Future Neutrino Experiments

Weili Zhong
Lawrence Berkeley
National Laboratory

HQL10@ LNF, Frascati, Italy
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Villa Aldobranidini, Frascati

Neutrino Mixing

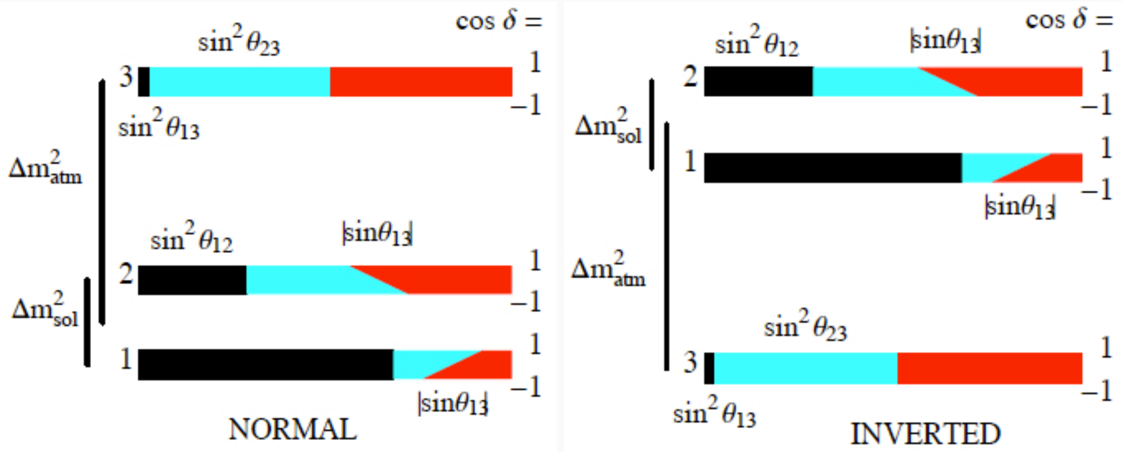
$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle$$

Parameterize the PMNS Matrix

$$\underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar, reactor}} \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & \boxed{\sin\theta_{13}e^{-i\delta}} \\ 0 & 1 & 0 \\ \boxed{-\sin\theta_{13}e^{i\delta}} & 0 & \cos\theta_{13} \end{pmatrix}}_{\text{reactor and accelerator}} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\text{Atmospheric, accelerator}} \underbrace{\begin{pmatrix} e^{i\delta_1} & 0 & 0 \\ 0 & e^{i\delta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}}$$

Known: (PDG 2010)

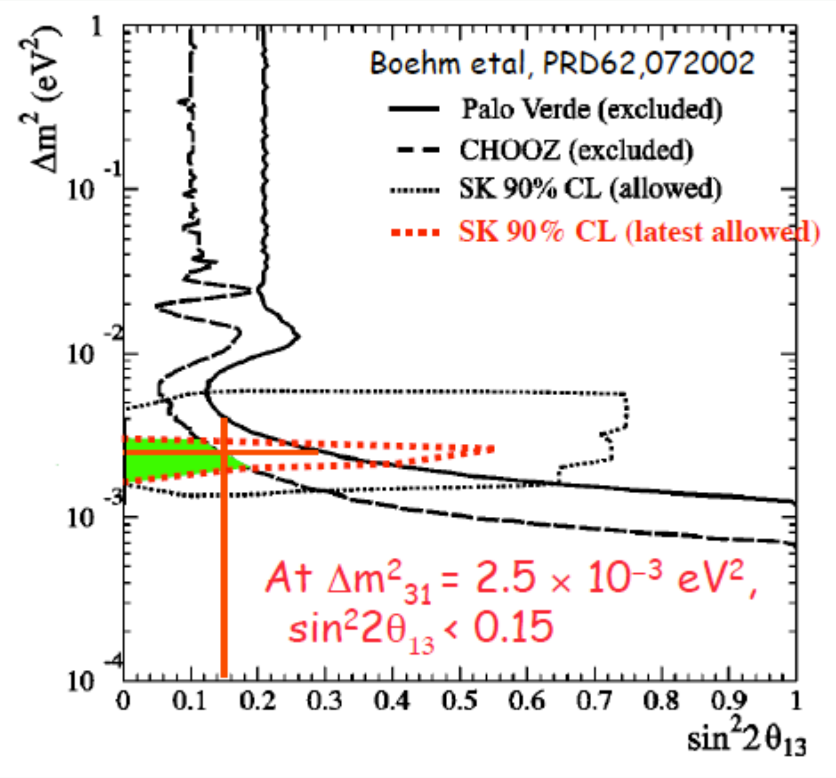
$$\sin^2(2\theta_{12}) = 0.87 \pm 0.03$$
$$\sin^2(2\theta_{23}) > 0.92$$
$$\Delta m^2_{21} = (7.59^{+0.19}_{-0.21}) \times 10^{-5}\mathrm{eV}^2$$
$$|\Delta m^2_{32}| = (2.43 \pm 0.13) \times 10^{-3}\mathrm{eV}^2$$



Unknown: θ_{13}, δ_{cp}, sign(Δm^2_{32})

Last Unknown Mixing Angle θ_{13}

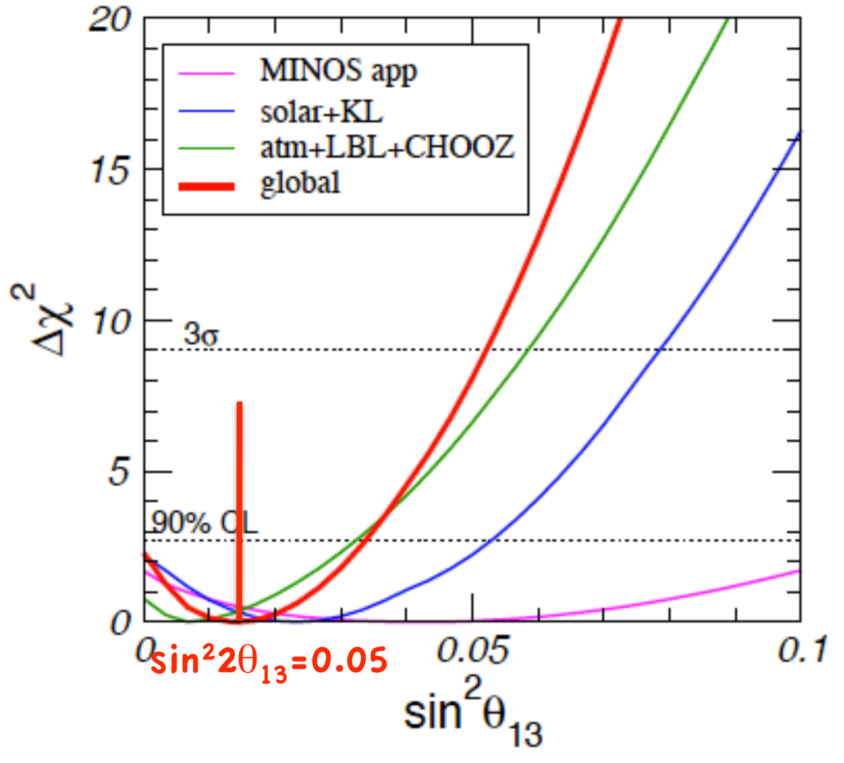
Experiment limit



At $\Delta m^2_{31} = 2.5 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{13} < 0.15$

Global fitting

arXiv: 0808.2016v3

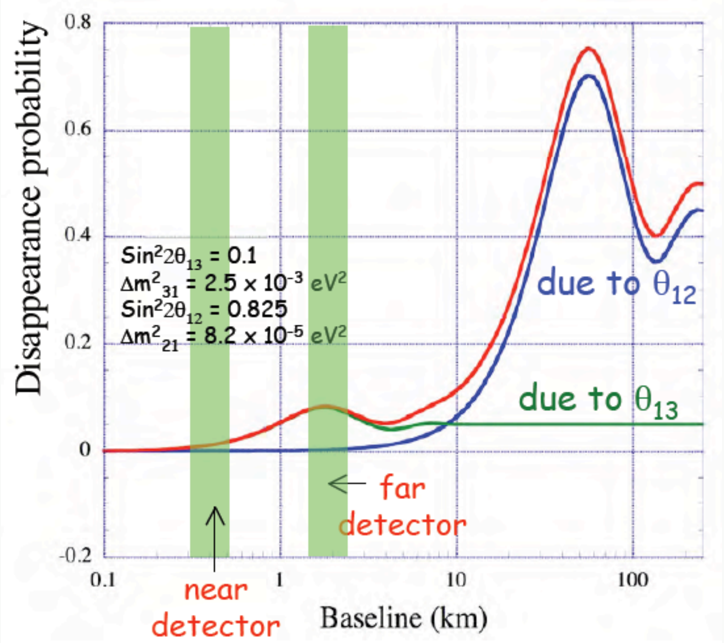


$\sin^2 2\theta_{13}=0.05$

Measure $\sin^2 2\theta_{13}$ to a sensitivity of 0.01

θ_{13} in Reactor Neutrino Experiment

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$



- Low energy $\bar{\nu}_e$: 1.8MeV to 10MeV
- Clean measurement of θ_{13}: matter effect negligible, no coupling from δ_{cp}
- Inverse beta decay: cross section is well known
- Near/Far: exact $1/r^2$ extrapolation
- No neutral current background
- Gd-loaded liquid scintillator improves background suppression.

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

Prompt: e^+ annihilation Delay: neutron capture

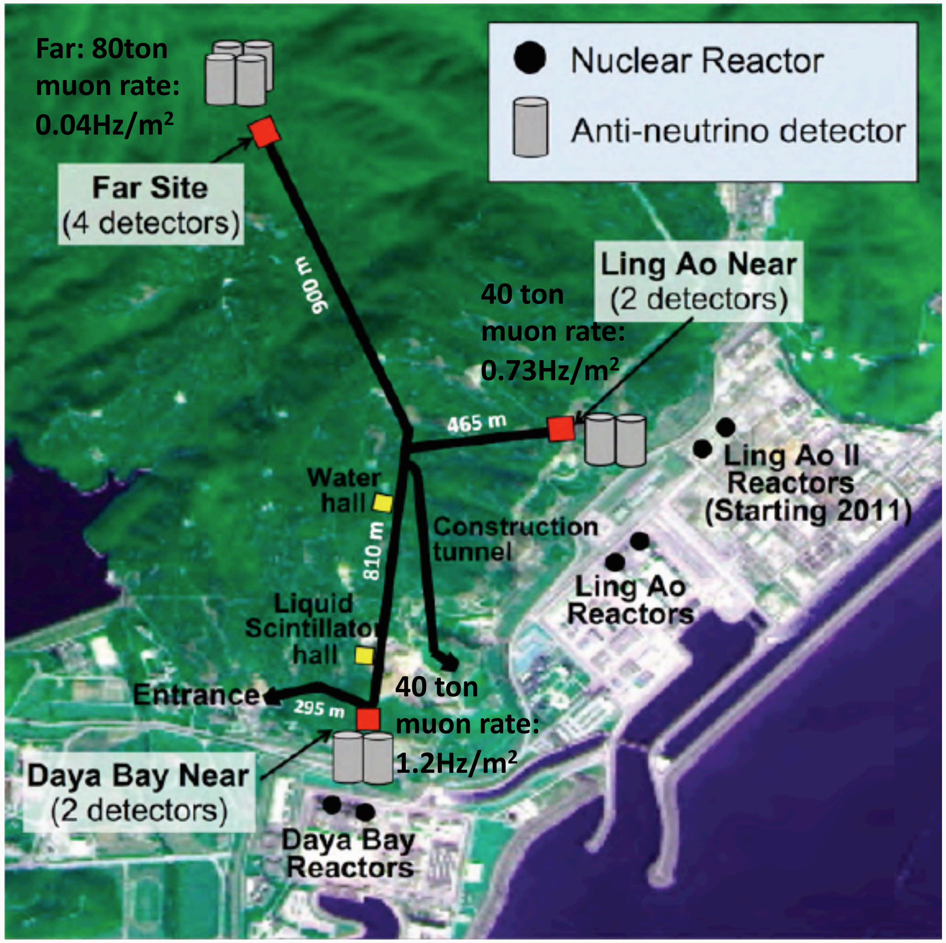
Neutrino events: coincidence in time and energy

