The Hyper-Kamiokande Experiment

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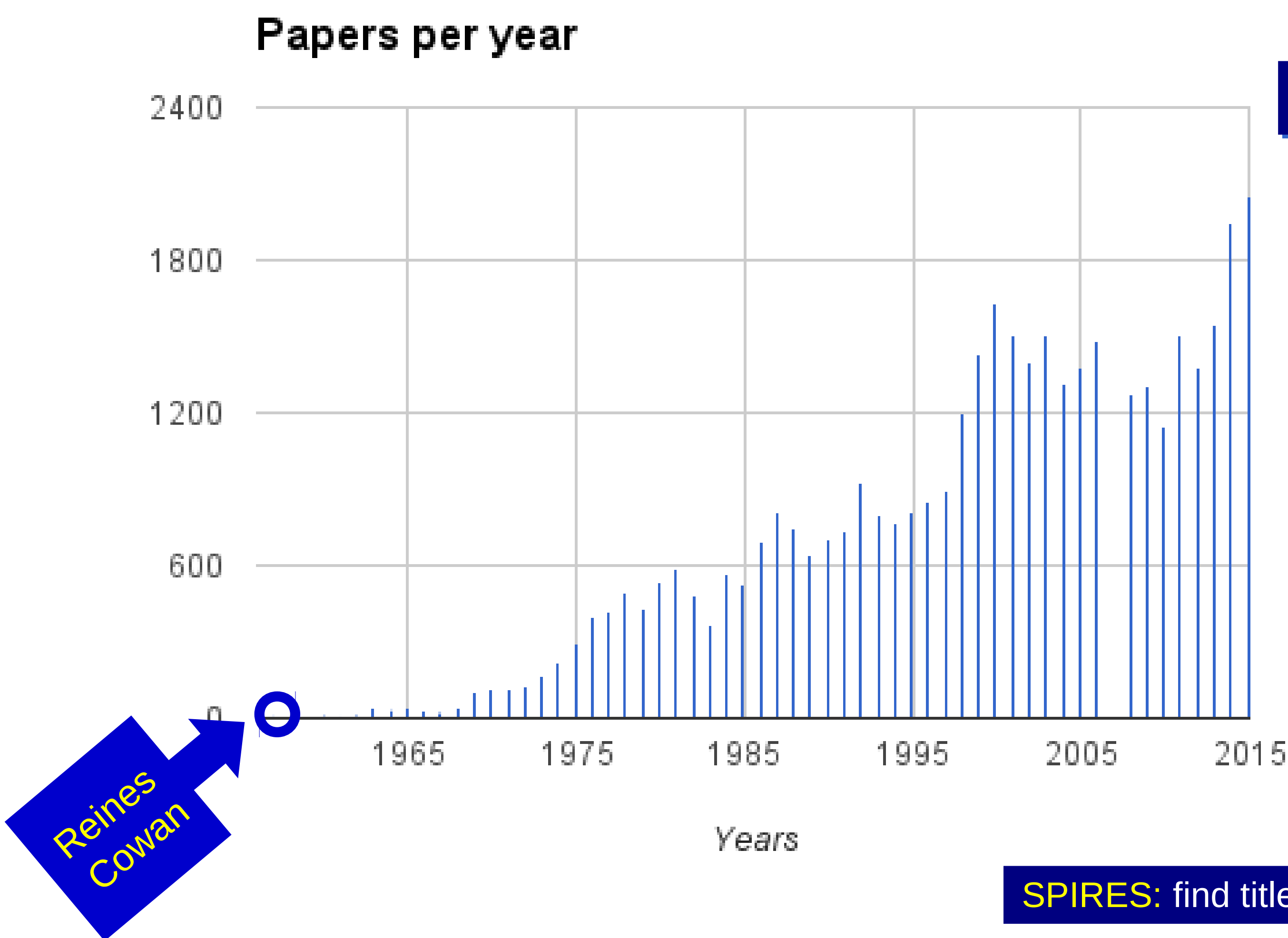
Colloquium
Nikhef, December 4, 2015

The Unceasing March of Neutrinos

- Neutrinos are difficult to corner, but technology is beginning to catch up.
- As the study of their nature develops their importance is being understood revealing an essential component to understand the Universe.



~42 000 Papers

Milestones:

1956 discovery of ν's

1968 solar ν anomaly

1987 supernova ν's

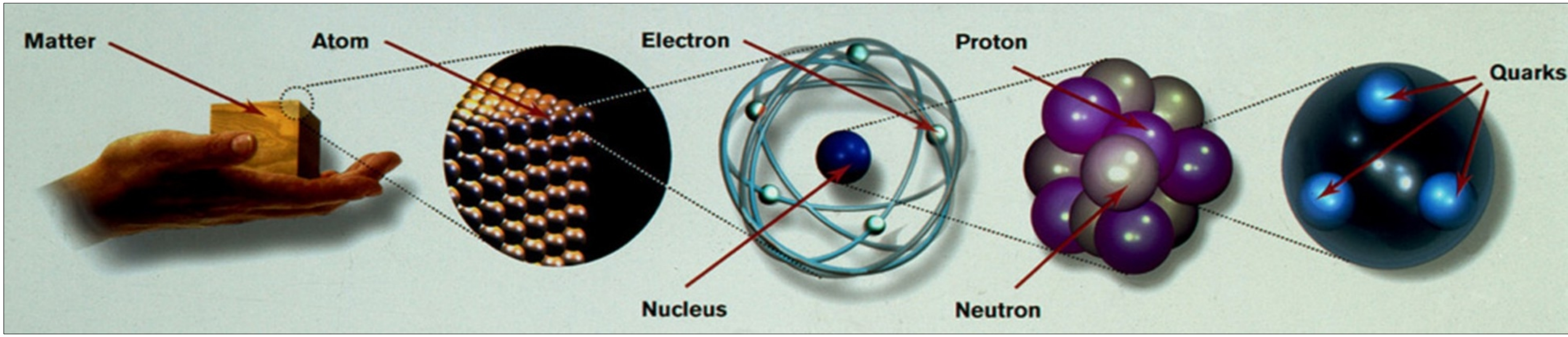
1998 atmospheric ν's

2001 solar ν's

2012 ν_e appearance

SPIRES: find title NEUTRINOS and date XX

Periodic System of Elementary Particles



	Quarks		Leptons	
	Charge -1/3	Charge +2/3	Charge -1	Charge 0
1st Family	Down d	Up u	Electron e	e-Neutrino ν_e
2nd Family	Strange s	Charm c	Muon μ	μ-Neutrino ν_μ
3rd Family	Bottom b	Top t	Tau τ	τ-Neutrino ν_τ

Strong Interaction (8 Gluons)

Electromagnetic Interaction (Photon)

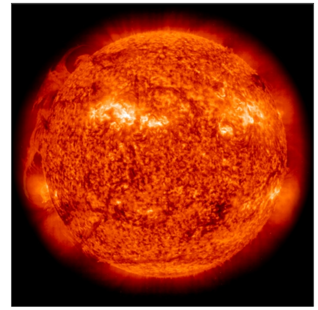
Weak Interaction (W and Z Bosons)

Gravitation (Gravitons?)

Higgs

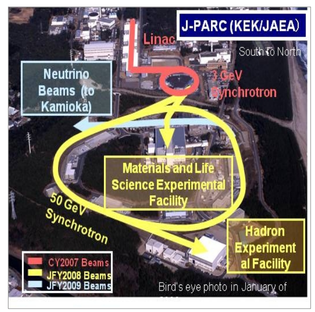
Where do Neutrino Appear in Nature?

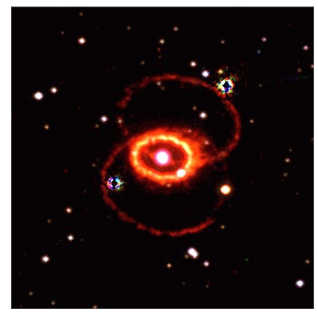
Nuclear Reactors



Sun

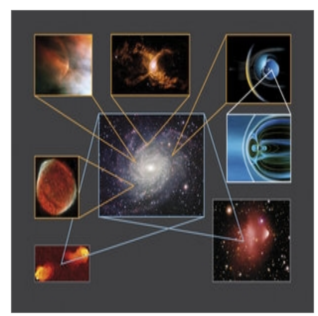
Particle Accelerators





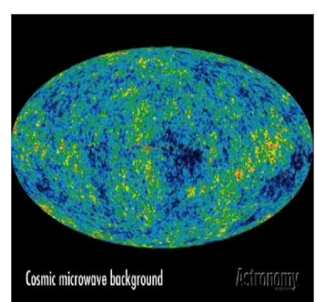
Supernovae
(Stellar Collapse)
SN 1987A

Earth Atmosphere



Astrophysical
Accelerators

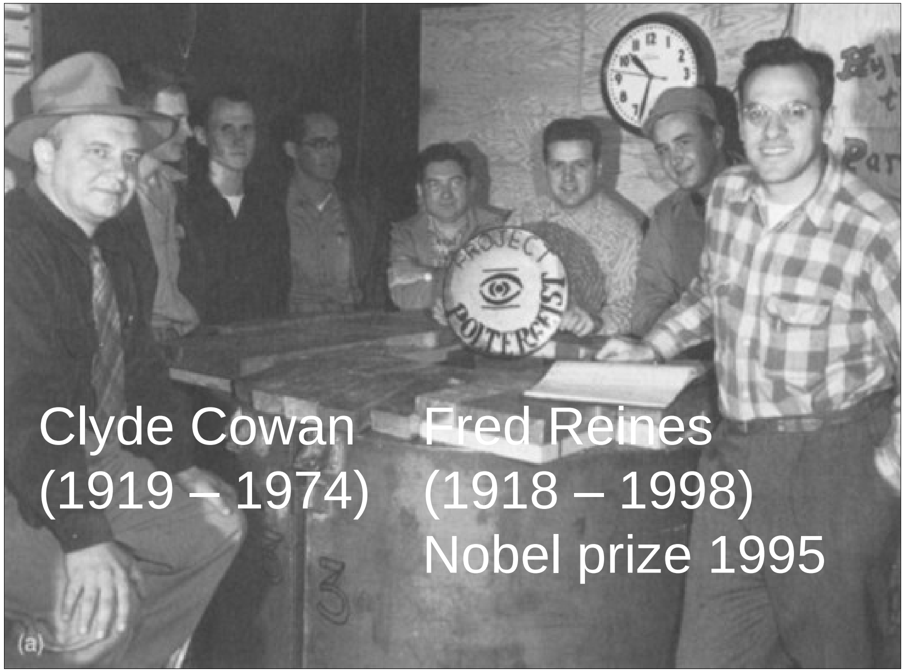
Earth Crust
(Natural Radioactivity)

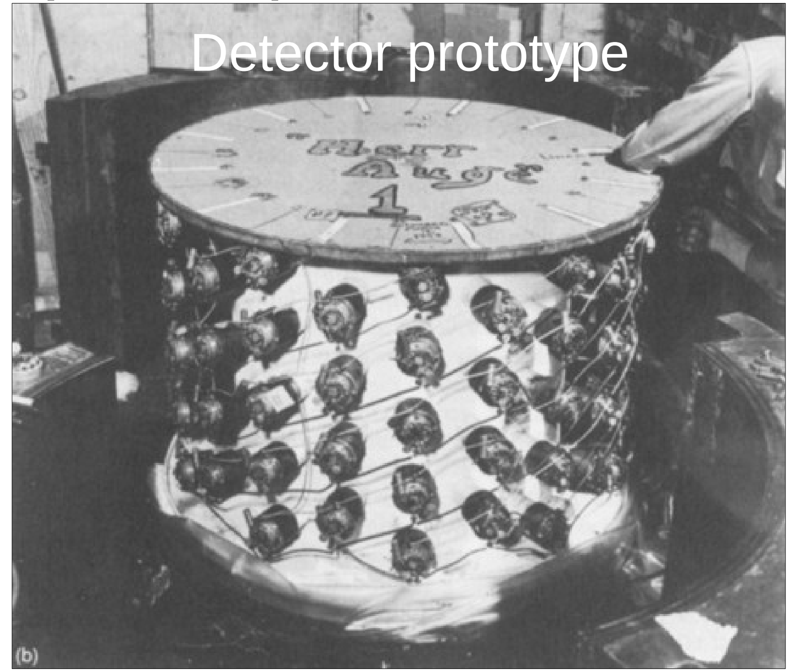


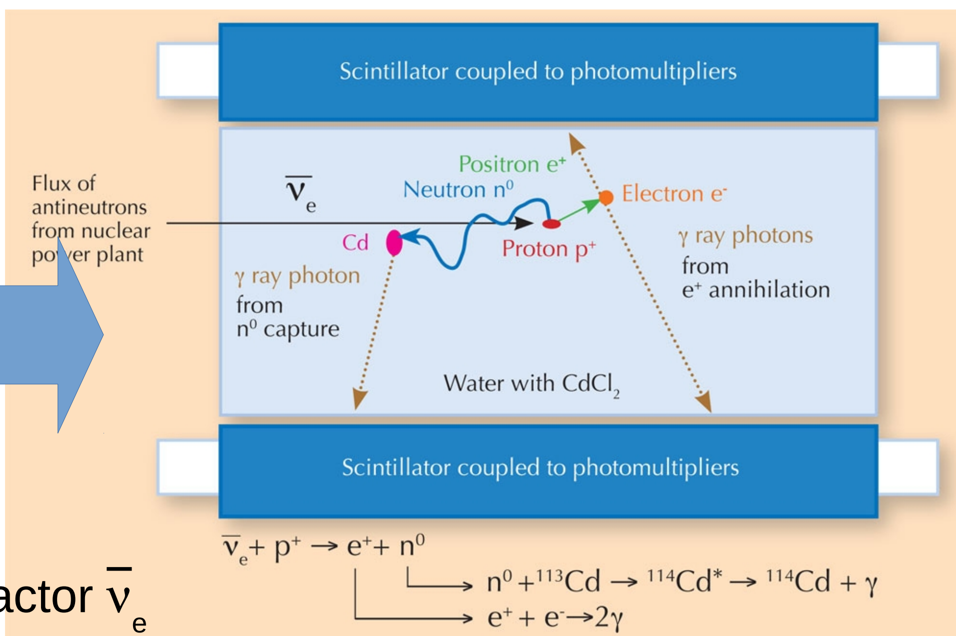
Cosmic Big Bang
(Today 330 n/cm^3)
Indirect Evidence

First Detection (1954-'56)

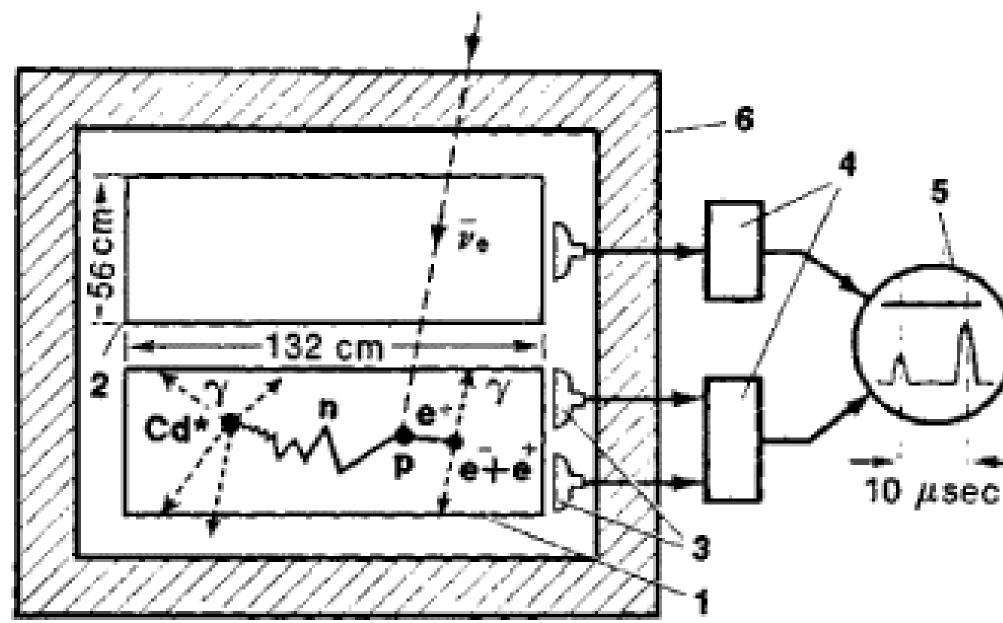
@ Savannah Power power plant



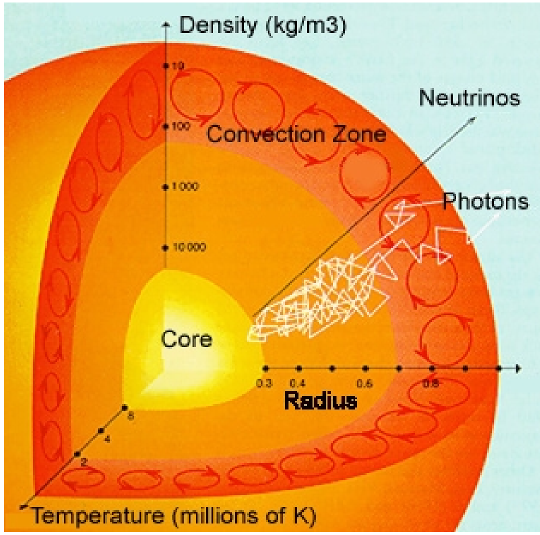




Reactor $\overline{\nu}_e$



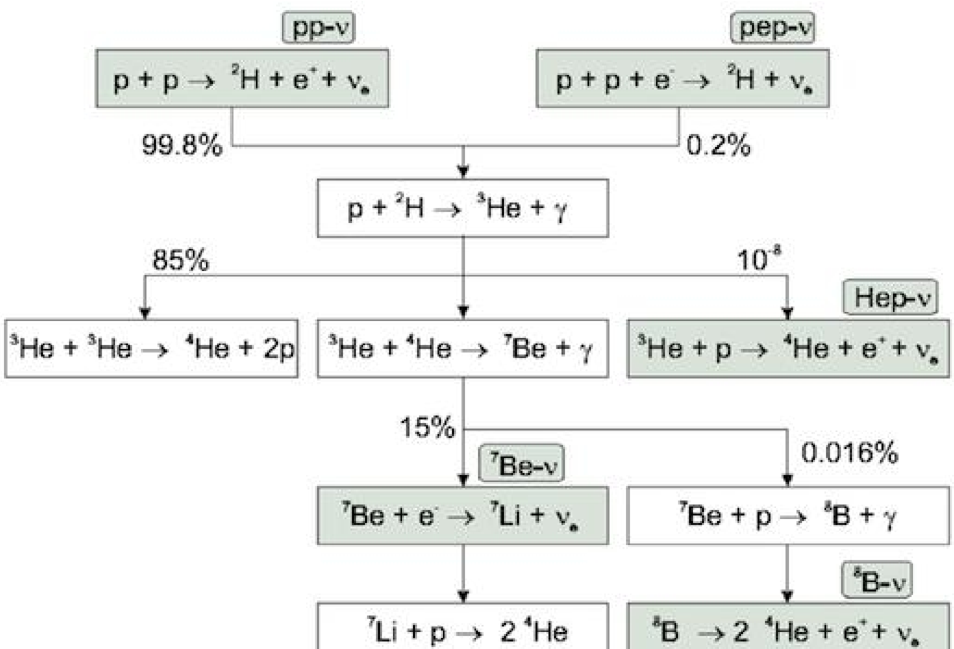
Neutrinos from the Sun

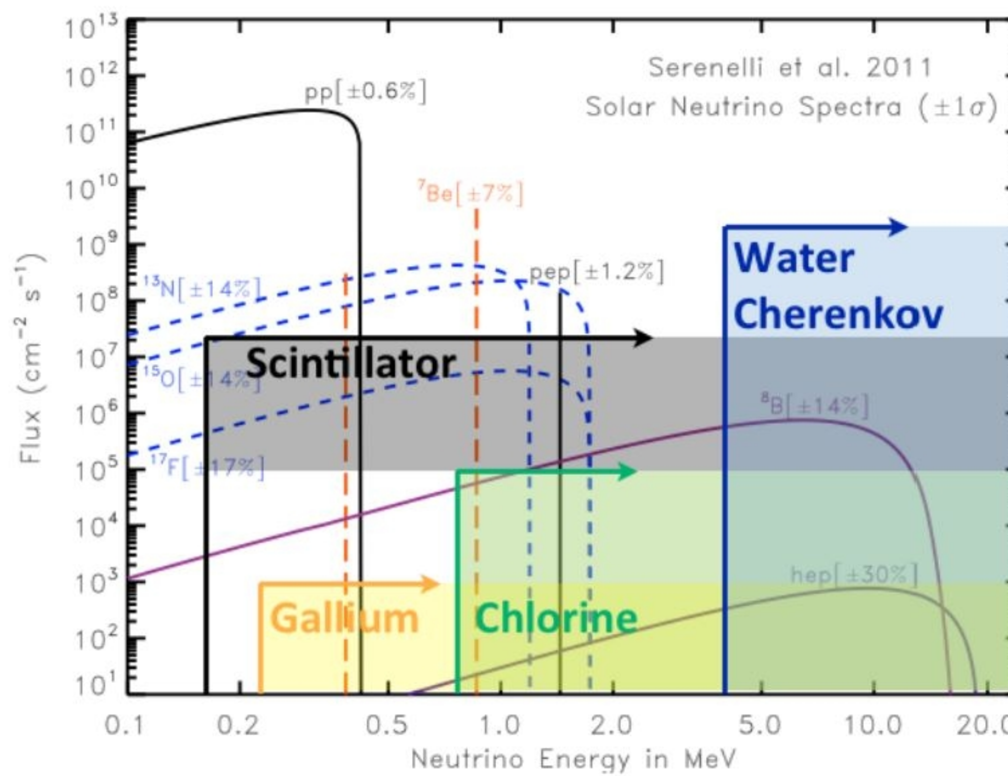


Solar radiation: 98% light (photons)

2% neutrinos

At Earth 66 billion neutrinos/cm^2 sec





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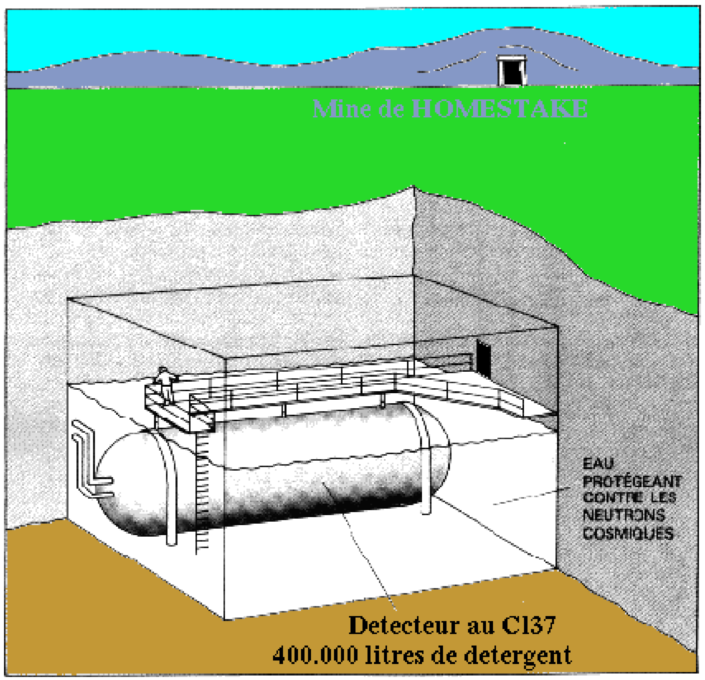
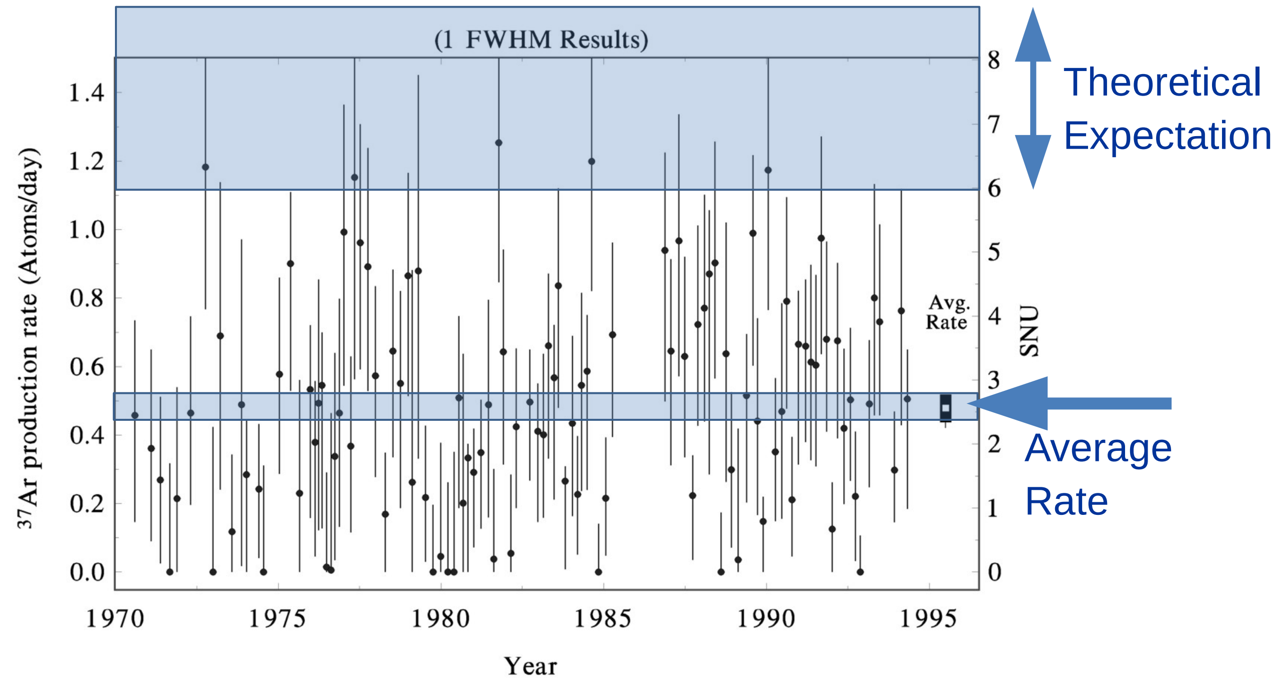


ApJ 496:505, 1998



Detect solar ν by inverse β-decay:

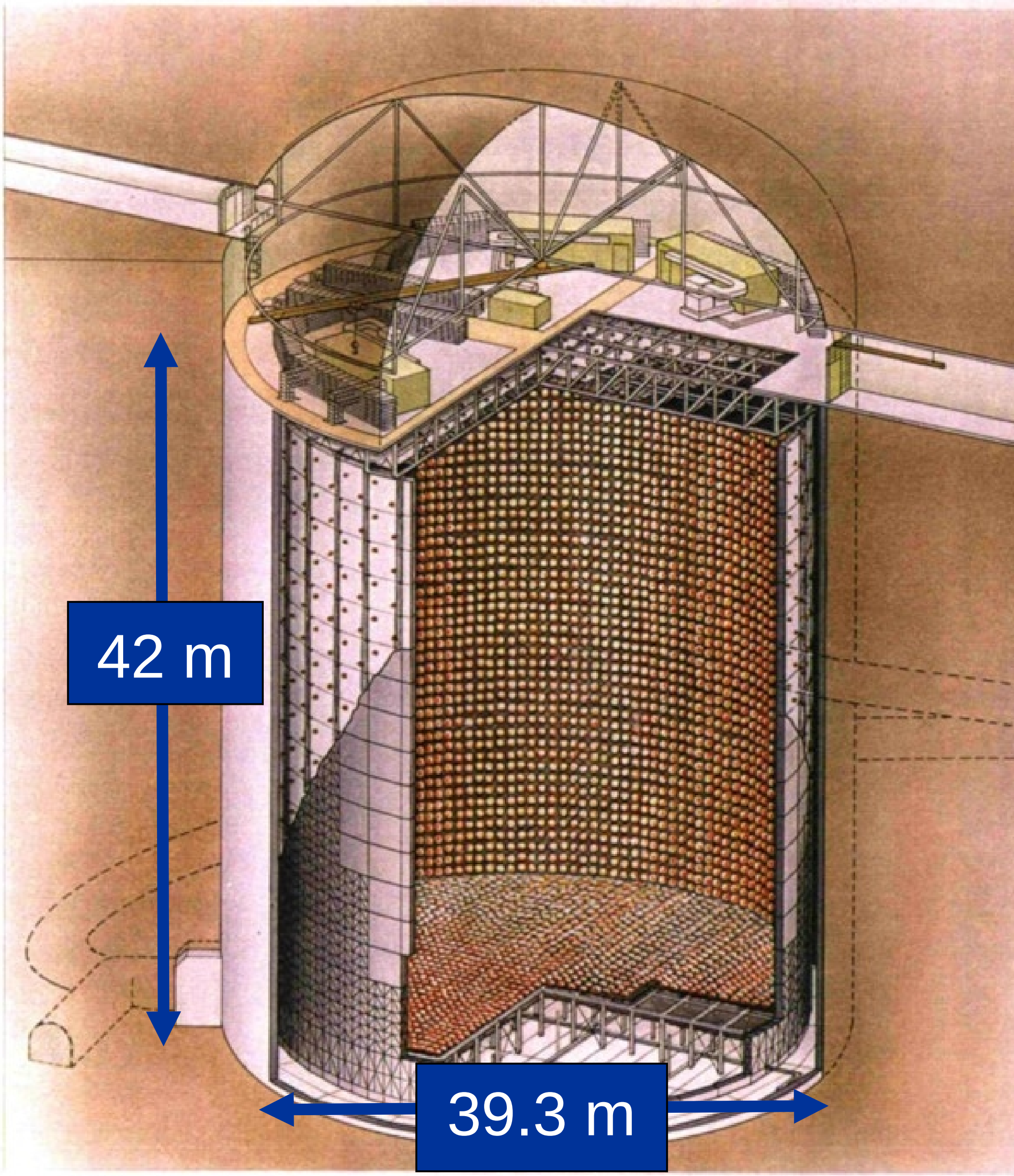
$\nu + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$

where the ^{37}Ar has 35 day half-life.

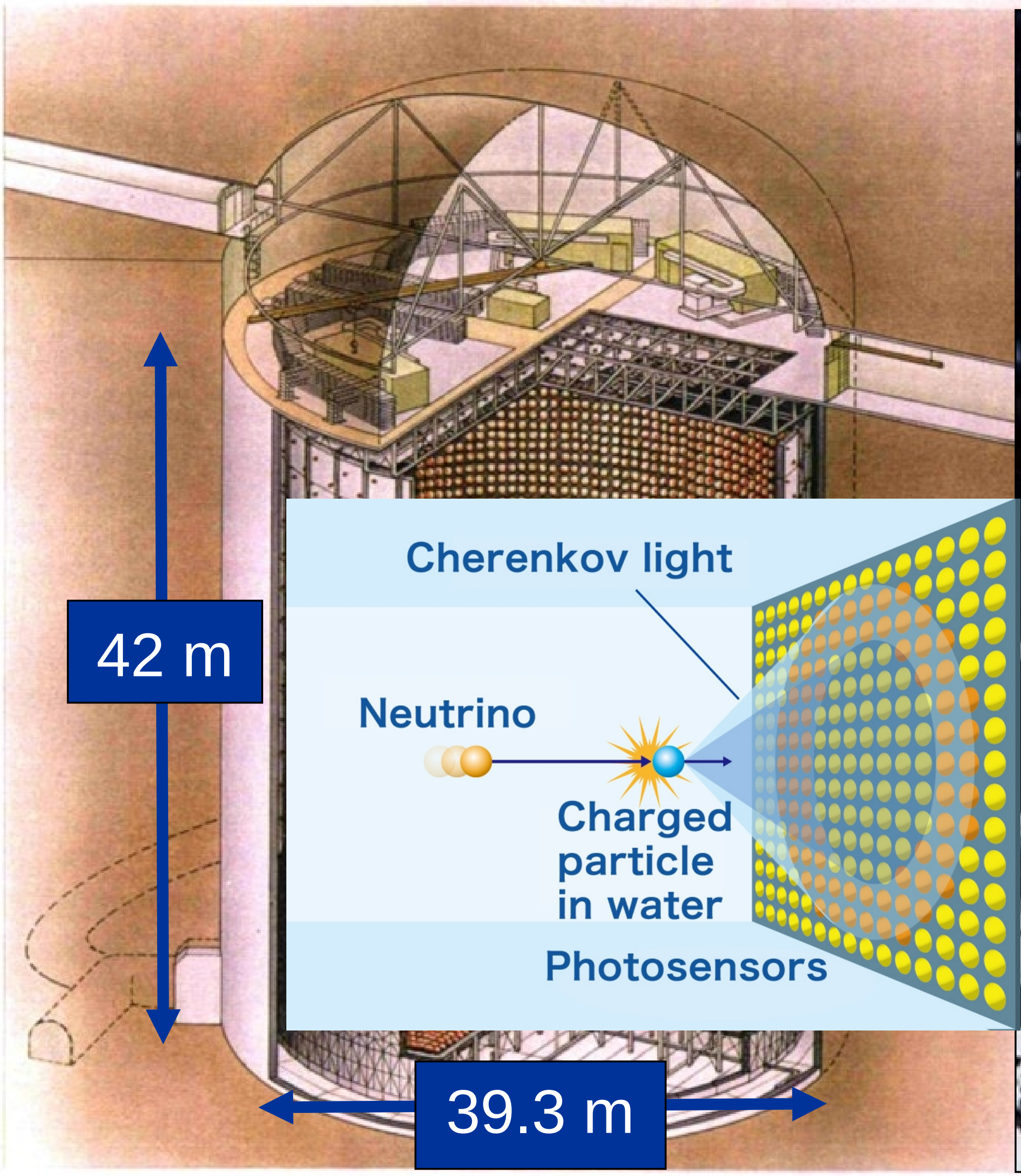
Expect one ^{37}Ar atom every 17h β-decay.

