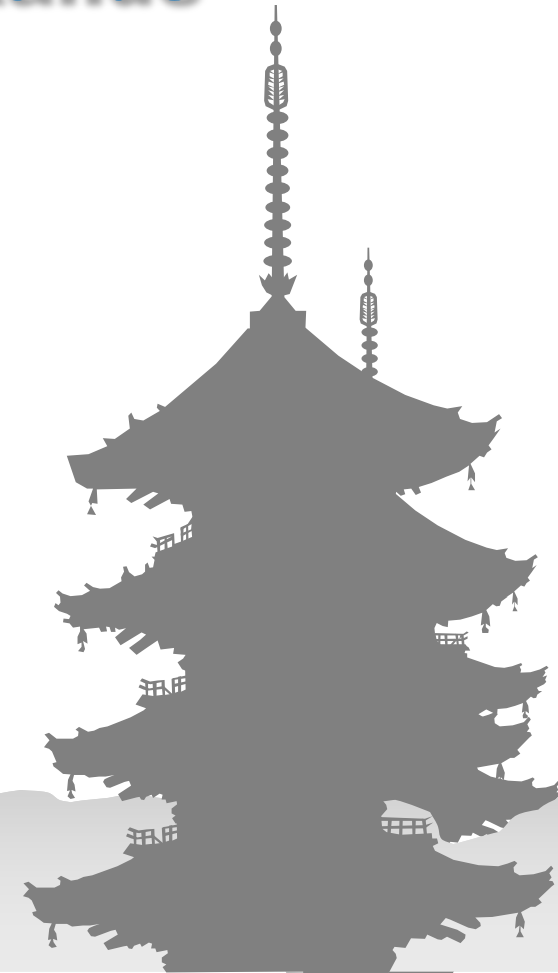


L'après-T2K pour la mesure d'une violation CP leptonique

Le projet Hyper-Kamiokande

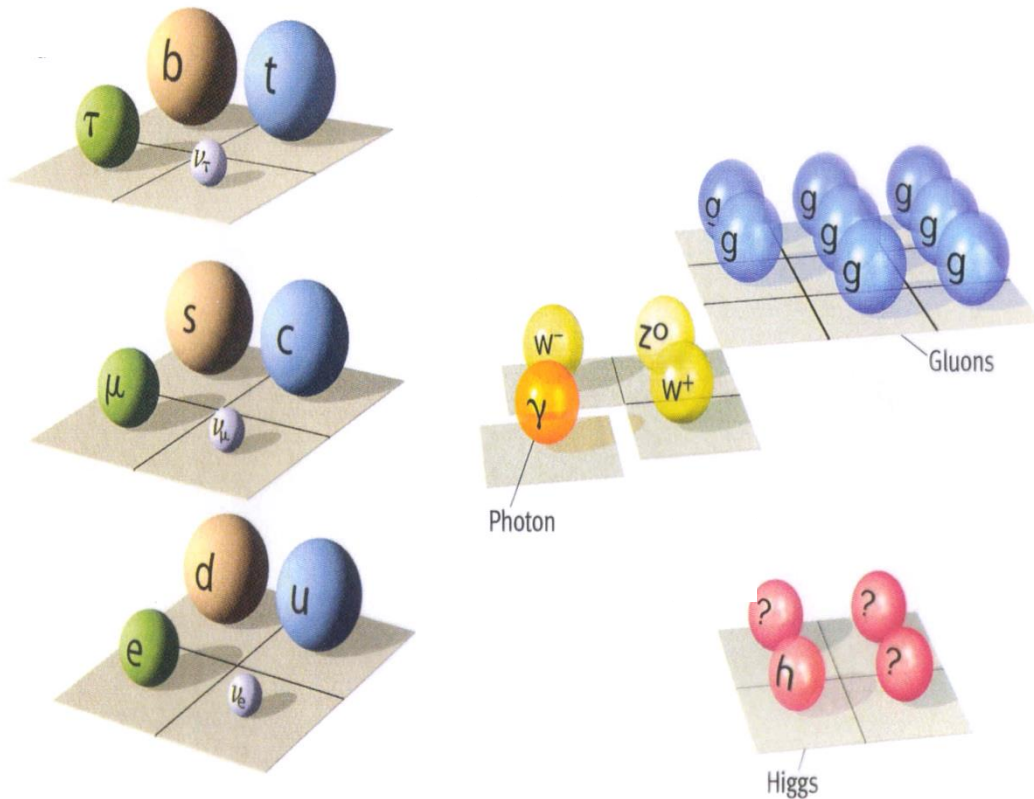


Michel Gonin - 23 mai 2013 - CS LLLR



Le modèle standard de la physique des particules

26 paramètres libres dont 8 pour les neutrinos



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Flavor States



Mass States



Mass 1

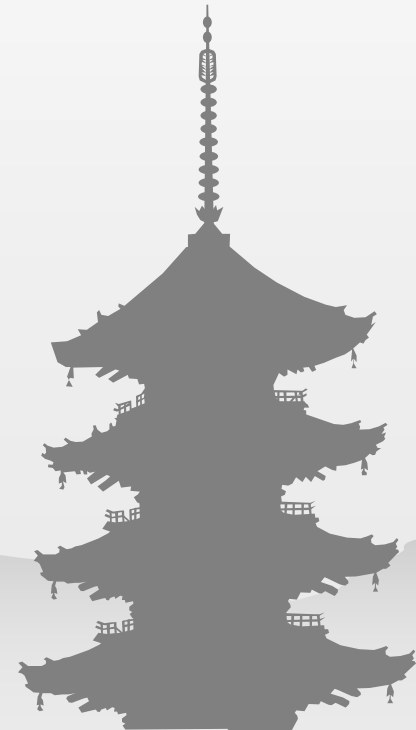
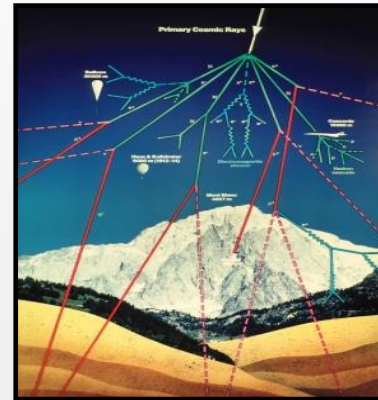
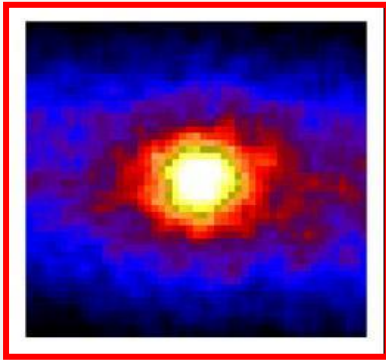
Mass 2

Mass 3

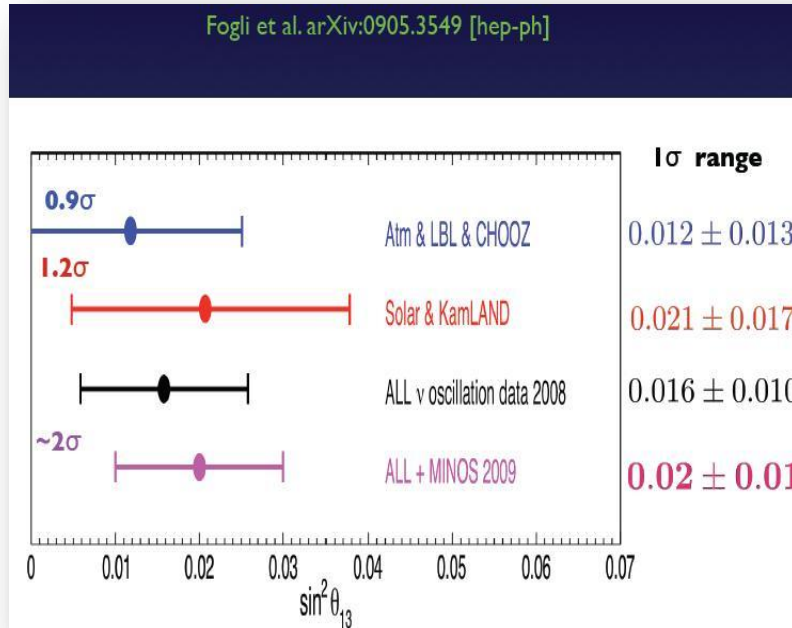
Mesure des angles de mélange

$$\theta_{12} = 33.6^\circ \pm 1.0^\circ$$
$$\theta_{23} = 45^\circ \pm 6^\circ$$

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



La matrice de mélange



θ_{13}

← Avant 2012

Le futur programme de la physique des neutrinos dépendait fortement de la valeur de θ_{13}

Pour les études CP, θ_{13} devait être différent de zéro



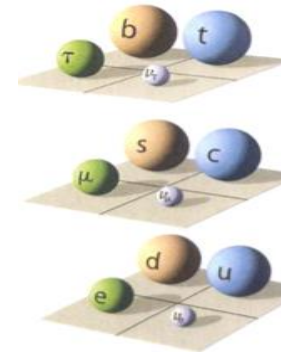
"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature".



◆ états de masse \neq états de saveur

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

◆ 3 générations de particules



◆ 3 angles de mélange, tous différents de zéro



Violation CP $\delta \neq 0$

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

Oscillation quantique sur 300 km

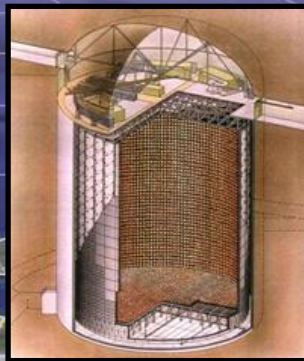
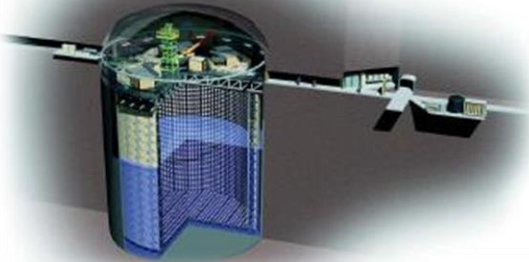


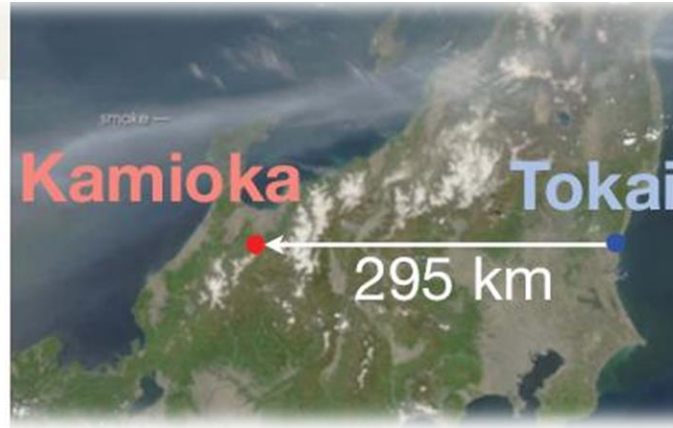
Image NASA
© 2007 Europa Technologies
Image © 2007 TerraMetrics
© 2007 ZENRIN

T2K

Super-K@Kamioka



- Huge far detector

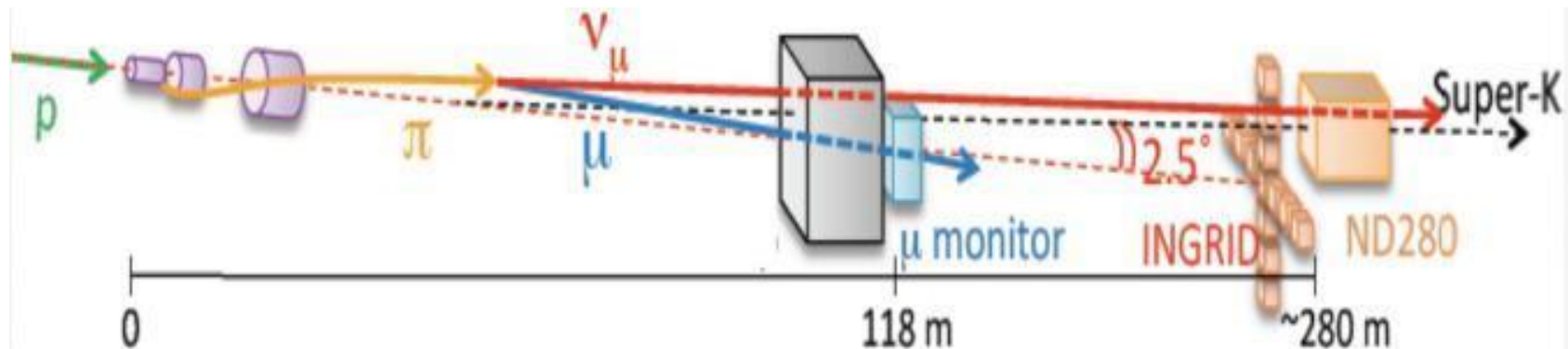


J-PARC Accelerator@Tokai



- Intense beam
- Near detectors

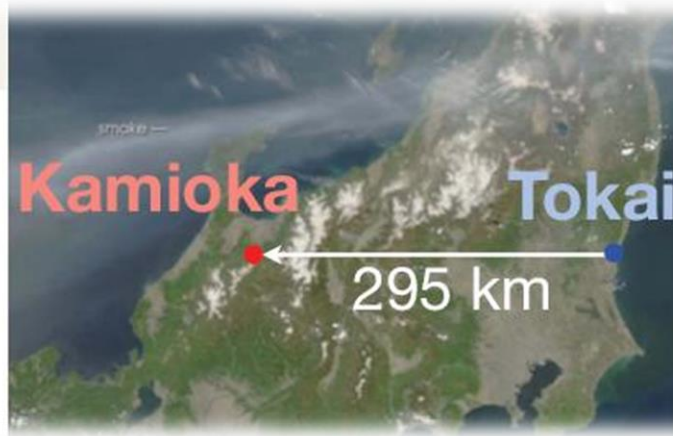
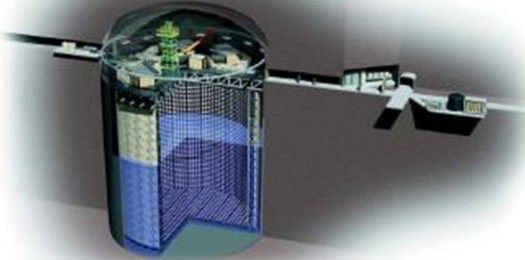
ν_{μ} beam



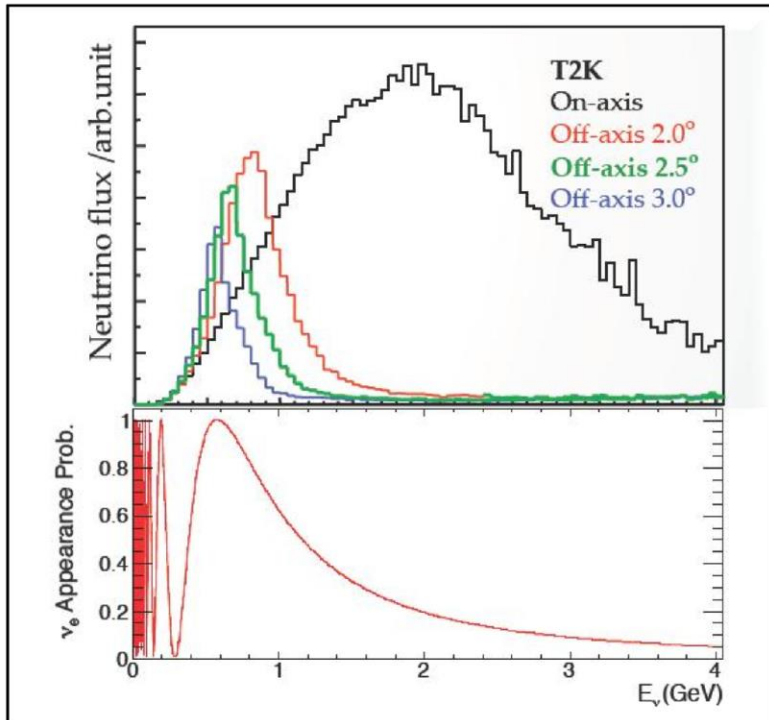
T2K



Super-K@Kamioka



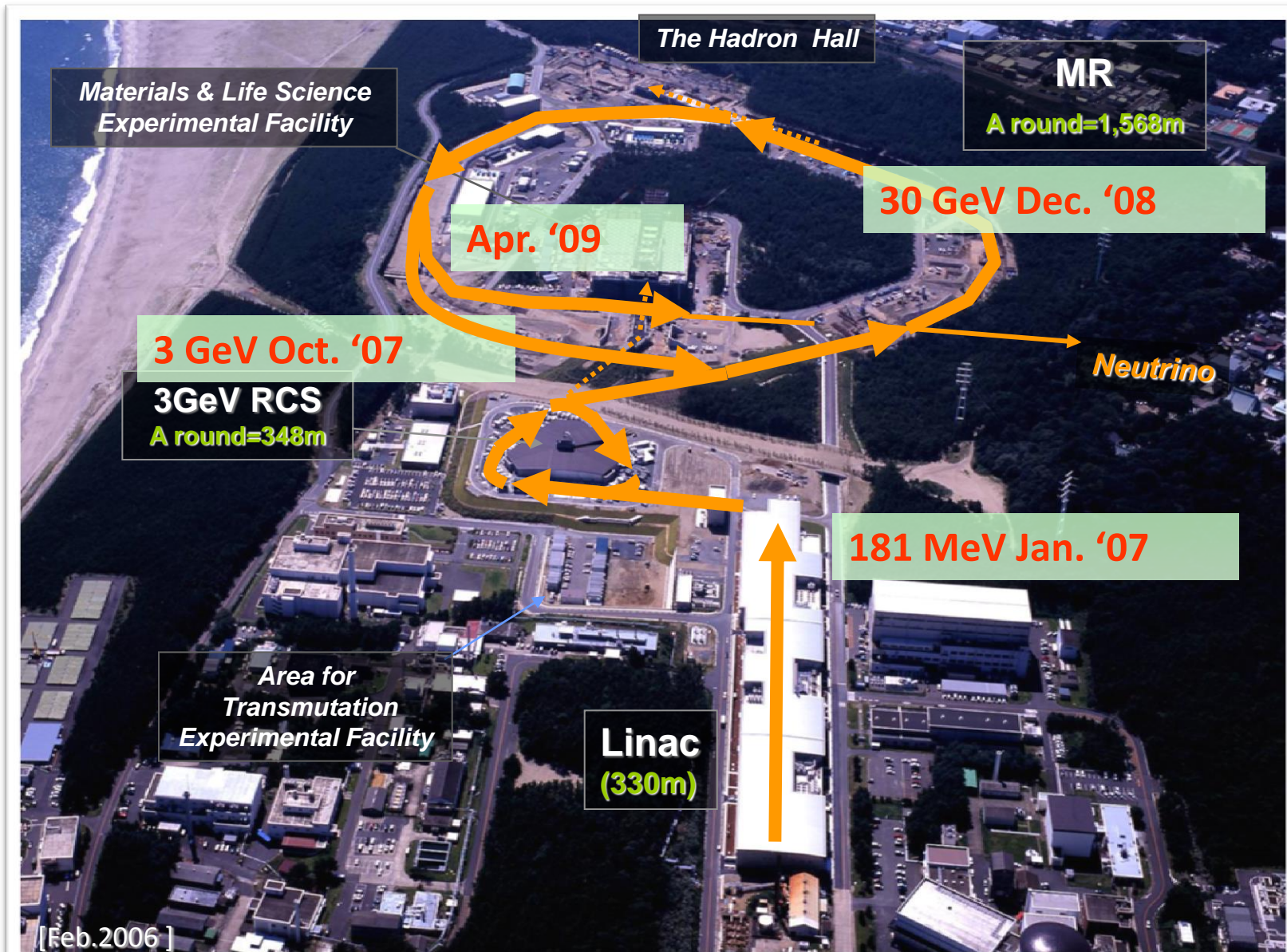
J-PARC Accelerator@Tokai



The Off-axis 'trick'

Oscillation probability at the Super Kamiokande detector

J-PARC Accelerators

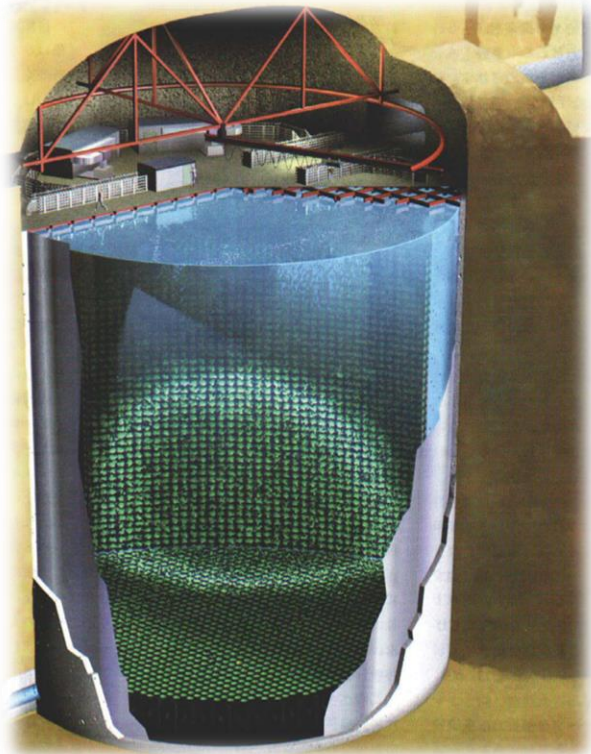


T2K Detectors

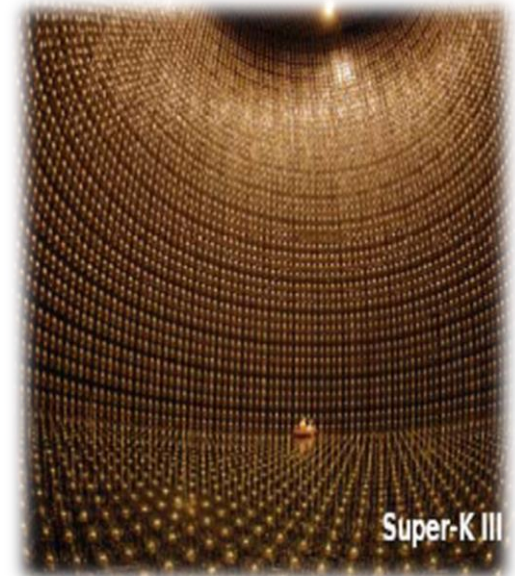


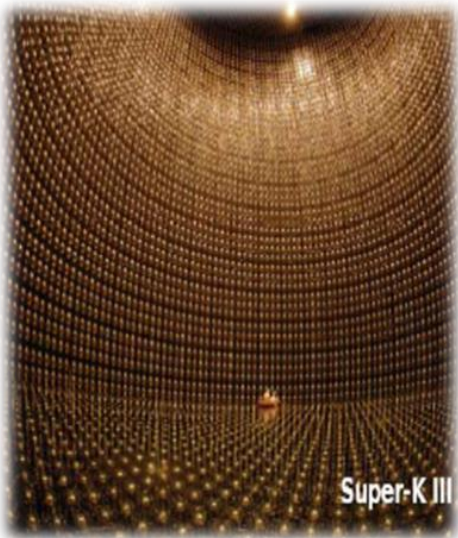
Far detector Super Kamiokande @ 295 km from the target

