Neutrino Experiments: Status and Perspectives

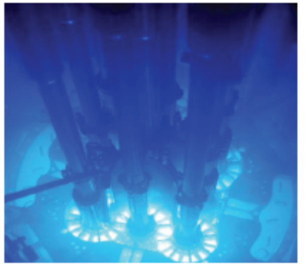
Weili Zhong 钟玮丽
Lawrence Berkeley National Laboratory

LHEP2010 – Nanning, Guangxi

11-18-2010

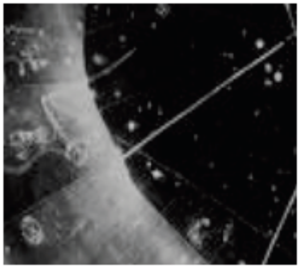
Introduction

- Neutrino mixing



θ_{13} and reactor neutrino experiments

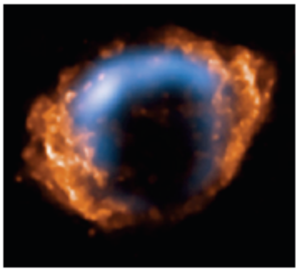
θ_{13}, δ_{cp}, mass hierarchy and accelerator neutrino experiments



LSND and sterile neutrino

Solar neutrino experiments

Cosmogenic neutrino and neutrino telescope



- Neutrino mass

Beta decay experiments

$0\nu\beta\beta$ decay experiments

LHC may help

Neutrino Mixing

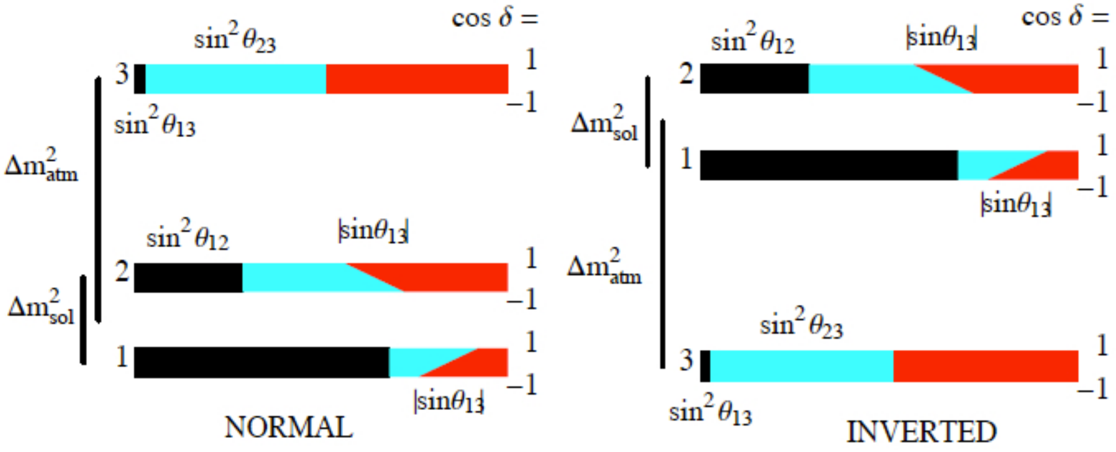
$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle$$

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)

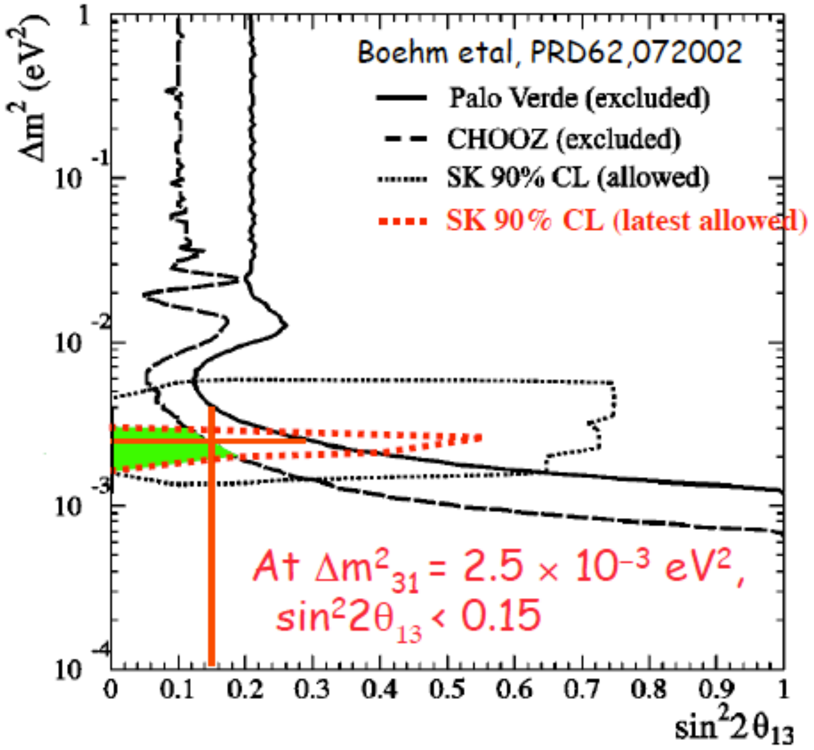
$$\sin^2(2\theta_{12}) = 0.87 \pm 0.03$$
$$\sin^2(2\theta_{23}) > 0.92$$
$$\Delta m^2_{21} = (7.59^{+0.19}_{-0.21}) \times 10^{-5}\mathrm{eV}^2$$
$$|\Delta m^2_{32}| = (2.43 \pm 0.13) \times 10^{-3}\mathrm{eV}^2$$



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

Last Unknown Mixing Angle θ_{13}

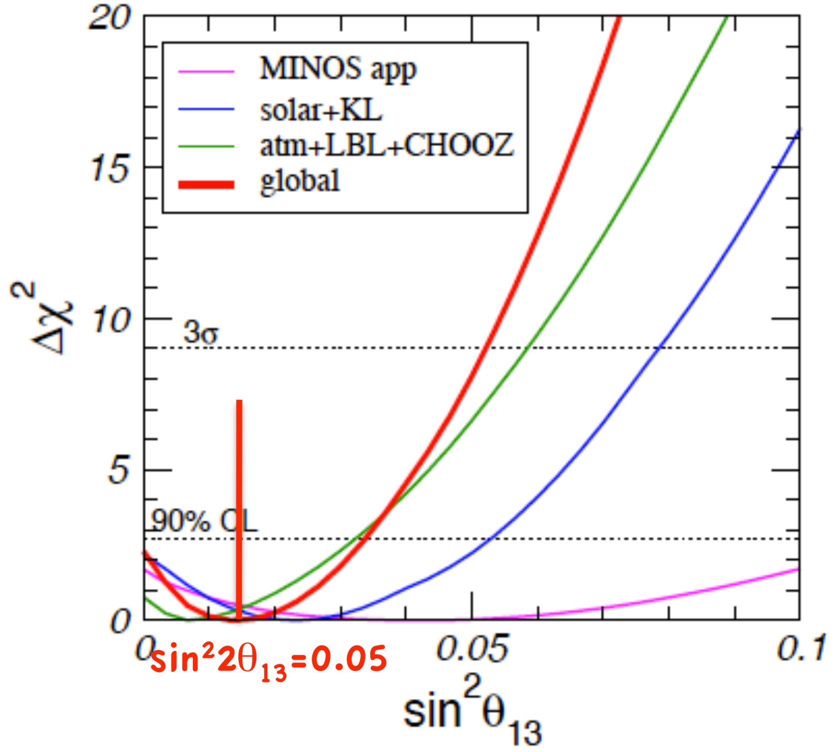
Experiment limit



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

Global fitting

arXiv: 0808.2016v3

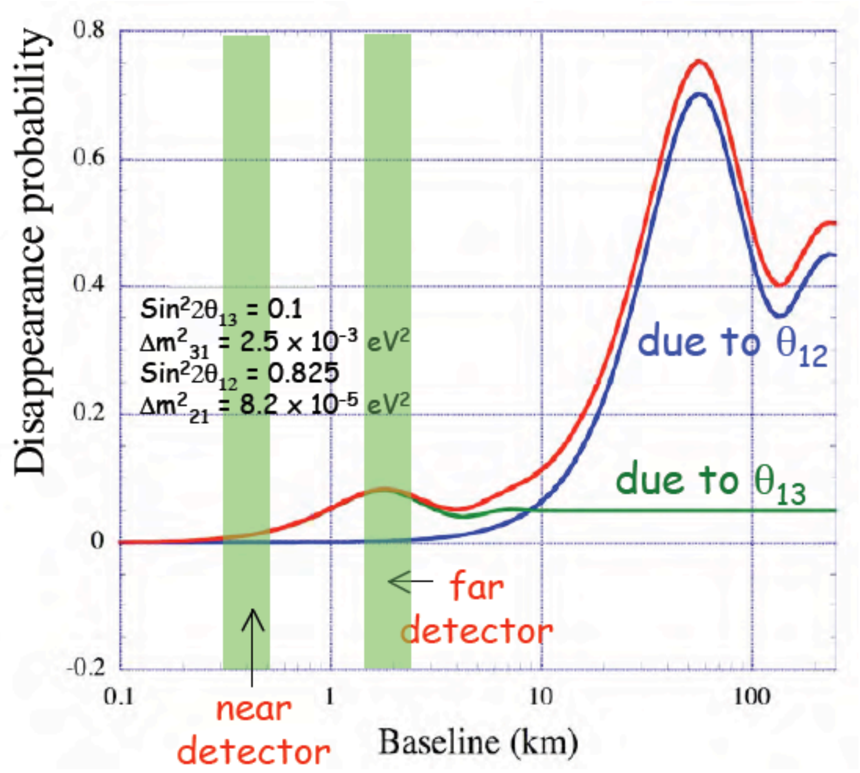


$\sin^2 2\theta_{13}=0.05$

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

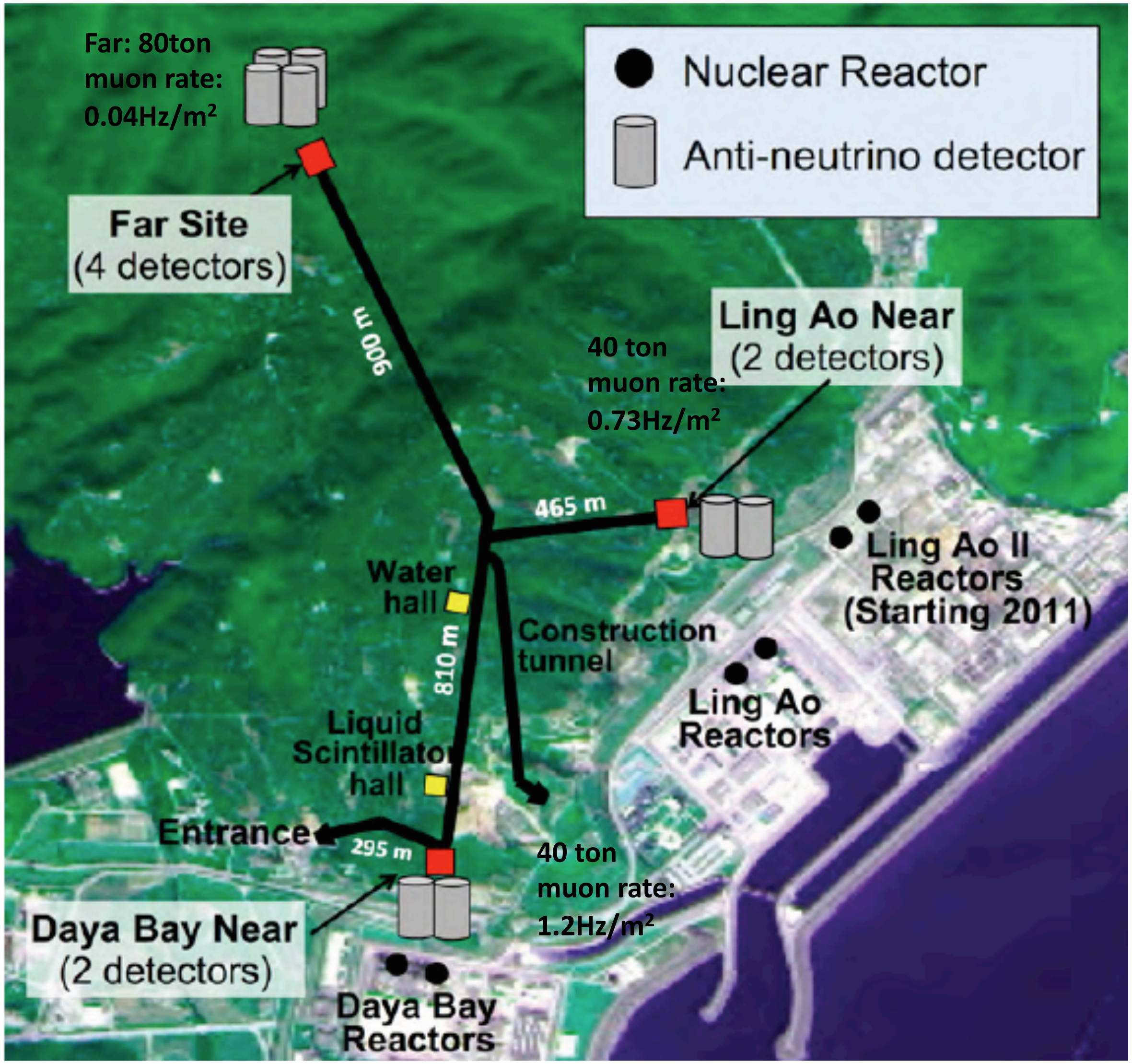
θ_{13} in Reactor Neutrino Experiment

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



- 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.

Daya Bay



Powerful reactors (increase statistics)

- 4 cores 11.6 GW
- 6 cores 17.4 GW from 2011

simple number:

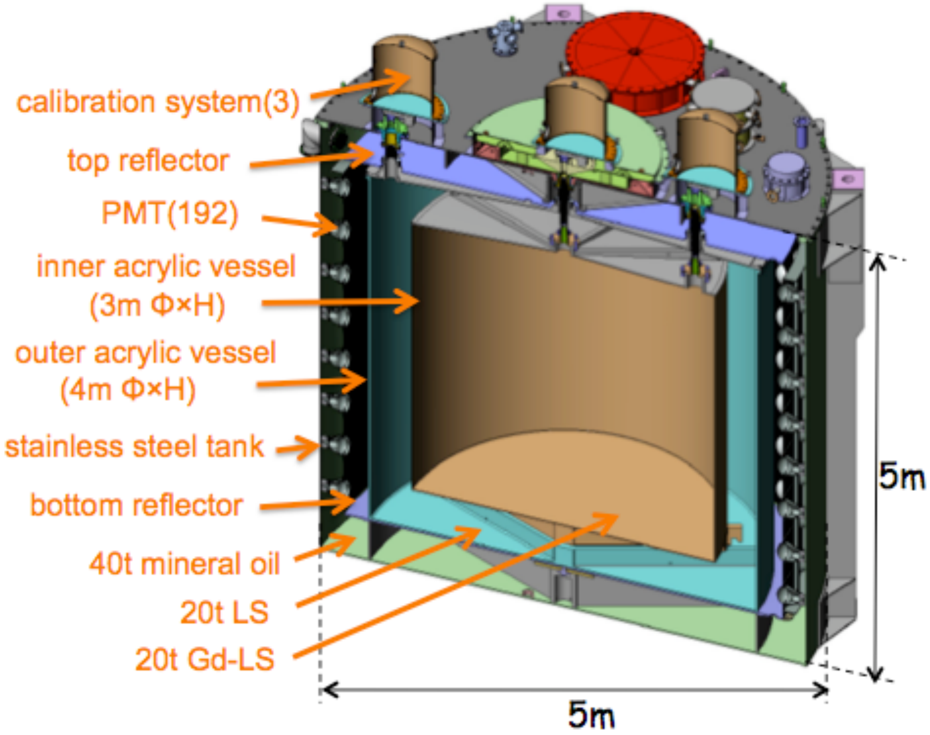
- typical reactor 3GWth
- 6×10^{20} ν/s

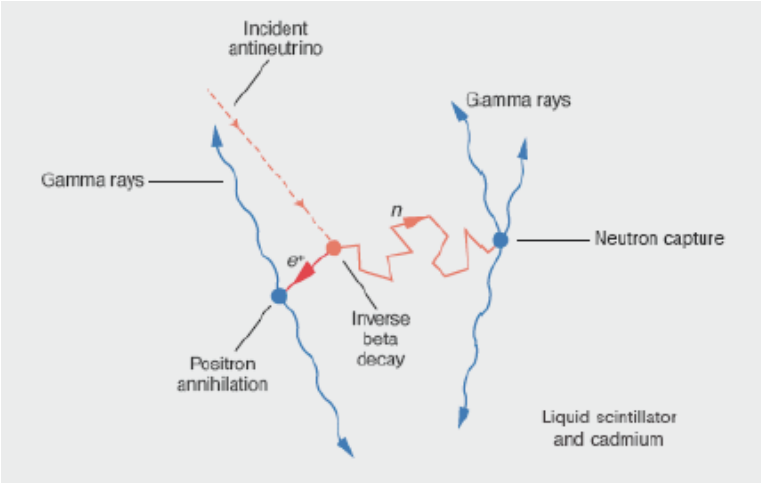
Optimize baseline to place detector

Go deeper underground (suppress background)

