Participation of LPNHE-Neutrino group in Japan – based accelerator neutrino program (from T2K to Hyper-Kamiokande)

- Boris A. Popov
  for LPNHE-neutrino group

T2K-II

The T2K-II project: the second phase of the T2K experiment

Alain Blondel[2], Margherita Buizza Avanzini[1], Olivier Drapier[1], Jacques Dumarchez[2], Frank Gastaldi[1], Claudio Giganti[*2], Michel Gonin[1], Mathieu Guigue[2], Jean-Michel Lévy[2], Thomas Mueller[1], Boris Popov[2], Benjamin Quilain[1] and Marco Zito[2]

[1]LLR Neutrino group, IN2P3/Ecole Polytechnique
[2]LPNHE Neutrino group, IN2P3/Sorbonne University

Hyper-K

The Hyper-Kamiokande experiment

Alain Blondel[2], Margherita Buizza Avanzini[1], Olivier Drapier[1], Jacques Dumarchez[2], Frank Gastaldi[1], Claudio Giganti[*2], Michel Gonin[1], Mathieu Guigue[2], Jean-Michel Lévy[2], Thomas Mueller[1], Pascal Paganini[1], Boris Popov[2], Benjamin Quilain[1], Stefano Russo[2] and Marco Zito[2]

[1]LLR Neutrino group, IN2P3/Ecole Polytechnique
[2]LPNHE Neutrino group, IN2P3/Sorbonne University

LPNHE Paris-Neutrino group members:

- Bernard Andrieu (CR)
- Claudio Giganti (CR/HDR)
- Mathieu Guigue (MdC SU)
- Jacques Dumarchez (DR)
- Jean-Michel Levy (benevole)
- Boris Popov (DR)
- + new members starting from 2019
- Ciro Riccio (invited researcher during 2019)
- Alain Blondel (DR)
- Marco Zito (DR)
- Viet Nguyen (PhD student, 2019-)
- + a new PostDoc (Adrien Blanchet) from January 2020
- + important contributions from former PhD students: Laura Zambelli (2010-2013), Pierre Bartet-Friburg (2013-2016), Matej Pavin (2014-2017), Simon Bienstock (2015-2018)

The group participates in the following experiments:

T2K → T2K-II [till 2026]
NA61/SHINE (for T2K/Fermilab neutrino beams, then for Hyper-Kamiokande/DUNE) [>2021]
Hyper-Kamiokande [2018-]

LPNHE Paris - ITA support (as of 2019):

- Jean-Marc Parraud (T2K Technical Coordinator @ LPNHE)
- Eric Pierre
- Francois Toussenel
- Julien Philippe
- Yann Orain
- Diego Terront
- Stefano Russo

+ William Ceria (till April,2019)

Support from IN2P3, ANR and SU

On top of the regular annual support from IN2P3 the group has recently obtained:

- EU grant (JENNIFER-II consortium) for scientific trips to Japan

- ANR grant (CG) [2-years postdoc + PhD student grant]

- SU “Emergence” grant (MG) [1-year postdoc + equipment]

LPNHE PARIS -Neutrino group research:

Main research topics:

- Precise measurements of neutrino and anti-neutrino oscillation parameters and search for CP-violation in the lepton sector
- Measurements of neutrino and anti-neutrino interaction cross sections
- Hadron production measurements for precise predictions of accelerator (anti-)neutrino fluxes

The group had and still has important responsibilities:

ND280-upgrade project leader (MZ → CG), T2K Oscillation Analysis convener (CG), T2K Beam group convener (BP), ND280-upgrade Simulation group convener (MG), ND280 Magnet operation, TPC operation, Publication Board members, Speakers Board members, Internal referees, NA61/SHINE Analysis coordinator, etc.

More than 50 publications during the last 5 years

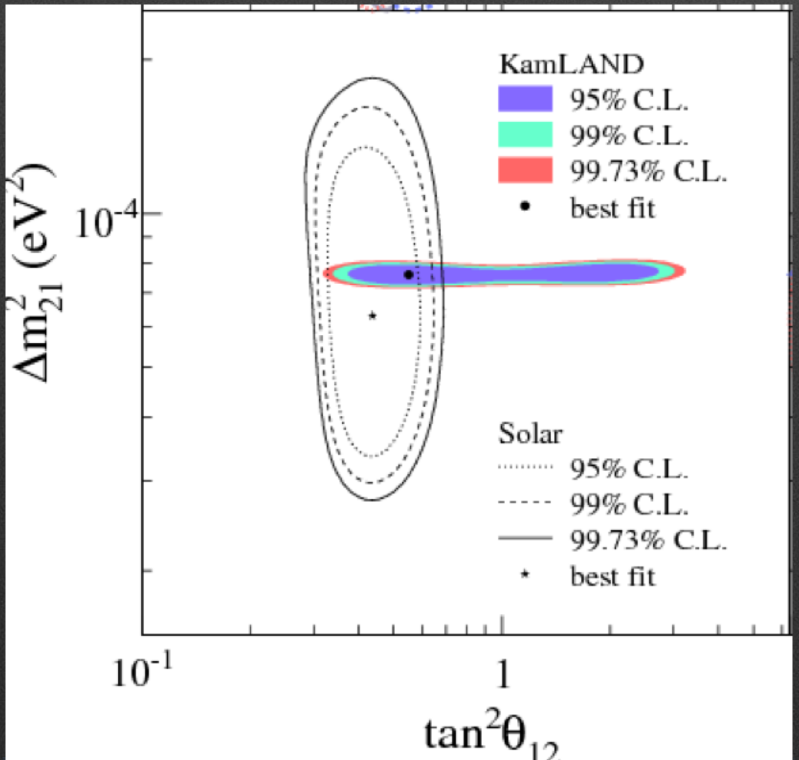
Awards: Le Prix “La Recherche” Physique (2012), Breakthrough Prize in Fundamental Physics (2016)

Neutrino oscillations

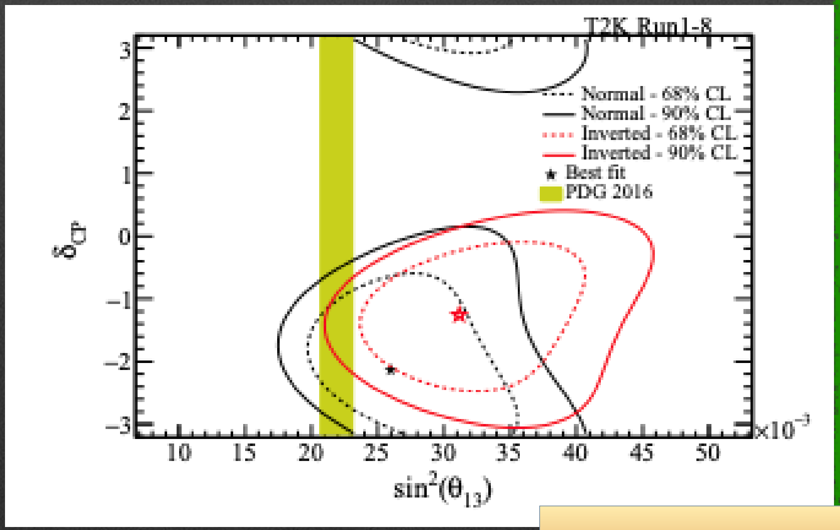
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

- 3 mixing angles
- 2 independent mass differences
- 1 CP violation phase → not yet measured

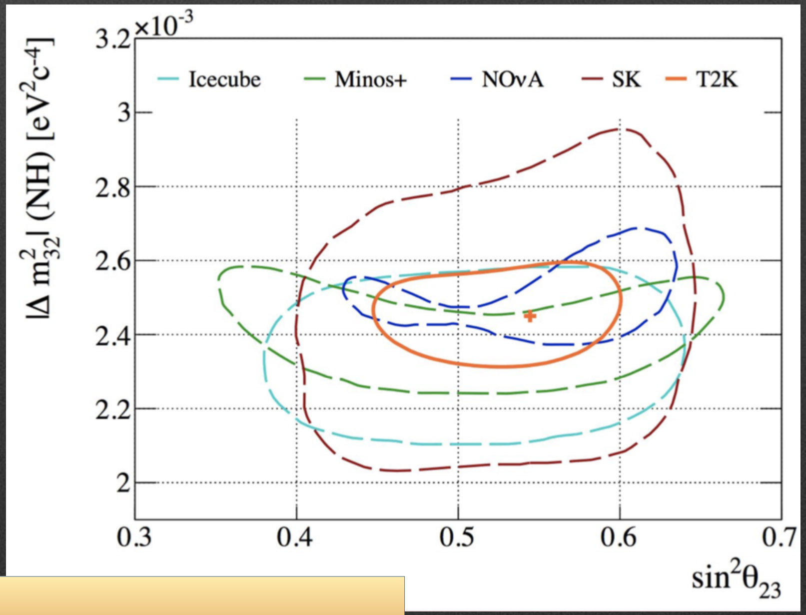
Solar neutrinos (SNO,SK,KamLand) → θ_{12}, Δm^2_{12}



Reactors (Daya Bay, RENO, DChooz) → θ_{13}
LBL (T2K, NOvA) → θ_{13}, δ_{CP}



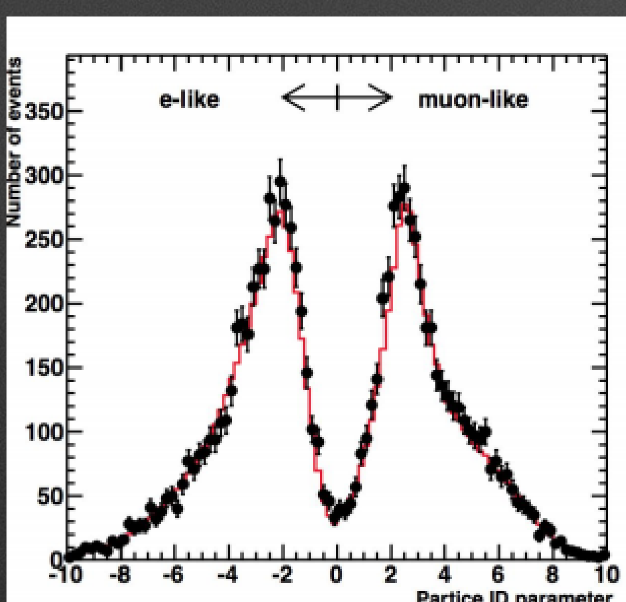
Atmospheric (SK, IceCUBE)
LBL (Minos, T2K, NOvA) → θ_{23}, $|\Delta m^2_{32}|$



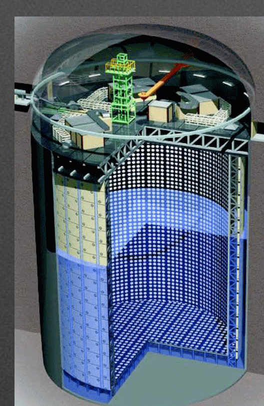
LBL experiments

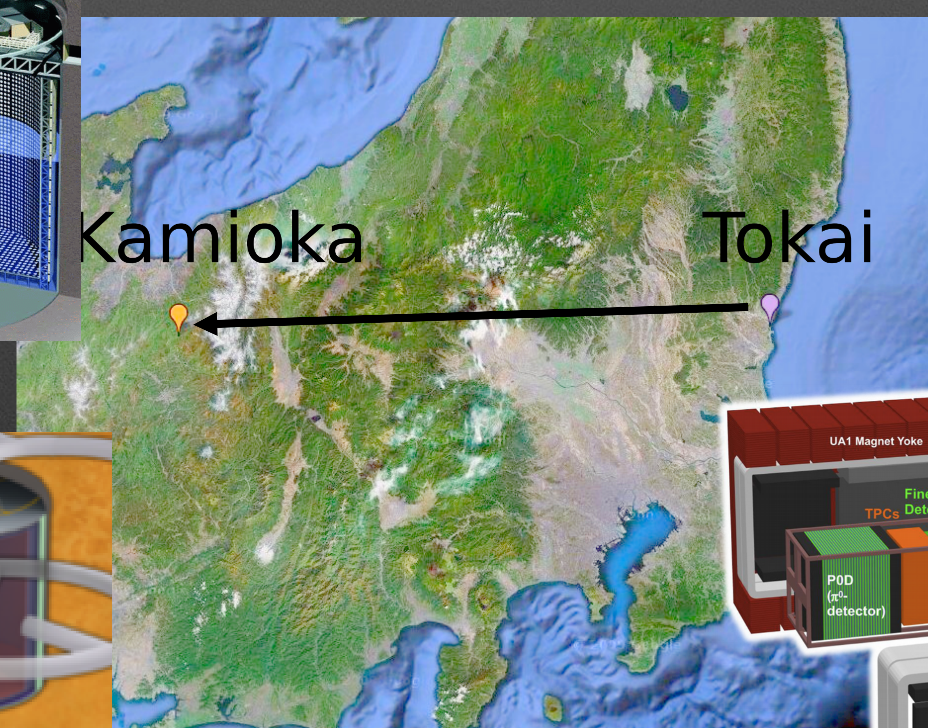
Tokai-to-Kamioka (SK or HK)

- High intensity ~600 MeV ν_μ off-axis beam produced at J-PARC (Tokai)
- Neutrinos detected at the Near Detector (ND280) and at the Far Detector, Super-Kamiokande (Hyper-Kamiokande) 295 km from J-PARC
- Main physics goals:
  - Observation of ν_e and $\bar{\nu}_e$ appearance → determine θ_{13} and δ_{CP}
  - Precise measurement of ν_μ and $\bar{\nu}_\mu$ disappearance → θ_{23} and Δm^2_{32}



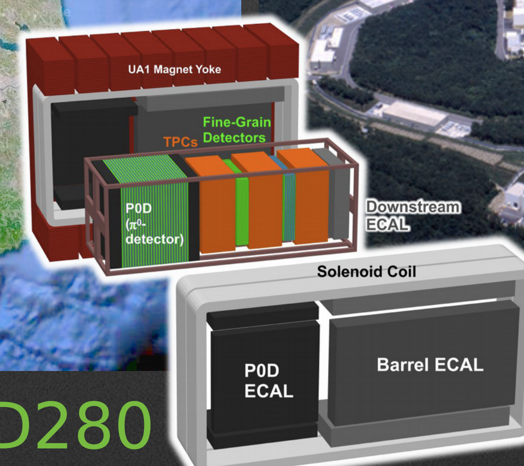
Super-Kamiokande





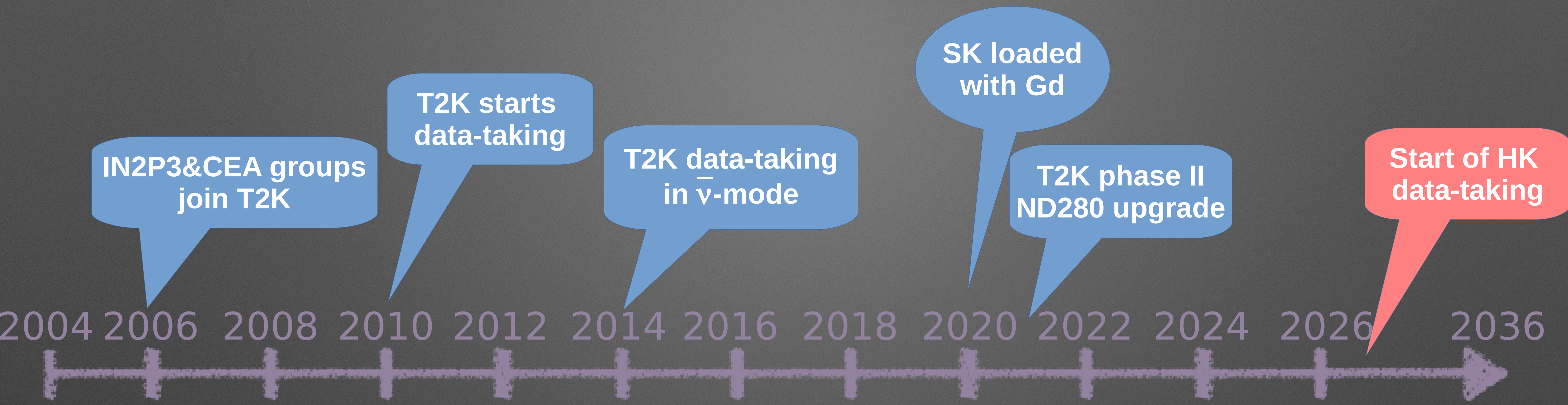
Hyper-Kamiokande

J-PARC accelerator:
Design power: 750 kW
(1.3 MW for HK)

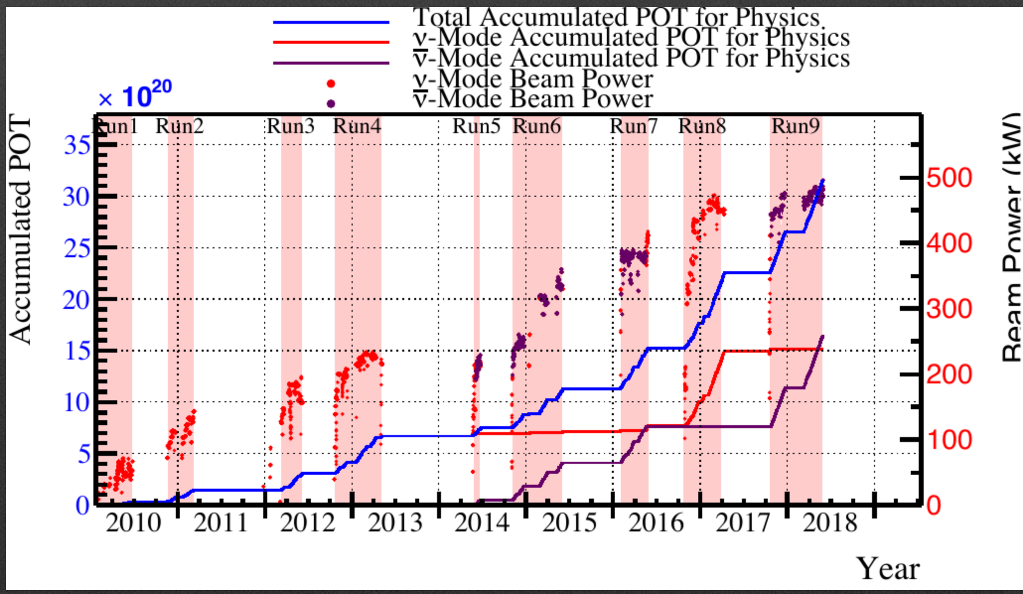


ND280

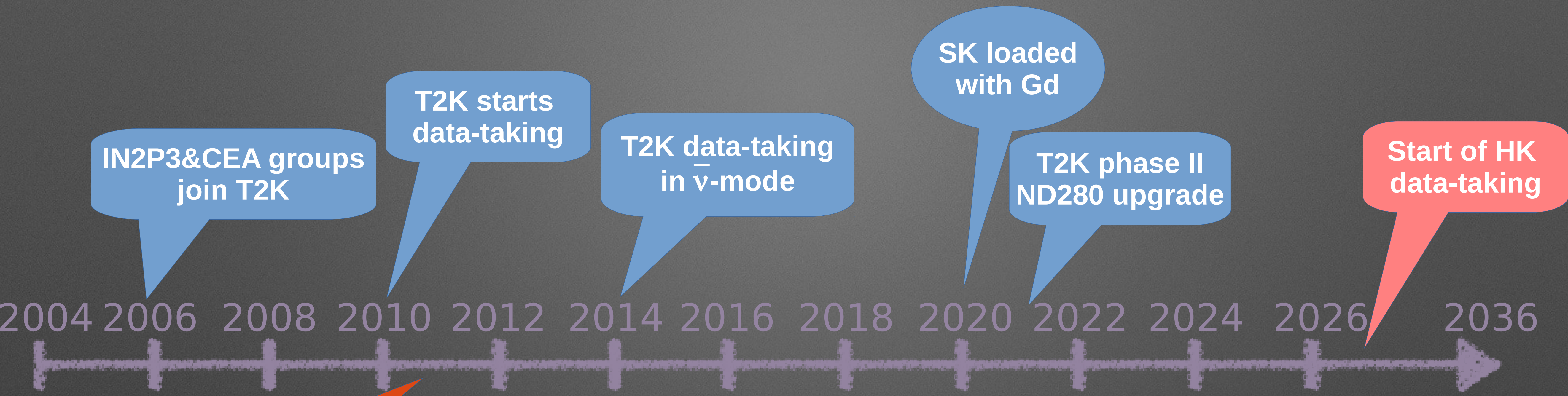
>30 year-long program



- 15 years of successful research by IN2P3 and CEA groups in Japan
- T2K is currently taking data (Run10)
- 15 exciting years to come
  - SK run with Gd
  - T2K phase II and Near Detector upgrade
  - Hyper-Kamiokande!

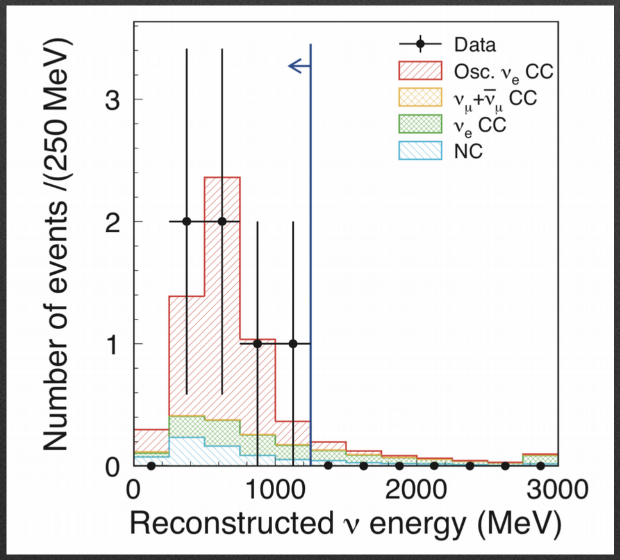


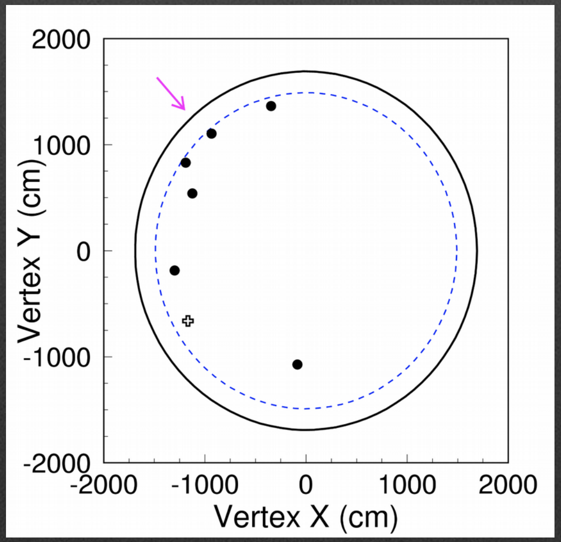
>30 year-long program

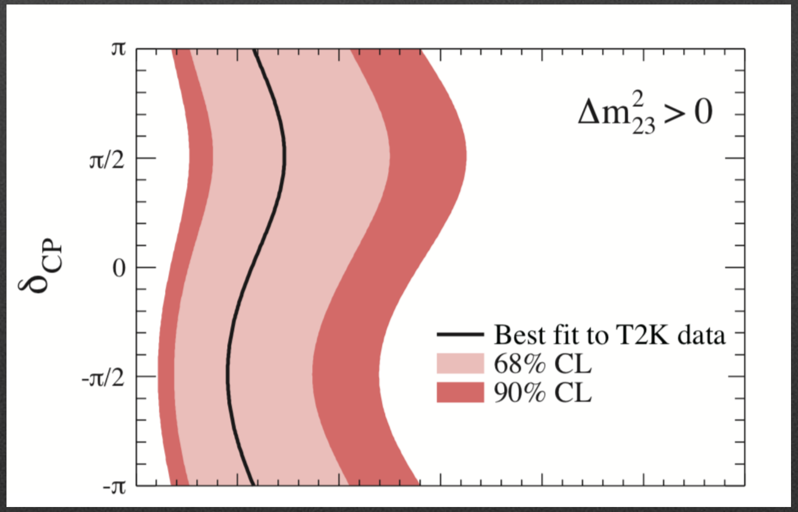


Hints of νe appearance
($\theta_{13} \neq 0$ @ 2.5σ)

Phys.Rev.Lett. 107 (2011) 041801







>30 year-long program

IN2P3&CEA groups join T2K

T2K starts data-taking

T2K data-taking in $\bar{\nu}$-mode

SK loaded with Gd

T2K phase II ND280 upgrade

Start of HK data-taking

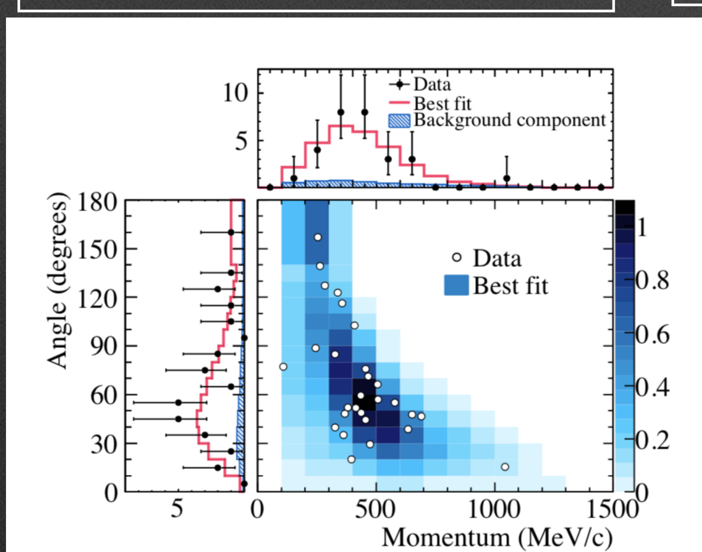
2004 2006 2008 2010 2012 2014 2016 2018 2020 2022 2024 2026 2036

Hints of νe appearance ($\theta_{13} \neq 0$ @ 2.5σ)

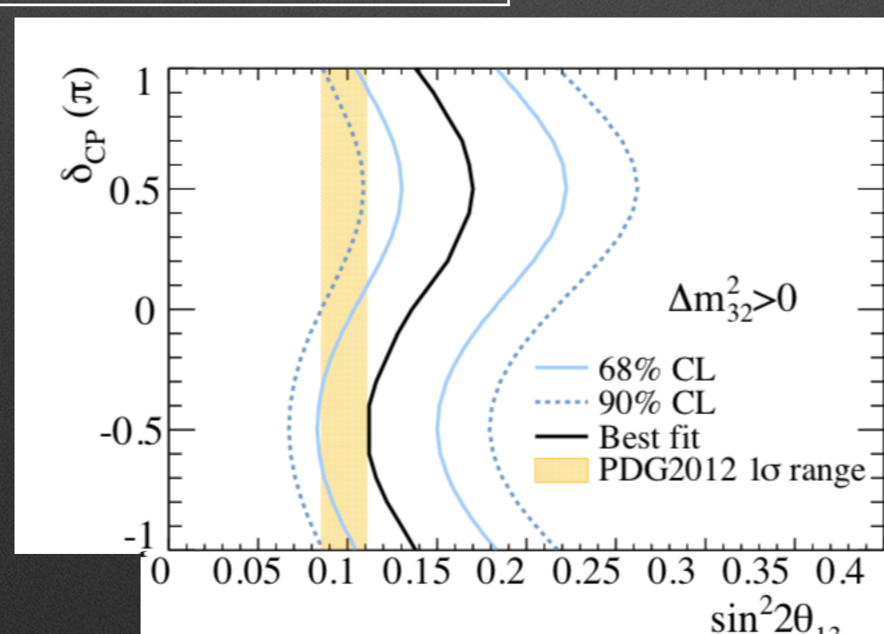
Observation of νe appearance ($\theta_{13} \neq 0$ @ 7.3σ)

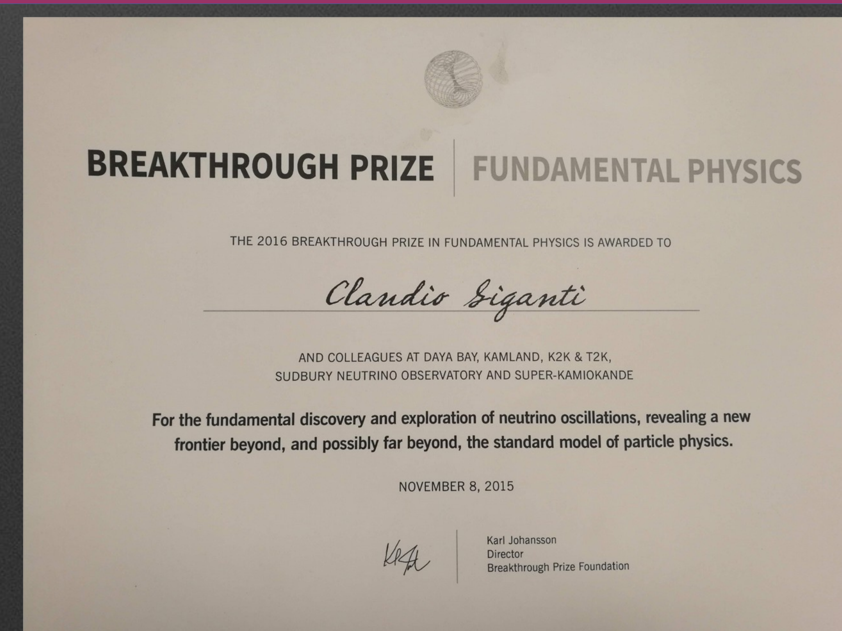
2016 Breakthrough prize in Physics to Daya Bay, Kamland, SK, SNO, K2K and T2K Collaborations

Phys.Rev.Lett. 107 (2011) 041801



Phys.Rev.Lett. 112 (2014) 061802





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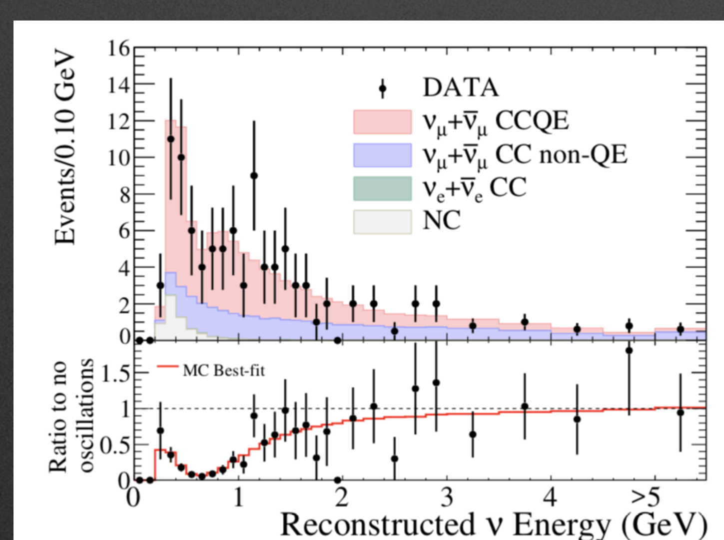
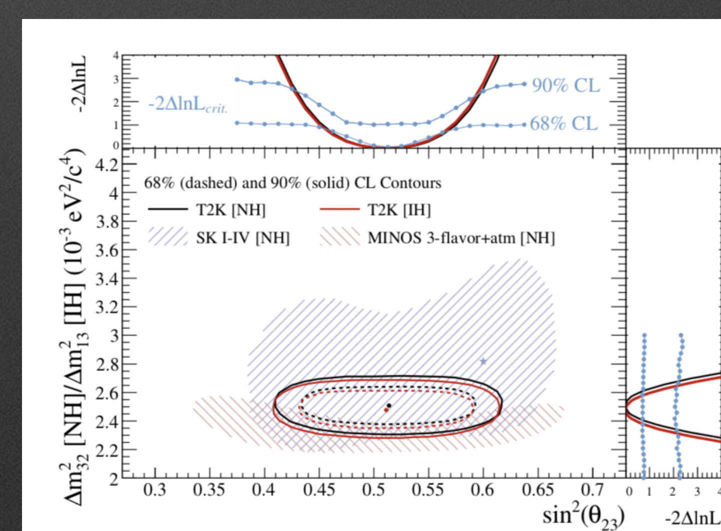
Phys.Rev.Lett. 112 (2014) 061802

World-best measurements of θ_{23} and Δm^2_{32}

Phys.Rev.Lett. 112 (2014) no.18, 181801





>30 year-long program

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Hints of νe appearance ($\theta_{13} \neq 0$ @ 2.5σ)

Observation of νe appearance ($\theta_{13} \neq 0$ @ 7.3σ)

World-best measurements of θ_{23} and Δm^2_{32}

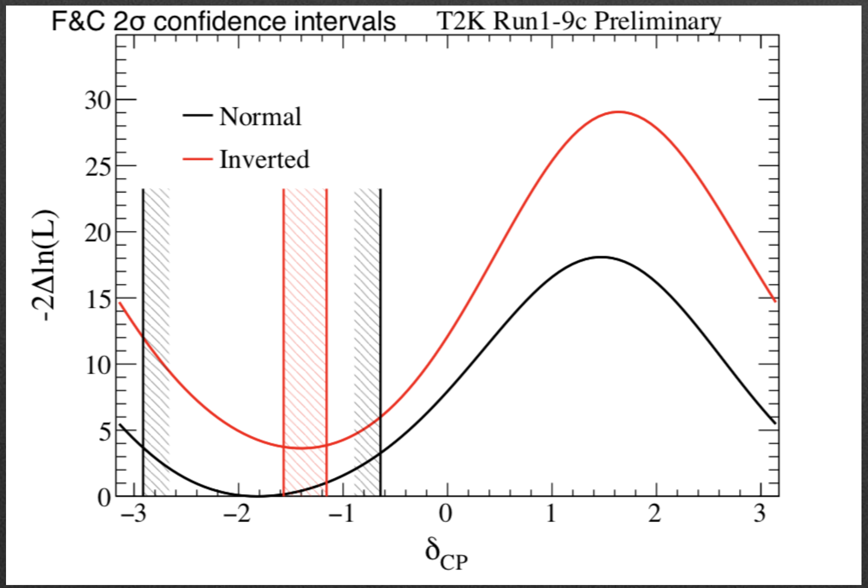
Hints of leptonic CP violation→ $\sin(\delta_{CP})=0$ excluded at 95%