- **Water Cherenkov detector** with 50 kton mass (22.5 kton Fiducial volume) located at 1km underground
- **Good performance** (momentum and position resolution, PID, charged particle counting) for sub-GeV neutrinos

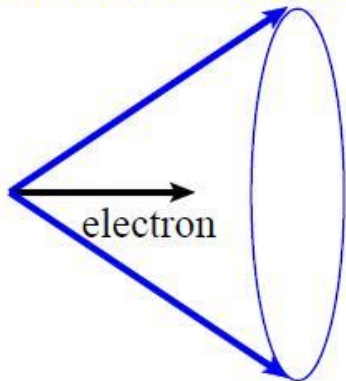


High ~ 40 meters
Diameter ~ 40 meters

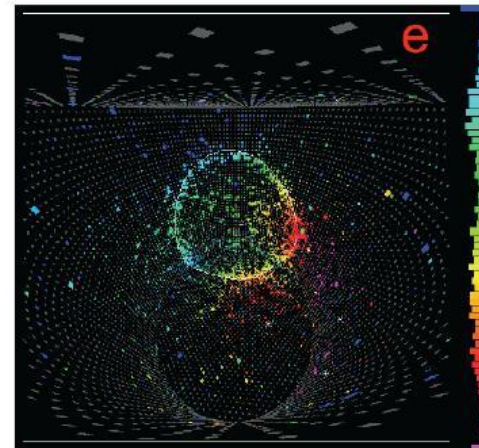
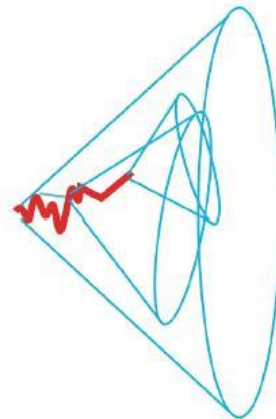




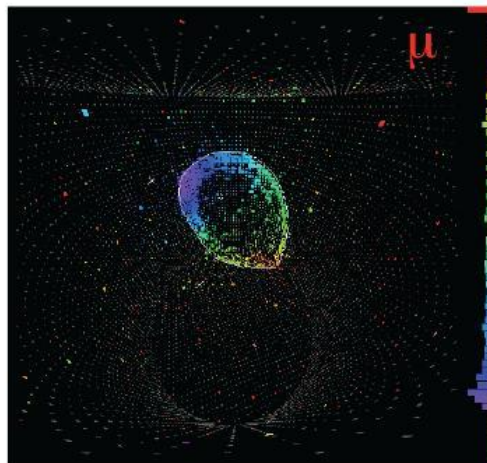
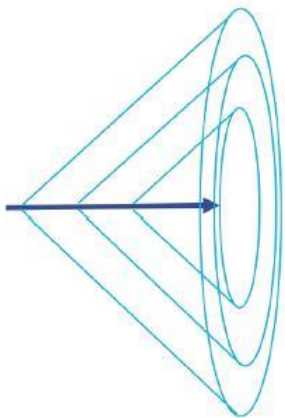
Cherenkov cone



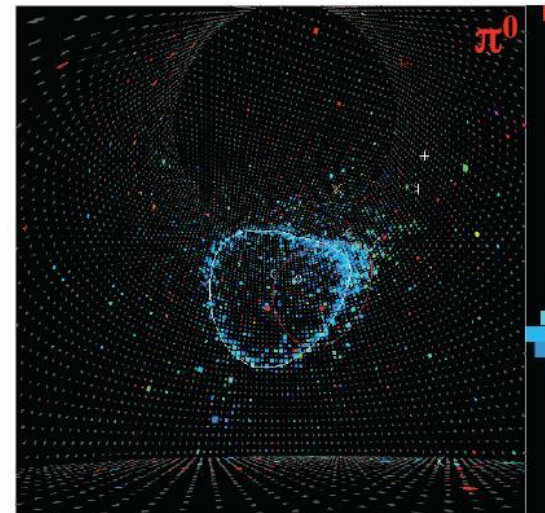
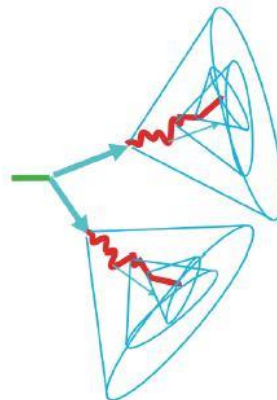
Super-K



Super-K

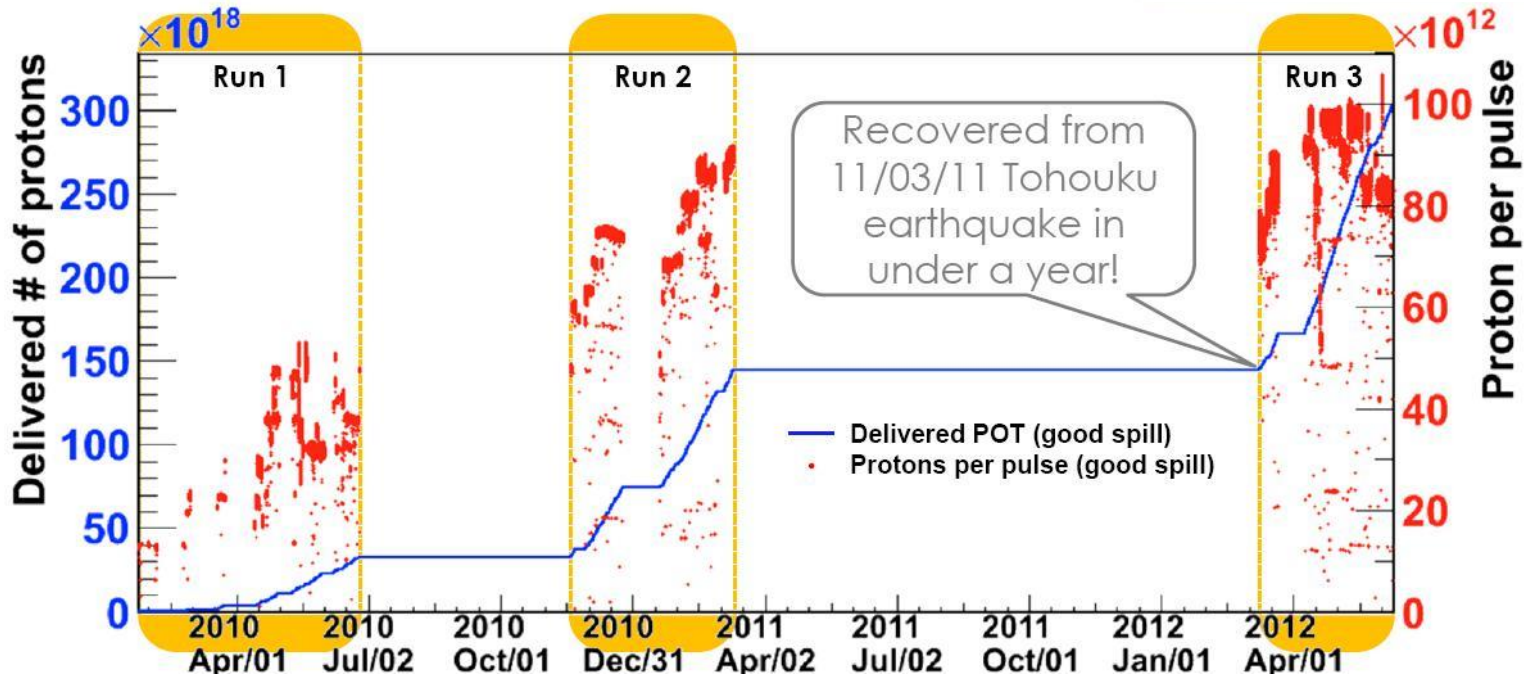


Super-K

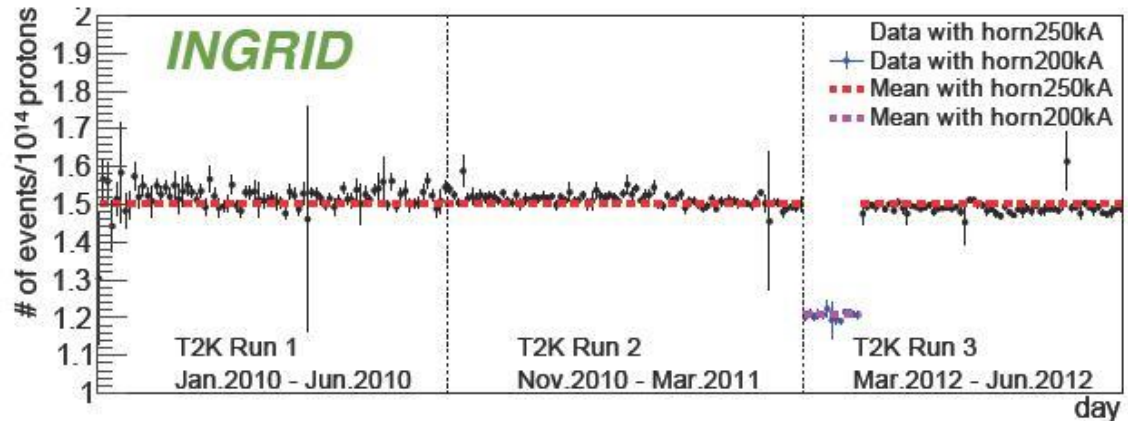


T2K Results

6% of data goal
 3.01×10^{20} POT

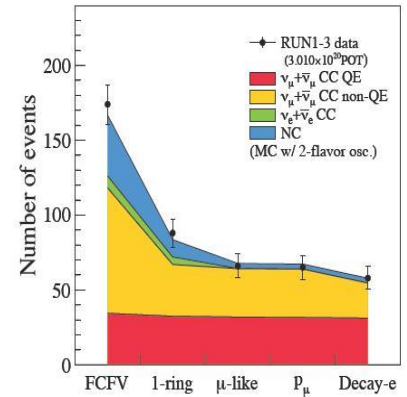
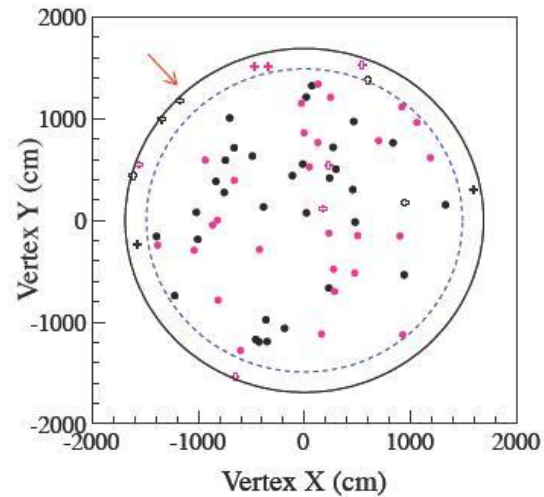
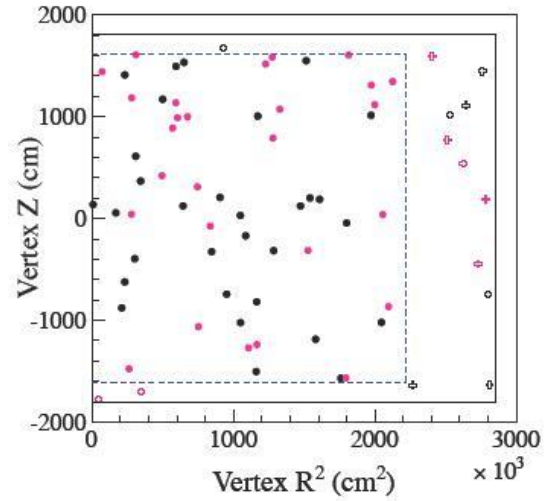
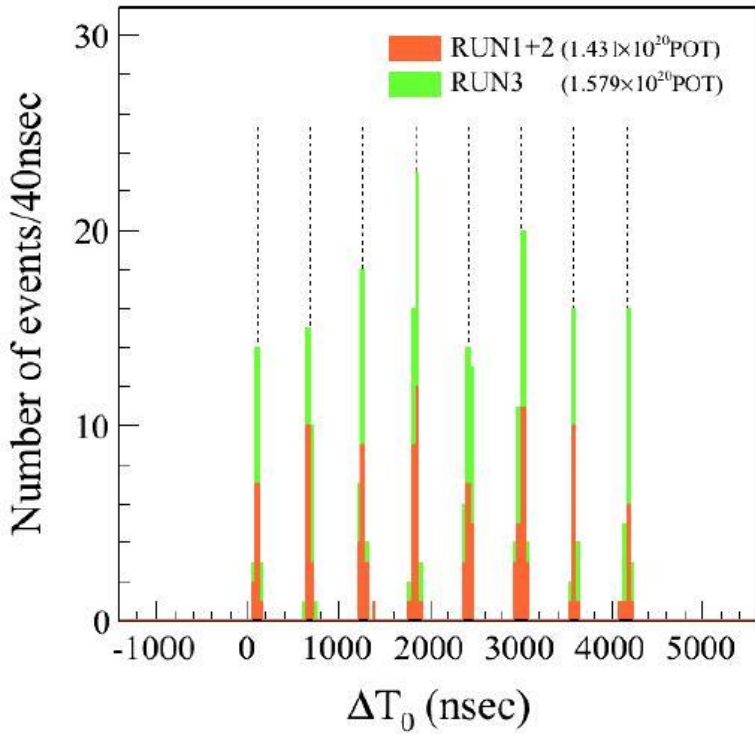


Data collected and analyzed



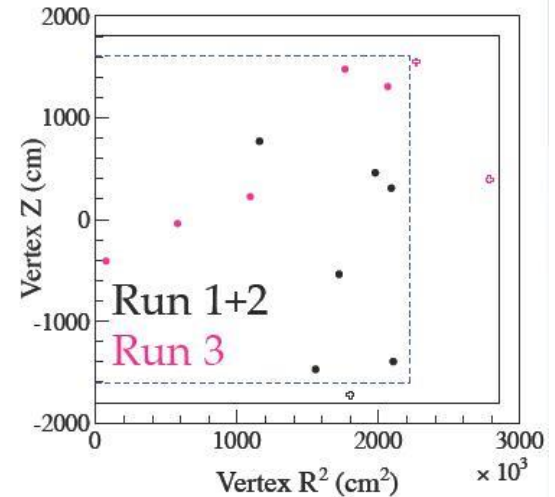
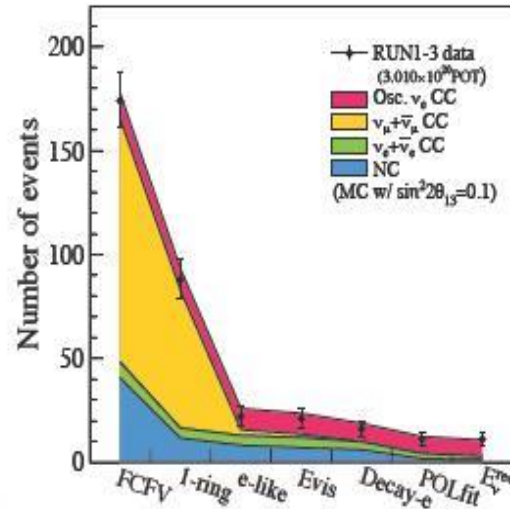
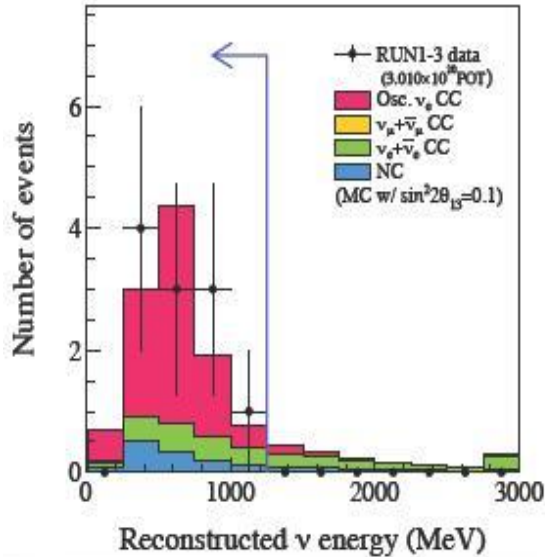
ν_μ disparition

J-PARC Accelerator@Tokai



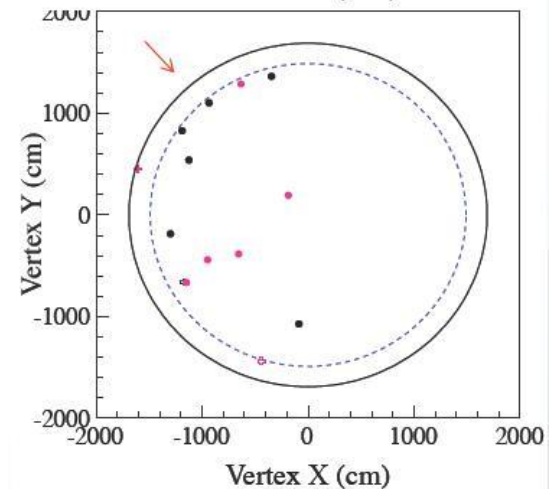
58 événements

ν_e apparition

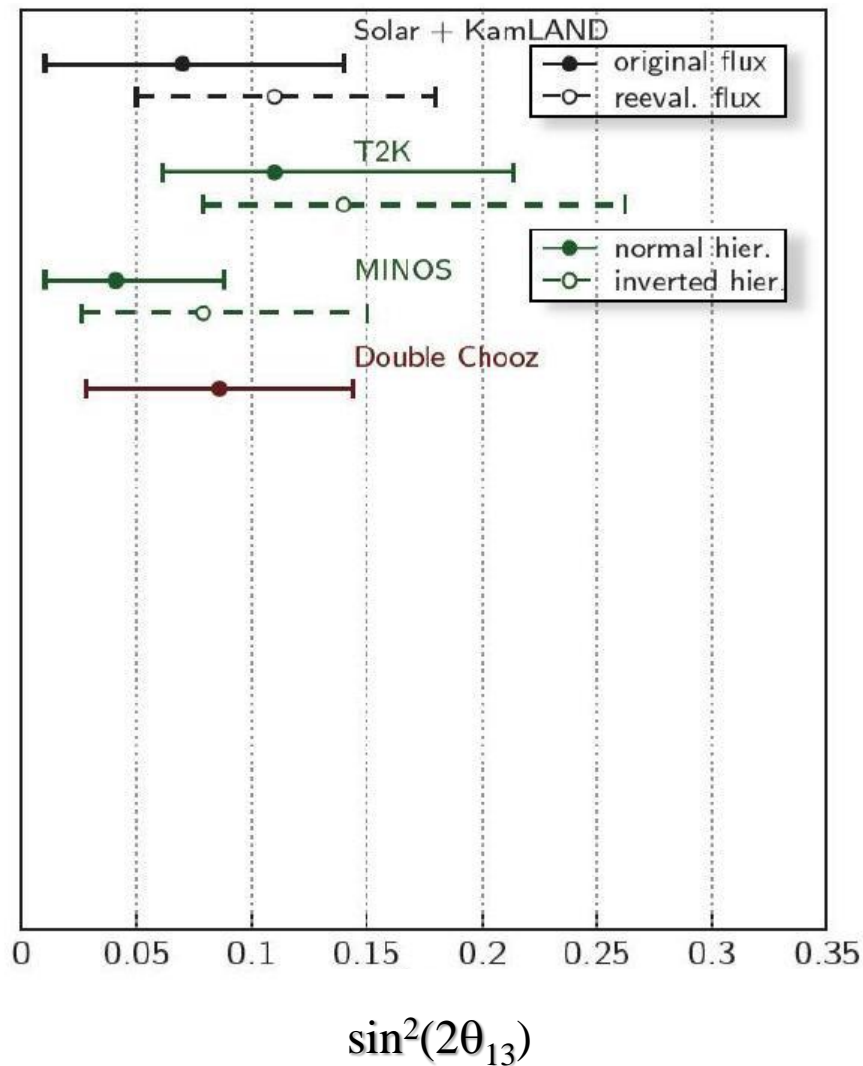
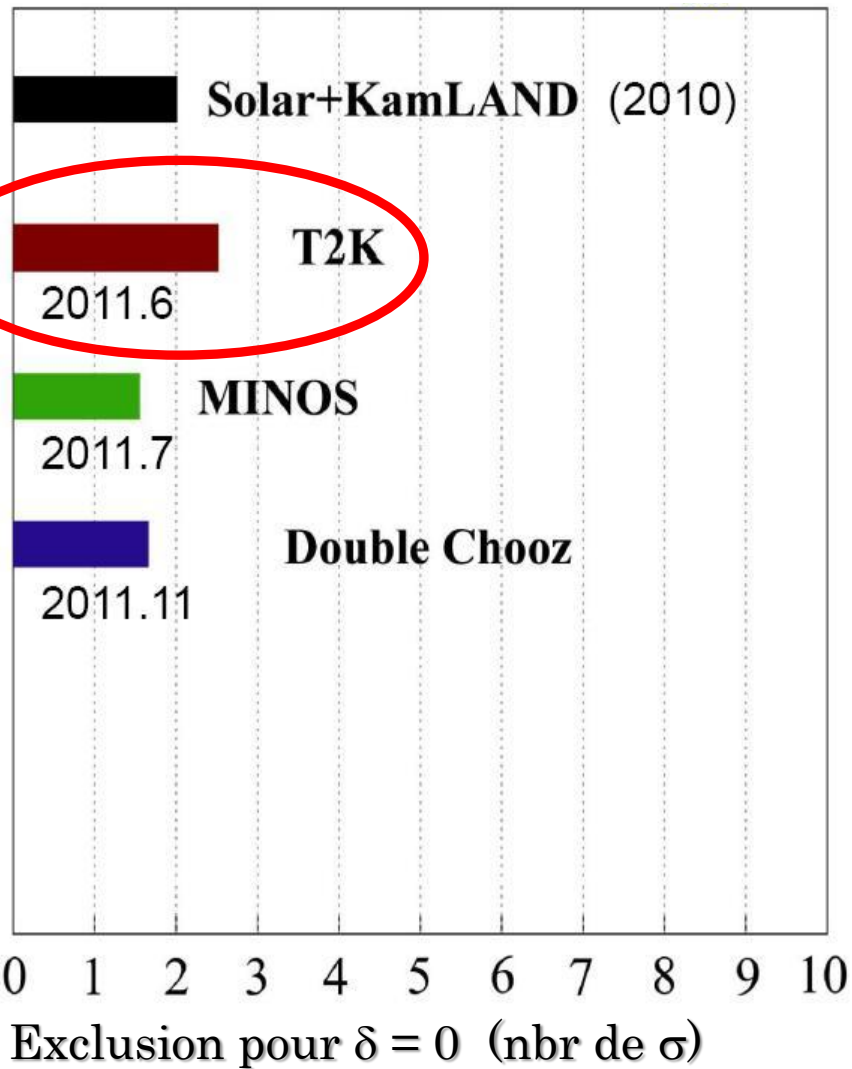


