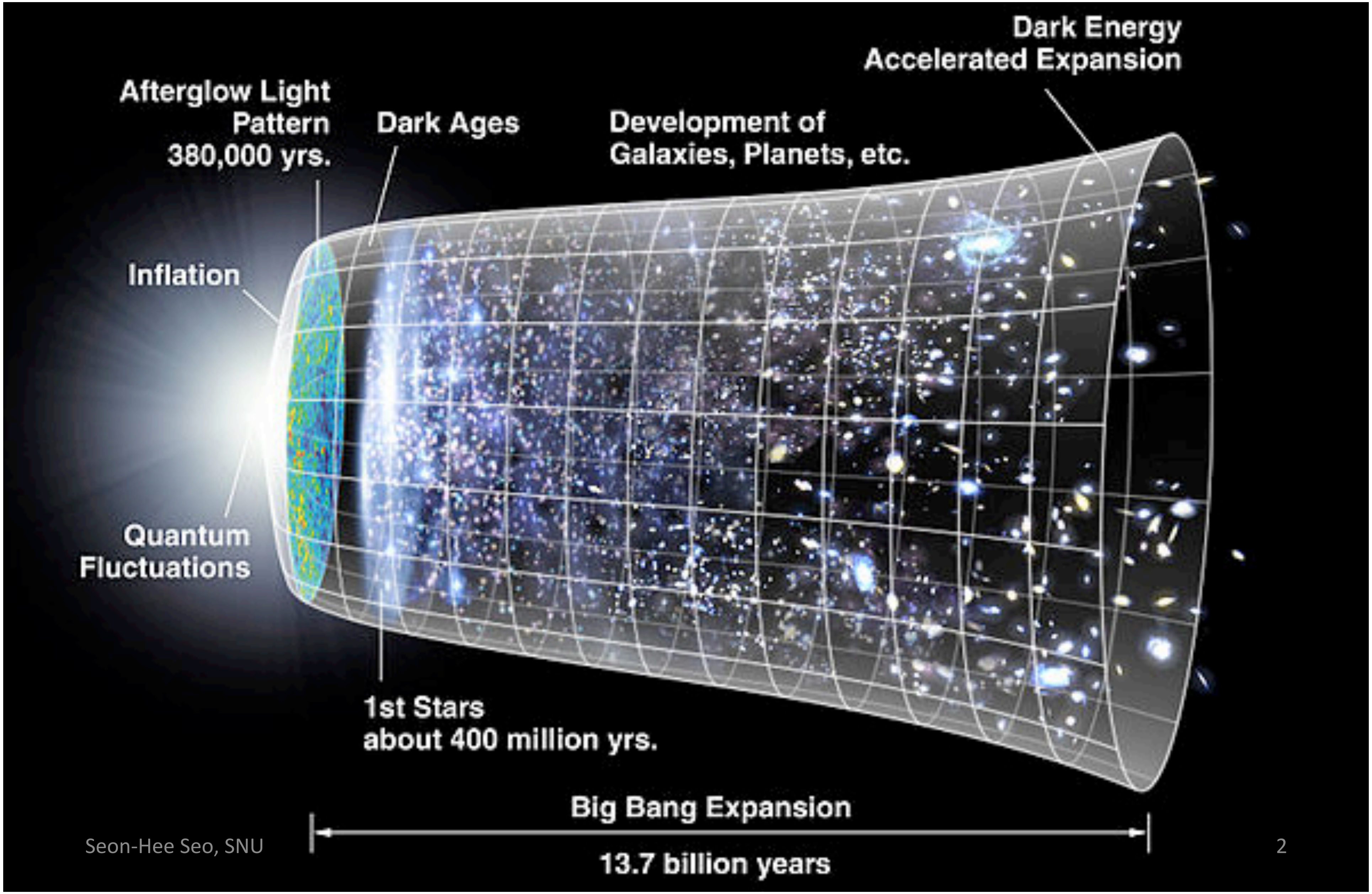
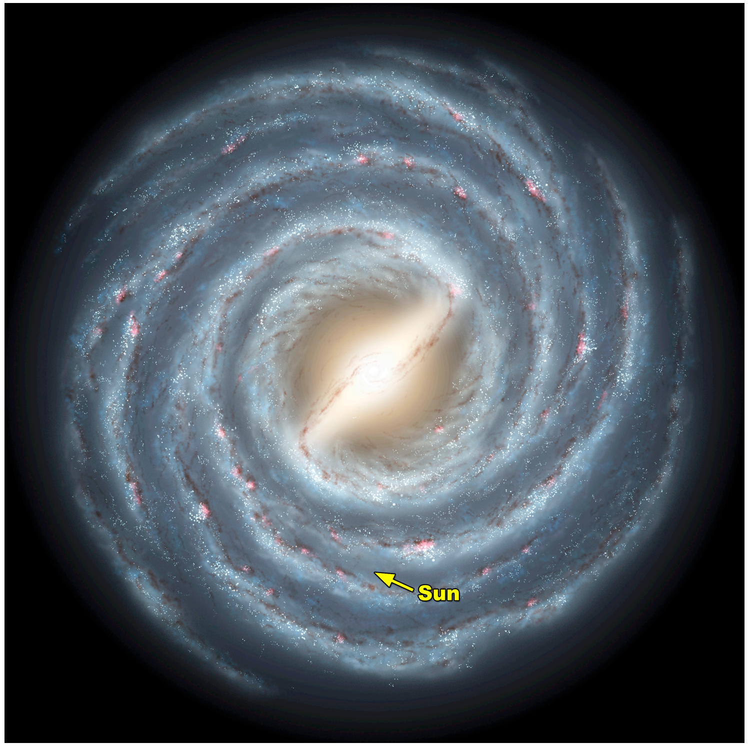
Dancing Neutrinos

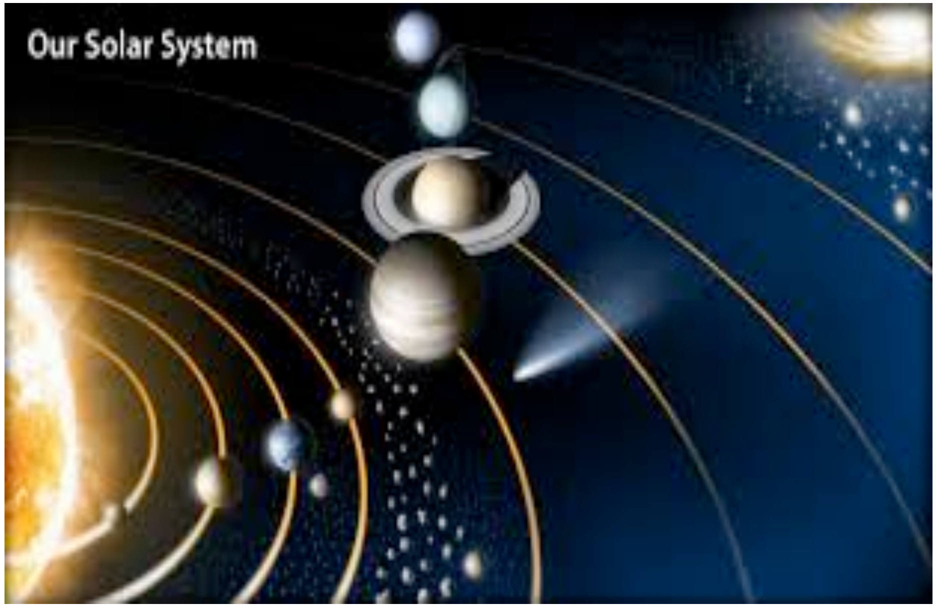
Seon-Hee Seo
(Sunny Seo)
Seoul National Univ.

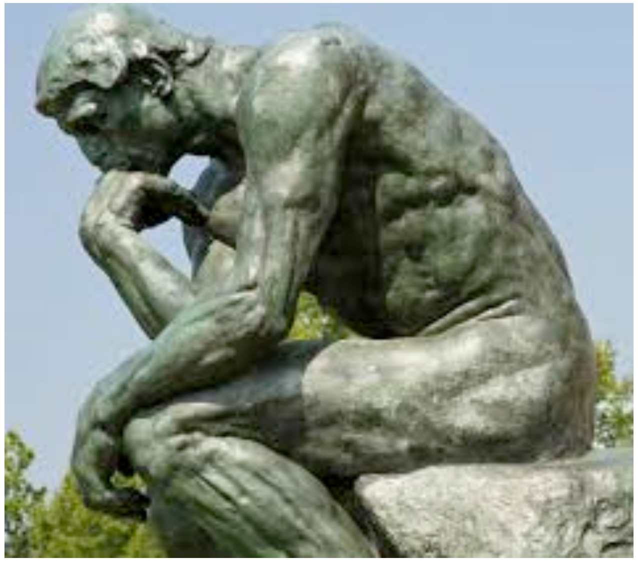
Physics Colloquium **Univ. of Hawaii** **Oct. 16, 2014**

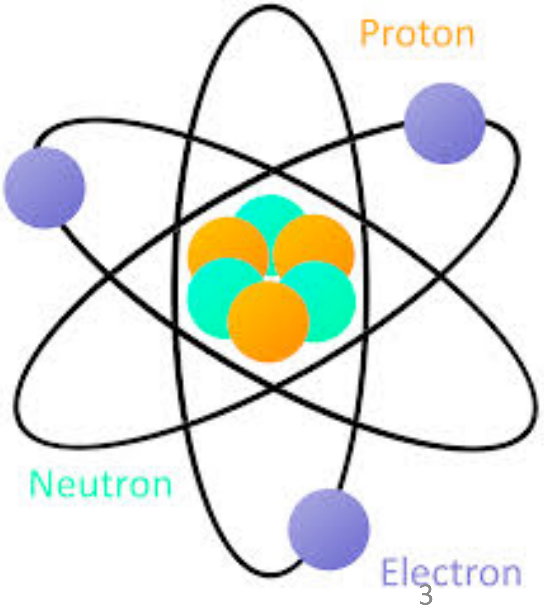
Our Universe




Sun

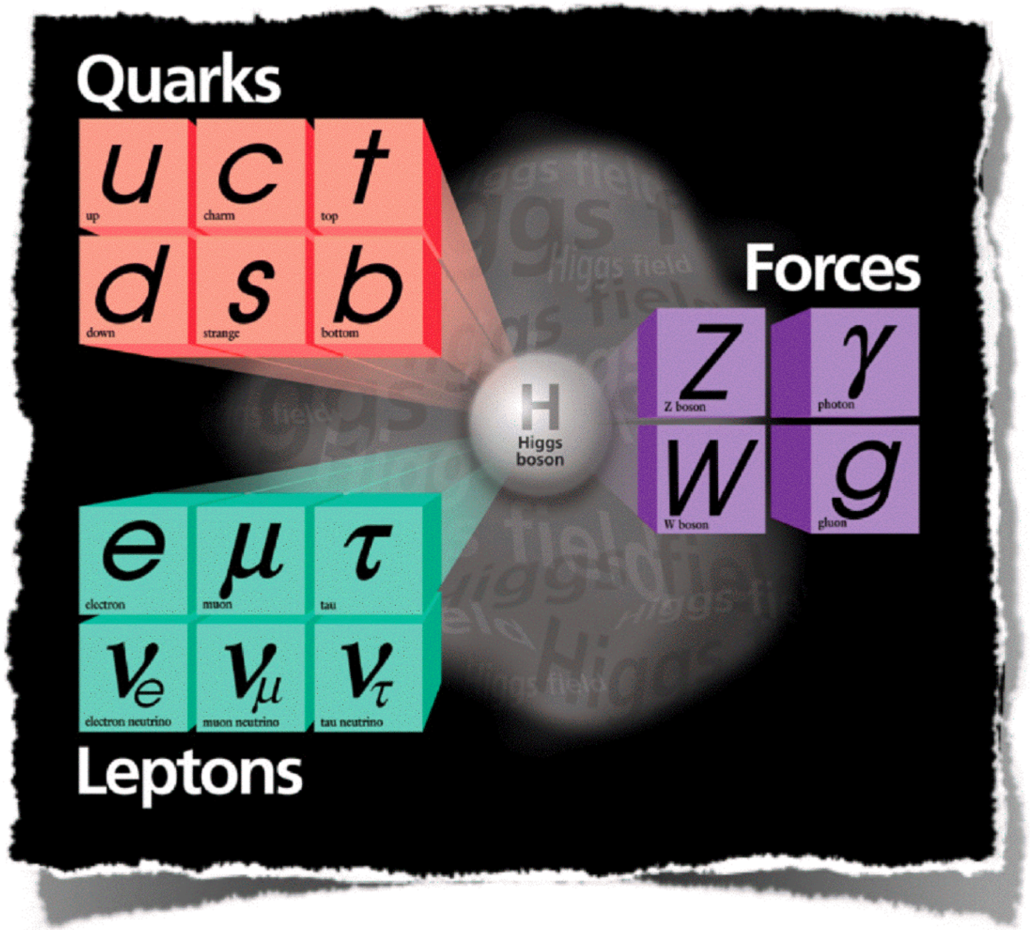

Our Solar System




Proton
Neutron
Electron

Standard Model

Standard Model (SM)



- ➢ Our visible universe is well described by SM.
- ➢ All particles in SM were discovered. (Higgs in 2012, finally..)

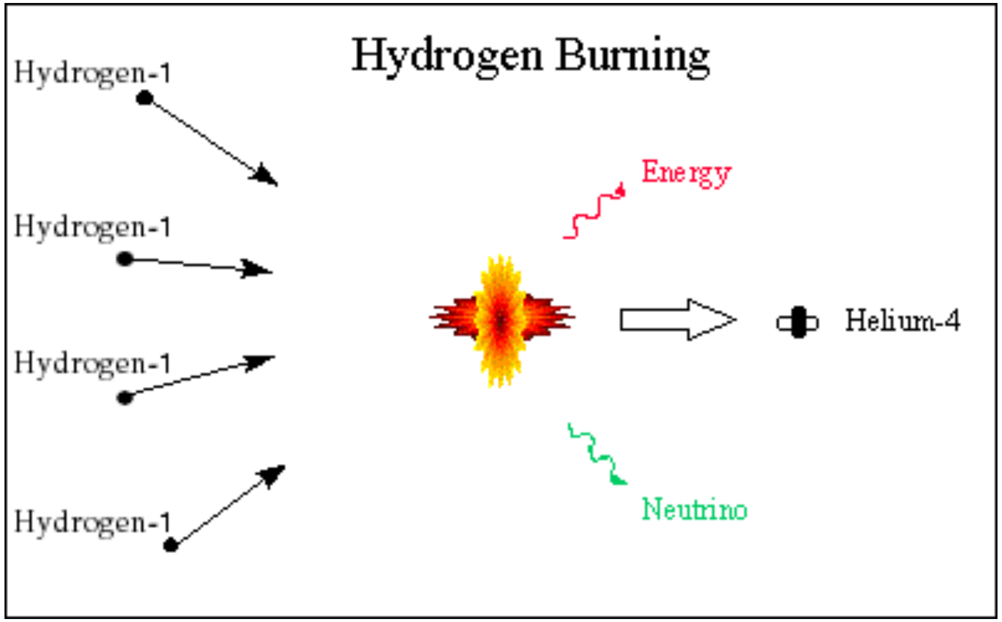
Total 37/114 Nobel Phys. Prizes in particle physics.

(1901-2014)

The END ?

Why Neutrinos Matter ?

- Neutrinos are fundamental particles but still remain mysterious !!



- We would not exist without neutrinos.

ex) Nuclear fusion process in the Sun.

Neutrino 101

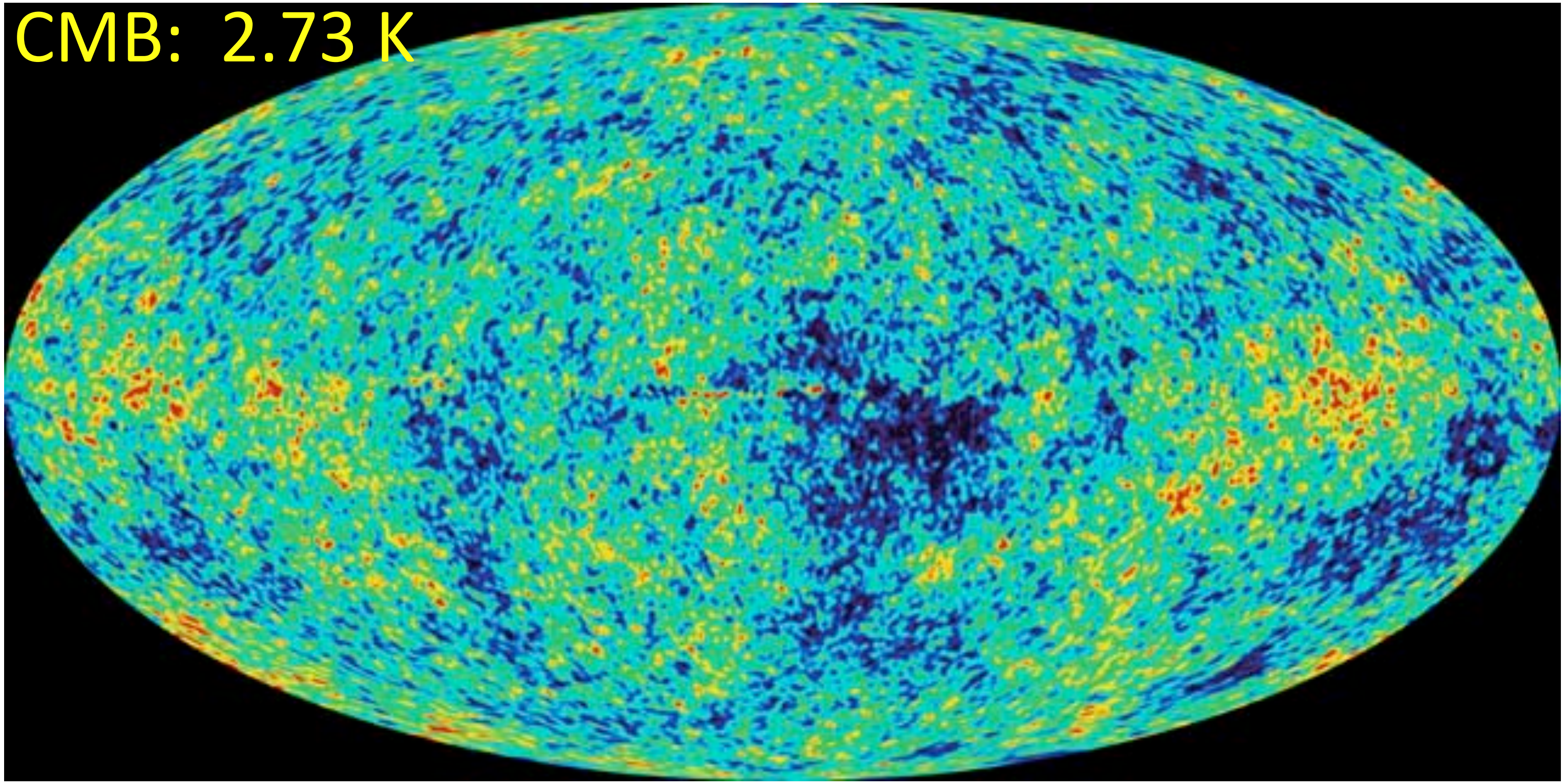
❑ Neutrino is the 2nd abundant particle after photon.

❑ Neutrino is more than 1,000,000 times lighter than e^- .

❑ Neutrino can travel close to the speed of light.

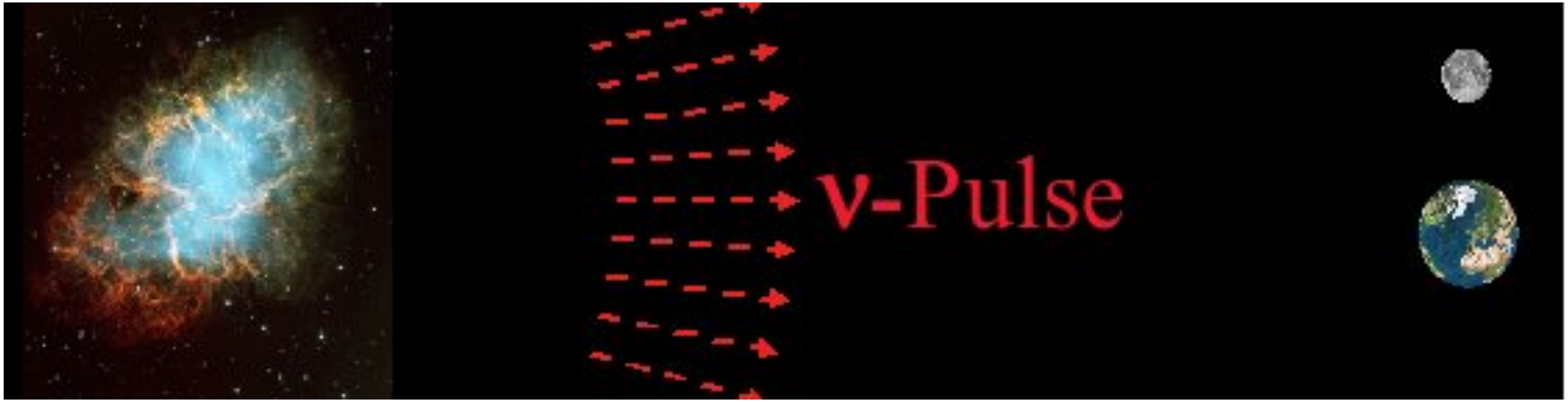
❑ Neutrino does not have a charge.

❑ Neutrino almost does not interact.

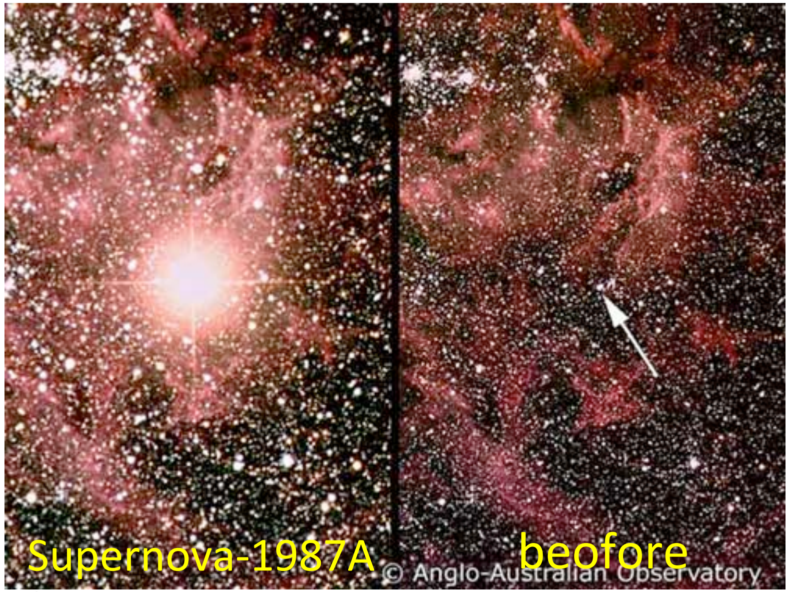


Big Bang ν : 1/3 billion/m^3,
Cosmic ν Background: 1.95 K

Oldest neutrino
in our universe
(CνB)



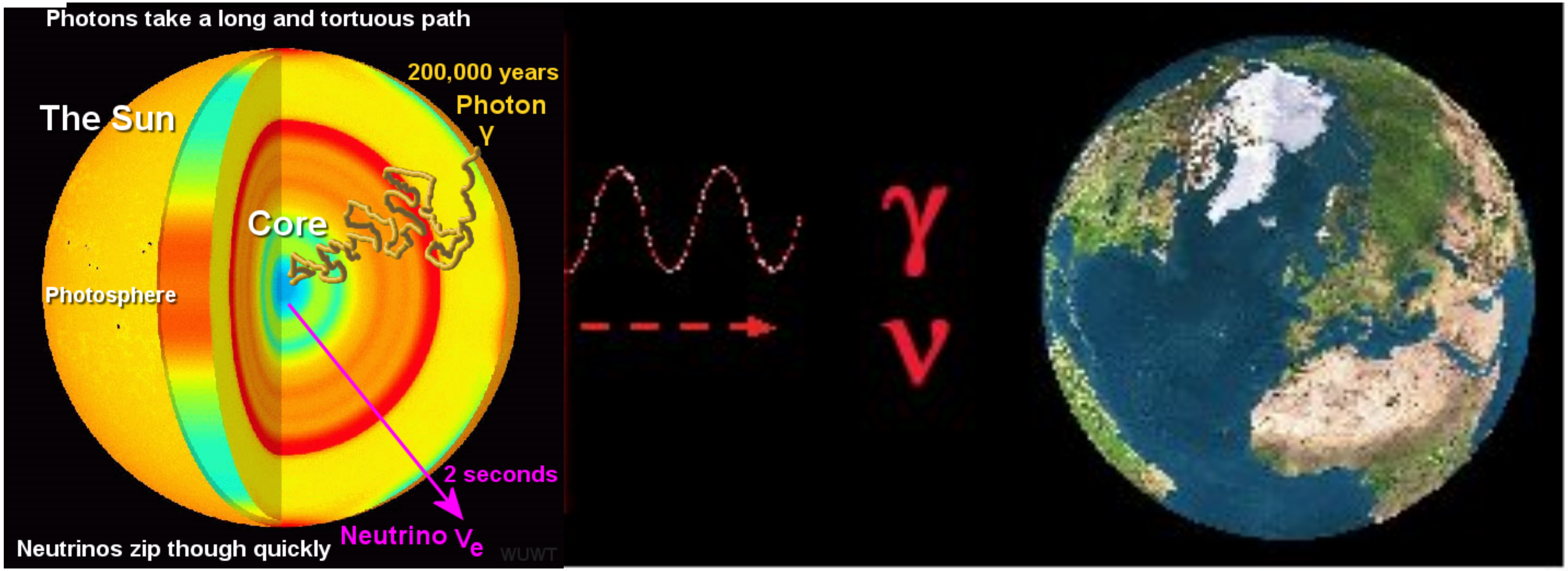
Supernova (SN) neutrinos



-- supernova: explosion at the end stage of a star's life.

-- all flavors of ν and $\bar{\nu}$ are produced from core collapsing SN.
(99% energy of the collapse is carried away by these ν).

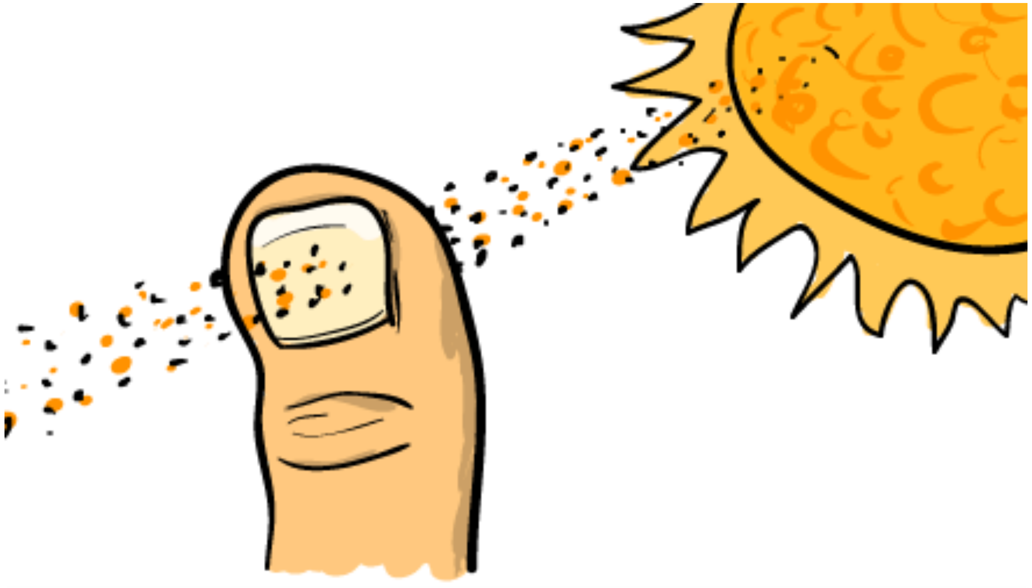
-- A total of 10^{58} ν production is expected.