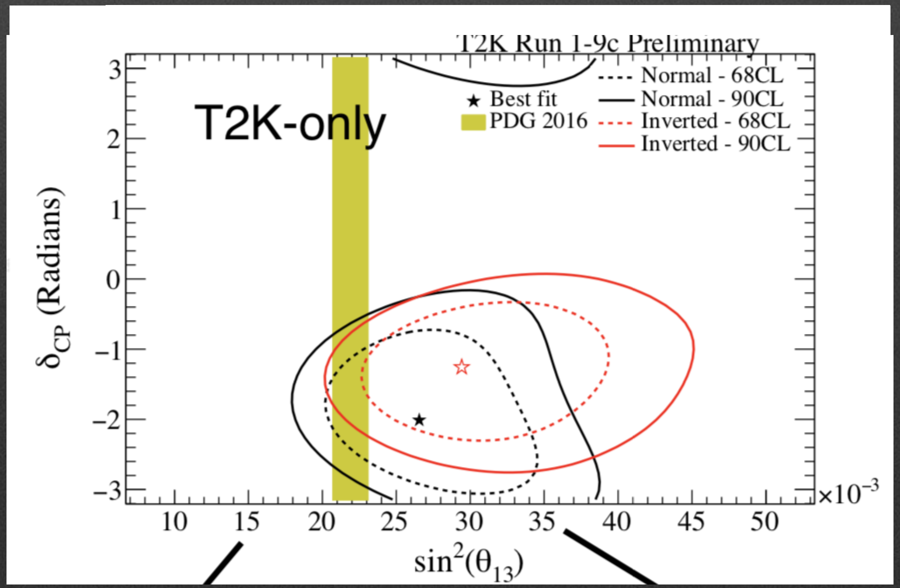
Phys.Rev.Lett. 107 (2011) 041801

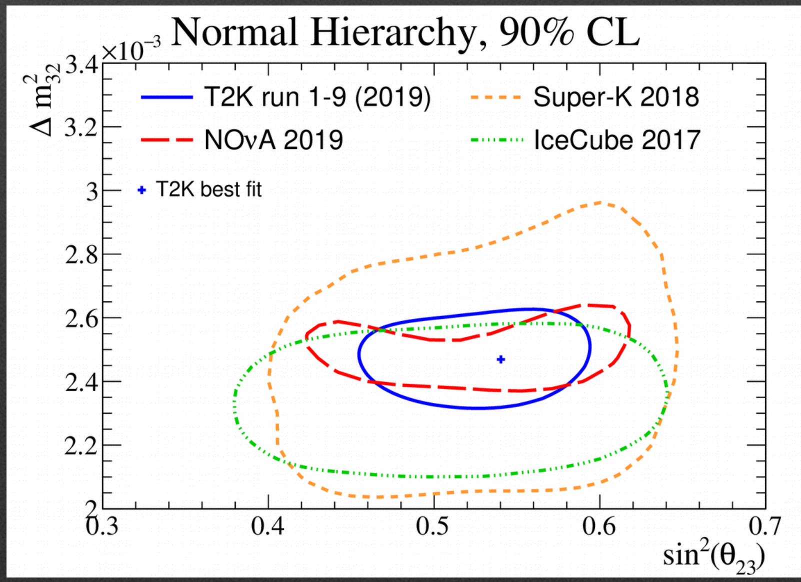
Phys.Rev.Lett. 112 (2014) 061802

Phys.Rev.Lett. 112 (2014) no.18, 181801

Phys.Rev.Lett. 121 (2018) no.17, 171802



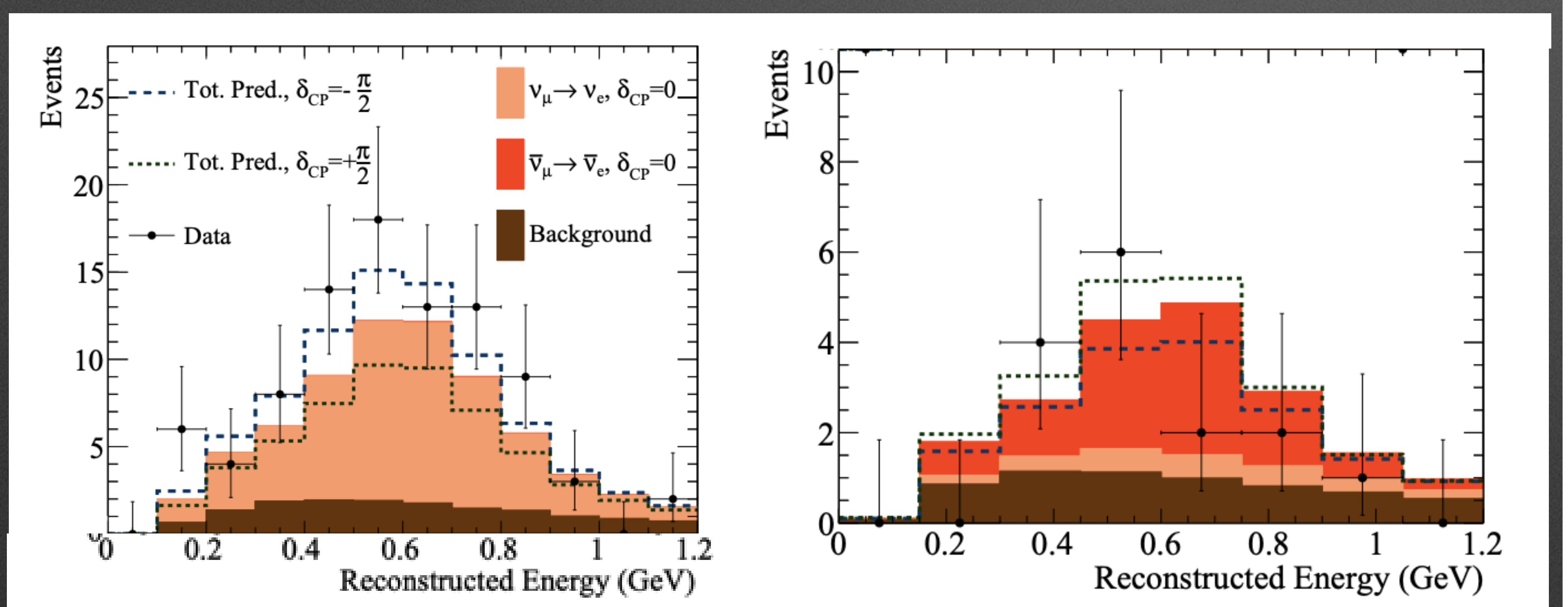


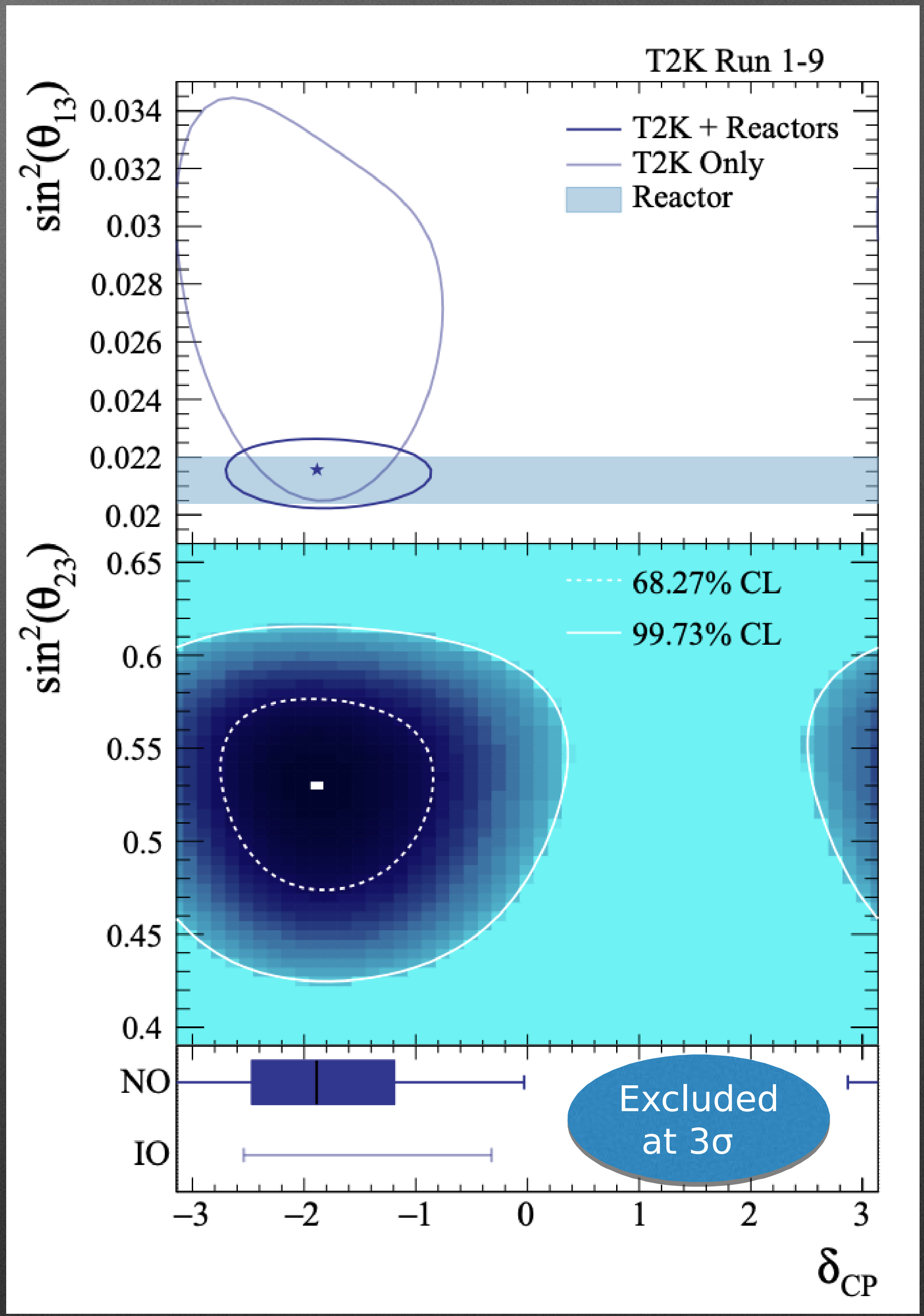


Hot of the press

- Paper submitted to Nature: [Constraint of the matter-antimatter symmetry violating phase in Neutrino oscillations]
- First 3σ exclusion for 46% (65%) of the δ_{CP} values in NO (IO)
- Need more data (and smaller systematics)!

ν-mode $\bar{\nu}$-mode

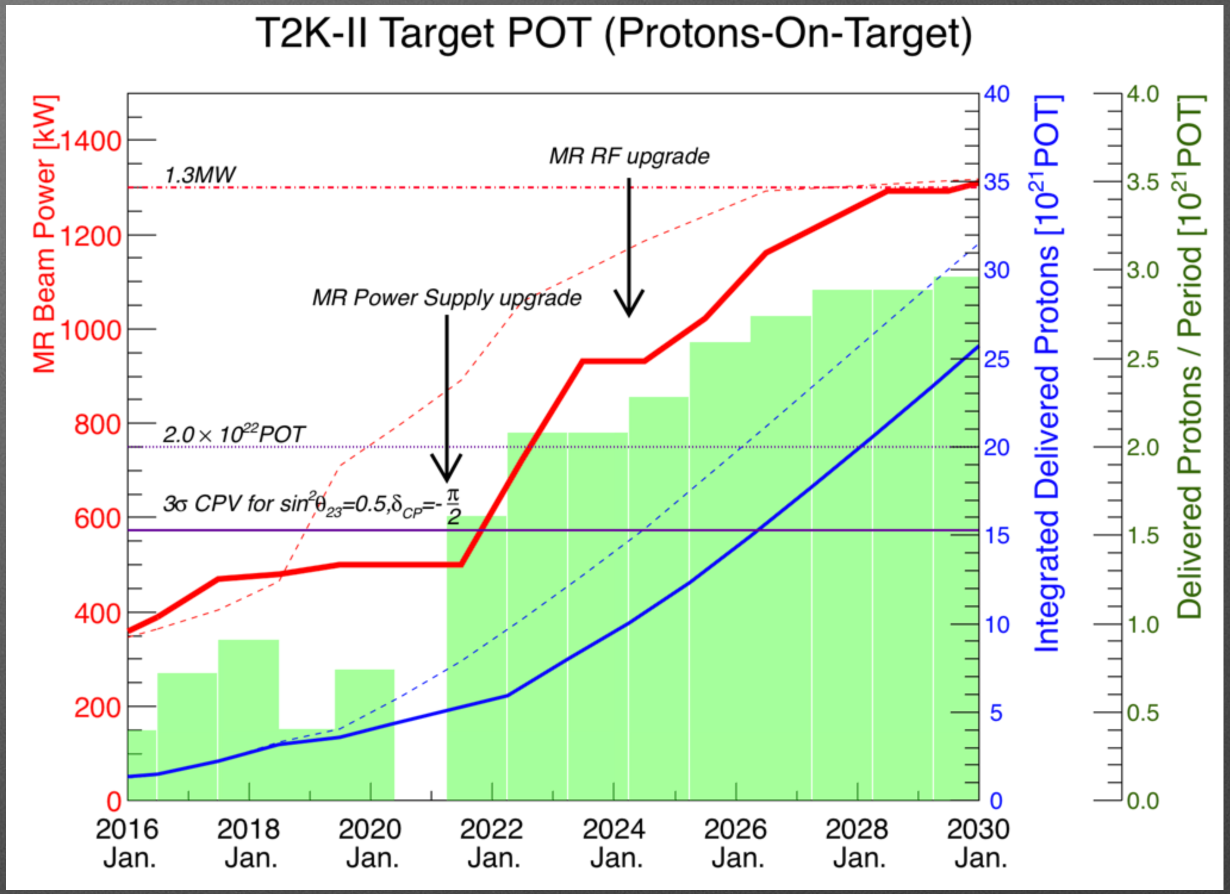


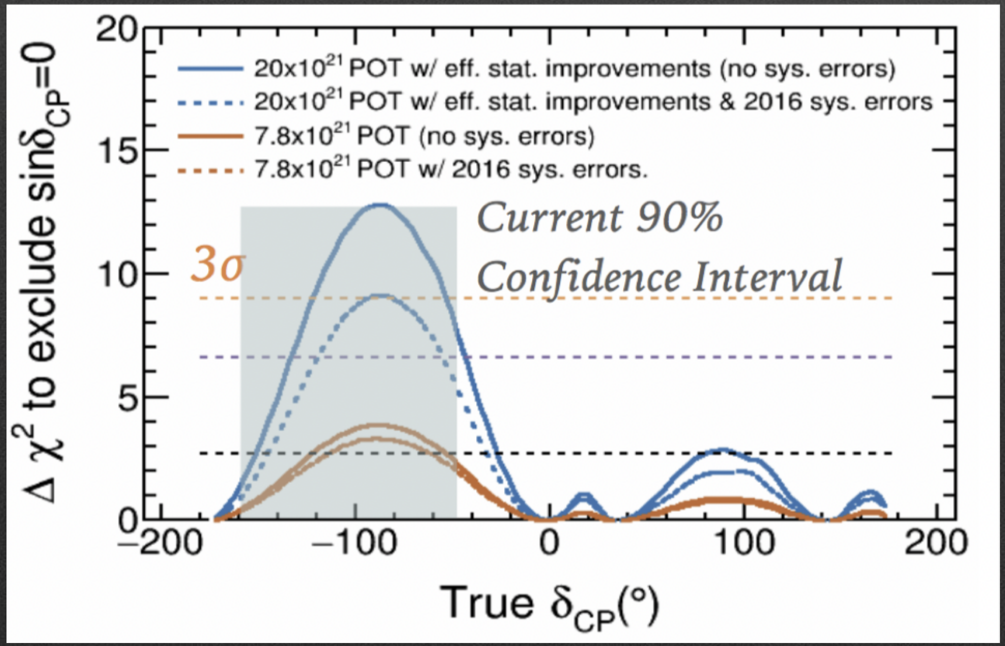


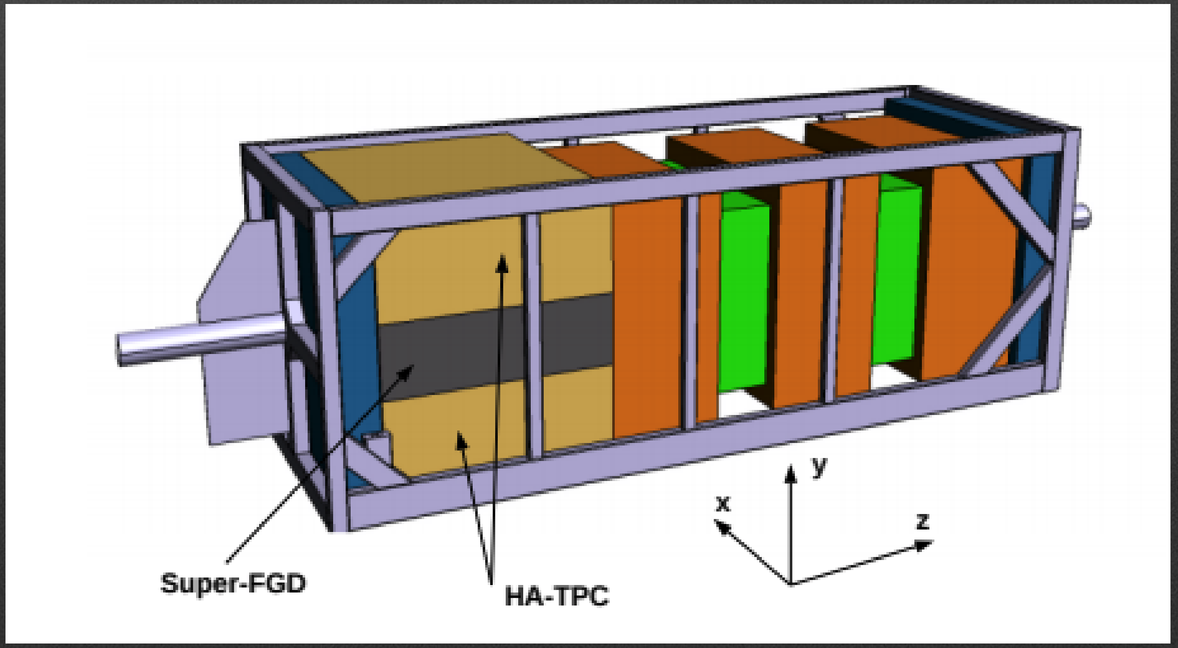
	ν-mode	$\bar{\nu}$-mode
Observed	**90**	**15**
Expected if **δ**CP=-π/2	81.7	17.2
Expected if **δ**CP=0	68.4	19.6

Second phase of T2K (T2K-II)

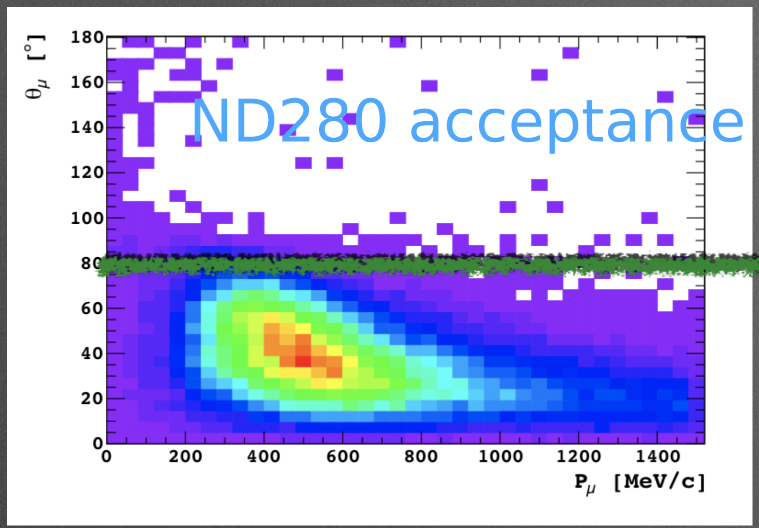
- Upgrade of J-PARC Main Ring (1.3 MW beam)
  - Approved and funded, will be done in 2021
- Goal: collect >10x10^{21} POT by 2026 → 3σ measurement of CP violation if δ_{CP}~-π/2
- Near Detector upgrade to reduce systematics from ~7% to ~4%
  - We will install the new detectors in 2021
  - Use the ND280 Upgrade detector also as initial Near Detector for HK
  - Funded by France (CEA+IN2P3), Italy, US, Japan, Spain, Poland, Russia, Germany, Switzerland
  - Leading role of the LPNHE group (project coordinator)
- Improvements of the Far Detector thanks to the SK-Gd project

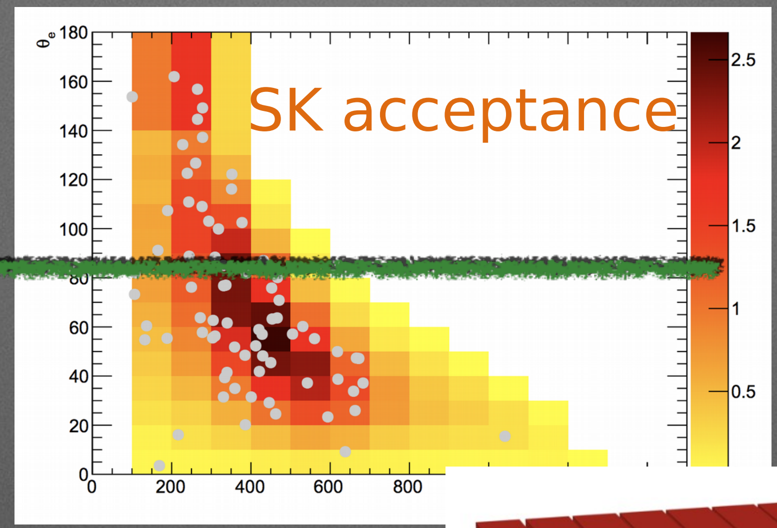


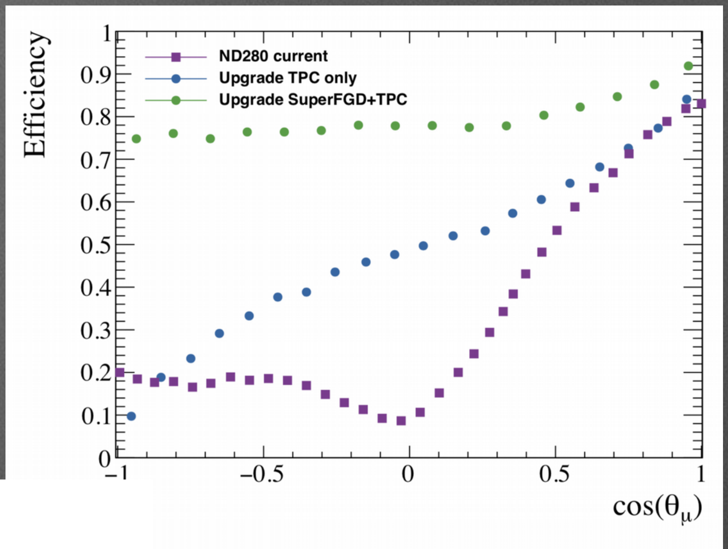




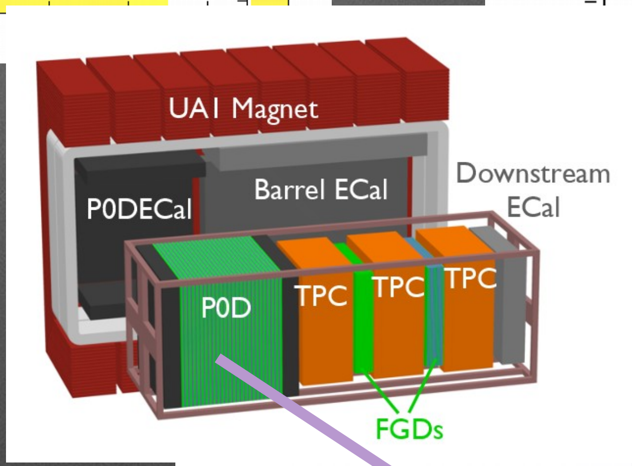
ND280 upgrade

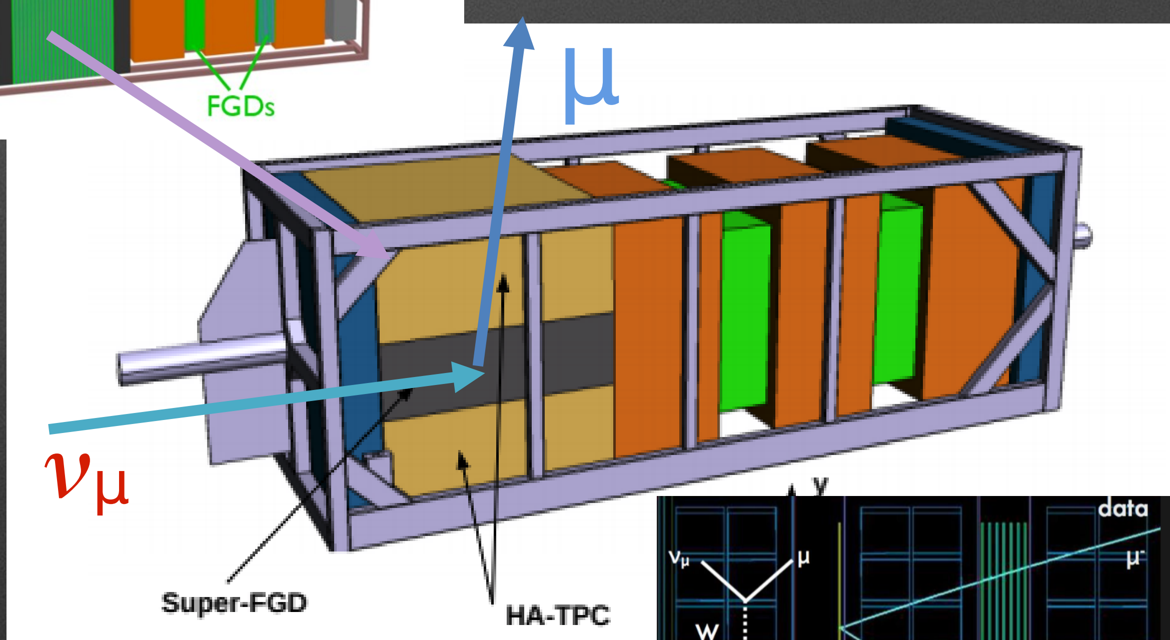


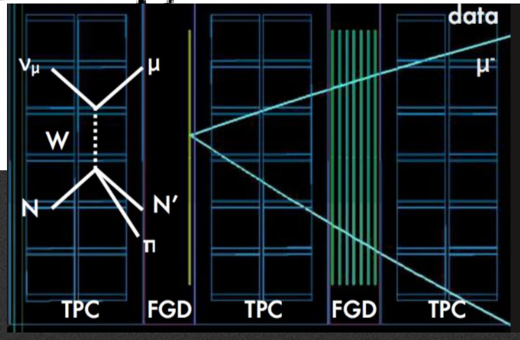




- Main strength of ND280 : magnetized detector → separate ν from $\overline{\nu}$ (cannot be done in SK or HK)
- Main limitation of ND280 : reduced angular acceptance → only forward going tracks are reconstructed with high efficiency
- An analysis dedicated to select tracks with high polar angles → 20% efficiency
- We can do better with an upgrade → Horizontal target and horizontal TPCs

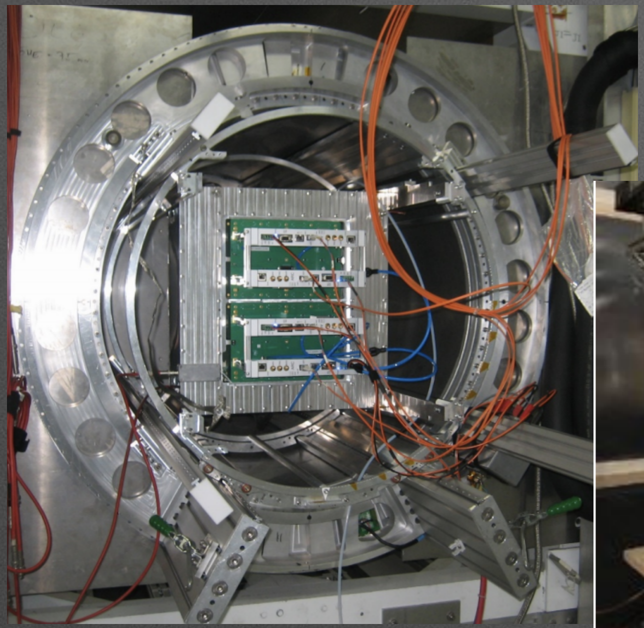
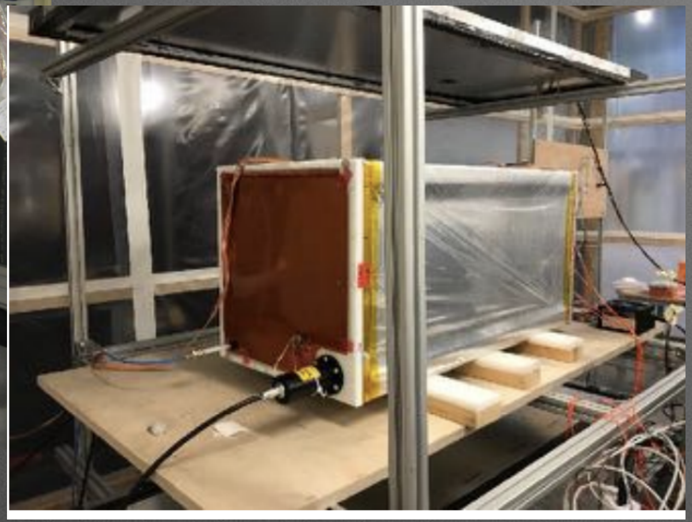






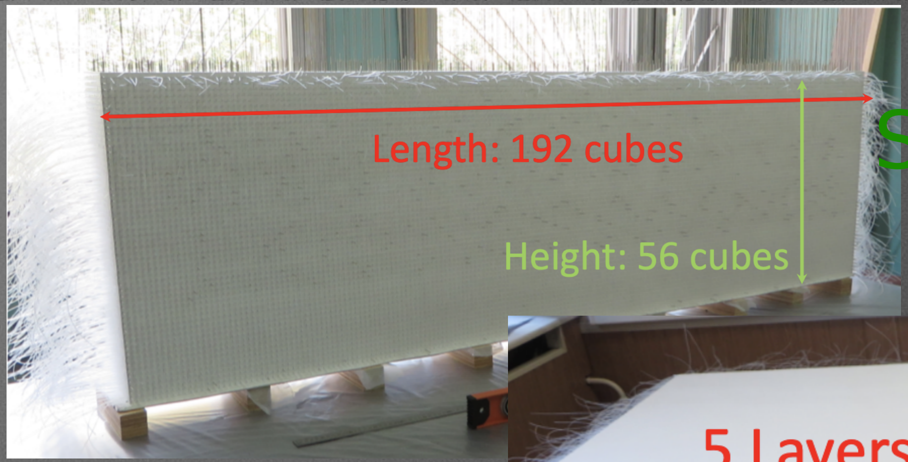
New detectors

High-Angle TPCs

- New TPCs instrumented with Resistive MicroMegas
- DESY and CERN Test beams
  - Spatial resolution ~200 µm
  - dE/dx resolution ~7% for 70 cm tracks
- First TPC expected by Summer 2020
- LPNHE responsible for the Front-End electronics and TPC DAQ based on embedded Linux

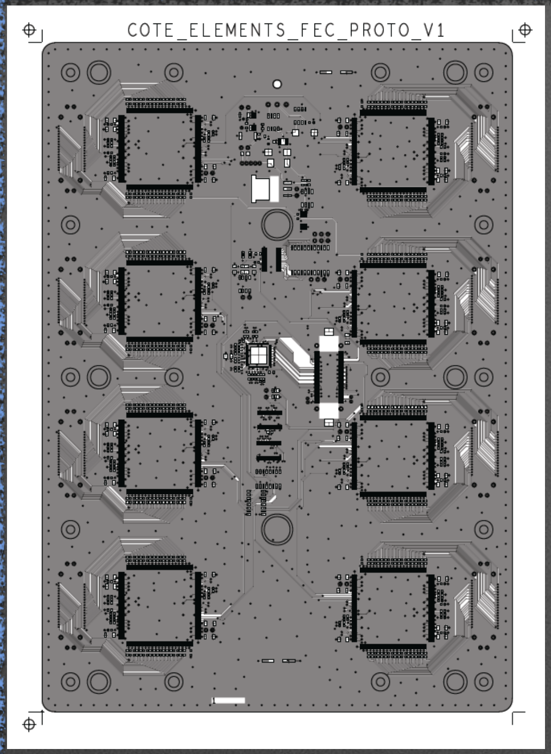
Super-FGD

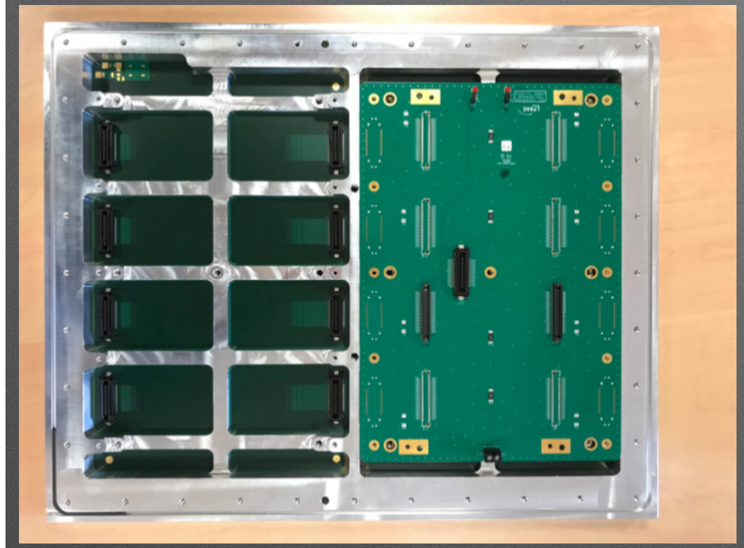


- New concept of detectors, 2×10^6 $1cm^3$ cubes
  - 25% of the cubes already built
  - All produced by Dec 2020
- Each read out by 3 WLS fibers
- Improve reconstruction of the hadronic part of the interactions
- LLR responsible for the Front-End electronics using CITIROC chips

LPNHE contributions

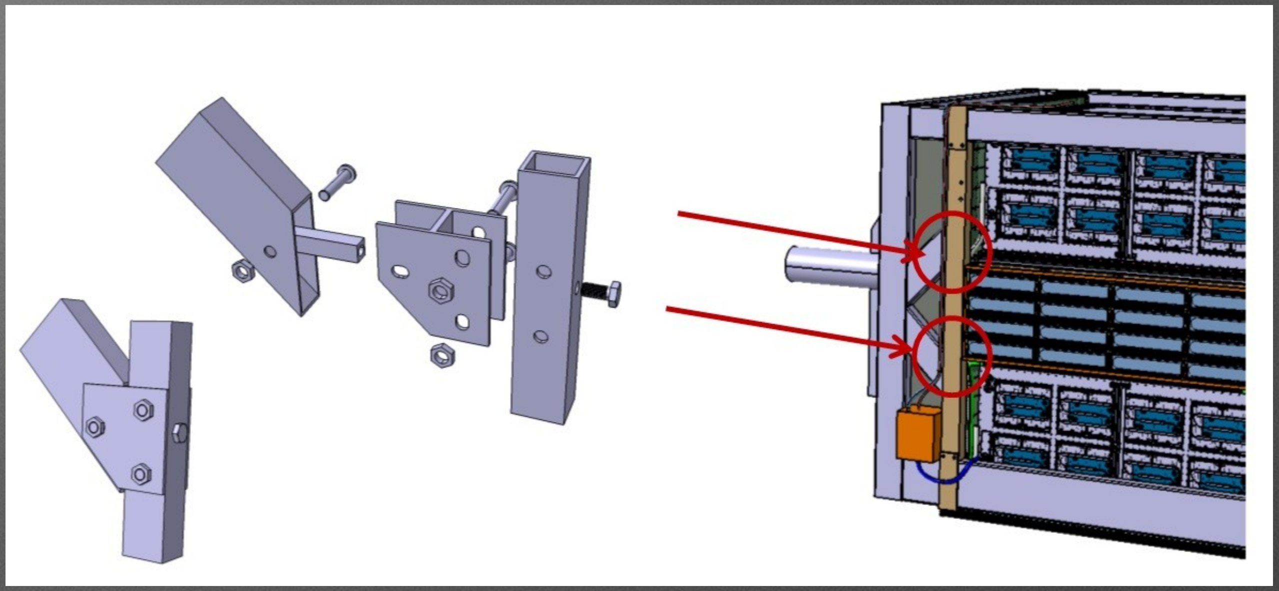
TPC electronics





- Design and production of 80 Front-End Cards (FEC) for TPC readout
  - FEC-mockup to validate floating connectors
  - First full FEC design is ready, prototype is being produced
- Test production by Summer 2020
- Full-scale production just after
- Installation in Japan by end 2021

Mechanics

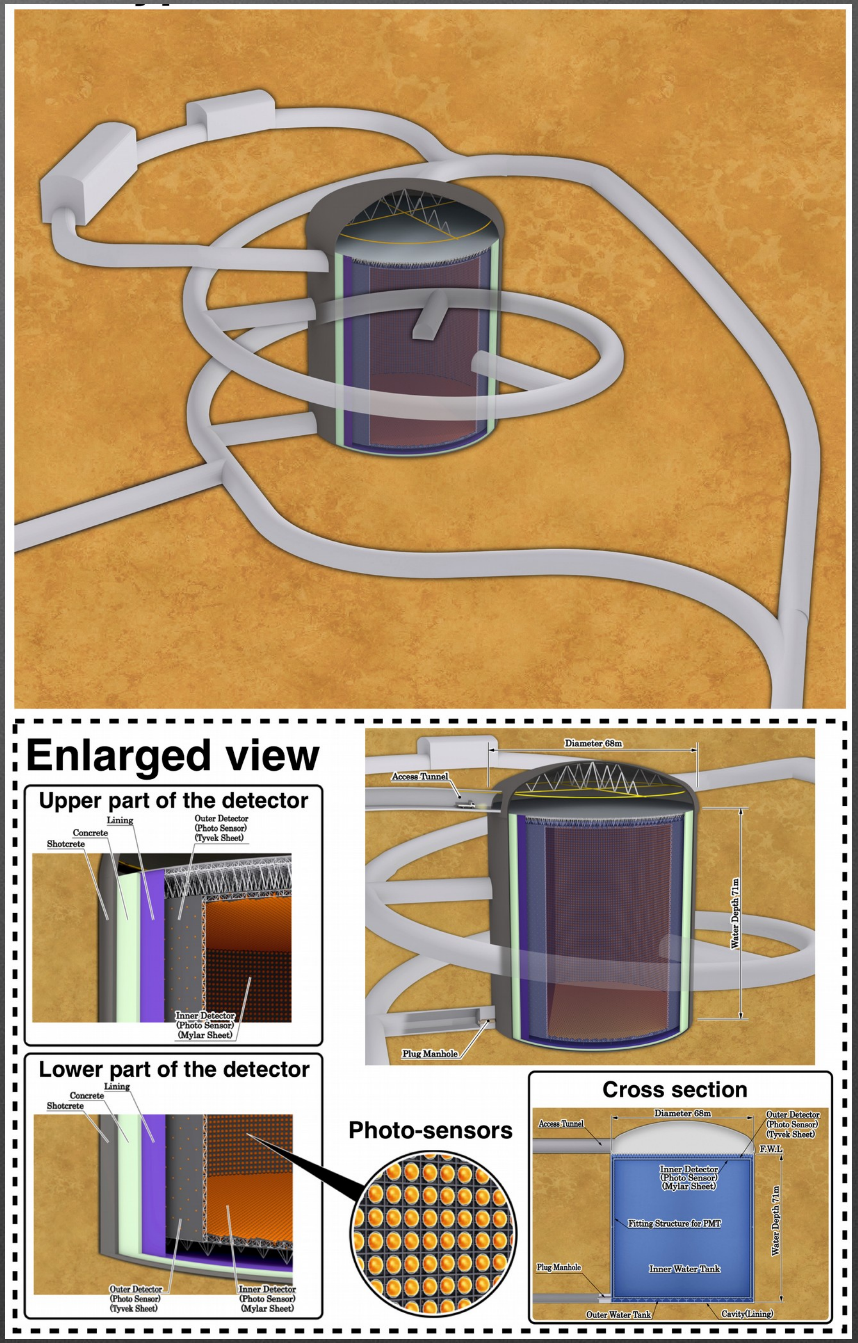


- Contributions to installation of new detectors in the existing basket
  - Design of basket modifications including finite element and seismic analysis
  - Global detector envelopes and service volume definitions
- FEC cooling system

Hyper-Kamiokande (HK)

New (3rd generation) experiment is being prepared by an international collaboration!