11 événements

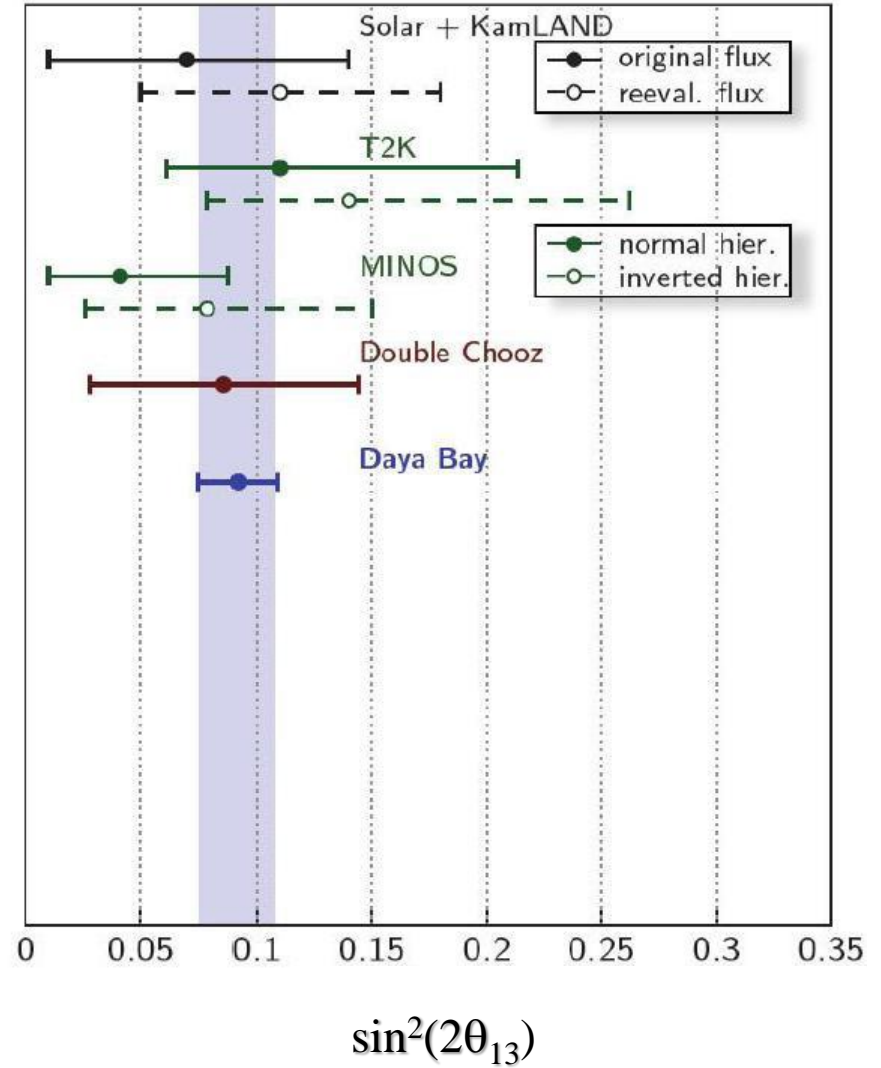
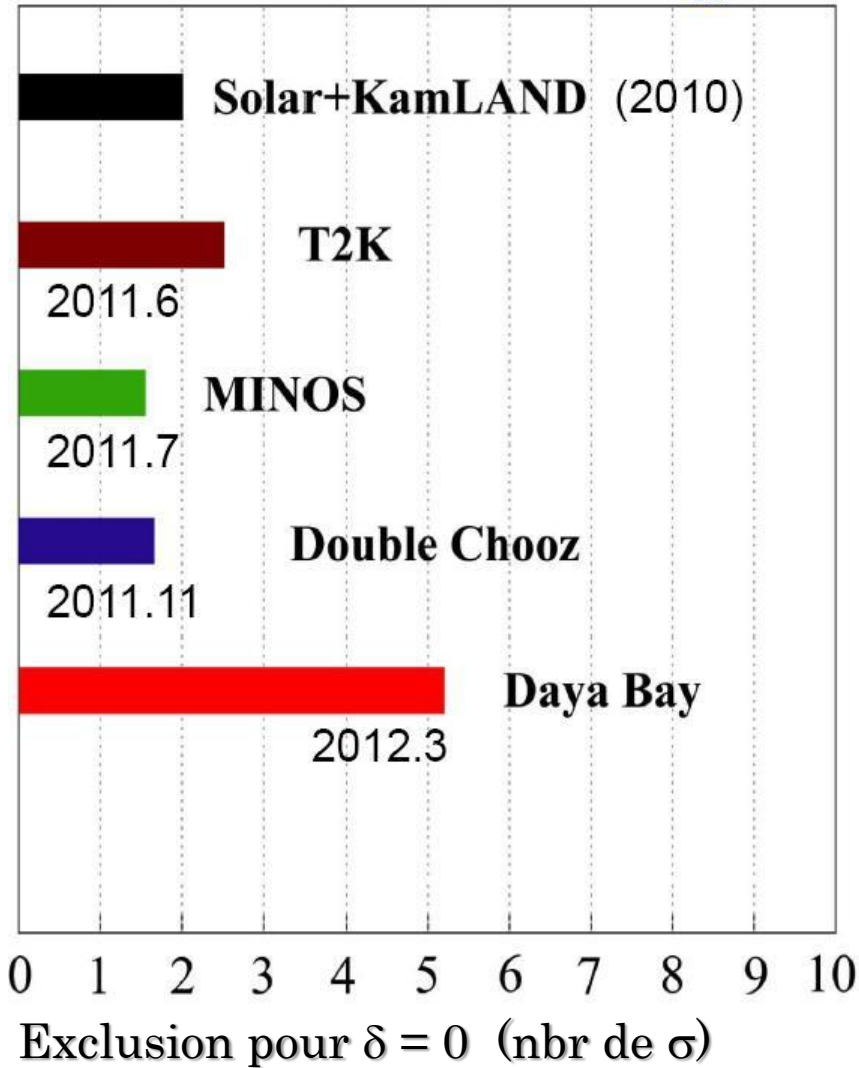
Event category	The predicted number of events	
	$\sin^2 2\theta_{13} = 0.0$	$\sin^2 2\theta_{13} = 0.1$
Total	3.22	10.71
ν_e signal	0.18	7.79
ν_e background	1.67	1.56
ν_μ background	1.21	1.21
$\bar{\nu}_\mu$ background	0.07	0.07
$\bar{\nu}_e$ background	0.09	0.09



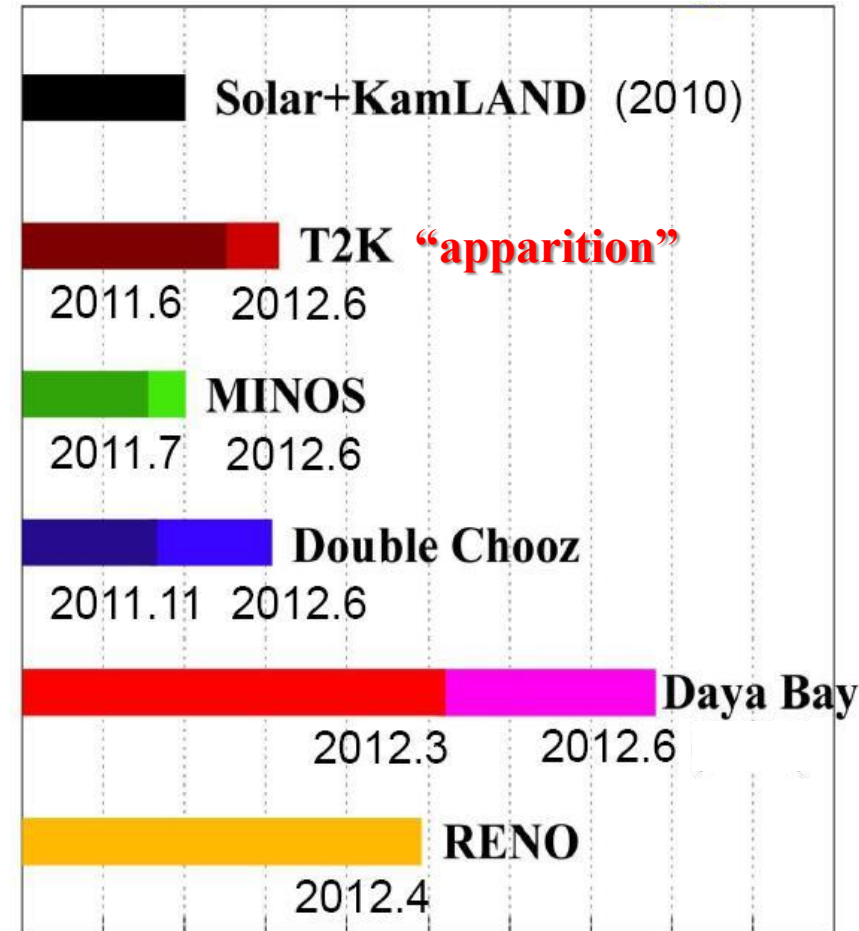
T2K et les autres expériences



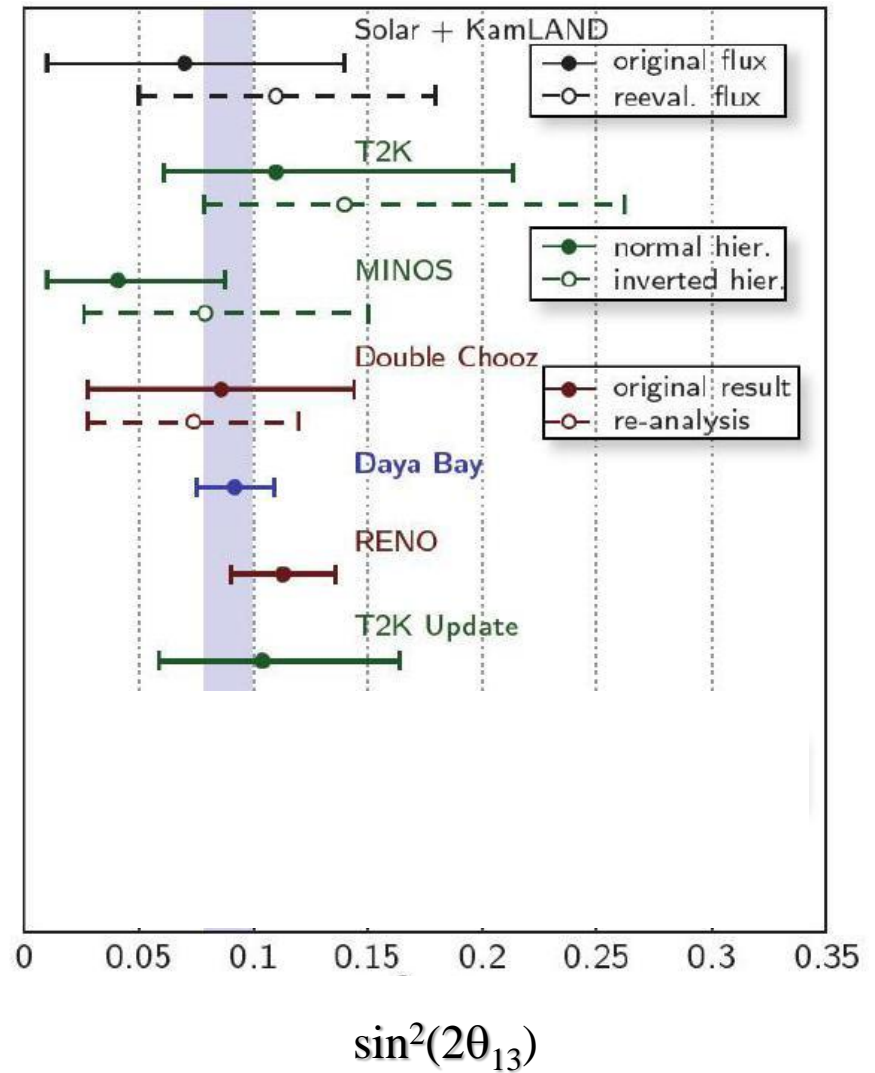
T2K et les autres expériences



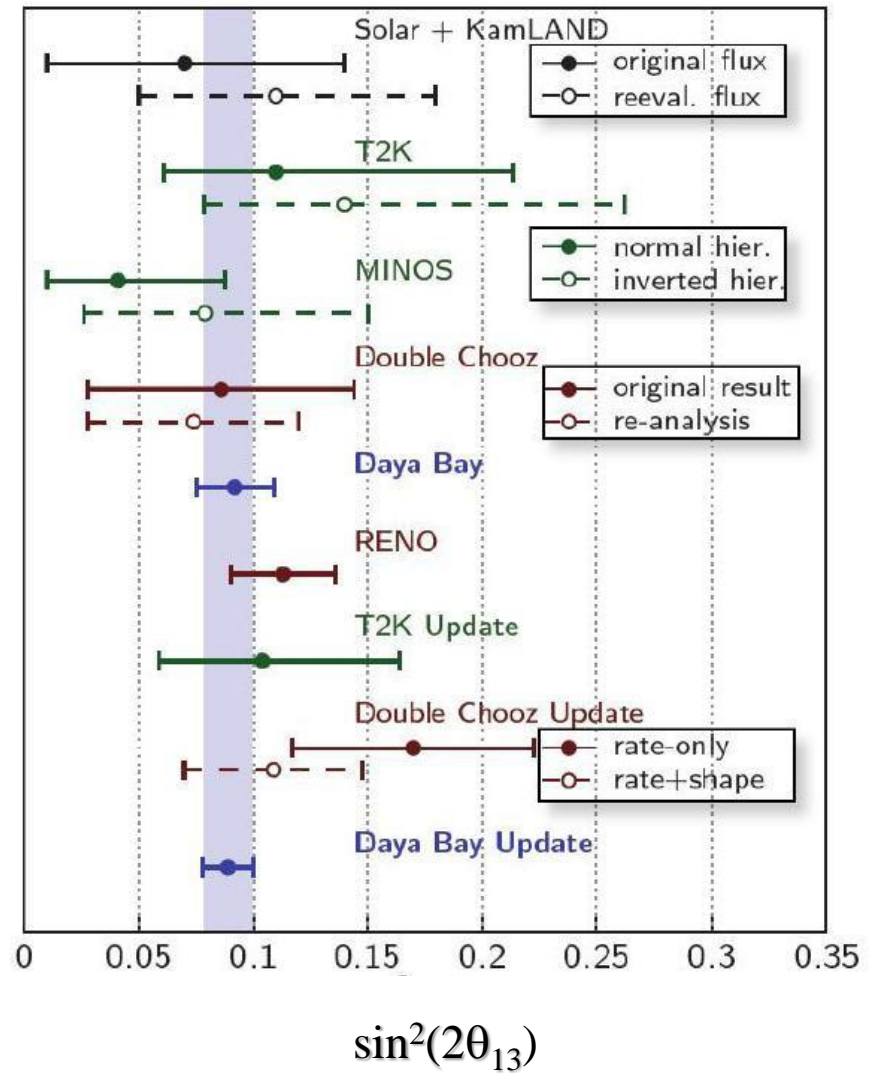
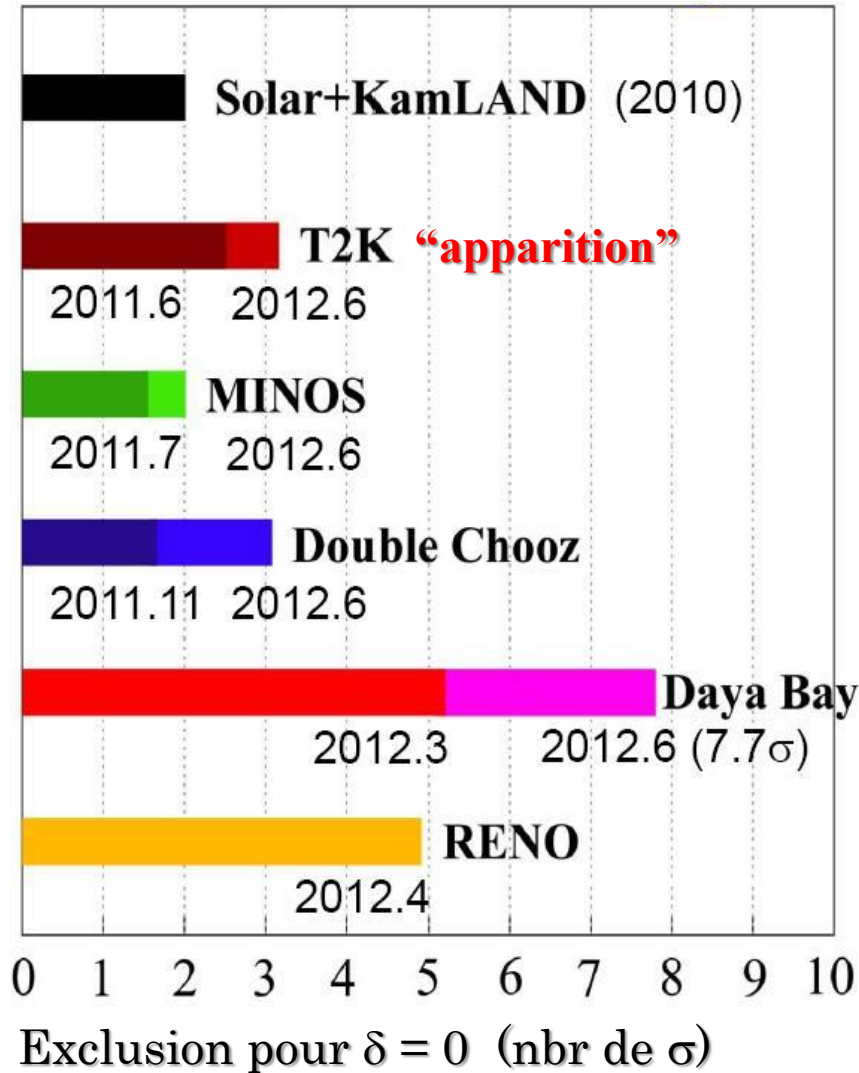
T2K et les autres expériences



Exclusion pour $\delta = 0$ (nbr de σ)