- Average (1970-1994)
  $2.56 \pm 0.16_{stat} \pm 0.16_{sys}$ SNU
  (SNU = Solar Neutrino Unit = 1 Absorption / sec / 10^{36} Atoms)
- Theoretical Prediction 6-9 SNU
- “Solar Neutrino Problem” since 1968, supported by other experiments as well.

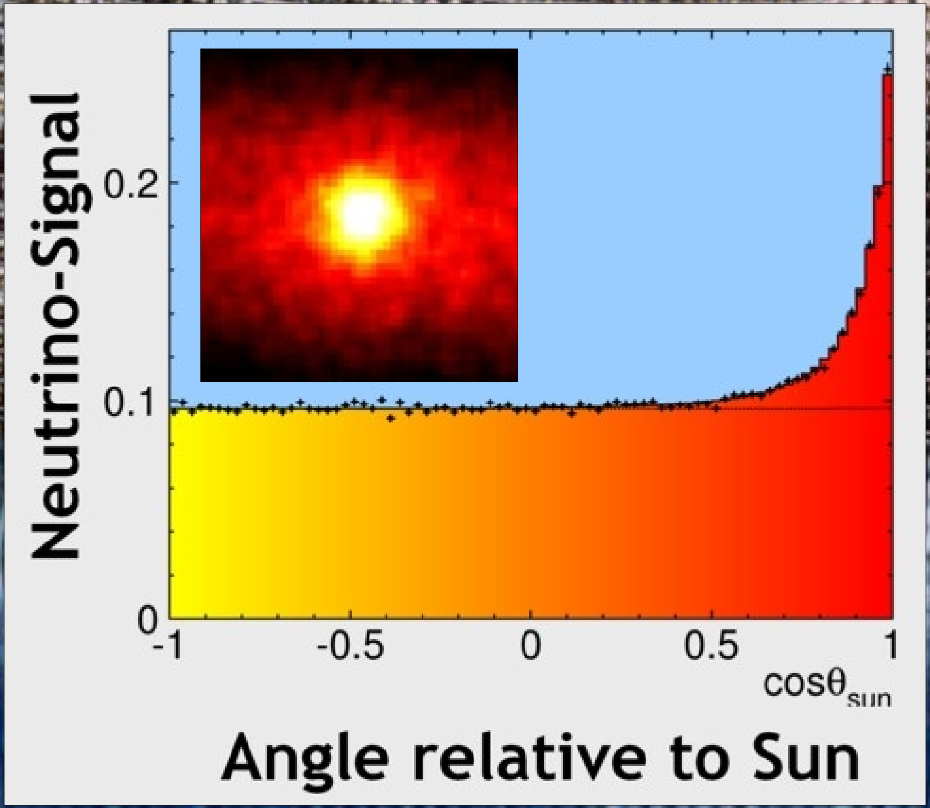
Super-Kamiokande Neutrino Detector, since 1996

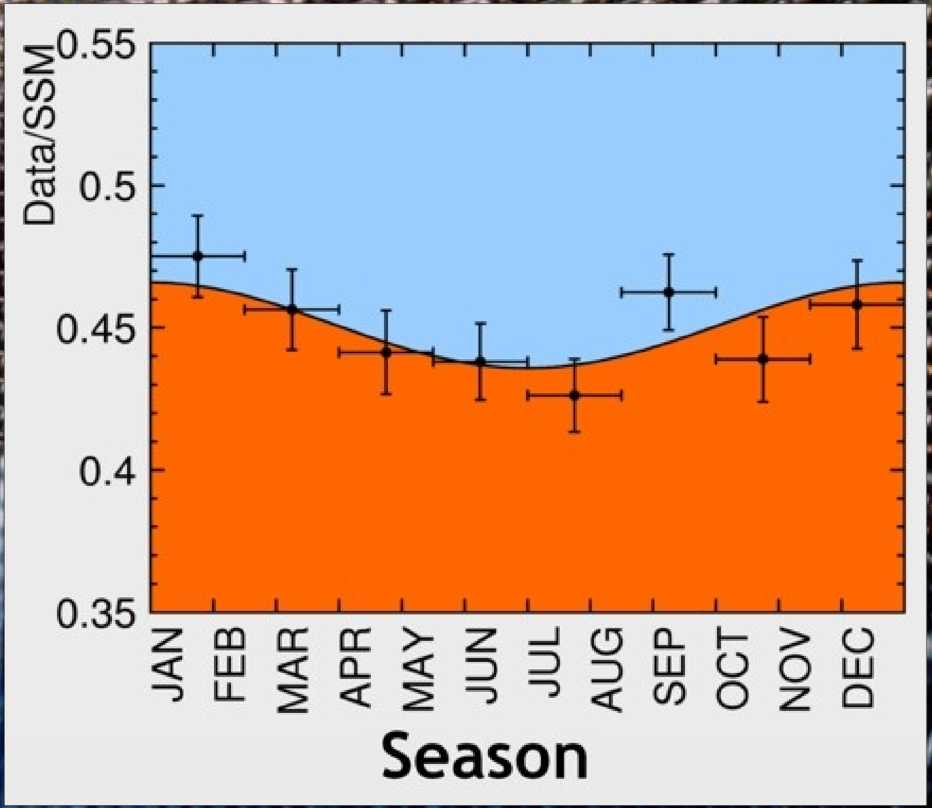


Super-Kamiokande Neutrino Detector, since 1996



Super-Kamiokande: Sun in the light of neutrinos





ca. 60,000 solar neutrinos measured in Super-K (1996–2012)

SNO Breakthrough

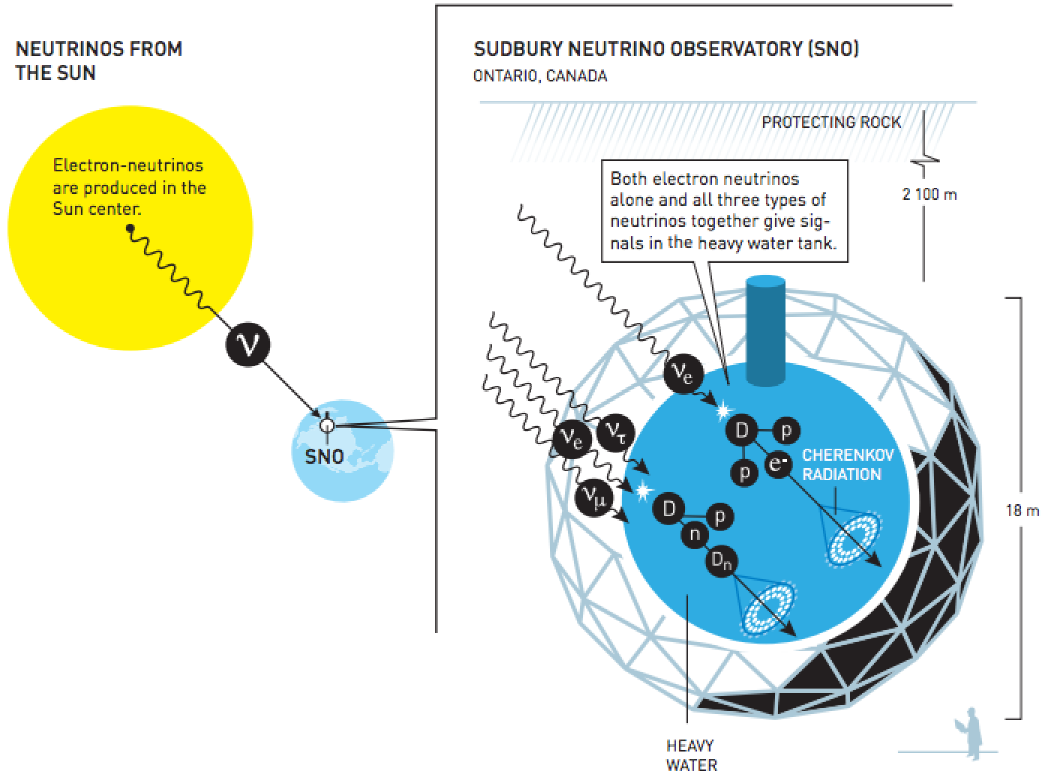
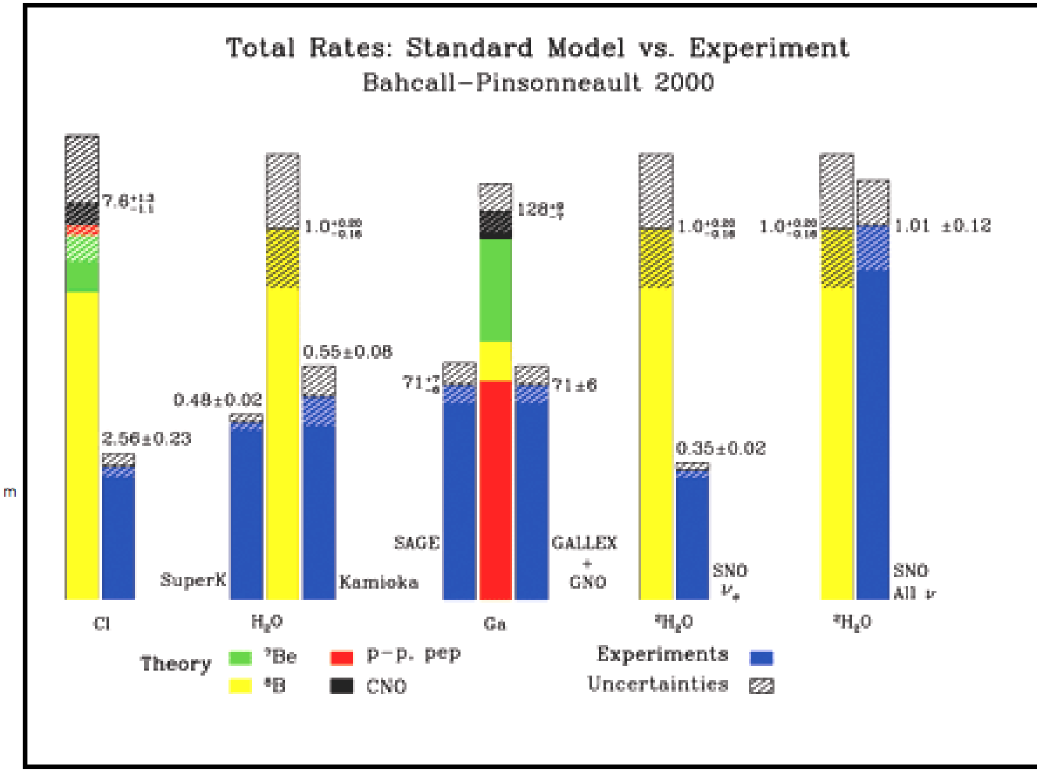


Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences

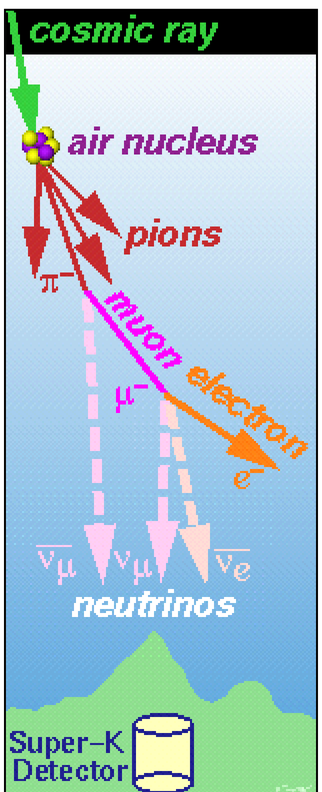


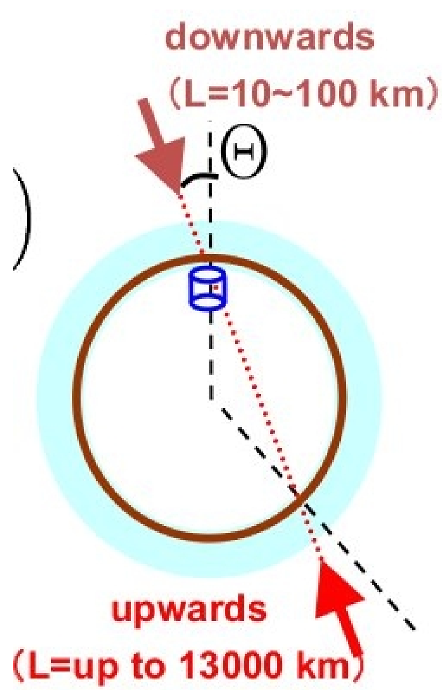
In 2002, the SNO results confirmed the hypothesis of neutrino oscillations for solar neutrinos observing not only electron neutrino disappearance but also active neutrino appearance using a D_2O target.

Super-Kamiokande Breakthrough

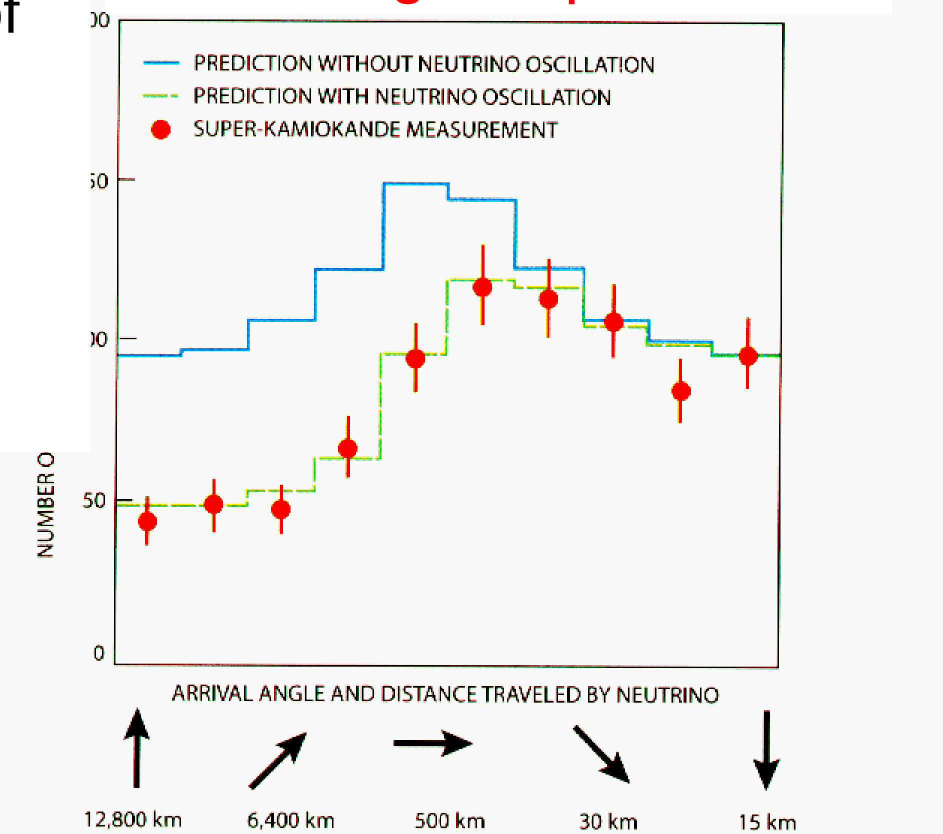
- Super-Kamiokande is a 50kton Water Cherenkov detector in the Kamioka mine.
- It is an upgrade of Kamioka, that started data-taking in 1996.
- Super-Kamiokande observed a depletion of μ-like events for neutrinos which transverse the Earth.
- Up / down difference!

$$\frac{\Phi^{Atm}_{\nu_\mu}(down)}{\Phi^{Atm}_{\nu_\mu}(up)} = 0.52^{+0.07}_{-0.06}(stat.) \pm 0.01(syst.)$$





Zenith angle dependence:



NUMBER OF HIGH-ENERGY MUON-NEUTRINOS seen arriving on different trajectories at Super-K clearly matches a prediction incorporating neutrino oscillations (*green*) and does not match the no-oscillation prediction (*blue*). Upward-going neutrinos (*plotted toward left of graph*) have traveled far enough for half of them to change flavor and escape detection.

2015 Physics Nobel Prize for Neutrino Oscillations

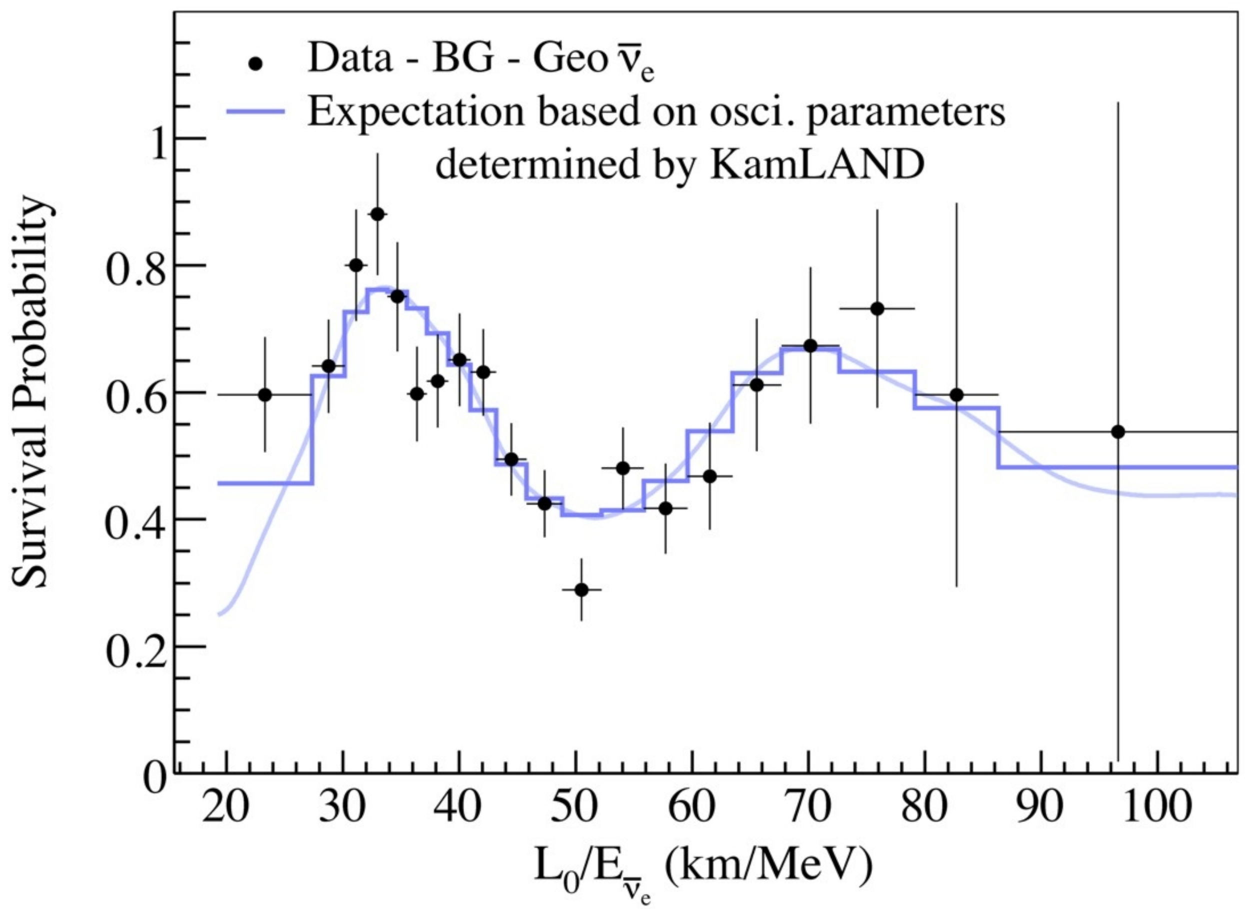
Takaaki Kajita
(1959)

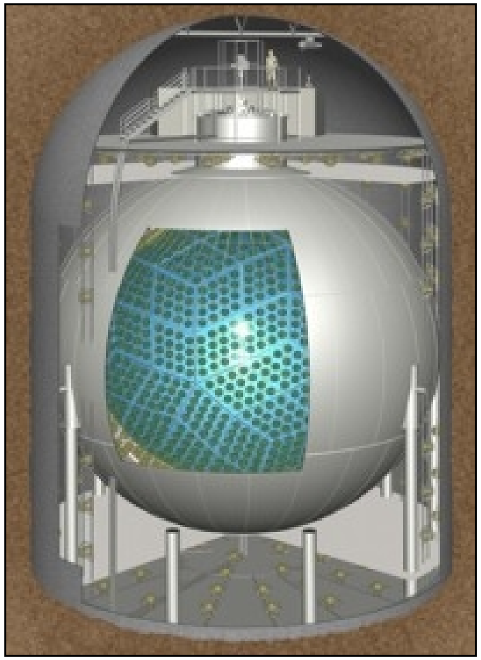
Arthur B. McDonald
(1943)

“for the discovery of neutrino oscillations, which shows that neutrinos have mass”

Oscillation of Reactor Neutrinos at KamLAND (Japan)

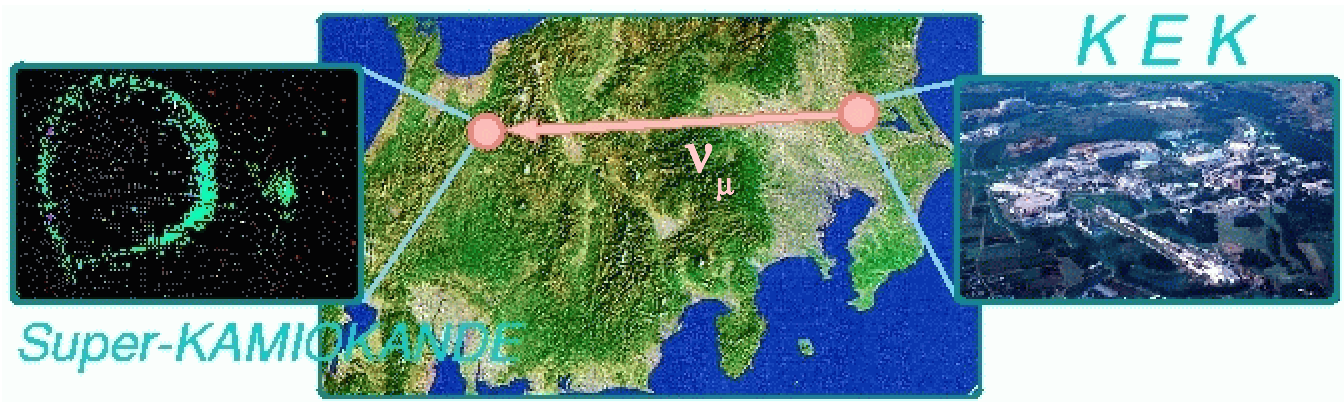
Oscillation pattern for anti-electron neutrinos from Japanese power reactors as a function of L/E



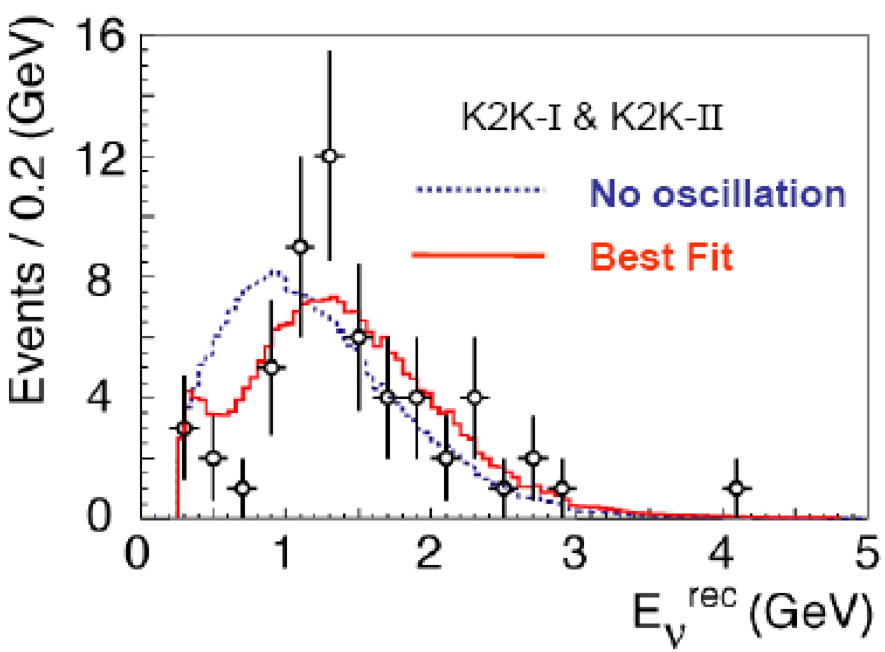


KamLAND Scintillator detector (1000ton)

Long Baseline Neutrino (LBN) Experiment

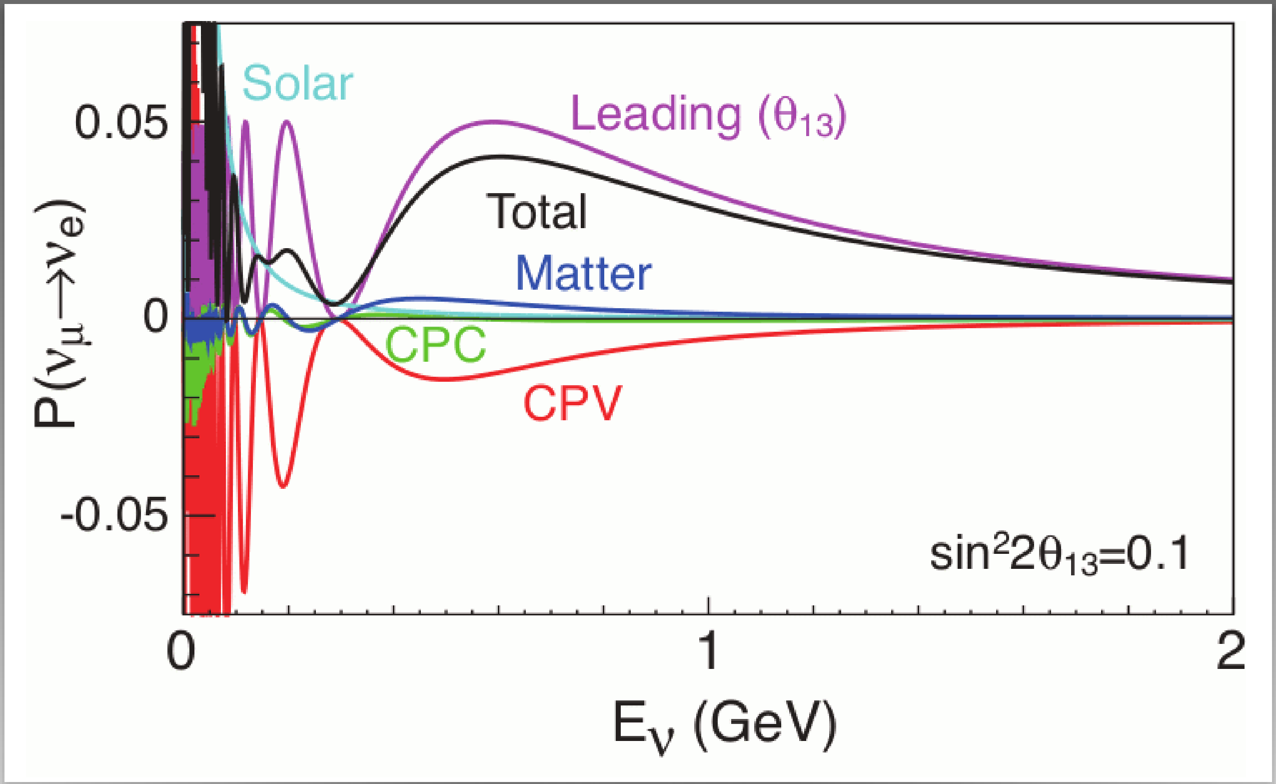


K2K Experiment (KEK to Kamiokande) measures precise neutrino oscillation parameters.



Confirms atmospheric neutrino oscillation parameters with controlled beam.

How to interpret the experimental results?

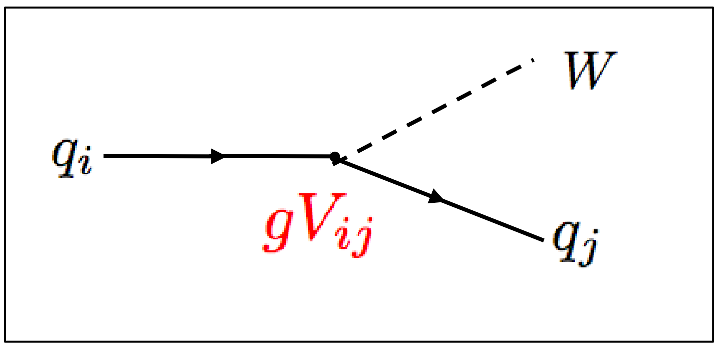


Neutrino Oscillations

- Neutrino oscillations imply that neutrinos have mass.
- First and so far only evidence of physics beyond the Standard Model of Particle Physics.

- Similar mechanism as in the quark oscillation (CKM matrix).
- Free parameters: 3 angles, 1 phase

CKM matrix



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

- PMNS (Pontecorvo, Maki, Nagakawa, Sakata) matrix for ν:

Flavour eigenstates (coupling to the W)

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

Mass eigenstates (definite mass)

Unitary PMNS mixing matrix

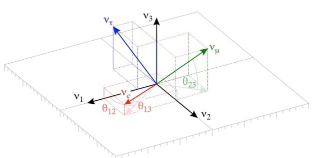
- For antineutrinos, $U \rightarrow U^*$

Neutrino Oscillations Framework

Free parameters usually written in terms of three rotation angles and 1 complex phase: θ_{12}, θ_{23}, θ_{13}, δ

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

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



θ_{23} : “atm.” mixing angle θ_{13} θ_{12} : “solar” mixing angle

The neutrino ν_ℓ is a coherent superposition of the states of neutrinos ν_j:

$$|\nu_l\rangle = \sum_j U^*_{lj} |\nu_j; \tilde{p}_j\rangle, \quad l = e, \mu, \tau$$

As neutrino propagate $|\nu_i(L)\rangle = e^{-im_i^2 L/2E} |\nu_i(0)\rangle$ the mass eigenstates interfere.