0.3b $\rightarrow + p \rightarrow D + \gamma$ *(2.2 MeV)* *(delayed)* 180μs

50kb $\rightarrow + Gd \rightarrow Gd^* \rightarrow Gd + \gamma$*'s (8 MeV)* *(delayed)* 28μs 0.1%Gd

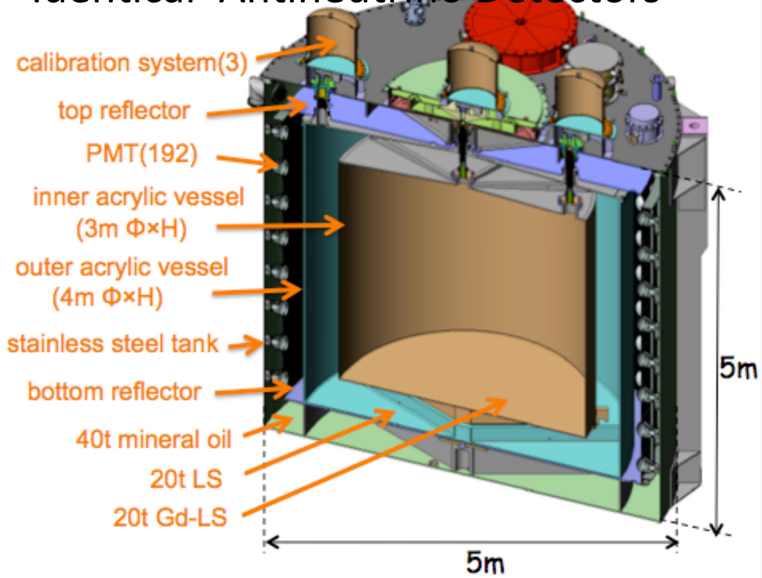
Daya Bay

Experimental Layout

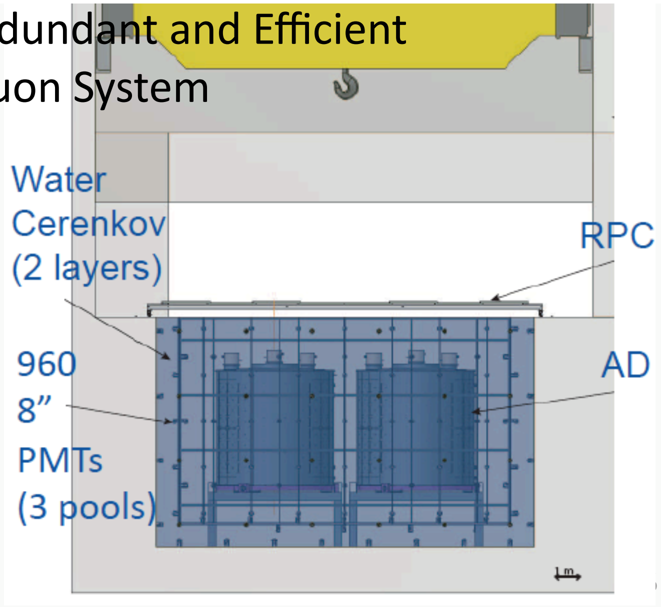


Powerful Reactors: 2.9×6=17.4GW.
Optimized baselines.
Deep underground.

‘Identical’ Antineutrino Detectors



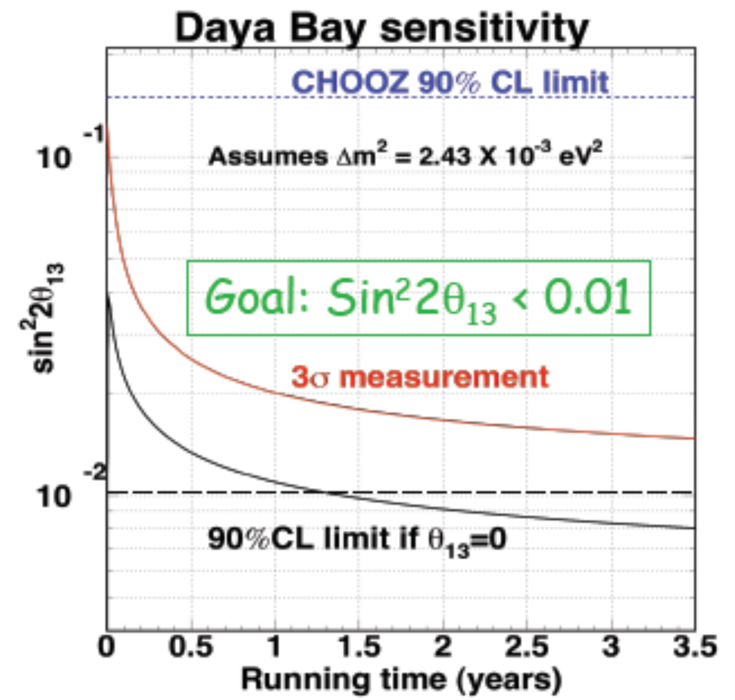
Redundant and Efficient Muon System



Sensitivity and Schedule

Expected signal and background rates per antineutrino detector

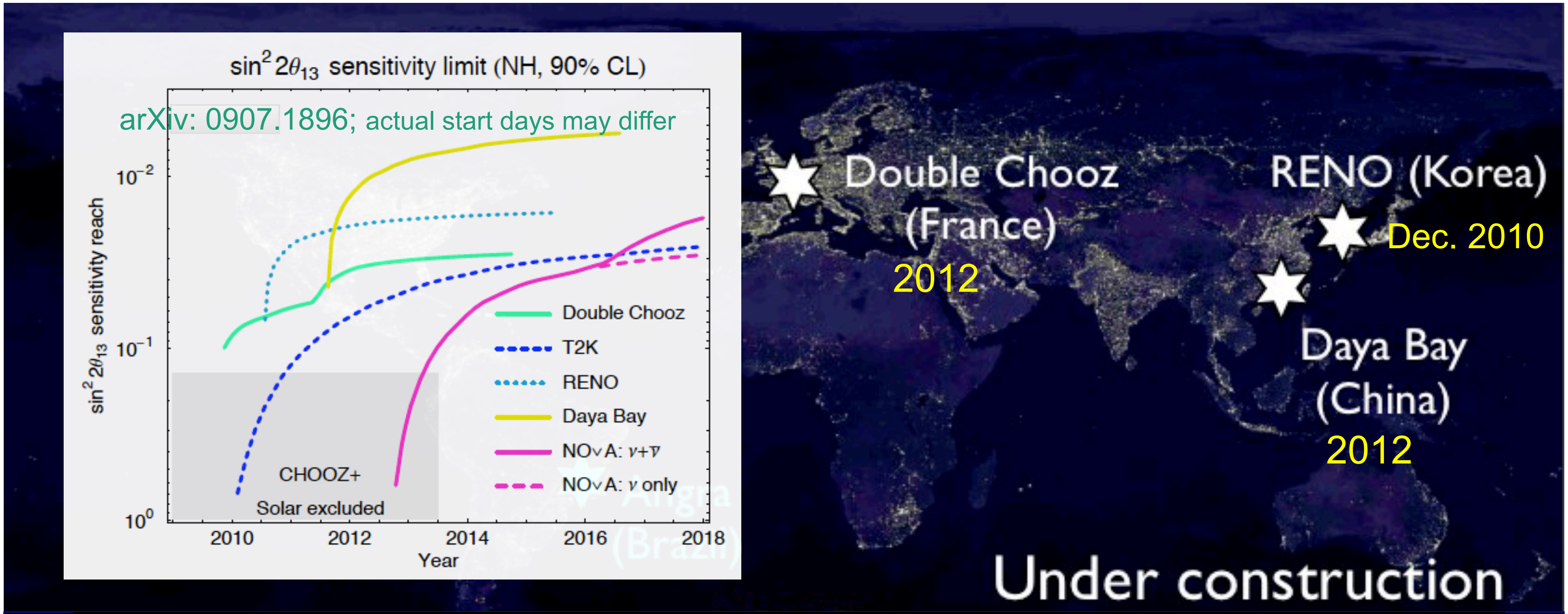
	Daya Bay Near	Ling Ao Near	Far Hall
Antineutrino Signal (events/day)	**840**	**740**	**90**
Overburden (m.w.e.)	260	300	870
Accidental Background/signal (%)	<0.2	<0.2	<0.2
Fast neutron Background/signal (%)	0.1	0.1	0.1
^{8}He/^{9}Li Background/signal (%)	0.3	0.2	0.2



Systematic and statistical uncertainty

Source	Uncertainty
Reactor	0.13%
Detector(per module)	0.38%
Statistics	0.2%

Experimental Hall	Physics Ready
Daya Bay Hall	Fall 2011
Ling Ao Hall	Spring 2012
Far Hall	Fall **2012**



	Thermal Power (GW)	Mass (Tons)	Near		Far		δ_{system} (%)
			Distance (m)	Depth (m.w.e.)	Distance (m)	Depth (m.w.e.)	
Double Chooz	8.5	10 / 10	400	115	1050	300	0.6
RENO	17.3	16 / 16	290	120	1380	450	0.5
Daya Bay	17.4	40, 40 / 80	363 &481	260 &300	1985 &1613	870	0.38

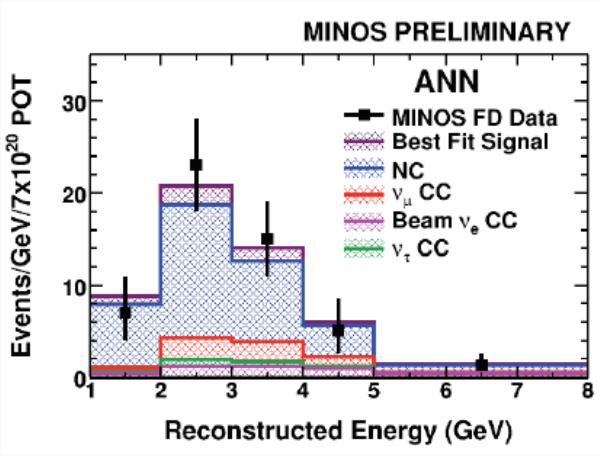
θ_{13} in Accelerator Neutrino Experiment

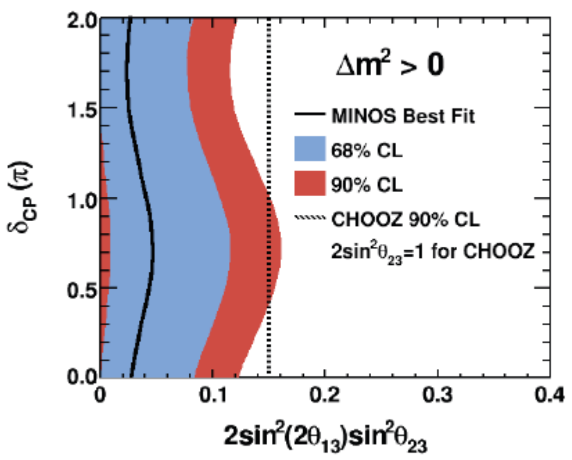
- Appearance probability of ν_e from ν_μ depends on values of θ_{13}, δ_{cp} and mass hierarchy.

