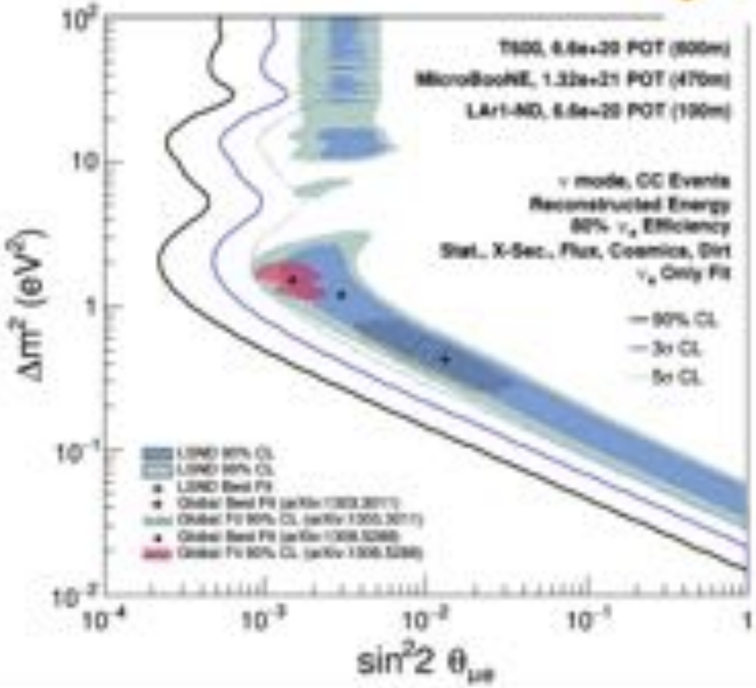
SBN Sensitivities

Jonathan Asaadi



Utilizing three similar detectors at three different distances along the same neutrino beam allows for a **<u>definitive measurement</u>** of the allowed sterile neutrino parameter space



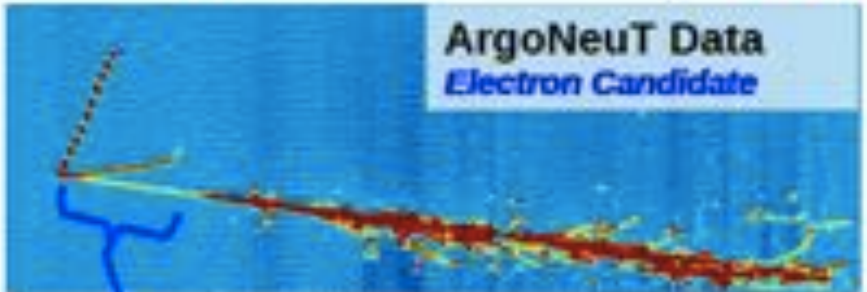


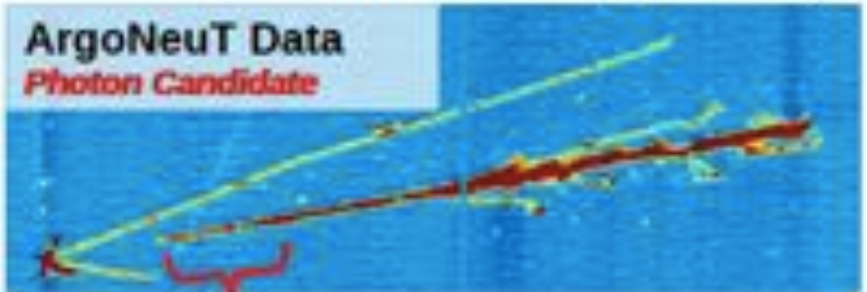
Anti ν data is also needed !

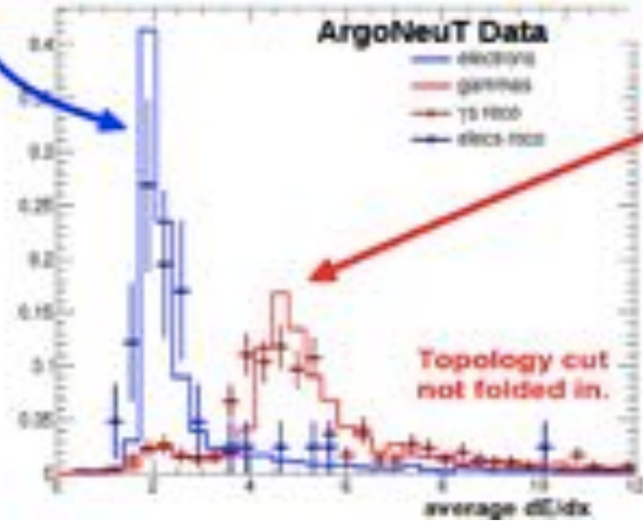
MicroBooNE

Jonathan Asaadi

- MicroBooNE will utilize the electron / photon discrimination power of LArTPC's to determine if the MiniBooNE excess is electron like *(from ν_e appearance)* or photon like *(unaccounted for background)*







By analyzing the topology and the dE/dX of the electromagnetic shower, disentangling the MiniBooNE low energy excess becomes possible

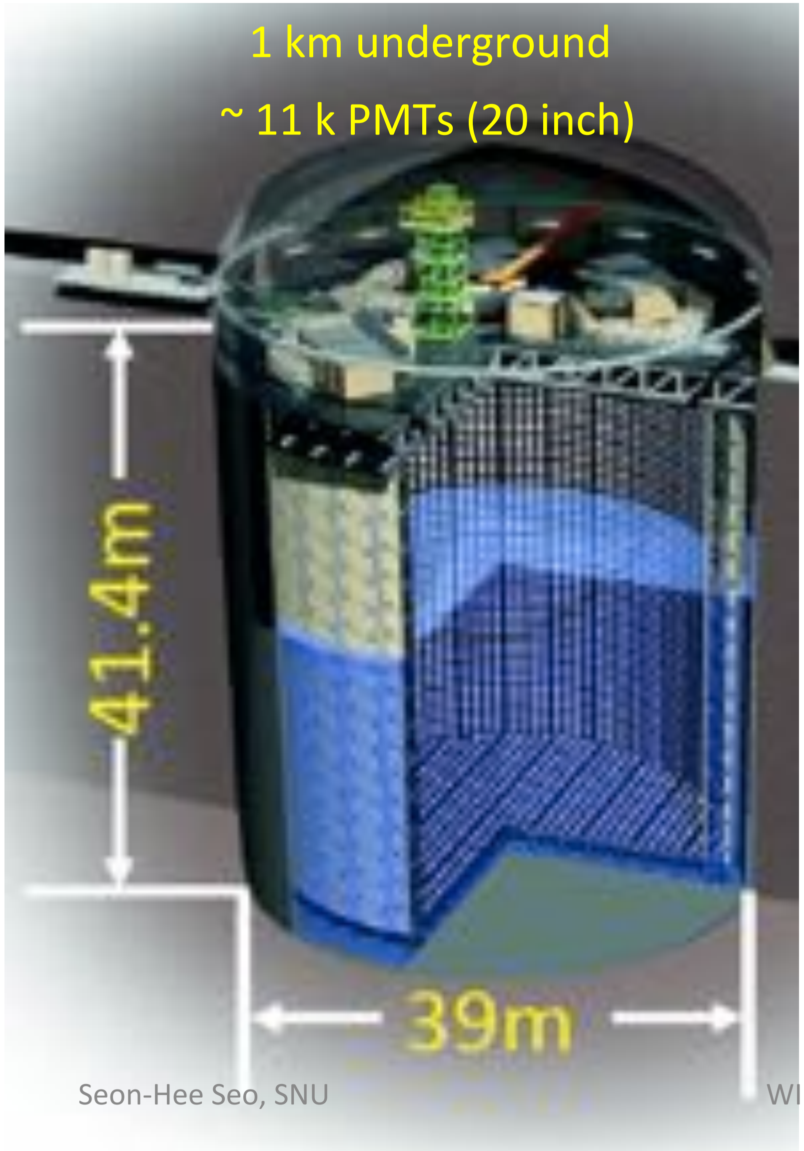
Atmospheric/Solar/SNR neutrinos

Super-K
GADZOOKS !
BOREXINO

Super-K

Yoshinari Hayato

50 kton Water Chrenkov detector: since 1996



Multi-purpose detector

Neutrino oscillation

- Accelerator neutrinos
- Atmospheric neutrinos
- Solar neutrinos

GUT

Proton decay

$p \rightarrow e^+ + \pi^0$

$p \rightarrow K^+ + \bar{\nu}$

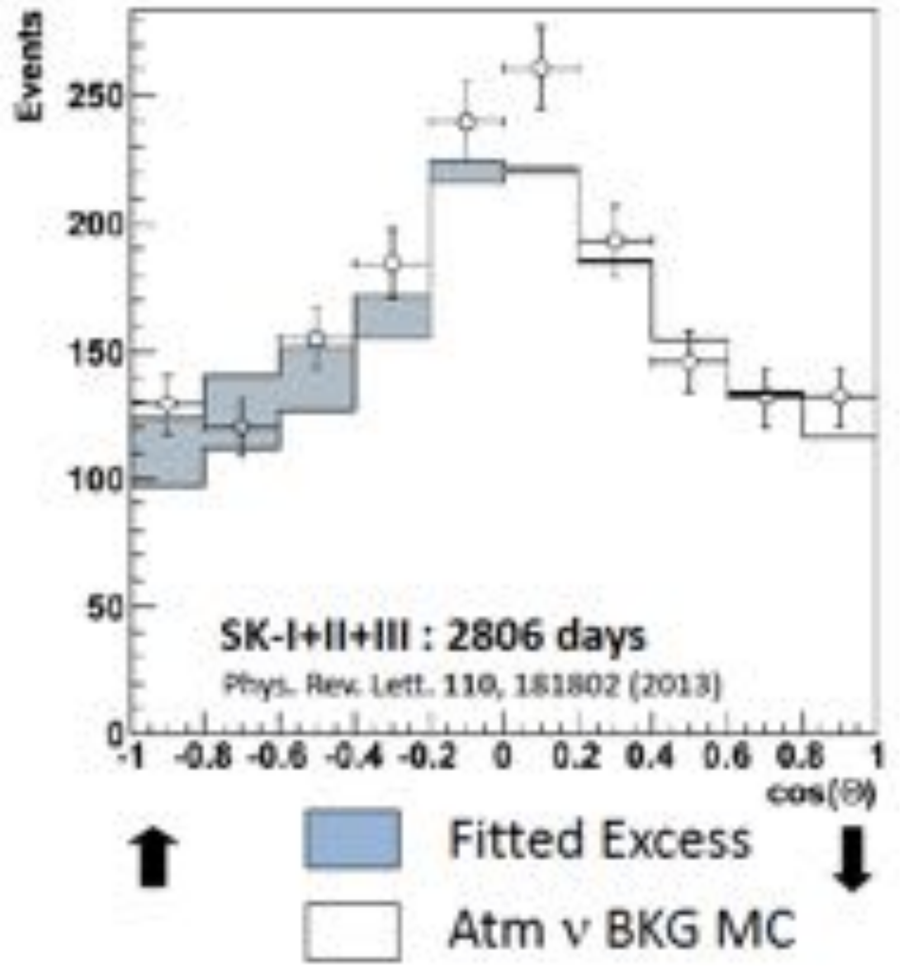
New physics

- WIMP search
- n-$\bar{n}$ oscillation
- dinucleon decay etc….

