ニュートリノ振動から大統一理論・究極理論へ

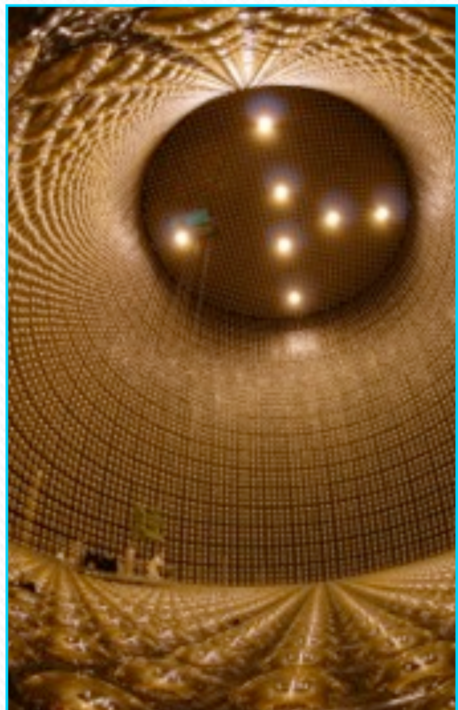
Progress and Future prospect of Neutrino Physics with the recent results from the T2K experiment

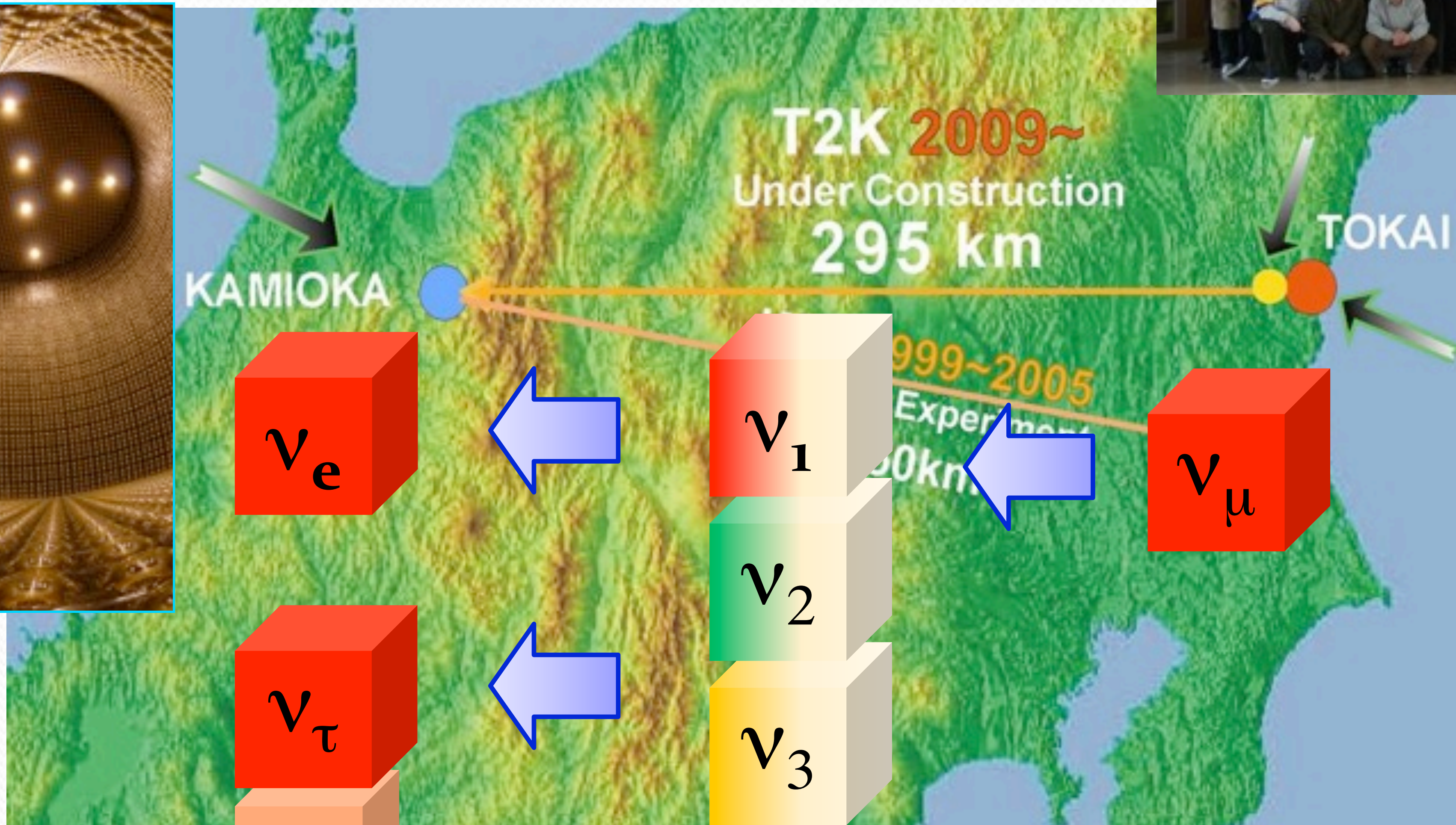
T. Nakaya (Kyoto)

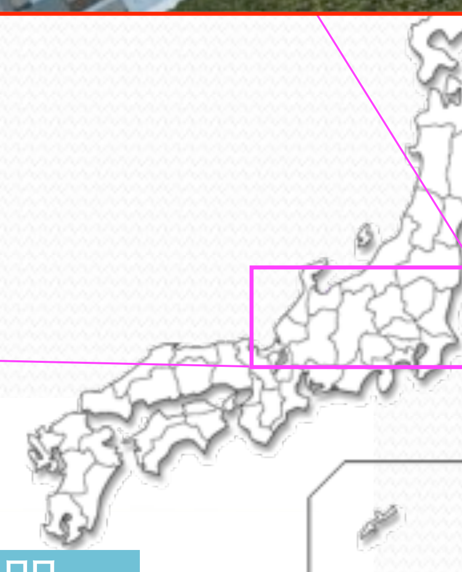
T2K
Kyoto University
Kyoto
Osaka
Kobe
Super-K
J-PARC
295km
Kanazawa
Tsu
Nagoya
Gifu
Nagano
Japan
Kofu
Shizuoka
Maebashi
Hachioji
Saitama
Kanagawa
Tokyo
Yokohama
Kawasaki
Funabashi
Chiba
Mito
Niigata
Sado
Awa-shima
Honshu
Fukushima
E133°
E135°
E137°
E139°
E141°
N35°
N37°
Image NASA
© 2007 Europa Technologies
Image © 2007 TerraMetrics
© 2007 ZENRIN
©2007 Google™
Pointer 36° 23'41.59" N 139° 11'54.71" E elev 665 m
Streaming 100%
Eye alt 223.17 km

T2K Experiment

Tokai-to(2)-Kamioka





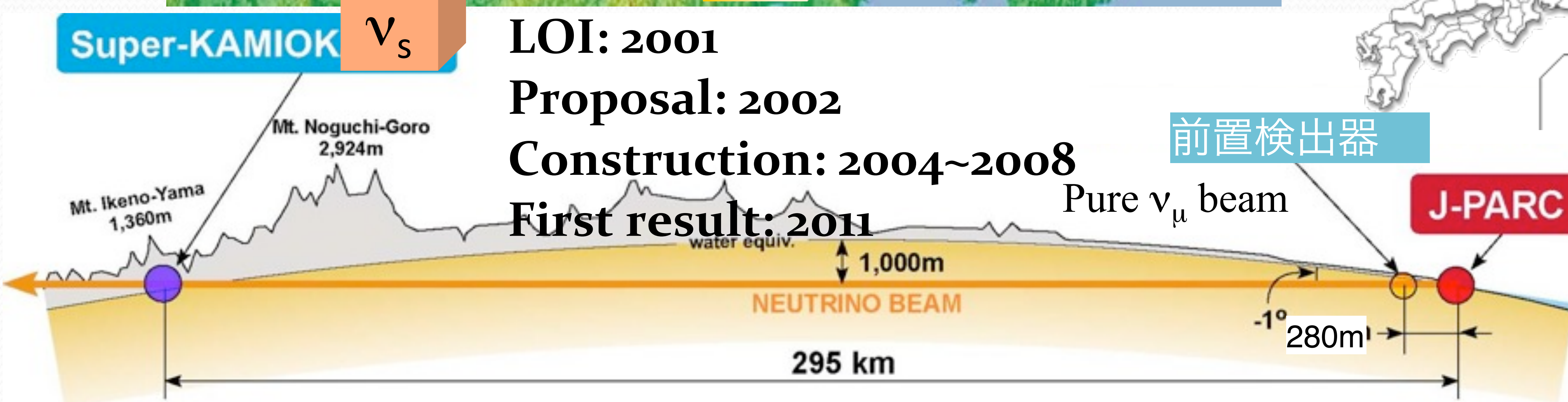


LOI: 2001

Proposal: 2002

Construction: 2004~2008

First result: 2011



Outline

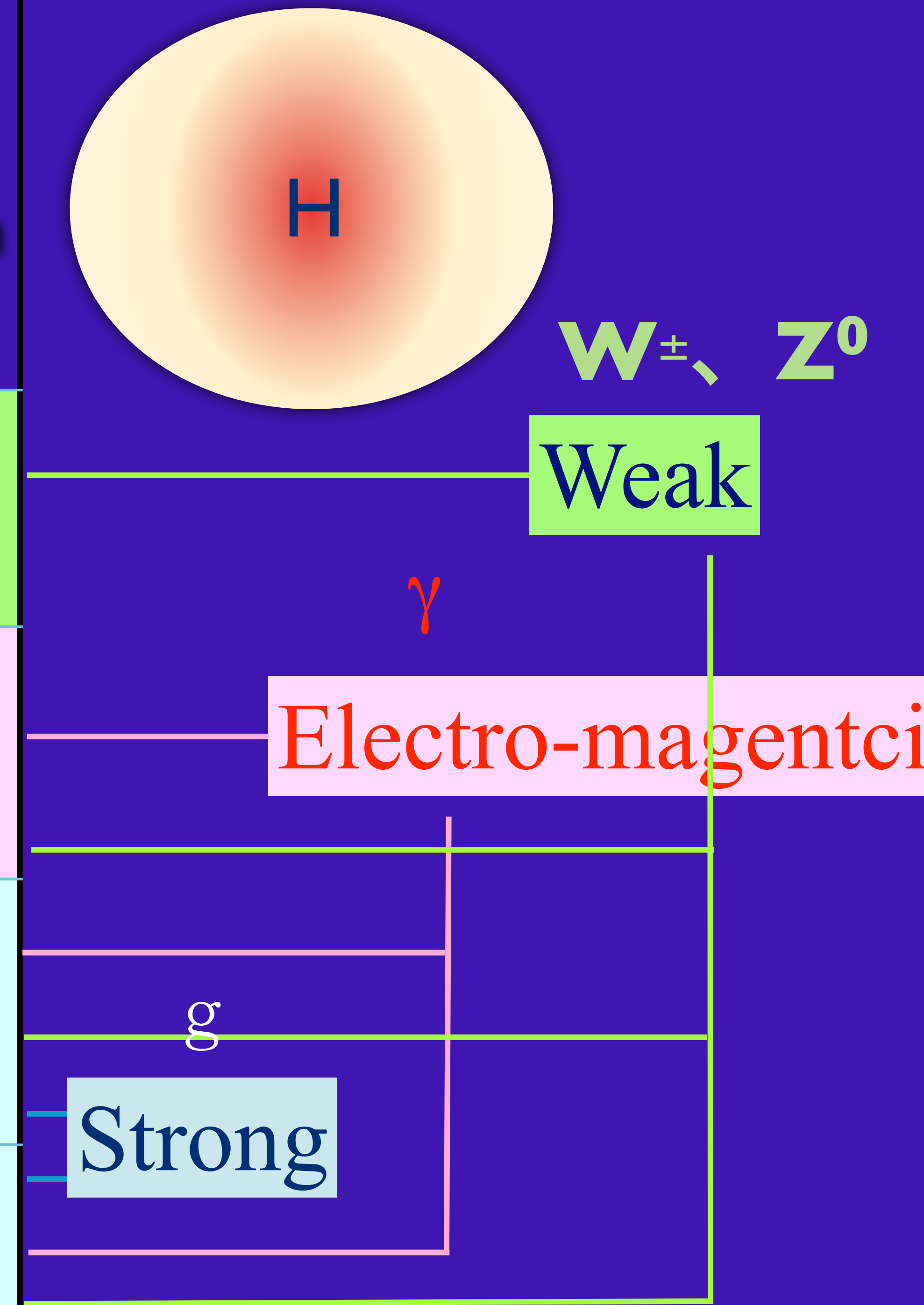
1. Introduction to Neutrino Physics
2. Achievement and goals of the T2K Experiment.
    1. Discovery of $\nu_\mu \rightarrow \nu_e$
    2. Goal of T2K
3. A Next Generation Neutrino Experiment to probe the Grand Unification Theory.
    1. Hyper-Kamiokande
    2. (Intensity Frontier by J-PARC accelerator)
4. Summary

Neutrino Physics

SUSY

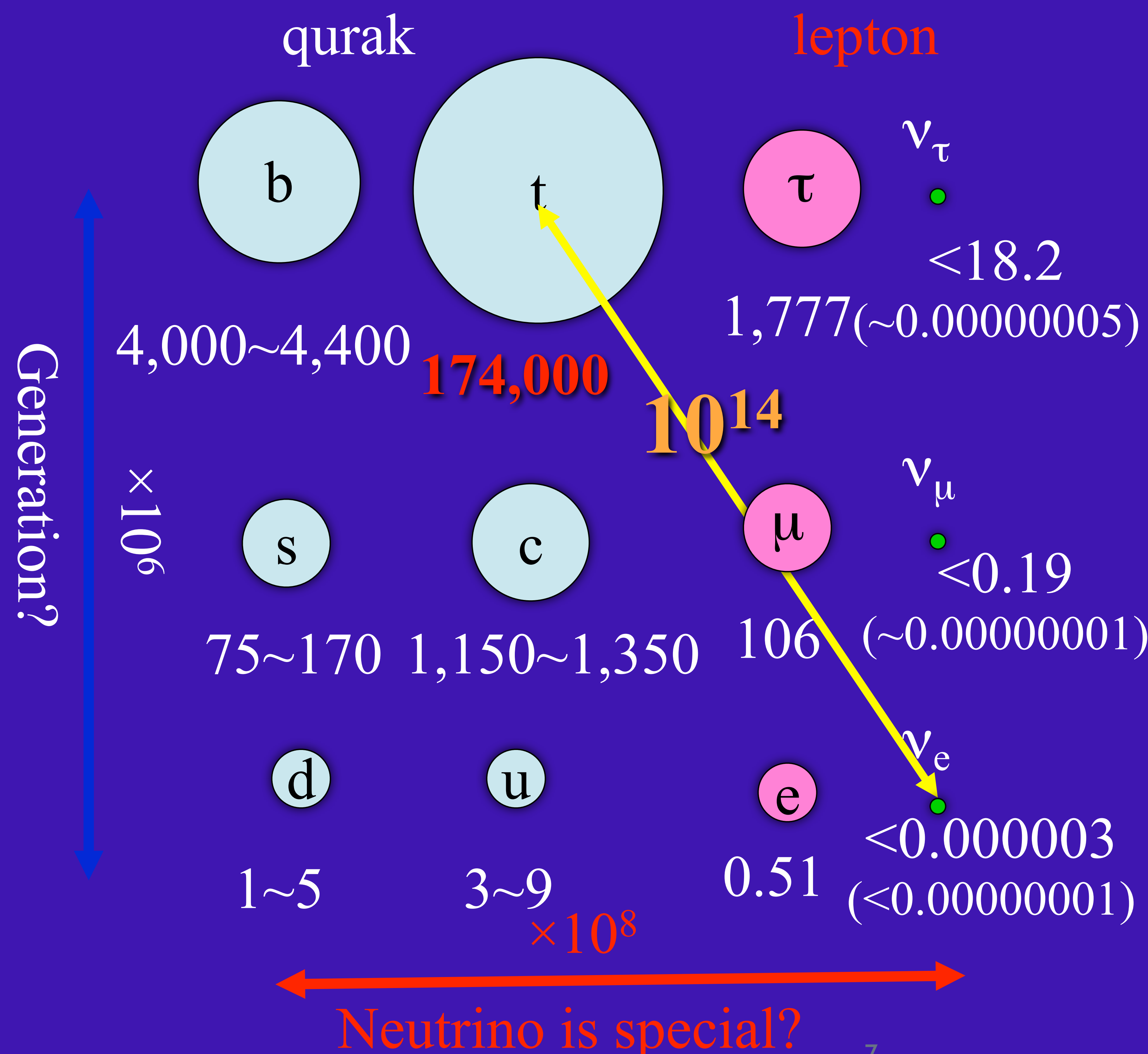
Particles and Force

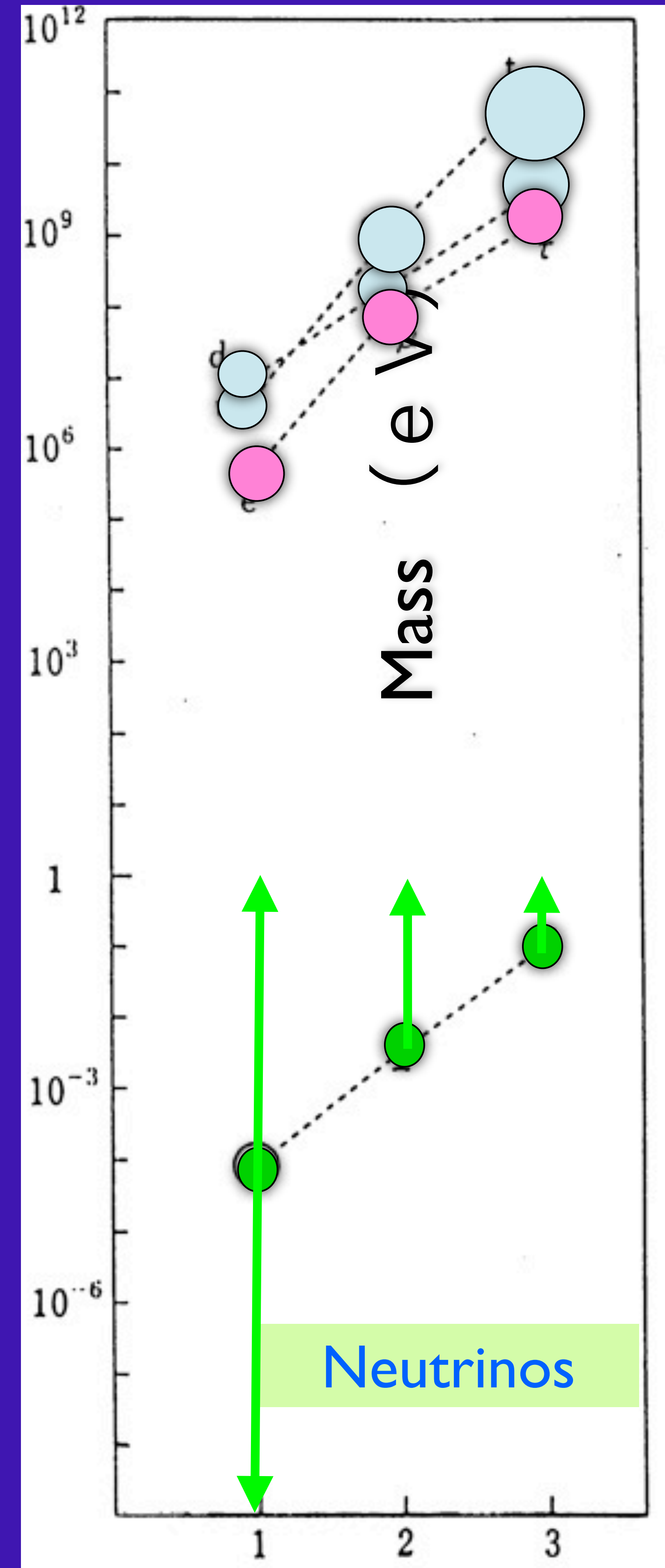
	Charge	1st Generation	2nd Generation	3rd Generation
Lepton	0	ν_e	ν_μ	ν_τ
	-1	e	μ	τ
Quark	2/3	u	c	t
	-1/3	d	s	b



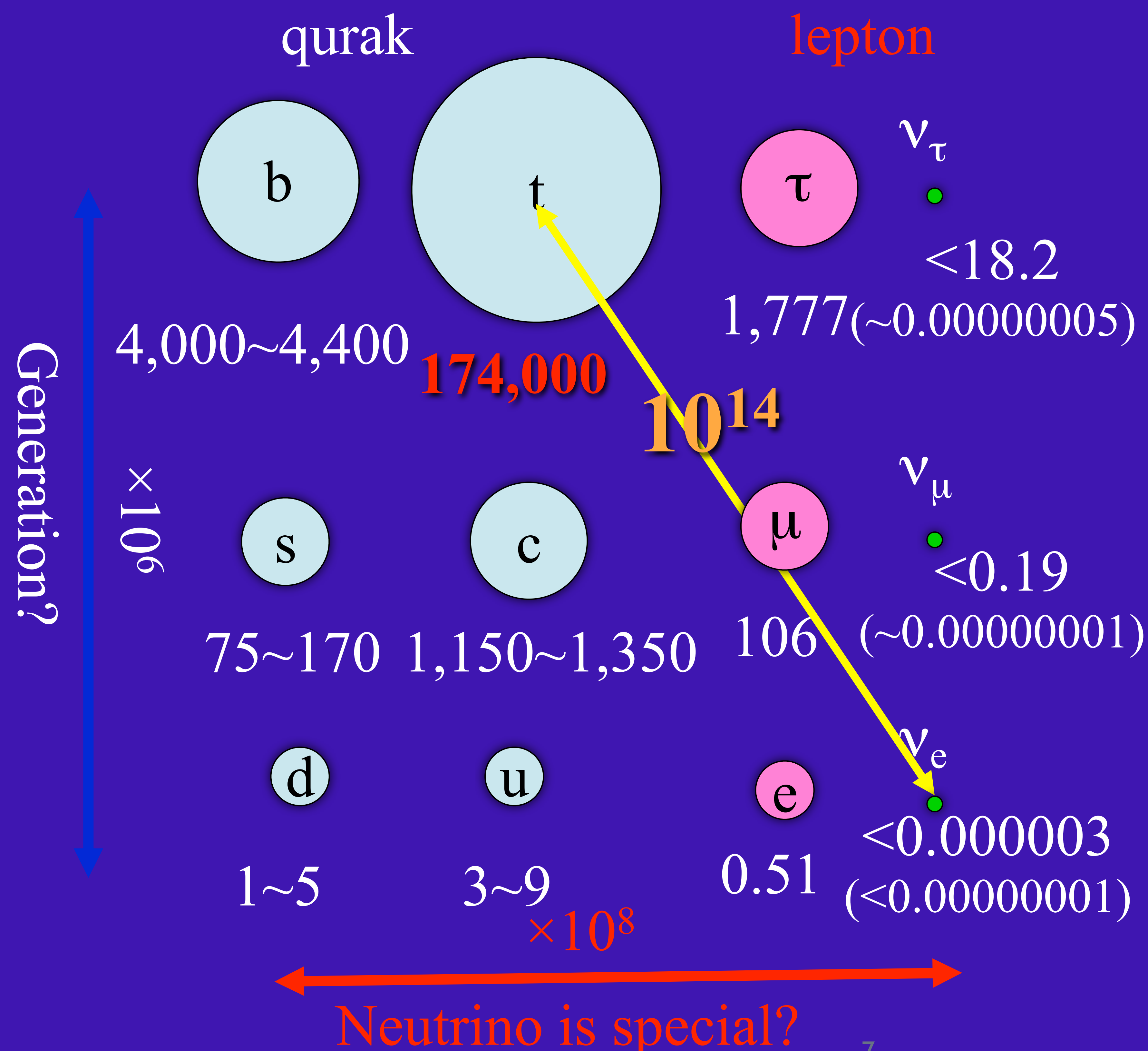
+Anti-particles

Mass


qurak
lepton
b
t
τ
ν_τ
<18.2
4,000~4,400
174,000
1,777
(~0.00000005)
10^{14}
Generation?
$\times 10^6$
s
c
μ
ν_μ
<0.19
75~170
1,150~1,350
106
(~0.00000001)
d
u
e
ν_e
<0.000003
(<0.00000001)
1~5
3~9
0.51
$\times 10^8$
Neutrino is special?


