



Hyper-Kamiokande

IN2P3 contributions to Hyper-Kamiokande

Benjamin Quilain (LLR - CNRS/Ecole polytechnique)

on behalf of HK-IN2P3 in close collaboration with CEA-IRFU

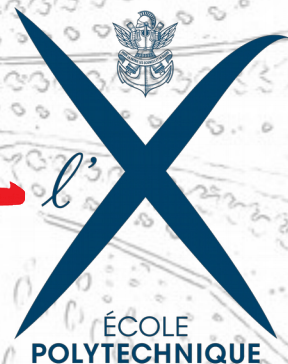


I L $\wedge$ N C F

International Laboratory for **A**strophysics,
Neutrino and **C**osmology Experiments

IN2P3
Les deux infinis

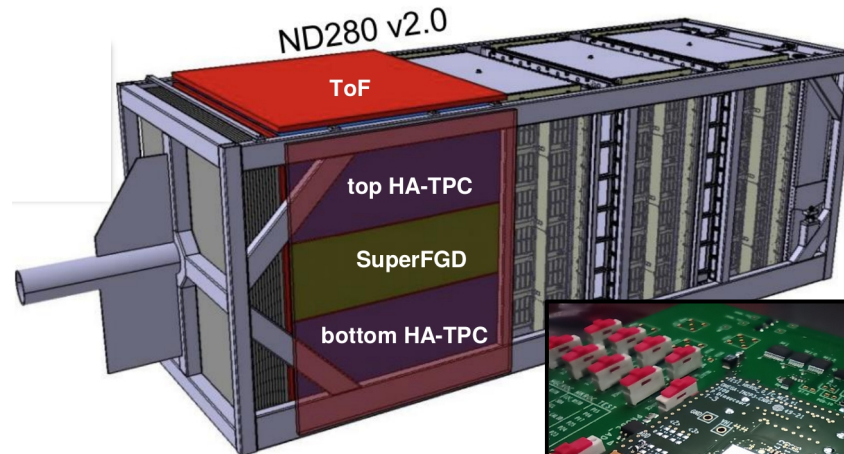
Ω MEGA
Microelectronics



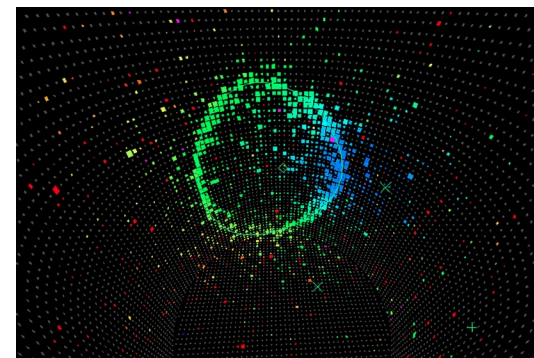
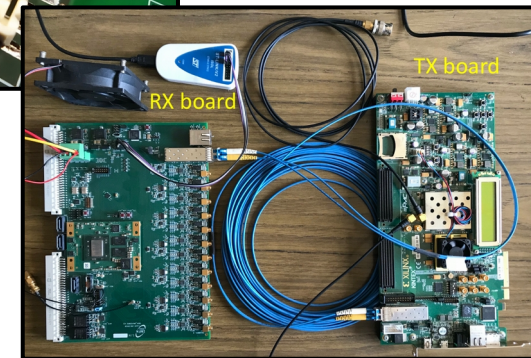
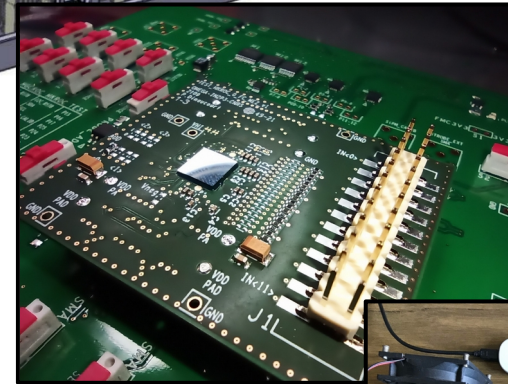
Conseil Scientifique de l'IN2P3, 2022/10/27

Summary of proposed contributions

One year ago, IN2P3-HK groups made the following proposal @CS :



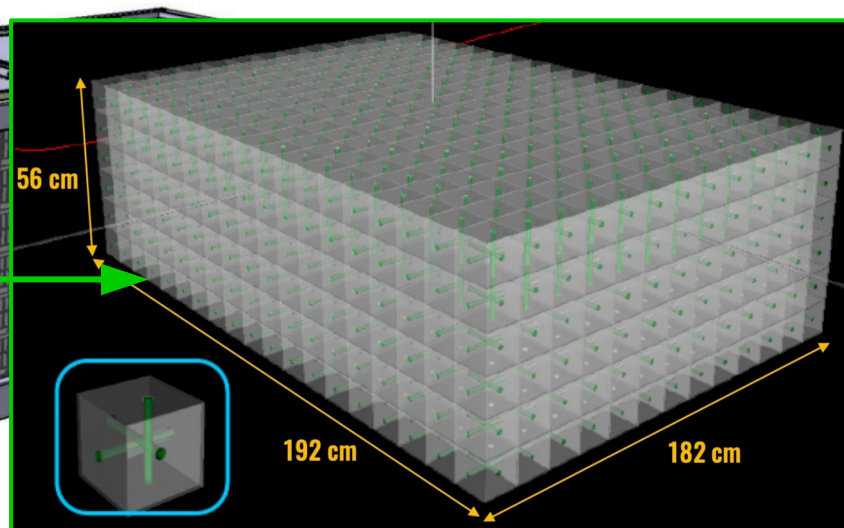
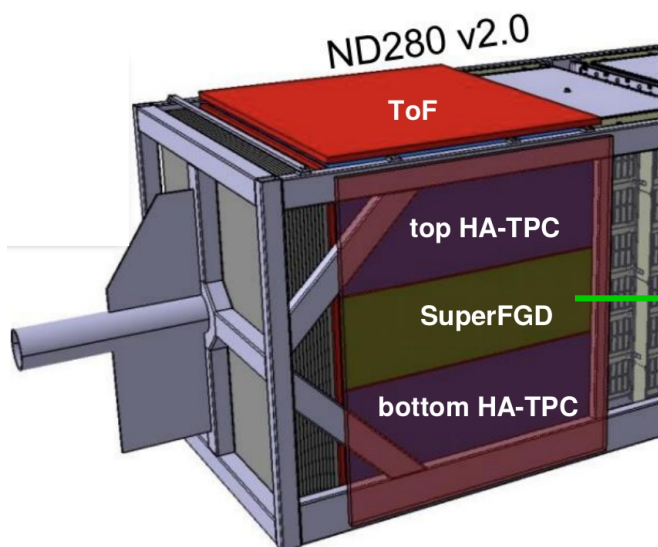
- The ND280-upgrade.
- HKROC complete digitizer for ID & OD.
- Time generation & clock distribution at Far Detector.
- Shared-item cost & assembly.
- CC-IN2P3 : HK Tier 1 computing system.





I. The ND280-upgrade

The ND280-upgrade : super-FGD



super-FGD :

- A massive target (2t).
- A high granularity tracker : 2 millions scintillating cubes of 1 cm-side.

2 million cubes @JPARC

(July 2022)



Front-end electronics



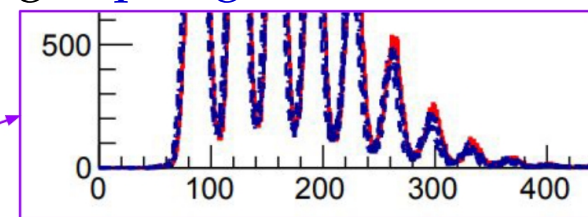
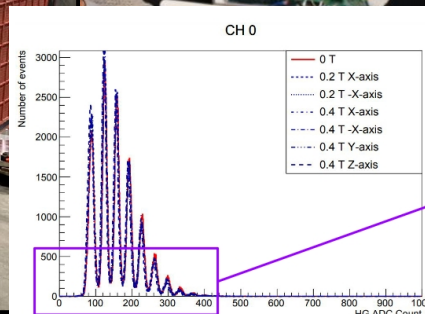
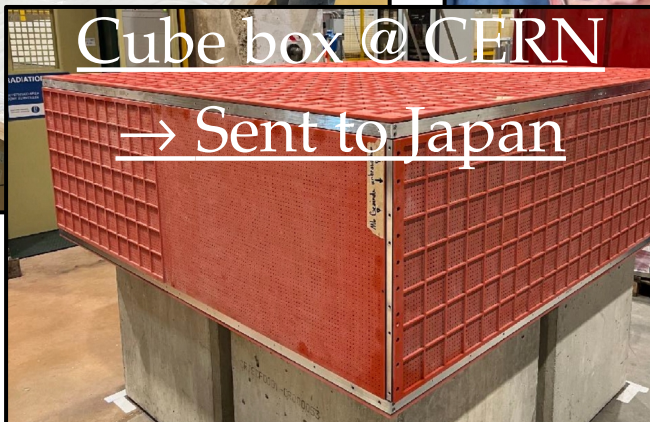
- Front-end final prototype validated.