Neutrino astrophysics

- Super nova burst neutrino
- Super nova relic neutrino

Super-K: Atmospheric ν



- 3 flavor ν oscillation analysis:
1 σ preference to NH & 2nd octant
(using 4538 days data)

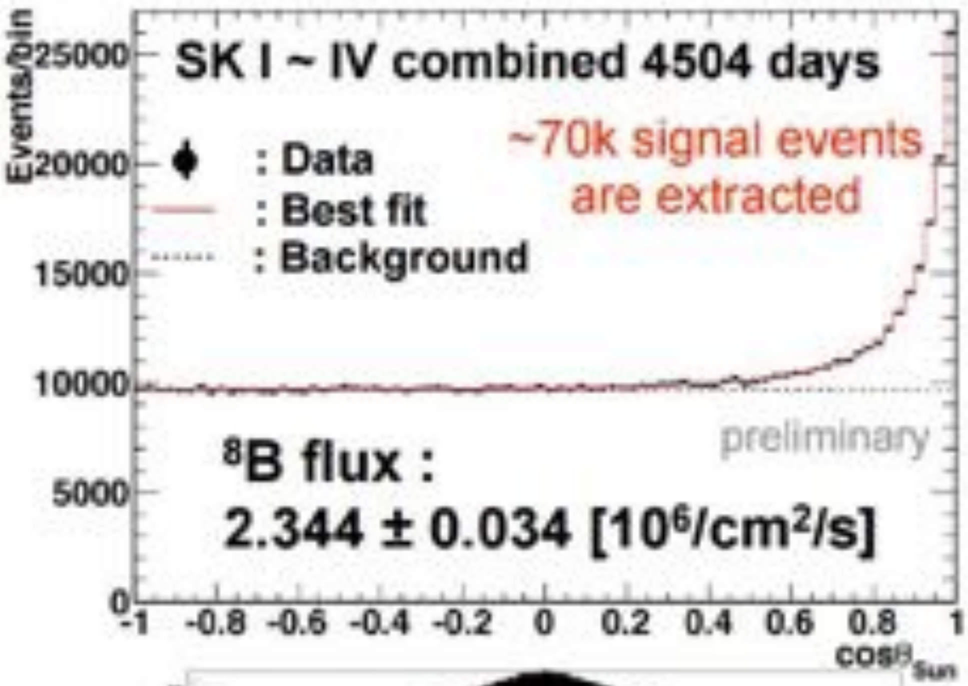
- No evidence of sterile ν:
for 3+N model:
$|U_{\mu 4}|^2 < 0.041$ @90% CL

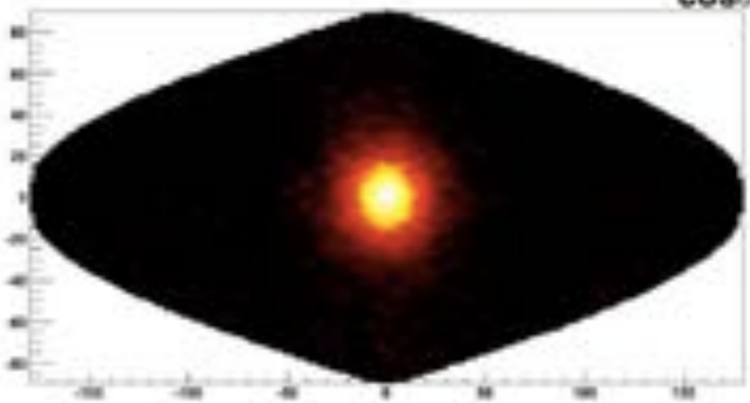
- neutron tagging effi. (20.5%):
Atm. ν oscillation, proton decay

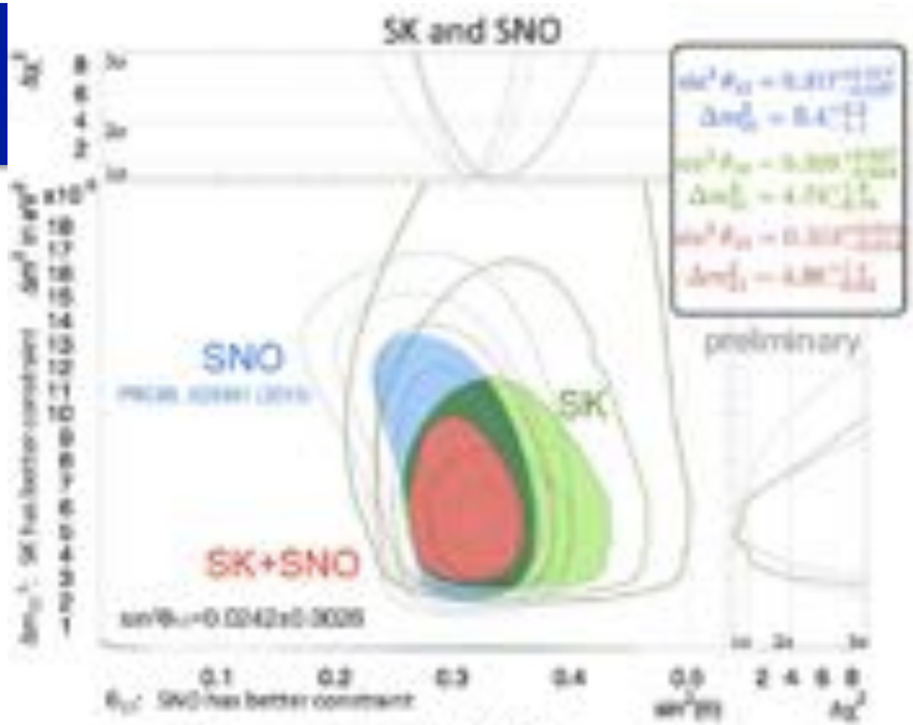
Yoshinari Hayato

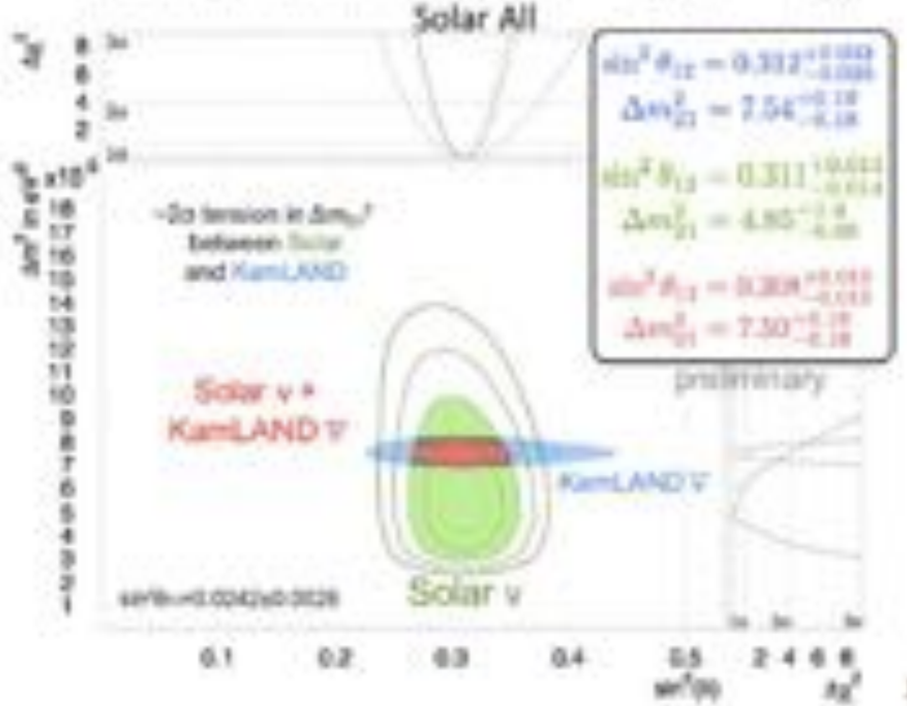
ν_τ appearance (2806 days)
180.1 ±44.3 (stat) +17.8-15.2 (sys) events(3.8σ)