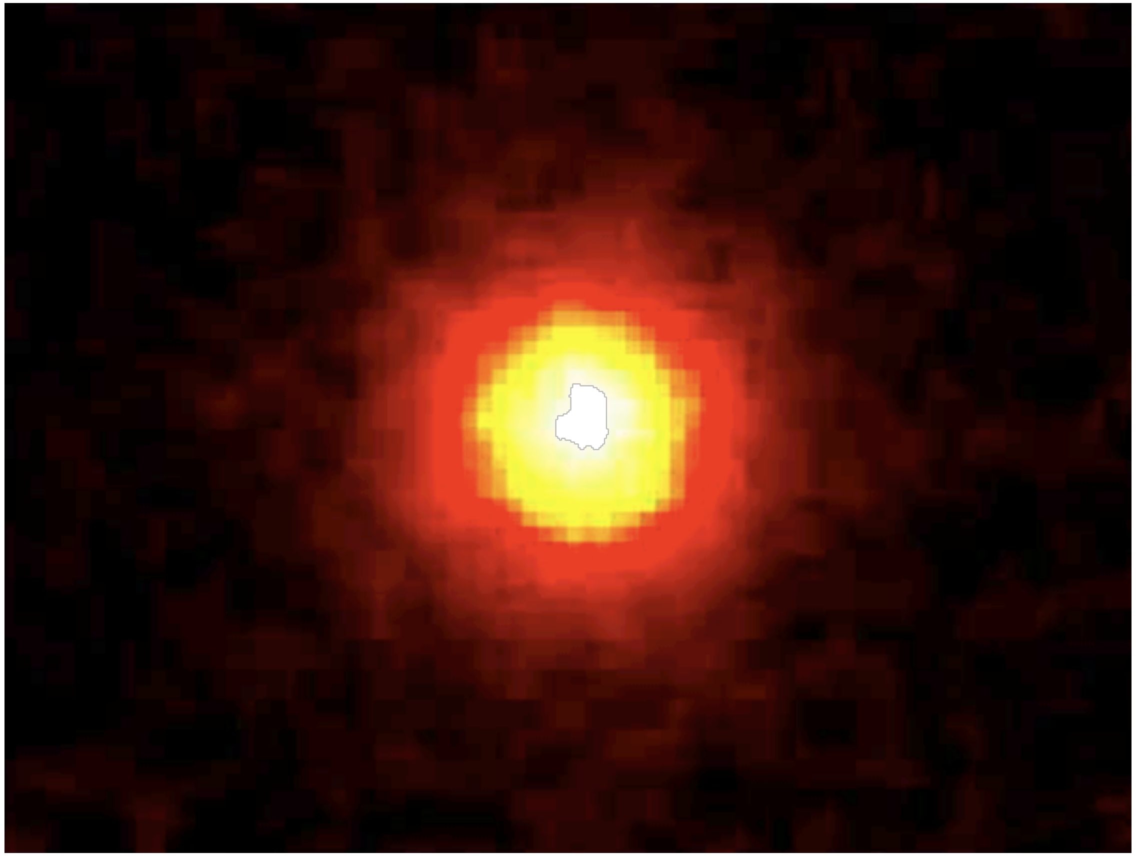
Solar neutrinos:

-- Electron neutrinos
from solar nuclear fusion

-- 65 billion solar neutrinos
per cm^2 per sec
(Day & Night)



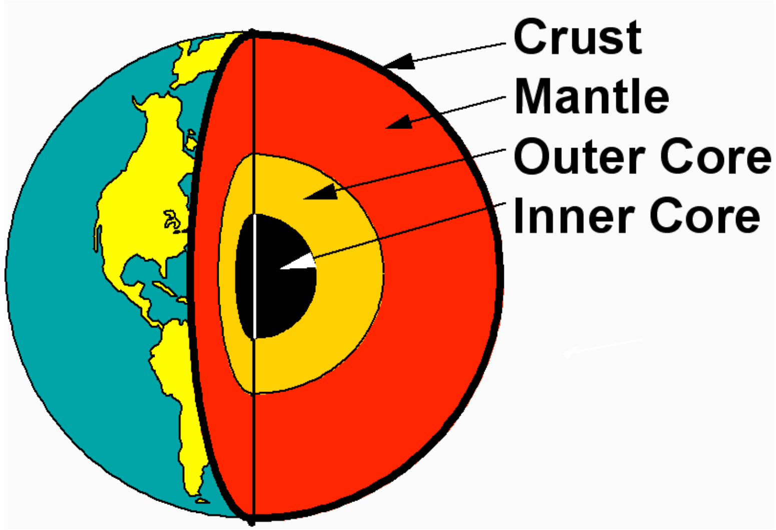
The Sun

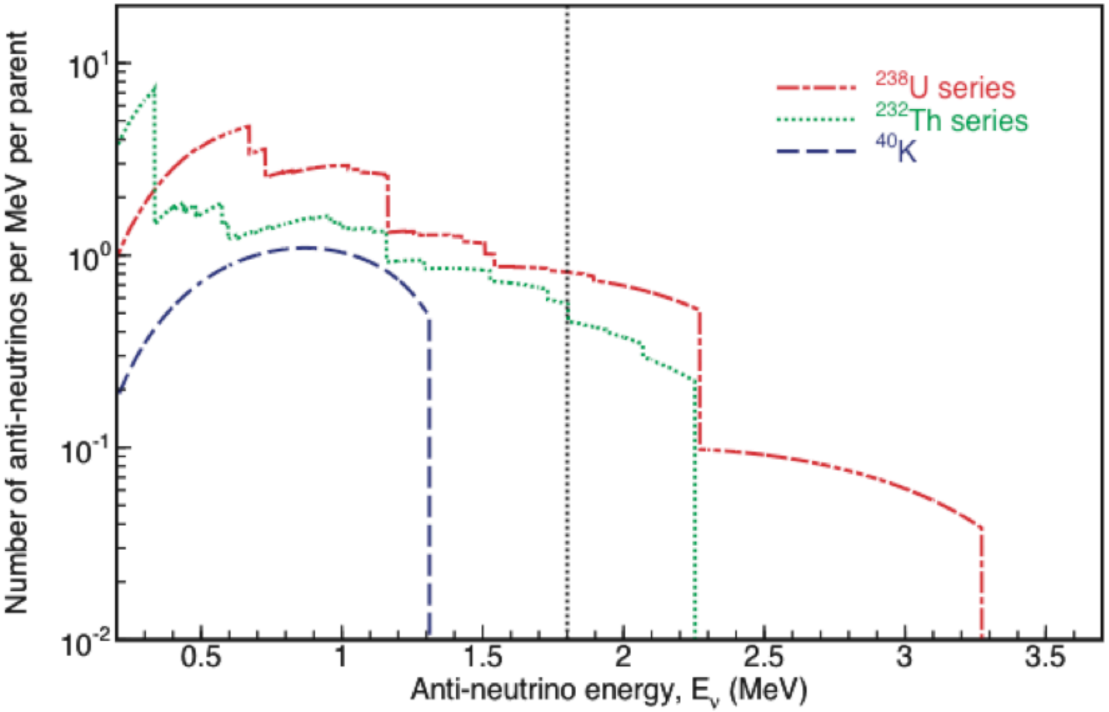


Sun image seen through neutrinos detected by Super-K experiment

- > 12 years of exposure by huge ν telescope (Super-K: 1-4)
- Actual Sun corresponds to 1/2 pixel in the center of the picture.

Earth Interior



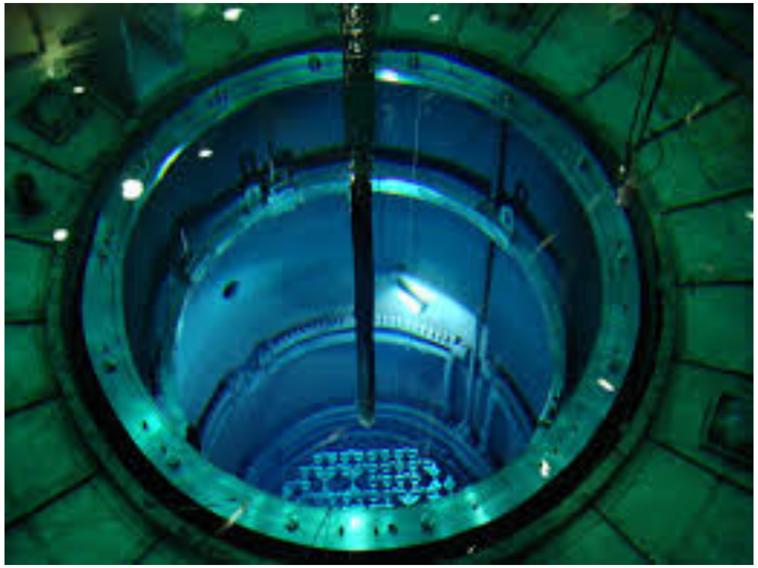


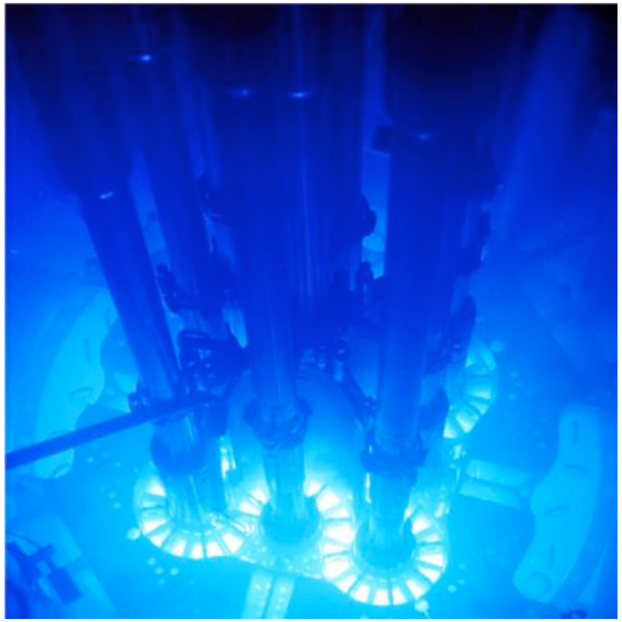
Geo neutrinos

Electron anti-neutrinos
from ^{238}U, ^{232}Th, & ^{40}K inside Earth interior .

-- Will reveal the mechanism inside the Earth interior.

-- 1 million & 10 million per cm^2 per sec (model dependent).





Reactor neutrinos

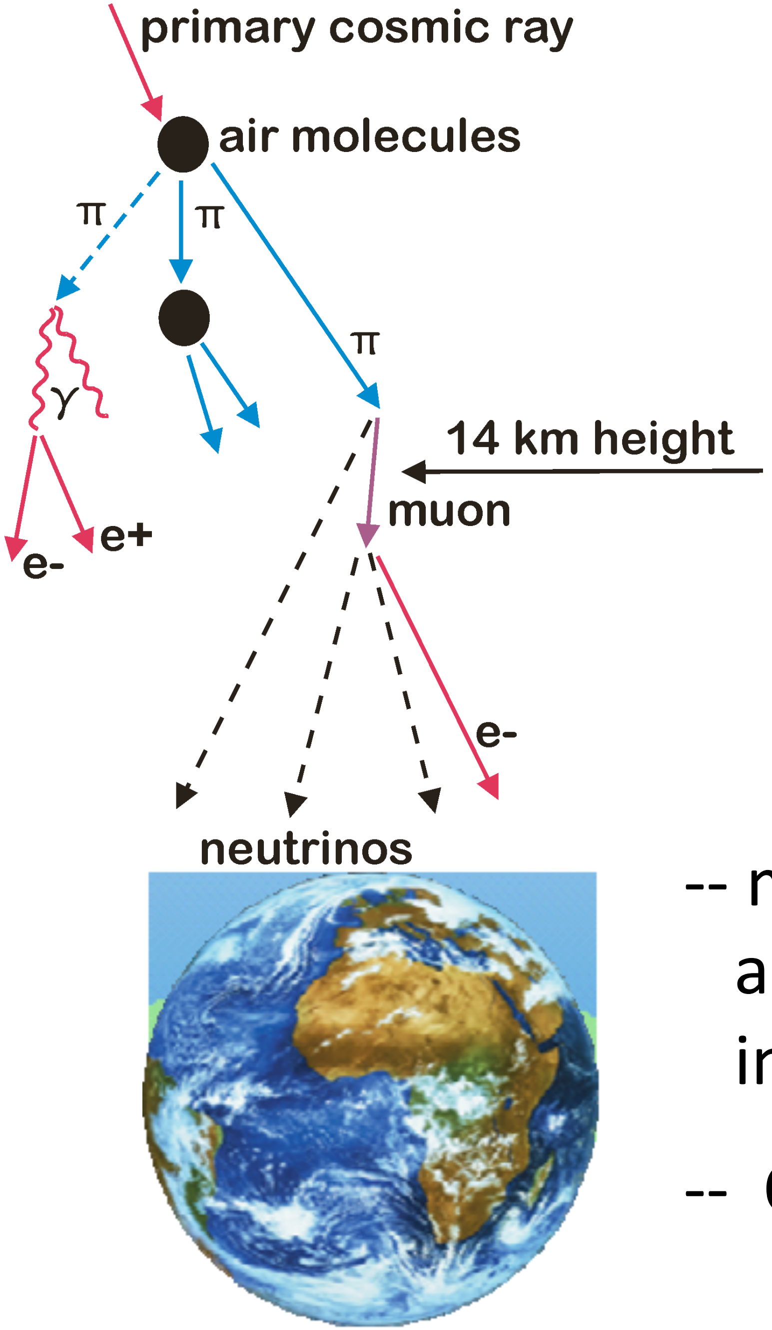
-- Electron anti-neutrinos from ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu fission

-- 2 x 10^{20} /sec per GW_{th} (typically 2.5 GW_{th} per commercial reactor core)

Accelerator neutrinos

-- typically muon neutrino production.

-- neutrino rate depends on beam intensity.



Conventional ν:

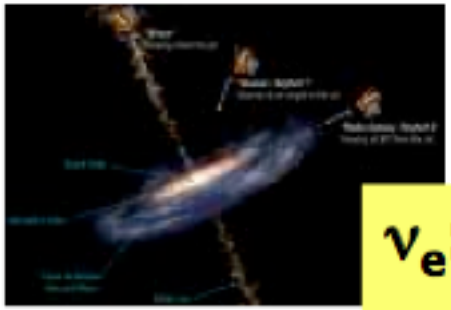
$$p + p \rightarrow \pi^- / \pi^+ \rightarrow \mu \, \nu_\mu \rightarrow (e) \, \nu_e \, \nu_\mu \nu_\mu$$

$$\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$$

Atmospheric neutrinos

-- muon neutrinos, electron neutrinos are produced from cosmic ray interactions in the atmosphere.

-- O(100) atm. ν per cm^2 per second @ 10 MeV (energy dependent)

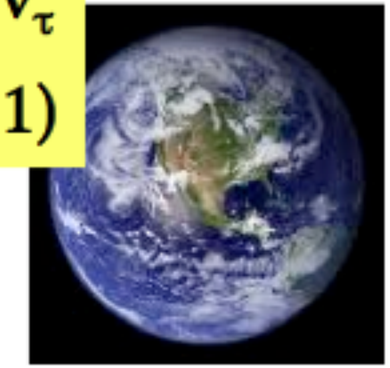


$$p + (p \text{ or } \gamma) \rightarrow \pi^0 \rightarrow \gamma\,\gamma$$
$$\rightarrow \pi^\pm \rightarrow \mu^\pm \nu_\mu \rightarrow e^\pm \nu_e \nu_\mu$$

$\nu_e : \nu_\mu : \nu_\tau$
$(1 : 2 : 0)$

(maximal $\nu_\mu \leftrightarrow \nu_\tau$ mixing)
oscillation

$\nu_e : \nu_\mu : \nu_\tau$
$(1 : 1 : 1)$



- Galactic ν
- Extra-galactic ν

Astrophysical neutrinos

-- muon neutrinos, electron neutrinos are produced from pp or pγ interactions at/near the source.

-- All three flavors arrive in the Earth !

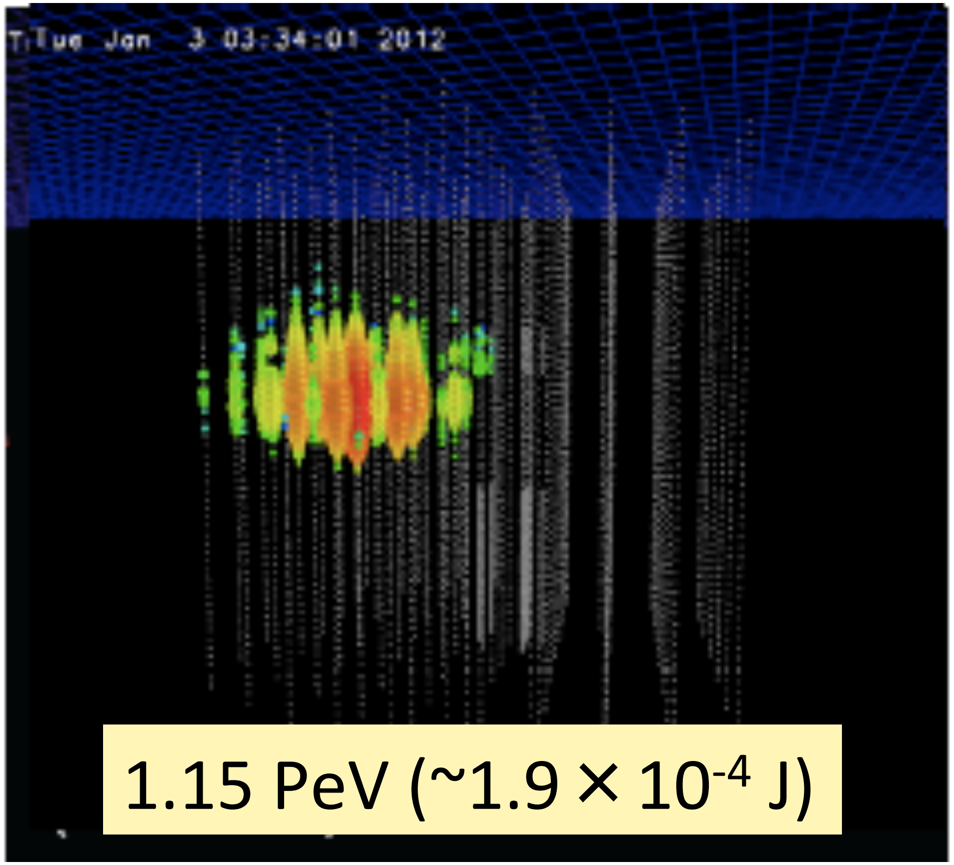
-- Smallest population among other origin of neutrinos.

-- IceCube claimed first observation of these neutrinos in 2012.

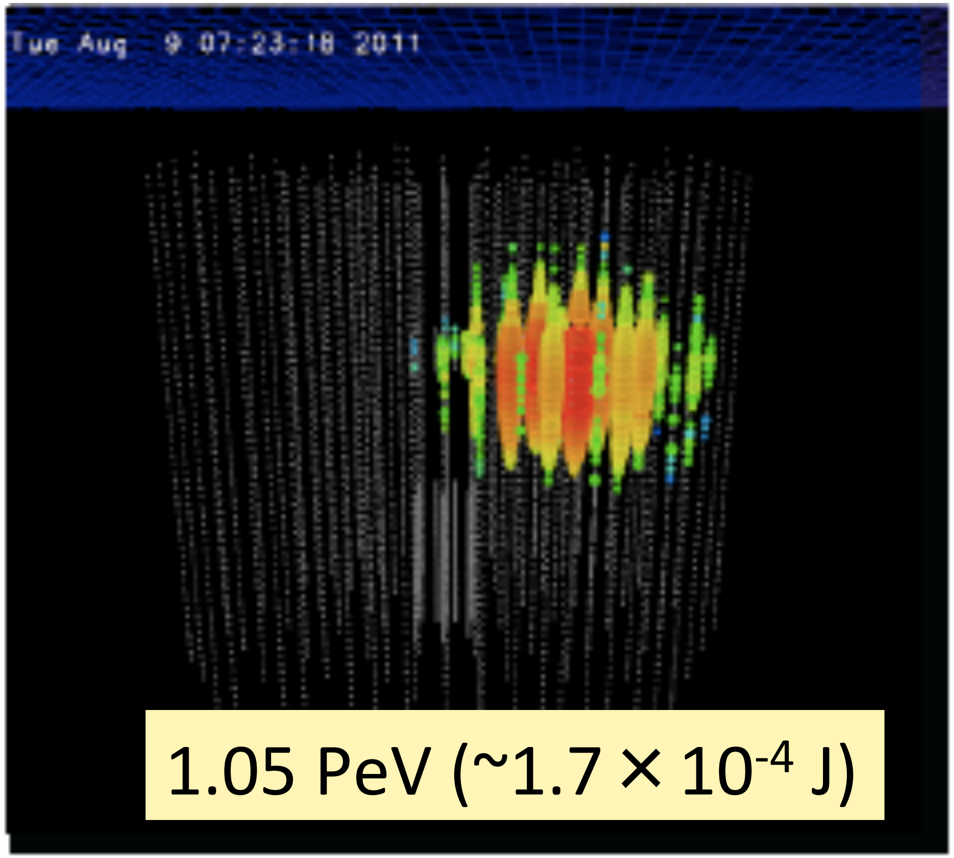
Astrophysical Neutrinos ?!

PRL 111 (2013) 021103

1 PeV = 10^{15} eV



1.15 PeV (~1.9×10^{-4} J)



1.05 PeV (~1.7×10^{-4} J)

- 5.7 σ with additional 35 candidate events.

Results submitted to PRL (May, 2014)

IceCube

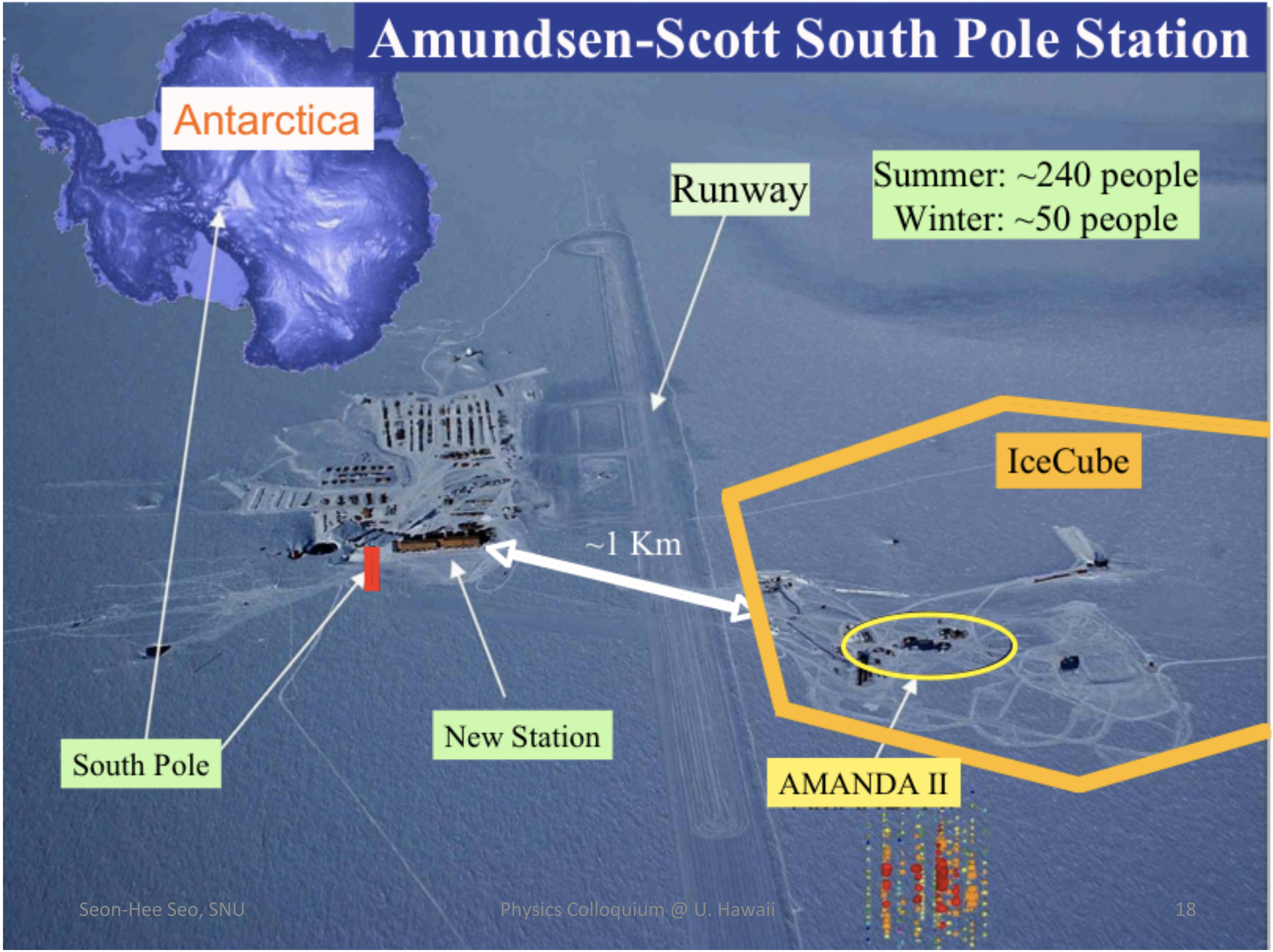
Astrophysical neutrino search

Open up a window to neutrino astronomy !

2007-2012:
@ Stockholm Univ.

2004-2007:
@ Penn State Univ.

