Perspectives for Neutrino Physics in Japan - Towards Hyper-Kamiokande

Claudio Giganti
for LLR and LPNHE neutrino groups

Super-K

The Super-Kamiokande Gadolinium experiment

Margherita Buizza Avanzini[1], Olivier Drapier[1], Michel Gonin[1], Thomas Mueller[1], Pascal Paganini[1] and Benjamin Quilain[1]

[1]LLR Neutrino group, IN2P3/Ecole Polytechnique

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

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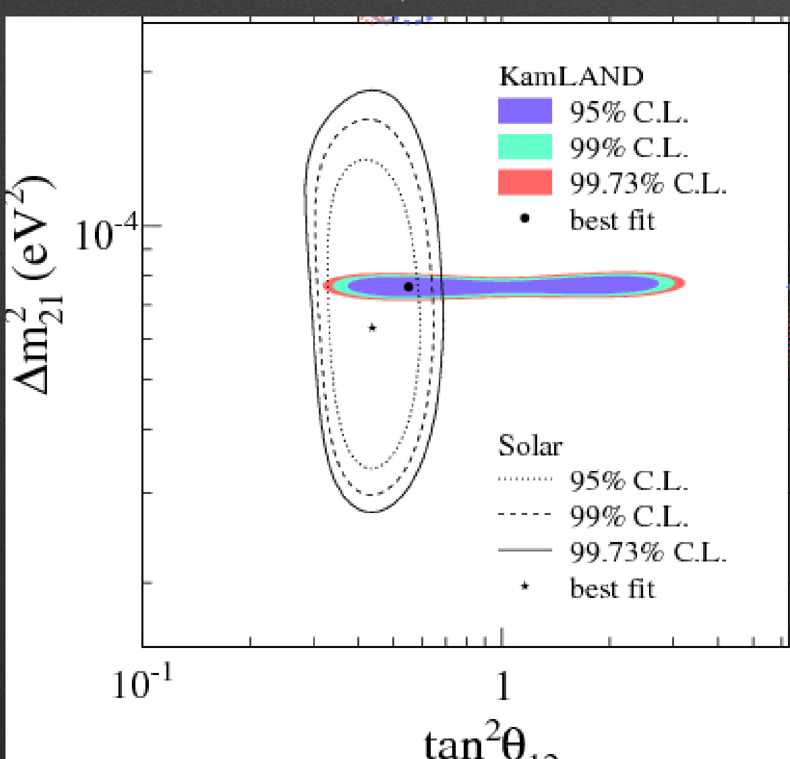
[1]LLR Neutrino group, IN2P3/Ecole Polytechnique
[2]LPNHE Neutrino group, IN2P3/Sorbonne University

Neutrino oscillations

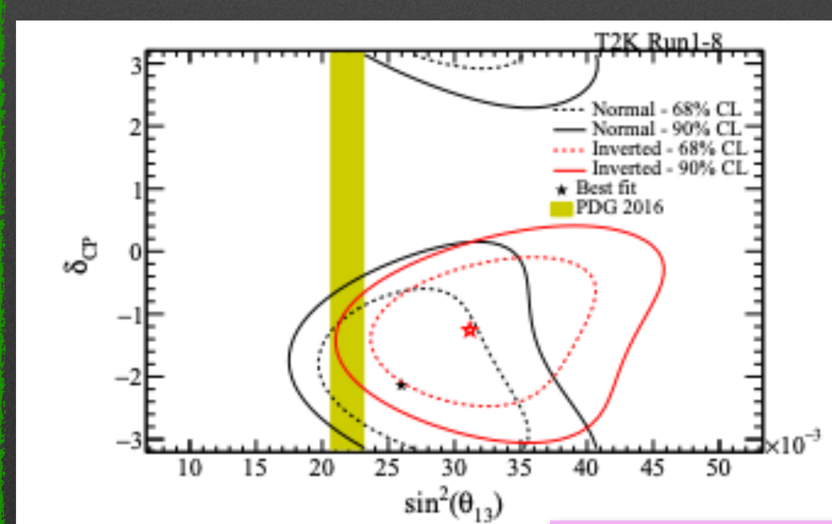
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}1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

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

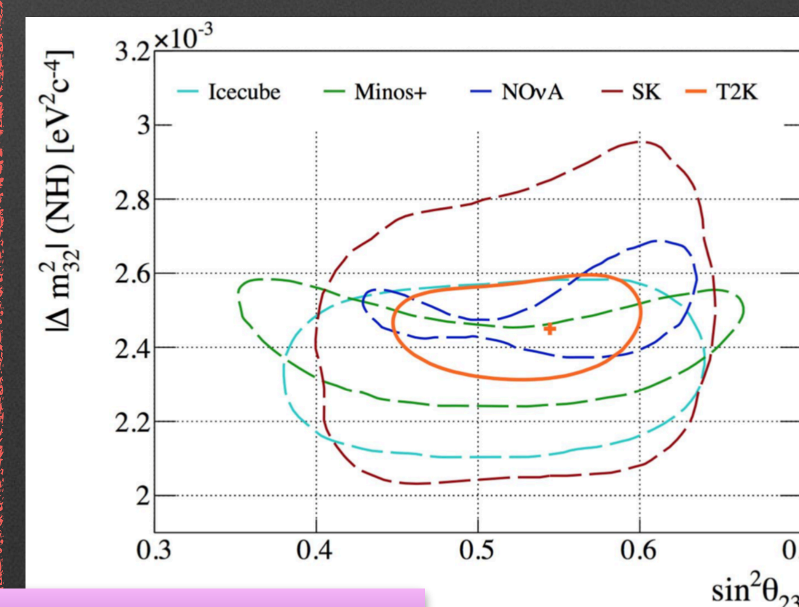
Solar (SNO, KamLand) → θ_{12}, Δm_{12}



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



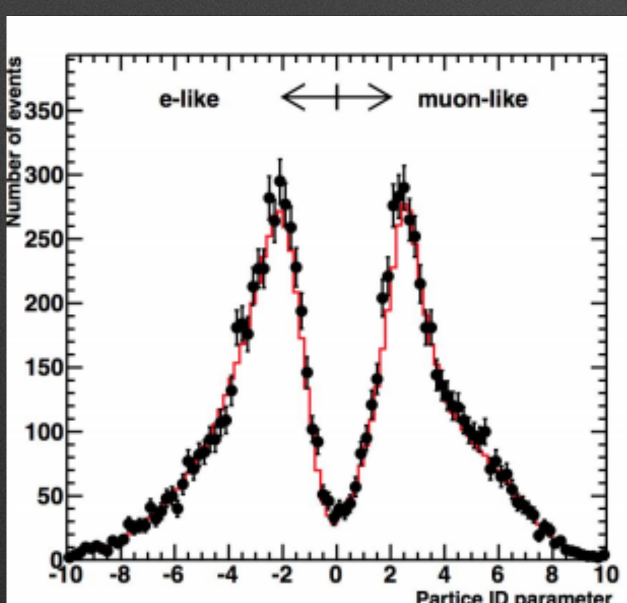
Atmospheric (SK, IceCUBE)
LBL (Minos, T2K, NOνA)
→ θ_{23}, Δm_{32}



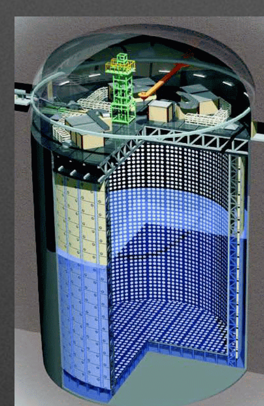
LBL experiments

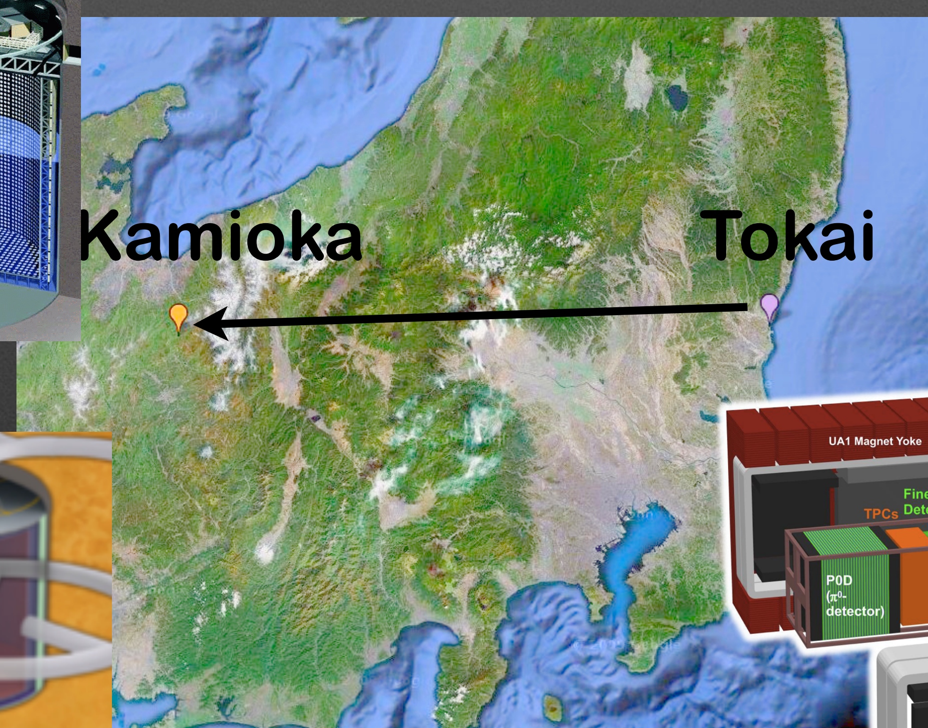
Tokai to Kamioka (SK or HK)

- High intensity ~600 MeV ν_μ beam produced at J-PARC (Tokai, Japan)
- 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 $\overline{\nu}_e$ appearance → determine θ_{13} and δ_{CP}
  - Precise measurement of ν_μ and $\overline{\nu}_\mu$ disappearance → θ_{23} and Δm^2_{32}



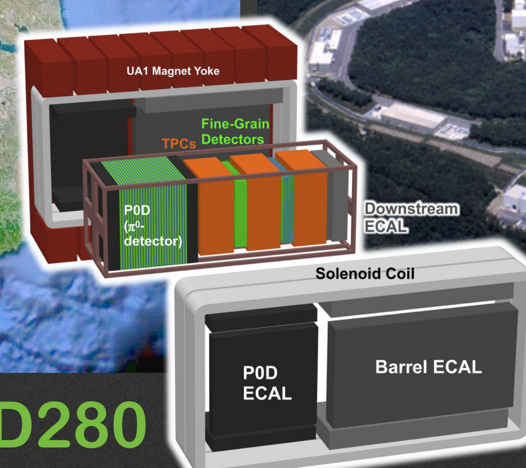
Super-Kamiokande





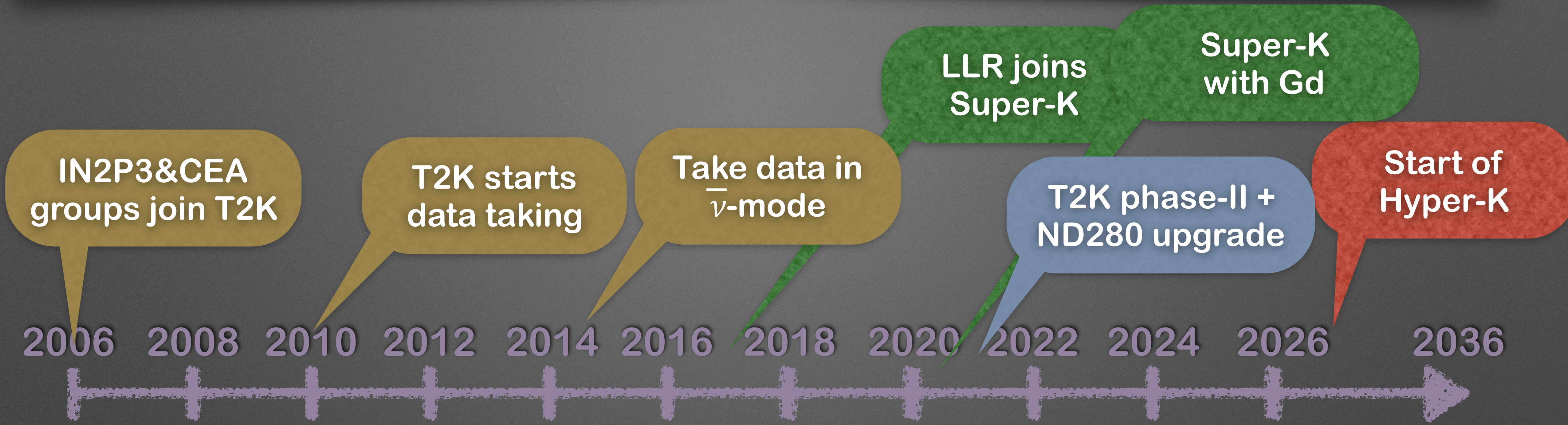
J-PARC accelerator:
Design power: 750 kW
(1.3 MW for HK)

Hyper-Kamiokande



ND280

>30 years program



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

>30 years program

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

IN2P3&CEA groups join T2K

T2K starts data taking

Take data in $\overline{\nu}$-mode

LLR joins Super-K

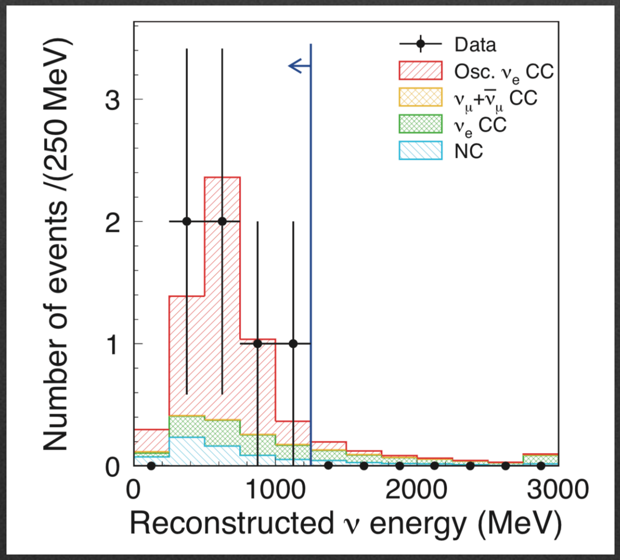
Super-K with Gd

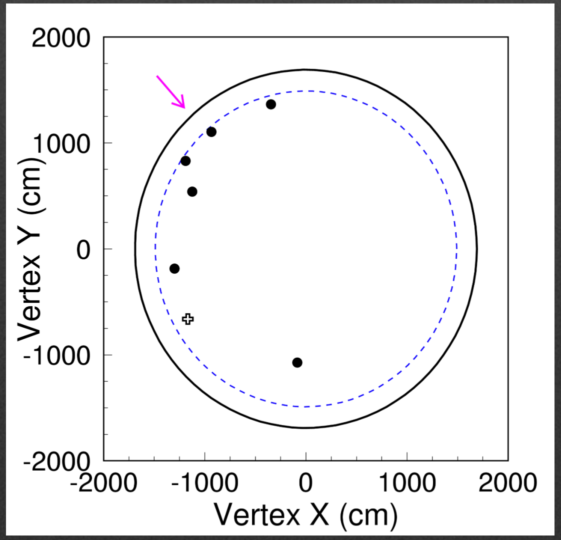
T2K phase-II + ND280 upgrade

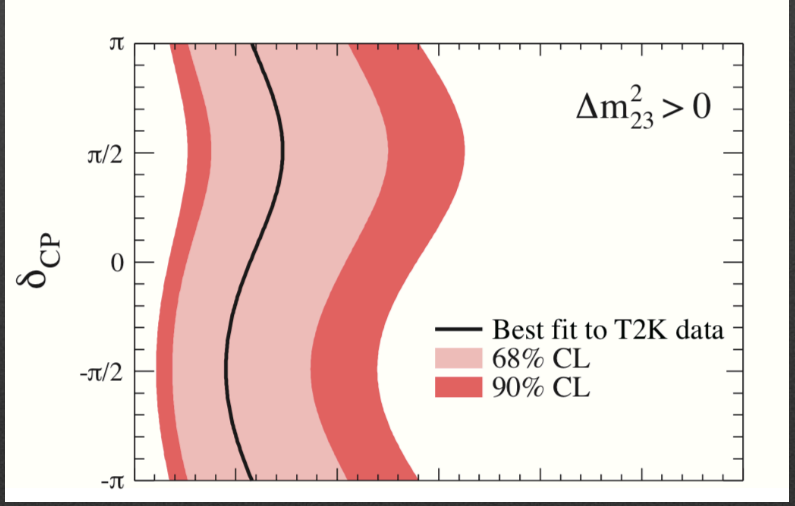
Start of Hyper-K

Hints of ν_e appearance ($\theta_{13}\neq0$@2.5σ)

Phys.Rev.Lett. 107 (2011) 041801







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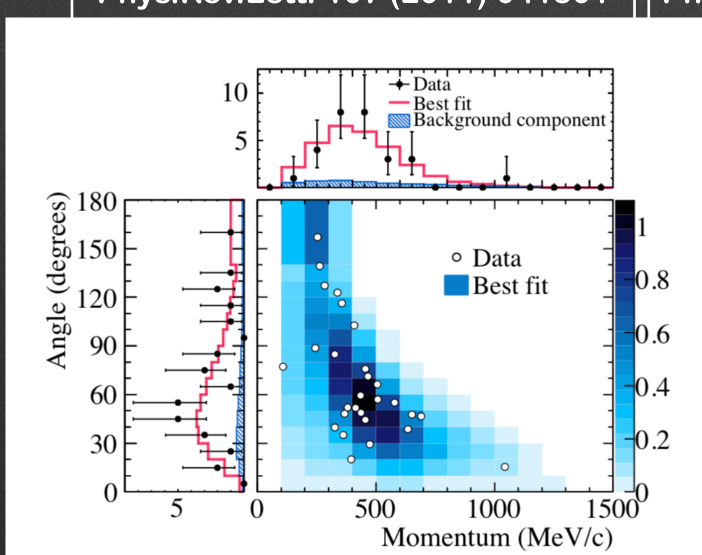
Hints of ν_e appearance ($\theta_{13}\neq0$@2.5σ)

Observation of ν_e appearance ($\theta_{13}\neq0$@7.3σ)

2016 Breakthrough prize to Daya Bay, Kamland, SK, SNO, K2K and T2K collaboration

Phys.Rev.Lett. 107 (2011) 041801



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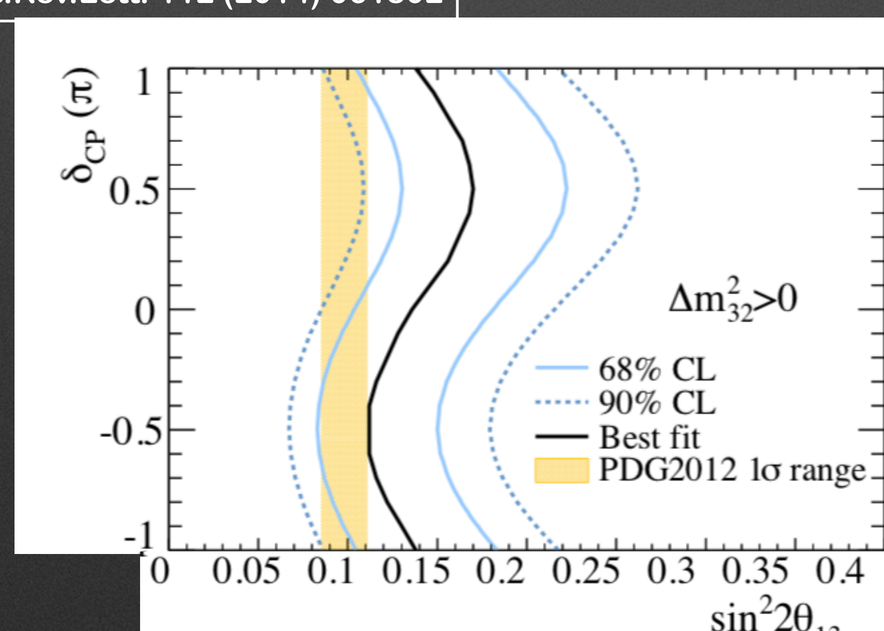

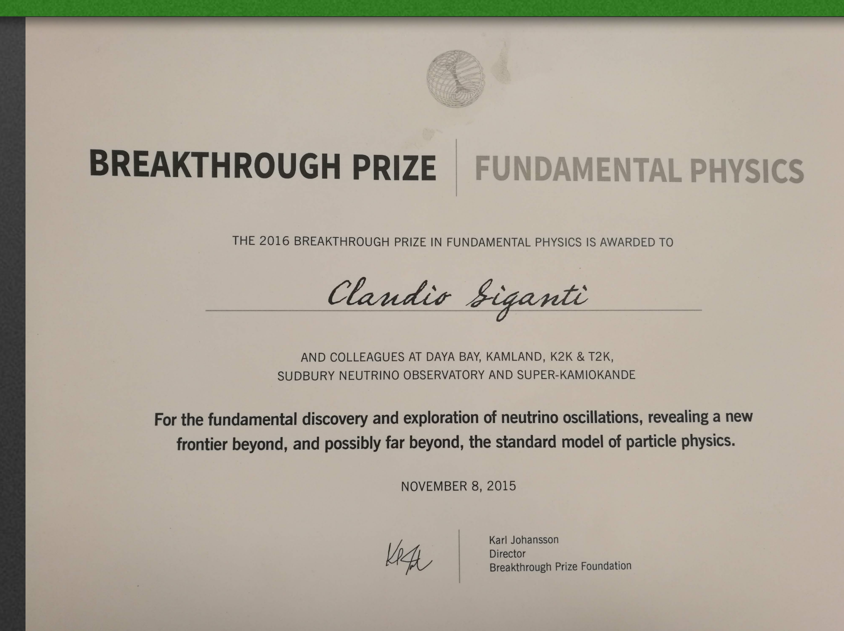

>30 years program

IN2P3&CEA groups join T2K

T2K starts data taking

Take data in $\bar{\nu}$-mode

LLR joins Super-K

Super-K with Gd

T2K phase-II + ND280 upgrade

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Precise measurement of θ_{23}, Δm^2_{32}