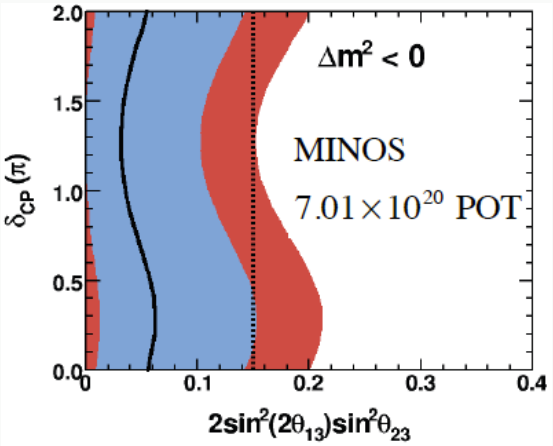
$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \approx\ & \sin^2(2\theta_{13})\sin^2(\theta_{23})\sin^2\left(1.27\Delta m^2_{31}\frac{L}{E}\right)+\\
& \sin^2(2\theta_{12})\cos^2(\theta_{23})\sin^2\left(1.27\Delta m^2_{21}\frac{L}{E}\right)+\\
& \sin(2\theta_{13})\sin(2\theta_{23})\sin(2\theta_{12})\sin\left(1.27\Delta m^2_{31}\frac{L}{E}\right)\sin\left(1.27\Delta m^2_{21}\frac{L}{E}\right)\cos\left(1.27\Delta m^2_{32}\frac{L}{E}\pm\delta_{CP}\right)
\end{aligned}
$$

MINOS results: expected (based on ND data): 49.1±7.0(stat.)±2.7(syst.), observed: 54 in FD, a 0.7σ excess. Phys. Rev. D 82, 051102

For $\delta_{cp}=0$, $\sin^2 2\theta_{23}=1$, $|\Delta m^2_{32}|=2.43\times10^{-3}\,\mathrm{eV}^2$: $\sin^2 2\theta_{13}<0.12$(NH),0.20 (IH) at 90% C.L.

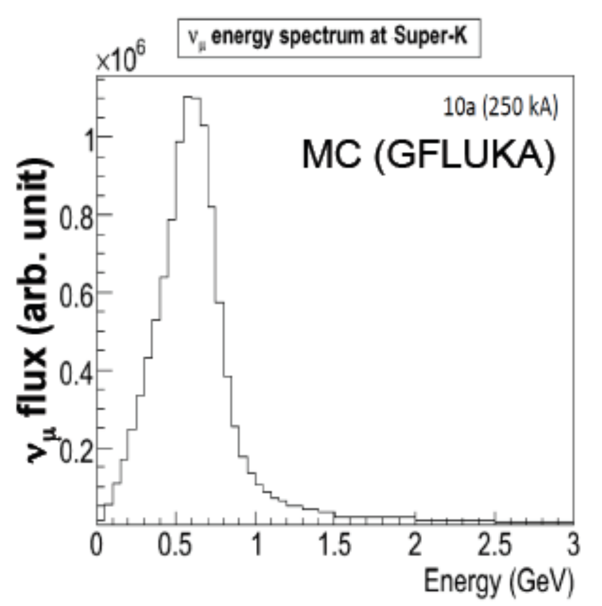


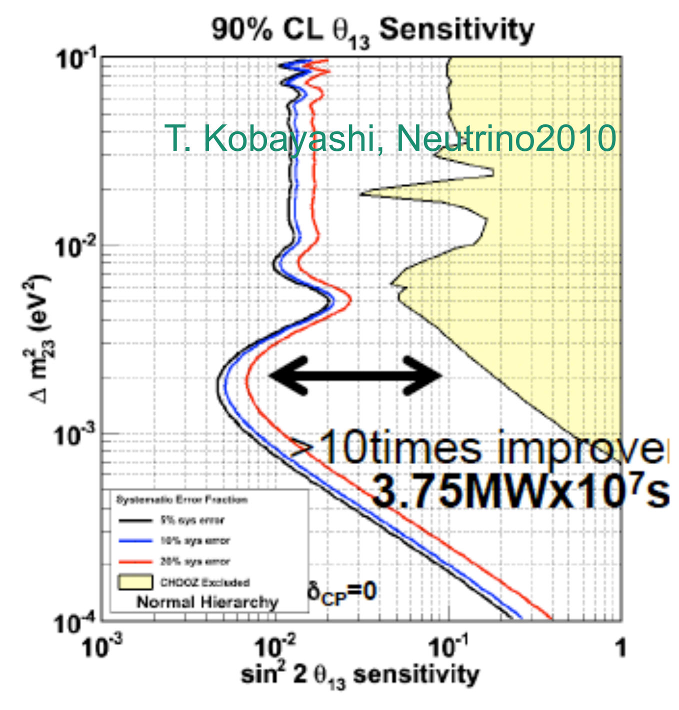




T2K

- High intensity neutrino beam from J-PARC
- Narrow band beam tuned at oscillation maximum
  - 2.5deg off-axis, peak ~600MeV
  - Quasi Elastic CC dominate: $\nu_l + n \rightarrow l^- + p$
- Near detector @280m
  - On-axis detector "INGRID"
    - Intensity and direction (profile)
  - Off-axis (toward SuperK direction)
    - Absolute flux/spectrum/ν_e
- Far detector: SuperK, 50KT @295km
- Schedule:
  - data taking started in Jan. 2010, beam power ~50KW
  - After Nov. 2010, from ~100KW towards 0.75MW
- Goal: Accumulate $0.75\text{KW} \times 5 \times 10^7$sec
  - ν_e appearance: $\sin^2 2\theta_{13}$ ~0.008 (90%CL), 0.018(3σ)
  - Precise measurement of ν_μ disappearance.





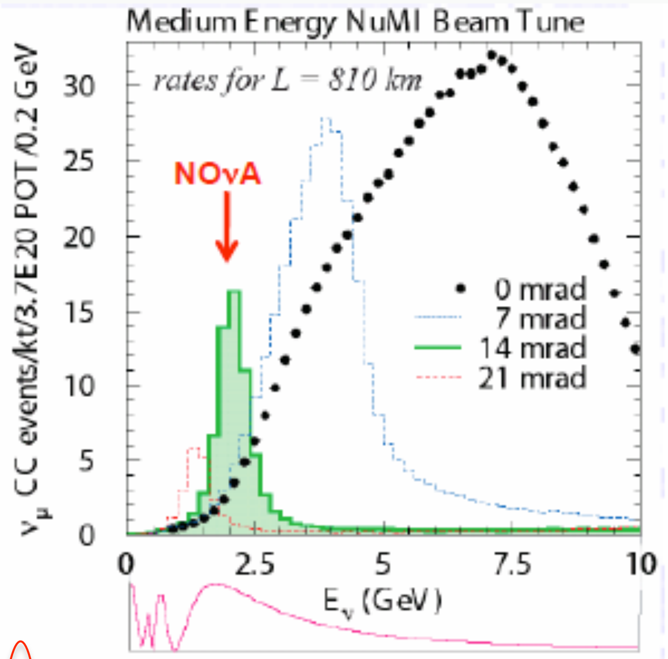
T. Kobayashi, Neutrino2010

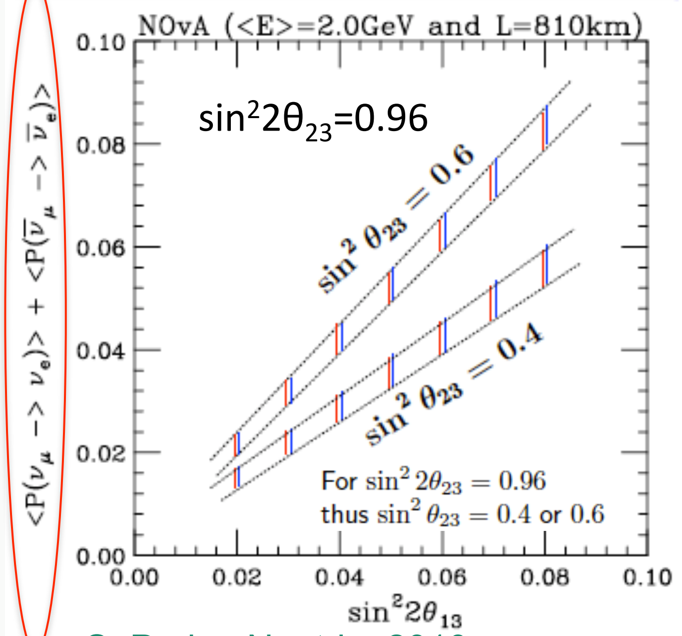
>10times improve

$3.75\text{MW}\times 10^7$s

NOVA

- High intensity neutrino beam from Fermi Lab NuMI beam: upgrade to 0.7MW in Fall, 2011.
- Narrow band beam at oscillation maximum
  - 14mrad, peak ~2GeV
  - Near detector: ~12m off-axis, Far detector:~12km off-axis
- Near and far detector: tracking liquid scintillator calorimeters
- Near detector: 23t, ~1km
- Far detector: 15kt, 810km
  - Sensitive to neutrino mass hierarchy
- Goal: measure $\sin^2 2\theta_{13}$ and θ_{23}
- Schedule: data taking in 2013, and first run will last six years.