Amundsen-Scott South Pole Station



Antarctica

Runway

Summer: ~240 people
Winter: ~50 people

IceCube

~1 Km

South Pole

New Station

AMANDA II

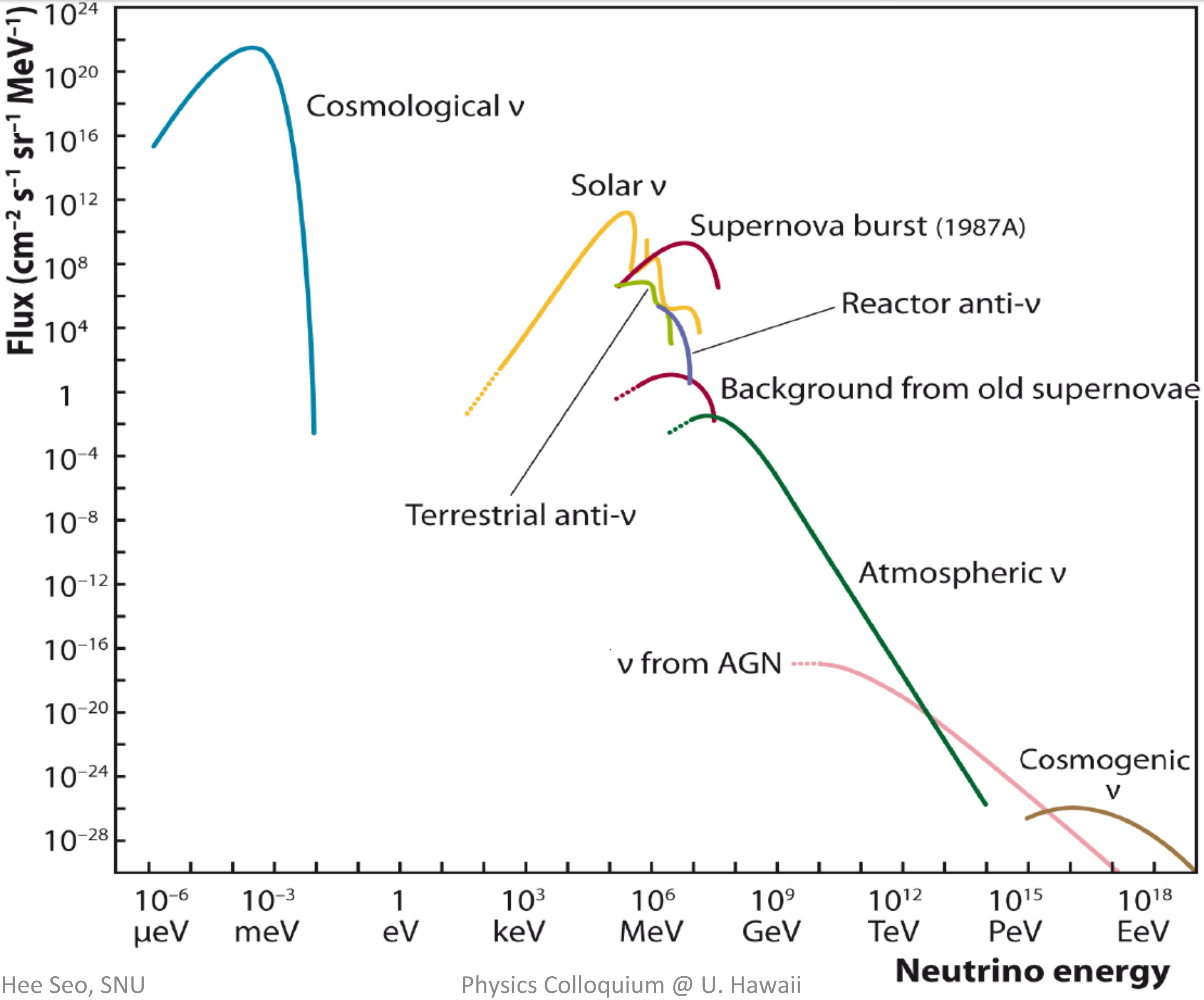
Me @ South Pole

Astrophysical neutrino search

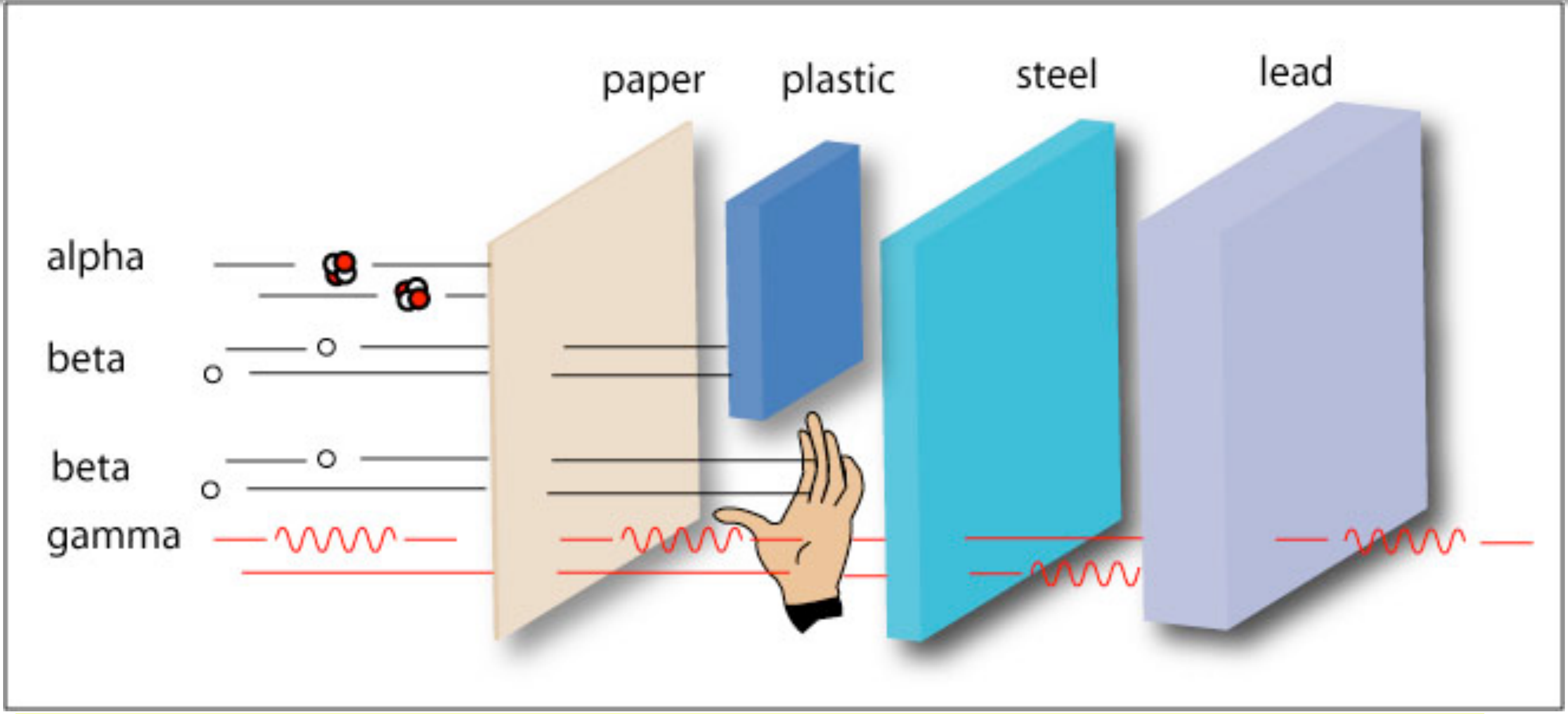
IceCube: 2004 - 2012

01.31.2006

Neutrino Flux & Energy Ranges



Neutrinos: Ghost Particles

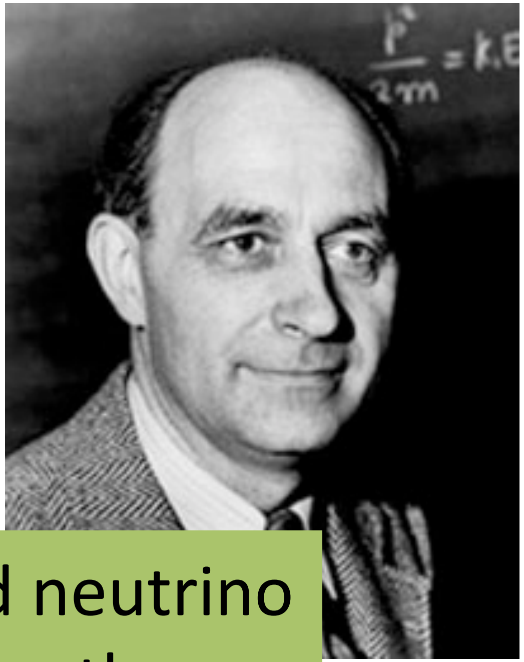


Neutrinos pass through:

→ about 1 light year thickness of lead is needed to stop half of neutrinos.

→ Hard to detect. No worry for neutrino irradiation.

1930 Pauli postulated neutrino
to explain beta decay problem
(3 body kinematics but only 2 particles seen)

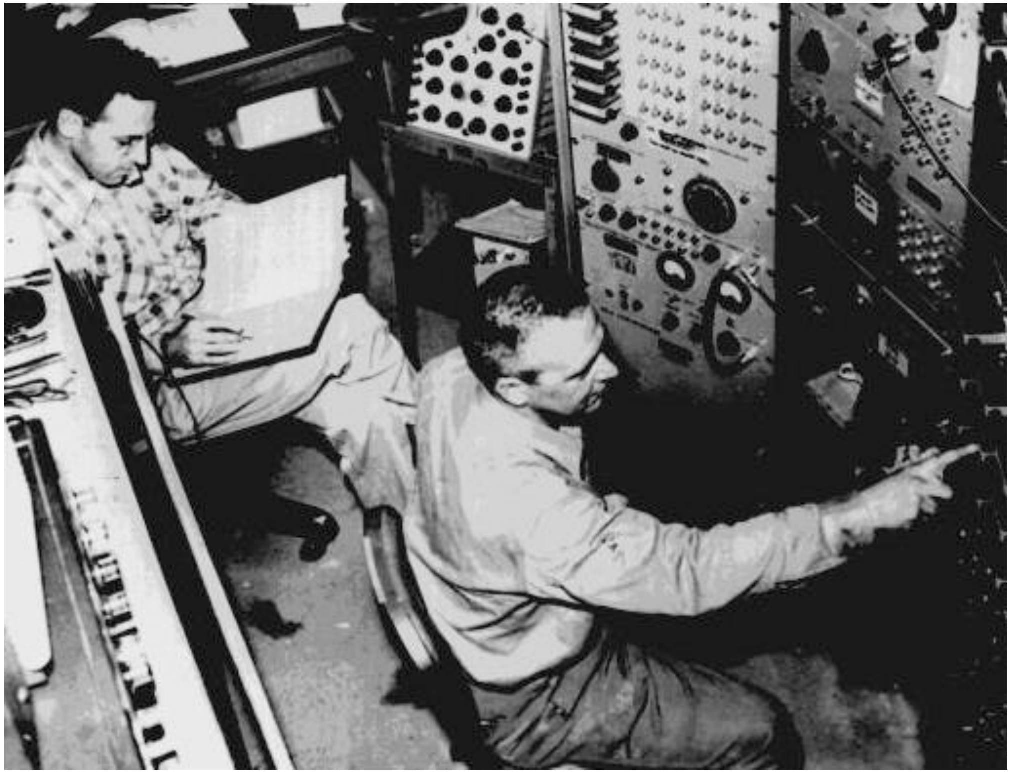


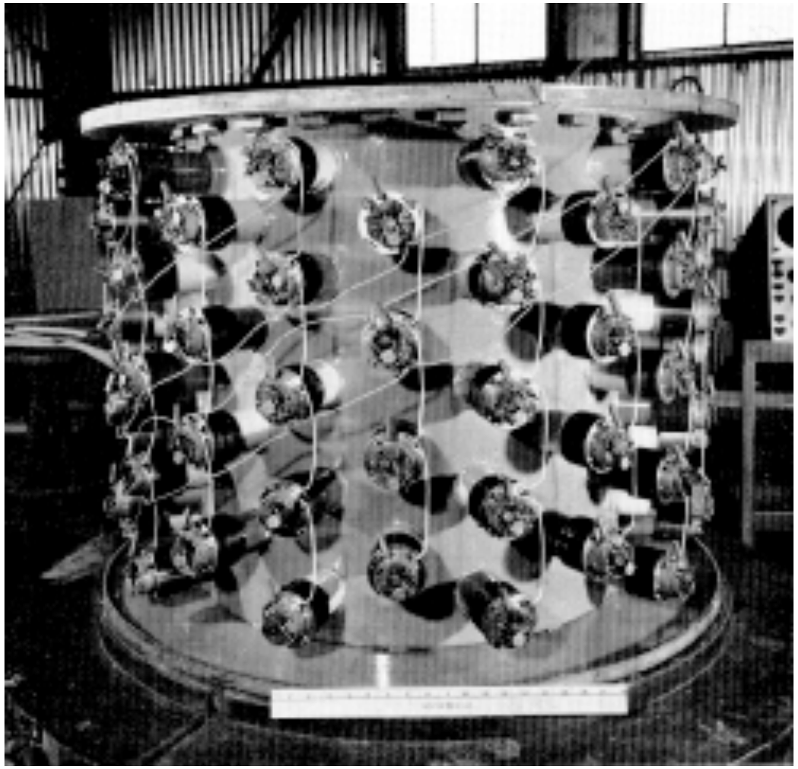
1933 Fermi baptized neutrino
In his weak interaction theory

1957 Pontecorvo suggested
Neutrino mass and oscillation

Бруно Понтекорво

First discovery of neutrinos in 1956 !
→ Nobel Prize in 1995 to Reines & Cowan



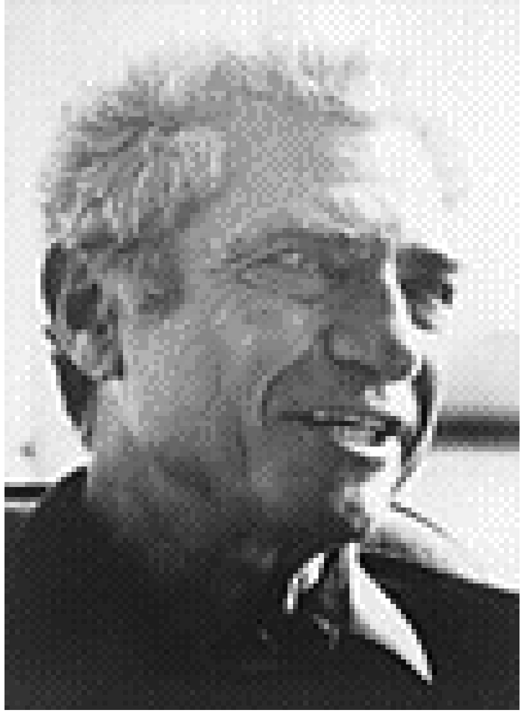


Using reactor neutrinos @ Savannah River, S. Carolina

Muon neutrinos discovery in 1962 in BNL
→ Nobel Prize in 1988.

Lederman

Schwartz

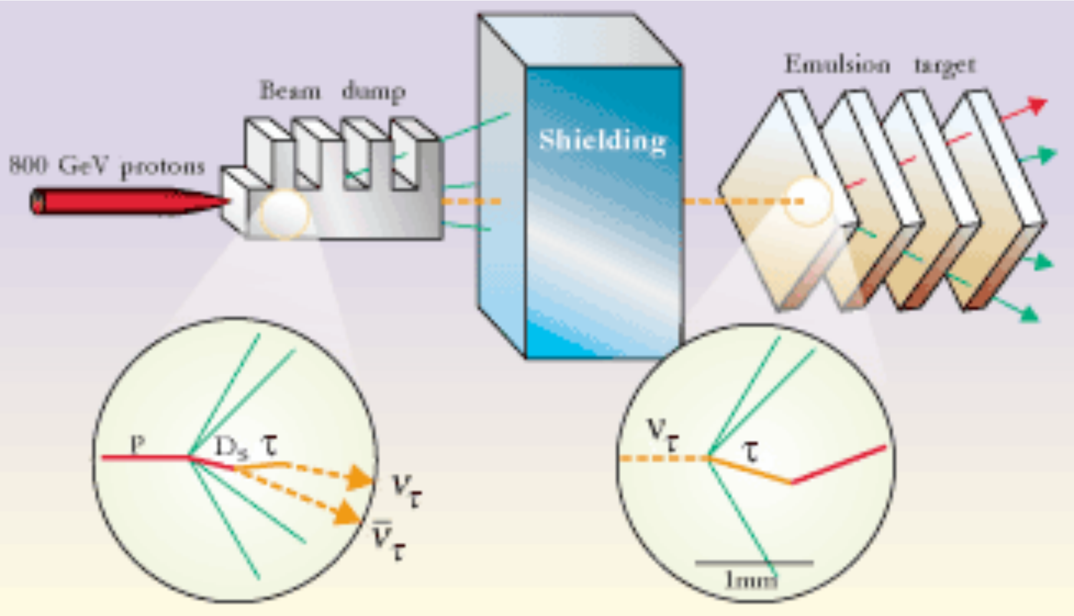


Steinberger

Tau neutrino discovery in 2000 in Fermilab (DONUT)

DONUT = Direct Observation of NU Tau

Not this one



Observed 4 ν_τ events

$$\left\{ \nu_e ,\ \nu_\mu ,\ \nu_\tau \right\}$$

3 flavors of ν in SM

Neutrino are
generated or detected
In flavor eigen-state.

$$\{\nu_e, \nu_\mu, \nu_\tau\}$$

3 flavors of ν in SM

Neutrino are generated or detected In flavor eigen-state.

$$\{\nu_1, \nu_2, \nu_3\}$$

3 mass eigen-state of ν

When neutrinos travel, they exist as mass eigen-state.

$\{\nu_e, \nu_\mu, \nu_\tau\}$

Generation, detection

3 flavors of ν in SM

$\{\nu_1, \nu_2, \nu_3\}$

When traveling

3 mass eigen-state of ν

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

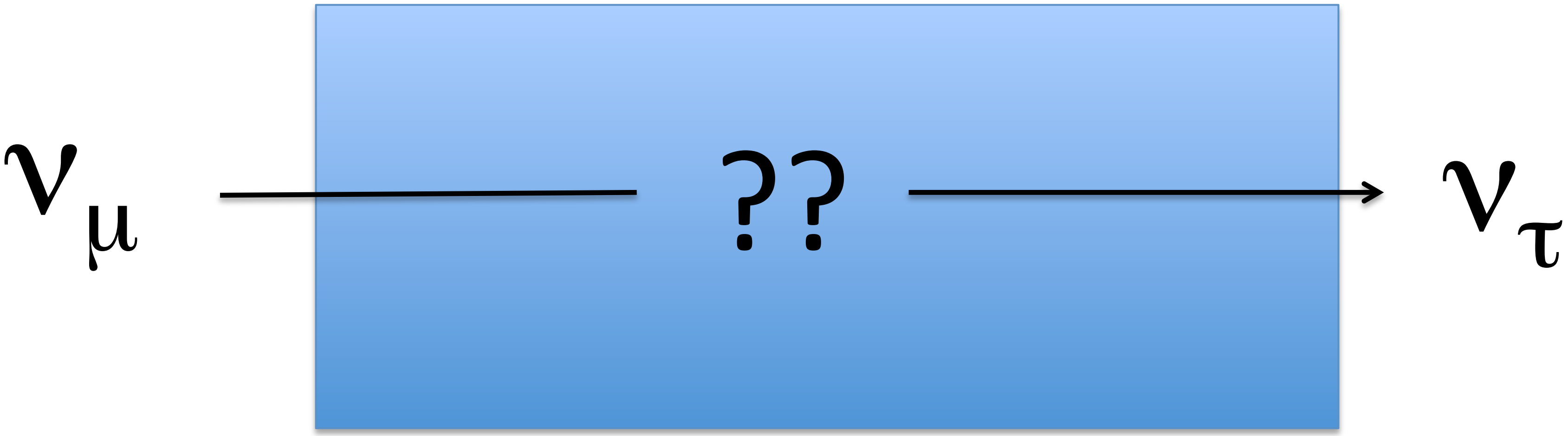
- Pontecorvo
- Maki
- Makagawa
- Sakaga

PMNS matrix in 1962

production

traveling

detection

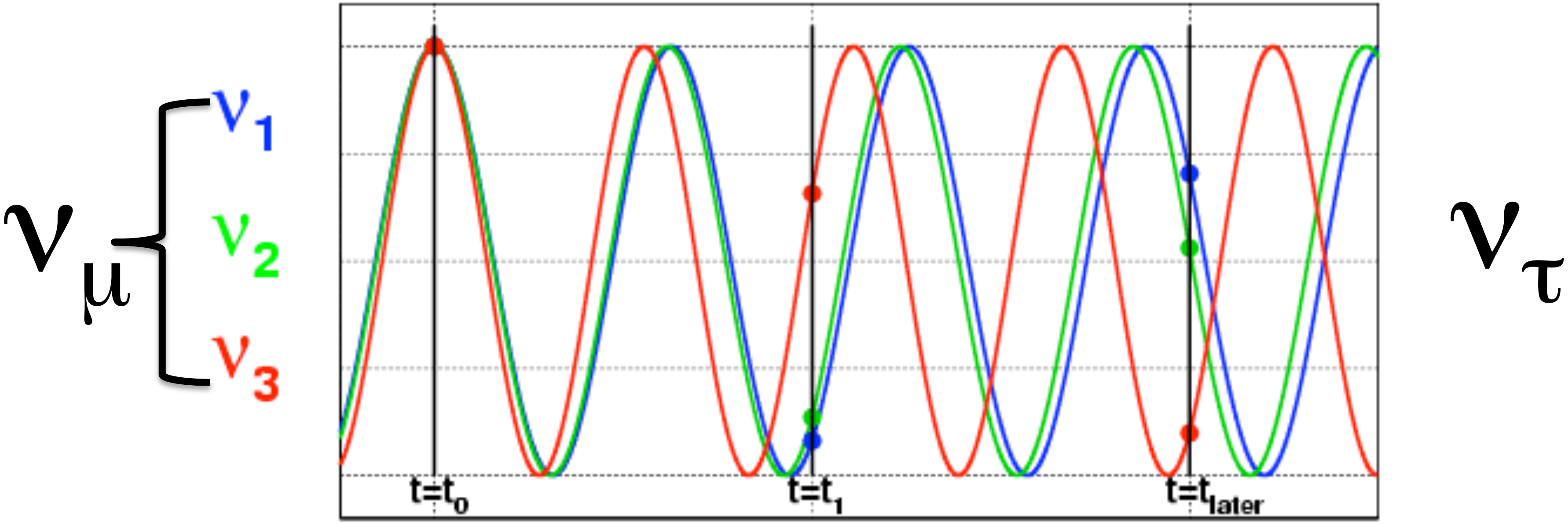


ν_μ → ?? → ν_τ

production

traveling

detection



ν_μ $\left\{ \begin{array}{l} \nu_1 \\ \nu_2 \\ \nu_3 \end{array} \right.$

ν_τ

(only schematic)

PMNS matrix

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

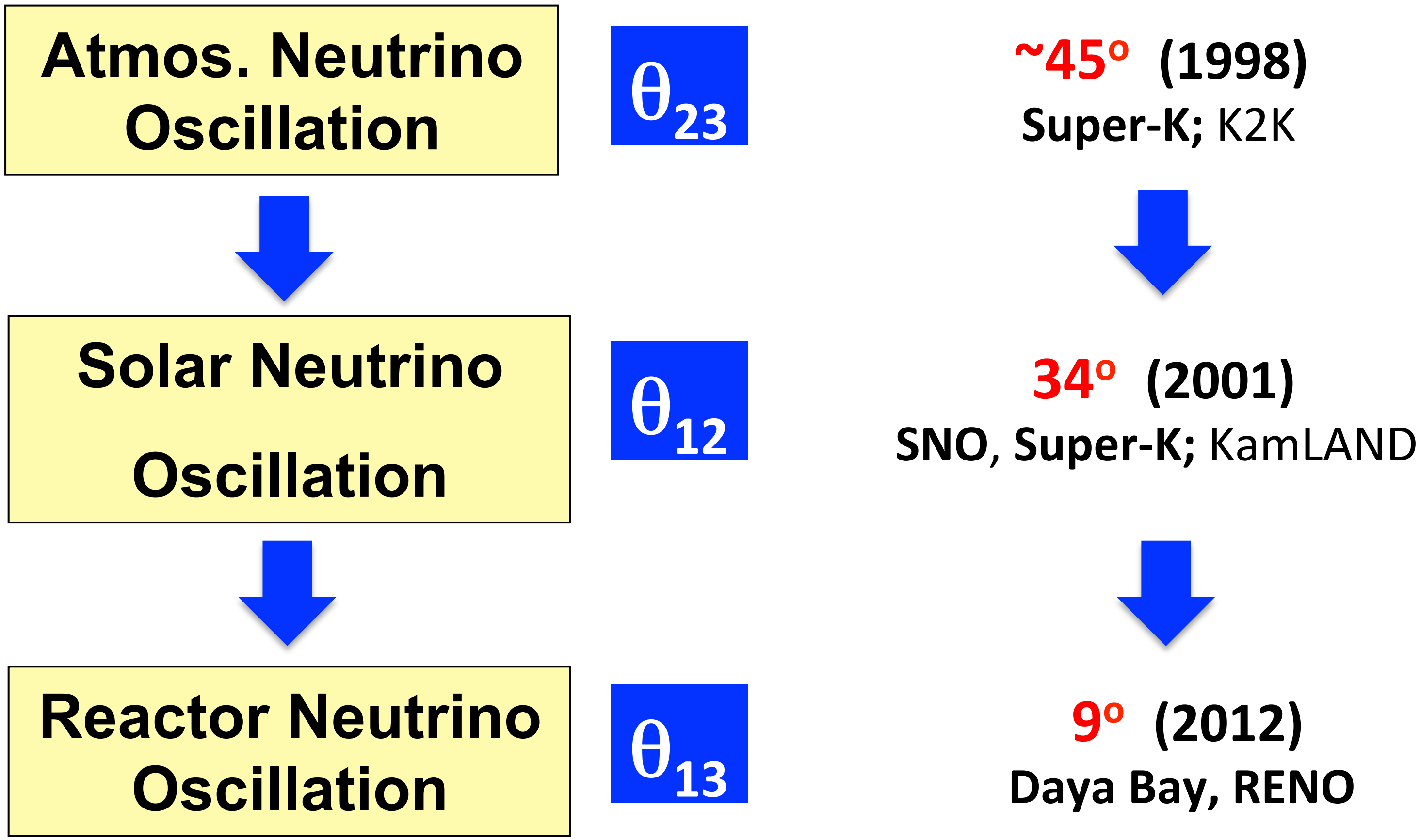
$$= \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12}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

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

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

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

Neutrino Oscillation



Atmos. Neutrino Oscillation

θ_{23}

~45° **(1998)**

Super-K; K2K

Solar Neutrino Oscillation

θ_{12}

34° **(2001)**

SNO, **Super-K;** KamLAND

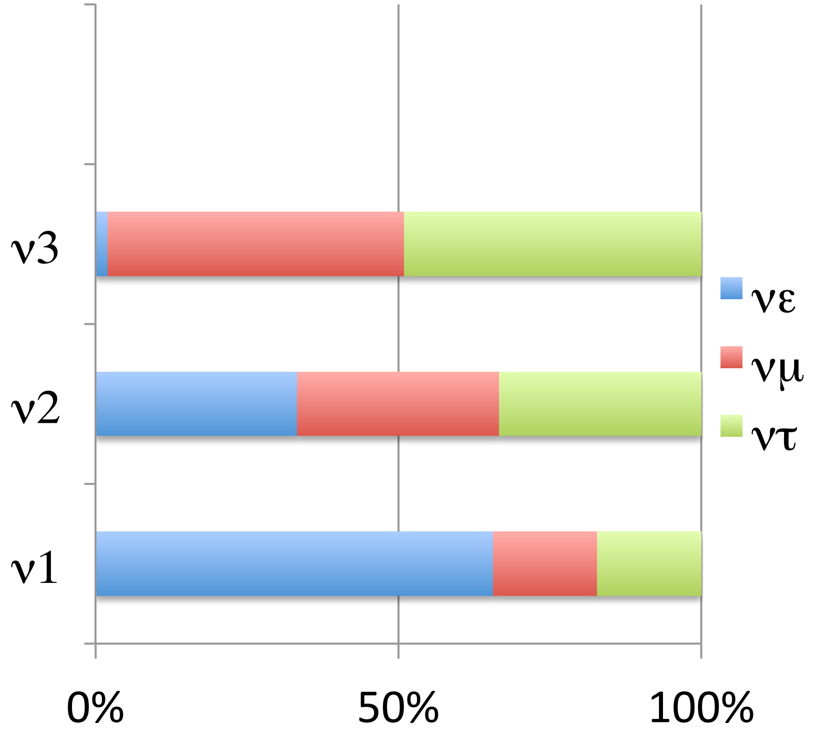
Reactor Neutrino Oscillation

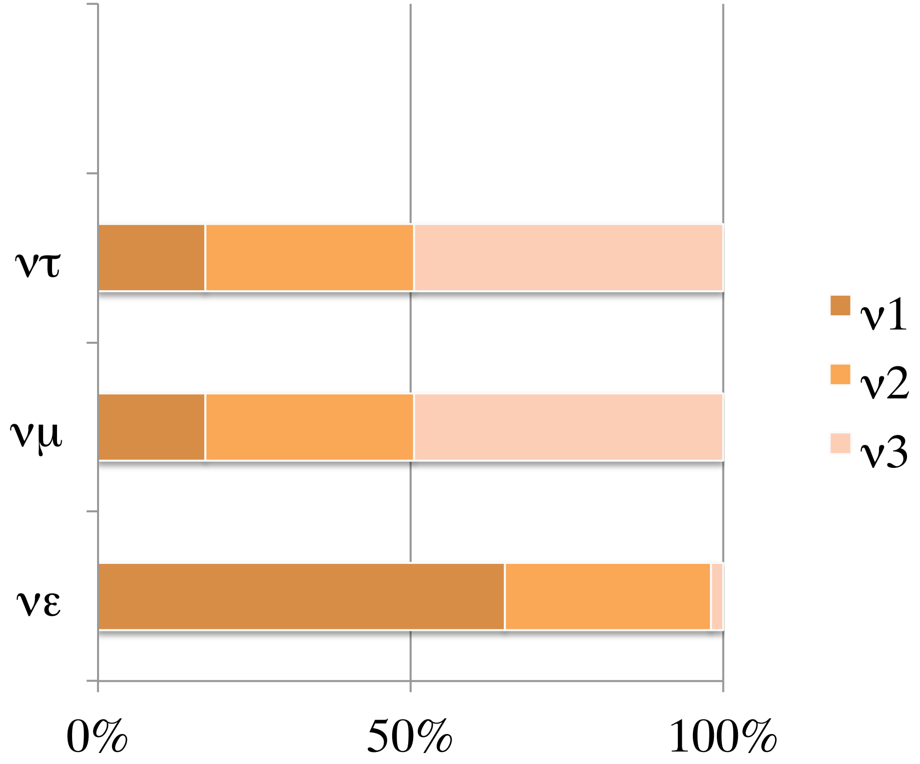
θ_{13}

9° **(2012)**

Daya Bay, RENO

Fractional ν components





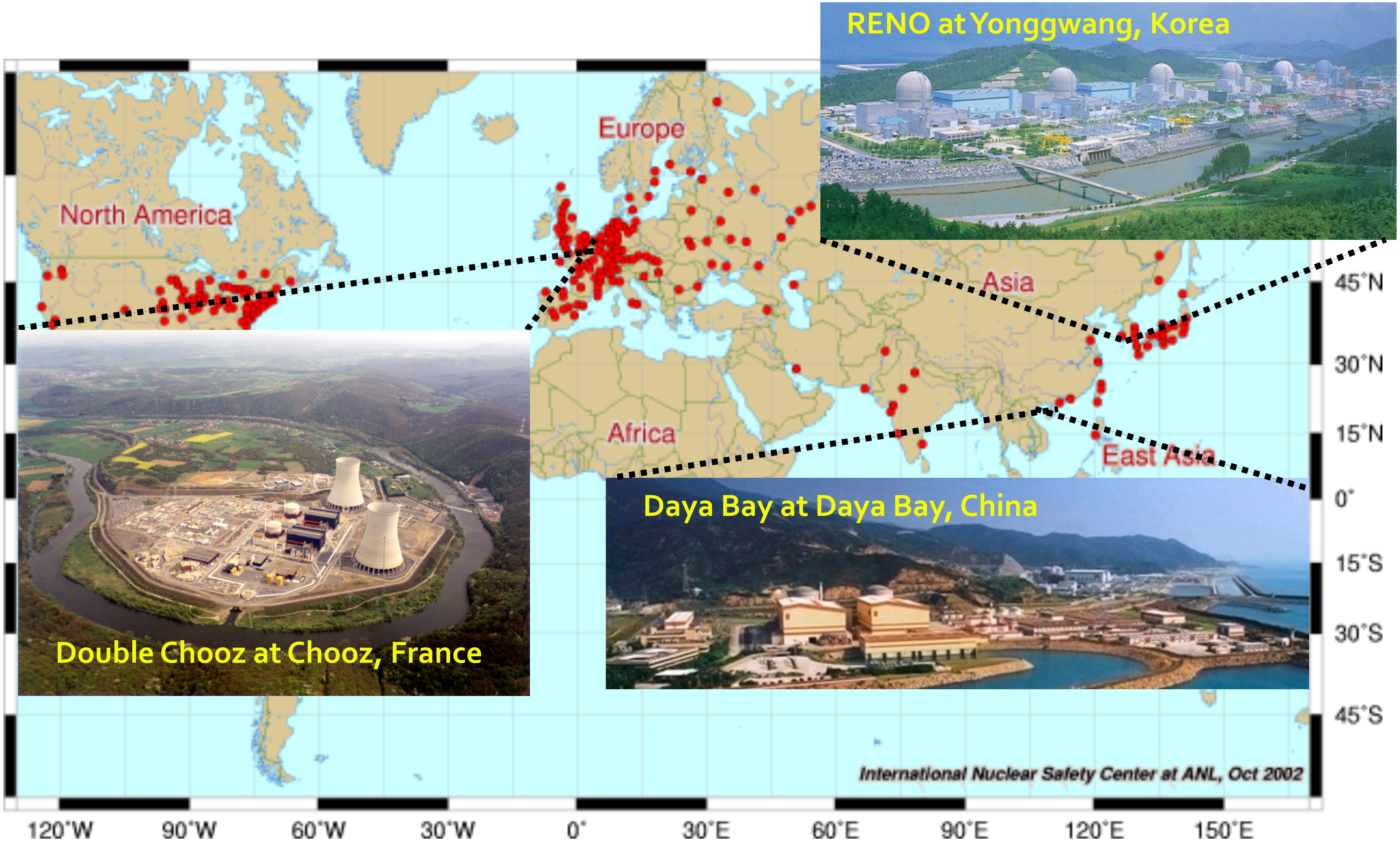
Why θ_{13} ?