- Vertical slice tests:
→ Winter 2022

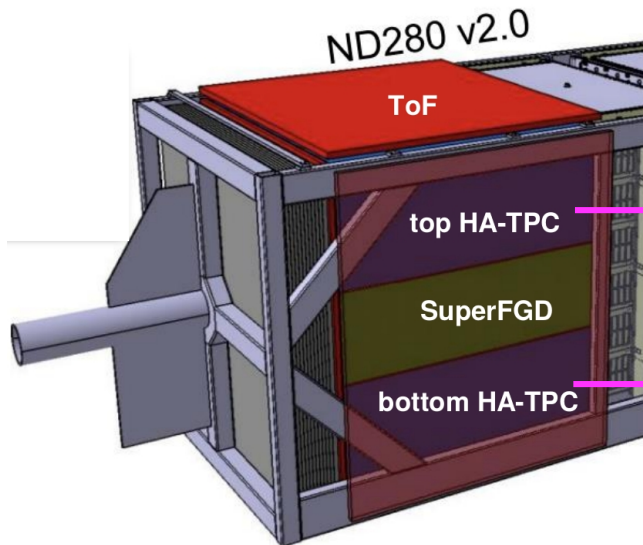
- Installation & commissioning : **spring 2022.**

Cube box @ CERN

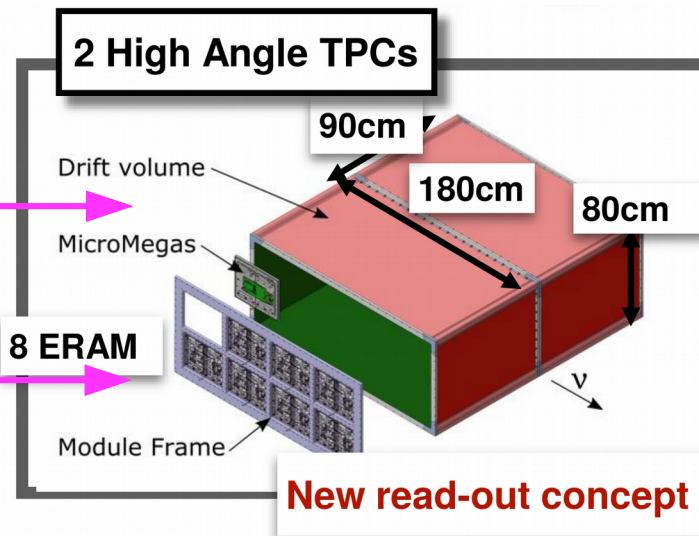
→ Sent to Japan



The ND280-upgrade : high-angle TPCs

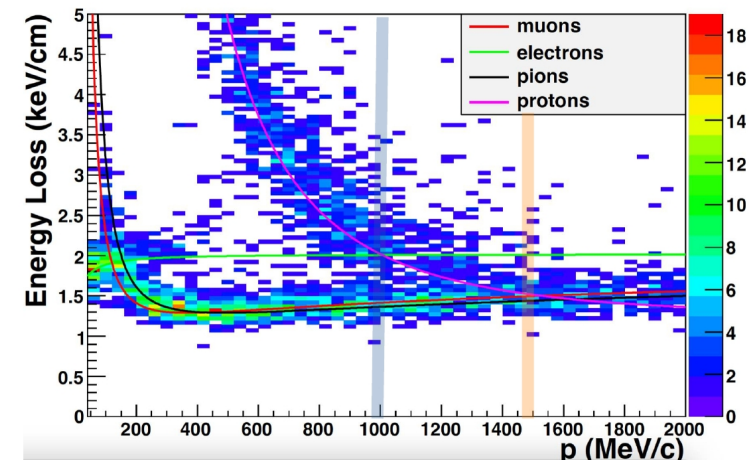
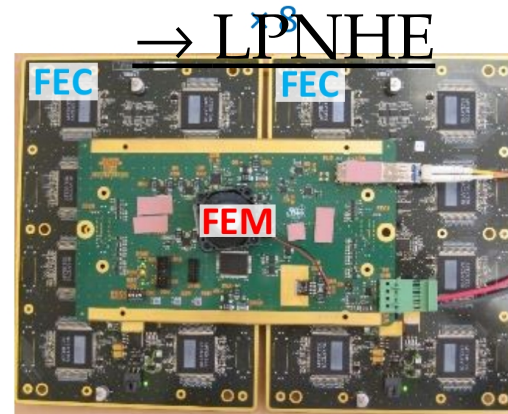


Test beam at CERN



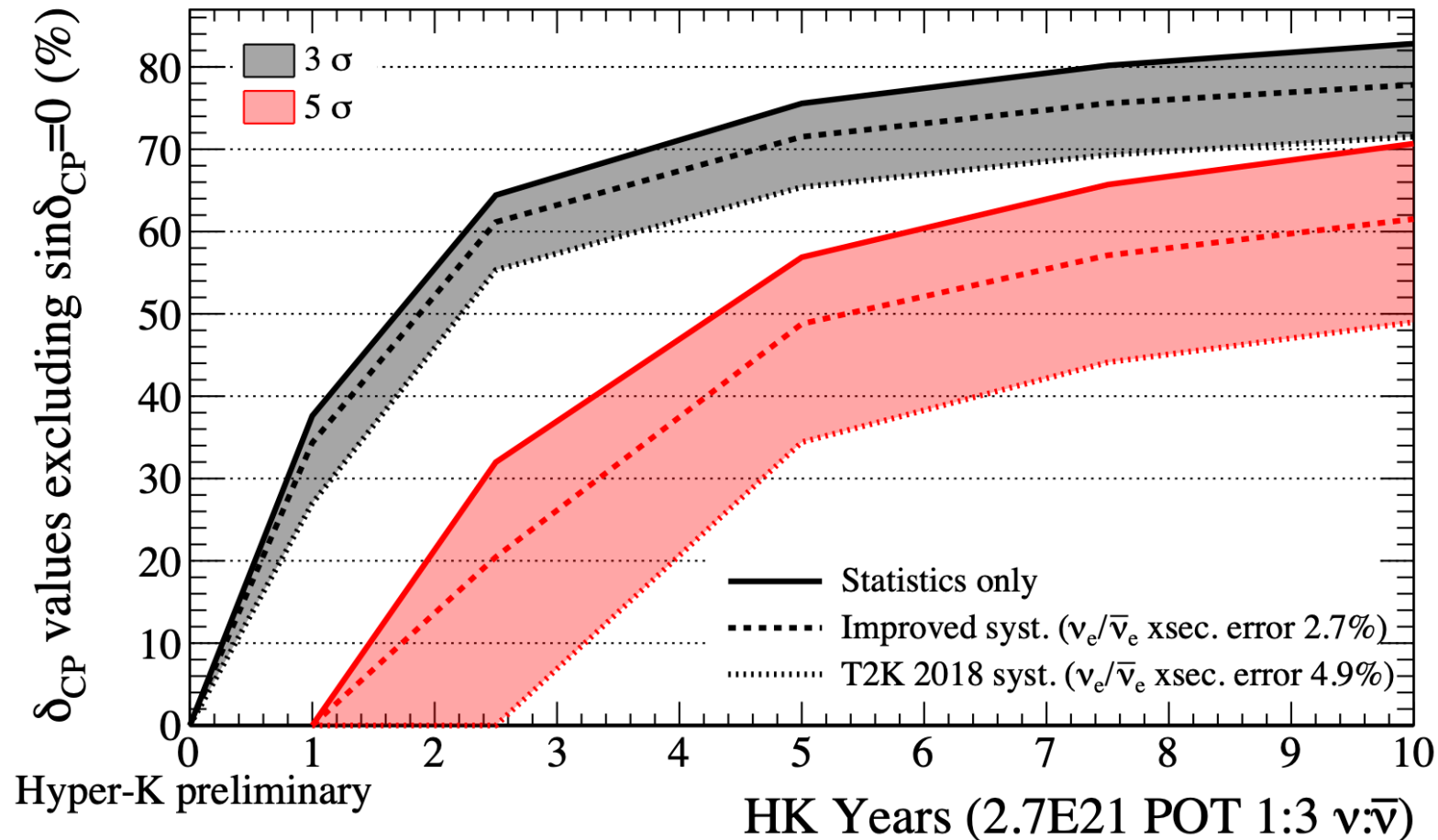
Front-end electronics

- High-angle TPCs :
- Allow an almost 4π PID & momentum reconstruction for μ & π .



- Full upgrade : operating from 2023 at T2K → When HK starts :
 - Upgrade + INGRID (IN2P3) : only near detectors in HK !
 - HK will benefit of years of running to constrain the systematics.

How ND280-upgrade is critical for HK ?



With the ND280 upgrade :

- If CPV maximal : gain at least 1.5 year on CP violation discovery.
- Otherwise : gain +20 % on 5σ exclusion contours at a given time.

→ The ND280-upgrade is a cornerstone of the HK strategy.

The background of the slide features a complex visualization of a particle detector's hit pattern. It consists of a dense grid of small, multi-colored squares (red, green, blue, yellow) arranged in a way that suggests a curved, cylindrical structure, likely representing the geometry of a detector like the ATLAS or CMS. The pattern is more concentrated in the center and fades out towards the edges.