Phys.Rev.Lett. 107 (2011) 041801

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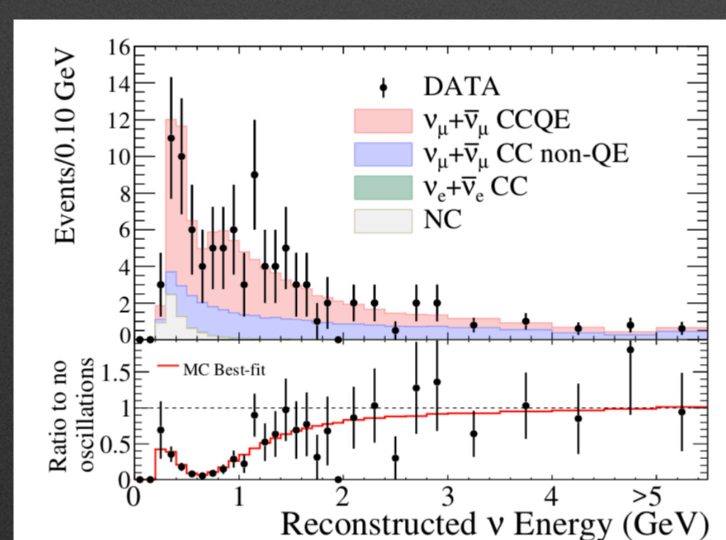
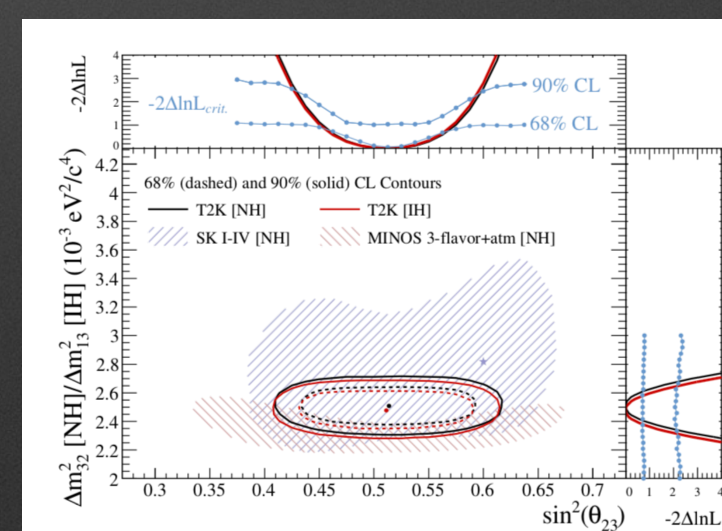
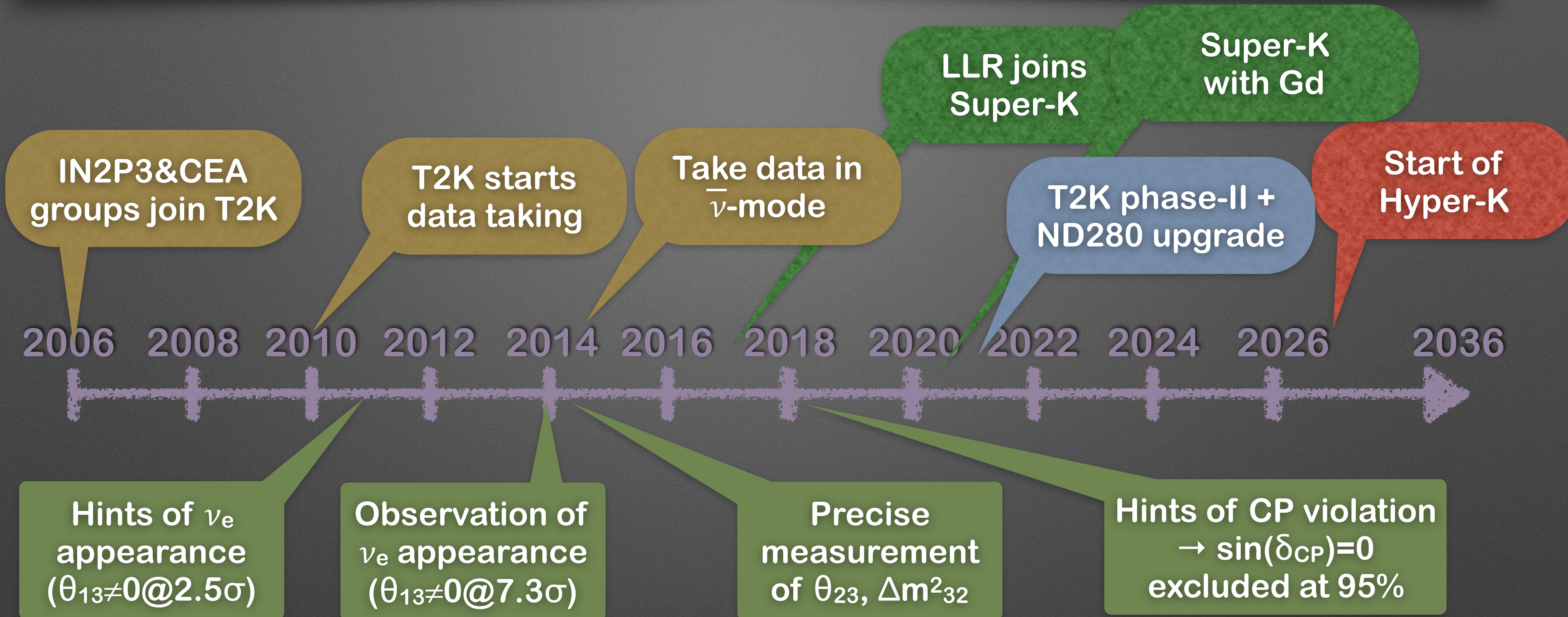
Phys.Rev.Lett. 112 (2014) no.18, 181801





>30 years program



Phys.Rev.Lett. 107 (2011) 041801

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

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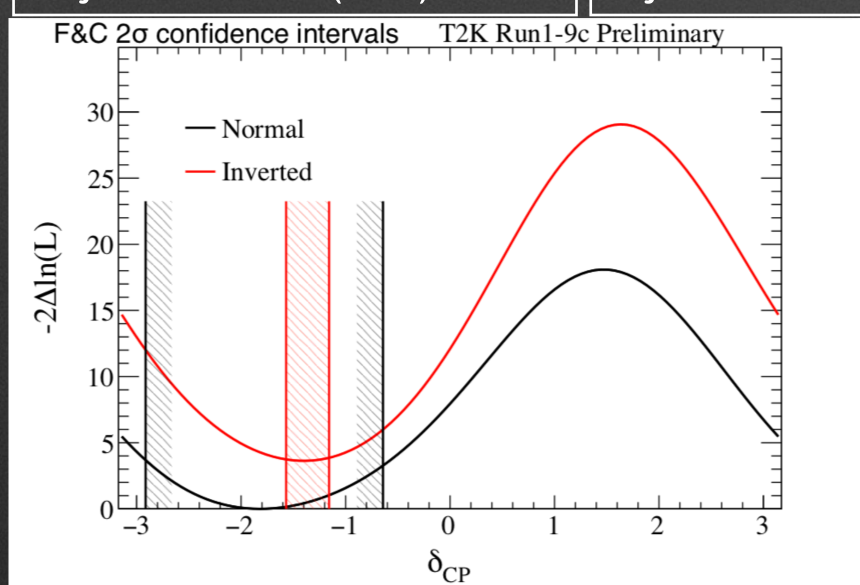
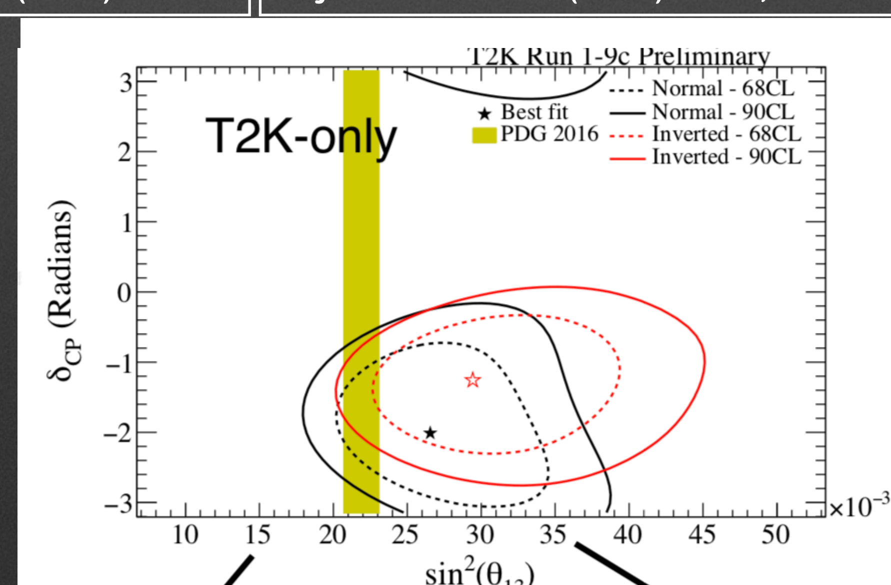
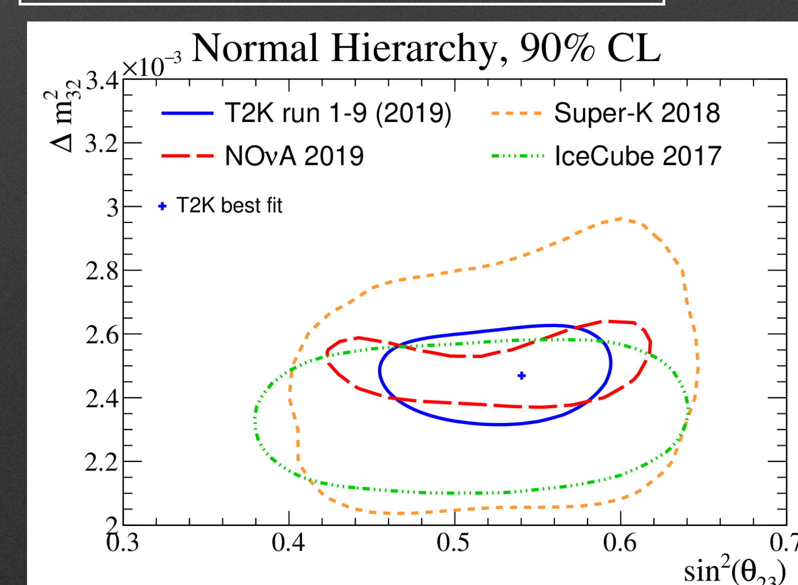
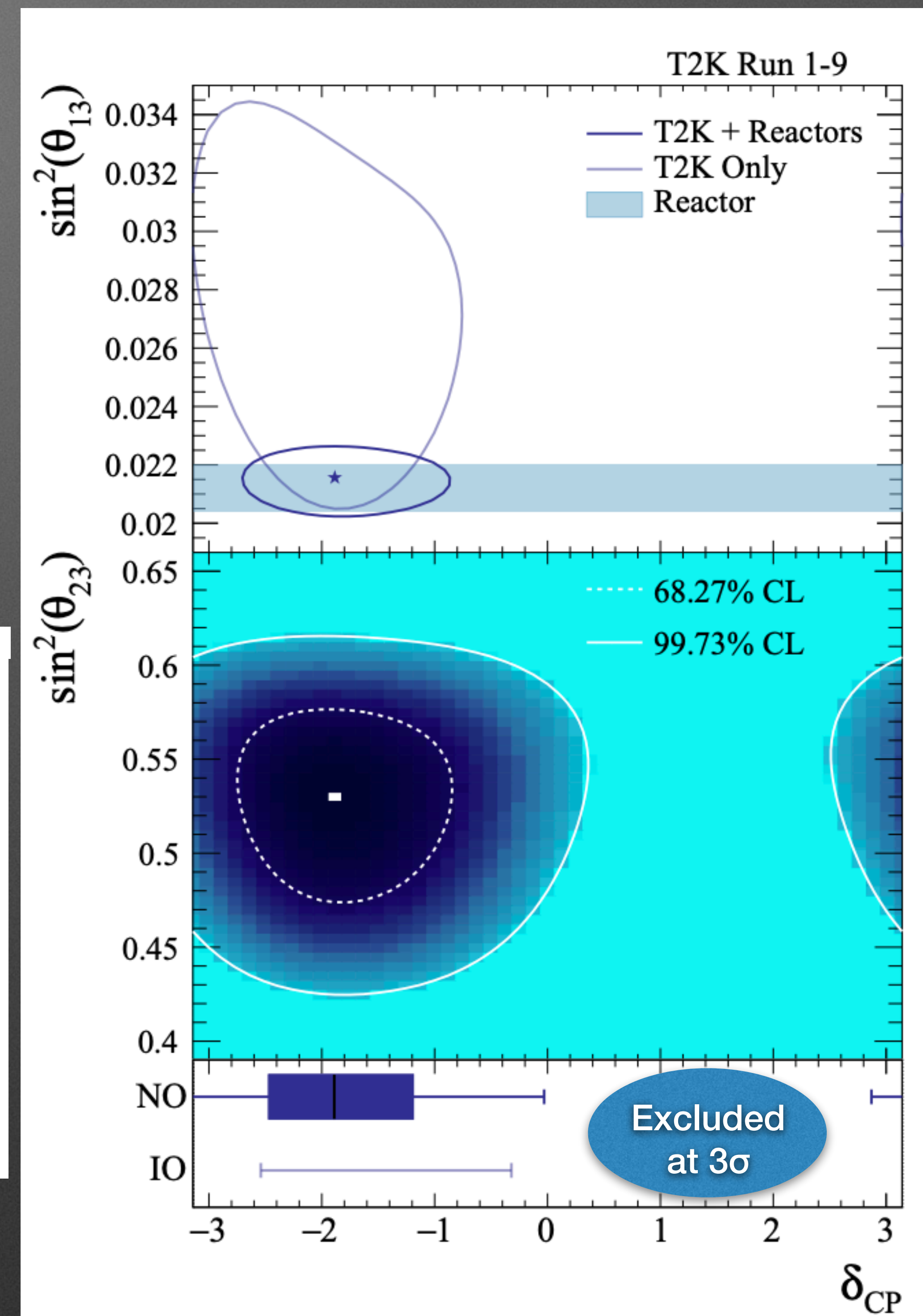




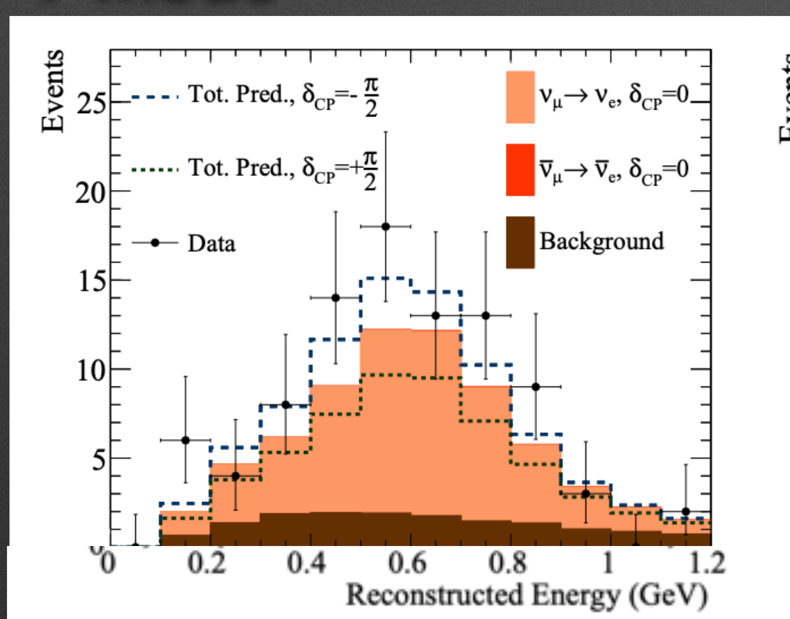


Hot of the press

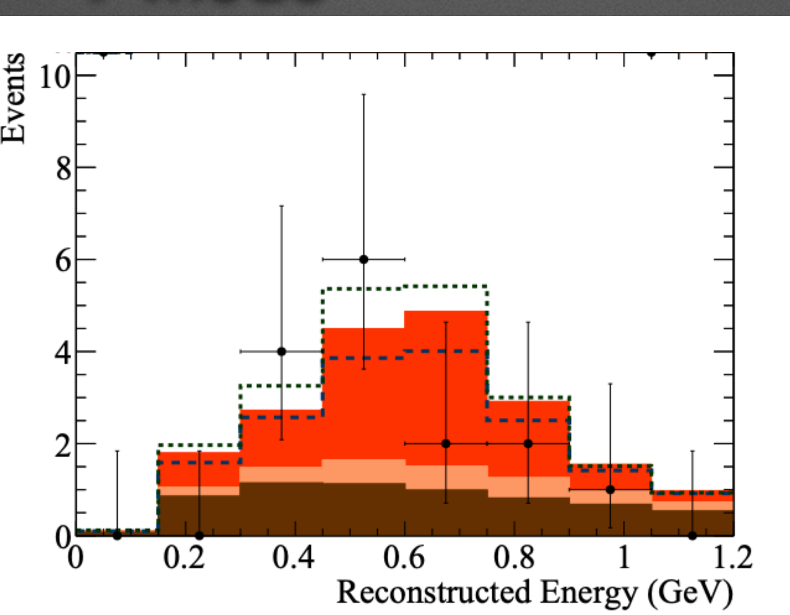
- Paper submitted to Nature: Constraint of the matter-antimatter symmetry violating phase in Neutrino oscillations
- First 3σ exclusion for 46% (65%) of the δ_{CP} values in NO (IO)
- Need more data (and smaller systematics)!



ν-mode



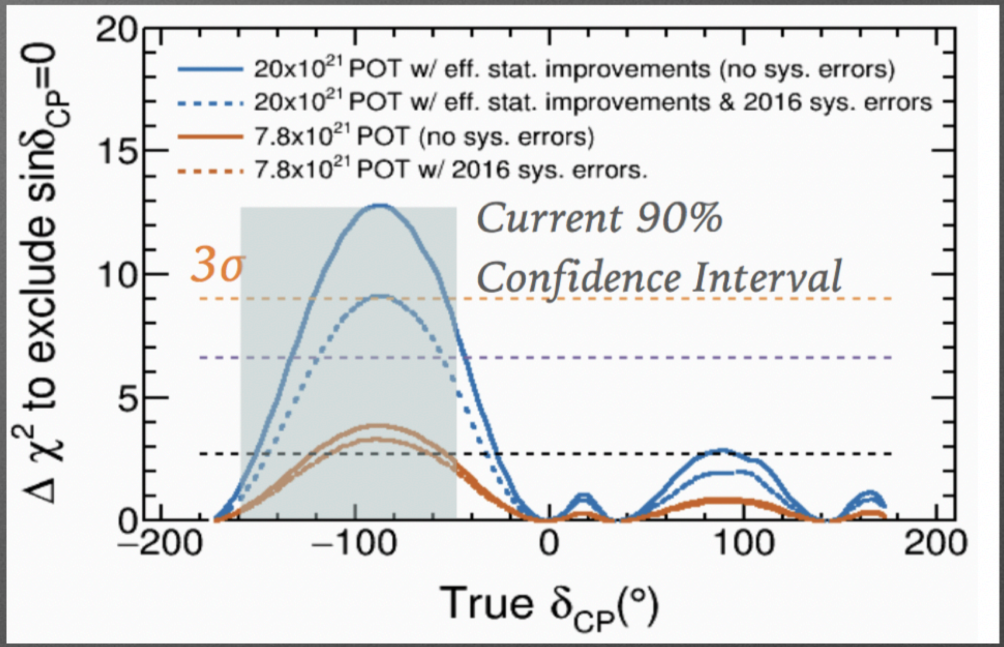
$\bar{\nu}$-mode

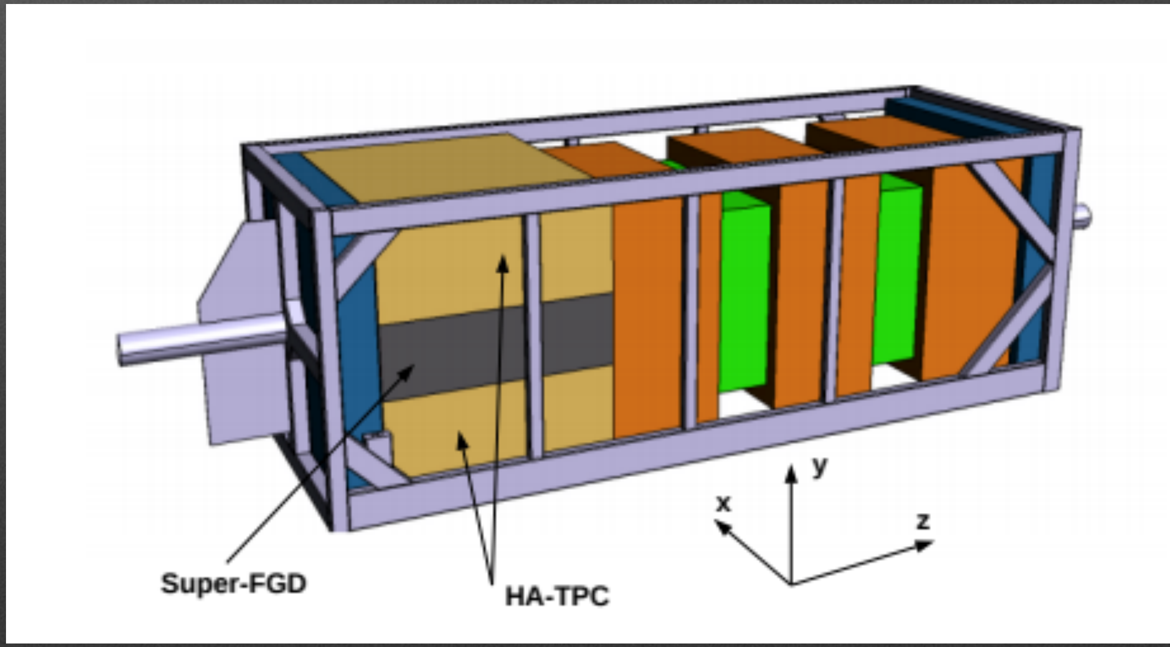


	ν-mode	$\bar{\nu}$-mode
Observed	***90***	***15***
Exp (δ_{CP}=-π/2)	*81.7*	*17.2*
Exp (δ_{CP}=0)	*68.4*	*19.6*