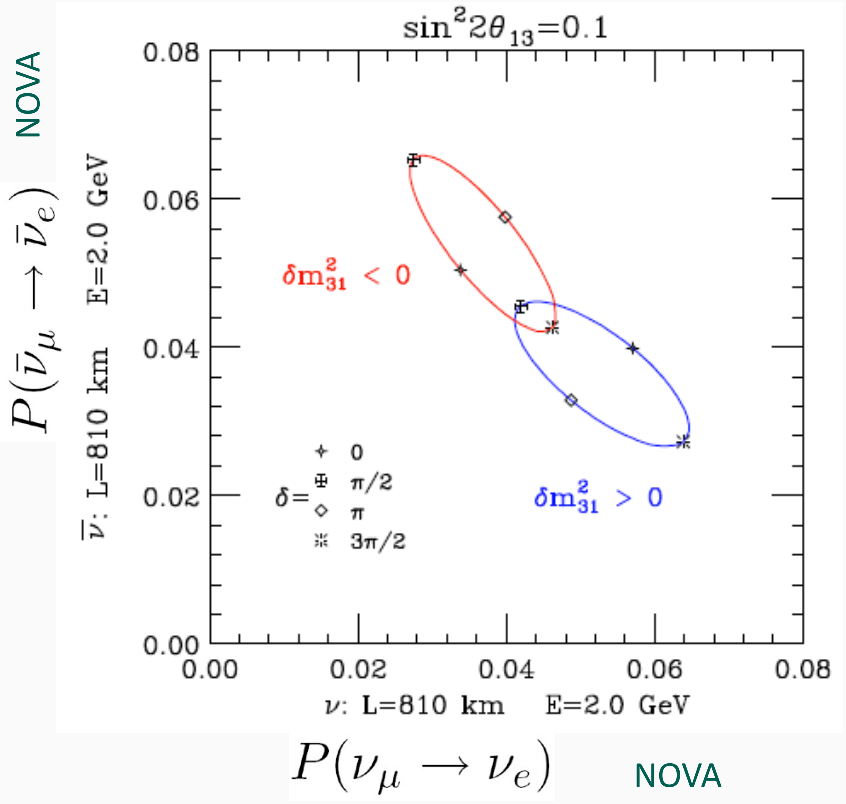


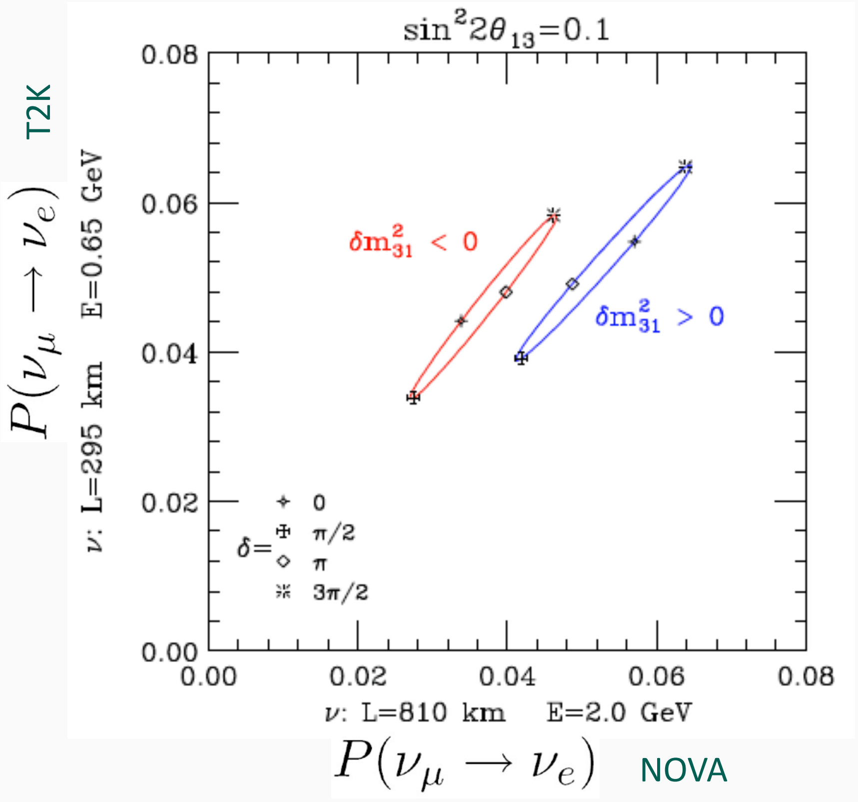


S. Parke, Neutrino2010

Combination of T2K and NOVA: Mass Hierarchy and δ_{cp}

- NOVA will run in neutrino mode and anti-neutrino mode to explore mass hierarchy.
- Combine T2K and NOVA data to reduce degeneracy.

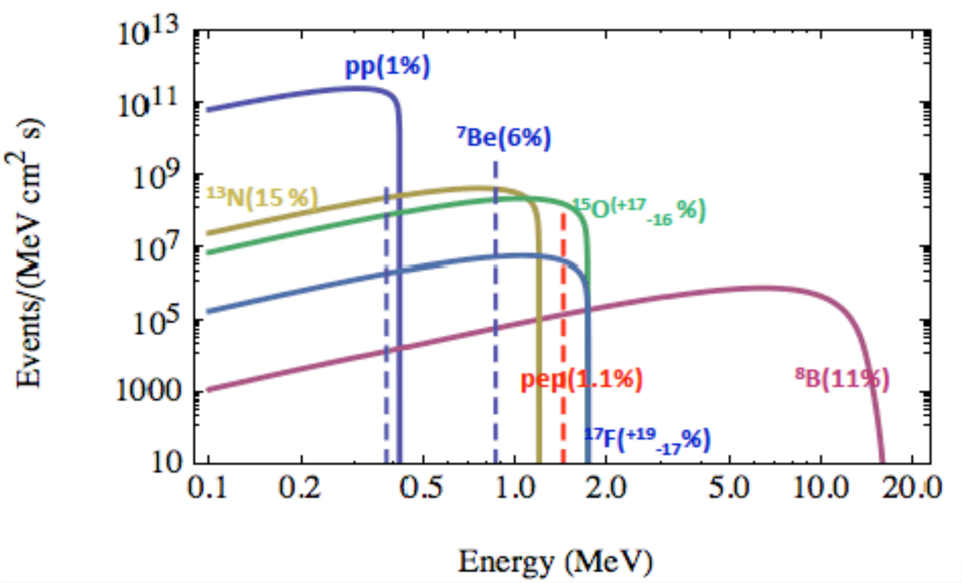


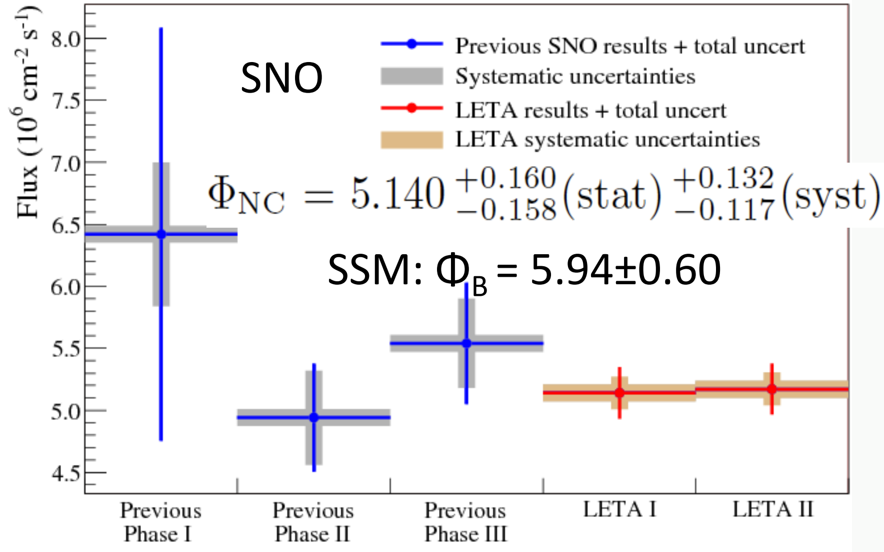


arXiv: Hep-ph/0609011v1

See more details in Mark's talk yesterday

Solar Neutrino

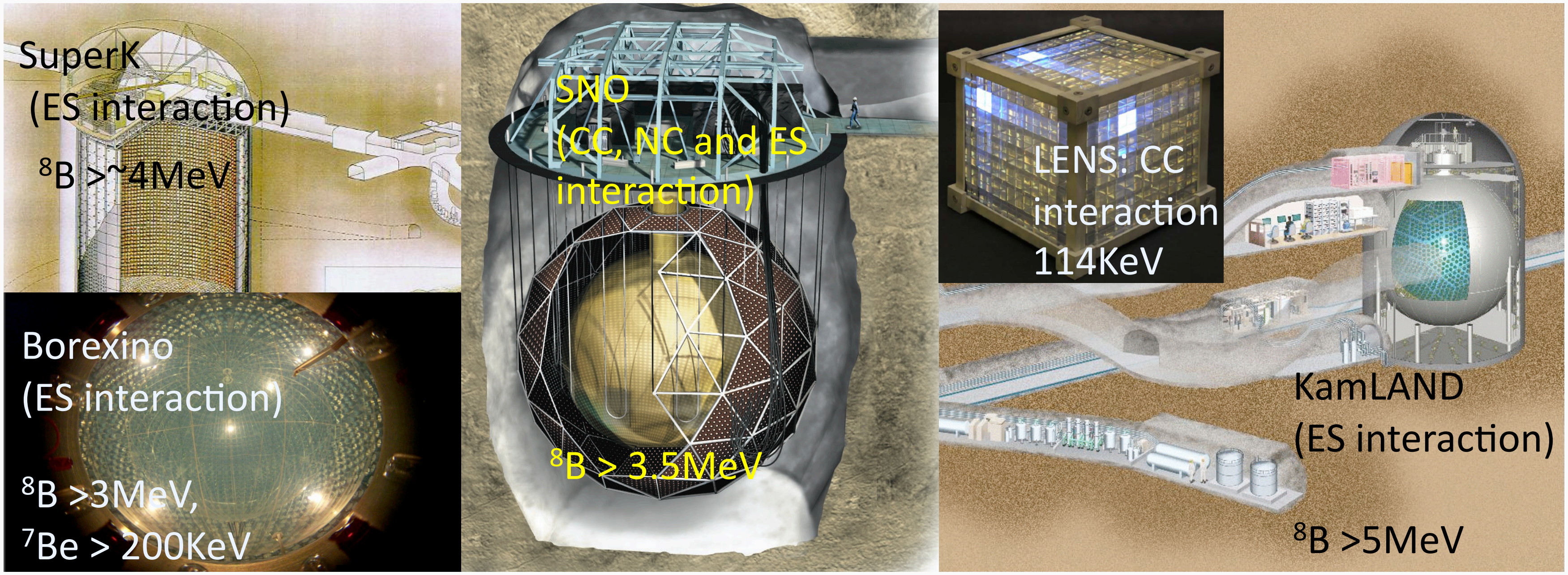




SNO

$$\Phi_{NC} = 5.140 ^{+0.160}_{-0.158}(\text{stat}) ^{+0.132}_{-0.117}(\text{syst})$$