II. The far detector electronics

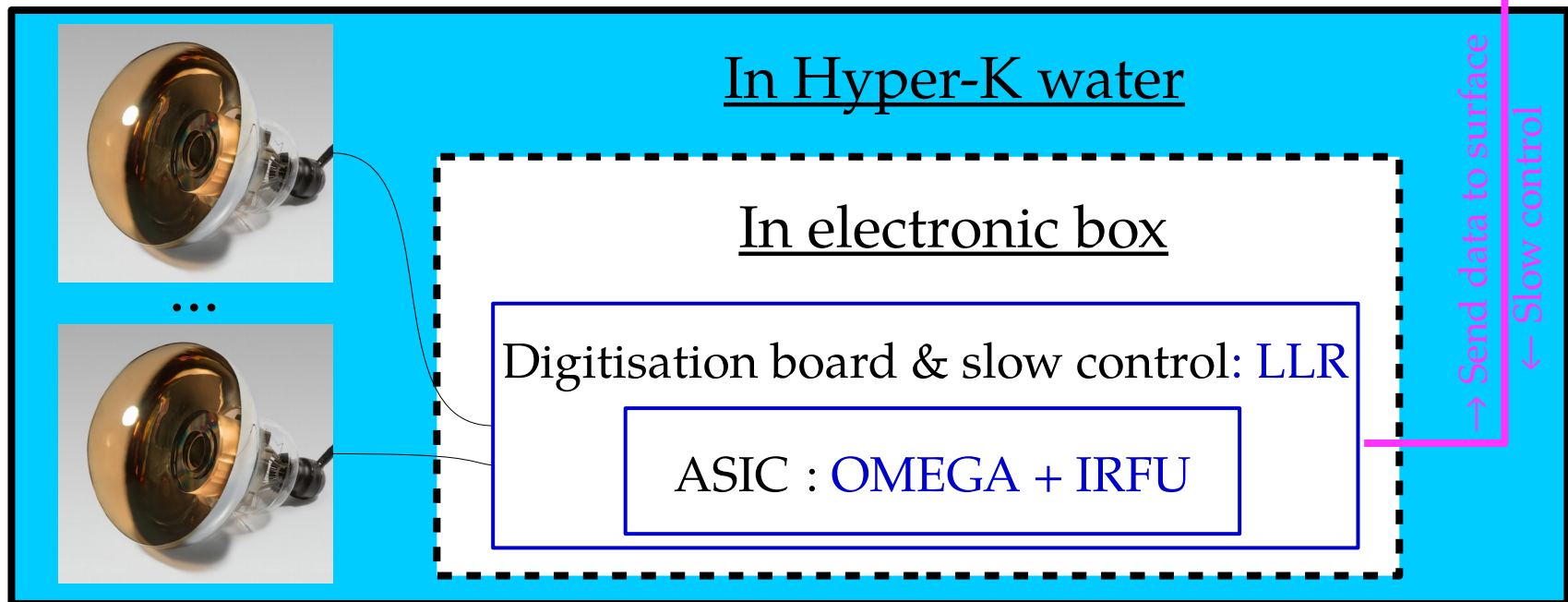
HK far detector electronics

- The whole HK physic signal will rely on 20k PMTs of 50 cm.

- PMT signal to be readout by electronics [under water](#) :

→ 24 channels/PMTs read in one stainless steel box under water.

Clock generation & distribution
LPNHE + IRFU

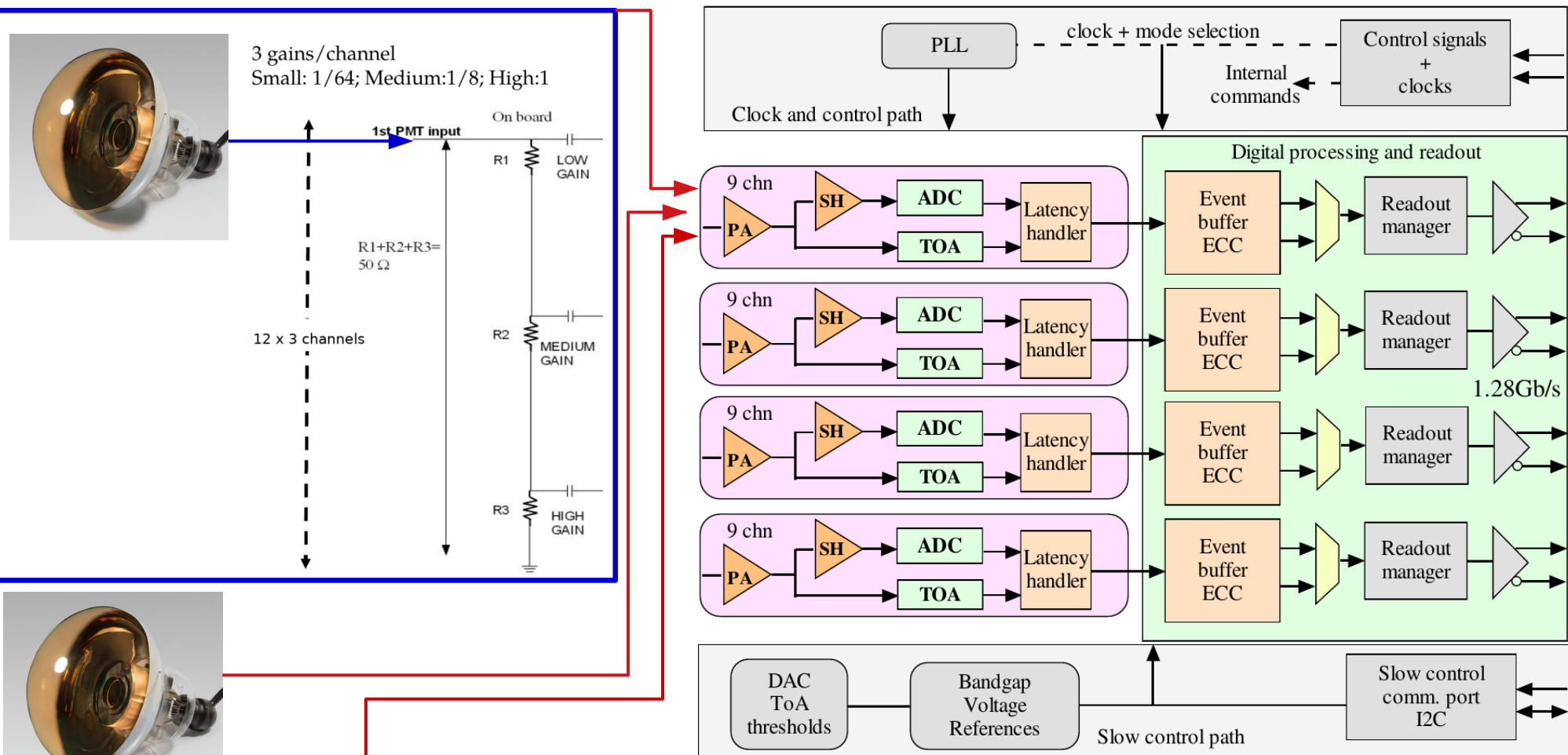


France's proposal : develop the whole PMT read-out digitization & synchronization systems

→ Absolutely central role in HK & synergy IN2P3-IRFU.

The HKROC digitizer

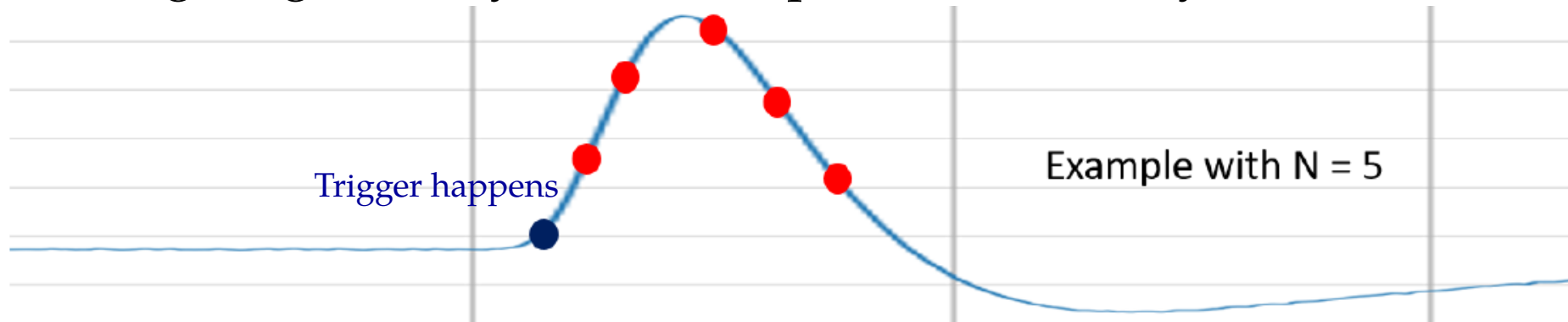
- Based on HKROC chip : 12 PMTs $\leftrightarrow$ 36 channels (high,medium,low gain)



- TSMC CMOS 130nm etching.
- Dynamic range from 0 – 2500 pC : 3 gains / channel.
- 4 readout / ASIC @1.28 Gb/s : 1 readout $\leftrightarrow$ 3 PMTs.
- If 1 PMT trigger : read all 3 PMTs of 1 readout.

Overview of the HKROC digitizer

- HKROC is a waveform-like digitiser @40 MHz → 1 point every 25 ns.
→ Charge digitized by $N = 1 \rightarrow 7$ points (chosen by slow-control).