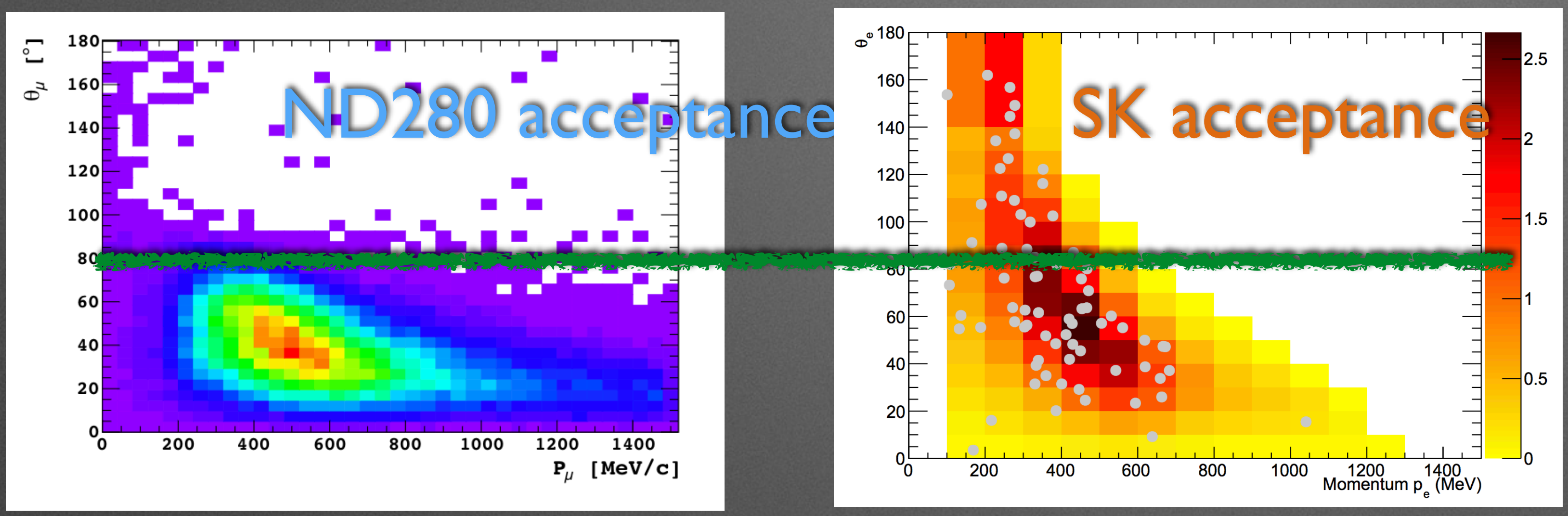
T2K phase-II

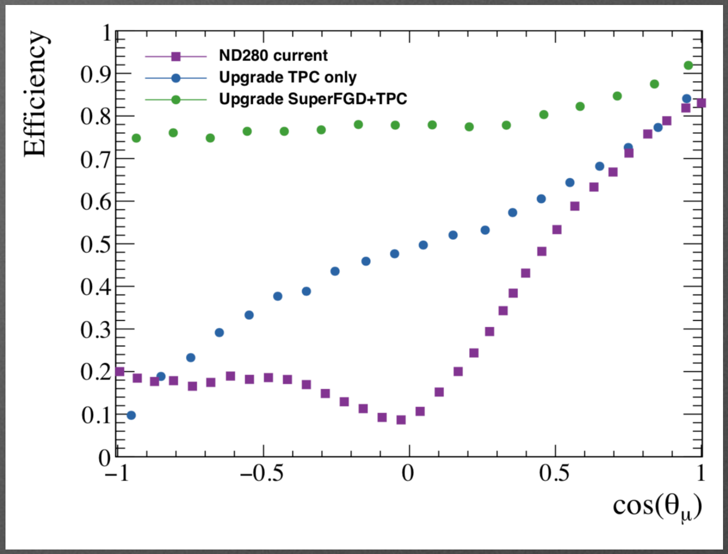
- Upgrade of J-PARC Main Ring (1.3 MW beam)
  - Approved and funded, will be done in 2021
- Goal: collect >10×10^{21} POT by 2026 → 3σ measurement of CP violation if δ_{CP}~$-\pi/2$
- Near Detector upgrade to reduce systematics from ~7% to ~4%
  - We will install the new detectors in 2021
  - Use the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





ND280 upgrade



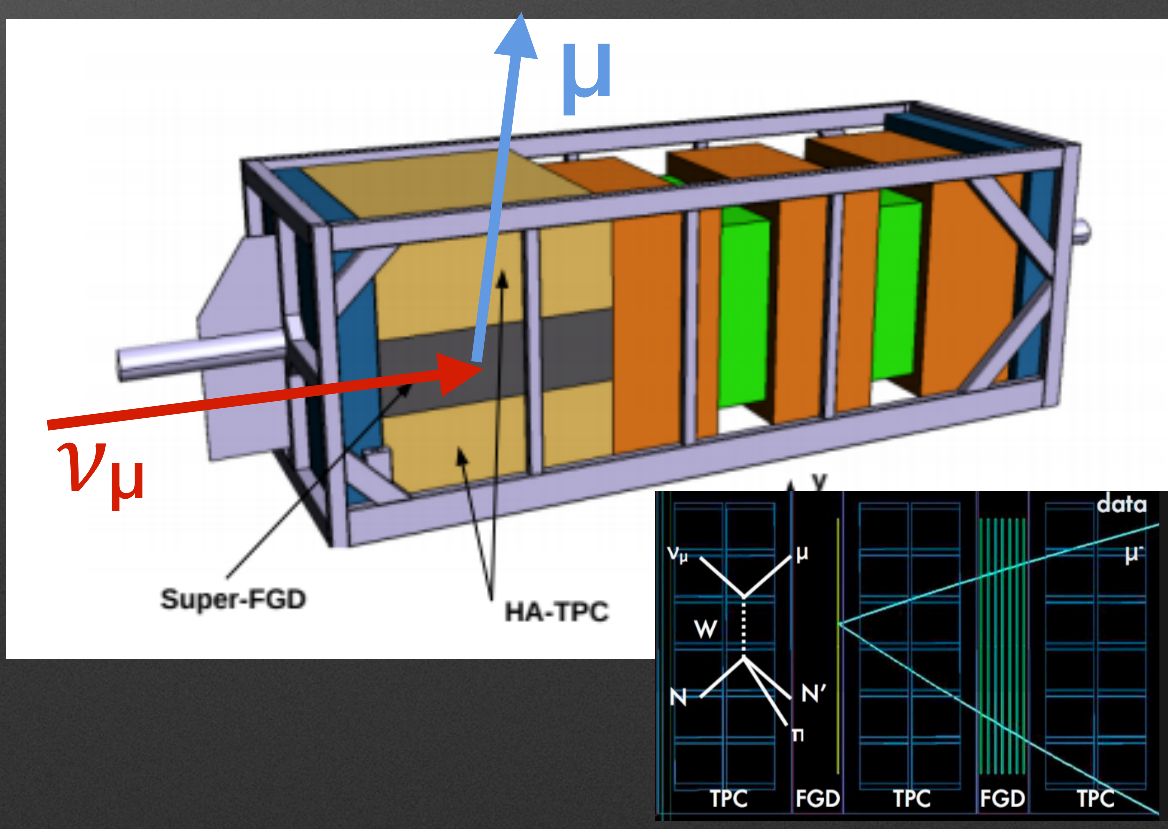


- Main strength of ND280 : magnetized detector → separate ν from $\bar{\nu}$ (cannot be done in SK or HK)

- Main limitation of ND280 : reduced angular acceptance → only forward going muons are selected with high efficiency

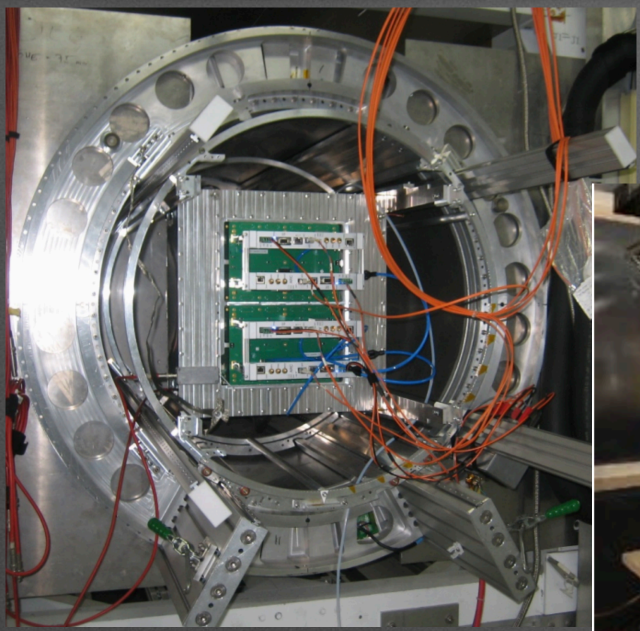
- An analysis dedicated to select tracks with high polar angles → 20% efficiency

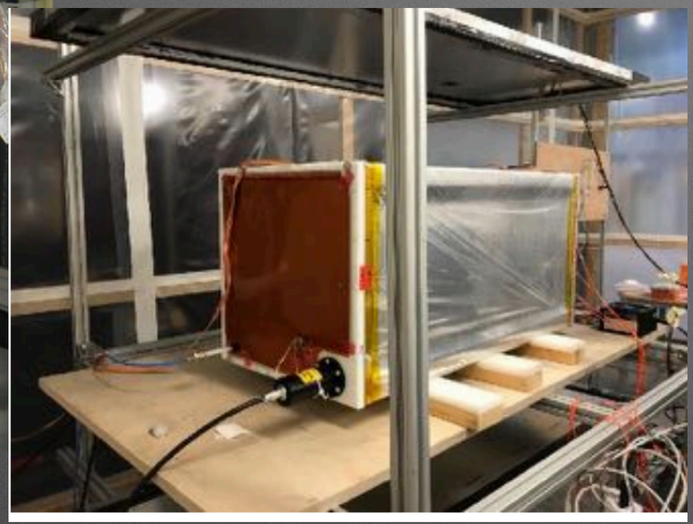
- We can do better with an upgrade → Horizontal target and horizontal TPCs



New detectors

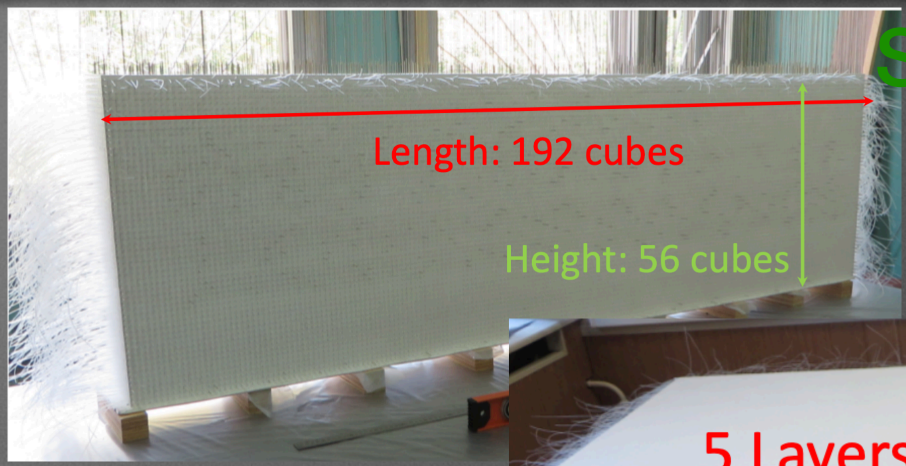
High-Angle TPCs





- 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

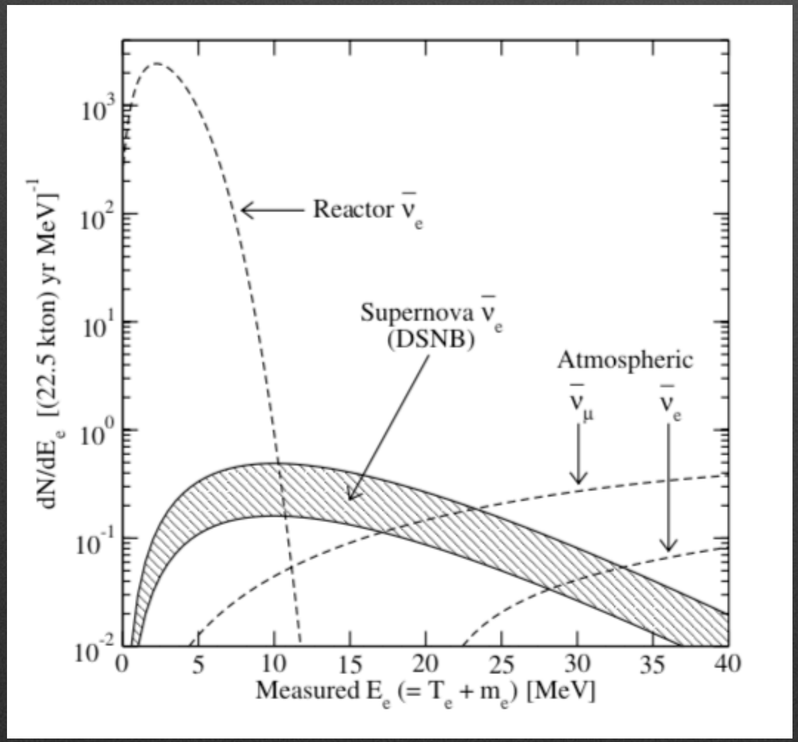
Super-FGD

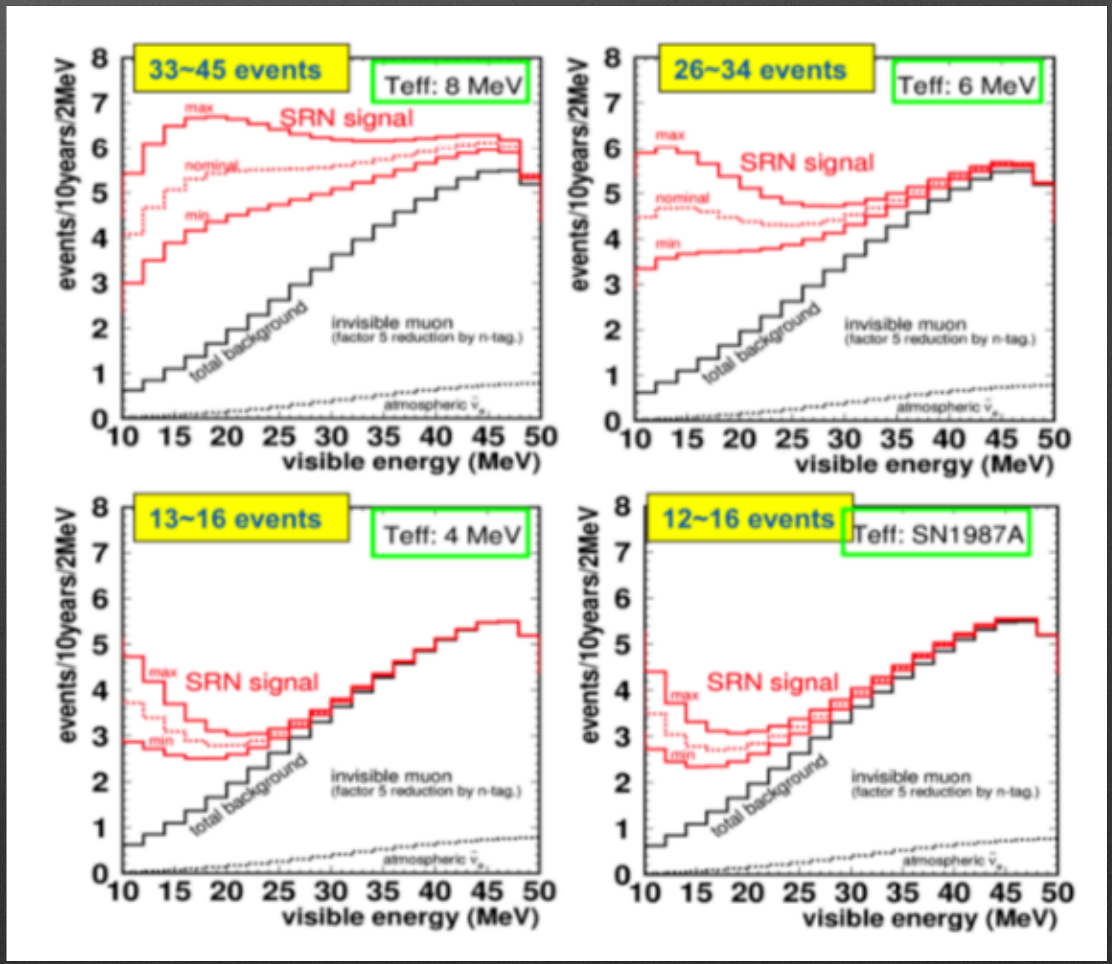


- New concept of detectors, 2×10^6 $1 cm^3$ cubes
  - 25% of the cubes already built
  - All produced by Dec 2020
- Each read by 3 WLS
- Improve reconstruction of the hadronic part of the interactions
- LLR responsible for the Front-End electronics using CITIROC chips

SK-Gd

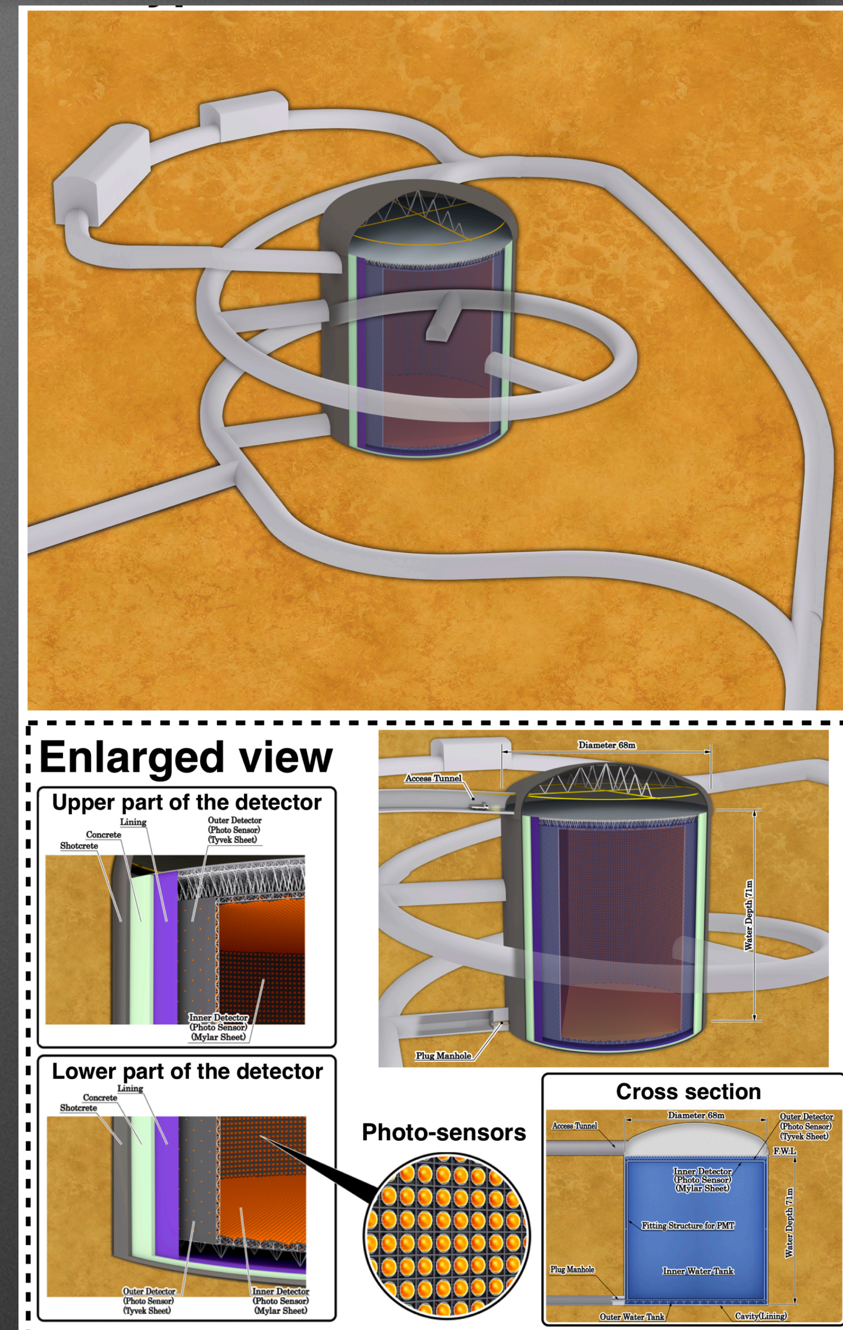
- Huge repair work in 2018 to prepare the loading of SK with Gadolinium
- SK ready to be loaded with Gd in 2020 (0.02% → 0.2% in a second phase)
- Enhance neutron tagging capability → crucial to distinguish ν from $\bar{\nu}$ → detect SN-relic antineutrinos from IBD (3-5 events per year are expected)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





Hyper-Kamiokande

- Extremely well established Water Cherenkov technology
  - 190 kton FV (SK 22.5)
  - 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
- August 2019 → MEXT approved HK and required budget for construction to the Ministry of Finance
- Begin construction in 2020, start operation in 2027



MEXT Statement

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

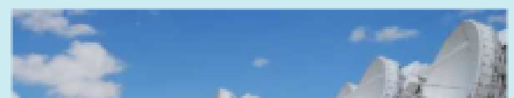
Next generation of neutrino project with a 260 kton detector and the J-PARC upgrade. The project will reveal the mysteries in elementary particles and the Universe by the observation of proton decays and the neutrino researches including CP violation.