10^{12}
10^9
10^6
10^3
1
10^{-3}
10^{-6}
Mass (eV)
Neutrinos
1
2
3

Mass



qurak
lepton
b
t
τ
ντ
<18.2
(~0.00000005)
4,000~4,400
174,000
1,777
10^14
Generation?
×10^6
s
c
μ
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<0.19
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75~170
1,150~1,350
106
d
u
e
νe
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(<0.00000001)
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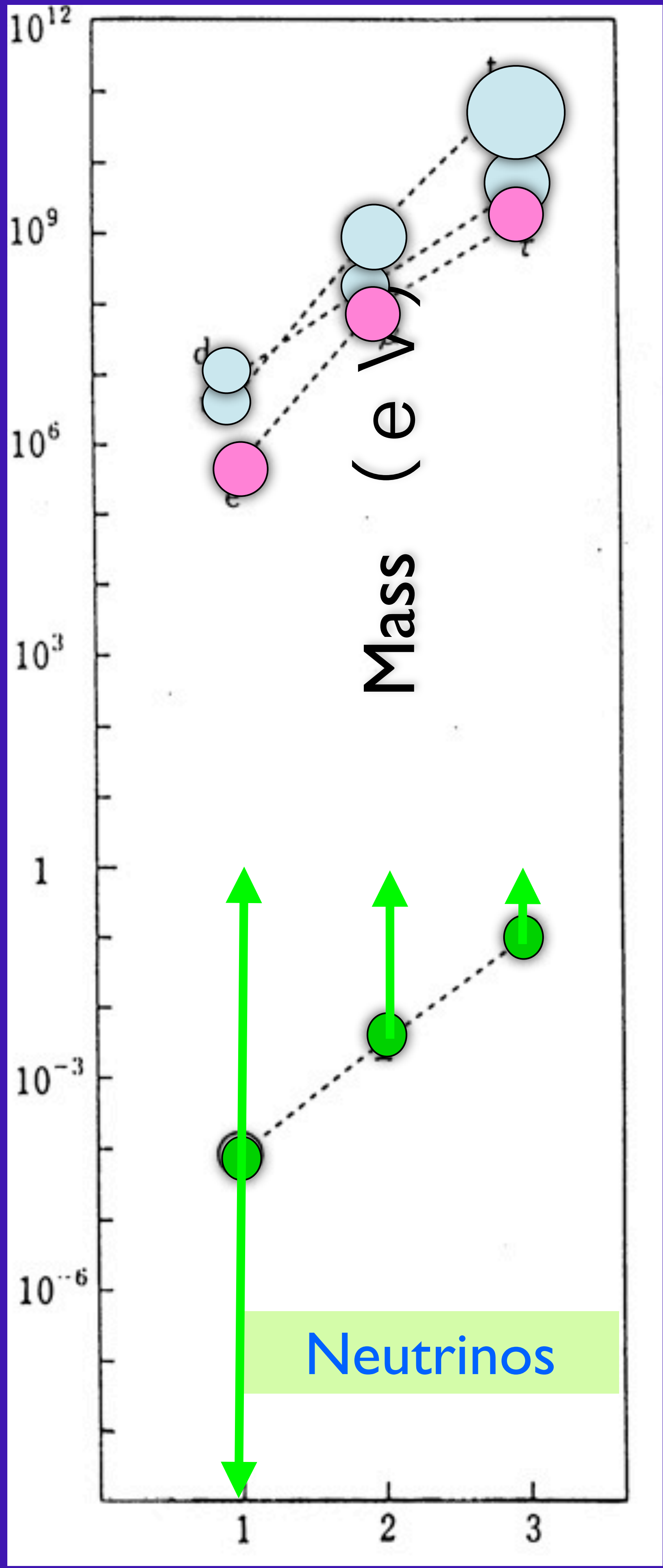
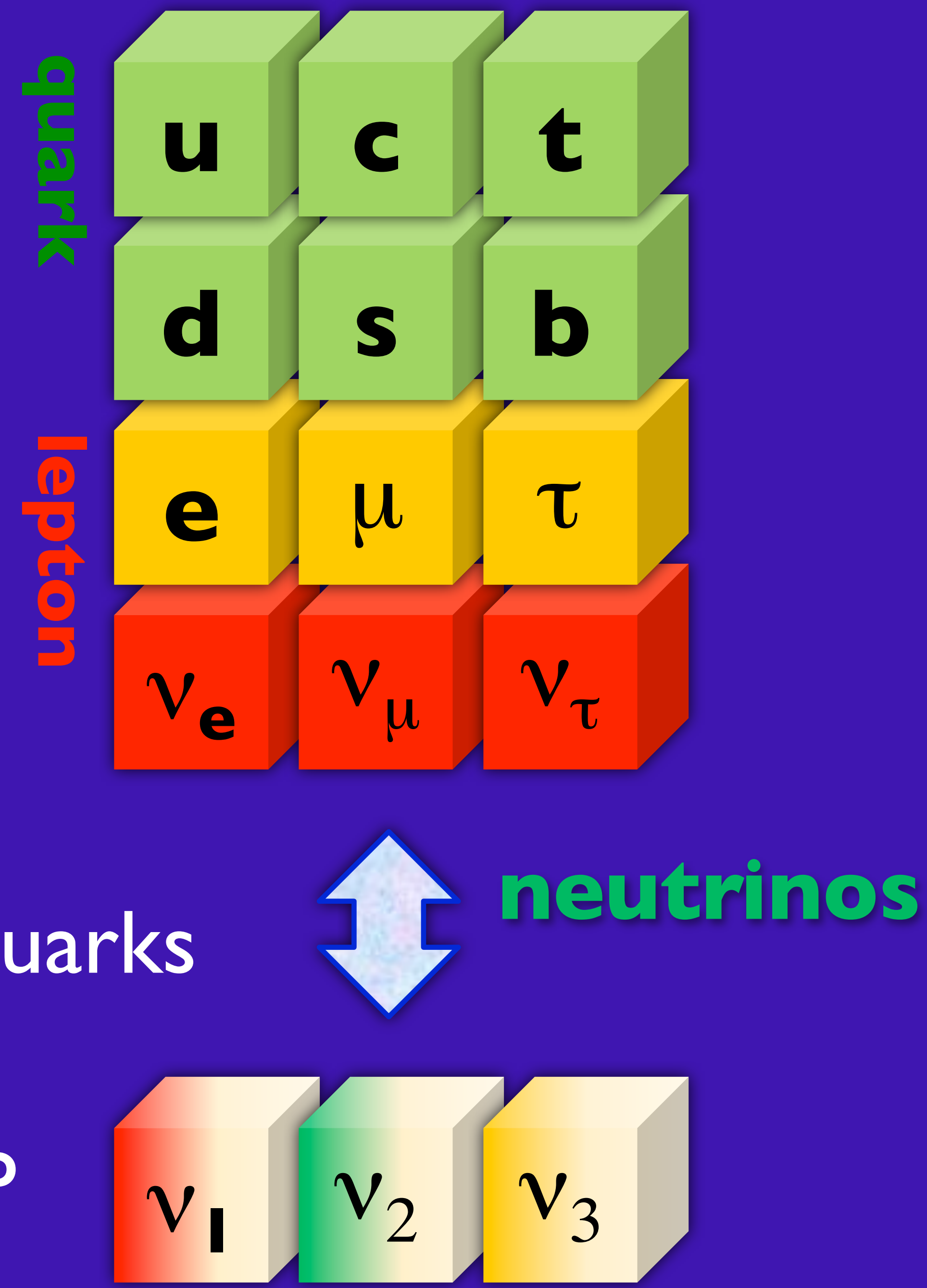
3~9
0.51
×10^8
Neutrino is special?



10^12
10^9
10^6
10^3
1
10^-3
10^-6
Mass (eV)
Neutrinos
1
2
3

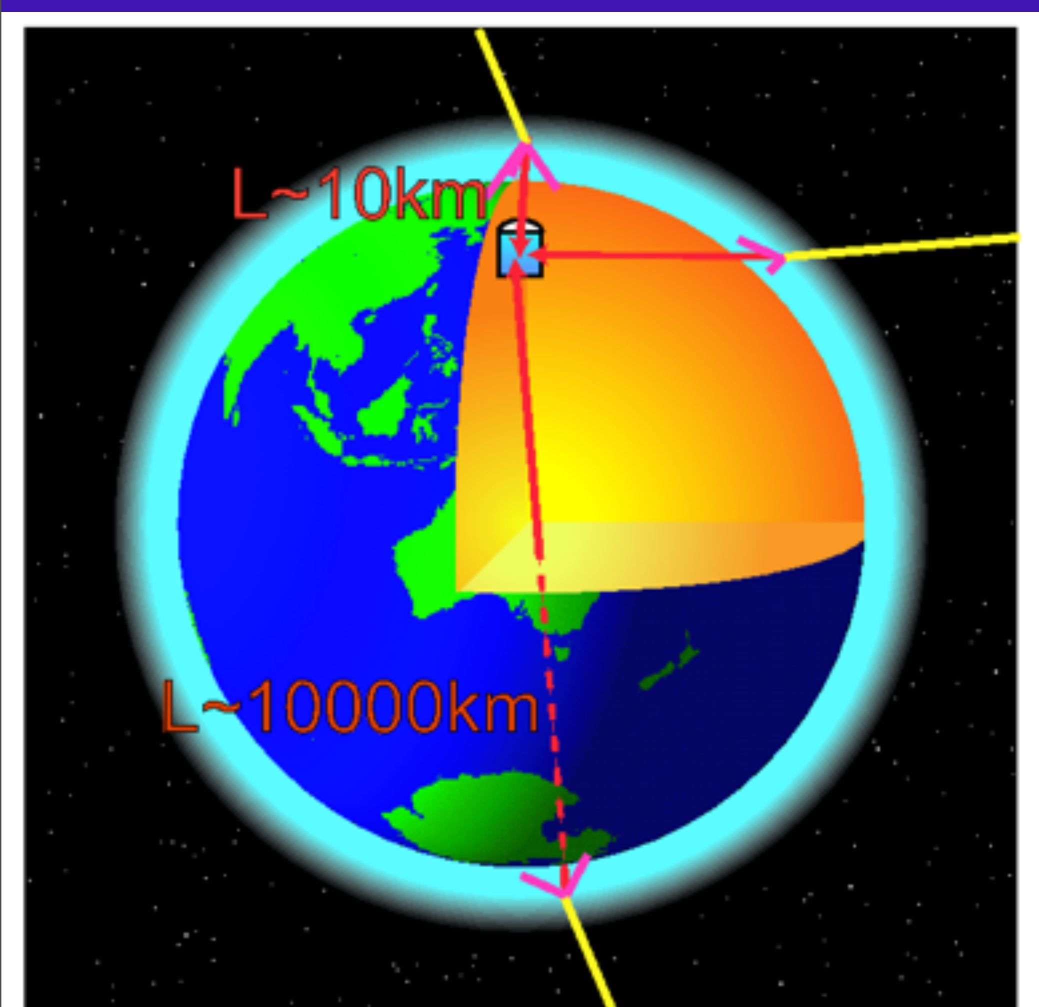
Neutrinos

- Week interactions only
  - Small mass
    - Origin in physics beyond the standard model?
  - Mixing
    - 3 neutrinos are mixed
    - Different mixing patterns from that of quarks
      - What symmetry exists?
    - No experimental information on the CP symmetry

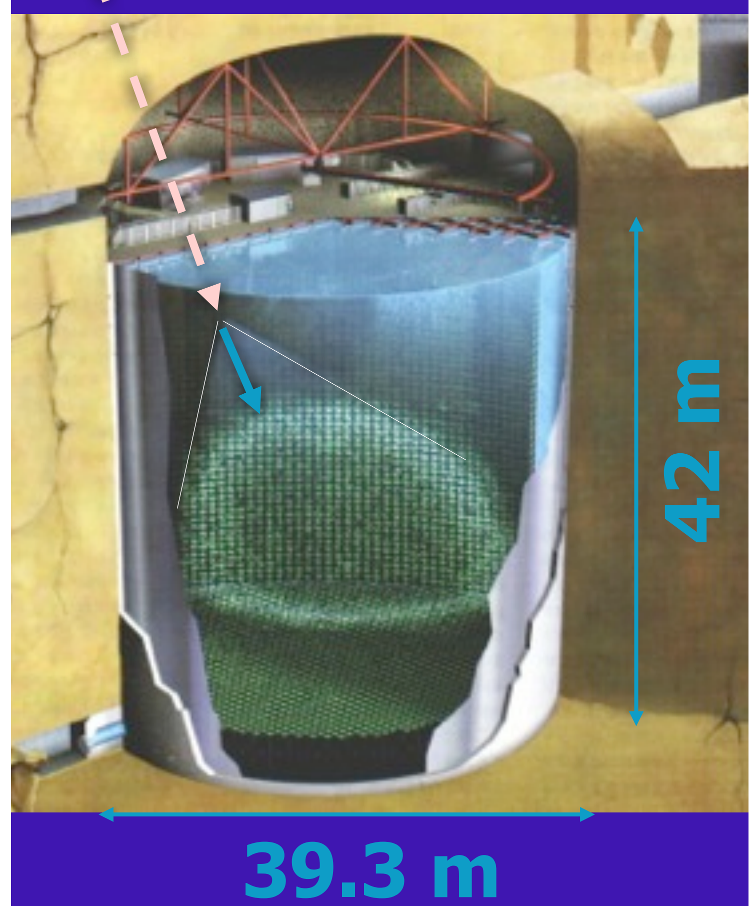


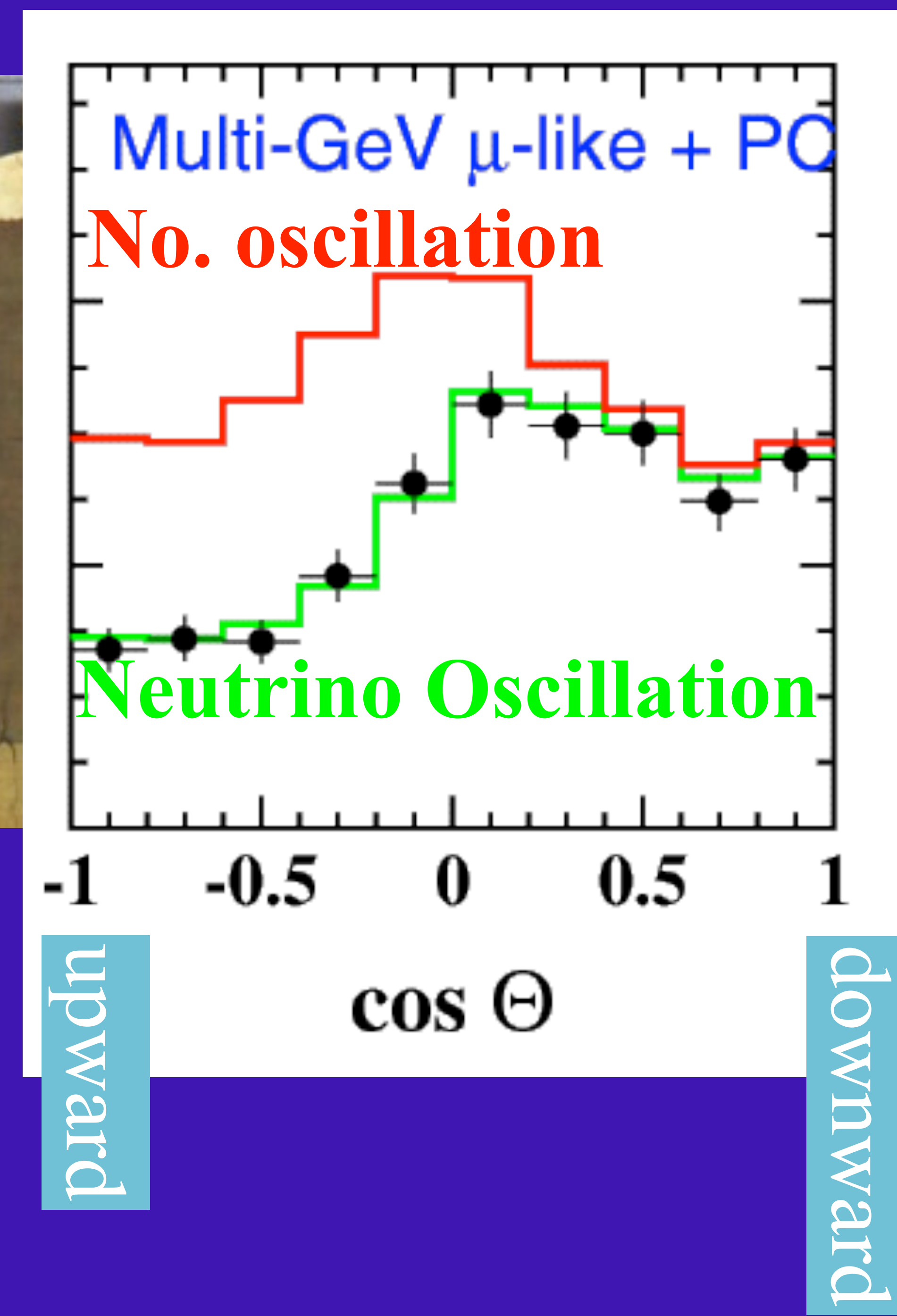
Much exciting to study neutrinos after the discovery of neutrino oscillation in 1998

Discovery of neutrino oscillation(1998)
Evidence of neutrino mass



Super-Kamiokande





Mixing Matrix

Kobayashi-Maskaw matrix

Weak state

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Mass state

Mixing Matrix

Kobayashi-Maskaw matrix

Weak state

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Mass state

Maki-Nakagawa-Sakata matrix

Weak state

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

Mass state

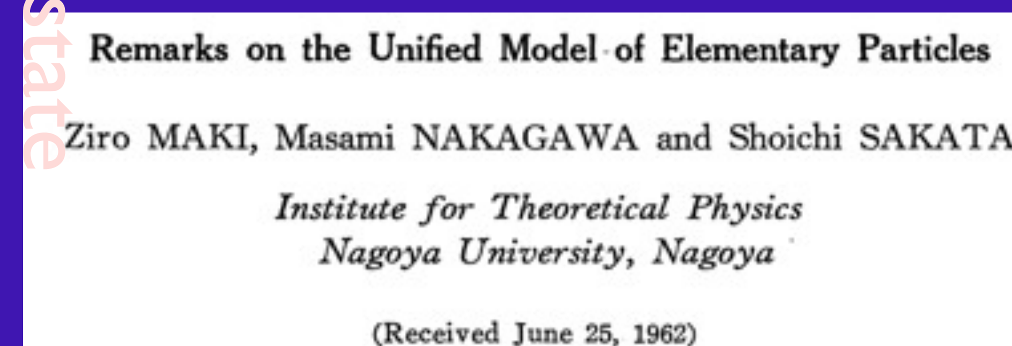
Mixing Matrix

Kobayashi-Maskaw matrix

Weak state

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Mass state



Remarks on the Unified Model of Elementary Particles

Ziro MAKI, Masami NAKAGAWA and Shoichi SAKATA

Institute for Theoretical Physics
Nagoya University, Nagoya

(Received June 25, 1962)

Maki-Nakagawa-Sakata matrix

Weak state

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

Mass state

Mixing Matrix

Kobayashi-Maskaw matrix

Weak state

a) The weak neutrinos must be re-defined by a relation

$$\left.\begin{array}{l}\nu_e=\nu_1 \cos\delta-\nu_2 \sin\delta,\\ \nu_\mu=\nu_1 \sin\delta+\nu_2 \cos\delta.\end{array}\right\}\qquad(2\cdot18)$$

The leptonic weak current (2·9) turns out to be of the same form with (2·1). In the present case, however, weak neutrinos are *not stable* due to the occurrence of a virtual transmutation $\nu_e \rightleftarrows \nu_\mu$ induced by the interaction (2·10). If the mass difference between ν_2 and ν_1, i.e. $|m_{\nu_2}-m_{\nu_1}|=m_{\nu_2}$ *) is assumed to be a few Mev, the transmutation time $T(\nu_e \rightleftarrows \nu_\mu)$ becomes $\sim 10^{-18}$ sec for fast neutrinos with a momentum of ~Bev/c. Therefore, a chain of reactions such as[10)]

$$\pi^+ \to \mu^+ + \nu_\mu, \qquad (2\cdot19a)$$

$$\nu_\mu + Z(\text{nucleus}) \to Z' + (\mu^- \text{ and/or } e^-) \qquad (2\cdot19b)$$

is useful to check the two-neutrino hypothesis only when $|m_{\nu_2}-m_{\nu_1}| \lesssim 10^{-6}$ Mev

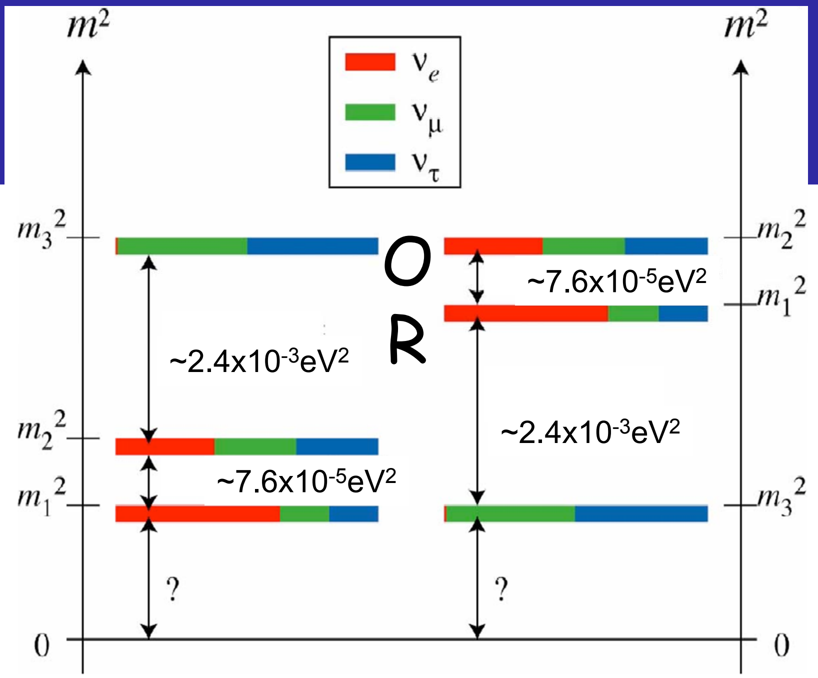
Particles

SAKATA

$$\begin{pmatrix}\nu_\tau\end{pmatrix} \quad \begin{pmatrix}V_{\tau 1} & V_{\tau 2} & V_{\tau 3}\end{pmatrix} \begin{pmatrix}\nu_3\end{pmatrix}$$

Mass state

Neutrino mixing



3 mixing angles: $\theta_{12}, \theta_{13}, \theta_{23}$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$s_{ij} = \sin\theta_{ij},\ c_{ij} = \cos\theta_{ij}$$

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric
Beam

Beam
Reactor
(atmospheric)

Solar
Reactor

$$U_{PMNS} \sim \begin{pmatrix} 0.8 & 0.55 & 0.15 \\ -0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

Neutrinos

δ～unknown

$$U_{CKM} \sim \begin{pmatrix} 0.97 & 0.23 & 0.004 \\ 0.23 & 0.97 & 0.04 \\ 0.008 & 0.04 & \sim 1 \end{pmatrix}$$

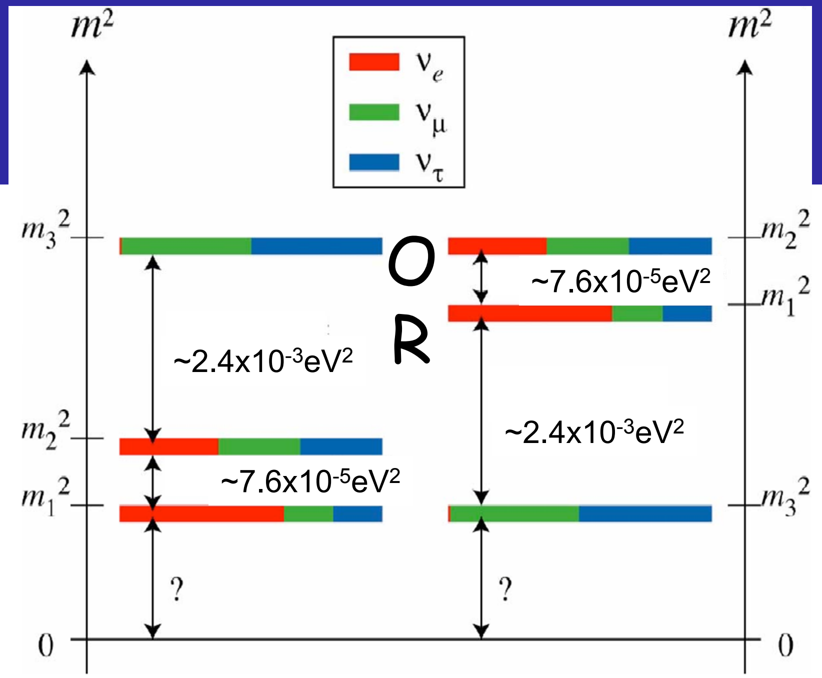
Quark

δ=60°

- **Mixing and Mass**
  - **Neutrinos：Democratic**
  - Quarks: Hierarchical

Neutrino mixing

3 mixing angles: θ_{12}, θ_{13}, θ_{23}



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Δm_{12}^2

Δm_{23}^2 ($\sim m_{13}^2$)

$s_{ij} = \sin\theta_{ij}$, $c_{ij} = \cos\theta_{ij}$

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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Quark

δ=60°

- **Mixing and Mass**
  - **Neutrinos：Democratic**
  - Quarks: Hierarchical

Status of Neutrino Oscillation

??? LSND anomaly ???