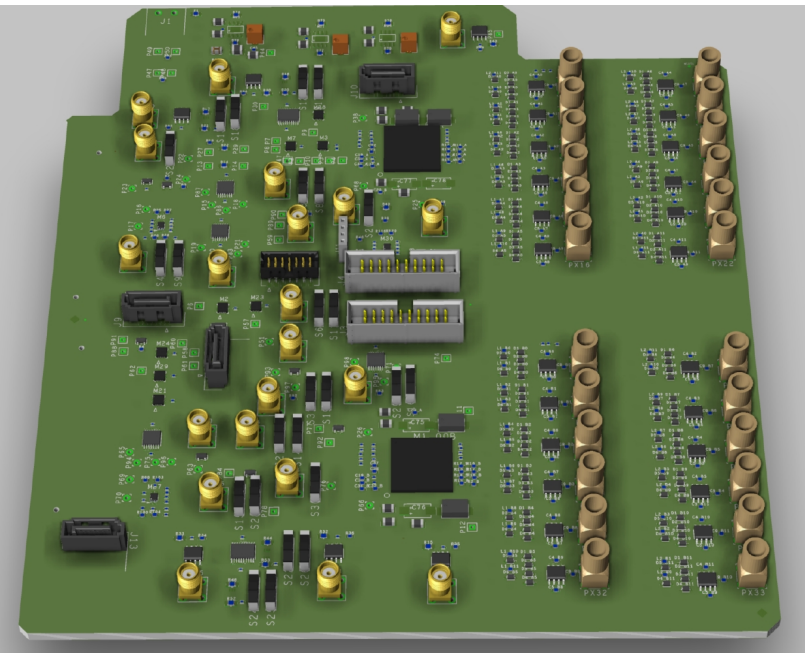
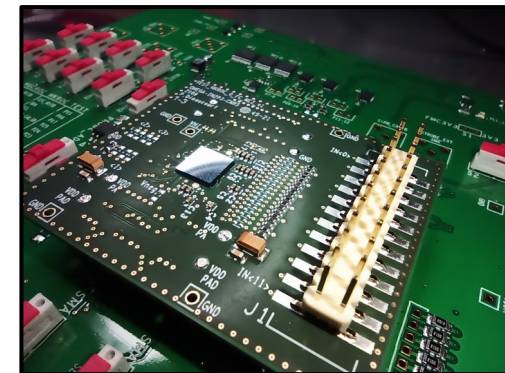


- HKROC digitizer : 24 PMT channels readout by 2 HKROC ASIC.

HKROC prototype v1

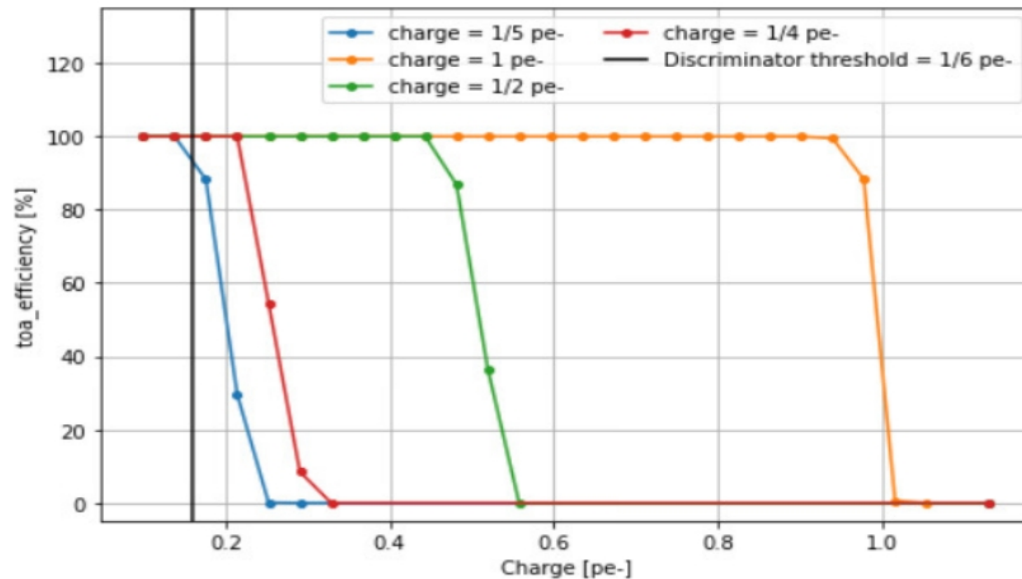
- Started R&D in summer 2020 : Make a chip in 2 years → Challenging schedule :
 1. Receive chip in Dec. 2021.
 2. Provide tested chip by end of June 2022.

- No delay in 2 years :
→ Chip came back in Jan. 2022 (pandemic).
→ Worked hard to finalize tests for June.



HKROC digitizer - trigger & timing results

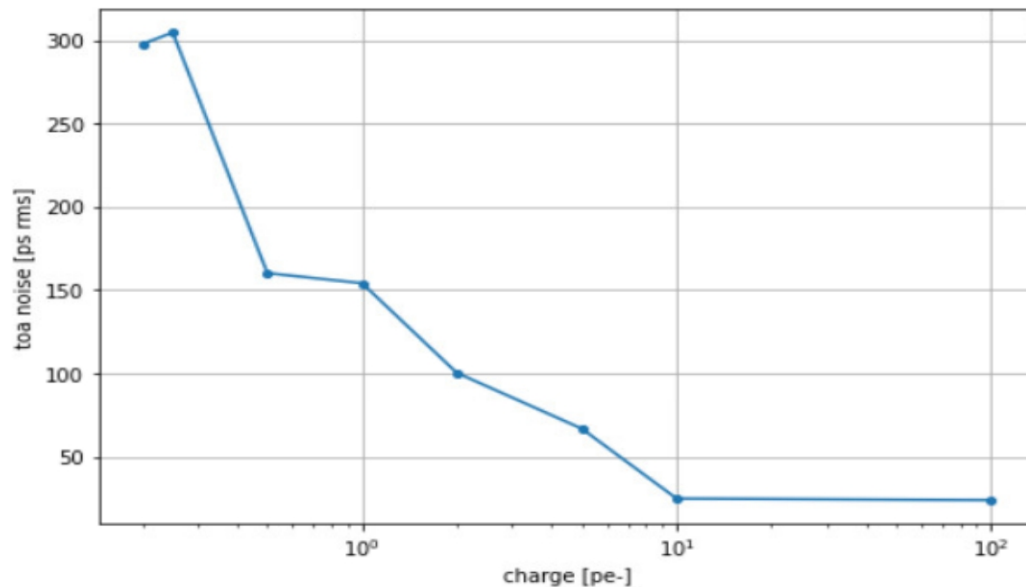
- HKROC-digitizer v1 received & completely tested in few months.



- Set threshold at 1/6 p.e.

- Hit efficiency :
90 % for 1/5 p.e events
~100 % if $\geq 1/4$ p.e

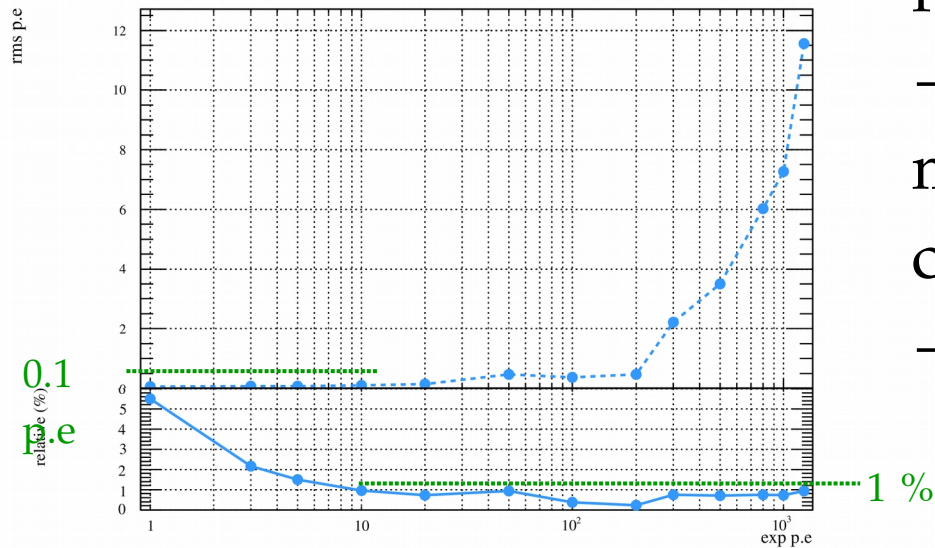
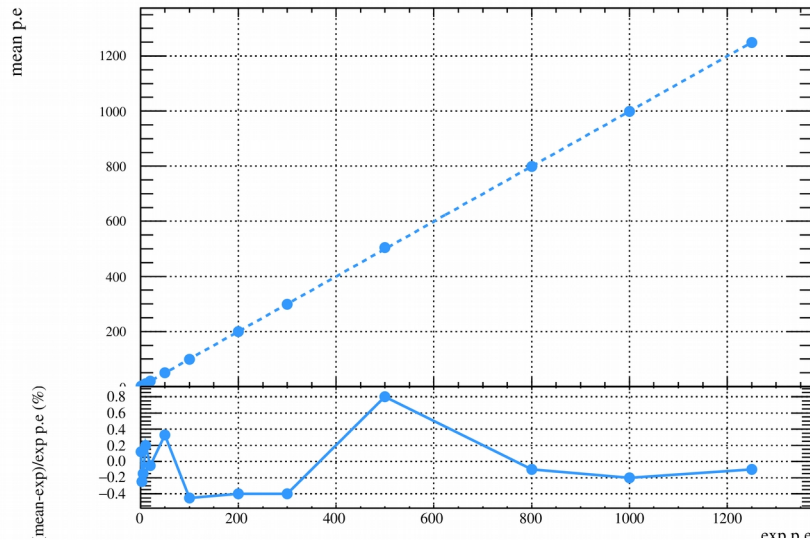
- Very low noise : < 1 Hz.