Near/Far relative measurement (reduce systematical uncertainties)

Antineutrino Detection





Prompt: e^+ annihilation

Delay: neutron capture

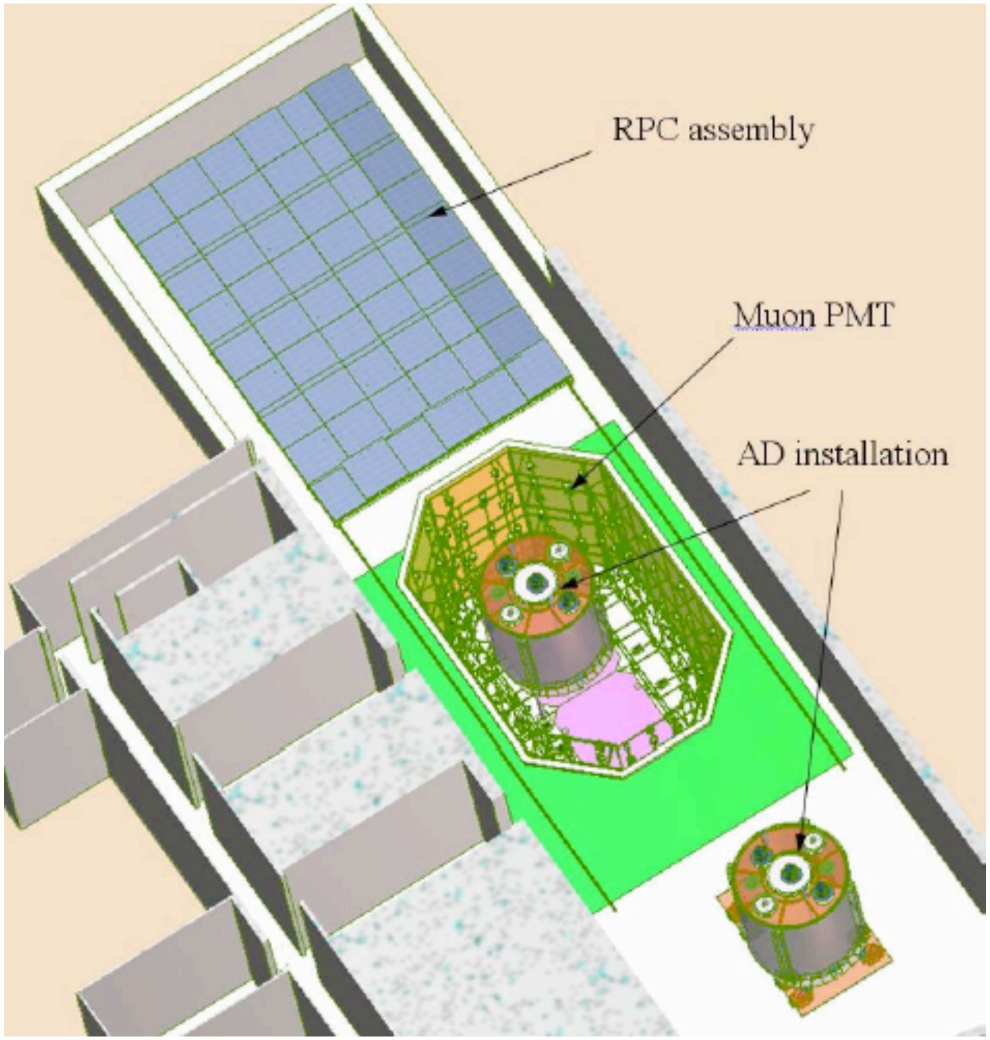
Neutrino events: coincidence in time and energy

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

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

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

Redundant and Efficient Muon System



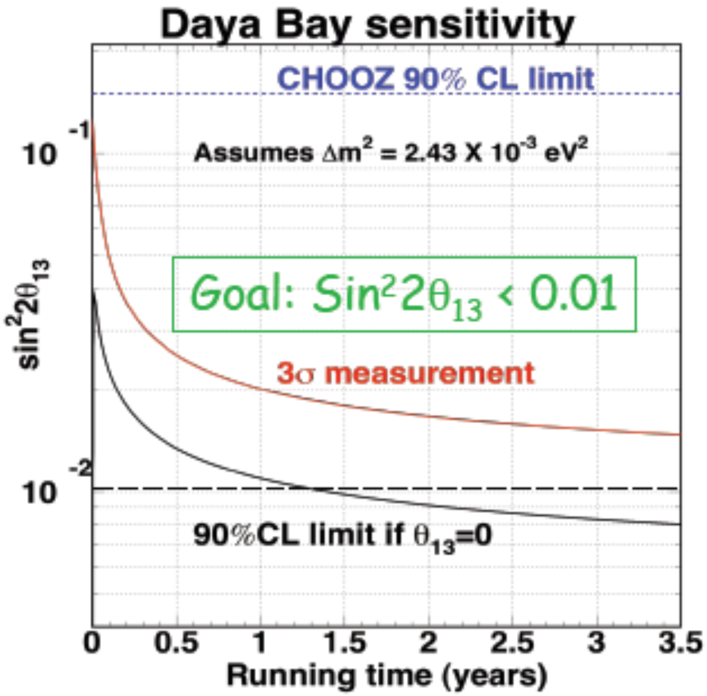
- AD are placed in water pool
  - Surrounded by 2.5m water
  - Shield γ and neutron
- Multiple muon tagging detectors:
  - Water pool serves as Cherenkov detector to tag muon
  - Water pool is optically separated into inner/outer regions
  - Two Layers of Cherenkov detectors to do cross check
  - RPC at the top of water pool serves as muon tracker
  - Combined efficiency

  > (99.5 ± 0.25) %

Sensitivity and Schedule

Expected signal and background rates per antineutrino detector

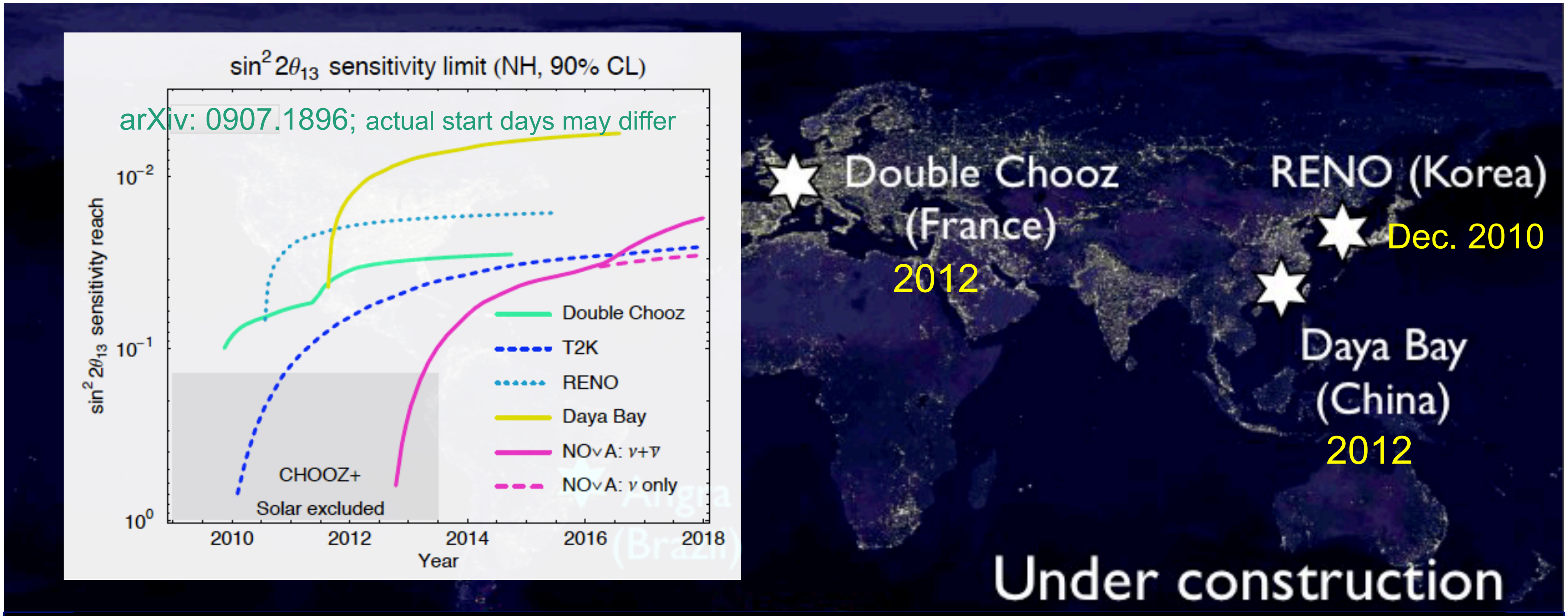
	Daya Bay Near	Ling Ao Near	Far Hall
Antineutrino Signal (events/day)	**840**	**740**	**90**
Overburden (m.w.e.)	260	300	870
Accidental Background/signal (%)	<0.2	<0.2	<0.2
Fast neutron Background/signal (%)	0.1	0.1	0.1
^{8}He/^{9}Li Background/signal (%)	0.3	0.2	0.2



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

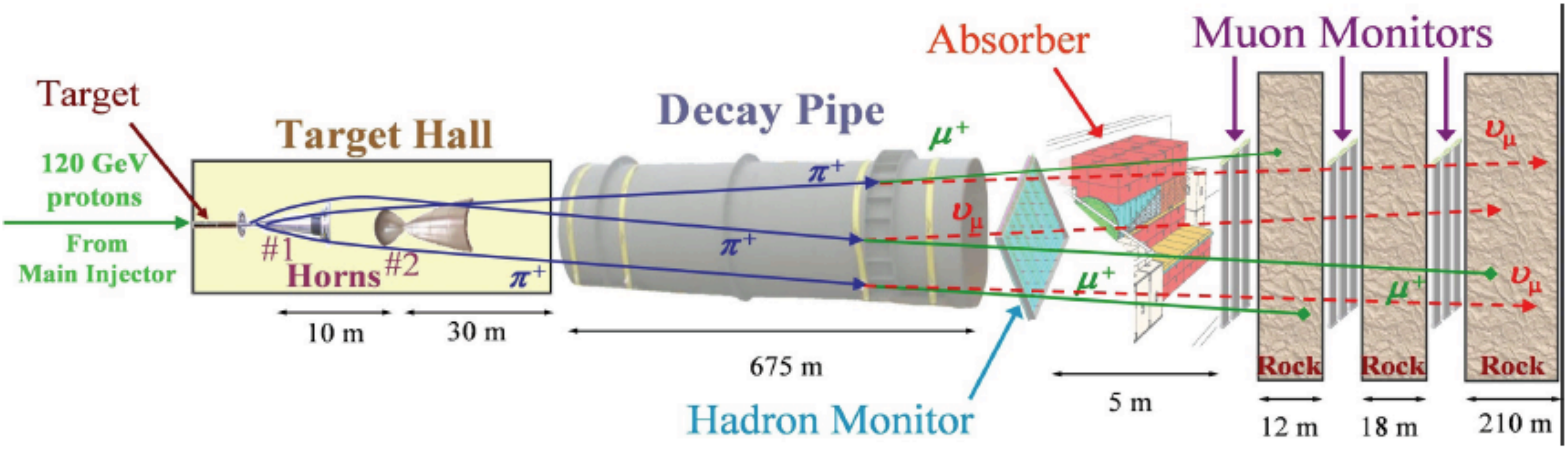
θ_{13} in Accelerator Neutrino Experiment

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

$$
\begin{aligned}
P_{e\mu} \quad & \simeq \quad \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2[(1-\hat{A})\Delta_{31}]}{(1-\hat{A})^2} \\
& \pm \quad \alpha \sin 2\theta_{13} \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \\
& \qquad \times \sin(\Delta_{31}) \frac{\sin(\hat{A}\Delta_{31})}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta_{31}]}{(1-\hat{A})} \\
& + \quad \alpha \sin 2\theta_{13} \cos\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \\
& \qquad \times \cos(\Delta_{31}) \frac{\sin(\hat{A}\Delta_{31})}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta_{31}]}{(1-\hat{A})} \\
& + \quad \alpha^2 \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(\hat{A}\Delta_{31})}{\hat{A}^2} \, .
\end{aligned}
\tag{31}
$$

$$\hat{A} = \frac{A_{CC}}{\Delta m^2} = \pm \frac{2\sqrt{2}\, E\, G_F\, n_e}{\Delta m^2} \, . \qquad \alpha \equiv \Delta m^2_{21}/\Delta m^2_{31} \simeq 0.03$$

Neutrino beam from hadron accelerator



- KEK / NuMI / BooNE / CERN / J-PARC neutrino beams use same basic principles
- Typically fluxes are composed of:
  - ~90+% ν_μ from focused π^+ and K^+ decays
  - ~5% $\bar{\nu}_\mu$ from incompletely defocused π^- and K^- decays
  - ~1% $\nu_e+\bar{\nu}_e$ from μ and K decays

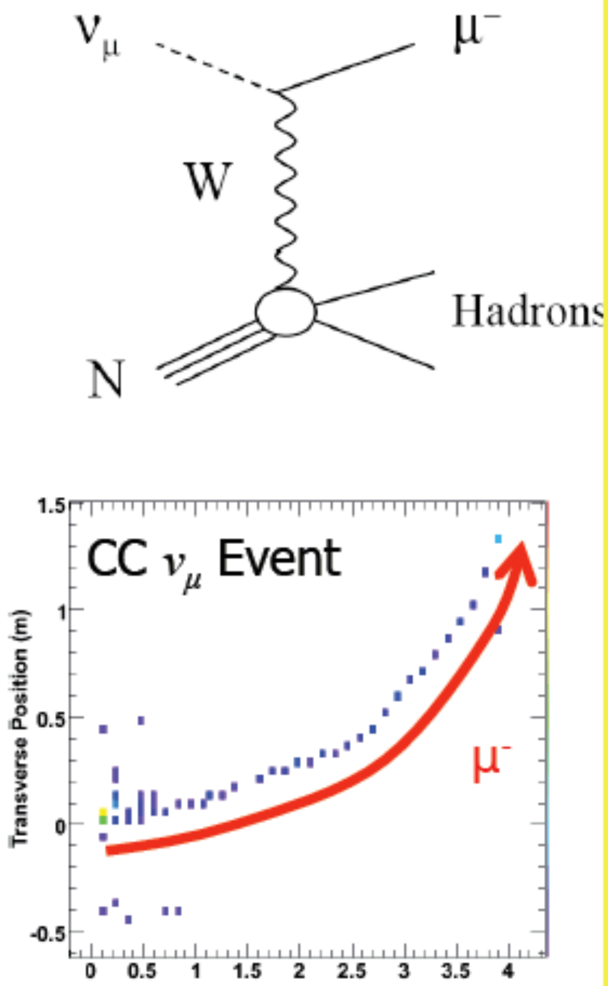
MINOS

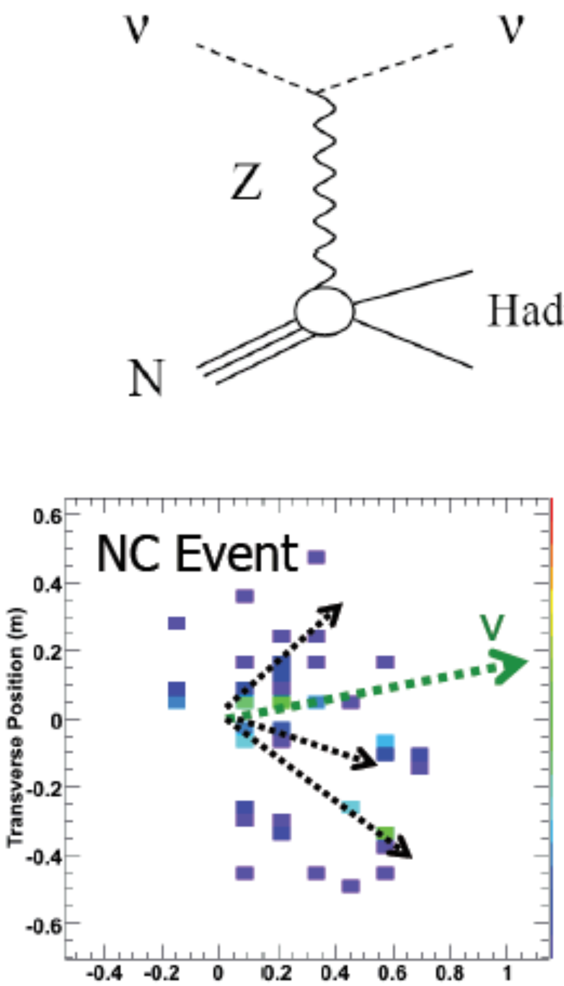
- Tracking sampling calorimeters
  - Steel absorber (2.5cm thick)
  - Scintillator strip (4.1 cm wide)
- Magnetized
  - Muon energy and distinguish μ^+,μ^-