Super-K: Solar ν



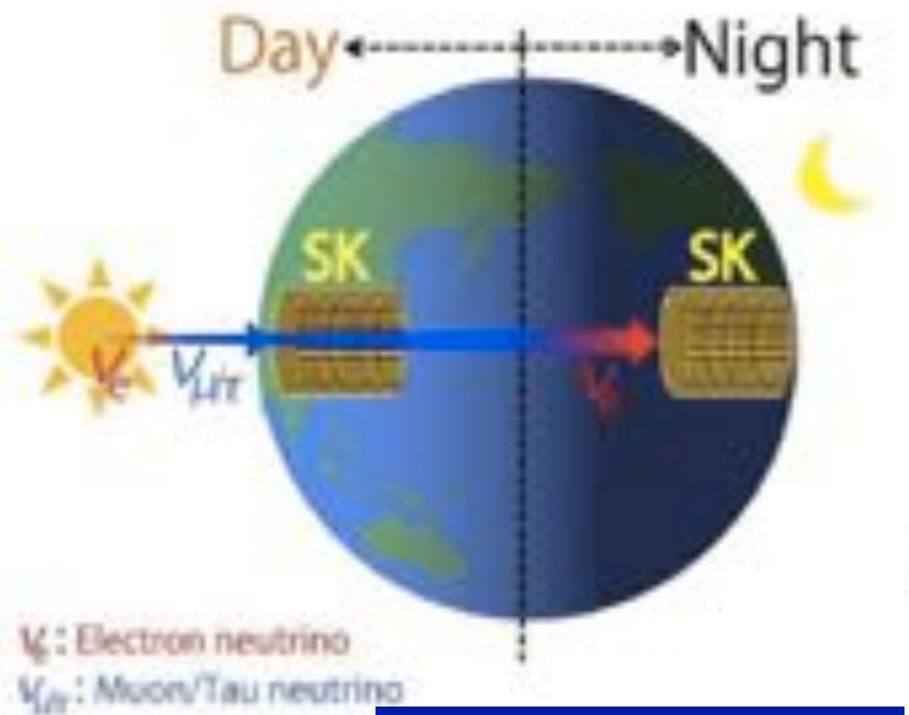






Pierce Weatherly

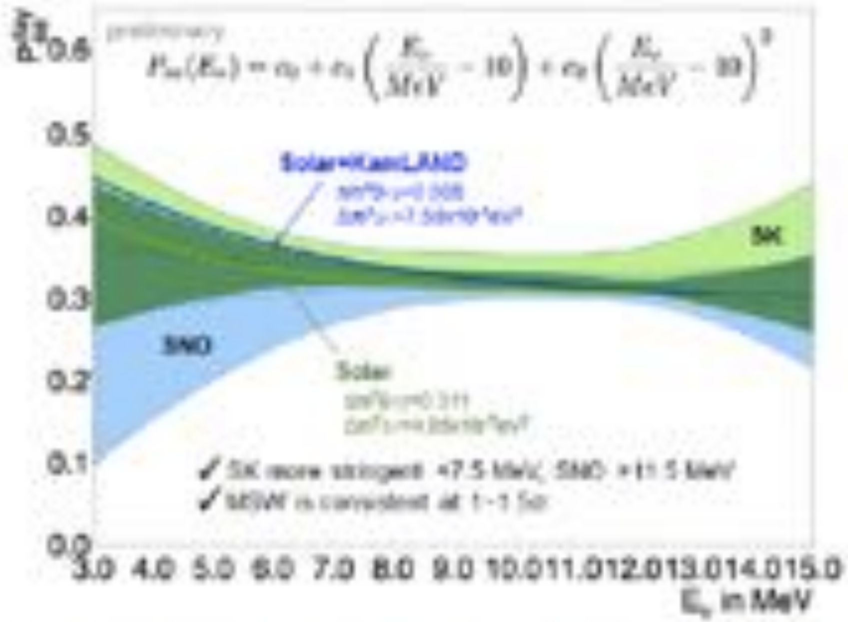
Super-K: Solar ν

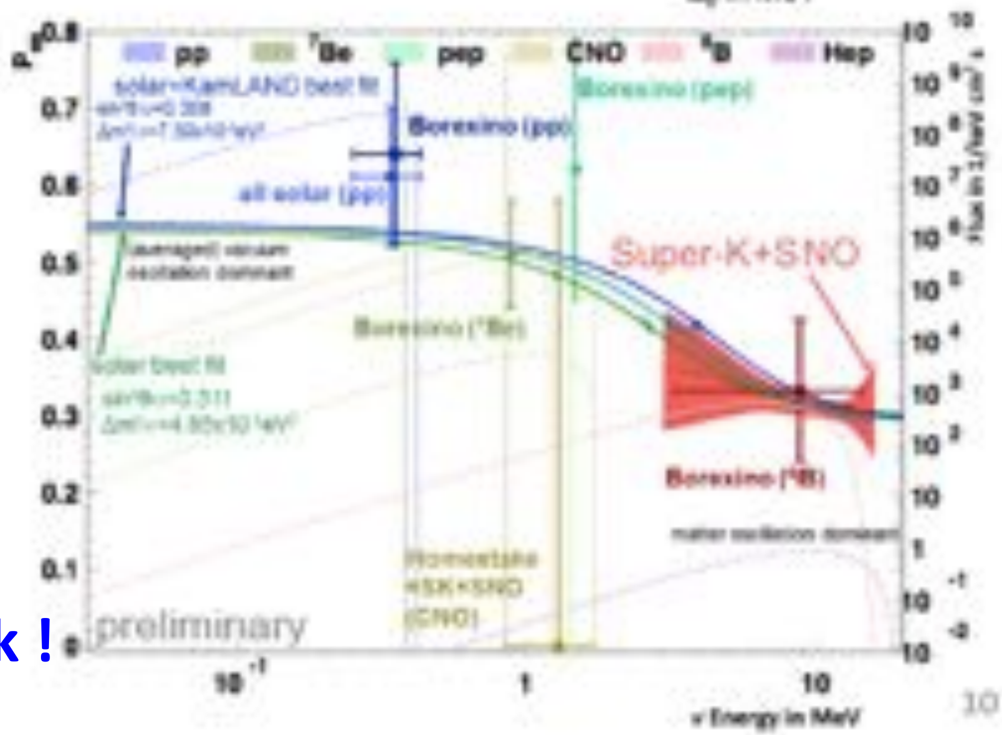


Pierce Weatherly

Day Night asymmetry: ~ 3 σ

→ evidence for MSW effect

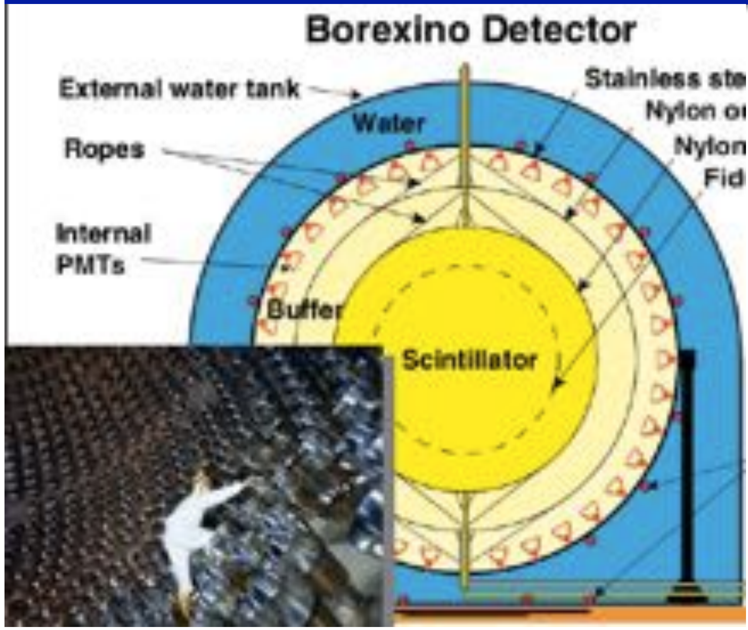




See also A. Smirnov's plenary talk !

BOREXINO: Solar ν

Nicola, Rossi



13.7 m stainless sphere diameter
- ~ 1000 tons of pseudocumene (PC)
- ~300 tons Inner Vessel
- Ultrapure Water Tank

~2200 (PMTs)

Down to 150 keV solar ν

Solar Neutrinos
- **First measurement** of the interaction rate of the ^{7}**Be** mono-energetic **862 keV** solar neutrinos with accuracy of 5%
- **Exclusion** of any significant **day-night asymmetry** of the ^{7}Be solar neutrino flux
- **First direct observation** of the mono-energetic 1440 keV **pep** solar neutrinos
- Set of the **strongest upper limit of the CNO** solar neutrinos flux
- **Measure of the** ^{8}**B** solar neutrinos with an energy **threshold of 3 MeV**
- **First spectroscopic measurement of the pp** spectrum.

GADZOOKS !

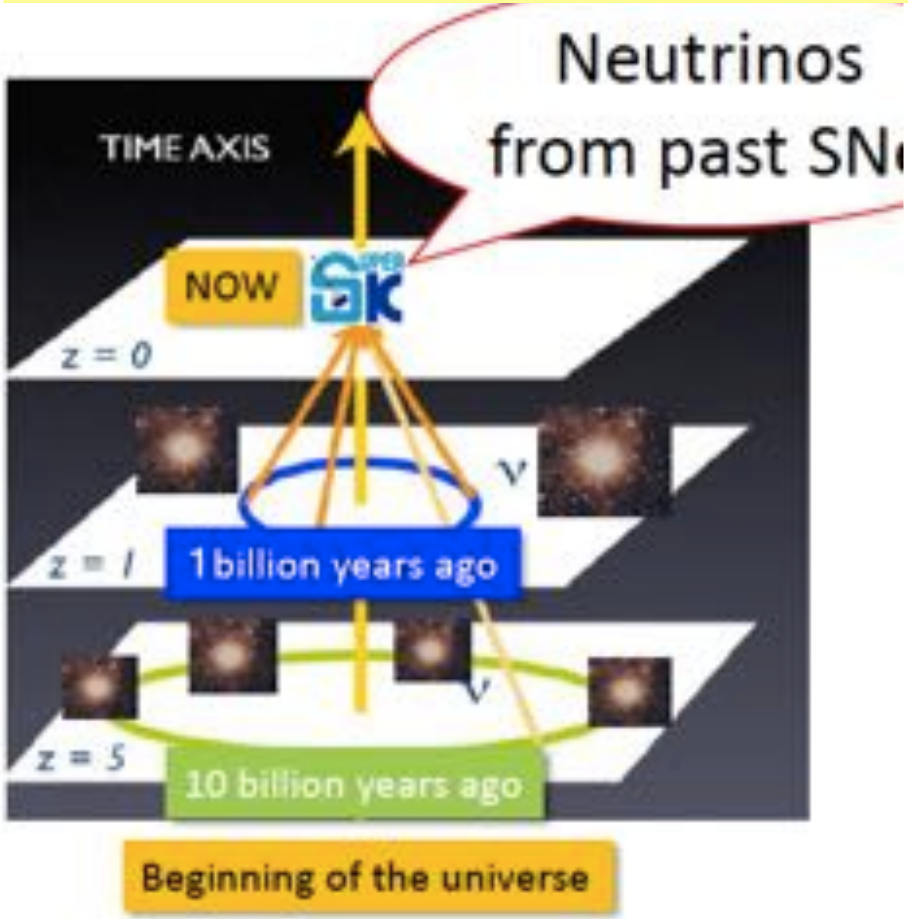
M. Ikeda

Gadolinium Antineutrino Detector Zealously Outperforming Old Kamiokande, Super!