Atmospheric neutrinos

ν_μ **deficit (ν_τ appearance)**

Δm_{23} region

- $\Delta m_{23} \sim 2.5\times10^{-3}\,eV^2$
- $\sin^2 2\theta_{23} \sim 1.0$

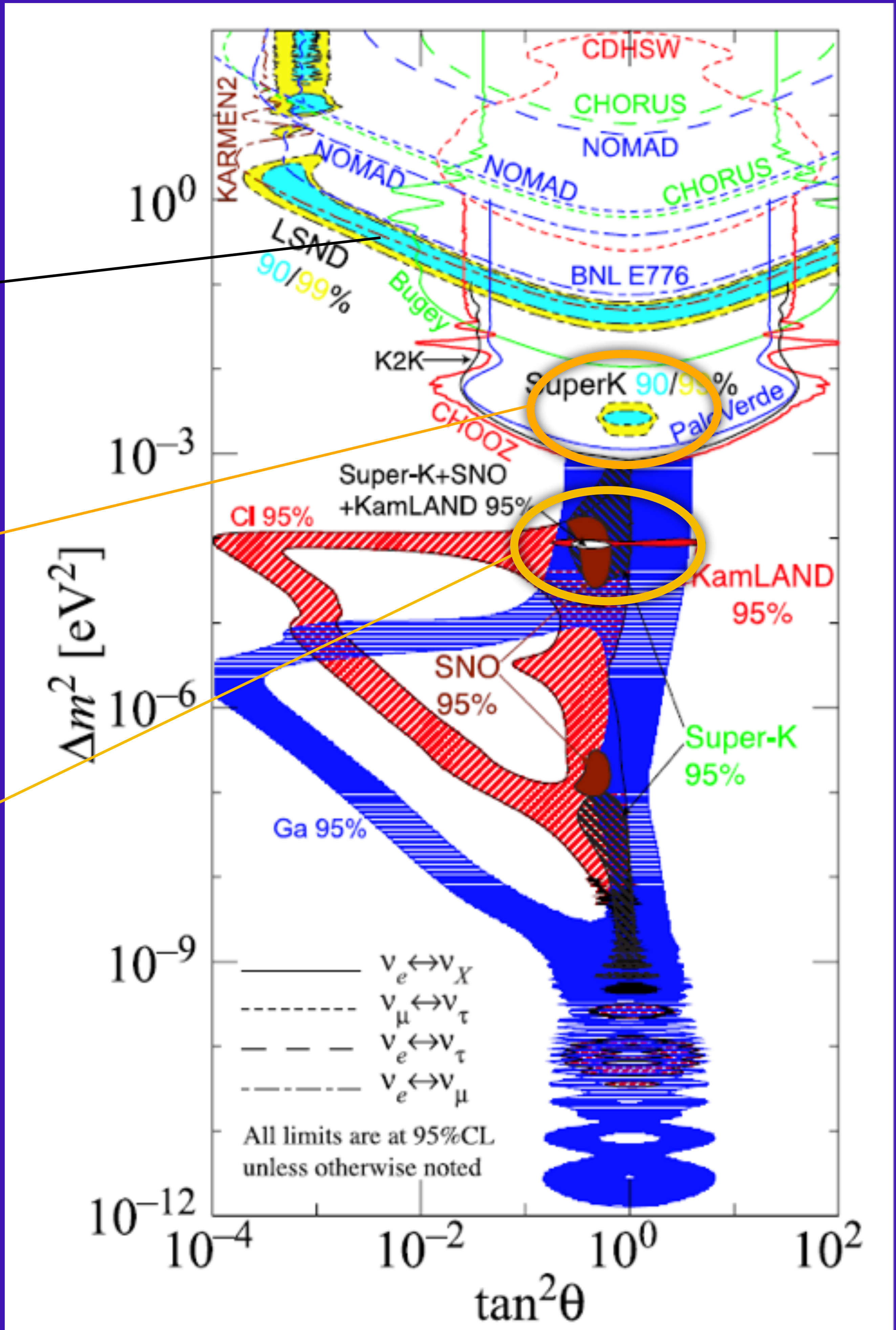
solar neutrinos

ν_e **deficit (NO NC deficit)**

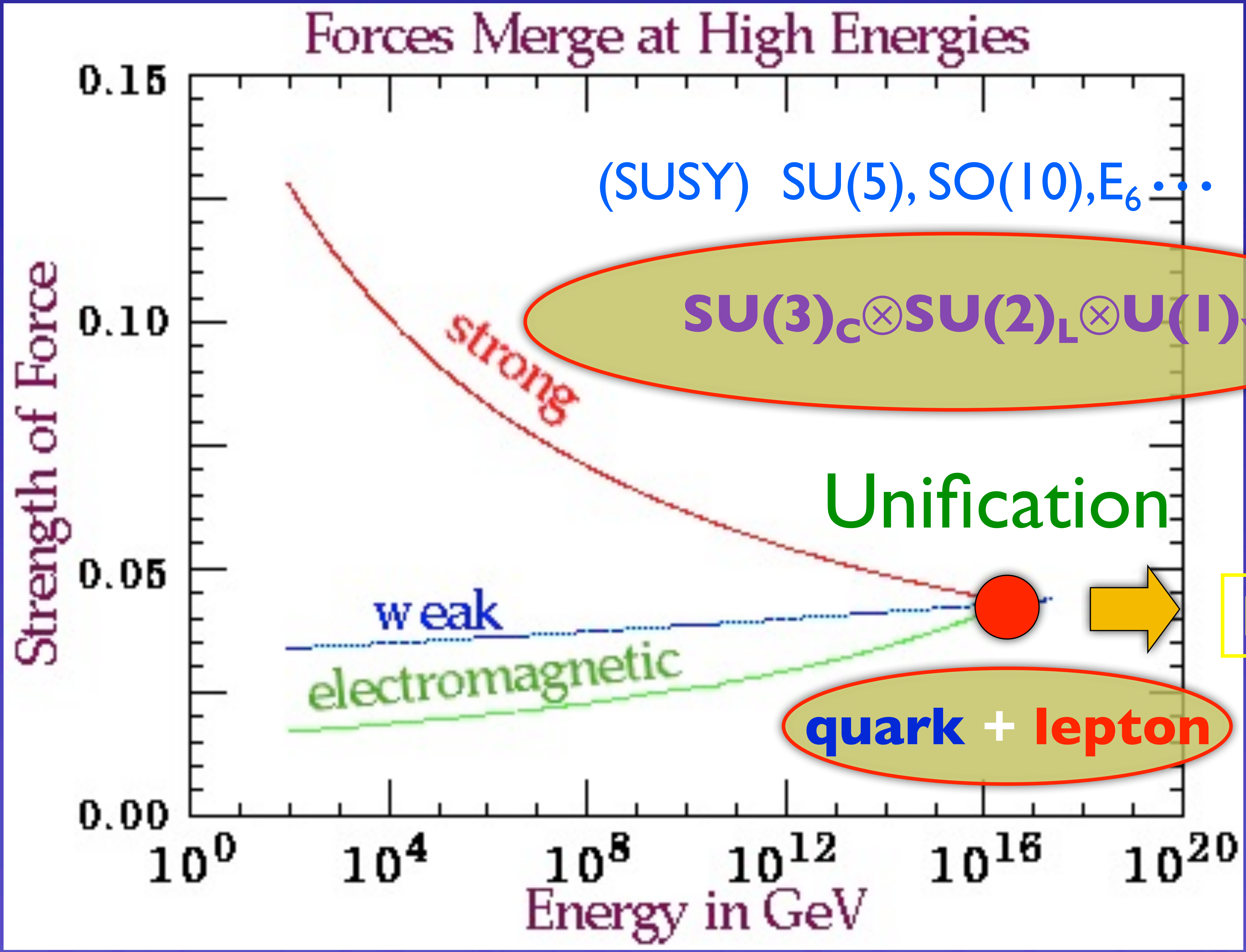
Δm_{12} region

- $\Delta m_{12} \sim 7.9\times10^{-5}\,eV^2$
- $\sin^2 2\theta_{12} \sim 0.82$

θ_{13} discovered in 2011



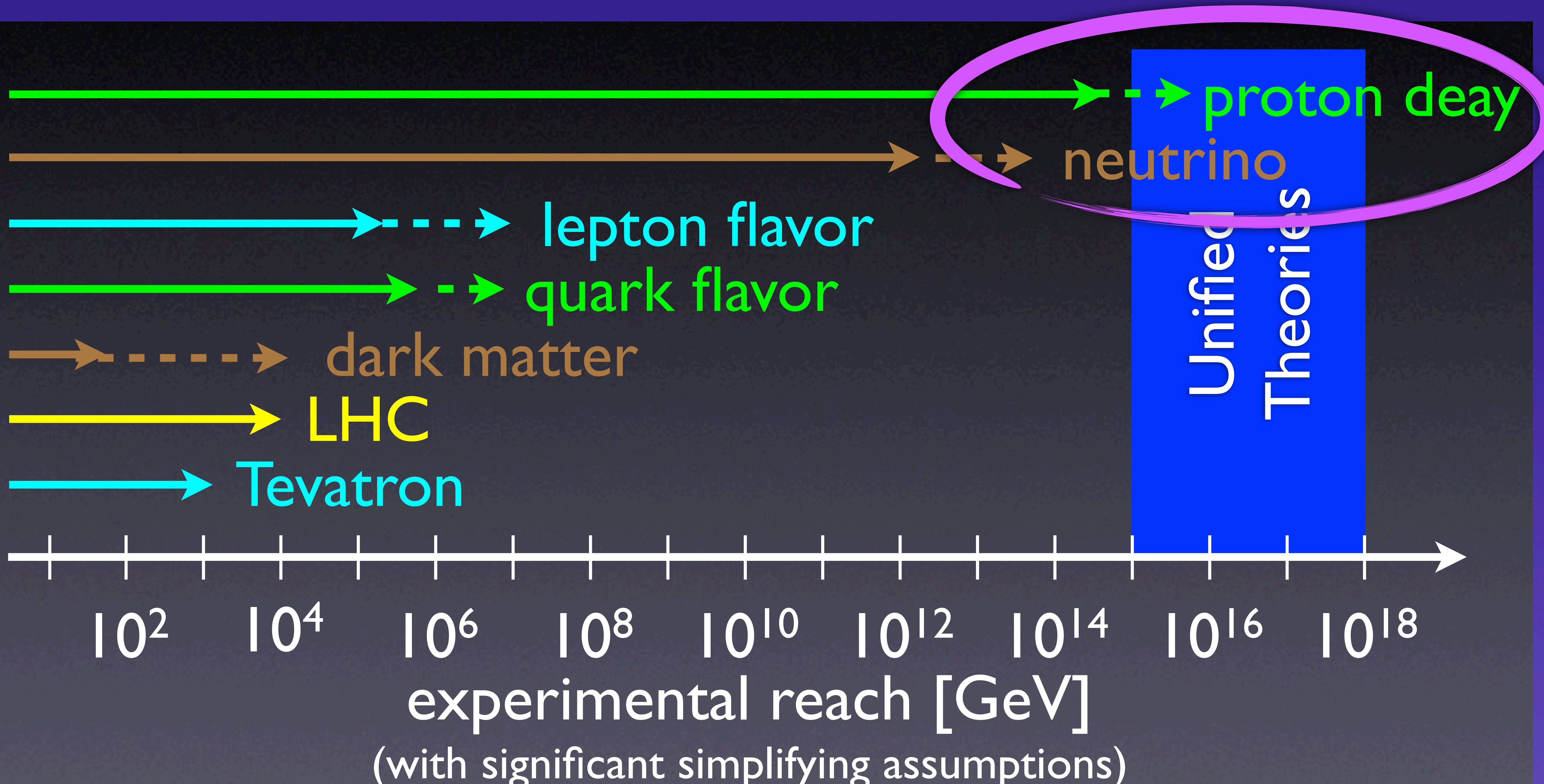
Grand Unified Theory (GUT)



Proton Decay

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

A window to GUT



courtesy Zoltan Ligeti

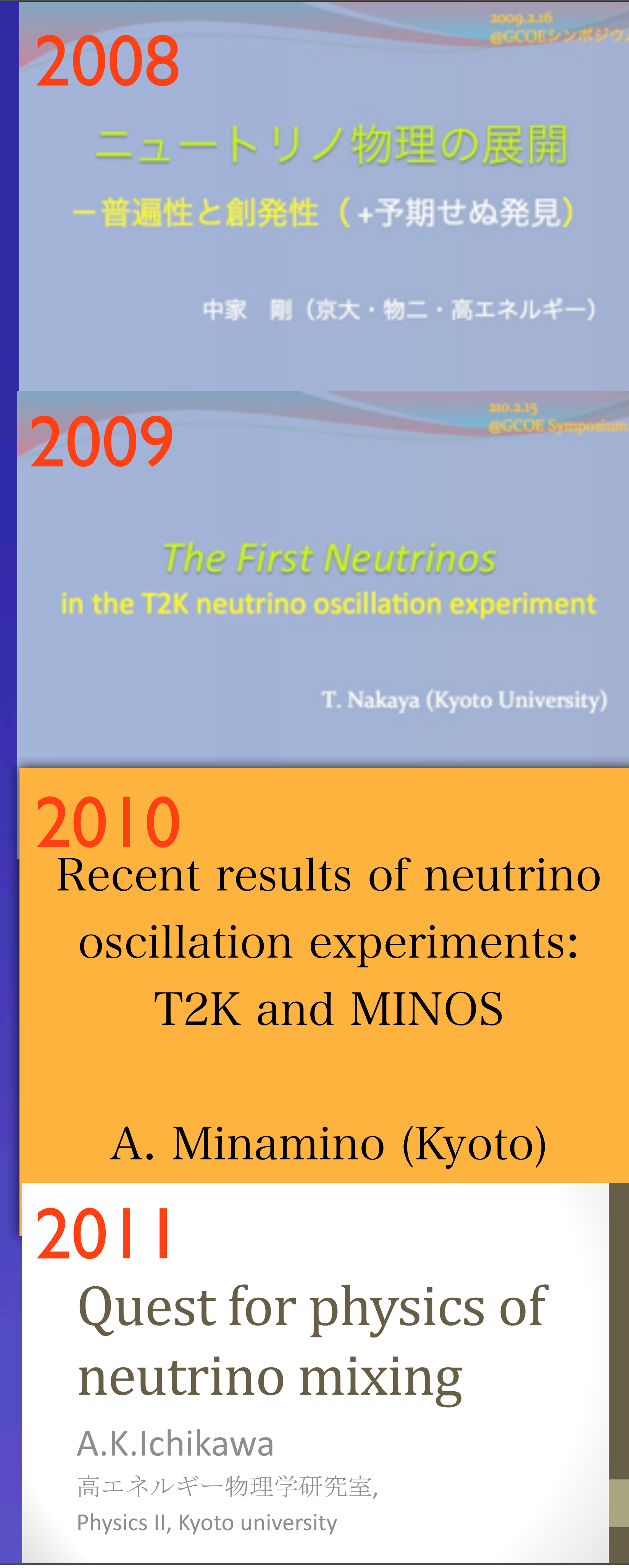
H. Murayama

Discovery of

$\nu_\mu \rightarrow \nu_e$ $(\theta_{13} \neq 0)$

History of T2K&GCOE

- **2008：** Finish the preparation of the T2K experiment
- **2009：** First Beam. Commissioning.
- **2010：** Physics Data Taking start
  - One (First) ν_e event detected.
- **2011：**
  - $\nu_\mu \rightarrow \nu_e$ （$\theta_{13} \neq 0$） **evidence**
  - Great East Japan Earthquake
- **2012：**
  - $\nu_\mu \rightarrow \nu_e$ （$\theta_{13} \neq 0$） discovery
  - A proposal of the next generation neutrino experiment: **Hyper-Kamiokande**



2009.2.16
@GCOEシンポジウム

2008

ニュートリノ物理の展開

ー普遍性と創発性（+予期せぬ発見）

中家　剛（京大・物二・高エネルギー）

210.2.15
@GCOE Symposium

2009

The First Neutrinos

in the T2K neutrino oscillation experiment

T. Nakaya (Kyoto University)

2010

T2K 2010 result

2011

Quest for physics of neutrino mixing

A.K.Ichikawa

高エネルギー物理学研究室,

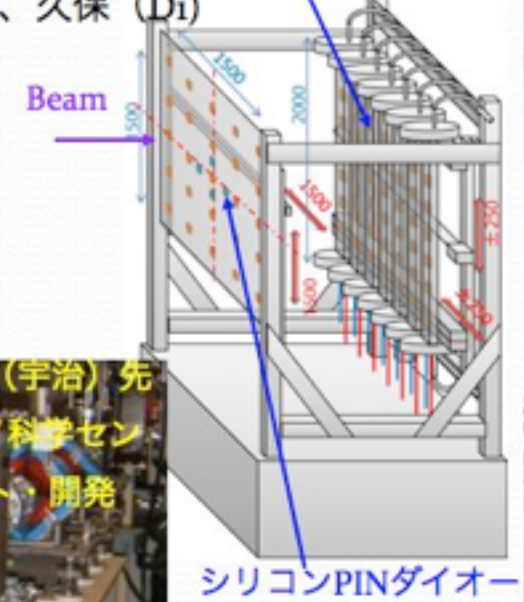
Physics II, Kyoto university

ニュートリノビームをモニター

2008

- π→μν崩壊のμを観測。

設計、製作：
松岡（D2)、久保（D1）



3日

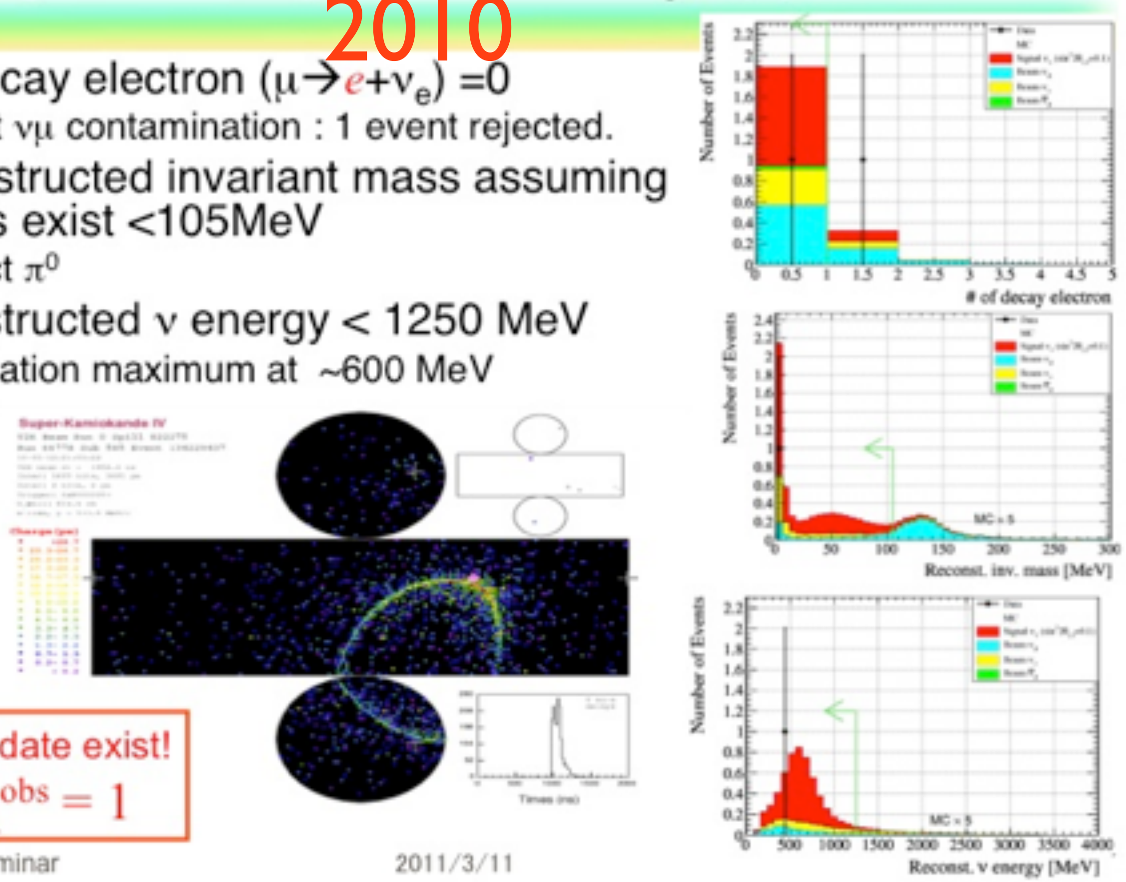
2009

The First Neutrino Beam April 23rd, 2009

Background rejection for ν_e appearance

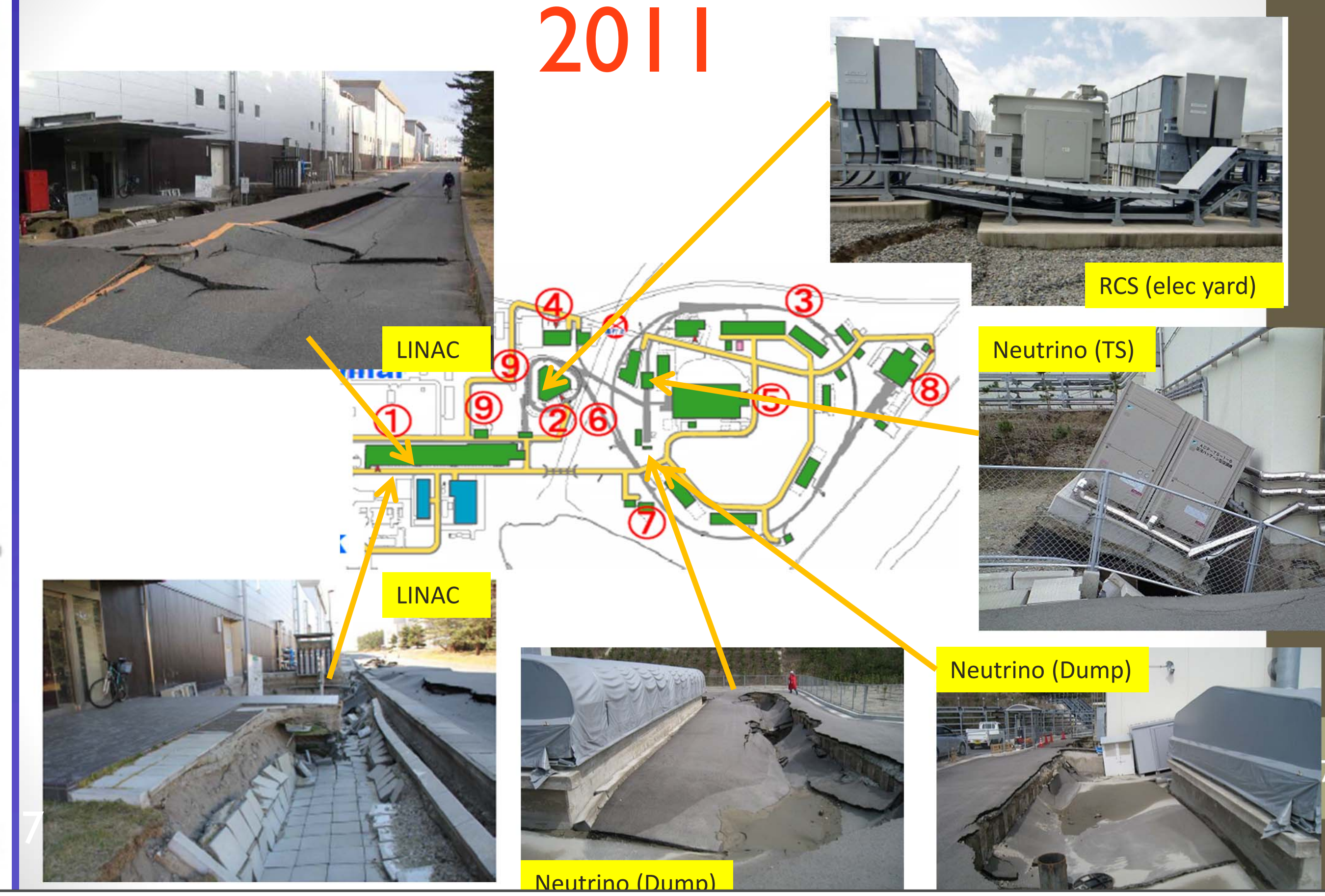
2010

- # of decay electron ($\mu \rightarrow e + \nu_e$) =0
  - Reject νμ contamination : 1 event rejected.
- Reconstructed invariant mass assuming 2γ rings exist <105MeV
  - Reject π^0
- Reconstructed ν energy < 1250 MeV
  - Oscillation maximum at ~600 MeV