- Functionally equivalent
  - Segmentation
  - Material
  - Mean B field

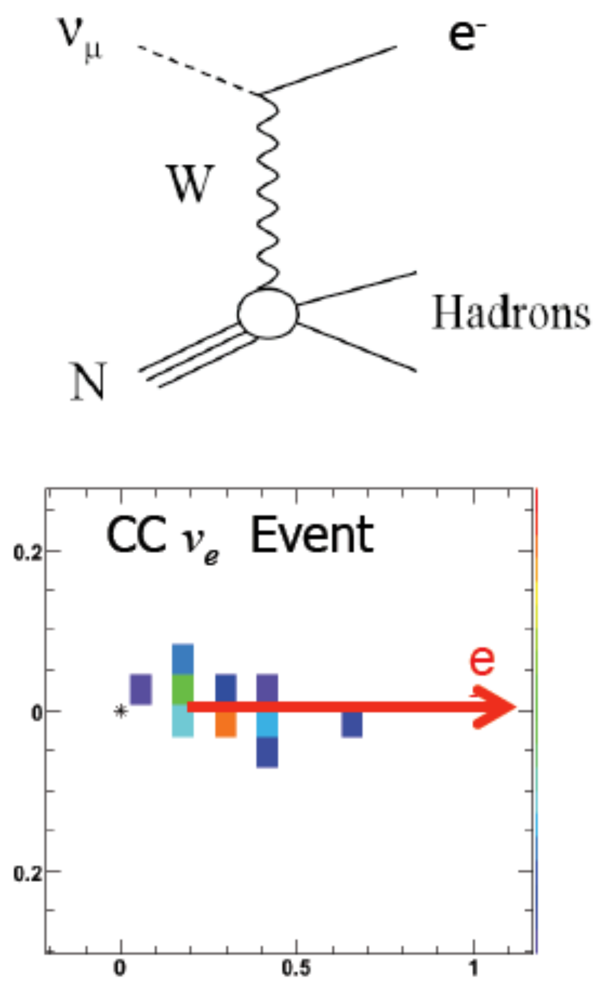
- NuMI beam line at Fermi Lab.
- L/E ~ 500Km/GeV, Δm^2_{atm}
- Two detectors

MINOS Event Topologies

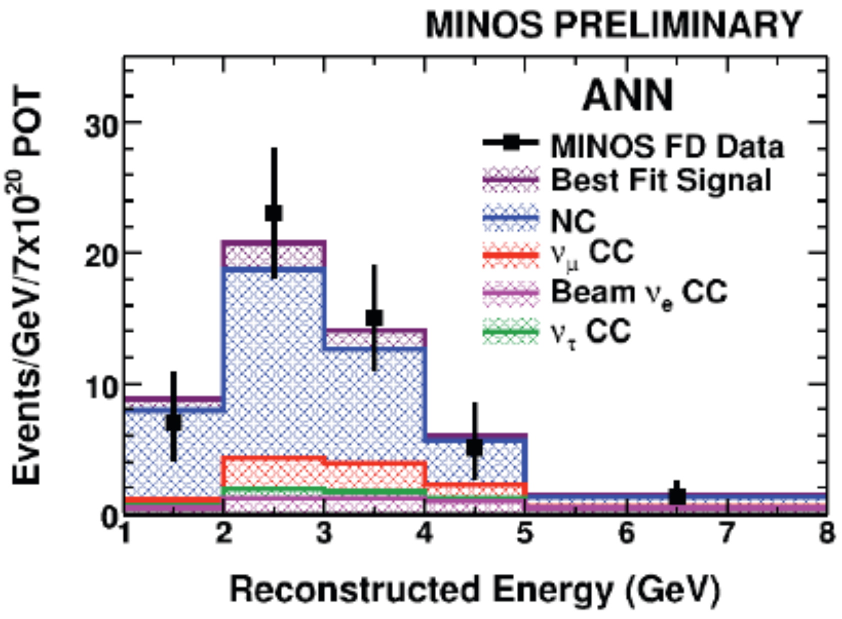




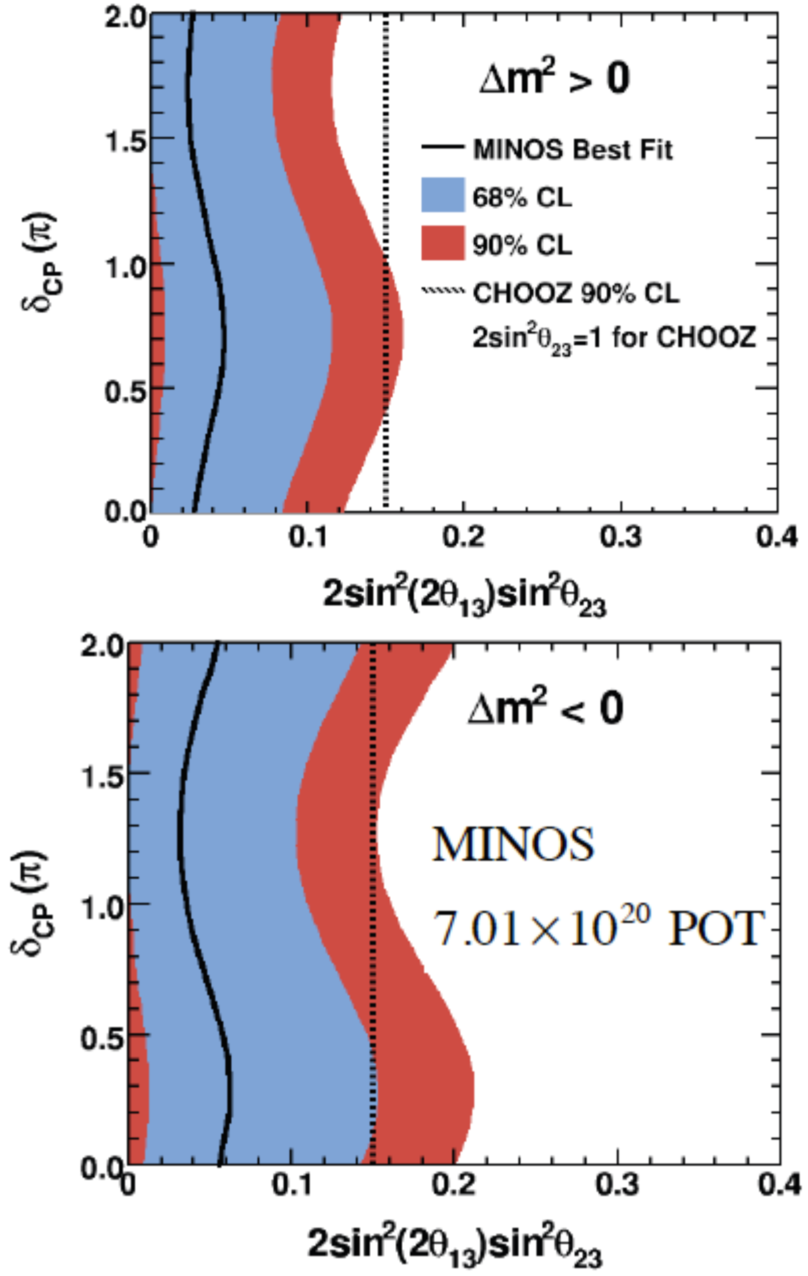
backgrounds



ν_e signal



Phys. Rev. D 82, 051102



For $\delta_{cp}=0$, $\sin^2 2\theta_{23}=1$,
$|\Delta m^2_{32}|=2.43\times10^{-3}\text{eV}^2$:

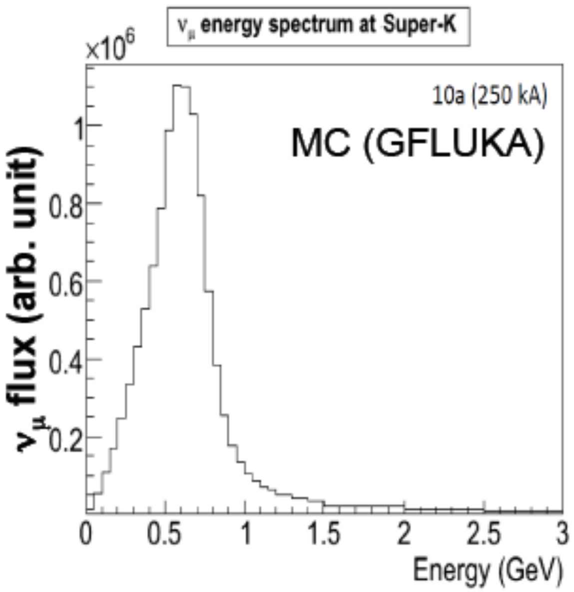
49.1±7.0(stat.)±2.7(syst.) expected

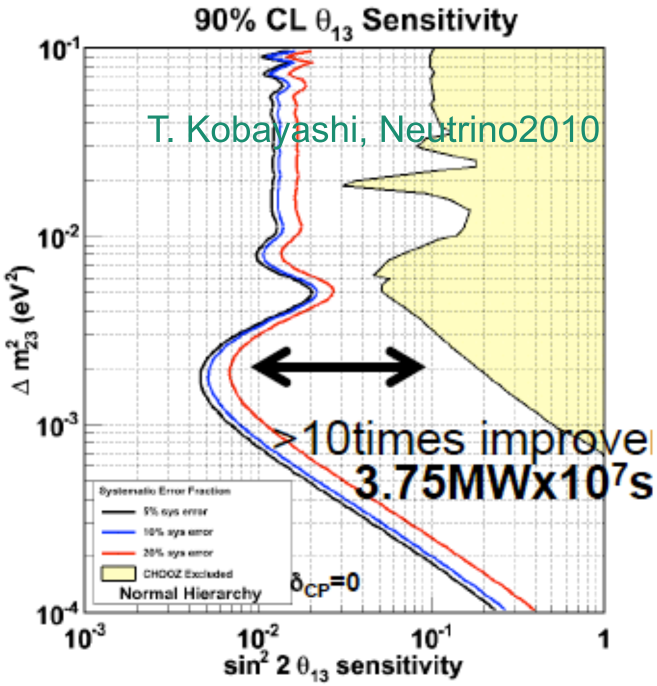
54 observed, a 0.7σ excess.

$\sin^2 2\theta_{13}<0.12$ (NH, 90% C.L.)
$\text{Sin}^2 2\theta_{13}<0.20$ (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.





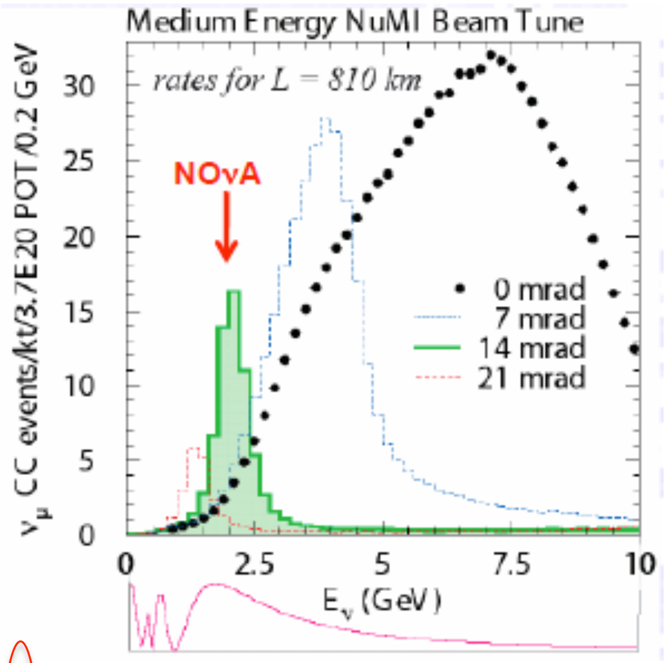
T. Kobayashi, Neutrino2010

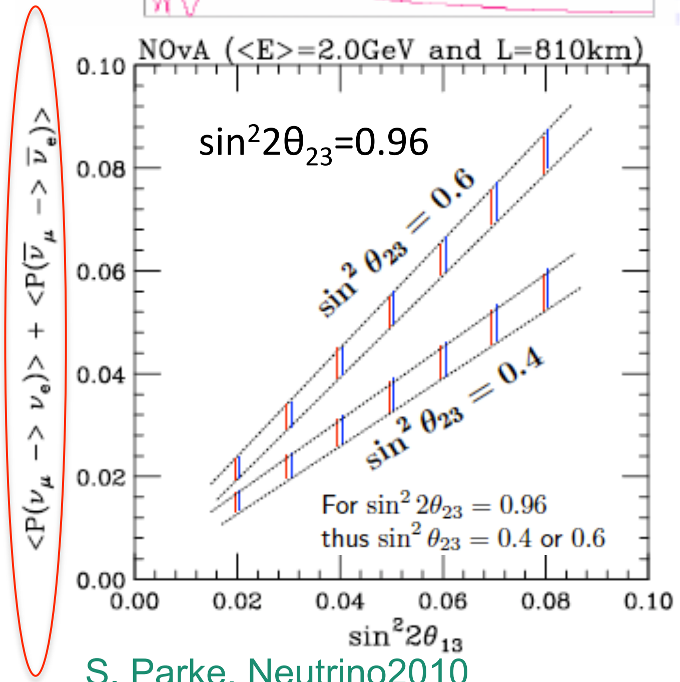
>10times improve

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

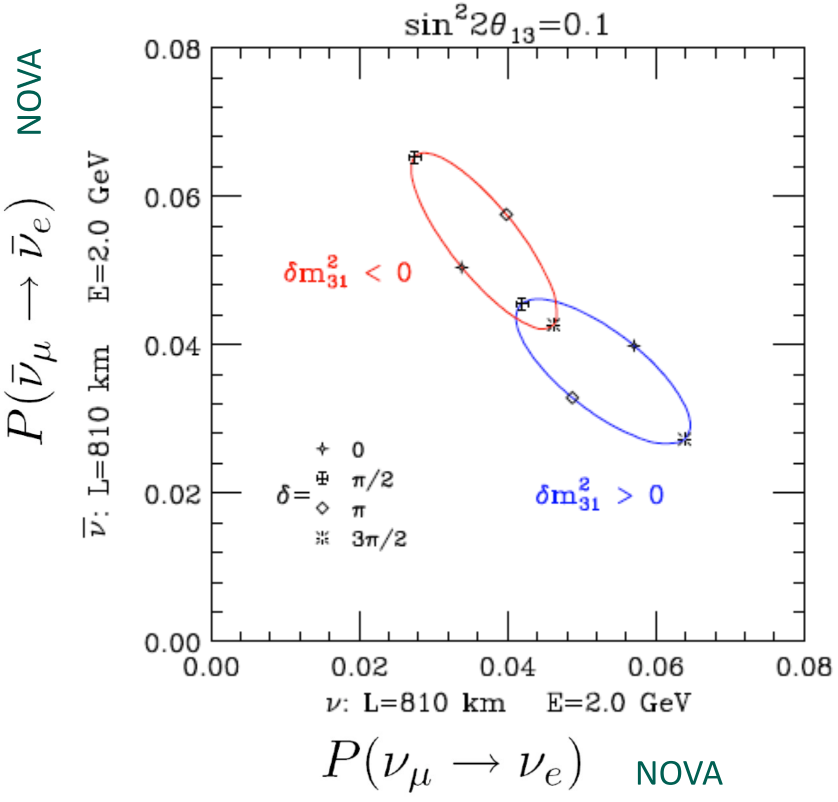


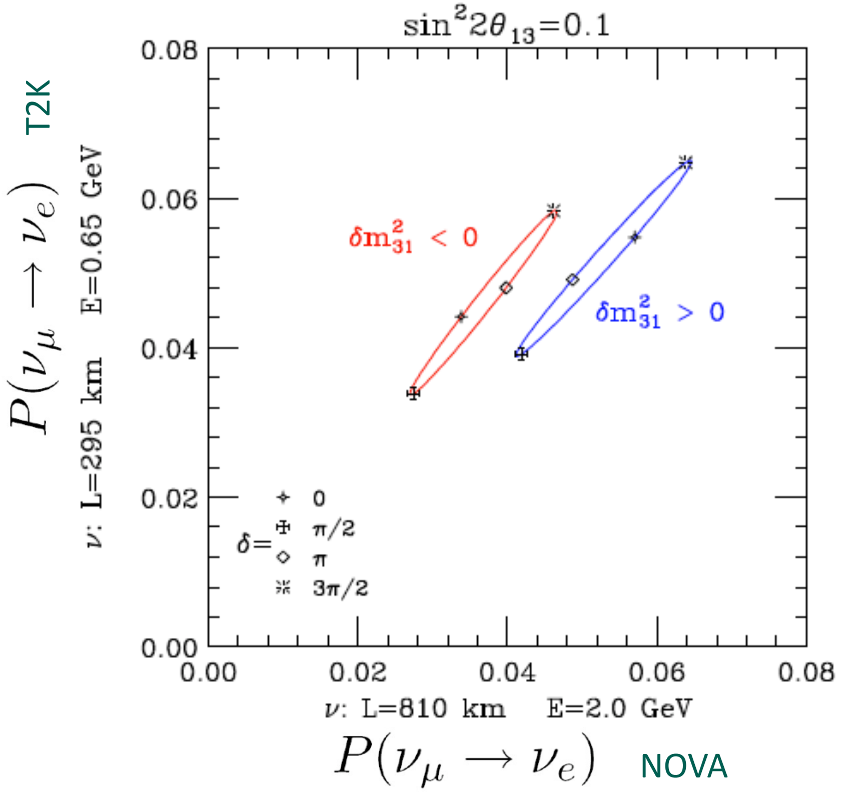


S. Parke, Neutrino2010

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.