SSM: $\Phi_B = 5.94 \pm 0.60$



SuperK
(ES interaction)
^{8}B >~4MeV

Borexino
(ES interaction)
^{8}B >3MeV,
^{7}Be > 200KeV

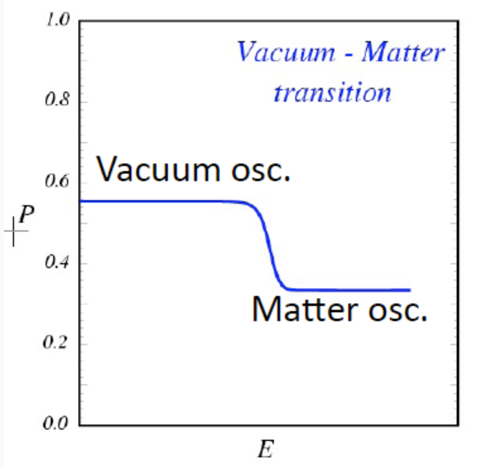
SNO
(CC, NC and ES interaction)
^{8}B > 3.5MeV

LENS: CC
interaction
114KeV

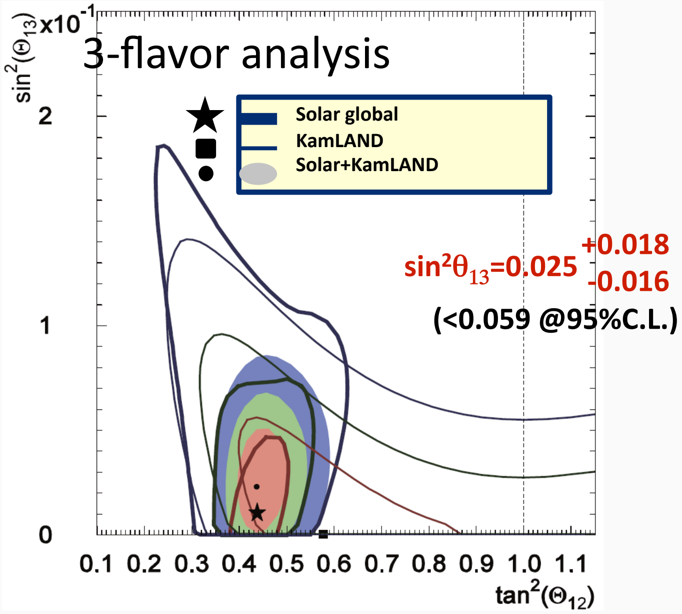
KamLAND
(ES interaction)
^{8}B >5MeV

Solar Neutrino Experiments

- Further study of matter-enhanced oscillation
  - Low E neutrino: vacuum-matter transition
  - Spectrum distortion: matter effect in the sun
  - Day/night asymmetry: matter effect in the earth
- Improvement in precision of mixing parameters
  - Solar (+KamLAND) supply constrain on θ_{13}
  - More precise measurement on solar parameters.
- Further information on Solar Models

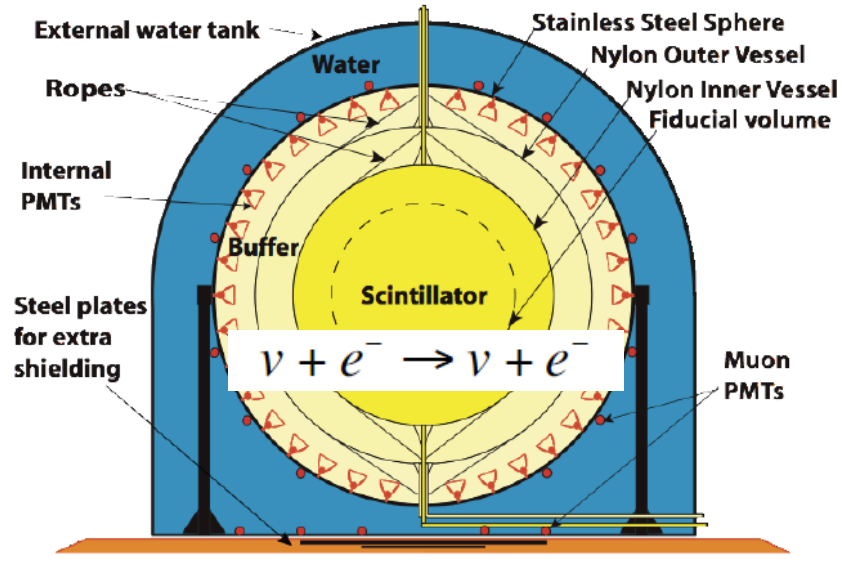


Y. Takeuchi, Neutrino2010



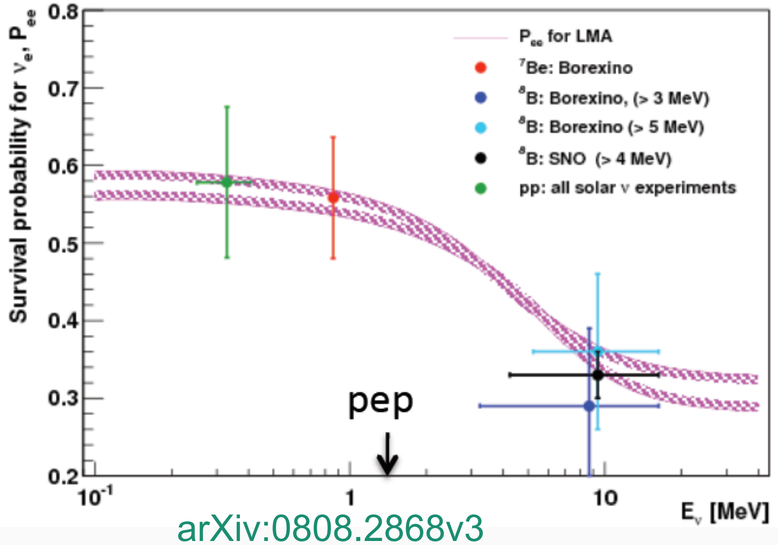
Borexino

Liquid Scintillator Detector



$$\nu + e^- \rightarrow \nu + e^-$$

Detected ^{7}Be(vacuum) and ^{8}B(mass) in same detector



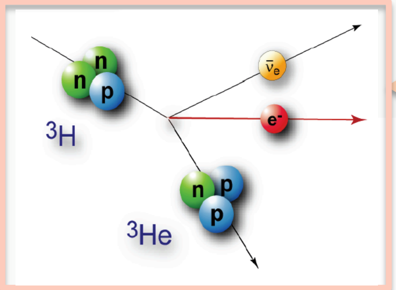
arXiv:0808.2868v3

- 100t (fiducial volume) liquid scintilaltor Detector for sub-MeV solar neutrinos
- Low threshold: 200KeV
- Ultralow background: a few tens cpd/100t, it's a few 10^{-9}Bg/kg
  - 3800m (mwe) depth in LNGS, and ultra-clean liquid scintillator
- Day/night asymmetry from ^{7}Be
  - A_{ND}=2(N-D)/(N+D)=0.007±0.073(stat.) No obvious day/night asymmetry.
- pp-chain flux in SSM only has 1% uncertainty: improve the precision of solar mixing parameters. Flux measurement of pep, CNO, pp….

See more details in Michael's talk yesterday

Neutrino Mass

Beta Decay

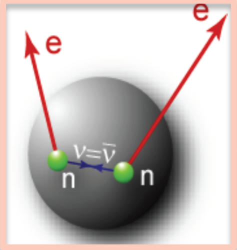


$$m_{\nu_e}^2 = \sum_i |U_{ei}|^2 \cdot m_{\nu_i}^2$$

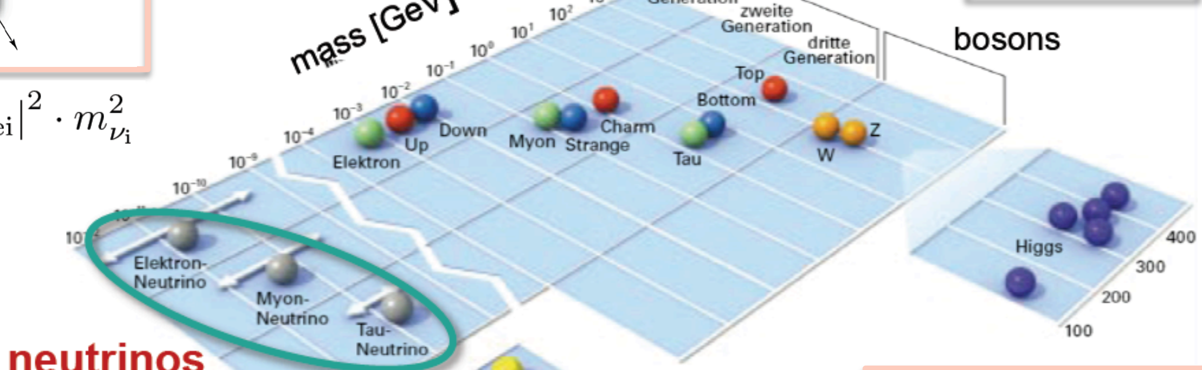
$m_\nu < 2.3$eV

$m_{\beta\beta} < 0.35$eV, evidence?

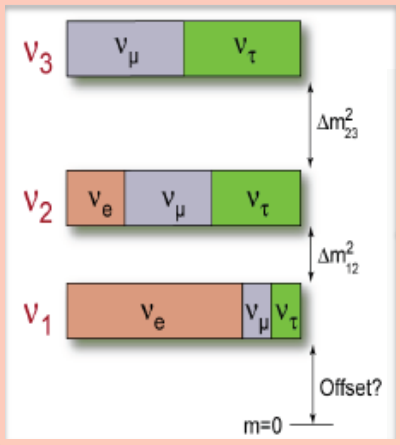
Double Beta Decay



$$m_{\beta\beta} = \left| \sum_i U_{ei}^2 \cdot m_{\nu_i} \right|$$



Neutrino Oscillation

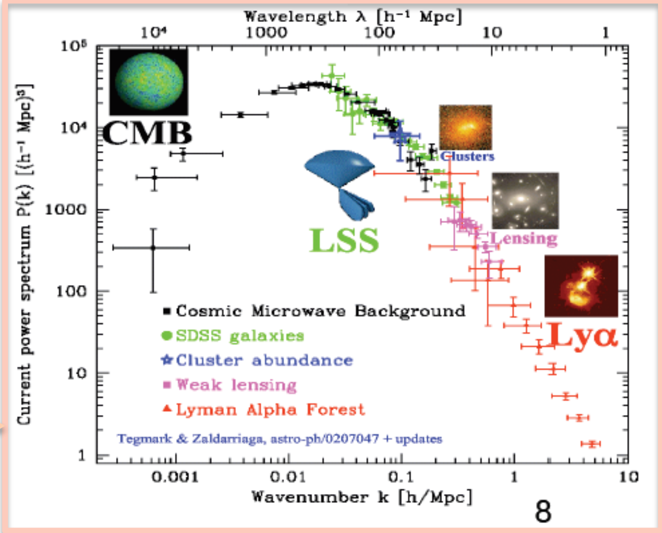


0.04eV ($\sqrt{\Delta m^2_{atm}}$)< m (heaviest ν_i)