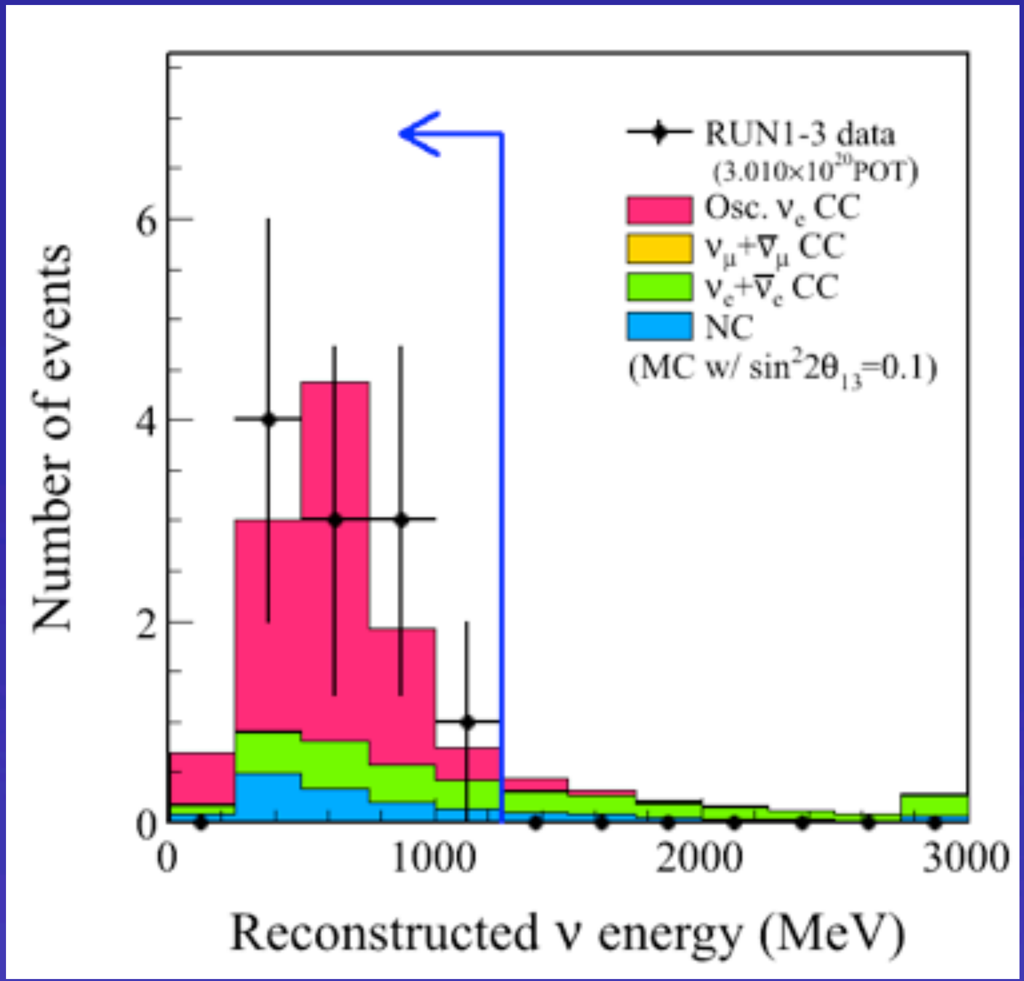


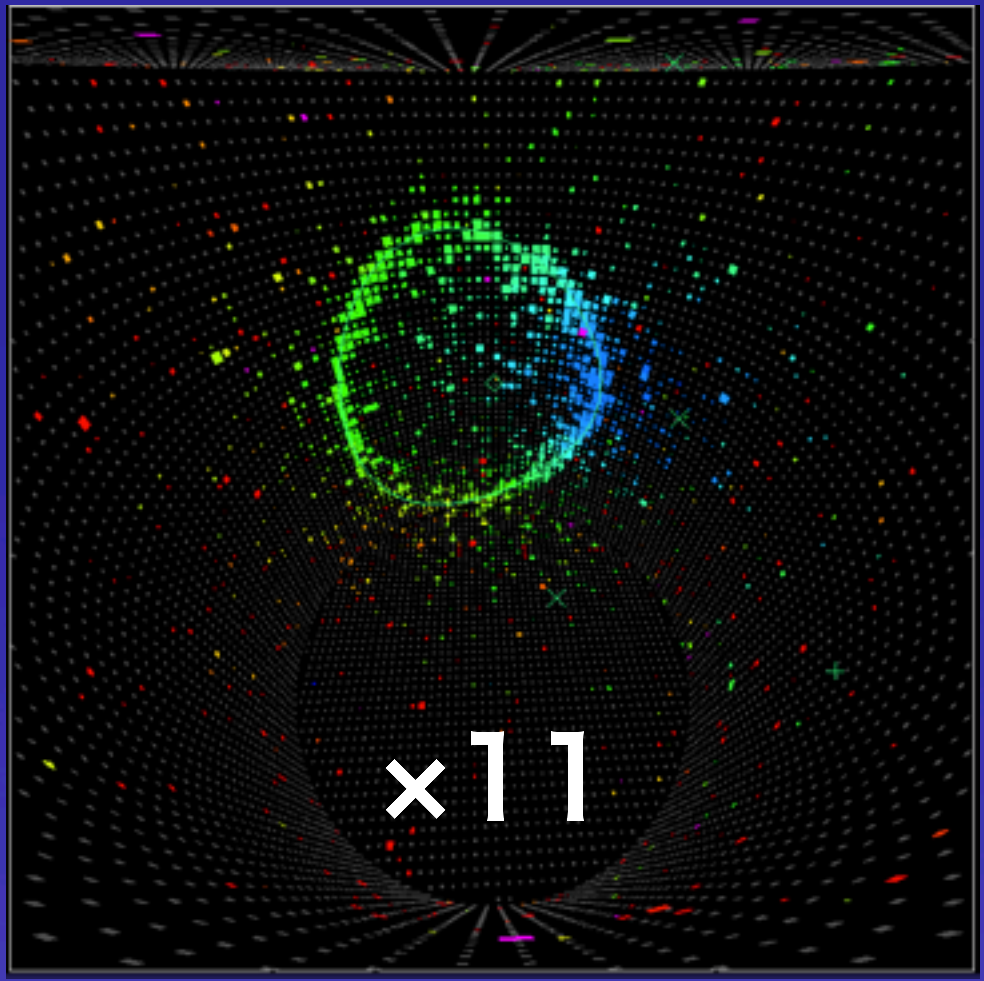
1 candidate exist!
$N_{SK}^{obs} = 1$

2011



T2K result

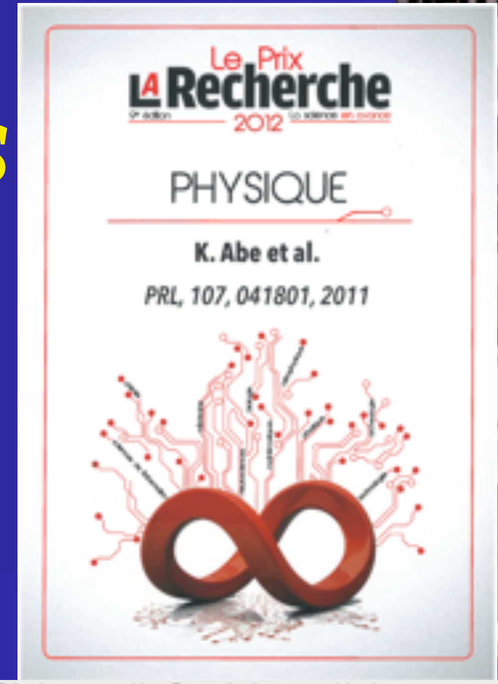




- **Evidence of $\nu_\mu \to \nu_e$**
  - PRL 107 (2011) 041801 Citation：**501**
  - 3 types of neutrinos are mixed
  - Open a window to study CP violation in neutrinos

Impact of T2K results

- Top 10 Physics breakthroughs in IOP 2011
- Le Prix La Recherche in 2012
- NEUTRINO2012 @ Kyoto

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Physics World reveals its top 10 breakthroughs for 2011

Dec 16, 2011 13 comments

VACUUM PUMPS TWISTORR TECHNOLOGY

7th place: Catching the flavour of a neutrino oscillation

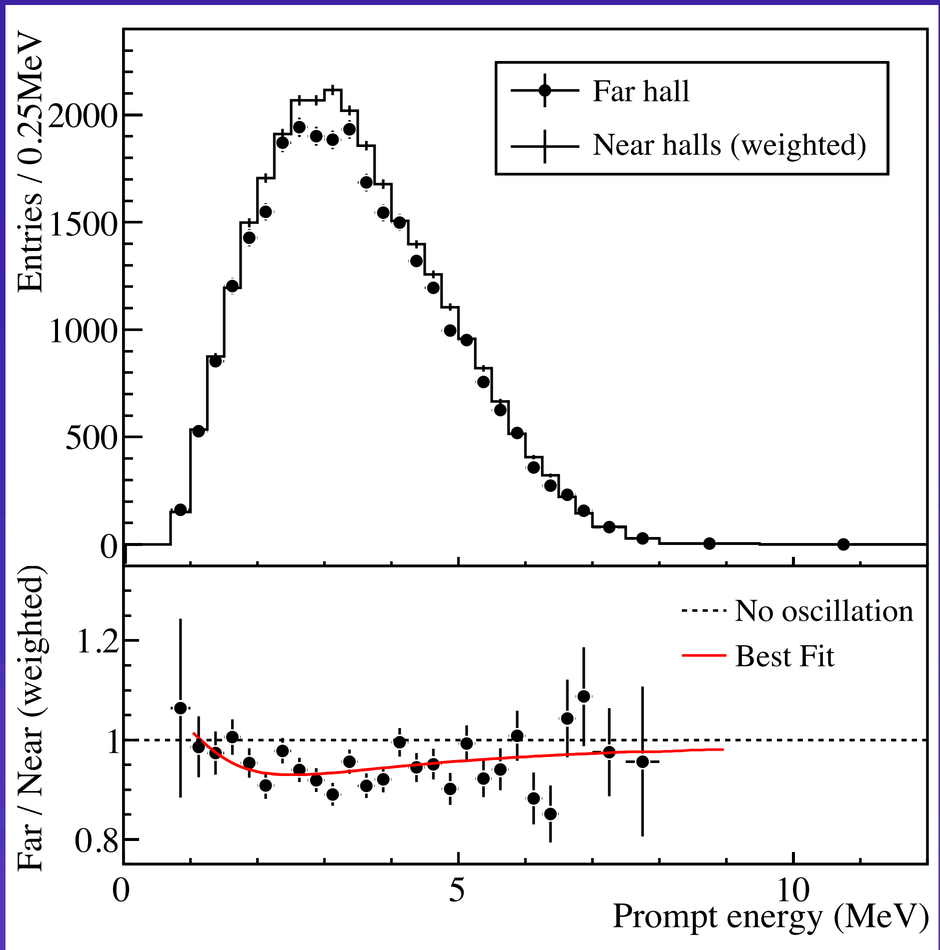
Seventh place is awarded to the international team of physicists working on the Tokai-to-Kamioka (T2K) experiment in Japan. The researchers fired a beam of muon neutrinos 300 km underground to a detector, where they found that six neutrinos had changed, or "oscillated", into electron neutrinos. While the measurement is not good enough to claim the discovery of the muon-to-electron neutrino oscillation, it is the best evidence yet that one "flavour" of neutrino can oscillate into another.

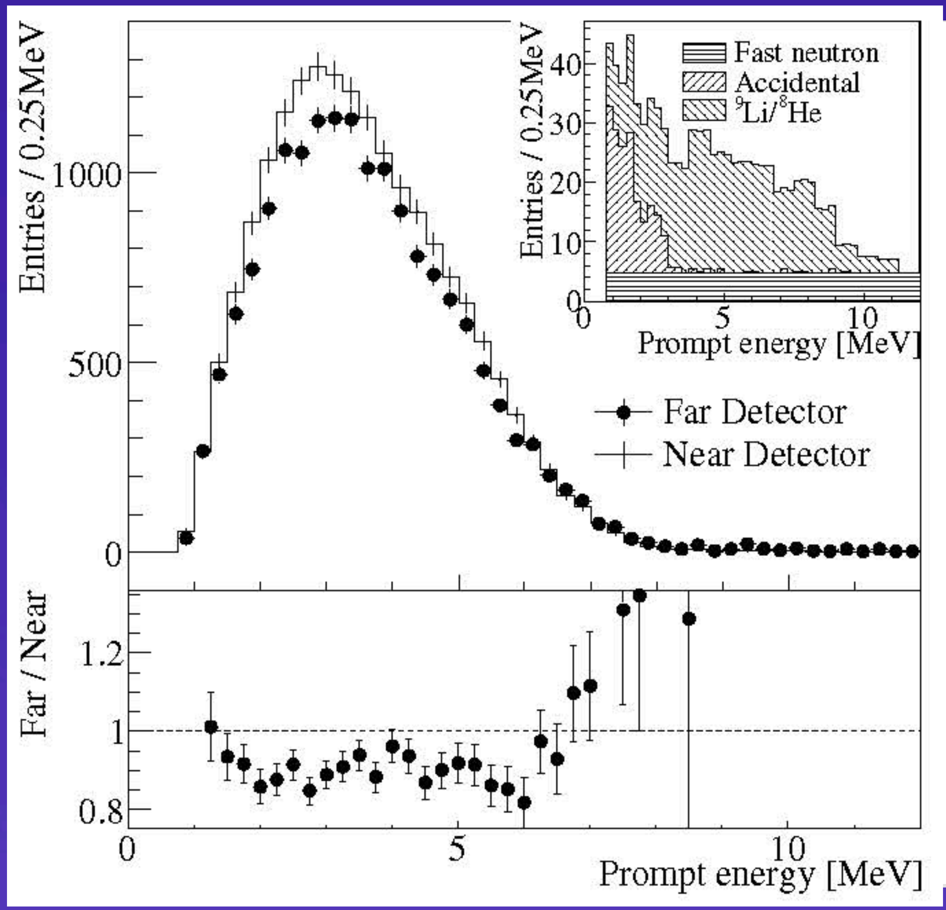
Reactor $\bar{\nu}$ results

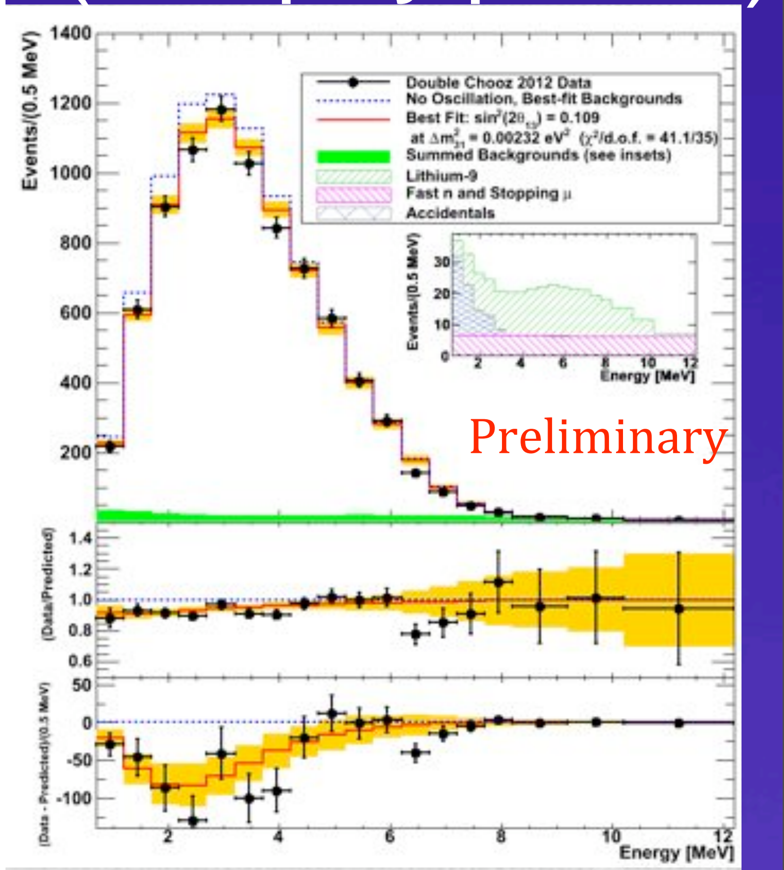
Daya Bay (China-US)

RENO (Korea)

Double Chooz (Europe-Japan-US)







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

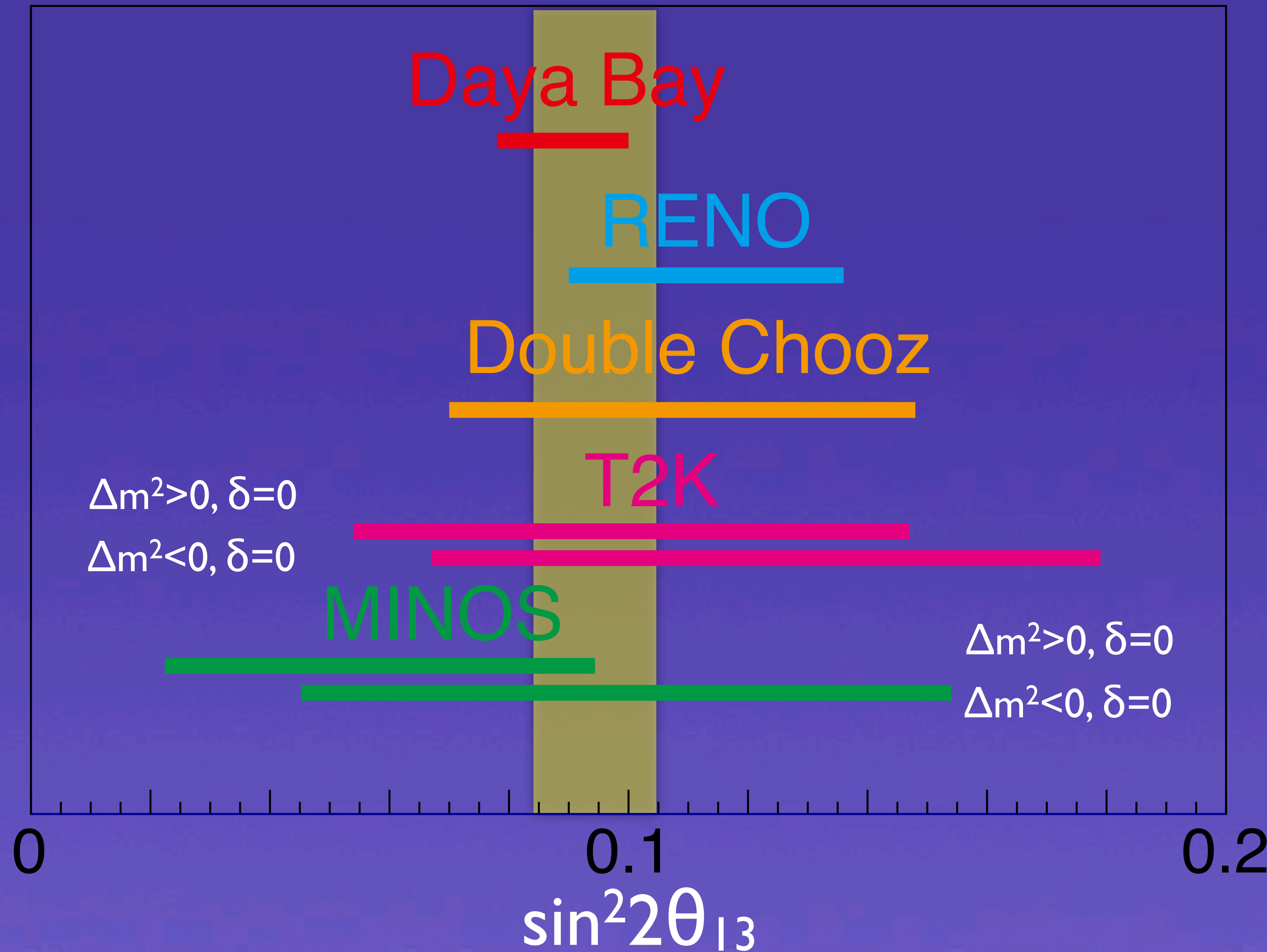
$0.113 \pm 0.013(stat) \pm 0.019(syst)$

0.089±0.010(stat)±0.005(syst)

0.109 ±0.030(stat) ±0.025(syst)

Observation of $\bar{\nu}_e$ disappearance

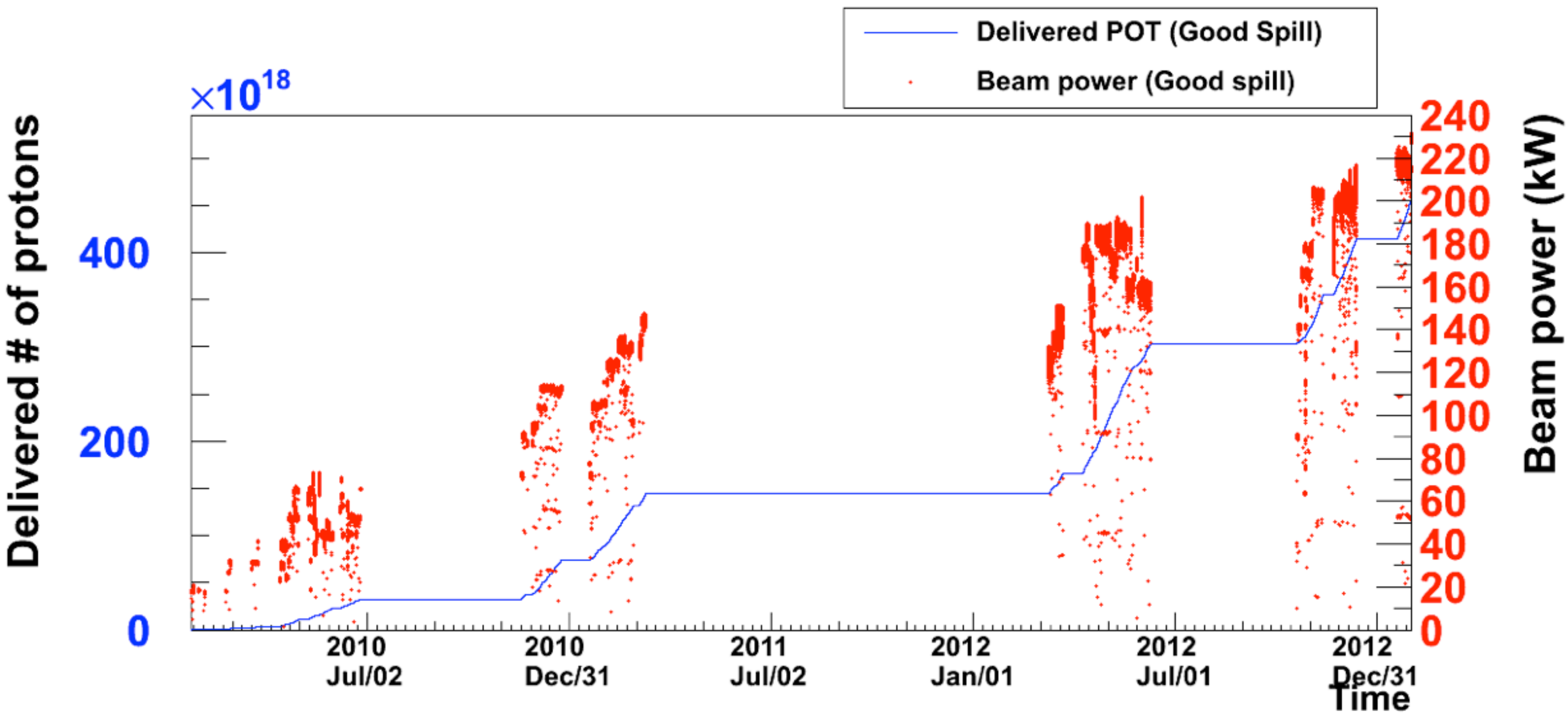
2011-2012: $\theta_{13} \neq 0$ Discovery



Open the window to neutrino CP study

Status of J-PARC accelerator

Integrated POT so far (Power history)



~230kW Beam Power achieved (design: 750kW)

T2K Goal

Now

Evidence of ν_e appearance (99.92% probability) with 3×10^{20} protons data

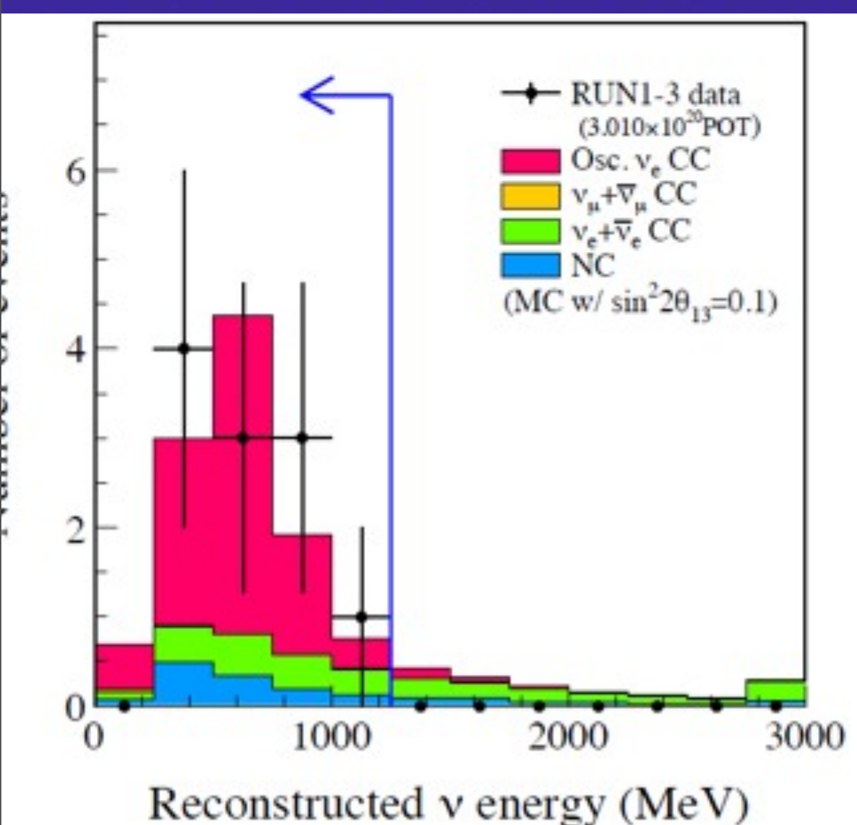
future

J-PARC
More beam power

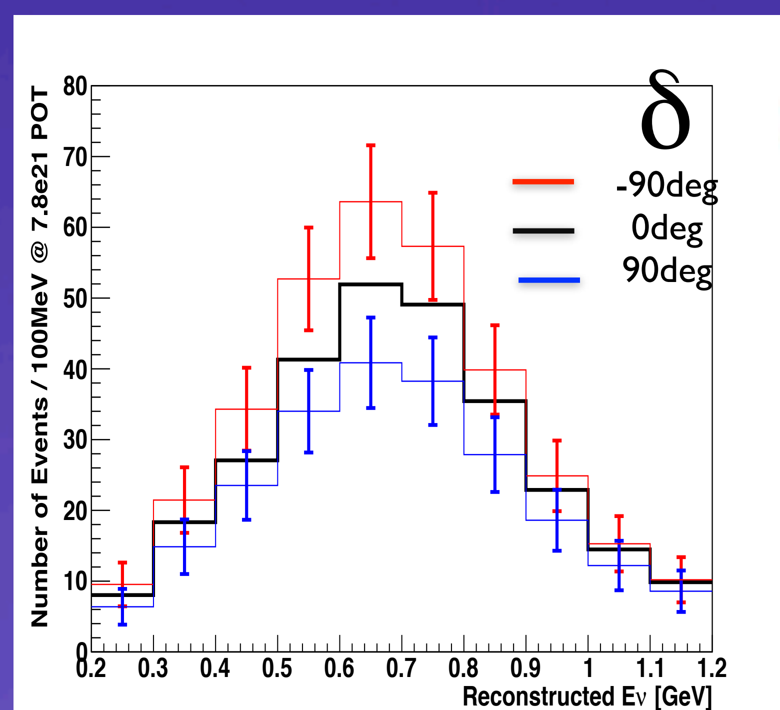
Proposal
30 times more data (78×10^{20} protons)