- TDC resolution :
150 ps @1 p.e [300 ps required]
 ≤ 30 ps @ 10 p.e [200 ps required]

→ Excellent agreement with HK₁₁ requirements.

HKROC digitizer - Charge results

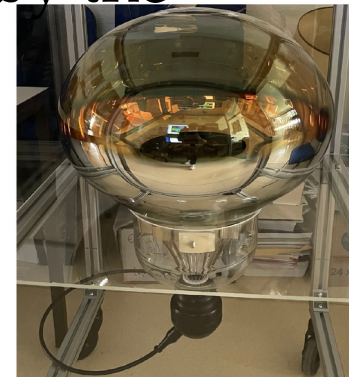


- Charge linearity $< \pm 1\%$ [1 to 1250 p.e.]

- Charge resolution :
 < 0.1 p.e @ ≤ 10 p.e, $< 1\%$ otherwise.

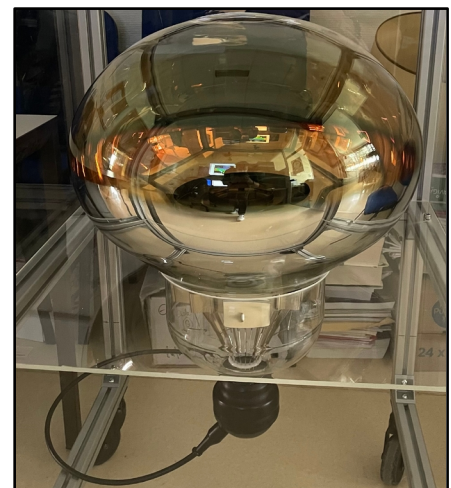
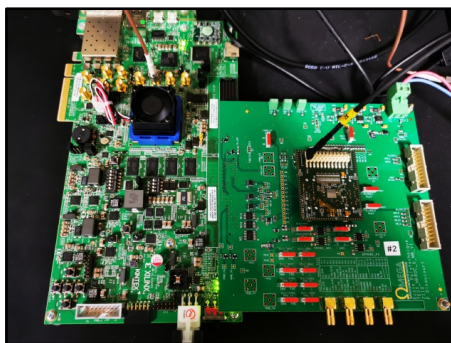
→ All characteristics fulfill HK requirements & confirmed w/ PMT.
→ Large improvements w/ HKROC much beyond requirements by the collaboration

→ Ex: dead-time ↓ **from**
 $1\ \mu\text{s} \rightarrow 30\ \text{ns}$.



- HKROC project has been **on-time & is a huge technical achievement** that has only been possible thanks to the great collaboration between the IRFU, OMEGA & LLR + financial support from X & IN2P3.

Summary of the digitizer measurements



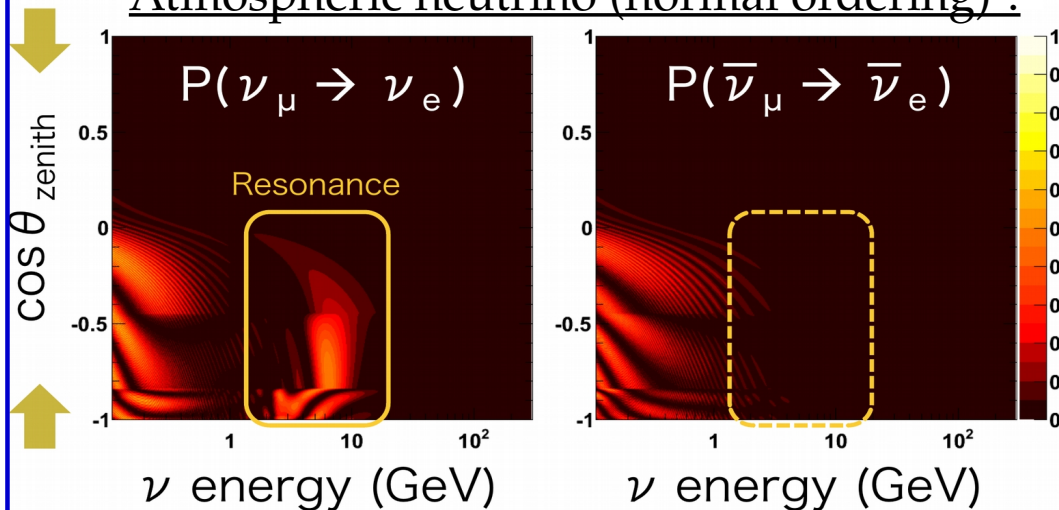
Item measured	Performances
Trigger efficiency at 1/6 p.e.	> 90% for 1/5 p.e signals 100% for $\geq 1/4$ p.e signals
Trigger noise at 1/6 p.e.	< 1 Hz (No trigger observed in 10 s)
TDC resolution	150 ps at 1 p.e, 70 ps at 5 p.e, 25 ps > 10 p.e Validated with PMT
Charge linearity	< 0.5% in high & medium gain channels < 1% in low gain channel up to 1250 p.e Validated with PMT
Charge resolution	< 0.1 p.e for signals up to 10 p.e < 1% for signal 40 – 300 p.e and > 750 p.e < 2.4% for all other cases. Will be improved by reducing the unnecessary voltage division. Validated with PMT
Dead-time & pile-up	≤ 30 ns for two signals of same amplitude ≤ 30 ns for a prompt ≤ 5 p.e and secondary of 1 p.e < 1 μ s for a prompt signal ≤ 850 p.e and secondary 1 p.e
Maximal hit-rate w/ 100% eff.	415 kHz in normal mode 950 kHz in SN-mode Potential extension beyond to be studied.
Cross-talk	Hit probability in neighbouring channel of a 1250 p.e signal is < 0.1% <i>Note that cross-talk found at ASIC level, but cut by FPGA. Identified and will be removed in ASIC v2.</i>
Maximal hit-rate w/ 100% eff.	415 kHz in normal mode 950 kHz in SN-mode Potential extension beyond to be studied.
Temperature dependency ²	time resolution $\Delta T = 1$ ps/ $^{\circ}$ C gain variation $\Delta Q = 0.05\%/^{\circ}$ C (no correction)
Resistance to HV	Unprotected ASIC received 10 ⁸ 5V injection without any impact on performances



HKROC digitizer - Impact on physics

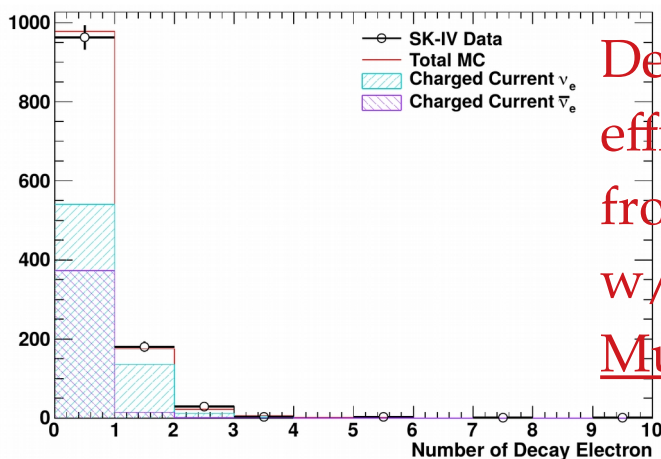
- Large impact on physics : ν mass ordering & Supernova ν .

Atmospheric neutrino (normal ordering) :

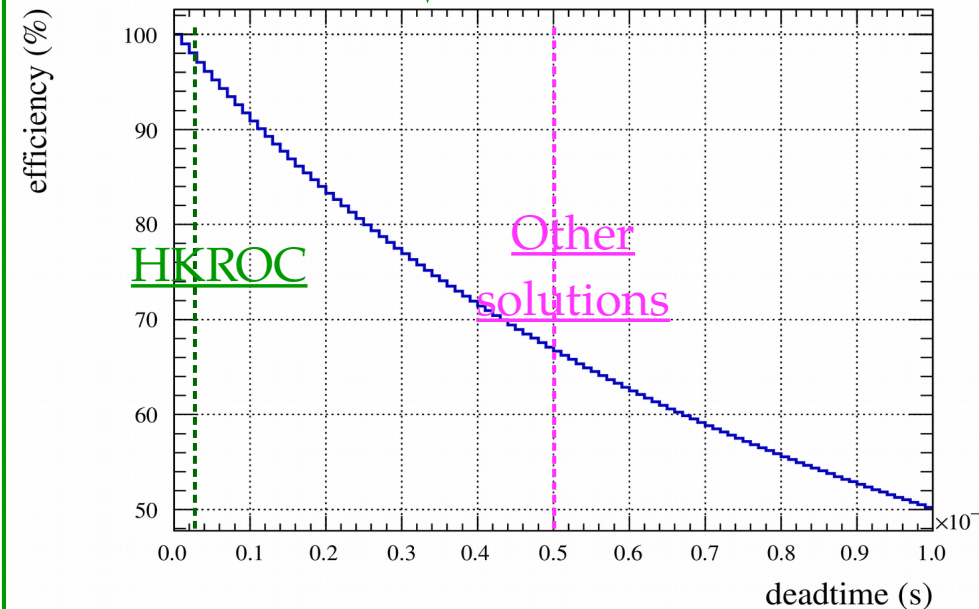


- Normal hierarchy : $\uparrow \nu_\mu \rightarrow \nu_e$.
- Inverted hierarchy : $\uparrow \bar{\nu}_\mu \rightarrow \bar{\nu}_e$.