$m_1 + m_2 + m_3 < (0.4\text{-}1.0)$eV

$$\Omega_\nu h^2 = \frac{\Sigma m_\nu}{93.2eV}$$

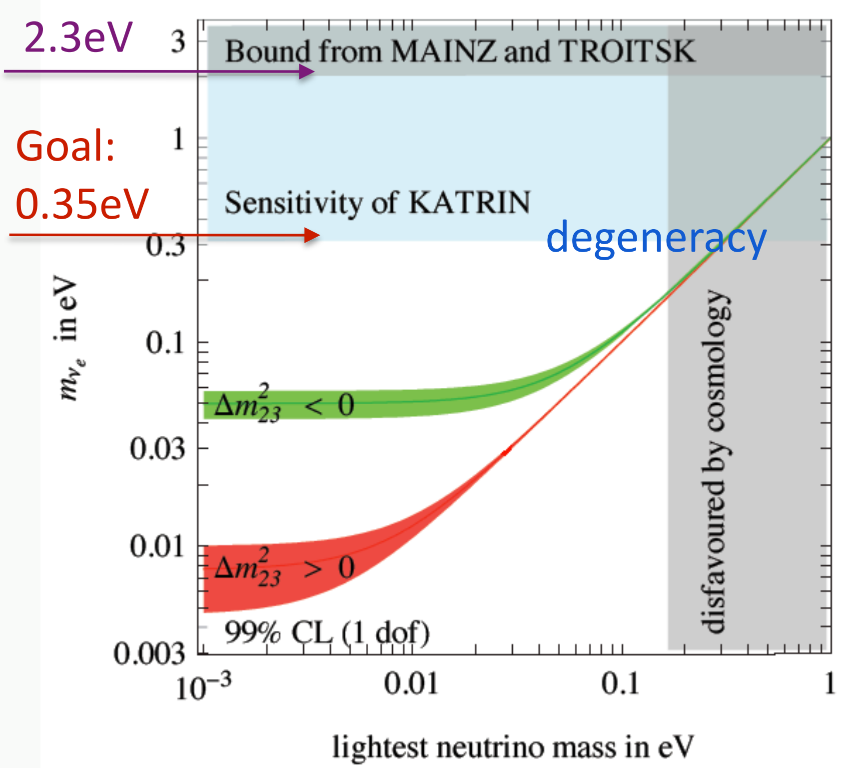
Cosmology



Mass Measurement

Beta Decay

- Model independent
  - Majorana or Dirac, CP phase
  - Nuclear matrix element
- Squared neutrino mass (absolute)
- Current discovery potential: degeneracy



2.3eV

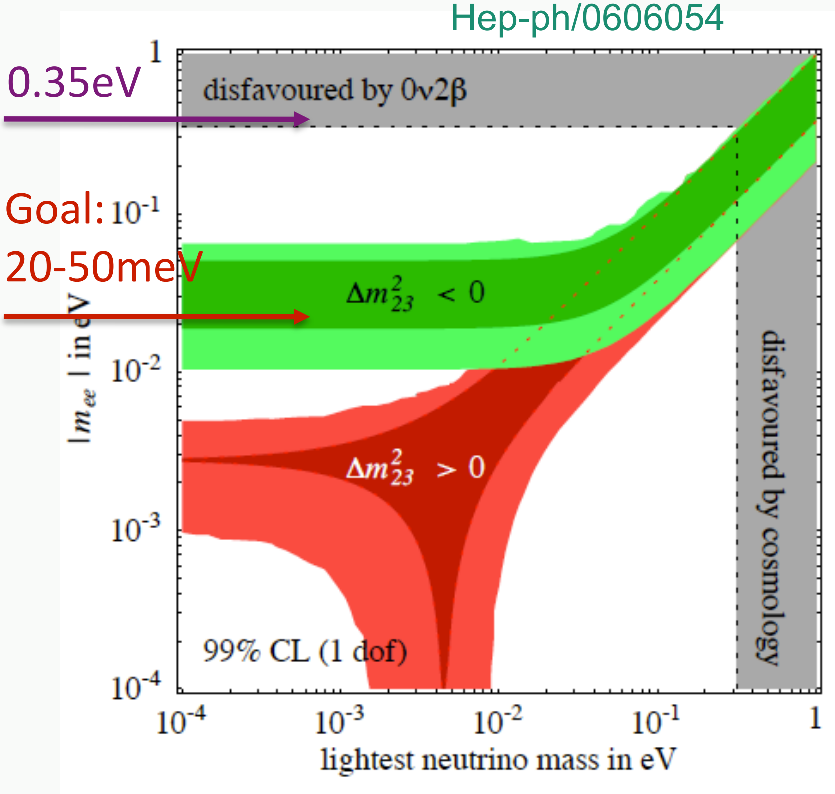
Goal: 0.35eV

degeneracy

0νββ Decay

- Model dependent
- Majorana neutrino
- Effective neutrino mass
- Current discovery potential: IH

Hep-ph/0606054



0.35eV

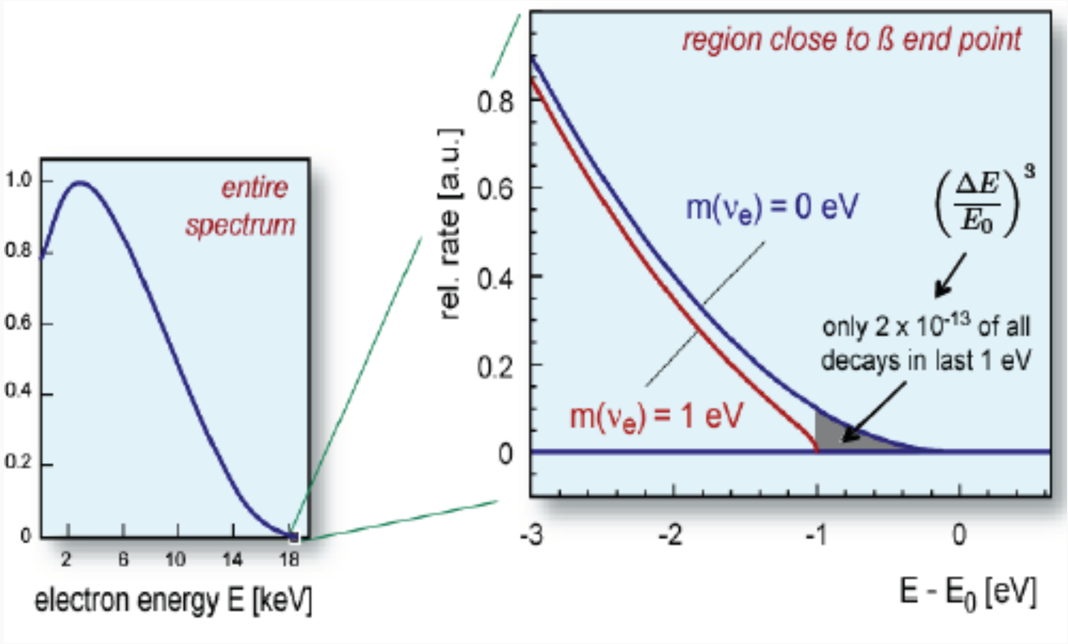
Goal: 20-50meV

Beta Decay

Model-Independent Measurement: Kinematics and energy conservation

$$\frac{\mathrm{d}\Gamma_i}{\mathrm{d}E} = C \cdot p \cdot (E + m_e) \cdot (E_0 - E) \cdot \sqrt{(E_0 - E)^2 \underbrace{- m_i^2}_{(\nu-\text{mass})^2}} \cdot F(E,Z) \cdot \theta(E_0 - E - m_i)$$

If $m_\nu \neq 0$: shift the endpoint and change the shape

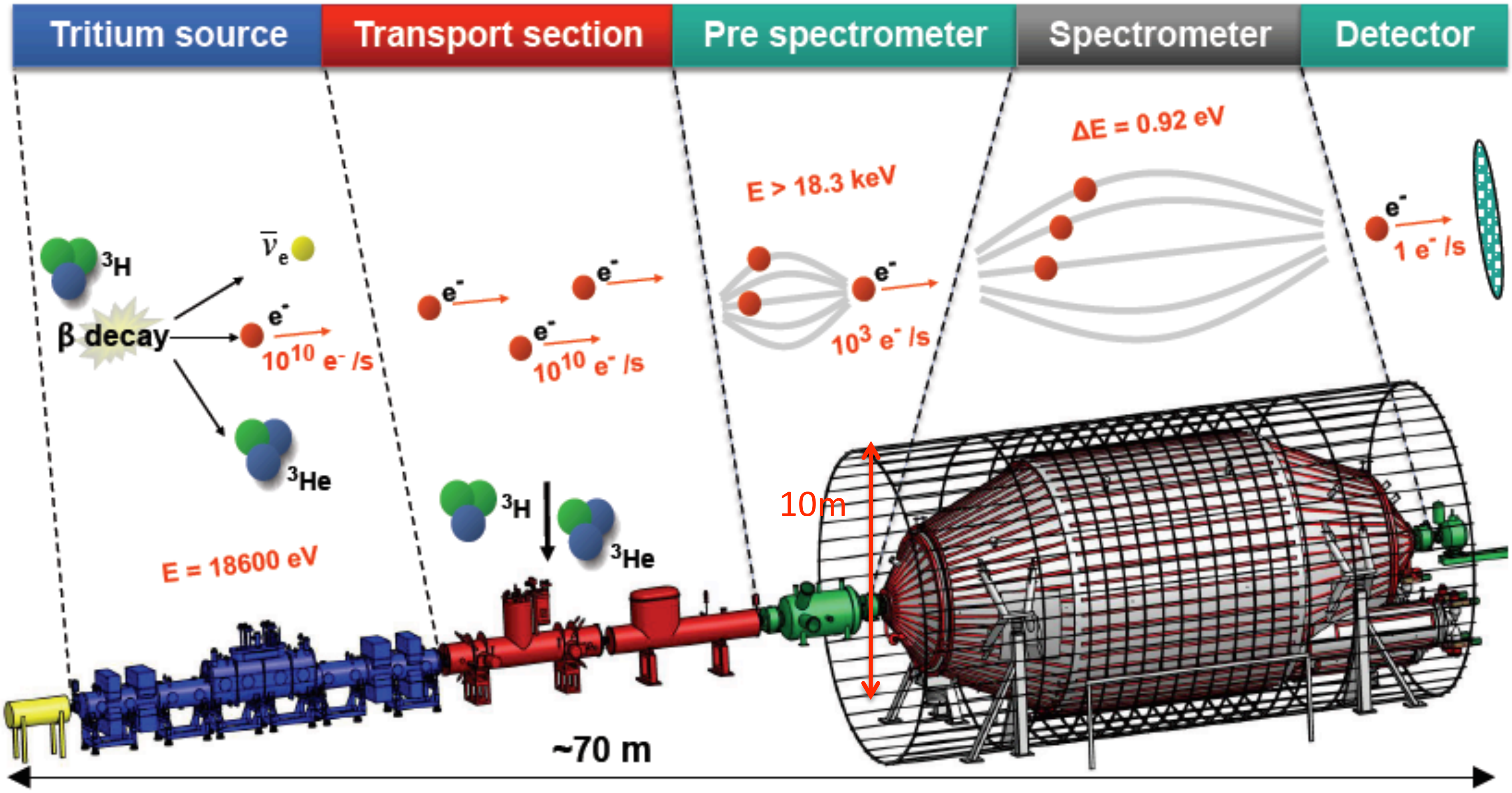


Measure the region close to endpoint:

- ✓ Low endpoint beta source
- ✓ High count rate
- ✓ High energy resolution
- ✓ Extremely low background

KATRIN

Tritium source, endpoint 18.6KeV, $t_{1/2}$ 12.3y, high activity 10^{11}β/s



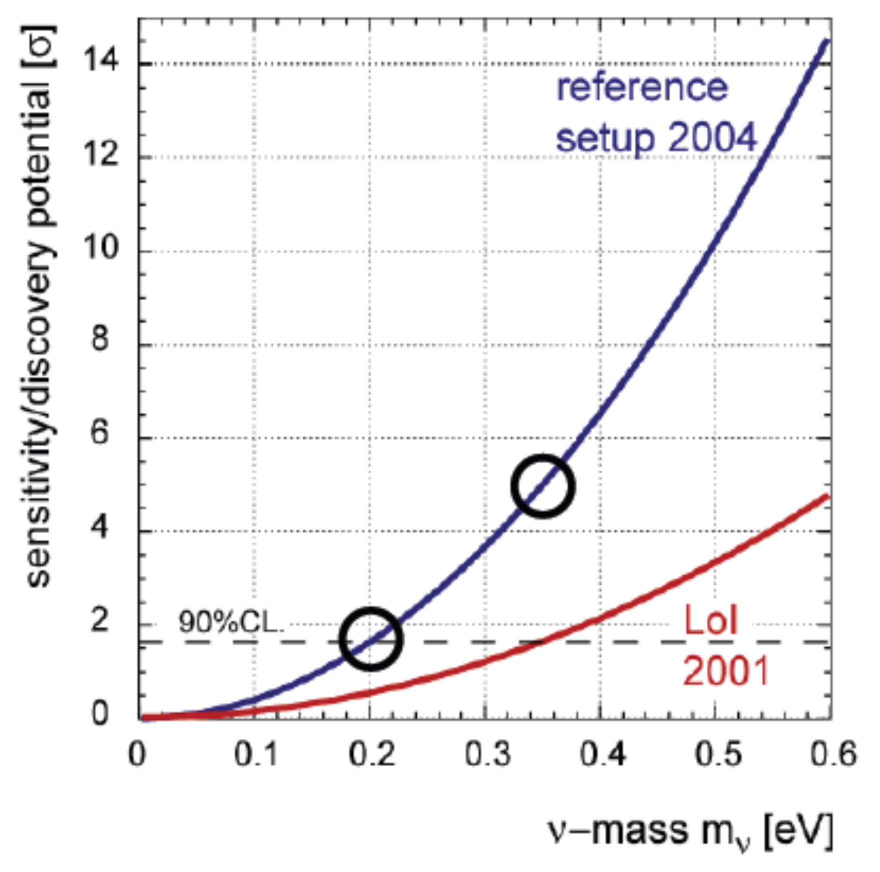
Schedule: Start main spectrometer test in 2011,

Commissioning of completed setup in 2012.

KATRIN Sensitivity

T. Thümmer, Neutrino2010

Three years data taking (5 years real time)



HyperKATRIN: 300m diameter

Discovery potential:

$m_\nu = 0.35\text{eV}$ (5σ)

Sensitivity:

$m_\nu < 0.2\text{eV}$ (90% C.L.)

$$\Delta m^2_{tot} = (\ \Delta m^4_{stat} + \Delta m^4_{stat}\ )^{1/2}$$
$$\approx 0.025\ \text{eV}^2/\text{c}^4$$

Limit of KATRIN:

Source and detector are separate

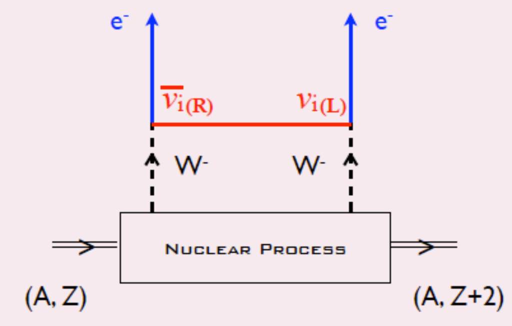
MARE experiment

(^{187}Re, endpoint 2.47KeV, $t_{1/2}$ 4.32×10^{10}y):

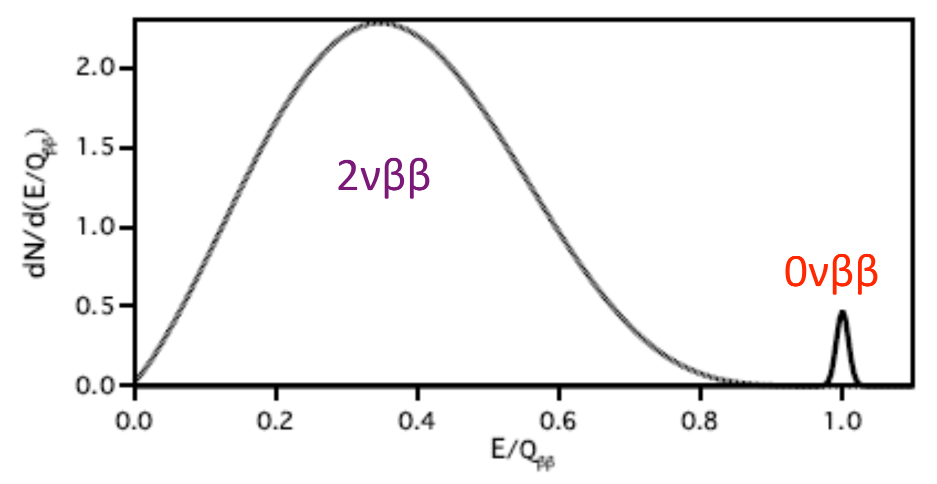
Use bolometer technology, source is detector. MARE2: ~0.2eV

Neutrinoless Double Beta Decay

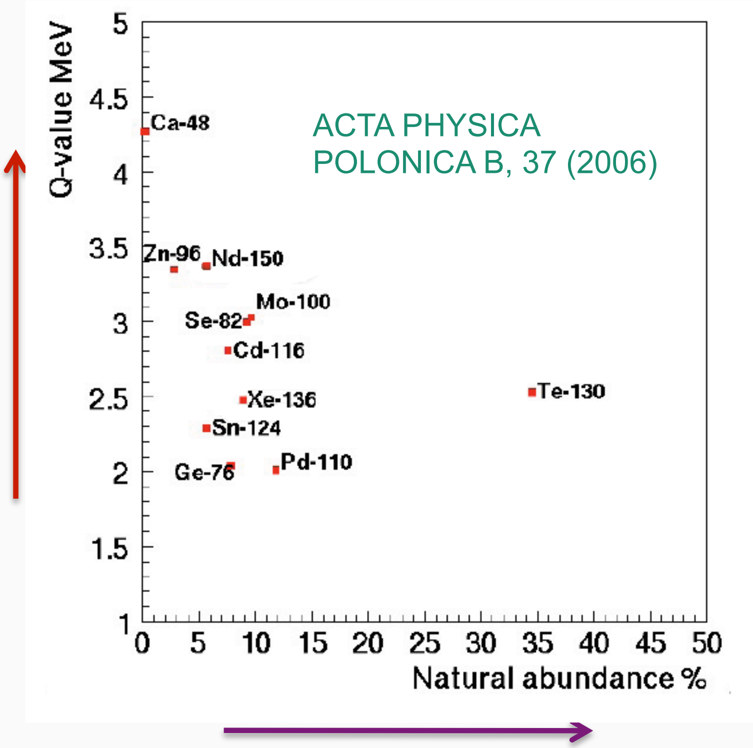
- 0νββ: ΔL≠0, lepton number violation.
- Standard interpretation: light, massive majorana neutrinos ($\nu = \bar{\nu}$)
- Other machenisms: negligible…
- Even-even nucleus of larger $Q_{\beta\beta}$



$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)|M_{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$



0νββ is strongly suppressed compared to 2νββ



ACTA PHYSICA POLONICA B, 37 (2006)

Neutrinoless Double Beta Decay

Requirement:

- ❑ Source (is detector) mass: ~100kg - ~1ton
- ❑ Extremely low Background: a few cts/keV•t•y
  - ○ Go deep underground, material purification…
- ❑ Good energy resolution
- ❑ Nuclear matrix element uncertainty
  - ○ need several experiments with different nuclei

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)|M_{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

$\sim 10^{27}$ y

20-50 meV

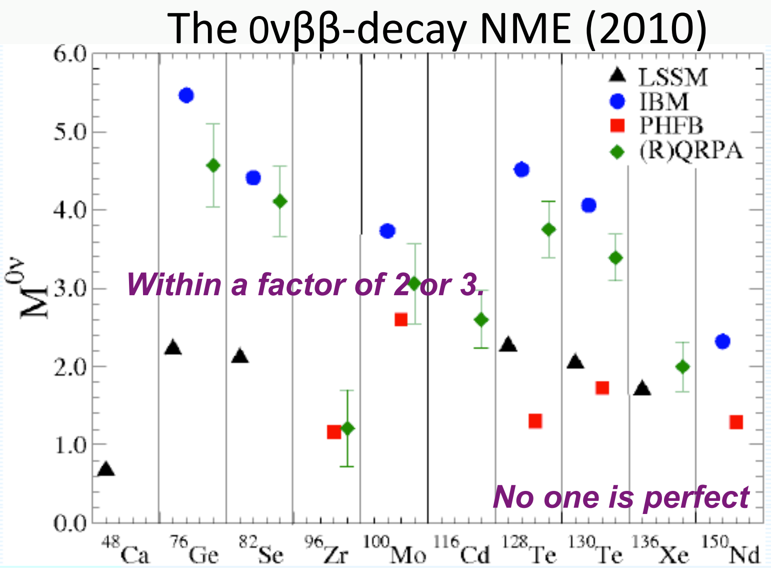
Sensitivity:

$$T^{0\nu}_{1/2} \propto \left(\frac{\epsilon a}{W}\right)\sqrt{\frac{Mt}{b\Delta(E)}}$$

t: year

M: mass

b: background, *Δ(E):* energy resolution

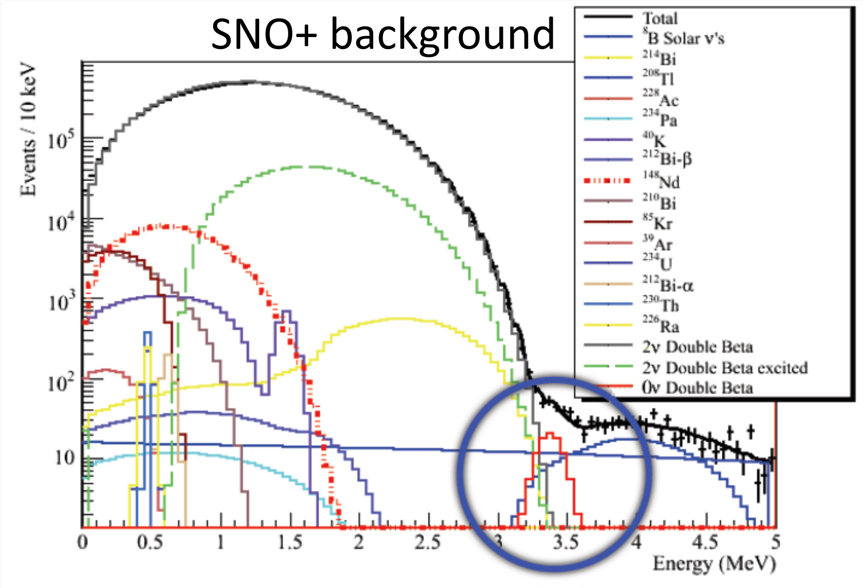


The 0νββ-decay NME (2010)

Within a factor of 2 or 3.