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

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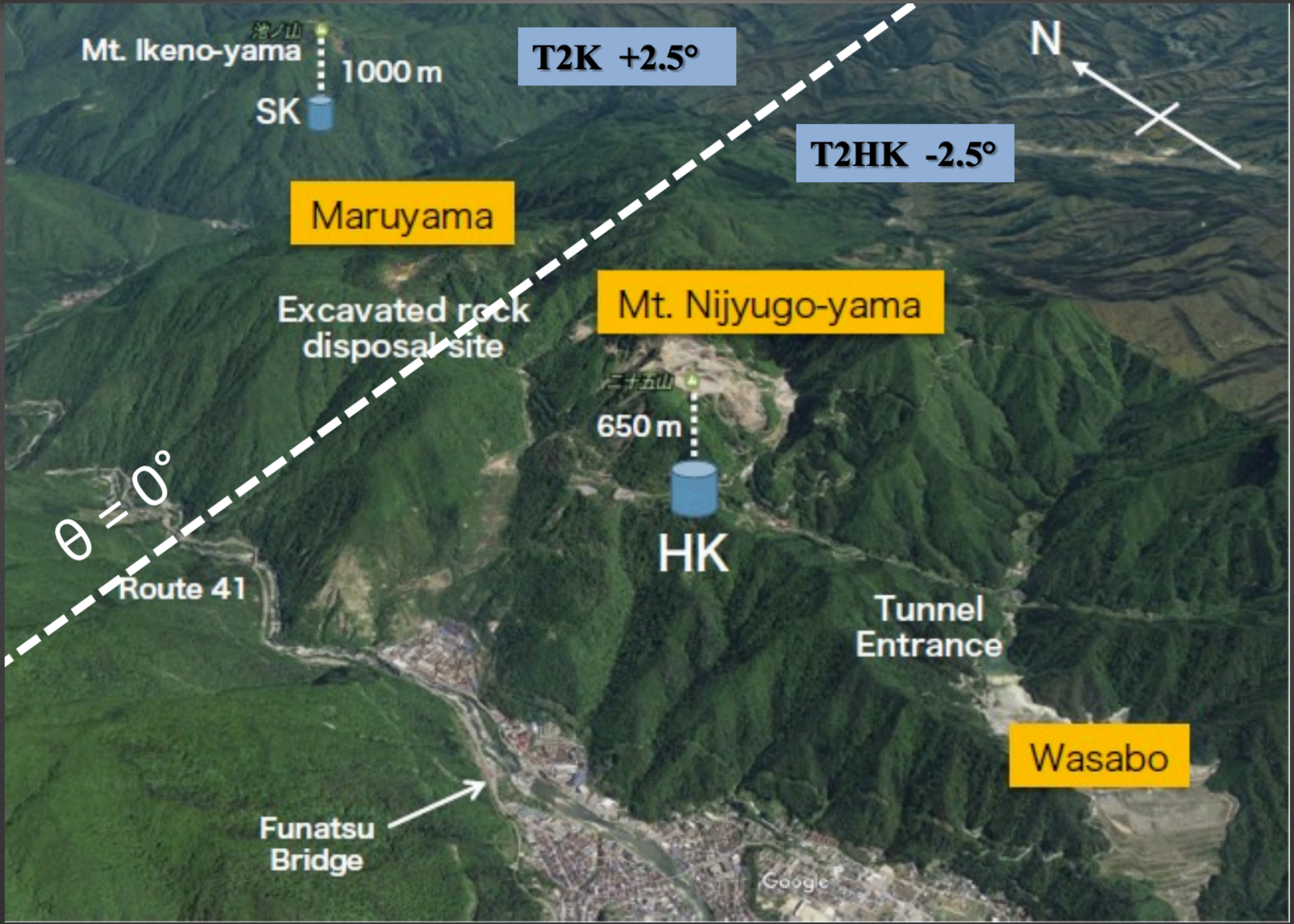
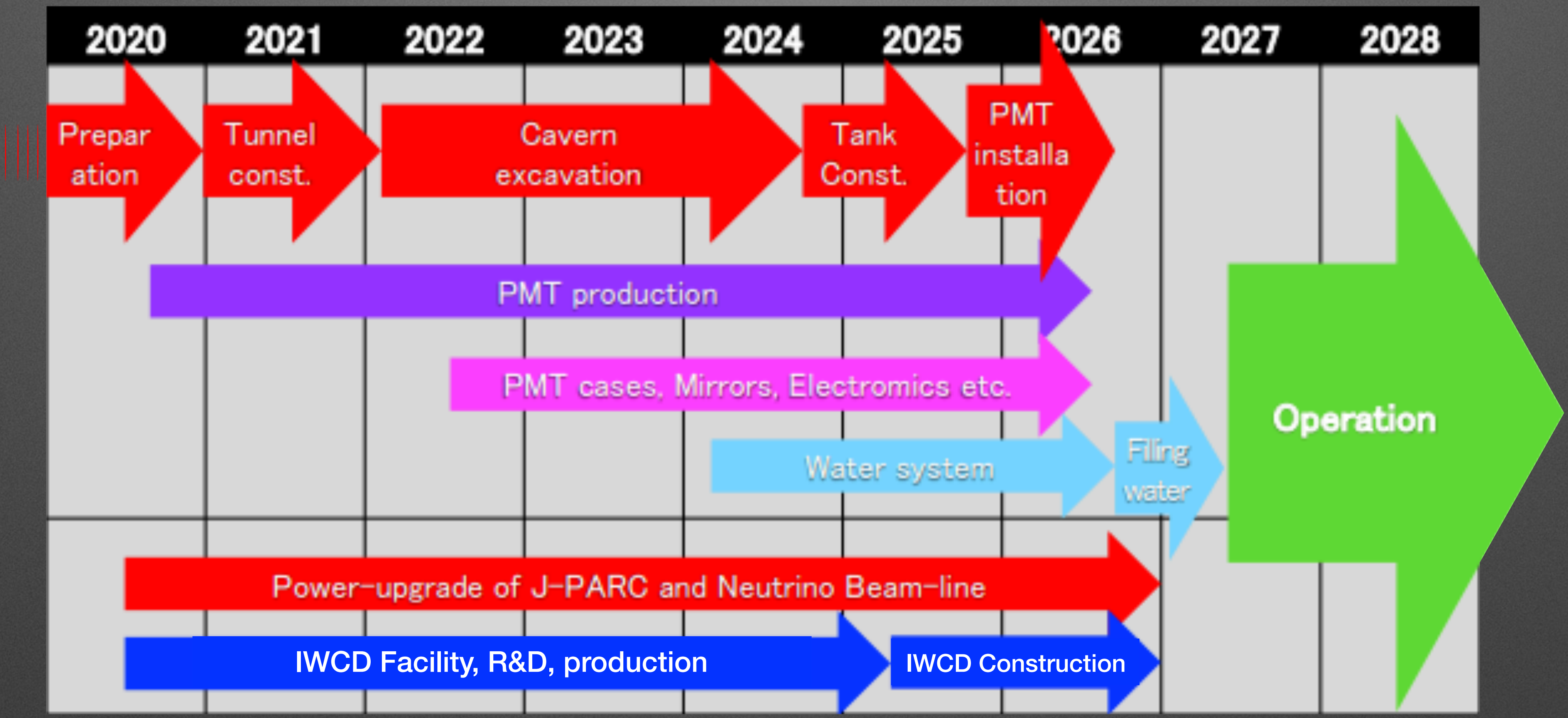
HK : Where



- Possibility for a 2nd detector in Korea being explored

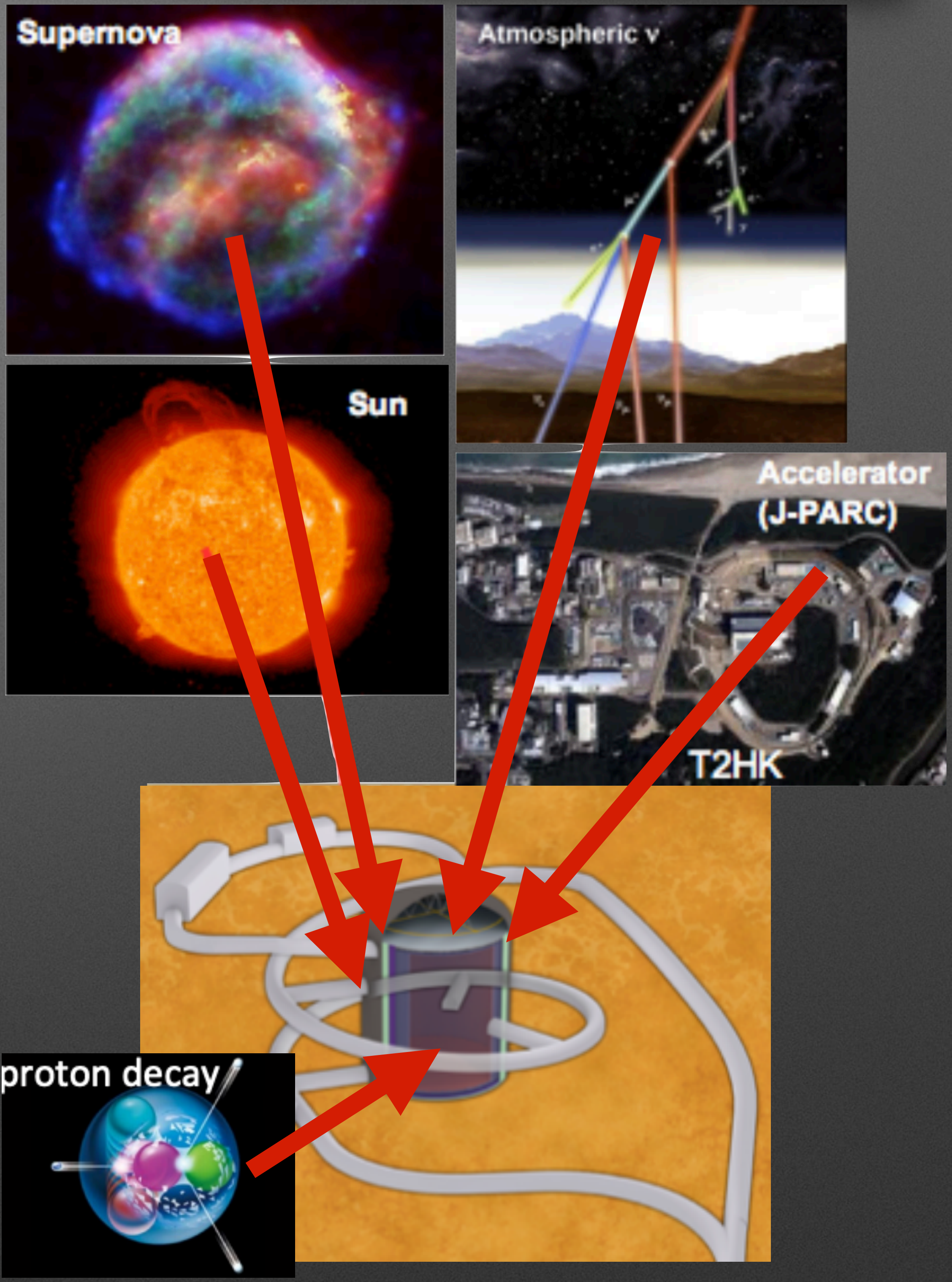
HK : When



- 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

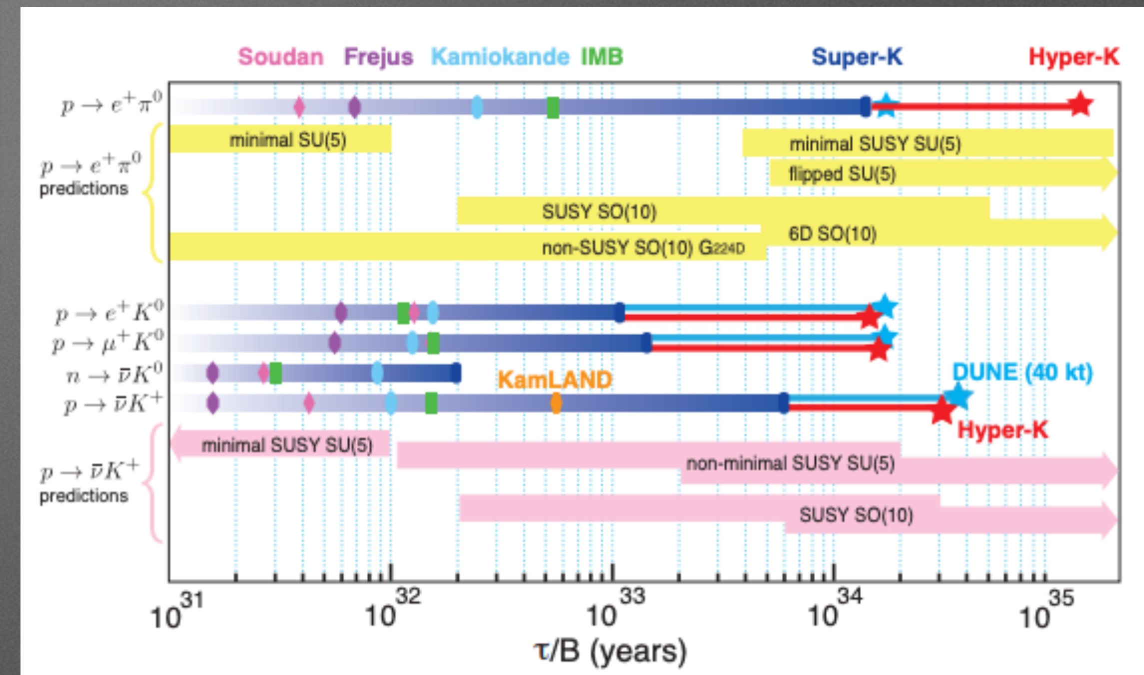
HK : Why

- Neutrino oscillation physics
  - 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
- Surprises

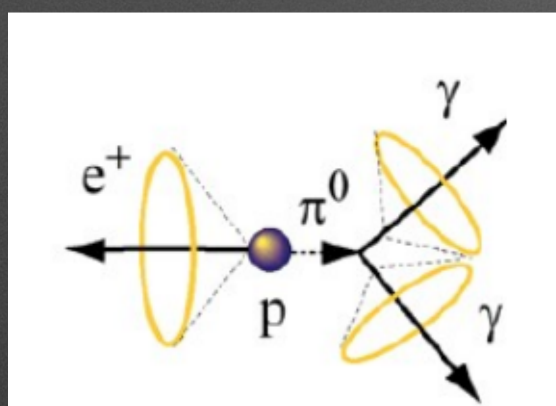


Proton-decay

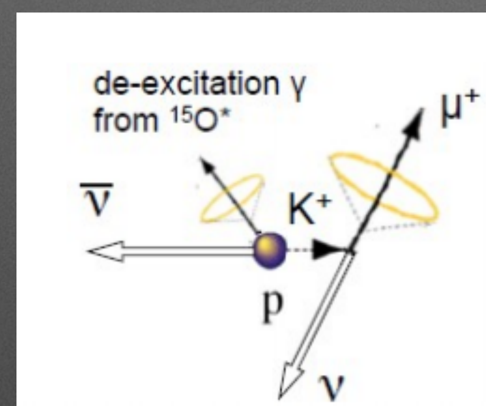
Sensitivity to many different modes
Surpass SK by ~1 order of magnitude in the leading $p \rightarrow e^+ + \pi^0$