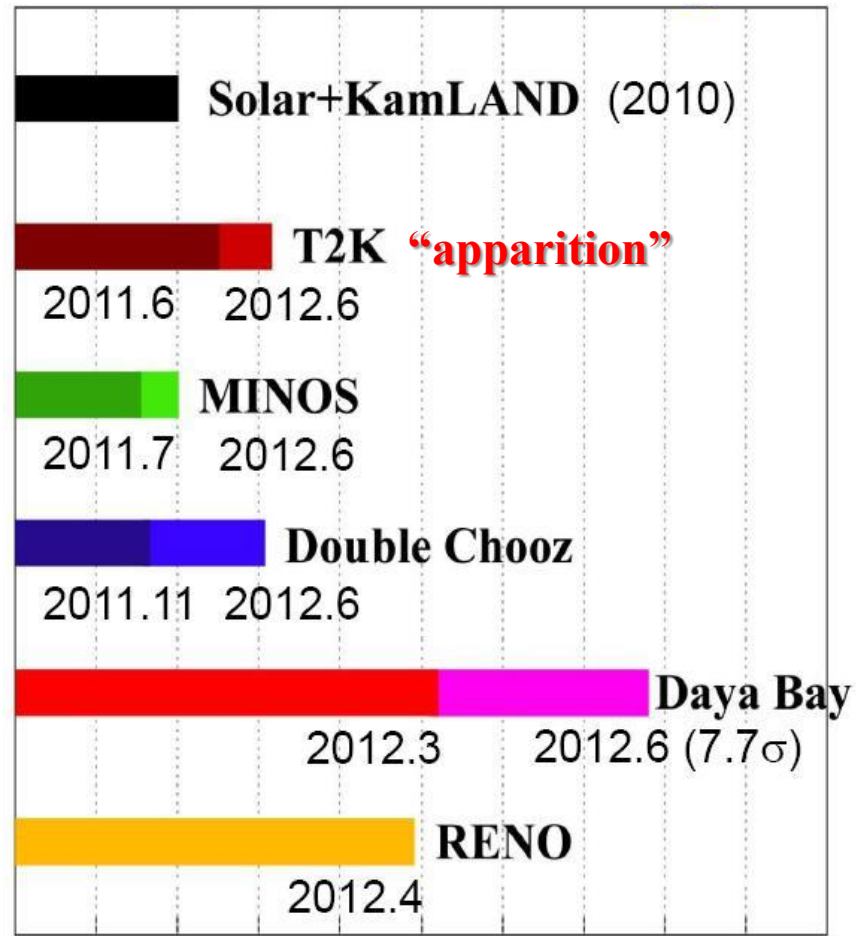
T2K et les autres expériences



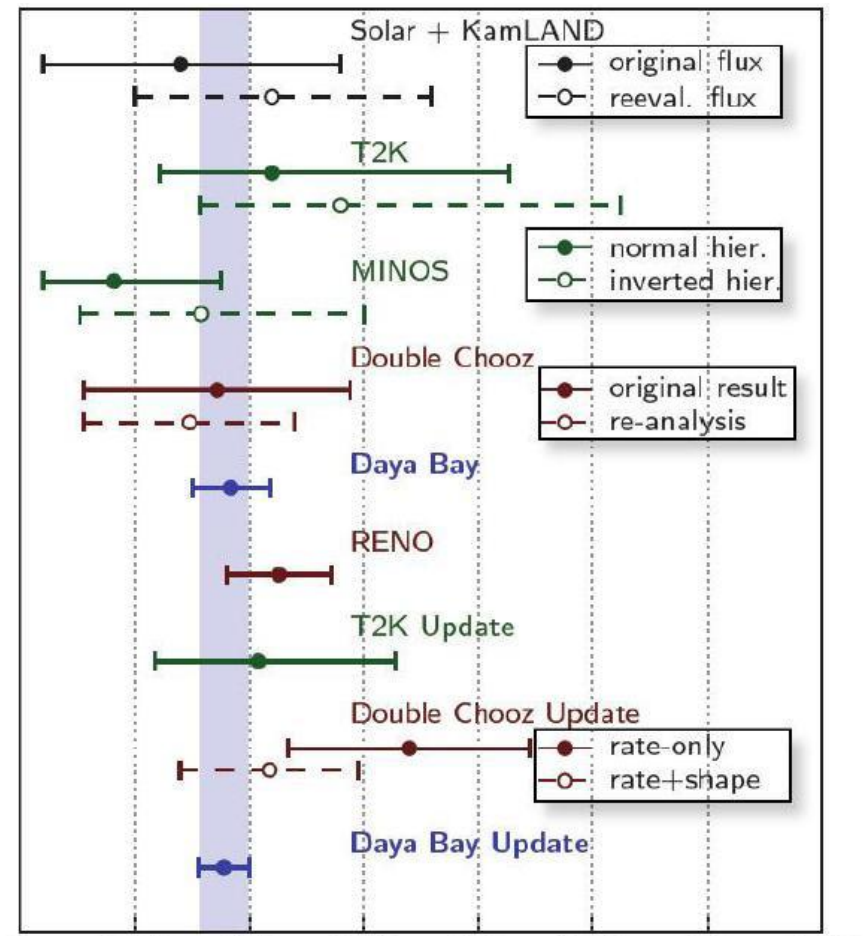


$$\theta_{13} = 9.1^\circ \pm 0.6^\circ$$

Nouveaux résultats T2K cet été



Exclusion pour $\delta = 0$ (nbr de σ)



$\sin^2(2\theta_{13})$

$$\theta_{13} = 9.1^\circ \pm 0.6^\circ$$

3.01 x 10²⁰ POT
6% of data goal

11 événements d'apparition à ~ 3σ

Nouveaux résultats T2K cet été

~ 7 x 10²⁰ POT
14% of data goal

~ 26 événements d'apparition ? > 5σ ?

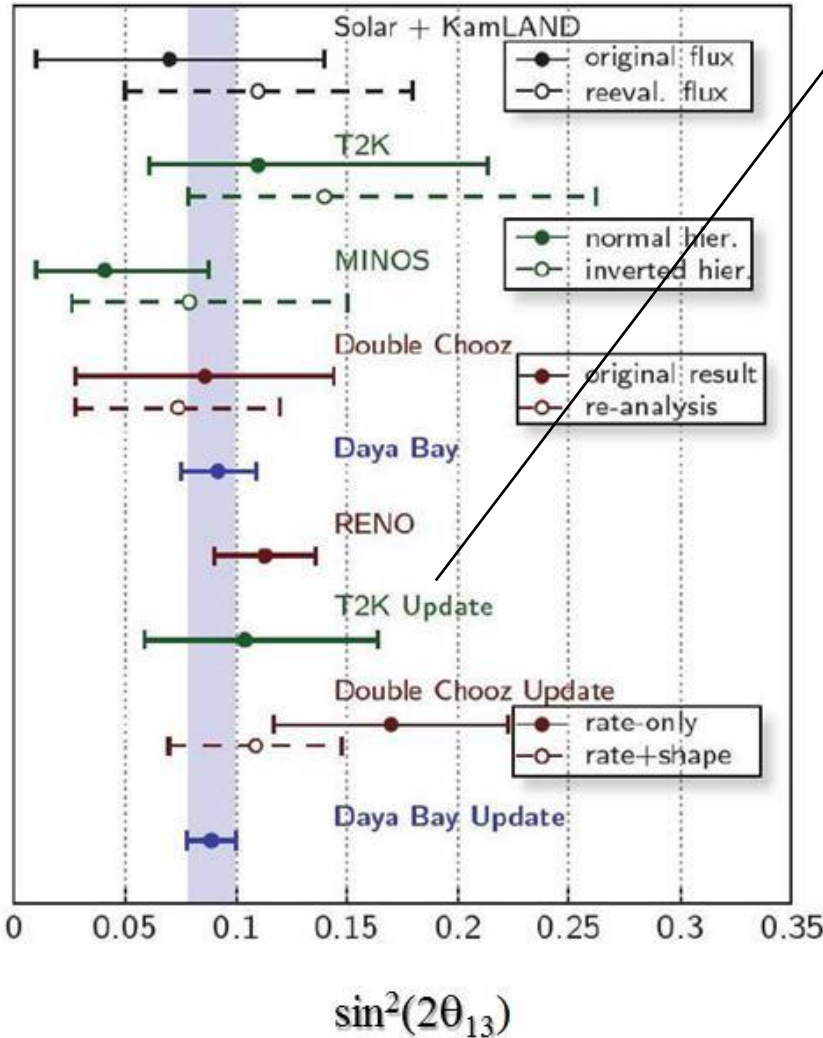
5 x 10²¹ POT
100% of data goal

~ 200 événements d'apparition

Tokai-to-Kamioka (T2K) Long Baseline Neutrino Oscillation Experiment Proposal

	ν_μ CC BG	ν_μ NC BG	beam ν_e BG	ν_e CC signal
Fully-contained, $E_{vis} \geq 100\text{MeV}$	2215	847	184	243
1 ring e-like, no decay-e	12	156	71	187
$0.35 \leq E_\nu^{rec.} \leq 0.85\text{GeV}$	1.8	47	21	146
e/π^0 separations	0.7	9	13	103

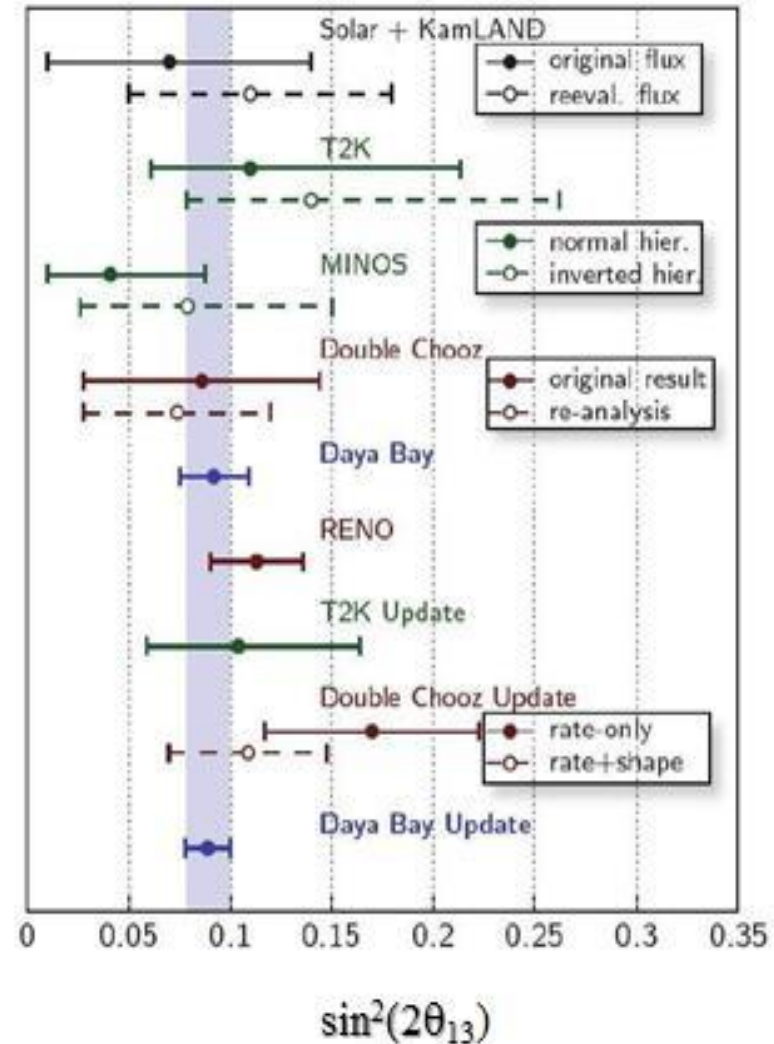
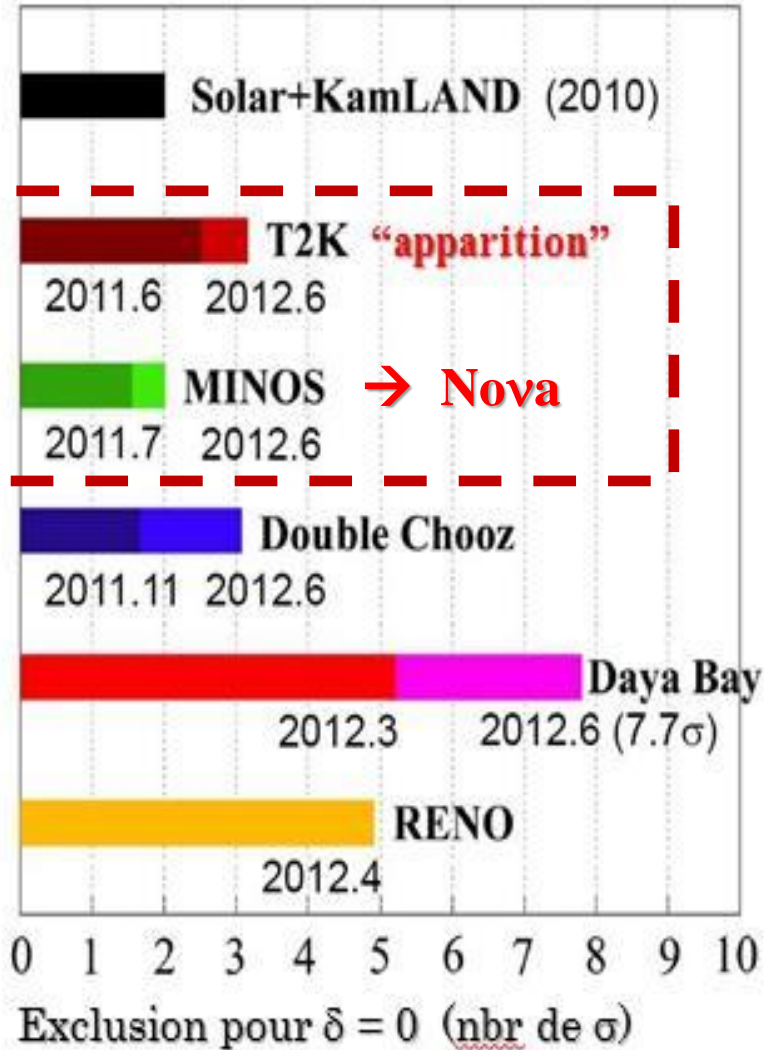
Table 1.3: The number of events selected by the ν_e appearance analysis, as predicted by NEUT Monte Carlo for 5×10^{21} POT exposure.




$$\sin^2(2\theta_{13})$$

T2K Perspective

phase δ
CP



Letter of Intent:
The Hyper-Kamiokande Experiment
— Detector Design and Physics Potential —

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K. Nishijima,⁹ Y. Nishimura,¹² Y. Obayashi,^{12,14} K. Okumura,¹³ M. Sakuda,⁷ H. Sekiya,^{12,14}
M. Shiozawa,^{12,14}  A. T. Suzuki,³ Y. Suzuki,^{12,14} A. Takeda,^{12,14} Y. Takeuchi,^{3,14}
H. K. M. Tanaka,¹¹ S. Tasaka,¹ T. Tomura,¹² M. R. Vagins,¹⁴ J. Wang,¹⁰ and M. Yokoyama^{10,14}

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¹⁰*University of Tokyo, Department of Physics, Bunkyo, Tokyo 113-0033, Japan*

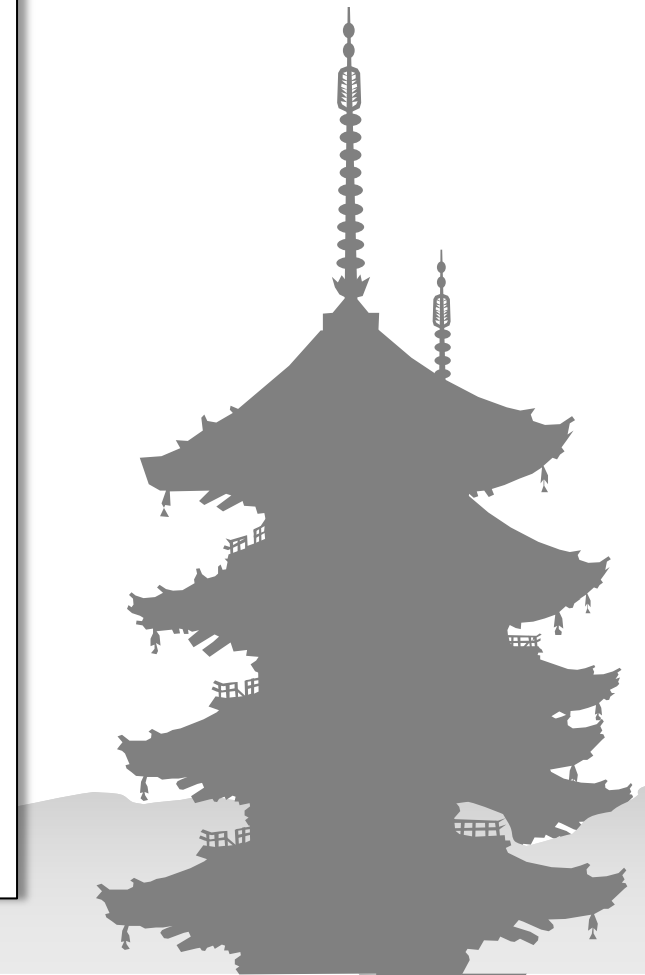
¹¹*University of Tokyo, Earthquake Research Institute, Bunkyo, Tokyo 113-0032, Japan*

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Research Center for Cosmic Neutrinos, Kashiwa, Chiba 277-8582, Japan*

¹⁴*University of Tokyo, Institute for the Physics and Math-
ematics of the Universe, Kashiwa, Chiba 277-8583, Japan*

(Dated: September 16, 2011)



Mesure de θ_{13}

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

$$\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E_\nu}$$

C=cos S=sin



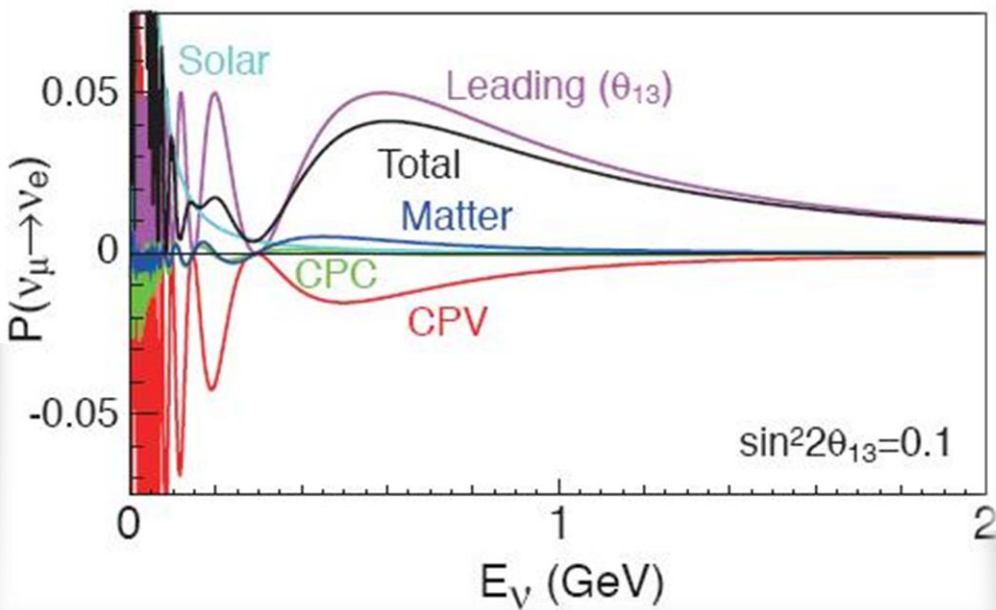
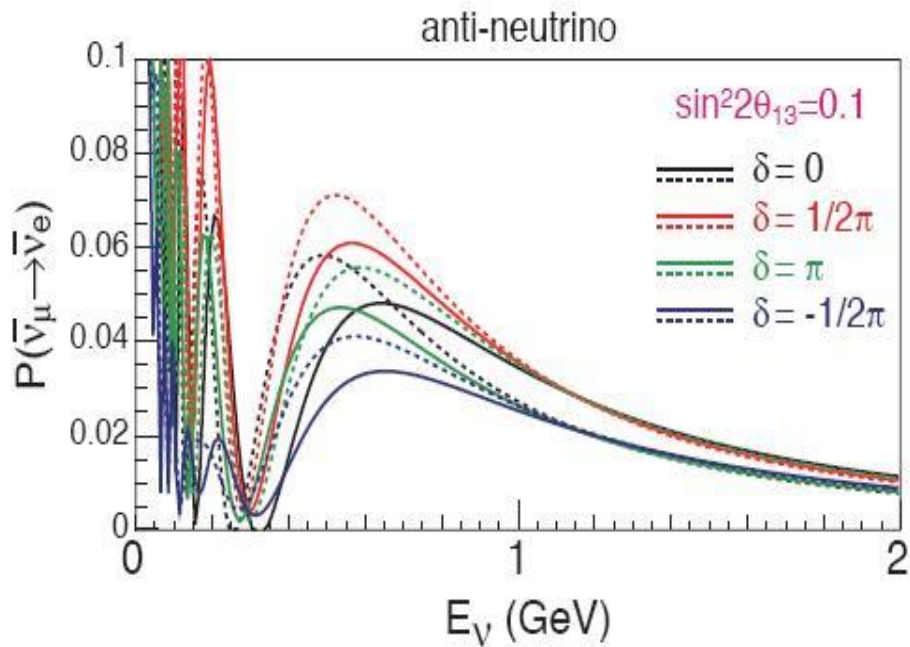
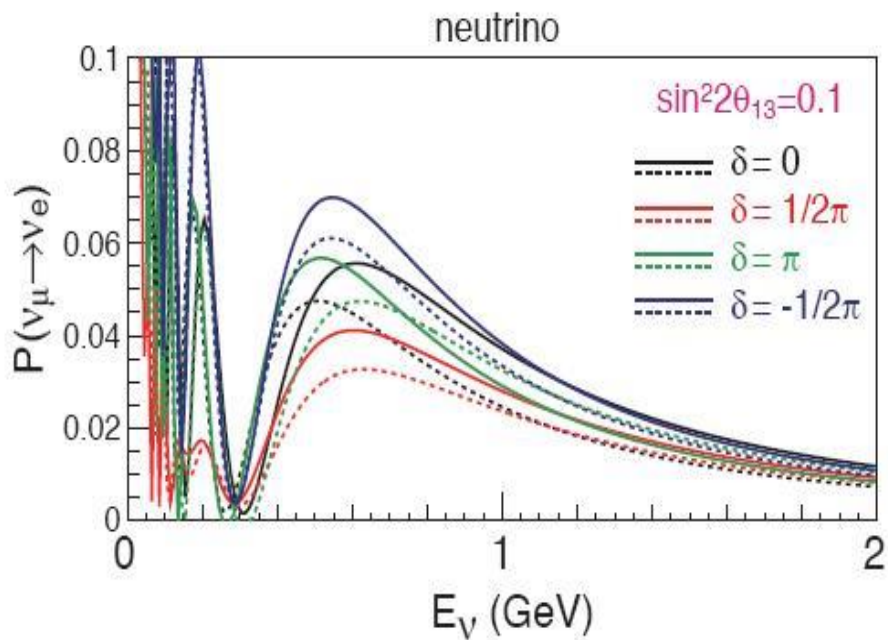
$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \quad \begin{array}{l} a \rightarrow -a \\ \delta \rightarrow -\delta \end{array}$$