Probability to observe ν_β from flavour ν_α

$$P_{\alpha\to\beta} = |\langle\nu_\beta|\nu_\alpha(t)\rangle|^2 = \left|\sum U^*_{\alpha i} U_{\beta i} e^{-im_i^2 L/2E}\right|^2$$

Dependence on $U_{\alpha\beta}$ and

- L(km): Distance the neutrino has travelled
- E(GeV): Energy of the neutrino
- $\Delta m_{ij}^2(eV^2) = m_i^2 - m_j^2$: mass splitting

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}\left[U_{\beta i} U^*_{\alpha i} U^*_{\beta j} U_{\alpha j}\right] \sin^2\left(\frac{\Delta m_{ij}^2 L}{4E}\right) + 2\sum_{i>j} \mathrm{Im}\left[U_{\beta i} U^*_{\alpha i} U^*_{\beta j} U_{\alpha j}\right] \sin\left(\frac{\Delta m_{ij}^2 L}{2E}\right)$$

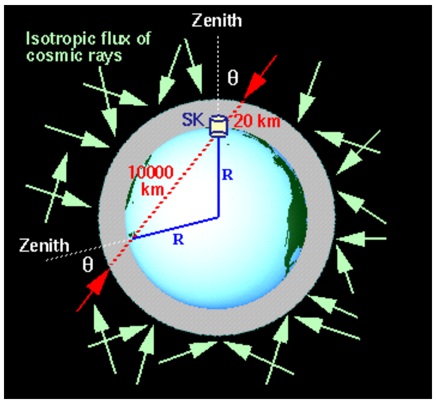
If neutrinos have no mass, or degenerate masses, no interference is possible

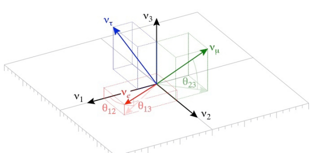
Neutrino Oscillations Framework

Free parameters usually written in terms of three rotation angles and 1 complex phase: θ_{12}, θ_{23}, θ_{13}, δ

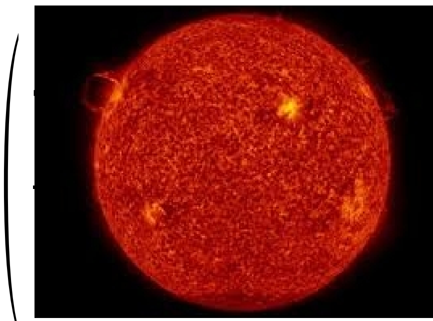
$$\left(c_{ij}=\cos\theta_{ij}, s_{ij}=\sin\theta_{ij}\right)$$

$$U_{PMNS}=$$





$$\begin{pmatrix} +c_{13} & 0 & +s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & +c_{13} \end{pmatrix}$$



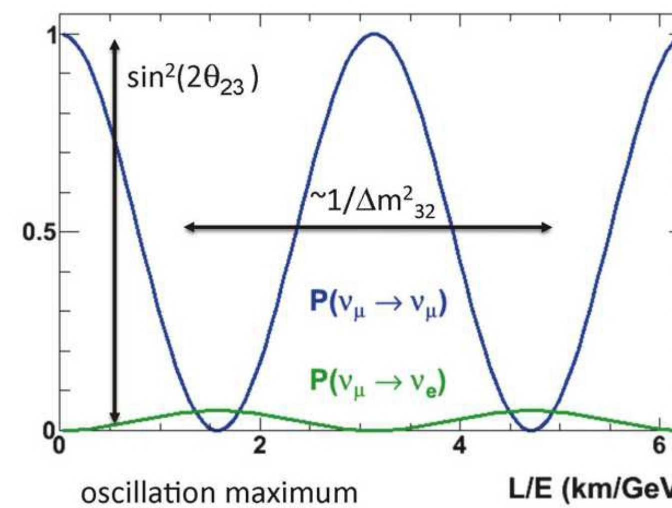
$39° < \theta_{23} < 53°$
Atmospherics and LBN experiments

$7° < \theta_{13} < 11°$
Reactor and LBN experiments

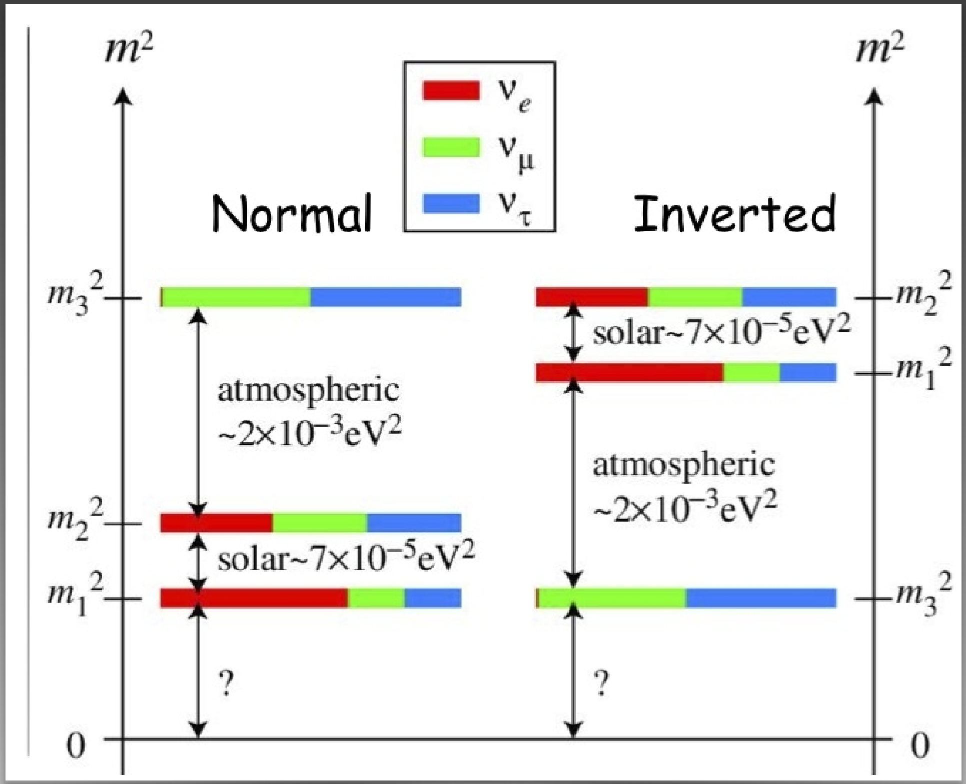
$33° < \theta_{12} < 37°$
Solar and KamLAND experiments

$6.99 < \Delta m^2_{12} < 8.18\ 10^{-5}\ eV^2$ (Solar)
$2.23 < \Delta m^2_{23} < 2.61\ 10^{-3}\ eV^2$ (Atm. And LBN)

Three flavour effects suppressed because:
$\Delta m^2_{21} << \Delta m^2_{31}$ and $\theta_{31} << 1$
→ Dominant oscillations well described by effective 2 flavour oscillations.



Mass Hierarchy

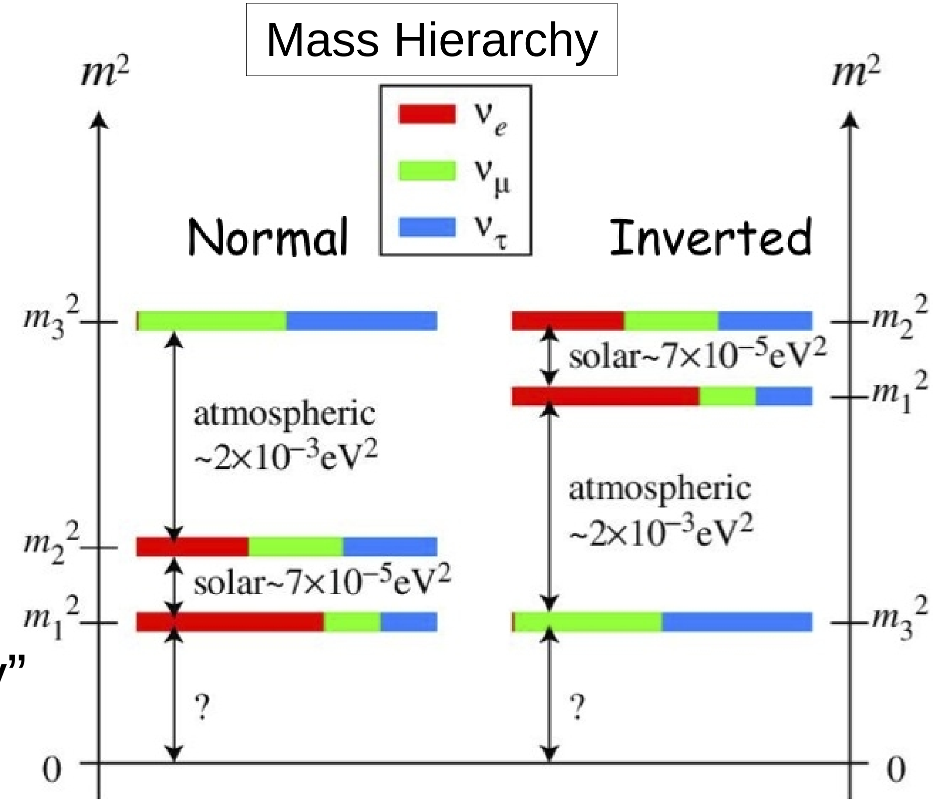


Measured Mass Splittings

Two observed mass splittings, determined from atmospheric and solar neutrino experiments, respectively:

- Δm^2 (atmospheric) = $|\Delta m^2_{32}| \sim 2.4 \times 10^{-3}\ eV^2$
- Δm^2 (solar) = $\Delta m^2_{21} \sim 7.6 \times 10^{-5}\ eV^2$

The sign of $|\Delta m^2_{32}|$, or the "mass hierarchy" is still unknown:



- *Normal* mass hierarchy is like quarks (m_1 *is lightest,* $\Delta m^2_{32} > 0$)
- *Inverted* mass hierarchy has m_3 lightest ($\Delta m^2_{32} < 0$)

Summary of Mass Hierarchy Strategies

Widths indicate main uncertainty

- LBNE (now DUNE)/NOVA: δ_{CP}
- JUNO: σ_E (3.0-3.5%)
- ORCA/PINGU/INO: θ_{23}

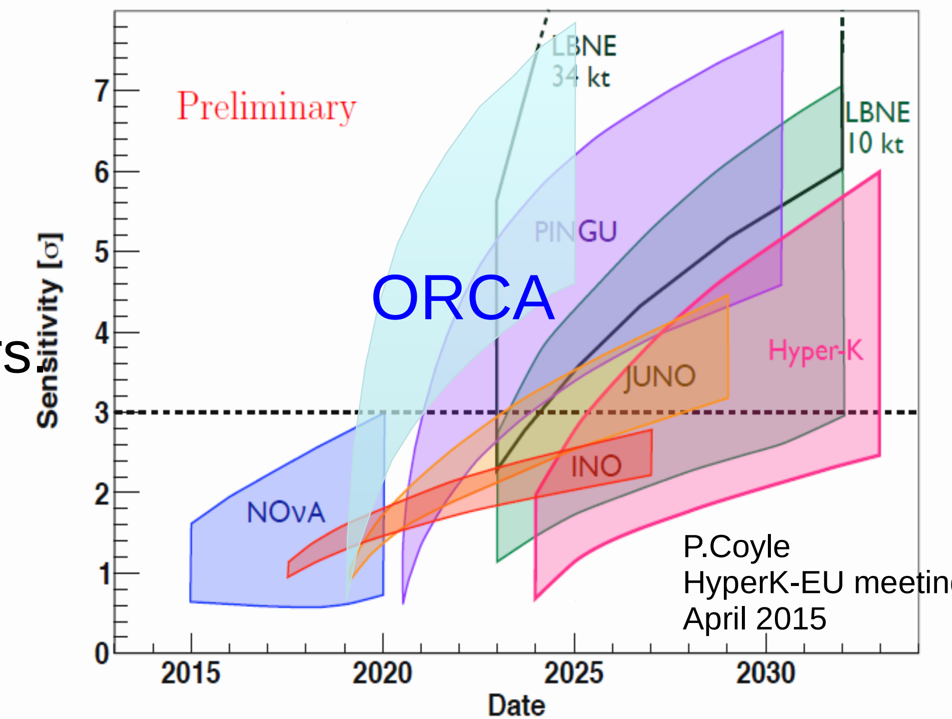
Other projections assume worst case pars

LBNE from LBNE-doc-8087-V10

PINGU from DeYoung, April 2014

ORCA from P Coyle, April 2015

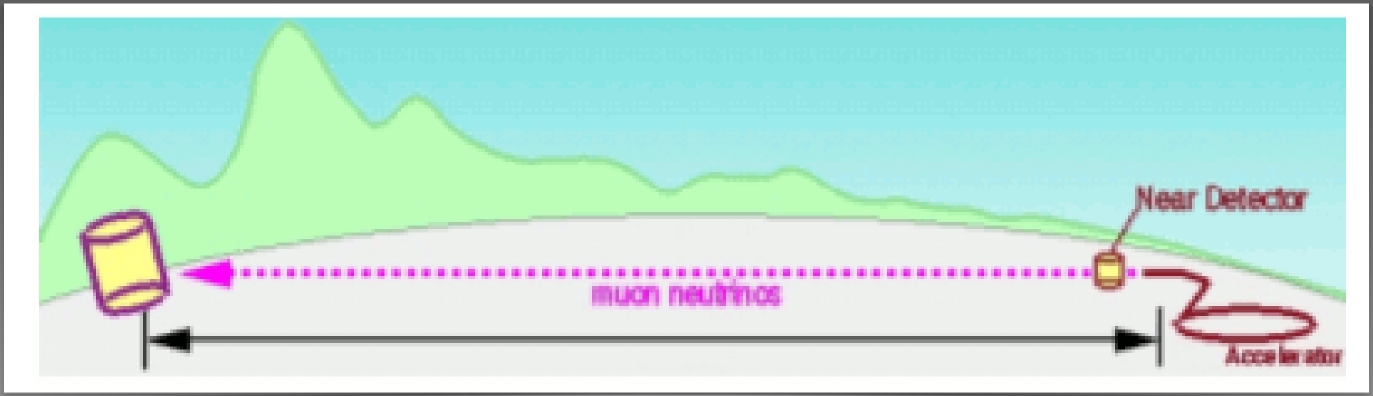
Others M. Blennow et al., JHEP 1403 (2014) 028.



Three approaches to mass hierarchy measurement. * see later slides

	Long Baseline Beam (e.g. NOvA, NOvA + T2K, DUNE, etc.)	Atmospherics (e.g. DUNE*, Hyper-K*, INO, ORCA, PINGU)	Reactor Long Baseline (e.g. Juno, RENO-50)
Benefit	Robust, clean signal	Predictable Timescale/cost	Independent technology
Risk (osc. params)	δ_{CP}, θ_{23}	θ_{23}	-
Challenges	Timescale	Energy res, directional res, particle ID	Energy resolution

LBN Experiments



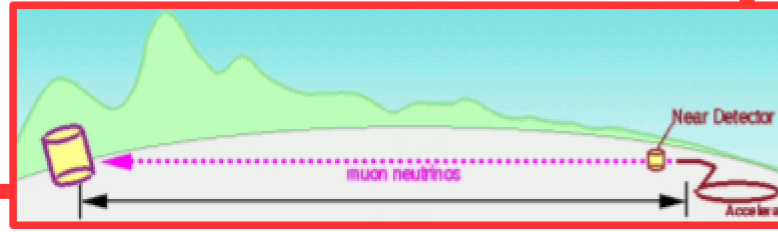
$\nu_\mu \rightarrow \nu_e$ Probability

ν_μ and anti(ν_μ) beams produced @ accelerators

BASELINE
- L ~300 Km - 1300 Km (depending on the experiment)

ENERGY
- E between ~0.6 GeV^{-20} GeV

E/L ~ 10^{-3}eV^2



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- ν_e appearance: sensitive to θ_{13} + $(\Delta m^2)_{23}$+ θ_{23}
- ν_μ disappearance: sensitive to $(\Delta m^2)_{23}$+ θ_{23}
- ν_τ appearance: sensitive to $(\Delta m^2)_{23}$+ θ_{23}
- Sensitivity also for θ_{23} octant, δ_{CP}, mass hierarchy

$\nu_\mu \rightarrow \nu_e$ Probability

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

$$P(\nu_\mu \rightarrow \nu_e) = 4c_{13}^2 s_{13}^2 s_{23}^2 \cdot \sin^2 \Delta_{31}$$ Leading term θ_{13}

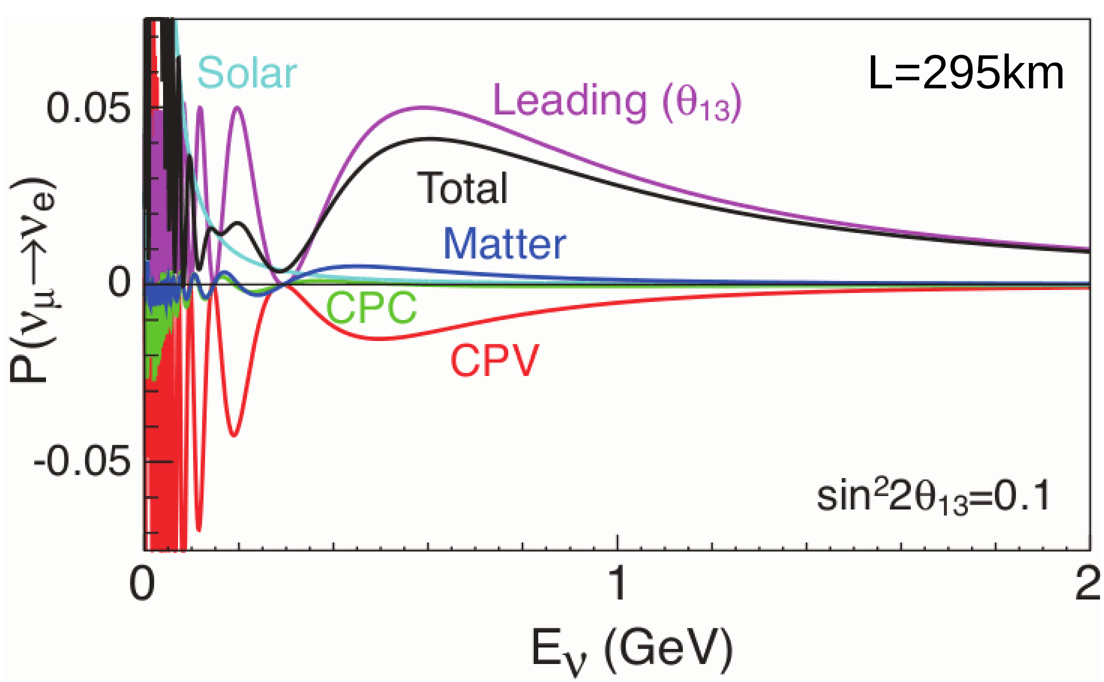
CP conserving $$+8c_{13}^2 s_{12} s_{13} s_{23}(c_{12}c_{23}\cos\delta_{CP} - s_{12}s_{13}s_{23}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21}$$

CP violating ($\delta \rightarrow -\delta$ for $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$) $$-8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin\delta_{CP} \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21}$$

Solar $$+4s_{12}^2 c_{13}^2 (c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta_{CP}) \cdot \sin^2\Delta_{21}$$

Matter $$-8c_{13}^2 s_{13}^2 s_{23}^2 \cdot \frac{aL}{4E_\nu}(1-2s_{13}^2) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31}$$
$$+8c_{13}^2 s_{13}^2 s_{23}^2 \frac{a}{\Delta m_{31}^2}(1-2s_{13}^2) \cdot \sin^2\Delta_{31}, \qquad (7)$$

where Δ_{ij} is $\Delta m_{ij}^2 L/4E_\nu$, and $a = 2\sqrt{2}G_F n_e E_\nu = 7.56 \times 10^{-5}[\mathrm{eV}^2] \times \rho[\mathrm{g/cm}^3] \times E_\nu[\mathrm{GeV}]$.



Leading Term μ $\sin^2 2\theta_{13}$

CPV Term μ $\sin 2\theta_{13}$

Matter Effect μ $\sin^2 2\theta_{13}$

For large $\sin^2 2\theta_{13}$:

Signal ↑, CP Asymmetry ↓,

Matter/CP ↑

$\nu_\mu \rightarrow \nu_e$ Probability

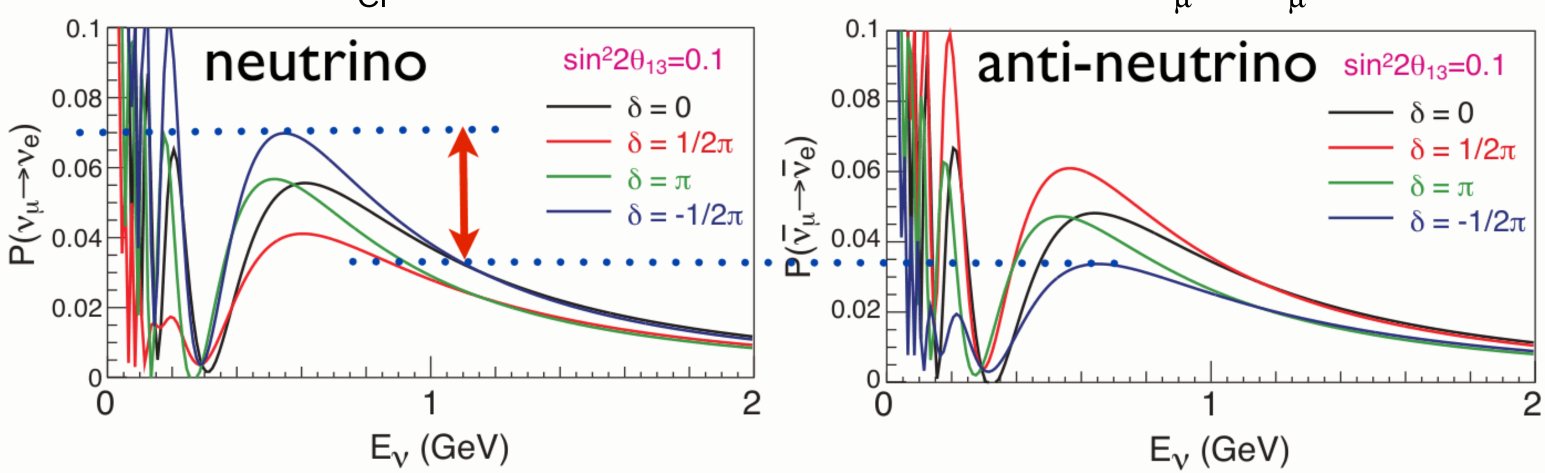
$$
\begin{aligned}
P(\nu_\mu \rightarrow \nu_e) \;=\;& 4c_{13}^2 s_{13}^2 s_{23}^2 \cdot \sin^2\Delta_{31} && \text{Leading term } \theta_{13} \\
\text{CP conserving} \quad & +8c_{13}^2 s_{12} s_{13} s_{23} (c_{12}c_{23}\cos\delta_{CP} - s_{12}s_{13}s_{23}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
\text{CP violating} \quad & -8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin\delta_{CP} \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
\text{Solar} \quad & +4s_{12}^2 c_{13}^2 (c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta_{CP}) \cdot \sin^2\Delta_{21} \\
\text{Matter} \quad & -8c_{13}^2 s_{13}^2 s_{23}^2 \cdot \frac{aL}{4E_\nu}(1-2s_{13}^2) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \\
& +8c_{13}^2 s_{13}^2 s_{23}^2 \frac{a}{\Delta m_{31}^2}(1-2s_{13}^2) \cdot \sin^2\Delta_{31}, \qquad (7)
\end{aligned}
$$

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

$\delta \rightarrow -\delta$ for $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

where Δ_{ij} is $\Delta m_{ij}^2 L/4E_\nu$, and $a = 2\sqrt{2}G_F n_e E_\nu = 7.56 \times 10^{-5}[\mathrm{eV}^2] \times \rho[\mathrm{g/cm}^3] \times E_\nu[\mathrm{GeV}]$.

Sensitivity to δ_{CP} greatly improved by running in ν_μ & $\bar{\nu}_\mu$ modes:



BUT: a $\nu_\mu/\bar{\nu}_\mu$ asymmetry is induced both by CPV and matter effect (both δ_{CP} and a change sign going from ν to $\bar{\nu}$) ;

- ALSO: the matter terms depend on Mass Hierarchy=> complicated interplay with δ_{CP}

Difference $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ as large as ~±25% at nominal (δ=0)

$\nu_\mu \rightarrow \nu_e$ Probability

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

$$P(\nu_\mu \to \nu_e) = 4c_{13}^2 s_{13}^2 s_{23}^2 \cdot \sin^2\Delta_{31}$$ Leading term θ_{13}

CP conserving $$+8c_{13}^2 s_{12}s_{13}s_{23}(c_{12}c_{23}\cos\delta_{CP} - s_{12}s_{13}s_{23}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21}$$

CP violating ($\delta \to -\delta$ for $P(\bar{\nu}_\mu \to \bar{\nu}_e)$) $$-8c_{13}^2 c_{12}c_{23}s_{12}s_{13}s_{23}\sin\delta_{CP} \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21}$$

Solar $$+4s_{12}^2 c_{13}^2(c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta_{CP}) \cdot \sin^2\Delta_{21}$$

Matter $$-8c_{13}^2 s_{13}^2 s_{23}^2 \cdot \frac{aL}{4E_\nu}(1-2s_{13}^2) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31}$$
$$+8c_{13}^2 s_{13}^2 s_{23}^2 \frac{a}{\Delta m_{31}^2}(1-2s_{13}^2) \cdot \sin^2\Delta_{31}, \quad (7)$$

where Δ_{ij} is $\Delta m_{ij}^2 L/4E_\nu$, and $a = 2\sqrt{2}G_F n_e E_\nu = 7.56 \times 10^{-5}[\mathrm{eV}^2] \times \rho[\mathrm{g/cm}^3] \times E_\nu[\mathrm{GeV}]$.

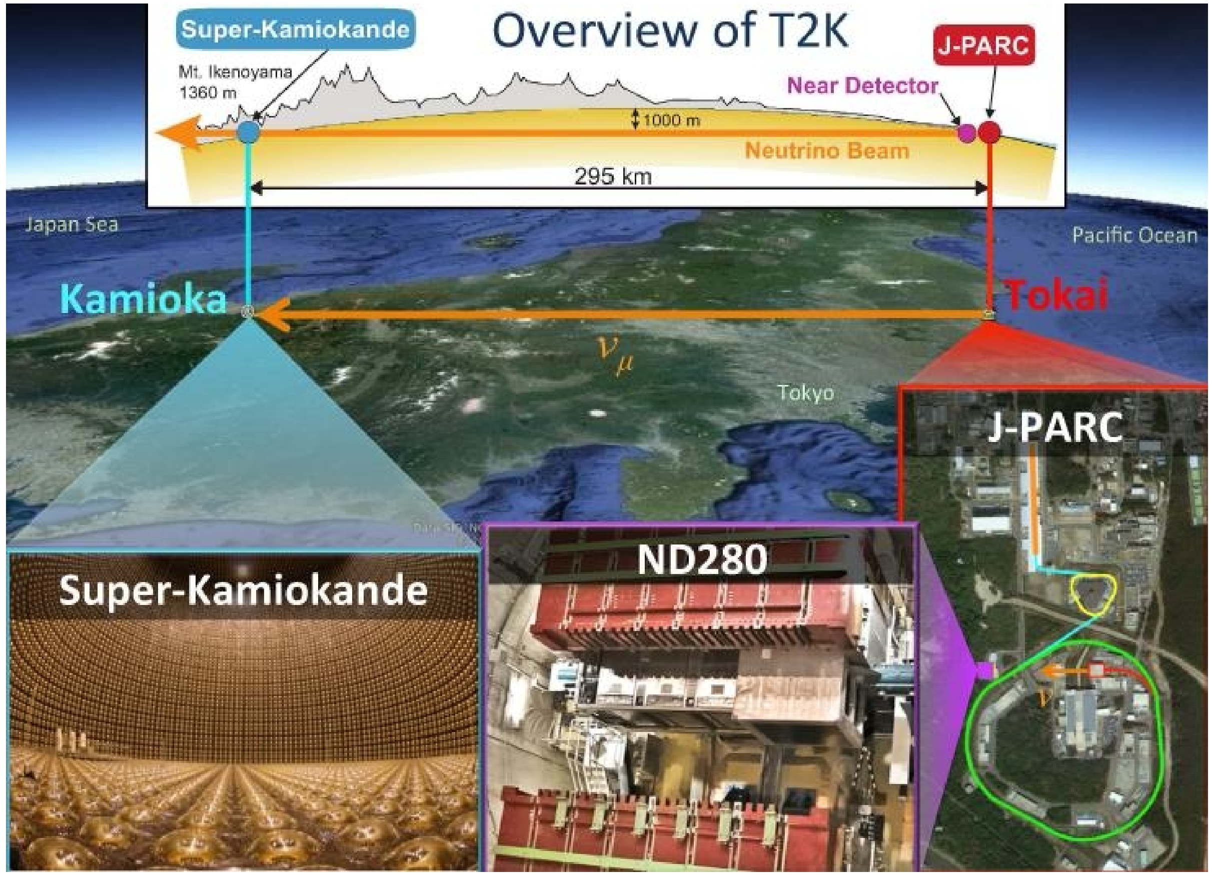
Combination with ν_μ disappearance helps constraining some of the parameters (for example, Δm^2_{23} and θ_{23})

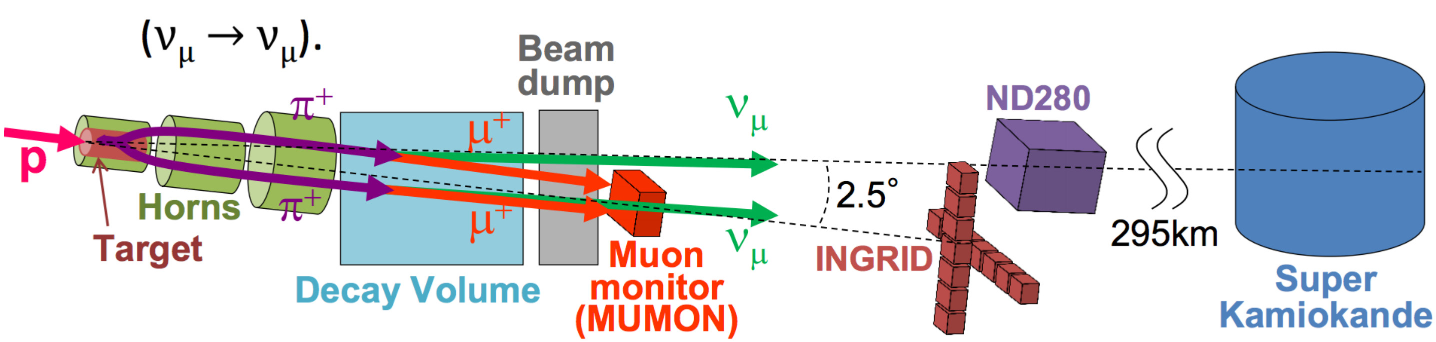
$$P(\nu_\mu \to \nu_\mu) \simeq 1 - 4\cos^2(\theta_{13})\sin^2(\theta_{23})[1-\cos^2(\theta_{13}) \times \sin^2(\theta_{23})]\sin^2(1.267\Delta m^2 L/E_\nu),$$

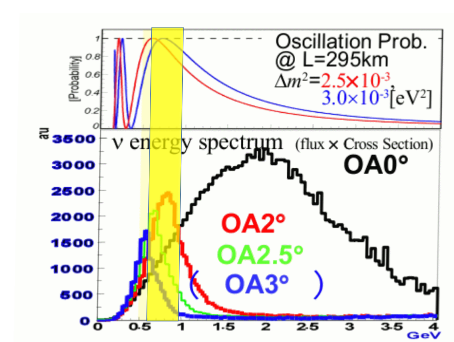
Long Baseline Experiments

Experiment	Status	E_ν (GeV)	L (Km)	E/L (eV^2)	ν beam	ν type
T2K	Running	0.6	295	$2x10^{-3}$	KEK J-PARC	ν_μ /anti-ν_μ
MINOS	Completed	2	735	$2.5x10^{-3}$	Fermilab NuMI	ν_μ /anti-ν_μ
MINOS$^+$	Running	5	735	$6.8x10^{-3}$	Fermilab NuMI	ν_μ /anti-ν_μ
NOVA	Running	2	810	$2.5x10^{-3}$	Fermilab NuMI	ν_μ /anti-ν_μ
OPERA	Completed	17	730	$2.3x10^{-2}$	CERN CNGS	ν_μ
DUNE	Future	5	1300	$3.8x10^{-3}$	Fermilab newbeam	ν_μ /anti-ν_μ
HYPERK	Future	0.6	295	$2x10^{-3}$	KEK J-PARC (improved)	ν_μ /anti-ν_μ