- ✓ To complete 3 ν mixing angle matrix (PMNS).
- ✓ To open a window for leptonic CP phase measurement
  LBNO, LBNE, Hyper-K (θ_{13} != 0)

$$P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \propto \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos\theta_{13} \sin\delta$$

- ✓ To allow neutrino mass hierarchy measurement
  (← requires not too small θ_{13})
- ✓ To allow precise measurement of atm. neutrino oscillation parameters

Reactor θ_{13} Experiments



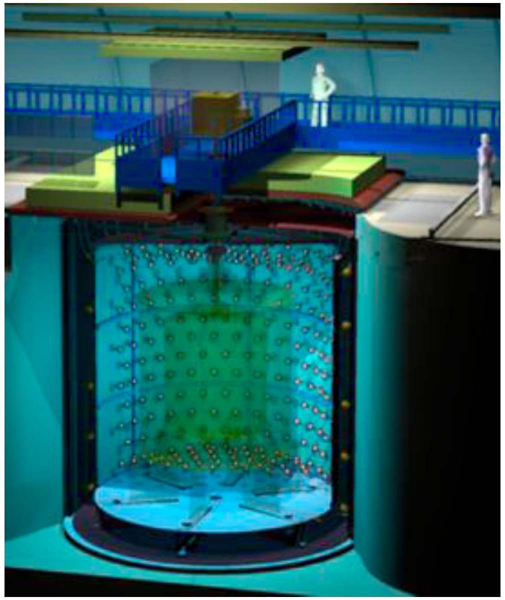
RENO at Yonggwang, Korea

Double Chooz at Chooz, France

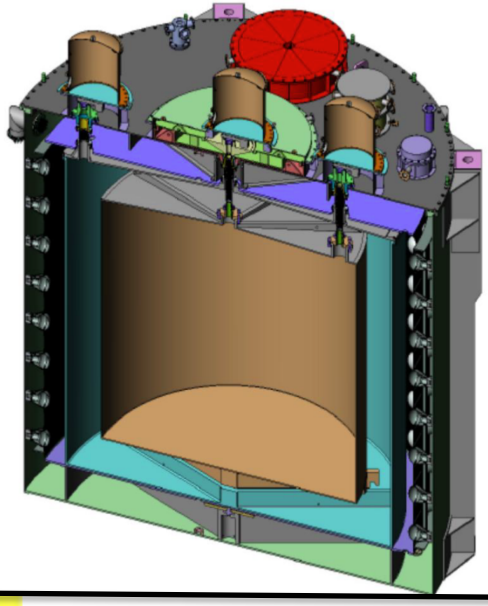
Daya Bay at Daya Bay, China

International Nuclear Safety Center at ANL, Oct 2002

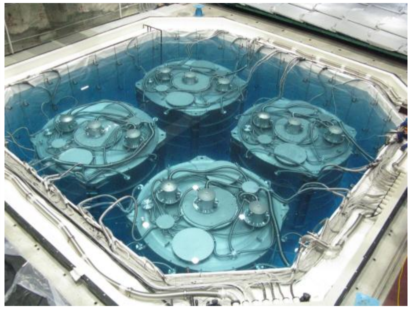
θ_{13} Reactor Neutrino Detectors

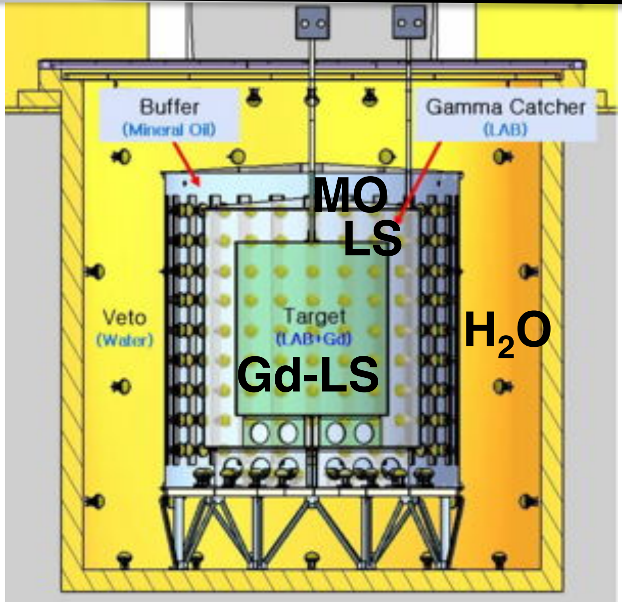


DOUBLE CHOOZ

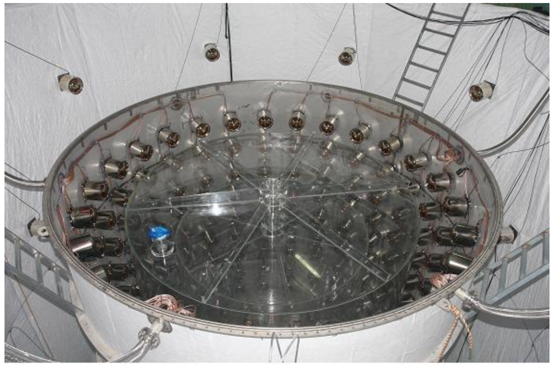


Daya Bay θ_{13}

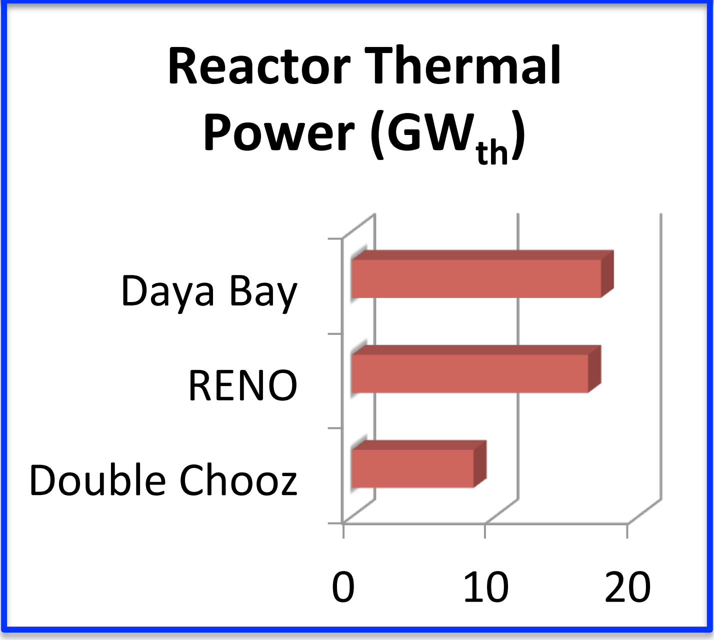


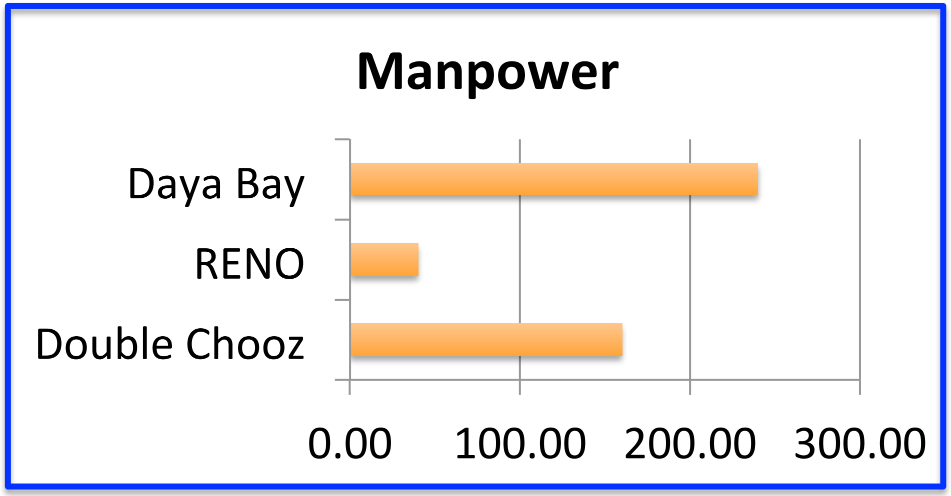


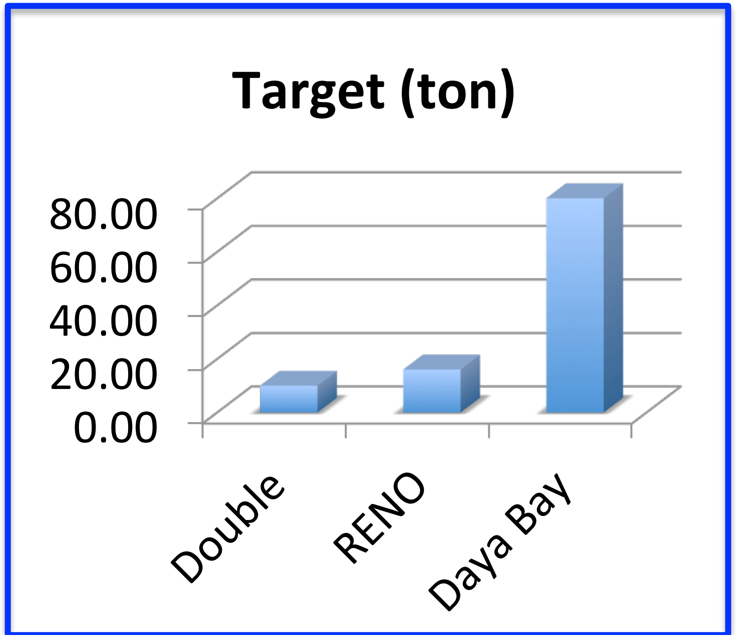
RENO
ν θ_{13}



Comparisons

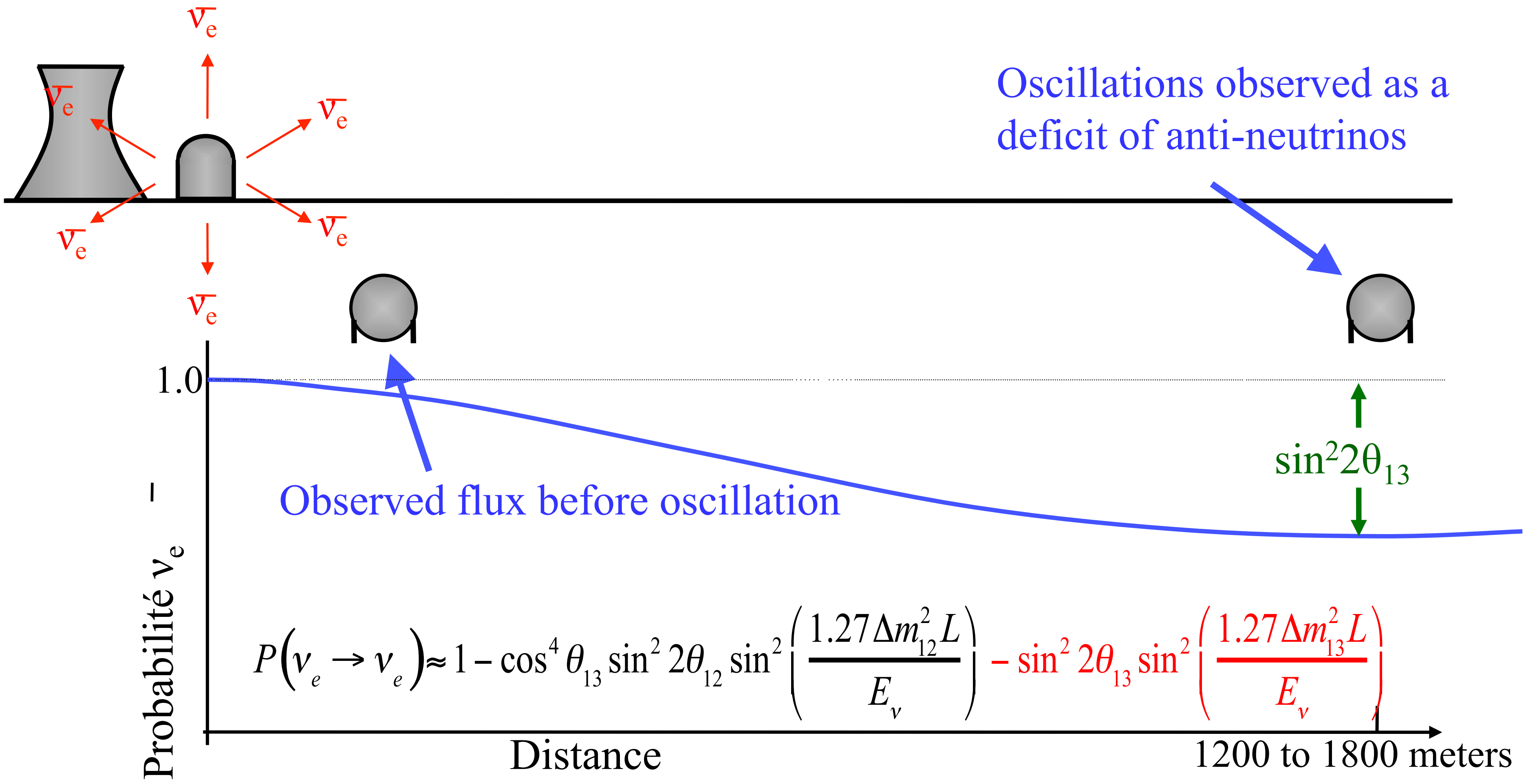






RENO was the 1^{st} exp to take data using both near & far detectors ! in June, 2011.

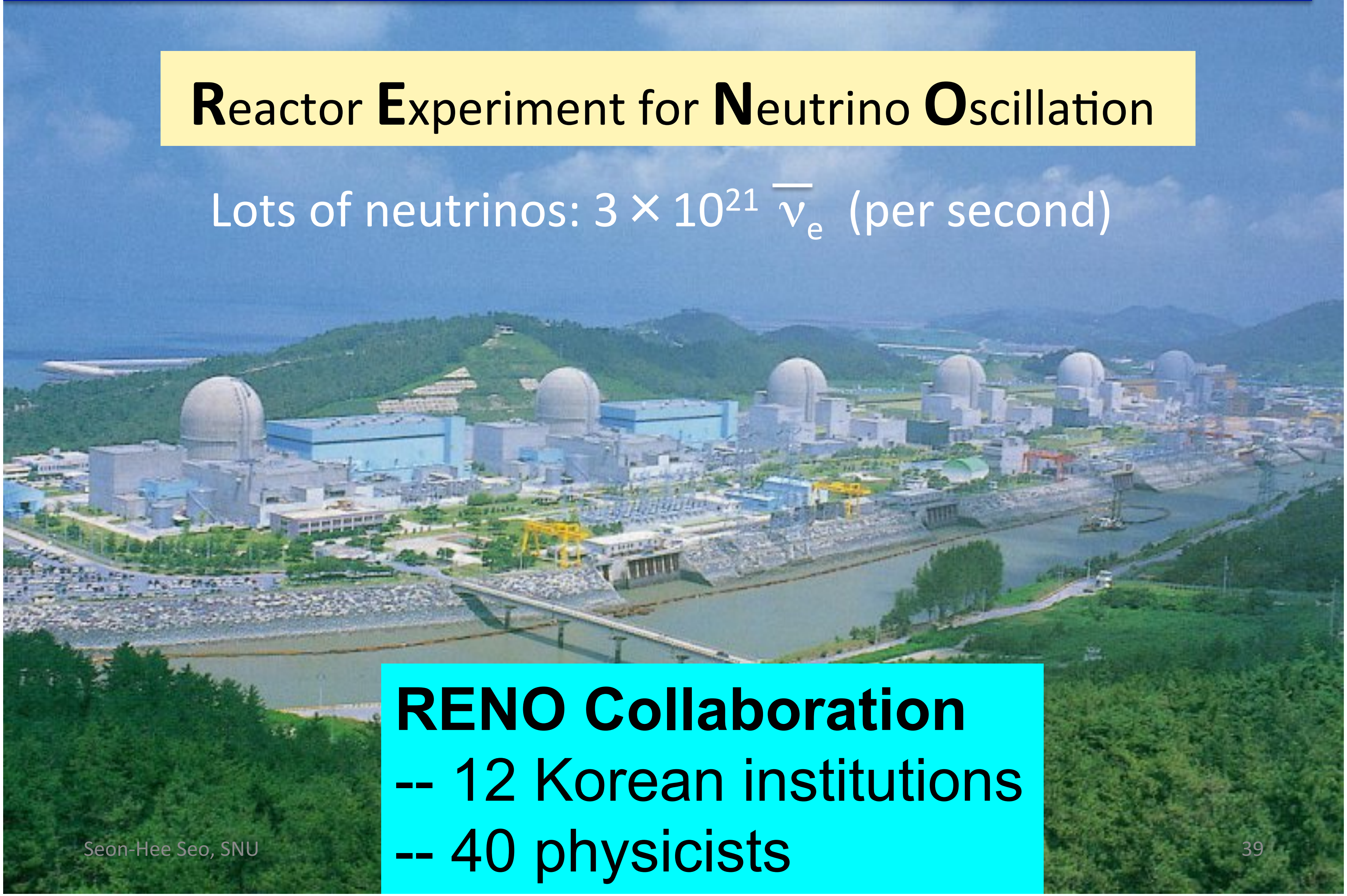
How to measure θ_{13} ?



$$P(\nu_e \rightarrow \nu_e) \approx 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{1.27\Delta m_{12}^2 L}{E_\nu}\right) - \sin^2 2\theta_{13}\sin^2\left(\frac{1.27\Delta m_{13}^2 L}{E_\nu}\right)$$

☐ Find disappearance of $\bar{\nu}_e$ fluxes due to neutrino oscillation as a function of energy using multiple, identical detectors to reduce the systematic errors in 1% level.

RENO



Reactor **E**xperiment for **N**eutrino **O**scillation

Lots of neutrinos: 3×10^{21} $\overline{\nu}_e$ (per second)

RENO Collaboration

-- 12 Korean institutions

-- 40 physicists

RENO Collaboration

11 institutions and 40 physicists in Korea

- Chonbuk National University
- Chonnam National University
- Chung-Ang University
- Dongshin University
- GIST
- Gyeongsang National University
- Kyungpook National University
- Sejong University
- Seoul National University
- Seoyeong University
- Sungkyunkwan University

- **Total cost : $10M**
- Start of project : **2006**
- The first experiment running with both near & far detectors since **Aug. 2011**

YongGwang (靈光) :

Reactor **E**xperiment for **N**eutrino **O**scillation

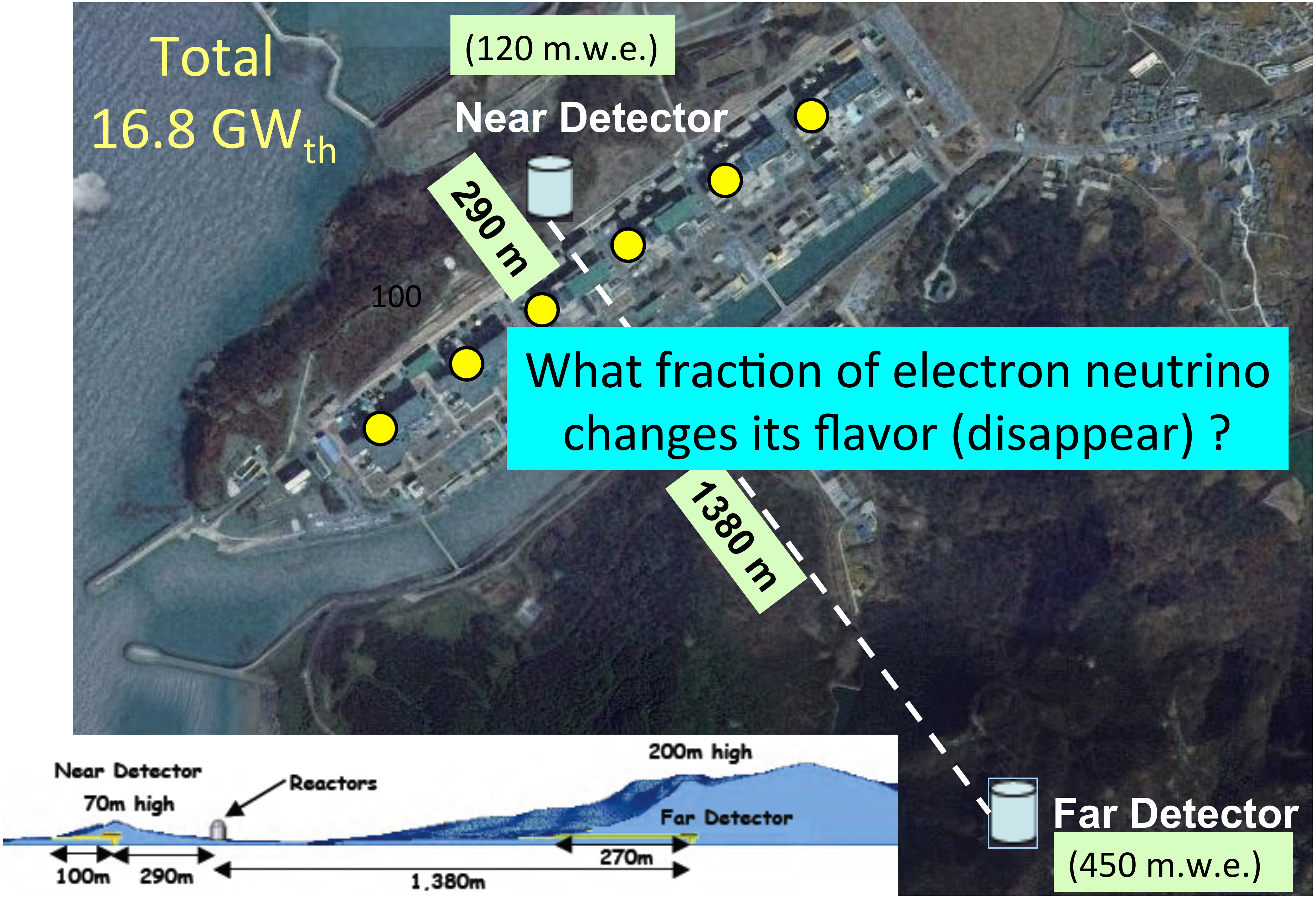
RENO Location: YongGwang S. Korea

YongGwang (靈光) :

means “Glorious light”

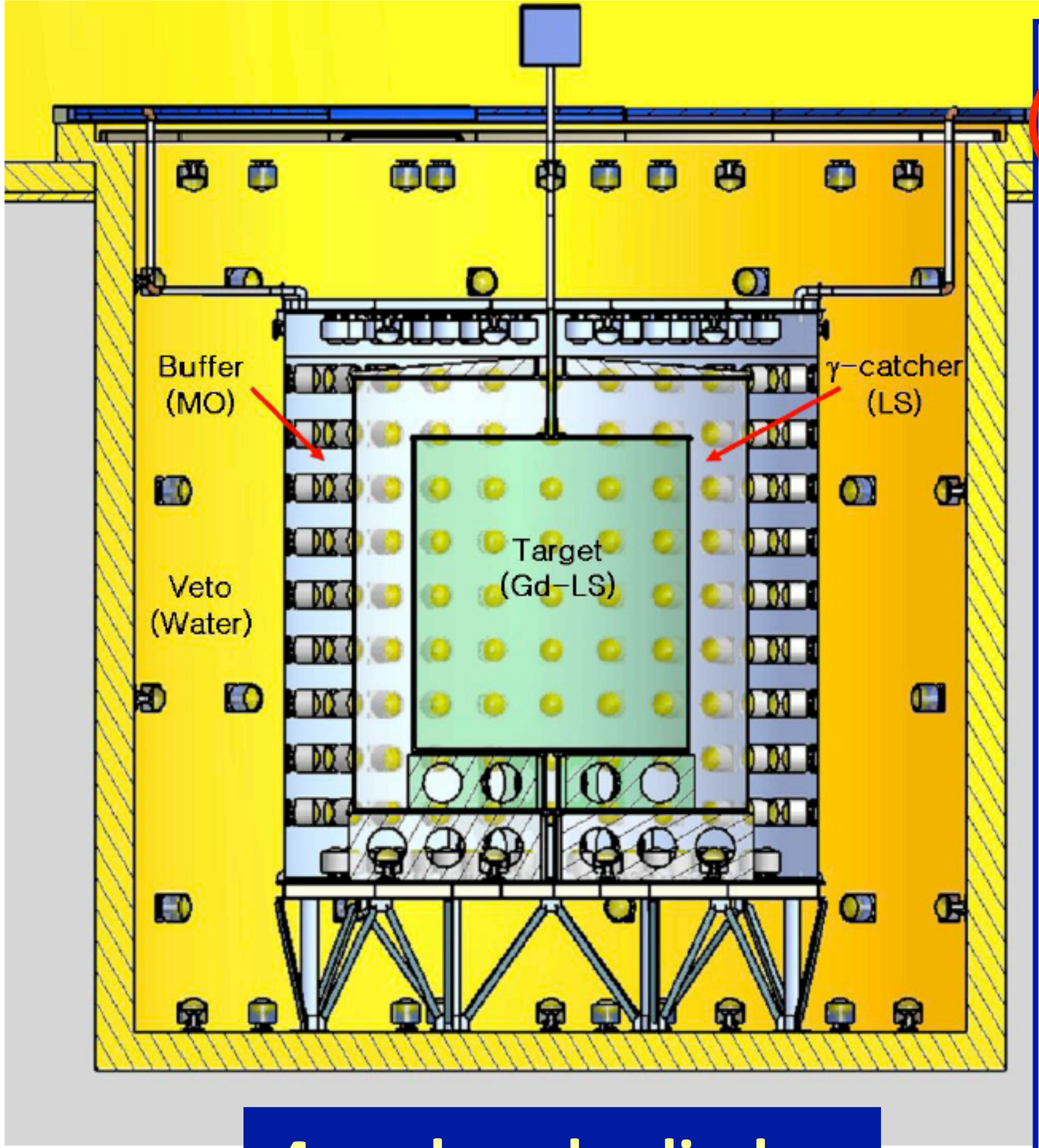
~ 4 hours driving distance from Seoul

RENO Experimental Setup



What fraction of electron neutrino changes its flavor (disappear) ?