→ Decay-e are central to separate $\nu_e / \bar{\nu}_e$.



Decay-e hit
efficiency increased
from 68 % → 98 %
w/ HKROC for
Multi-GeV events

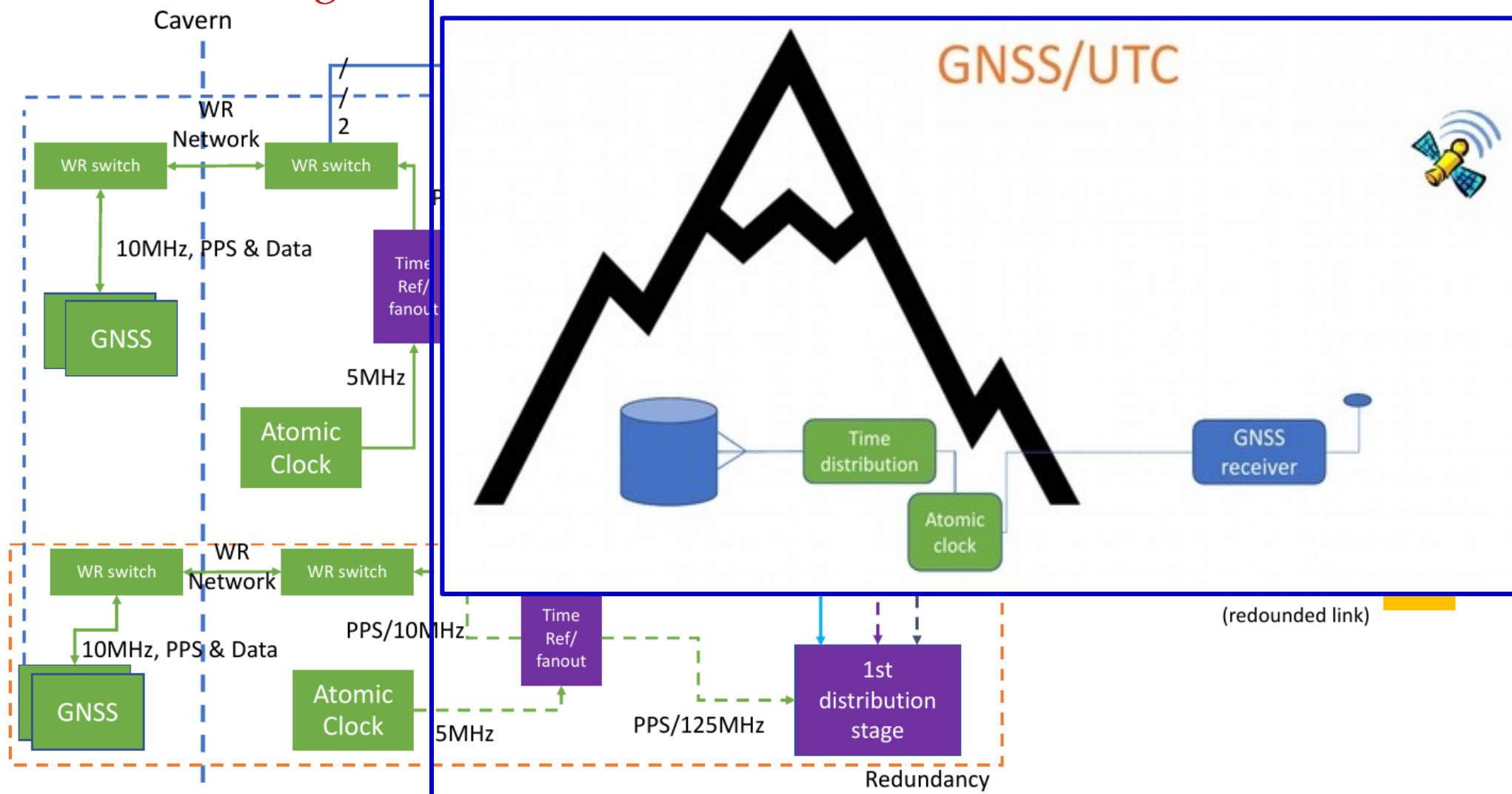


- For 1MHz [Betelgeuse] : HKROC allows to significantly increase efficiency from 67 % to 92.5 % compared to other solutions.

Overall view of the timing system

Time-generation :

- Provides local time w/ high stability to synchronize HK w/ v beam & other multi-messenger detectors