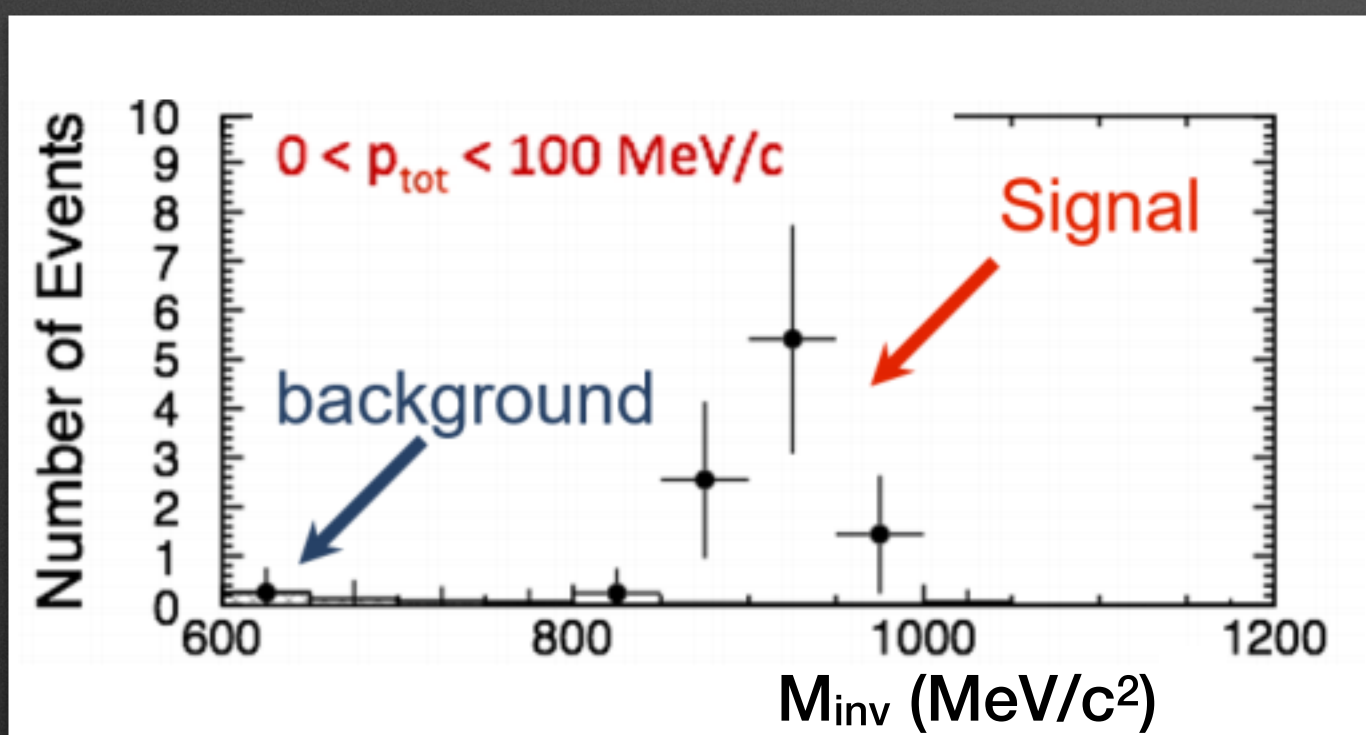


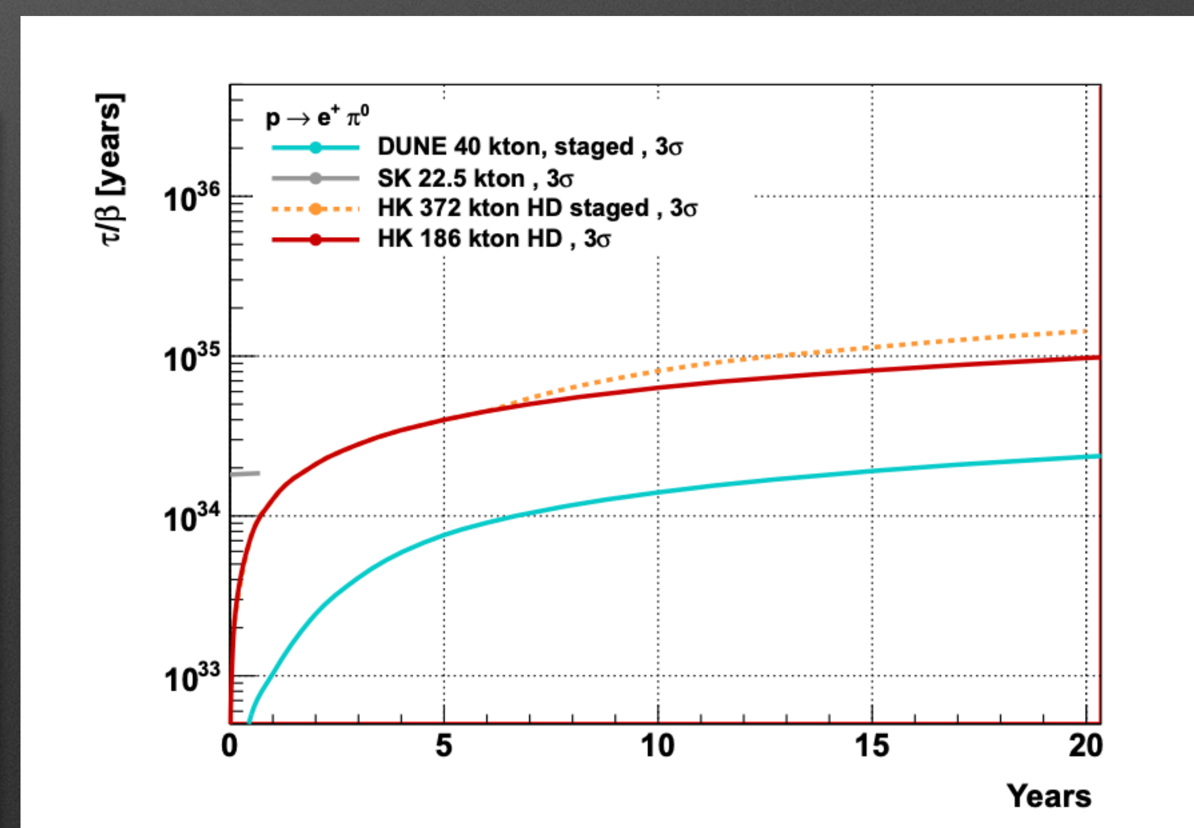
$p \rightarrow e^+ + \pi^0$



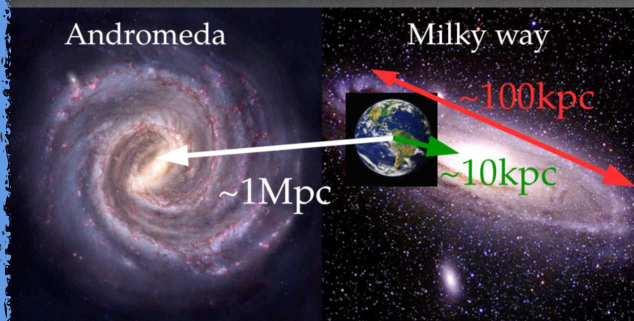
$p \rightarrow K^+ + \nu$

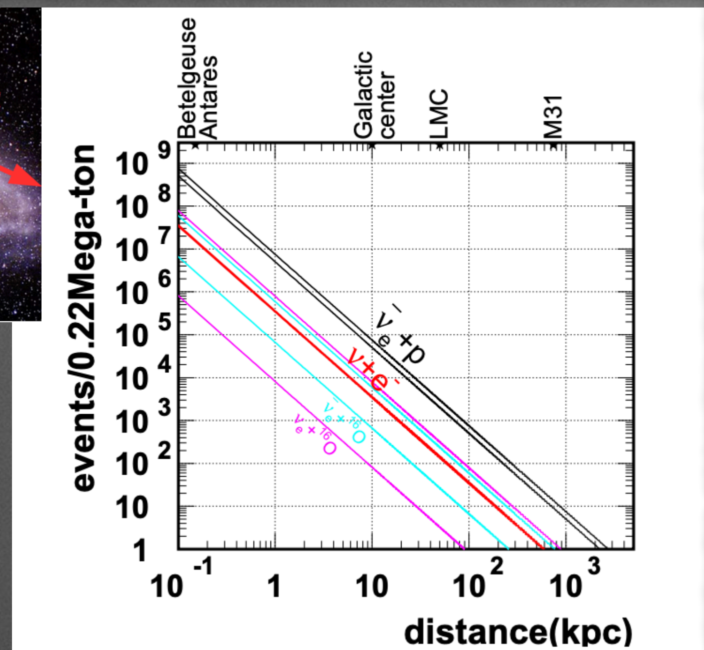




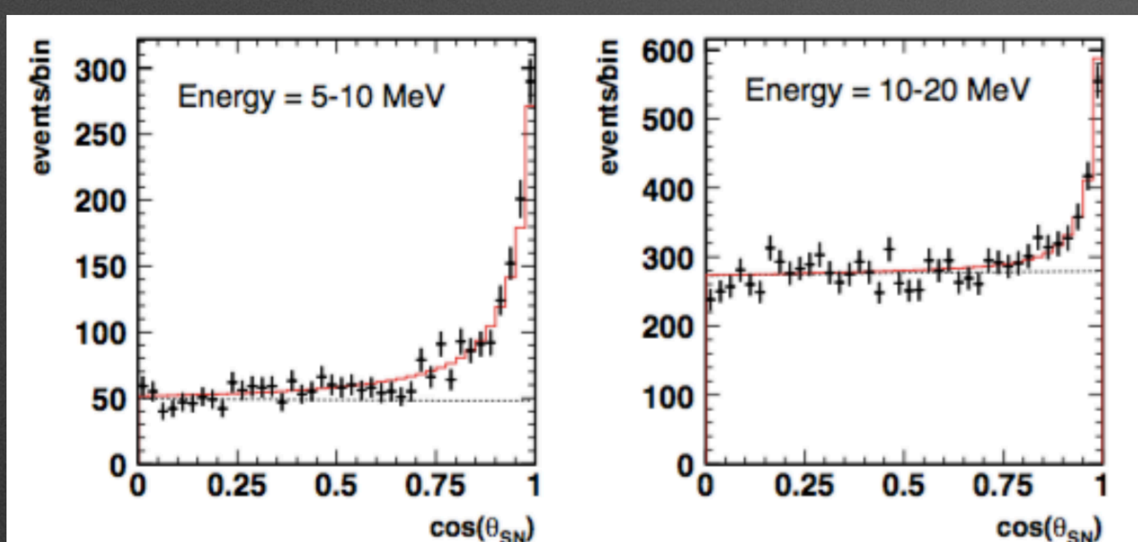


Supernovae neutrinos

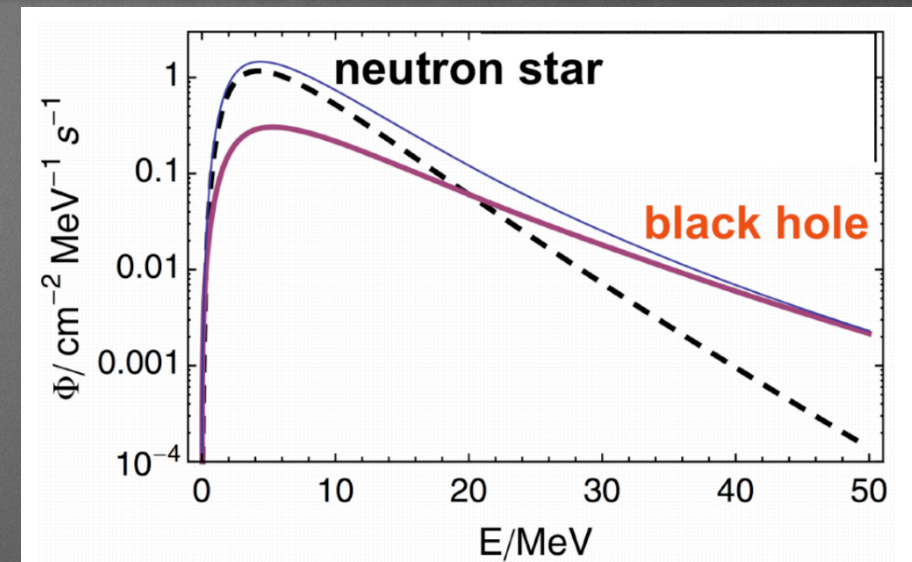


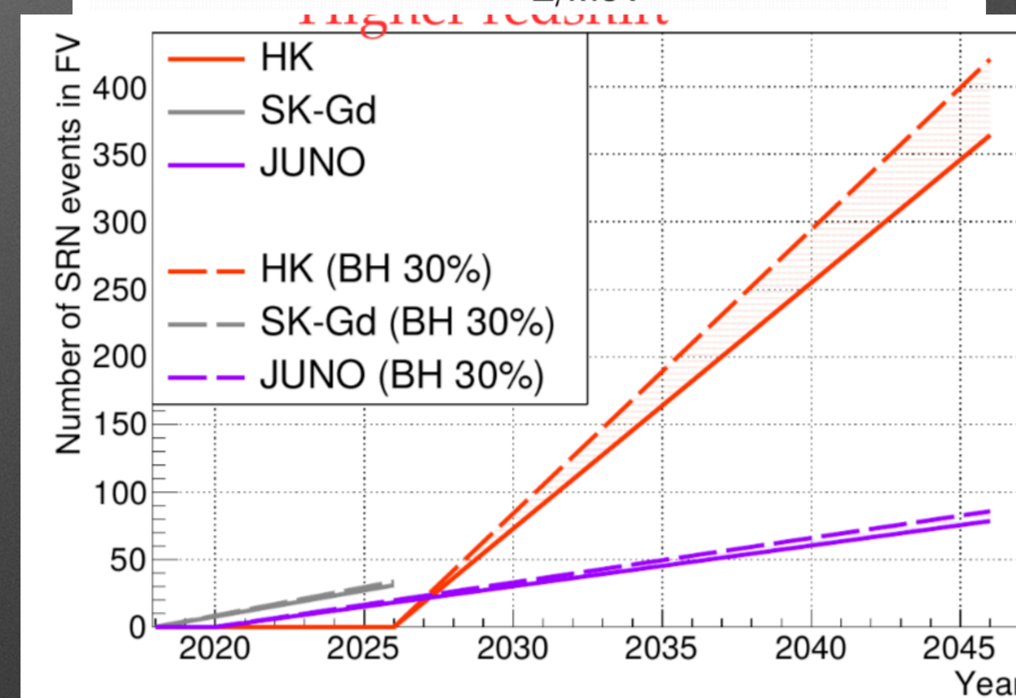


- IBD: huge statistics → SN model
- ES: directionality



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



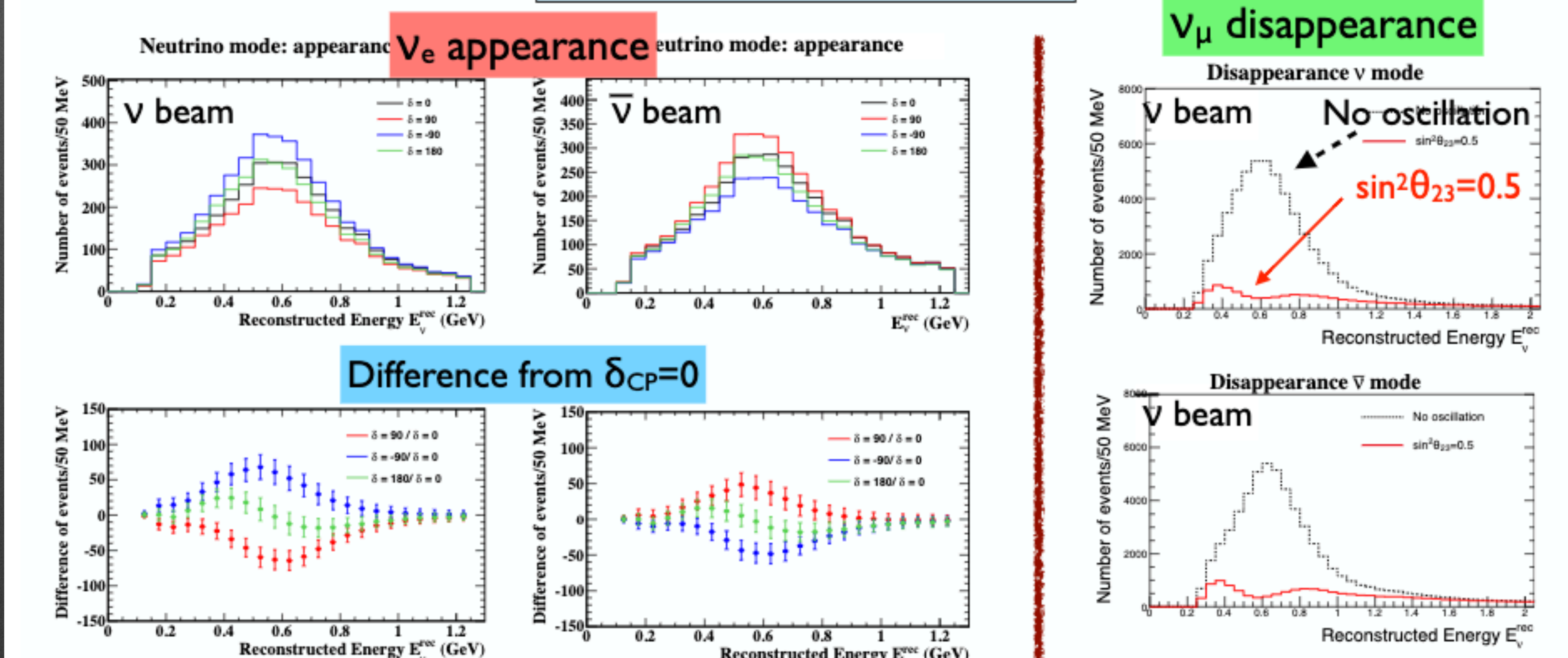


- After discovery of SRN in SK-Gd we will perform precision measurement with HK
- Constraints on cosmic star history

Long-baseline physics

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

10 years (13MW×10^7s)

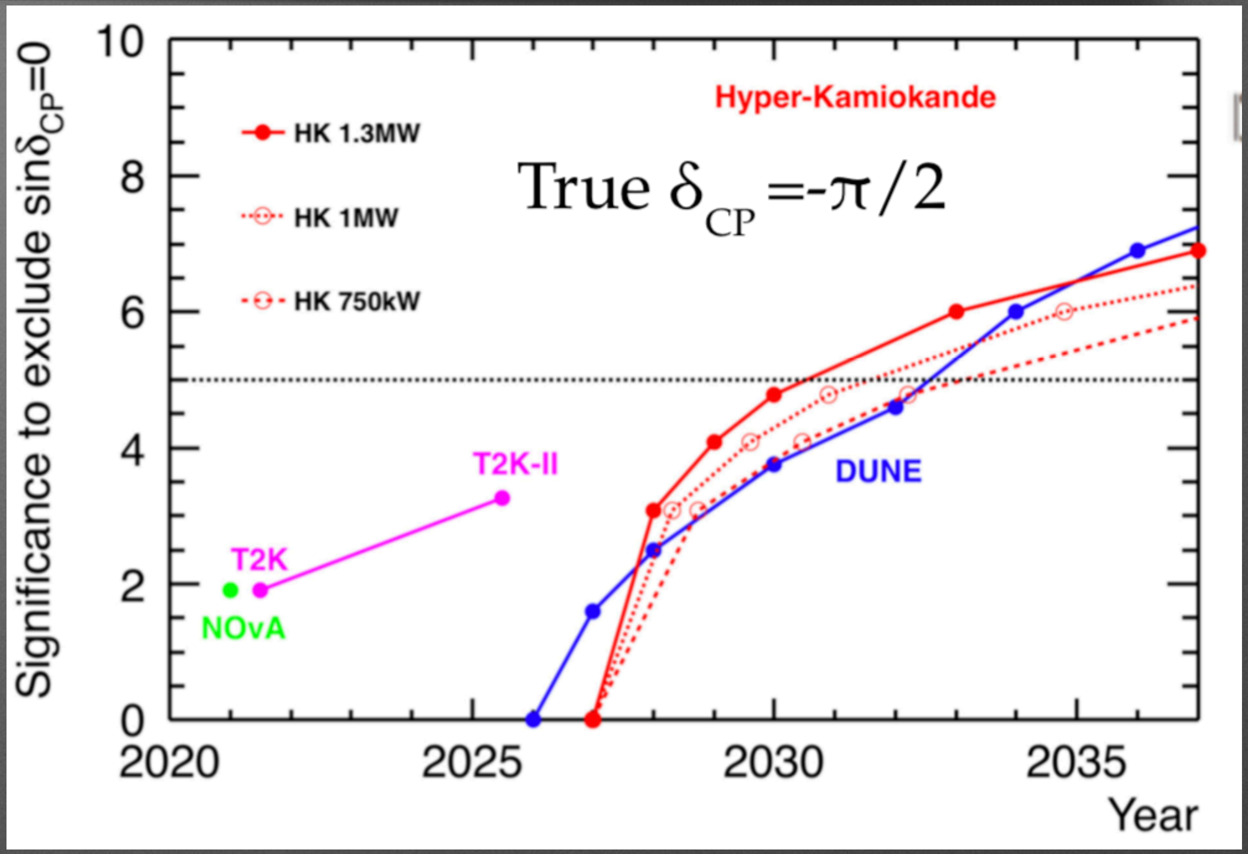


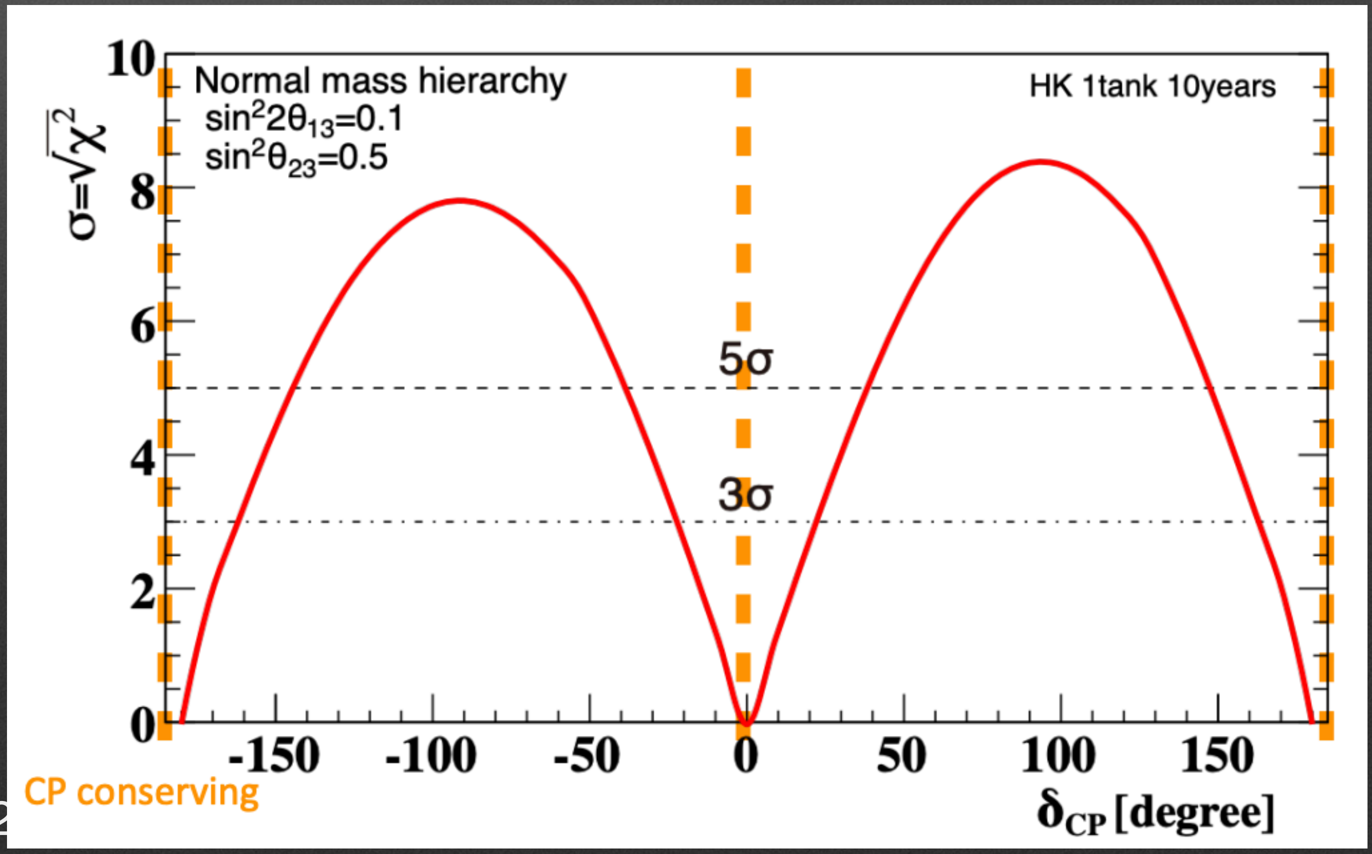
δCP=-π/2	Signal $\nu_\mu \rightarrow \nu_e$	Signal $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	BCG	Total
ν-mode	**1643**	15	400	2058
$\bar{\nu}$-mode	206	**1183**	517	1906

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

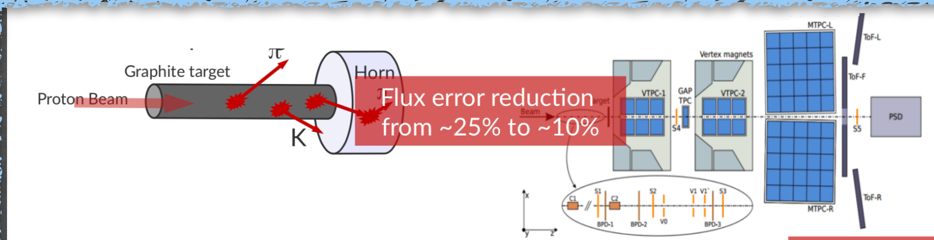
CP Violation

* Exclusion of sin(δCP)=0
  * 8σ for δCP ~ ± π/2
  * >3σ (5σ) significance for 76% (57%) of δCP space
  * Precision on δ_{CP} between 7° and 20°
* Sensitivity will be further enhanced by combination with atmospheric neutrinos
* Assume systematics uncertainties of ~4% (currently 7% for T2K)

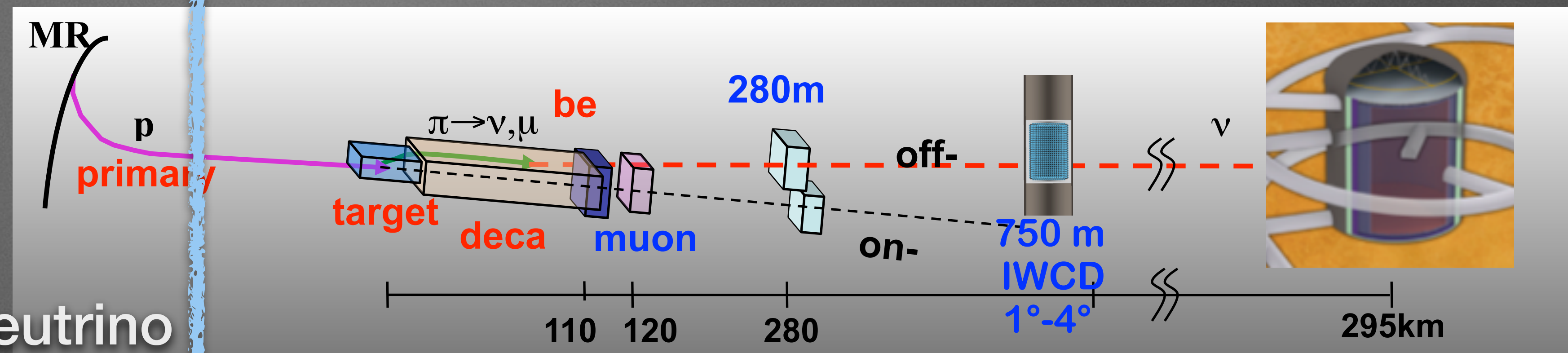


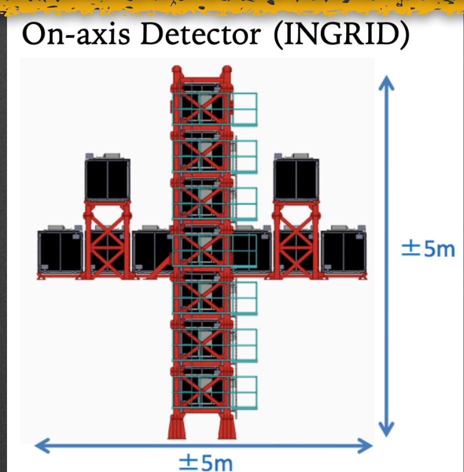


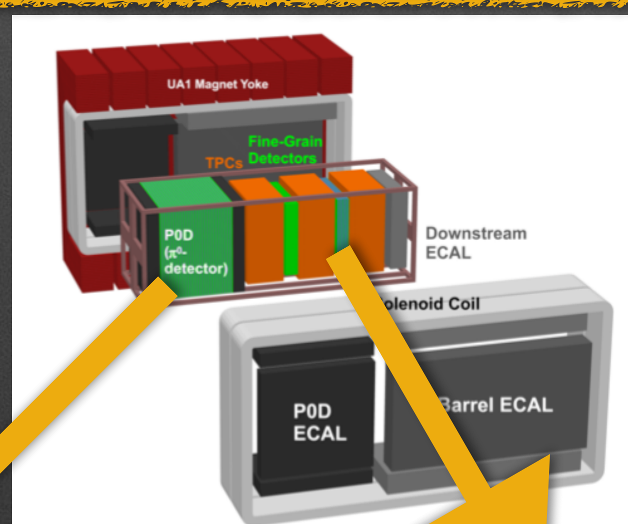
Systematics and Near Detectors

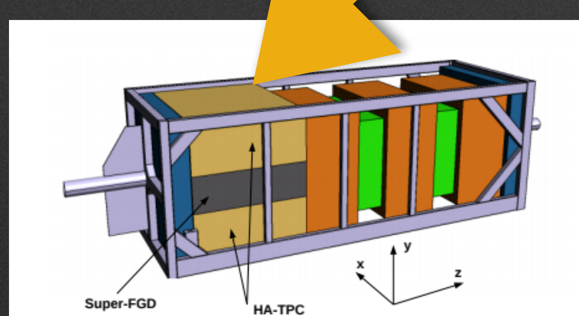


- NA61 hadron-production experiment @CERN
- T2K → uncertainties on the neutrino flux ~5% thanks to NA61
- New measurements planned for HK