The RENO Detector



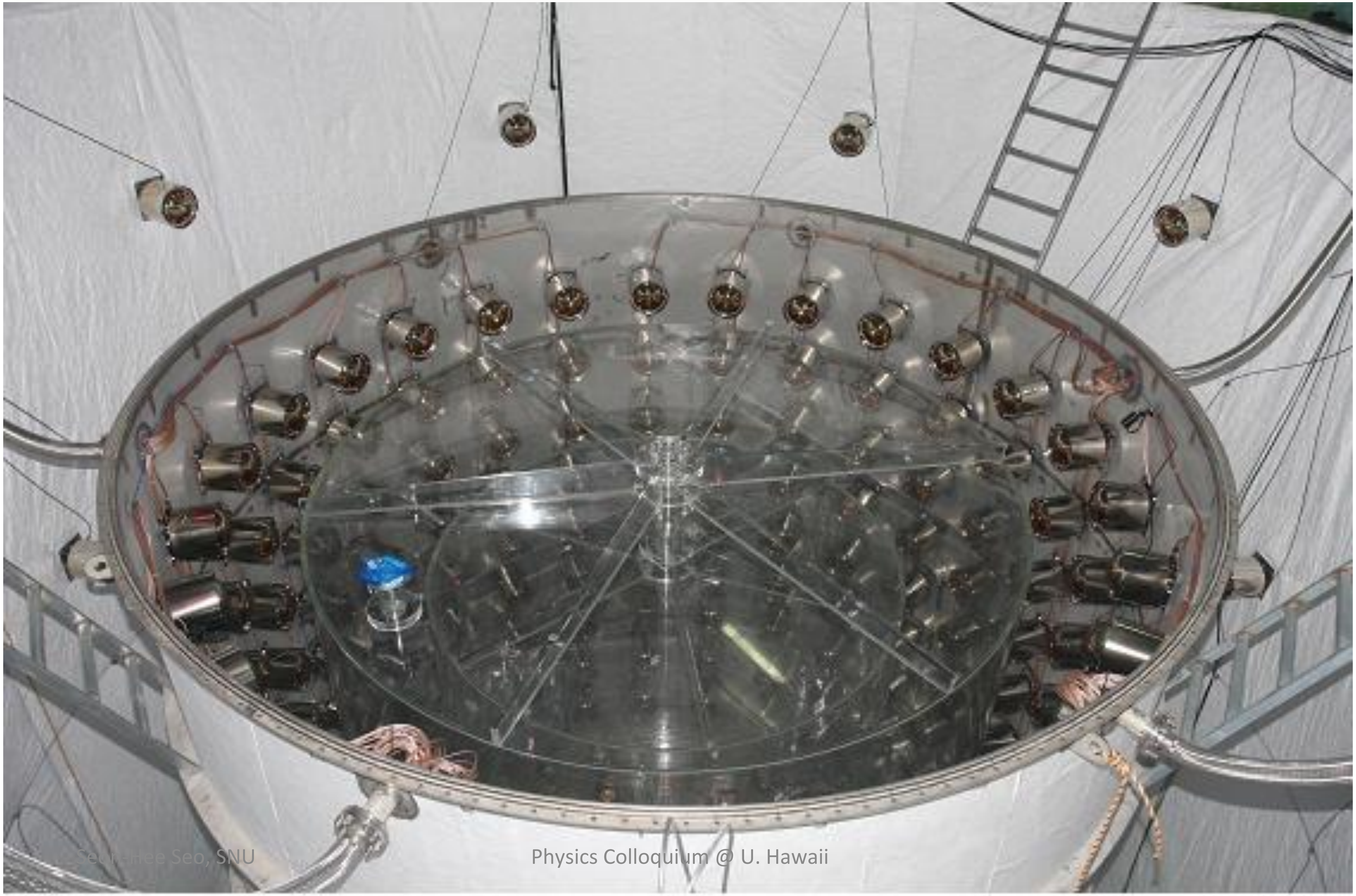
4 enclosed cylinders

- **Target : 16.5 ton Gd-LS**
  (R=1.4m, H=3.2m)
- **Gamma Catcher :**
  30 ton LS
  (R=2.0m, H=4.4m)
- **Buffer :** 65 ton mineral oil
  (R=2.7m, H=5.8m)
- **Veto :** 350 ton water
  (R=4.2m, H=8.8m)

-- 354 ID 10 “ PMTs

-- 67 OD 10” PMTs

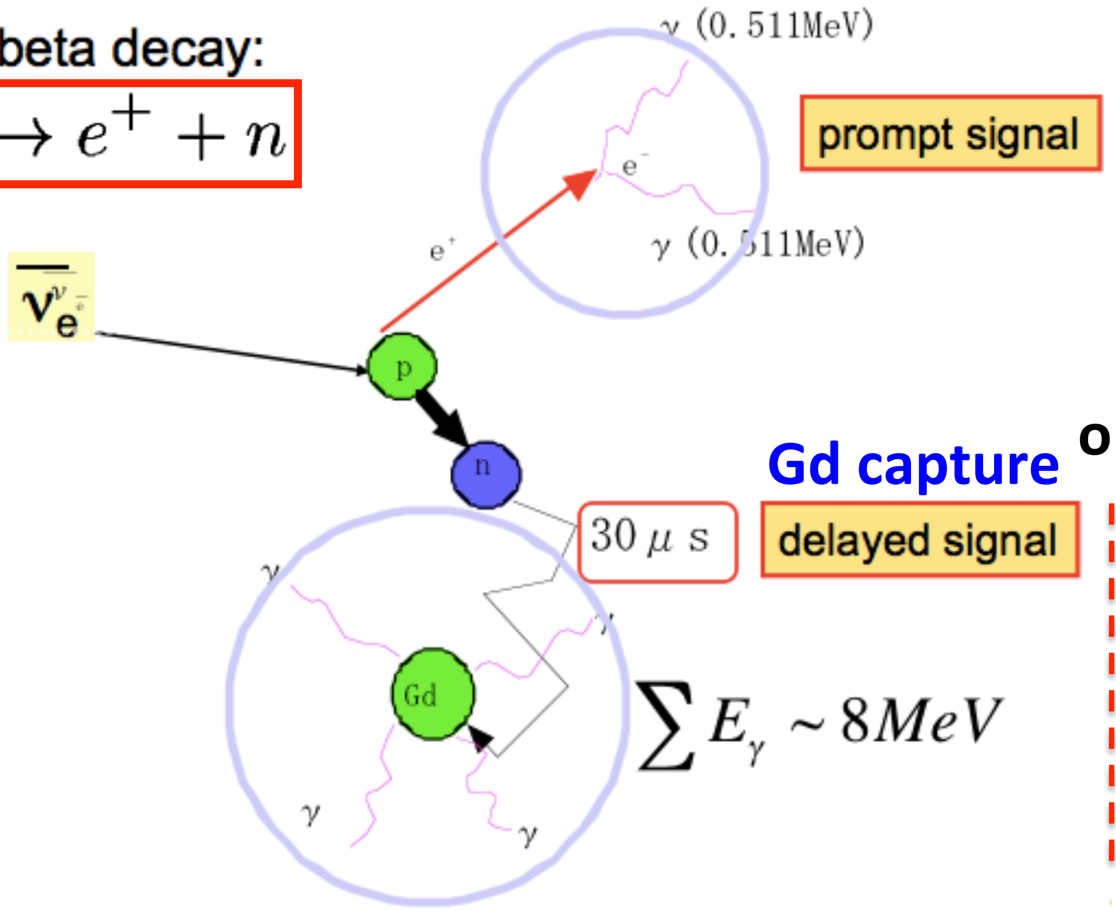
The RENO Detector



Detection Principle of Reactor Neutrinos

Inverse beta decay:

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



Gd capture or **H capture**

Delayed signal

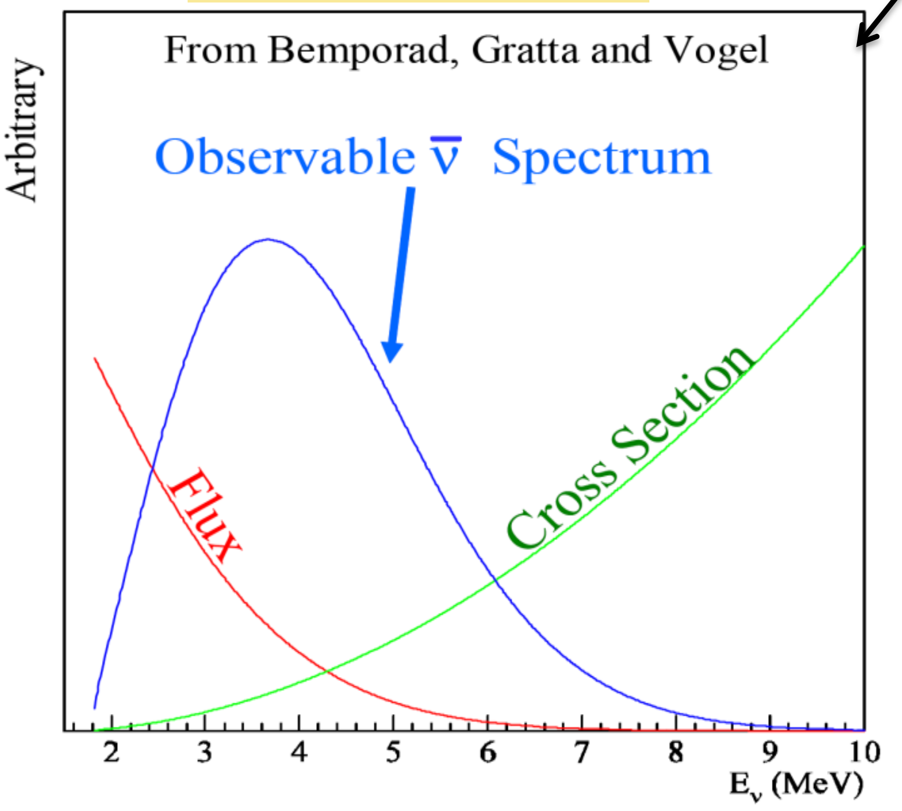
~200 μs

~ **2.2** MeV

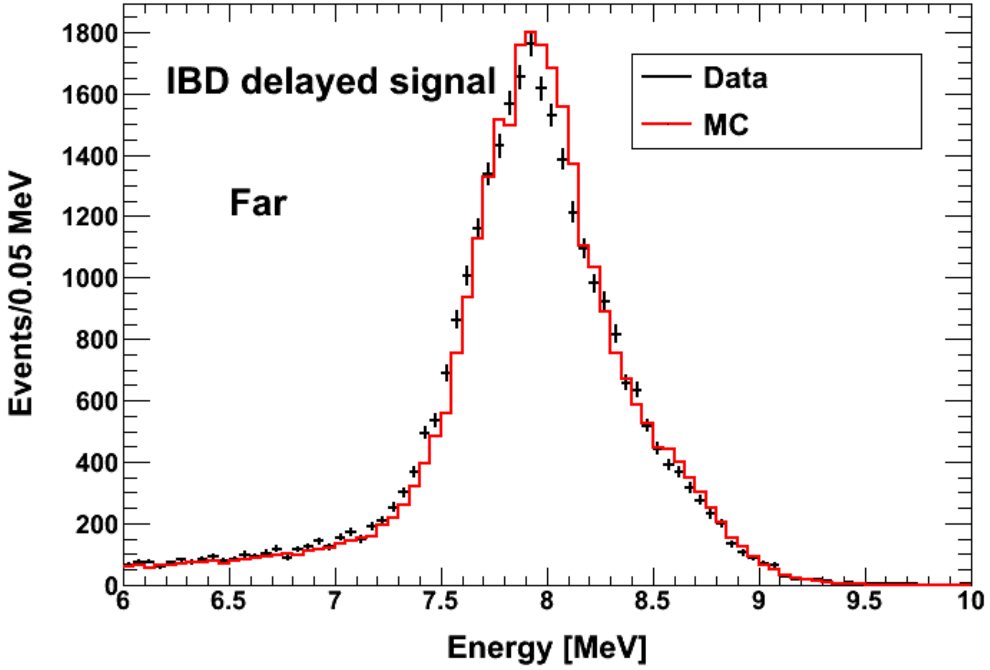
- Prompt signal (e^+) : 1 MeV 2γ's + e^+ kinetic energy (E = 1~10 MeV)
- Delayed signal (n) : 8 MeV γ's from neutron's capture by **Gd** or **H**
  ~30 μs or ~200 μs

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

Prompt signal


From Bemporad, Gratta and Vogel

delayed signal



$$E_{\bar{\nu}} \cong T_{e^+} + \underbrace{T_n}_{\textit{10-40 keV}} + \underbrace{(M_n - M_p) + m_{e^+}}_{\textit{1.8 MeV}}$$

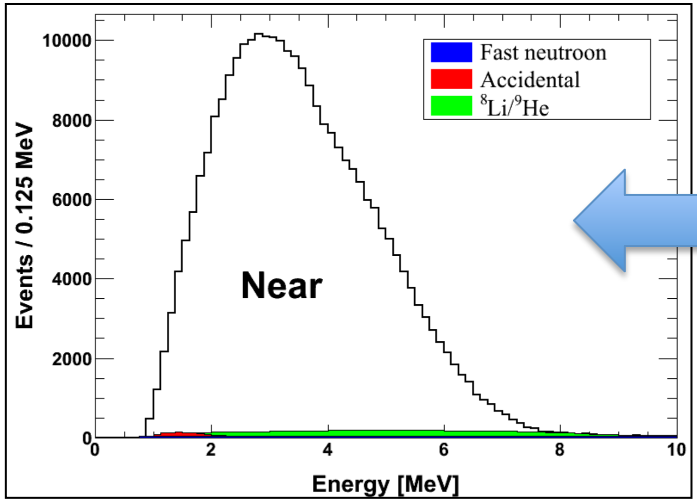
Signal: IBD Pair

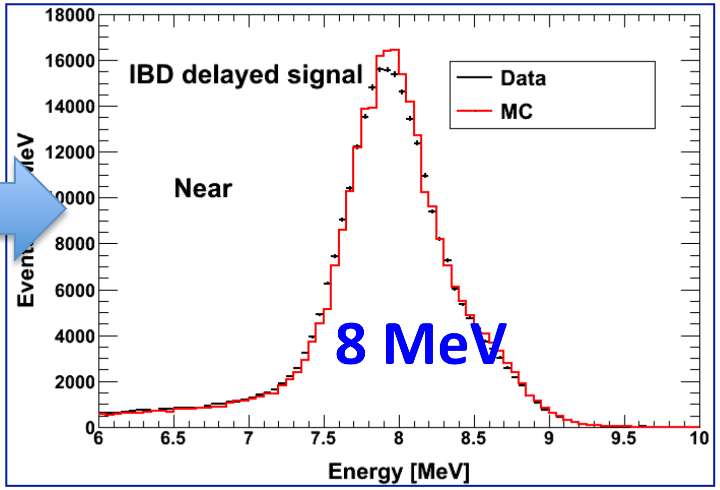
Prompt signal (S1)

Delayed signal (S2)

n-Gd IBD

~30 μs

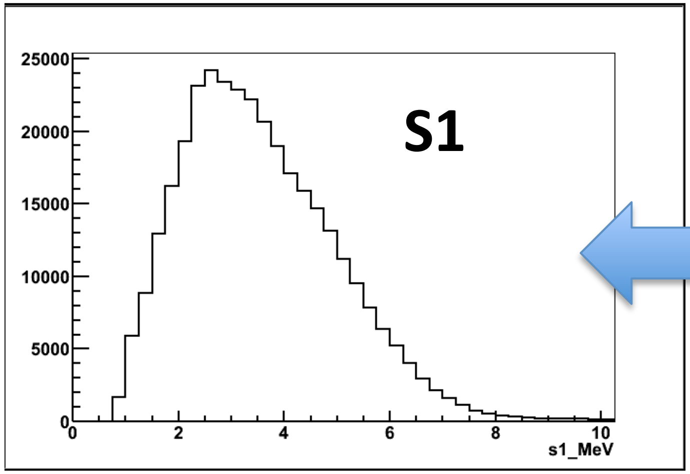


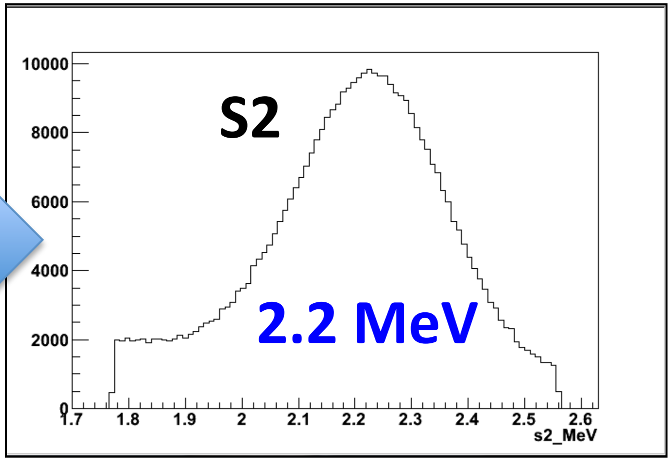


8 MeV

n-H IBD

~200 μs





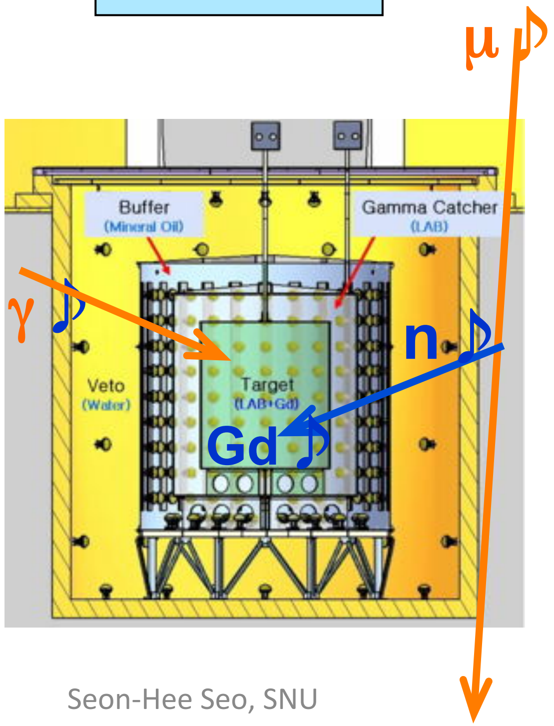
2.2 MeV

Suppresses background a lot !

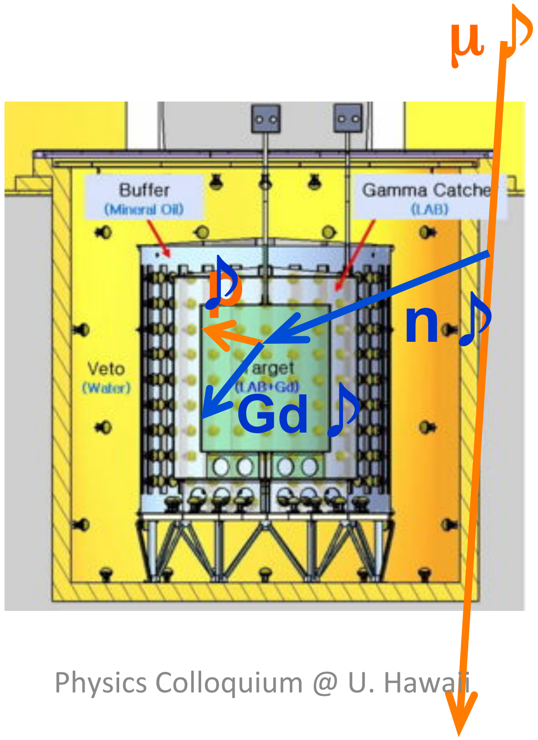
Backgrounds

- Accidental coincidence between prompt and delayed signals
- Fast neutrons produced by muons, from surrounding rocks and inside detector (n scattering : prompt, n capture : delayed)
- **^{9}Li/^{8}He** β-n followers produced by cosmic muon spallation

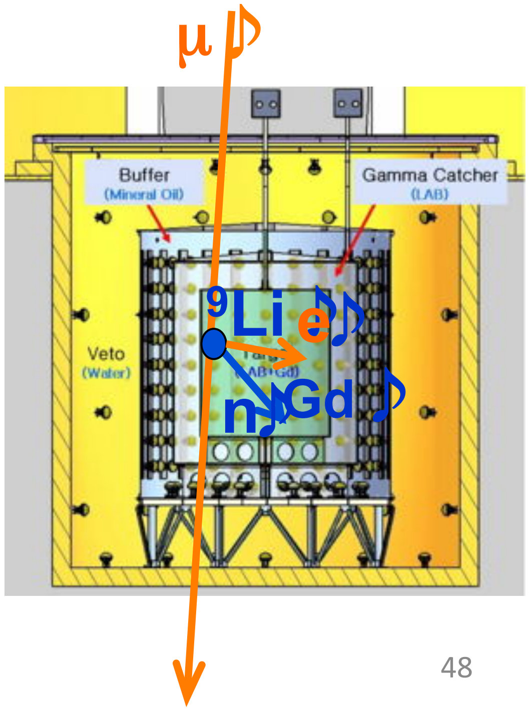
Accidentals



Fast neutrons



^{9}Li/^{8}He β-n followers



RENO Status

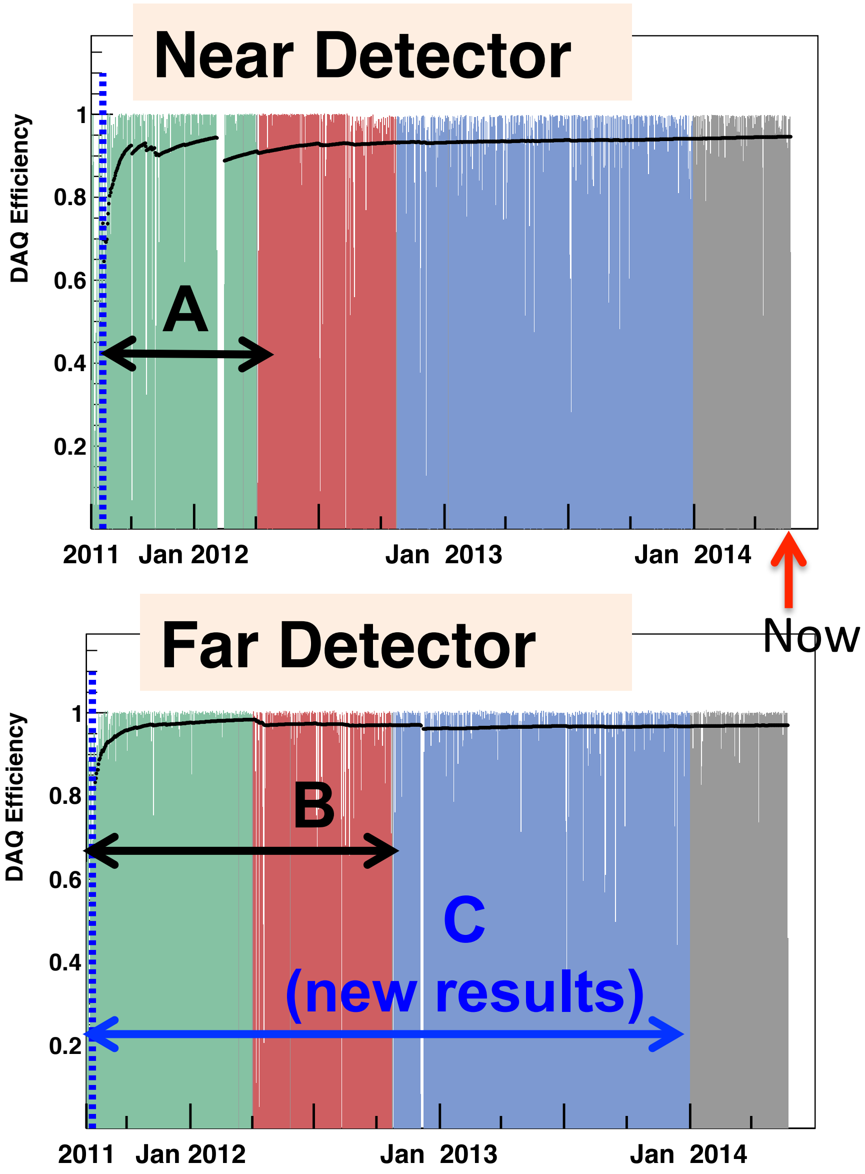
- Data taking began on Aug. 1, 2011 with both near and far detectors.
  (DAQ efficiency : ~95%)

- **A** (220 days) : **First θ_{13} result**
  [11 Aug, 2011~26 Mar, 2012]
  PRL 108, 191802 (2012)

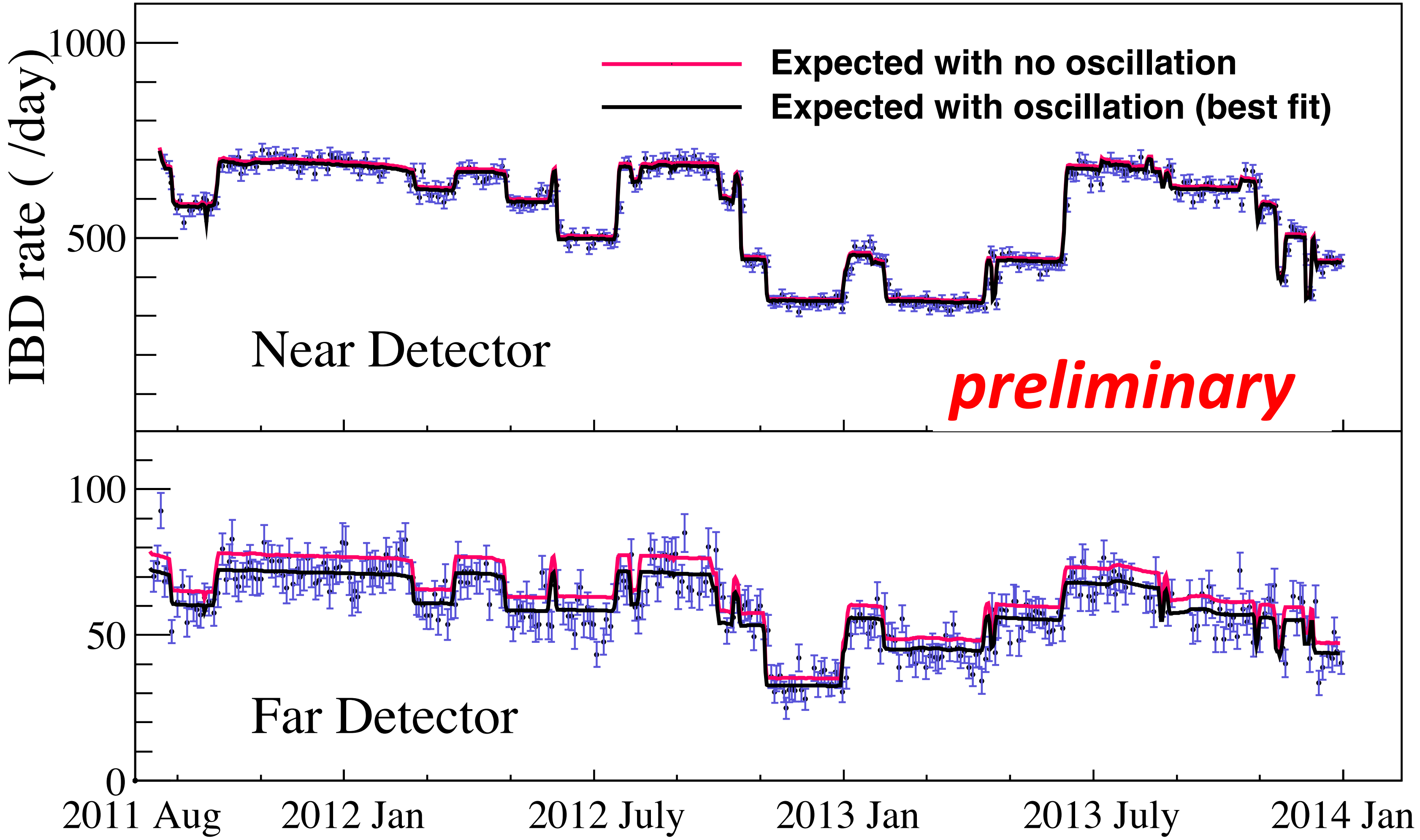
- **B** (403 days) : **Improved θ_{13} result**
  [11 Aug, 2011~13 Oct, 2012]
  NuTel 2013, TAUP 2013, WIN 2013

- **C** (~800 days) : New θ_{13} **result Shape +rate analysis** (in progress)
  [11 Aug, 2011~31 Dec, 2013]

- Total observed reactor neutrino events as of today : **~ 1.5M** (Near), **~ 0.15M** (Far)
  → Absolute reactor neutrino flux measurement in progress
  [reactor anomaly & sterile neutrinos]

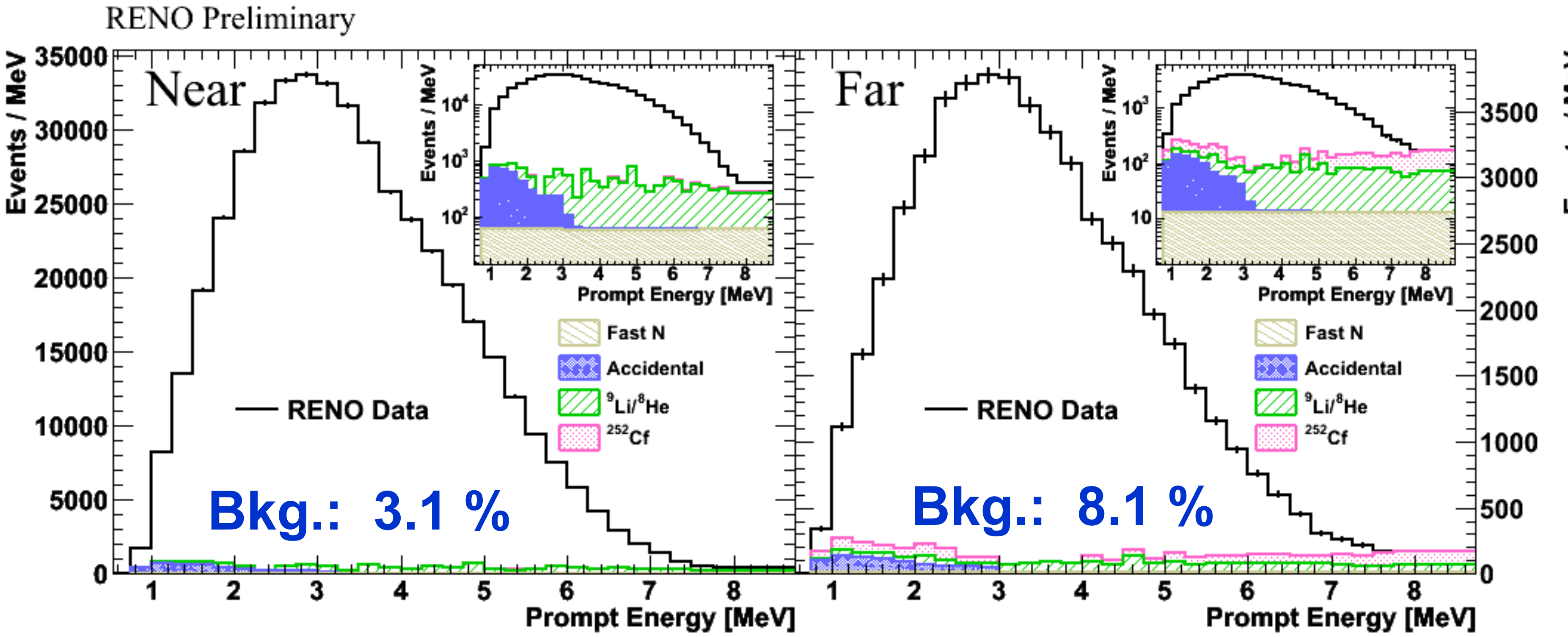


Observed Daily Neutrino Rate



- Observed points have very good agreement with prediction.
- It's the accurate ν flux (or thermal power) measurement.