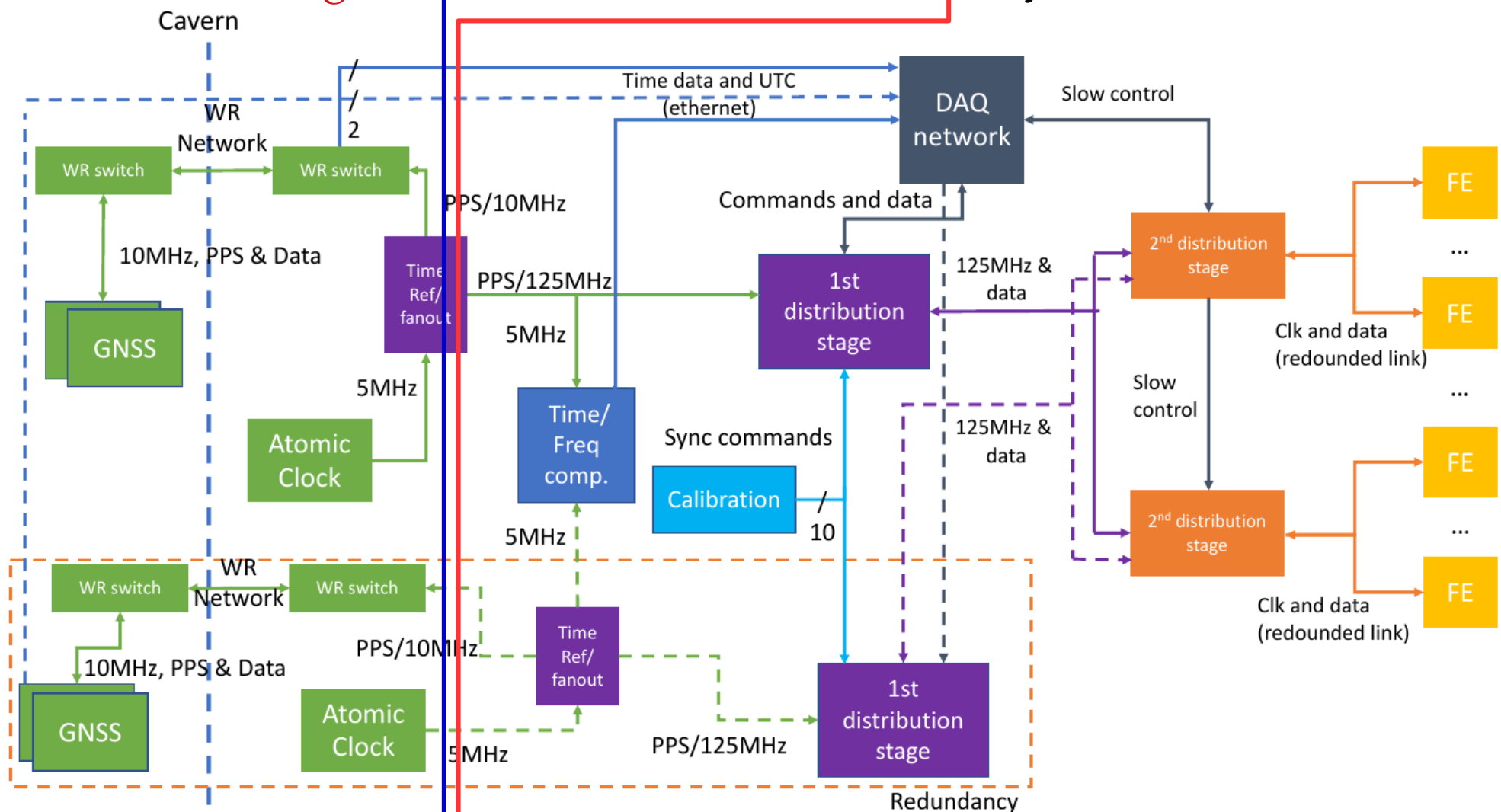
Overall view of the timing system

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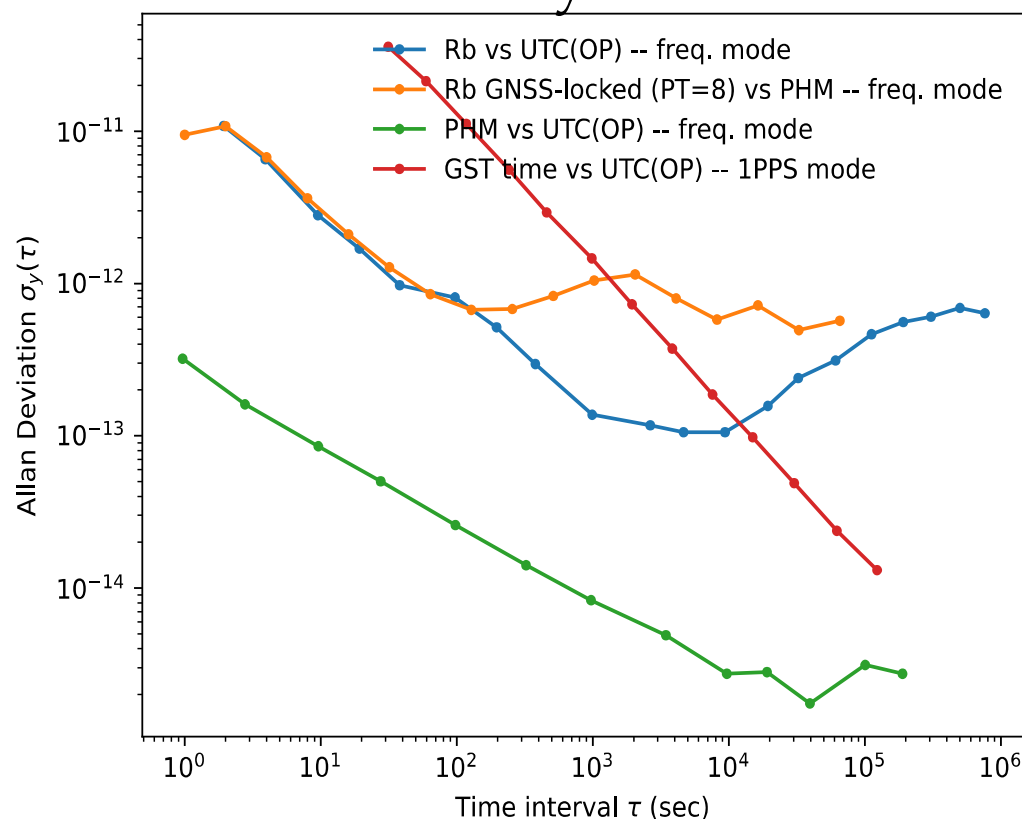
Time-distribution :

- Distribute the local time to all digitizers, and synchronize them.



Time-generation

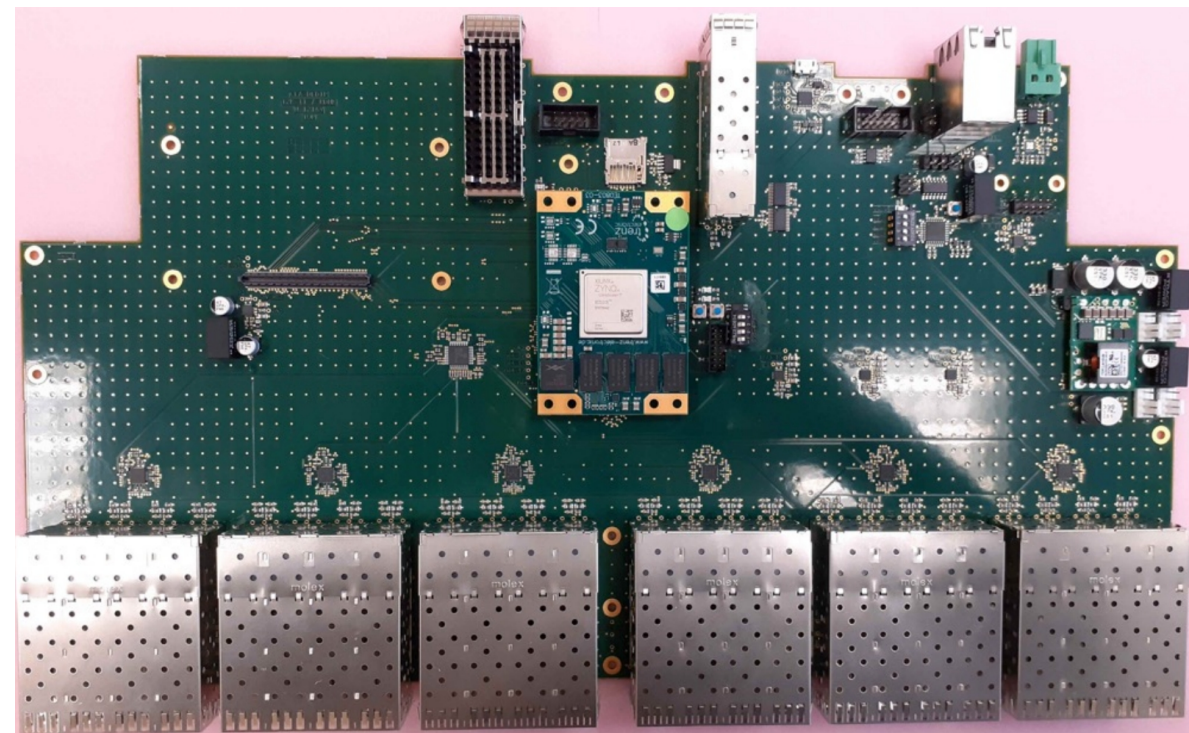
- Local time PPS generated by a 5 MHz Rb atomic clock.
- 2 GNSS receivers connected to same antenna to measure the difference between local PPS & UTC time → Transform local time to UTC.
- Collaboration w/ SYRTE (→ French National time) to create a generic time distribution system usable on other experiments.



- Absolute time requirements for HK : ± 100 ns.
- Largely achieved w/ our system based on Rb clock. ✓
→ Deviation of 10^{-12} s/day.
- Wish $\uparrow$ accuracy in future (v mass measurements etc.) ✓
→ Reach 10^{-12} s w/ corrections.

First stage distribution

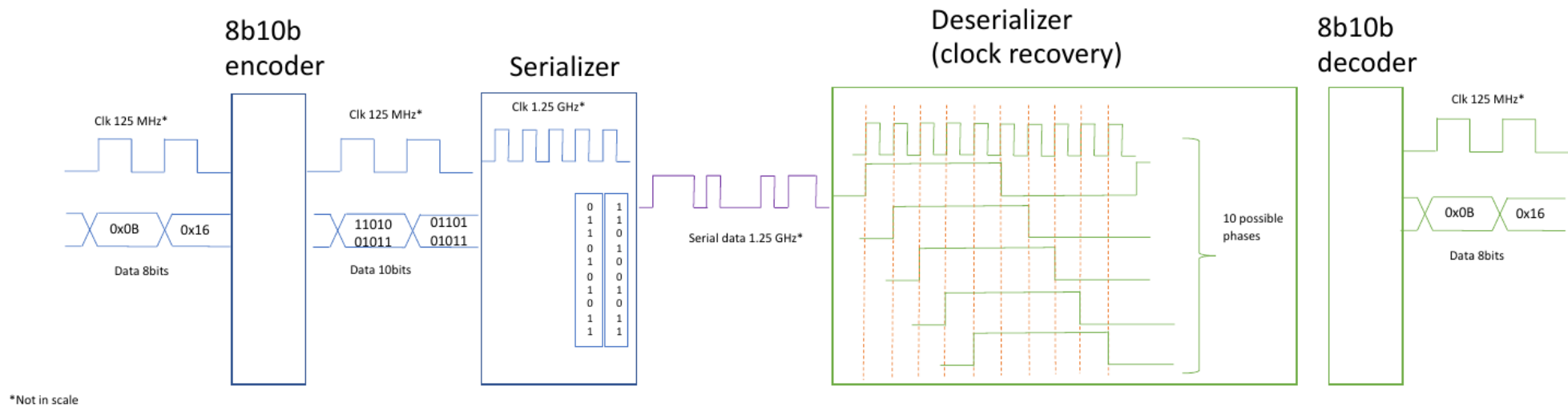
- First stage is on surface :
 1. Generates the 125 MHz clock for Hyper-K from the 5 MHz of the atomic clock.
 2. Broadcasts this clock and synchronize command to 2nd stage.
- CEA-IRFU has realized the 1st distribution stage very first prototype.