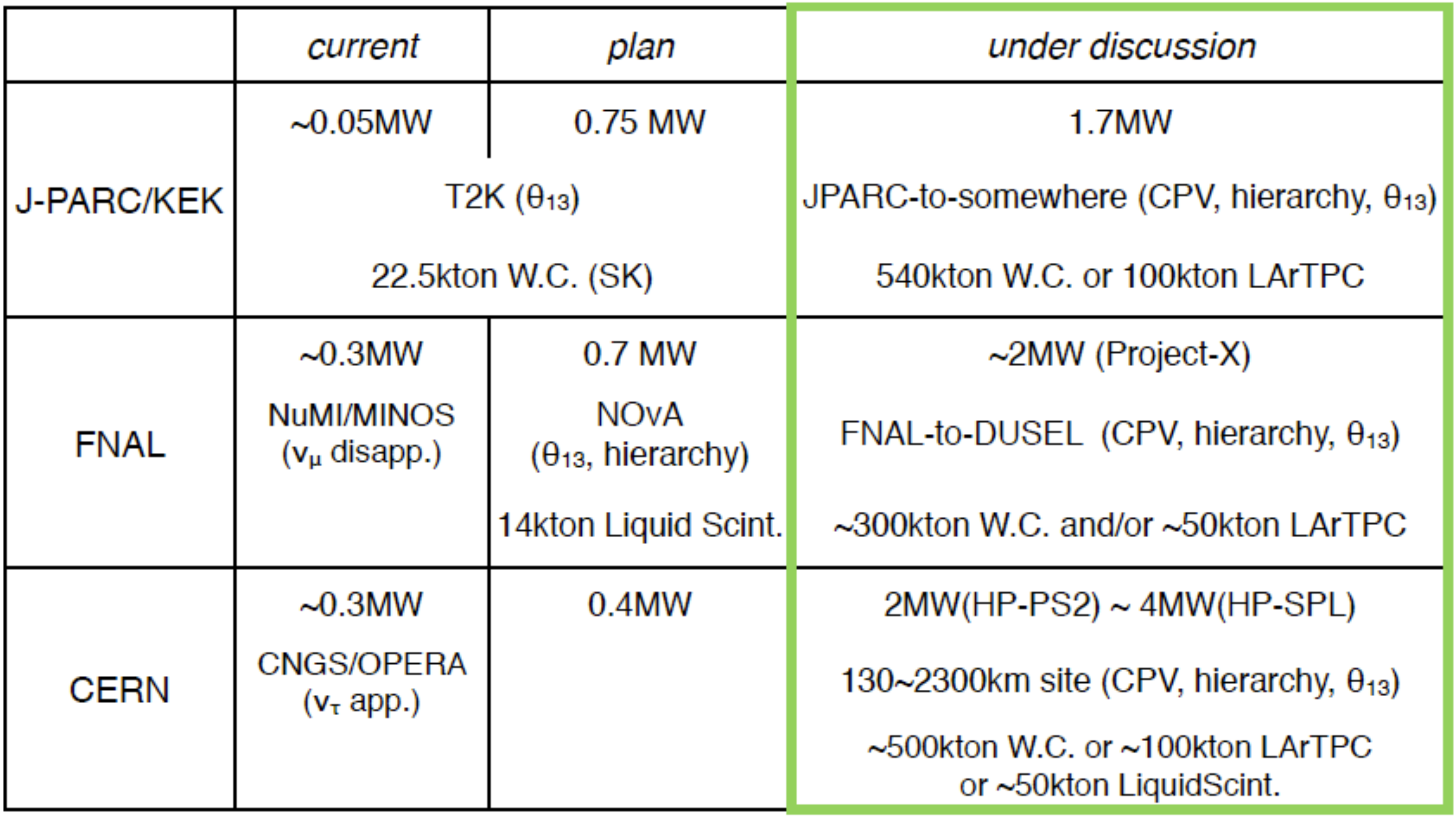




arXiv: Hep-ph/0609011v1

Superbeam Long Baseline Neutrino Experiments

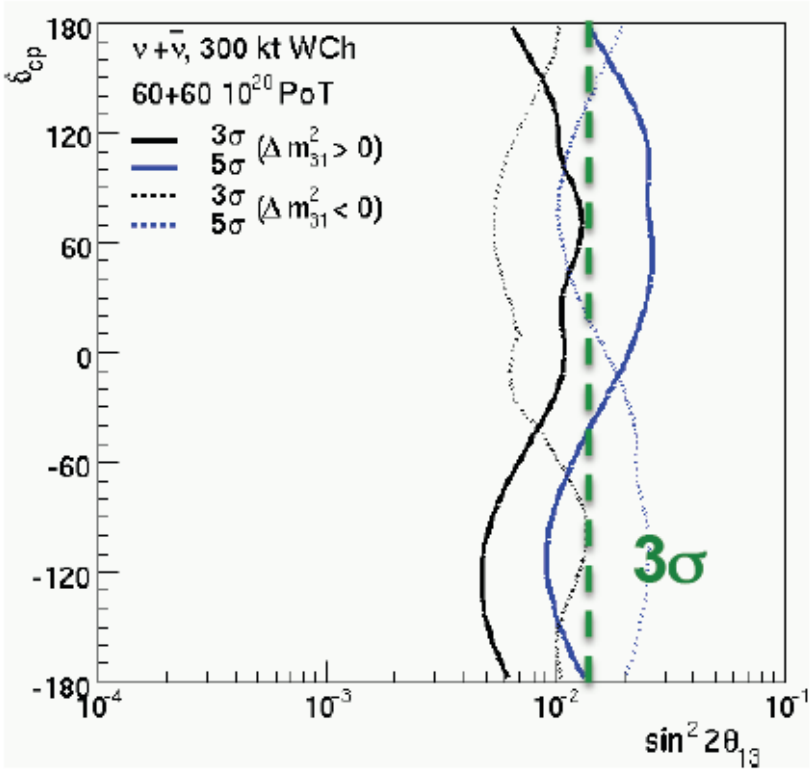
- Multi MW super beam, longer baseline, giant detector

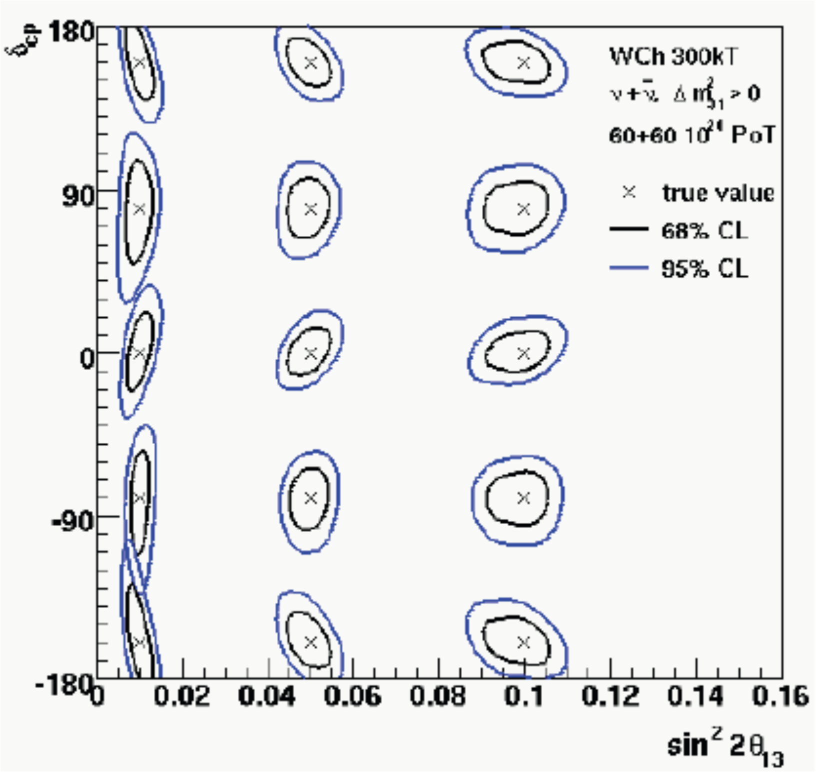


	current	*plan*	*under discussion*
J-PARC/KEK	~0.05MW T2K (θ_{13}) 22.5kton W.C. (SK)	0.75 MW	1.7MW JPARC-to-somewhere (CPV, hierarchy, θ_{13}) 540kton W.C. or 100kton LArTPC
FNAL	~0.3MW NuMI/MINOS (ν_μ disapp.)	0.7 MW NOvA (θ_{13}, hierarchy) 14kton Liquid Scint.	~2MW (Project-X) FNAL-to-DUSEL (CPV, hierarchy, θ_{13}) ~300kton W.C. and/or ~50kton LArTPC
CERN	~0.3MW CNGS/OPERA (ν_τ app.)	0.4MW	2MW(HP-PS2) ~ 4MW(HP-SPL) 130~2300km site (CPV, hierarchy, θ_{13}) ~500kton W.C. or ~100kton LArTPC or ~50kton LiquidScint.

Sensitivity to CPV and Hierarchy（FNAL-DUSEL）

- 300Kt Water Cherenkov detector
- 700KW, 120GeV, 2×10^7 s/yr, 8+8 years

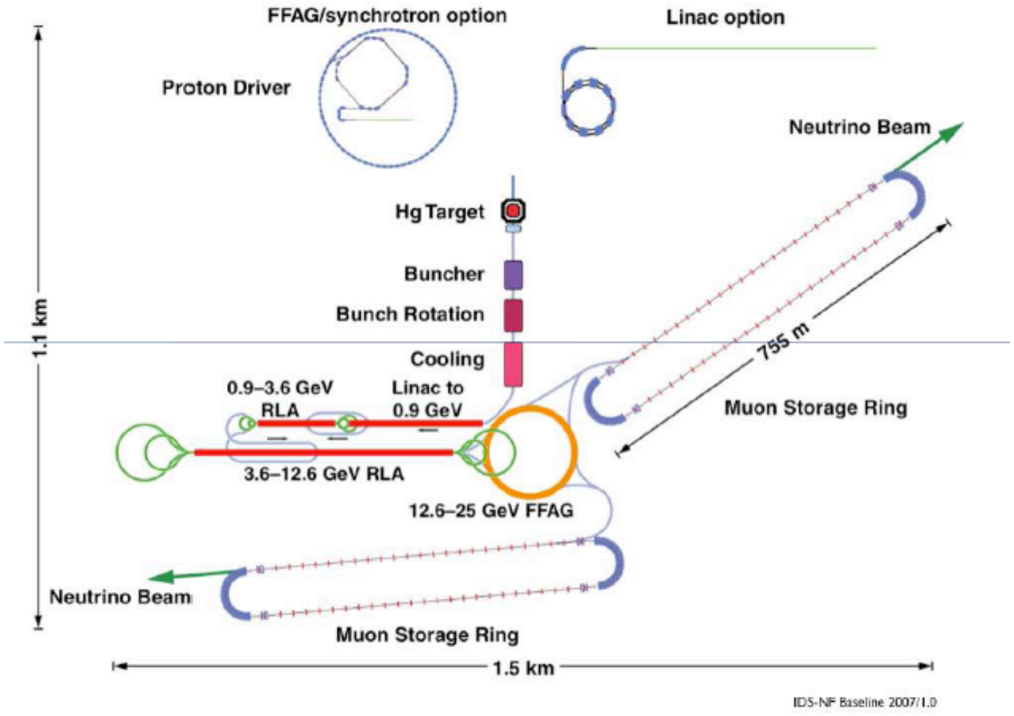




arXiv: 0705.4396

Neutrino Factory and Beta Beam

- Neutrino factory: produce neutrinos by muon decay in the straight section of storage ring
  - Discovery potential: close to full parameters space and down to very small $\sin^2 2\theta_{13}$
  - IDS-NF: R&D for proton driver, muon cooling, muon acceleration, detector



IDS-NF Baseline 2007/1.0

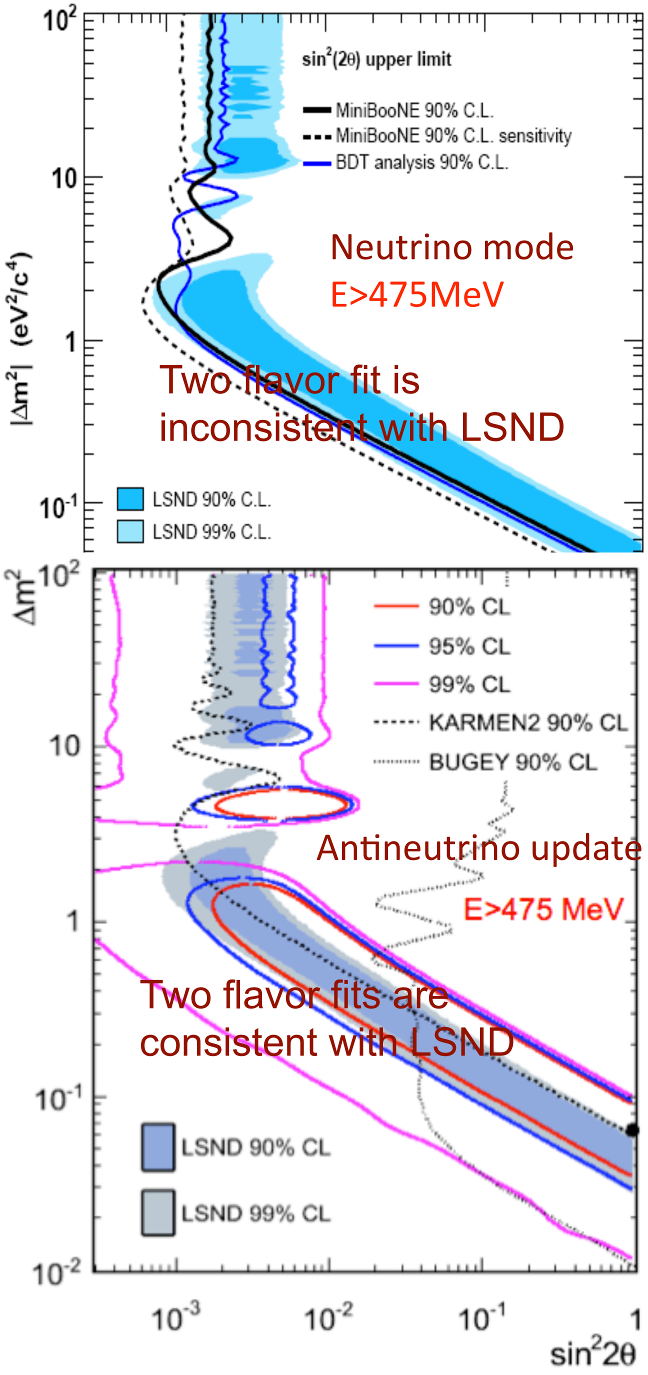
Stored $\mu^- \to e^- \nu_\mu \bar{\nu}_e$	
Disappearance	**Appearance**
$\bar{\nu}_e \to \bar{\nu}_e \to e^+$	$\bar{\nu}_e \to \bar{\nu}_\mu \to \mu^+$ $\bar{\nu}_e \to \bar{\nu}_\tau \to \tau^+$
$\nu_\mu \to \nu_\mu \to \mu^-$	$\nu_\mu \to \nu_e \to e^-$ $\nu_\mu \to \nu_\tau \to \tau^-$

All channels potentially available at the Neutrino Factory.

- Beta beam: neutrinos by beta decay in the straight section of storage ring.
  - Flavor-clean electron neutrino beam (EURISOL etc.)

LSND Anomaly

- LSND: $|\Delta m^2| \sim 1\text{eV}^2$ (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}.