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

$$\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E_\nu}$$

C=cos S=sin

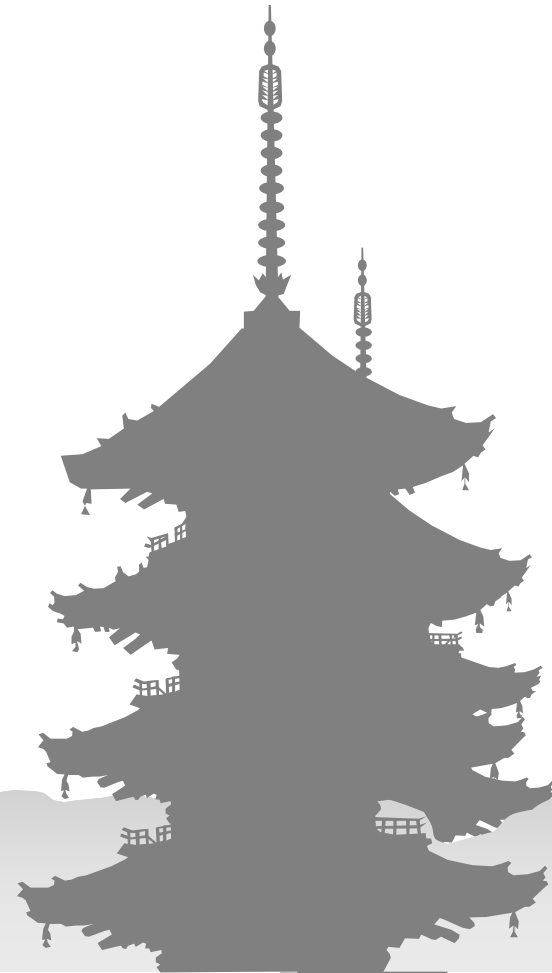
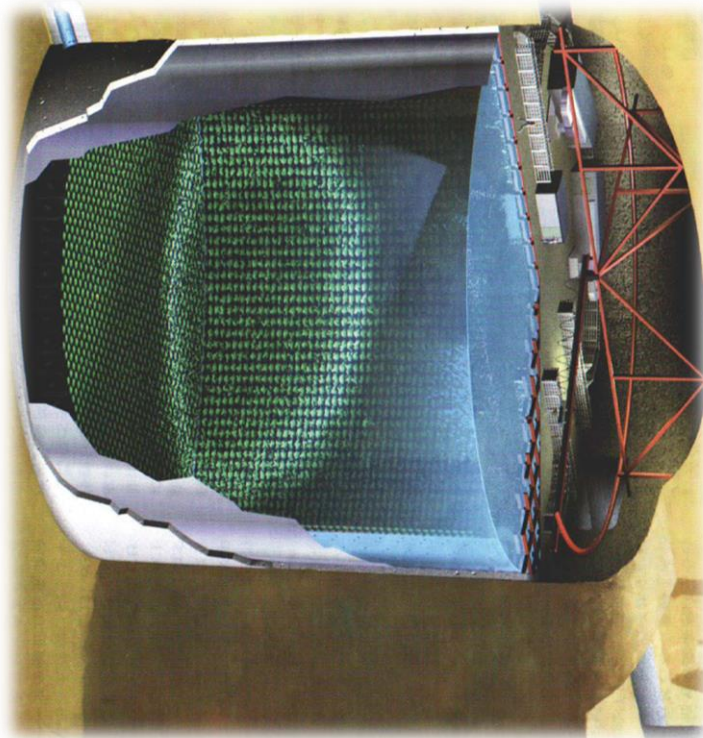
Measure CPV



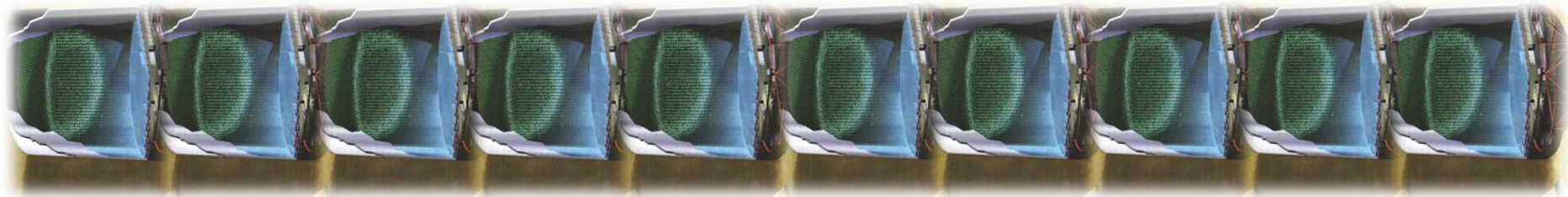


Le projet Hyper-Kamiokande

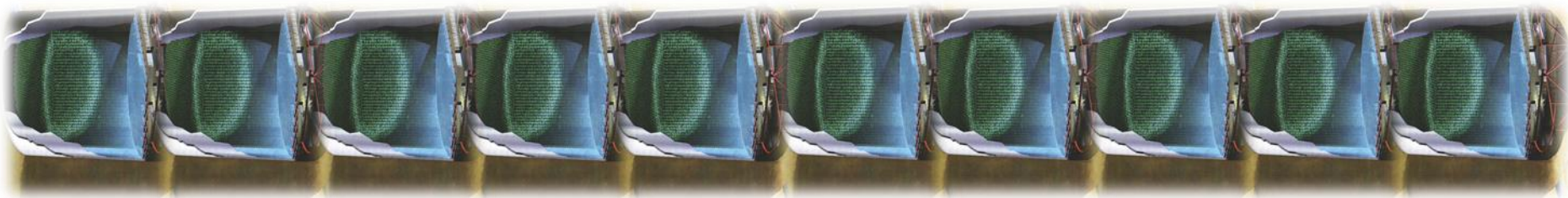
Super-K



Le projet Hyper-Kamiokande

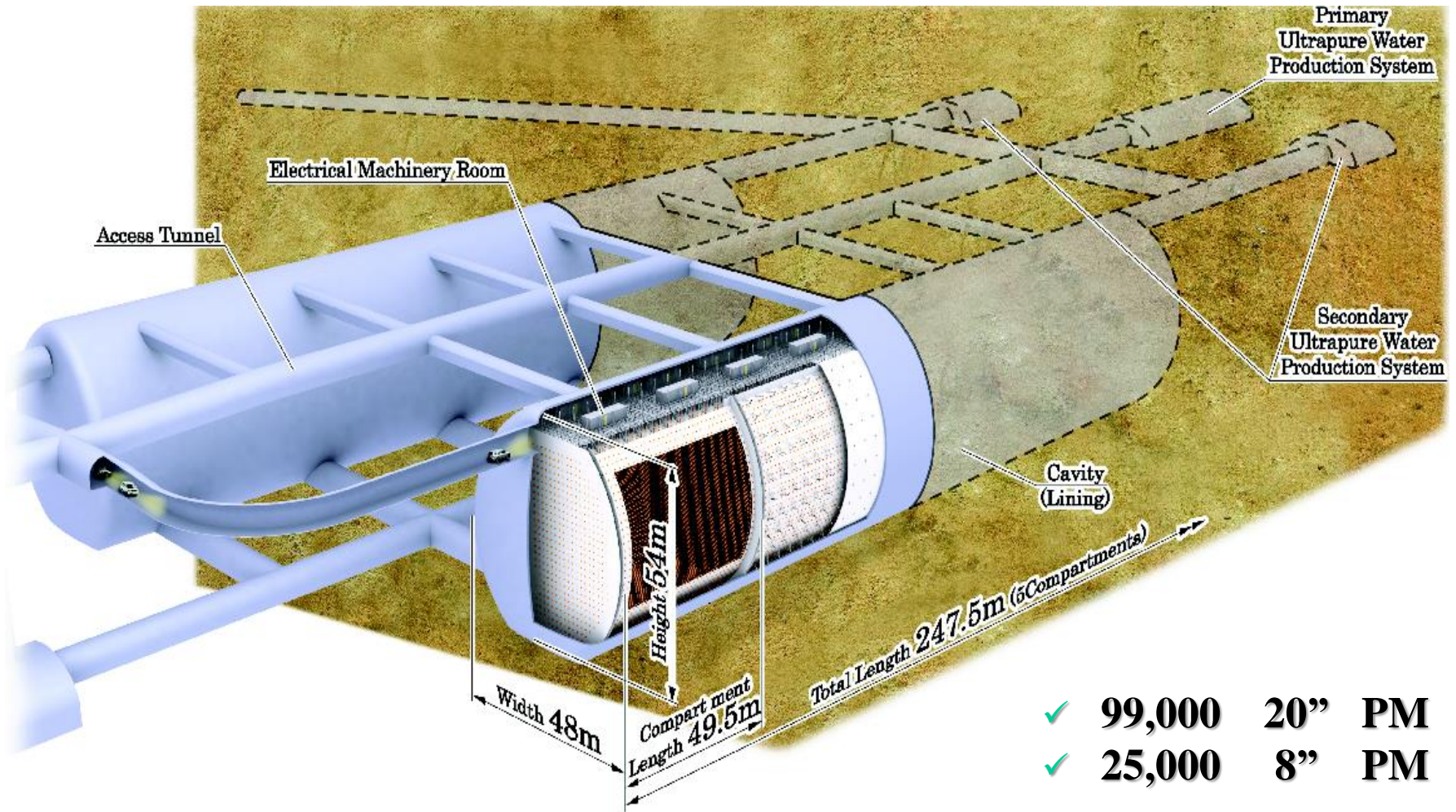


+



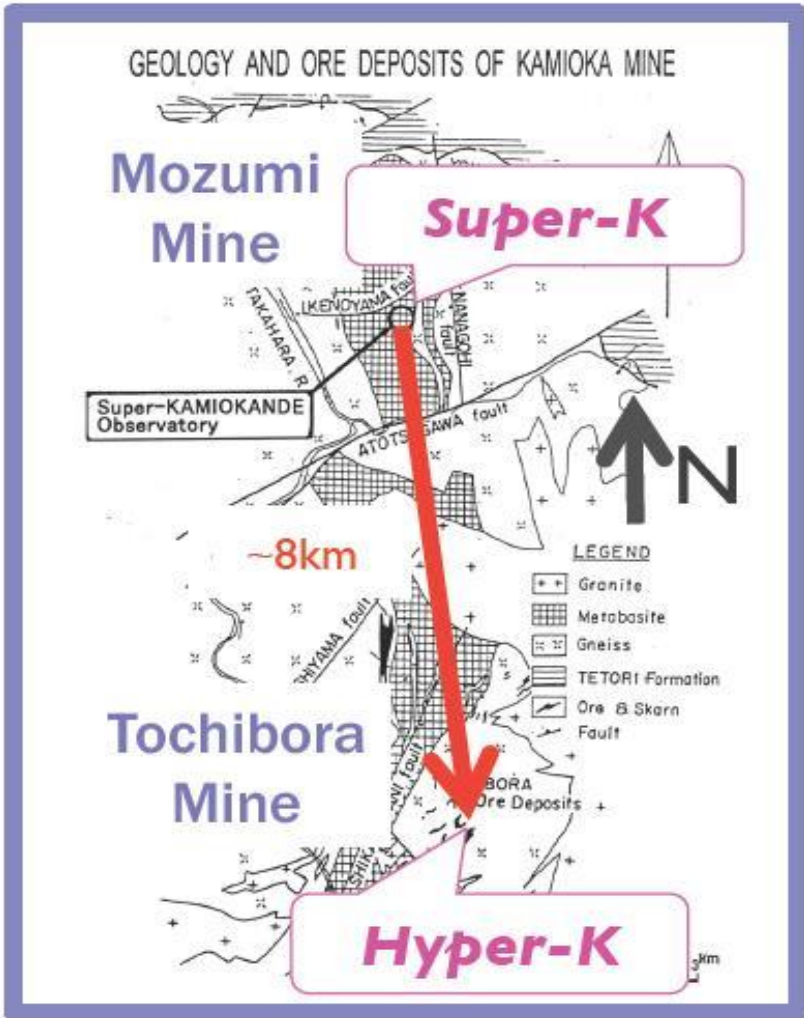
20 Super-Kamiokande

Le projet Hyper-Kamiokande

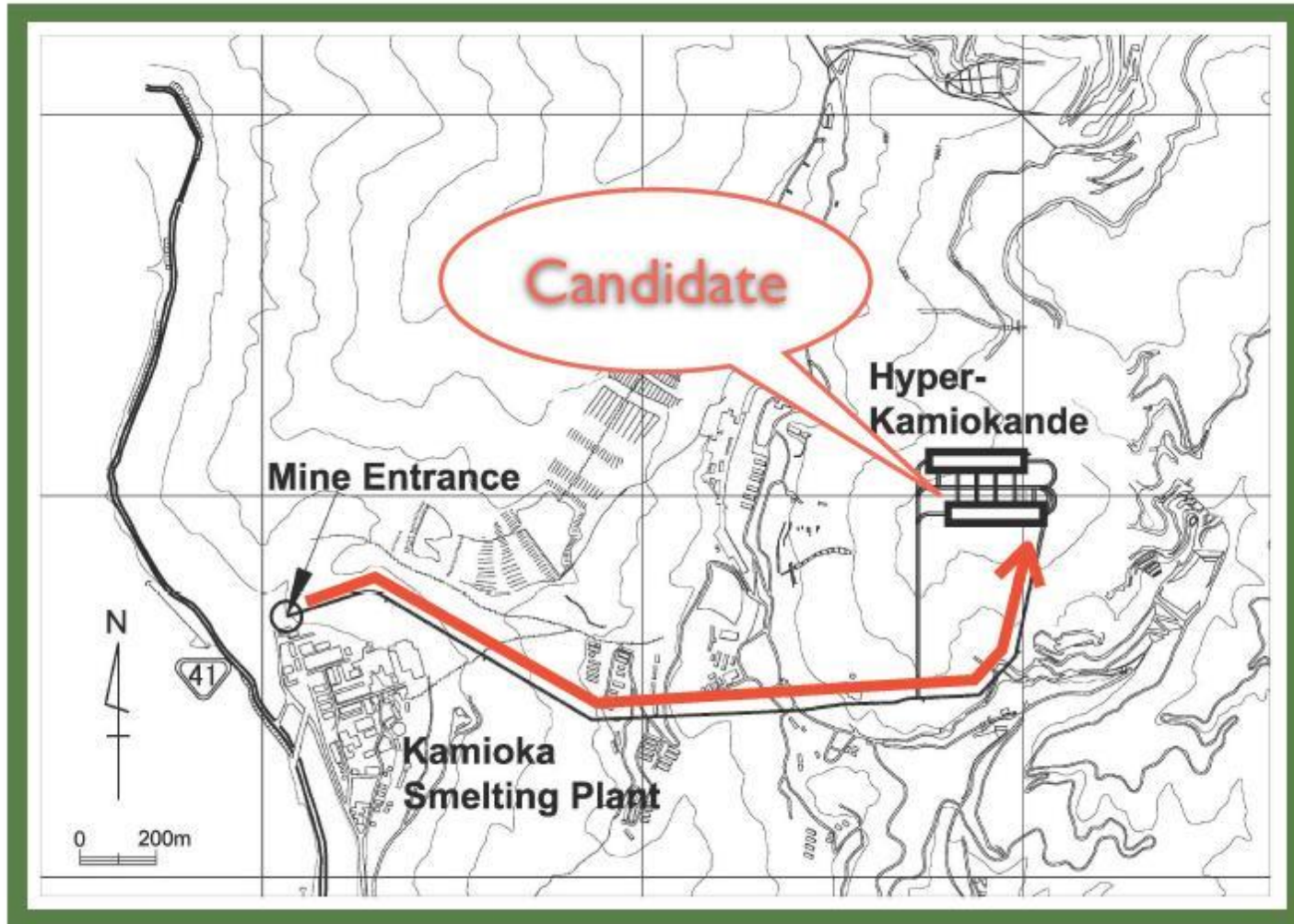


Détecteur Tcherenkov à eau d'une méga tonne

Le projet Hyper-Kamiokande



Le projet Hyper-Kamiokande



Belt conveyer tunnel
L=1,677m, 15%

Belt conveyer tunnel
L=1,242m, 15%

Maru-yama
(rock disposal)

Tank caverns
50 × 50 × 250m
x 2 tanks

Water
purification
room

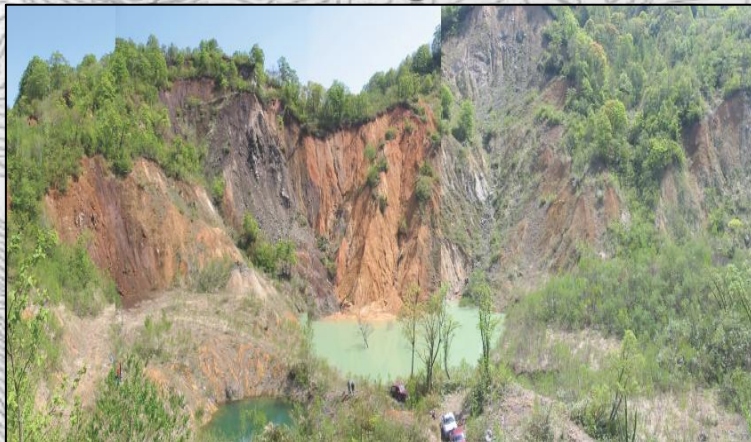
Approach tunnel
(L=475.8m, 10%)

5 ans pour les travaux

Belt conveyer tunnel
L=1,553m, 15%

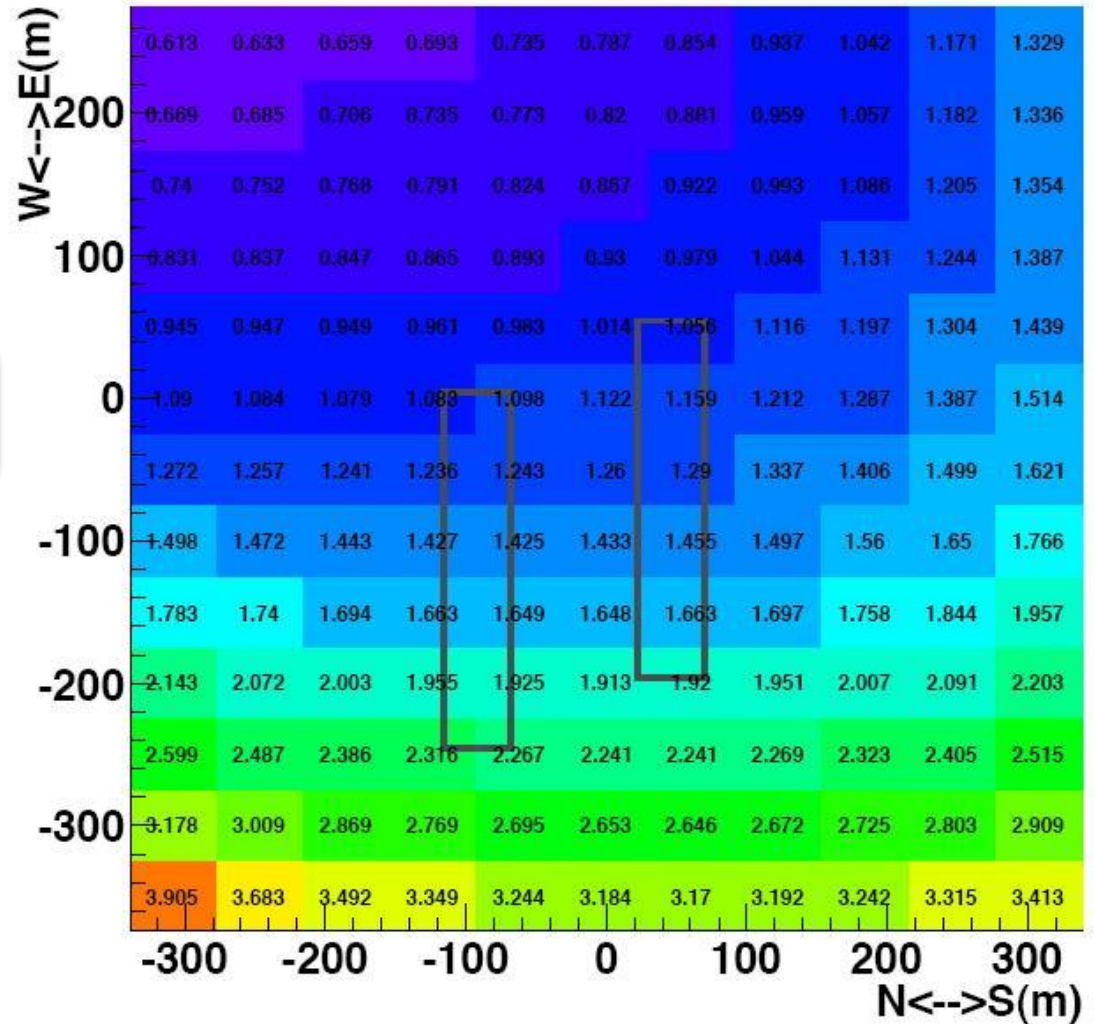
Access
tunnel
L=2,400m, 6%

Mine
entrance



Bruit de fond cosmique (muons)