Oscillation Searches at T2K



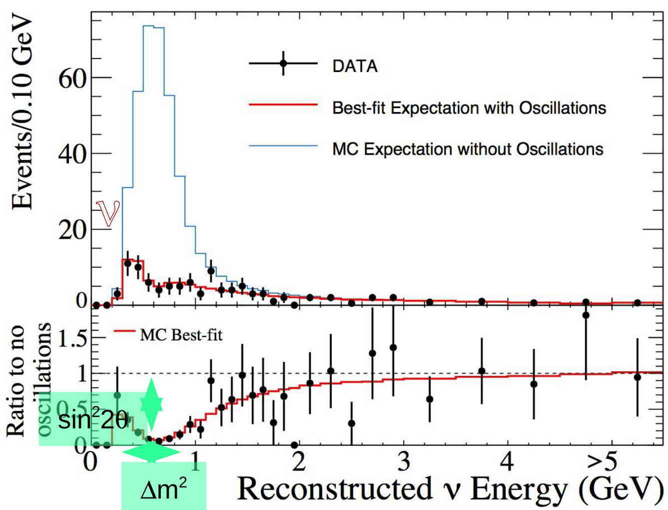




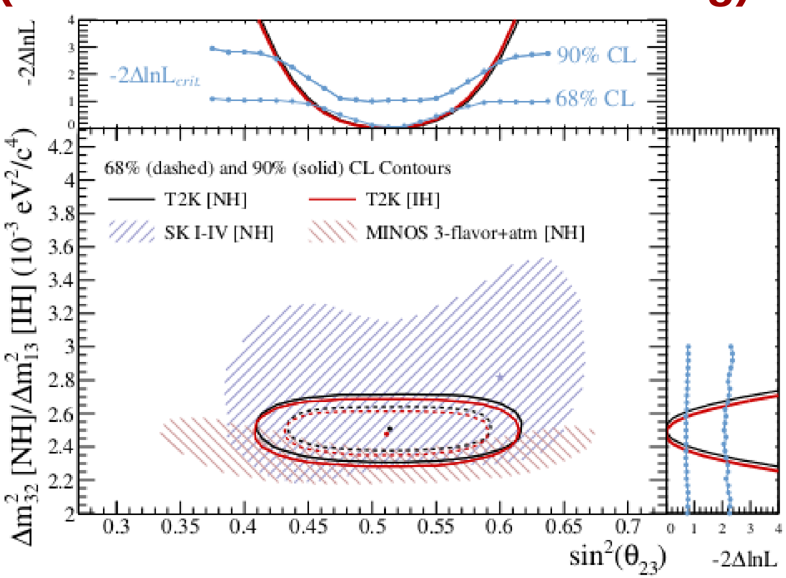
ν_e Appearance & ν_μ Disappearance

ν_μ disappearance

(arxiv:1403.1532)



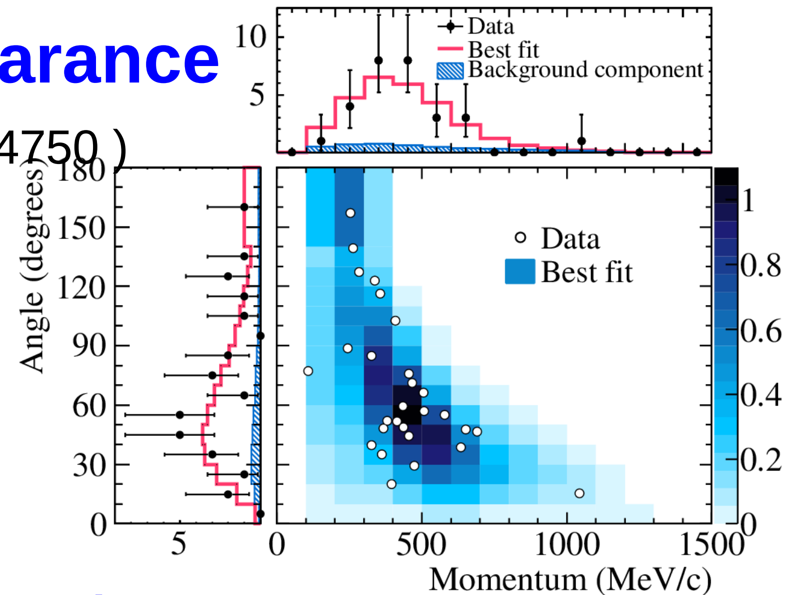
World's most precise θ_{23} determination (consistent with maximal mixing)



ν_e appearance

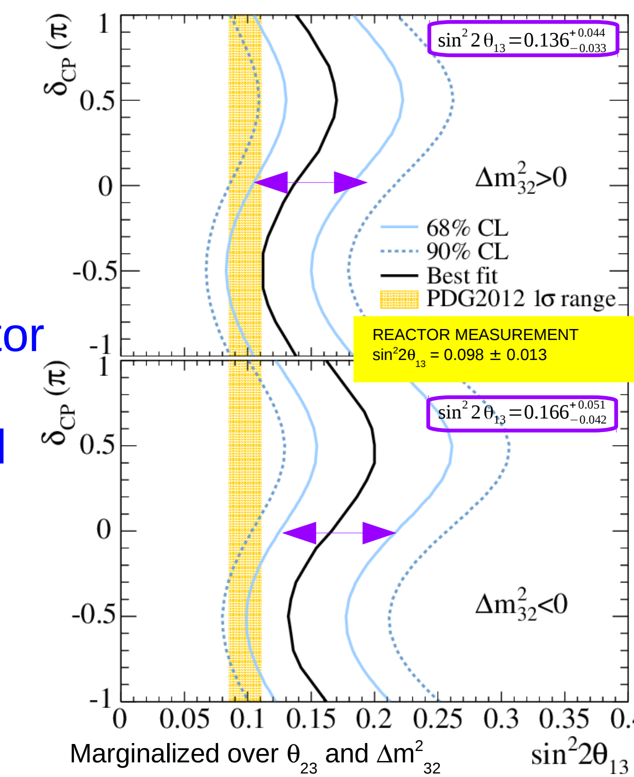
(arXiv:1311.4750)

Maximum likelihood fit in (p_e,θ_e)



$\theta_{13} \neq 0$ confirmed at 7.3σ.

Due to δ_{CP}-$\sin^2\theta_{13}$ correlation, when applying the reactor constraint, region with $\sin^2 2\theta_{13}$ small as possible is favoured.



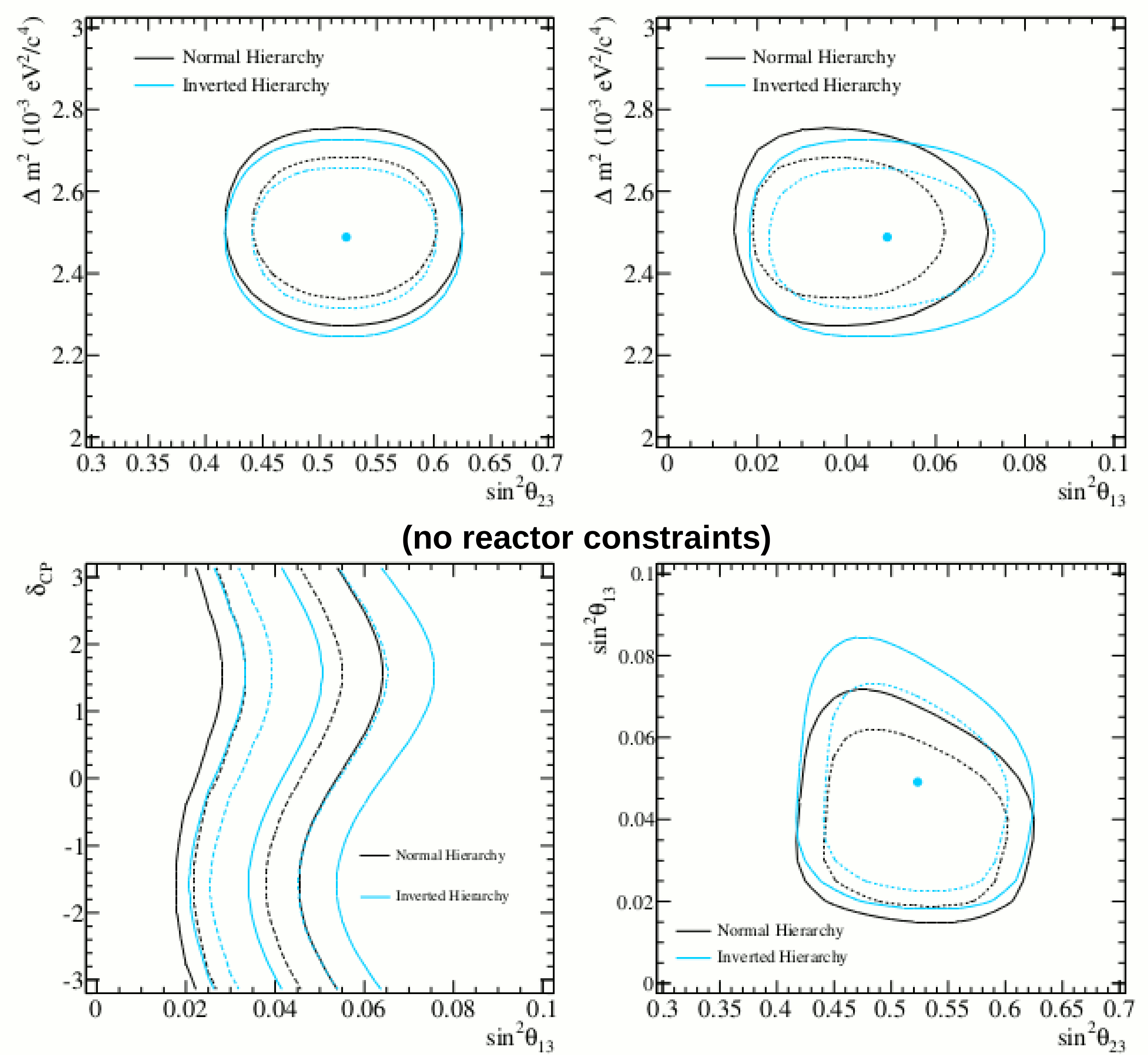
T2K Joint Results

Combined appearance + disappearance analysis!

[arXiv:1502.01550]
2010-2013 data runs:
10% of total expected data

Simultaneous ν_e and ν_μ fit under a three flavour oscillation hypothesis: vary δ_{CP}, Δm^2_{23}, θ_{23}, θ_{13}. Frequentist approach.

- Maximal θ_{23}.
- Larger θ_{13} than reactors.
- Negligible χ^2 for mass hierarchy.



T2K Joint Results

Combined appearance + disappearance analysis!

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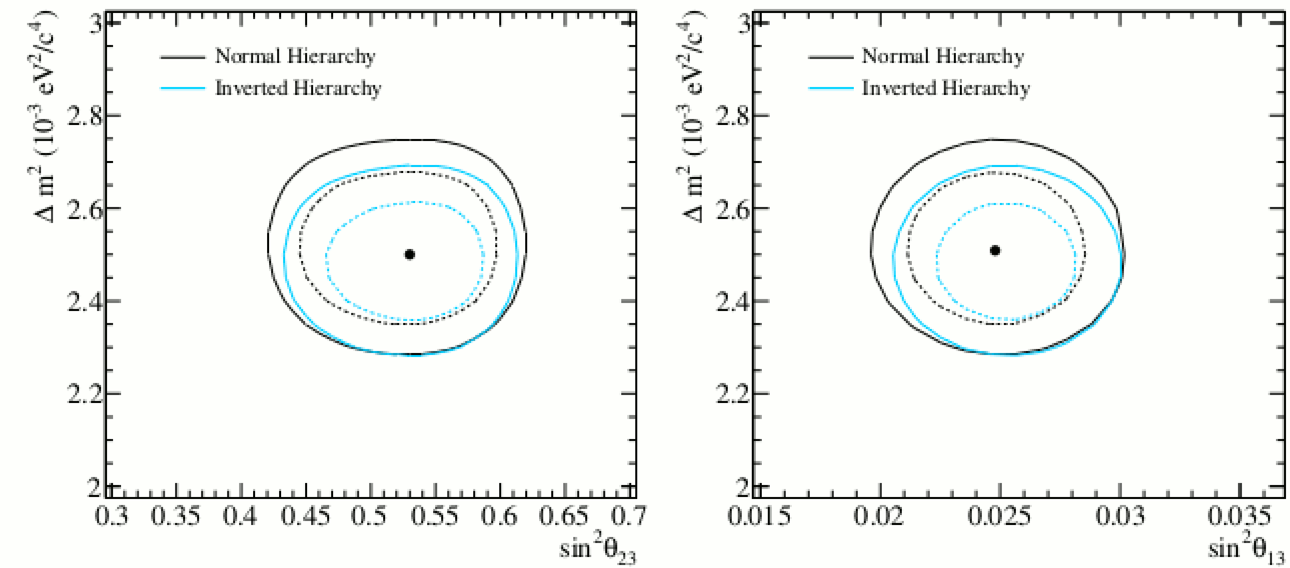
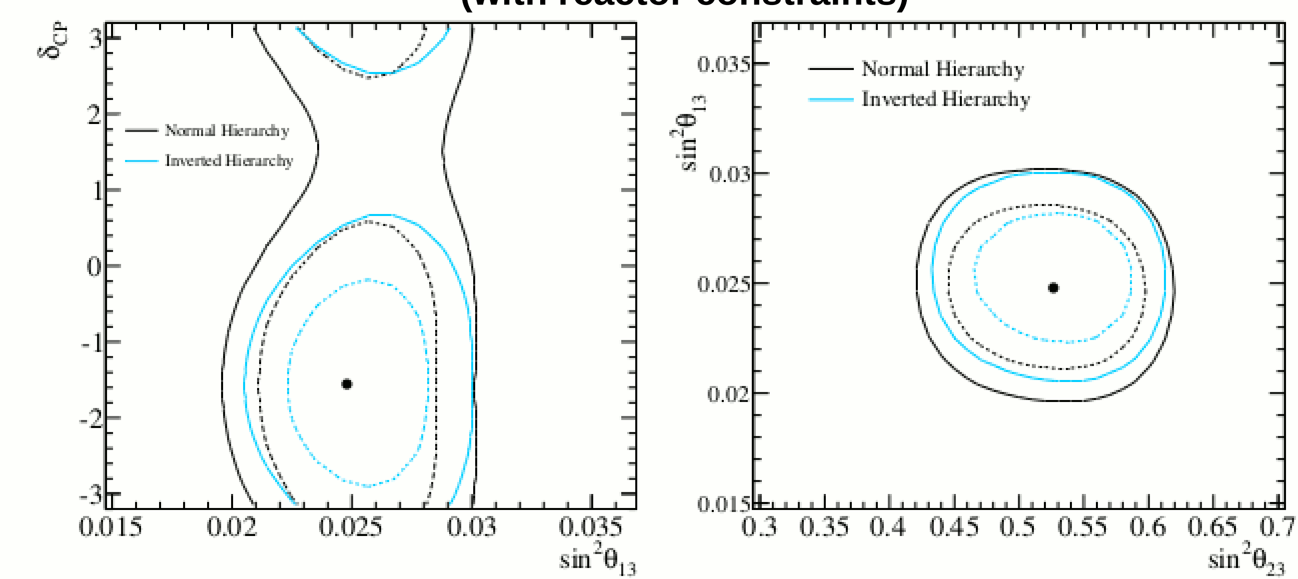
2010-2013 data runs:
10% of total expected data

Simultaneous ν_e and ν_μ fit under a three flavour oscillation hypothesis: vary δ_{CP}, Δm^2_{23}, θ_{23}, θ_{13}. Frequentist approach.

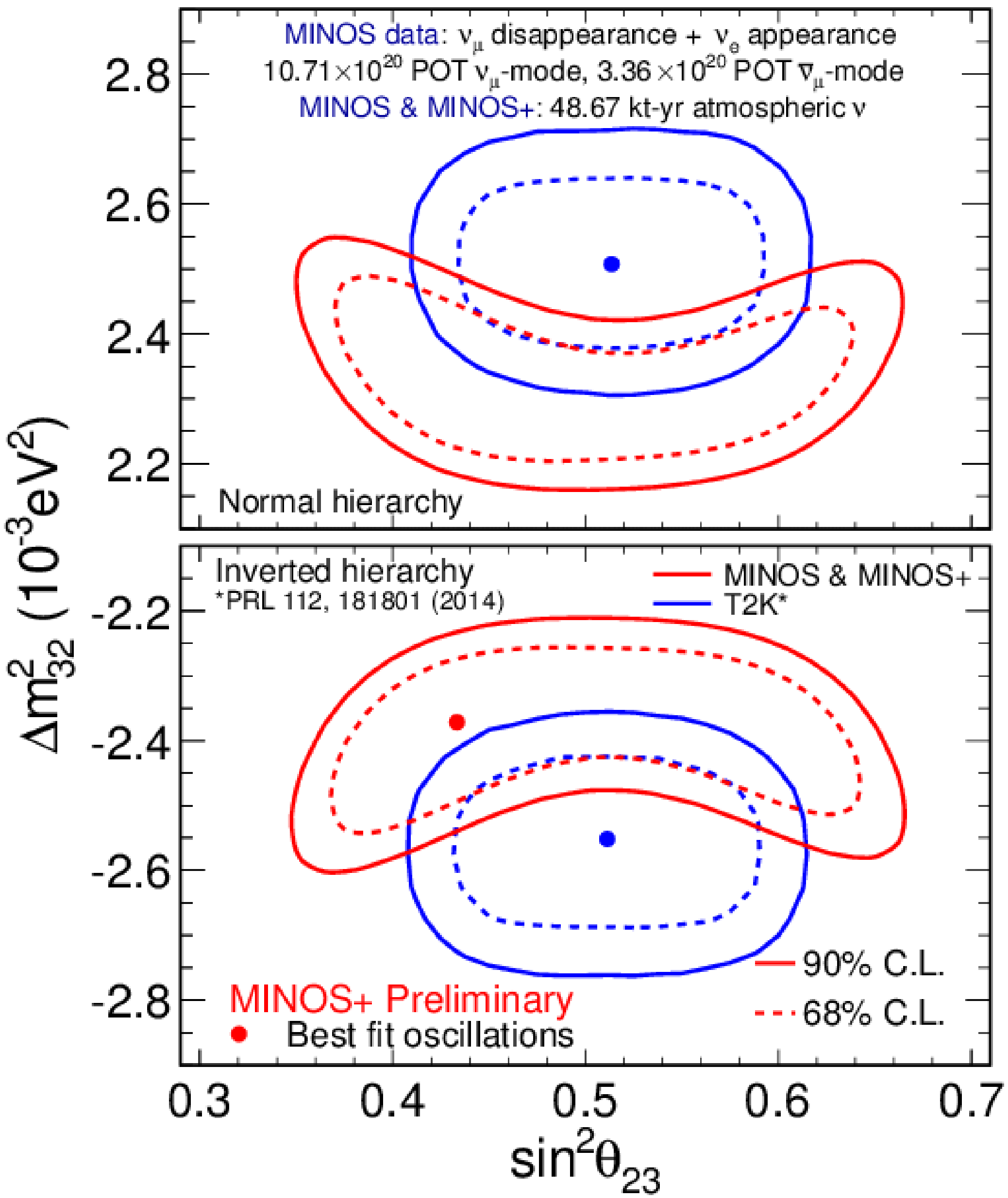
Combined with reactor experiments: hints towards $\delta_{CP} = -\pi/2$



(with reactor constraints)



MINOS/MINOS+ Results



[arXiv:1502.07715]
New results from a three-flavour combined disappearance and appearance analysis,
Beam and atmospheric neutrino data.

Best fit (IH):

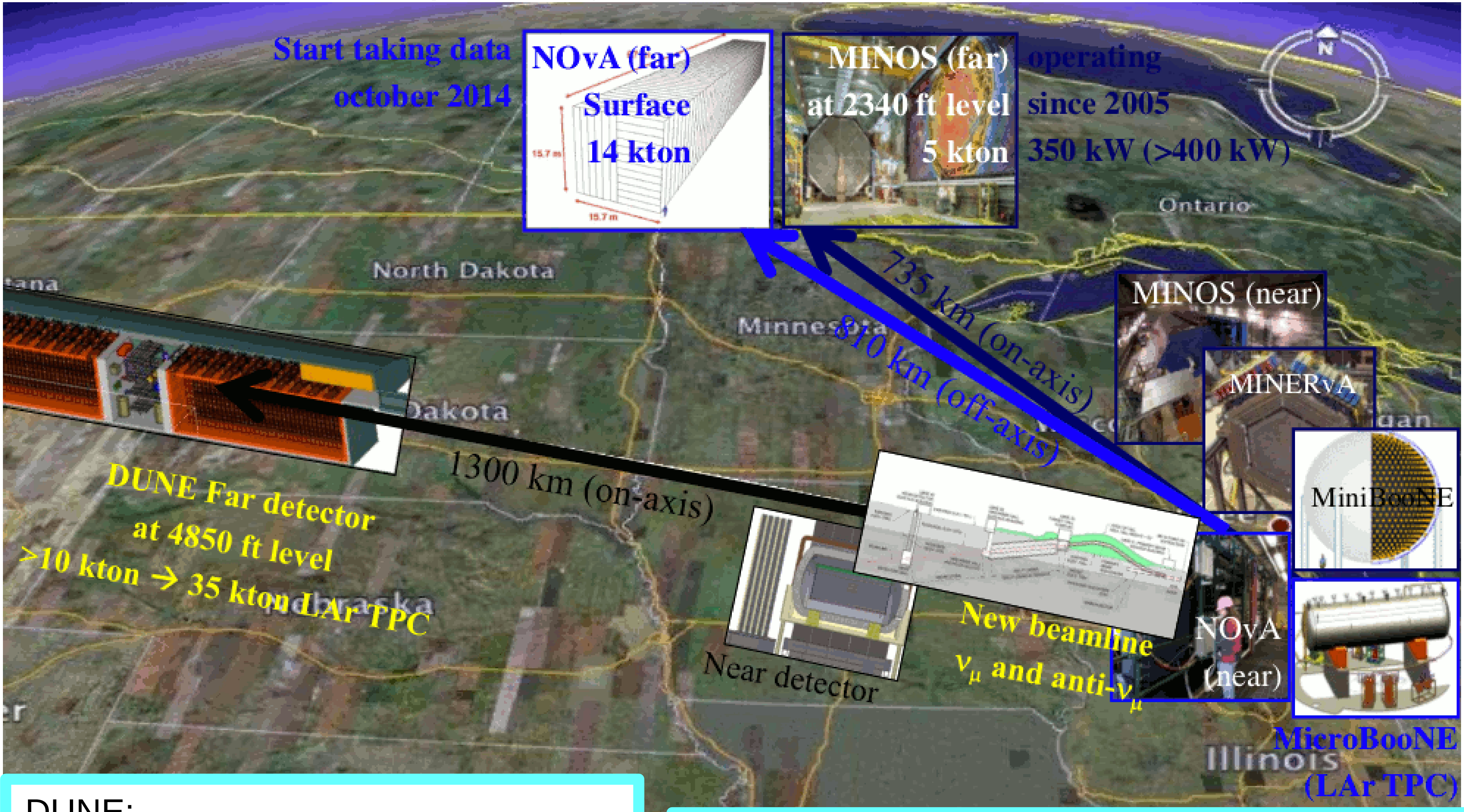
$$\sin^2 2\theta_{23} = 0.43^{+0.19}_{-0.05}$$

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

- **Most precise $|\Delta m^2_{23}|$ measurement.**
- Consistent with maximal mixing.
- Marginal preference for IH and lower octant of θ_{23}

DUNE

Deep Underground Neutrino Experiment



DUNE:
40 kt LAr-TPC Far Detector (1300 km baseline)
- Near Detector systems
- Science collaboration

LBNF (Long-baseline Neutrino Facility)
- 1.2 MW wide-band ν beam, upgradable to 2.4 MW
- Conventional facilities at Fermilab and SURF
- Cryostats and cryogenic systems at SURF

DUNE Scientific Strategy

Three main pillars

1) LBL Neutrino Physics

- CPV in the leptonic sector
- Mass Hierarchy
- Precision oscillation physics (θ_{23} octant, …)
- Testing 3-flavour paradigm

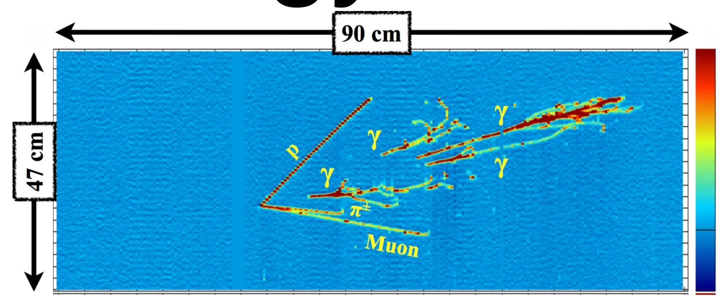
2) Nucleon Decay

- Targetting SUSY-favoured modes, e.g. $p \rightarrow K^+ \bar{\nu}$

3) Astro-particle Physics

- Core collapse super-nova, sensitivity to ν_e

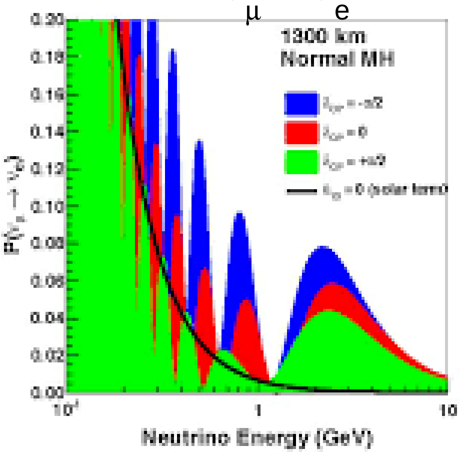
+ Precision neutrino physics in the near neutrino detector



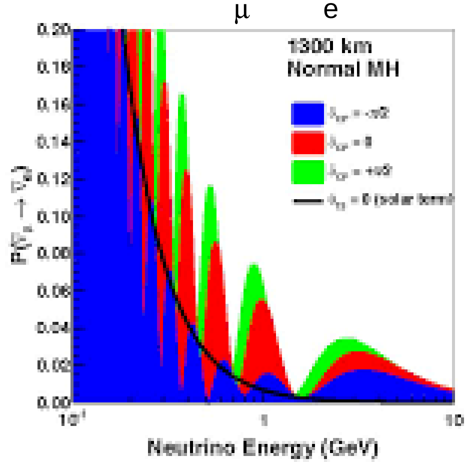
Example DIS event
(courtesy of ArgoNeuT collaboration)

22

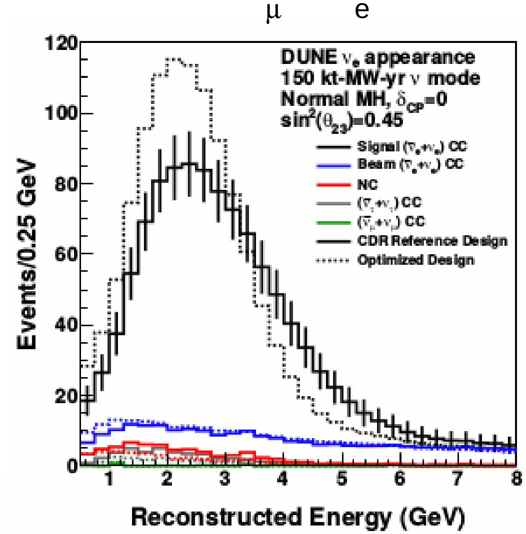
$\nu_\mu \rightarrow \nu_e$



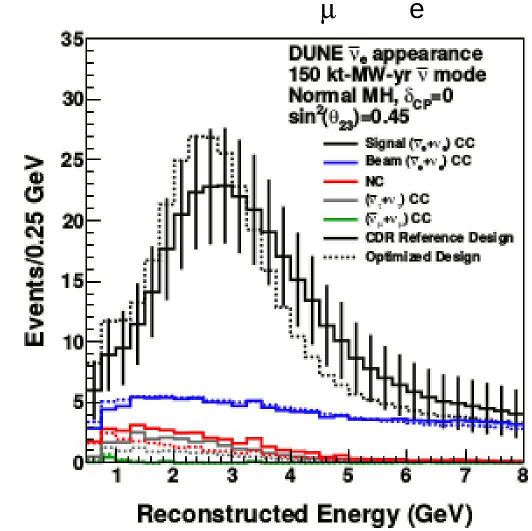
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$



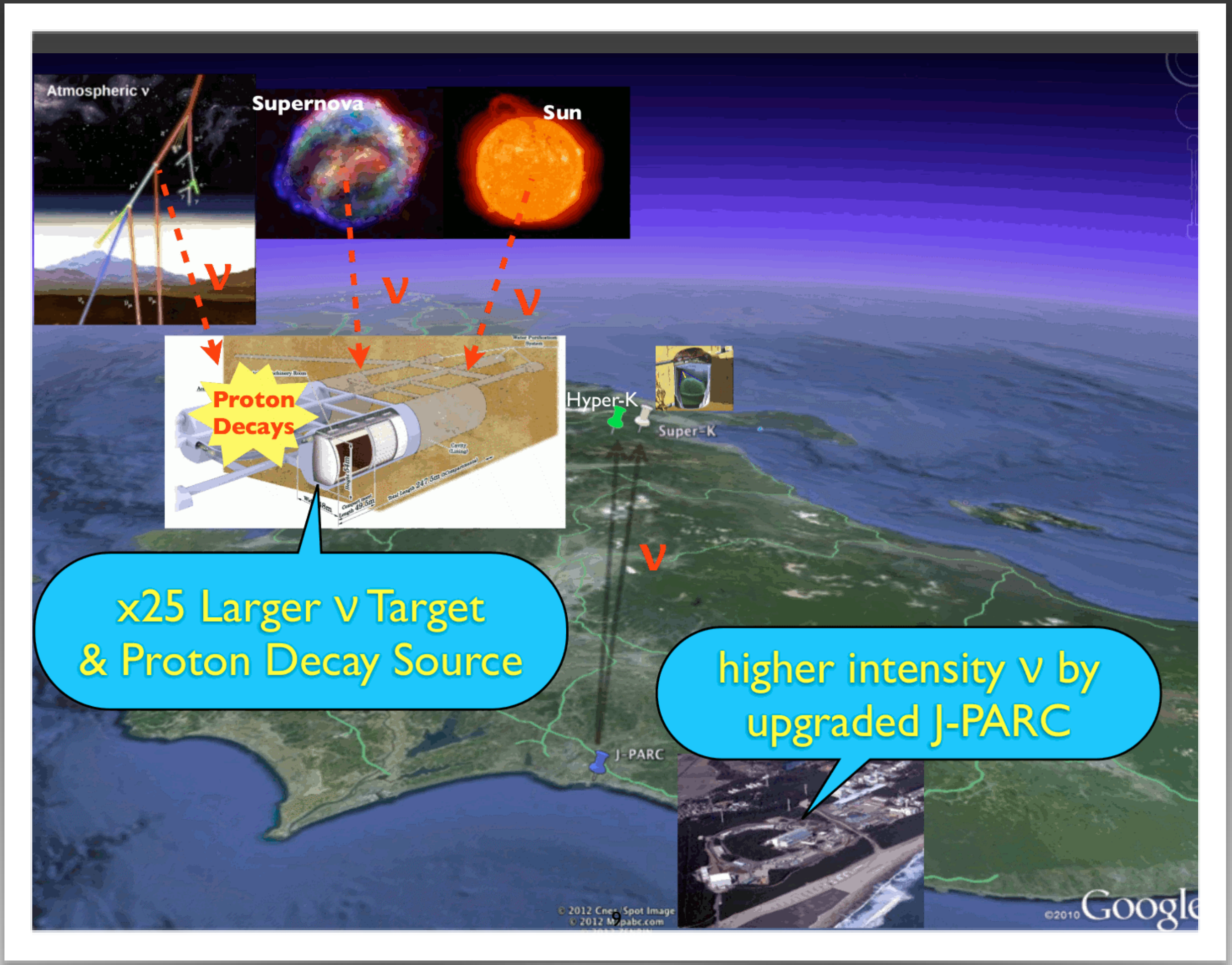
$\nu_\mu \rightarrow \nu_e$



$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$



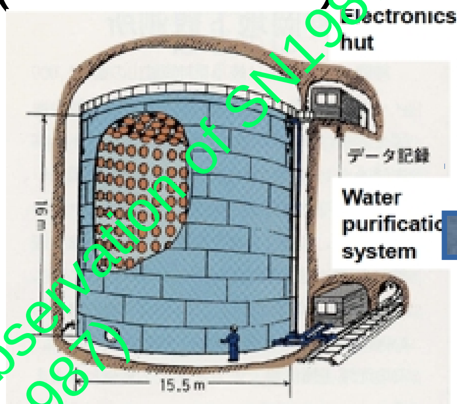
Hyper-Kamiokande



Kamiokande Evolution

Three generations of large Water Cherenkov in Kamioka

Kamiokande
(1983-1996)

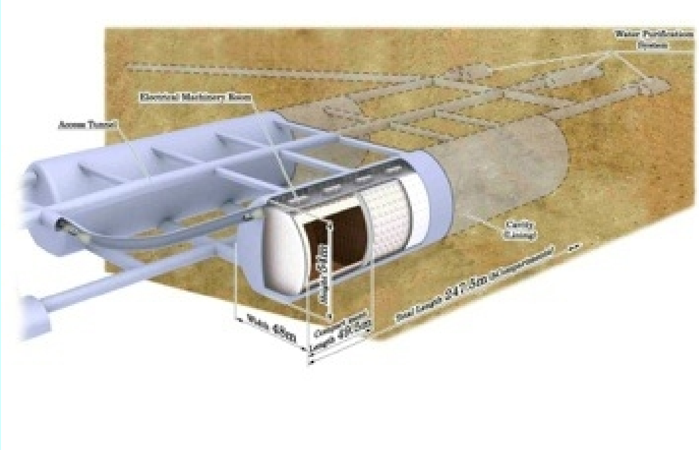


3kton

Super-Kamiokande
(1996-)

50kton

Hyper-Kamiokande
(202?-)



1Mton=1000kton

(560kton fiducial)

Observation of SN1987A
(1987)

Discovery of neutrino oscillation (1998)

Observation of electron neutrino appearance
(w/ beam, T2K, 2013)

x17

x20
(x25 fiducial mass)

Hyper-K Proto-Collaboration

Inaugural Symposium, Kashiwa, January 31, 2015

KEK-IPNS and UTokyo-ICRR
signed a MoU for cooperation
on the Hyper-Kamiokande project.