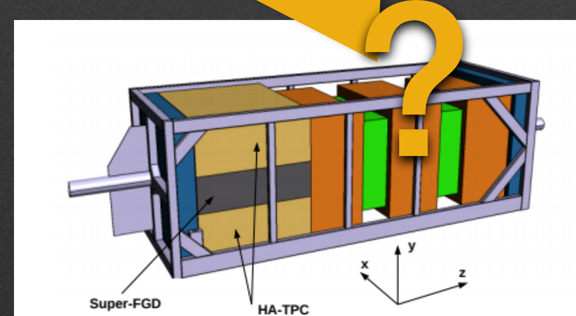




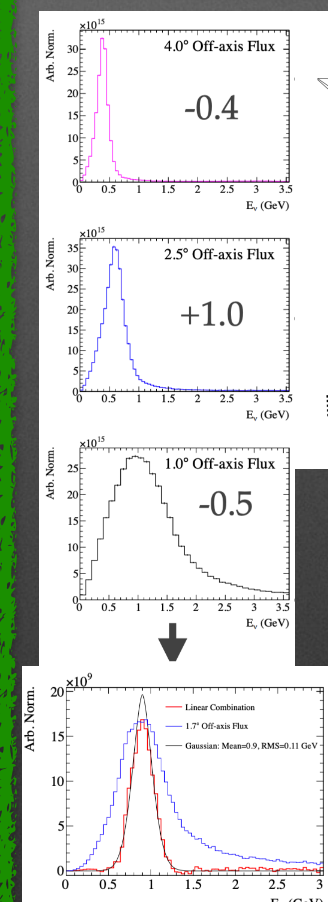


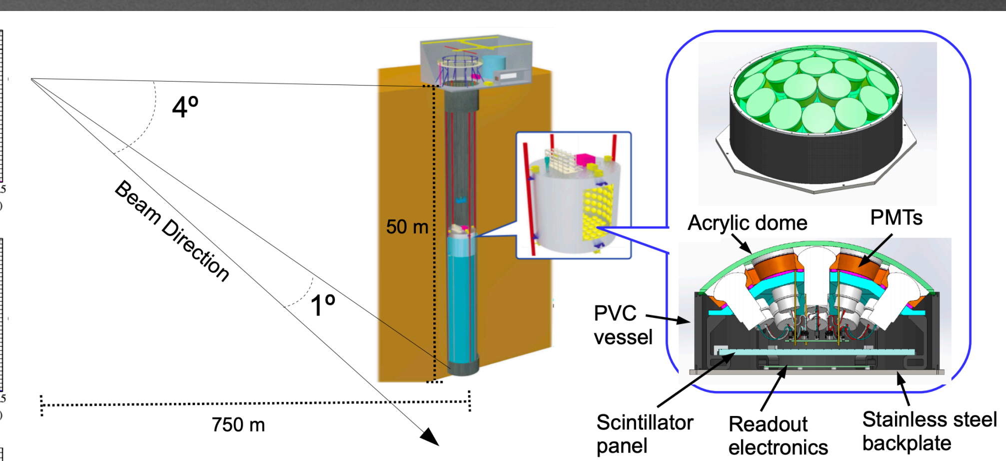


2021



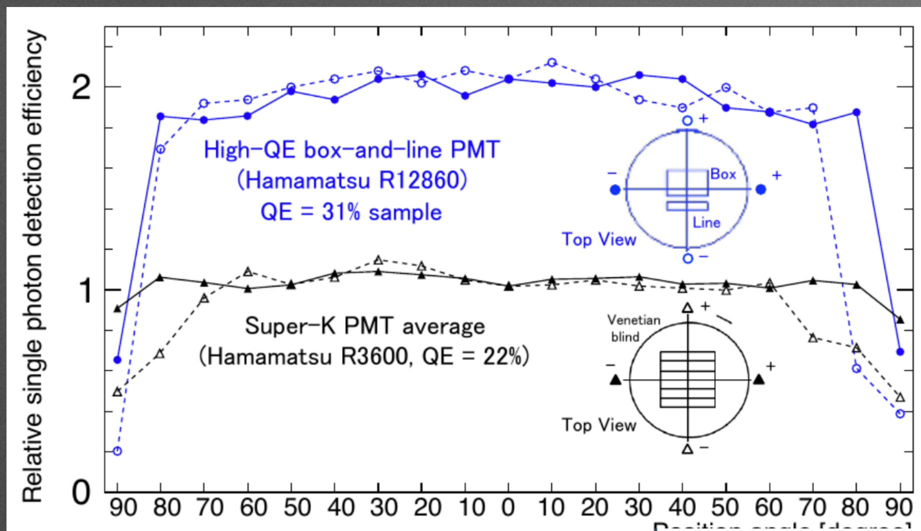
2030?

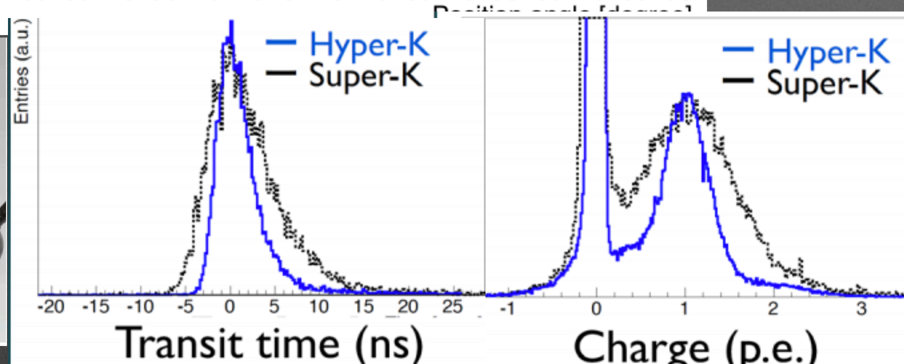




- Intermediate WC detector
- 1 kton mass
- Instrumented with ~500 multi-PMTs
- Movable position to scan different off-axis angles

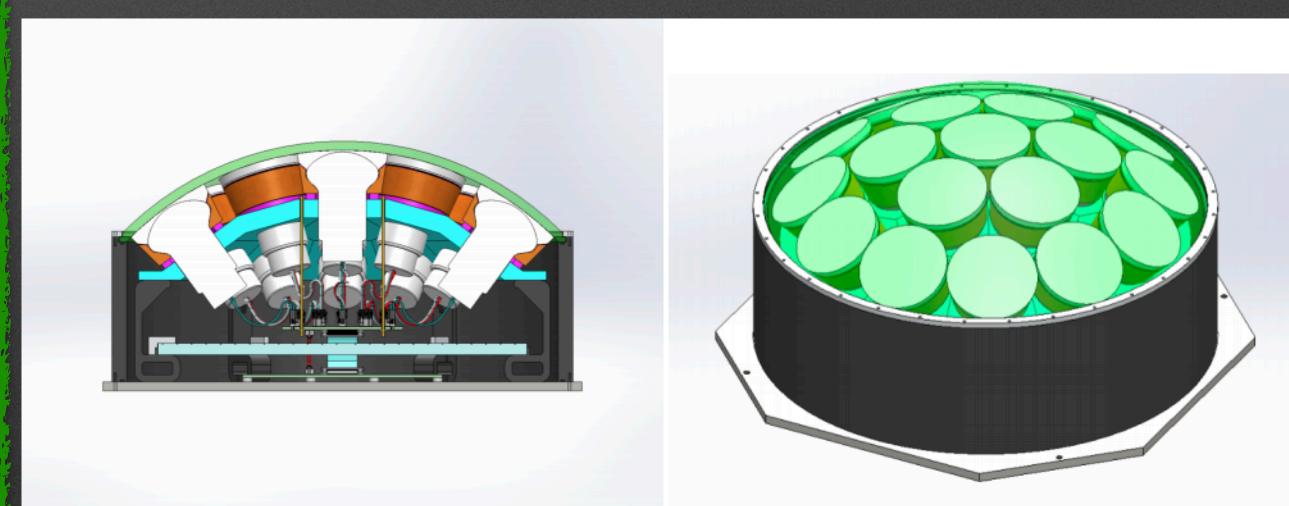
Hyper-K photo-detection system





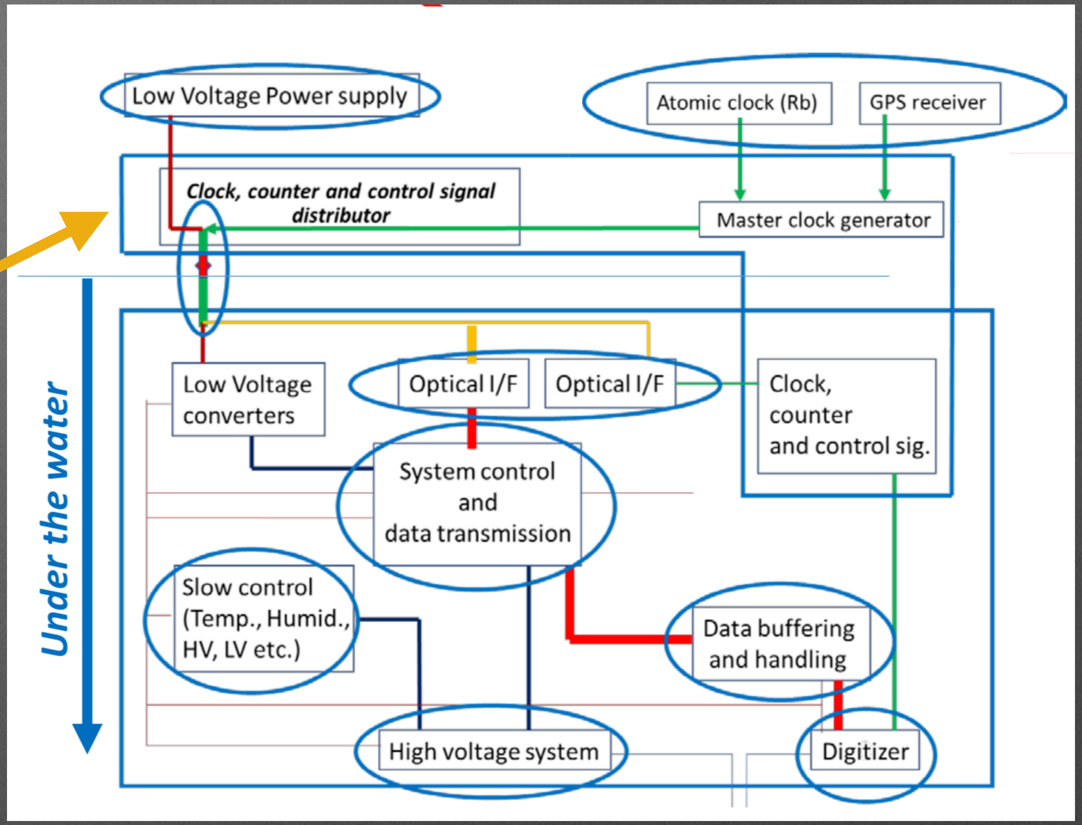
- HK will be instrumented with “box-and-line” 20'' PMTs
- At least 20k modules
- 31% QE (2 times better than SK)
- Better transit time spread

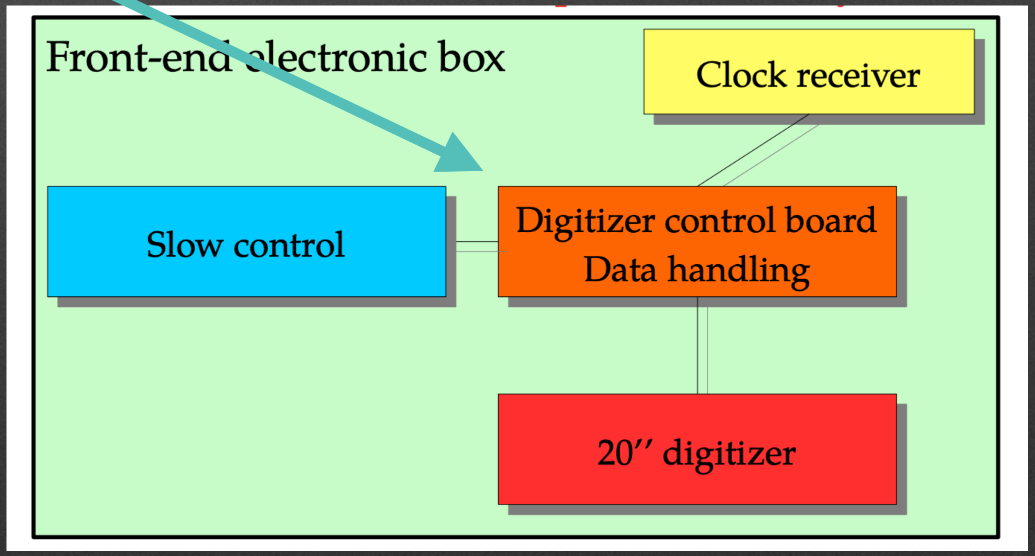
- Array of 19 3” PMTs
- Baseline option for IWCD
- Possibility to add 5k or 10k m-PMTs in HK (depending on funding)
  - Would improve vertex reconstruction and energy resolution at low energy
- Good opportunity for France
  - Synergies with KM3Net and with JUNO small PMTs



IN2P3 contributions

- NA61/SHINE hadron-production measurements for HK and further ND280 upgrades
- 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





Conclusions

* IN2P3 groups have a strong participation to the extremely successful ν oscillations program in Japan
  * T2K phase II and ND280 Upgrade → CP violation at 3σ by 2026
  * SK-Gd → Observation of Supernova relic neutrinos
* Excellent news for Hyper-Kamiokande, the next generation neutrino observatory
  * Experiment approved by MEXT
  * 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, Gravitational Waves,…)
* IN2P3 (and CEA) contributions being defined → right time to join HK!

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

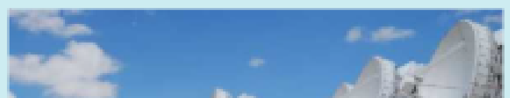
Next generation of neutrino project with a 260 kton detector and the J-PARC upgrade. The project will reveal the mysteries in elementary particles and the Universe by the observation of proton decays and the neutrino researches including CP violation.

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〕



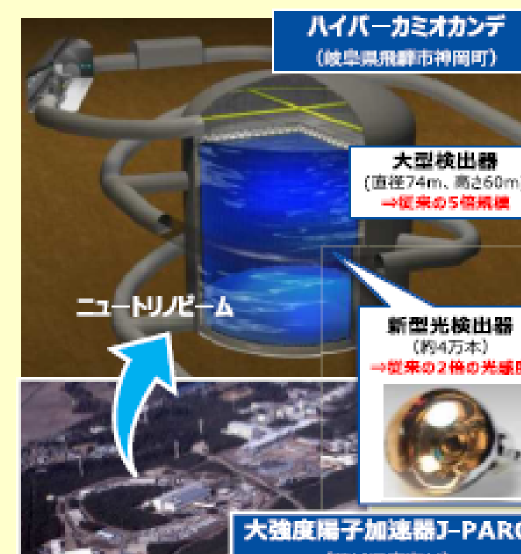
巨大ブラックホールの「影」の撮影に世界で初めて成功した国際プロジェクトに参加し、高い感度の観測機能により、その成果に大きく貢献。

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

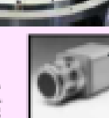
ハイパーカミオカンデ（HK）計画の推進
〔東京大学宇宙線研究所〕
〔高エネルギー加速器研究機構〕



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】

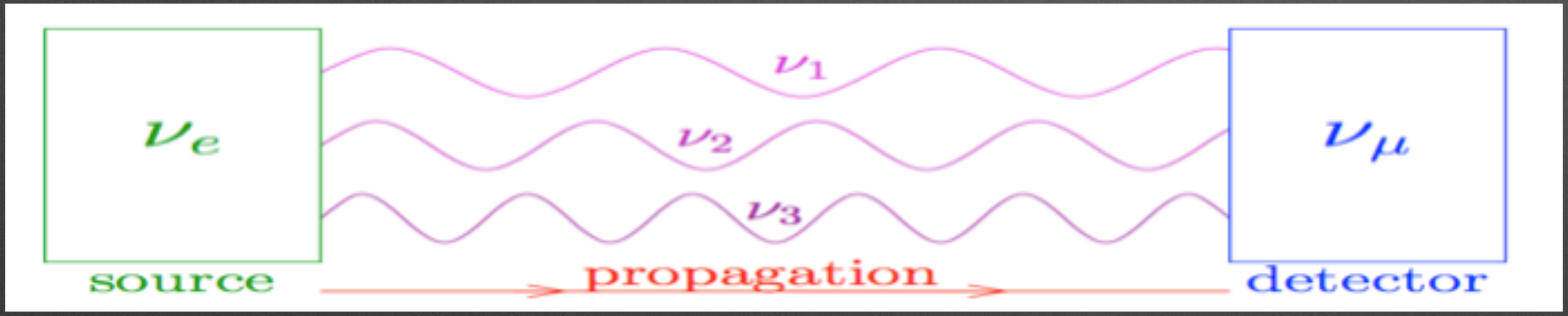
＜産業等への波及＞

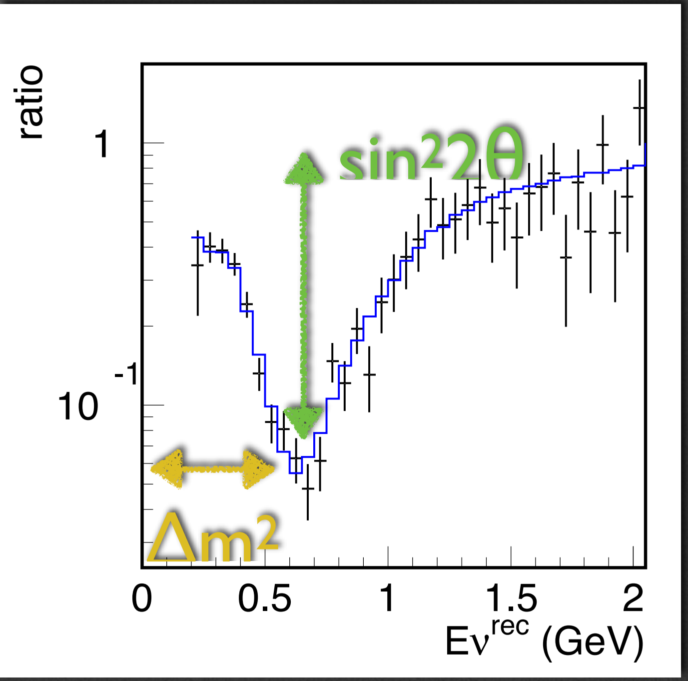
○ 産業界と連携した最先端の研究装置開発により、イノベーションの創出にも貢献
（事例）・【すばる望遠鏡】超高感度カメラ技術⇒医療用X線カメラへの応用
・【放射光施設】加齢による毛髪のハリ・コシの低下が毛髪内の亜鉛と関係性を解明⇒亜鉛を毛髪に浸透させる新しいヘアケア技術の開発・製品化に成功



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

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

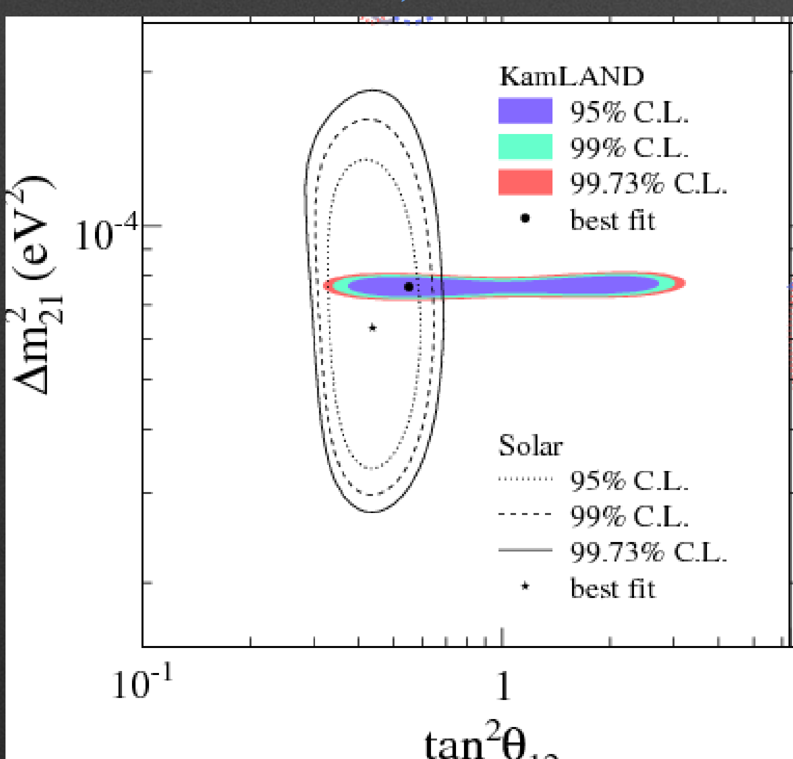
PMNS matrix

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

- 3 mixing angles
- 2 independent mass differences
- 1 CP violation phase

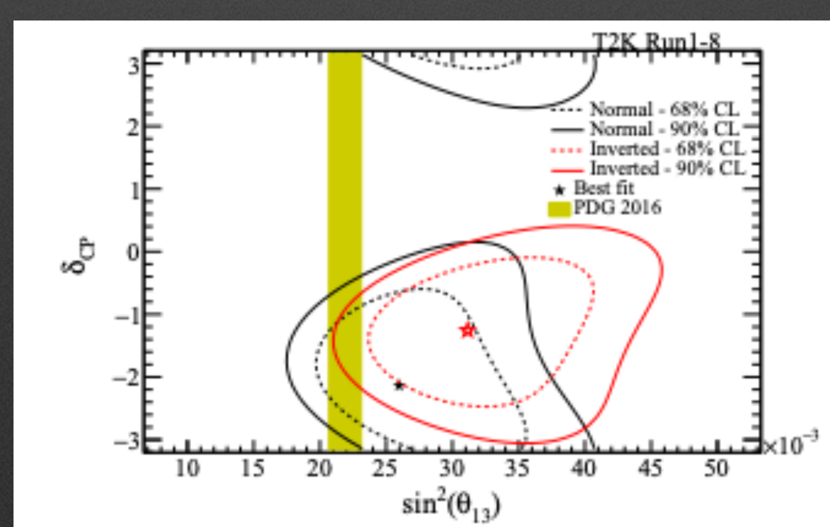
θ_{13} is precisely known, some indications also for δ_{CP}

Solar (SNO, KamLand) → θ_{12}, Δm_{12}



Reactors (Daya Bay, RENO, DChooz) → θ_{13}

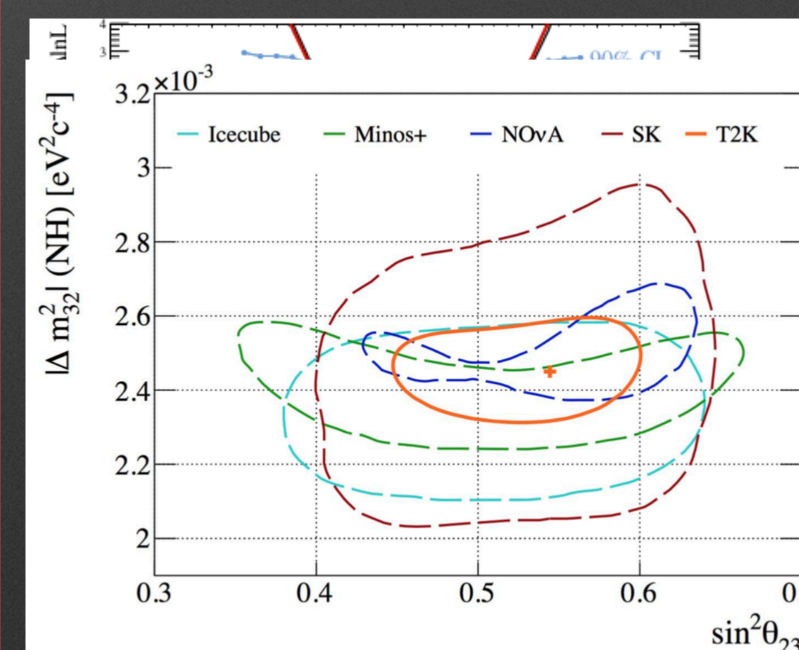
LBL (T2K, NOνA) → θ_{13}, δ_{CP}



Atmospheric (SK, IceCUBE)