Measured Spectra of IBD Prompt Signal



Bkg.: 3.1 %

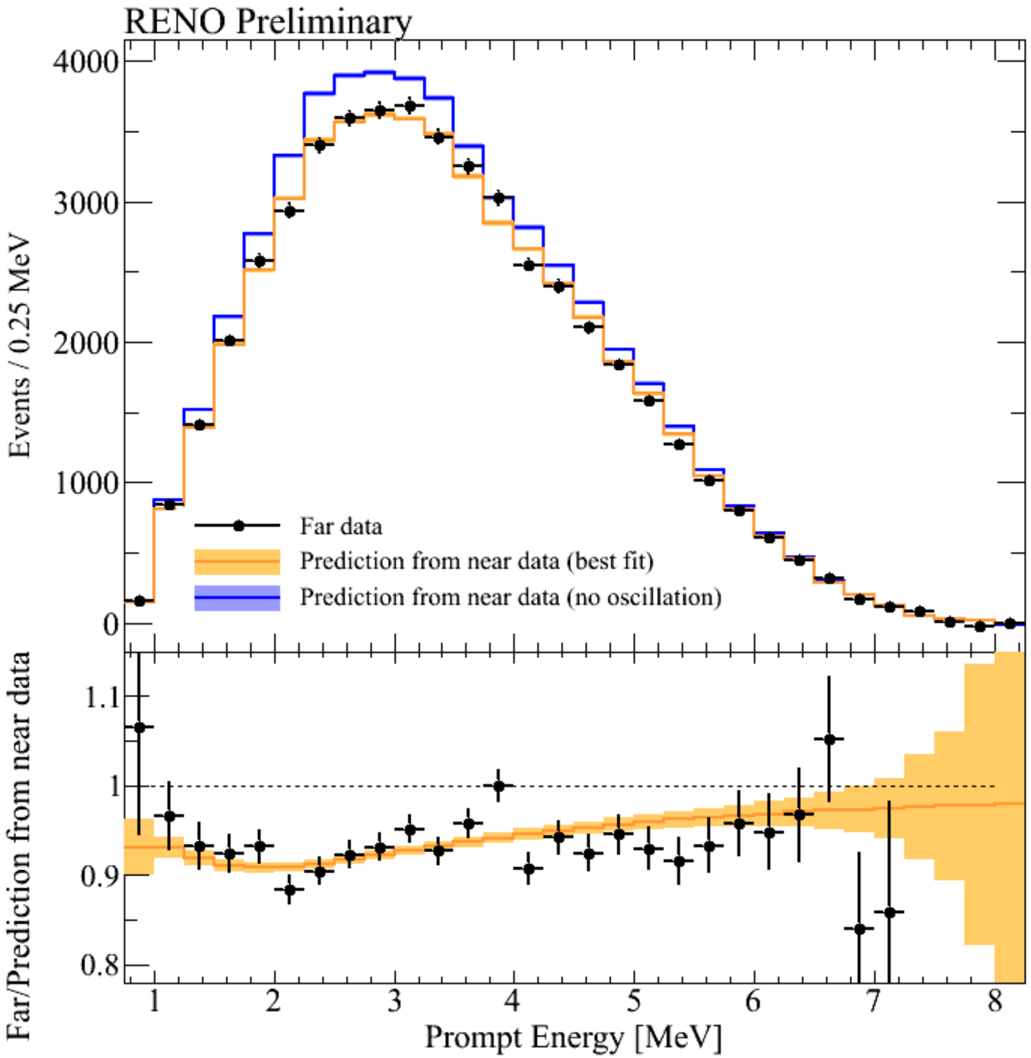
Bkg.: 8.1 %

Near Live time = 761.11 days
# of IBD candidate = 457,176
# of background = 14,165 (3.1 %)

Far Live time = 794.72 days
# of IBD candidate = 53,632
# of background = 4366 (8.1 %)

θ_{13} Measurement by RENO

$\sin^2(2\theta_{13}) = 0.101 \pm 0.008$ (stat.) $\pm$ 0.010 (sys.)



Preliminary Rate-only Result

(~800 live days)

Neutrino 2014

Shape analysis is in progress…

Stay tuned !

The final result will be released soon.

New θ_{13} Measurement by Rate-only Analysis

Preliminary result

C data set (~800 days)

$$\sin^2(2\theta_{13}) = 0.101 \pm 0.008\ (\text{stat.}) \pm 0.010\ (\text{sys.})$$

Neutrino 2014

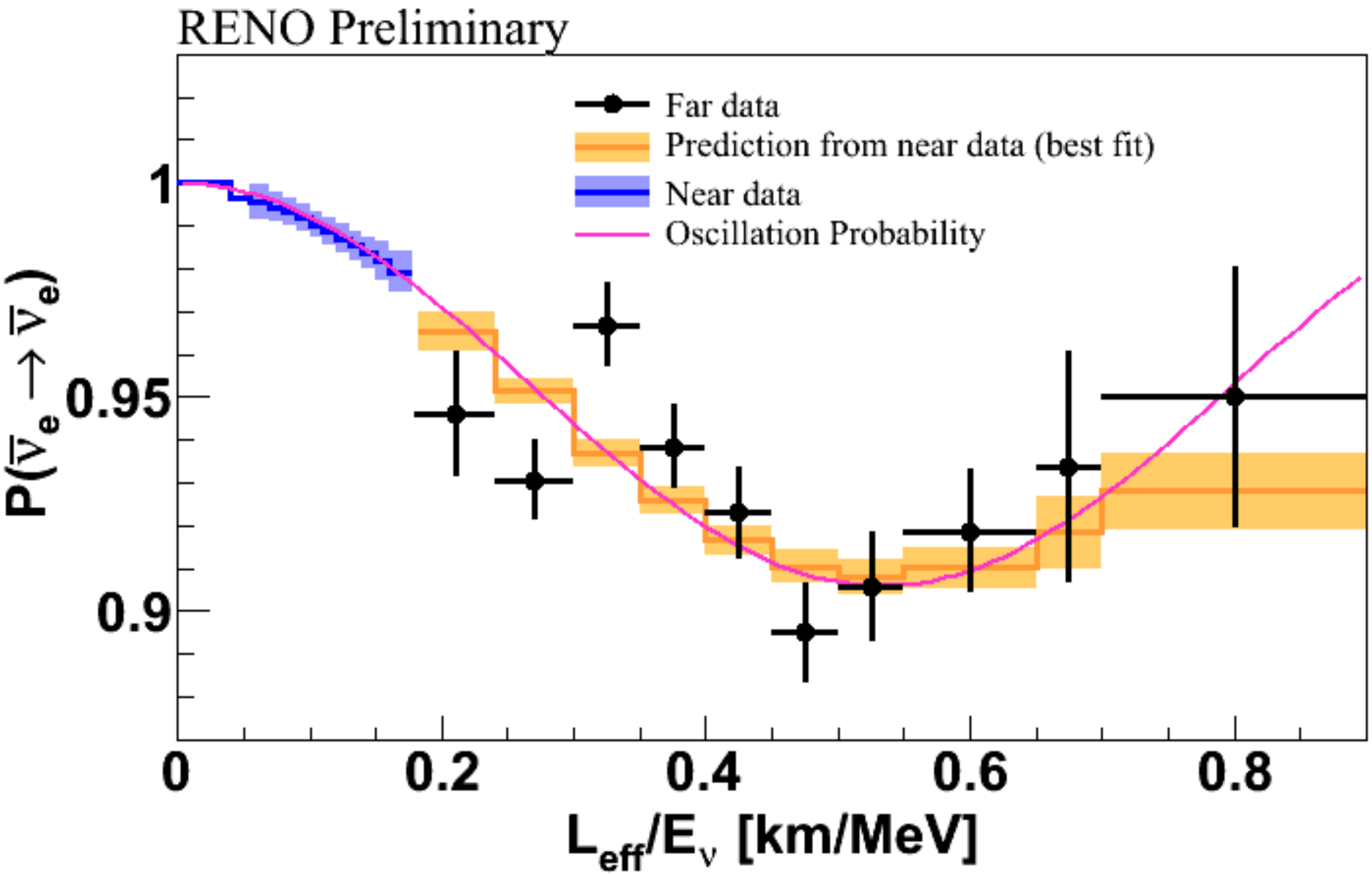
History of RENO measurements:

$\sin^2 2\theta_{13} = 0.113 \pm 0.023$ 4.9 σ (Neutrino 2012)

$\rightarrow 0.100 \pm 0.016$ 6.3 σ (TAUP/WIN 2013)

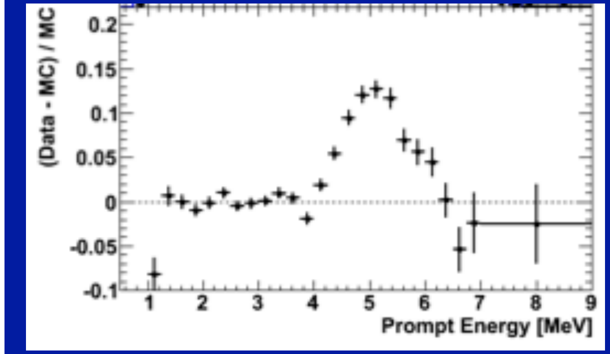
$\rightarrow$ 0.101 +/- 0.013 7.8 σ (Neutrino 2014)

Reactor Neutrino Disappearance on L/E

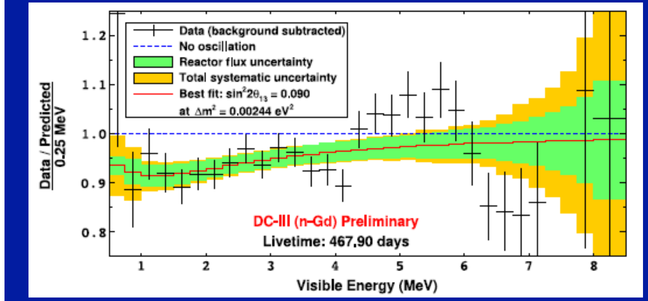


The 5 MeV Excess was observed !

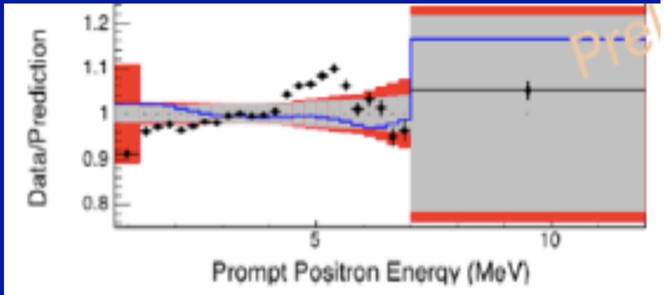
RENO



Double Chooz

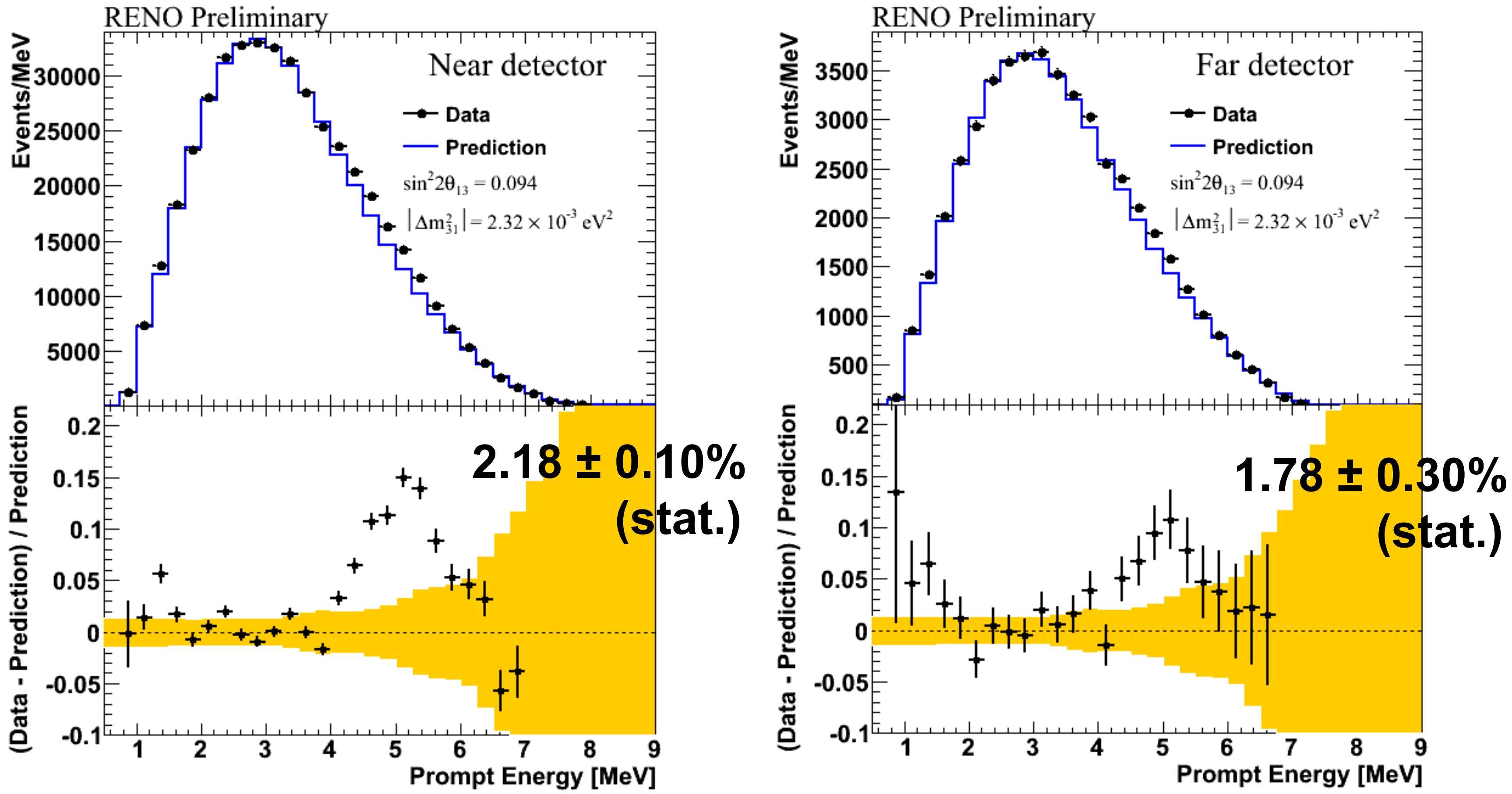


Daya Bay



I will talk about RENO’s 5 MeV Excess.

Observation of a New Reactor Neutrino Component at 5 MeV in RENO



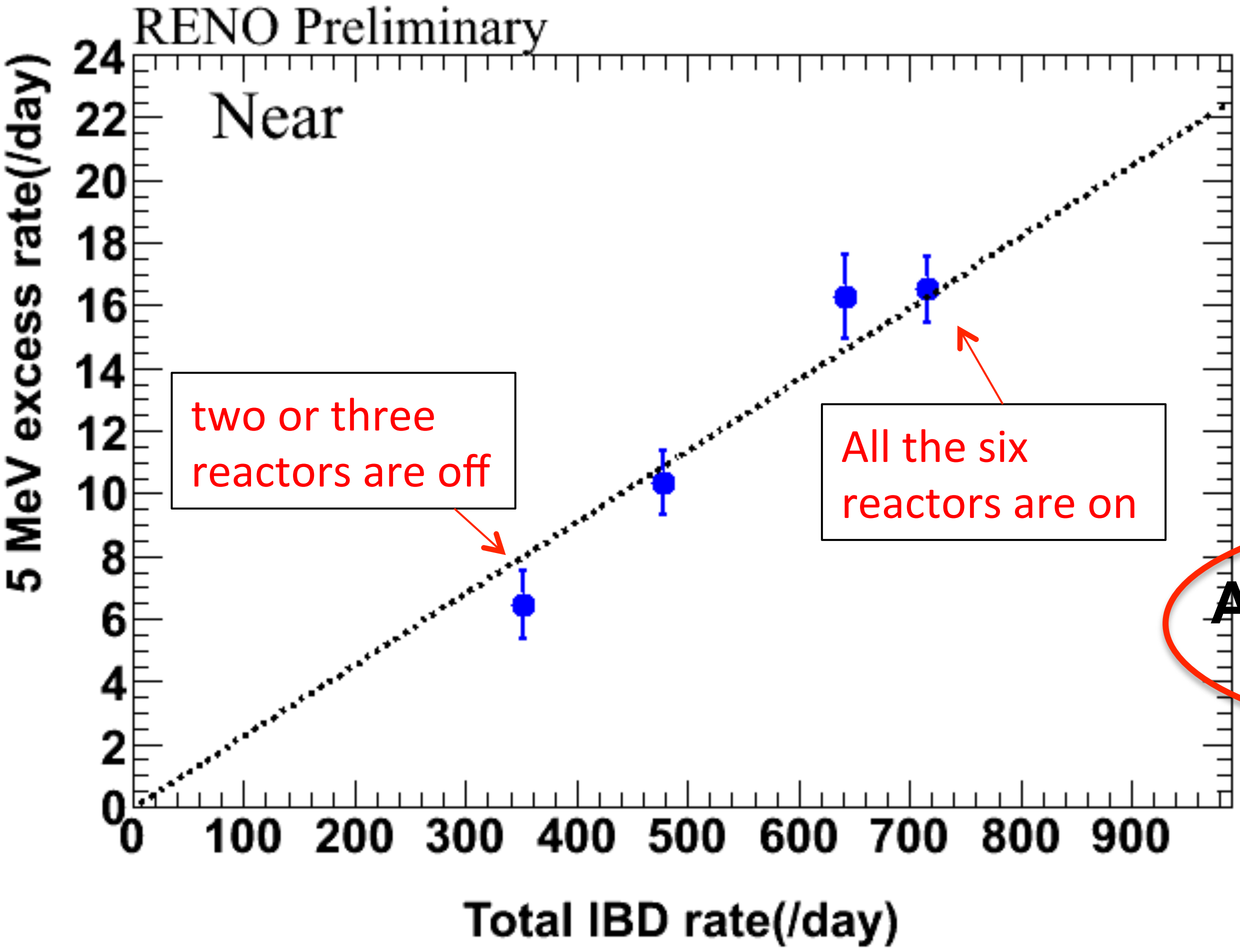
2.18 ± 0.10% (stat.)

1.78 ± 0.30% (stat.)

Fraction of 5 MeV excess (%) to expected flux **[2011 Huber+Mueller]**

- Near : 2.18 ± 0.40 (experimental) ± 0.49 (expected shape error)
- Far : 1.78 ± 0.71 (experimental) ± 0.49 (expected shape error)

Correlation of 5 MeV Excess with Reactor Power



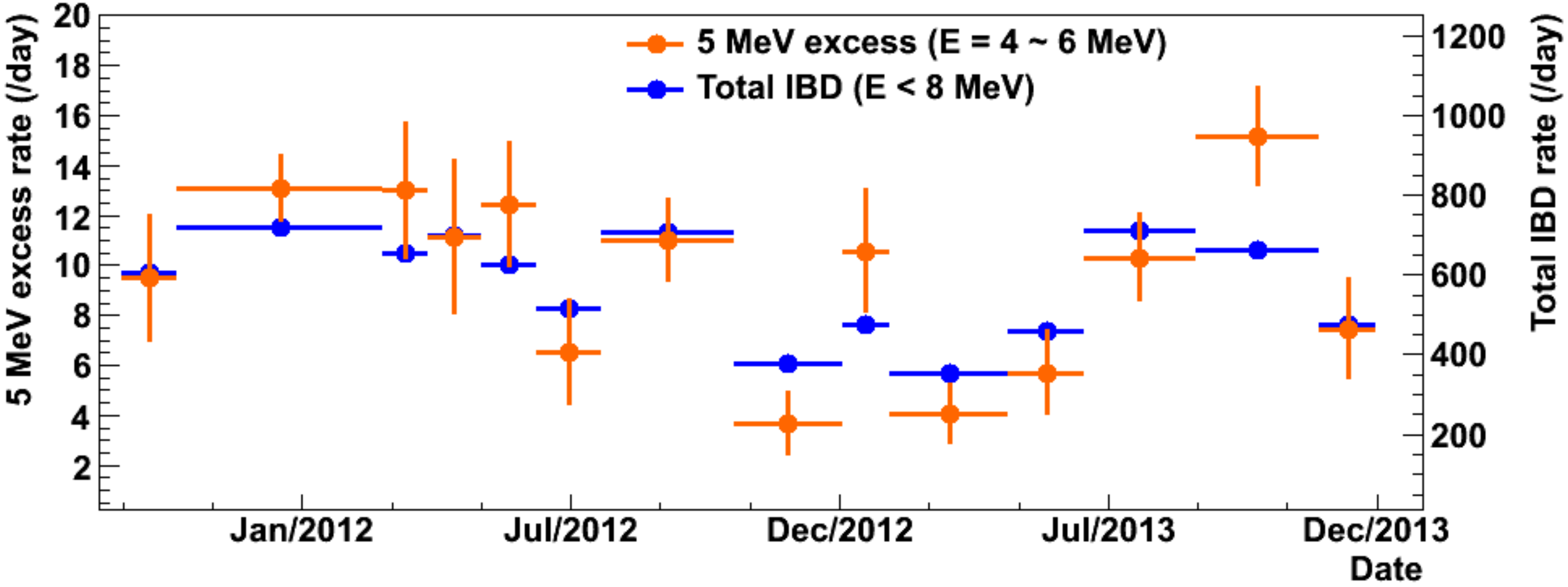
two or three reactors are off

All the six reactors are on

5 MeV excess has a clear correlation with reactor thermal power !

A new reactor neutrino component !!

Correlation of 5 MeV Excess with Reactor Power



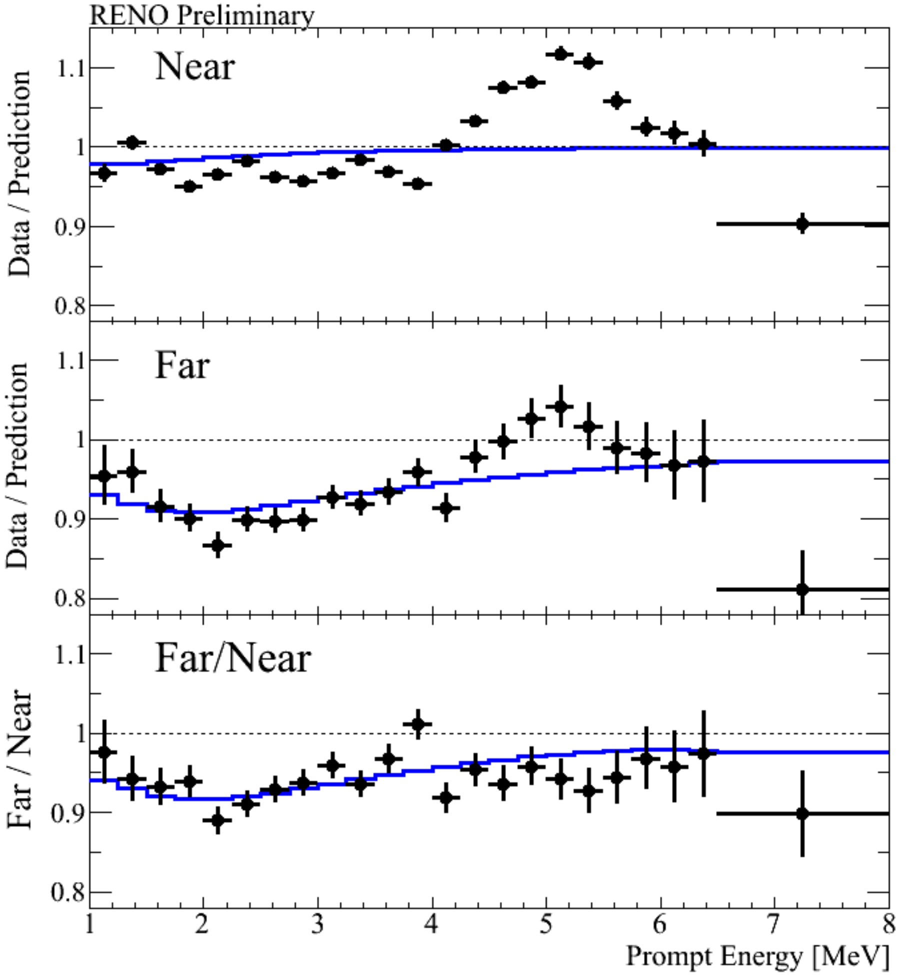
5 MeV excess has
a clear correlation with
reactor thermal power !

A new reactor neutrino component !!