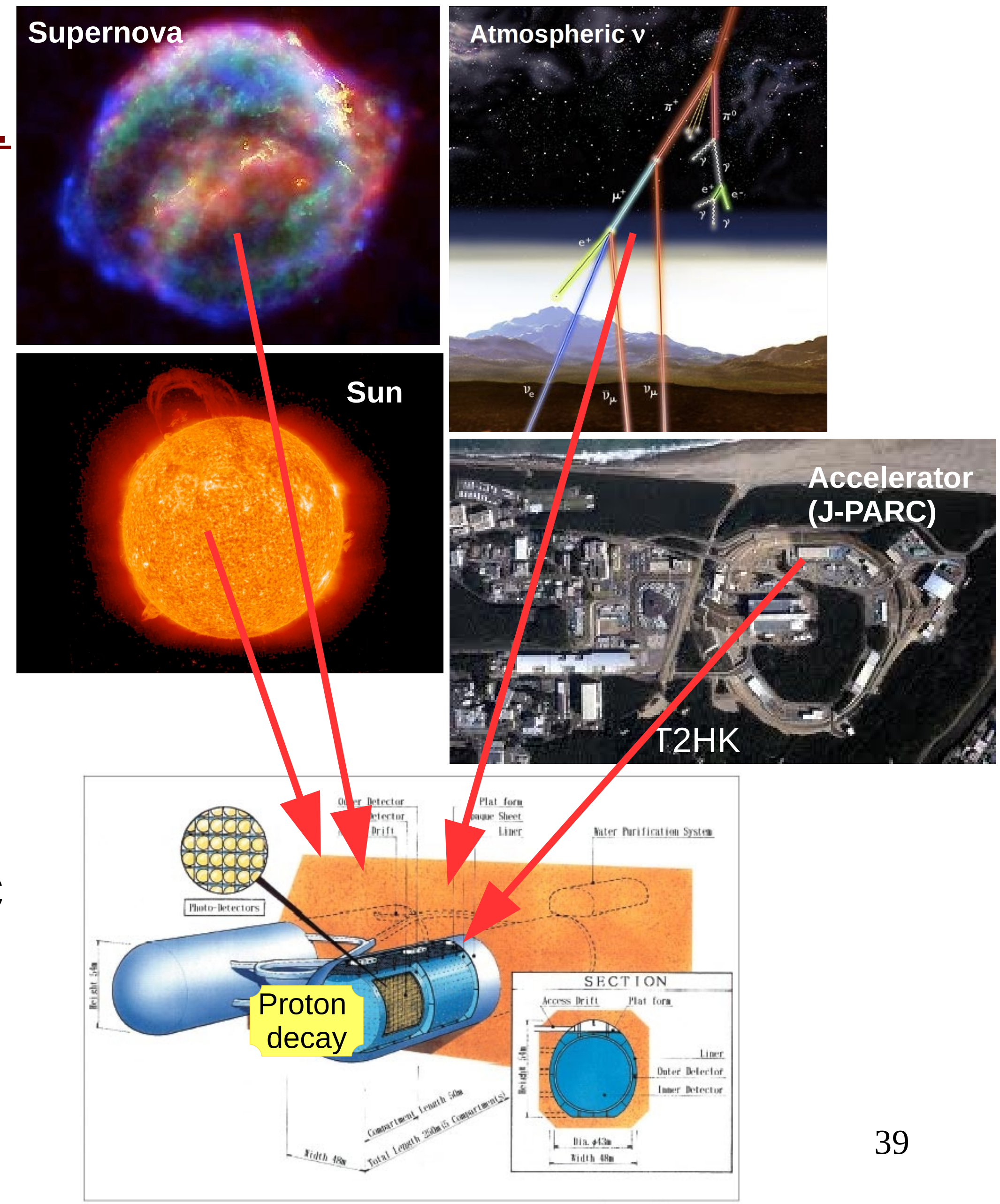
Important moment.
The proto-collaboration is born.

First Meeting of the proto-collaboration: June 29-July 1, @Kashiwa

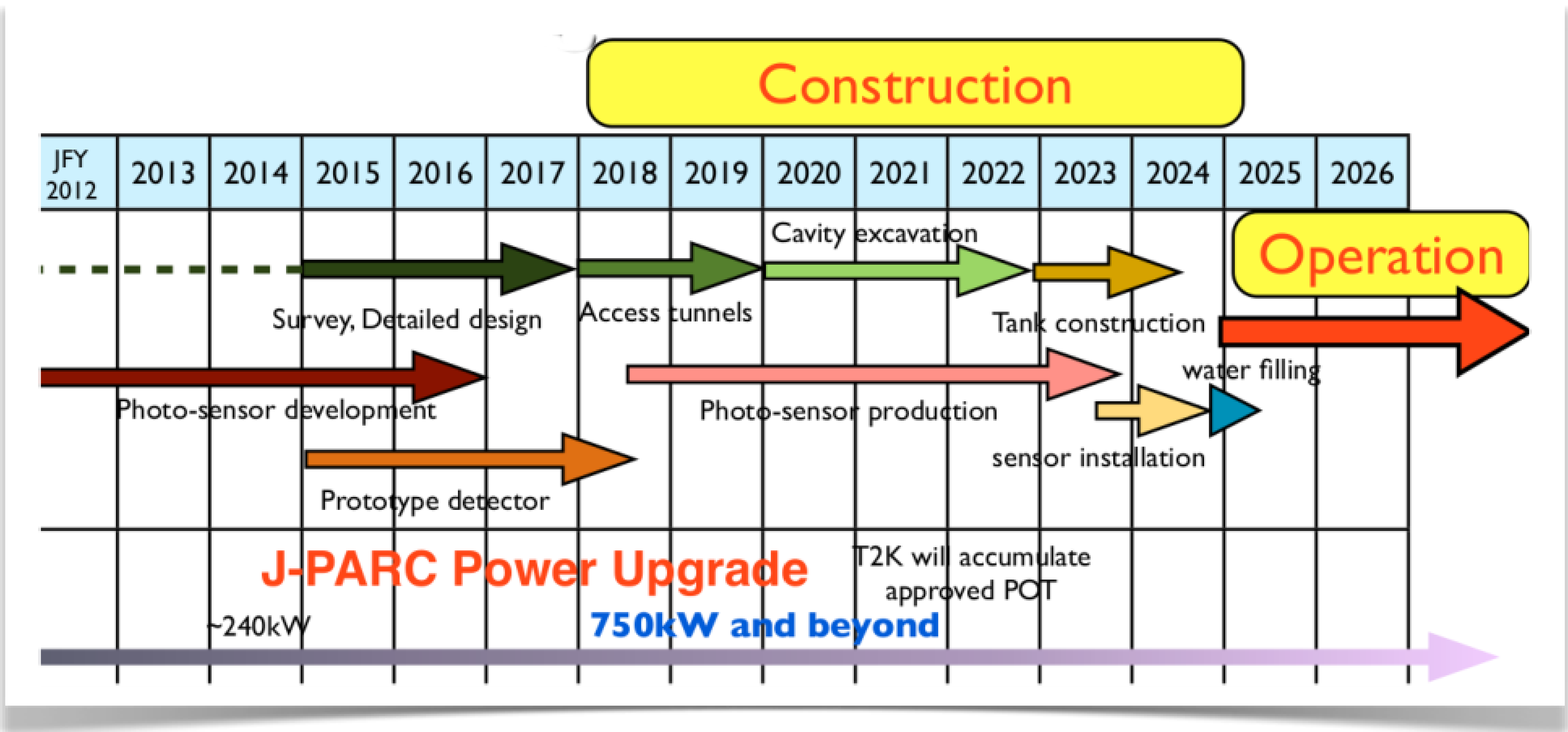
The Hyper-K Project

Multi-purpose neutrino experiment.
Wide-variety of scientific goals:

- Neutrino oscillations:
  - Neutrino beam from J-PARC
  - Atmospheric neutrinos
  - Solar neutrinos
- Search for proton decay
- Astrophysical neutrinos
(supernova bursts, supernova relic neutrinos, dark matter, solar flare, …)

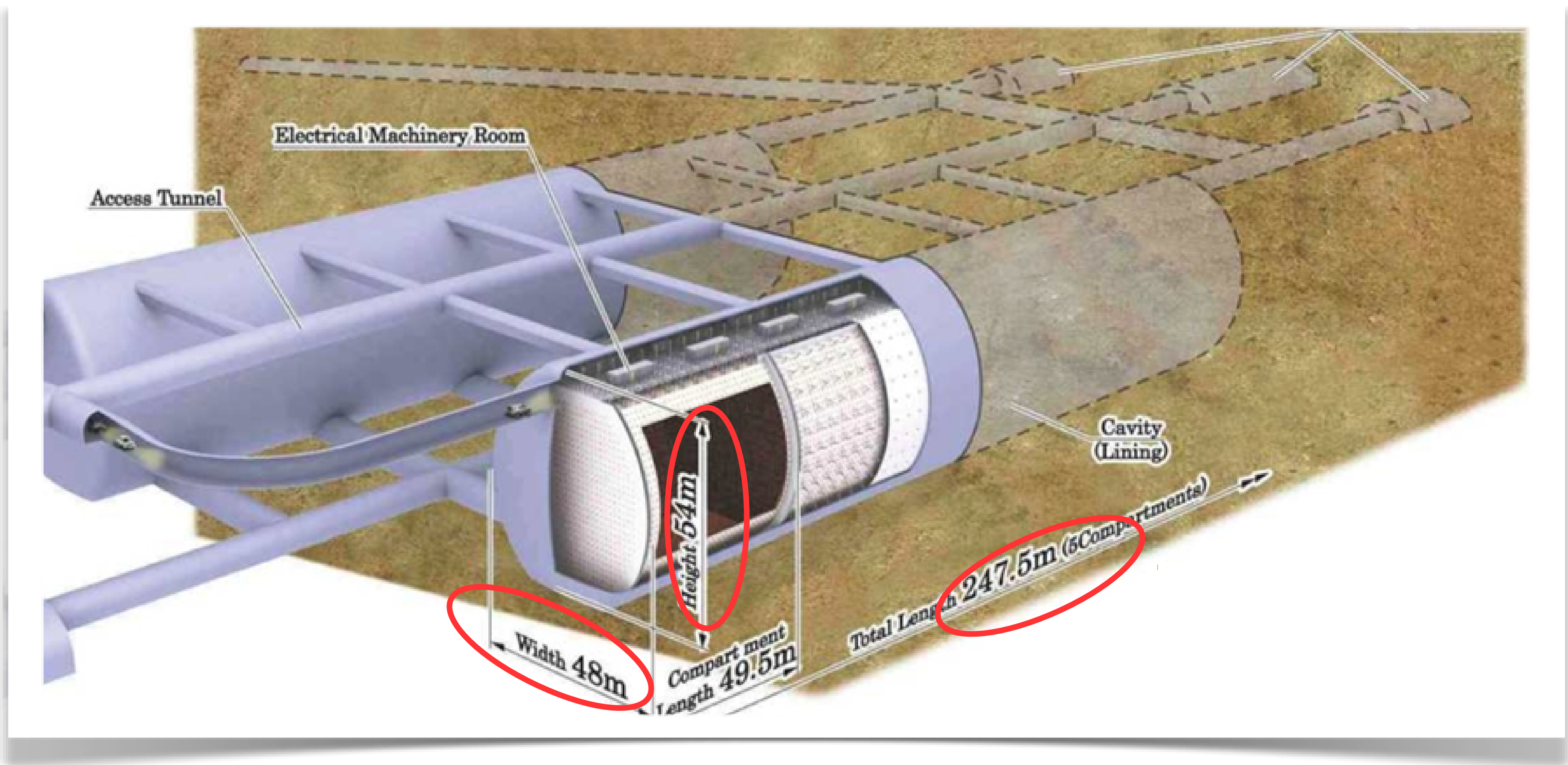


The Hyper-Kamiokande Timeline

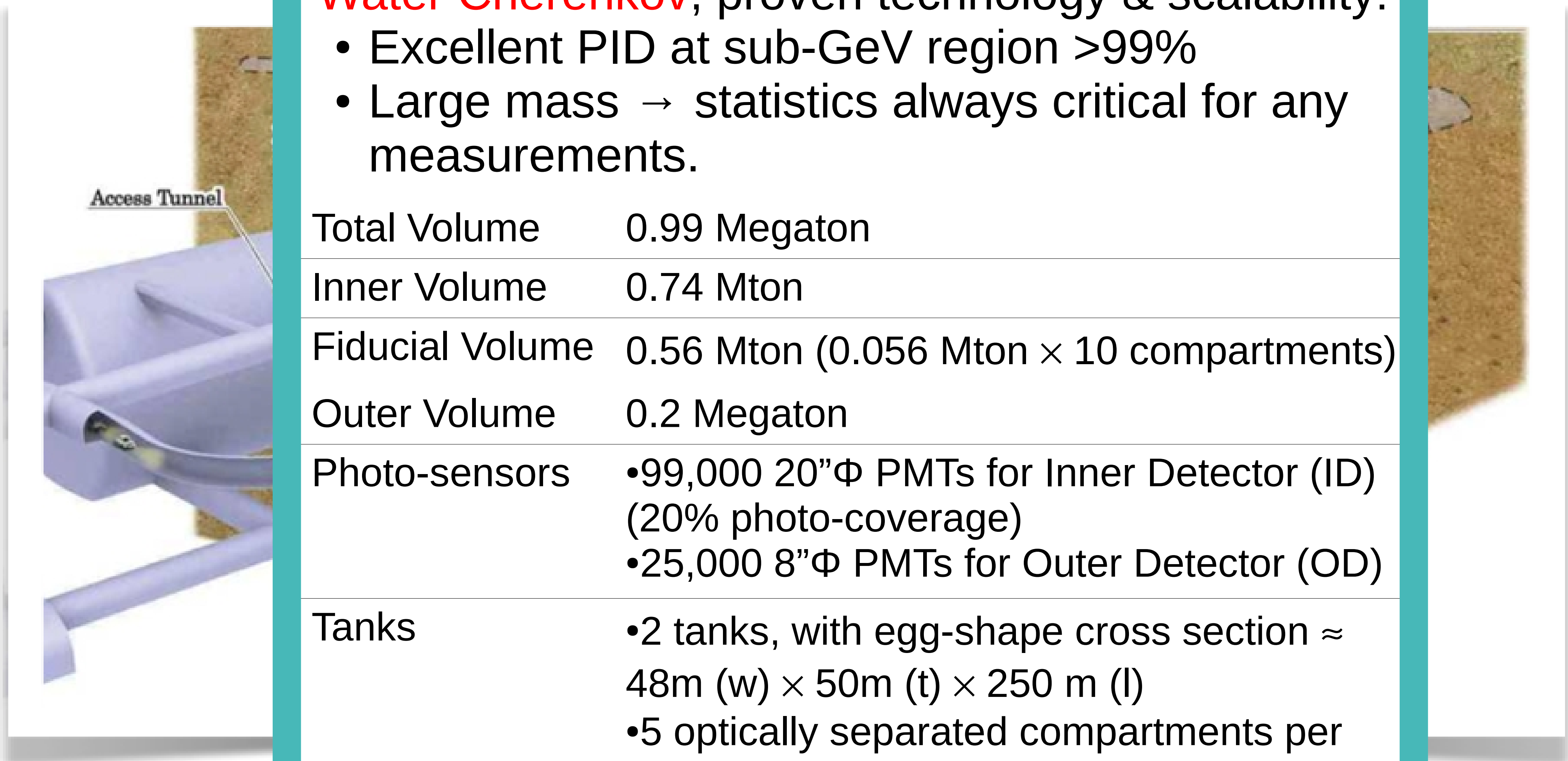


~2017 Major design decisions finalized
~2018 Construction starts
~2025 Data taking start
> 2025 Discoveries!

The Hyper-Kamiokande Detector



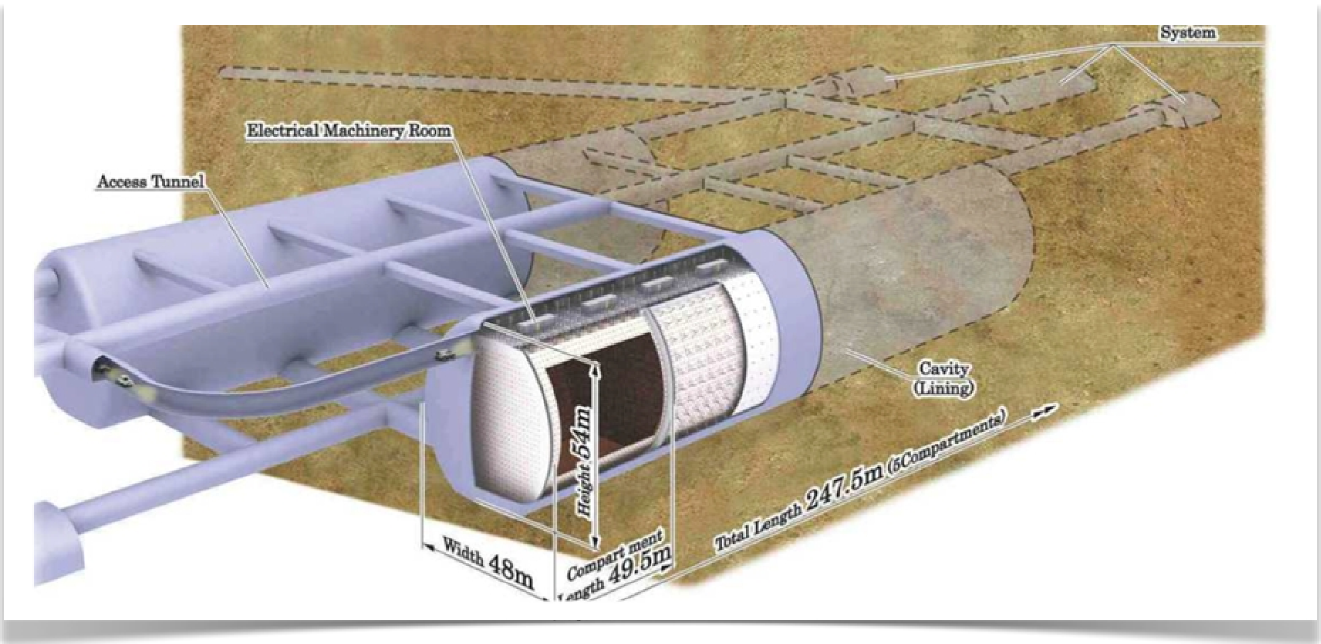
The Hyper-Kamiokande Detector

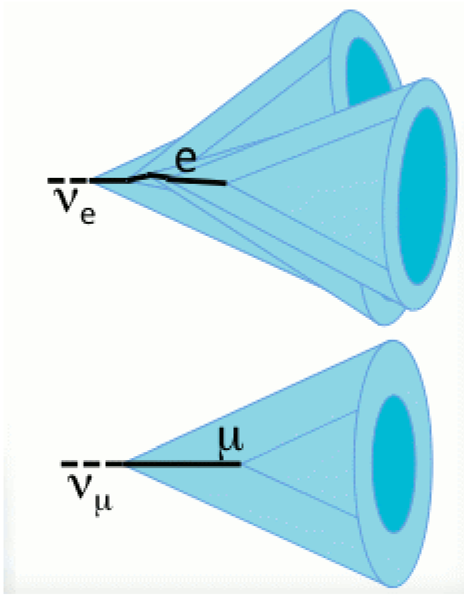


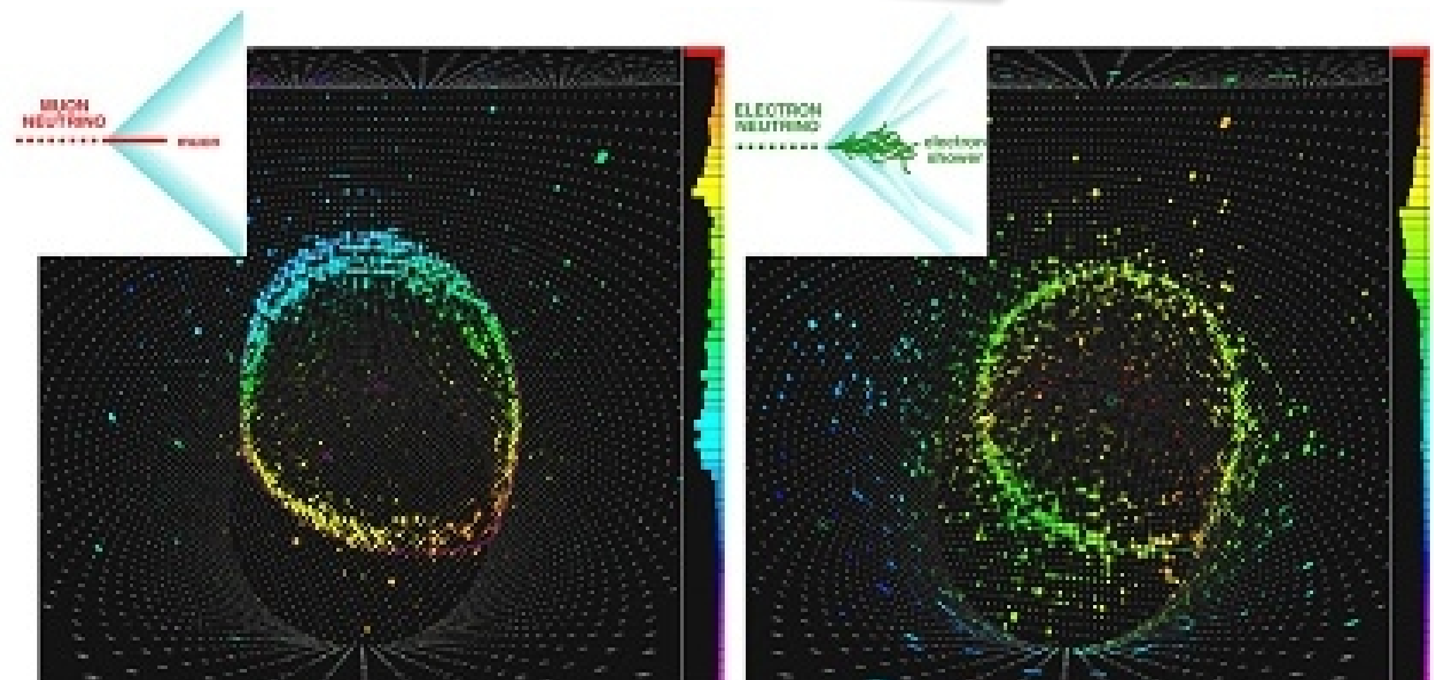
- Water Cherenkov, proven technology & scalability:
  - Excellent PID at sub-GeV region >99%
  - Large mass → statistics always critical for any measurements.

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 Detector (ID) (20% photo-coverage) •25,000 8”Φ PMTs for Outer Detector (OD)
Tanks	•2 tanks, with egg-shape cross section ≈ 48m (w) × 50m (t) × 250 m (l) •5 optically separated compartments per tank

The Hyper-Kamiokande Detector



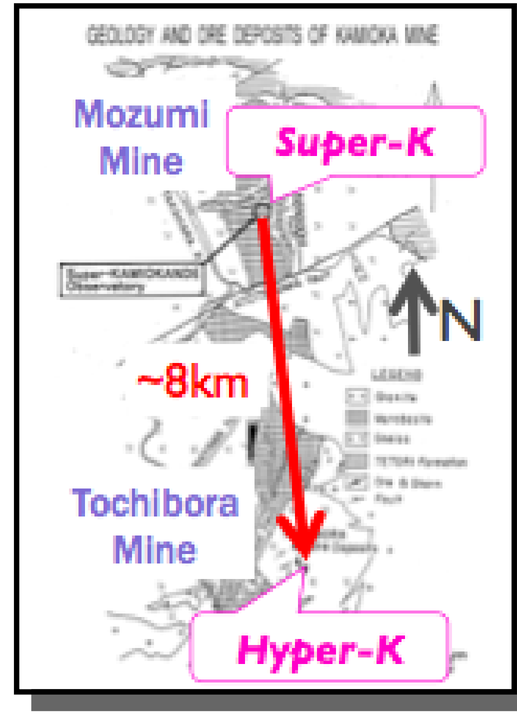


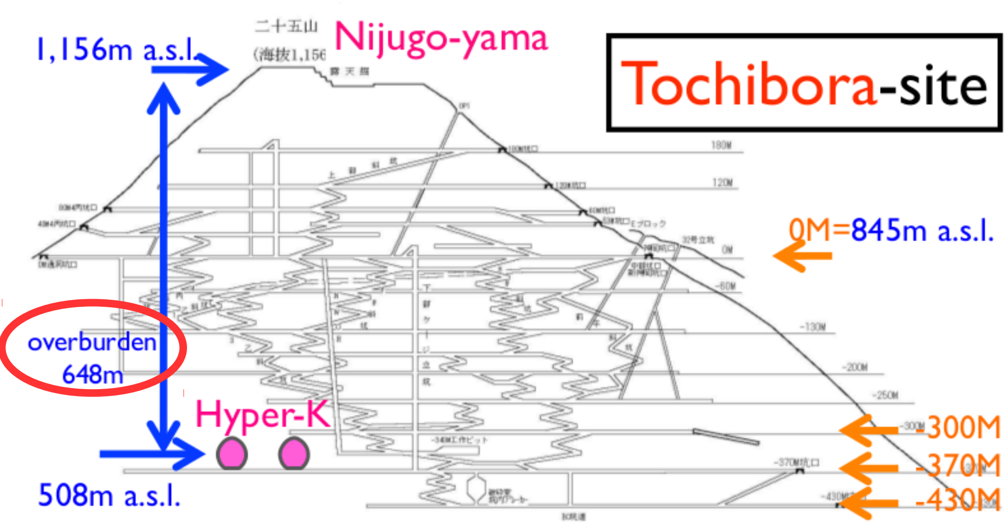


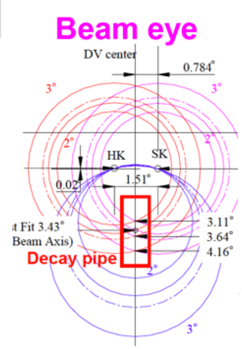
Site(s) and Cavern(s)

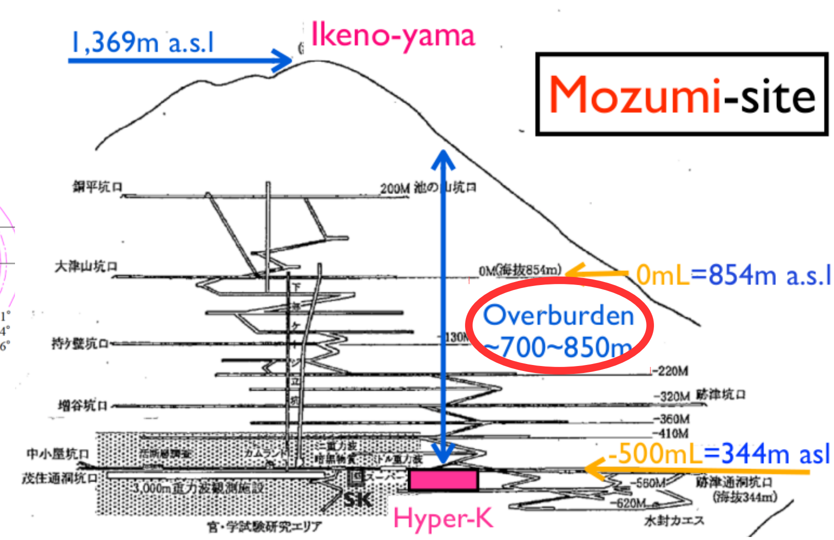
Two sites are being investigated:

- Tochibora mine:
  - ~8km South from Super-K
  - Identical baseline (295km) and off-axis angle (2.5º) to Super-Kamiokande
- Mozumi mine (same as Super-K)
  - Deeper than Tochibora
- Rock quality in the two sites similar
- Confirmed HK cavern can be built w/ existing techniques





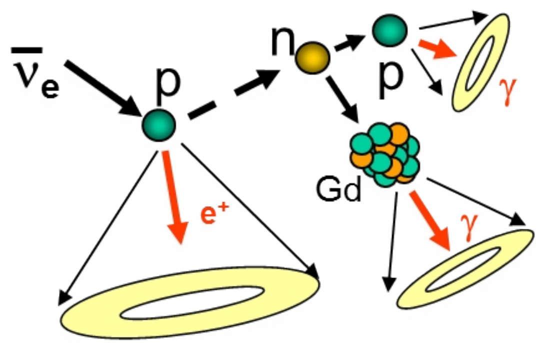




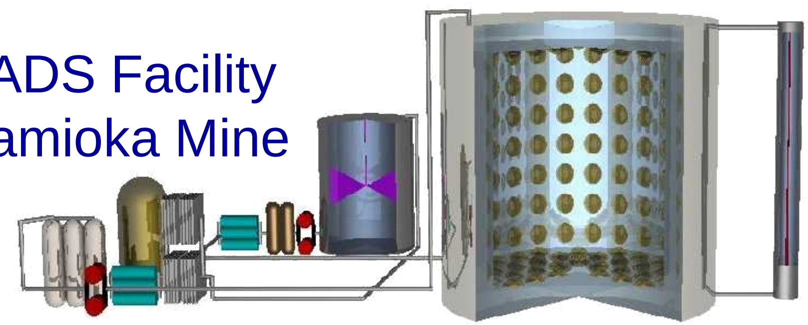
Gadolinium Option

Beacom and Vagins, *Phys. Rev. Lett.*, 93:171101, 2004

- Gd-doping proposed in 2004 mainly to greatly enhance supernova neutrino detection => neutron capture.
- Can also help beam physics and proton decay searches.
- R&D programme started with EGADS (200ton scale model of Super-K)
- Now finishing → Super-K will run with the Gd-doping
- Considered as possible option for Hyper-K



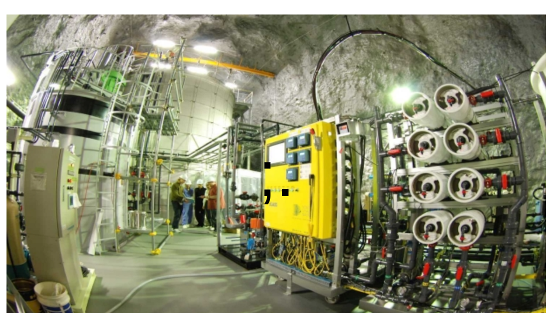
EGADS Facility
in Kamioka Mine



April 2015: fully loaded (0.2%) with Gd sulfate, and functioning perfectly.