- **Precision Neutrino Physics**

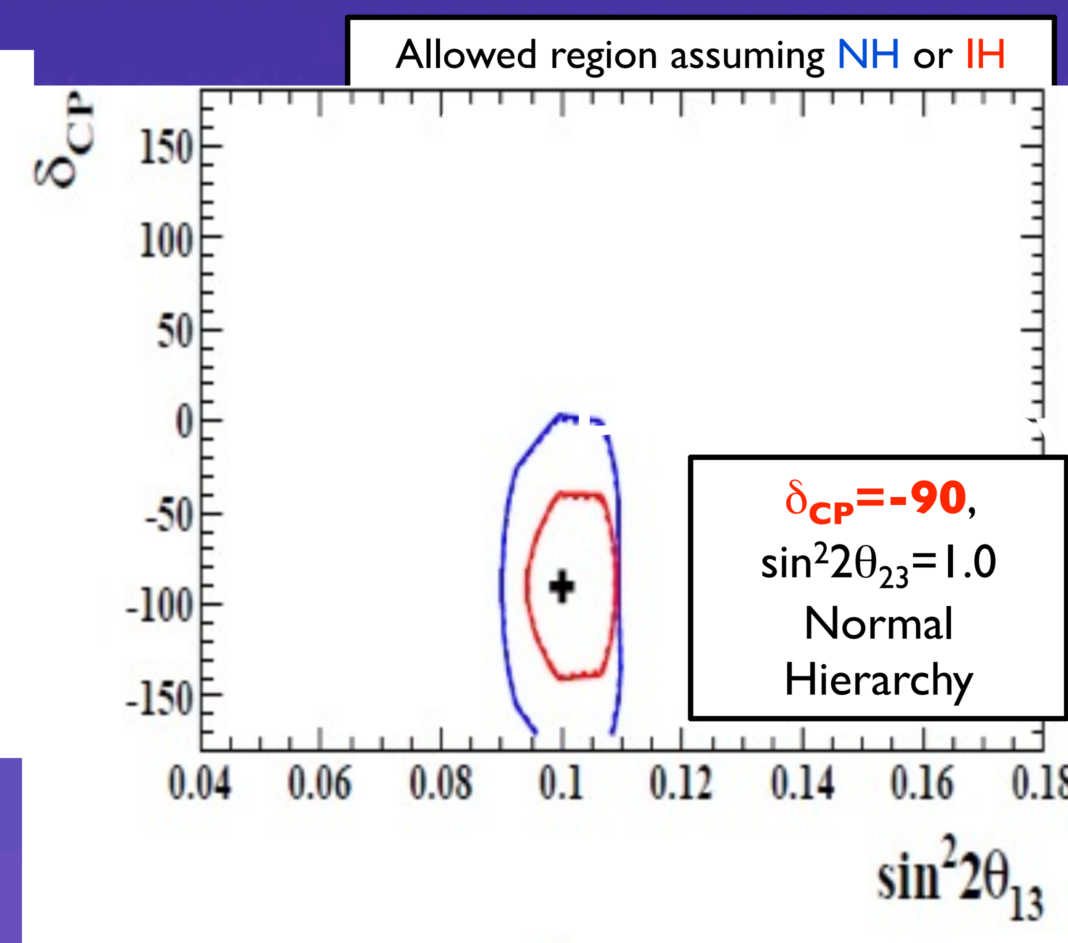
A hint of ν CP violation



Open the window to study ν CP violation



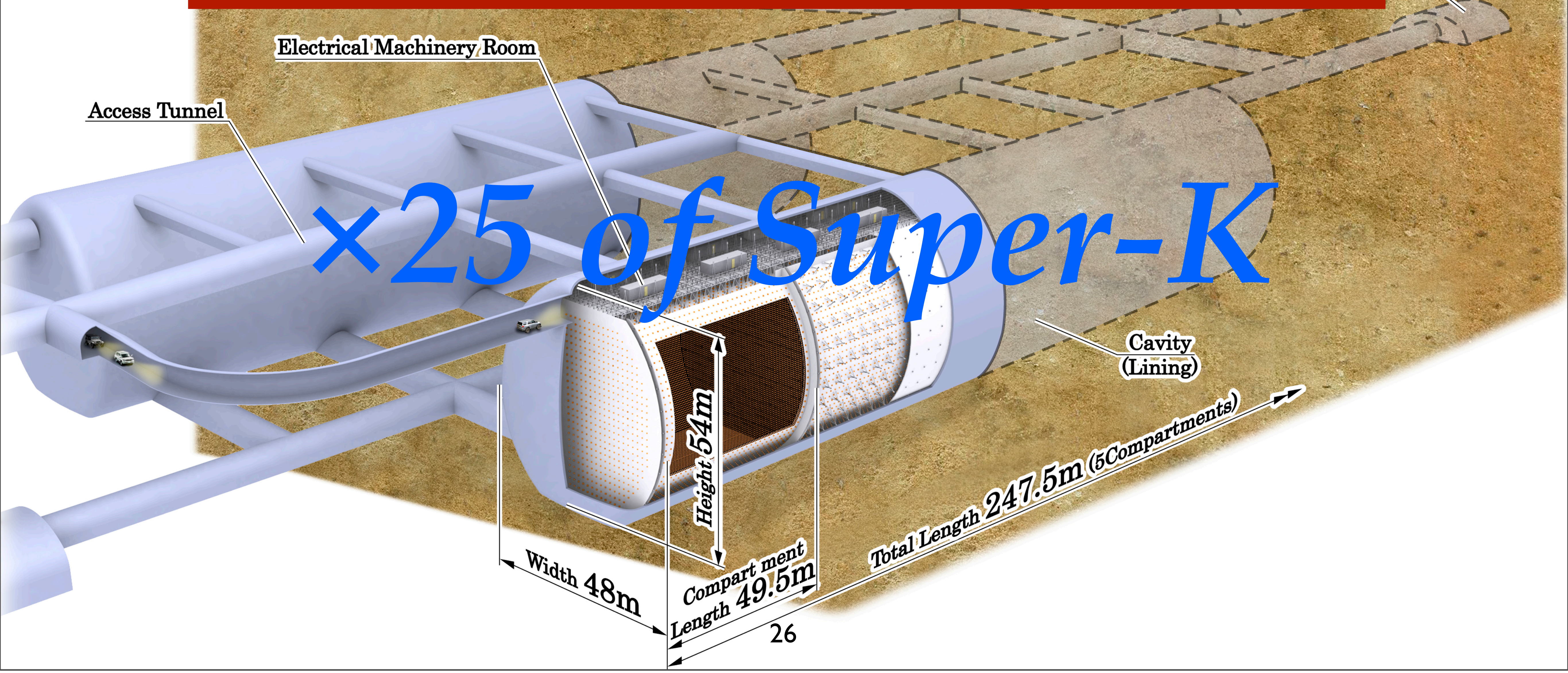
Reconstructed ν energy (GeV)



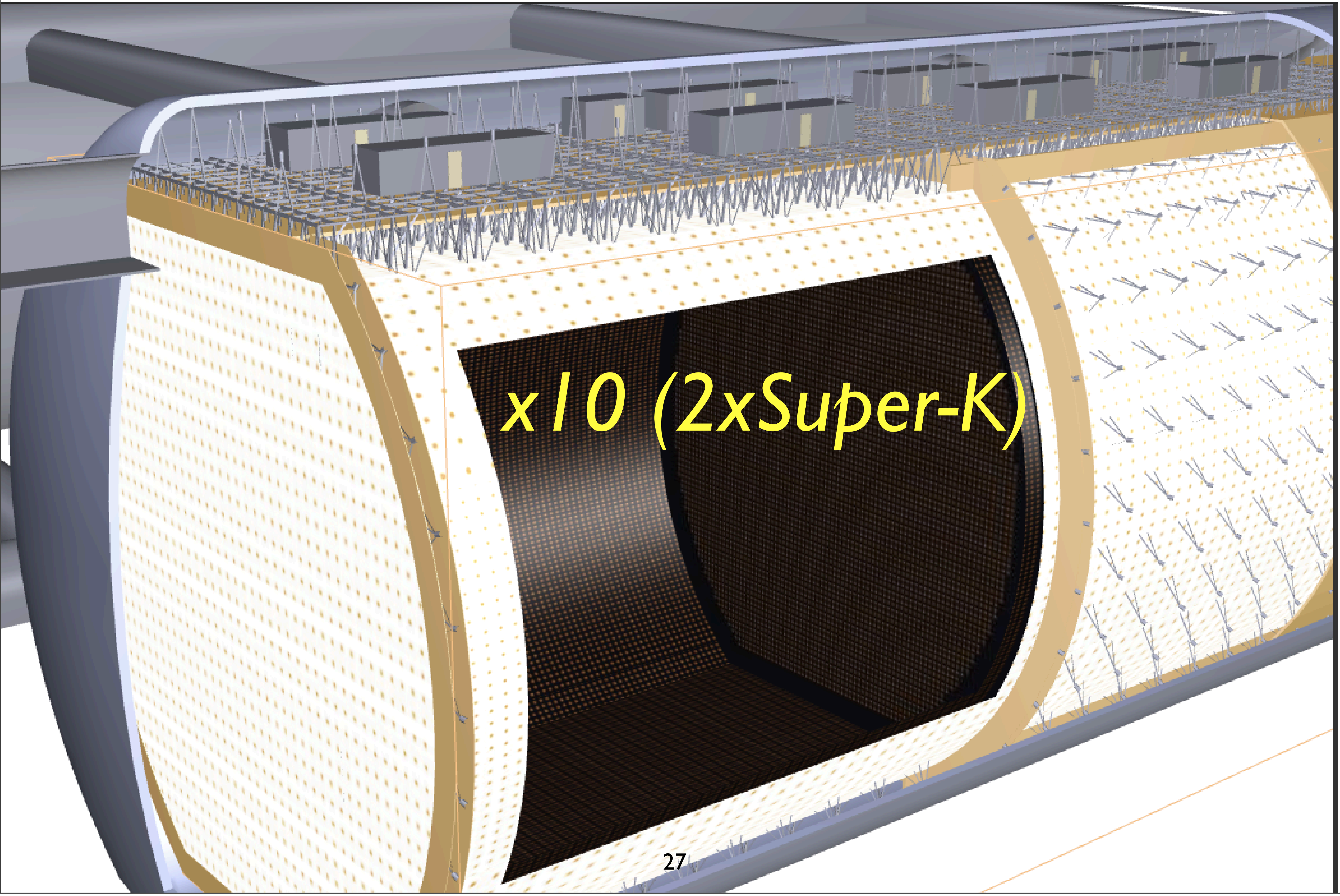
ν CP violation
&
Proton Decay
toward
Grand Unified Theory

Design of Hyper-Kamiokande

Total Volume	0.99 Megaton
Inner Volume	0.74 Mton
Fiducial Volume	0.56 Mton (0.056 Mton × 10 compartments)
Outer Volume	0.2 Megaton
Photo-sensors	99,000 20”Φ PMTs for Inner Det. (20% photo-coverage) 25,000 8”Φ PMTs for Outer Det.



Zoom



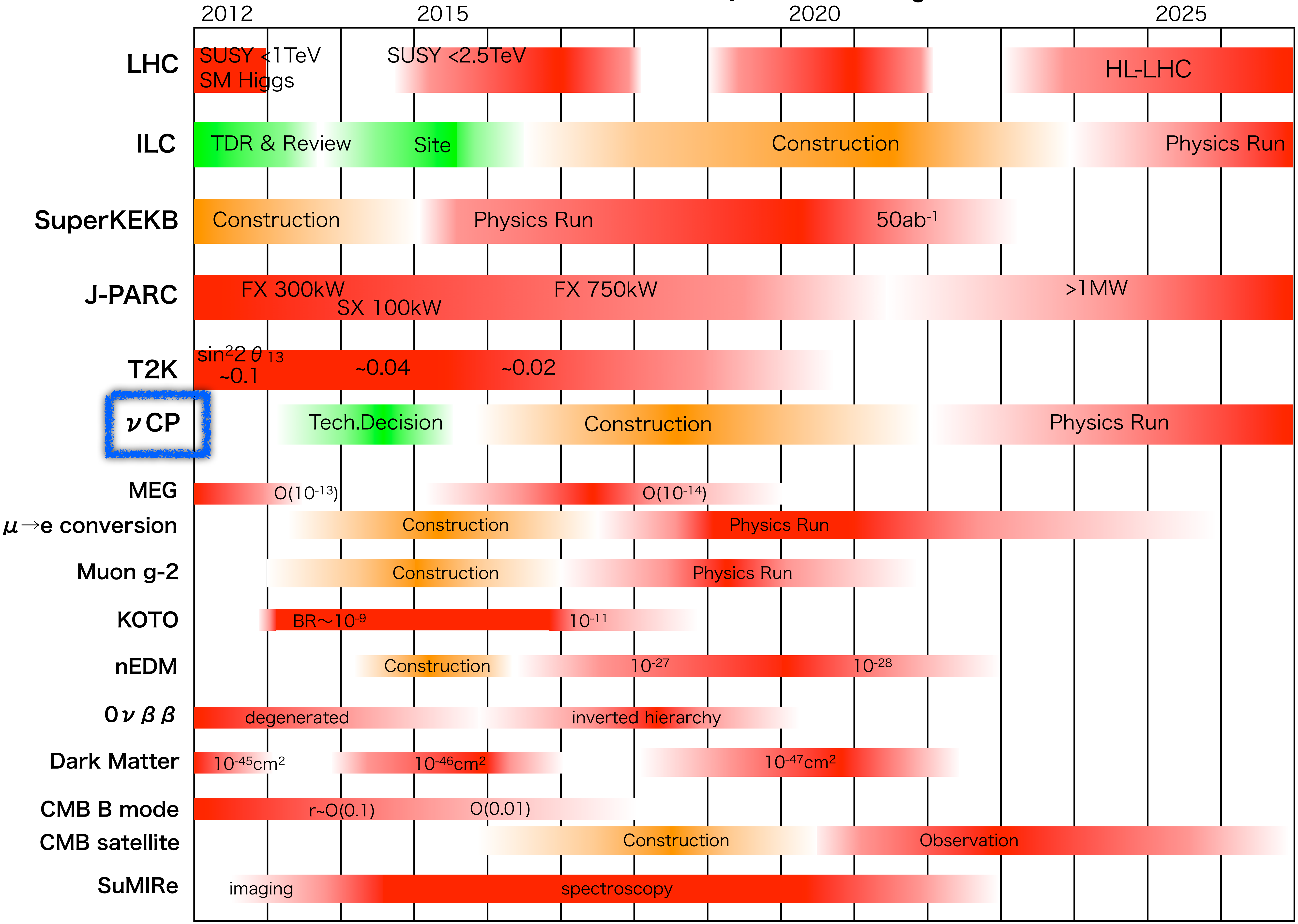
Japan HEP community

Recommendations

The committee makes the following recommendations concerning large-scale projects, which comprise the core of future high energy physics research in Japan.

- **Should a new particle such as a Higgs boson with a mass below approximately 1 TeV be confirmed at LHC, Japan should take the leadership role in an early realization of an e^+e^- linear collider.** In particular, if the particle is light, experiments at low collision energy should be started at the earliest possible time. In parallel, continuous studies on new physics should be pursued for both LHC and the upgraded LHC version. Should the energy scale of new particles/physics be higher, accelerator R&D should be strengthened in order to realize the necessary collision energy.
- **Should the neutrino mixing angle θ_{13} be confirmed as large, Japan should aim to realize a large-scale neutrino detector through international cooperation, accompanied by the necessary reinforcement of accelerator intensity, so allowing studies on CP symmetry through neutrino oscillations.** This new large-scale neutrino detector should have sufficient sensitivity to allow the search for proton decays, which would be direct evidence of Grand Unified Theories.

Timelines of Current/Future Projects




x50 of T2K
for νCP
Atmospheric ν
Supernova
Sun
ν
ν
ν
Water Purification System
Proton
Decays
Cavity (Lining)
Total Length 247.5m (8Compartments)
Compartment Length 49.5m
Height 54m
Hyper-K
Super-K
ν
x25 Larger ν Target
& Proton Decay Source
higher intensity ν by
upgraded J-PARC
J-PARC
x2 (year
or power)
30
©2010 Google

Physics in Hyper-K

arXiv:1109.3262 [hep-ex]

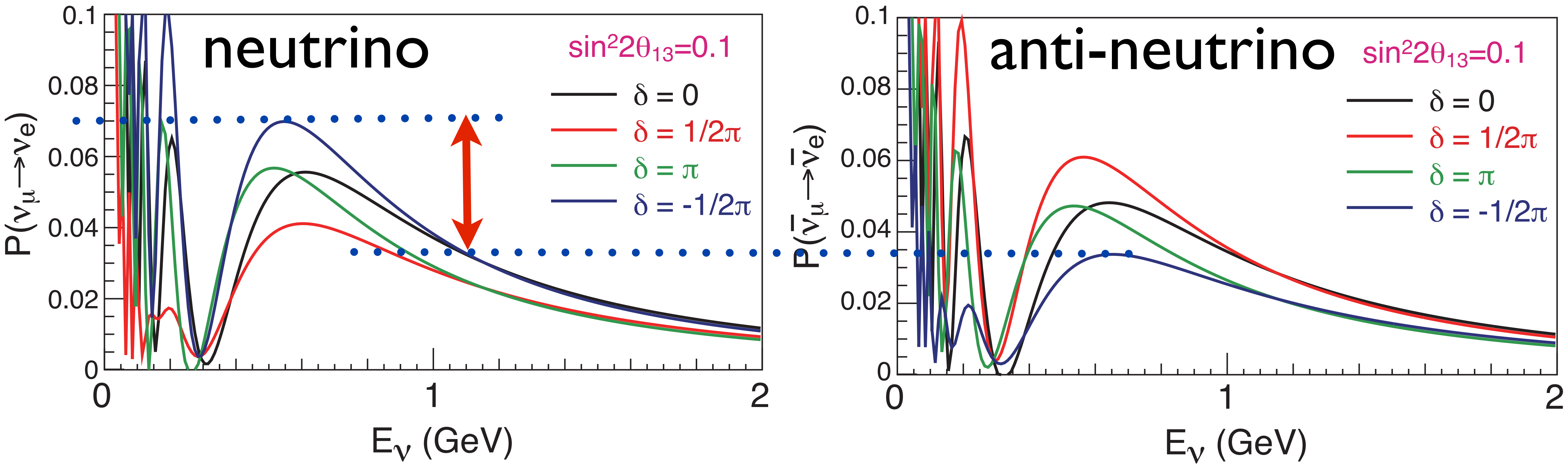
- Accelerator Neutrino Beam
- Atmospheric Neutrinos
- Solar Neutrinos
- Astrophysical Neutrinos
    - Supernova, Dark Matter, Solar flare, etc..
- Neutrino geophysics
- Nucleon Decay

Neutrino Oscillations w/ CPV

GUT

Measuring CP asymmetry w/ J-PARC ν beam

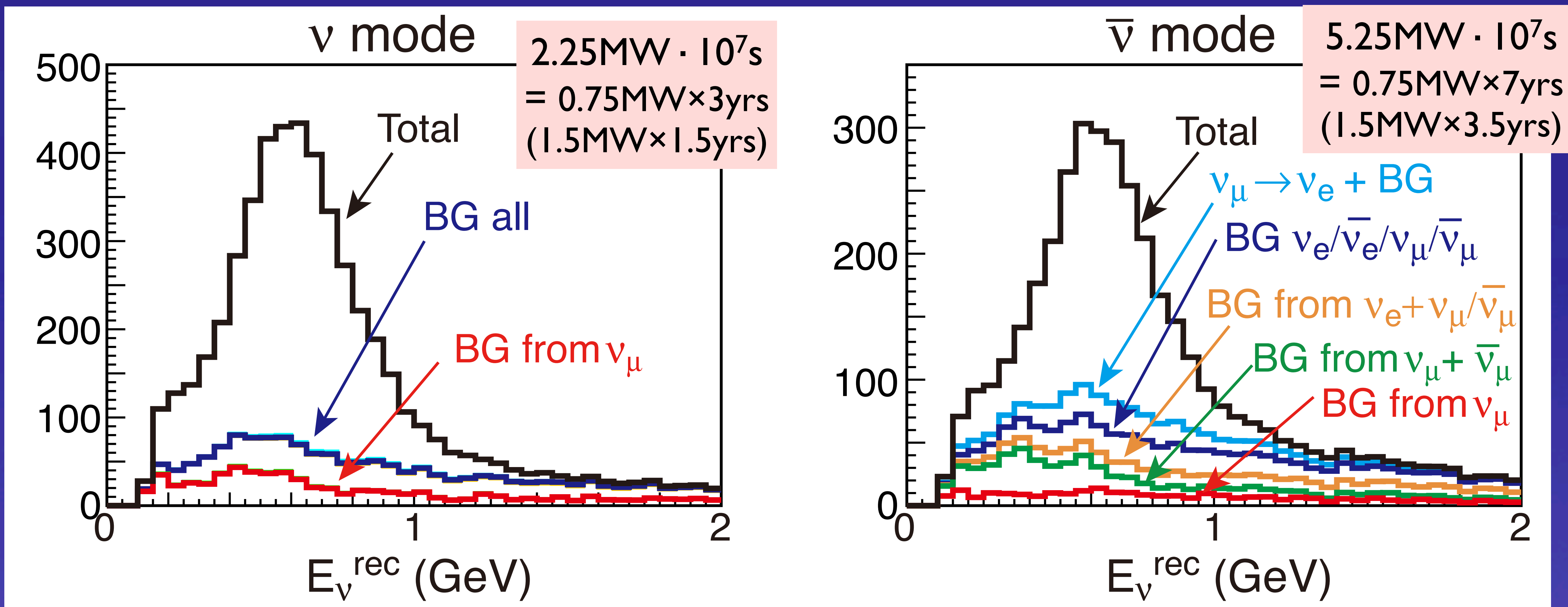
$P(\nu_\mu \rightarrow \nu_e)$ appearance probability (normal hierarchy)



- Comparison between $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
  - as large as ±25% from nominal.
  - Sensitive to exotic (non-MNS) CPV

ν_e candidate events after selection

$\sin^2 2\theta_{13}=0.1, \delta=0$, normal MH



	Signal ($\nu_\mu \to \nu_e$ CC)	Wrong sign appearance	$\nu_\mu/\bar{\nu}_\mu$ CC	beam $\nu_e/\bar{\nu}_e$ contamination	NC
ν (2.25MW · 10^7s)	3,560	46	35	880	649
$\bar{\nu}$ (5.25MW · 10^7s)	1,959	380	23	878	678

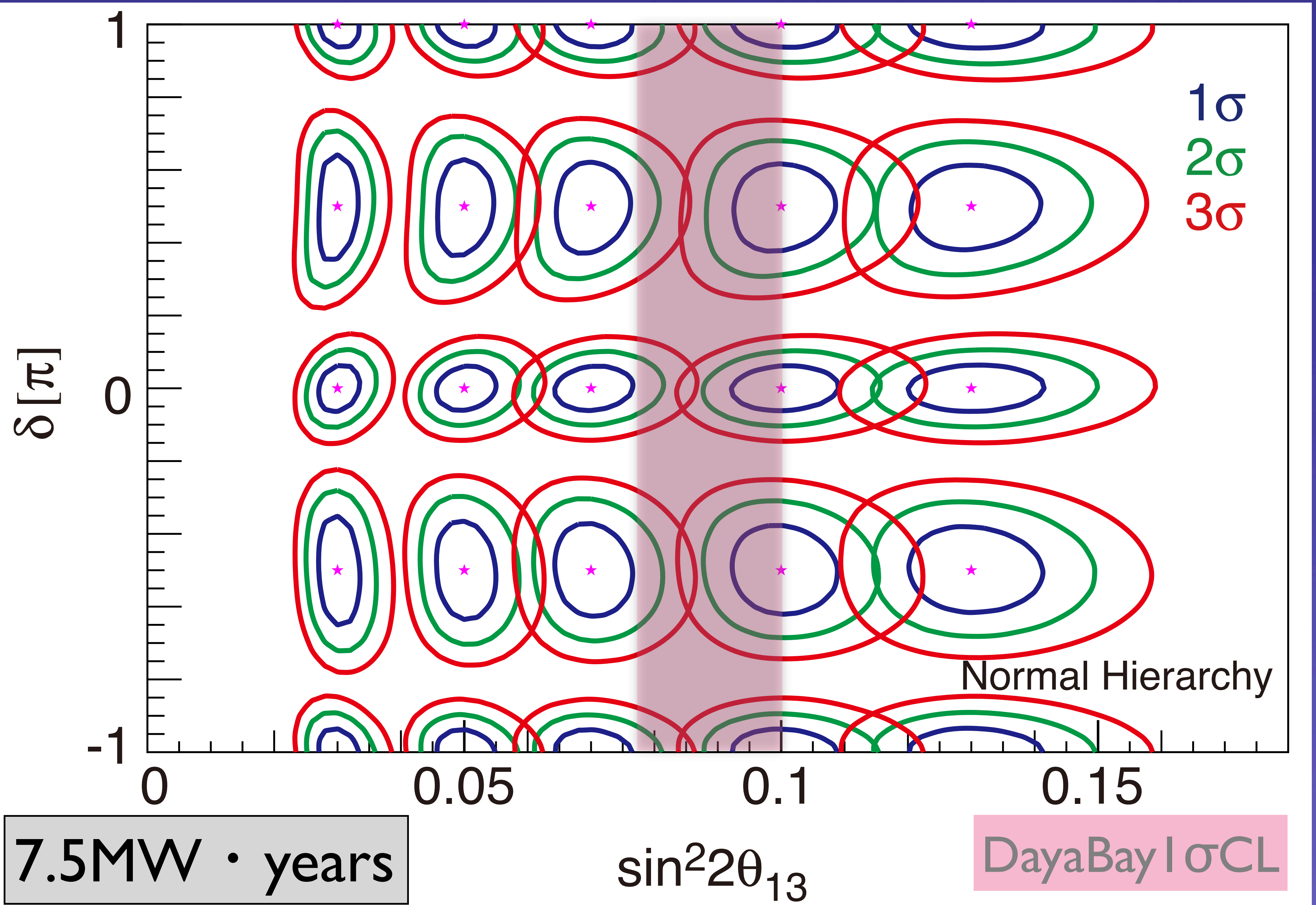
2000-4000 signal events expected for each of ν and $\bar{\nu}$

CPV parameter δ sensitivity

Normal mass hierarchy (known)