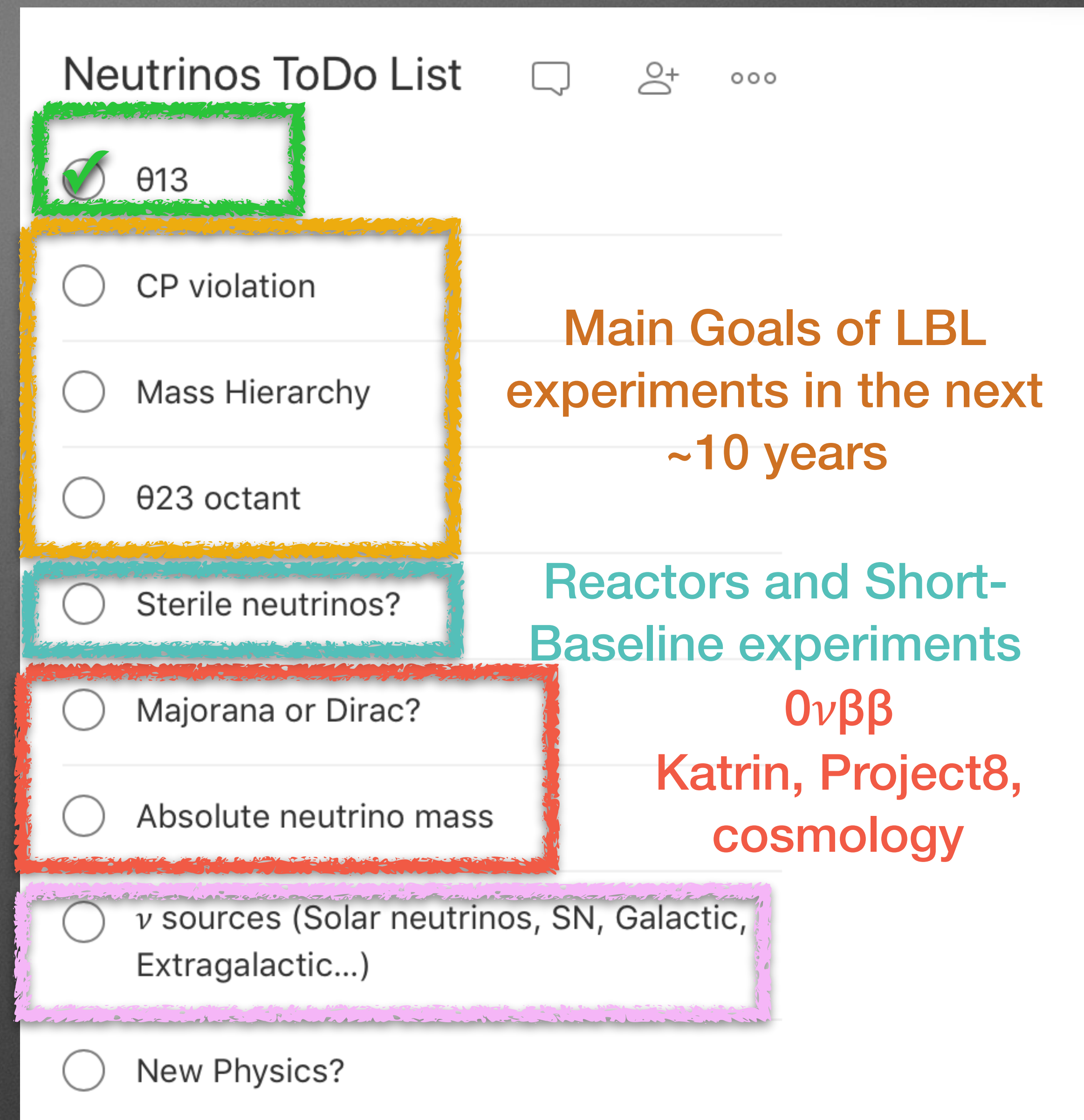
LBL (Minos, T2K, NOνA)

→ θ_{23}, Δm_{32}



Open questions

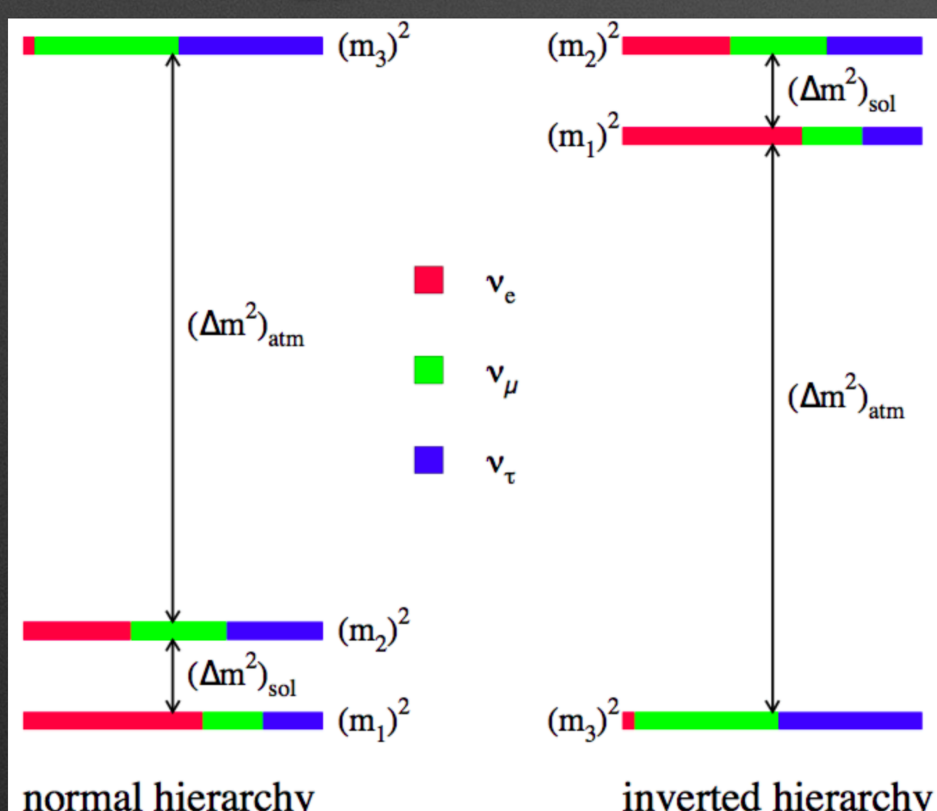
- Neutrino oscillations → "guaranteed" measurements for T2K and HK
- Multi-messenger astronomy with neutrinos is starting now → SK, HK
- Nature of neutrinos (Dirac or Majorana) and their mass → $0\nu\beta\beta$ experiments, Katrin, Project-8, cosmology

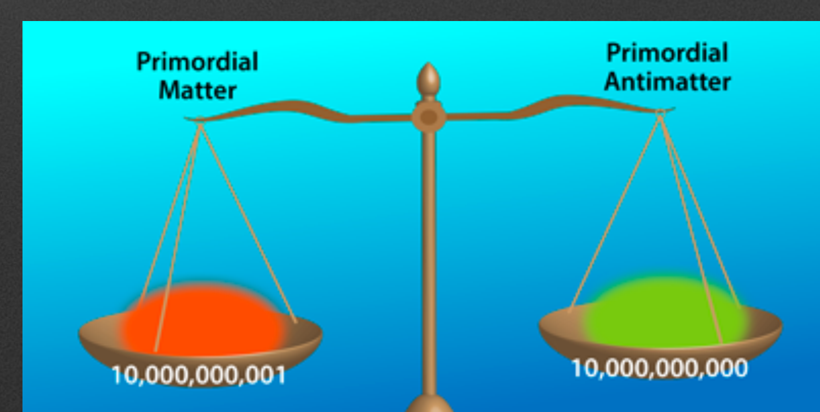


Main Goals of LBL experiments in the next ~10 years

Reactors and Short-Baseline experiments

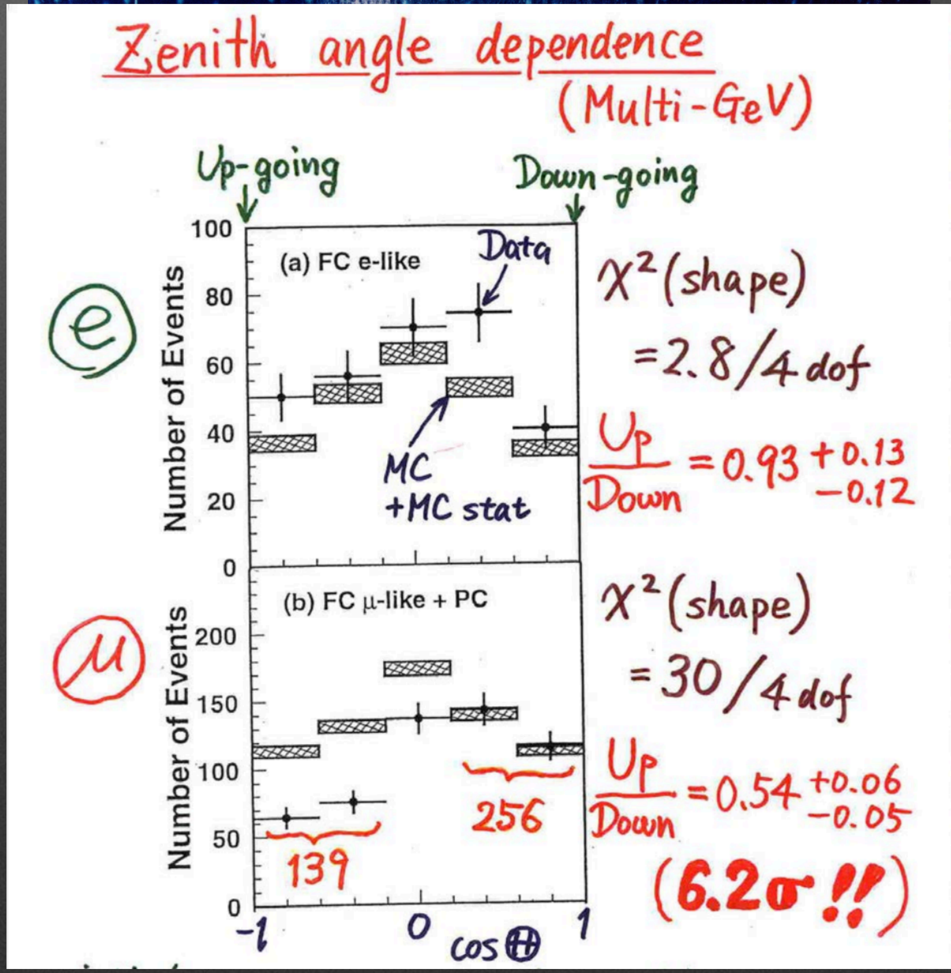
$0\nu\beta\beta$
Katrin, Project8, cosmology

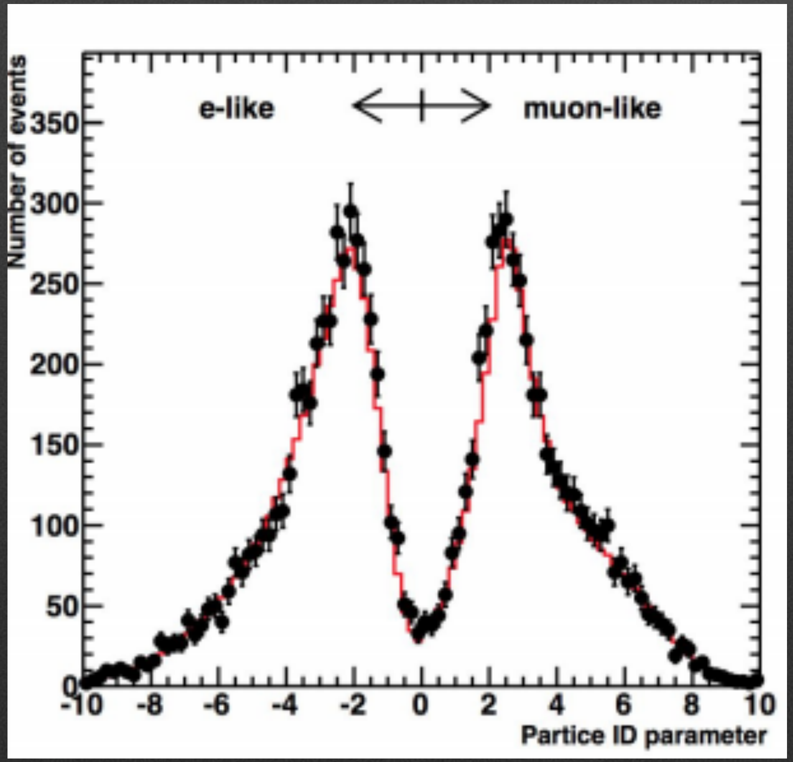




Super-Kamiokande

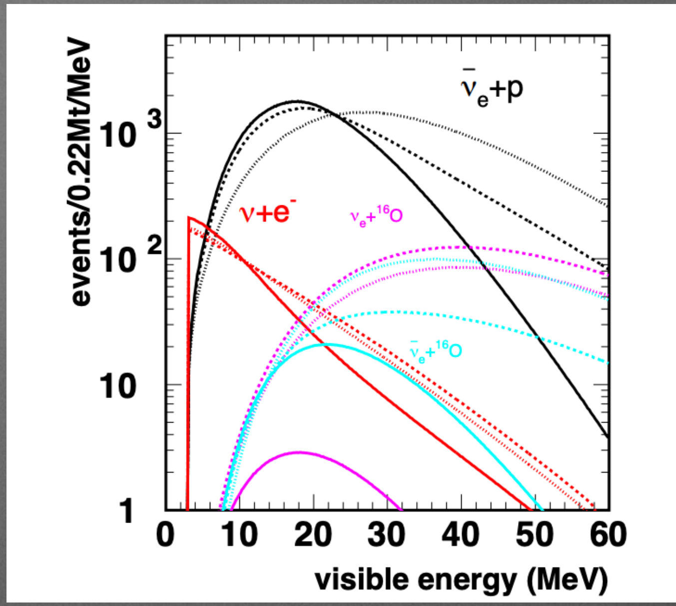
- 50 kton Water Cherenkov detector
    - ~11000 PMTs for ID, ~2000 for OD
- 1000 m underground at Kamioka mine operated since 1996
- Very good PID capabilities to distinguish between ν_e and ν_μ thanks to shape of Cherenkov ring → <1% misidentification probability



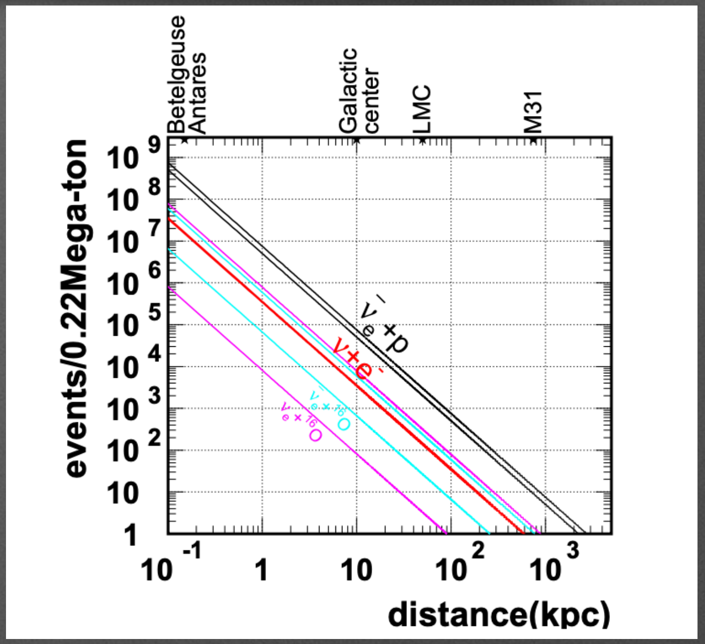


Supernovae Explosions

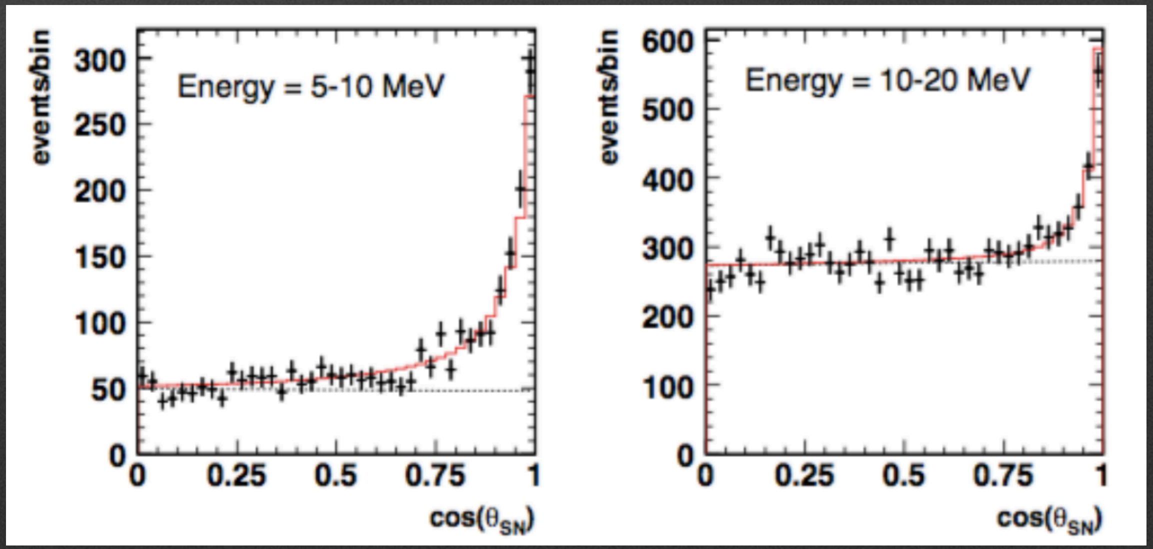
- Neutrinos carry out ~99% of the total energy released in a SN burst
- HK will mostly sensitive to $\overline{\nu}e$ through inverse β-decay, but also other channels can be inspected
- Point to the SN
- Study energy spectrum and time profile → distinguish between different models for SN explosions
-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



10 kpc

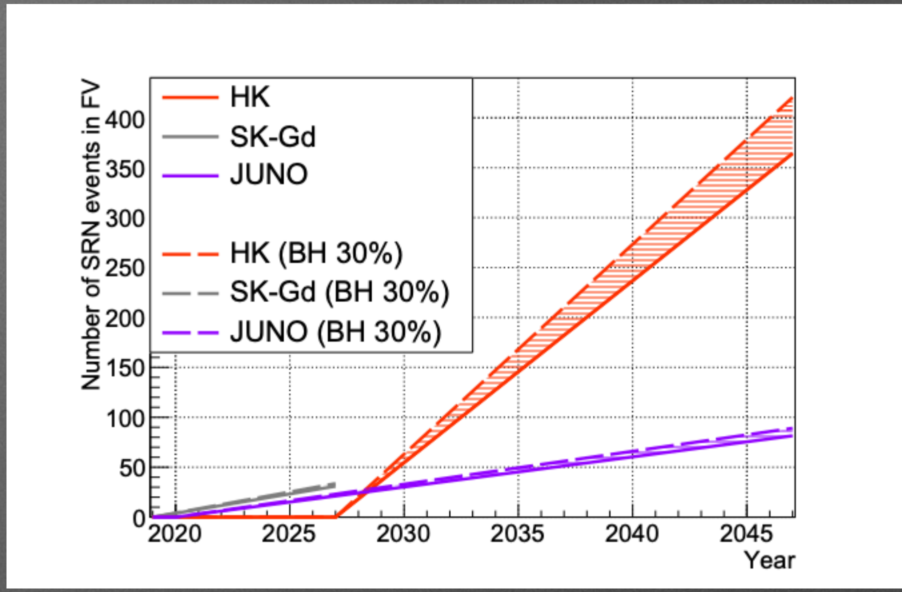


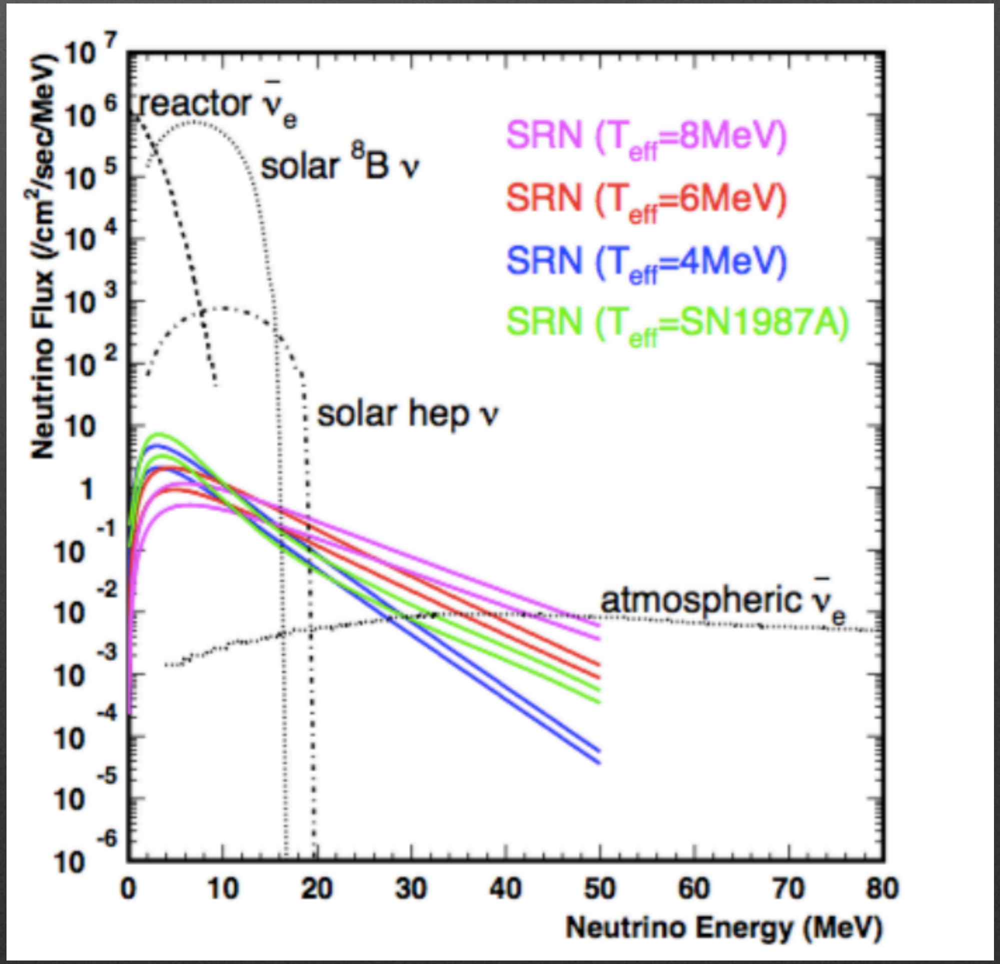
Neutrino source	Single Tank (220 kt Full Volume)	2 Tanks (440 kt Full Volume)
$\bar{\nu}_e + p$	50,000 - 75,000 events	100,000 - 150,000 events
$\nu + e^-$	3,400 - 3,600 events	6,800 - 7,200 events
$\nu_e +^{16} O$ CC	80 - 7,900 events	160 - 11,000 events
$\bar{\nu}_e +^{16} O$ CC	660 - 5,900 events	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