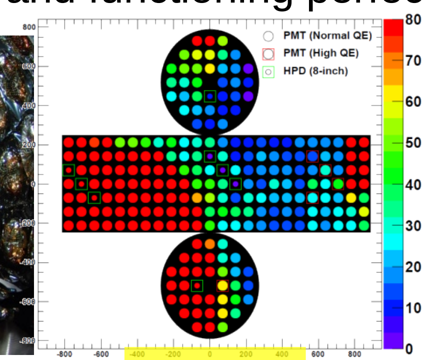
EGADS:

12/2009



11/2011

8/2013

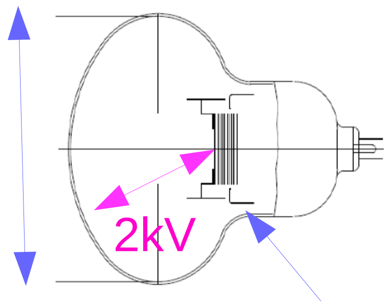


6/2015

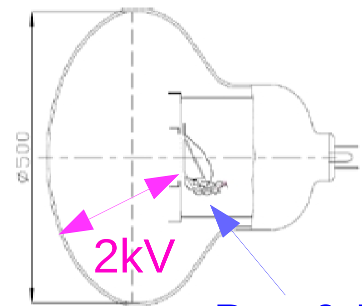
Photosensors Candidates

R&D going to get better performance and lower costs

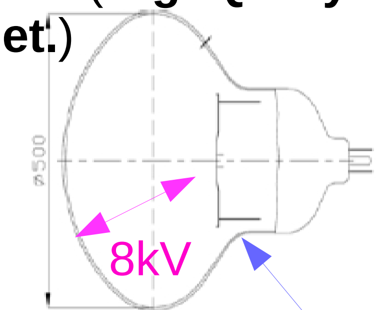
Established (**SK PMT**)



R&D (**HighQE/CE PMT**)



R&D (**HighQE hybrid det.**)



	Established (SK PMT)	R&D (HighQE/CE PMT)	R&D (HighQE hybrid det.)
Quantum Eff. (QE)	22%	30%	30%
Collection Eff. (CE)	80%	93%	95%
Timing resol (FWHM)	5.5 nsec	2.7nsec	1nsec

SK PMT
- Super-K ID PMTs
- Used for ~20 years →Guaranteed
- Complex production → Expensive

HighQE/CE PMT
- Under development
- Better performance
- Same technology → Lower risk

HighQE hybrid det.
- Under development
- Far better performance
- Simple structure →Lower cost
- New technology →Higher risk

Photosensors covered by protective case (currently under R&D)

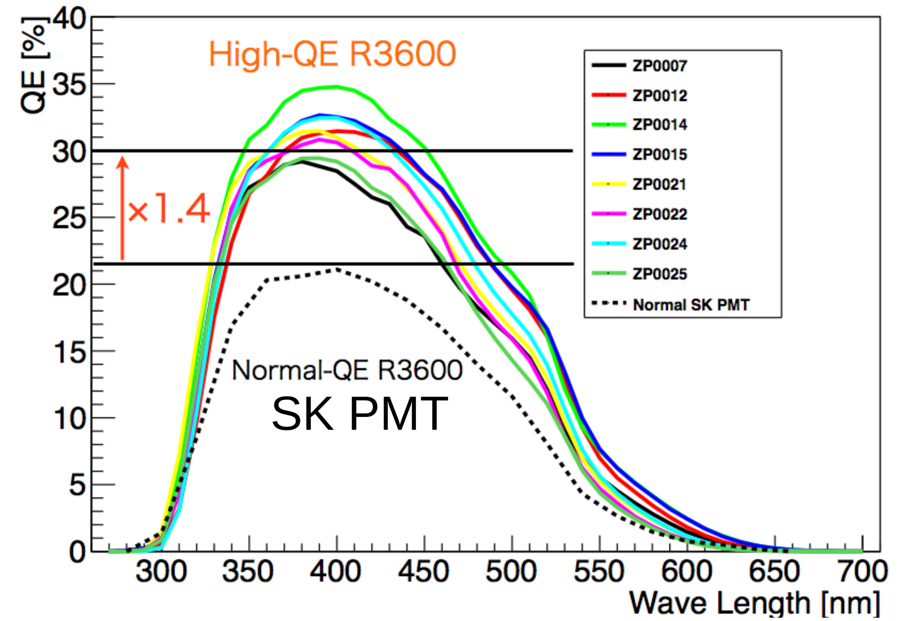
Lower Risk ⟷ Higher Performance

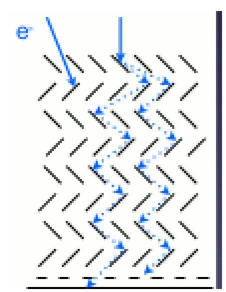
High QE achieved

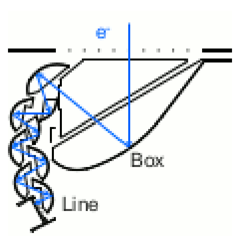
R&D&work with Hamamatsu.
Stability tests under way.

- Higher QE photocathode –
  - ~22% → ~30%

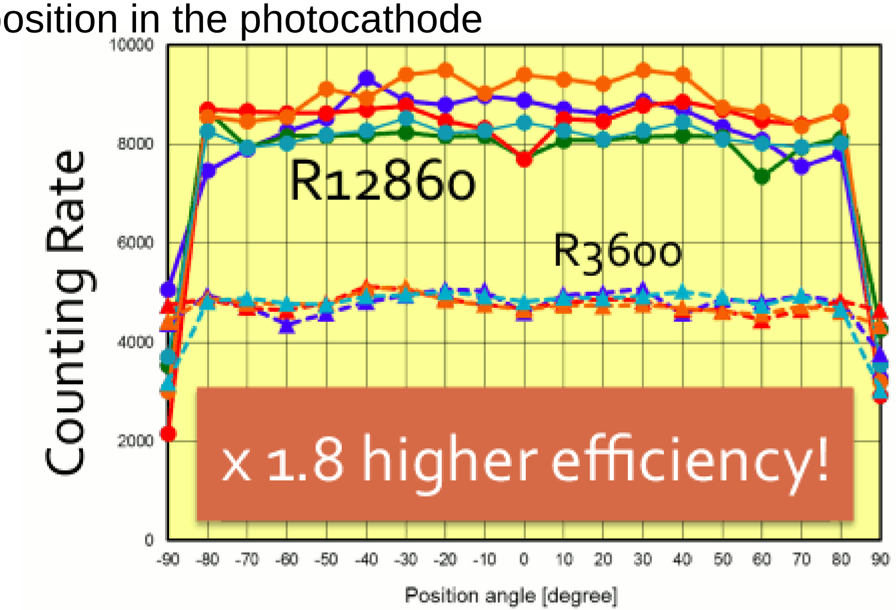
- Higher Collection Efficiency by improved dynode structure:
  - Venetian Blind type:
    - Various drift parts
    - May miss a dynode
  - Box Line type:
    - Unique drift path
    - High timing and 1PE Q Res.
    - Large acceptance → high CE







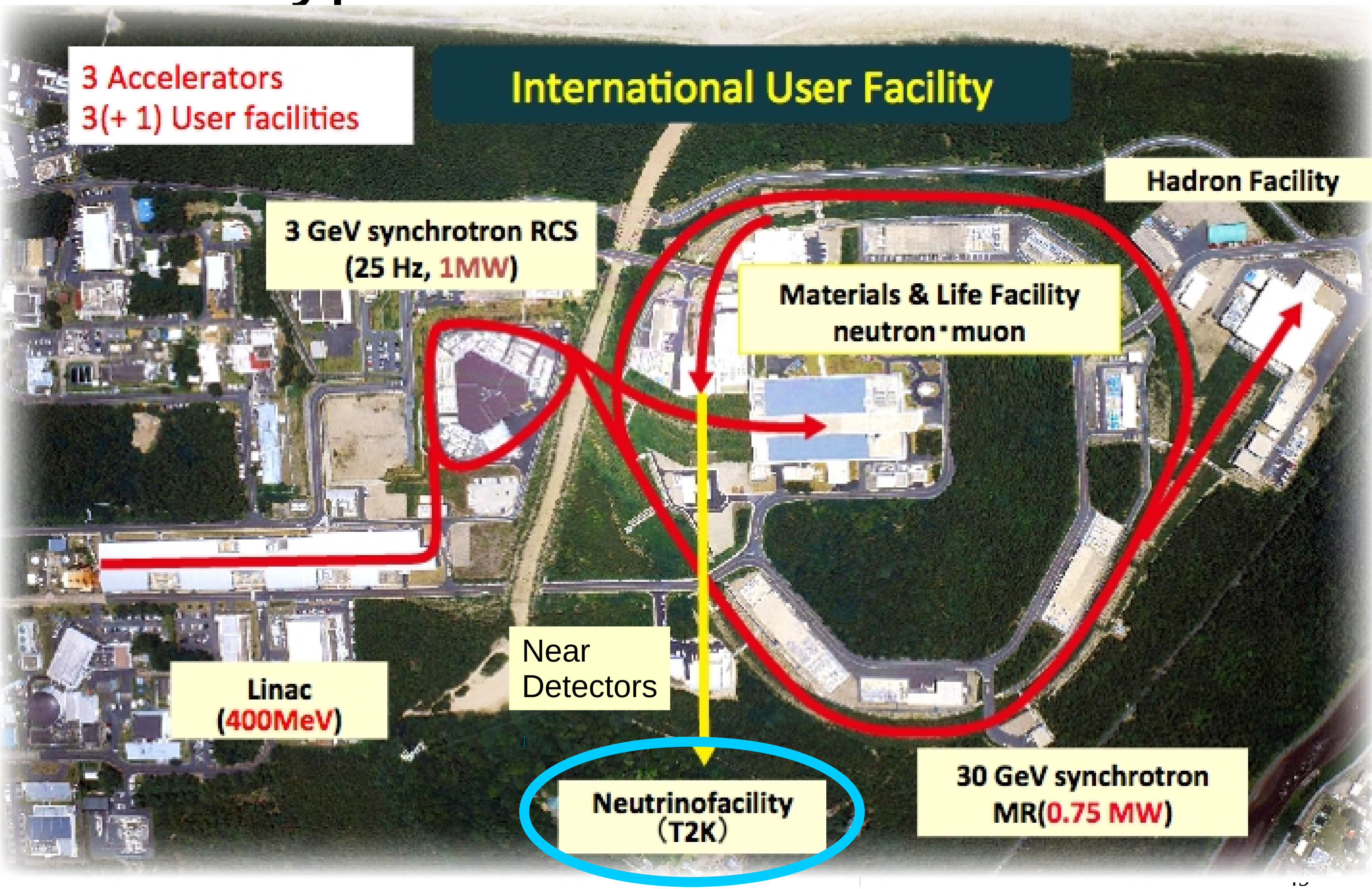
Single photodetection efficiency as a function of the position in the photocathode



World-wide R&D

- Intense R&D world wide, but large number of things to do.

Hyper-Kamiokande Beam

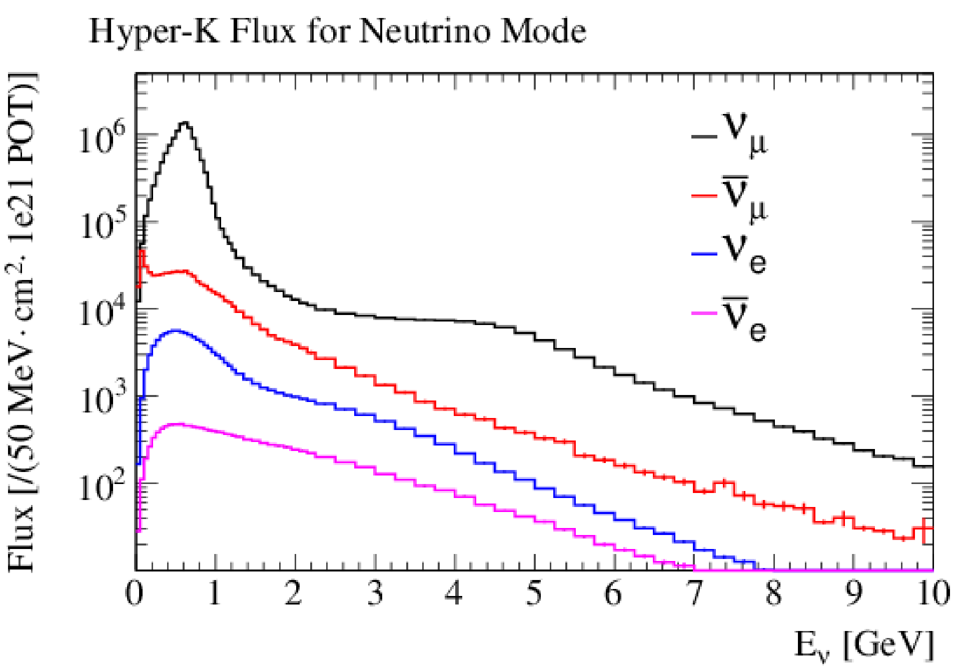


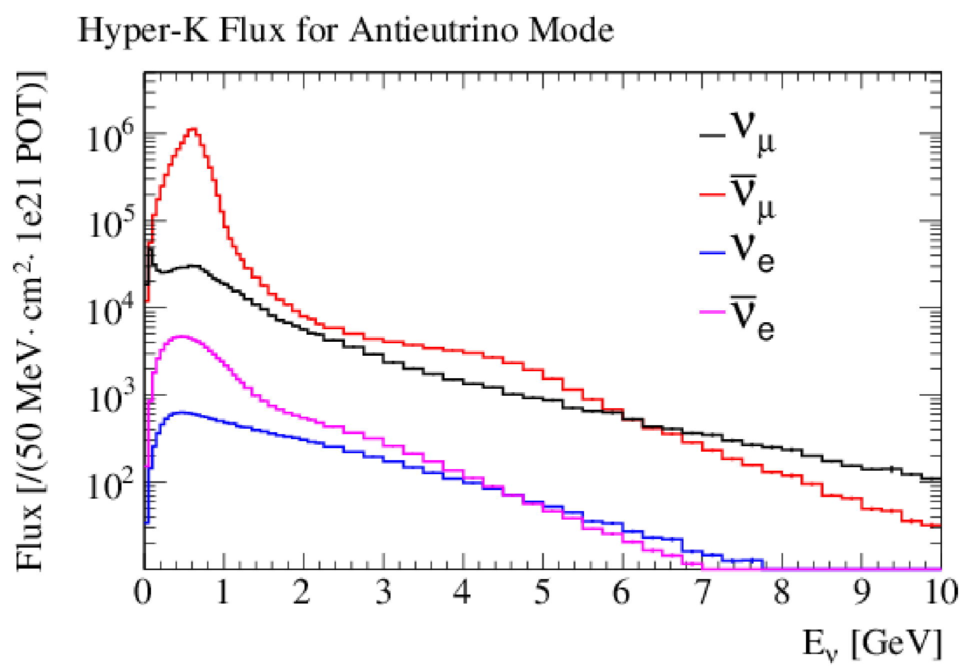
Neutrino Flux for Hyper-Kamiokande

- At least 750kW expected at the starting of the experiment.
- Assumed **7.5MW × $\mathbf{10^7}$ s** (1.56 × 10^{22} POT) for the following sensitivity studies
  - 10 years are needed if 750kW per 10^7s/year
  - 5 years assuming 1.5MW per 10^7s/year
  - Nominal beam sharing between ν and $\bar{\nu}$-mode beams

    ν-mode: $\bar{\nu}$-mode => 1 : 3

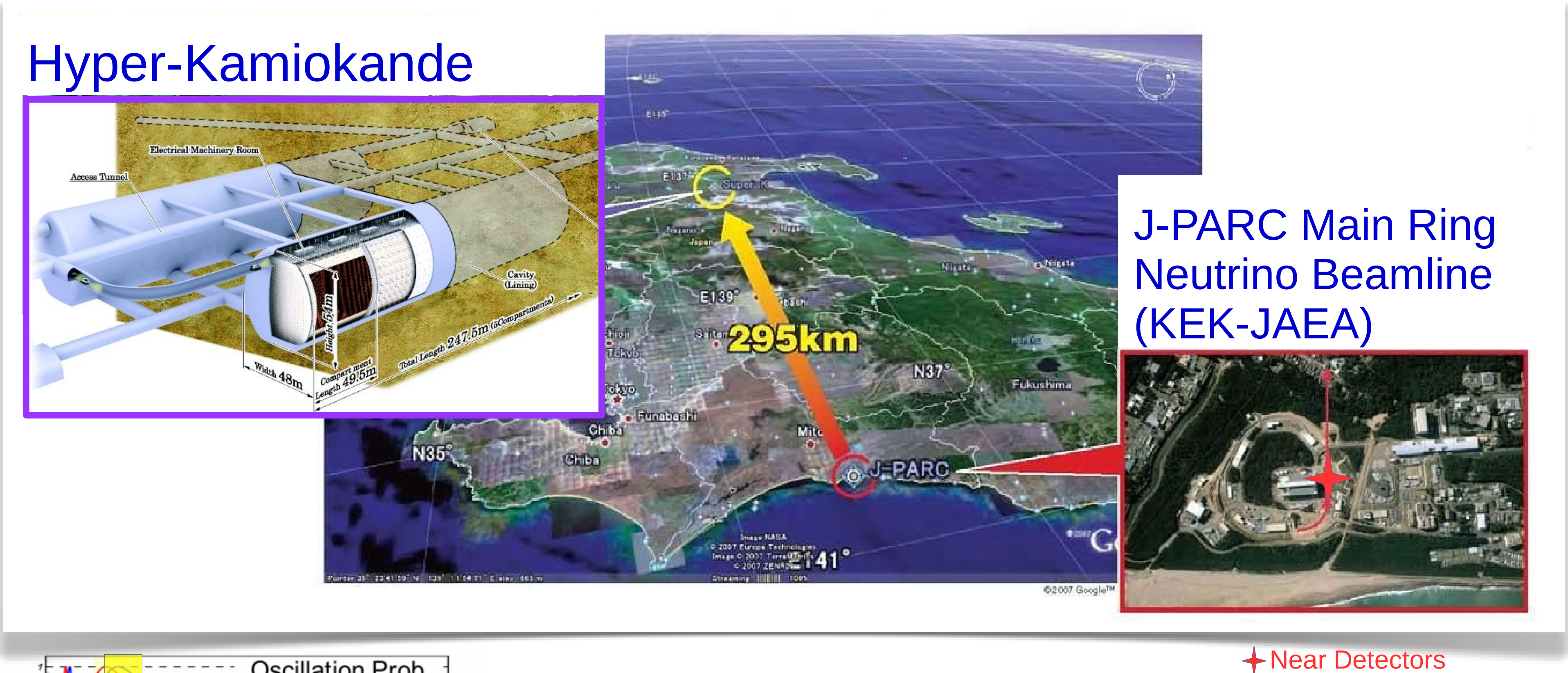
Expected unoscillated neutrino flux at Hyper-K

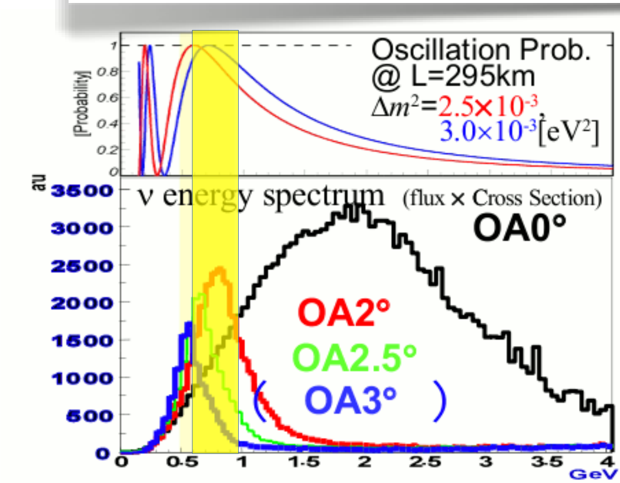




Tokai to Hyper-Kamiokande

Use upgraded J-PARC neutrino beam line (same as T2K) with expected beam power 750kW, 2.5° off-axis angle.

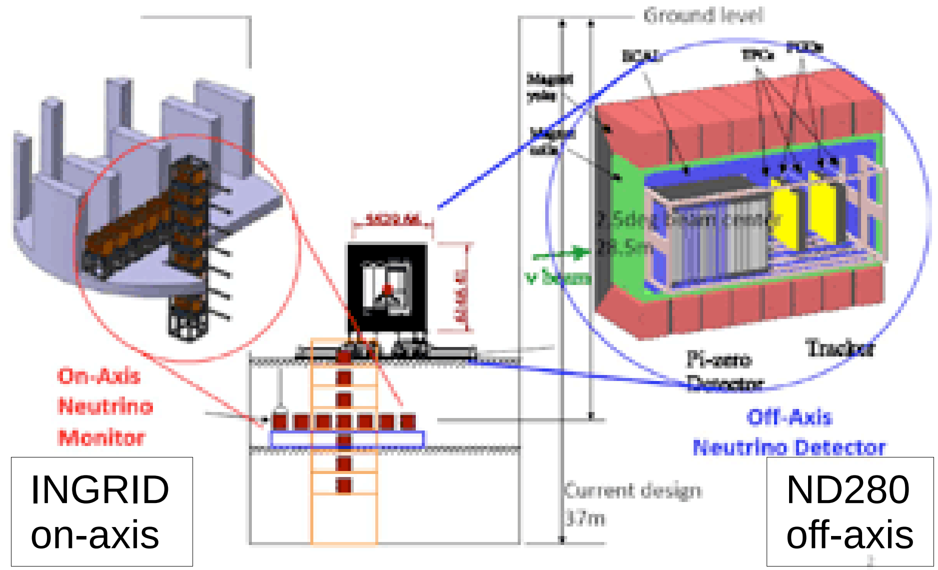




- Narrow-band beam at ~600MeV at 2.5° off-axis
- Take advantage of Lorentz Boost and 2-body kinematics in $\pi^+ \rightarrow \mu^+ \nu_\mu$
- Pure ν_μ beam with ~1% ν_e contamination

Near Detectors

T2K: suit of near detectors at 280m from the target



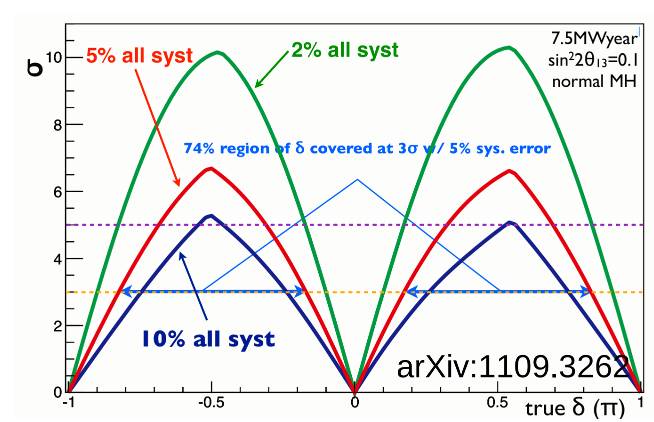
Under investigation three complementary options:

- Refurbished ND280/INGRID detectors
- New detectors in the 280m pit
- New "intermediate" WC detector at ~1-2km

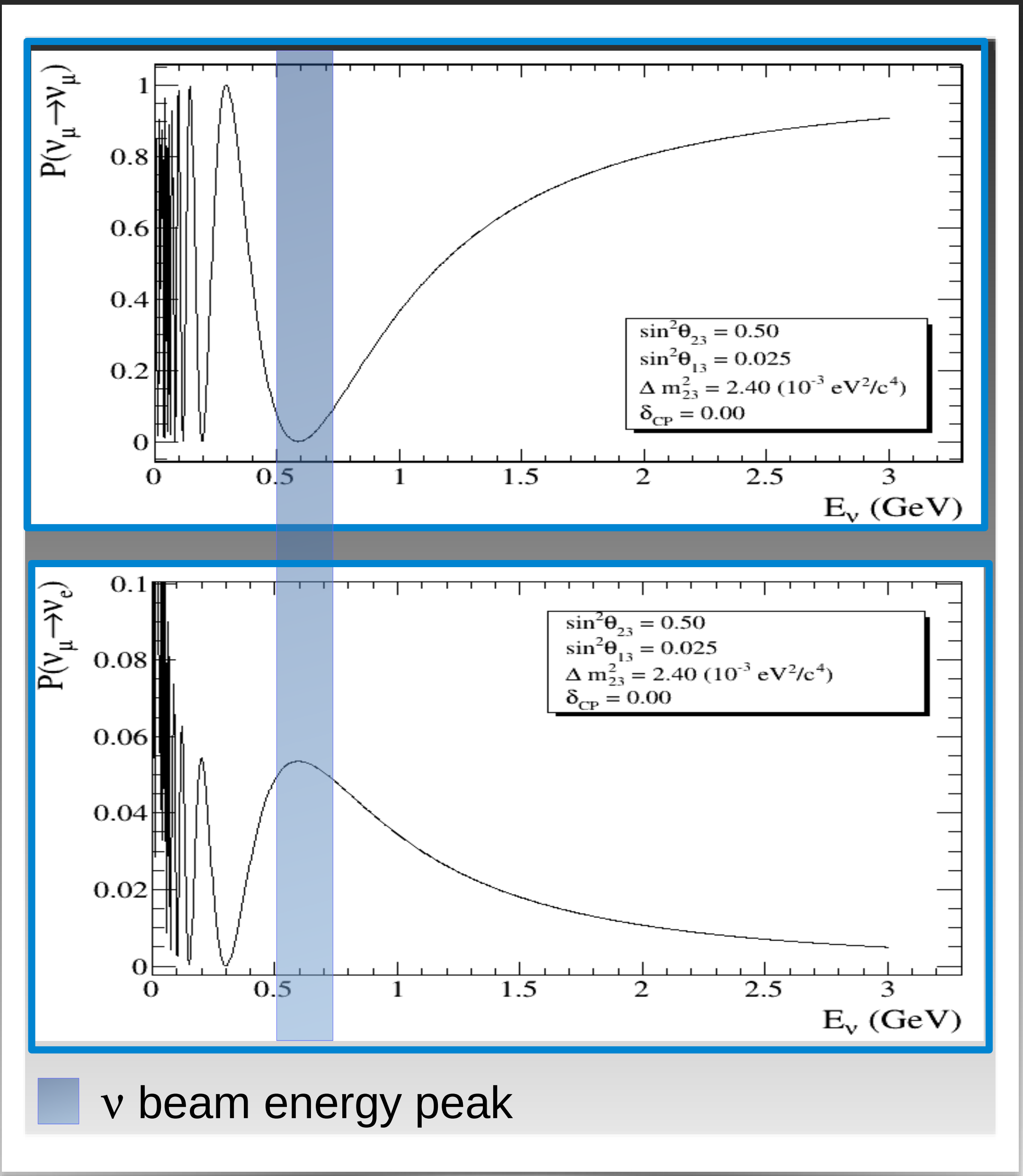
Optimization criteria based on reducing systematic errors for oscillations.

Current T2K systematic errors for oscillations

ν_e	Systematic sources(%)	ν_μ
3.1	Flux & Combined Cross-Sections	2.7
4.7	Independent Cross Sections	5.0
2.4	Pi Hadronic Interactions (FSI)	3.0
2.7	SK Detector Efficiencies	4.0
6.8	**TOTAL**	**7.6**

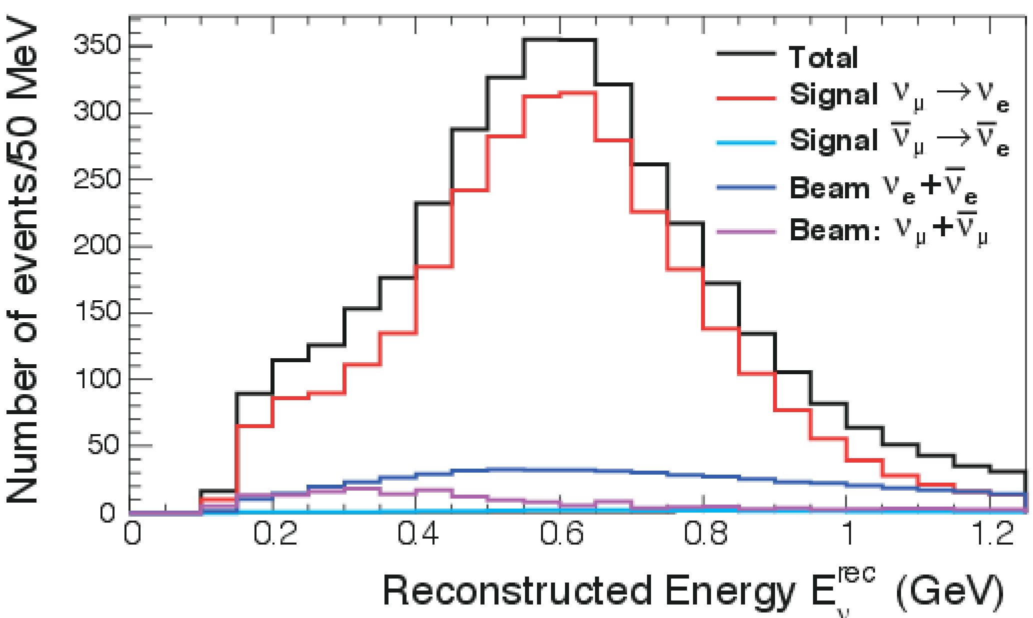


The Physics Potential

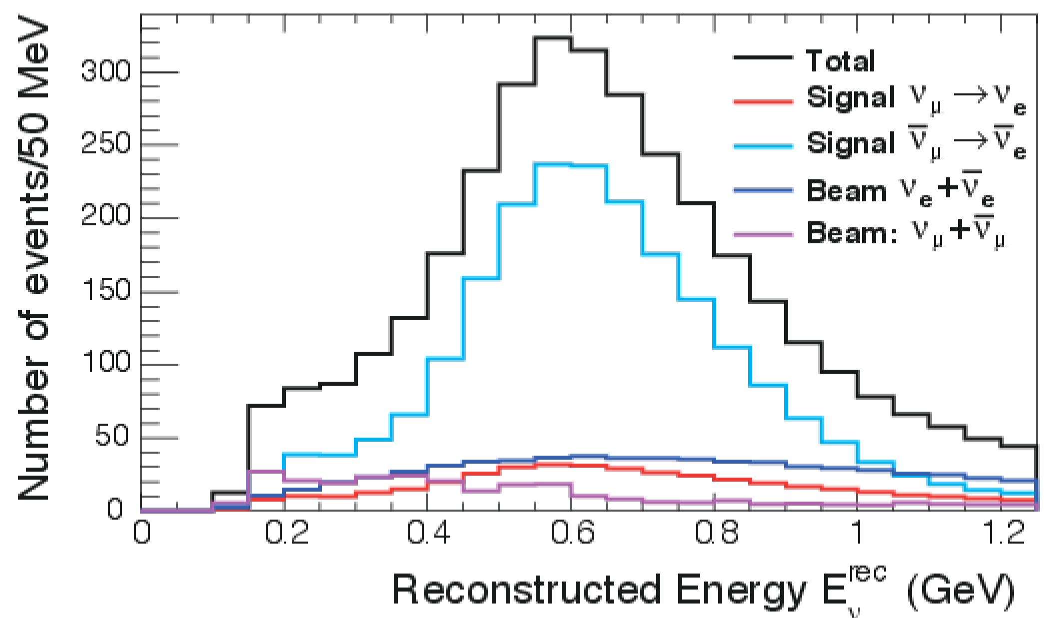


Expected Events

Appearance ν mode



Appearance $\bar{\nu}$ mode

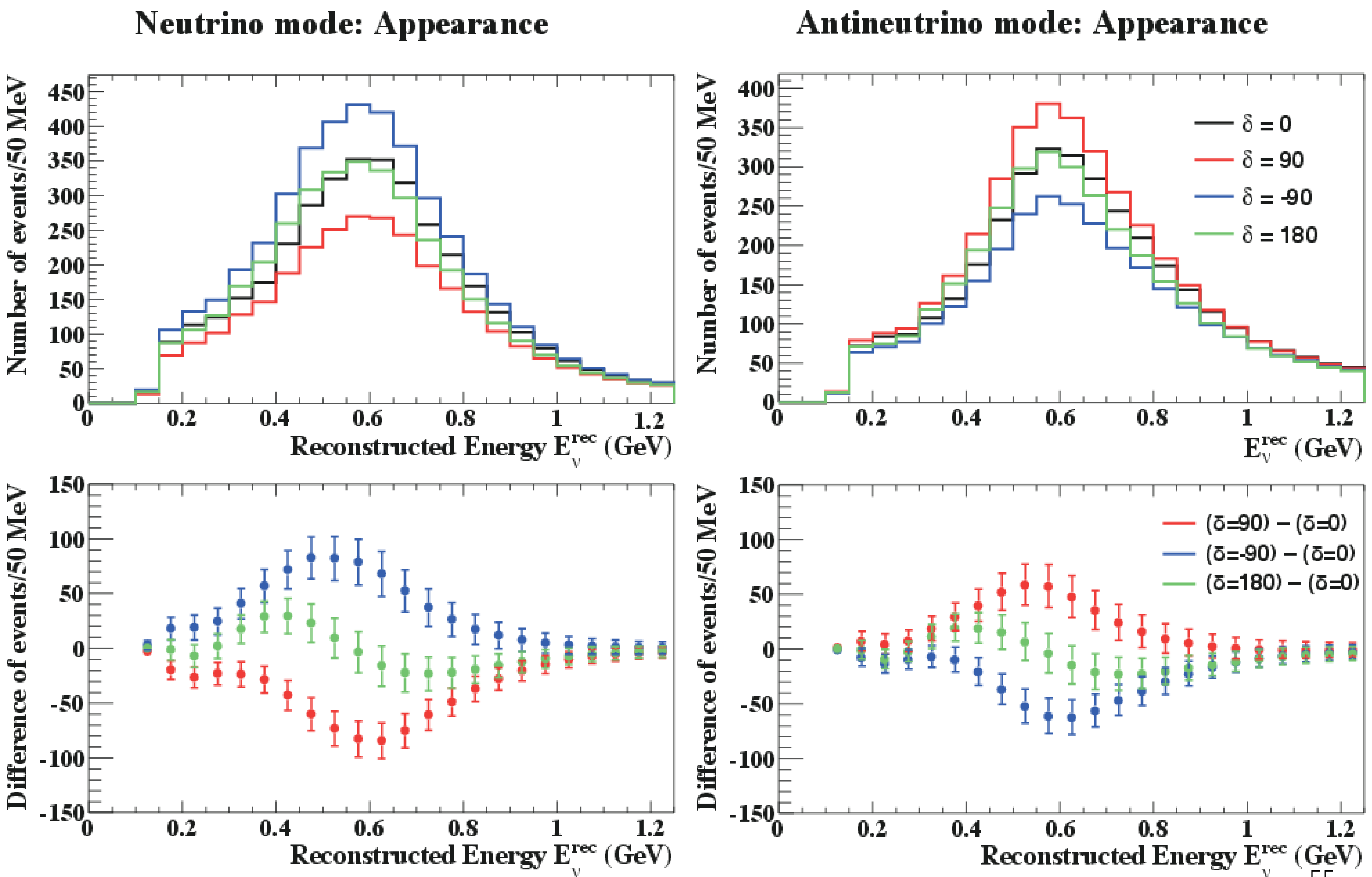


Appearance	Signal		Background					Total
	$\nu_\mu \to \nu_e$	$\bar{\nu}_\mu \to \bar{\nu}_e$	ν_μ	$\bar{\nu}_\mu$	ν_e	$\bar{\nu}_e$	NC	
ν mode	3016	28	11	0	503	20	172	3750
$\bar{\nu}$ mode	396	2110	4	5	222	265	265	3397

Disappearance	ν_μ	$\bar{\nu}_\mu$	ν_e	$\bar{\nu}_e$	NC	$\nu_\mu \to \nu_e$	Total
ν mode	17225	1088	11	1	999	49	19372
$\bar{\nu}$ mode	10066	15597	7	7	1281	6	26964

Large expected number of events. NH, $\sin^2 2\theta_{13} = 0{,}1$ and $\delta_{CP} = 0$

Expected Events



Hyper-K Sensitivity to δ_{CP}

- Based on experience and prospects of T2K.
- Three main categories of systematic uncertainties:
  - **Flux and cross section uncertainties** constrained by the fit to current ND.
  - **Cross section uncertainties not constrained** by the fit to current ND data: errors reduced as more categories of samples are added to ND fit.
  - **Uncertainties on the far detector** reduced as most of them are estimated by using atmospheric neutrinos as a control sample (larger stat at Hyper-K).