5% systematics on signal, ν_μ BG, ν_e BG, $\nu/\bar{\nu}$

$\sin^2 2\theta_{23}=1$



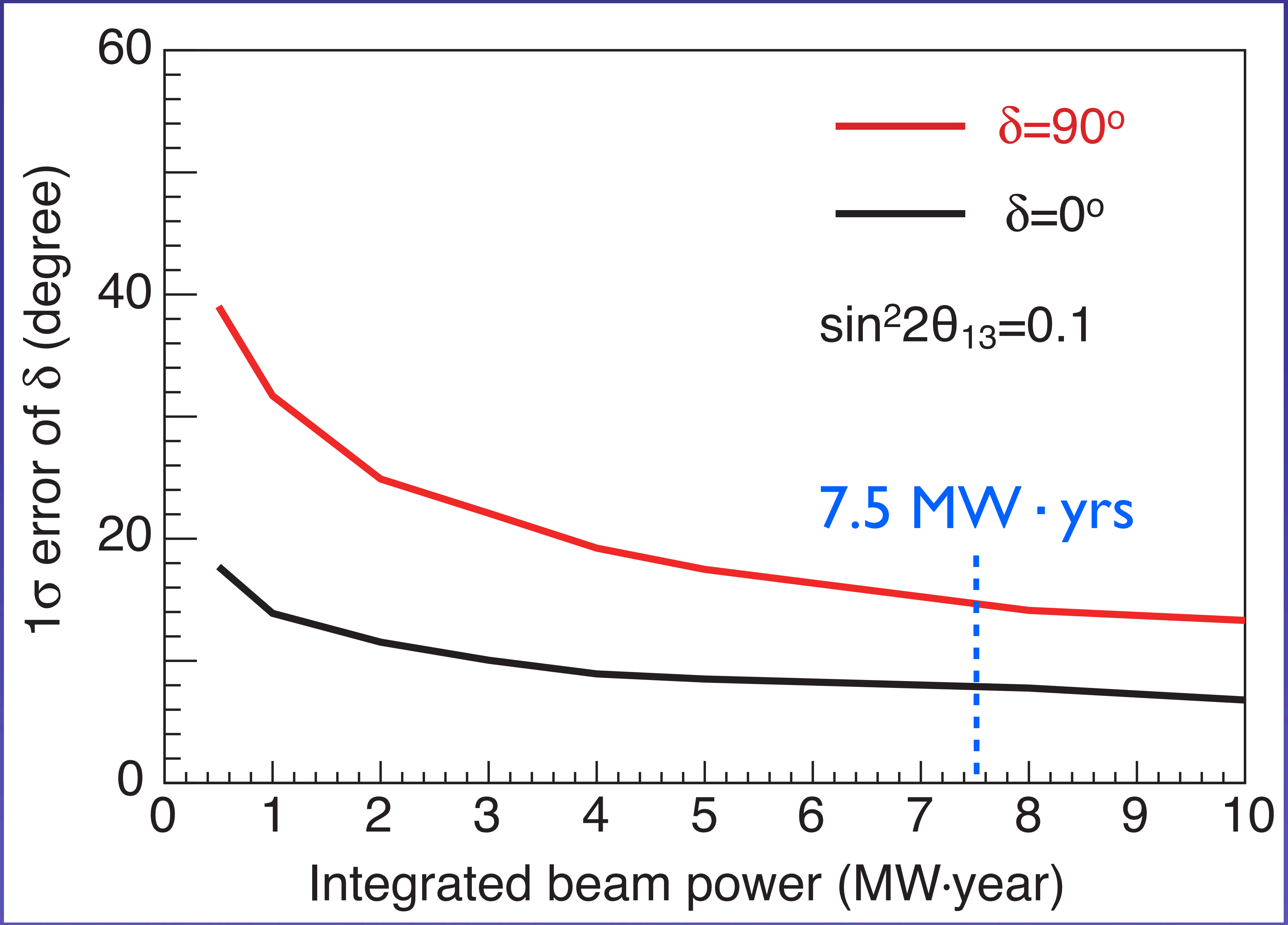
7.5MW・years

- Good sensitivity for CPV
- modest dependence on θ_{13} value

δ resolution

Normal mass hierarchy (known)

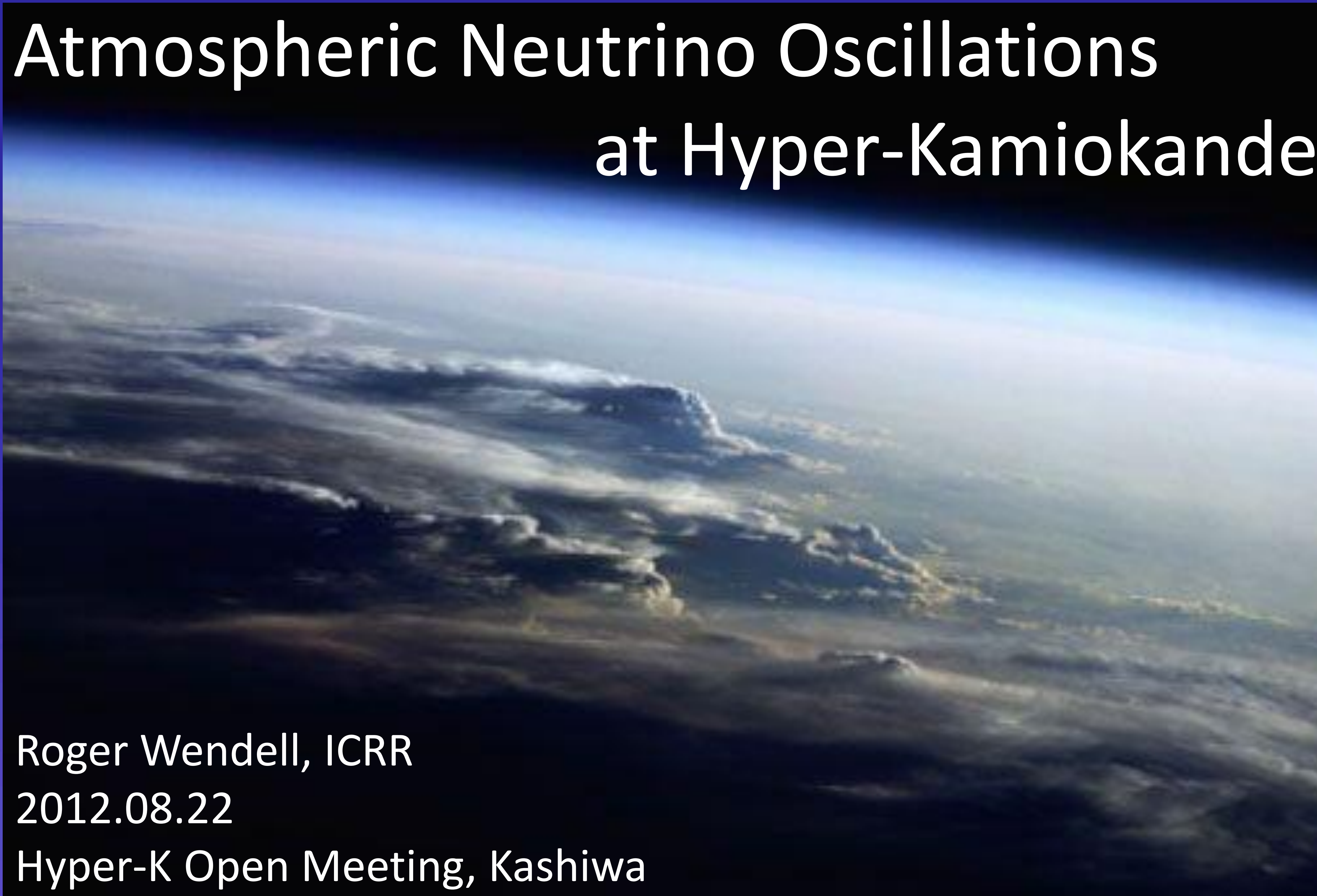
$\sin^2 2\theta_{13}=0.1$



- δ precision < 20° (δ=90°)
  < 10° (δ= 0°)
- modest dependence on θ_{13}

13年2月12日火曜日

Atmospheric Neutrino Oscillations at Hyper-Kamiokande



Roger Wendell, ICRR

2012.08.22

Hyper-K Open Meeting, Kashiwa

3-flavor oscillations in atmospheric ν

NuclPhysB669,255(2003)

NuclPhysB680,479(2004)

$$\frac{\Phi(\nu_e)}{\Phi_0(\nu_e)} - 1 \approx P_2(r\cdot\cos^2\theta_{23}-1)$$

Solar term

$$-r\cdot\sin\tilde\theta_{13}\cdot\cos^2\tilde\theta_{13}\cdot\sin 2\theta_{23}(\cos\delta\cdot R_2-\sin\delta\cdot I_2)$$

Interference term (δCP)

$$+2\sin^2\tilde\theta_{13}(r\cdot\sin^2\theta_{23}-1) \qquad (3)$$

θ_{13} resonance term

$\mathbf{r}$: μ/e flux ratio (~2 at low energy)

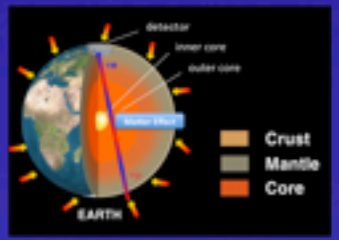
$P_2 = |A_{e\mu}|^2$: 2ν transition probability $\nu_e \rightarrow \nu_{\mu\tau}$ in matter

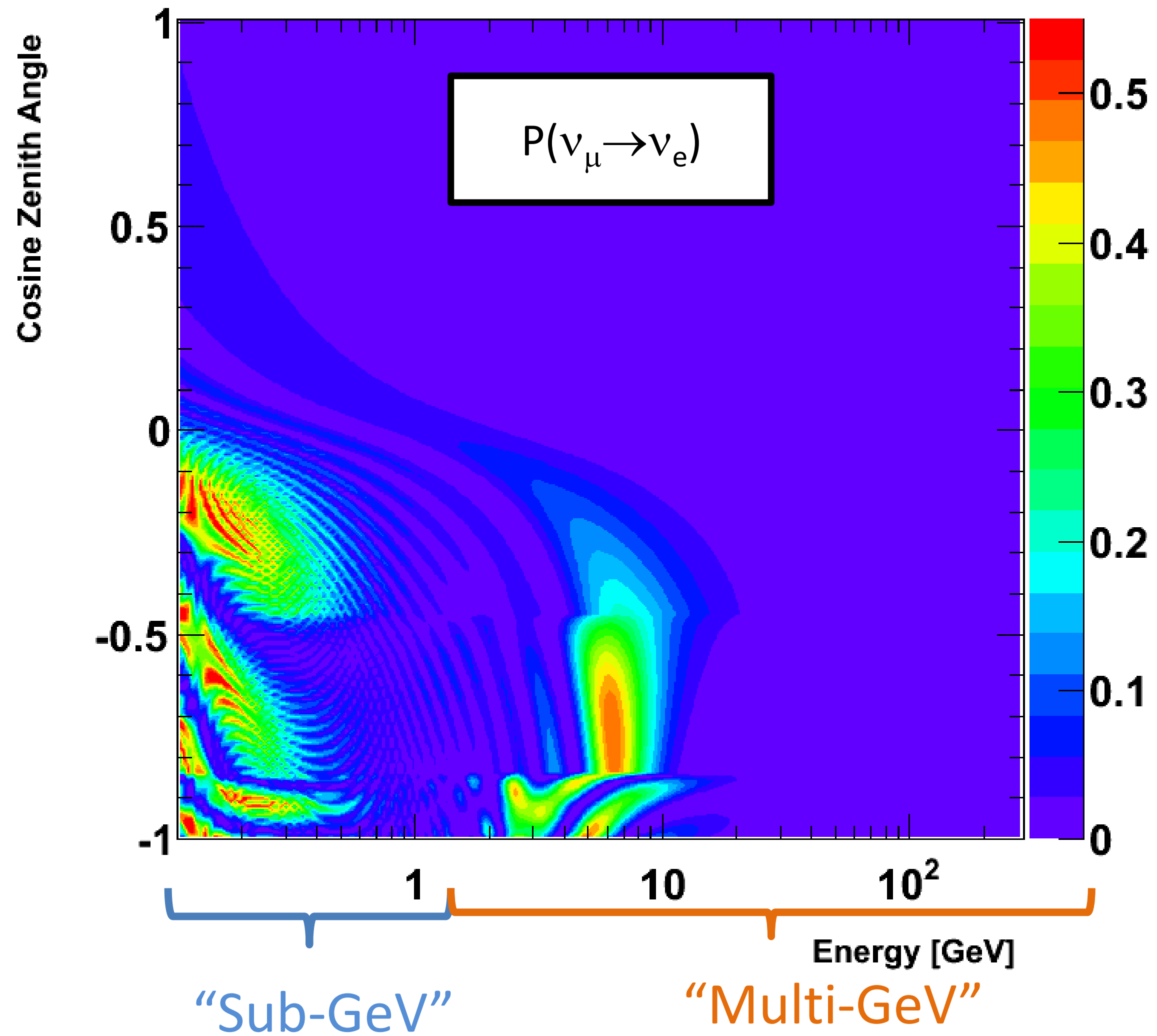
$R_2 = \mathrm{Re}(A^*_{ee}A_{e\mu})$

$I_2 = \mathrm{Im}(A^*_{ee}A_{e\mu})$

A_{ee} : survival amplitude of the 2ν system

$A_{e\mu}$: transition amplitude of the 2ν system

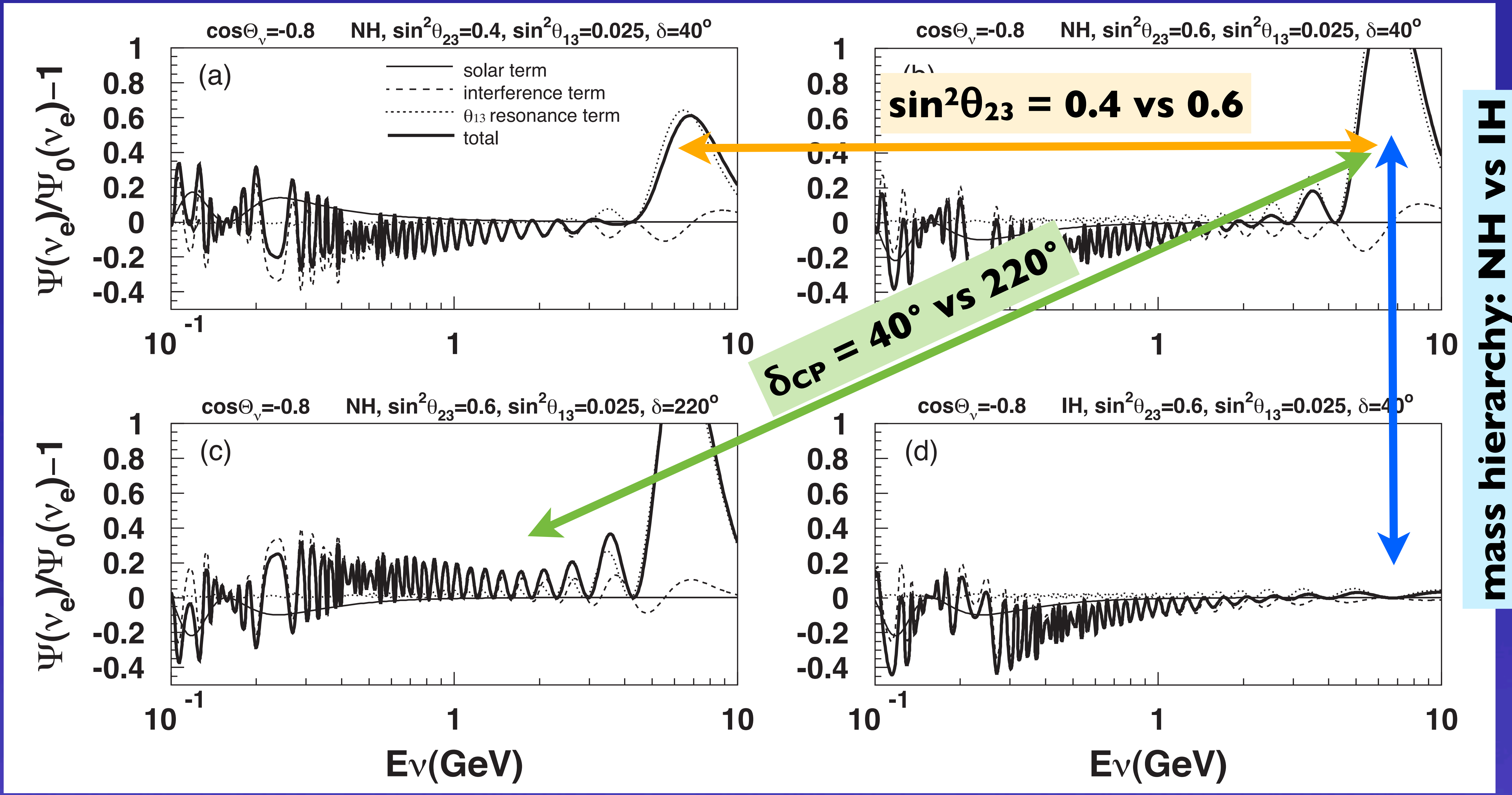




ν_e appearance (and ν_μ distortion) is expected due to MSW effect in the Earth's matter

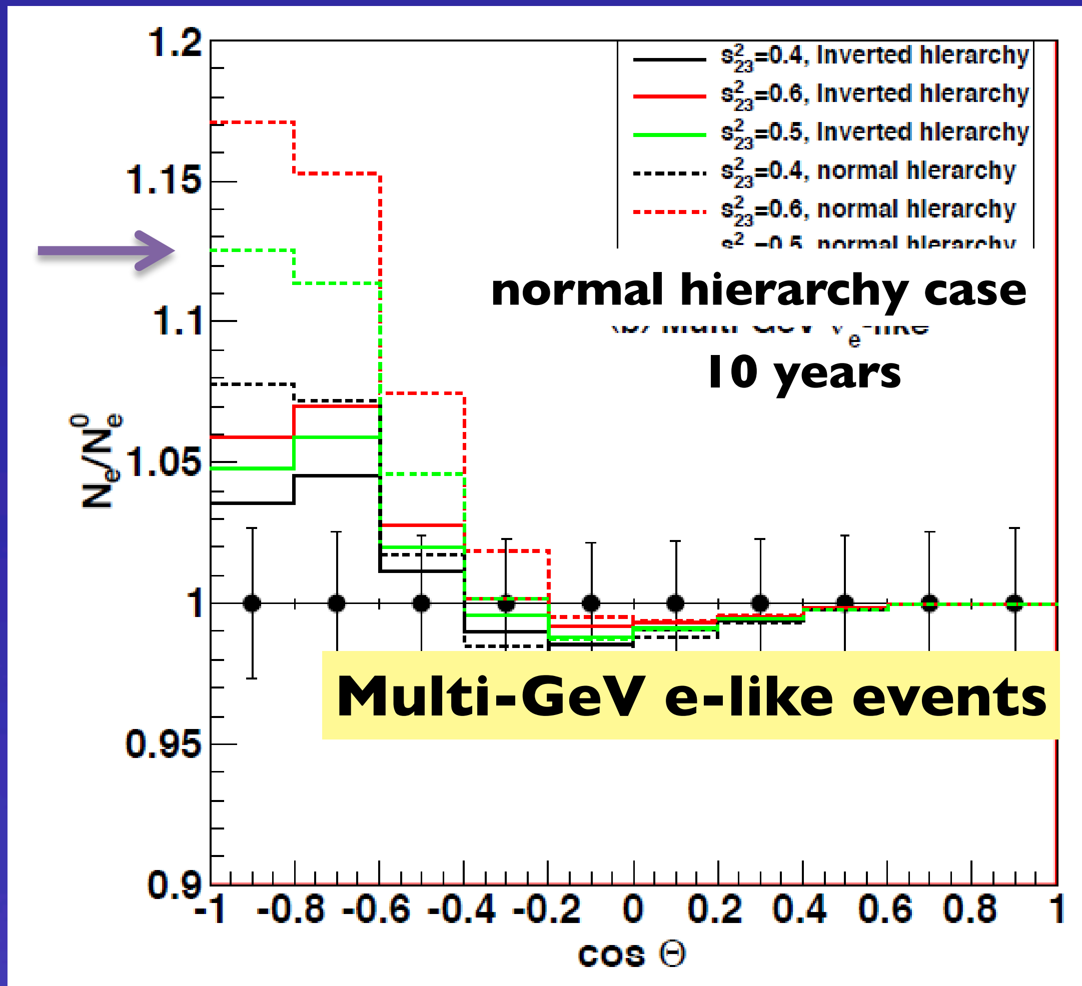
- happens in ν in the case of normal mass hierarchy
- in anti-ν in inverted mass hierarchy

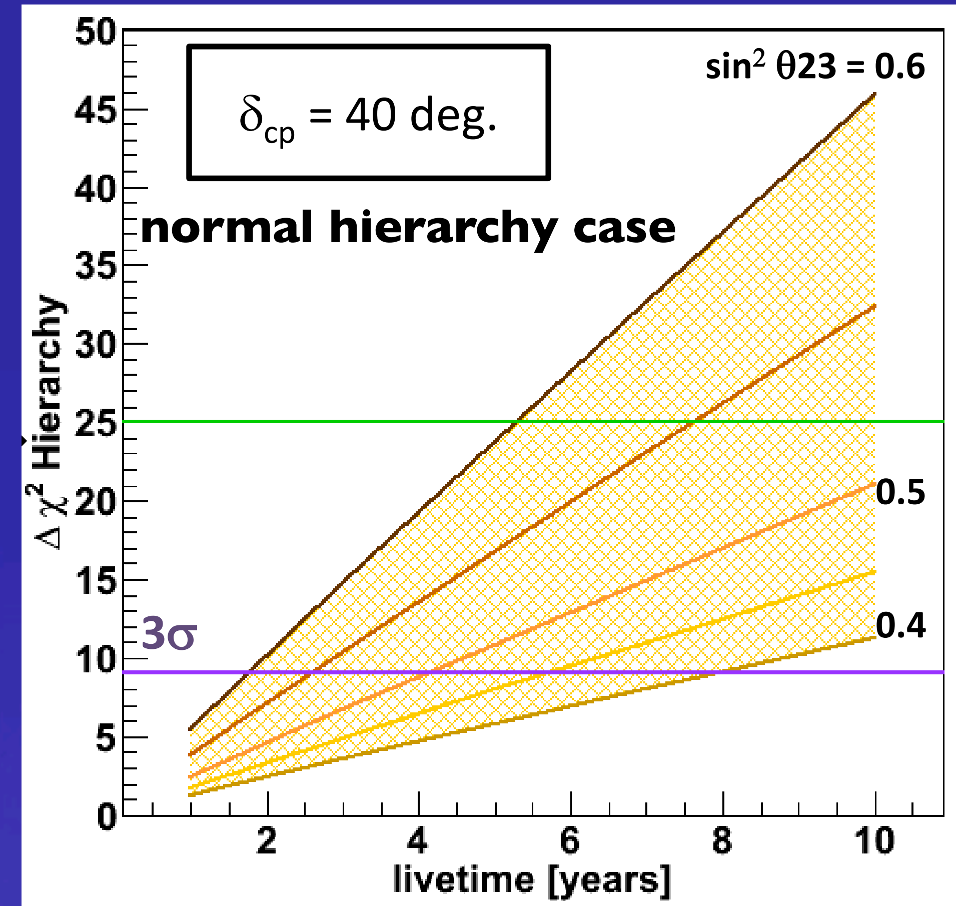
Large θ_{13} value gives us a good chance to discriminate mass hierarchy.