➢ **Committee has started reviewing this project.**

- Goal: discovery of SN relic n
- Sensitivity: few for 10 yrs

[10, 30] MeV search window
To remove BKG to enhance signal, dissolve 0.2 % Gd



EGADS   To study Gd water quality

Evaluating Gadolinium's Action on Detector Systems

200 m^3 tank with 240 PMTs

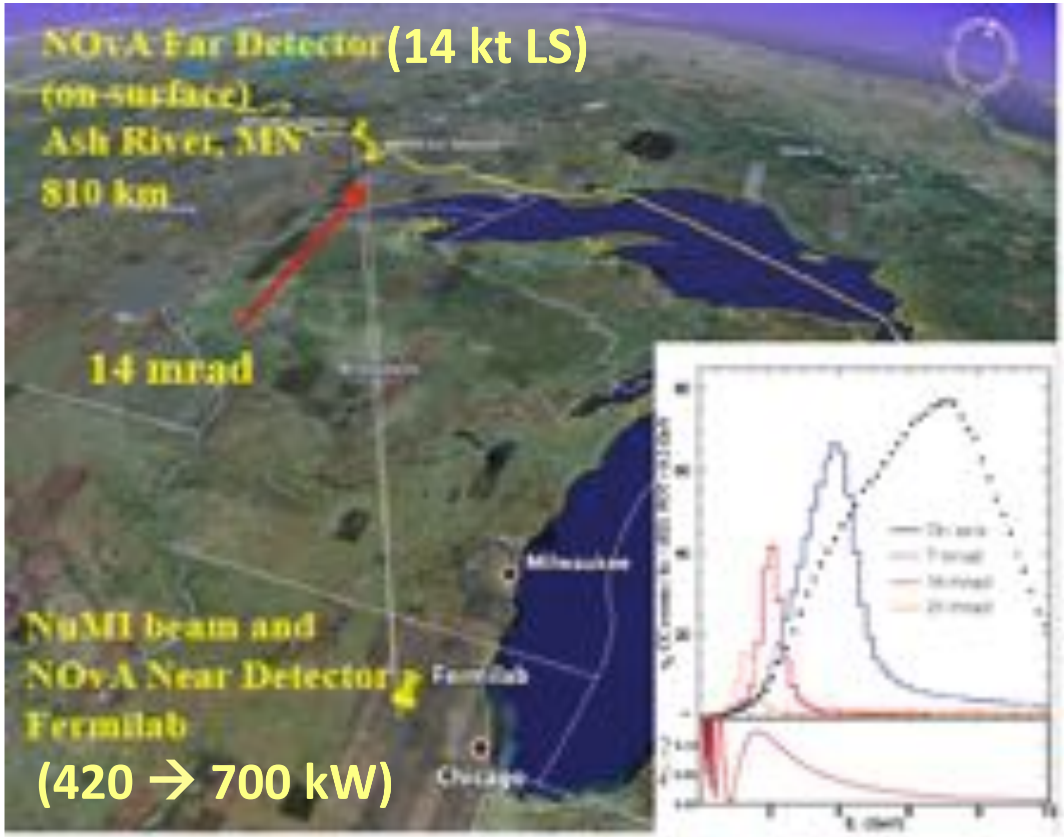
Long baseline neutrinos

NOvA
T2K
MINOS/MINOS+

NOvA

JianMing Bian

NuMI Off-Axis ν_e Appearance Experiment



- Construction: 2009-2014
- Cosmic bkg rejection:
  40 M → 1
- 1st year data is being analyzed.
  (420 kW; 1.9x10^{20} POT)

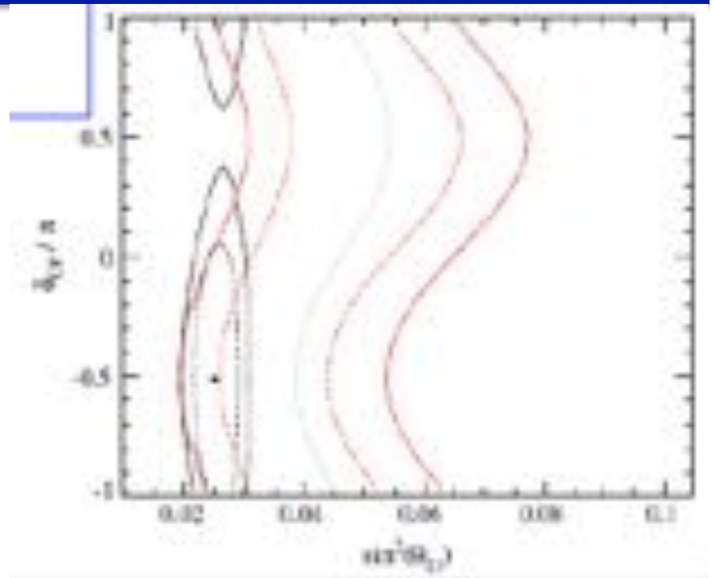
  → ν_e appearance results
  are expected by this fall.

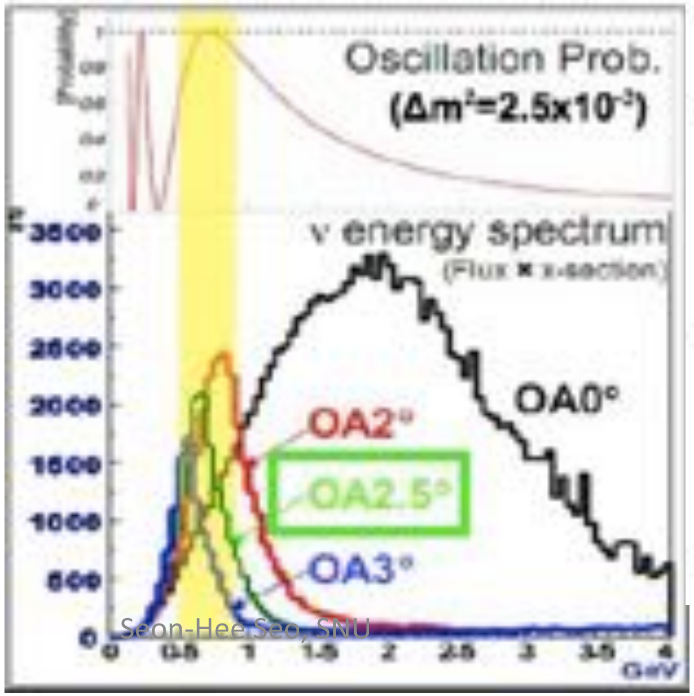
T2K

Justina Lagoda

Tokai 2 Kamioka

PRD91, 072010 (Apr. 2015)





- recent T2K oscillation analyses:
  - combined ν_μ+ν_e analysis with reactor constraint
    - preference for values of δ_{CP} around -π/2
    - weakly favored normal hierarchy and octant $\sin^2\theta_{23} > 0.5$
  - first $\bar{\nu}_\mu$ disappearance result
    - consistent with T2K ν_μ disappearance measurements and MINOS $\bar{\nu}_\mu$ disappearance result
  - analysis of $\bar{\nu}_e$ appearance is underway

MINOS/MINOS+

Adam Schreckenberg

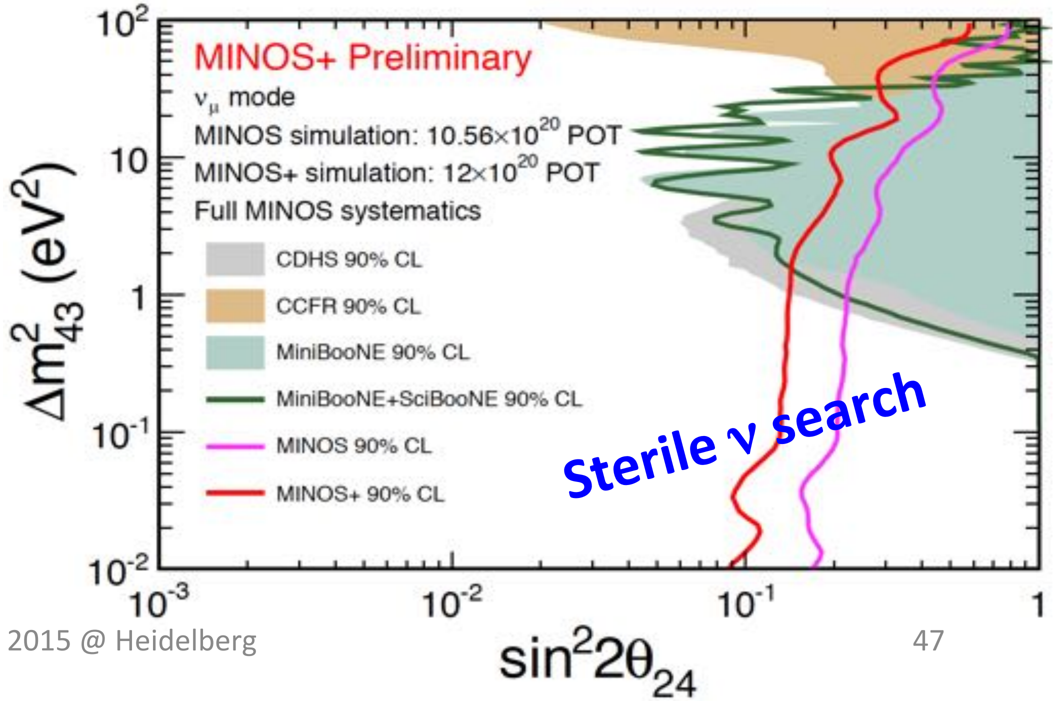
MINOS 3 ν osc best fit

Inverted Hierarchy

$|\Delta m^2_{32}| = 2.37^{+0.11}_{-0.07} \times 10^{-3}\text{eV}^2$

$\sin^2\theta_{23} = 0.43^{+0.19}_{-0.05}$

$0.36 < \sin^2\theta_{23} < 0.65$ (90% C.L.)



Future R&D

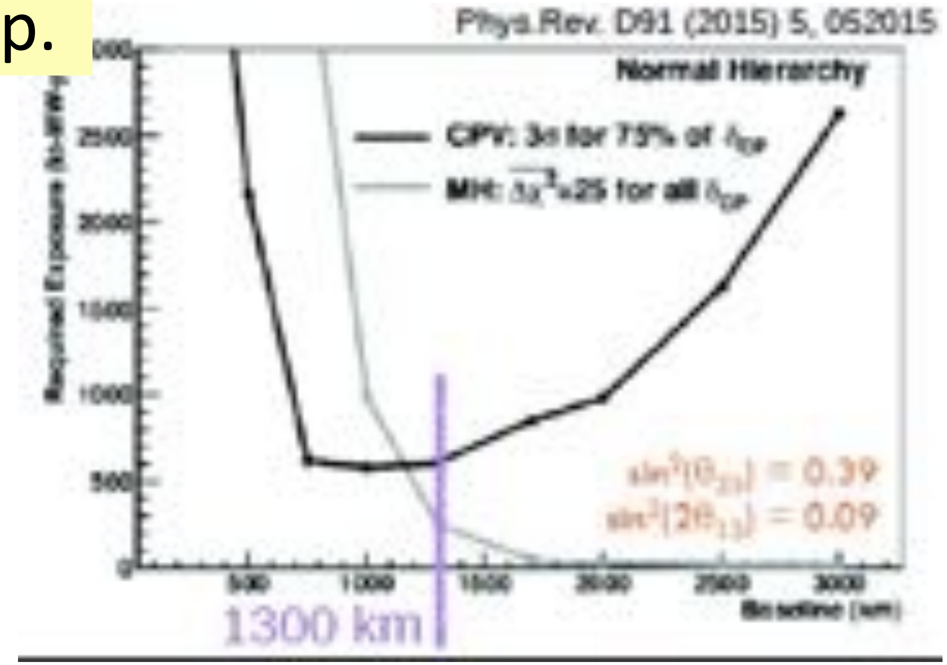
DUNE
LBNO-DEMO (WA105)
ESSnuSB
CHIPS

DUNE

Daniel Cherdack

Deep **U**nderground **N**eutrino **E**xp.