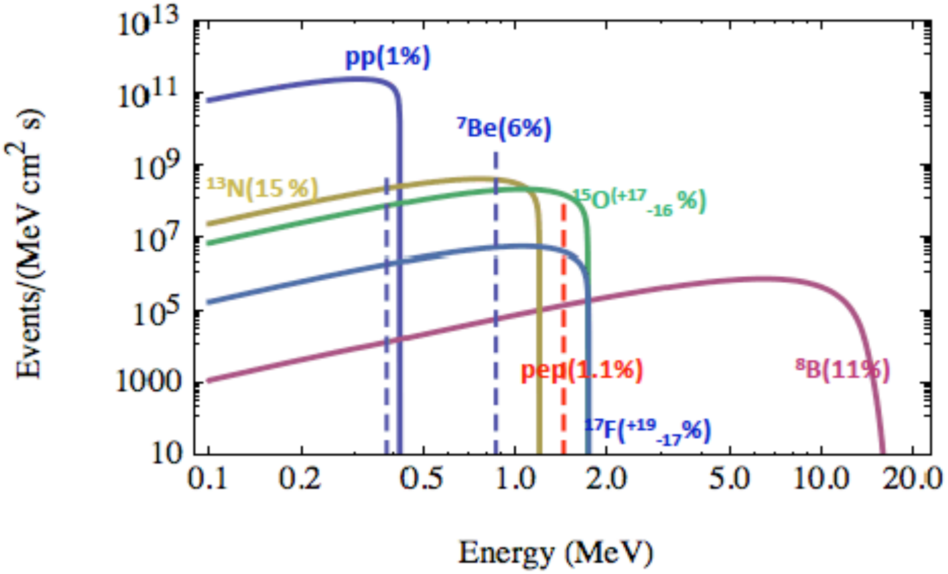
Neutrino mode
E>475MeV

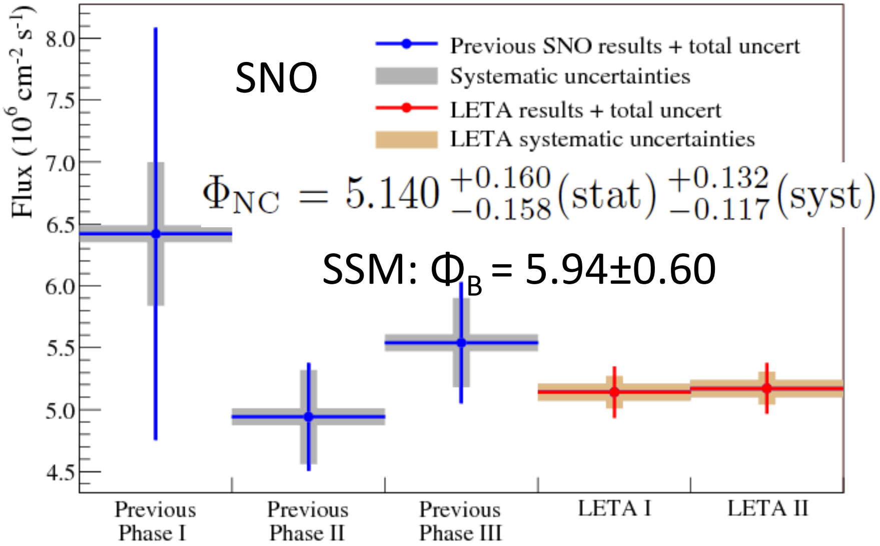
Two flavor fit is inconsistent with LSND

Antineutrino update
E>475 MeV

Two flavor fits are consistent with LSND

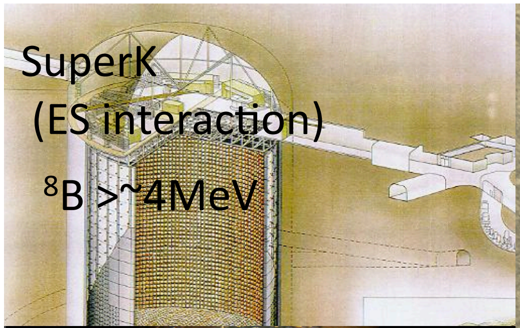
Solar Neutrino



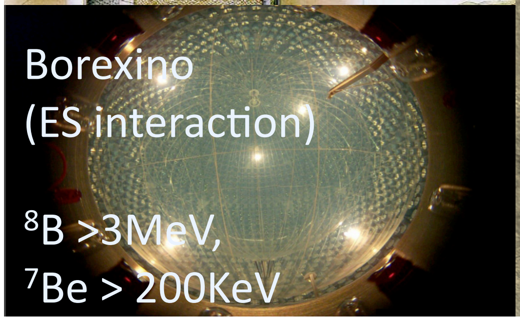


$$\Phi_{\mathrm{NC}} = 5.140\ ^{+0.160}_{-0.158}(\mathrm{stat})\ ^{+0.132}_{-0.117}(\mathrm{syst})$$

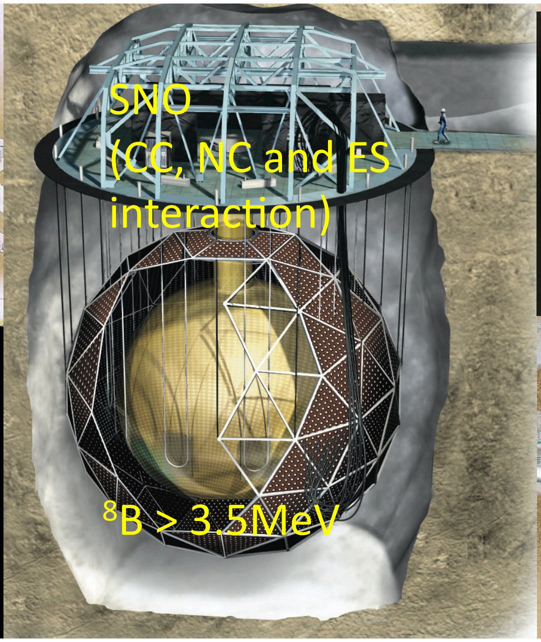
SSM: Φ_B = 5.94±0.60



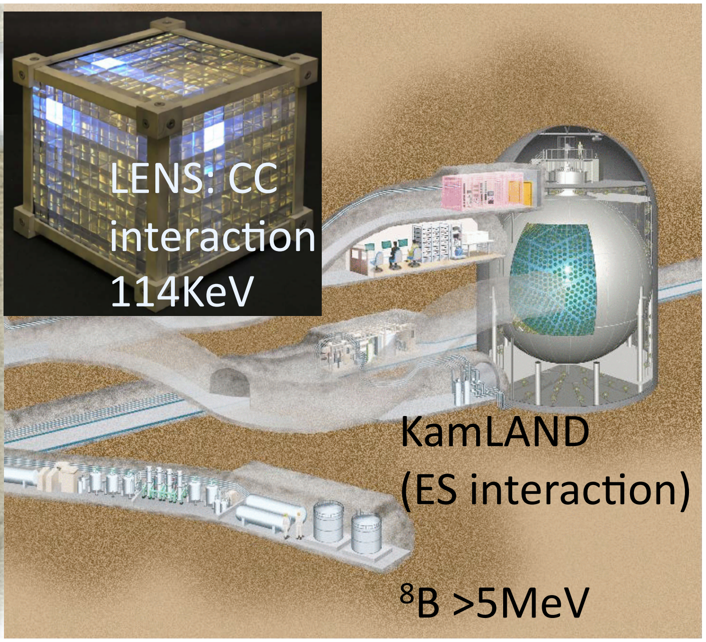
SuperK
(ES interaction)
^{8}B >~4MeV



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



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

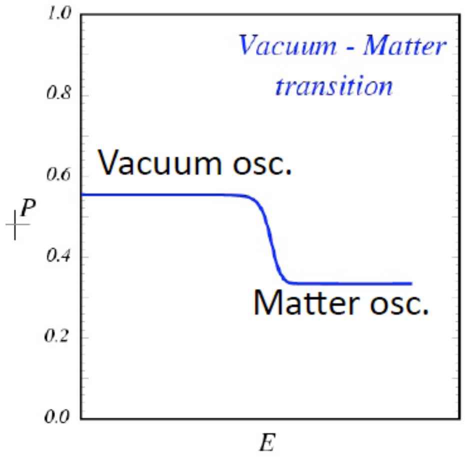


LENS: CC interaction
114KeV

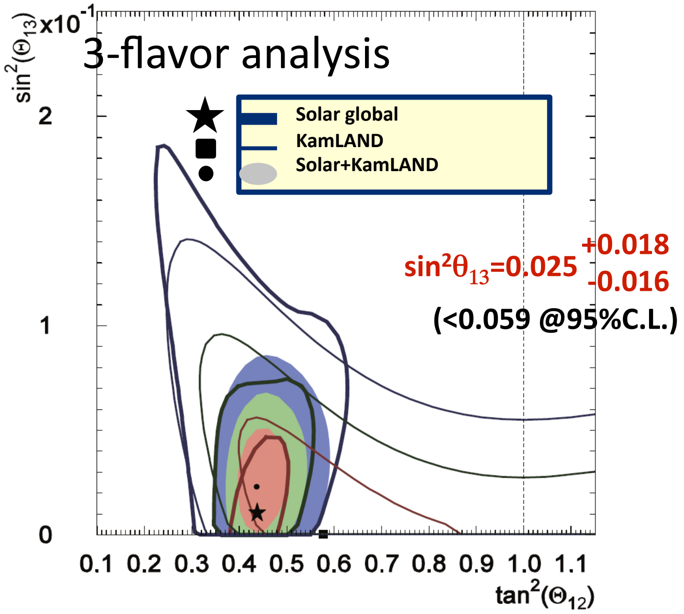
KamLAND
(ES interaction)
^{8}B >5MeV

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

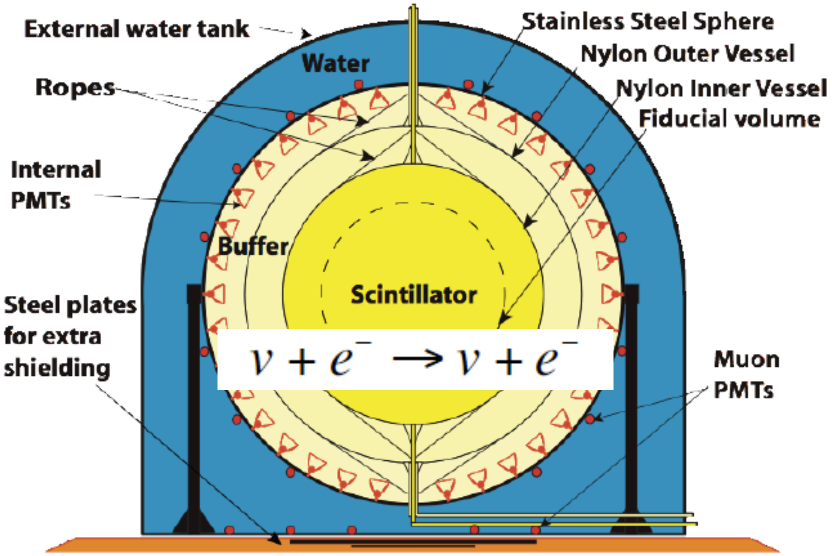


Y. Takeuchi, Neutrino2010



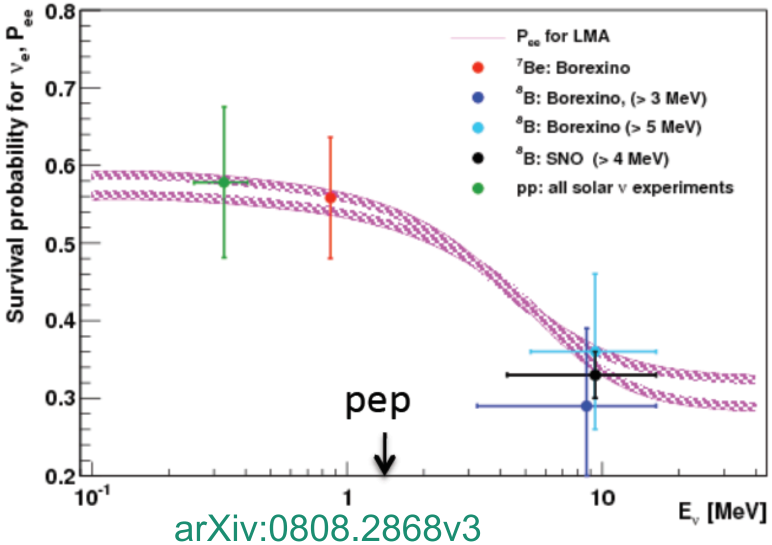
Borexino

Liquid Scintillator Detector



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

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



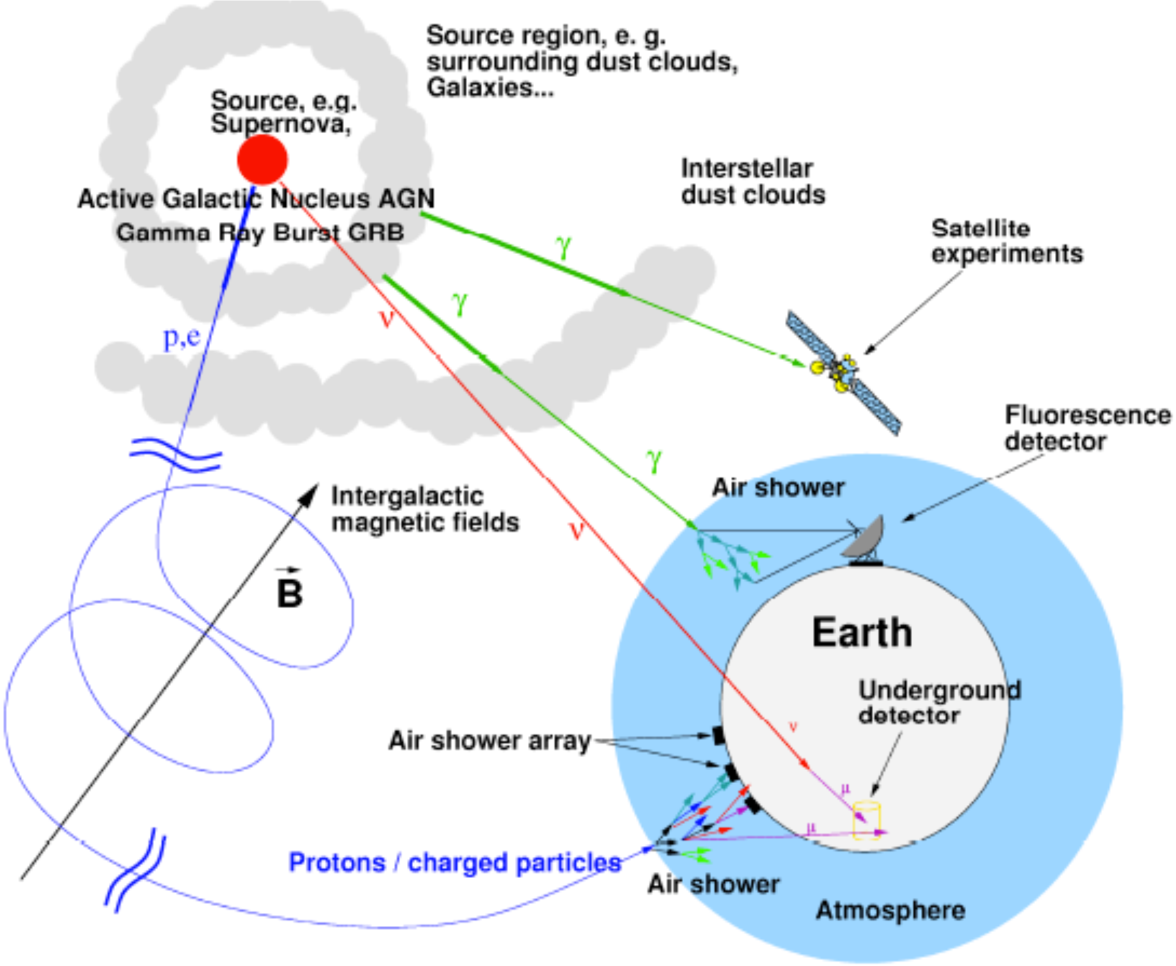
arXiv:0808.2868v3

- 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….

High Energy Neutrinos

- Production: p+p or p+γ gives pions which give neutrinos

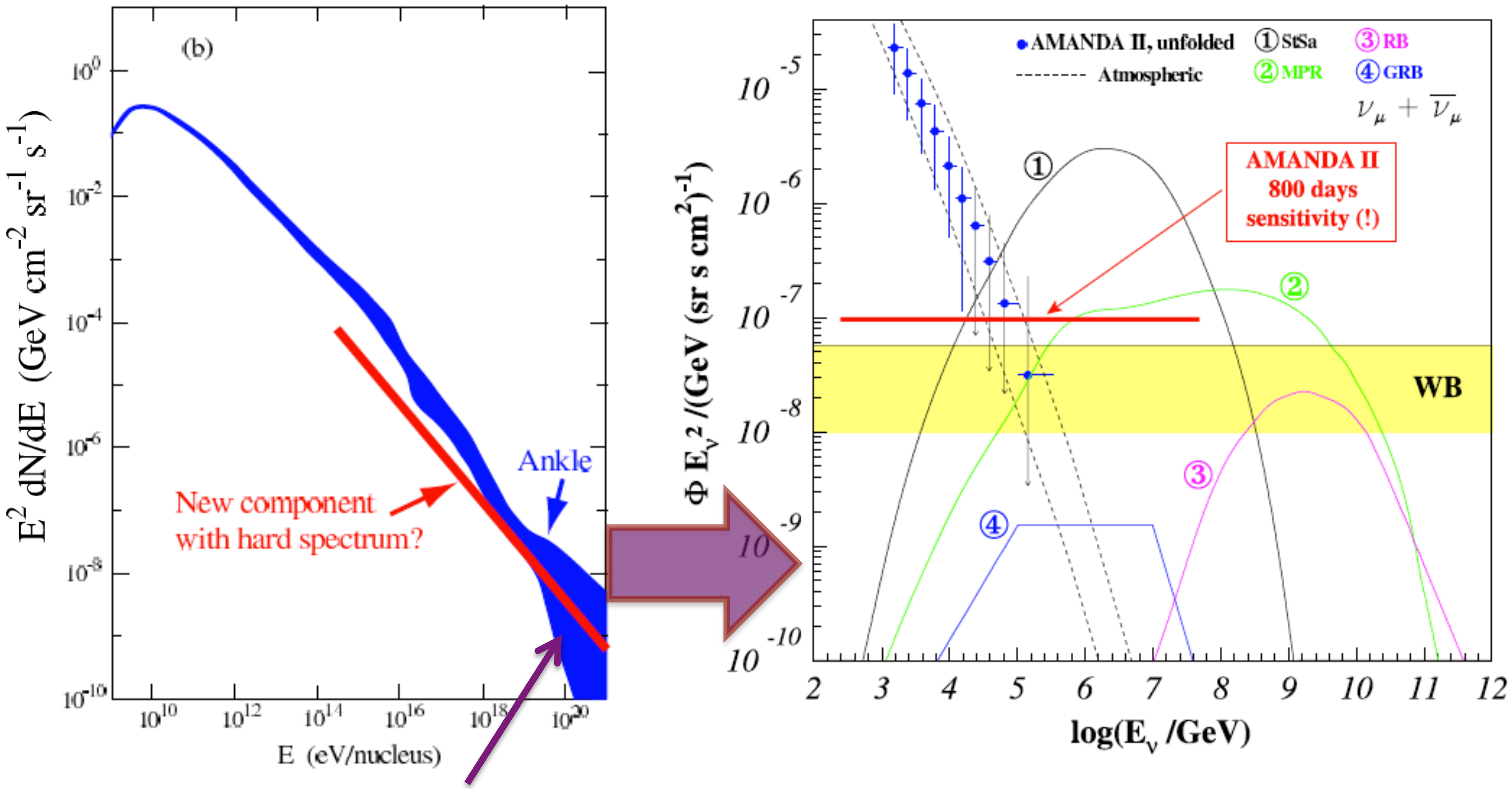
$$p+\gamma \rightarrow \Delta^{+} \rightarrow \begin{cases} n+\pi^{+} \\ p+\pi^{0} \end{cases} \qquad \begin{aligned} \pi^{+} &\rightarrow \mu^{+}+\nu_{\mu}\,, \\ & \mu^{+} \rightarrow e^{+}+\bar{\nu}_{\mu}+\nu_{e} \end{aligned}$$