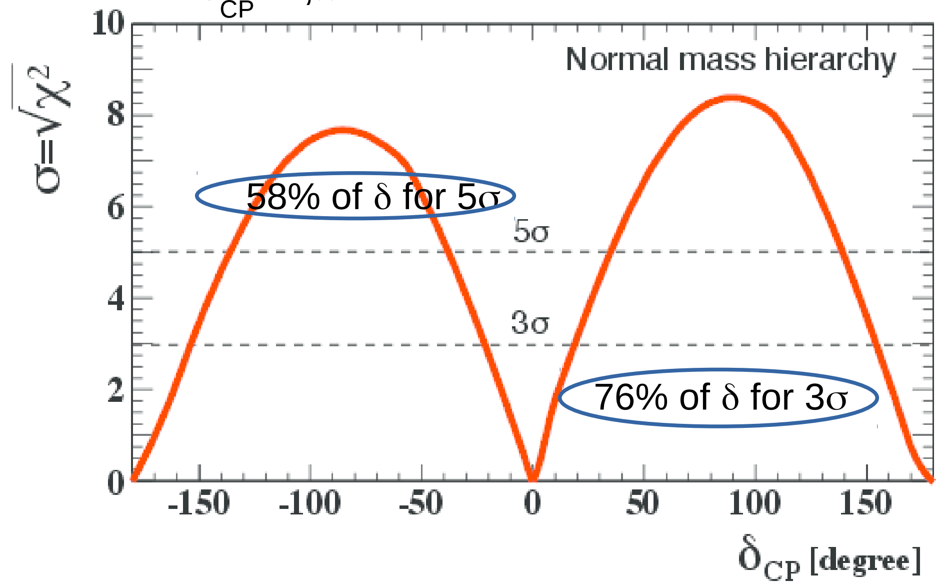
Errors (%) on the expected number of events				
	ν mode		$\bar{\nu}$ mode	
	ν_e	ν_μ	ν_e	ν_μ
Flux & Near Detector (ND)	3.0	2.8	5.6	4.2
ND-independ. xsect	1.2	1.5	2.0	1.4
Far Detector	0.7	1.0	1.7	1.1
Total	3.3	3.3	6.2	4.5

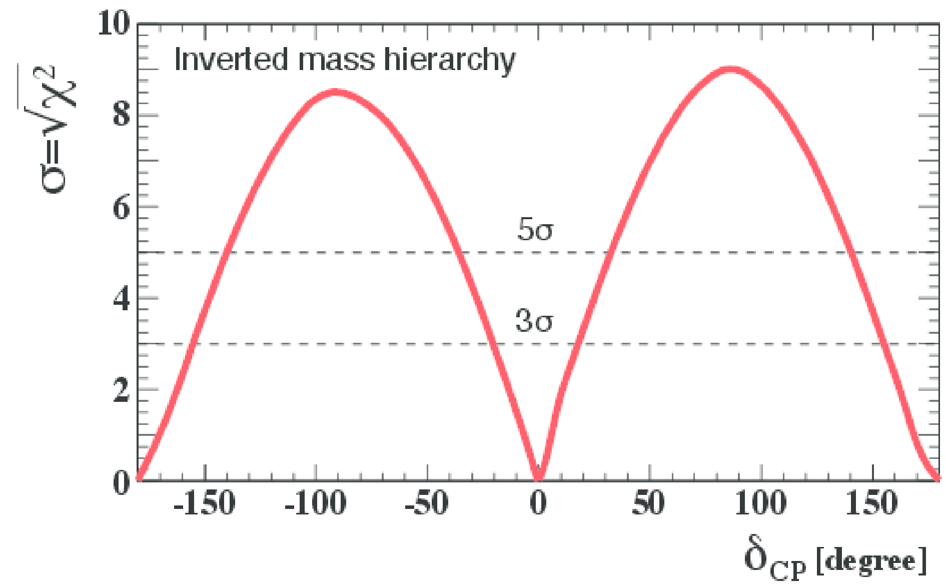
- Planning to update errors and thus sensitivities based on the discussions on the T2K upgrade.

Hyper-K Sensitivity to δ_{CP}

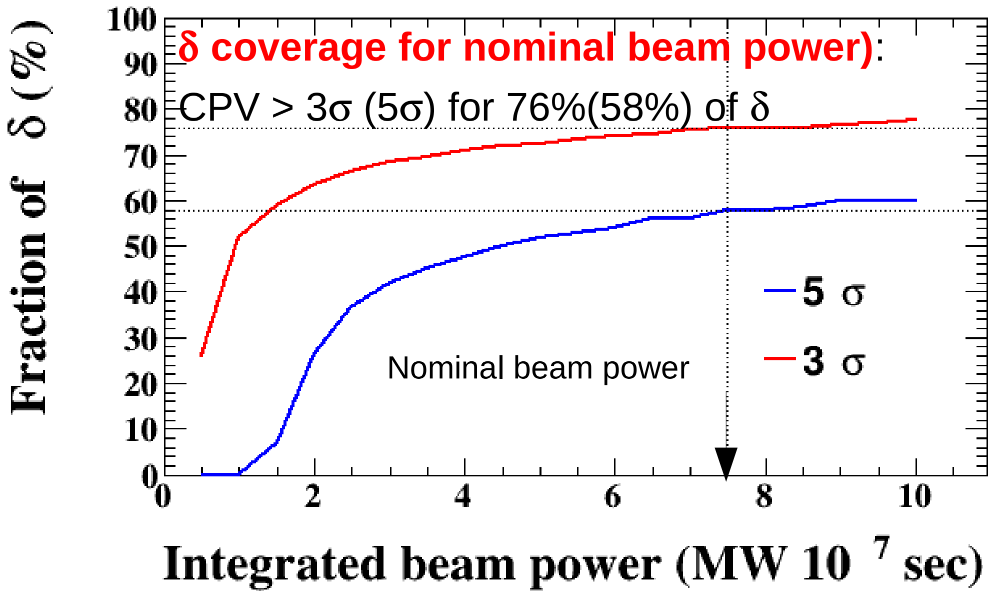
CPV discovery sensitivity

to δ_{CP}=0,π w/ MH known

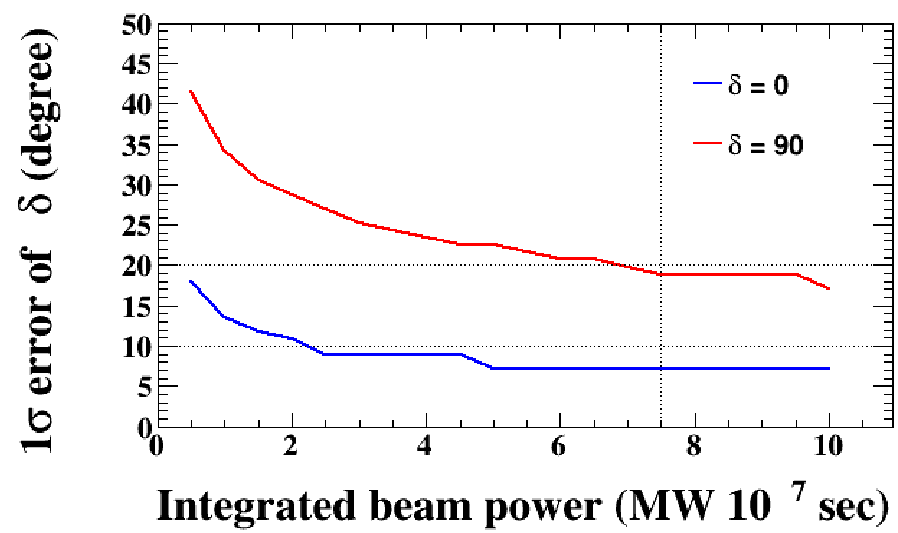




Fractional region of δ(%) for CPV (sin δ ≠0) > 3,5 σ



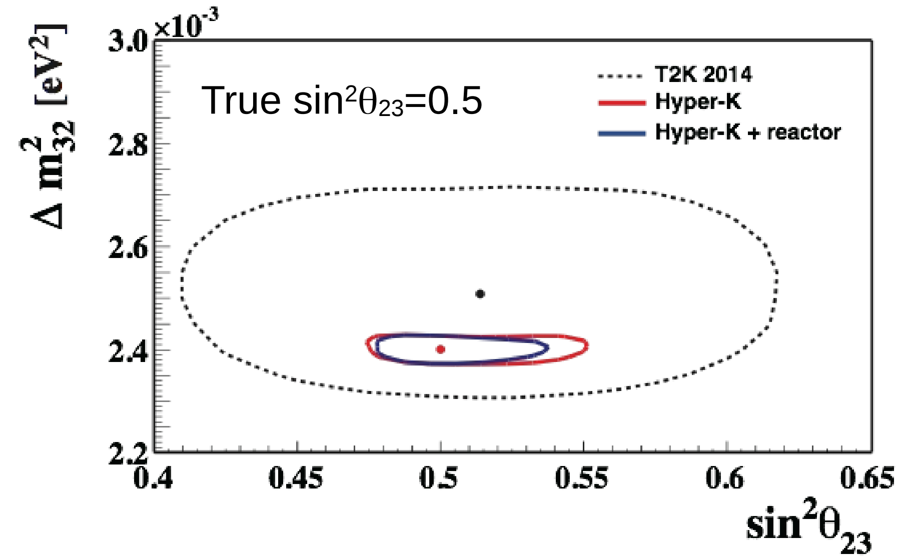
1σ uncertainty of δ as a function of the beam power: < 19°(6°) for δ = 90°(0°)

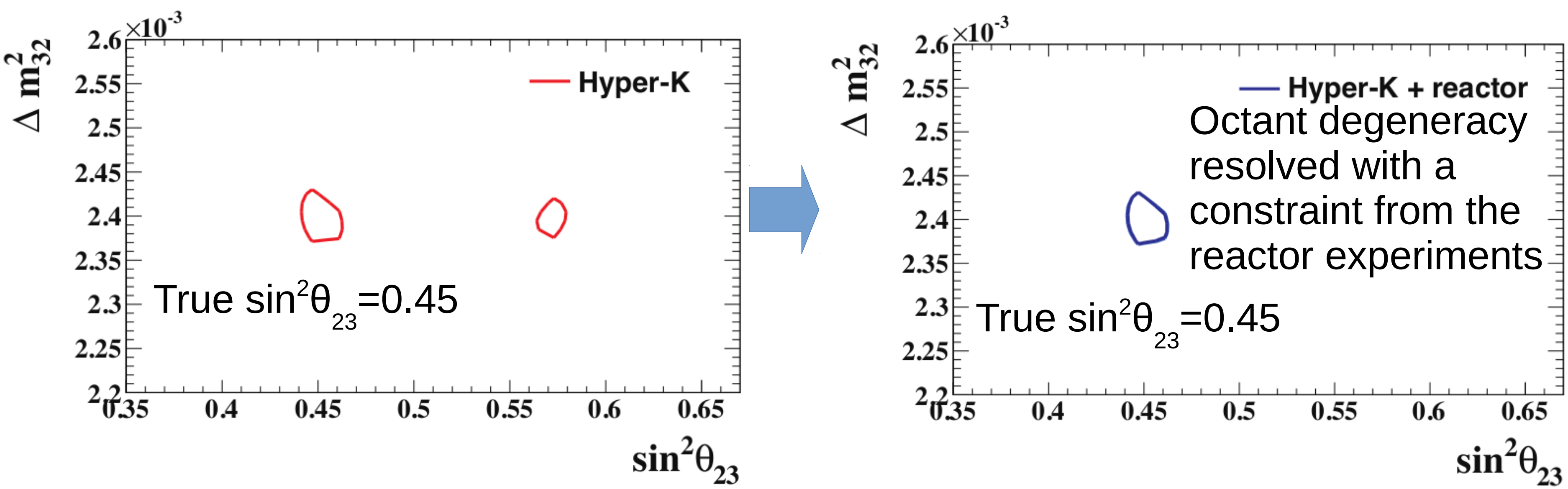


Sensitivity to θ_{23} and Δm^2_{23}

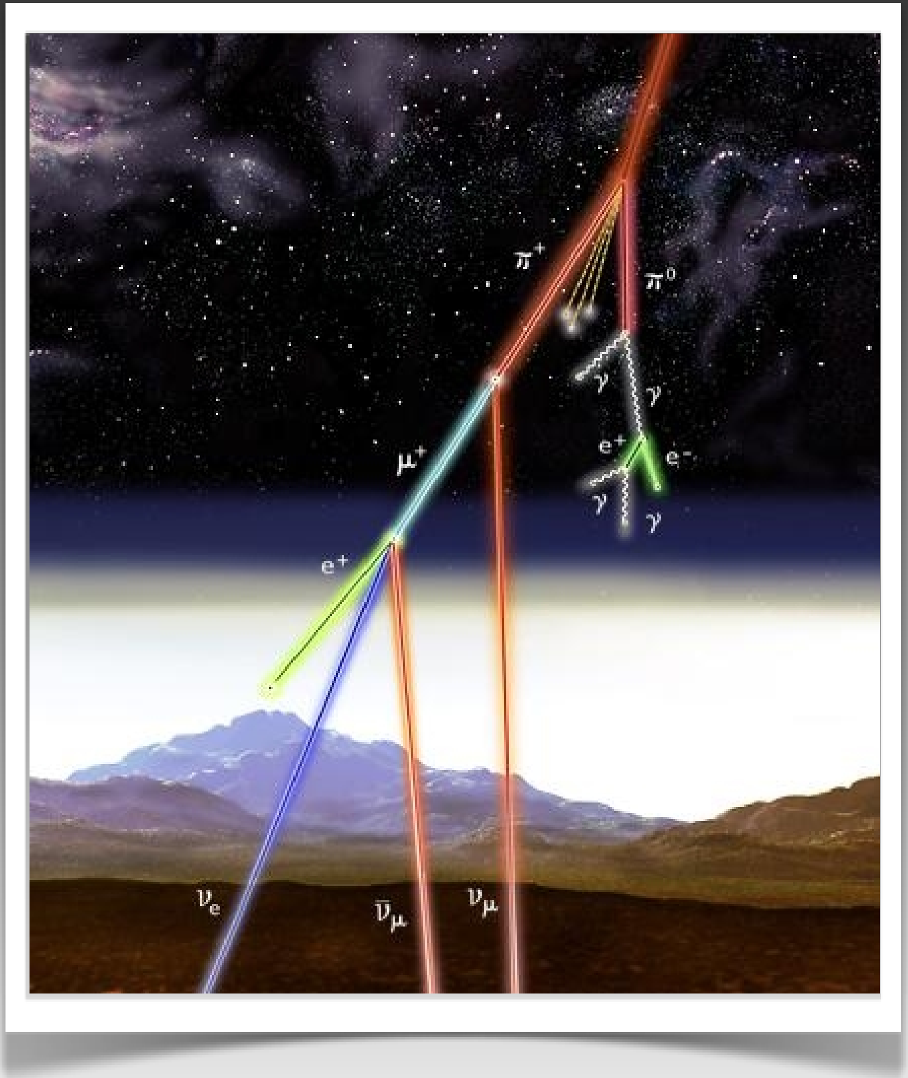
- $\sin^2 2\theta_{23}$ and Δm^2_{23} free parameters as well as $\sin^2 2\theta_{13}$ and δ_{CP} in the fit.
- Octant resolution w/ reactor θ_{13}: ~3σ wrong octact rejection for $\sin^2\theta_{23}$<0.46 or >0.56

True $\sin^2\theta_{23}$	1σ err $\sin^2\theta_{23}$	1σ err Δm^2_{23} ($10^{-5}eV^2$)
0.45	0.006	1.4
0.50	0.015	1.4
0.55	0.009	1.5

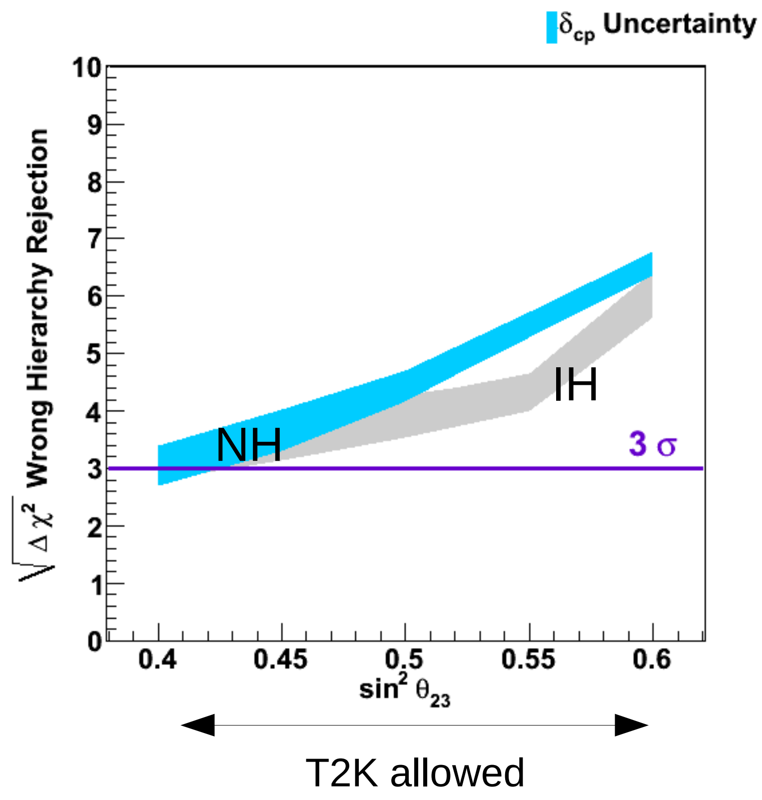


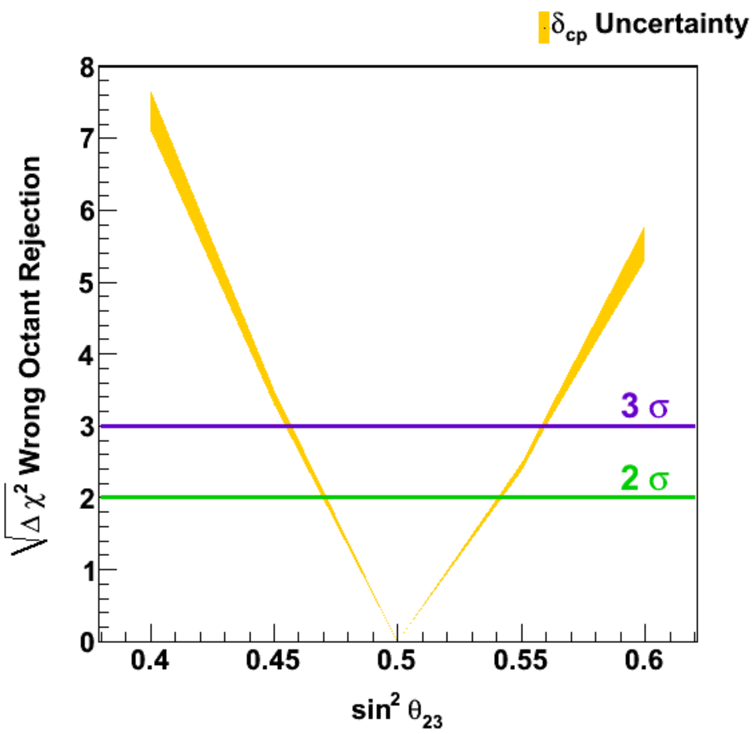


Atmospheric Neutrinos



Hyper-K Sensitivity to MH

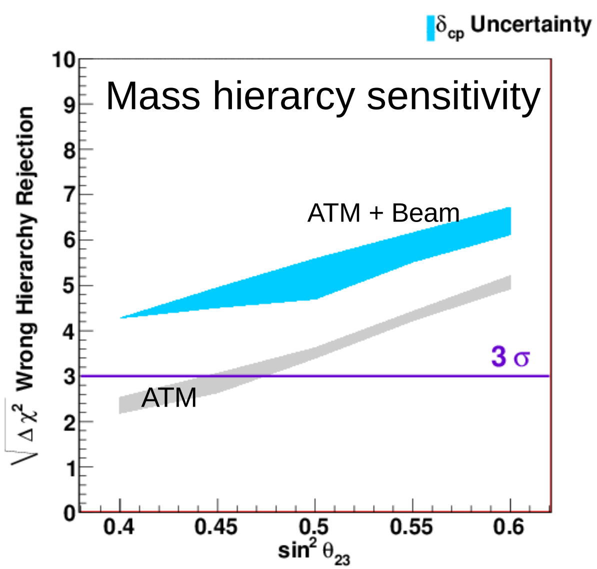


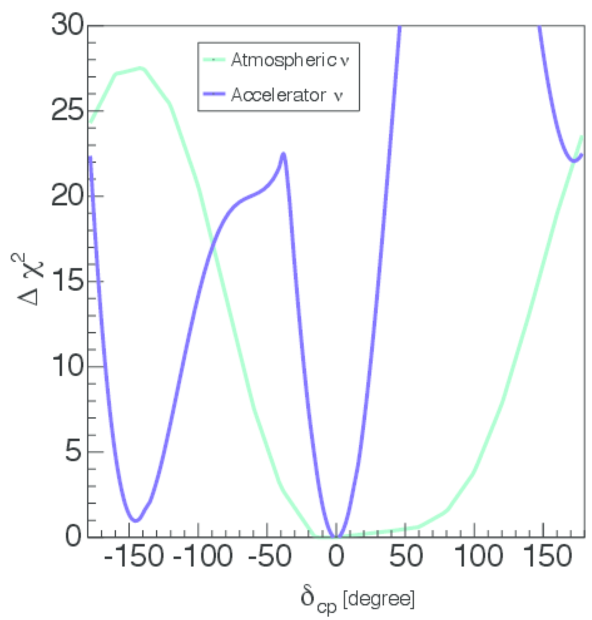


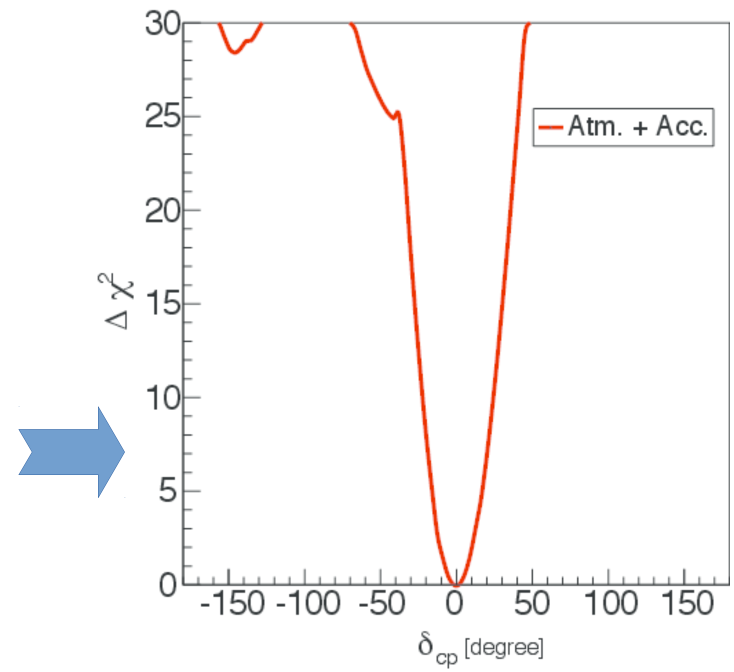
- Assuming 10y data taking:
  - Expect better than ~3σ sensitivity to the mass hierarchy using atmospheric neutrinos alone.
  - 3σ octant determination possible when $|\theta_{23}$ -45º$|$< 8º

Combined ATM & Beam Analysis

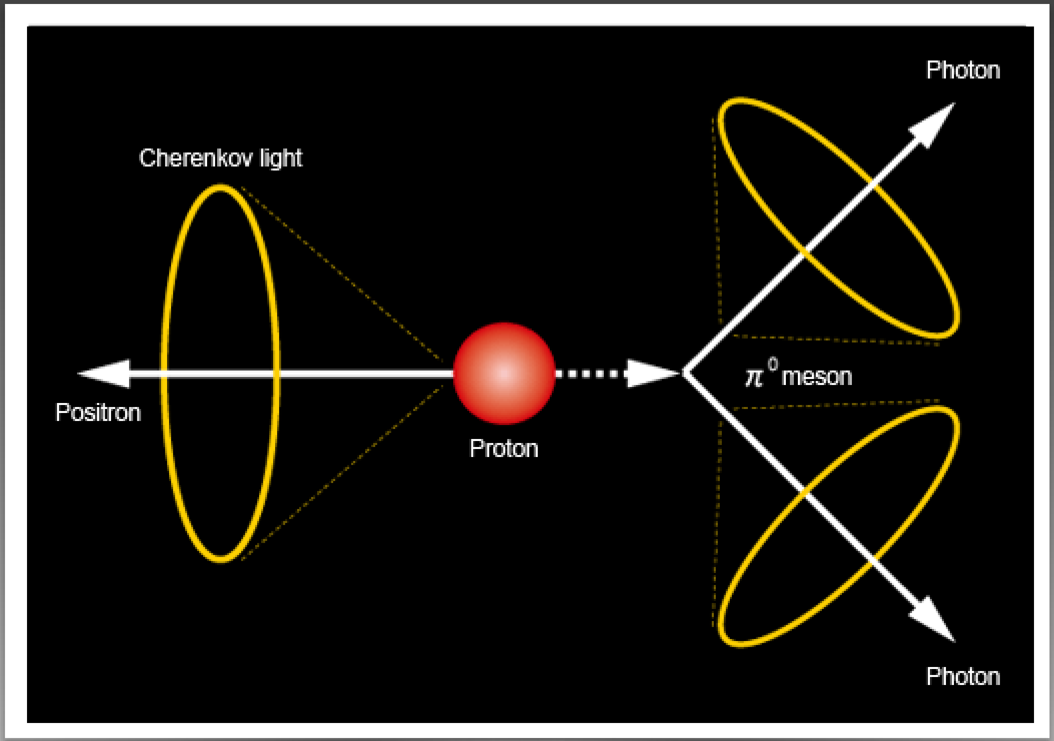
- Hyper-K will observe both accelerator and atmospheric neutrinos.
- Physics capability can be enhanced by combining the two analyses.
- Improved overall MH sensitivity
- Second minimum for beam analysis if MH not known.
- ATMP can discriminate MH, but worse measurement of CP.
- Both measurements can resolve fake solution and provice a precise measurement of CP.







Proton Decay

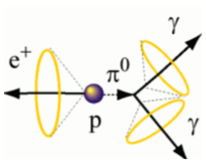


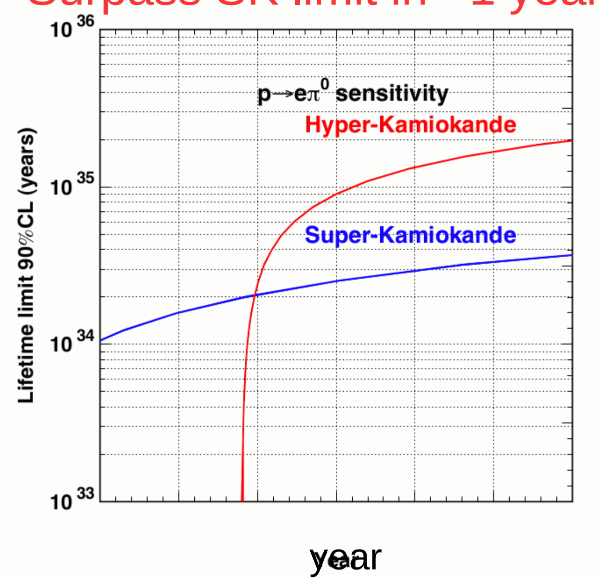
arXiv:1109.3262

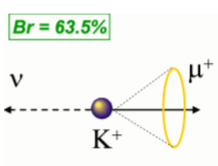
Proton Decay Sensitivity

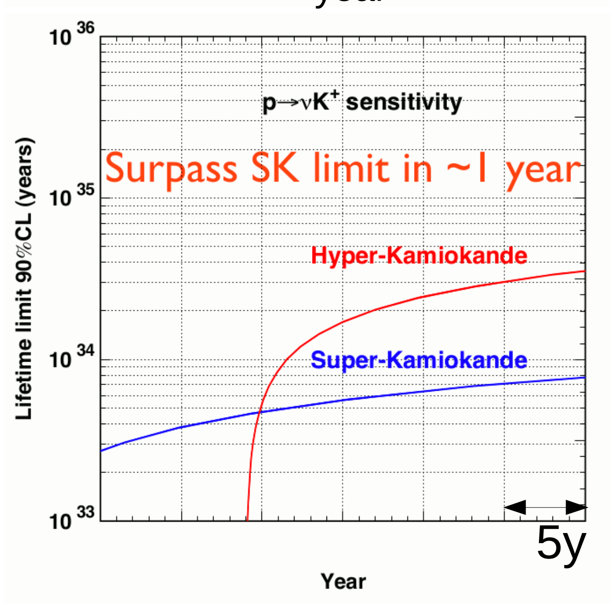
Proton decay is one of the few unobserved effects of the various proposed Gran Unificatied Theories.