- Baseline: 1300 km (S. Dakoda)
- Megawatt beam covering 1st, 2nd osc. Max
- Near & Far detectors
- LArTPC: 40 kt @Far
- 6~10 yrs running
- 50% ν, 50% anti ν



Single vs. <u>double phase LArTPC</u>

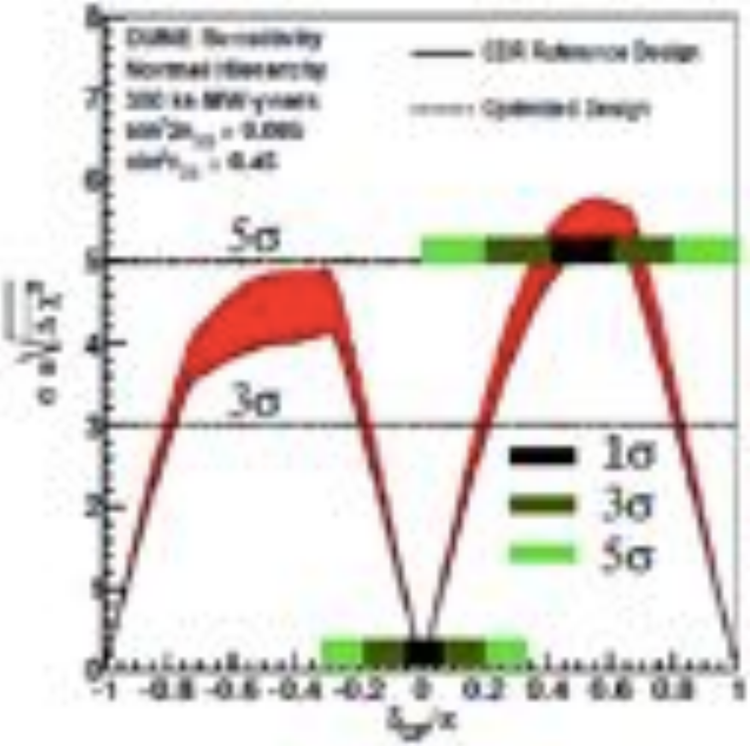
R&D: LBNO-DEMO (WA105)

(CERN neutrino platform)

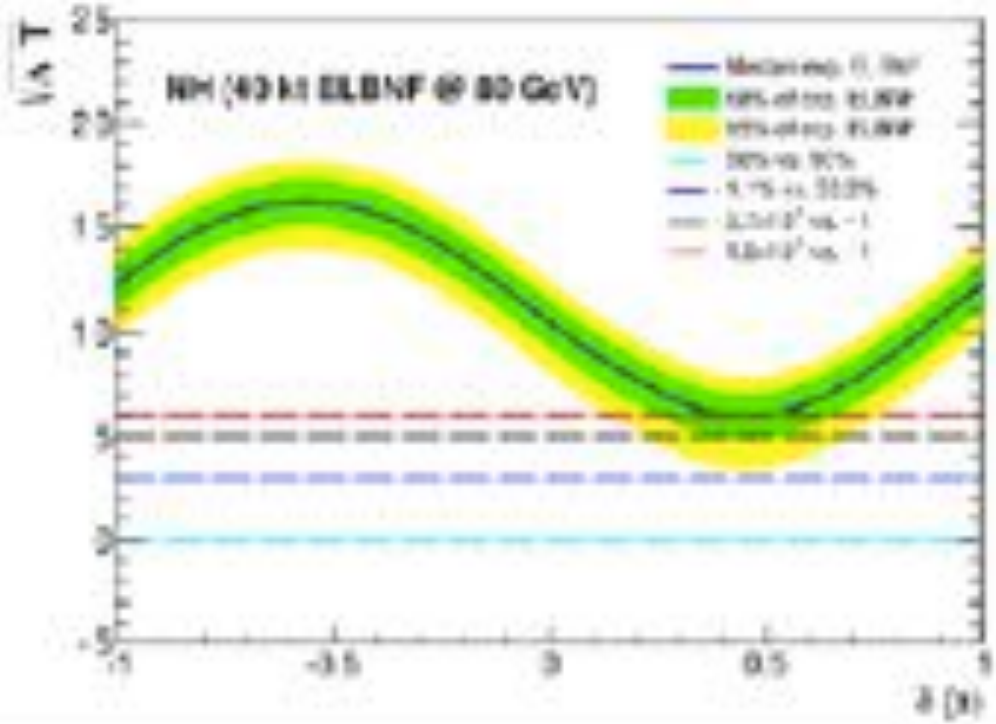
Sebastien Murphy

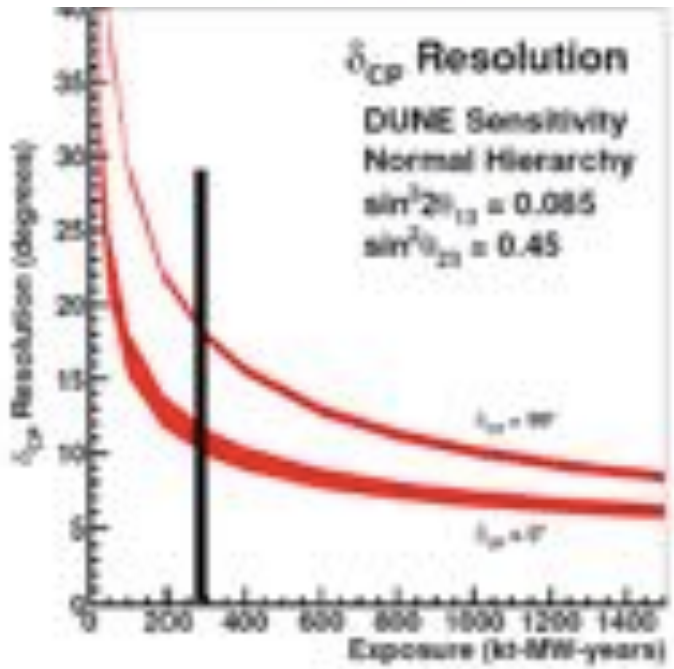
DUNE

Daniel Cherdack



DUNE Sensitivities

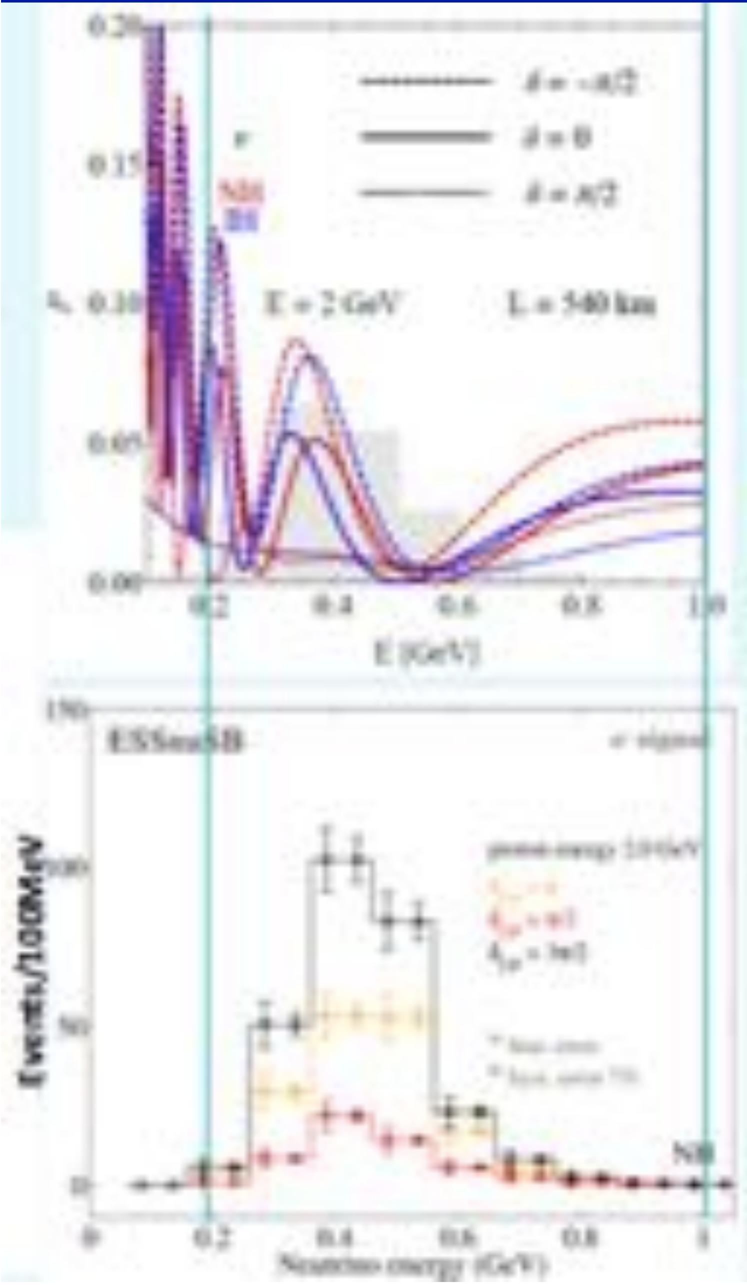




5 σ mass ordering determination: 2034~2035

ESSnuSB @2nd Maxima

Tord Ekelöf

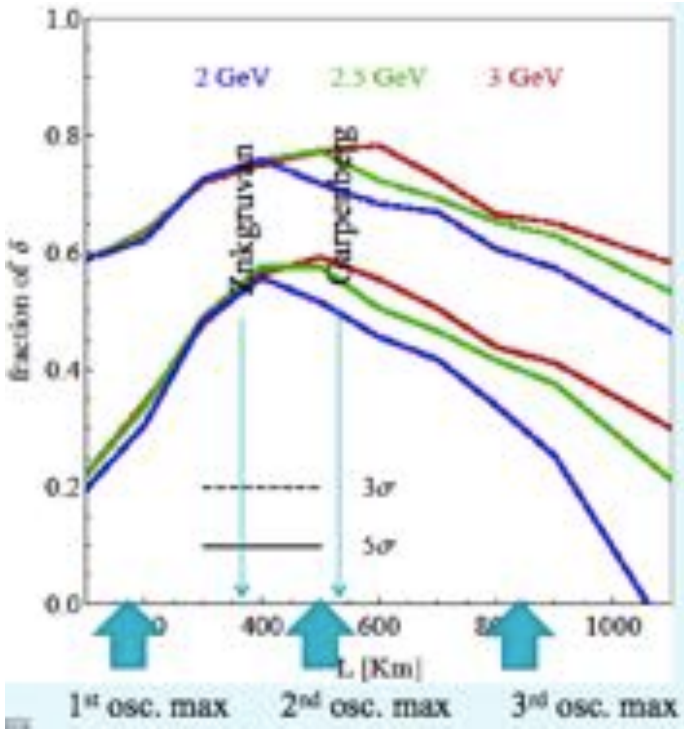


ESS Lund to Garpenberg mine: 540 km

- **Complementary to DUNE**
  WC detector: 0.5 Mt fiducial volume
  better coverage of δ & better sensitivity
- Data taking in 10 yrs if no politics
- **Adding a ν facility to ESS**