- Extremely well established Water Cherenkov technology
  - 190 kton fiducial volume (SK 22.5 kton)
  - Instrumented with up to 40k PMTs
- HK will be the most sensitive observatory for rare events (proton decay, SN neutrinos, …)
- Search for CP violation in lepton sector
  - Upgrade of J-PARC neutrino beam (1.3 MW)
  - Near and Intermediate detector complex



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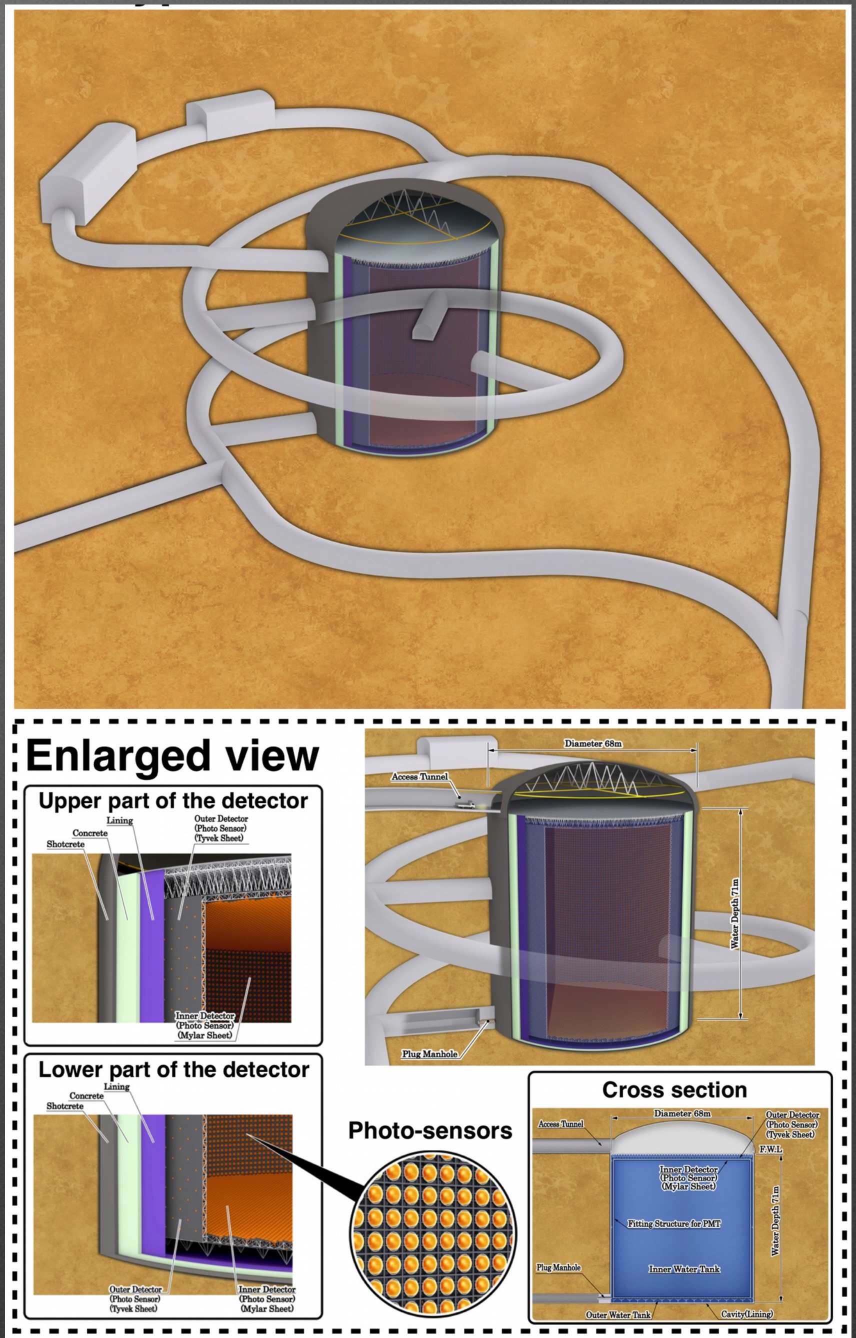
- Search for CP violation in lepton sector
  - Upgrade of J-PARC neutrino beam (1.3 MW)
  - Near and Intermediate detector complex
- August 2019 → MEXT approved HK and requested budget for construction to the Ministry of Finance
- Begin construction in 2020, start operation in 2027



<u>MEXT Statement</u>

In addition to the ongoing 13 large-scale projects, the next-generation neutrino research project Hyper-Kamiokande, will be newly launched in FY2020

Release by MEXT on Aug. 29, 2019

(MEXT) will start the next-generation neutrino research project "Hyper-Kamiokande" in JFY2020.

○ **日本学術会議**において科学的観点から策定した**マスタープラン**を踏まえつつ、専門家等で構成される**文部科学省の審議会**において戦略性・緊急性等を加味し、**ロードマップを策定**。

○ ロードマップの中から大規模学術フロンティア促進事業として実施するプロジェクトを選定の上、国立大学法人運営費交付金等の基盤的経費により戦略的・計画的に推進。原則、**10年間の年次計画を策定**し、審議会における**厳格な評価・進捗管理**を実施。

○ 現行の13プロジェクトに加え、**令和2年度より、ニュートリノ研究の次世代計画である「ハイパーカミオカンデ計画」に新たに着手。**

主な成果

○ **ノーベル賞受賞につながる画期的研究成果**
（受賞歴：H14小柴昌俊氏、H20小林誠氏、益川敏英氏、H27梶田隆章氏）

○ **年間約1万人の共同研究者が集結**し、国際共同研究を推進。このうちの**半数以上が外国人**

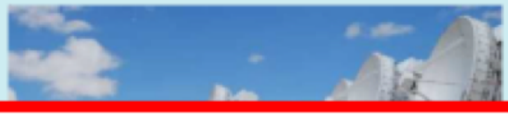
Next generation of neutrino project with a 260 kton detector and the J-PARC upgrade. The project will reveal the mysteries in elementary particles and the Universe by the observation of proton decays and the neutrino researches including CP violation.

天文学･宇宙物理学分野	論文数	Top10%割合	国際共著割合
すばる望遠鏡	644	18.5%	86.3%
アルマ望遠鏡	878	27.3%	89.0%
日本全体	8,938	12.9%	68.0%
世界全体	103,445	9.6%	50.6%

※ 大学共同利用機関法人自然科学研究機構が「InCites」（Web of Science）に基づき、2013-2017の5か年に出版された天文学・宇宙物理学分野の論文（article,review）を分析（2019年7月）。「日本全体」は、著作住所に日本を含む論文を抽出。

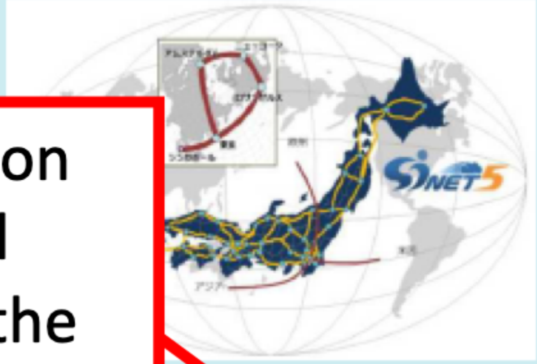
大規模学術フロンティア促進事業等の主な事業

大型電波望遠鏡「アルマ」による国際共同利用研究の推進
〔自然科学研究機構国立天文台〕



巨大ブラックホールの「影」の撮影に世界で初めて成功した国際プロジェクトに参加し、高い感度の観測機能により、その成果に大きく貢献。

新しいステージに向けた学術情報ネットワーク(SINET)整備
〔情報・システム研究機構国立情報学研究所〕



...等を高速通信回線ネットワークで...究の基盤を提供。全国900以上...機関、約300万人の研究者・学...**我が国の教育研究活動に必須の学術情報基盤**。

NEW ハイパーカミオカンデ(HK)計画の推進
〔東京大学宇宙線研究所〕
〔高エネルギー加速器研究機構〕

日本が切り拓いてきた**ニュートリノ研究の次世代計画**として、**超高感度光検出器**を備えた総重量26万トンの**大型検出器の建設**及び**J-PARCの高度化**により、**ニュートリノの検出性能を著しく向上**。素粒子物理学の大統一理論の鍵となる未発見の**陽子崩壊探索**や**CP対称性の破れなどのニュートリノ研究**を通じ、**新たな物理法則の発見、素粒子と宇宙の謎の解明を目指す。**【ロードマップ2017掲載事業】

<産業等への波及>

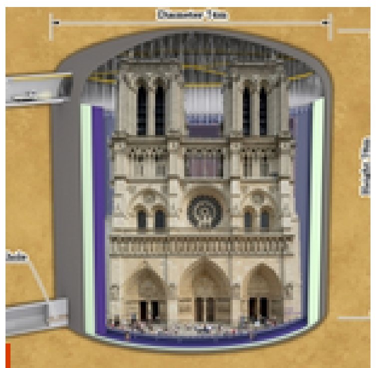
○ 産業界と連携した最先端の研究装置開発により、イノベーションの創出にも貢献

（事例）・【すばる望遠鏡】超高感度カメラ技術⇒**医療用X線カメラへの応用**
・【放射光施設】加齢による毛髪のハリ・コシの低下が毛髪内の亜鉛と関係性を解明⇒亜鉛を毛髪に浸透させる**新しいヘアケア技術の開発・製品化に成功**

HK @ IN2P3

Actualités Agenda International Vie de l'I

L'IN2P3 Recherche Innovation Formation Médiation scientifique



Accueil › Actualités

Le projet Hyper-Kamiokande approuvé par le MEXT

01 octobre 2019 PHYSIQUE DES NEUTRINOS

Le Ministère de la recherche et de l'enseignement japonais (MEXT) a décidé de lancer le projet Hyper-Kamiokande. Le coût de cette infrastructure de recherche dédiée à l'étude des neutrinos est estimé à environ 550 millions d'euros et sa construction pourrait démarrer dès avril 2020, tout près du site de l'expérience actuelle Super-Kamiokande localisée dans les montagnes nippones. Les premières prises de données sont attendues pour les années 2027-2028.

A- / A+

Contact(s)

Laurent Vacavant

Perrine Royole-Degieux

Partager ce contenu

Imprimer

Hyper-Kamiokande prendra la suite du projet T2K (Tokai to Kamiokande) actuellement en fonctionnement avec le réservoir Super-kamiokande. Il représente la nouvelle génération de détecteurs Tcherenkov à eau de très grande taille, une technique éprouvée pour la détection des neutrinos. Il est prévu que son volume d'eau utile, environ 200.000 tonnes, soit supérieur d'un facteur 10 à celui de son prédécesseur Super-Kamiokande. En détectant les neutrinos, le détecteur Hyper-Kamiokande sera à la fois un microscope exceptionnel pour observer les particules élémentaires et un télescope original pour observer le Soleil et les phénomènes cosmologiques très violents. Le projet Hyper-Kamiokande comprend un programme de physique extrêmement riche avec un potentiel de découvertes très important allant de l'étude de la violation matière antimatière dans le secteur leptonique, la recherche de désintégration du proton, l'étude des neutrinos d'origine astronomique, notamment les neutrinos émis lors d'effondrement de Supernovæ…

La collaboration Hyper-Kamiokande est actuellement composée de physiciens provenant de 13 pays de 3 continents différents. Les laboratoires LLR et LPNHE de l'IN2P3 déjà impliqués dans l'expérience T2K réfléchissent activement à participer à ce projet.

Contact

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Perrine Royole-Degieux
Chargée de communication
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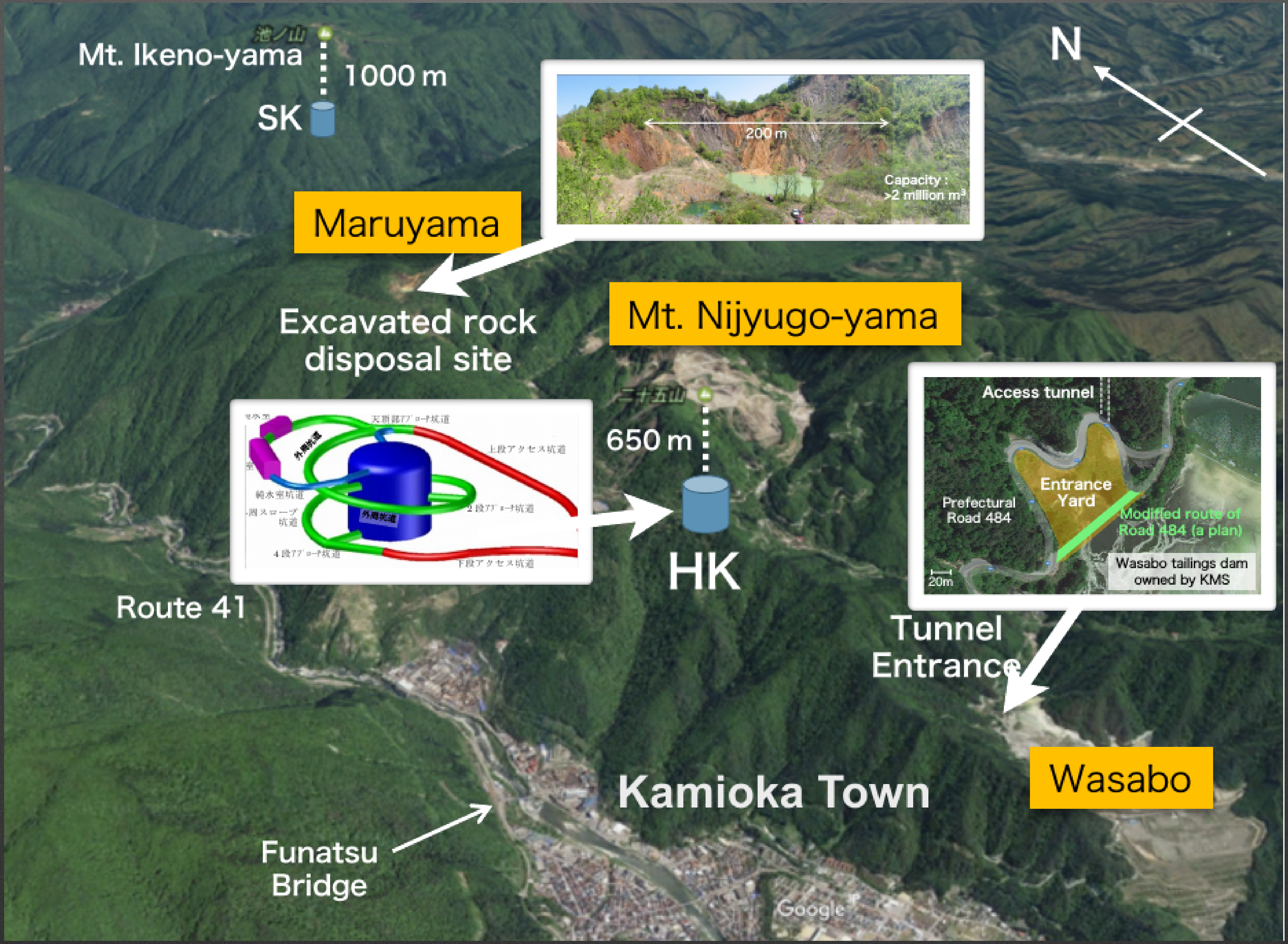
As announced by the IN2P3 directorate, the LPNHE physicists in close collaboration with LLR and CEA colleagues are actively thinking (and trying to take actions as well!) on participation in this project.

We have already identified some possible contributions.

Negotiations with the IN2P3 directorate are on-going.

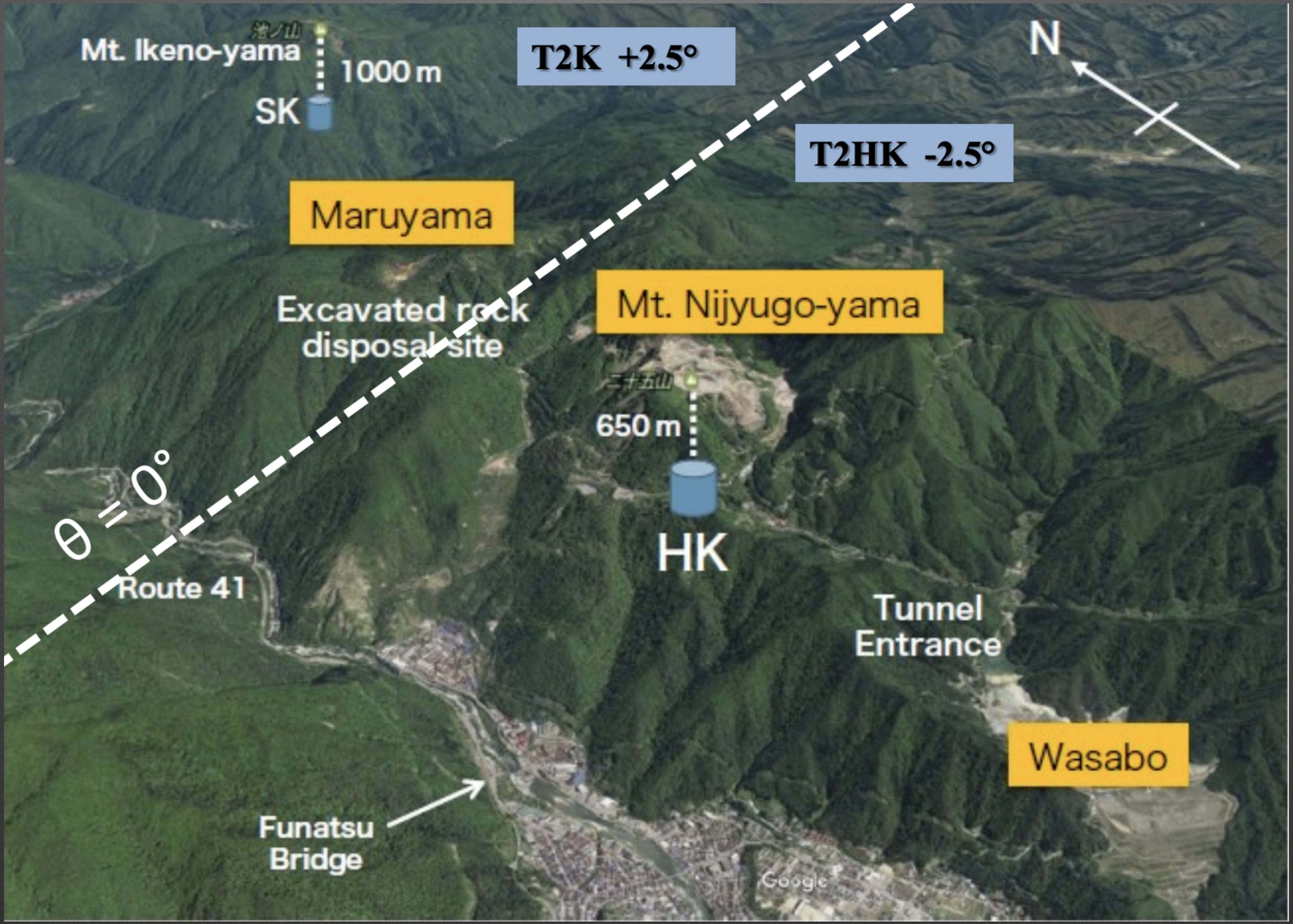
HK : Where



295 km from J-PARC

2.5 degrees off-axis (as SK)

HK : Where



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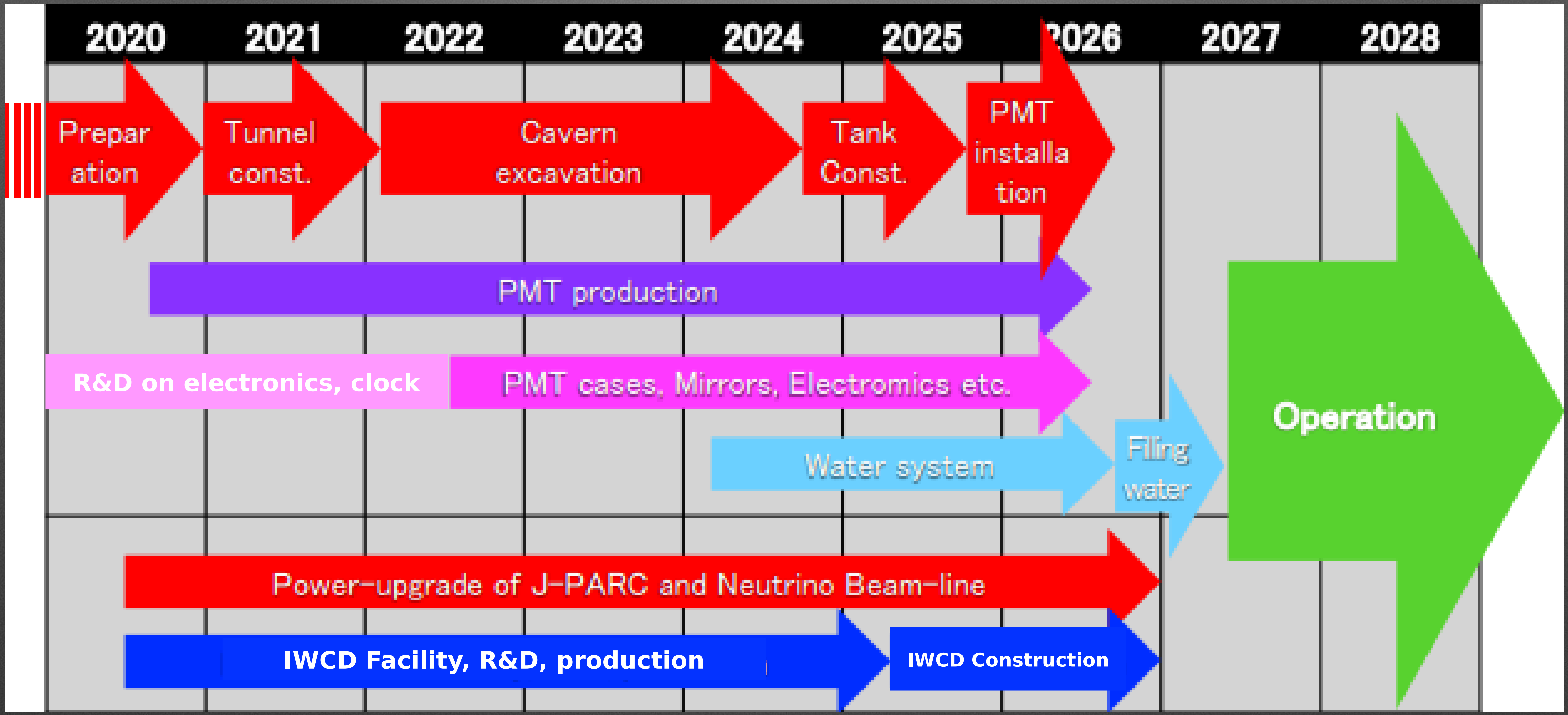
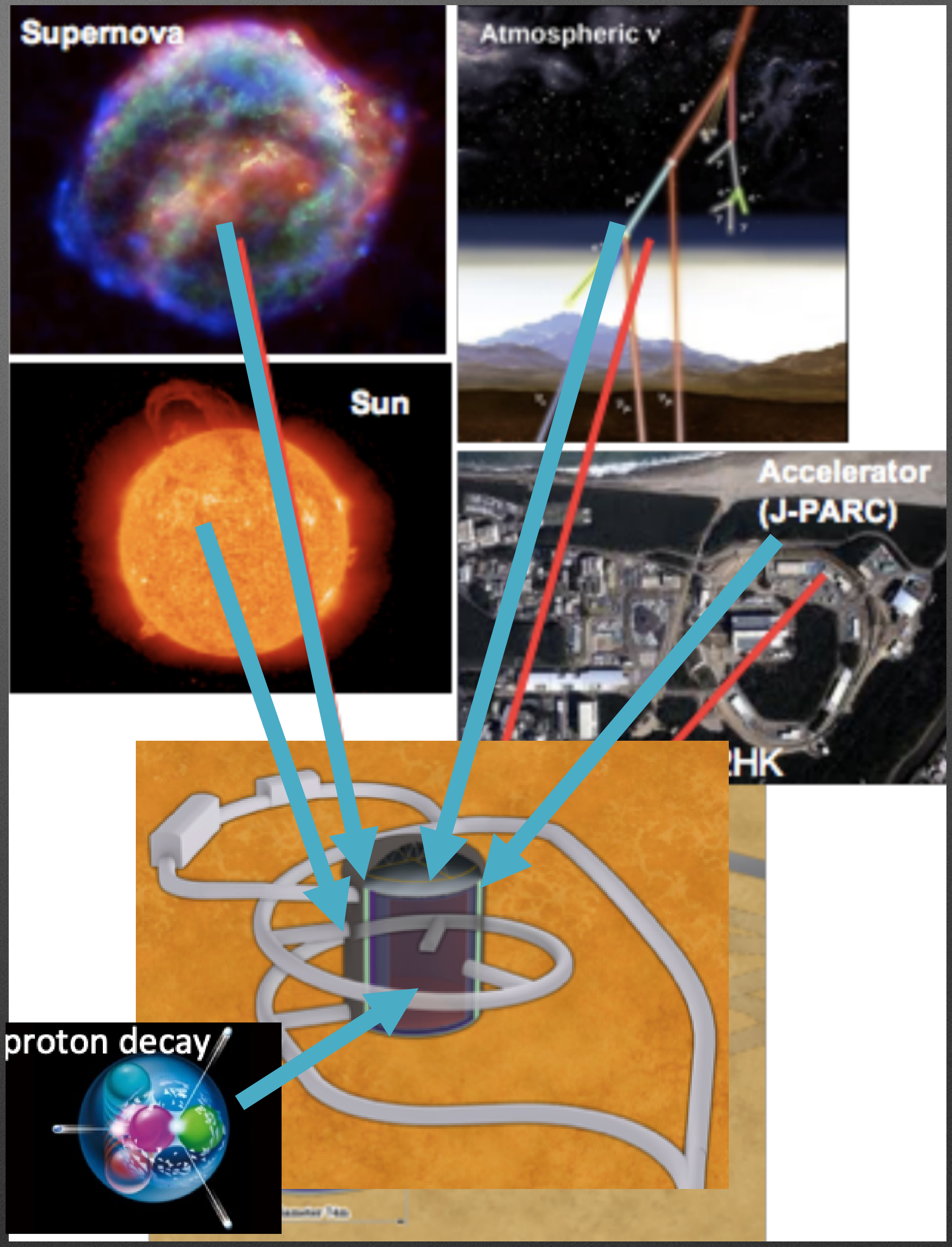


- Start Construction in 2020 (some preparatory work already started)
- Start data taking in JFY 2027
- Budget requested by MEXT to Ministry of Finance for Japanese part (~80% of the total cost of the experiment)
- International contributions being formalized

HK : Why

Broad scientific program in a wide energy rage

- Neutrino oscillation → CP violation
  - Combination of beam and atmospheric neutrinos
- Search for nucleon decay
  - ~10 times better sensitivity than SK
- Neutrino astrophysics
  - Solar ν
  - Atmospheric ν
  - SuperNovae burst
  - Relic SN neutrinos
- Geophysics
- Others



HK : Why

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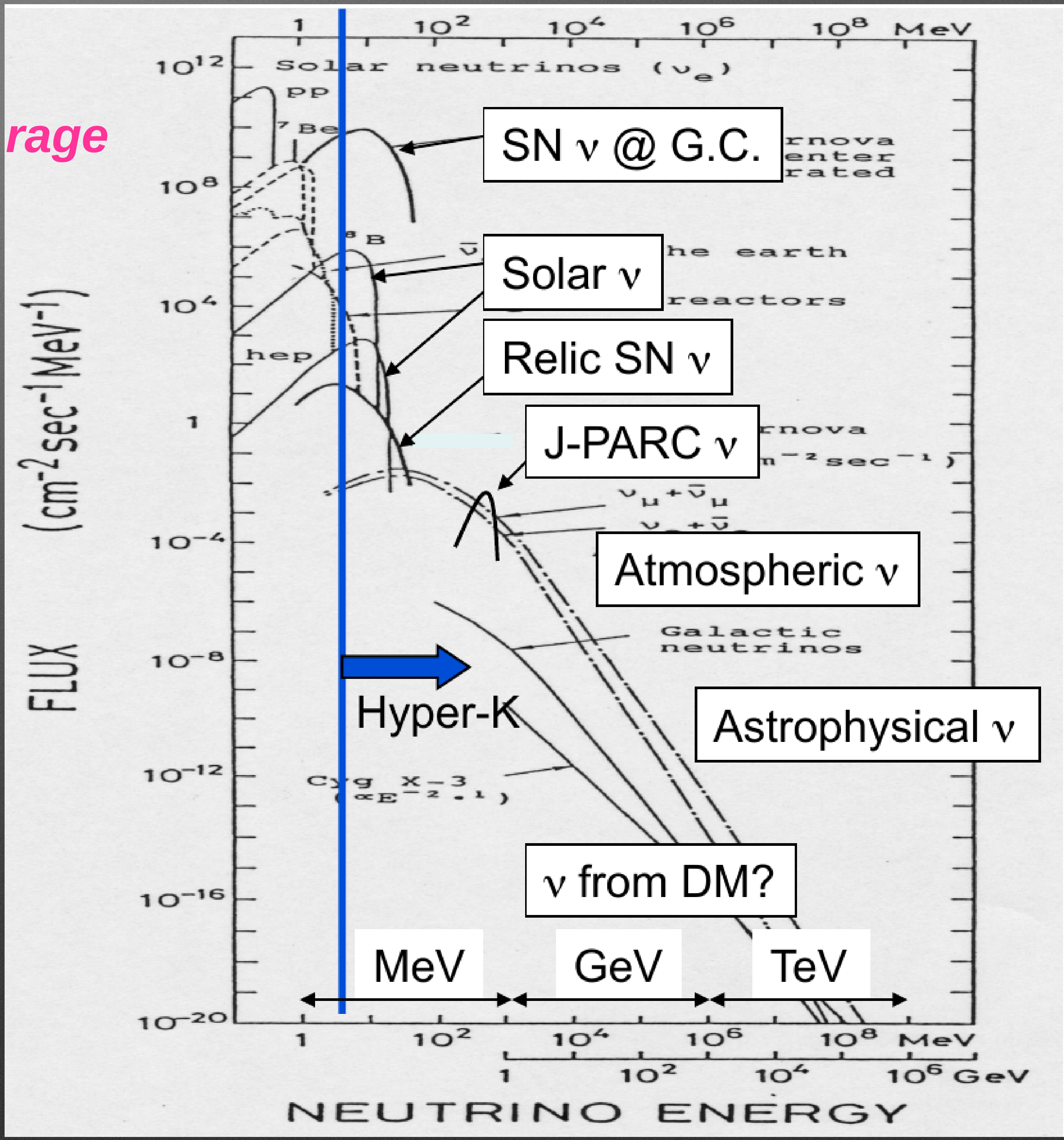
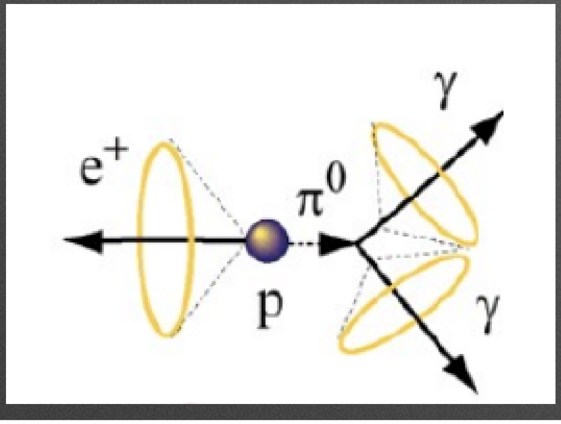