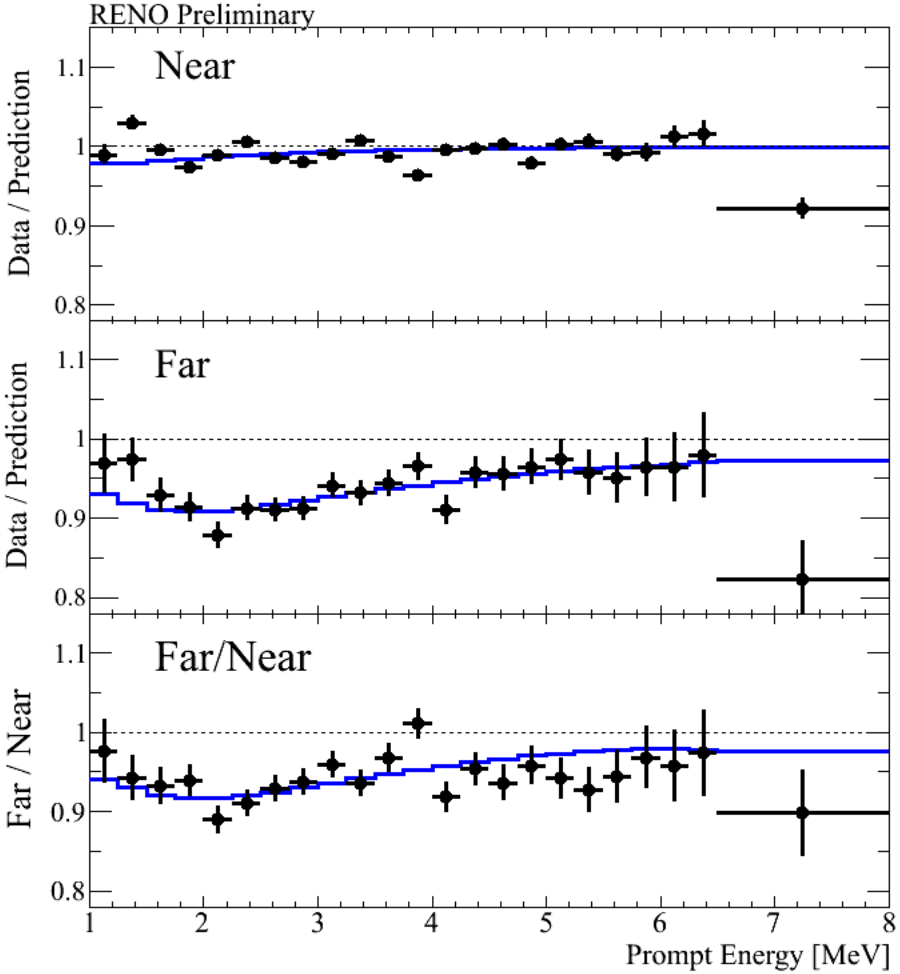
RENO: Shape Analysis for Δm_{ee}^2

In progress…. Stay tuned…

Without 5 MeV excess in prediction



With 5 MeV excess in prediction



Data & prediction **don't agree !**

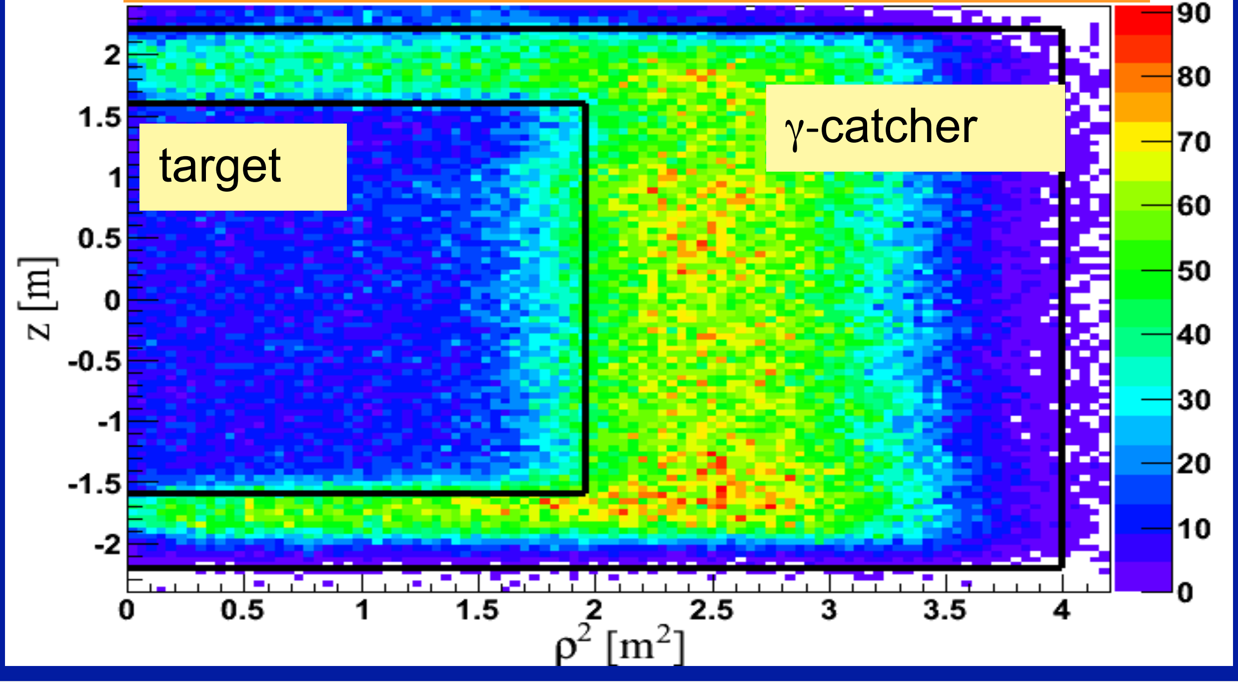
Data & prediction **agree !**

n-H Analysis

Motivation:

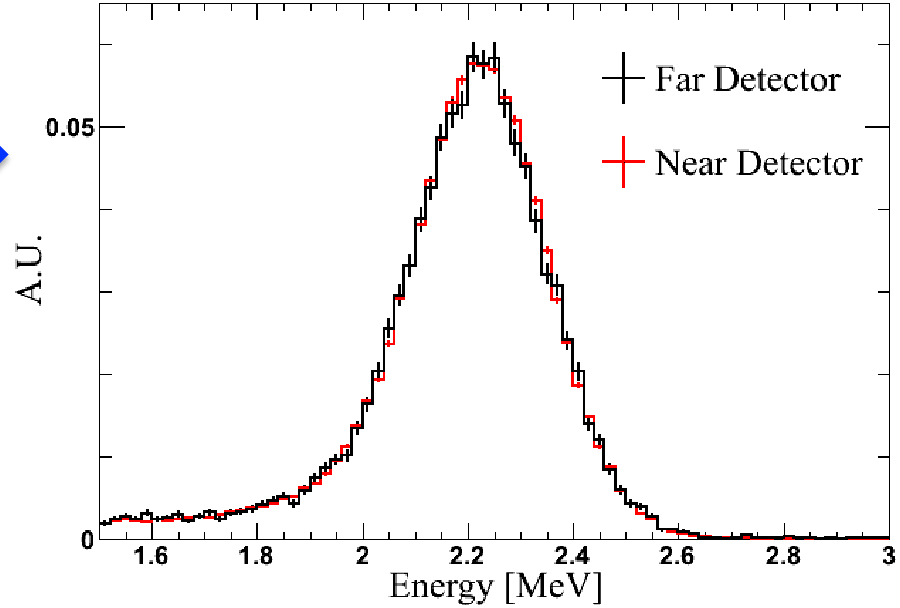
1. Independent measurement of θ_{13} value.
2. Consistency and systematic check on reactor neutrinos.

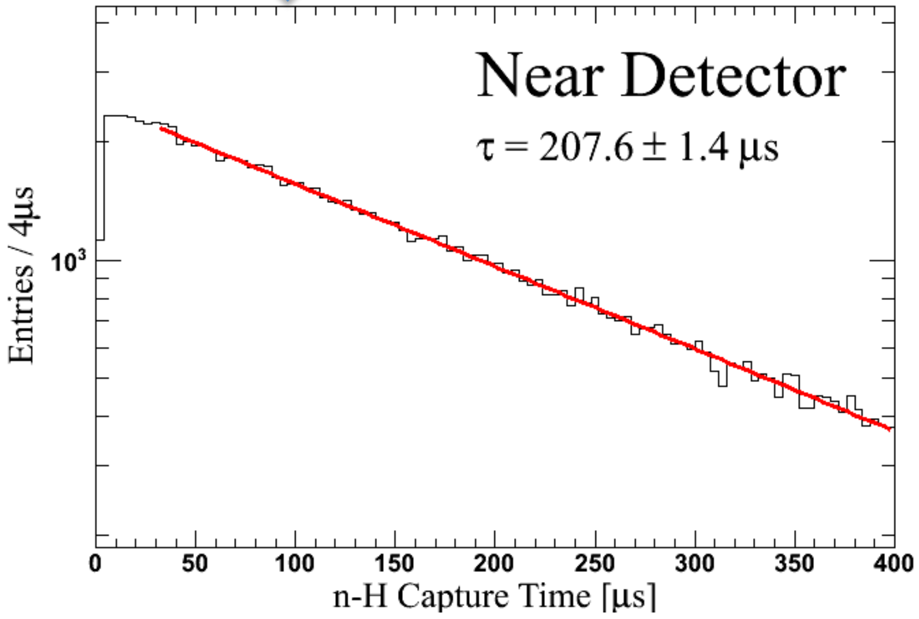
n-H IBD Event Vertex Distribution

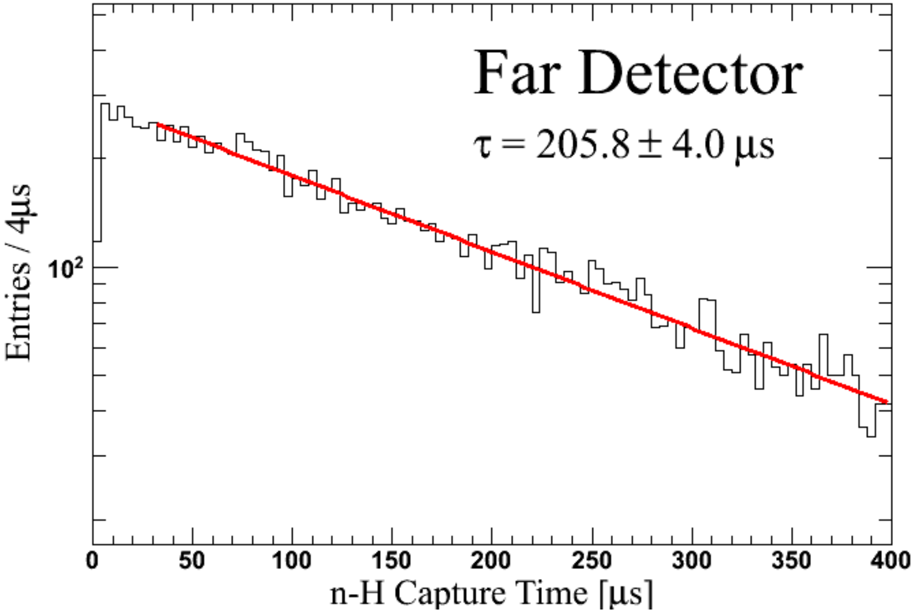


Features of n-H Events

- Delayed signal peak:
  2.2 MeV
- Mean coincidence time:
  ~ 200 μs







n-H Analysis: RENO

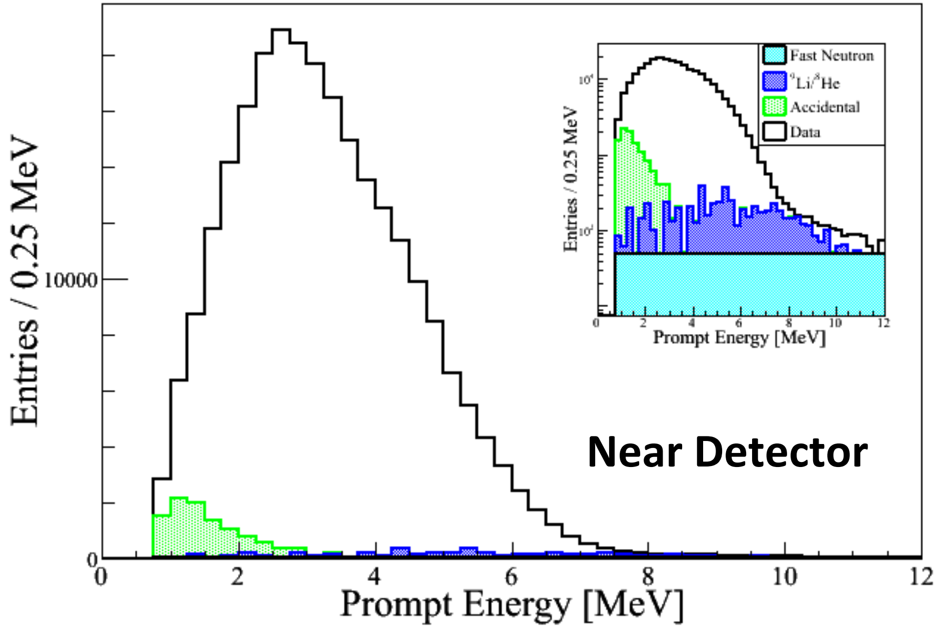
Very preliminary
Rate-only result (~400 days)

$$\sin^2 2\theta_{13} = 0.103 \pm 0.014(\text{stat.}) \pm 0.014(\text{syst.})$$

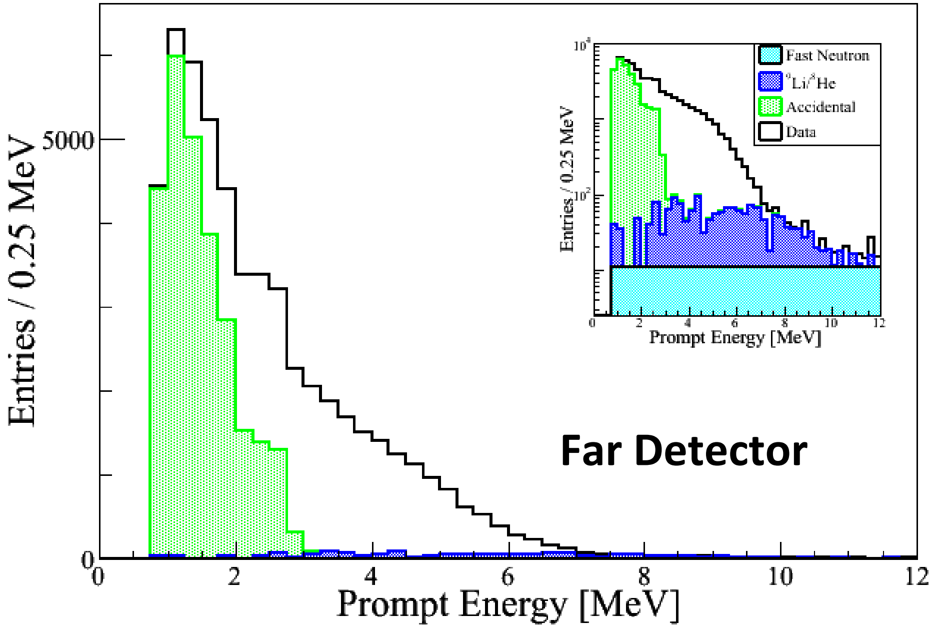
(Neutrino 2014) $\sin^2 2\theta_{13} = 0.095 \pm 0.015(\text{stat.}) \pm 0.025(\text{syst.})$

← *Removed a soft neutron background*
and reduced the uncertainty of the accidental background

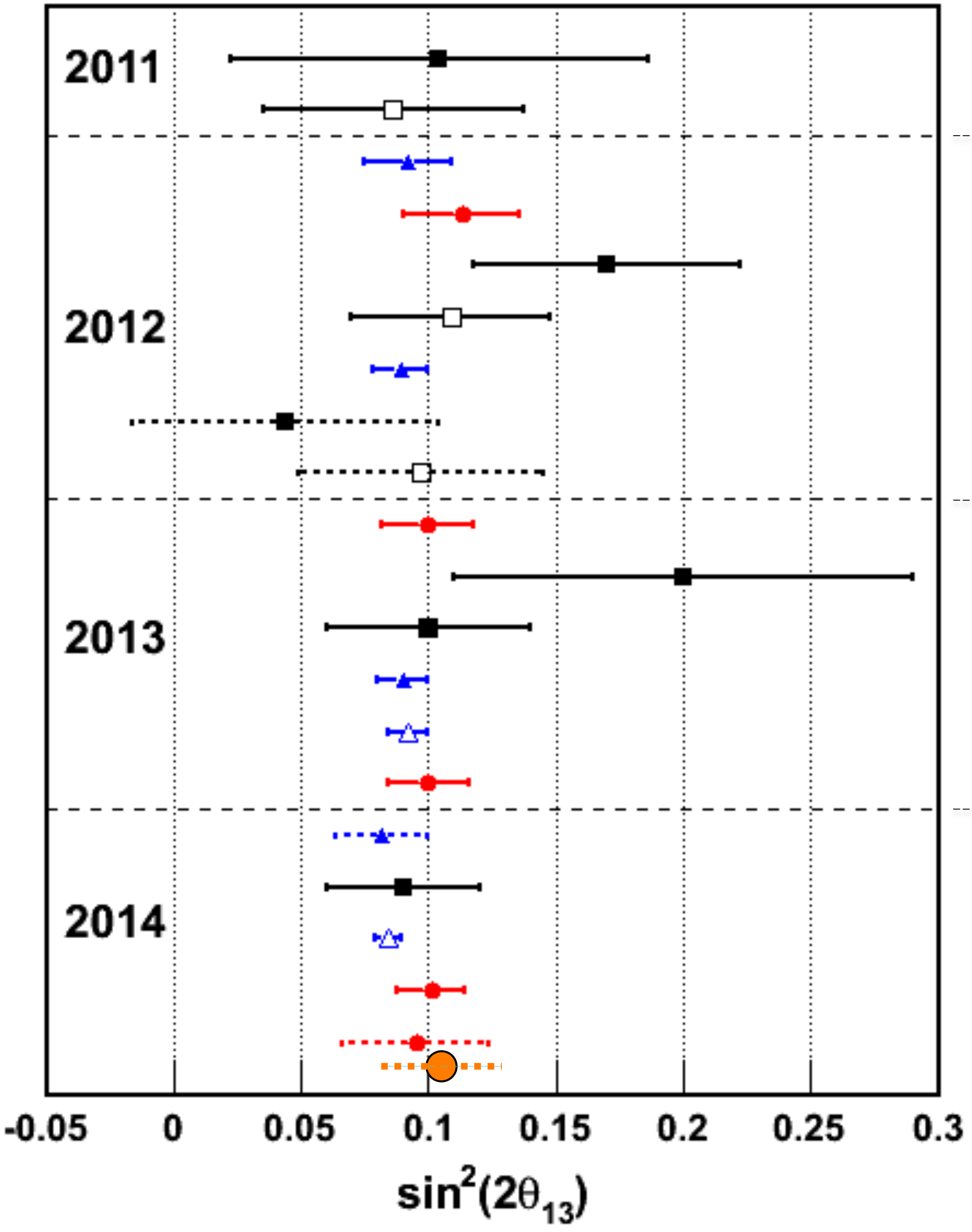
preliminary



preliminary



A Brief History of θ_{13} from Reactor Experiments



DC: 97 days	[1112.6353]
R+S	
DB: 49 days	[1203.1669]
RENO: 222 days	[1204.0626]
DC: 228 days	[1207.6632]
R+S	
DB: 139 days	[1210.6327]
DC: n-H	[1301.2948]
R+S	
RENO: 403 days	[NuTel2013]
DC: RRM analysis	[1305.2734]
R+S	
DB: 190 days	[1310.6732]
R+S	
RENO: 403 days	[TAUP2013]
DB: 190 days n-H	[Moriond2014]
DC: 469 days	[ν 2014]
DB: 563 days	[ν 2014]
RENO: 795 days	[ν 2014]
384 days n-H	[ν 2014]
RENO 384 days n-H	**[NOW 2014]**

Future Prospects on θ_{13}

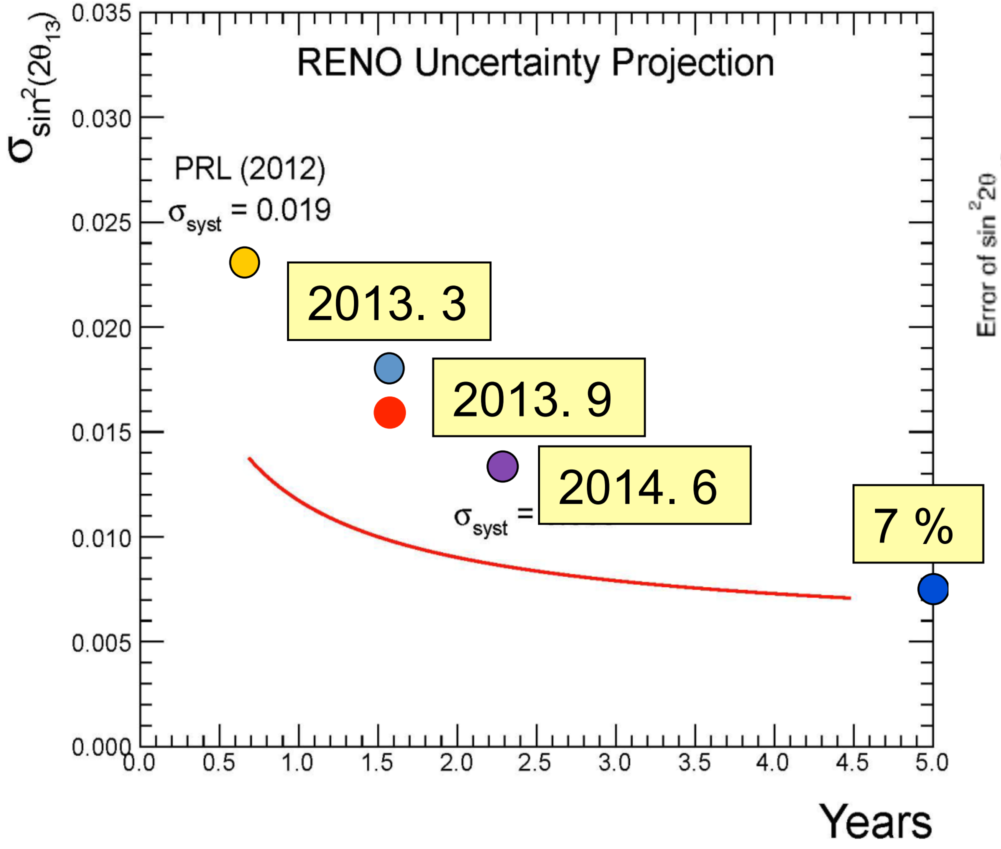
RENO

- 5 years of data : 7 %
  - **- stat. error : ±0.008 → ±0.005**
  - **- sys. error : ±0.010 → ±0.005**

Daya Bay

- 2017 (6 years of data) : 3 %

$\delta(\sin^2\theta_{13})\sim0.003,\ \delta(\Delta m^2_{ee})\sim0.07$

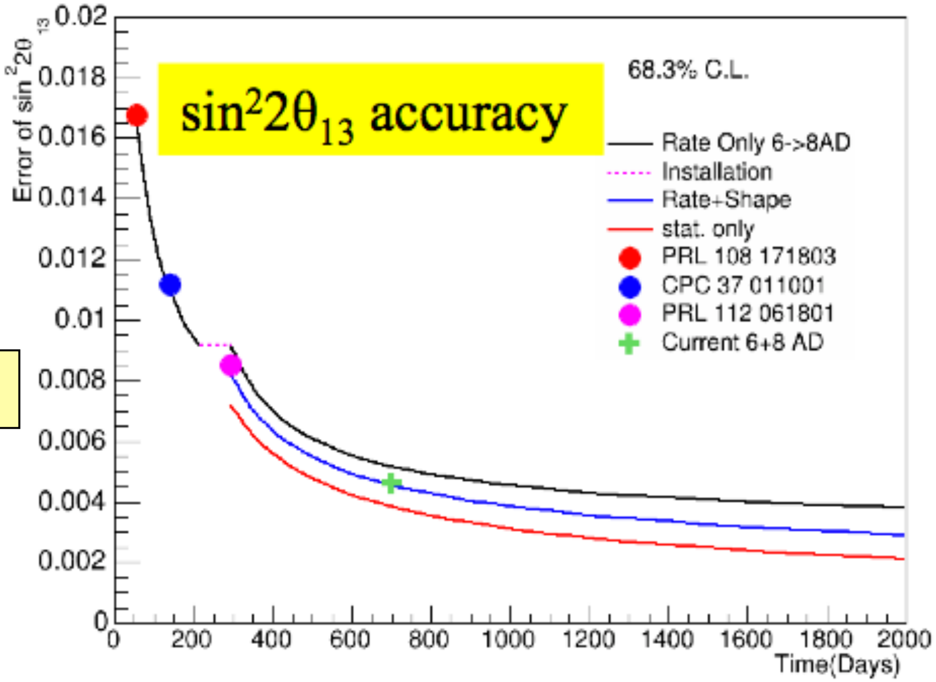


2013. 3

2013. 9

2014. 6

7 %

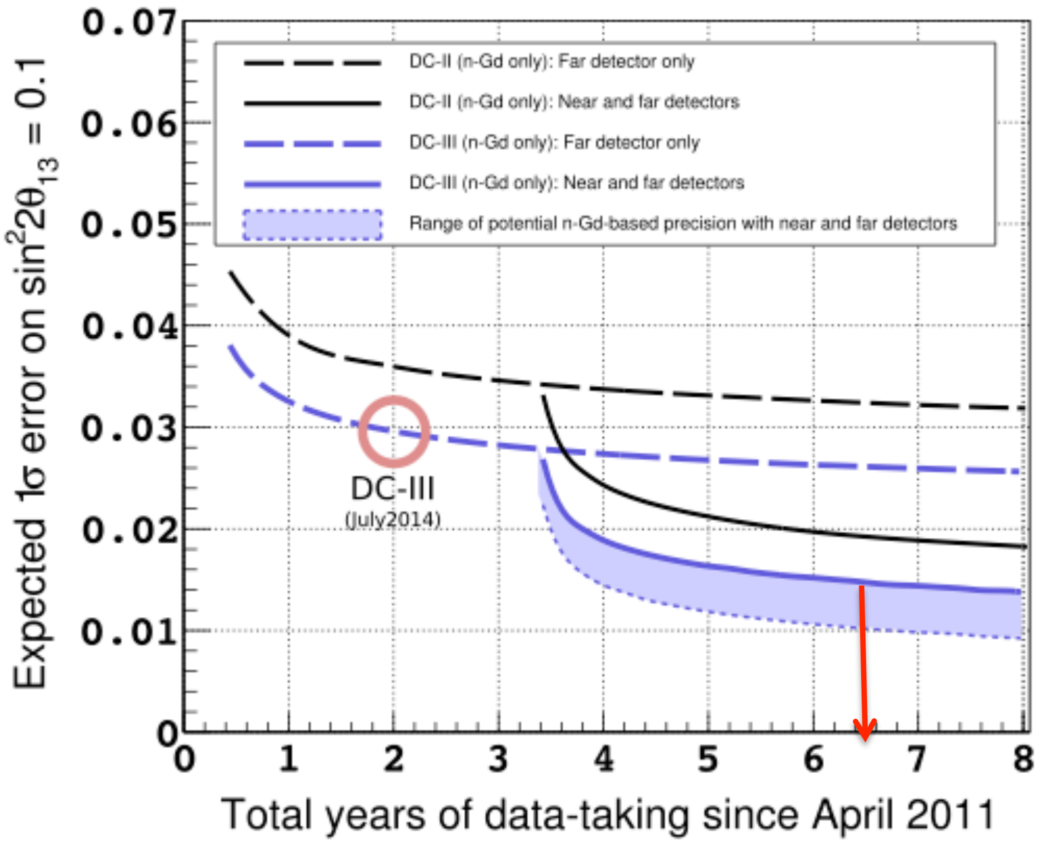


$\sin^2 2\theta_{13}$ accuracy

Future Prospects on θ_{13}

Double Chooz

- 3 years of Far & Near data : 15 -10 %



after θ_{13} measurement

Why θ_{13} ?

✓ To complete 3 ν mixing angle matrix (PMNS).