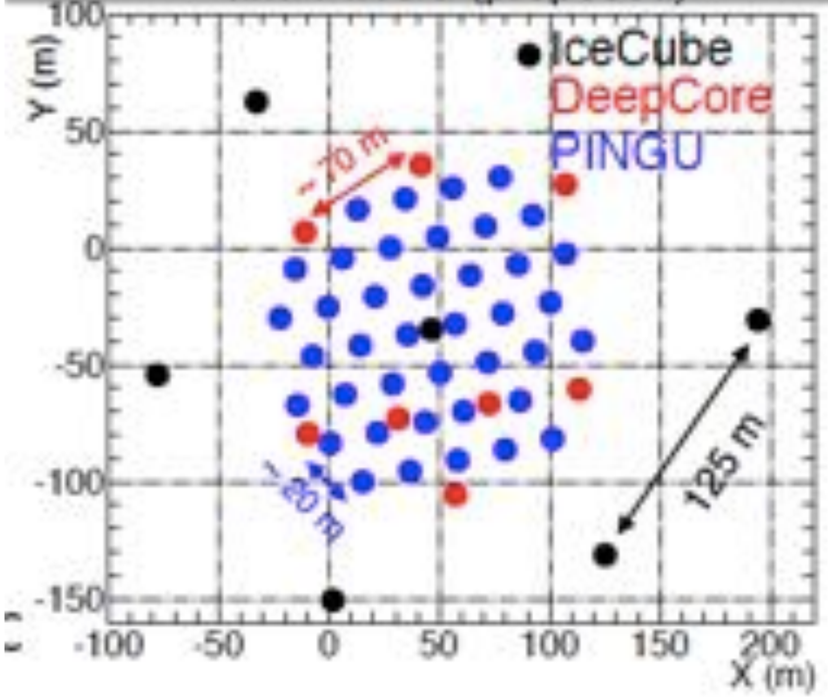
arXiv:1309.7922

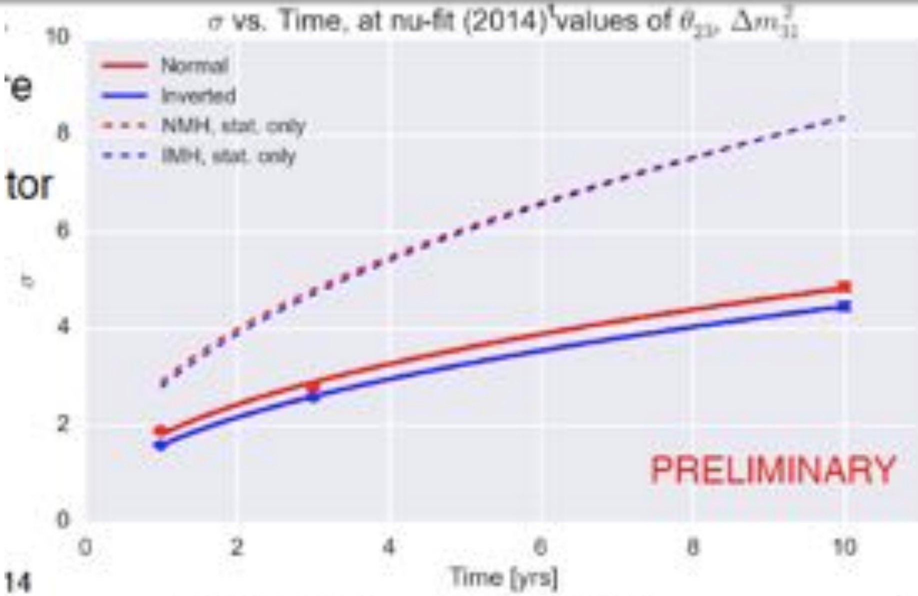
$\delta(3\pi/2)/\delta(\pi/2)$
$= 105/22$
$= 4.8$

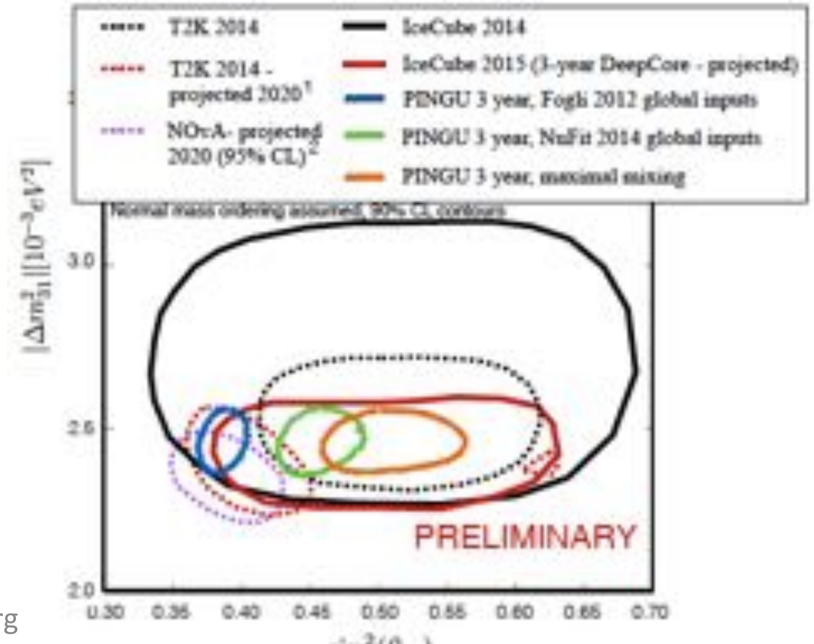


PINGU

Timothy Arlen







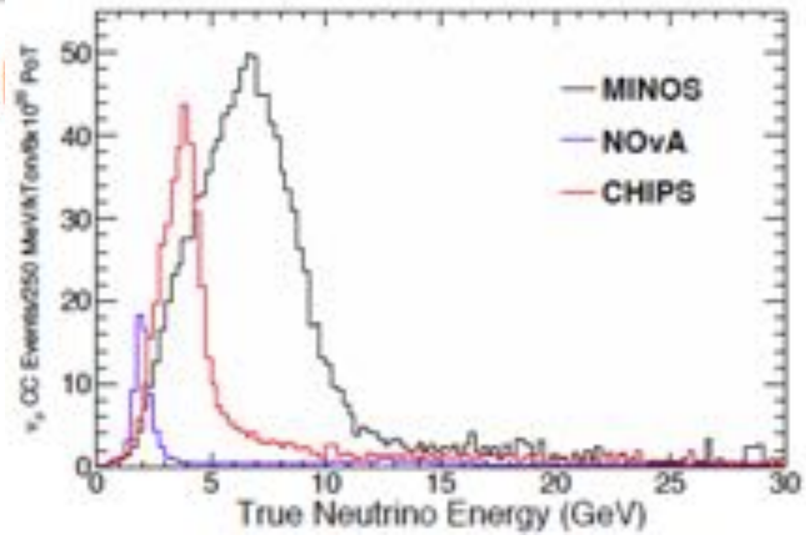
1 arxiv: 1409.7469

- 40 additional strings
  60 DOMs/string
- 3 k ν_τ/year →
  ν_τ appearance: 5 σ in a month
- Integral part of IceCube-Gen2

CHIPS

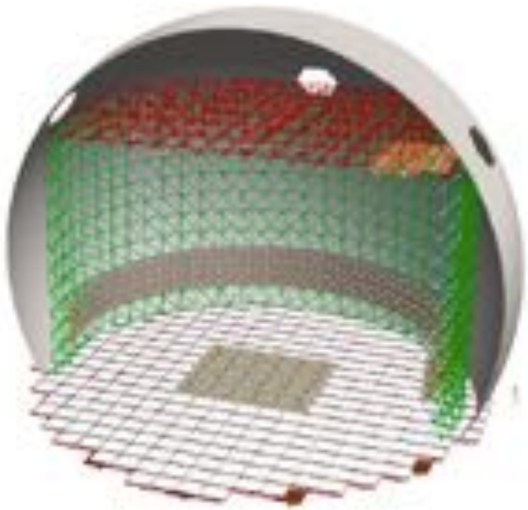
Marvin Marshak

CHerenkov detectors **I**n mine **P**it**S** (CH



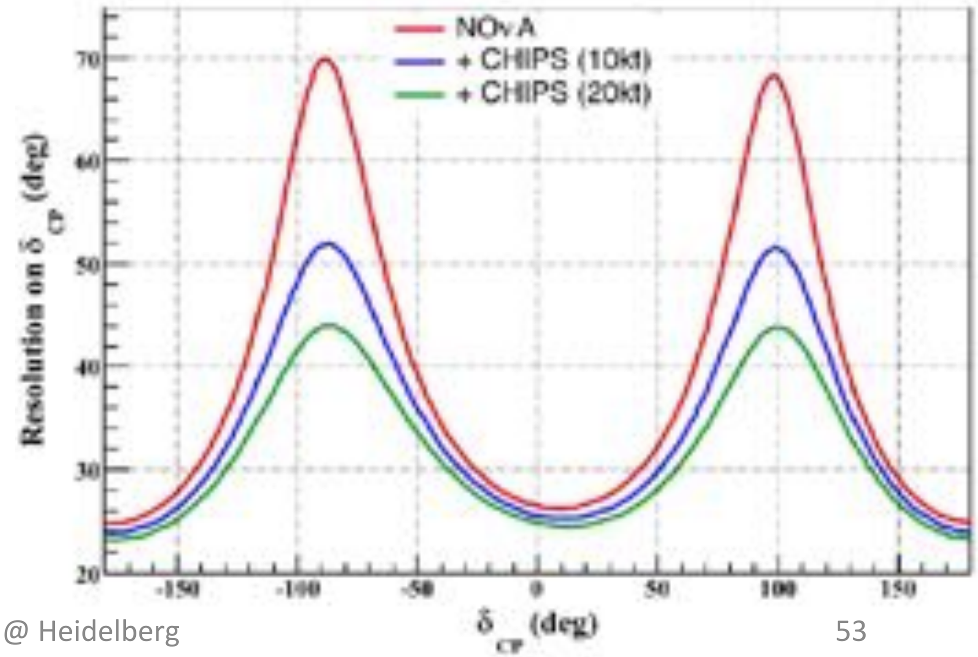
CHIPS-M

33 t WC, 4 DOMs
Under 60 m water
1st run: 2014-2015
2nd run: Aug. 2015



CHIPS-10kt

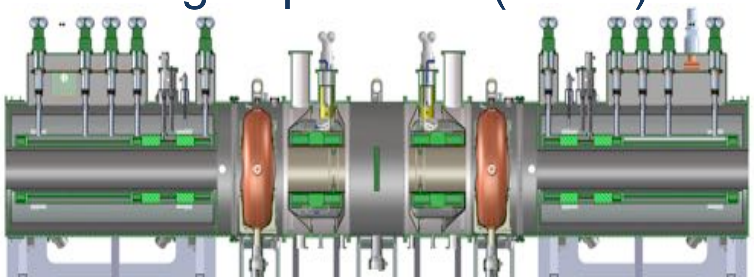
Install in 2017



MICE

Vittorio Palladino

International Muon Ionization Cooling Experiment (MICE)



- **MICE approved to:**
  - Design, build, commission and operate a realistic section of cooling channel
  - Measure its performance in a variety of modes of operation and beam conditions
    - Results will allow Neutrino Factory [and Muon Collider] complex to be optimised
- **Requirements:**
  - Normalised transverse emittance: 0.1%
    - Requires selection of 99.9% pure muon sample