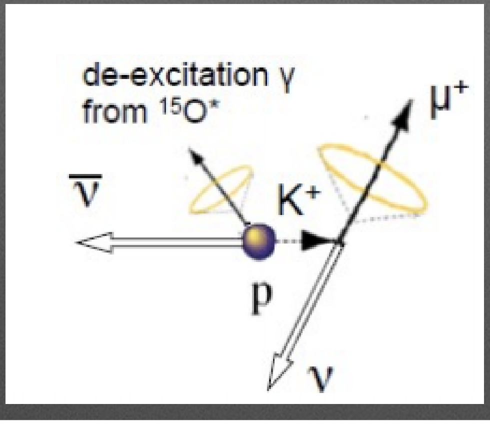
HK: Proton decay search

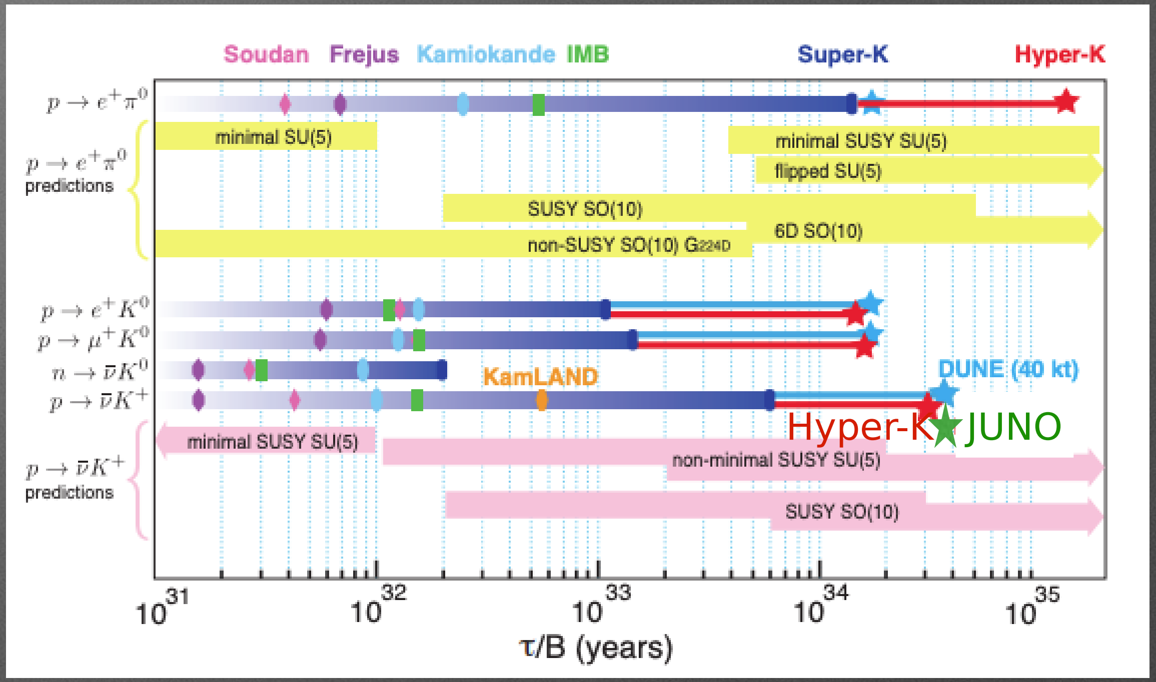
Sensitivity to many different modes
Surpass SK by one order of magnitude
in the leading $p \rightarrow e^+ + \pi^0$

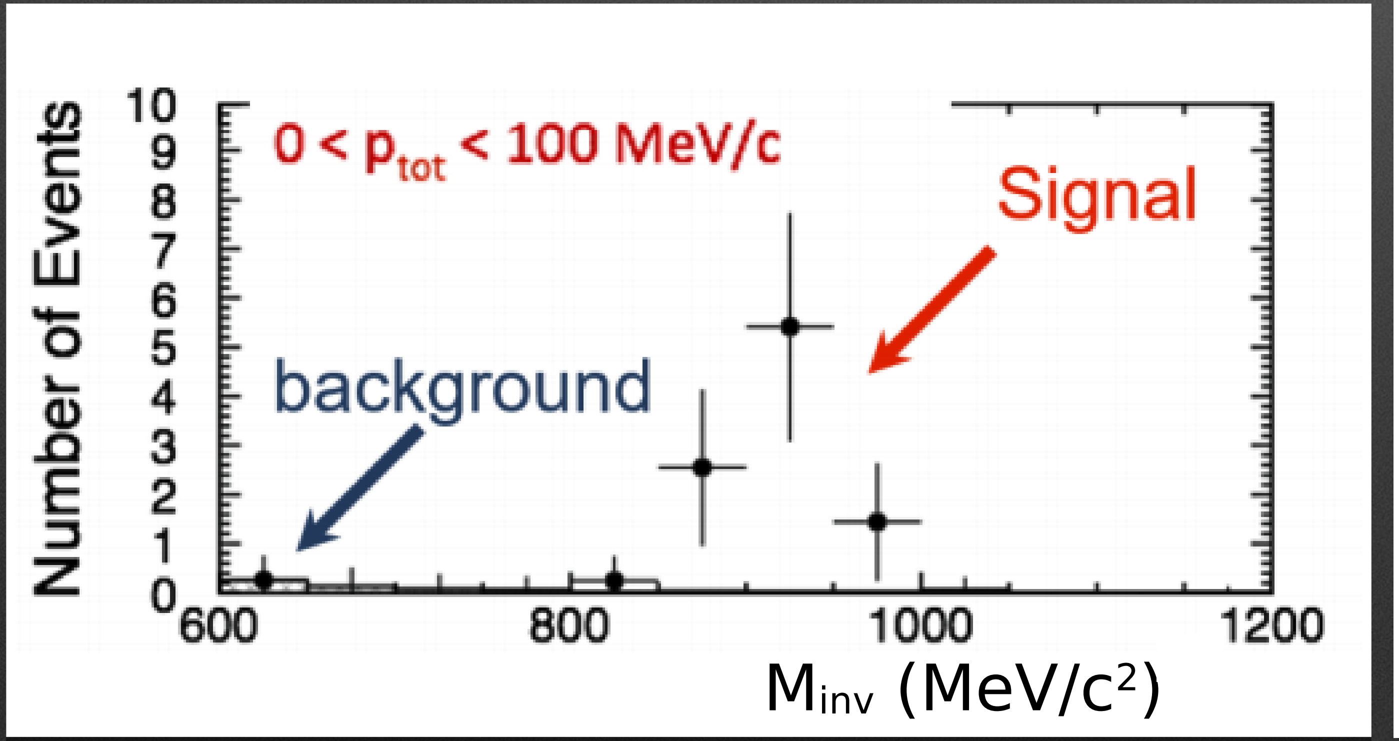
$p \rightarrow e^+ + \pi^0$

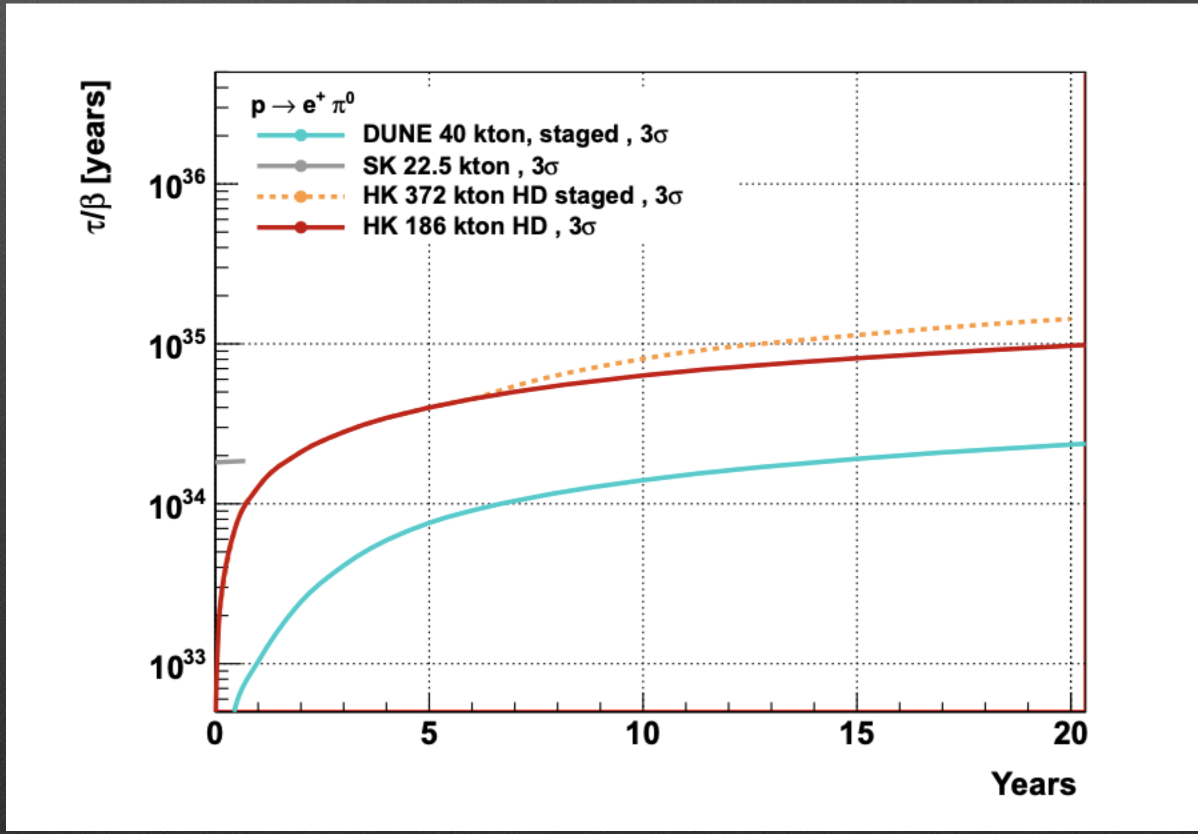
$p \rightarrow K^+ + \bar{\nu}$



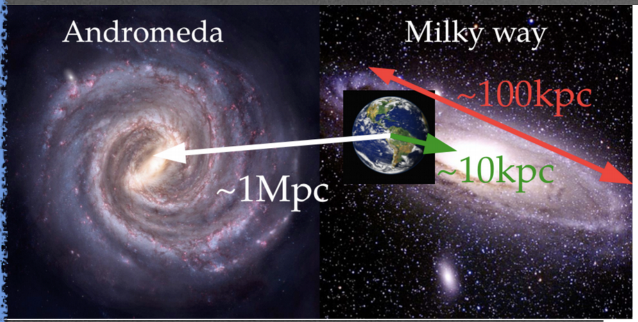


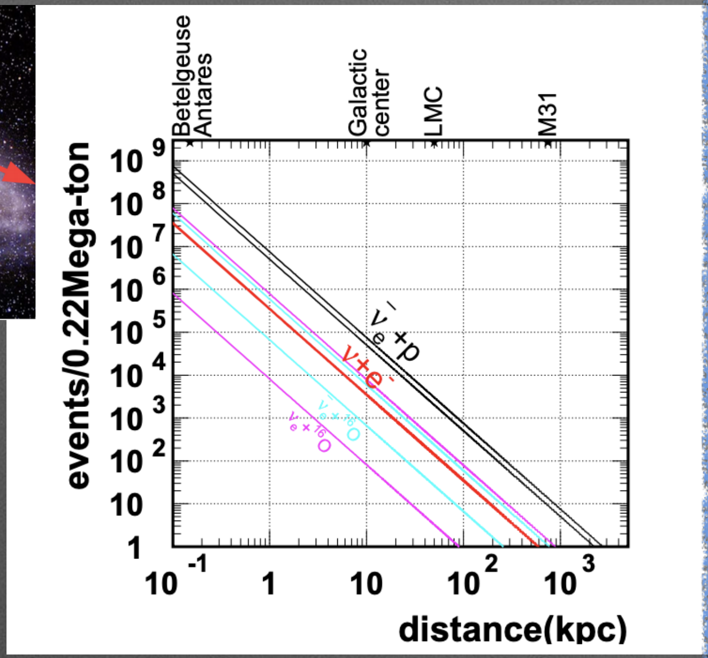




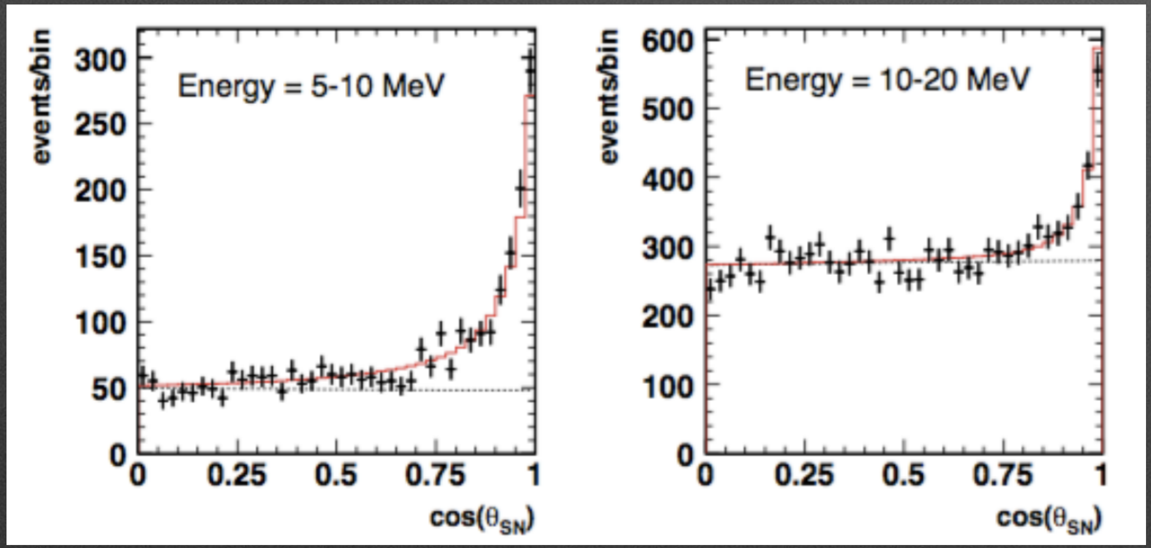


HK: Supernovae neutrinos

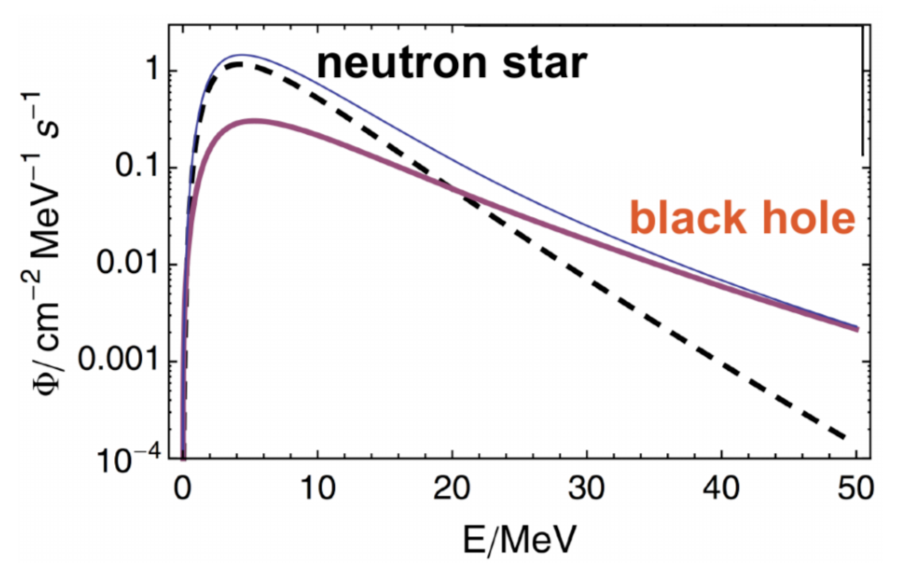


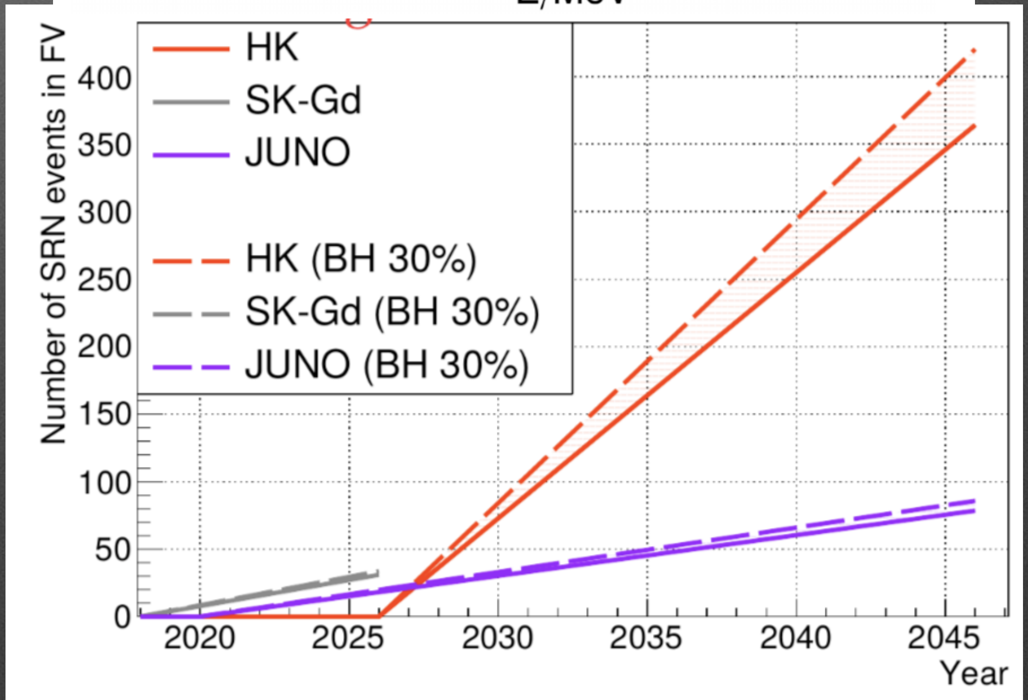


* IBD: huge statistics → SN model
* ES: directionality



* ~80k IBD and ~3k ES for SN explosions in the galactic center
* Sensitive also to SN explosions in Andromeda





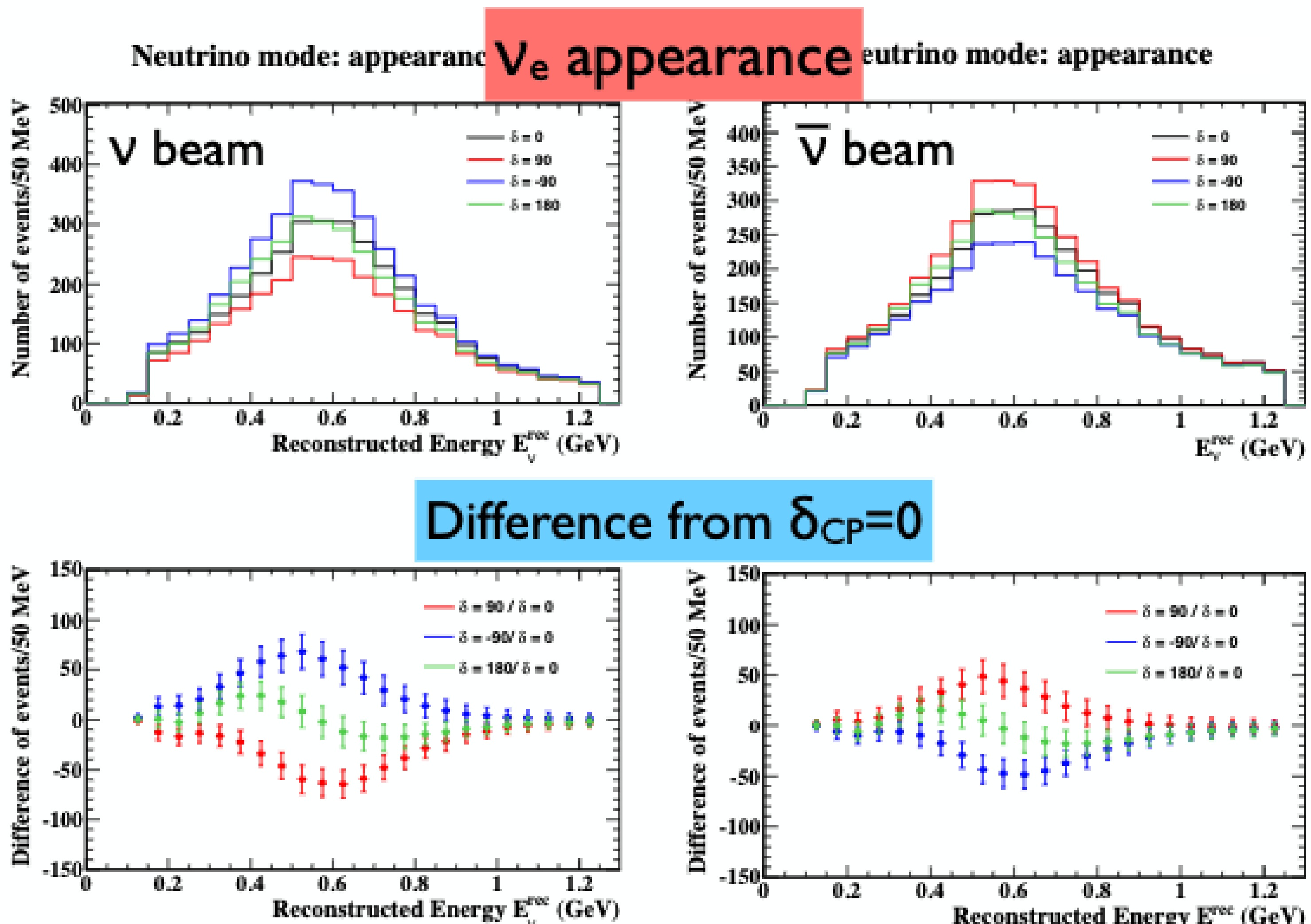
* If SRN will be observed in SK-Gd or JUNO we will perform precision measurement with HK
* Constraints on cosmic star history

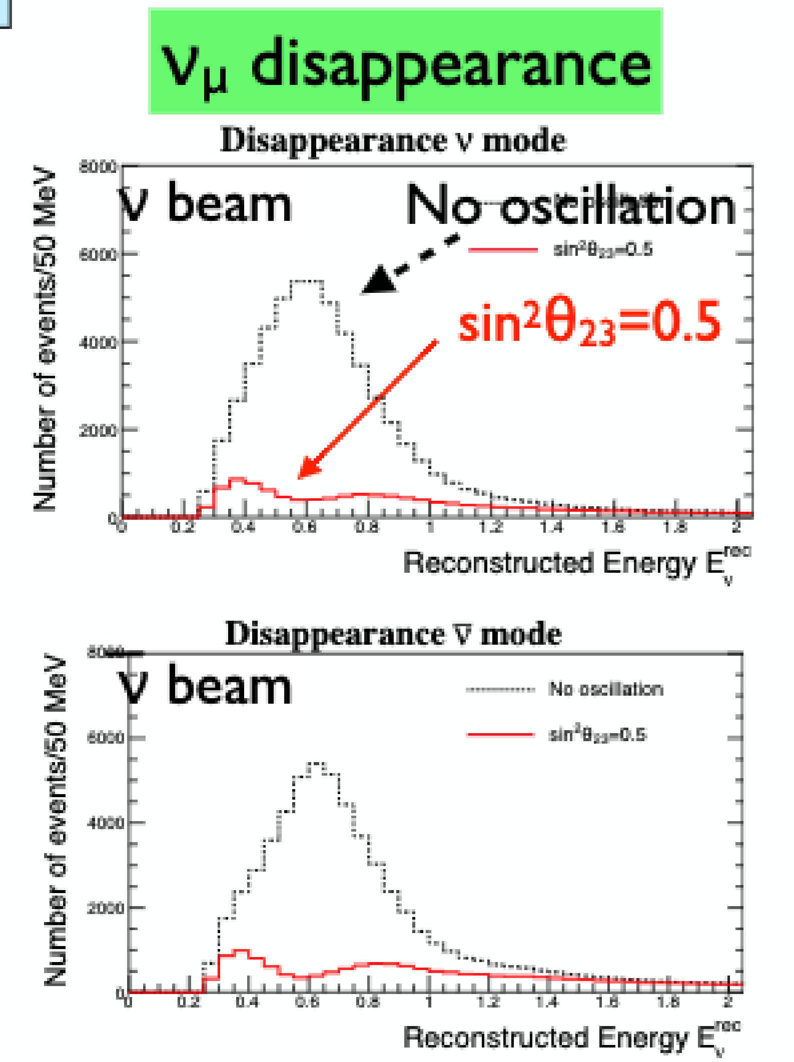
HK: Long-baseline physics

HK 1 tank

Assuming $\nu:\overline{\nu}$ = 1:3

10 years (13MW×10^7s)



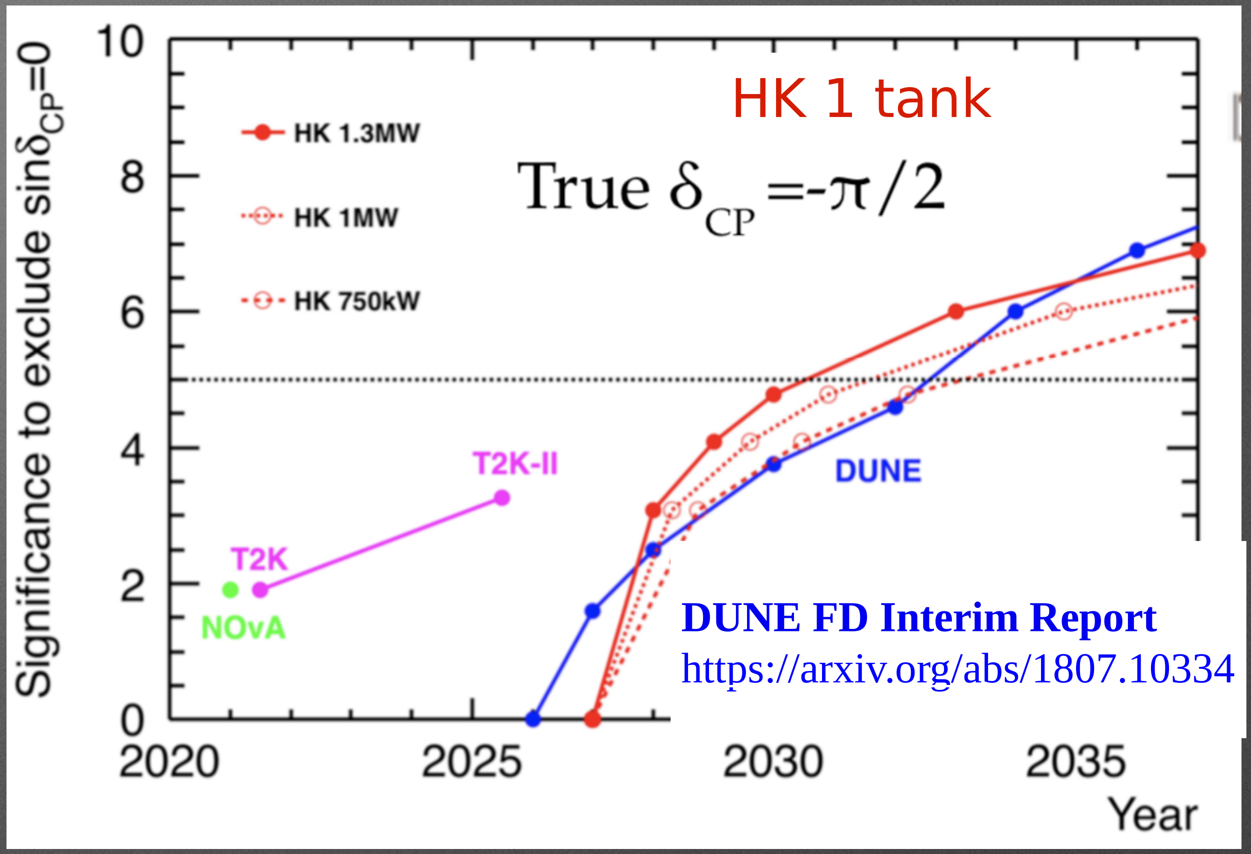


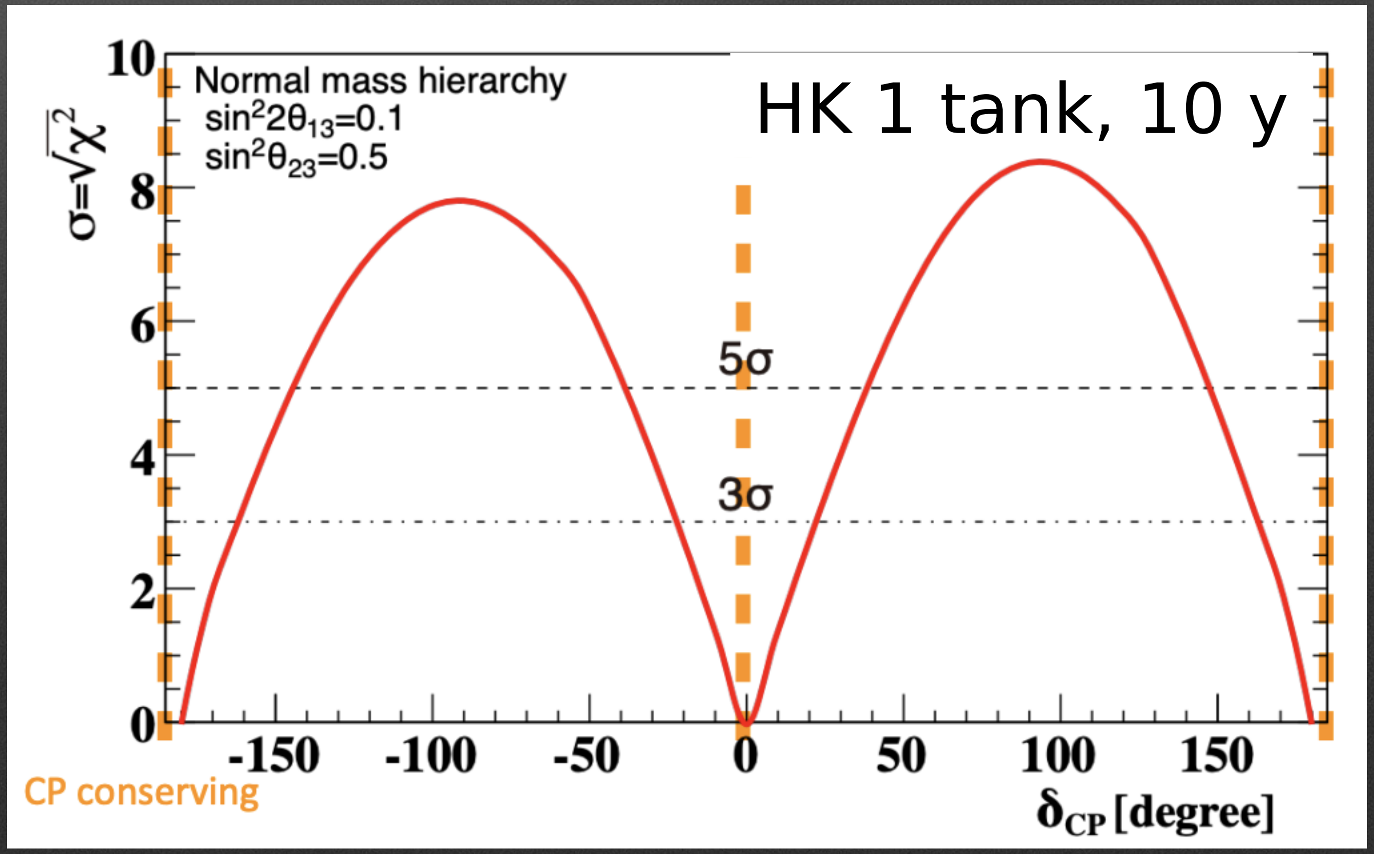
δCP=-π/2	Signal $\nu_\mu \rightarrow \nu_e$	Signal $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$	BGND	**Total**
ν-mode	***1643***	*15*	*400*	*2058*
$\overline{\nu}$-mode	*206*	***1183***	*517*	*1906*

Huge statistics → sensitivity to CP violation
Need to control systematics!