Alt= 508.0m

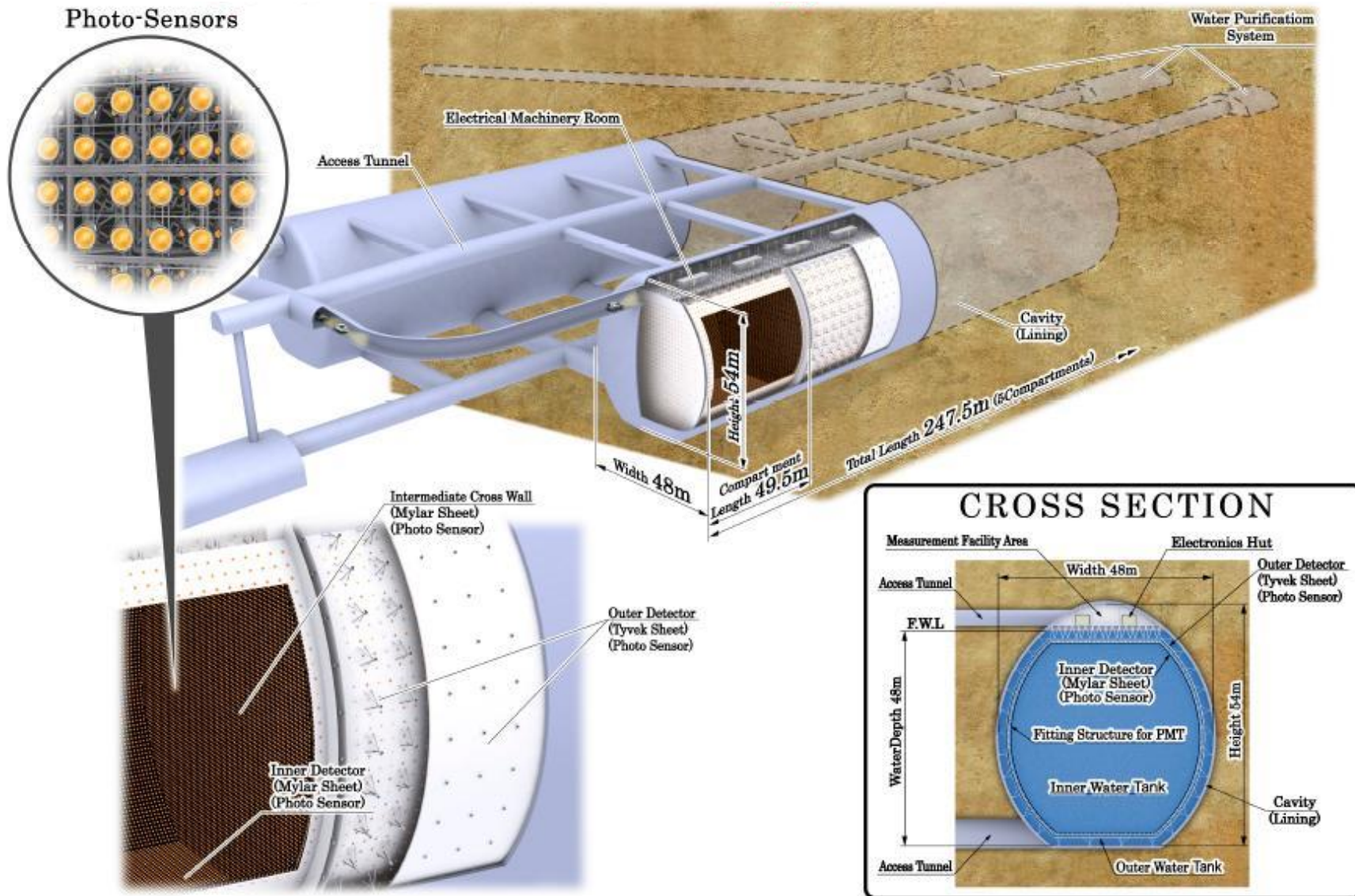


$\sim 1-2 \cdot 10^{-6} \text{ sec}^{-1} \text{ cm}^{-2}$

Comparé à SK :
 $\sim 0.1 - 0.2 \cdot 10^{-6} \text{ sec}^{-1} \text{ cm}^{-2}$



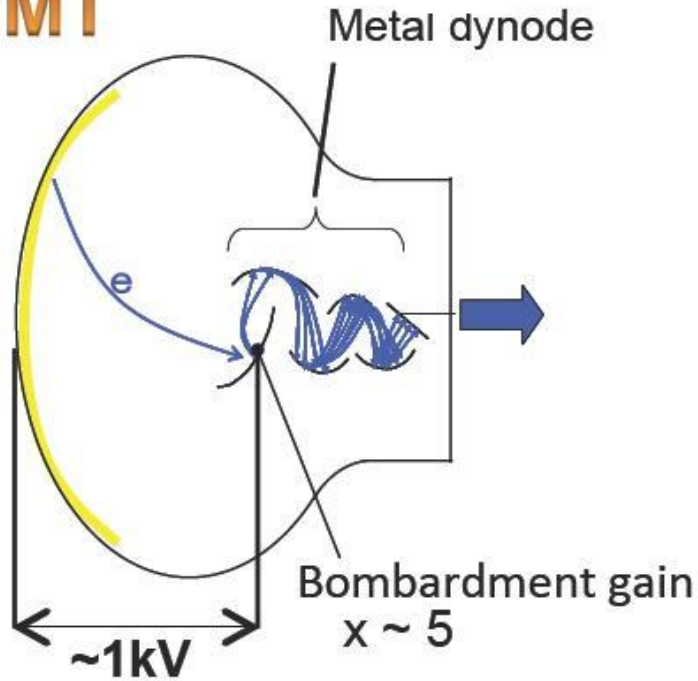
Le projet Hyper-Kamiokande



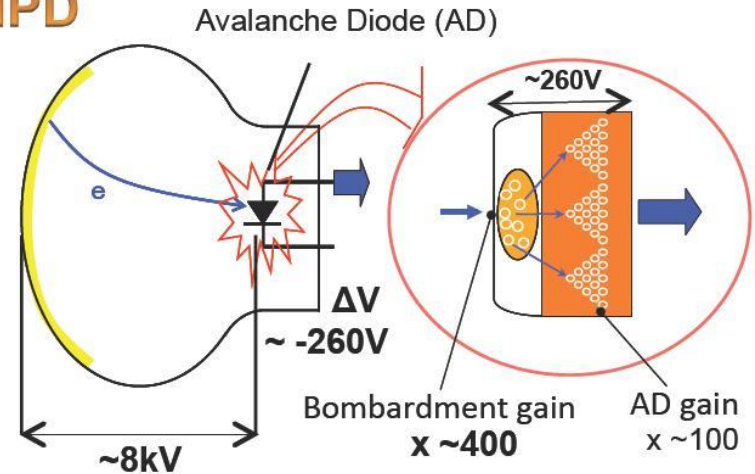
Objectif principal : réduction des coûts

Hybrid Photo-Detector (HPD)

PMT

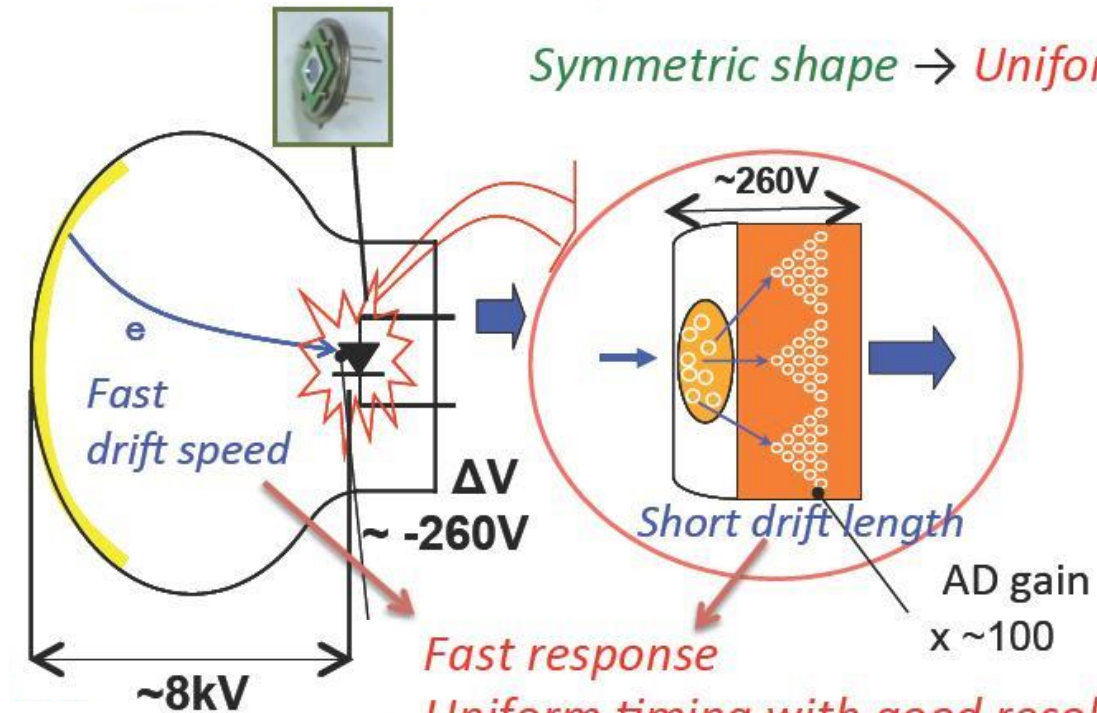


HPD

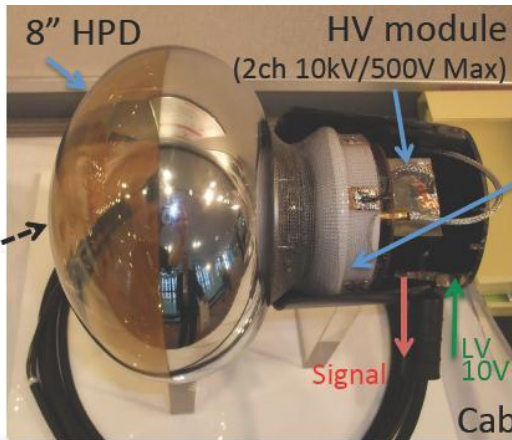


	PMT (20")	HPD (8")
HV	~1kV	~8kV
Gain	~10 ⁷	~10 ⁴ ~ 10 ⁵

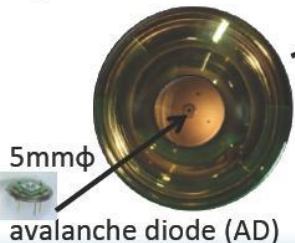
Hybrid Photo-Detector (HPD)



Fast response
Uniform timing with good resolution
 $\sigma t = 2.3\text{ns (PMT)} \rightarrow < 1\text{ns (HPD)}$

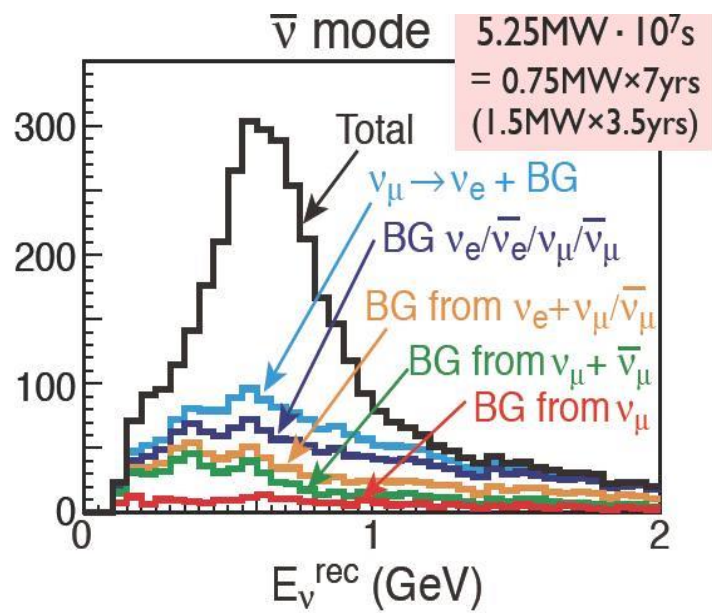
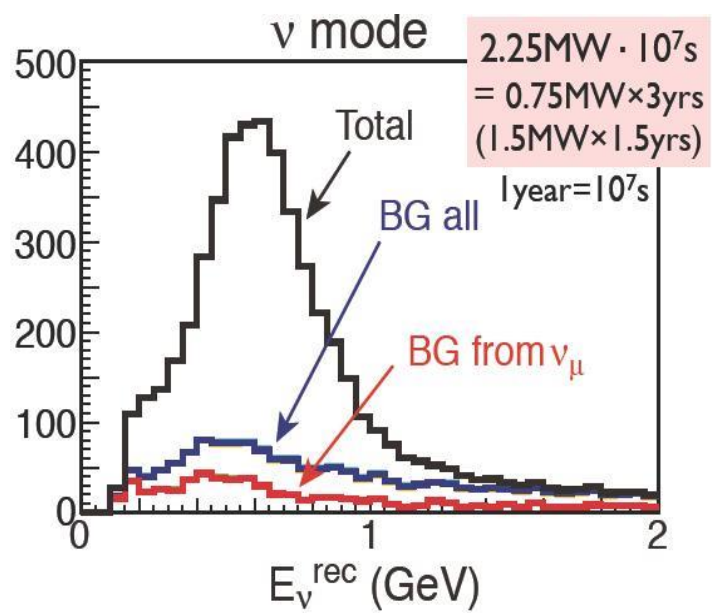


8" Photocathode
(sensitive $\lambda \sim 300 - 650\text{nm}$)



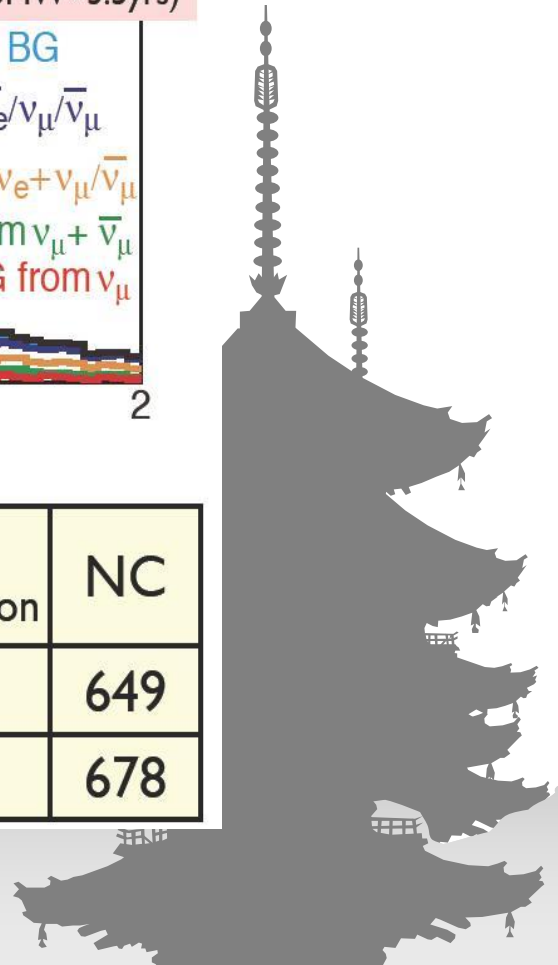
Performances et sensibilités

10 ans de prise de données à 700 KW

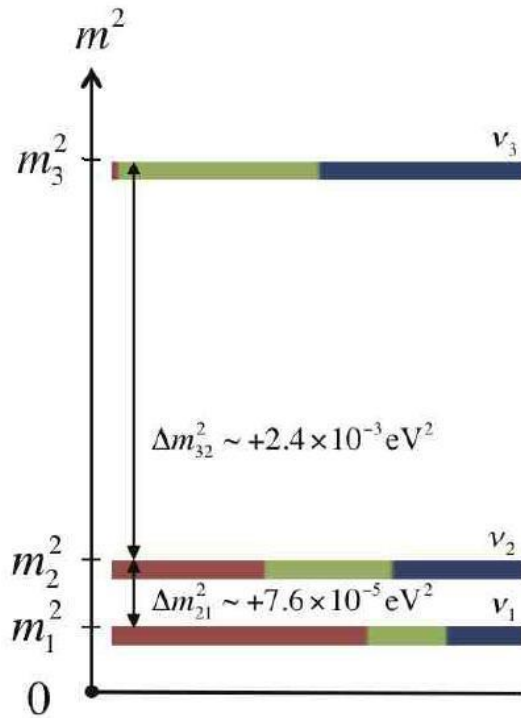


	Signal ($\nu_\mu \rightarrow \nu_e$ CC)	Wrong sign appearance	$\nu_\mu/\bar{\nu}_\mu$ CC	$\nu_e/\bar{\nu}_e$ contamination	NC
ν ($2.25\text{MW} \cdot 10^7\text{s}$)	3,560	46	35	880	649
$\bar{\nu}$ ($5.25\text{MW} \cdot 10^7\text{s}$)	1,959	380	23	878	678

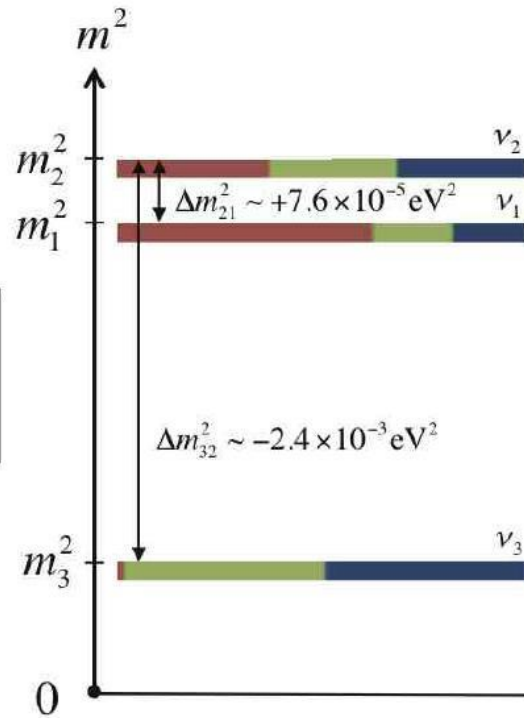
HM normale et $\delta = 0$



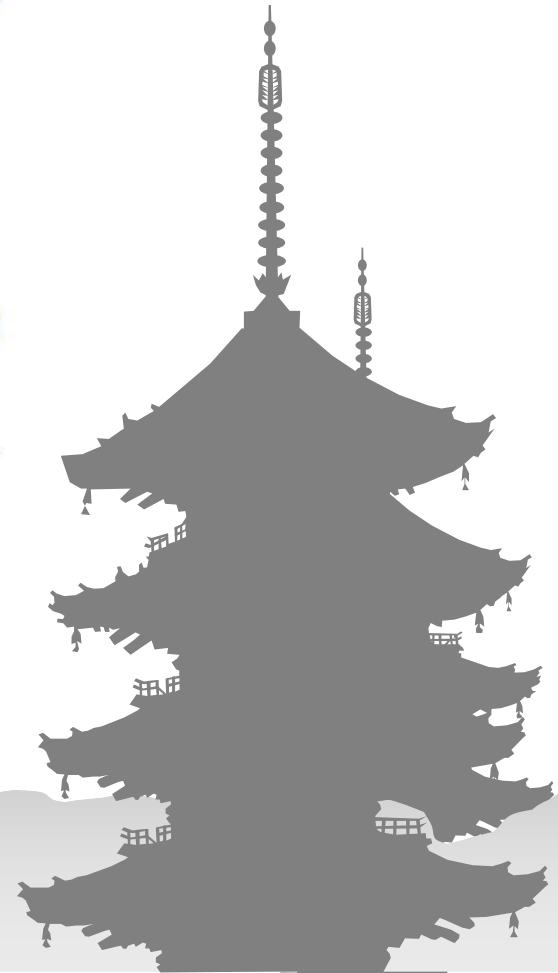
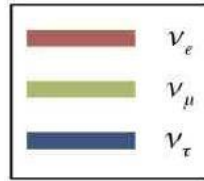
de l'importance de la « hiérarchie de masse »



Normale

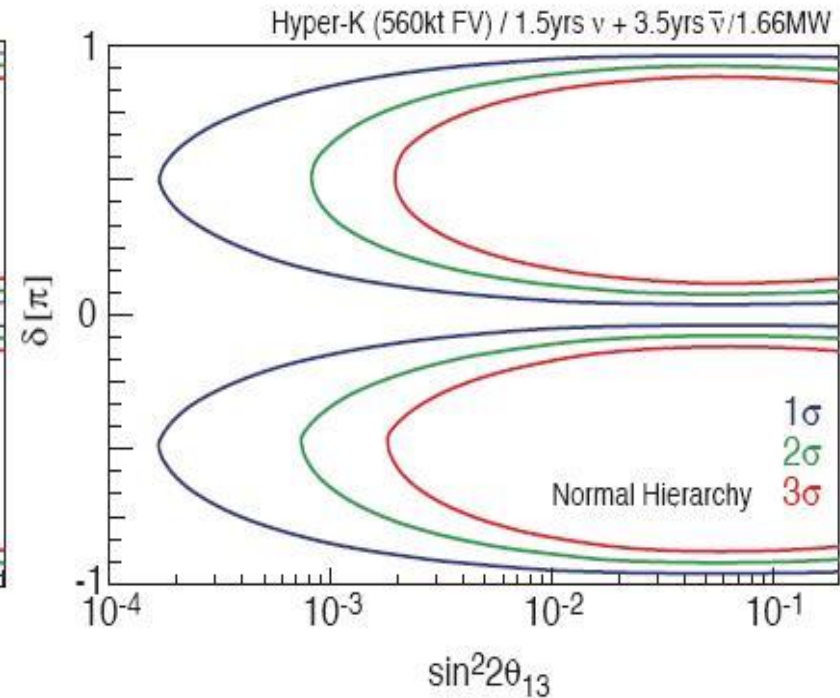
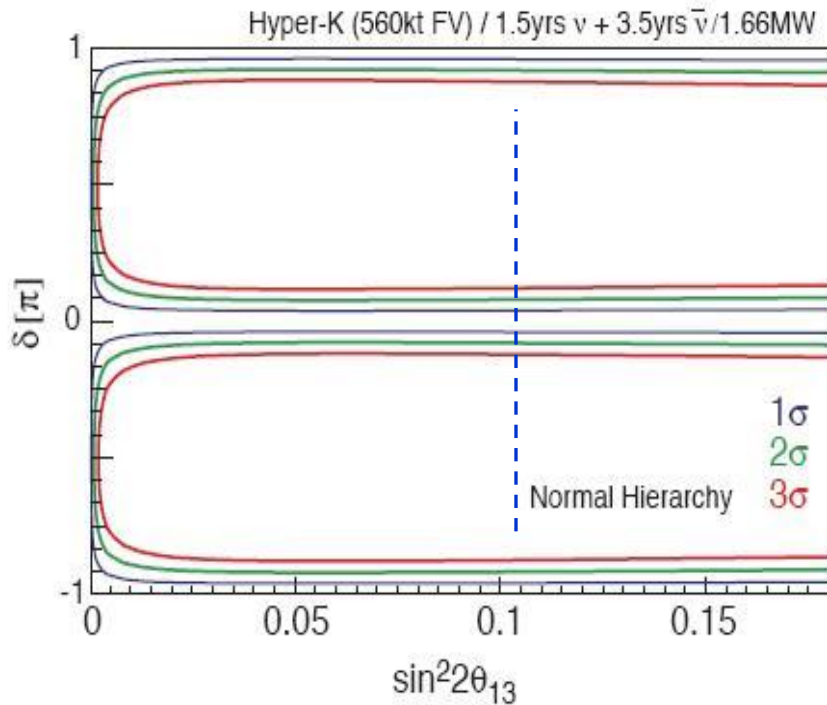