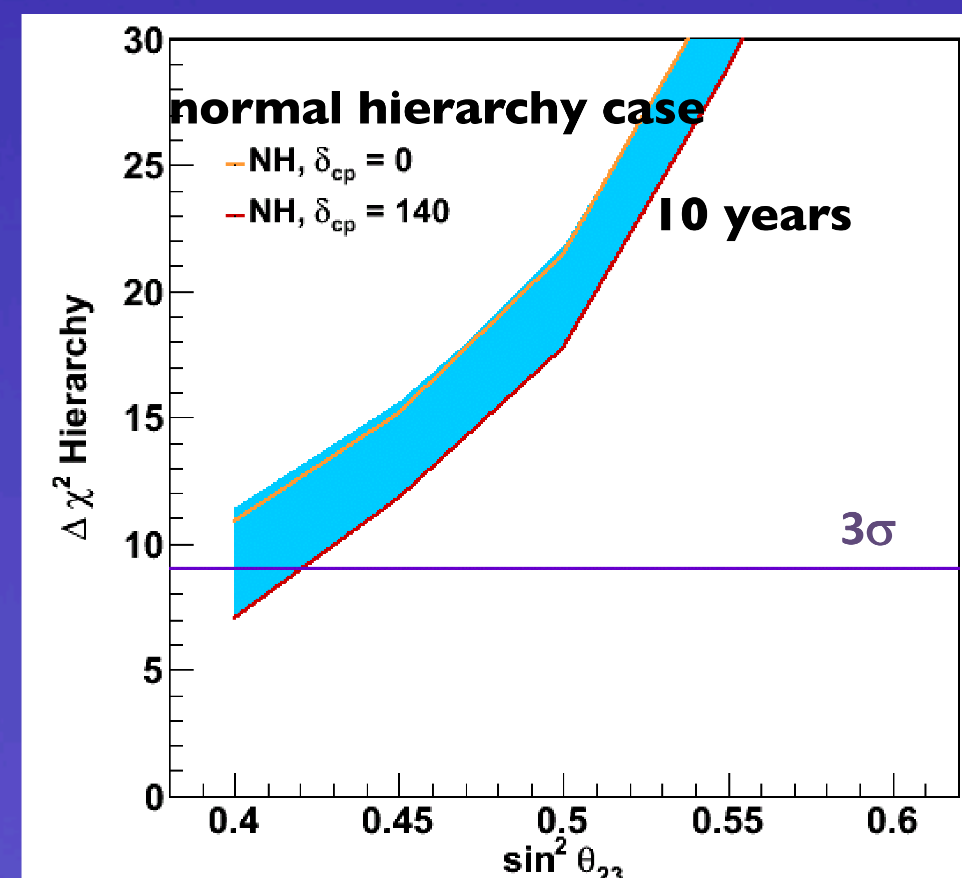
- Trough matter effect (MSW), we study
  - Mass hierarchy ⟹ Asymmetry between neutrinos and antineutrinos.
  - Octant of θ_{23} ⟹ Appearance (and $\nu_\mu \rightarrow \nu_\mu$ disappearance) interplay
  - δ_{CP} (and θ_{13}) ⟹ Magnitude of resonance effect

Mass Hierarchy Sensitivity

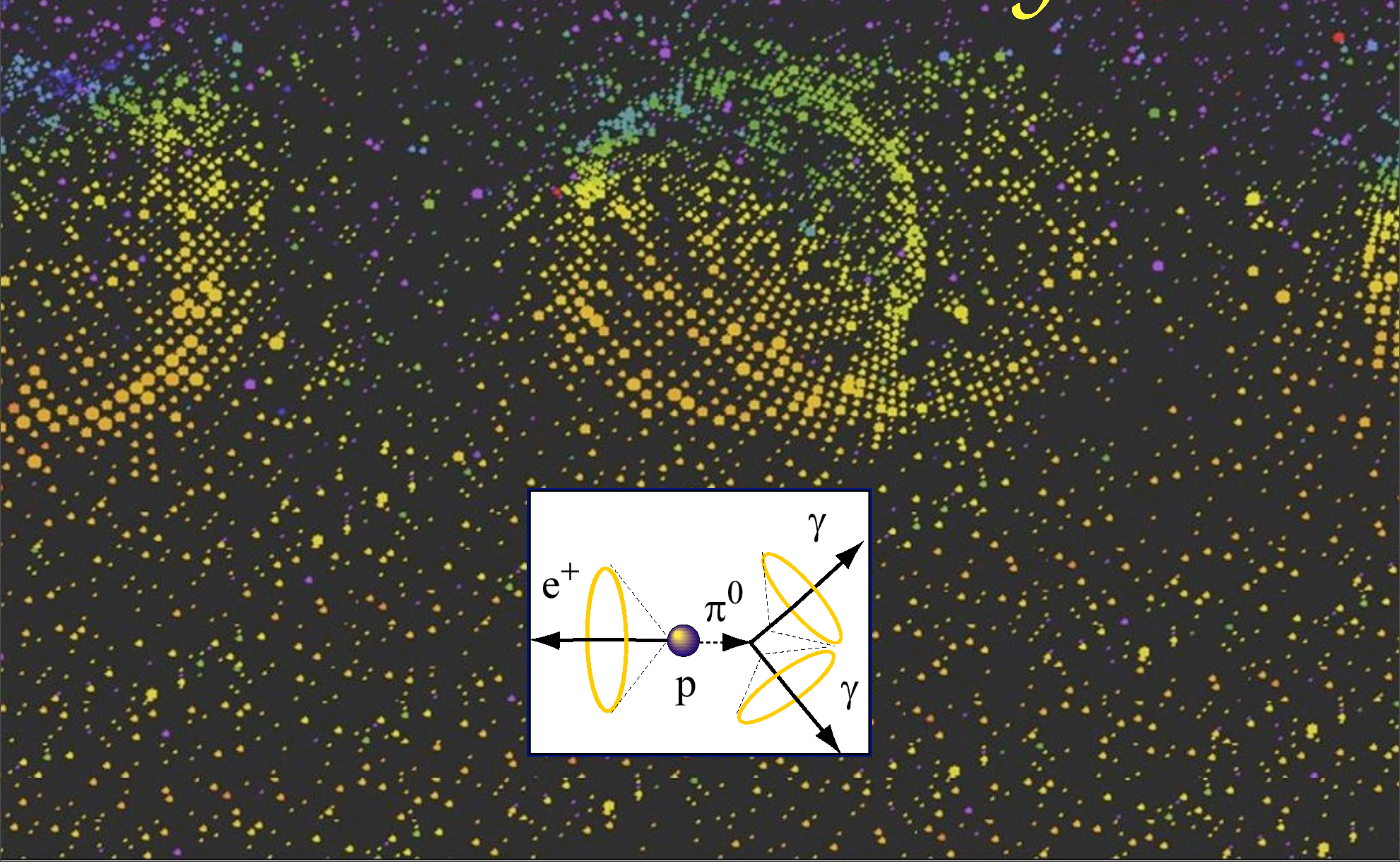




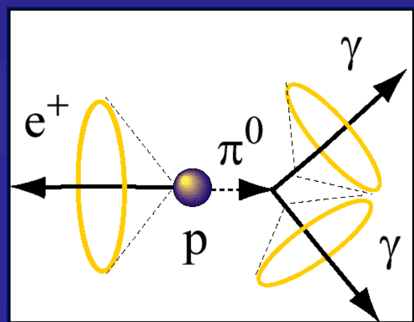
- Sensitivity depends on θ_{23}, δ and mass hierarch (a little).
- 3σ mass hierarchy determination for $\sin^2\theta_{23}>0.42$ (0.43) in the case of normal (inverted) hierarchy.

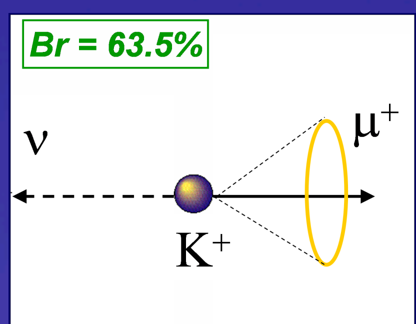


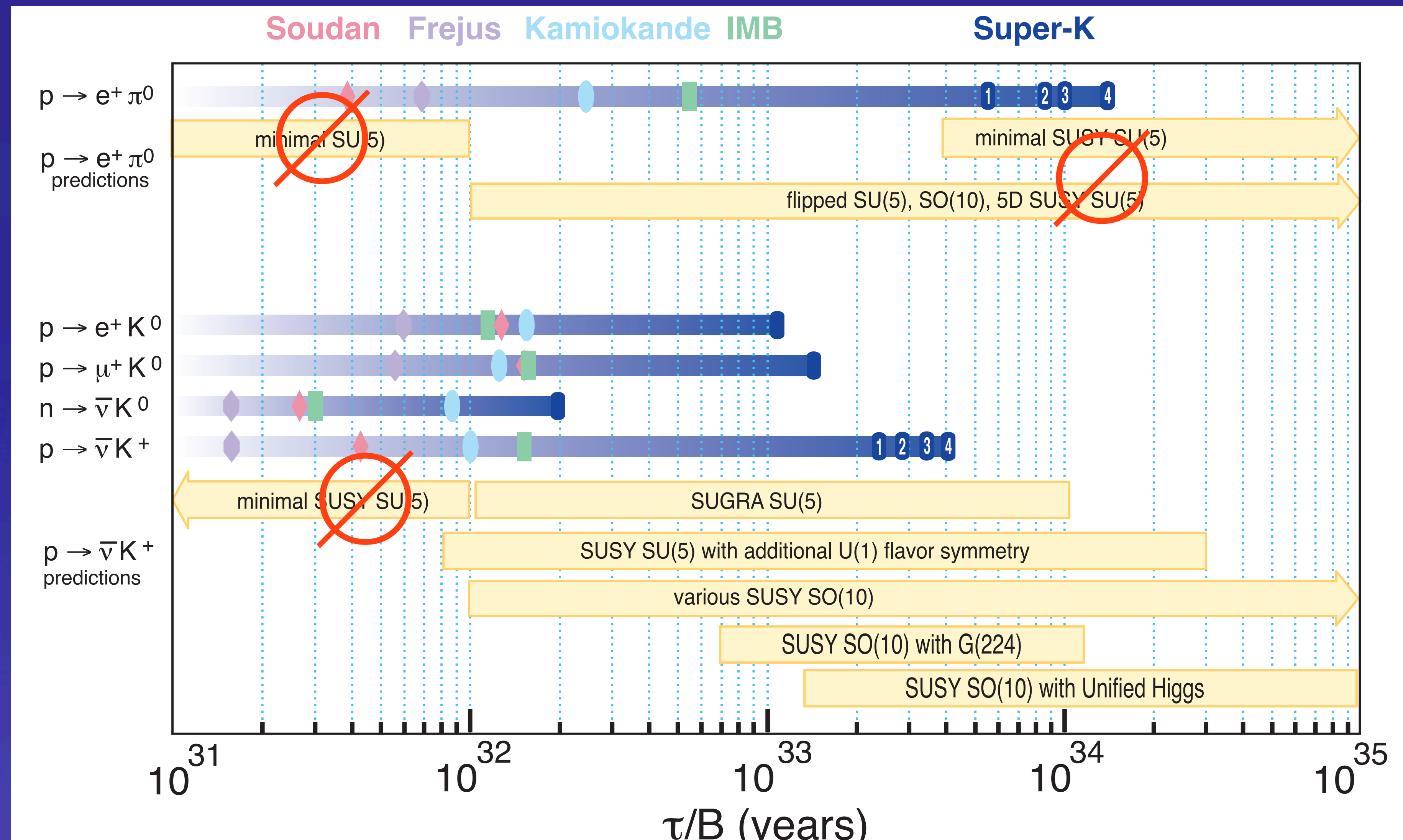
Nucleon Decays



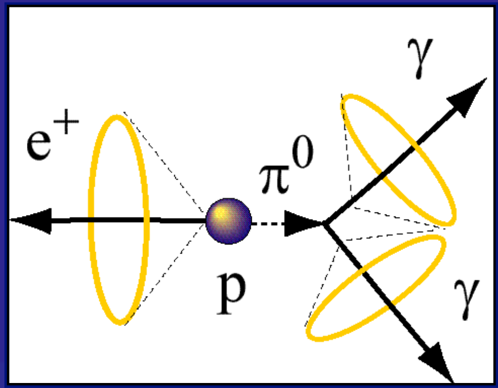
Experimental Limits







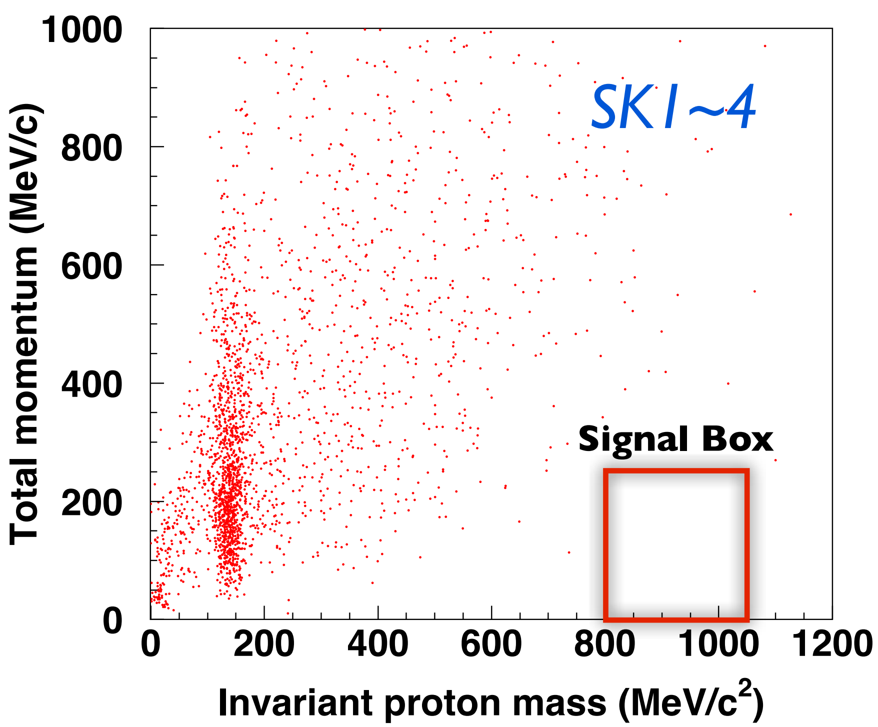
- Super-K gives most stringent limits for many decay modes.
  - $\tau(p \to e^+\pi^0) > 1.3\times10^{34}$ years (90%C.L. by 220kton・yrs data)
  - $\tau(p \to \nu K^+) > 4.0\times10^{33}$ years (90%C.L. by 220kton・yrs)
- No signal evidence has been found → giving constraints on models (GUTs)
  - Constraints on SUSY models (ex: R-parity conservation)
  - Exclude minimal *SU(5)* and minimal SUSY *SU(5) models.*

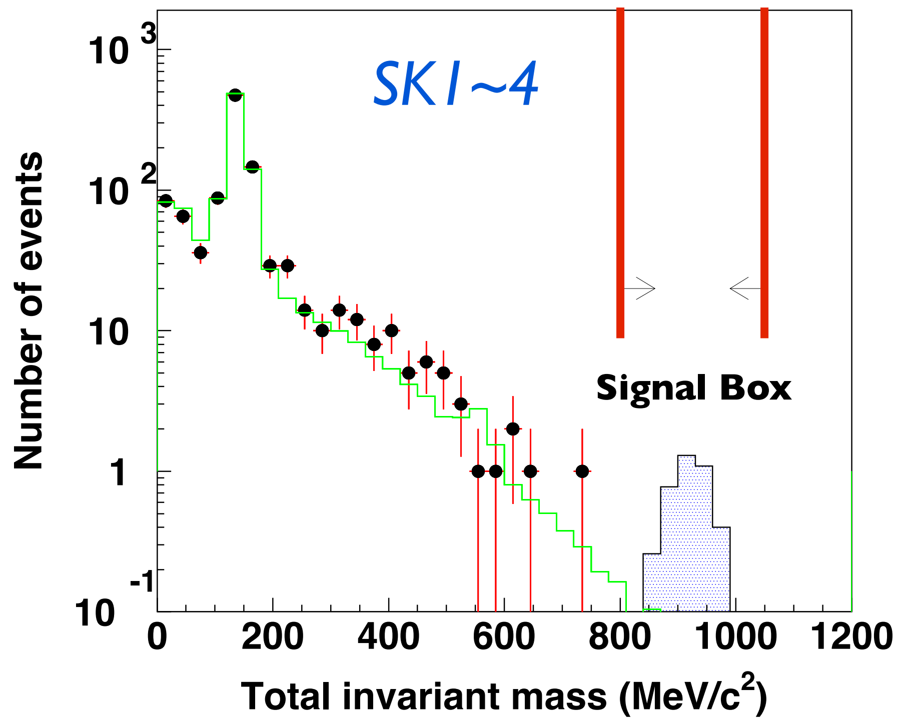


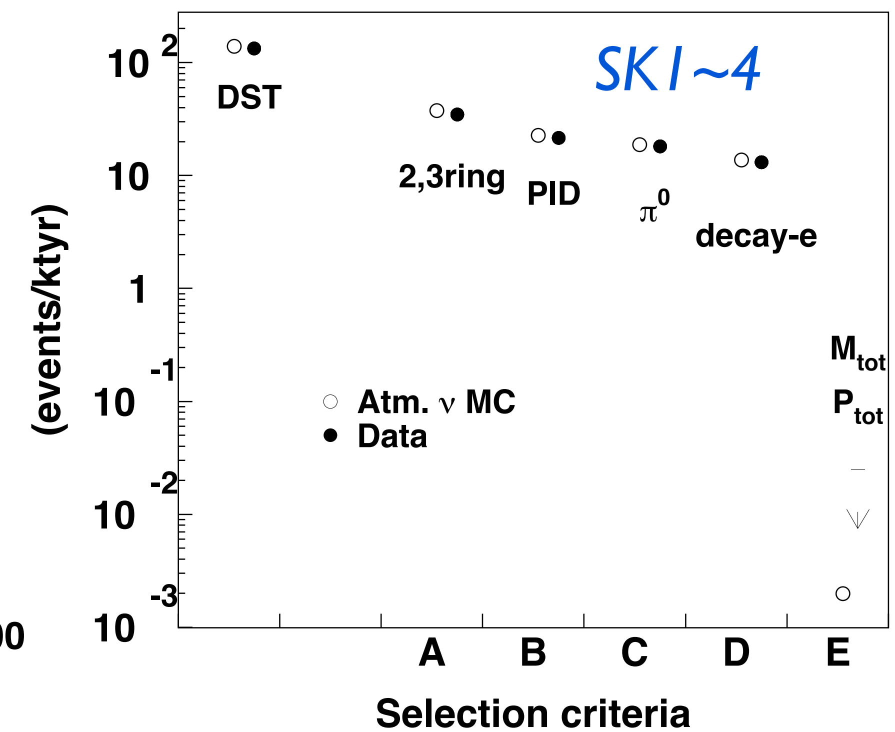
$p \rightarrow e^+ + \pi^0$ searches

Super-K data are consistent with BG MC.

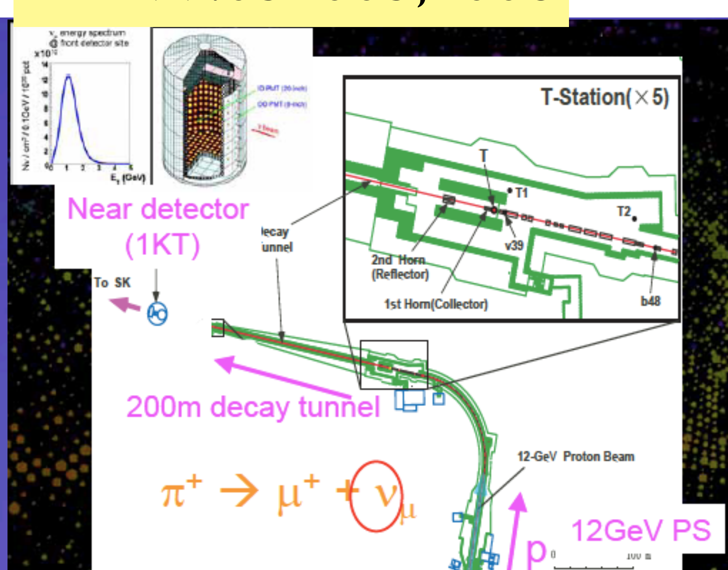
Super-K cut
- 2 or 3 Cherenkov rings
- All rings are showering
- $85 < M_{\pi 0} < 185 MeV/c^2$ (3-ring)
- No decay electron
- $800 < M_{proton} < 1050$ MeV/c^2
  $P_{total} < 250$ MeV/c







PRD77:032003,2008

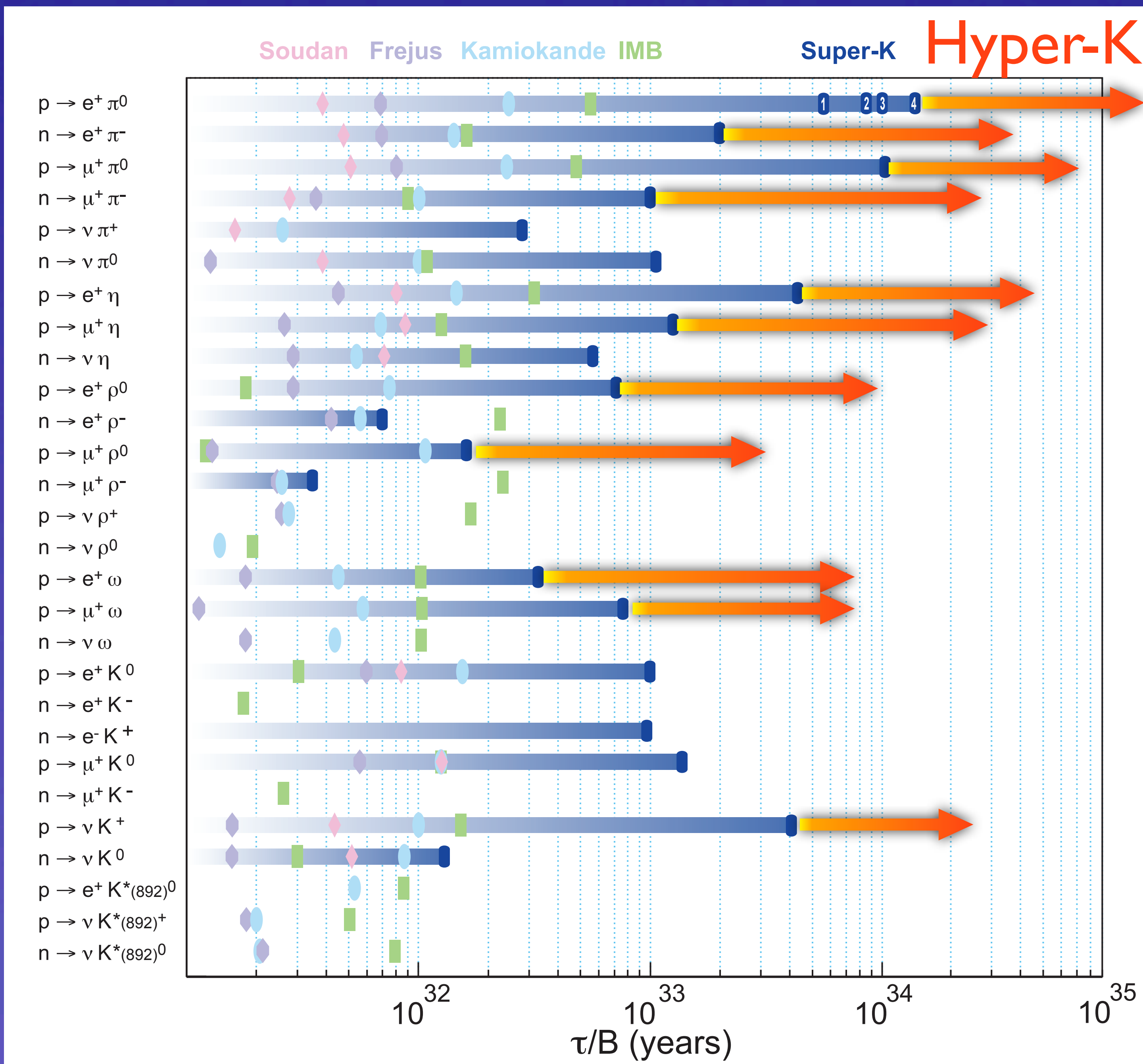


- BG measurement by accelerator ν (K2K)
  - BG=$1.63^{+0.42}_{-0.33}$(stat.)$^{+0.45}_{-0.51}$(syst.) (Mt×yrs)$^{-1}$ (Eν<3GeV)
  - Consistent w/ simulation 1.8±0.3(stat.)

BG in Hyper-K is under control.

Search for nucleon decays

- 10 times better sensitivity than Super-K.
    - only realistic plan to go beyond 10^{35} years for $p\rightarrow e^{+}+\pi^{0}$
- >3σ discovery is possible for lifetime beyond Super-K limits.