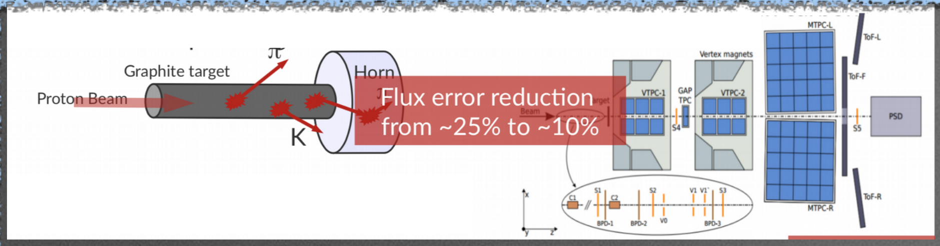
HK: CP Violation

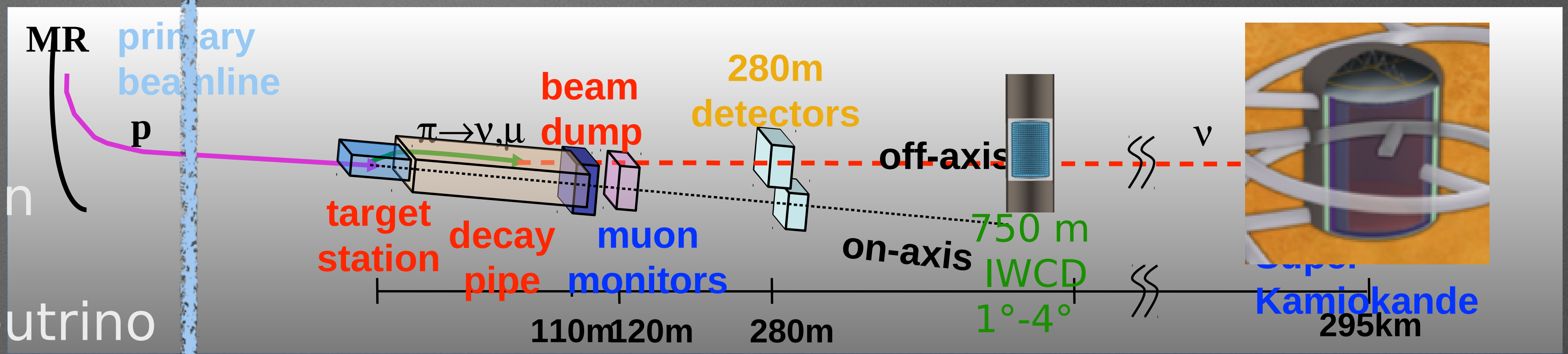
- Exclusion of sin(δ_{CP})=0
  - 8σ for δ_{CP} ~ ± π/2
  - >3σ (5σ) significance for 76% (57%) of δ_{CP} space
- Sensitivity will be further enhanced by combination with atmospheric neutrino measurements
- Assume systematics uncertainties of ~4% (currently 7% for T2K)



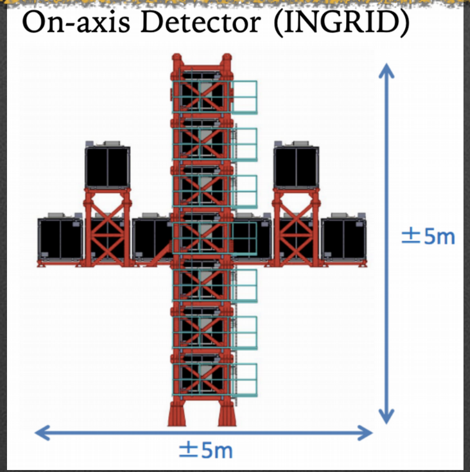


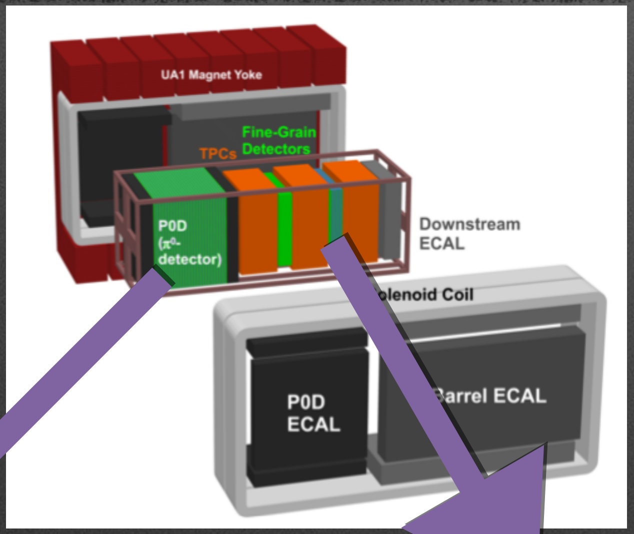
Systematics and Near Detectors

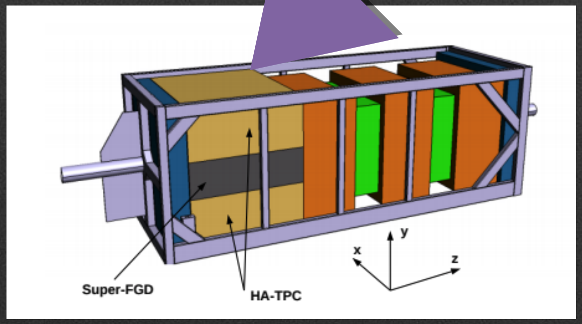


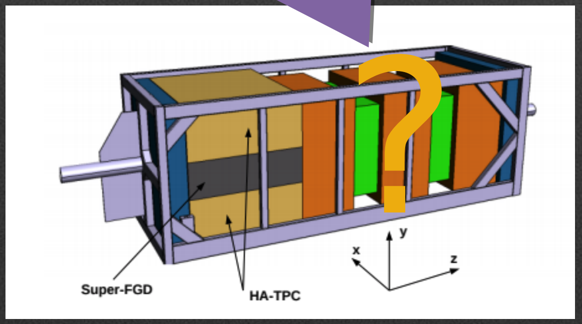


- NA61/SHINE hadron-production experiment @CERN
- T2K → uncertainties on the neutrino flux ~5% thanks to NA61/SHINE
- New measurements planned for HK

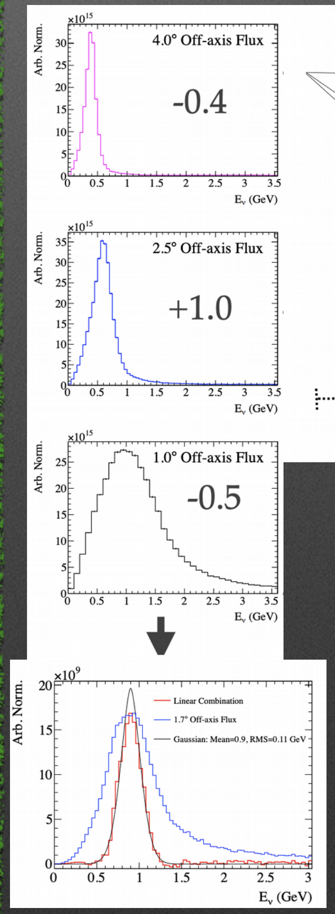


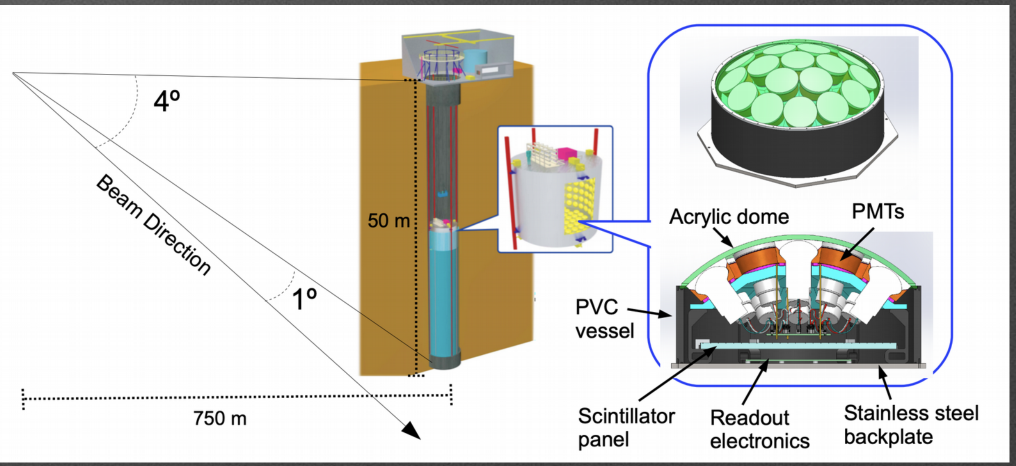






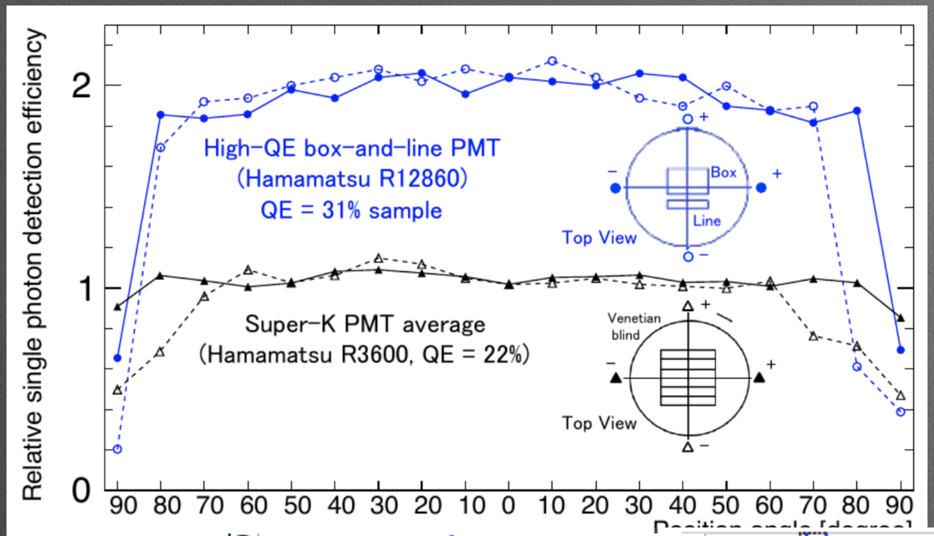
2021 2030?

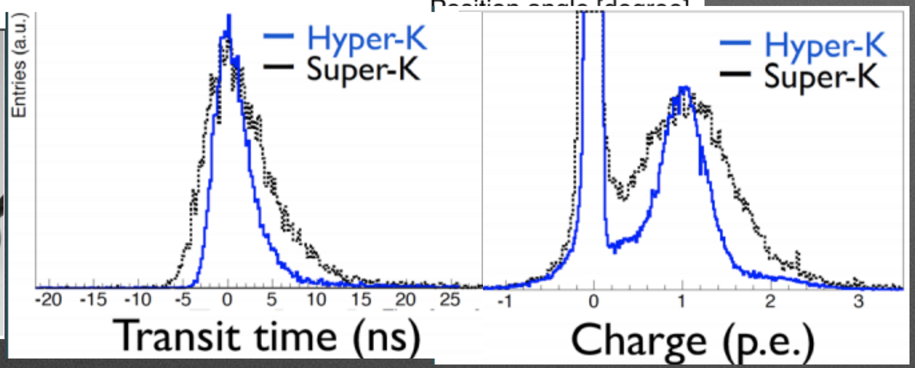




- Intermediate WC detector
- 1 kton mass
- Instrumented with ~500 multi-PMTs
- Movable position to scan different off-axis angles

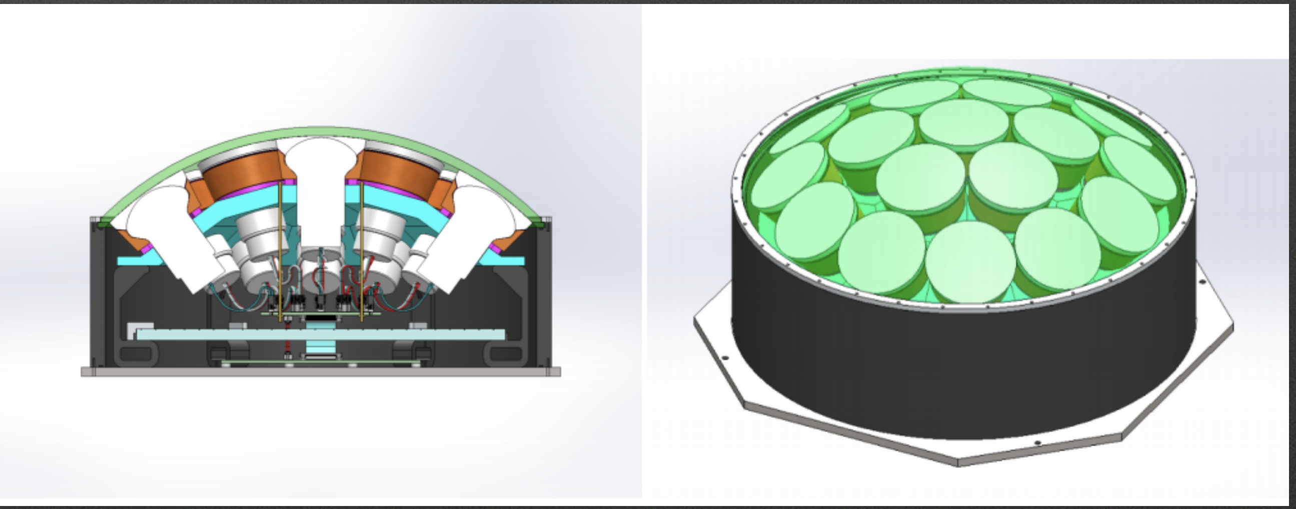
Hyper-K photo-detection system





- HK will be instrumented with “box-and-line” 20’’ PMTs
- At least 20k modules
- 31% QE (2 times better than SK)
- Better transit time spread

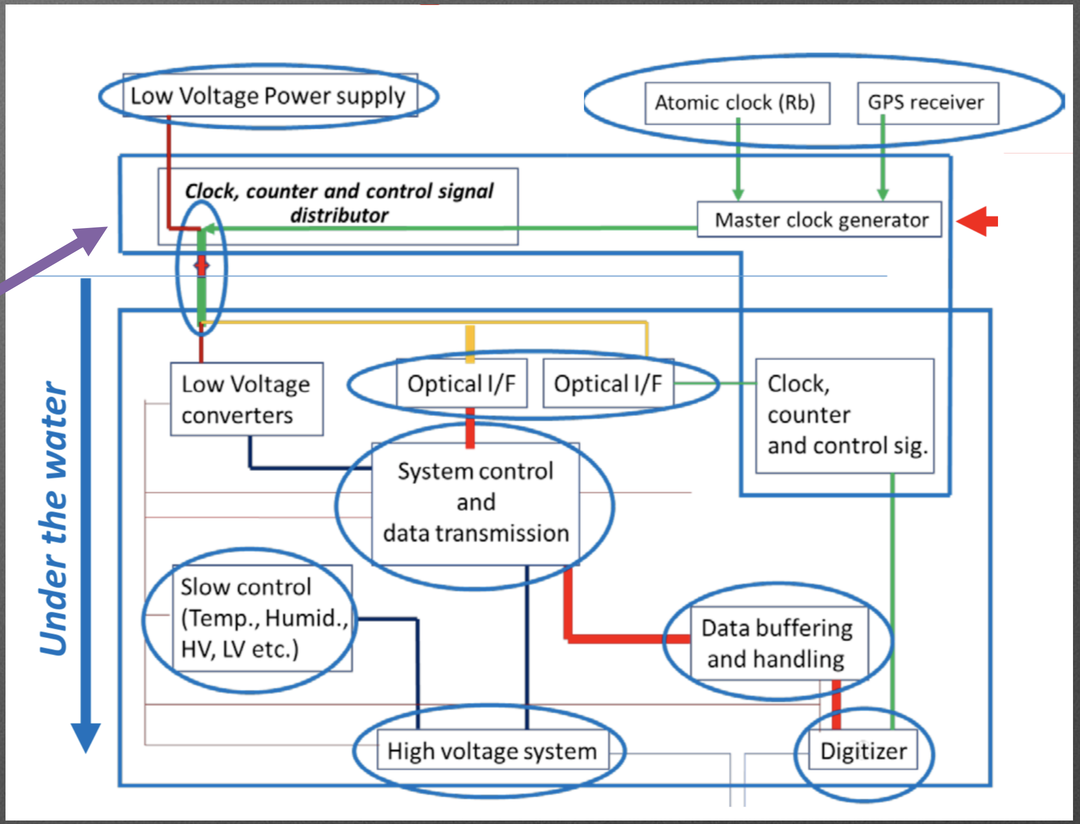
- Array of 19 3’’ PMTs
- Baseline option for IWCD
- Possibility to add up to 20k mPMTs in HK (depending on funding)
  - Would improve vertex reconstruction and energy resolution at low energy
- Good opportunity for France
  - Synergies with KM3Net and with JUNO small PMTs
  - Memphyno test setup @APC

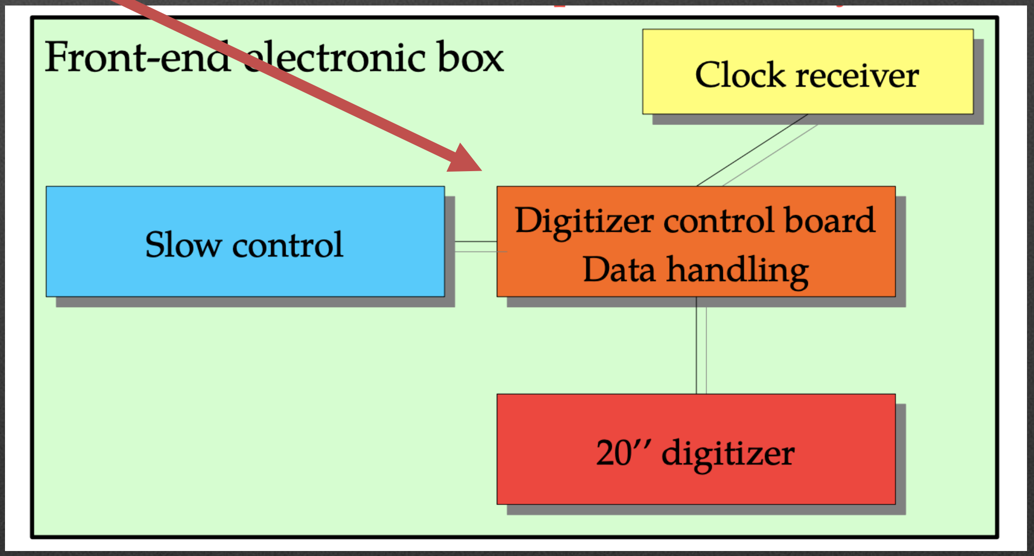


IN2P3&CEA contributions

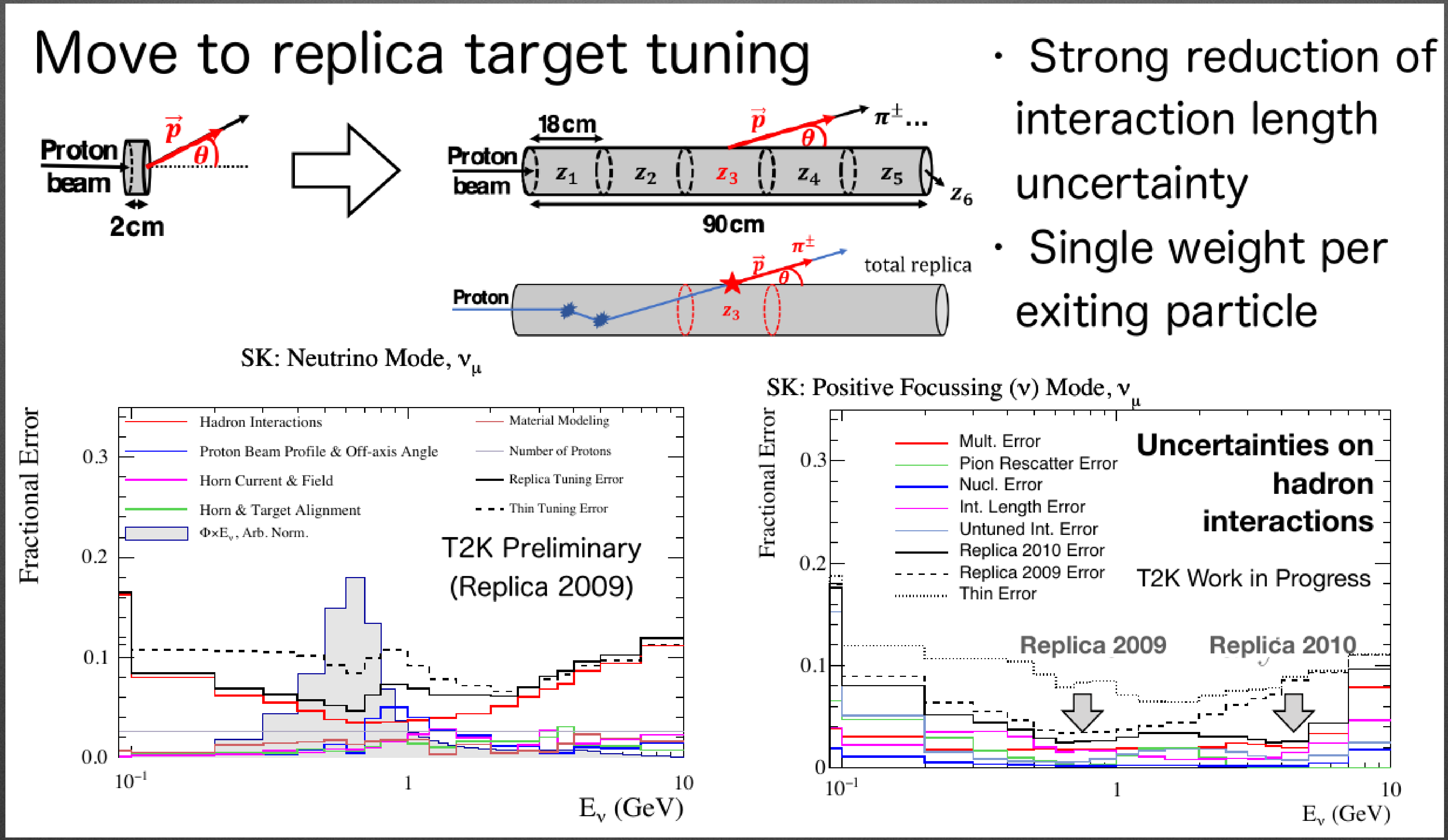
Discussions with other French groups (LLR/IN2P3 and CEA) are ongoing:

- NA61/SHINE hadron-production measurements for HK and significant involvement in the ND280 upgrade
- Contribution to the Far Detector centered around the electronics for the 20'' PMTs
  - Design and procurement of the clock distribution and time synchronization system for the 20'' PMTs (White Rabbit or Custom Made solution)
  - Front End digitizers (OMEGA chips) and front end boards for the 20'' PMTs
- Such contributions can eventually be extended to the Multi-PMTs in HK
  - Testing one prototype in Memphyno@APC
  - Test Beam experiment @CERN (LOI submitted to SPSC, ~100 mPMTs, data taking in 2022) → provide synchronization system, deploy few 20'' PMTs
- Computing → CC Lyon Tier-1 for HK



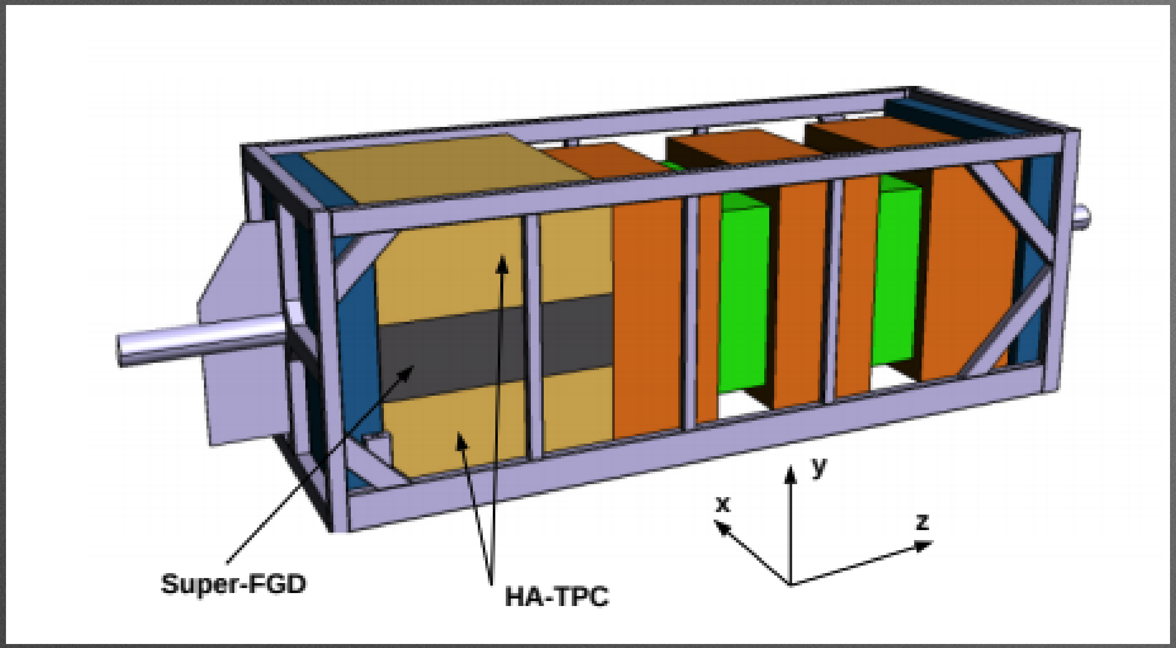


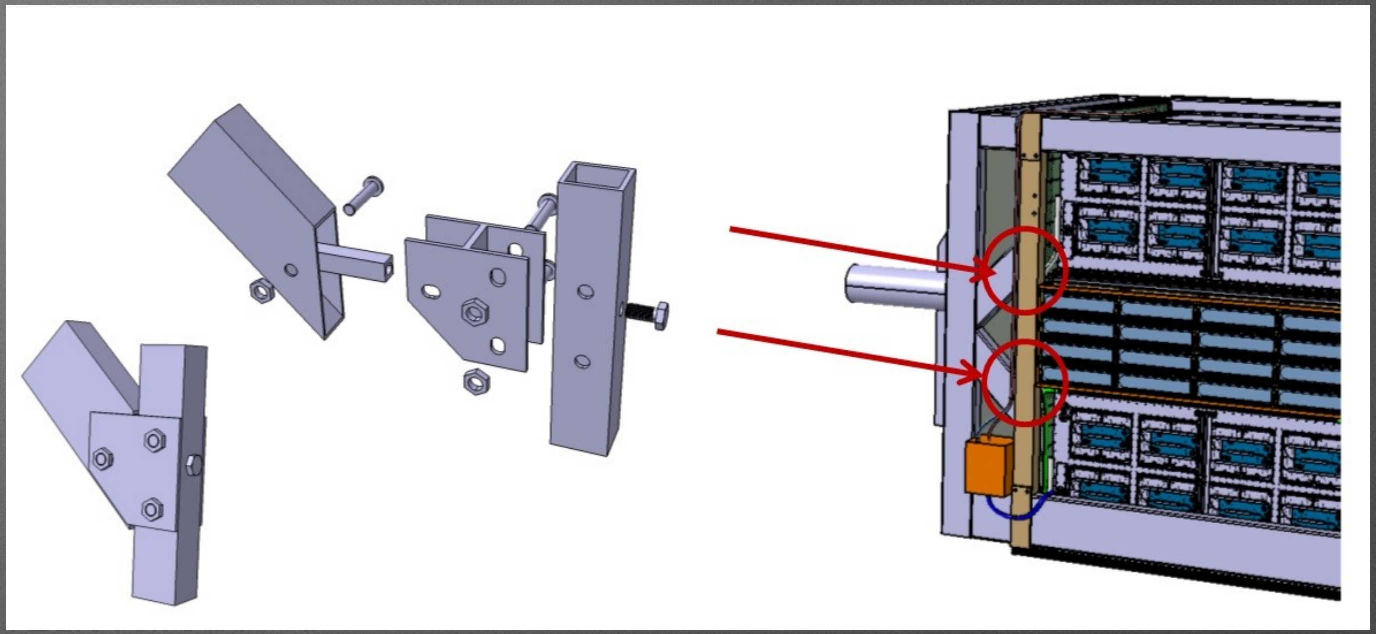
LPNHE/IN2P3 contributions (NA61)

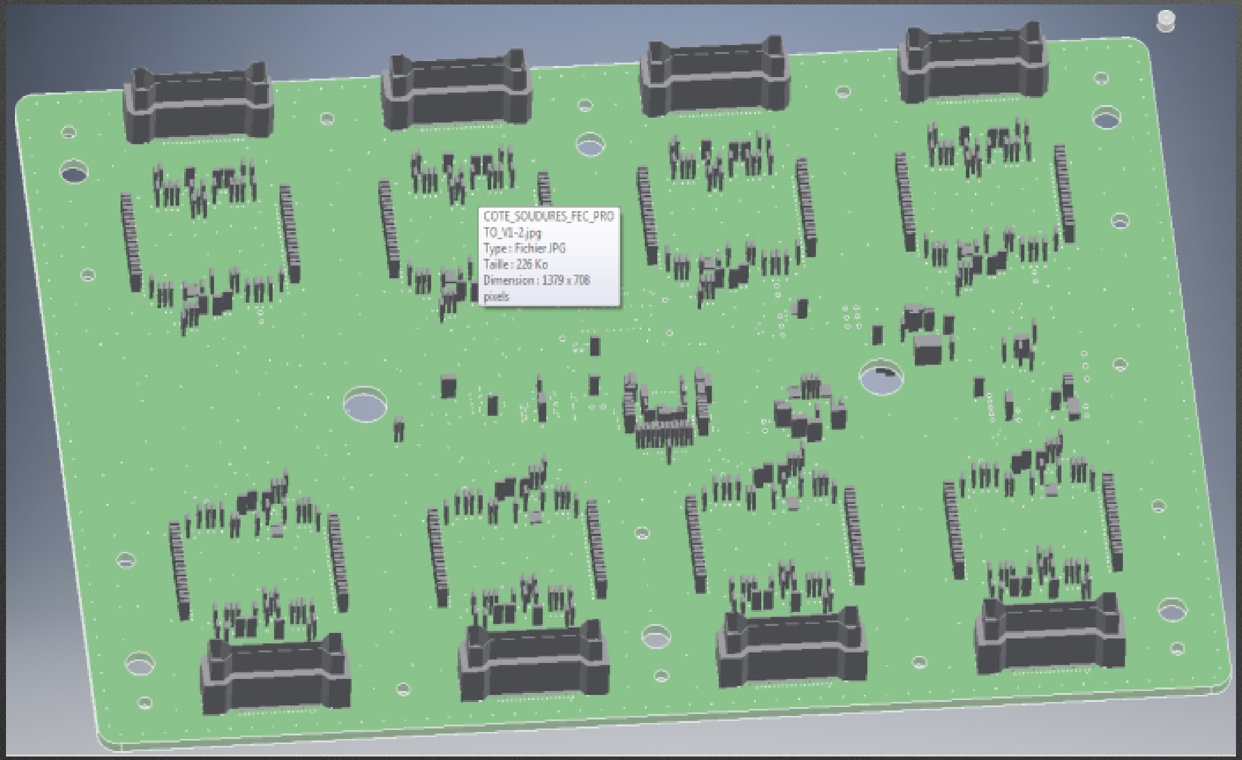


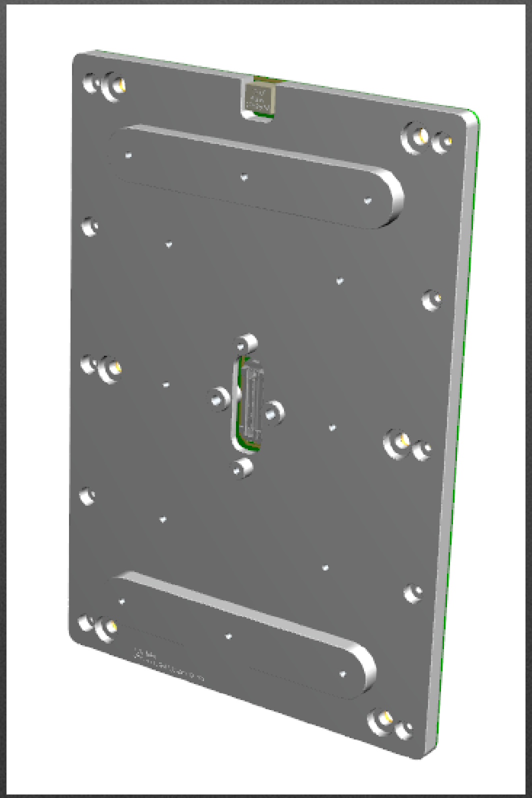
- Usage of NA61/SHINE replica-target measurements allow for further improvement in T2K (anti-)neutrino flux uncertainty (down to ~5%). Even better knowledge is desired for T2K-II and Hyper-K. New measurements are planned after the CERN LS2 (see CERN-SPSC-2018-008):
  - Improved measurements with T2K replica target, considering alternative target material – Super-Sialon ($Si_3N_4Al_2O_3$);
  - With additional tracking detectors surrounding the long target;
  - Hadron production with low momentum beam (<12 GeV/c).

LPNHE/IN2P3 contributions (ND280)





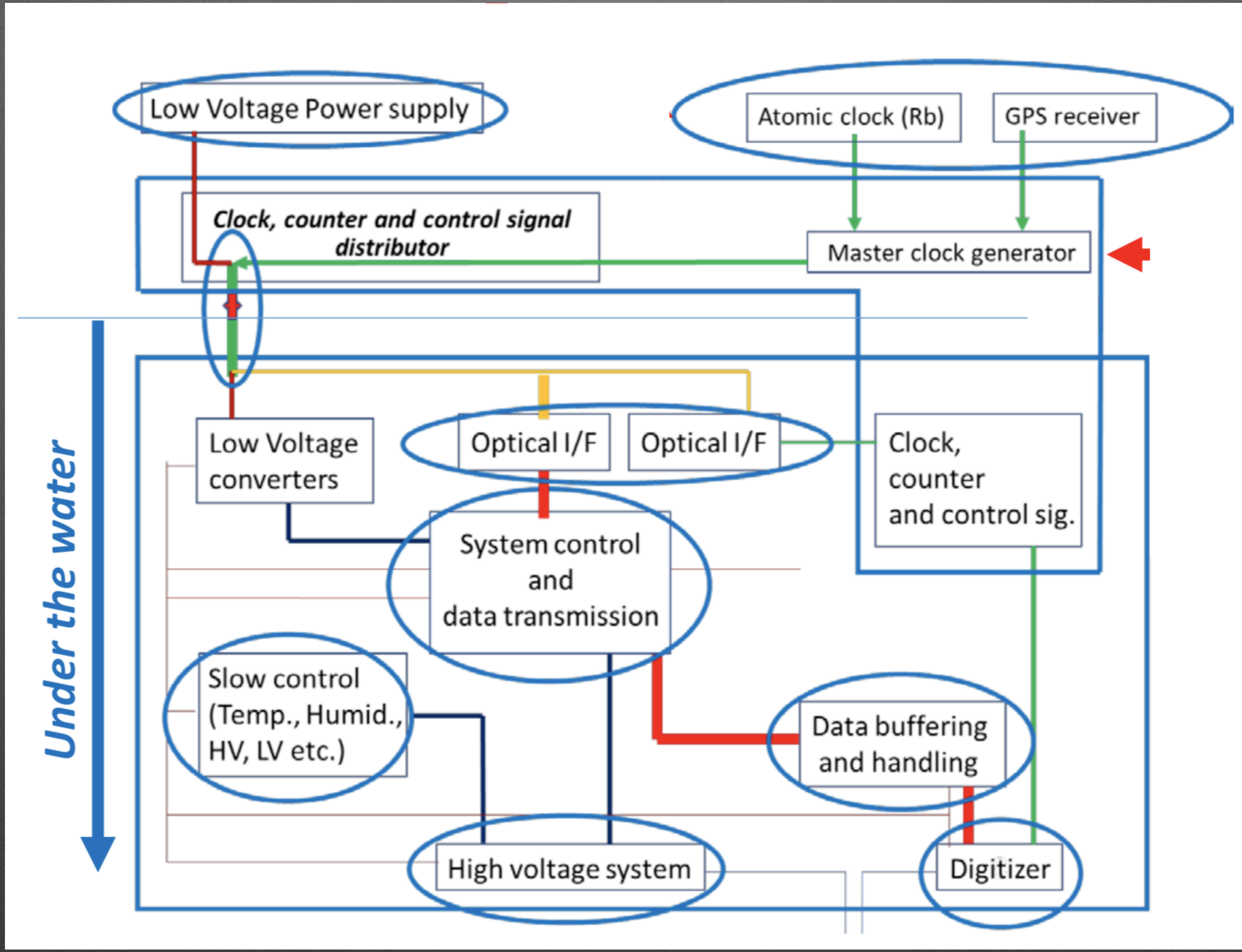


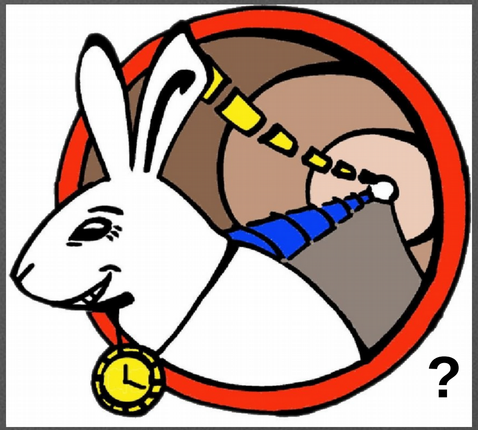


Our on-going contributions to the ND280-upgrade are also important for HK, since the upgraded detector will be taking data when the HK starts operation in 2027.