Neutrino Flux

Cosmic ray energy spectrum

Predicted neutrino energy spectra

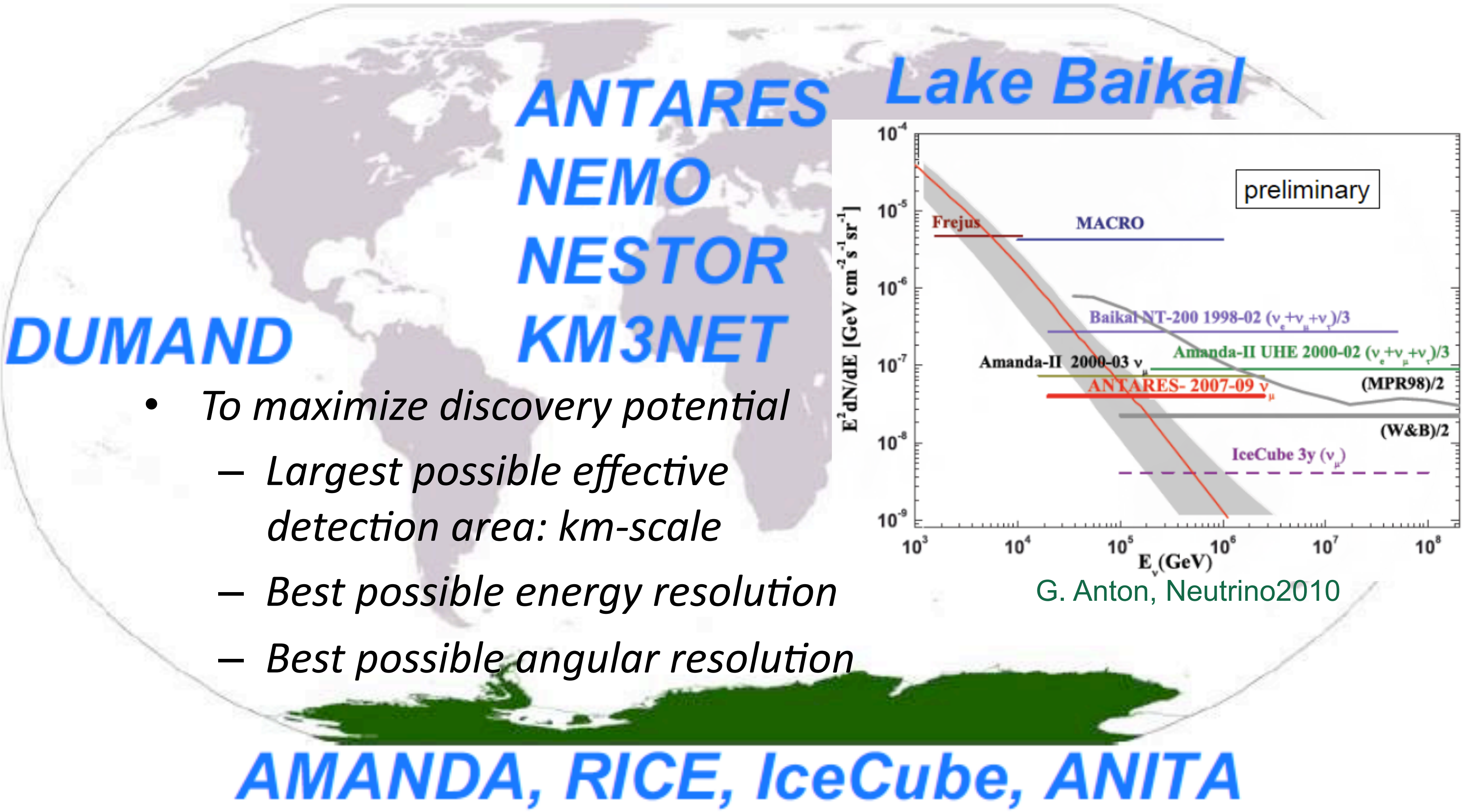


Protons from Extragalactic sources

One 10^{19}eV particle per km^3 per year per steradian.

ν_{μ}: 1~5×10^{-8}GeV/cm^2/s/sr

Neutrino Telescope



G. Anton, Neutrino2010

- *To maximize discovery potential*
  - *Largest possible effective detection area: km-scale*
  - *Best possible energy resolution*
  - *Best possible angular resolution*

IceCube

Final Configuration:

- 5160 DOMs / 86 strings

- O(100) neutrinos/day
O(10^8) muons/day

- threshold: ~10 GeV

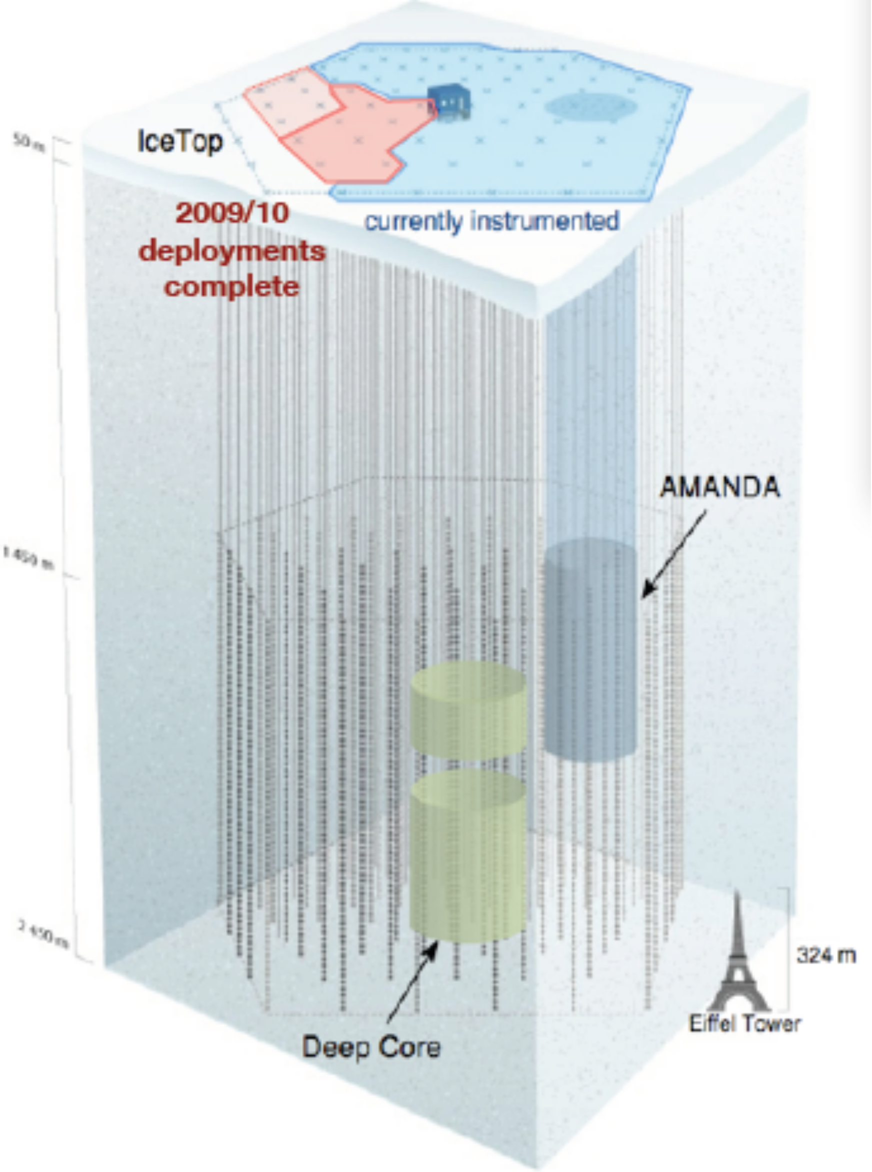
- angular resolution: 0.4-1 deg

Currently deployed:

4790 DOMs/ 79 strings

Data samples:

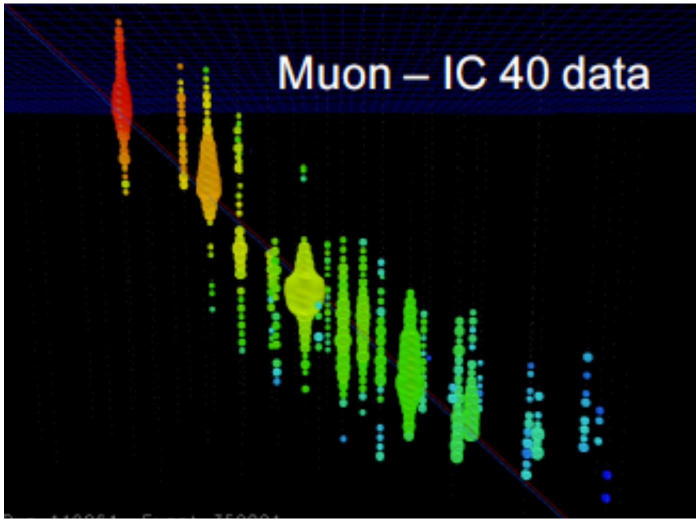
IceCube-22 IceCube-40
IceCube-59 IceCube-79

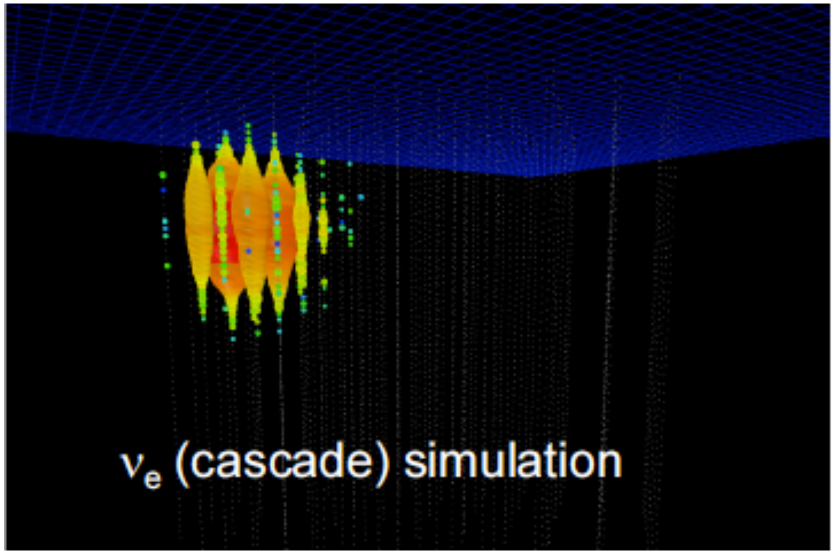


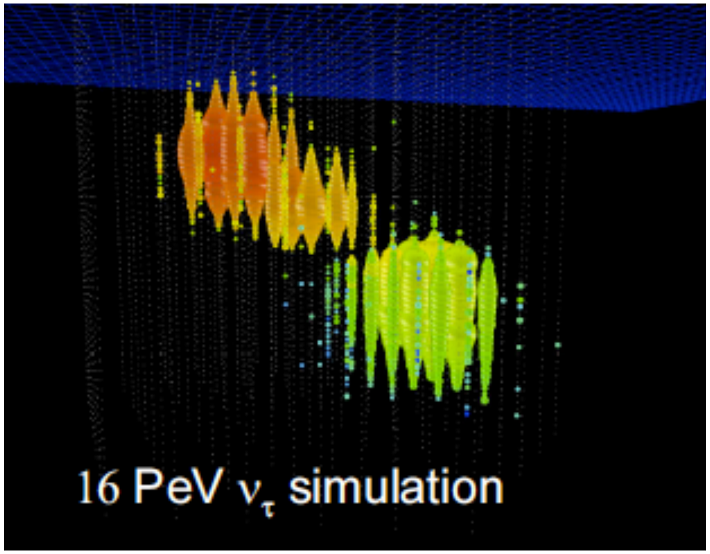
Flavor Identification

Flavor ratios can give additional information on constrain to $\sin^2 2\theta_{13}$ and δ_{cp}

- ν_μ: produce long μ track
  - Angular resolution ~1deg
- ν_e (CC), ν_x (NC): shower
  - Point source to cascade
  - Good energy resolution
- ν_τ: "double bang event": two showers
  - τ production and decay
  - Other topologies