Inverse



Découverte d'une violation CP

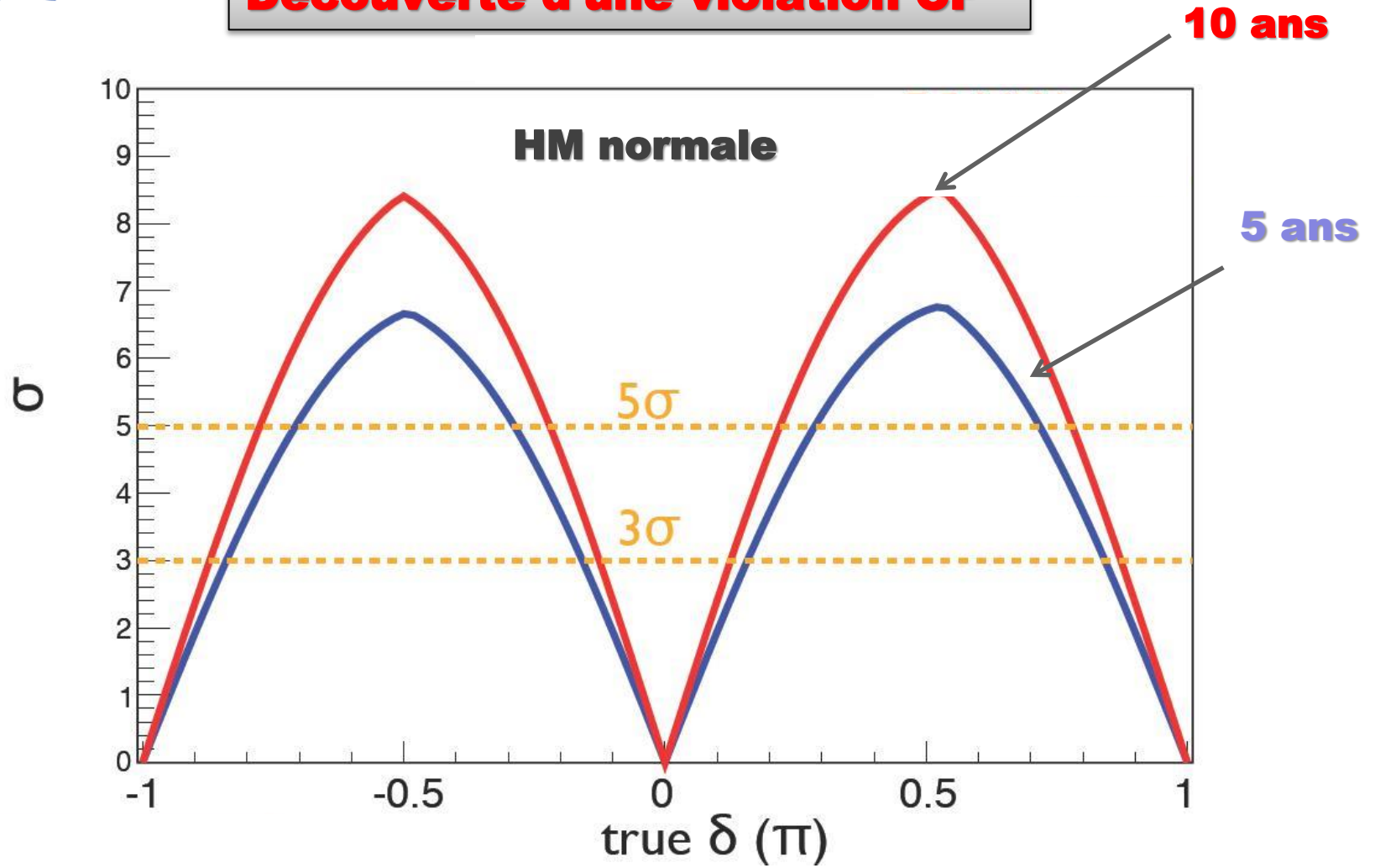
10 ans de prise de données à 700 KW



Exclusion de $\delta = 0$ à 74% (pour 3 σ)

Performances et sensibilités

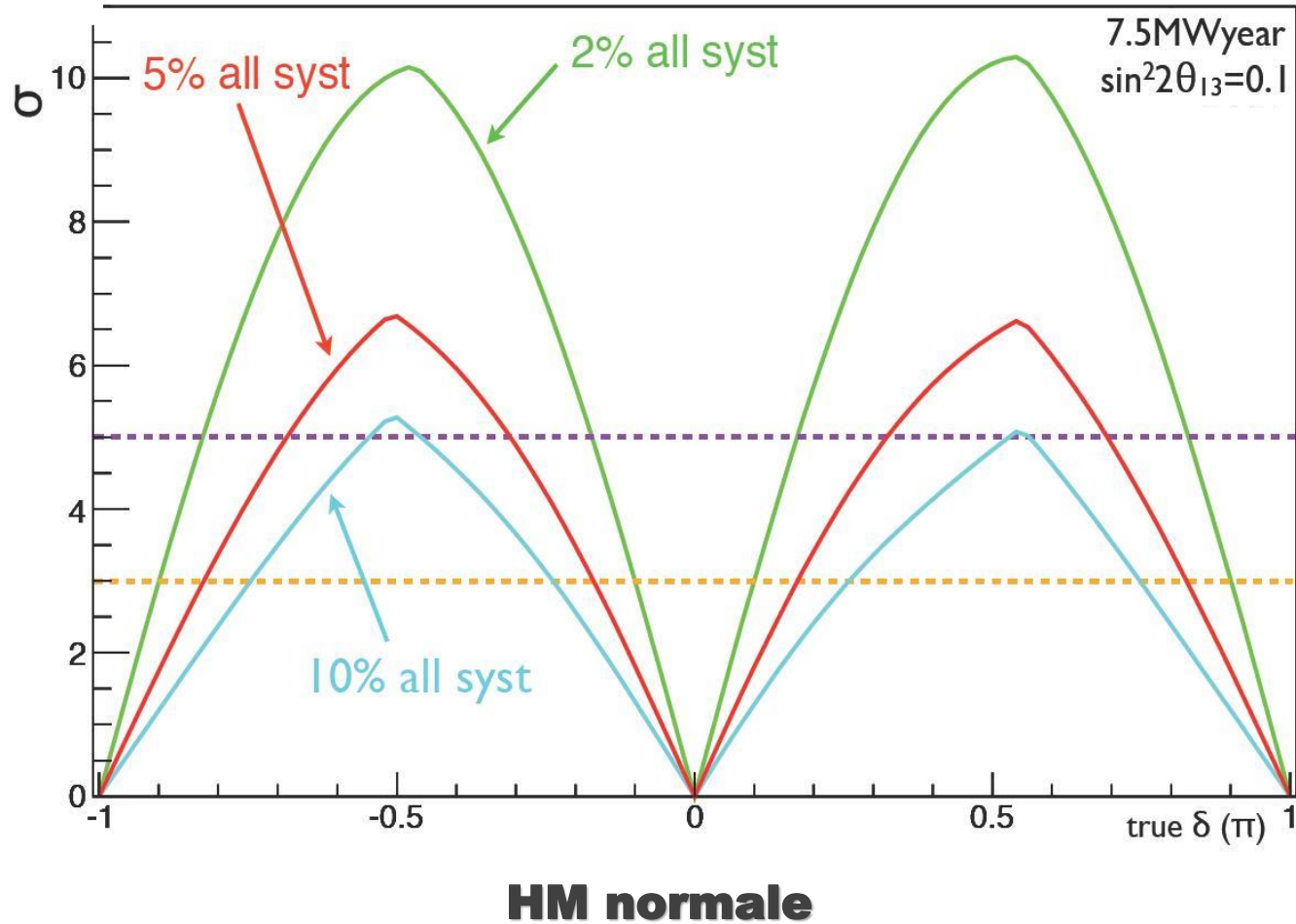
Découverte d'une violation CP



Exclusion de $\delta = 0$ à 74% (3σ) et 55% (5σ)

Performances et sensibilités

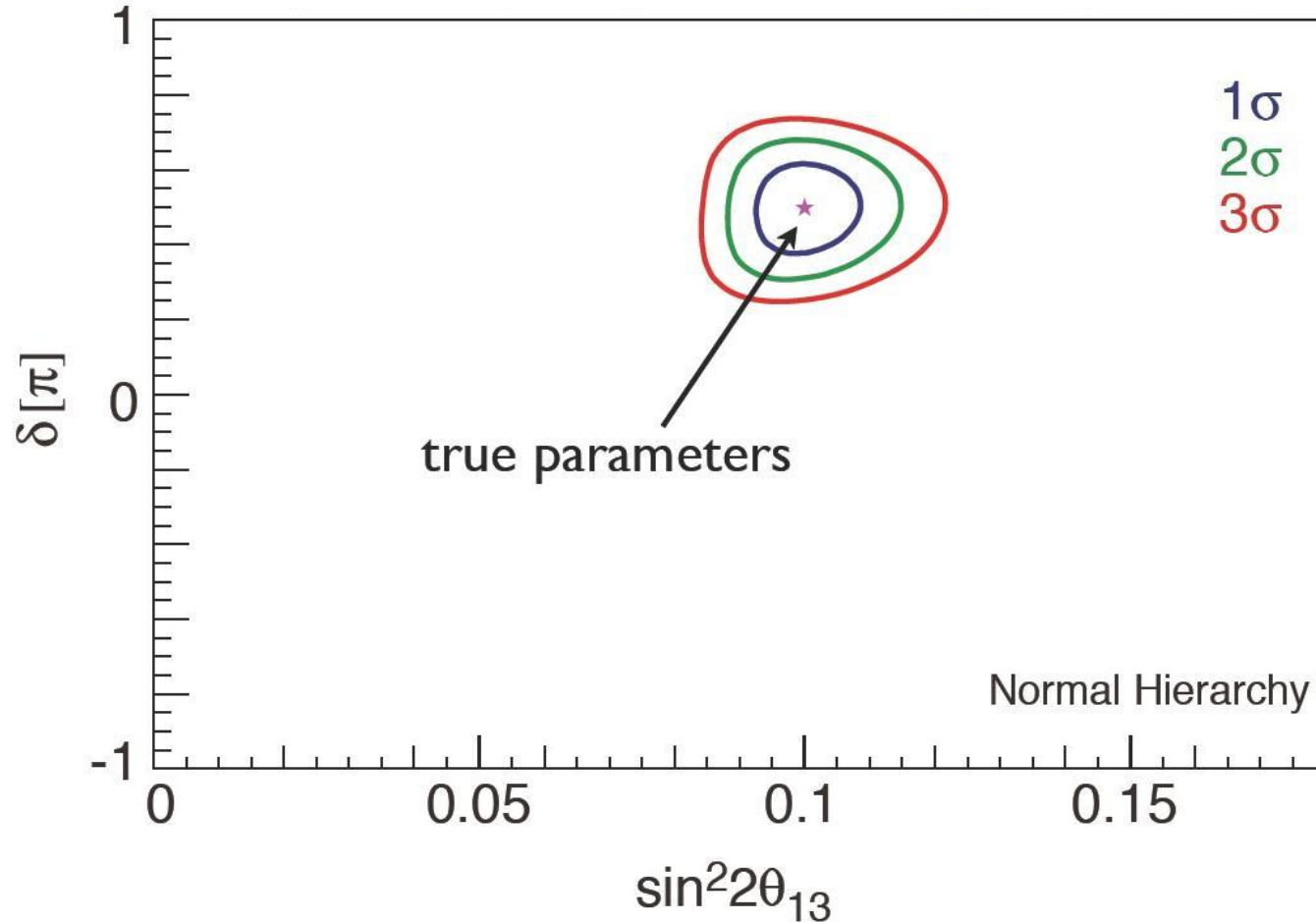
Découverte d'une violation CP



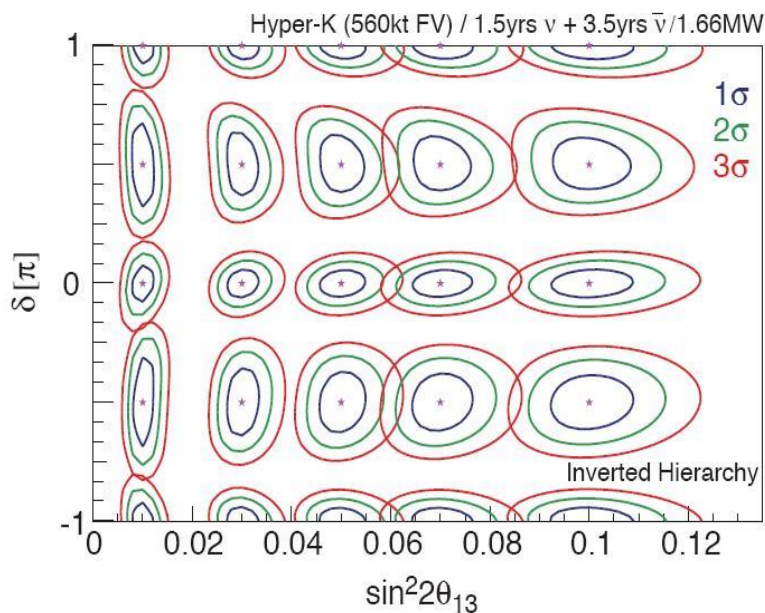
Influence des erreurs systématiques de HK

Performances et sensibilités

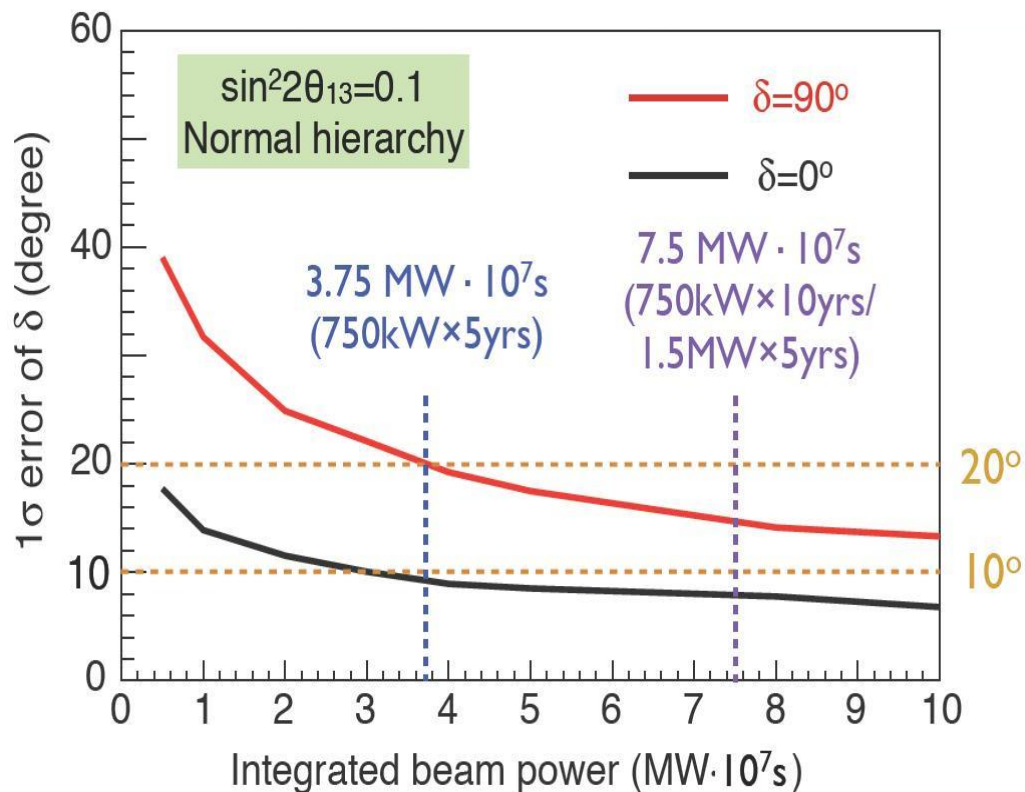
Mesure de la phase CP δ



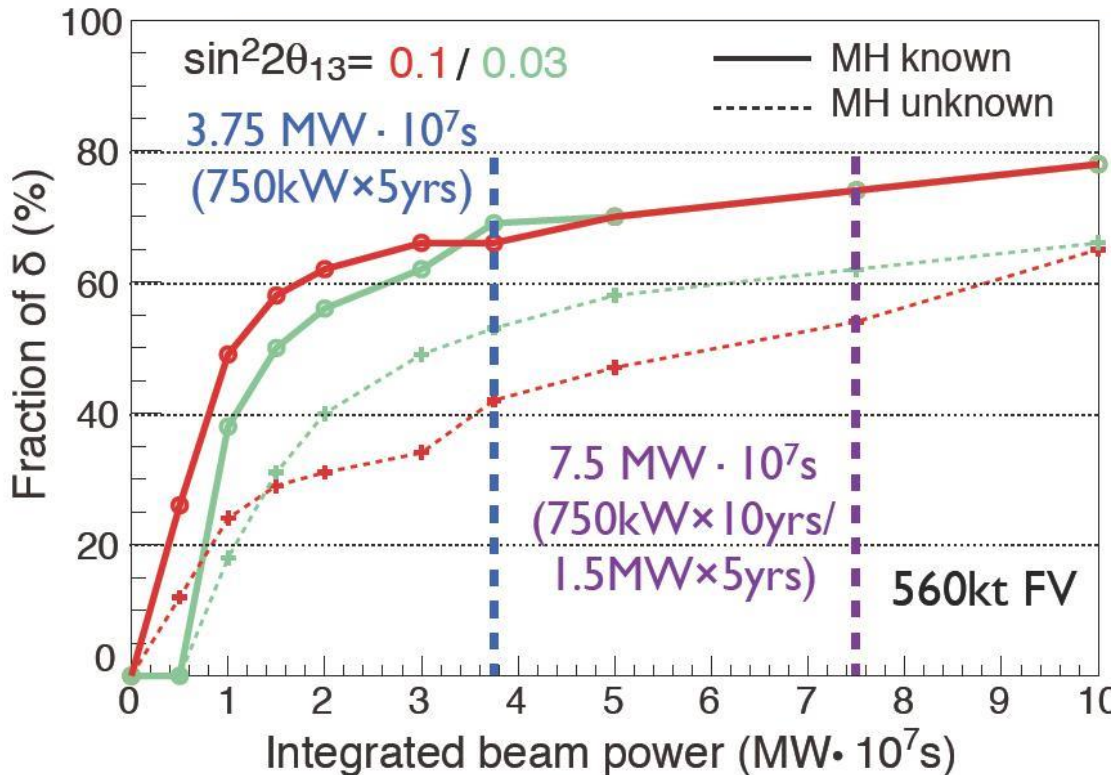
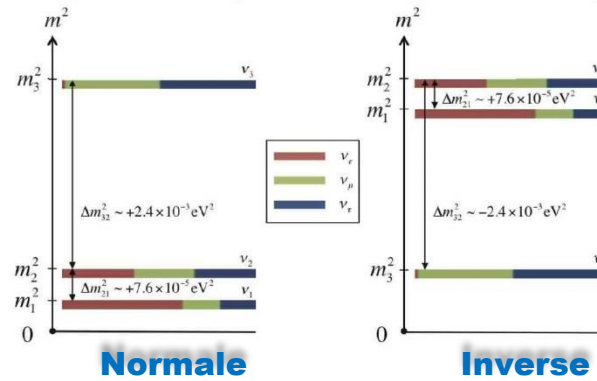
Mesure de la phase CP δ



Une erreur de $\sim 18^\circ$ pour une violation CP maximale



Performances et sensibilités

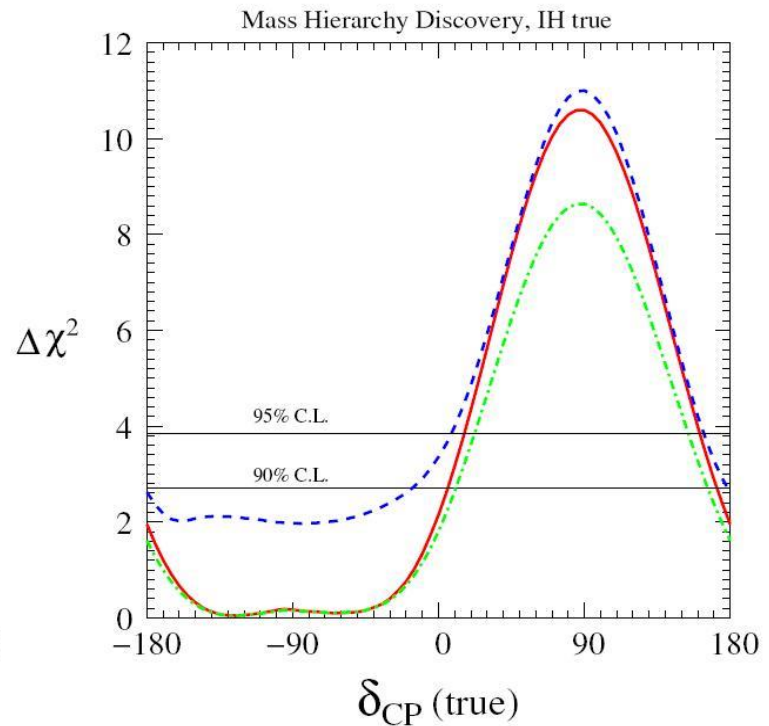
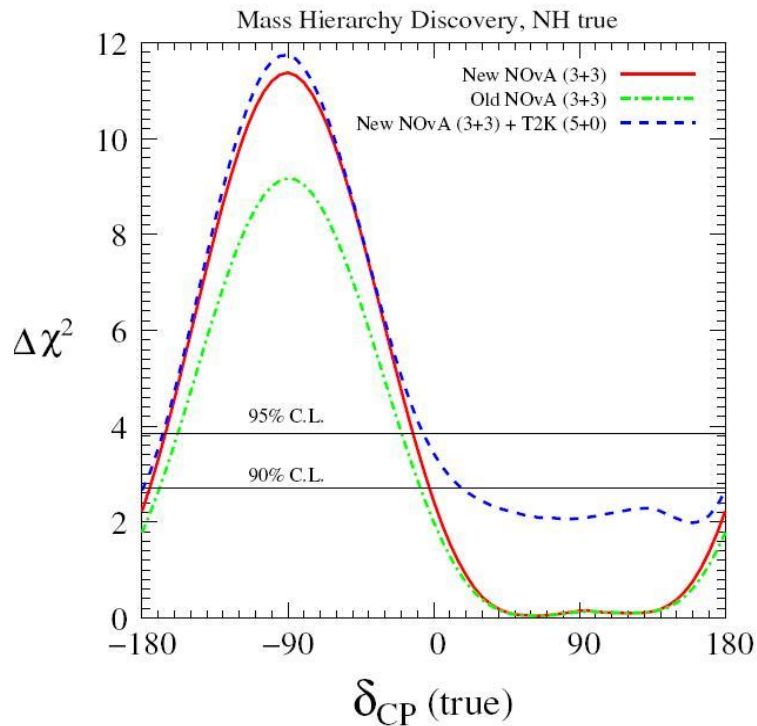
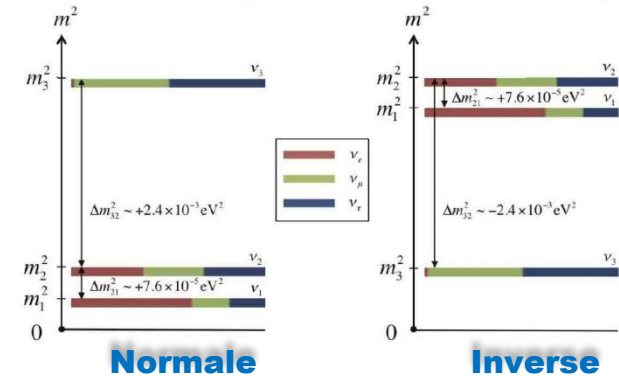


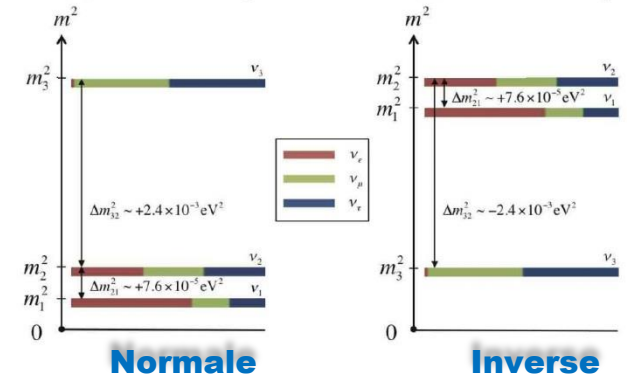
$$\sin^2 2\theta_{13} = 0.1$$

Integ. power (MW × 10 ⁷ s)	Mass hierarchy	
	known	unknown
3.75	69%	42%
7.5	74%	54%

Détermination de la Hiérarchie de Masse avant HK ?