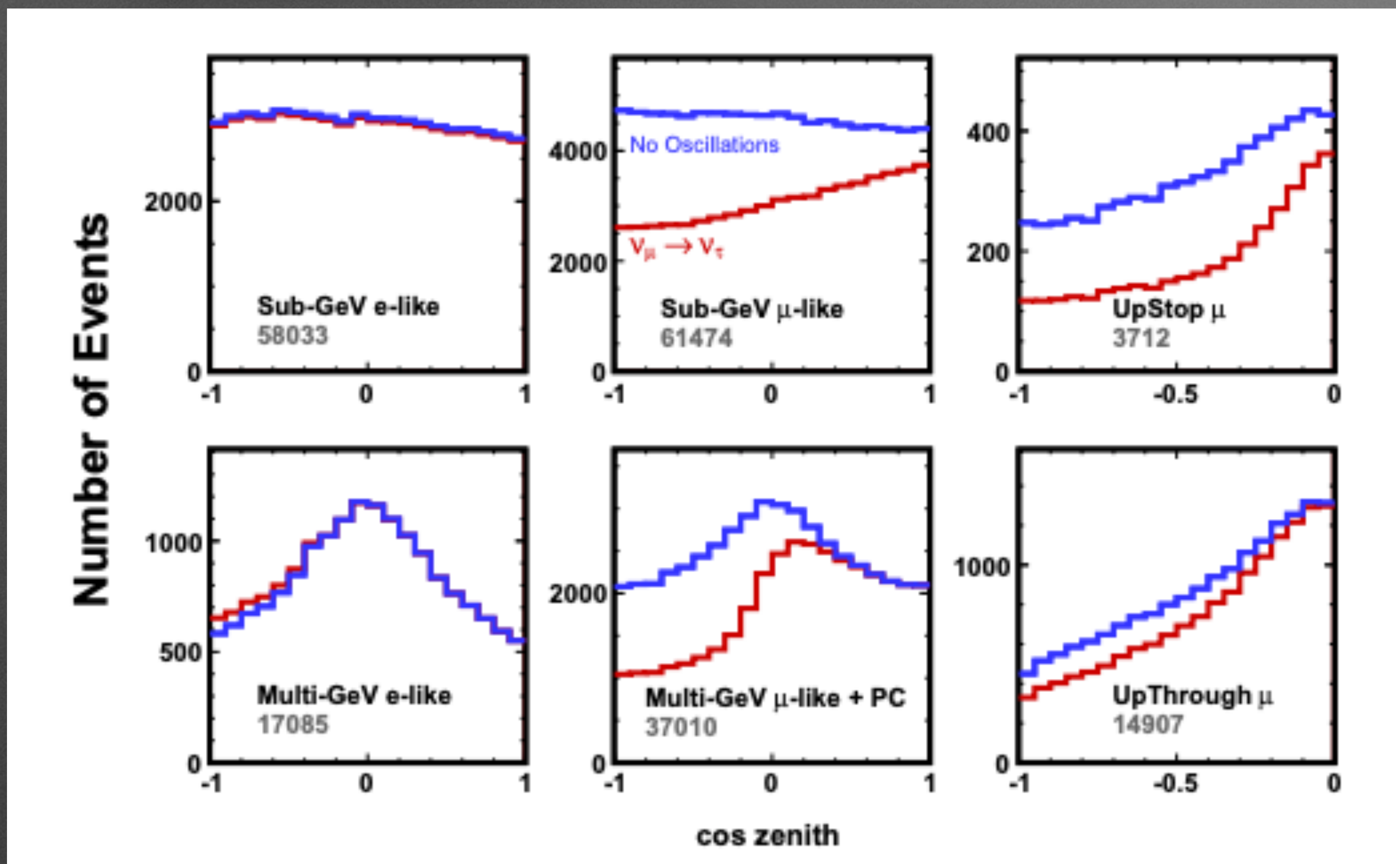
Supernovae Relic Neutrinos

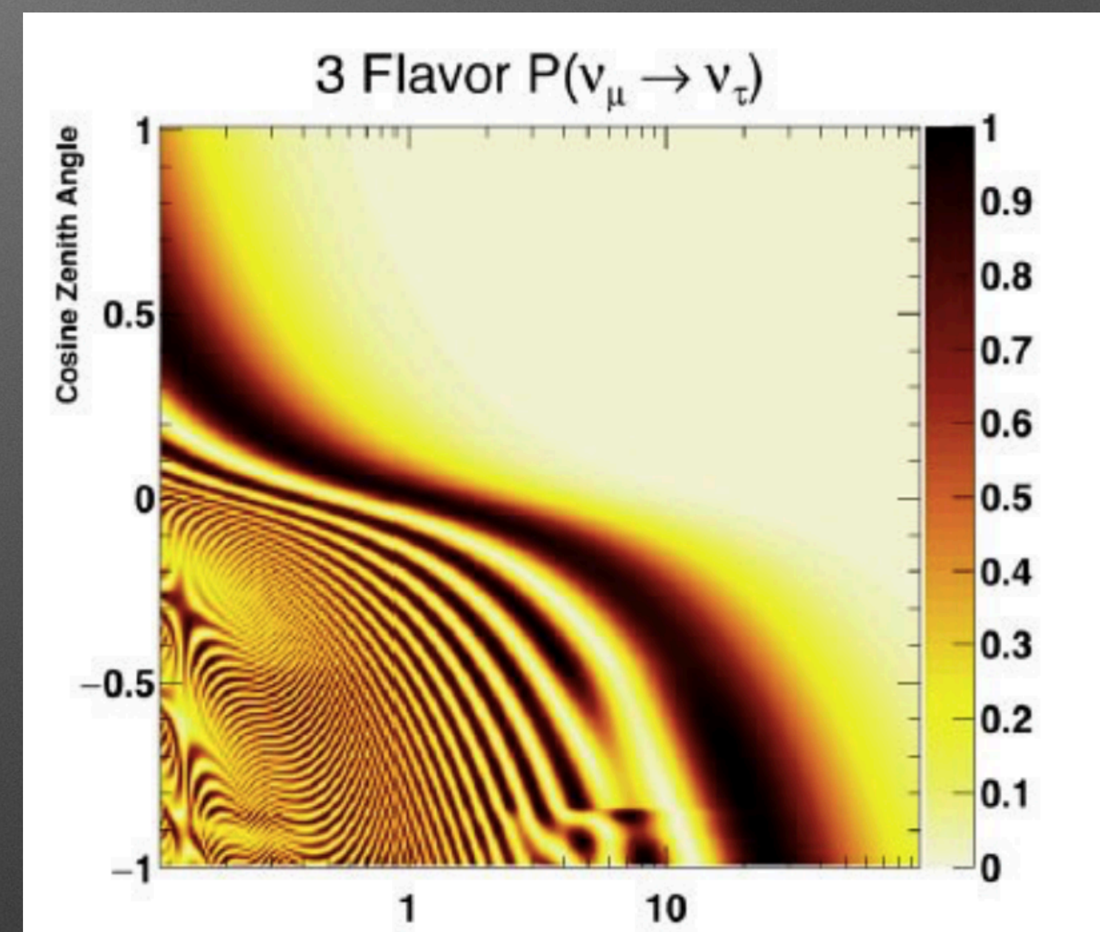
- Neutrinos produced by all the SN since the beginning of the Universe (SRN)
- Their detection is the main goal of the Super-Kamiokande upgrade (SK-Gd)
    - Addition of Gd in SK to tag the neutrons and distinguish $\bar{\nu}_e + p \rightarrow e^- + n$
- If SRN will be discovered by SK, the large size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

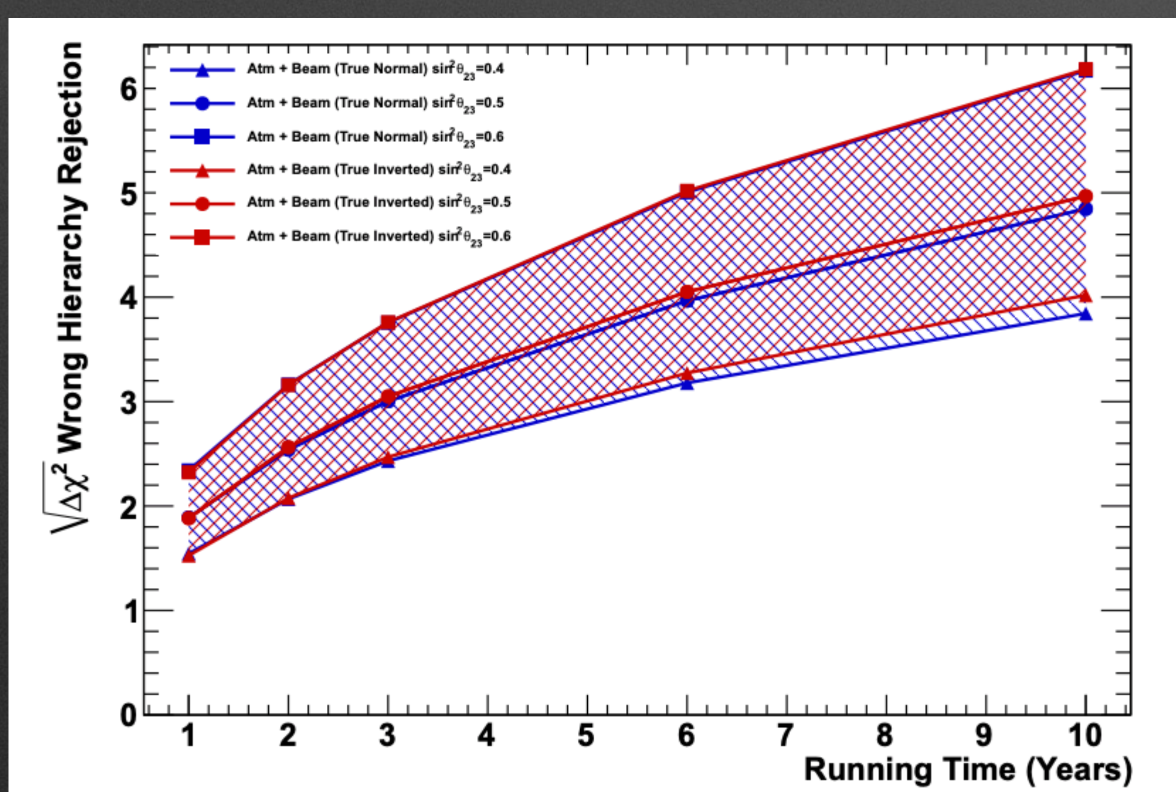


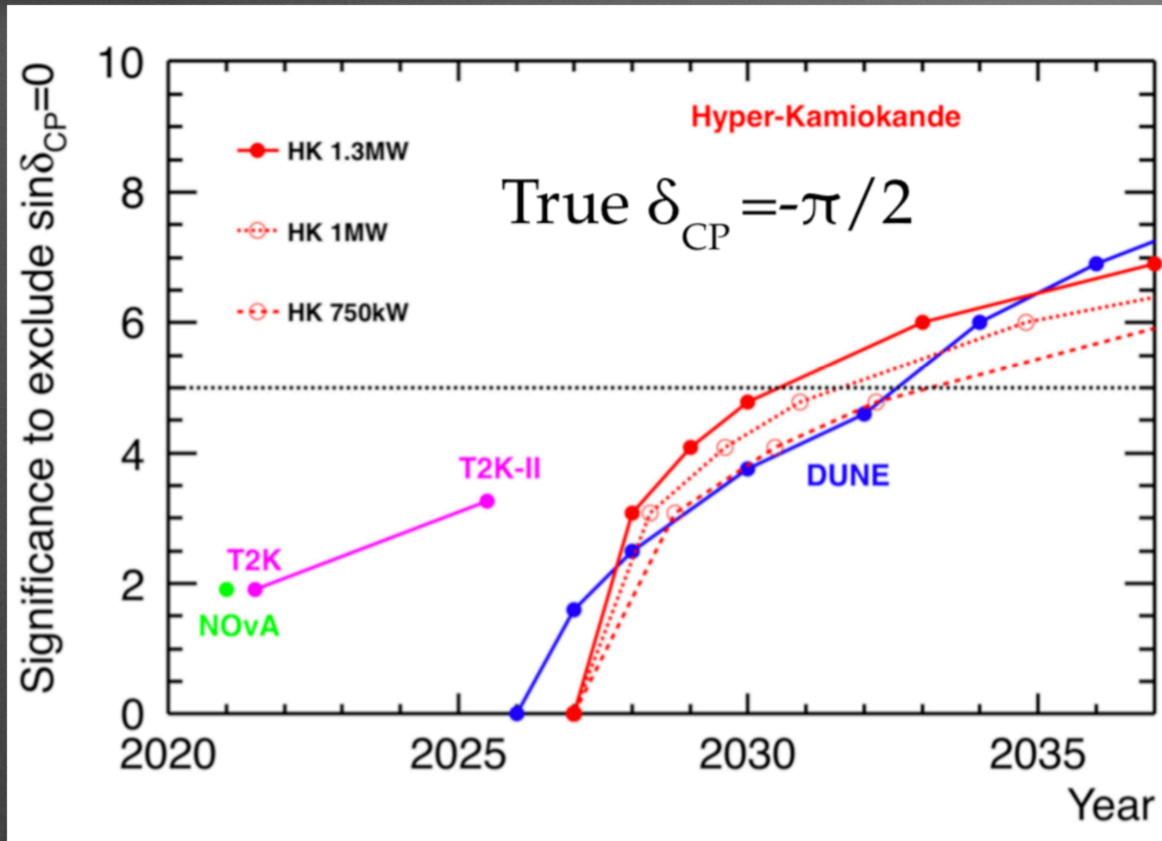


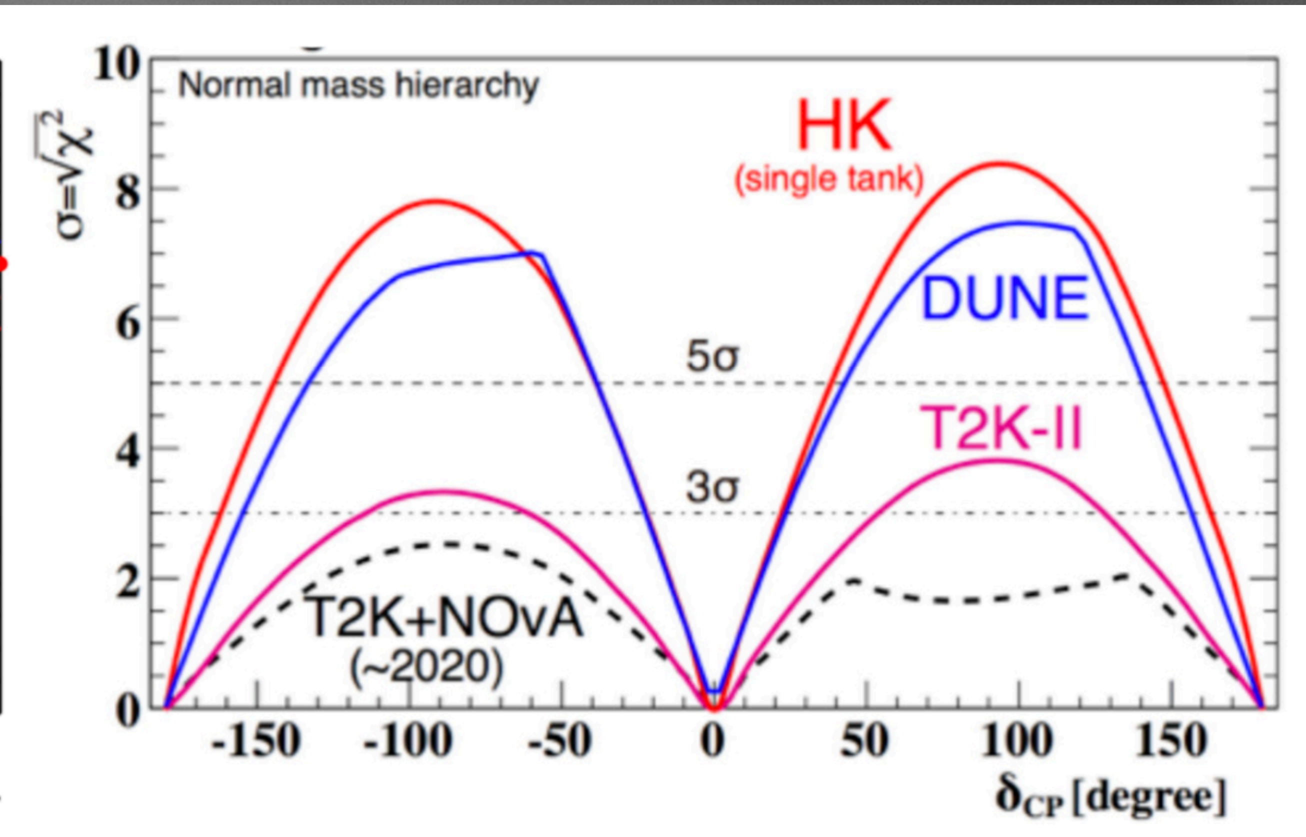
Atmospheric neutrinos

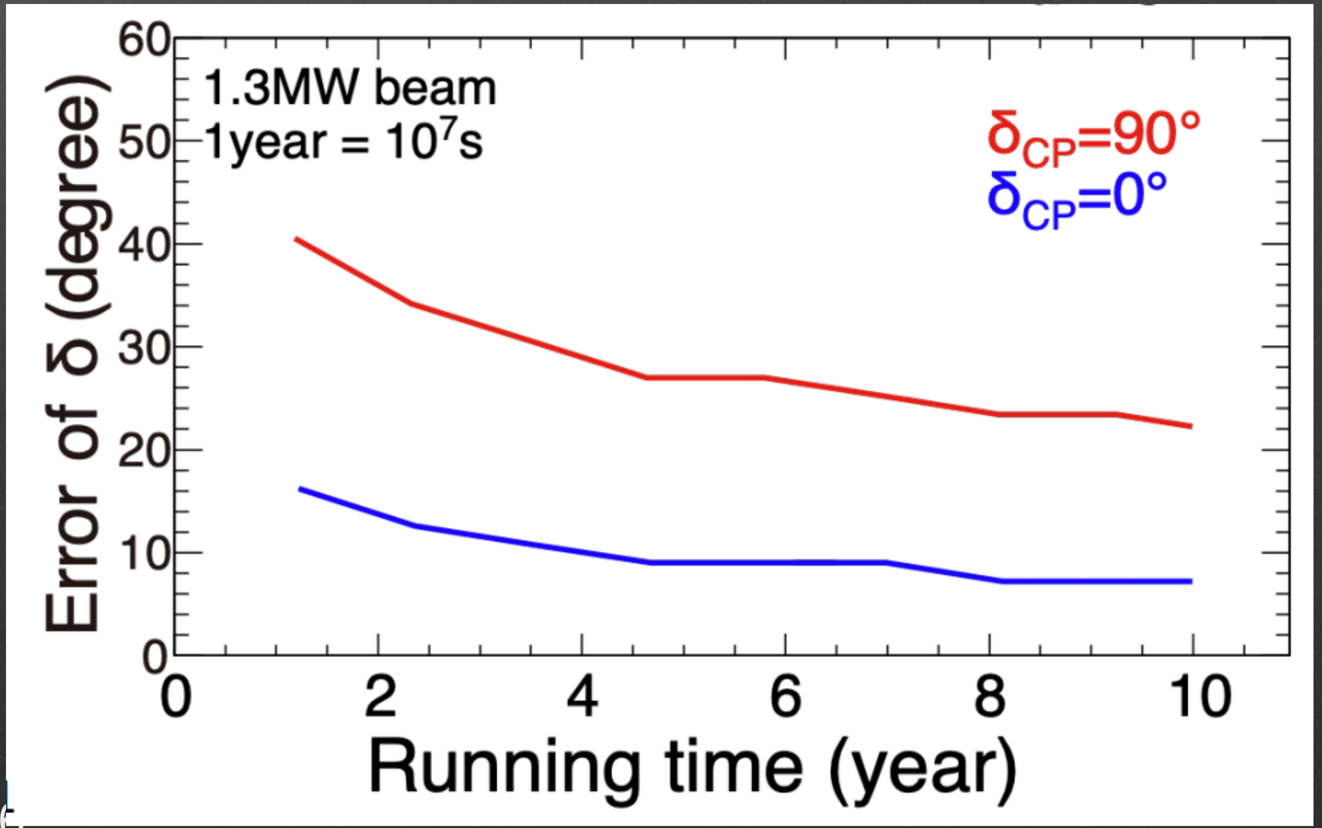







Significance to exclude $\sin\delta_{CP}=0$
Hyper-Kamiokande
HK 1.3MW
HK 1MW
HK 750kW
True $\delta_{CP}=-\pi/2$
T2K-II
T2K
NOvA
DUNE
Year


Normal mass hierarchy
$\sigma=\sqrt{\chi^2}$
HK
(single tank)
DUNE
5σ
T2K-II
3σ
T2K+NOvA
(~2020)
δ_{CP} [degree]


1.3MW beam
1year = 10^7s
$\delta_{CP}=90°$
$\delta_{CP}=0°$
Error of δ (degree)
Running time (year)