Lab resources already allocated (planned for the future)

LPNHE/IN2P3 contributions (clock)



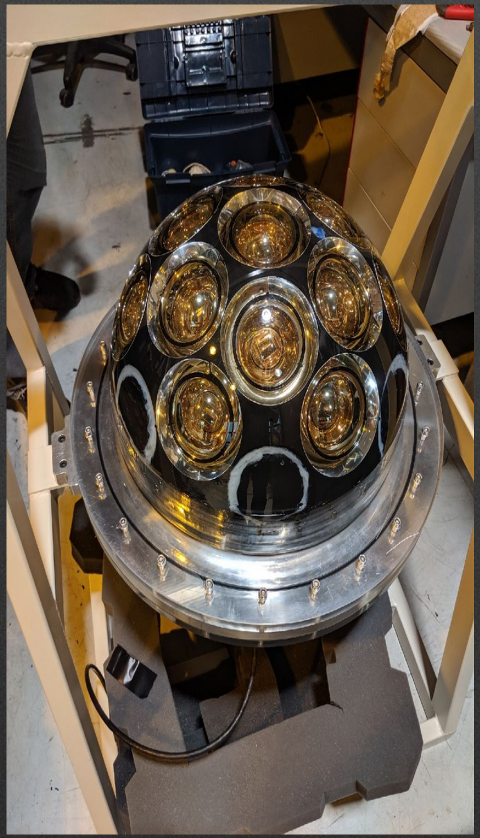


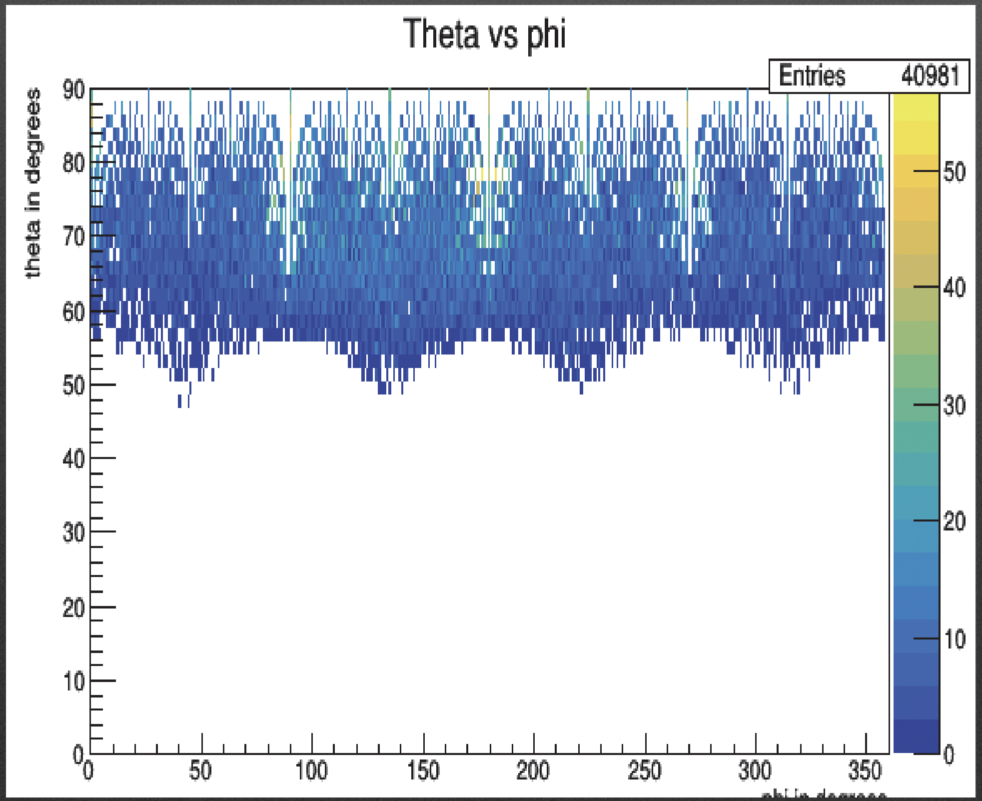
- Clock distribution and PMT synchronization is a critical part of the experiment: requirement is to have a timing resolution at the level of 1 ns with a maximum jitter of 100 ps RMS. This requires the distribution of a clock signal, synchronous with the GPS and a local atomic clock, to all Front-End nodes as well as signals to align local counters.
- System structured as a data exchange protocol. The bandwidth not occupied by timing information could be used to move (physics or slow control) data.
- Possible designs are based on White Rabbit protocol or custom solution

Estimated resources required from the lab (for clock only): 0.6 FTE x 5 years

LPNHE/IN2P3 contributions (mPMT)

- Existing setup called Memphyno @ APC is being used as a **test bench** for mPMTs developed for HK (KM3Net and other experiments): 2 x 2 x 2 m^3 water tank equipped with 4 identical scintillator trigger planes
- Can host up to 4 modules and can be used for tests of DAQ integration and clock synchronization
- Characterization of mPMTs (dark rate, response time, directionality, effects of mag. field and temperature) for HK simulation
- Scintillator hodoscope tested by Lucile Mellet (M1)
- mPMT developed in Italy for HK is currently taking data <u>in water</u>

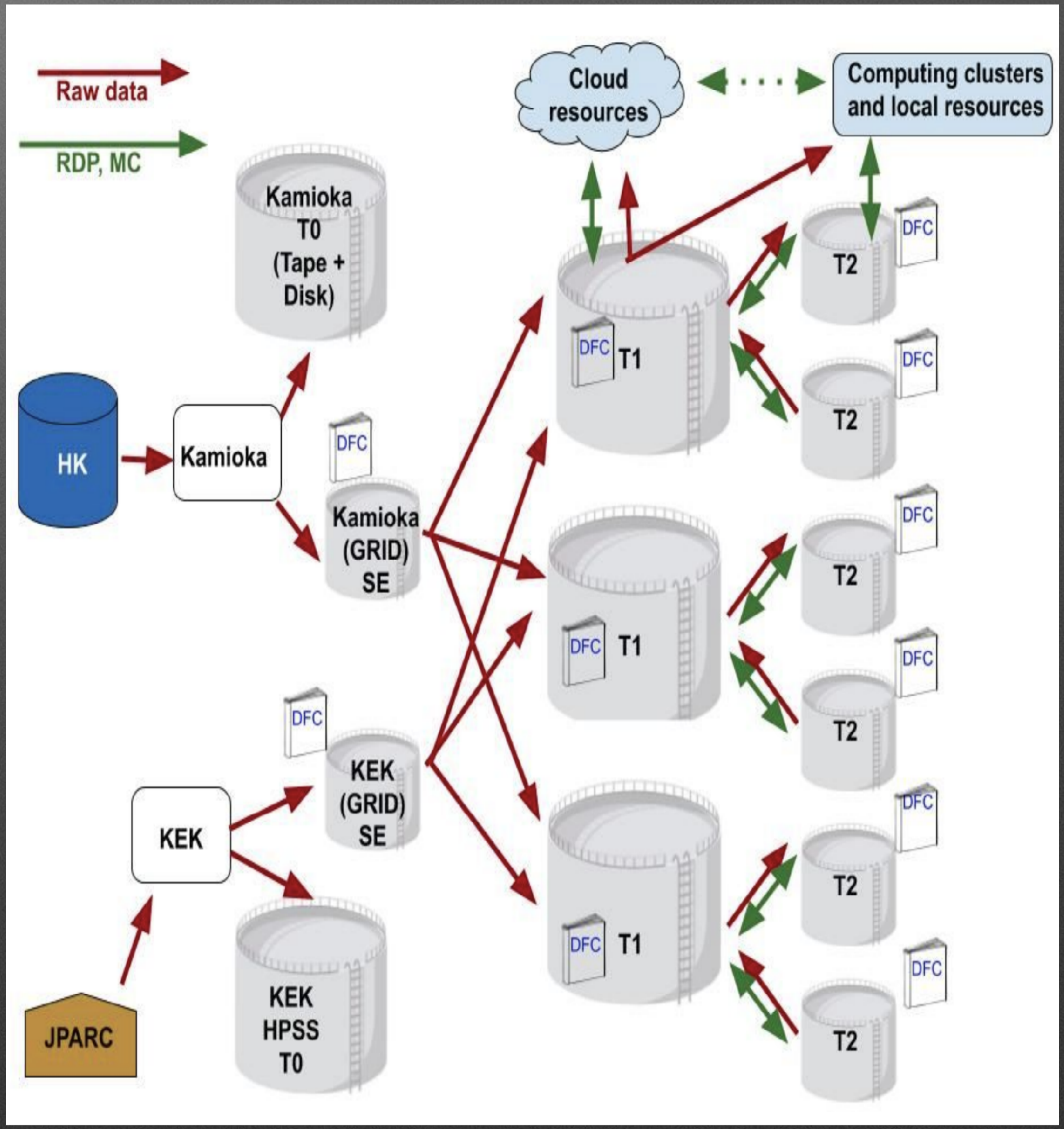




"Seed" money from SU. Estimated resources from the lab: 1-year postdoc, 0.1 FTE x 5 years

LPNHE/IN2P3 contributions (computing)

- Discussions with CC-IN2P3 to become a Tier-1 site for HK (already Tier-1 for LHC)
- First 10 years of operation: 25 PB (data + MC) [minimal request with only one copy of each file] and 880 MCPU*hours
- Partial replica of data files (e.g. for ND280)
- A lot of synergies with other experiments, e.g. Belle-II in the framework of JENNIFER-II consortium
- DIRAC framework with the core development team



Estimated resources required from the lab: 0.1 FTE x 10 years

Conclusions

- LPNHE-neutrino group continues its strong participation to the extremely successful ν oscillations program in Japan
  - T2K phase II and ND280 Upgrade → CP violation at 3σ by 2026 (support from the lab is very much appreciated!)
  - SK-Gd → Observation of Supernova relic neutrinos
- Excellent news for Hyper-Kamiokande, the next generation neutrino observatory
  - Experiment approved by MEXT, construction starts in April,2020
  - Profit of the extremely well known Water Cherenkov technology
  - Start data taking in 2027
  - Leading experiment in the search for CP violation in the leptonic sector
  - Most sensitive detector for proton decay
  - Observatory for neutrinos from different sources (Supernova, Sun, Atmosphere, ...)
- IN2P3 and CEA contributions are being defined → support from the lab is needed in order to participate in the Hyper-Kamiokande experiment with a visible contribution!

Back-up

Release by MEXT on Aug. 29, 2019

(MEXT) will start the next-generation neutrino research project "Hyper-Kamiokande" in JFY2020.

○ 日本学術会議において科学的観点から策定したマスタープランを踏まえつつ、専門家等で構成される文部科学省の審議会において戦略性・緊急性等を加味し、ロードマップを策定。

○ ロードマップの中から大規模学術フロンティア促進事業として実施するプロジェクトを選定の上、国立大学法人運営費交付金等の基盤的経費により戦略的・計画的に推進。原則、10年間の年次計画を策定し、審議会における厳格な評価・進捗管理を実施。

○ 現行の13プロジェクトに加え、令和2年度より、ニュートリノ研究の次世代計画である「ハイパーカミオカンデ計画」に新たに着手。

主な成果

○ ノーベル賞受賞につながる画期的研究成果
（受賞歴：H14小柴昌俊氏、H20小林誠氏、益川敏英氏、H27梶田隆章氏）

○ 年間約1万人の共同研究者が集結し、国際共同研究を推進。このうちの半数以上が外国人

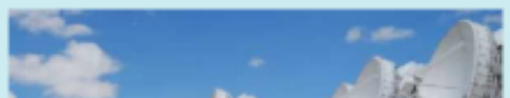
Next generation of neutrino project with a 260 kton detector and the J-PARC upgrade. The project will reveal the mysteries in elementary particles and the Universe by the observation of proton decays and the neutrino researches including CP violation.

天文学・宇宙物理学分野	論文数	Top10%割合	国際共著割合
すばる望遠鏡	644	18.5%	86.3%
アルマ望遠鏡	878	27.3%	89.0%
日本全体	8,938	12.9%	68.0%
世界全体	103,445	9.6%	50.6%

※ 大学共同利用機関法人自然科学研究機構が「InCites」（Web of Science）に基づき、2013-2017の5か年に出版された天文学・宇宙物理学分野の論文（article,review）を分析（2019年7月）。「日本全体」は、著作住所に日本を含む論文を抽出。

大規模学術フロンティア促進事業等の主な事業

大型電波望遠鏡「アルマ」による国際共同利用研究の推進
〔自然科学研究機構国立天文台〕



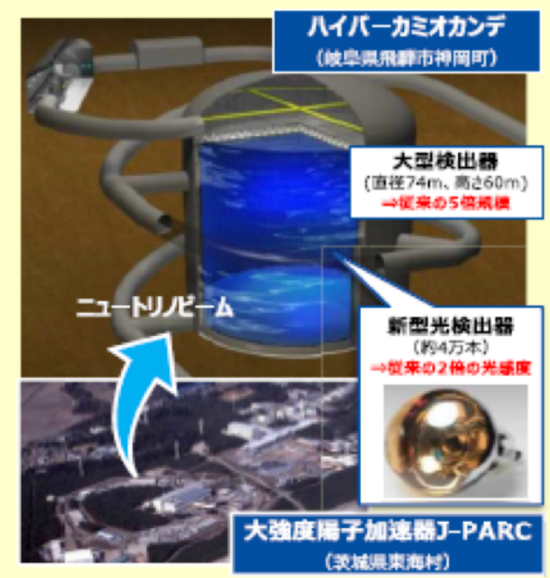
巨大ブラックホールの「影」の撮影に世界で初めて成功した国際プロジェクトに参加し、高い感度の観測機能により、その成果に大きく貢献。

新しいステージに向けた学術情報ネットワーク（SINET）整備
〔情報・システム研究機構国立情報学研究所〕

…等を高速通信回線ネットワークで…究の基盤を提供。全国900以上…機関、約300万人の研究者・学…我が国の教育研究活動に必須の学術情報基盤。

NEW

ハイパーカミオカンデ（HK）計画の推進
〔東京大学宇宙線研究所〕
〔高エネルギー加速器研究機構〕



日本が切り拓いてきたニュートリノ研究の次世代計画として、超高感度光検出器を備えた総重量26万トンの大型検出器の建設及びJ-PARCの高度化により、ニュートリノの検出性能を著しく向上。素粒子物理学の大統一理論の鍵となる未発見の陽子崩壊探索やCP対称性の破れなどのニュートリノ研究を通じ、新たな物理法則の発見、素粒子と宇宙の謎の解明を目指す。【ロードマップ2017掲載事業】

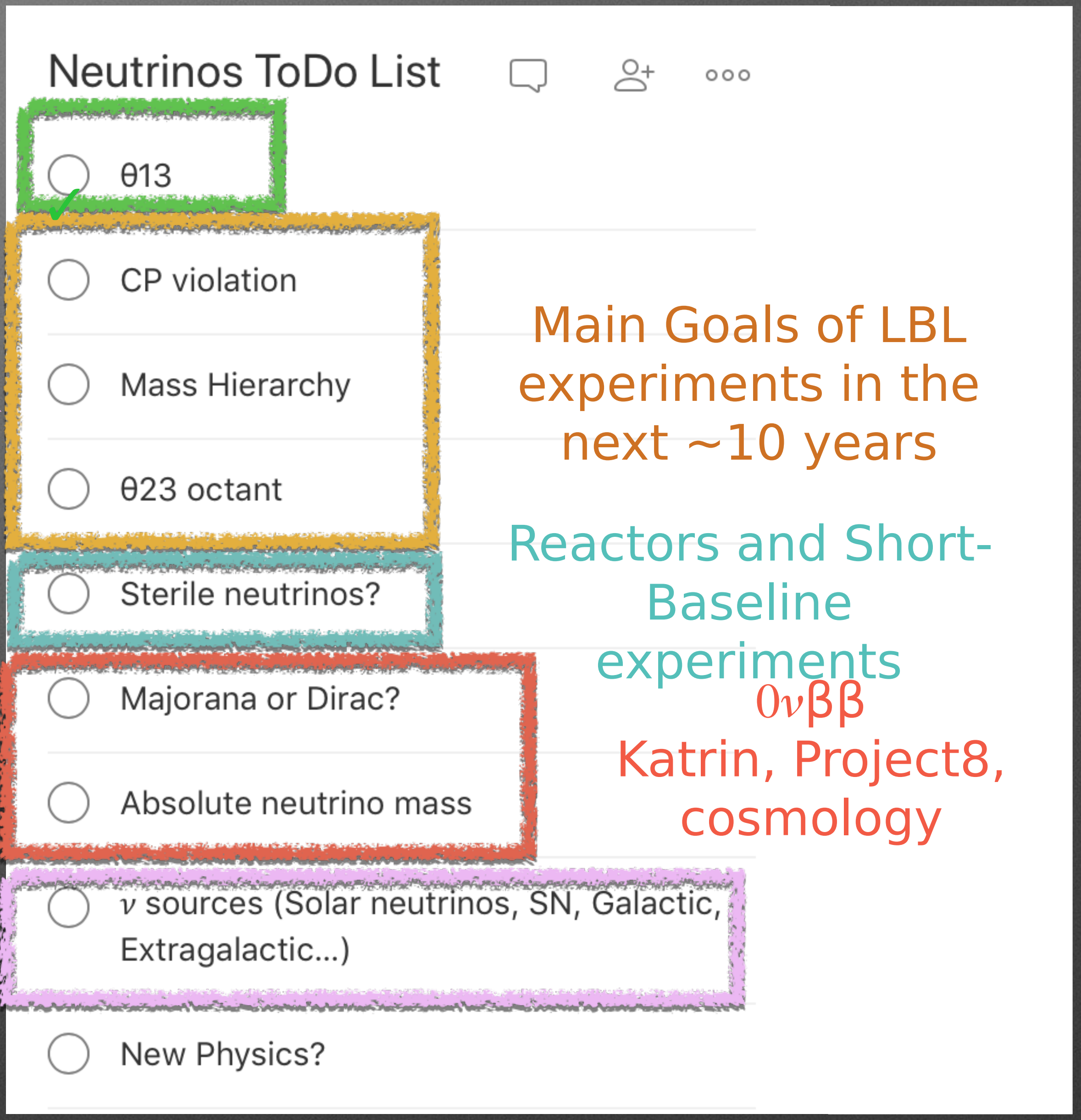
＜産業等への波及＞

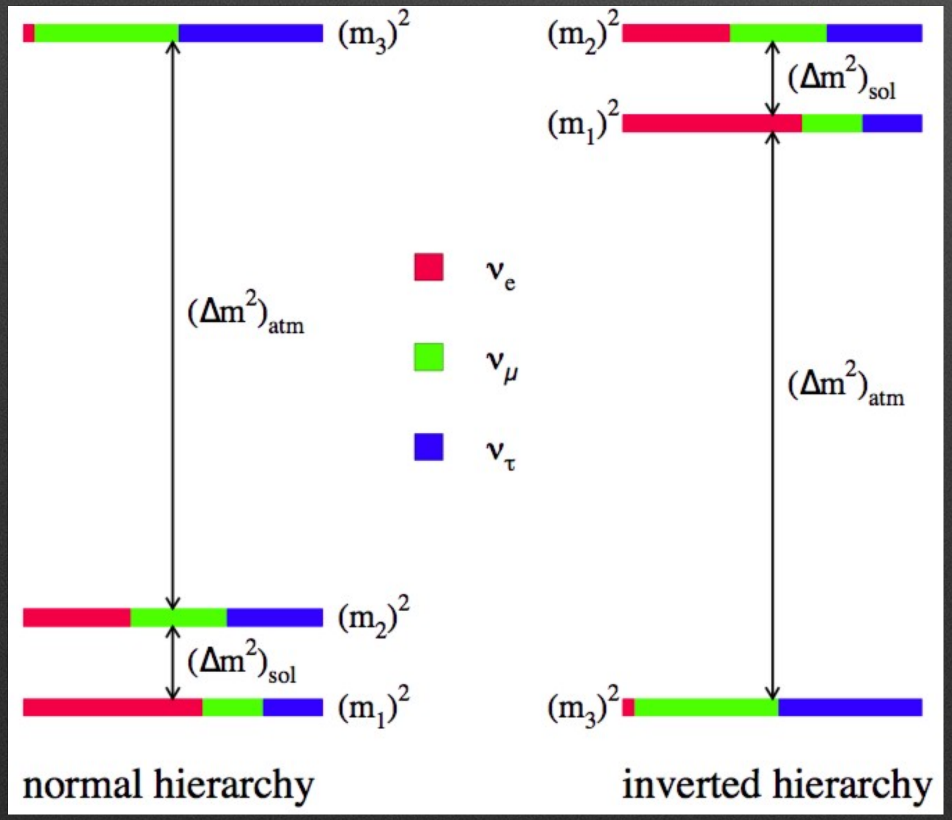
○ 産業界と連携した最先端の研究装置開発により、イノベーションの創出にも貢献

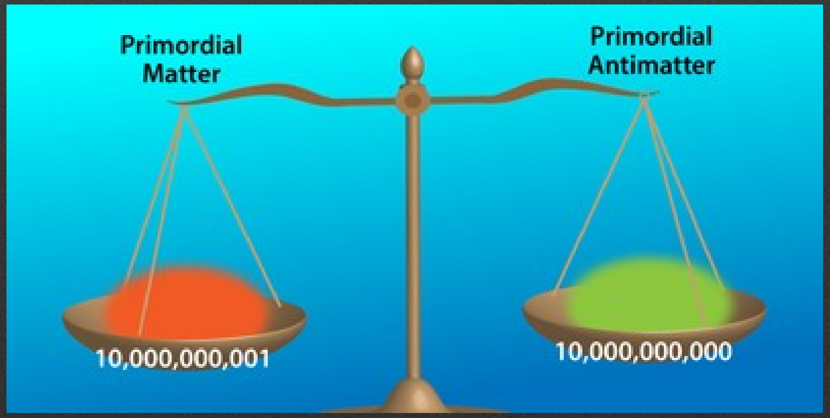
（事例）・【すばる望遠鏡】超高感度カメラ技術⇒医療用X線カメラへの応用
・【放射光施設】加齢による毛髪のハリ・コシの低下が毛髪内の亜鉛と関係性を解明⇒亜鉛を毛髪に浸透させる新しいヘアケア技術の開発・製品化に成功

Open questions

- Neutrino oscillations → "guaranteed" measurements for T2K and HK
- Multi-messenger astronomy with neutrinos is starting now → SK, HK
- Nature of neutrinos (Dirac or Majorana) and their mass → $0\nu\beta\beta$ experiments, Katrin, Project-8, cosmology

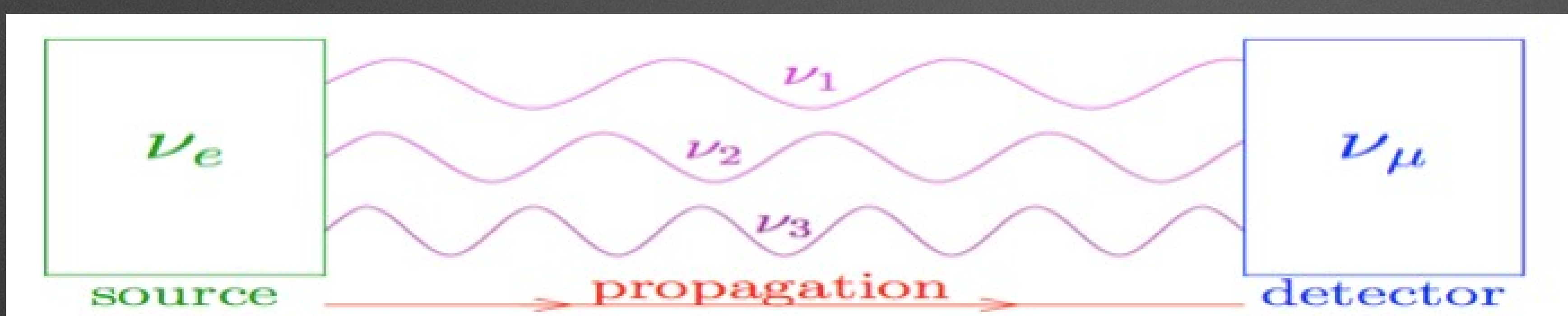






Neutrino oscillations

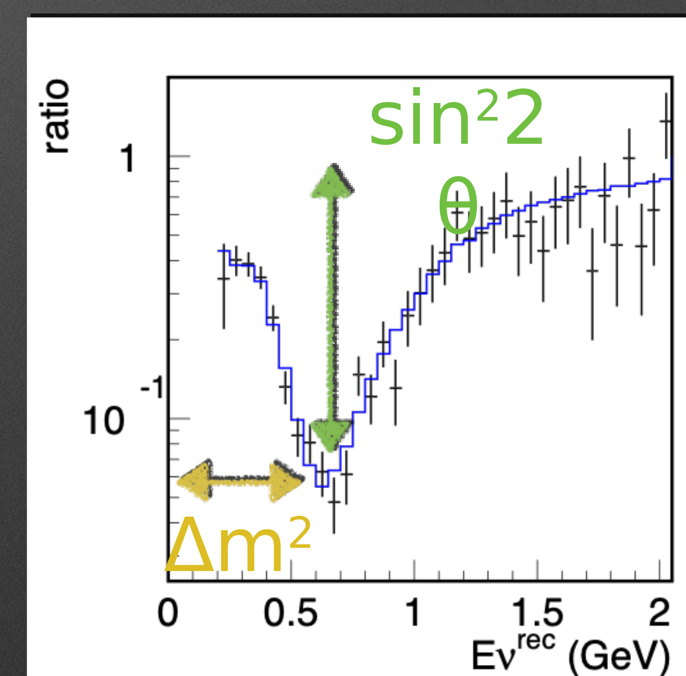
- First introduced by Bruno Pontecorvo in 1957
- Neutrinos are produced in flavor eigenstates ν_e, ν_μ, ν_τ that are linear combination of mass eigenstates ν_1, ν_2, ν_3
- Neutrinos propagate as mass eigenstates
- At the detection a flavor eigenstate is detected → it can be different from the one that was produced



ν_e produced in a mixture of $\nu_{1,2,3}$

$\nu_{1,2,3}$ travel at different speed because they have different masses → interference

Different mixture of $\nu_{1,2,3}$ → μ from ν_μ is detected



Neutrino oscillation implies massive neutrinos

$$P(\nu_e \rightarrow \nu_\mu) = \sin^2(2\theta)\sin^2(\Delta m^2_{12} L/E)$$

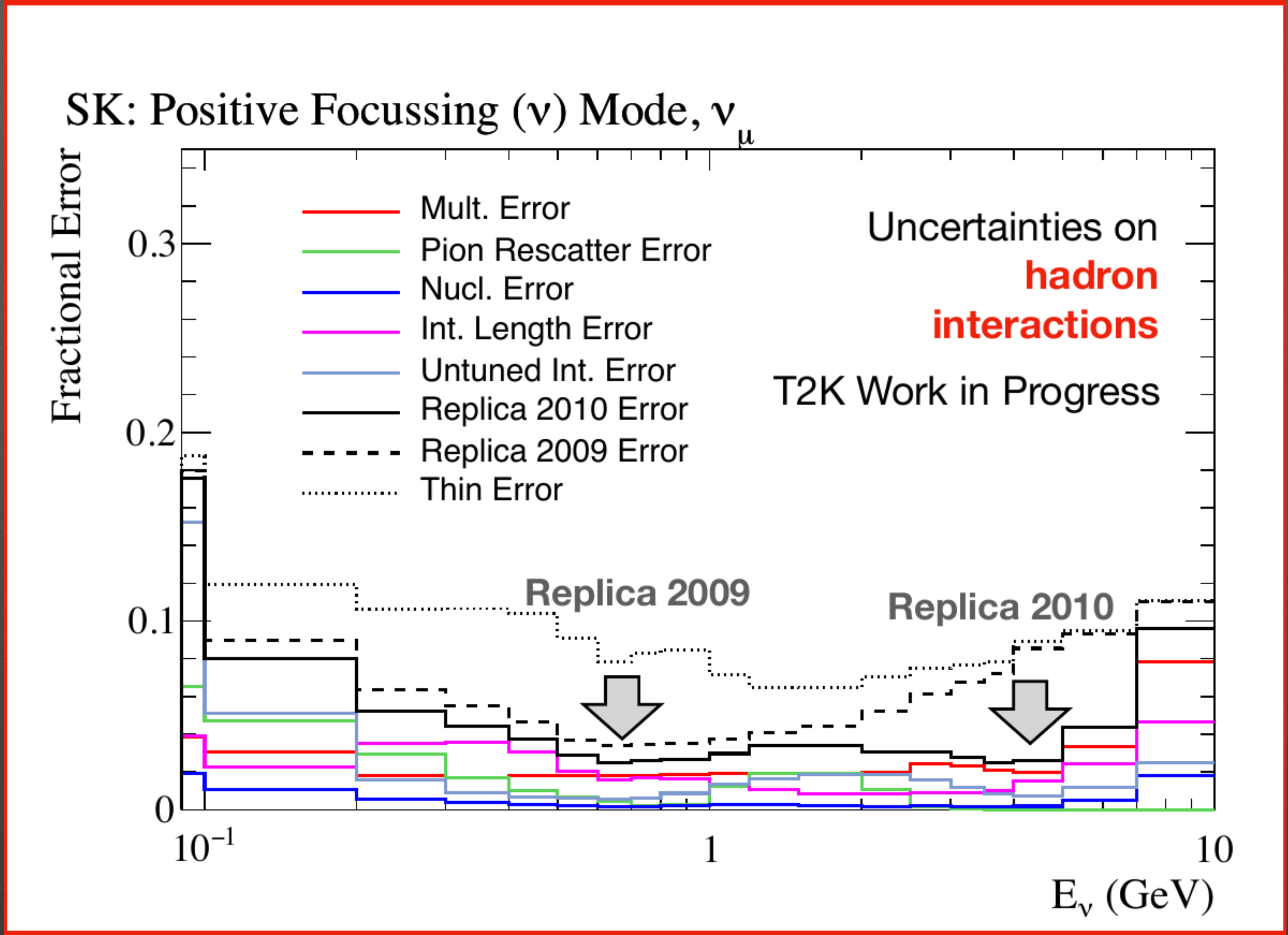
Neutrino Oscillations: Global Fits

NuFIT 4.1 (2019)

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 6.2$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
without SK atmospheric data	$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$
	$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$
	$\sin^2\theta_{23}$	$0.558^{+0.020}_{-0.033}$	$0.427 \to 0.609$	$0.563^{+0.019}_{-0.026}$	$0.430 \to 0.612$
	$\theta_{23}/^\circ$	$48.3^{+1.1}_{-1.9}$	$40.8 \to 51.3$	$48.6^{+1.1}_{-1.5}$	$41.0 \to 51.5$
	$\sin^2\theta_{13}$	$0.02241^{+0.00066}_{-0.00065}$	$0.02046 \to 0.02440$	$0.02261^{+0.00067}_{-0.00064}$	$0.02066 \to 0.02461$
	$\theta_{13}/^\circ$	$8.61^{+0.13}_{-0.13}$	$8.22 \to 8.99$	$8.65^{+0.13}_{-0.12}$	$8.26 \to 9.02$
	$\delta_{\rm CP}/^\circ$	222^{+38}_{-28}	$141 \to 370$	285^{+24}_{-26}	$205 \to 354$
	$\frac{\Delta m^2_{21}}{10^{-5}\ {\rm eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ {\rm eV}^2}$	$+2.523^{+0.032}_{-0.030}$	$+2.432 \to +2.618$	$-2.509^{+0.032}_{-0.030}$	$-2.603 \to -2.416$

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 10.4$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$
	$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$	$33.82^{+0.78}_{-0.75}$	$31.61 \to 36.27$
	$\sin^2\theta_{23}$	$0.563^{+0.018}_{-0.024}$	$0.433 \to 0.609$	$0.565^{+0.017}_{-0.022}$	$0.436 \to 0.610$
	$\theta_{23}/^\circ$	$48.6^{+1.0}_{-1.4}$	$41.1 \to 51.3$	$48.8^{+1.0}_{-1.2}$	$41.4 \to 51.3$
	$\sin^2\theta_{13}$	$0.02237^{+0.00066}_{-0.00065}$	$0.02044 \to 0.02435$	$0.02259^{+0.00065}_{-0.00065}$	$0.02064 \to 0.02457$
	$\theta_{13}/^\circ$	$8.60^{+0.13}_{-0.13}$	$8.22 \to 8.98$	$8.64^{+0.12}_{-0.13}$	$8.26 \to 9.02$
	$\delta_{\rm CP}/^\circ$	221^{+39}_{-28}	$144 \to 357$	282^{+23}_{-25}	$205 \to 348$
	$\frac{\Delta m^2_{21}}{10^{-5}\ {\rm eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ {\rm eV}^2}$	$+2.528^{+0.029}_{-0.031}$	$+2.436 \to +2.618$	$-2.510^{+0.030}_{-0.031}$	$-2.601 \to -2.419$

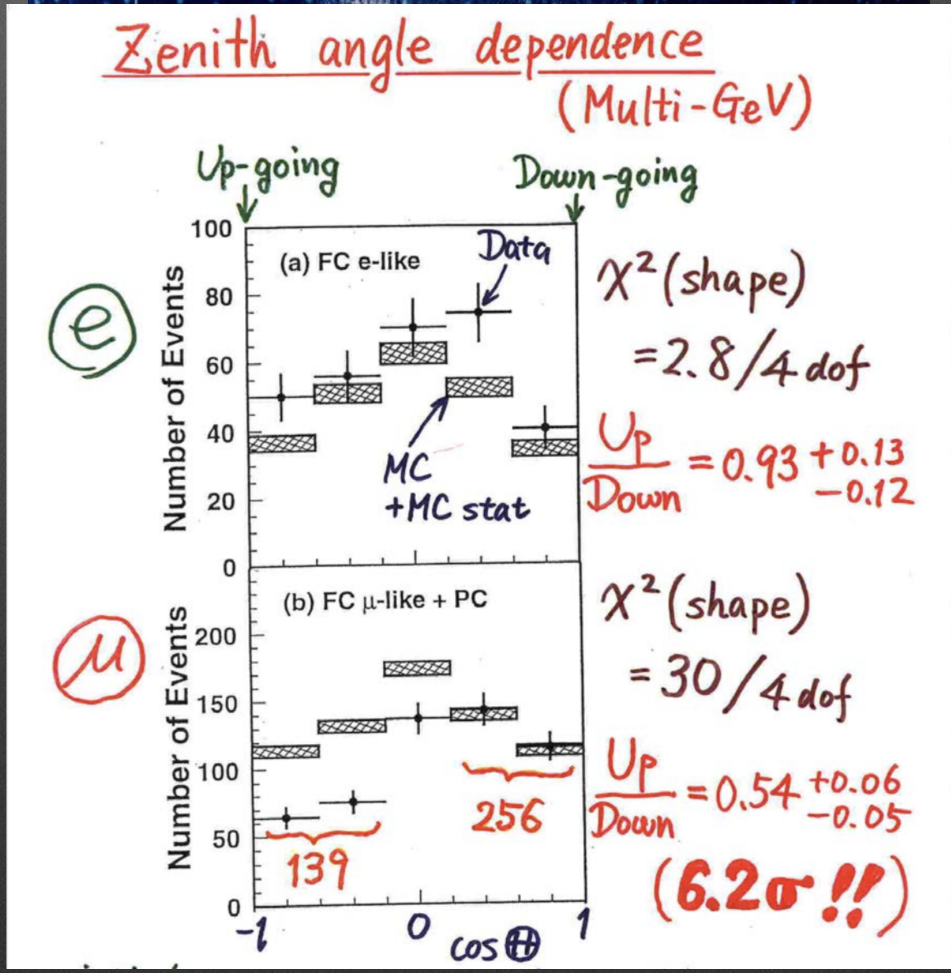
LPNHE/IN2P3 contributions (NA61)

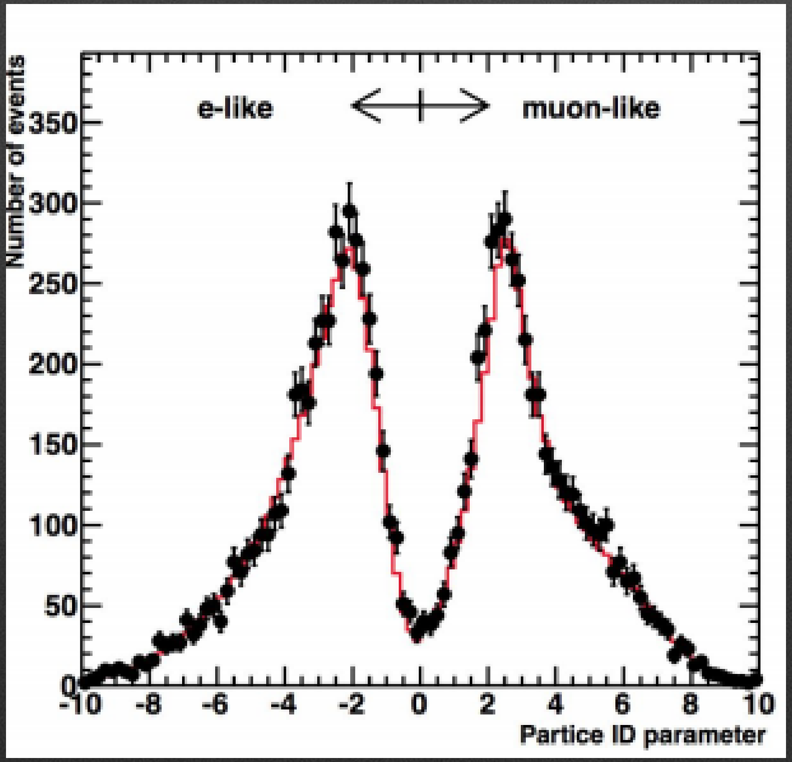


- Usage of NA61/SHINE replica-target measurements allow for further improvement in T2K (anti-)neutrino flux uncertainty (down to ~5%). Even better knowledge is desired for T2K-II and Hyper-K. New measurements are planned after the CERN LS2 (see CERN-SPSC-2018-008):
  - Improved measurements with T2K replica target, considering alternative target material – Super-Sialon ($Si_3N_4Al_2O_3$);
  - With additional tracking detectors surrounding the long target;
  - Hadron production with low momentum beam (<12 GeV/c).