Surpass SK limit in ~1 year

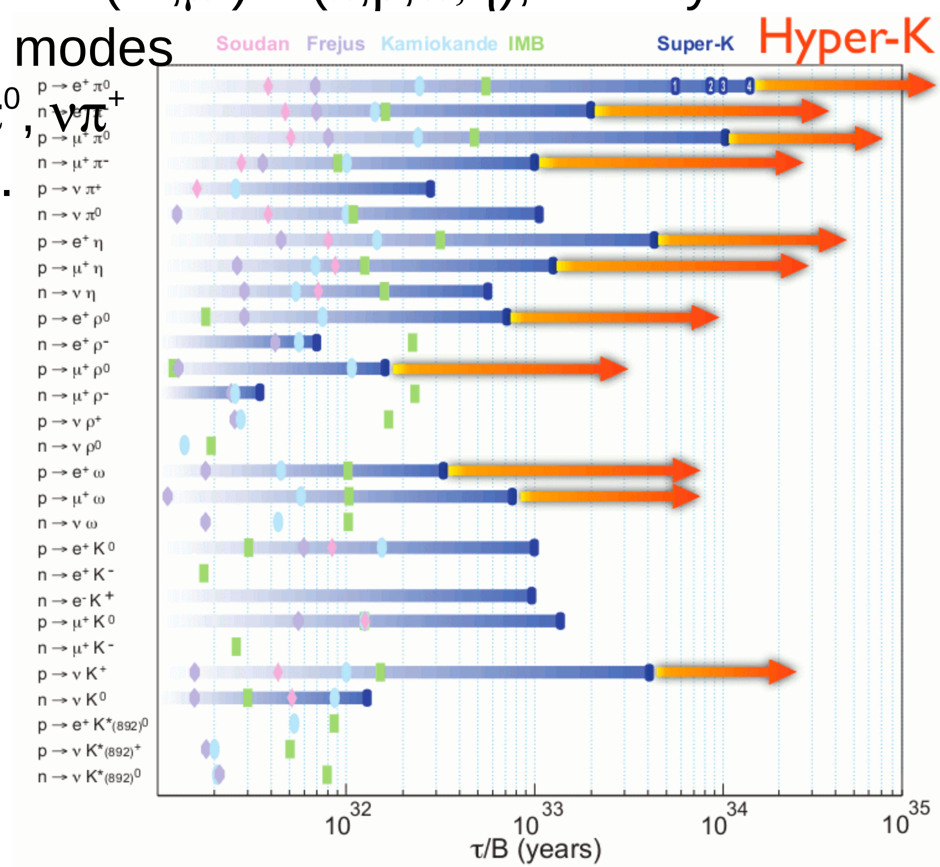




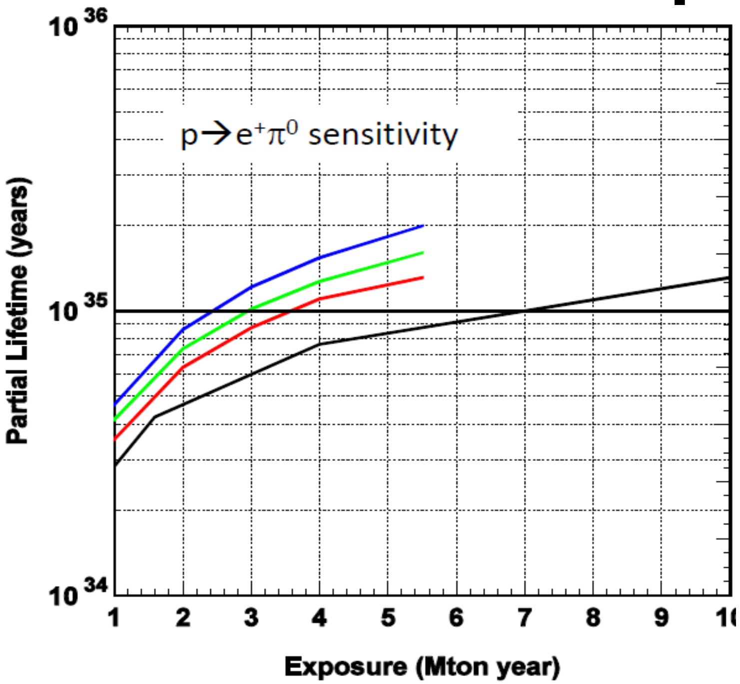




- 10 times better sensitivity than Super-K
- Hyper-K surpasses SK limits in ~1y
- Hyper-K is sensitive in every single mode
  - $p\to e^+\pi^0$: 1.3×10^{35} y at 90% CL
  - $p\to \bar{\nu}K^+$: 3×10^{34} y at 90% CL
  - Many other modes:
    - p,n → $(e^+,\mu^+) + (\pi,\rho,\omega,\eta)$; $10^{34\text{-}35}$y
    - K^0 modes
    - $\nu\pi^0$, $\nu\pi^+$
    - ….

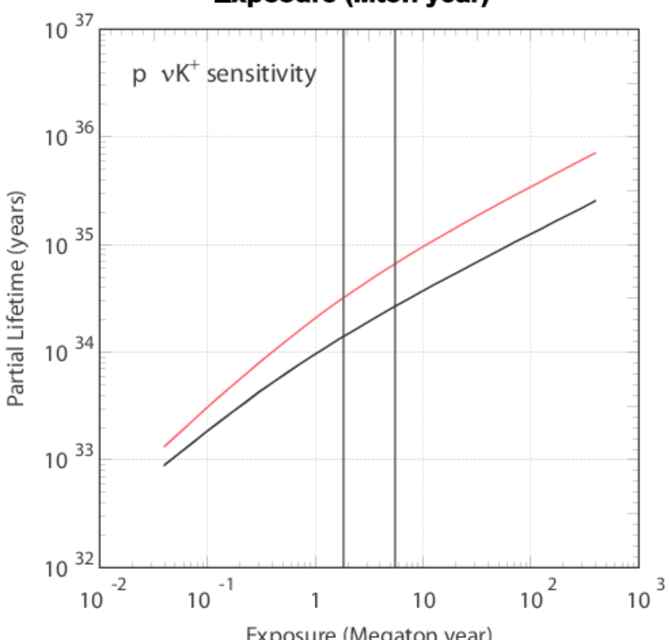


Proton Decay Sensitivity Improvements



- Baseline Analysis
- Improved Analysis cuts
- BKG Reduced by 50% (n-tagging)
- BKG Reduced by 70% (n-tagging)

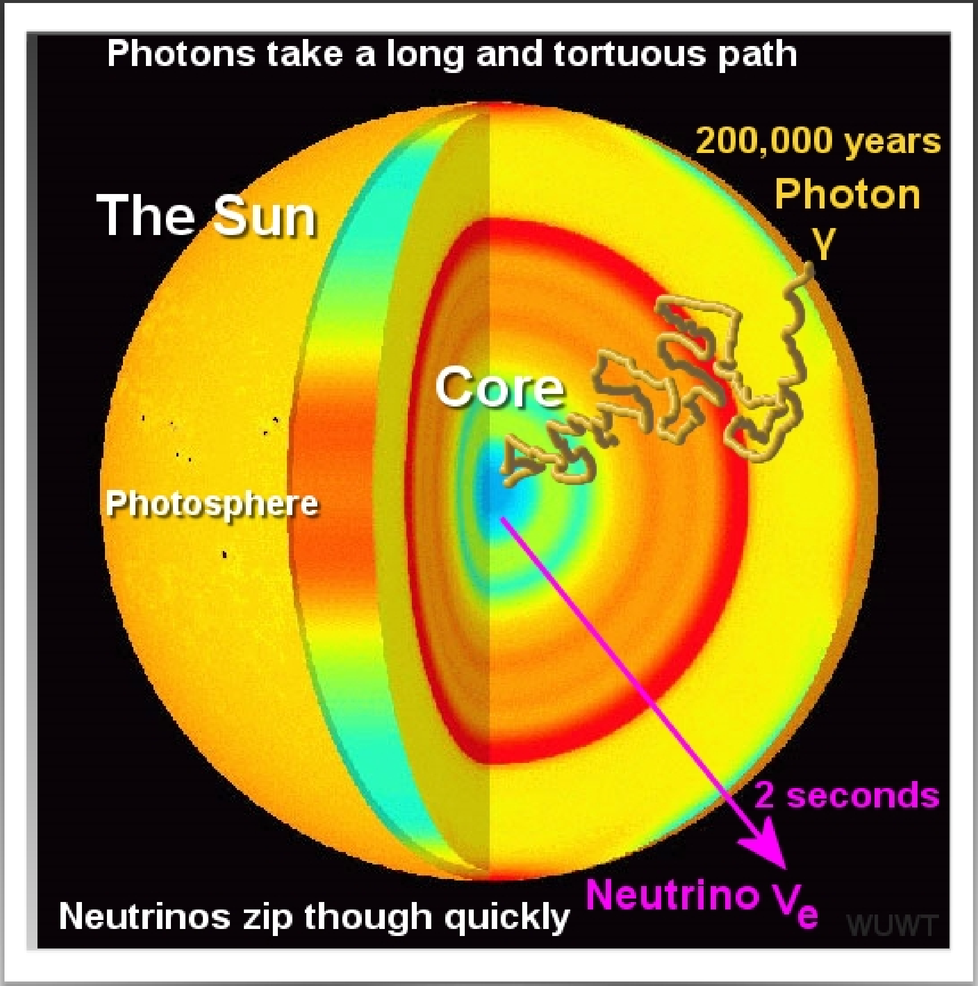
- Super-Kamiokande has demonstrated neutron tagging via
  - $n + p \rightarrow d + \gamma$ (2.2 MeV)
- Hyper-K's tagging depends on detector configuration, photocoverage, Gd doping etc.



- Baseline Analysis
- 40% photocoverage

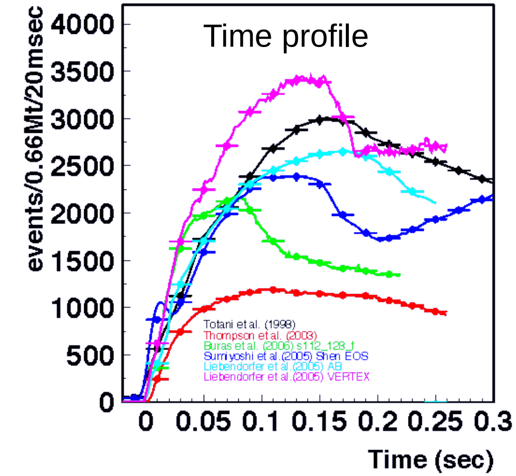
- Benefit from enhanced light collection to improve the signal efficiency.

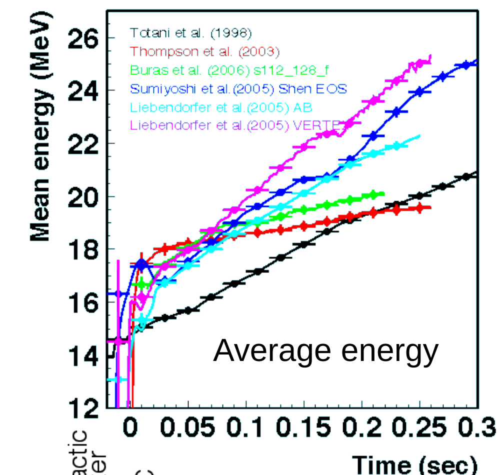
Astroparticle



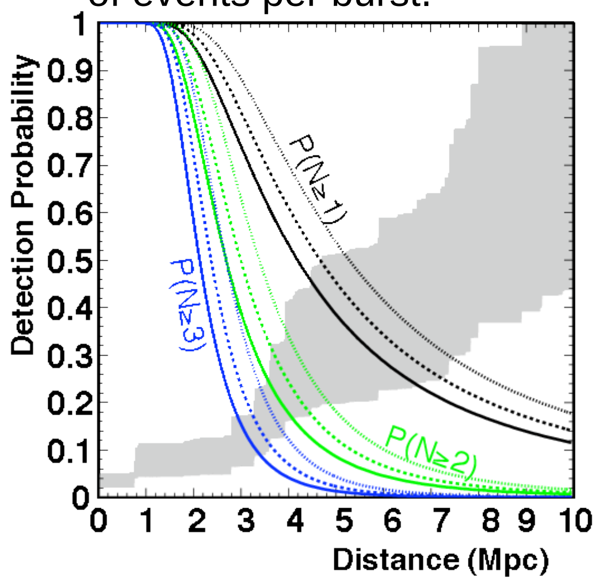
Supernovas

- Astrophysical neutrinos:
  - 200k ν's from Supernova at Galactic center (10kpc) → time variation & energy can be measured with high statistics. Important data to cross check explosion models

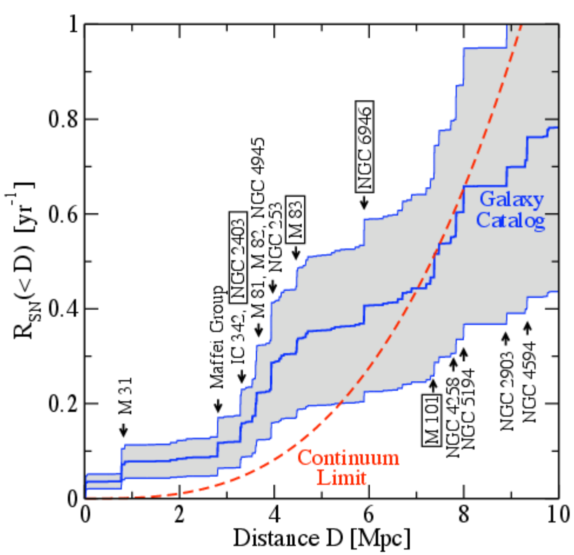


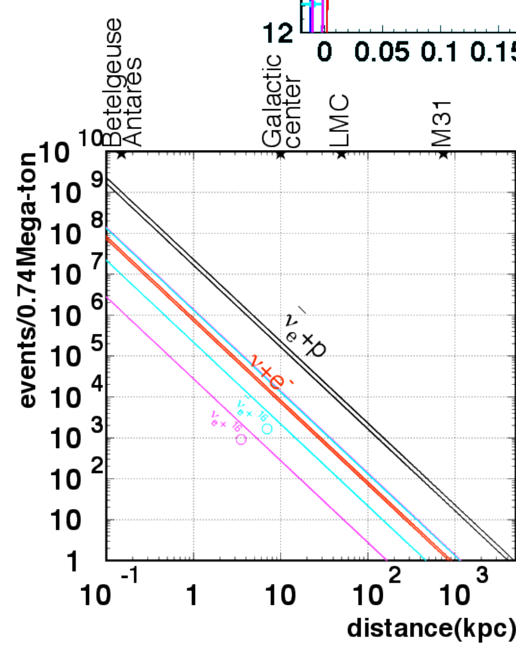


Detection probability of SN neutrinos versus distance. Color indicates the number of events per burst.



Cumulative calculated supernova rate vs distance for SN in nearby galaxies

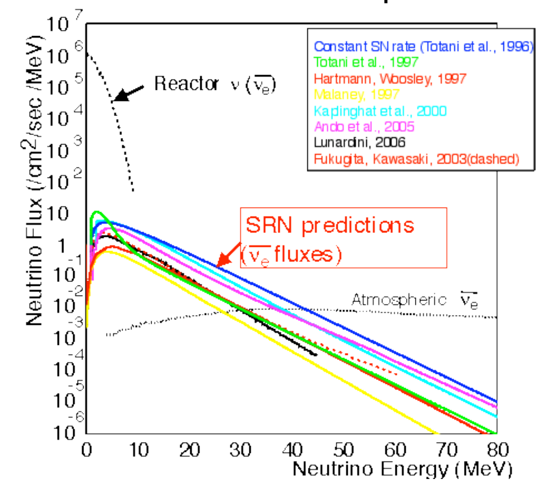


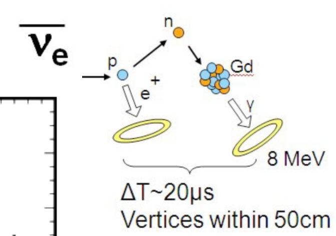


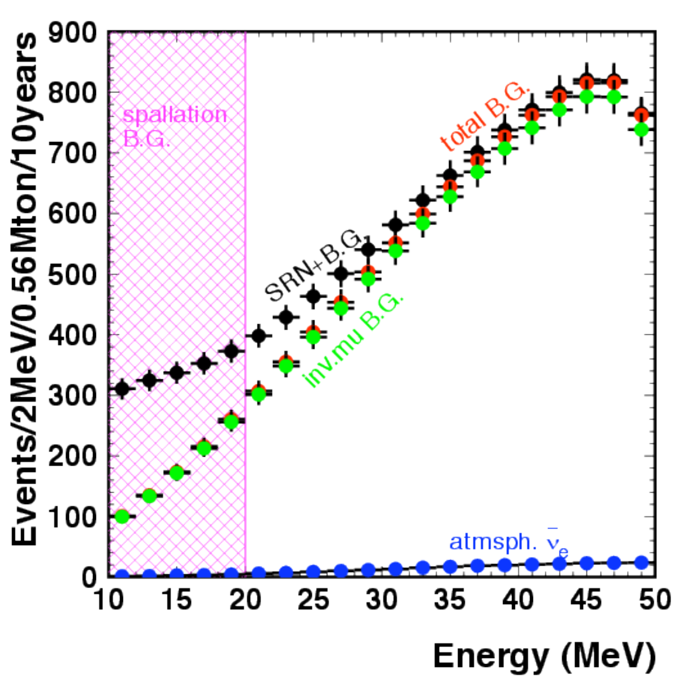
Supernova Relic Neutrinos

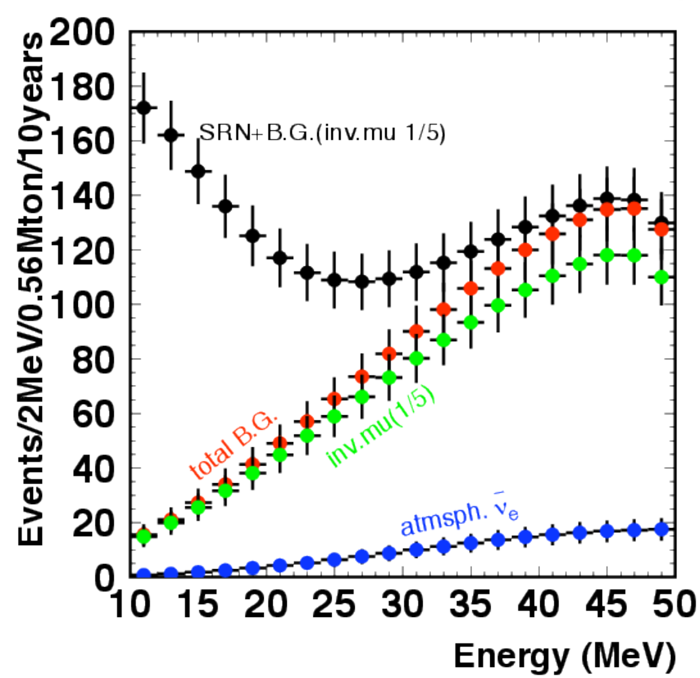
- It is estimated that 1017 supernova explosions have occurred over the entire history of the universe.
- The neutrinos produced by all of the supernova explosions since the beginning of the universe are caled supernova relic neutrinos (SRN)
- Dominants backgrounds are from spallation products and atmospheric neutrinos.
- Gadolinium can help in reducing the background

Predictions of SNR spectrum





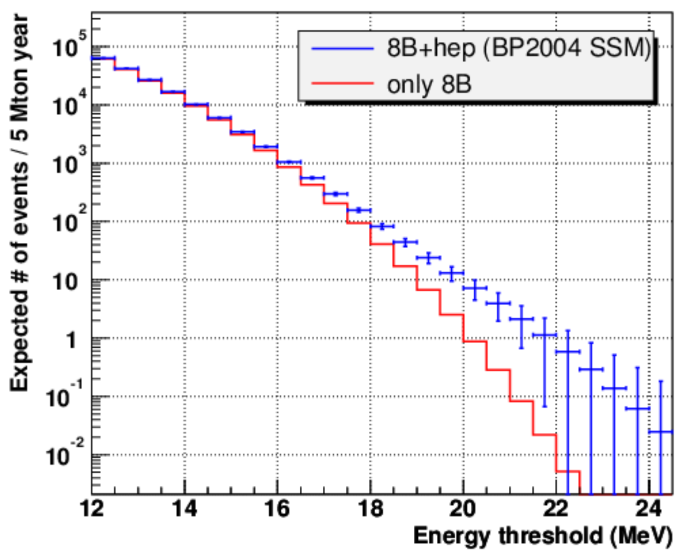




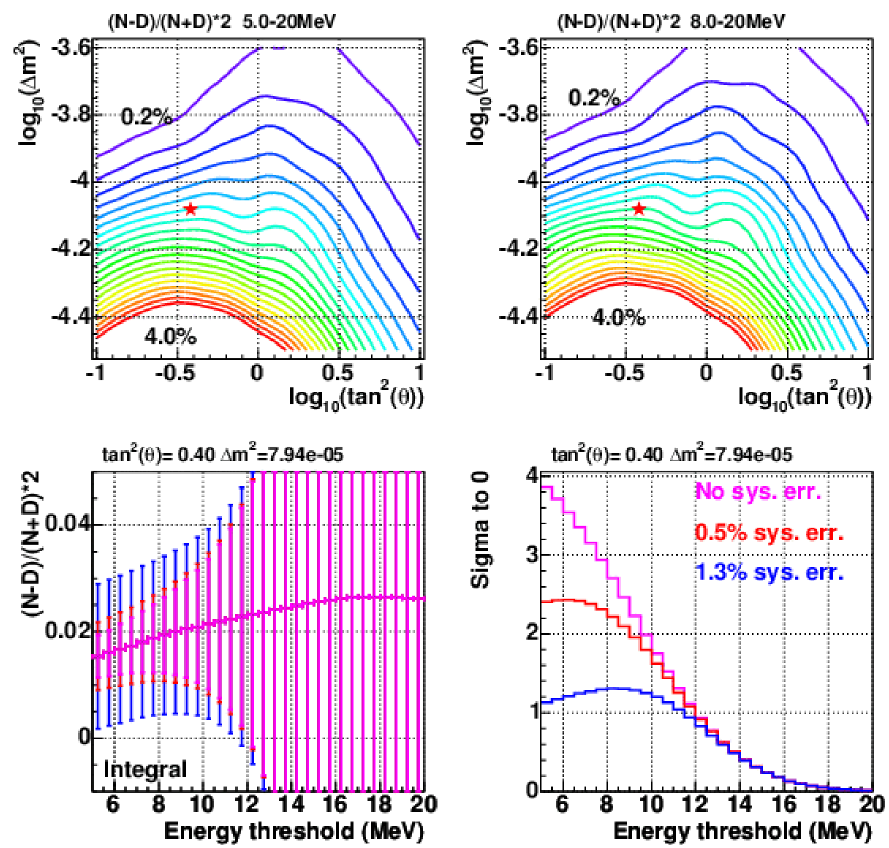
Solar Neutrinos

- Several aims:
  - Precise determination of neutrino oscillation parameters (current tension with KamLAND)
  - Improve precision of D/N asymmetry
  - Measure hep neutrinos (not yet seen)
  - Measure up-turn
- Main challenges:
  - Low energy radioactive background
  - Reduce neutrino energy

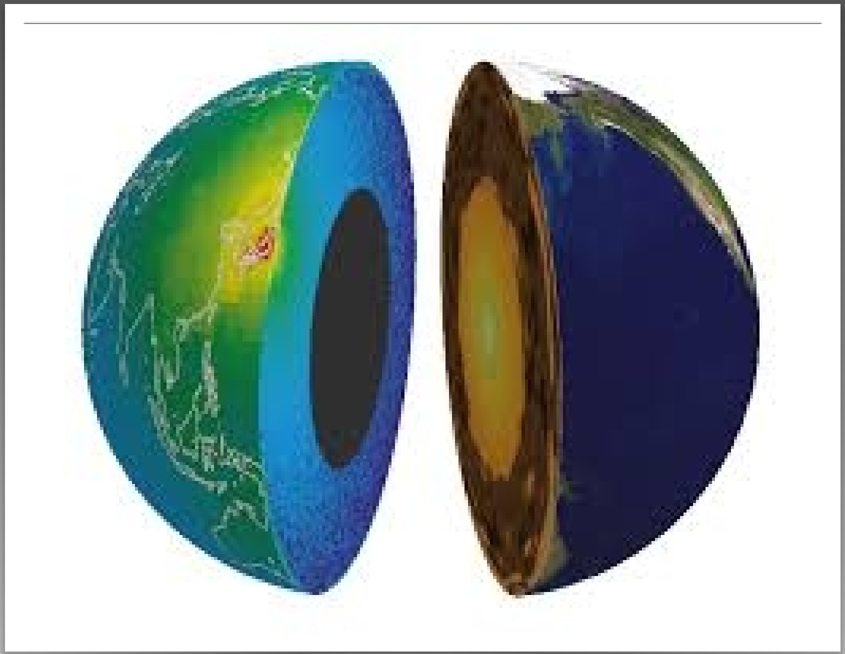
Expected solar neutrino fluxes with neutrino oscillations



Expected day/night asymmetry



Other Topics



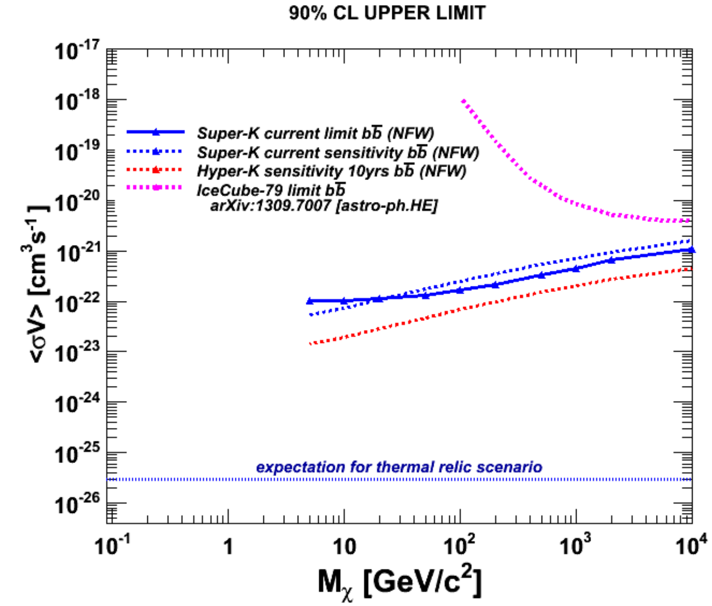
Other Topics

Hyper-Kamiokande is able to perform many other studies:

Indirect Searches for Dark Matter: looking from neutrinos due to the decay of WIMPs bound in strong gravitational potential

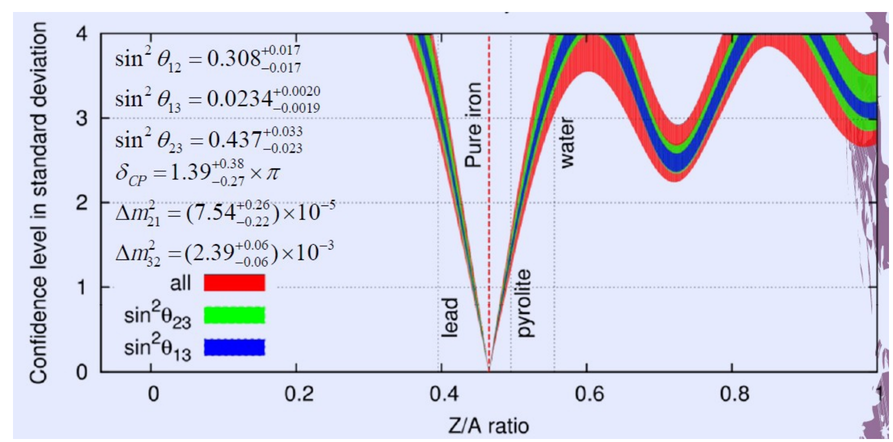
- Search for WIMPs in the galactic centre
- Search from WIMPs from the Sun

Expected limit on the WIMP velocity average annihilation cross sections



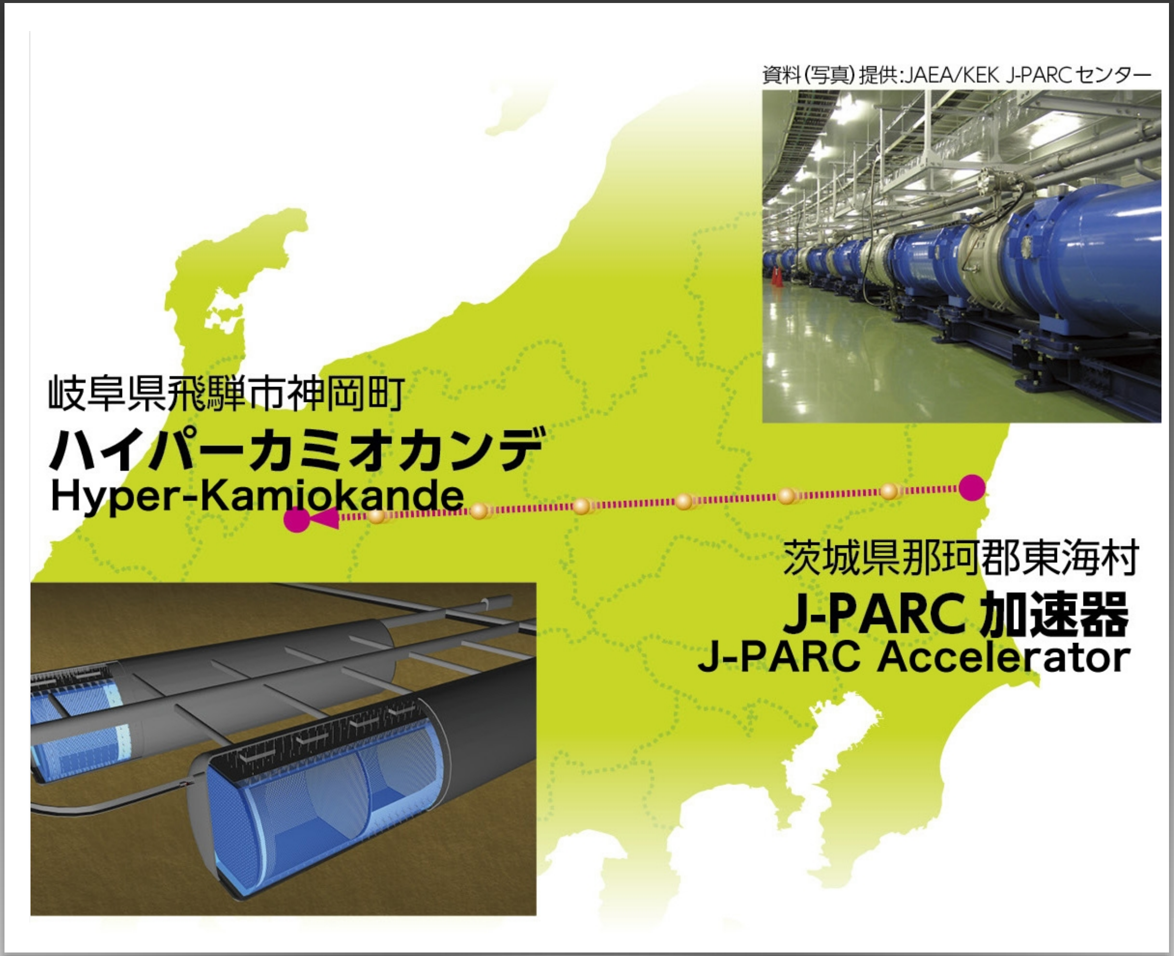
Geoneutrinos: with 10 years of ATM data Hyper-K can open the field of Earth Spectroscopy:

- First Z/A measurement, can exclude lead-based and water-based outer core
- Longer exposures more useful (want to discriminate iron from pyrolite)



Moreover: sterile neutrinos, Lorentz Violation, cross sections (at near detectors), transient astrophysical phenomena (solar flares, GBR, etc),..

Conclusions



Conclusions

- Neutrino physics has been steadily establishing in the last years as a major physics topics.

- Several experiments have and will investigate the neutrino nature.

- Hyper-K is a next generation neutrino experiment that is able to address the major questions in physics
  - CP Violation in the leptonic sector
  - Proton decay
  - Neutrino Mass hierarchy
  - Supernova
  - …

- Currently in the R&D phase. Aiming to take data in the next decade.