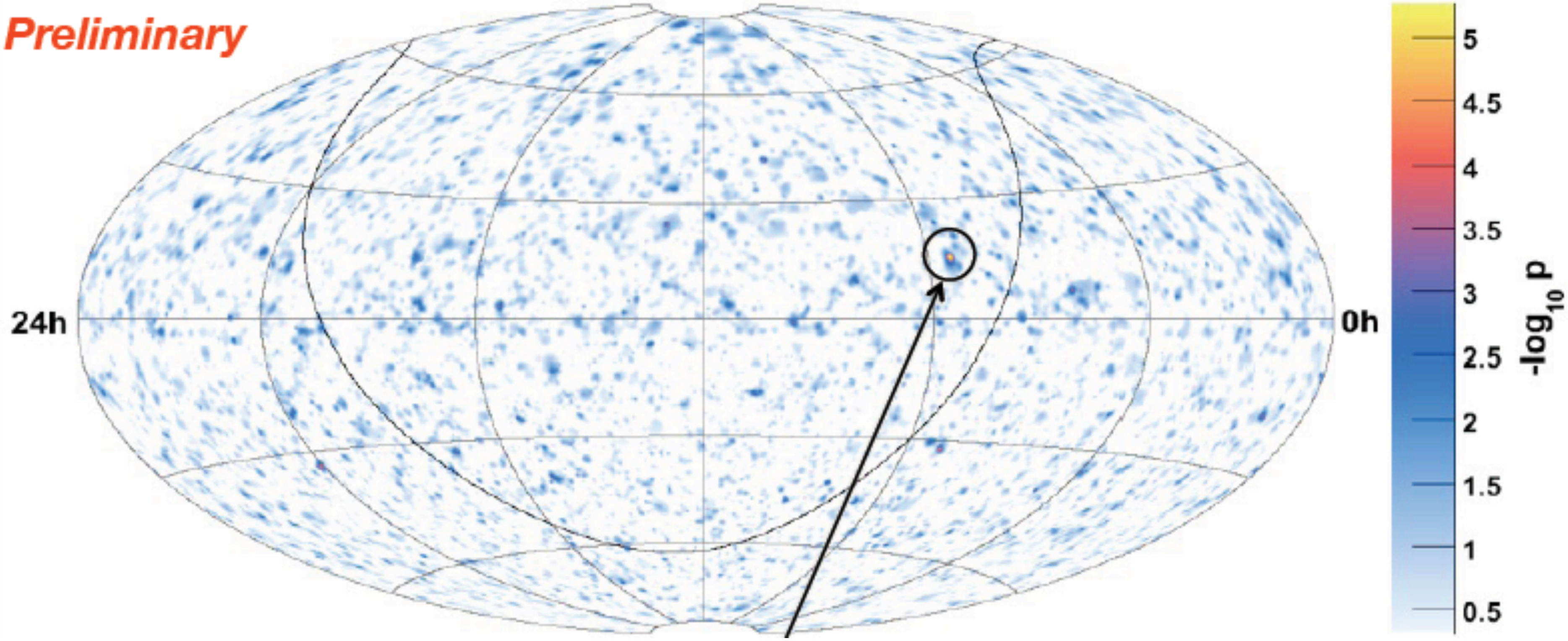




IC40: all-sky scan, significance map

- *No significant evidence of neutrino source.*

Analysis described in J. Dumm et al., 31st ICRC, Łódź 2009

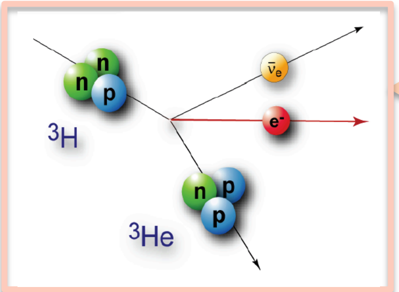


Ra=113.75, Dec=15.15

E. Resconi, Neutrino2010

Neutrino Mass

Beta Decay

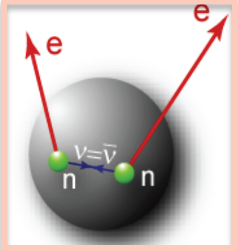


$$m_{\nu_e}^2 = \sum_i |U_{ei}|^2 \cdot m_{\nu_i}^2$$

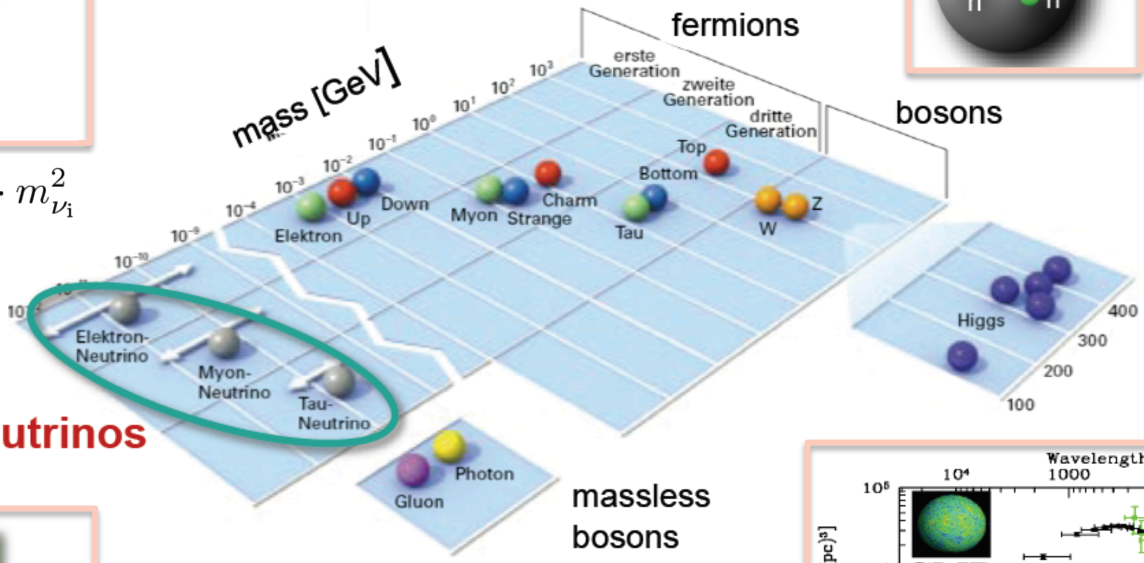
m_ν<2.3eV

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

Double Beta Decay



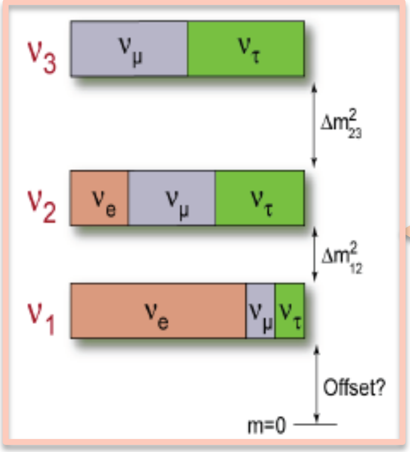
$$m_{\beta\beta} = \left| \sum_i U_{ei}^2 \cdot m_{\nu_i} \right|$$



neutrinos

massless bosons

Neutrino Oscillation

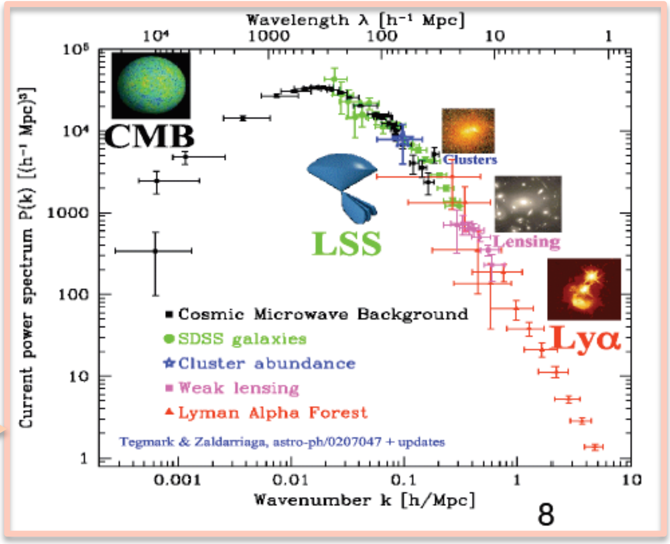


0.04eV ($\sqrt{\Delta m^2_{atm}}$)< m (heaviest ν_i)

$m_1 + m_2 + m_3 <$ (0.4-1.0)eV

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

Cosmology



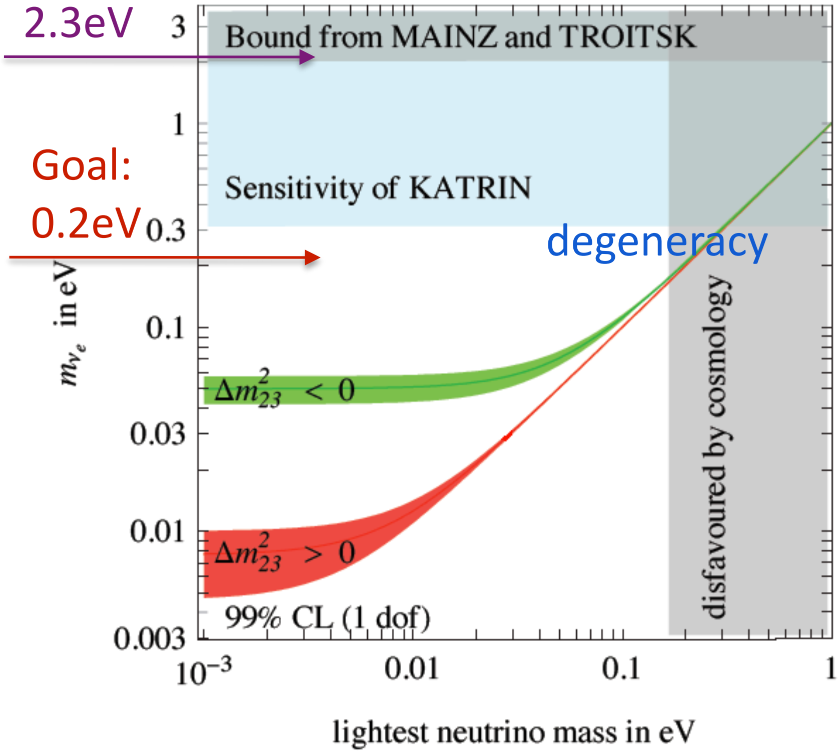
Mass Measurement

Beta Decay

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

0νββ Decay

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

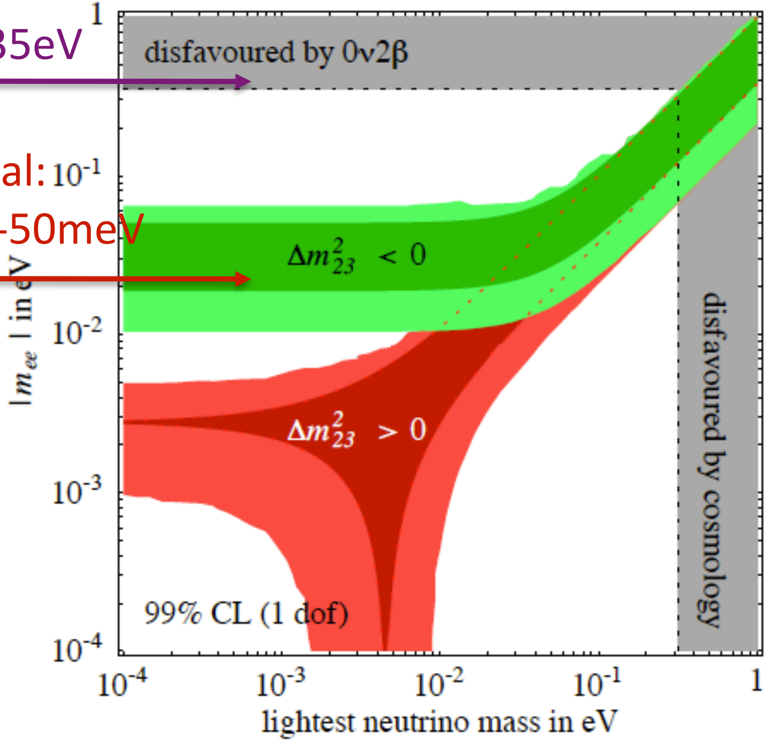


2.3eV

Goal:
0.2eV

degeneracy

Hep-ph/0606054



0.35eV

Goal:
20-50meV

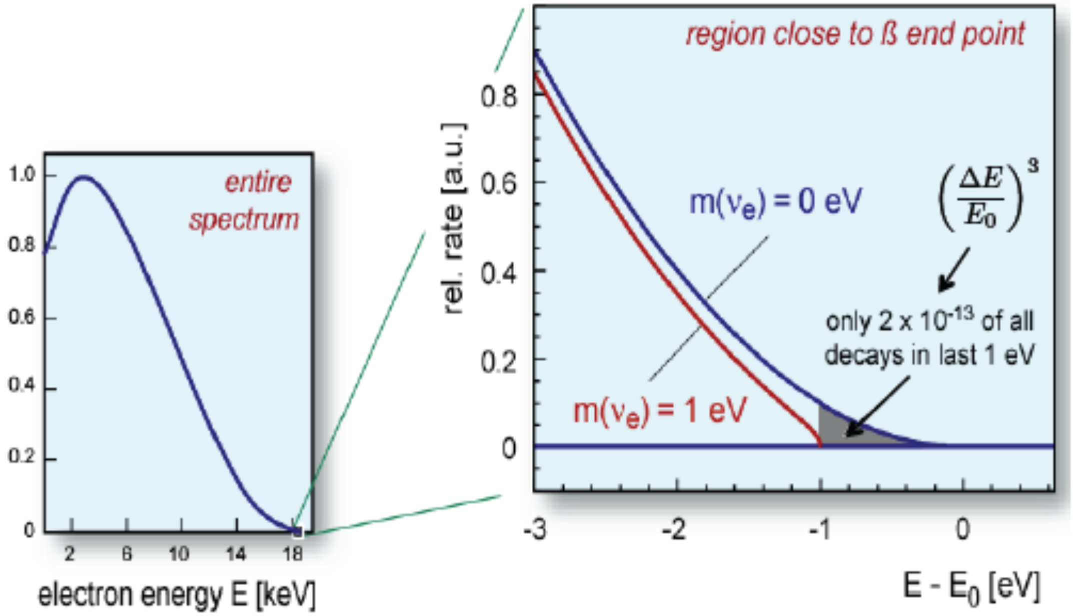
Beta Decay

Model-Independent Measurement: Kinematics and energy conservation

$$\frac{d\Gamma_i}{dE} = C \cdot p \cdot (E + m_e) \cdot (E_0 - E) \cdot \sqrt{(E_0 - E)^2 - m_i^2} \cdot F(E,Z) \cdot \theta(E_0 - E - m_i)$$

$(\nu\text{– mass})^2$

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

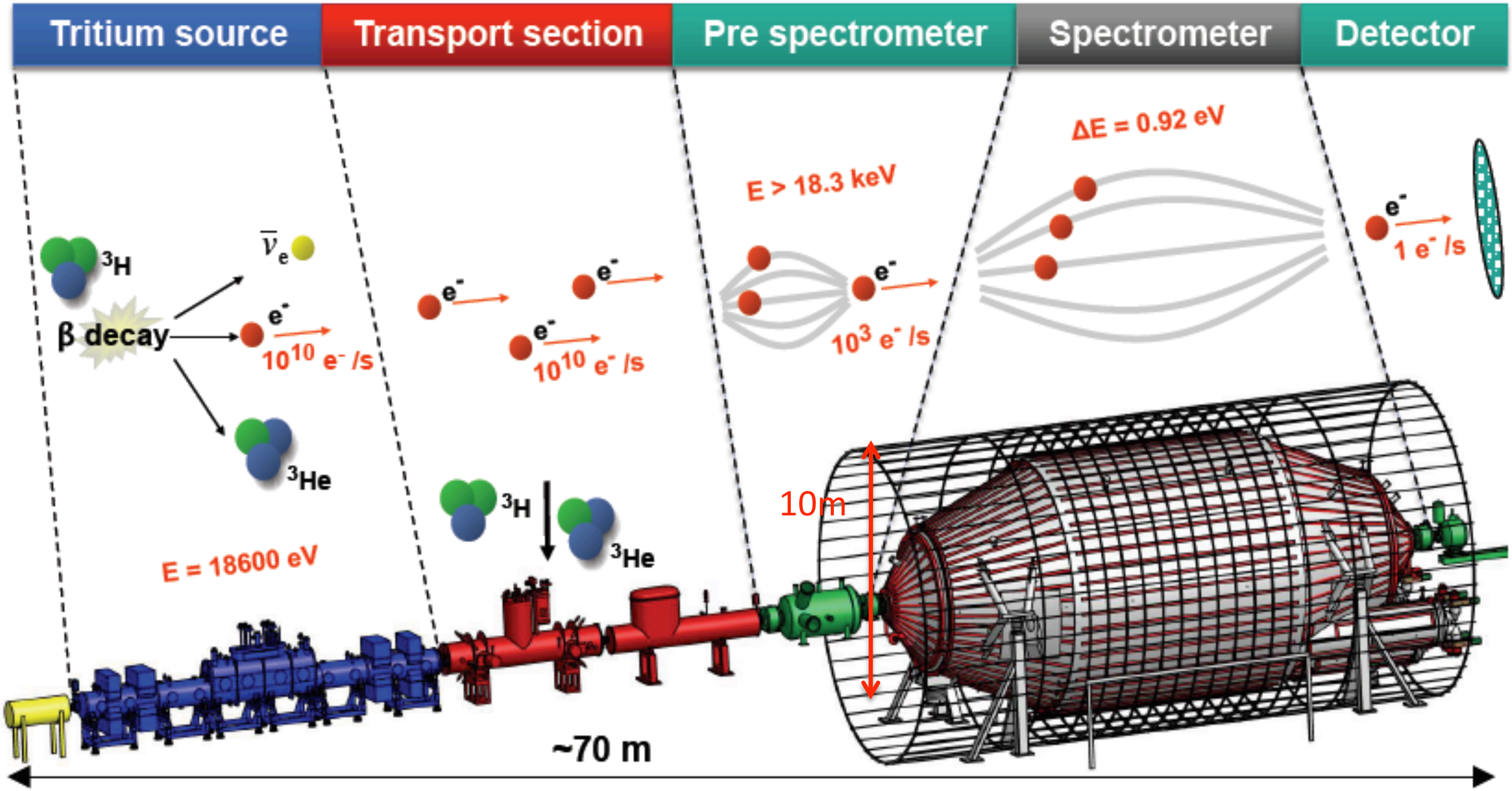


Measure the region close to endpoint:

- ✓ 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 $10^{11}\beta/s$



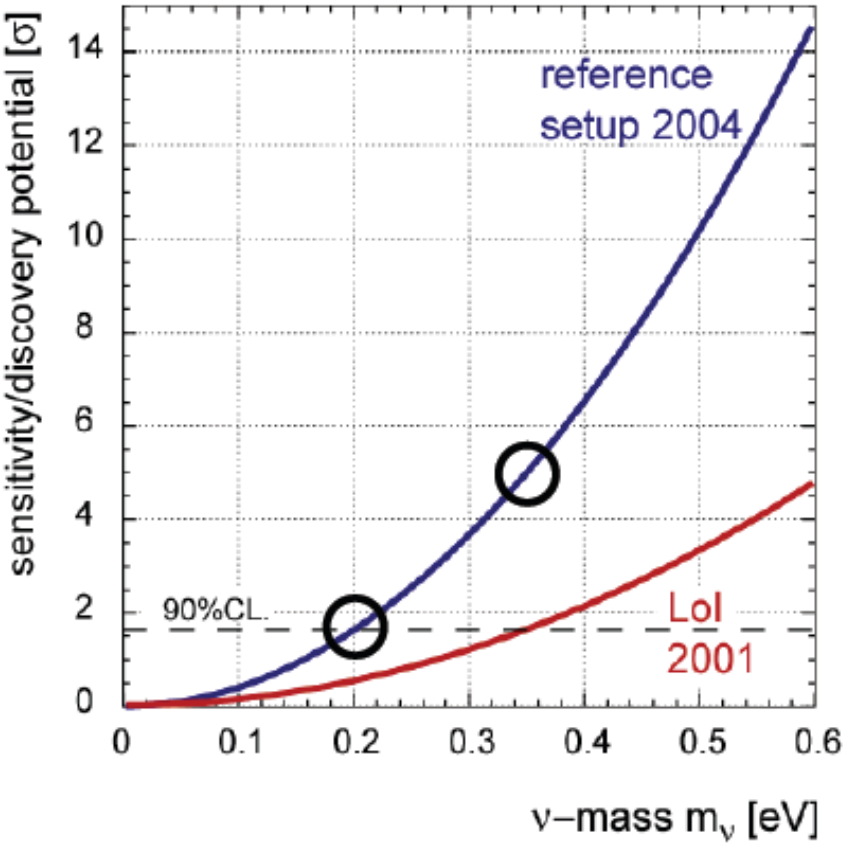
Schedule: Start main spectrometer test in 2011,

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_ν = 0.35eV (5σ)

Sensitivity:

m_ν < 0.2eV (90% C.L.)