Super-Kamiokande

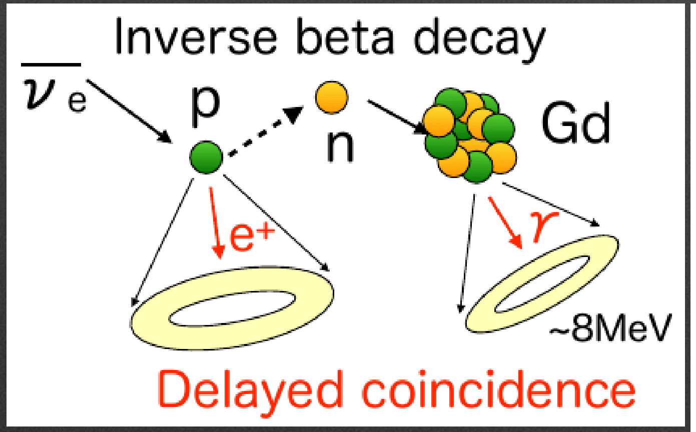
- 50 kton Water Cherenkov detector
  - ~11000 PMTs for ID, ~2000 for OD
- 1000 m underground at Kamioka mine operated since 1996
- Very good PID capabilities to distinguish between ν_e and ν_μ thanks to shape of Cherenkov ring → <1% misidentification probability



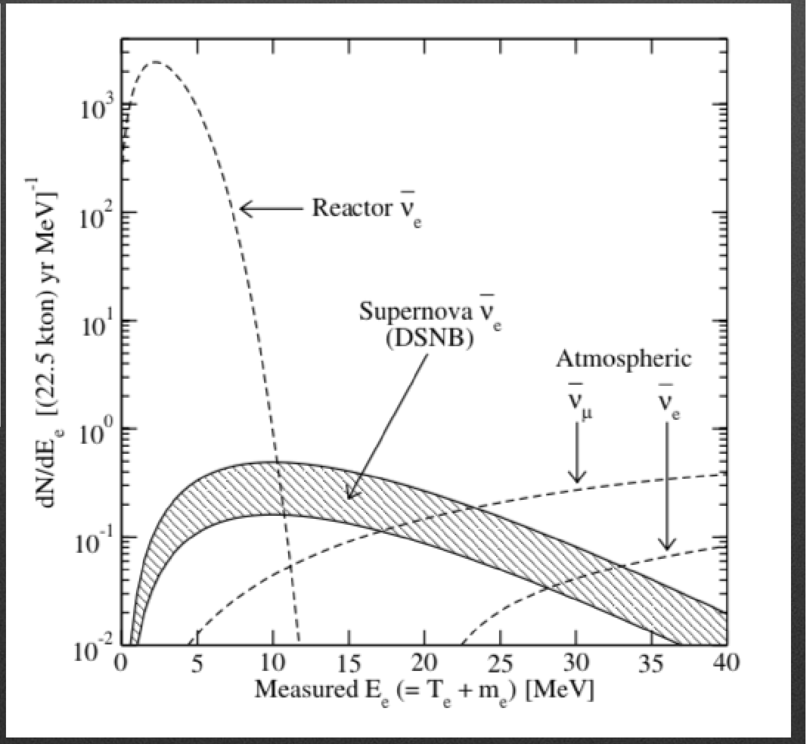


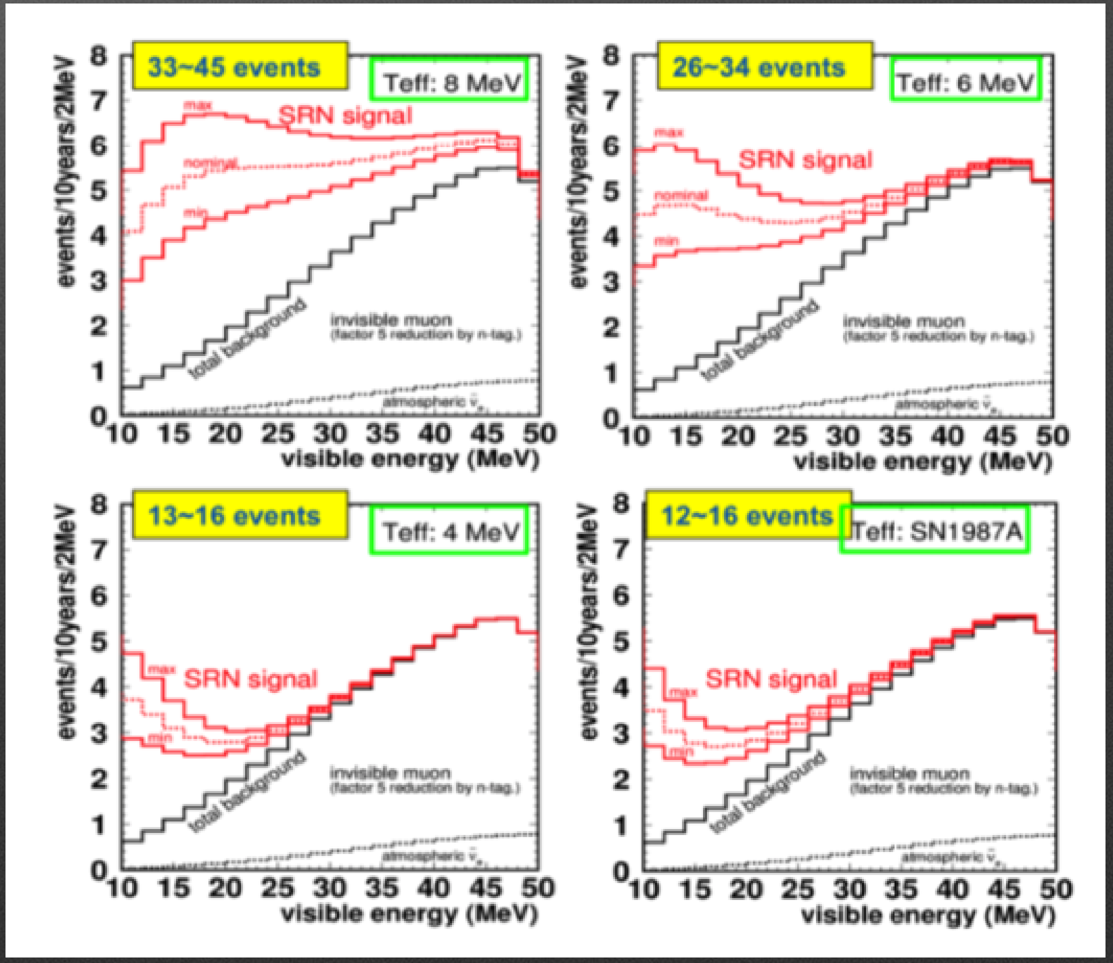
SK-Gd

- Important repair work in 2018 to prepare the loading of SK with Gadolinium
- SK ready to be loaded with Gd in 2020 (0.02% → 0.2% in a second phase)
- Enhance neutron tagging capability → crucial to distinguish ν from $\overline{\nu}$ → detect SN-relic antineutrinos from IBD (3-5 events per year are expected)
- The Gd loading will also be useful for T2K



~90% of neutrons are tagged in 0.2% $Gd_2(SO_4)_3$ (0.1% Gd)





From Kamiokande to HK

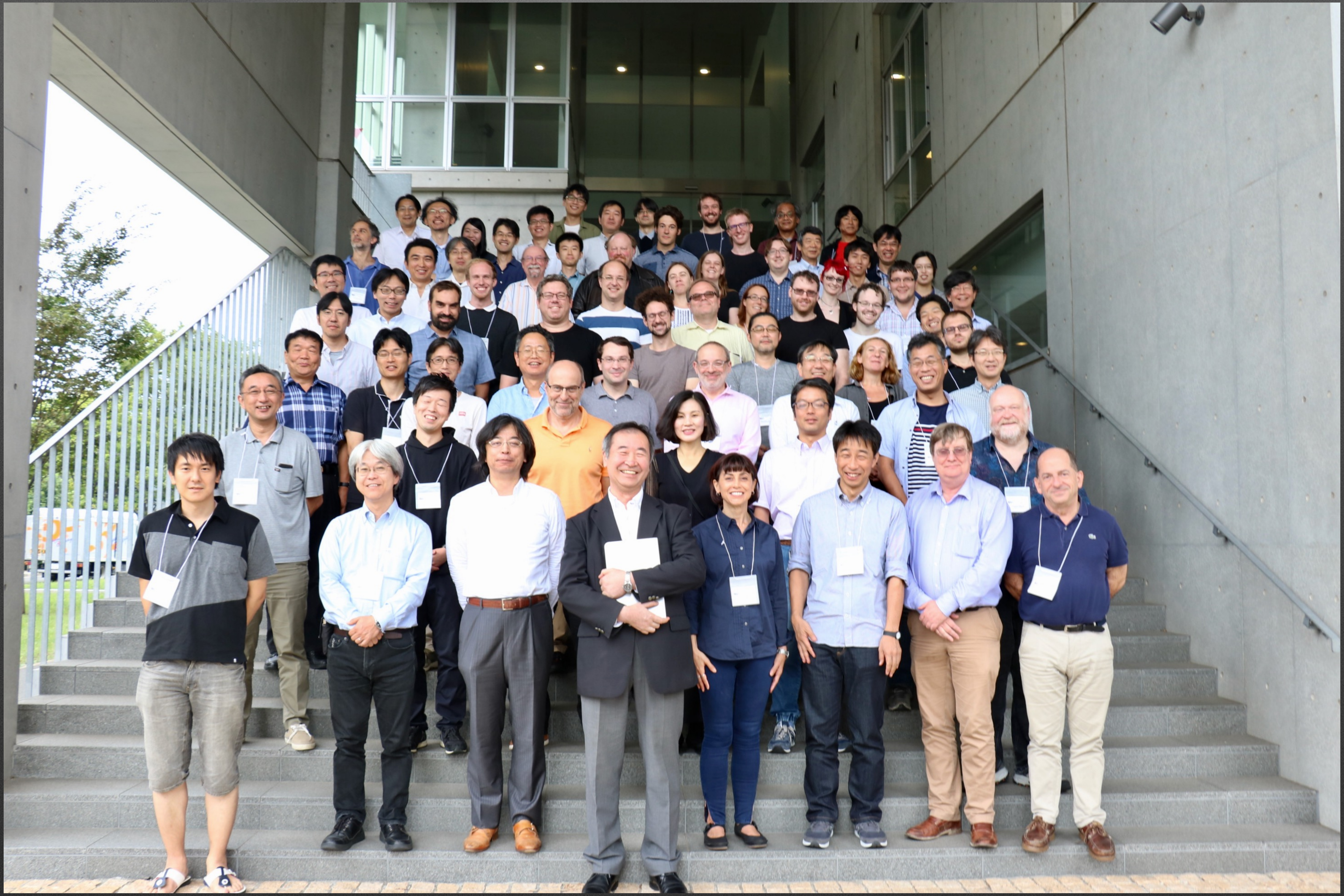
	KAM	SK	HK-1TankHD
Depth	1,000 m	1,000 m	650 m
Dimensions of water tank			
diameter	15.6 m ϕ	39 m ϕ	74 m ϕ
height	16 m	42 m	60 m
Total volume	4.5 kton	50 kton	258 kton
Fiducial volume	0.68 kton	22.5 kton	187 kton
Outer detector thickness	~ 1.5 m	~ 2 m	$1 \sim 2$ m
Number of PMTs			
inner detector (ID)	948 (50 cm ϕ)	11,129 (50 cm ϕ)	40,000 (50 cm ϕ)
outer detector (OD)	123 (50 cm ϕ)	1,885 (20 cm ϕ)	6,700 (20 cm ϕ)
Photo-sensitive coverage	20%	40%	40%
Single-photon detection efficiency of ID PMT	unknown	12%	24%
Single-photon timing resolution of ID PMT	~ 4 nsec	2-3 nsec	1 nsec

Expected HK sensitivities

1 tank x 10 years

Physics Target	Sensitivity	Conditions
Neutrino study w/ J-PARC ν		$1.3\,\mathrm{MW} \times 10^8$ sec
– CP phase precision	$< 23°$	@ $\sin^2 2\theta_{13} = 0.1$, mass hierarchy known
– CPV discovery coverage	76% ($3\,\sigma$), 57% ($5\,\sigma$)	@ $\sin^2 2\theta_{13} = 0.1$, mass hierarchy known
– $\sin^2\theta_{23}$	± 0.017	1σ @ $\sin^2\theta_{23} = 0.5$
Atmospheric neutrino study		10 years observation
– MH determination	$> 2.2\,\sigma$ CL	@ $\sin^2\theta_{23} > 0.4$
– θ_{23} octant determination	$> 3\,\sigma$ CL	@ $\lvert\theta_{23} - 45°\rvert > 4°$
Atmospheric and Beam Combination		10 years observation
– MH determination	$> 3.8\,\sigma$ CL	@ $\sin^2\theta_{23} > 0.4$
– θ_{23} octant determination	$> 3\,\sigma$ CL	@ $\lvert\theta_{23} - 45°\rvert > 2.3°$
Nucleon Decay Searches		1.9 Mton·year exposure
– $p \to e^+ + \pi^0$	7.8×10^{34} yrs (90% CL UL)	
	6.3×10^{34} yrs ($3\,\sigma$ discovery)	
– $p \to \bar{\nu} + K^+$	3.2×10^{34} yrs (90% CL UL)	
	2.0×10^{34} yrs ($3\,\sigma$ discovery)	
Astrophysical neutrino sources		
– ^{8}B ν from Sun	130 ν's / day	4.5 MeV threshold (visible energy) w/ osc.
– Supernova burst ν	54,000–90,000 ν's	@ Galactic center (10 kpc)
	$\sim$10 ν's	@ M31 (Andromeda galaxy)
– Supernova relic ν	70 ν's / 10 years	10–30 MeV, 4.2σ non-zero significance
– WIMP annihilation in the Earth		10 years observation
(σ_{SD}: WIMP-proton spin	$\sigma_{SD} = 10^{-40}\mathrm{cm}^2$	@ $M_{\mathrm{WIMP}} = 10\,\mathrm{GeV}$, $\chi\chi \to b\bar{b}$ dominant
dependent cross section)	$\sigma_{SD} = 10^{-44}\mathrm{cm}^2$	@ $M_{\mathrm{WIMP}} = 50\,\mathrm{GeV}$, $\chi\chi \to \tau^+\tau^-$ dominant

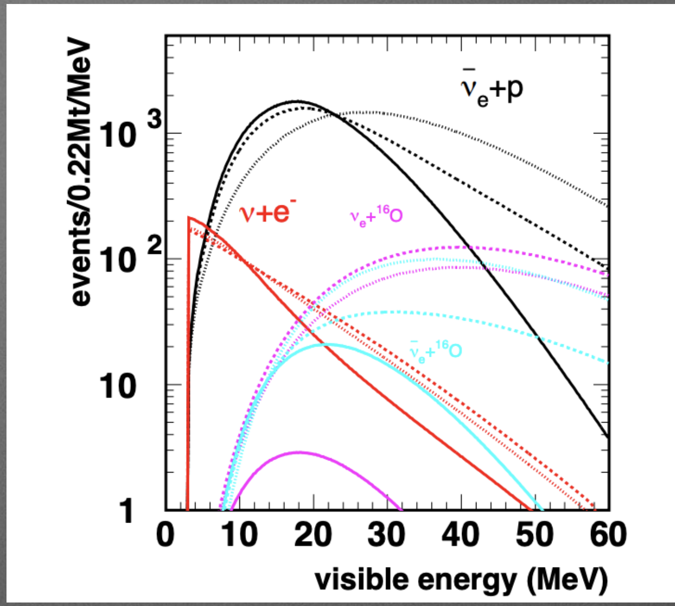
HK Proto-Collaboration

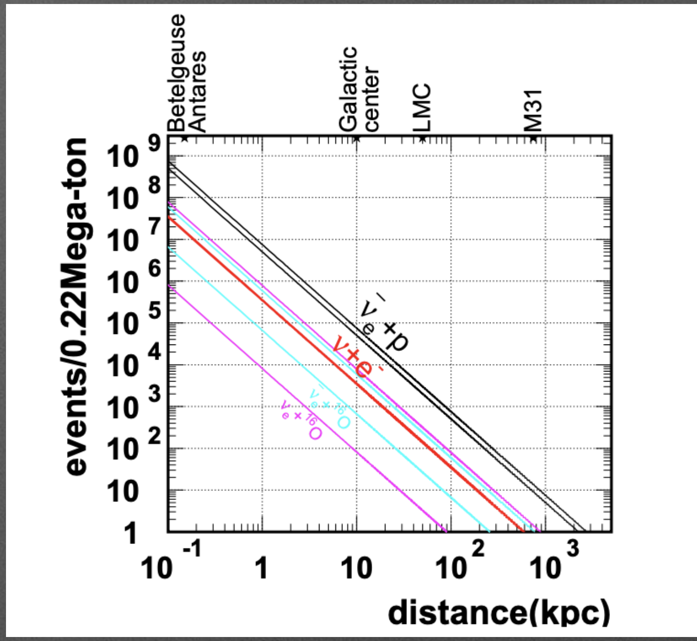


~75 institutions from 15 countries http://www.hyperk.org/

HK: Supernovae Neutrinos

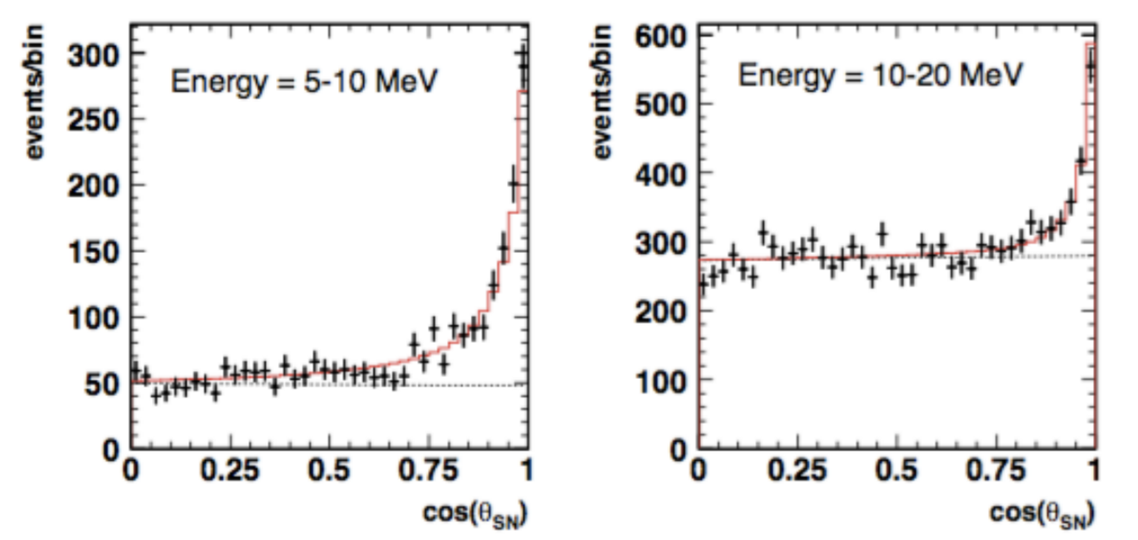
- Neutrinos carry out ~99% of the total energy released in a SN burst
- HK will mostly sensitive to $\bar{\nu}$e through inverse β-decay, but also other channels can be inspected
- Point to the SN
- Study energy spectrum and time profile → distinguish between different models for SN explosions
- Neutrino mass hierarchy determination?





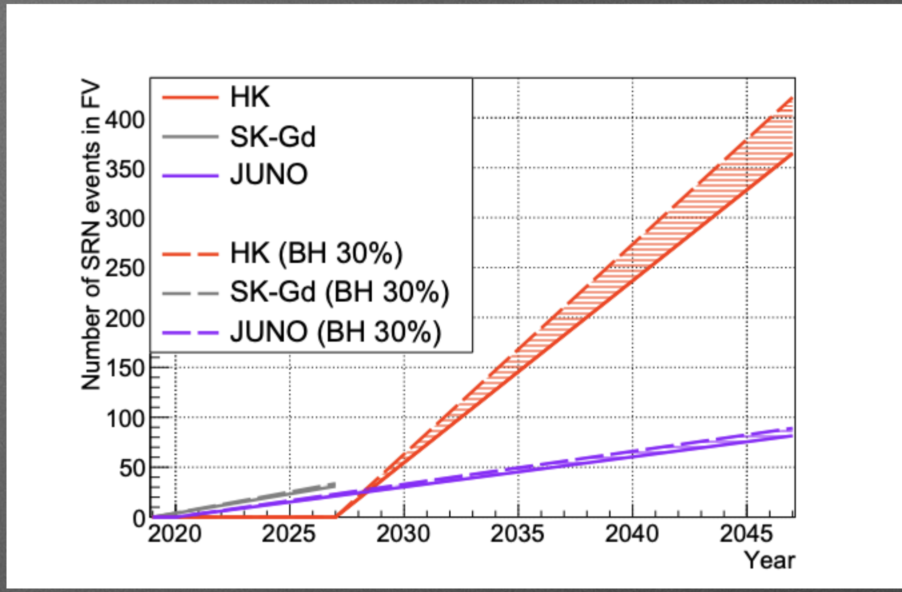
10 kpc

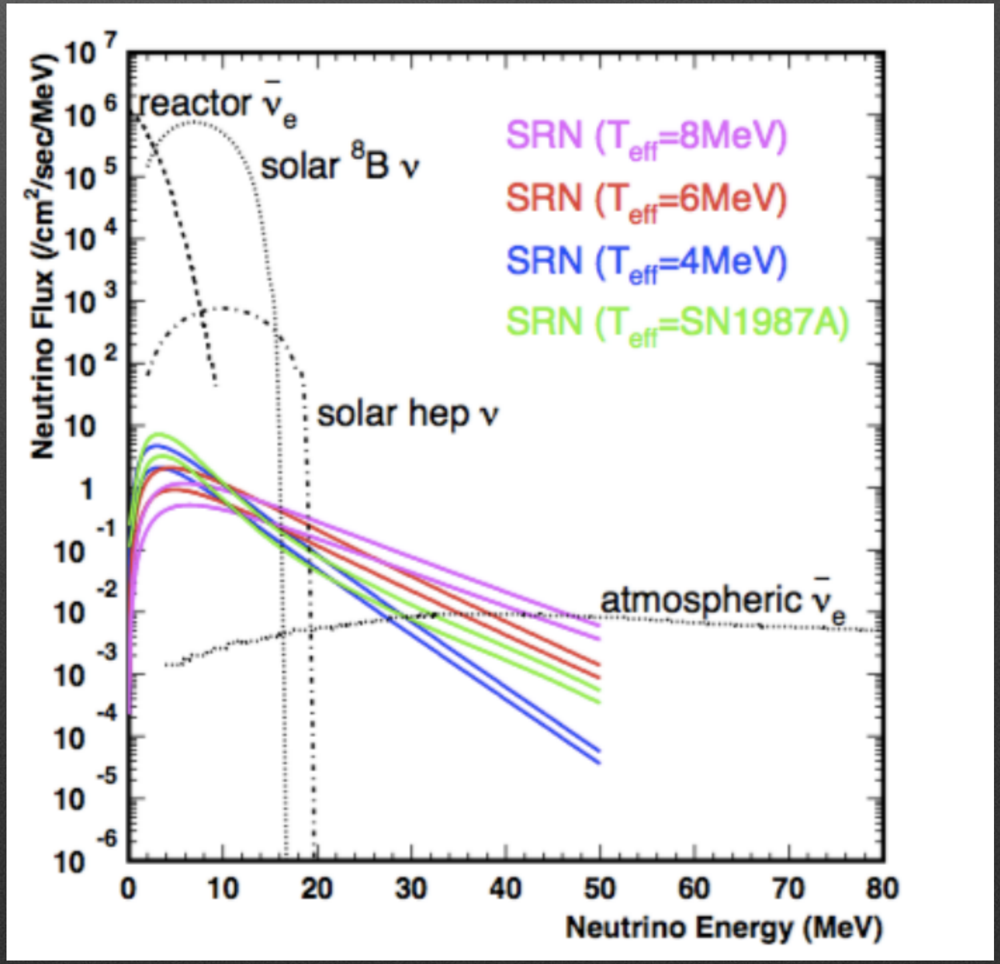
Neutrino source	Single Tank (220 kt Full Volume)	2 Tanks (440 kt Full Volume)
$\bar{\nu}_e + p$	50,000 - 75,000 events	100,000 - 150,000 events
$\nu + e^-$	3,400 - 3,600 events	6,800 - 7,200 events
$\nu_e +^{16} O$ CC	80 - 7,900 events	160 - 11,000 events
$\bar{\nu}_e +^{16} O$ CC	660 - 5,900 events	1,300 - 12,000 events
$\nu + e^-$ (Neutronization)	9 - 55 events	17 - 110 events
Total	54,000 - 90,000 events	109,000 - 180,000 events



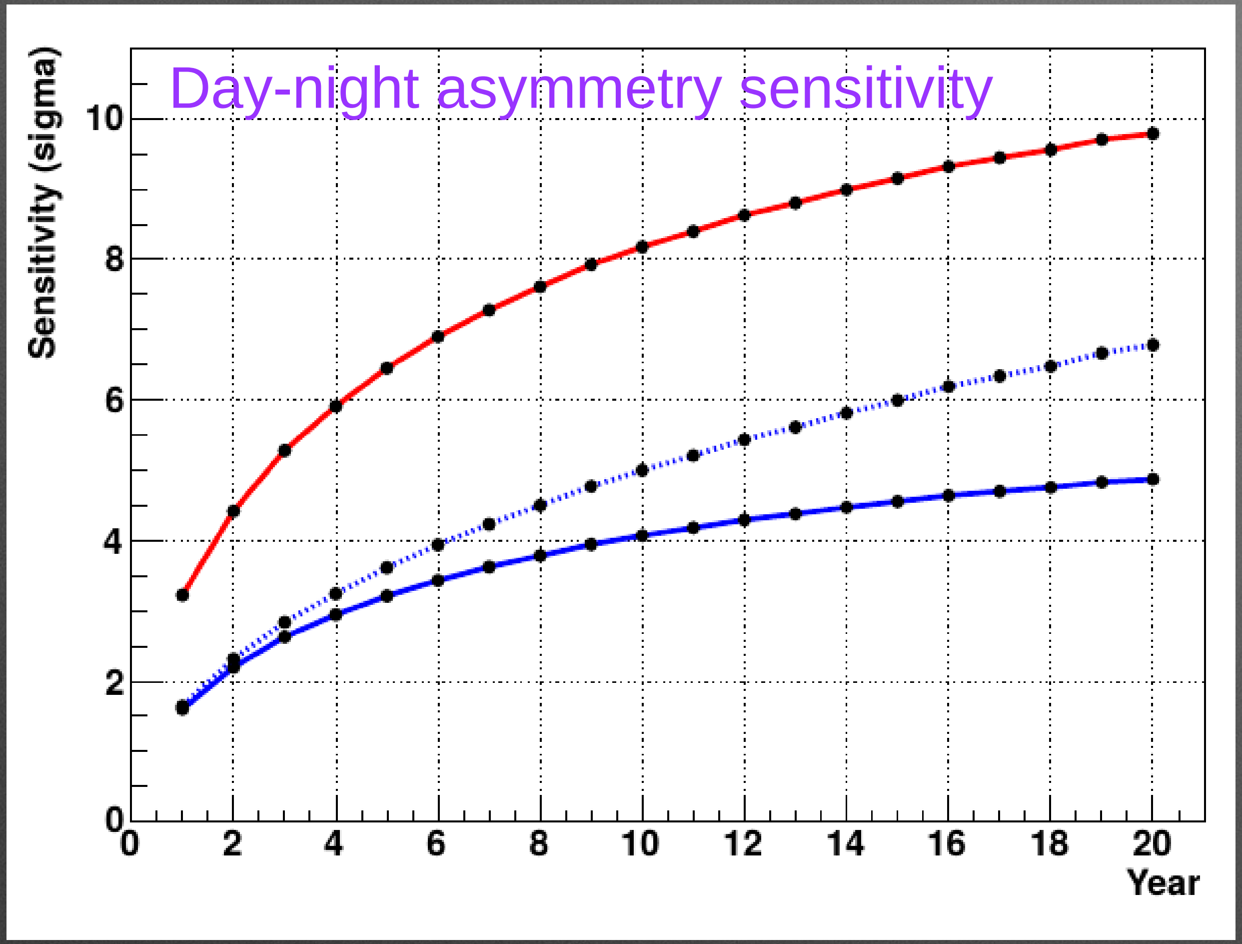
HK: Supernovae Relic Neutrinos

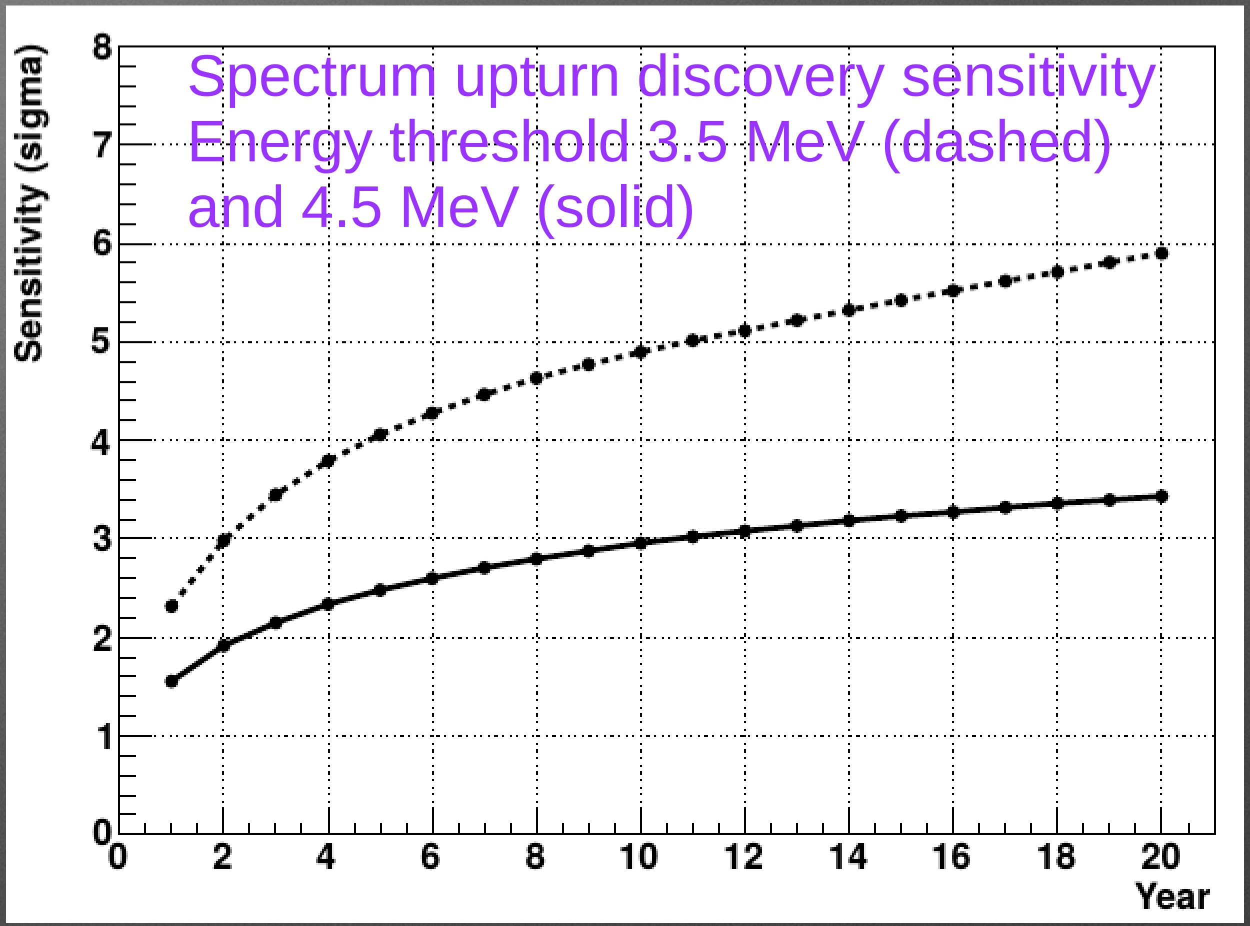
- Neutrinos produced by all the SN since the beginning of the Universe (SRN)
- Their detection is the main goal of the Super-Kamiokande upgrade (SK-Gd)
  - Addition of Gd in SK to tag the neutrons and distinguish $\bar{\nu}_e + p \rightarrow e^- + n$
- If SRN will be discovered by SK, the large size of HK will allow a detailed study of the history of the Universe through SRN