MICE will unlock the exploitation of muon accelerators by providing the essential demonstration of ionization cooling:

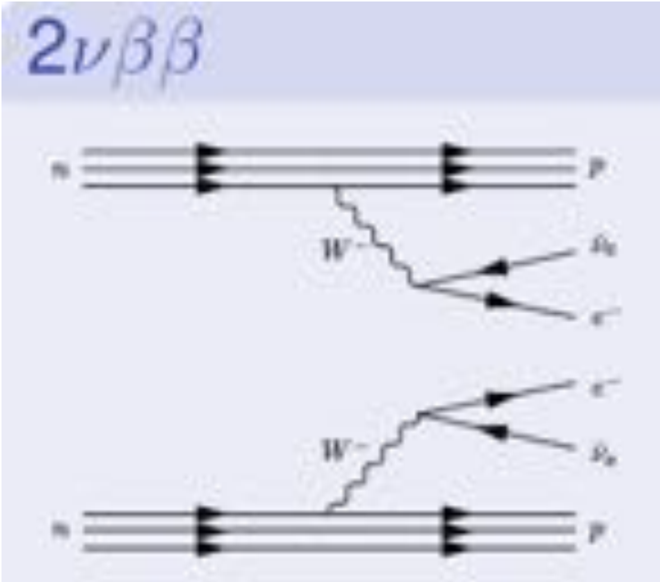
- **Starting *now*:**
  - Investigation of the effect of material, emittance, momentum on the cooling effect
- **Starting 2017:**
  - Demonstration of Ionization cooling;
  - Systematic study of factors that affect cooling performance

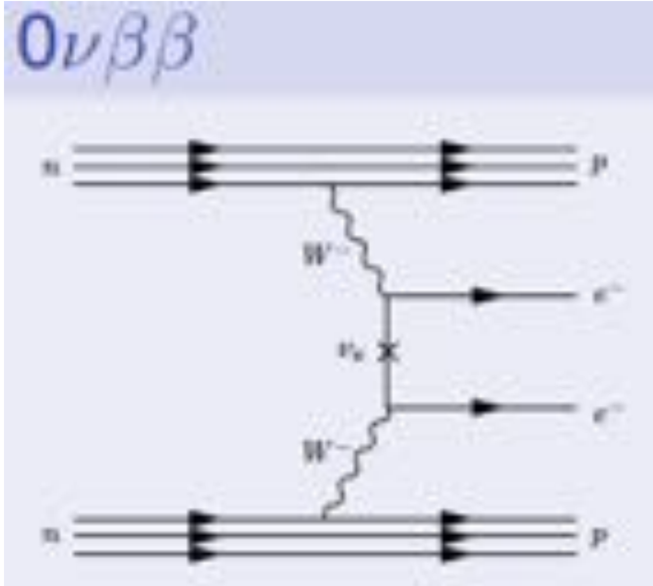
Double Beta Decay

GERDA
EXO/nEXO
CUORE-0/CUORE
AMoRE

Heavy neutrinos in LHC

Double Beta Decay





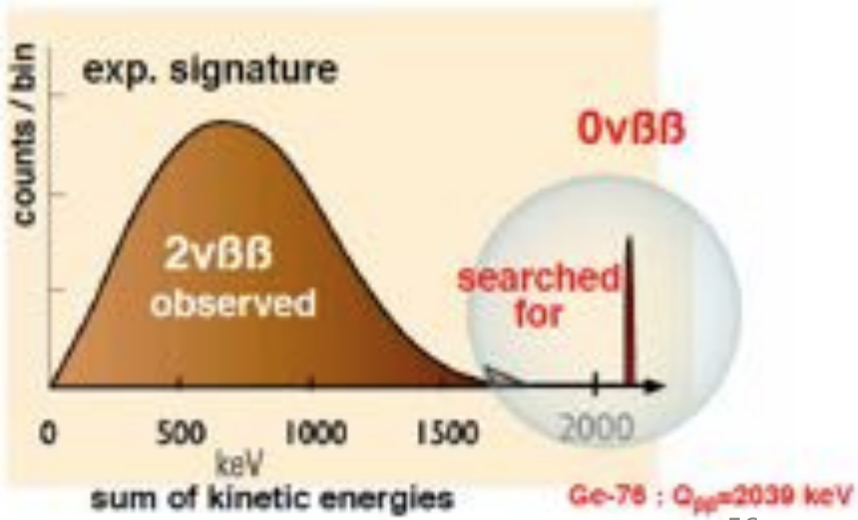
<u>0νββ</u>

If Majorana ν

If lepton number violated

Hint to Abs. neutrino mass

Hint to neutrino mass hierarchy



$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)|\mathcal{M}_{0\nu}(A,Z)|^2|m_{\beta\beta}|^2$$

effective Majorana mass:

$$|m_{\beta\beta}| \equiv \left|\sum_i U_{ei}^2 m_i\right| = \left|c_{12}^2\, c_{13}^2\, m_1 + s_{12}^2\, c_{13}^2\, m_2\, e^{i2\alpha} + s_{13}^2\, m_3\, e^{i2\beta}\right|$$

Sizable background case ;

$$T^{0\nu}_{1/2}(\exp) = (\ln 2) N_a \frac{a}{A} \varepsilon \sqrt{\frac{MT}{b\Delta E}}$$

b = background index in cts/(keV kg y)

ΔE = FWHM energy resolution at $Q_{\beta\beta}$ in keV

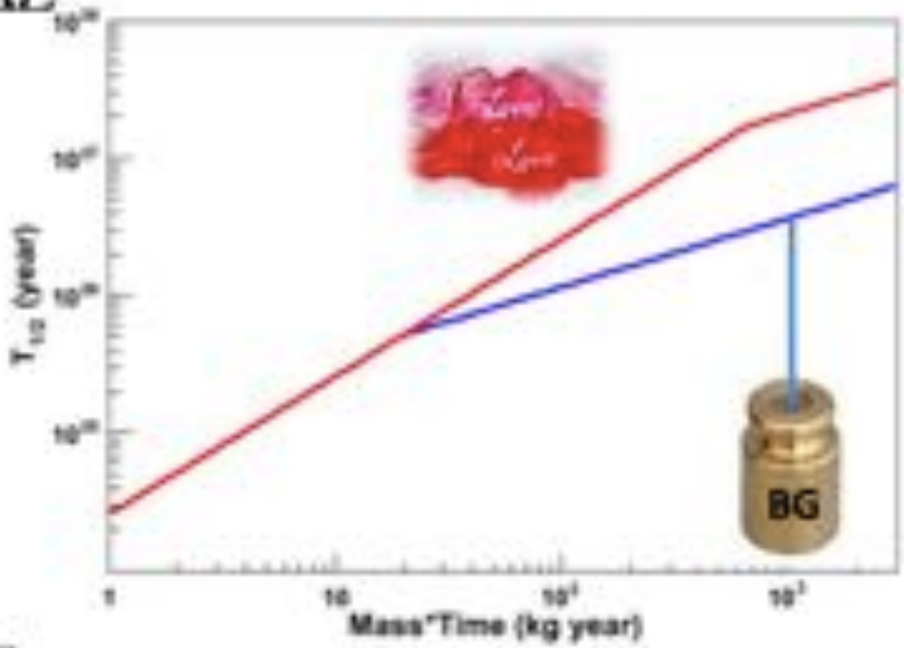
M = mass of detector in kg

A = mass number of candidate material

ε = detection efficiency at $Q_{\beta\beta}$

A = $\beta\beta$ isotope fraction (Enrichment)

T = measured time in years



"Zero" background case ;

$$T^{0\nu}_{1/2}(\exp) = (\ln 2) N_a \frac{a}{A} \varepsilon \frac{MT}{n_{CL}}$$

Current Status on DBD

Experiments	Isotopes	$T_{½}^{0\nu}$ (year) @ 90% CL	$<m_{\beta\beta}>$ [eV]	Speaker (WIN2015)
GERDA: I Phase II	^{76}Ge	> 2.1 X 10^{25} > 10^{26} (2yr)	0.25 - 0.42 ---	Matteo Agostini
KAMLAND-ZEN	^{136}Xe	> 1.9 X 10^{25}	0.14 - 0.34	**PRL 110 062502 (2015)**
EXO-200 nEXO	^{136}Xe	> 1.1 X 10^{25} > 6.6 X 10^{27} (5yr)	0.19 - 0.45 ---	Raymond Tsang
NEMO-3	^{100}Mo	> 1.1 X 10^{25}	0.34 - 0.87	**RRD 89 111101 (2014)**
CUORE-0 CUORE	^{130}Te	> 2.7 X 10^{24} > 9.5 X 10^{25} (5yr)	0.31 - 0.76 0.05 – 0.13	Fabio Bellini
SNO+	^{130}Te	> 7 X 10^{26} (5yr)	---	Valentina Lozza
AMoRE-pilot AMoRE-10 AMoRE-200	^{100}Mo	> 1.1 X 10^24 3 X 10^25 (2yr) 10^27 (4yr)	< 0.3 ~ 0.9 0.06 ~ 0.18 0.01 ~ 0.03	Loredana Gastaldo