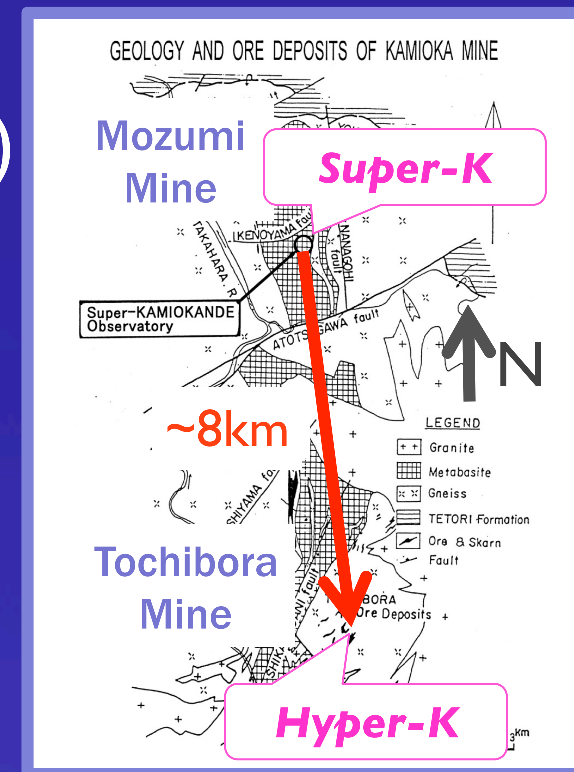


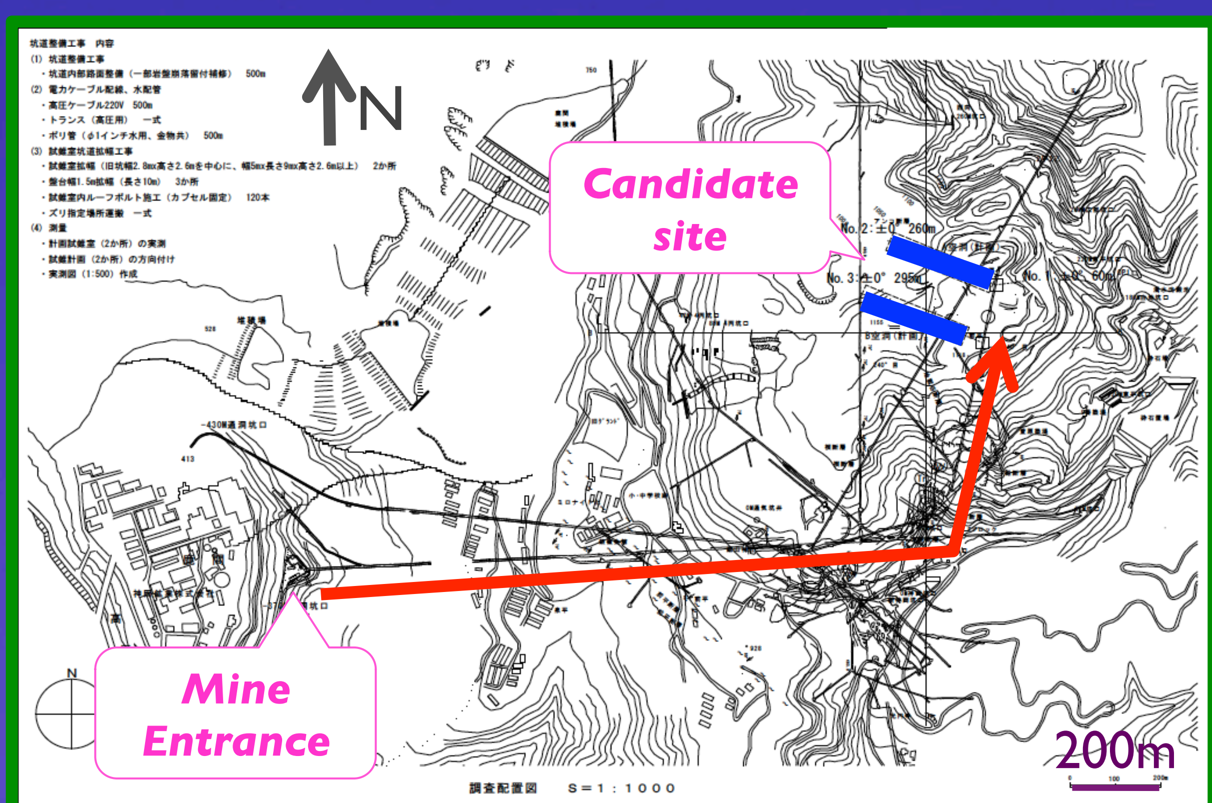
Hyper-K sensitivities

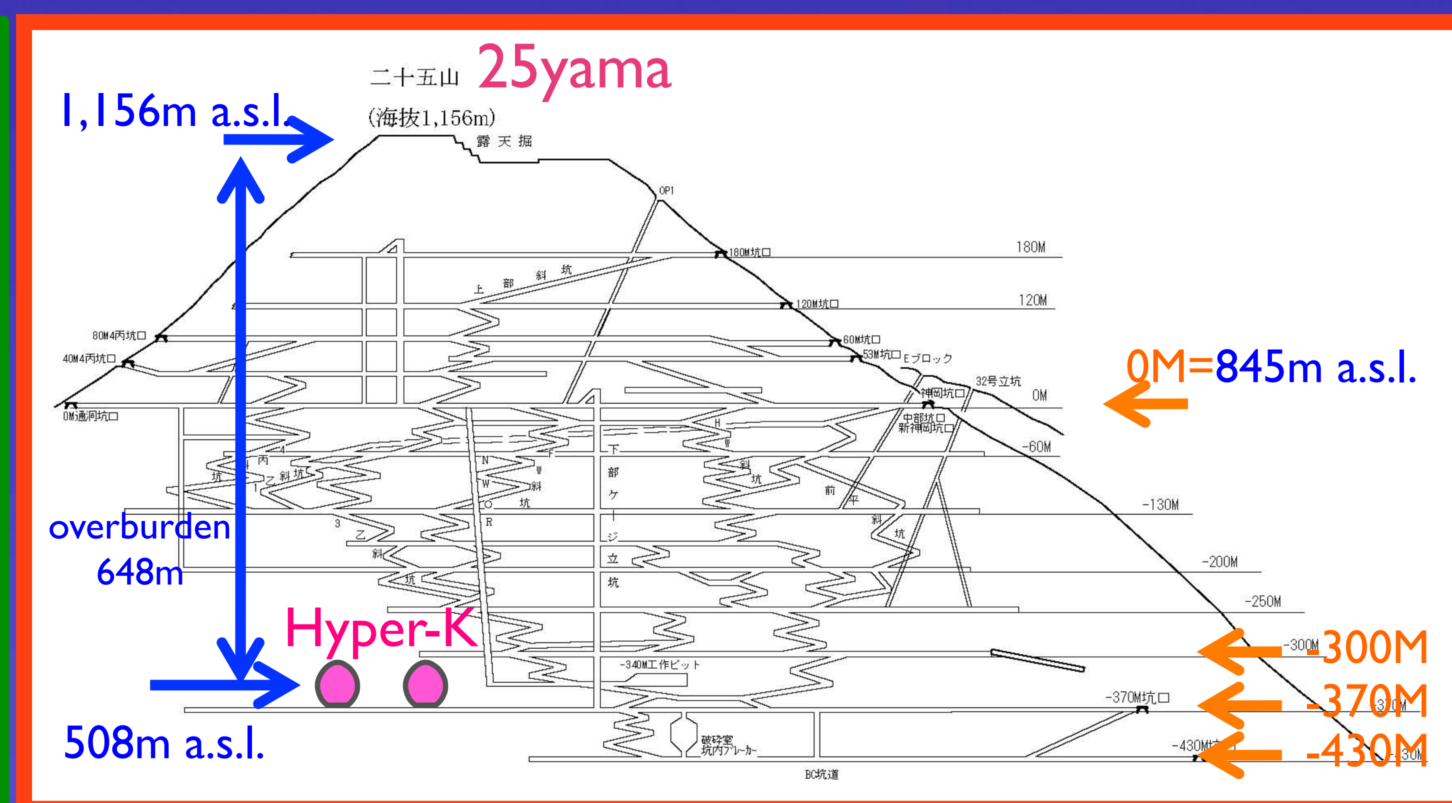
- $p\rightarrow e^{+}+\pi^{0}$
    - $\tau_{proton}/Br > 1.3 \times 10^{35}$ years @90%CL
    - 5.6Mton×years (10 Hyper-K years)
- $p,n\rightarrow (e^{+},\mu^{+})+(\pi,\rho,\omega,\eta)$
    - $O(10^{34\sim35})$years
- SUSY favored $p\rightarrow \nu+K^{+}$
    - 2.5×10^{34} years
- K^0 modes, $\nu\pi^0$, $\nu\pi^+$ possible
- Other various decay modes.
    - (B-L) violated modes
    - radiative decays $p\rightarrow e^{+}\gamma$, $\mu^{+}\gamma$
    - neutron-antineutron oscillation ($|\Delta B|=2$)
    - di-nucleon decays ($|\Delta B|=2$)
        - pp→XX..., nn→XX...

Hyper-K candidate site

- 8km south from Super-K
  - same T2K beam off-axis angle (2.5 degree)
  - same baseline length (295km)
- 2.6km horizontal drive from entrance
- under the peak of Nijuugo-yama
  - 648m of rock or 1,750 m.w.e. overburden
- 13,000 m³/day or 1megaton/80days natural water

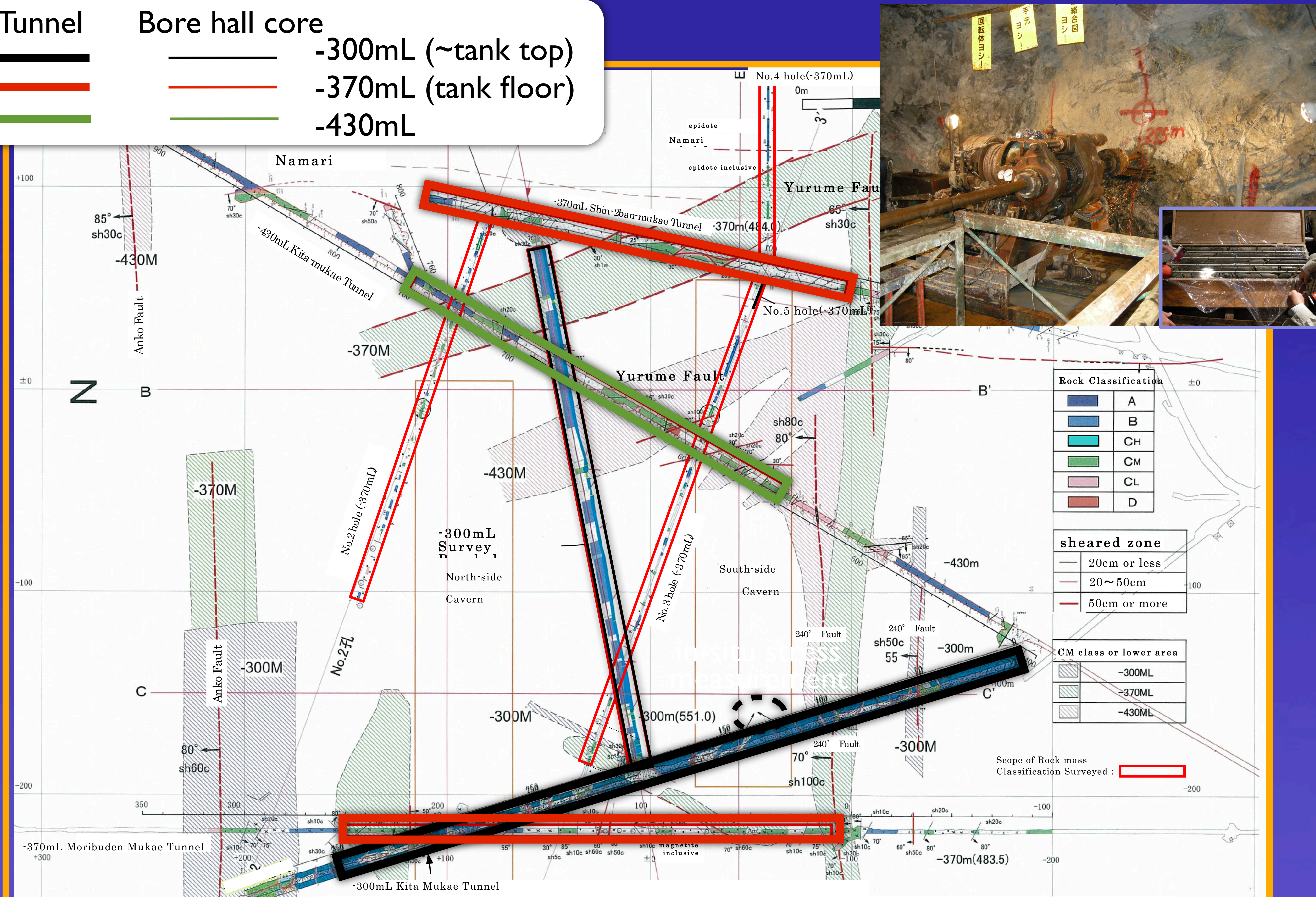




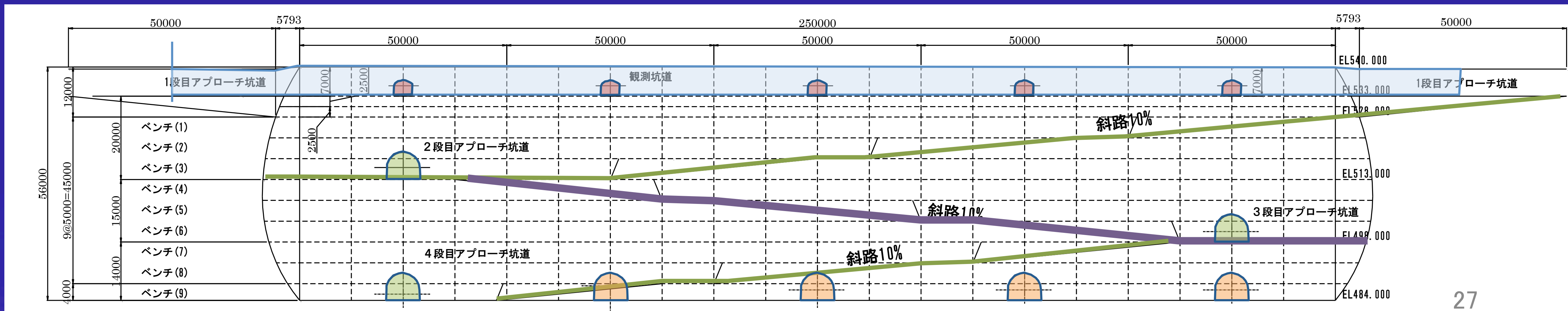


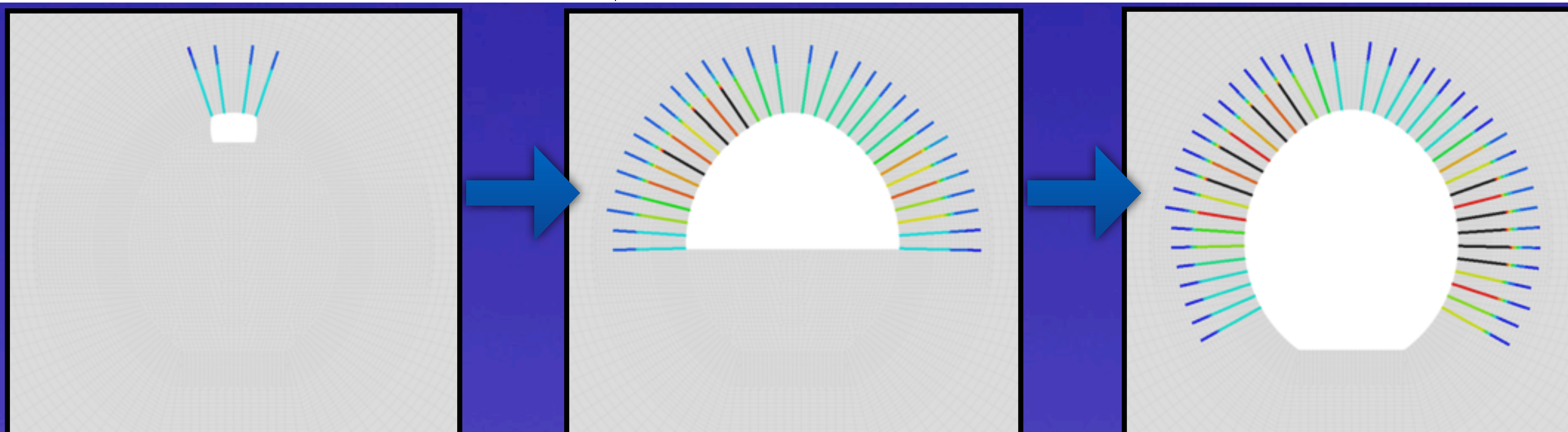
Overview of the geological survey

Tunnel	Bore hall core	
black thick line	black thin line	-300mL (~tank top)
red thick line	red thin line	-370mL (tank floor)
green thick line	green thin line	-430mL



Cavern analysis

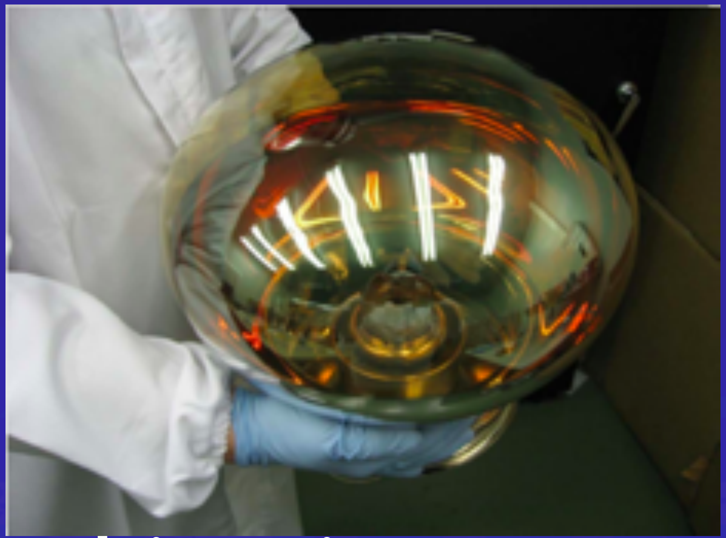




step-by-step calculations for each excavation benches

- cavity analysis (and PS anchor design) going on
- scheduling & costing ongoing

Photo-sensor development

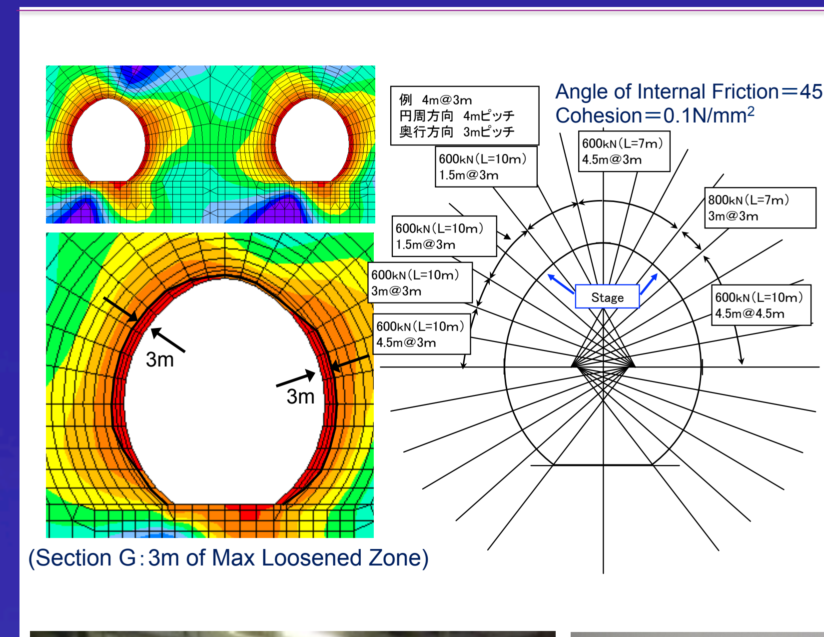


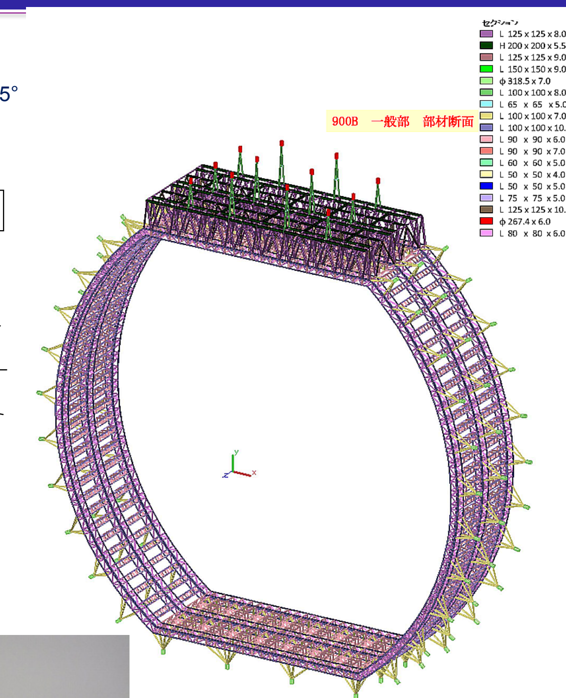
- Candidates for ID sensor
  - 20” Hybrid Photo Detector (HPD)
  - (New 20” PMT as backup)
- Proof test of 8” HPD in a water tank from this winter
- 20” HPD prototype is expected in ~a half year

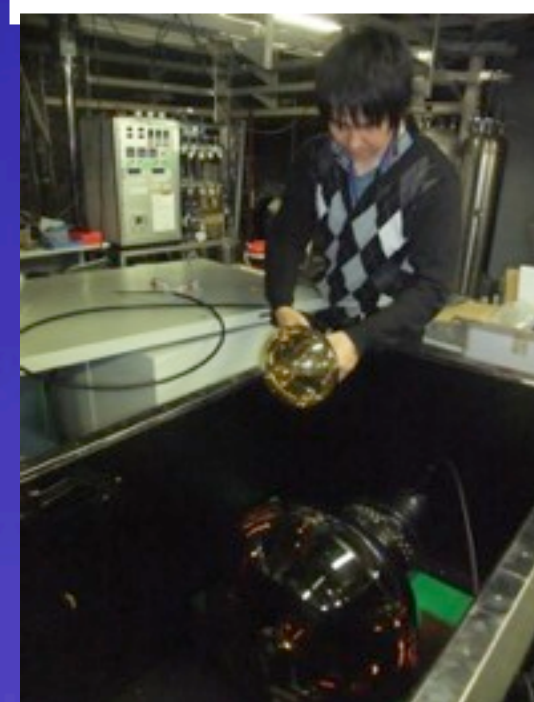
Preparation @ Kamioka

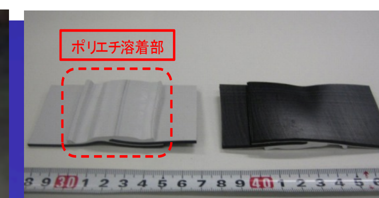
More Development works

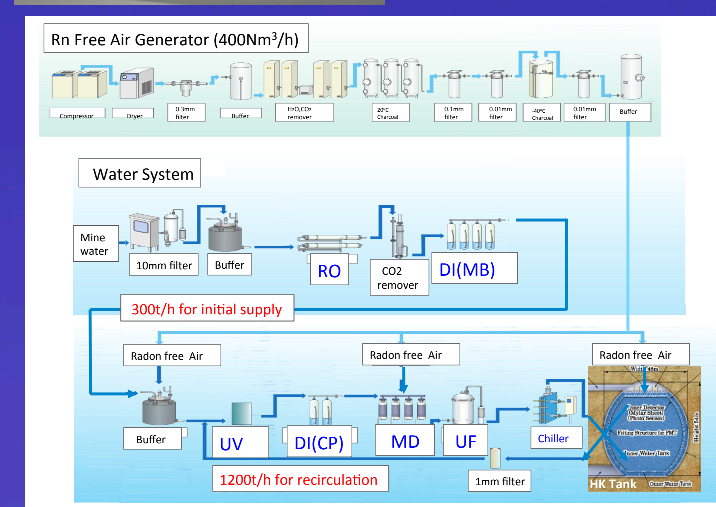
- Detector design optimization
  - tank shape, segmentation wall, tank liner, PMT support structure
- Water purification system, water quality control
- DAQ electronics (under water?)
- Calibration source deployment system
  - automated, 3D control
- Software development
  - Detector geometry optimization, enhance physics capabilities
- Physics potential studies
  - requirements for near detectors
- works in the international working group

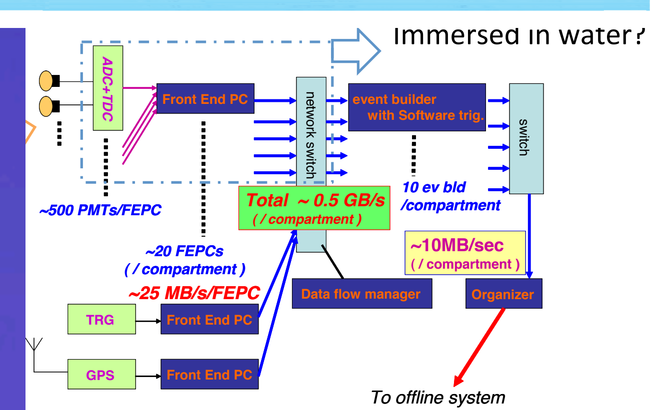












Outlook

- Good and timely progress in neutrino physics with the GCOE program.
- Exploring nature with neutrinos.
  - Goals of T2K (another 5 years or more)
    - Anti-neutrinos measurements will be proposed.
    - A hint of CPV
  - A proposal of the new experiment, Hyper-Kamiokande
    - Neutrino CP violation
    - Proton Decay for GUT

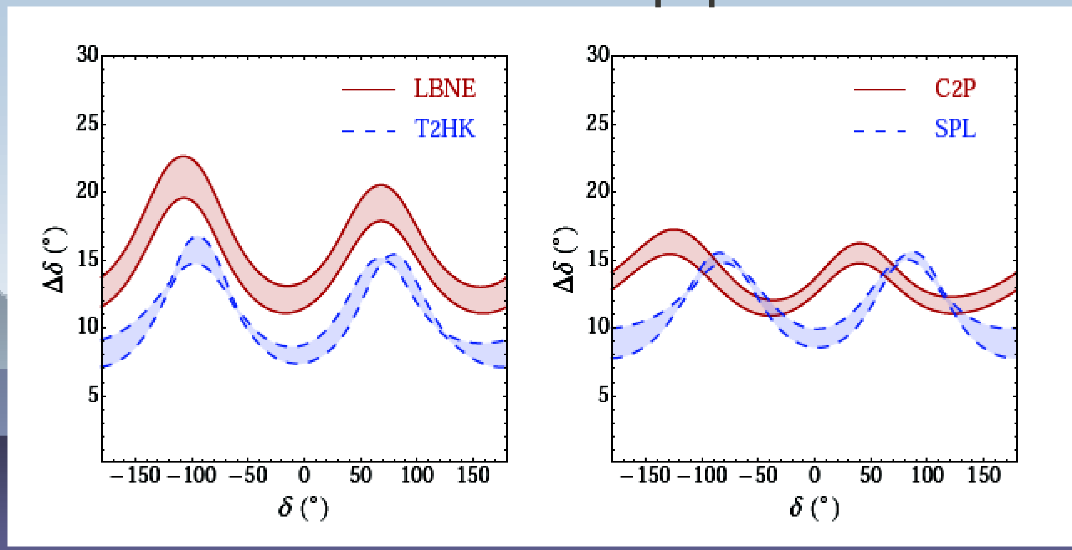
Backup

Long baseline projects

Project	Beam power MW	Fiducial Mass kt	Baseline km	MH	CPV 90%CL, (3σ)	Physics starts	Astrophysical program
LBNO	0.8	20->100	2300	Excellent	71 (44)	2023	Yes
T2HK	0.75	500	295	Little	86 (74)*	2023	Yes
LBNE	0.7	10	1300	OK	69 (43)	2022	No
Lund	5	440	365	Some	86 (70)	>2019	Yes
CERN-Canfranc	0.8-4	440	650	Some	80-88(80)	>2020	Yes

*: if mass hierachy is known

P. Coloma et al.hep-ph:1203.5651



T2HK: 4MW, 500 kt
LBNE: 0.8 MW,33 kt
C2P=LBNO : 0.8 MW, 100 kt

$\nu_\mu \rightarrow \nu_e$ probability

$$
\begin{aligned}
P(\nu_\mu \rightarrow \nu_e) \;=\; & 4C_{13}^2 S_{13}^2 S_{23}^2 \cdot \sin^2 \Delta_{31} \\
& +8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
& -8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
& +4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \cdot \sin^2 \Delta_{21} \\
& -8C_{13}^2 S_{12}^2 S_{23}^2 \cdot \frac{aL}{4E_\nu} (1 - 2S_{13}^2) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \\
& +8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{13}^2} (1 - 2S_{13}^2) \sin^2 \Delta_{31}
\end{aligned}
$$

Leading

CP violating (flips sign for $\bar{\nu}$)

Solar

Matter effect

Rich physics (with precise θ_{13} expected from reactor)

Leading term $\propto \sin^2 2\theta_{13}$

CPV term $\propto \sin 2\theta_{13}$

Matter effect $\propto \sin^2 2\theta_{13}$

For larger $\sin^2 2\theta_{13}$

signal ↑, CP asymmetry ↓

matter/CP ↑