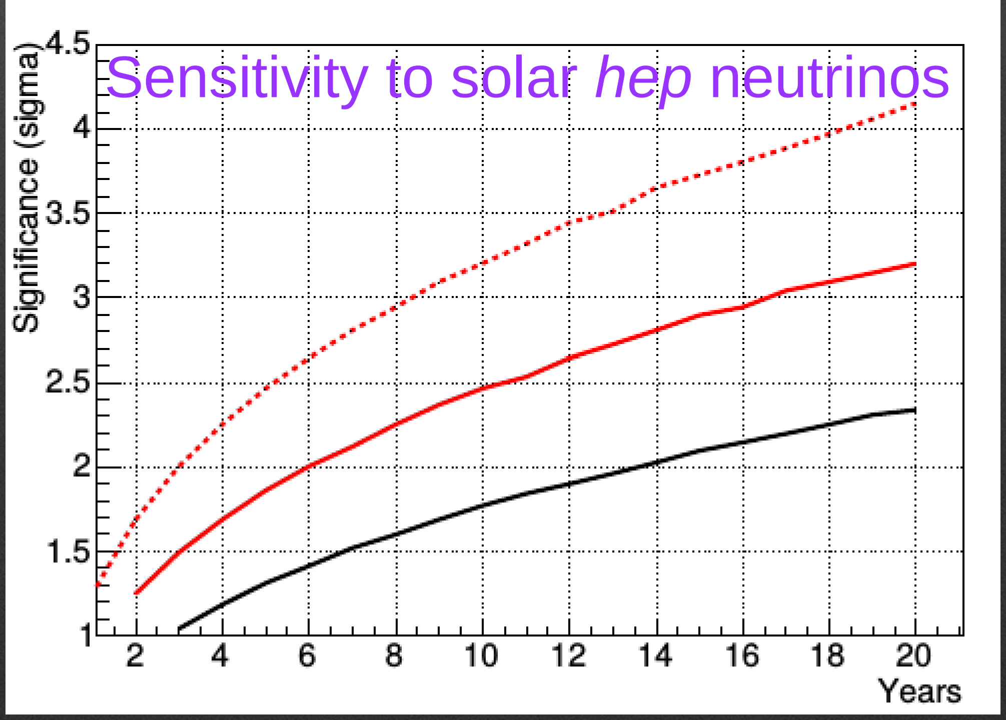




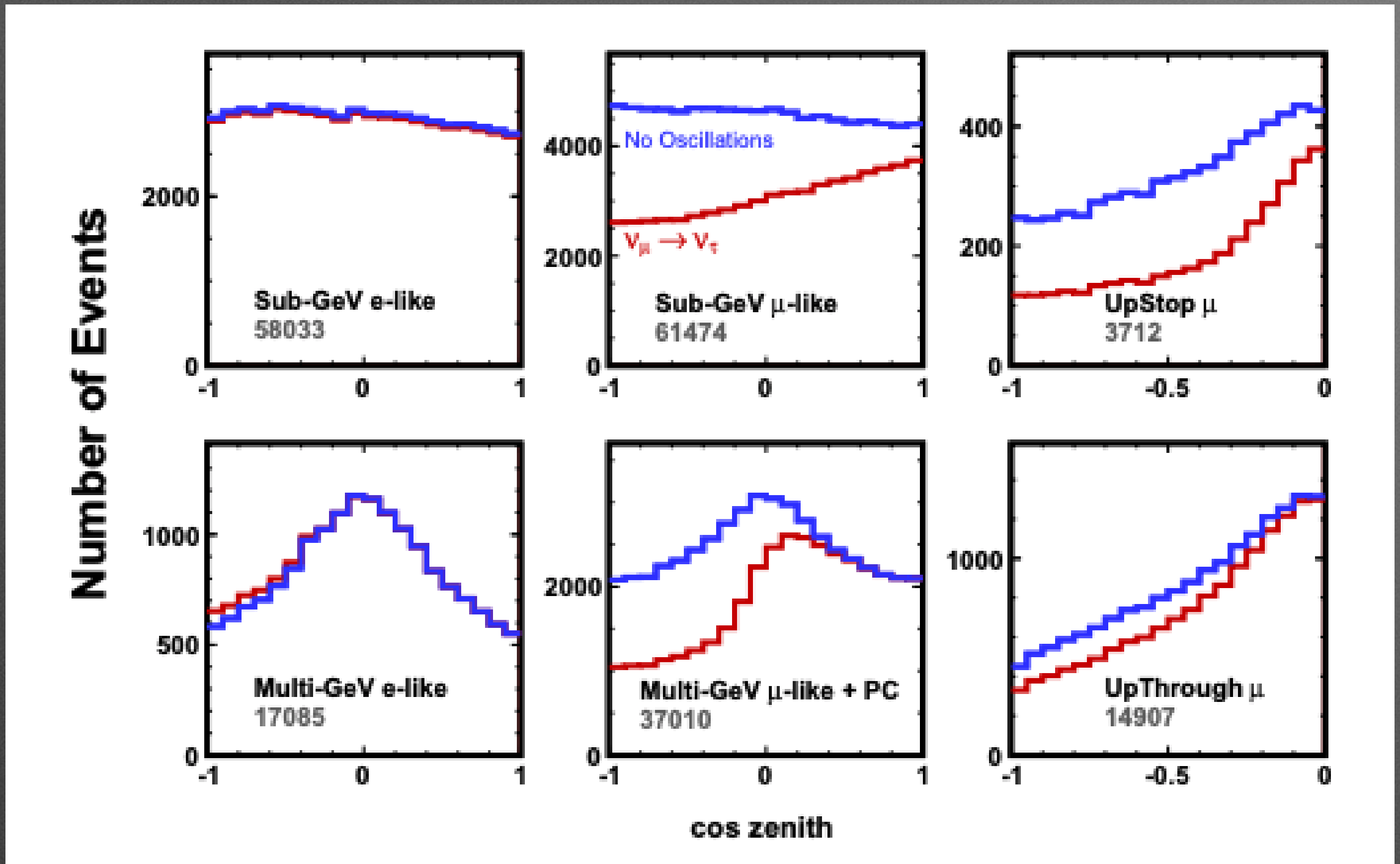
HK: Solar neutrinos

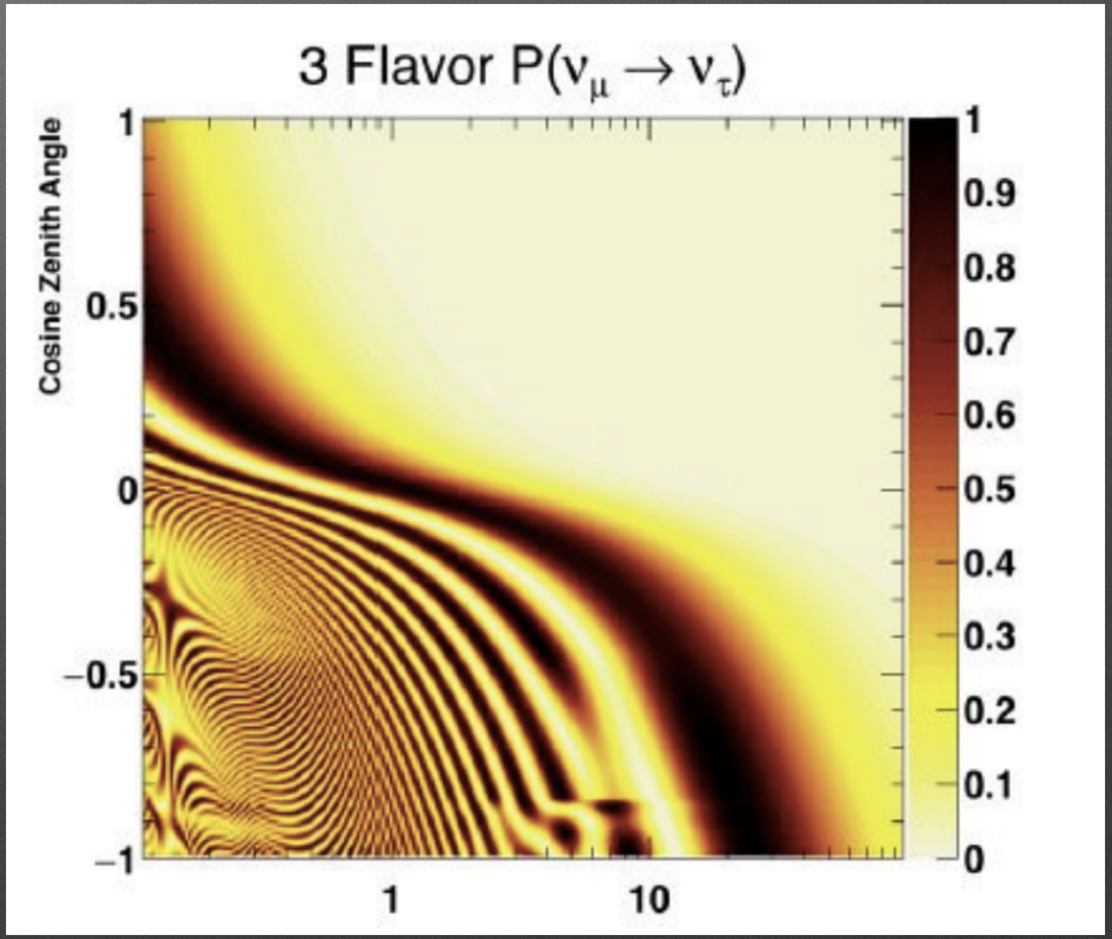


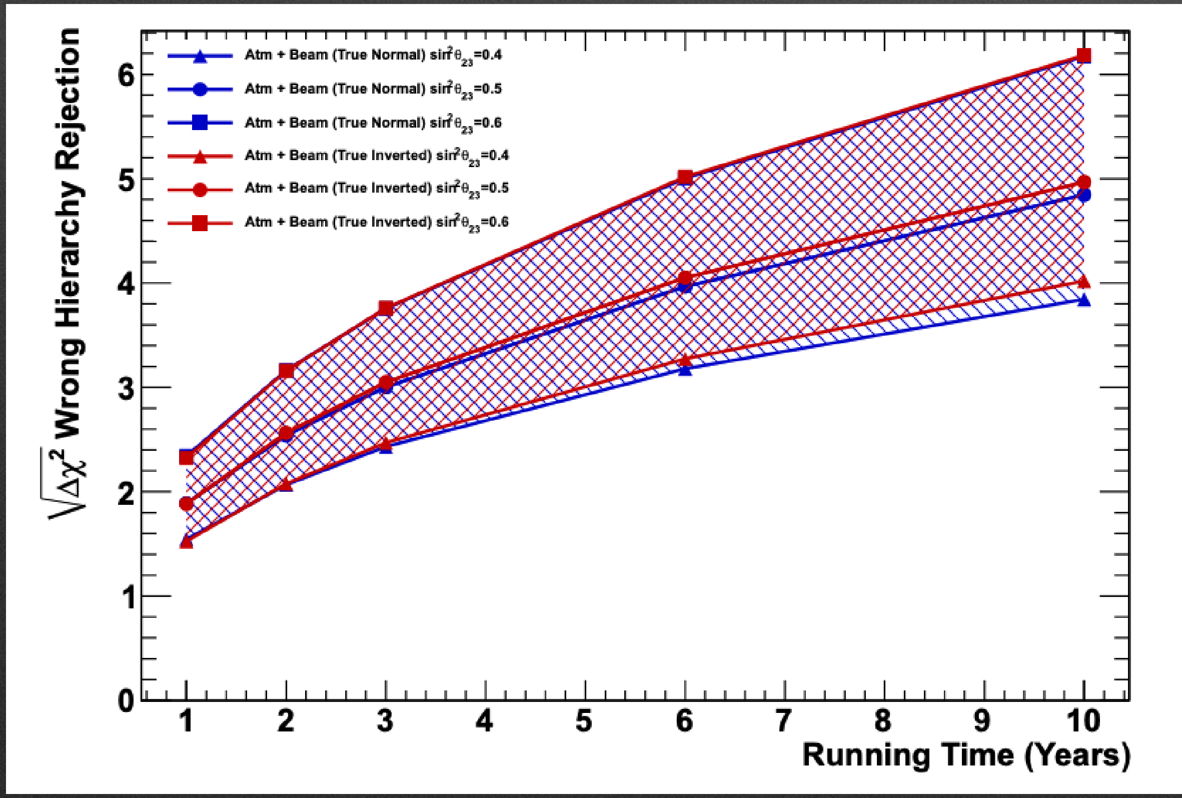




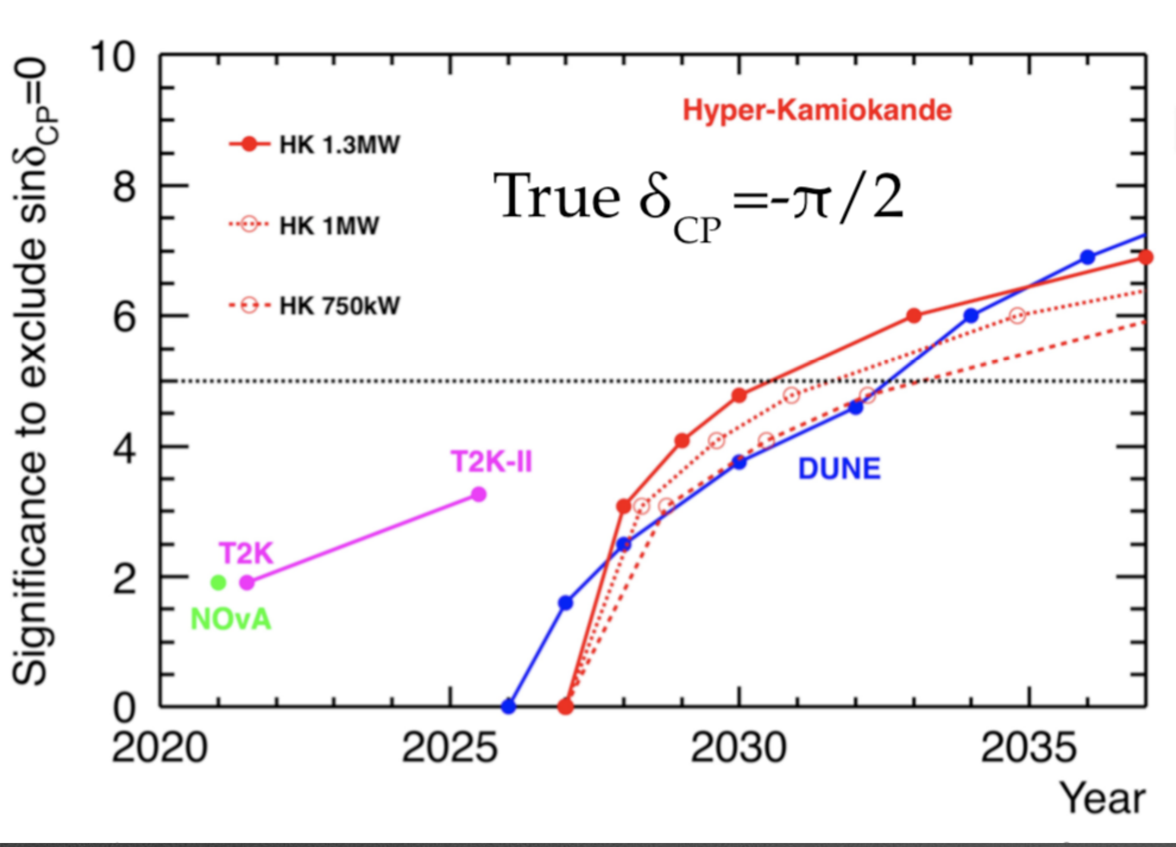
HK: Atmospheric neutrinos

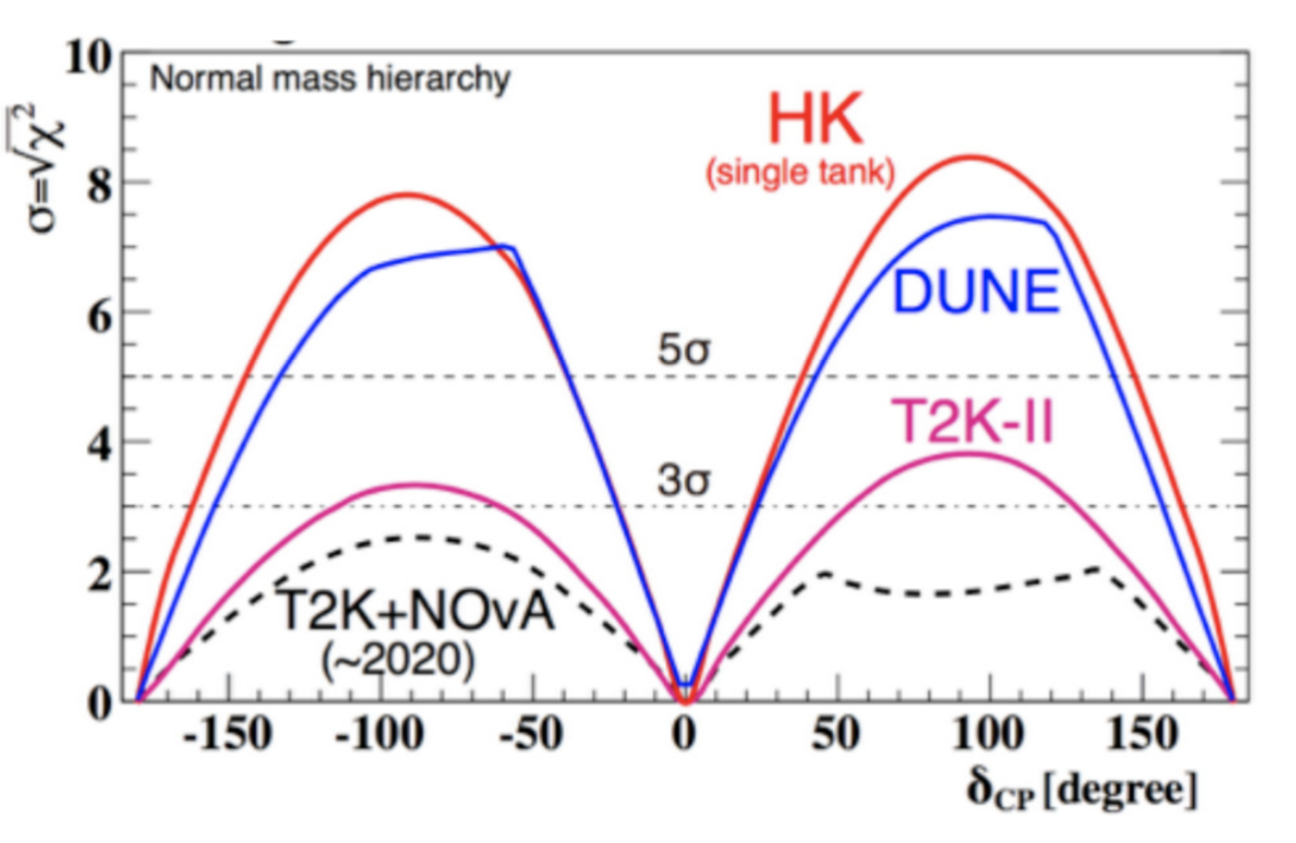


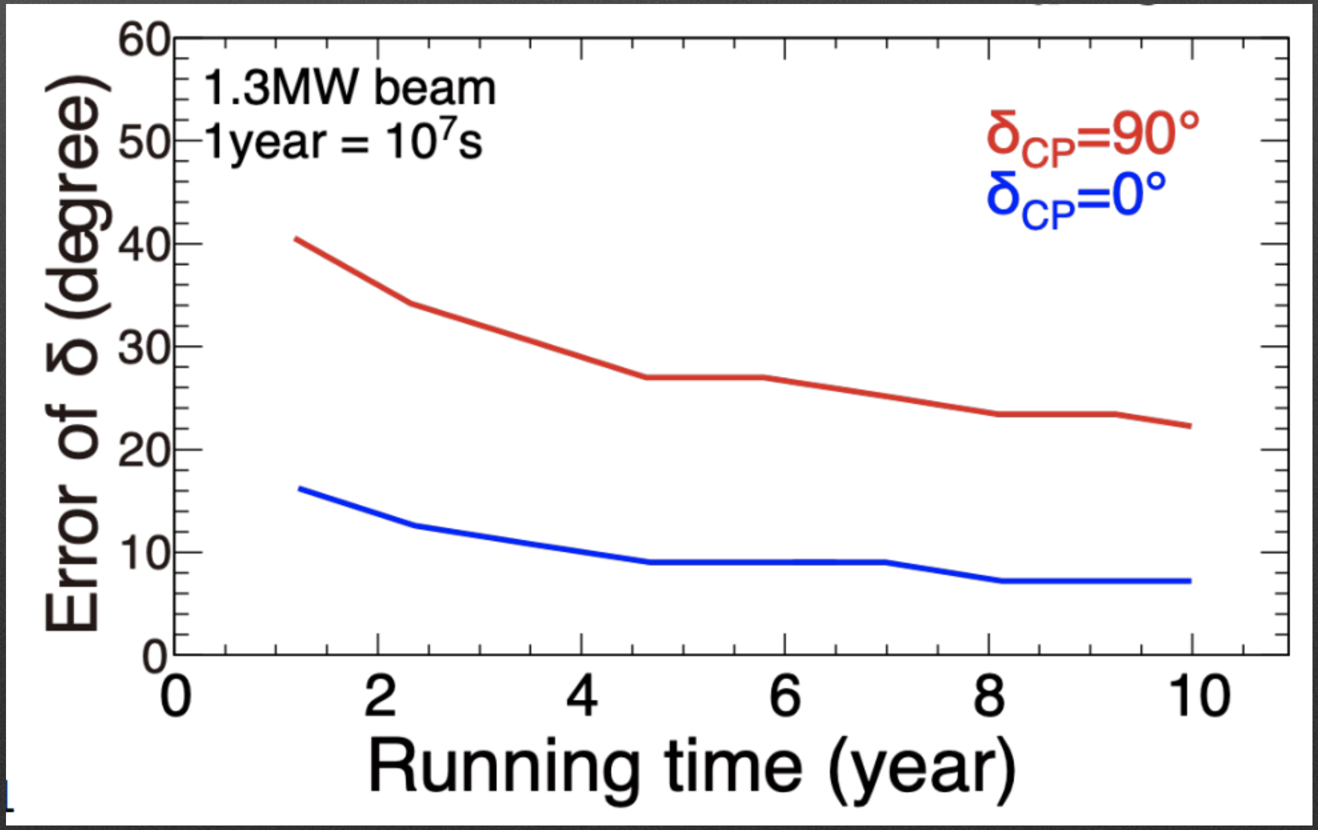




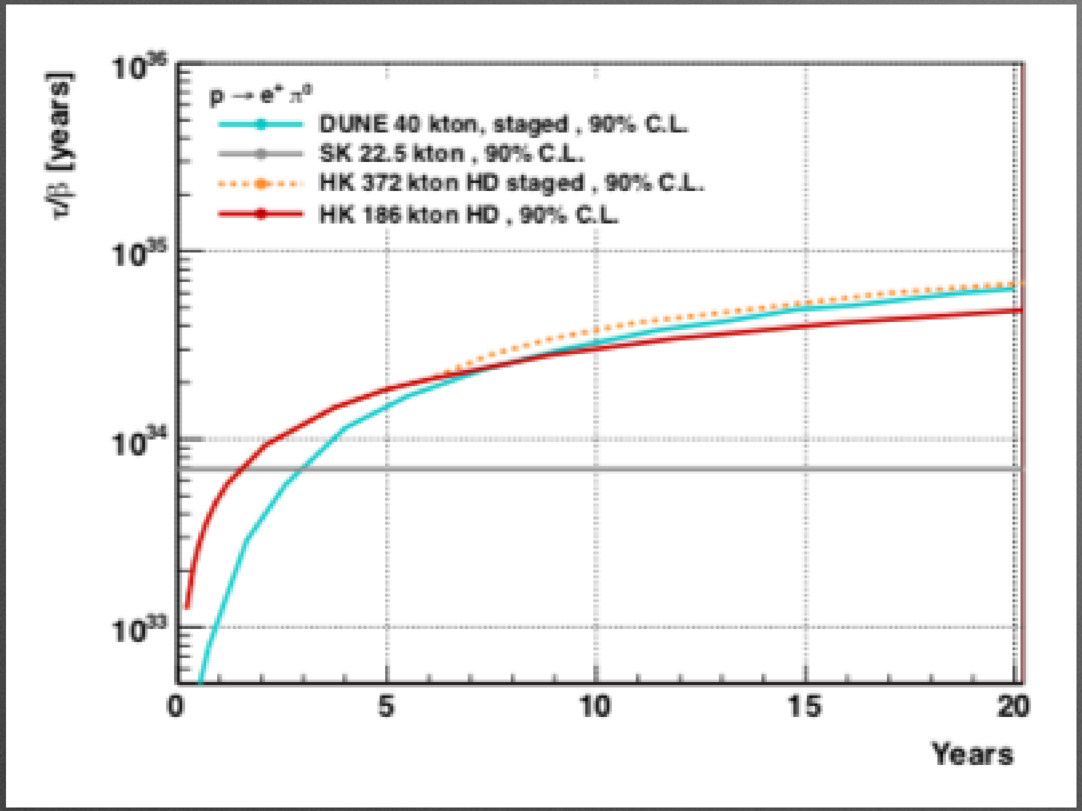
HK: δCP Sensitivities

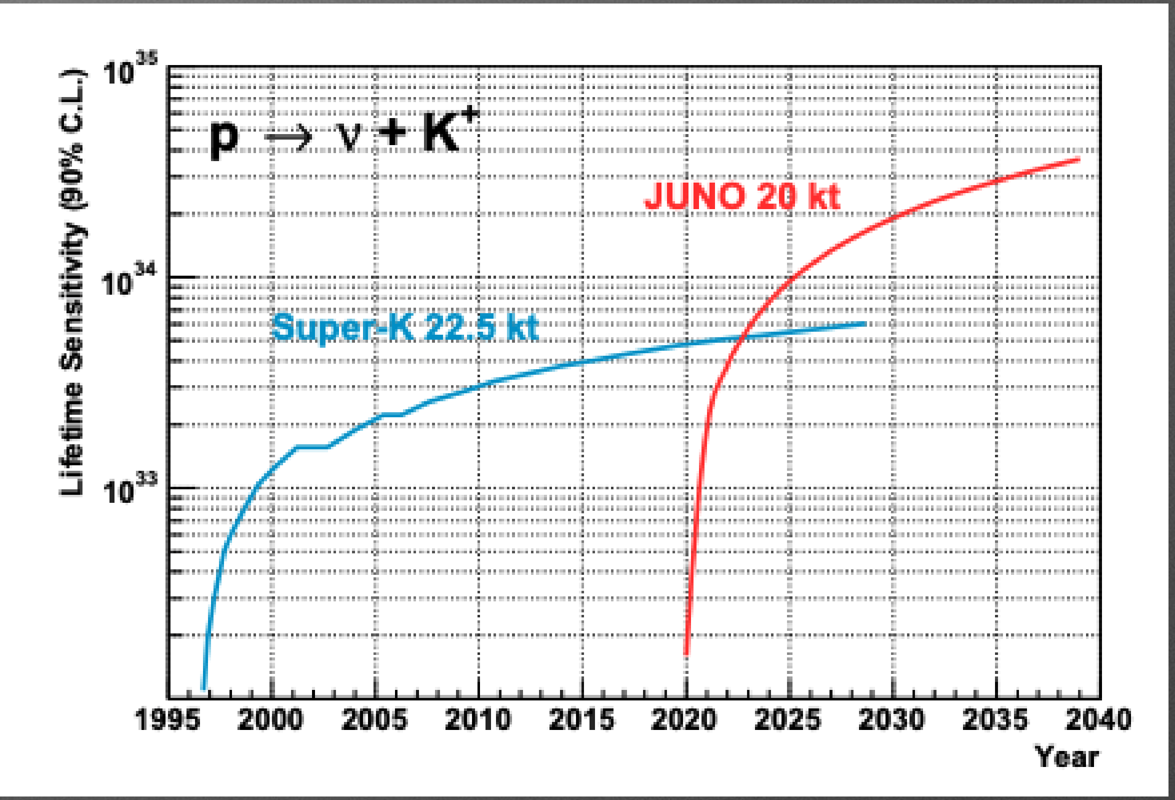






HK: Sensitivities to proton decay

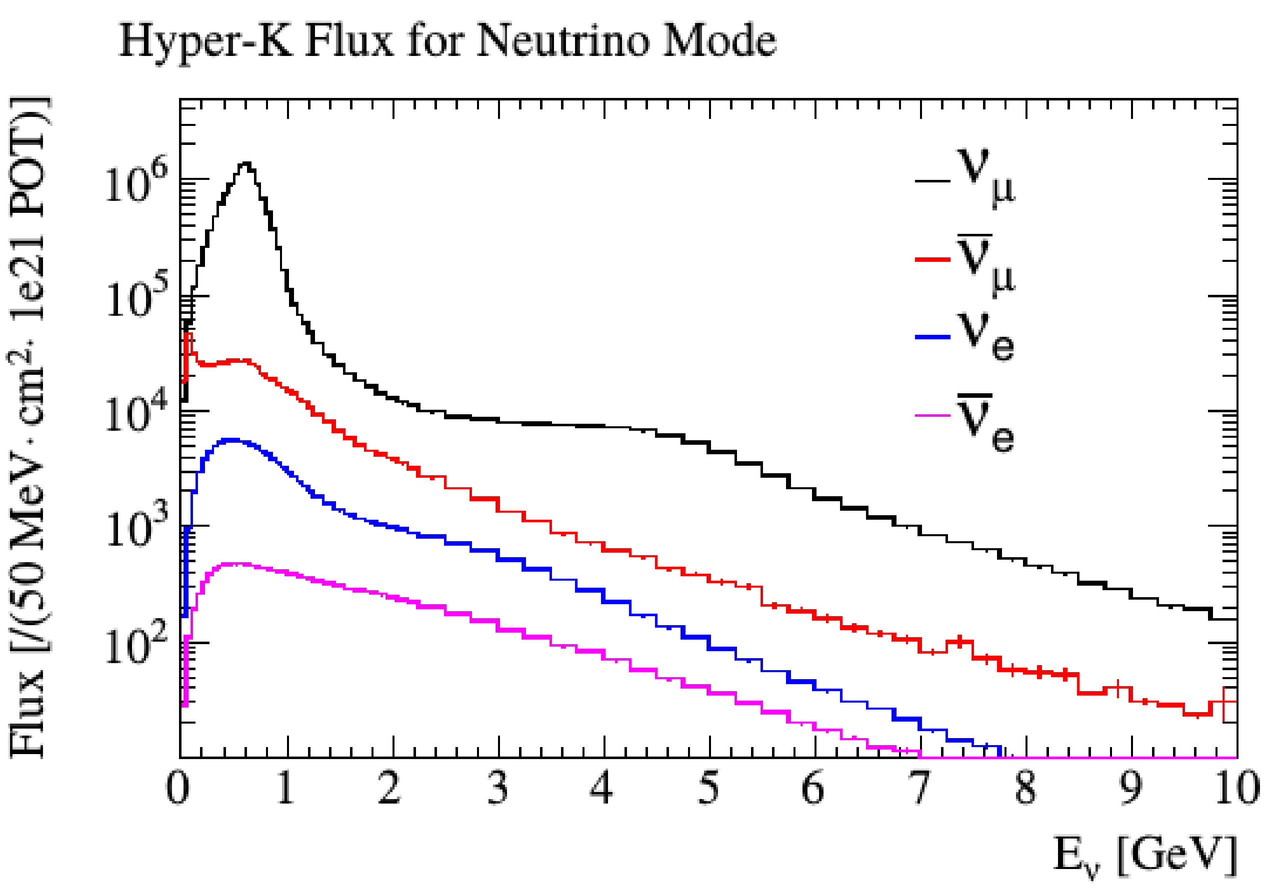


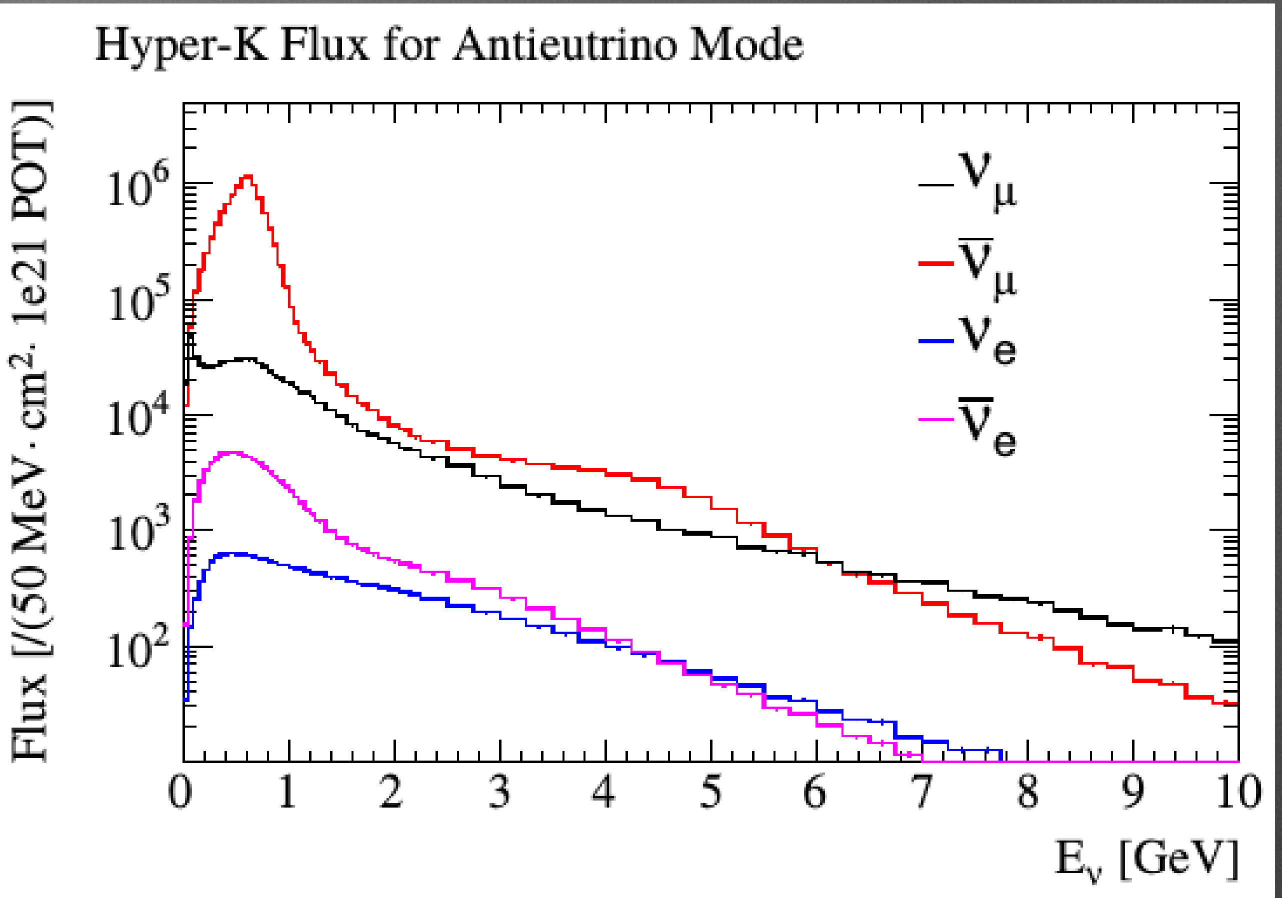


HK: Signal digitizer requirements

Trigger	self triggering for each channel
PMT impedance	$50\,\Omega$
Signal reflection	<0.1%
Discriminator threshold	<0.25PE (well below 1PE)
Processing speed/hit (channel dead time)	$<1\,\mu s$
Maximum hit rate	>1 MHz for each channel
Charge dynamic range	0.1 to 1250PE (0.2 to 2500 pC)
Charge resolution	RMS 0.05PE for signals below 25PE
Timing LSB	<0.5 ns
Timing resolution	RMS <0.3 ns at 1PE RMS <0.2 ns for signals above 5PE
Power consumption	<1 W per channel

HK: (anti-)neutrino fluxes





Parameter	Achieved	Original	Doubled rep-rate	Long-term Projection
Circumference			1,567.5 m	
Beam kinetic energy	30 GeV	50 GeV	30 GeV	30 GeV
Beam intensity	2.45×10^{14} ppp	3.3×10^{14} ppp	2.0×10^{14} ppp	3.2×10^{14} ppp
	3.1×10^{13} ppb	4.1×10^{13} ppb	2.5×10^{13} ppb	4.0×10^{13} ppb
[RCS equivalent power]	[575 kW]	[1 MW]	[610 kW]	[1 MW]
Harmonic number			9	
Bunch number			8 / spill	
Spill width			$\sim 5\,\mu$s	
Bunch full width at extraction	∼50 ns	–	∼50 ns	∼50 ns
Maximum RF voltage	280 kV	280 kV	560 kV	560 kV
Repetition period	2.48 sec	3.52 sec	1.32 sec	1.16 sec
Beam power	485 kW[a]	750 kW	750 kW	1340 kW

- Main Ring parameters (current and projected)
- Neutrino and anti-neutrino fluxes for 320 kA horn current

[a] As of 2018

T2HKK: Second Detector in Korea

- Strategy of HK is to build two identical detectors in stage
- First detector will be located in Tochibora mine in Japan
- Locations in Korea have been identified for the second detector
- This enhances physics capabilities of oscillation physics thanks to longer baseline (~1100 km)
  - Leptonic CP violation
  - Determination of neutrino mass ordering
  - Non-standard neutrino interactions
- Better precision on δ_{CP} can be achieved