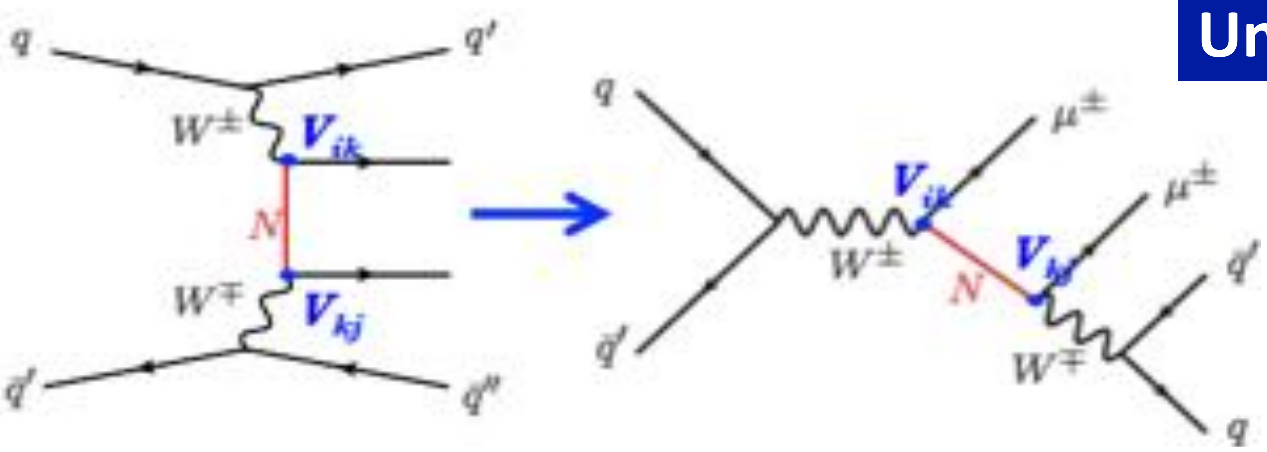
Presented talks in WIN 2015

C. Macolino@NeuTel2015

Experiment	Isotope	Mass of Isotope [kg]	Sensitivity $T^{0\nu}_{1/2}$ [yr]	Sensitivity $m_{\beta\beta}$ [eV]	Status
GERDA	^{76}Ge	18 40 1000	3×10^{25} 2×10^{26} * 6×10^{27}	$0.2 \div 0.4$ 0.1 0.03	running in progress R&D
CUORE	^{130}Te	200	1×10^{26}	$0.04 \div 0.1$	in progress
MAJORANA	^{76}Ge	40 1000	2×10^{26} 6×10^{27}	0.1 0.03	in progress R&D
EXO	^{136}Xe	200 1000	5×10^{25} 8×10^{26}	$0.08 \div 0.3$ $0.01 \div 0.03$	in progress R&D
SuperNEMO	^{82}Se	7 100	6.5 ' $\times 10^{24}$ 1×10^{26}	$0.2 \div 0.4$ $0.04 \div 0.10$	in progress R&D
KamLAND-Zen	^{136}Xe	400 1000	4×10^{26} * 1×10^{27}	0.06 0.02	in progress R&D
NEXT	^{136}Xe	100 1000	5×10^{25} 5×10^{26}	$0.08 \div 0.13$ $0.03 \div 0.07$	in progress R&D
SNO+	^{130}Te	200 800	1×10^{26} * 1×10^{27}	$0.06 \div 0.1$ $0.02 \div 0.06$	in progress R&D
AMoRE	**^{100}Mo**	**1-1.5 10 200**	**> 1.1 X 10^24 3 X 10^25 * 10^27**	**< 0.3 ~ 0.9 0.06 ~ 0.18 0.01 ~ 0.03**	**2015 R&D**

Heavy Neutrinos @ LHC

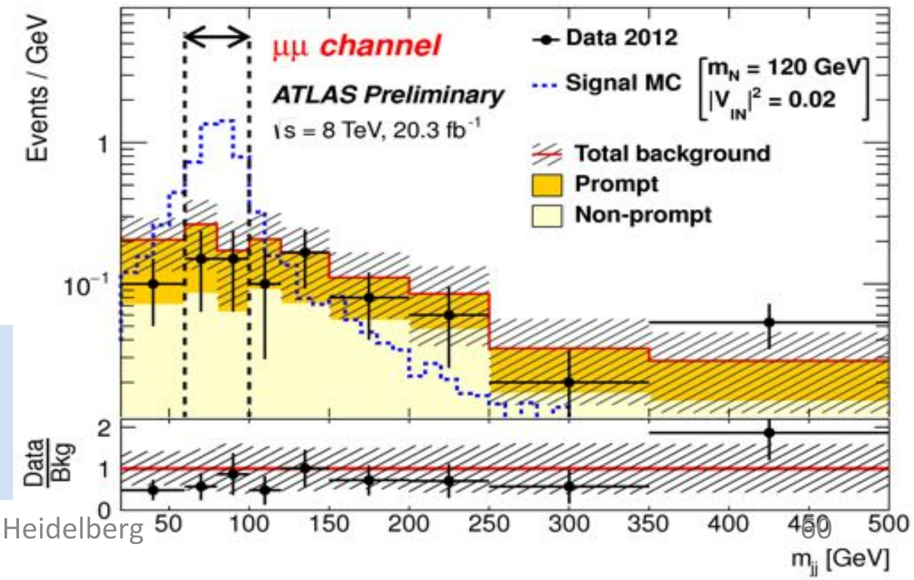
Un-ki Yang



LHC has explored Type I, III, and LRSM.

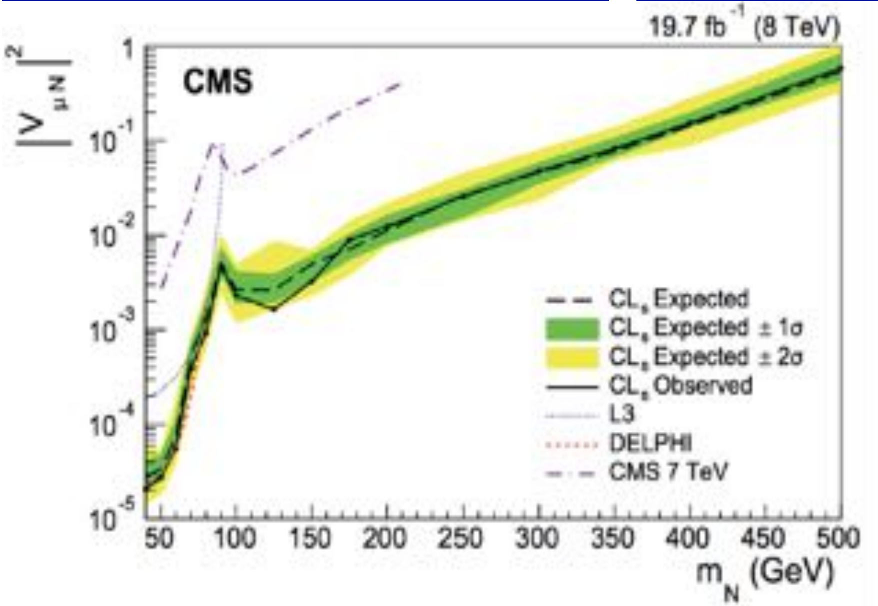
Fresh new results from ATLAS 3 days ago !!

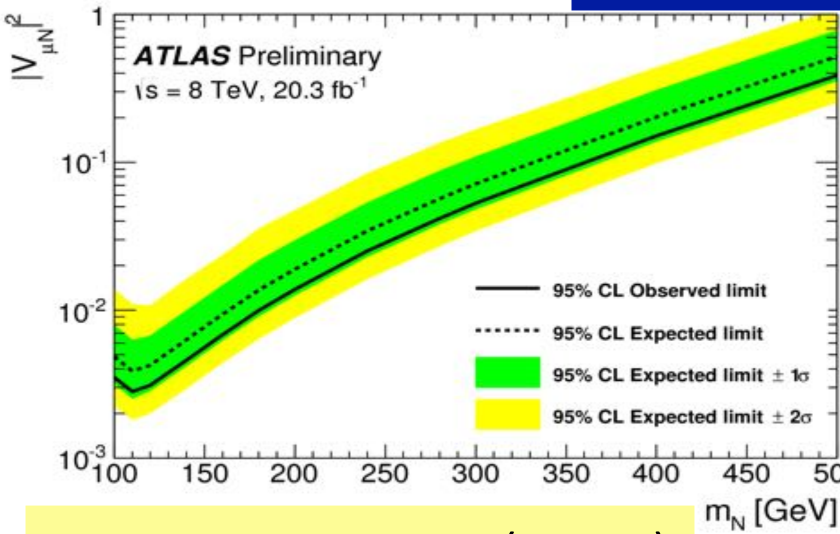
Type I →
SS dimuon + 2 jet



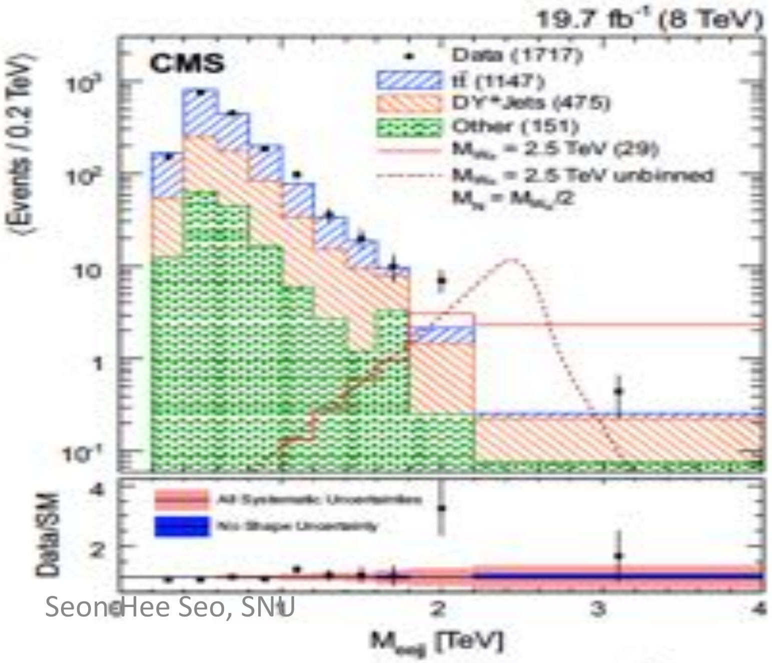
Heavy Neutrinos @ LHC

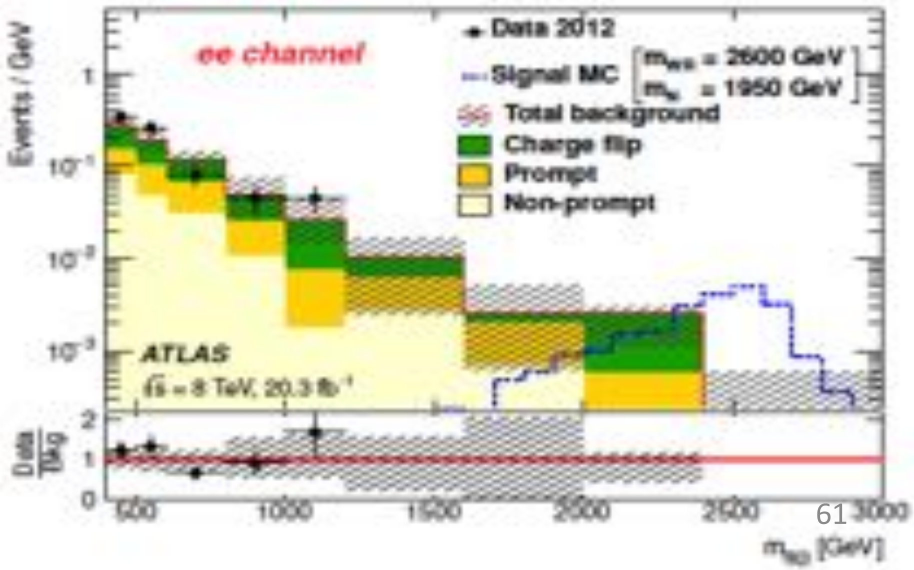
Un-ki Yang





2.8 S EXCESS IN CMS (SS+OS)
but no excess (SS) in ATLAS





Where is next surprise ?

Neutrino CP violation ?

Neutrino mass ordering ?

Sterile neutrinos ?

Absolute masses ?

Dirac or Majorana ?

Concluding Remark

We don't know where our nature
has kept her secrets.

Future is up to us !
(and to nature)

Let's be positive & continue searches !

Danke !

Thank you !

감사합니다 !