✓ To open a window for **leptonic CP phase** measurement

LBNO, LBNE, Hyper-K (θ_{13} != 0)

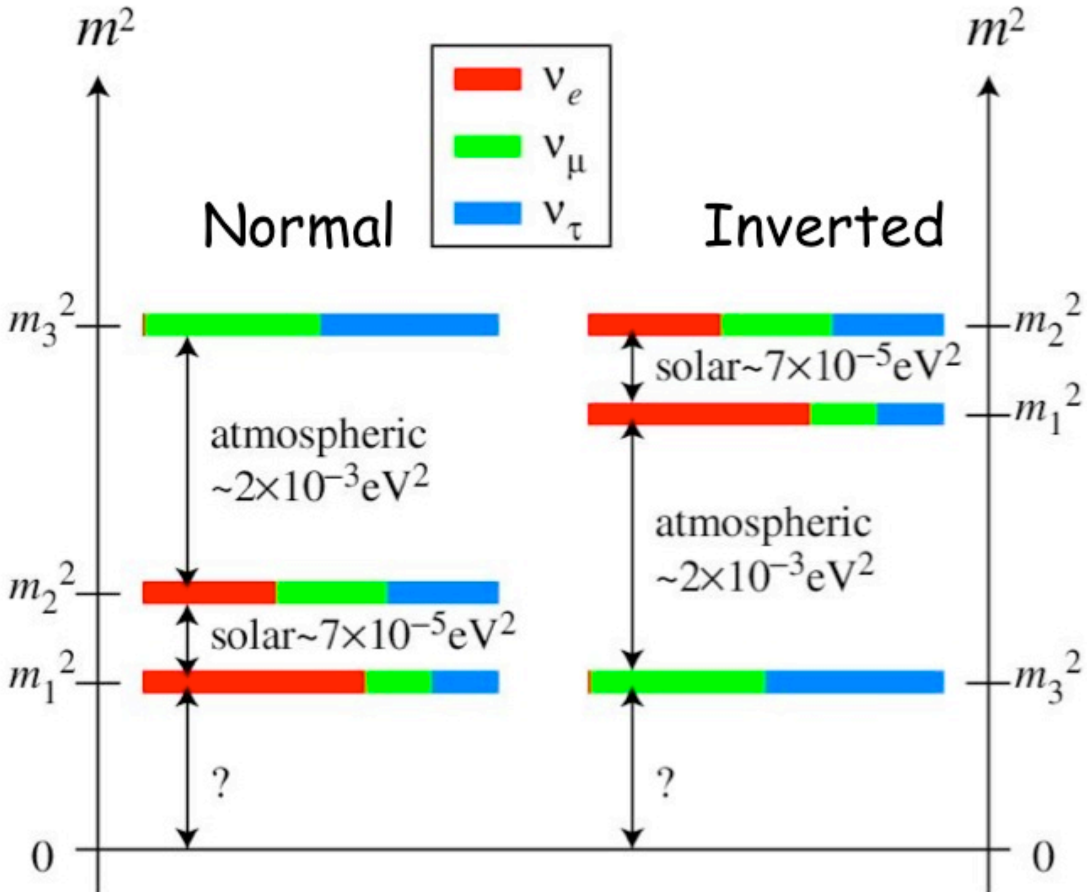
$$P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \propto \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos\theta_{13} \sin\delta$$

✓ To allow neutrino **mass hierarchy** measurement

(← requires not too small θ_{13})

✓ To allow precise measurement of atm. neutrino oscillation parameters

Q1. What are the mass ordering of the three neutrinos ?



Reactor:

RENO-50, JUNO

Accelerator:

LBNE, LBNO

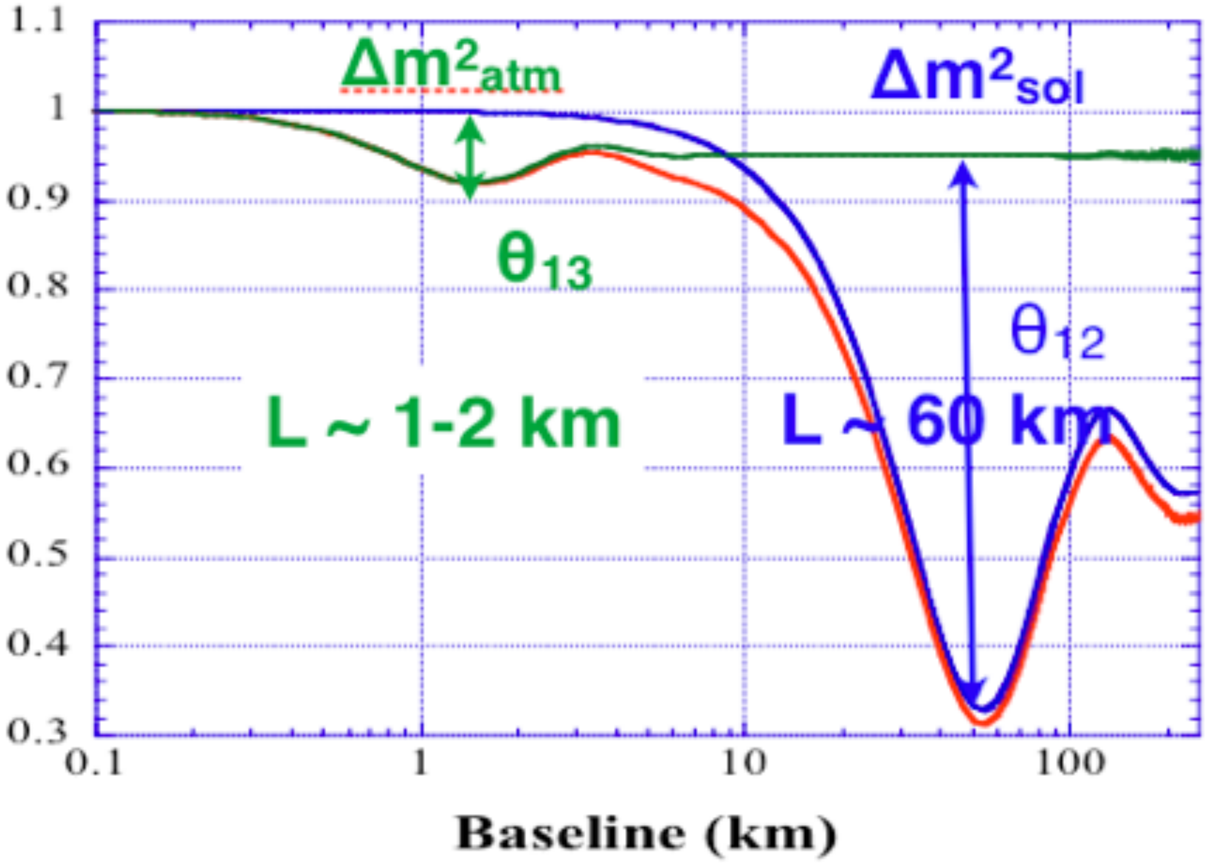
Hyper-K etc.

Astrophysical:

PINGU

Reactor Neutrino Oscillations

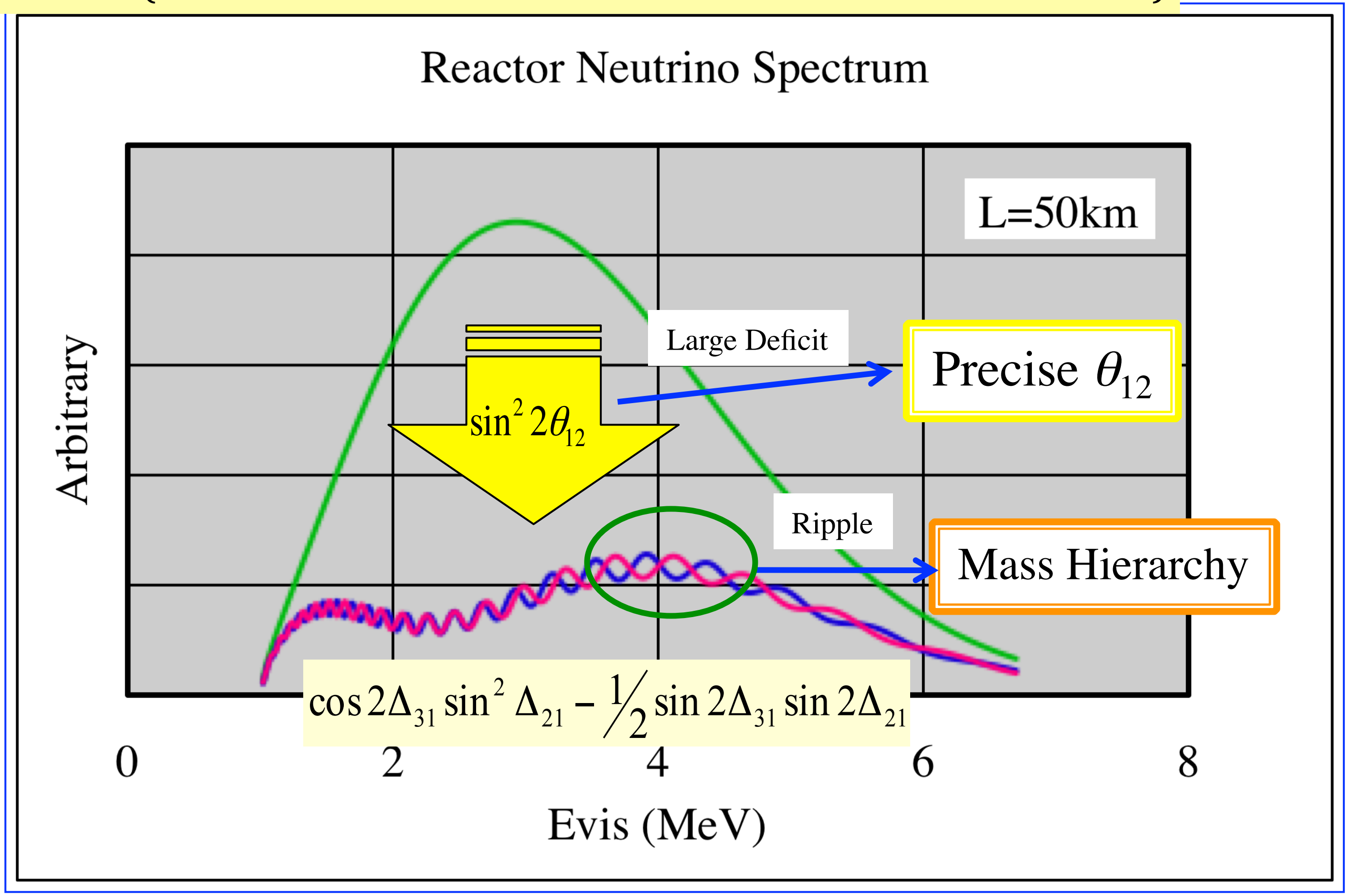
$$P(\nu_e \to \nu_e) \approx 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{1.27\Delta m_{12}^2 L}{E_\nu}\right) - \sin^2 2\theta_{13}\sin^2\left(\frac{1.27\Delta m_{13}^2 L}{E_\nu}\right)$$



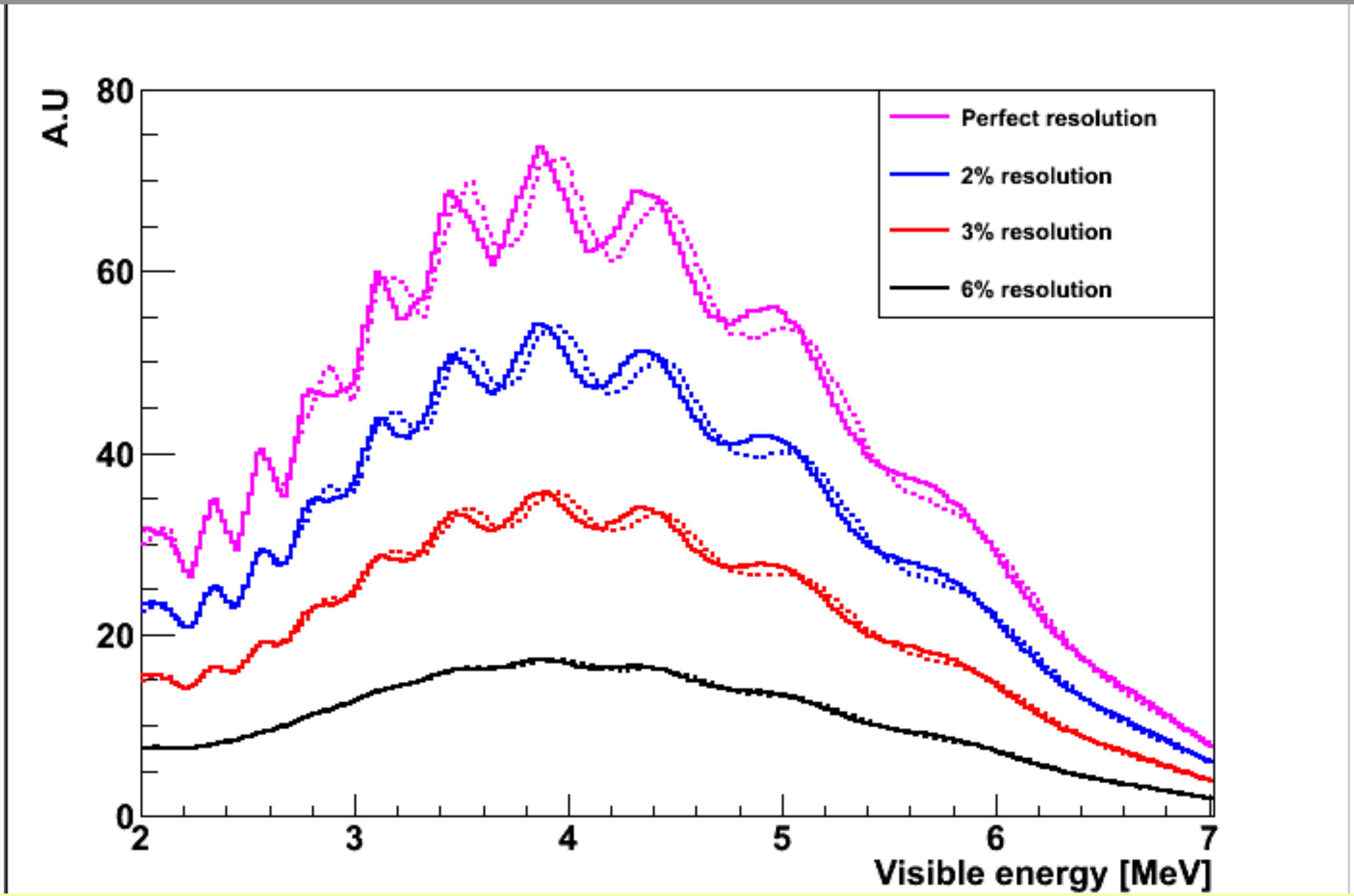
Reactor Neutrino Spectrum @ 50 km

$$P_R\left(\bar{\nu}_e \to \bar{\nu}_e\right) = 1 - \left\{ \begin{aligned} &\cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} + \sin^2 2\theta_{13}\sin^2\Delta_{31} \\ &+ \sin^2 2\theta_{13}\sin^2\theta_{12}\left(\cos 2\Delta_{31}\sin^2\Delta_{21} - \tfrac{1}{2}\sin 2\Delta_{31}\sin 2\Delta_{21}\right) \end{aligned} \right\}$$

$$\Delta_{ij} = \frac{1.27\cdot\Delta m_{ij}^2 L}{E_\nu}$$

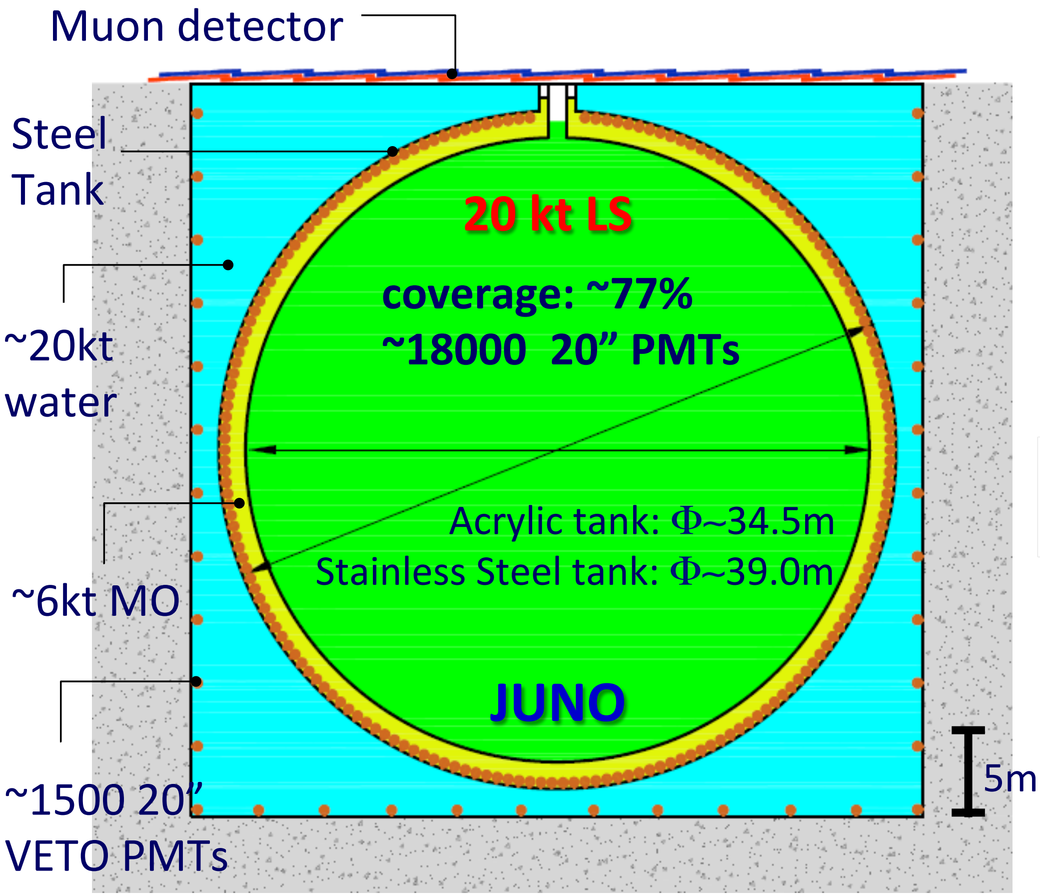


Energy Resolution for Mass Hierarchy

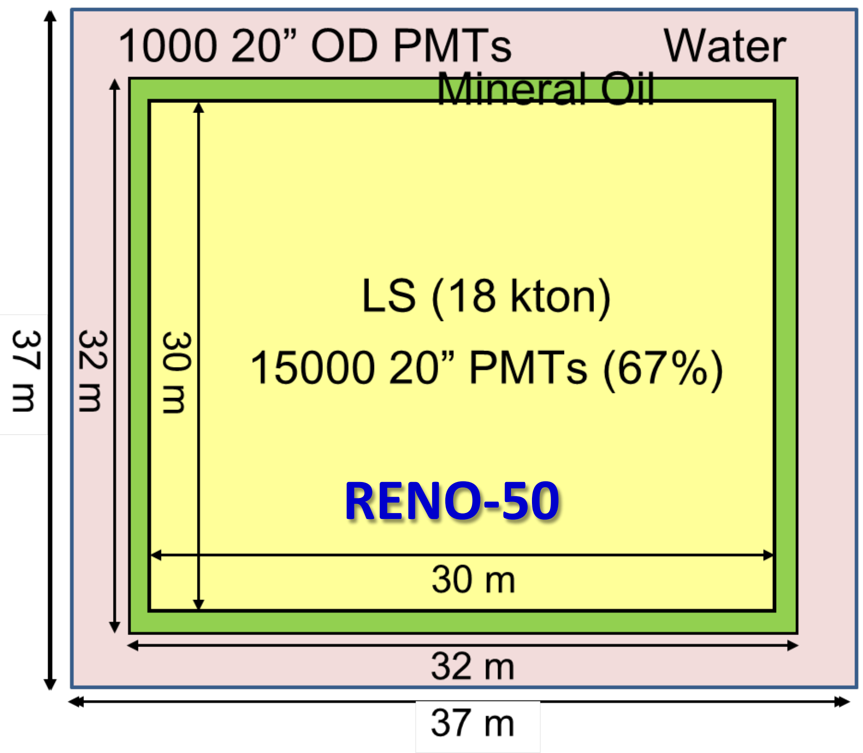


It is very challenging to determine neutrino mass hierarchy !

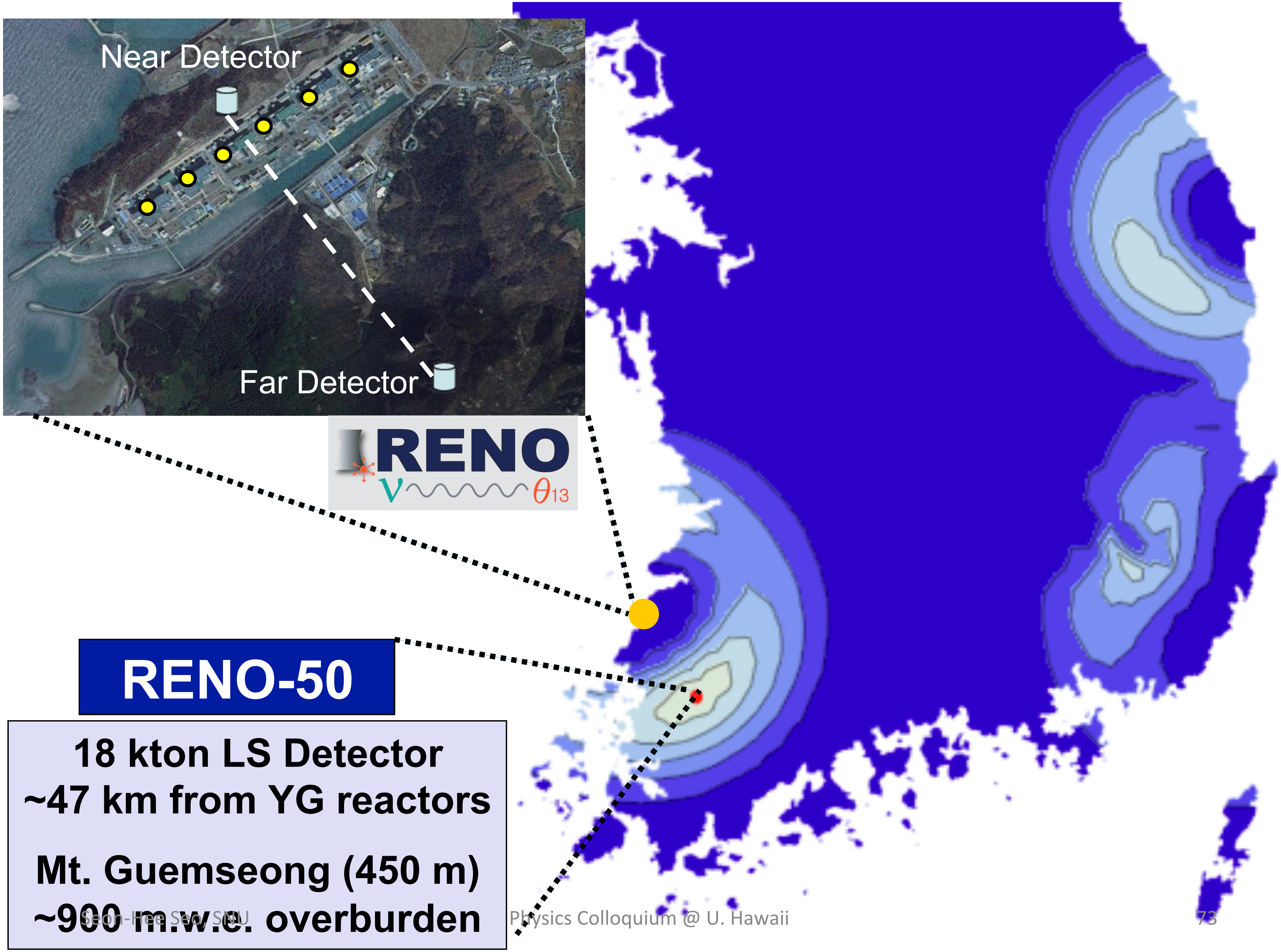
Challenge: high-precision, giant LS detector



@Neutrino 2014



	KamLAND	JUNO	RENO-50
LS mass	~1 kt	20 kt	18 kt
Energy Resolution	6%/	~3%/	~3%/
Light yield	250 p.e./MeV	1200 p.e./MeV	>1000 p.e./MeV



RENO-50

18 kton LS Detector
~47 km from YG reactors

Mt. Guemseong (450 m)
~900 m.w.e. overburden

◆ RENO can be used as near detector for RENO-50.
→ Reduces systematic error of nu flux.

While JUNO can not use Daya Bay detector as near detector.
→ To reduce neutrino interference effect from other reactors.

Y. Wang's talk
NuTel 2013

✧ Baseline difference should be < 500 m.

Li, Cao, Wang, Zhan: arXiv: 1303.6733

Ciuffoli, Evslin, Zhan: arXiv: 1302.0624

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

Fresh Good News

☐ $ 2 M grant from Samsung was awarded for RENO-50 R&D.

This grant will be used for R&D of

① Liquid scintillator purification.

② High QE PMT performance to reach 3% resolution.

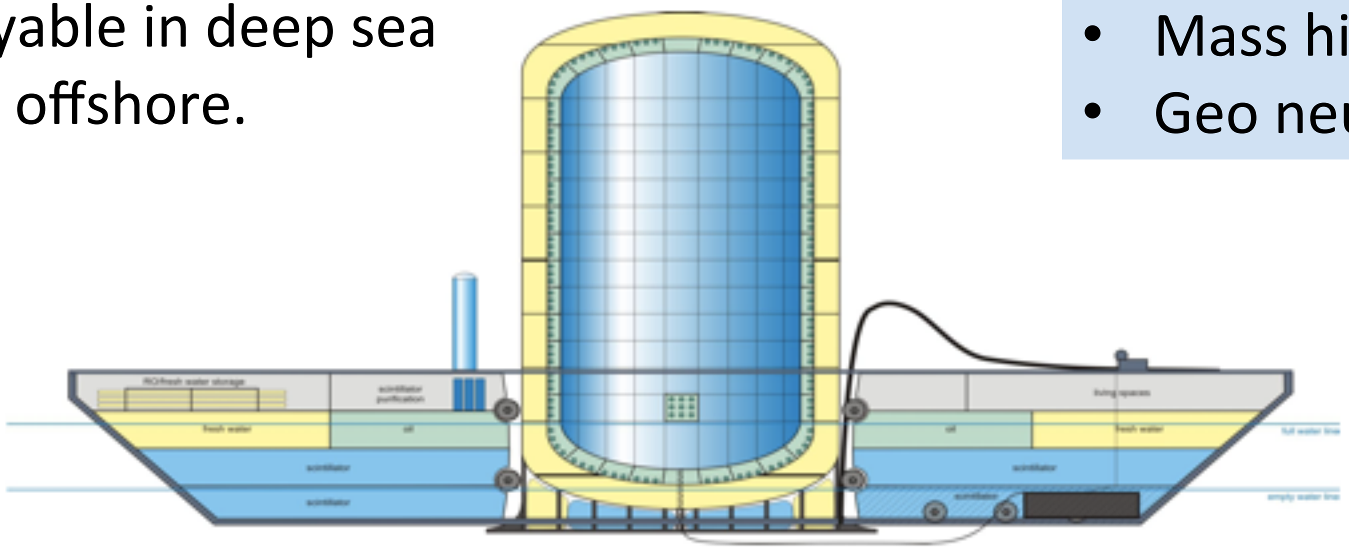
→ RENO-50 needs your collaboration !

Hano Hano

Hawaiian antineutrino observatory

-- 10 kton liquid scintillator detector
deployable in deep sea
50 km offshore.

- θ_{13}
- Mass hierarchy
- Geo neutrinos



Very clever idea !

More Big Questions

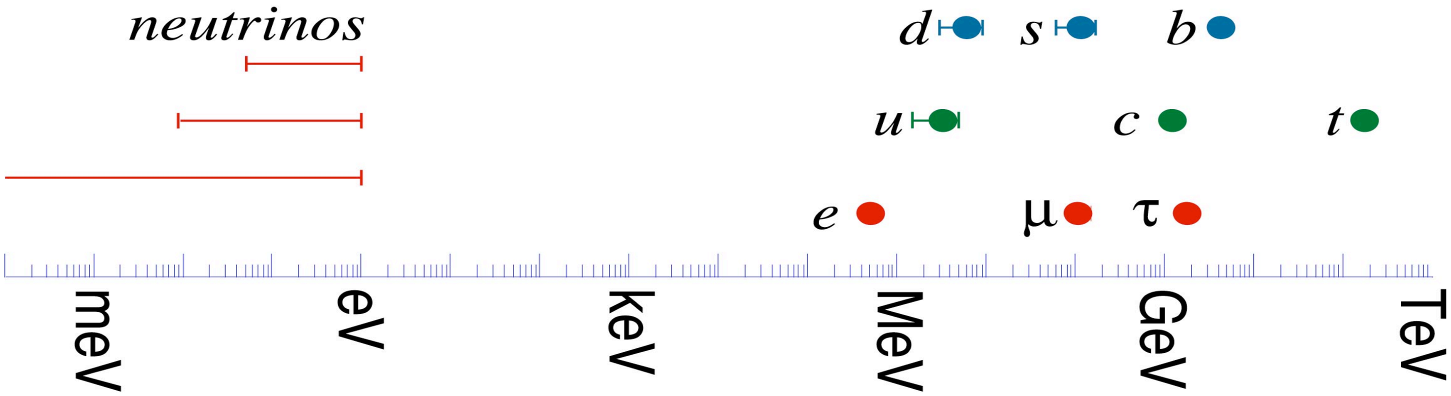
Q2. Why our universe is dominated by matter ?

Q3. Are there more than three types of neutrinos ?

Q4. Are neutrinos their own anti-particles ?

Q5. What are the absolute masses of neutrinos ?

Q6. What gives the mass to the neutrinos ?




MAHALO