En combinant les futurs résultats de T2K et Nova (USA), on pourra obtenir une détermination de HM à 3σ pour 50% de l'espace de phase δ



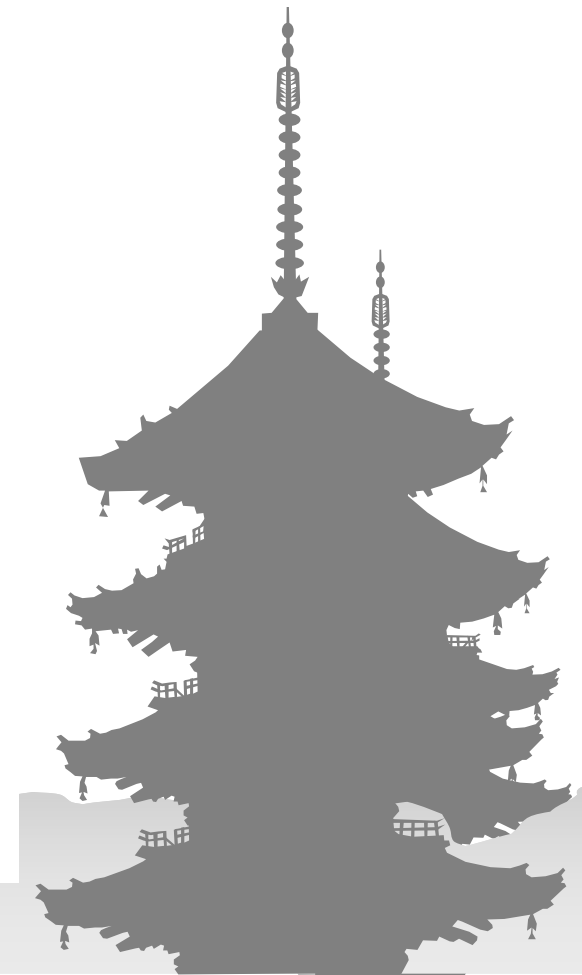
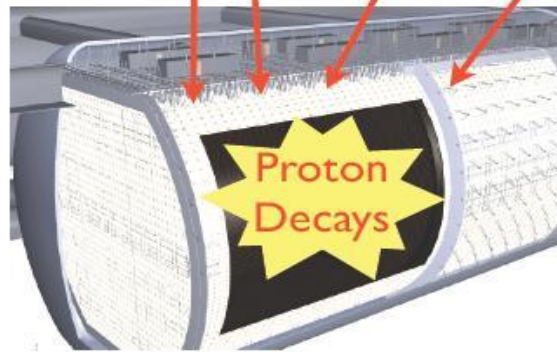
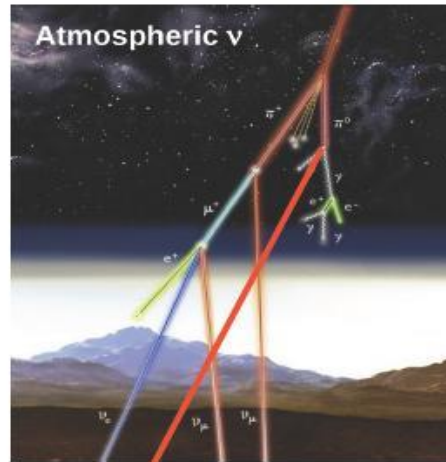
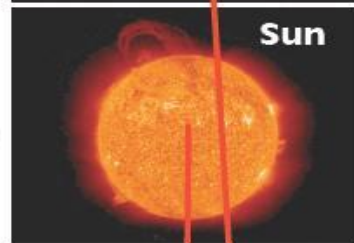


Neutrinos atmosphériques

Hierarchy	2σ	$\sin^2 2\theta_{23} > 0.96$	$\sin^2 2\theta_{23} > 0.96$	5 years
	3σ	$\sin^2 \theta_{23} > 0.4$	$\sin^2 \theta_{23} > 0.4$	10 years
Octant	2σ	$\sin^2 2\theta_{23} > 0.997$	$\sin^2 2\theta_{23} > 0.99$	5 years
	3σ	$\sin^2 2\theta_{23} > 0.99$	$\sin^2 2\theta_{23} > 0.97$	5 years

HK devient une expérience LB (L > 1000 km) pour les neutrinos atmosphériques et 10 ans de prise de données Exclusion à 3σ d'une mauvaise Hiérarchie de Masse

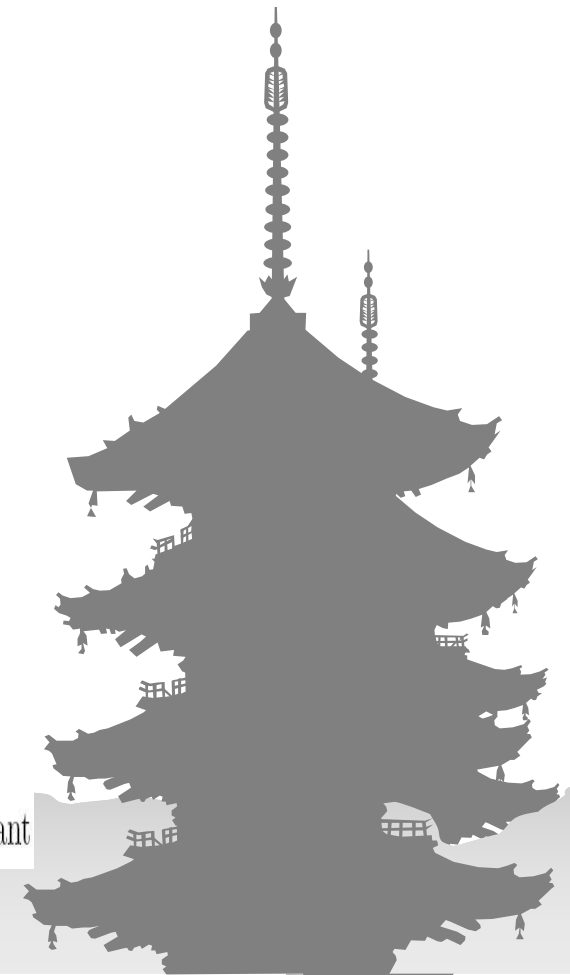
Performances et sensibilités



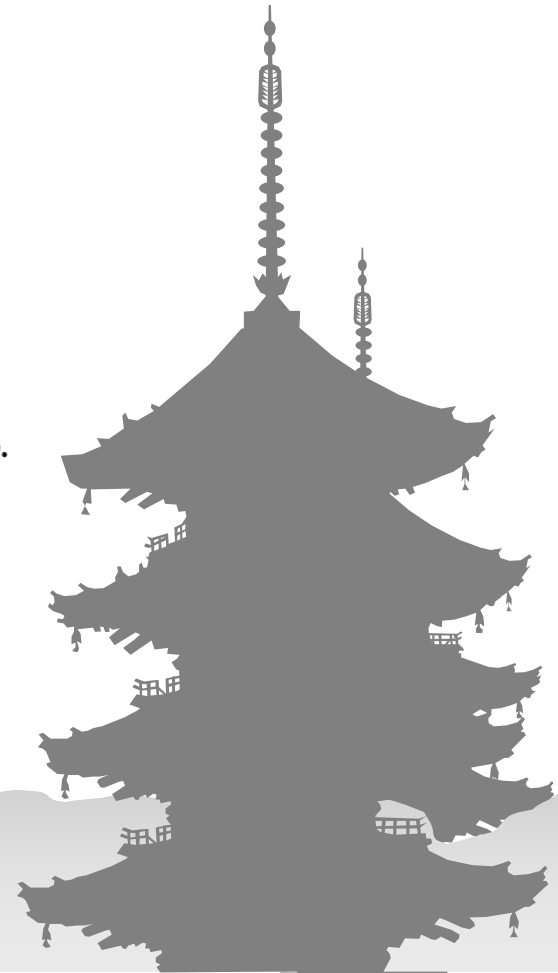
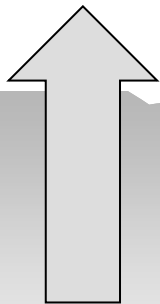
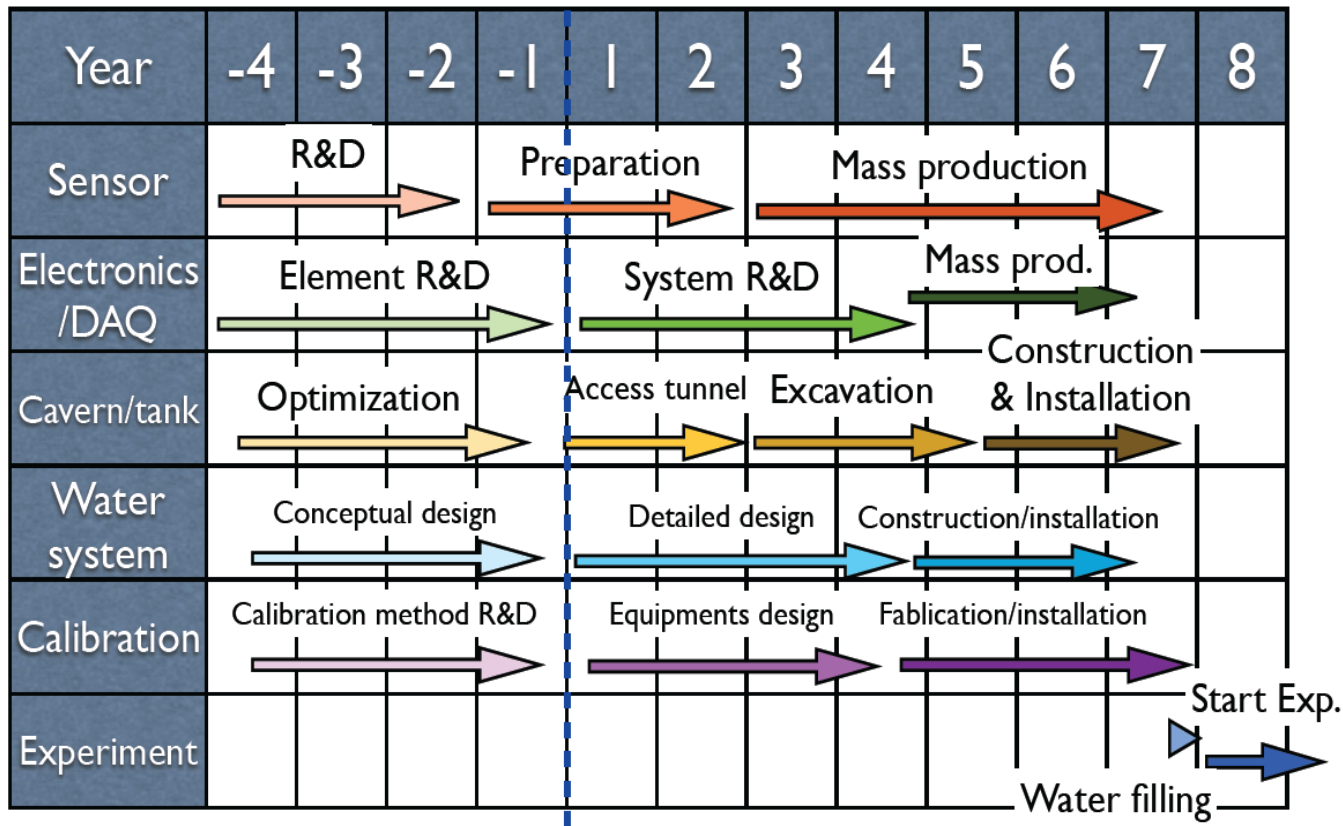


Astrophysical objects

- Supernova burst ν
 - 170,000~260,000 ν 's @ Galactic center (10 kpc)
 - 30~50 ν 's @ M31 (Andromeda galaxy)
- Supernova relic ν
 - 830 ν 's / 10 years
- WIMP annihilation at Sun
 - 5 years observation
 - $\sigma_{SD} = 10^{-39} \text{cm}^2$ @ $M_{\text{WIMP}} = 10 \text{ GeV}$, $\chi\chi \rightarrow b\bar{b}$ dominant
 - $\sigma_{SD} = 10^{-40} \text{cm}^2$ @ $M_{\text{WIMP}} = 100 \text{ GeV}$, $\chi\chi \rightarrow W^+W^-$ dominant

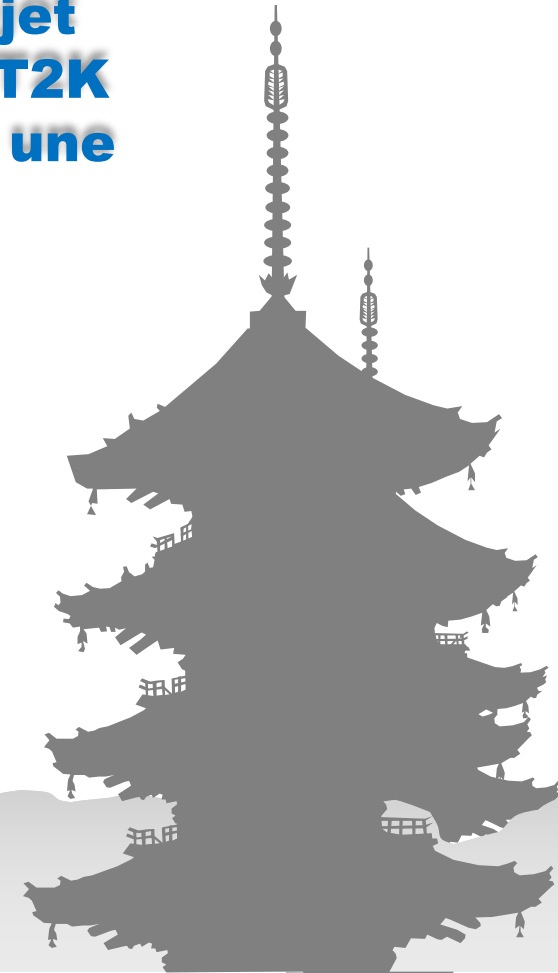
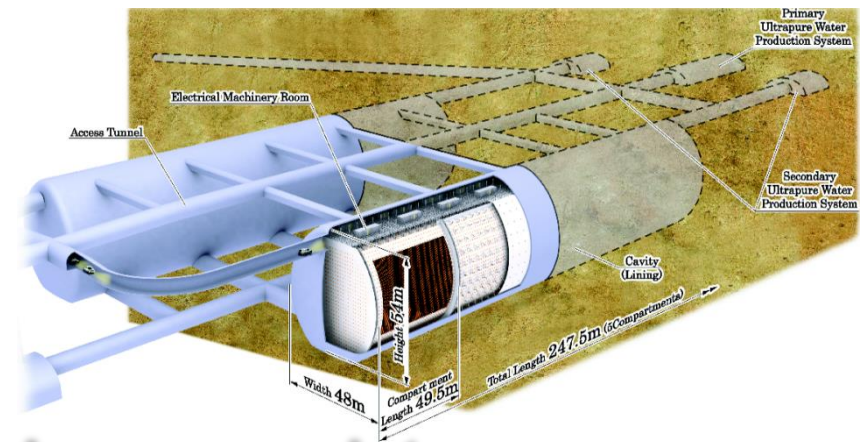


Un calendrier possible



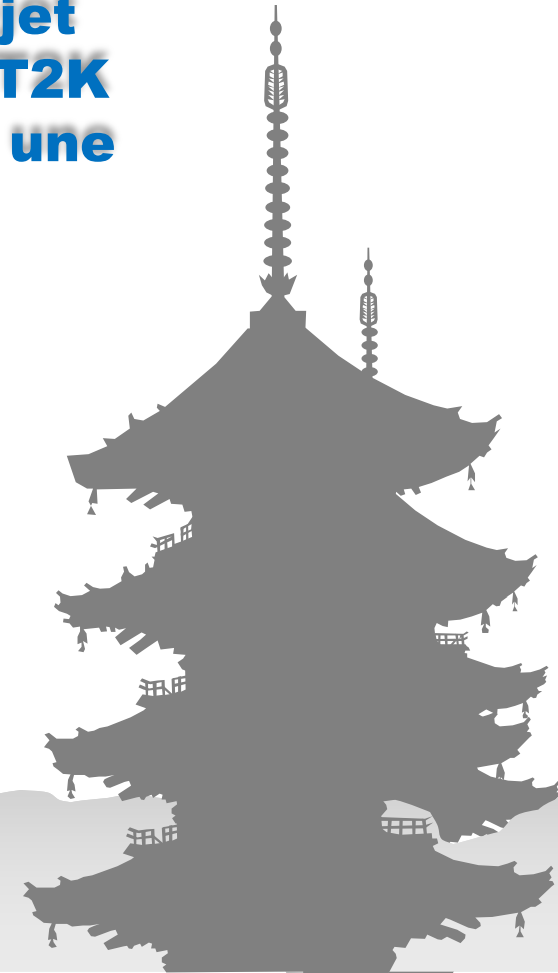
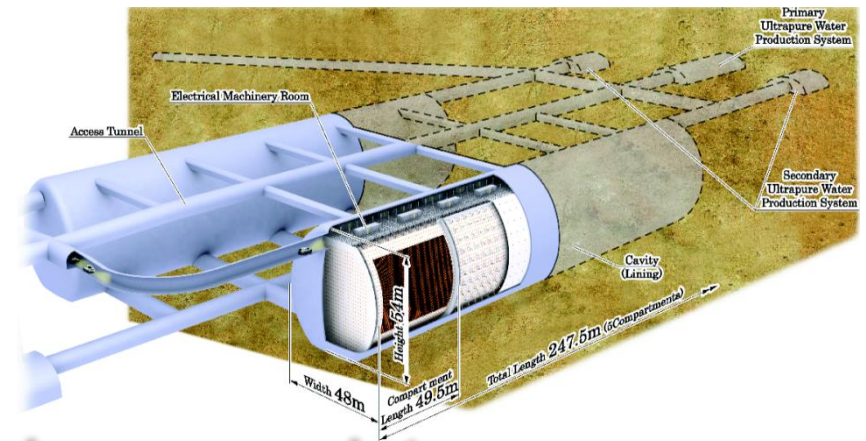
Conclusions

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- **Suite logique de notre participation dans T2K**
- **Les résultats récents sur theta13 ouvrent une voie royale aux projets MT**



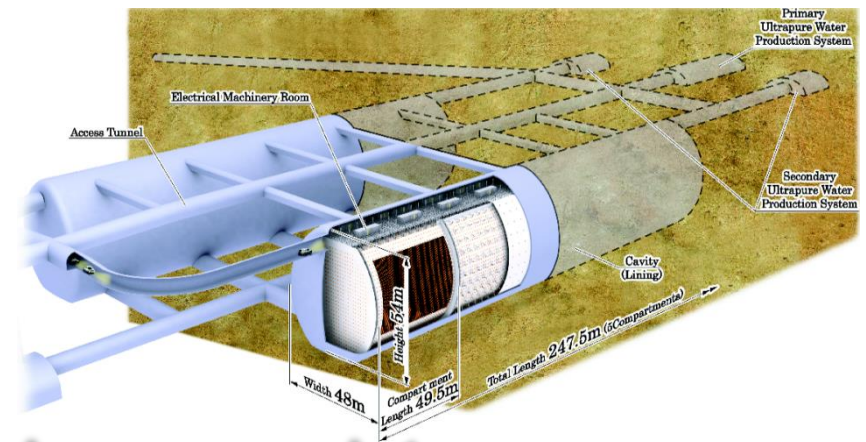
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- Un potentiel de découverte fondamentale très important
- Un détecteur unique pour des études au-delà du modèle standard



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→ Proposition de notre groupe de rejoindre la collaboration SK (CS IN2P3 juin)