$\Delta m^2_{tot} = (\Delta m^4_{stat} + \Delta m^4_{stat})^{1/2}$

$\approx 0.025\ eV^2/c^4$

Limit of KATRIN:

Source and detector are separate

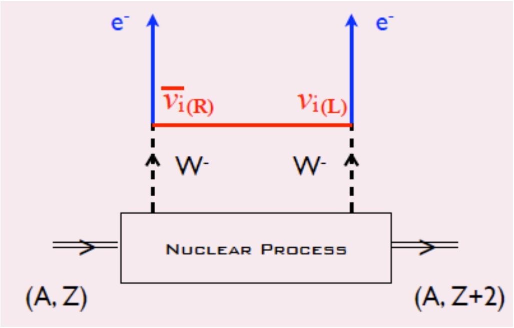
MARE experiment

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

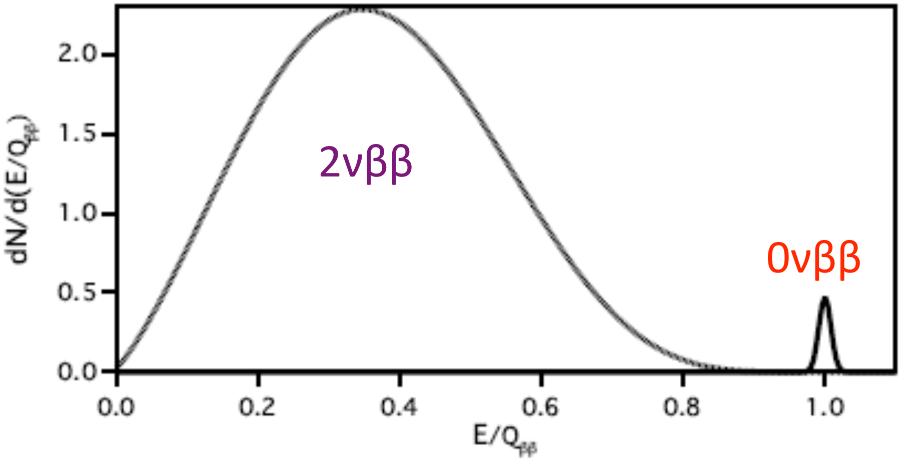
Use bolometer technology, source is detector. MARE2: ~0.2eV

Neutrinoless Double Beta Decay

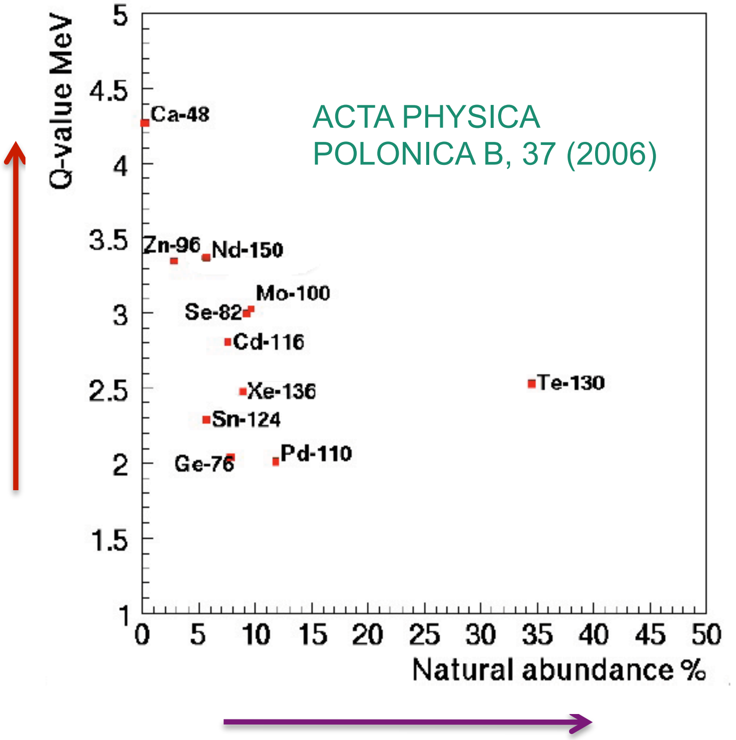
- 0νββ: ΔL≠0, lepton number violation.
- Standard interpretation: light, massive majorana neutrinos ($\nu = \overline{\nu}$)
- Other mechanisms: negligible…
- Even-even nucleus of larger $Q_{\beta\beta}$



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



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

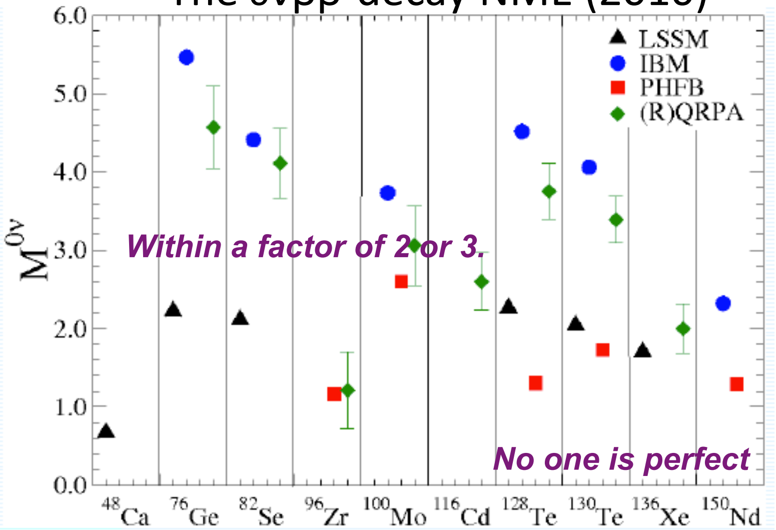
⇩ 20-50 meV

Sensitivity:

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

t: year
M: mass

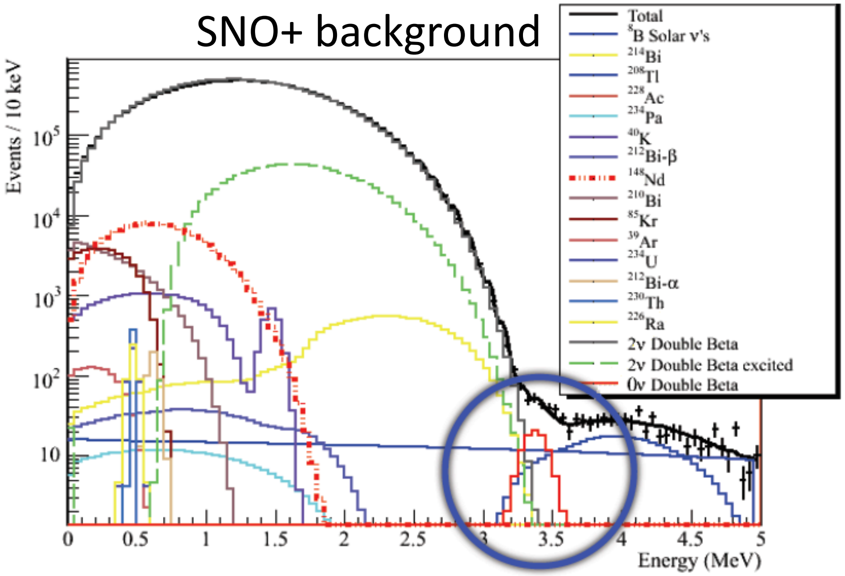
b: background, *Δ(E):* energy resolution


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

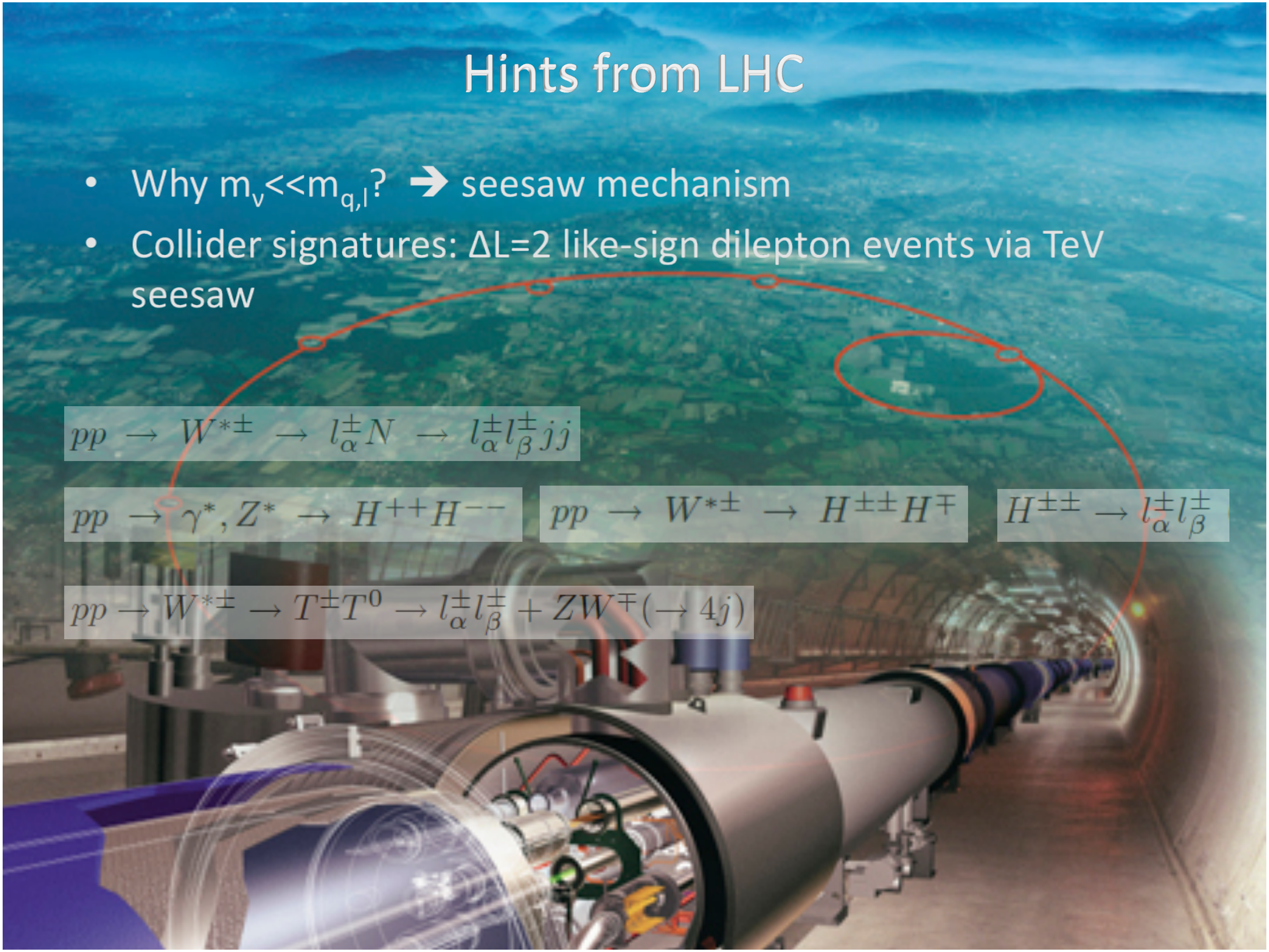
Name	Isotope	Technique	Mass	Location	Sensitivity	Time
CUORICINO	Te-130	Bolometer	11kg	LNGS	0.40eV	2003 - 2008
CUORE	Te-130	Bolometer	200kg	LNGS	0.22eV	2013 -
COBRA	Cd-116 …	Semiconductor	183kg	LNGS		
GERDA I/II	Ge-76	Semiconductor	18/40kg	LNGS	75-129meV	2009 (comiss.)
Majorana	Ge-76	Semiconductor	30kg	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…

Hints from LHC

- Why $m_\nu \ll m_{q,l}$? ➔ seesaw mechanism
- Collider signatures: ΔL=2 like-sign dilepton events via TeV seesaw



$$pp \to W^{*\pm} \to l^\pm_\alpha N \to l^\pm_\alpha l^\pm_\beta jj$$

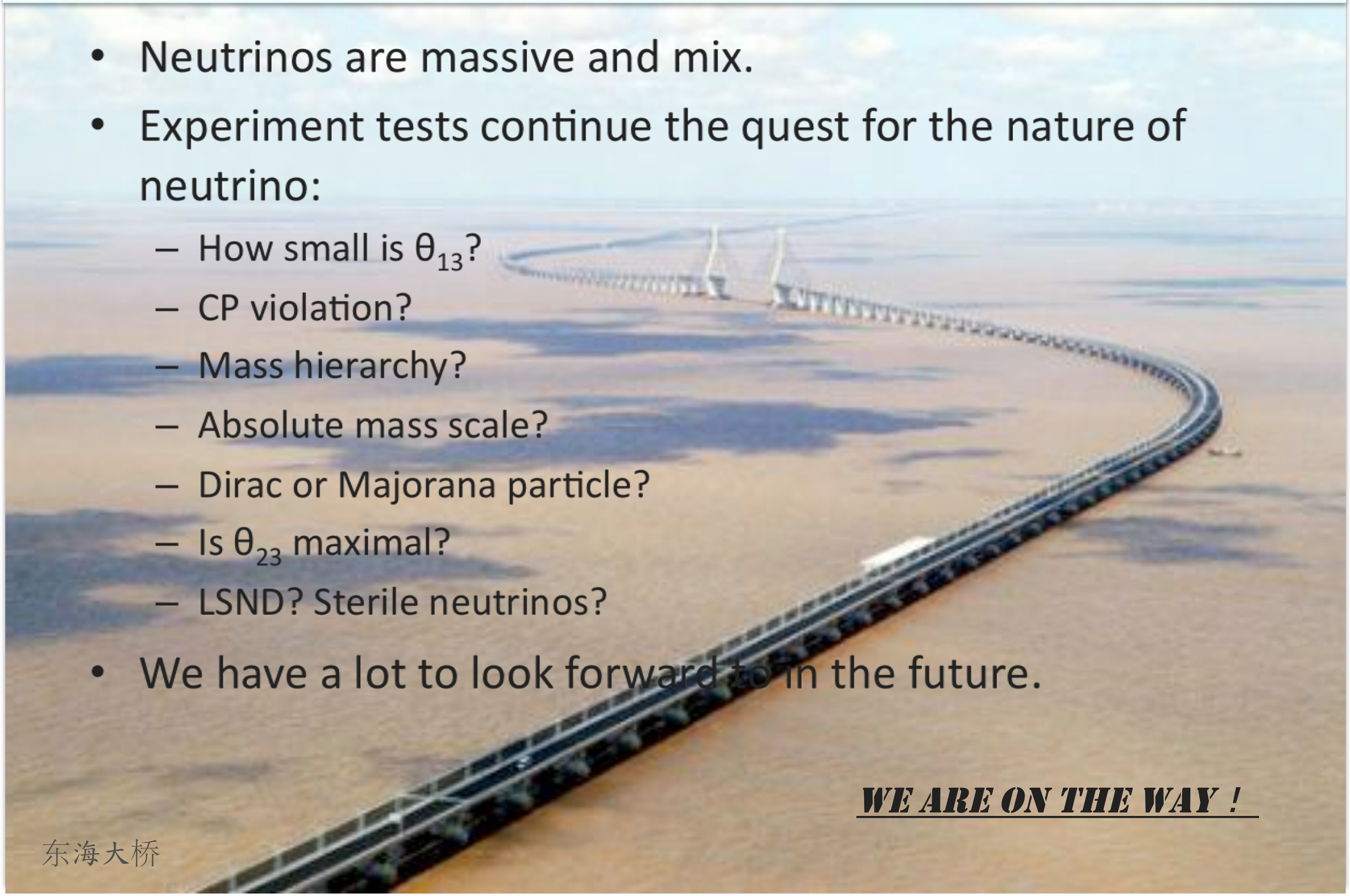
$$pp \to \gamma^*, Z^* \to H^{++}H^{--}$$

$$pp \to W^{*\pm} \to H^{\pm\pm}H^\mp$$

$$H^{\pm\pm} \to l^\pm_\alpha l^\pm_\beta$$

$$pp \to W^{*\pm} \to T^\pm T^0 \to l^\pm_\alpha l^\pm_\beta + ZW^\mp(\to 4j)$$

Conclusions



- Neutrinos are massive and mix.
- Experiment tests continue the quest for the nature of neutrino:
  - How small is θ_{13}?
  - CP violation?
  - Mass hierarchy?
  - Absolute mass scale?
  - Dirac or Majorana particle?
  - Is θ_{23} maximal?
  - LSND? Sterile neutrinos?
- We have a lot to look forward to in the future.

WE ARE ON THE WAY !

东海大桥