No one is perfect

F. Šimkovic, Neutrino2010



SNO+ background

K. Nakamura, Neutrino2010

0νββ Decay Experiments

Name	**Isotope**	**Technique**	**Mass**	**Location**	**Sensitivity**	**Time**
CUORICINO	Te-130	Bolometer	11kg	LNGS	0.40eV	2003 - 2008
CUORE	Te-130	Bolometer	200kg	LNGS	0.22eV	2013 -
COBRA	Cd-116 …	Semiconductor	183kg	LNGS		
GERDA I/II	Ge-76	Semiconductor	18/40kg	LNGS	75-129meV	2009 (comiss.)
Majorana	Ge-76	Semiconductor	30kg	DUSEL	20-41meV	2011 -
NEMO-3	Mo-100 ..	Tracking-calo	7kg	LSM	0.3-0.9eV	till 2010
SuperNEMO	Se-82 …	Tracking-calo	100+kg	LSM	40-110meV	2013 -
SNO+	Nd-150	Scintillator	44kg	SNOlab	150meV	2012 -
KamLAND-Zen	Xe-136	Scintillator	400kg	Kamioka	60meV	2011 -
CANDLES III	Ca-48	Scintillator	305kg	Kamioka		
EXO-200	Xe-136	Liquid TPC	200kg	WIPP	109-135meV	2009 (comiss.)
EXO	Xe-136	Gas TPC	1-10ton	SNOlab		

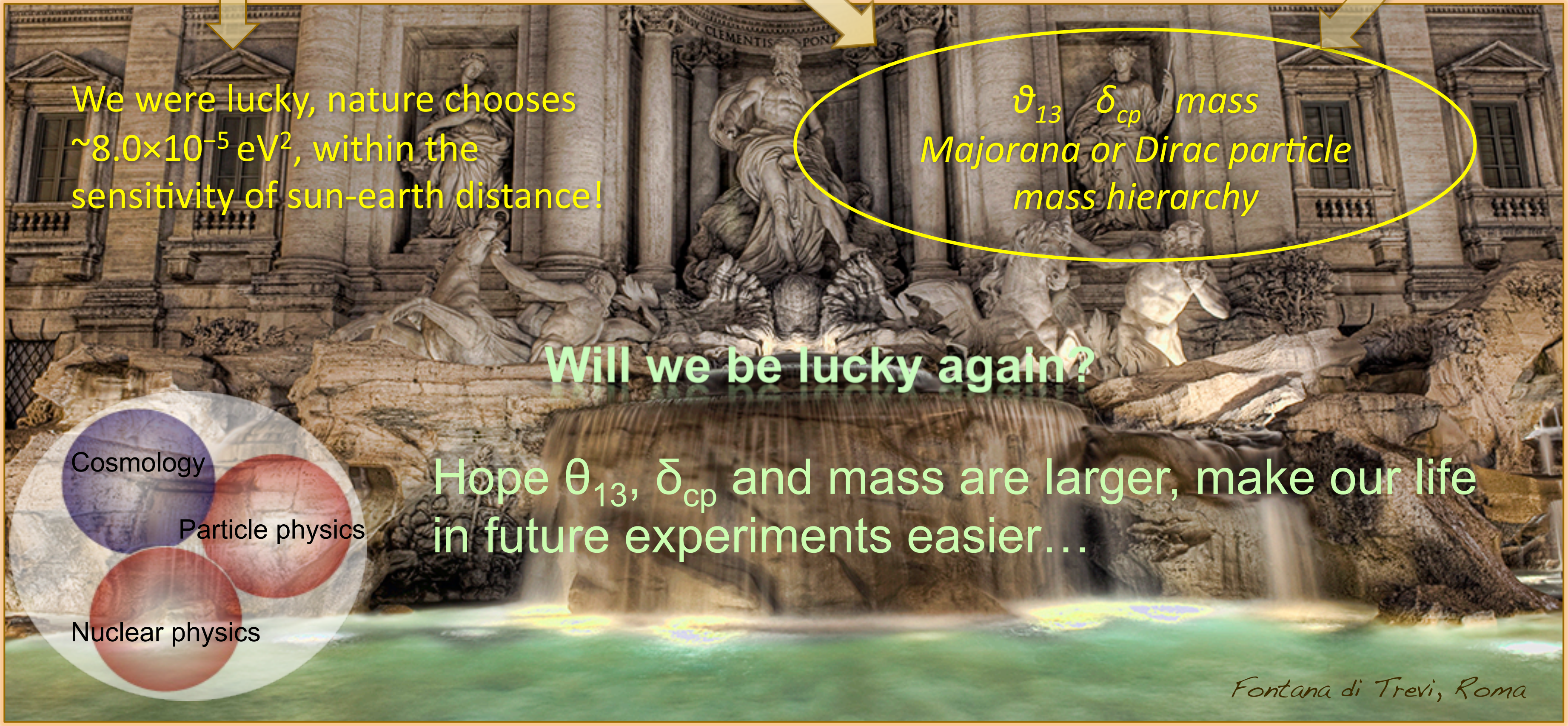
🟪 completed 🟦 construction or preparation 🟨 R&D

And some other experiments…

1930, Pauli: “neutron” for beta decay. 1933, Fermi: neutrino, beta decay theory.
➔ 1956: Cowan & Reines, $\bar{\nu}_e$. 1962: Schwartz et al. ν_μ. 2000: DONUT, ν_τ

1957, Pontecorvo: $\nu - \bar{\nu}$
1962, Maki, Nakagawa and Sakata: $\nu_\alpha - \nu_\beta$
➔ 1968, Davis – 2002, SNO: solar ν oscillation
1998, SuperK – 2004, K2K: atoms. ν Oscilla.

1936, Gamow & Teller: spin flip. 1937, Majorana: $\nu = \bar{\nu}$. 1958, Goldhaber et al.: ν_L
1959, Primakoff & Rosen (1938 Furry): $0\nu\beta\beta$ decay ➔?



We were lucky, nature chooses ~8.0×10^{-5} eV^2, within the sensitivity of sun-earth distance!

ϑ_{13} δ_{cp} mass
Majorana or Dirac particle
mass hierarchy

Will we be lucky again?

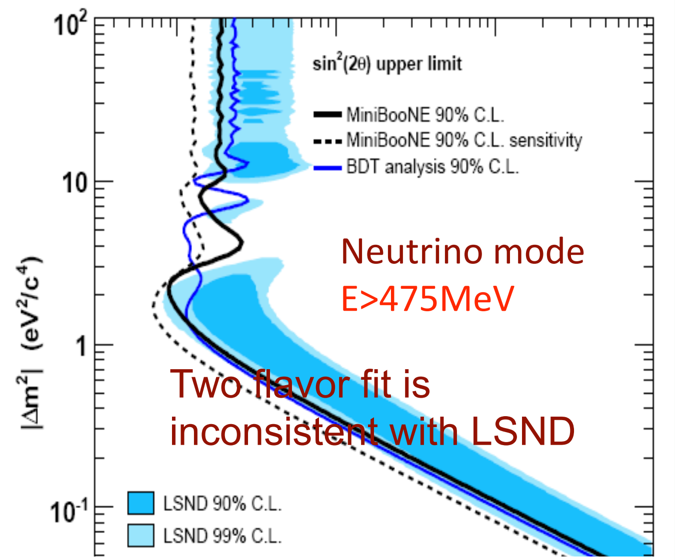
Hope θ_{13}, δ_{cp} and mass are larger, make our life in future experiments easier…

Fontana di Trevi, Roma

Backup

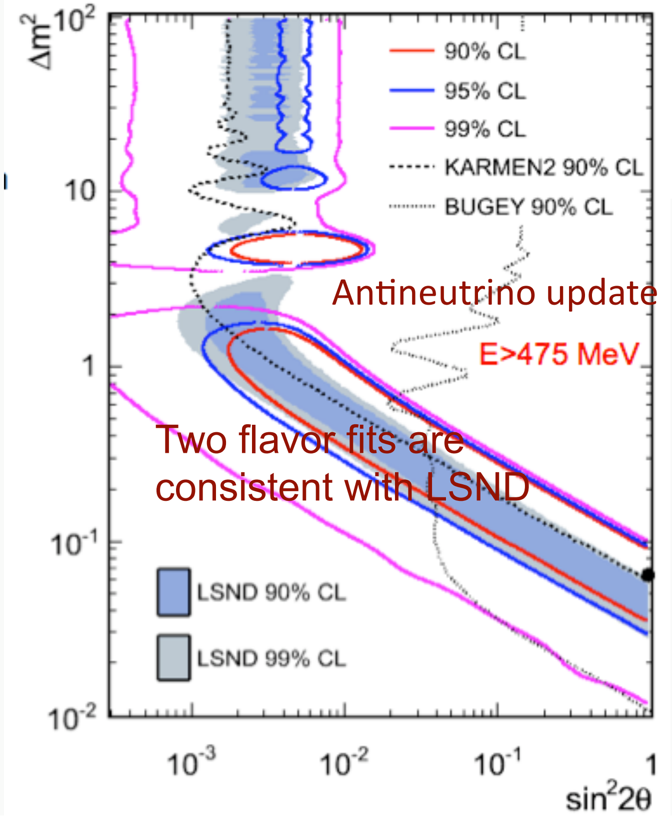
LSND Anomaly

- LSND: $|\Delta m^2|$~$1eV^2$ (L~30m, E~30MeV) inconsistent with solar and atmospheric results. Sterile neutrino?
- MiniBoone was designed to test LSND signal.
  - Same L/E (L~500m, E~500MeV).
  - Different systematic, energy, and event signature.
  - E<475MeV: electron-like events excess.
  - MiniBoone is running to improve statistics.
- MicroBoone at FNAL is following on.
- MINOS NC event rate is not diminished (f_s<0.22 (NH, 90%CL)), disfavored sterile neutrino appearance.
- Solar neutrino experiments: may detect sterile neutrino in pp-chain after θ_{13}.



Neutrino mode
E>475MeV

Two flavor fit is
inconsistent with LSND



Antineutrino update
E>475 MeV

Two flavor fits are
consistent with LSND