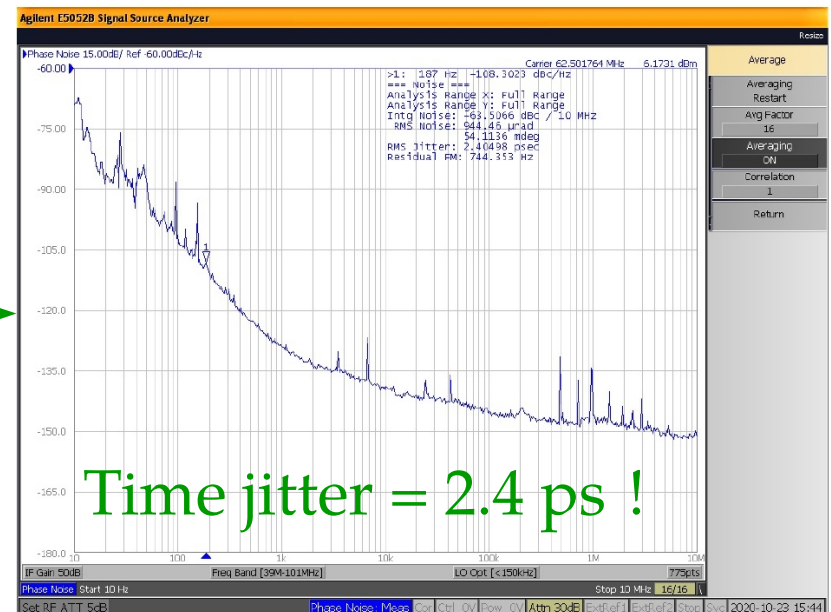
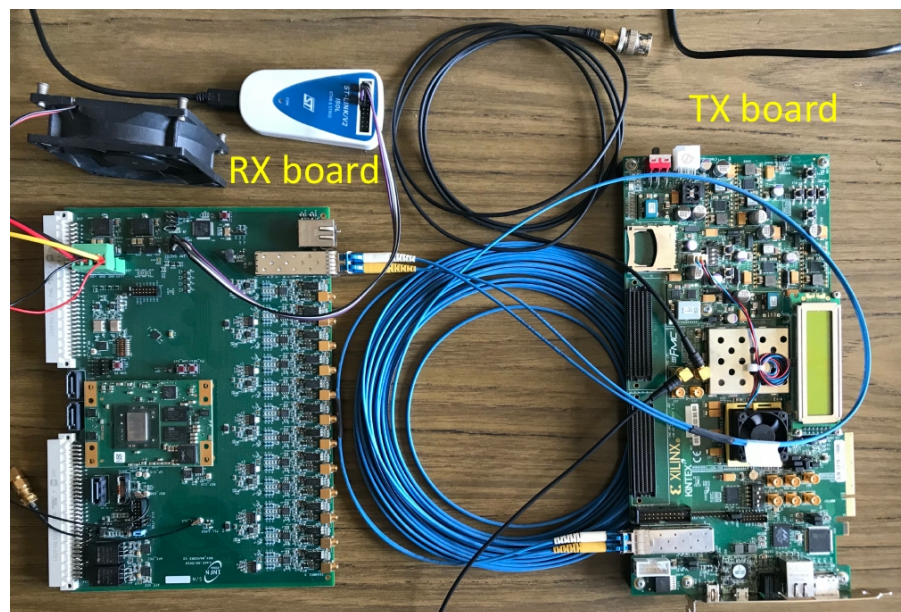
- The board has been received in April.
- Most of the tests are finalized.

Second stage distribution

- Second stage at surface & in water vessel :
→ Encodes, sends, & decodes the clock.

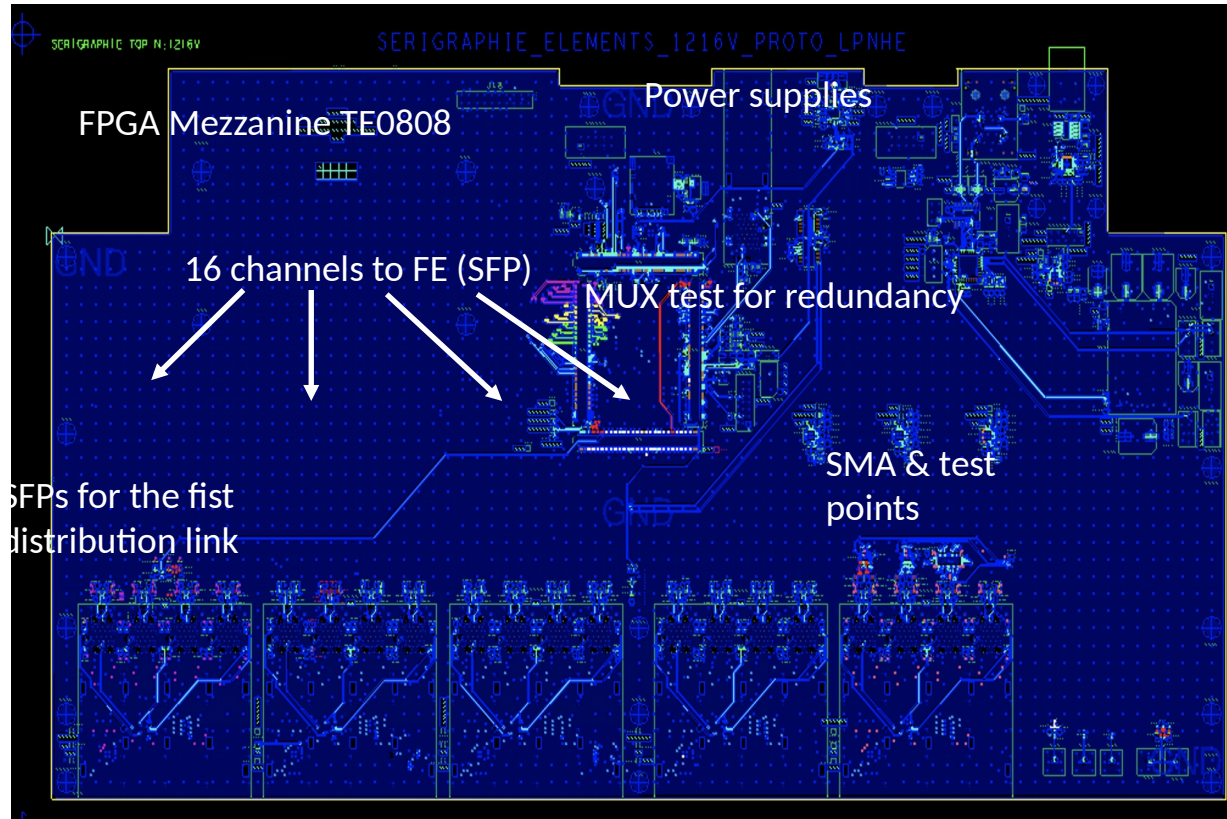


- Concept tested at LPNHE :

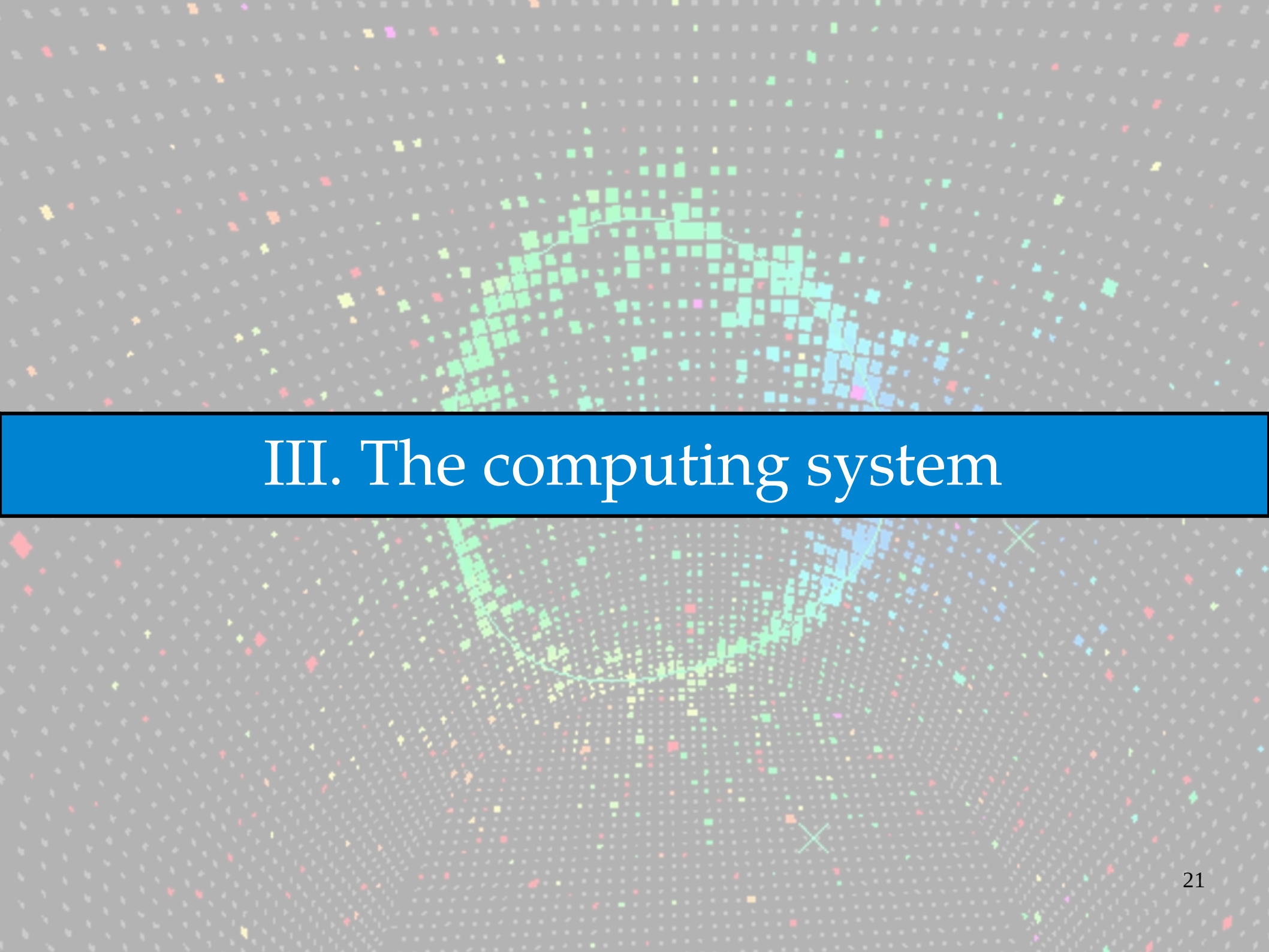


Second stage distribution

- Second stage prototype board : design finalized & send to fabrication.
→ Back at LPNHE on the 18th of November (2022).



- Firmware : under development using the same mezzanine (TE0808) and a motherboard EBV → On-going tests on the Front-end side.
- Software : Embedded under dev. Linux OS already installed and tested. Most peripherals control's sw already written.

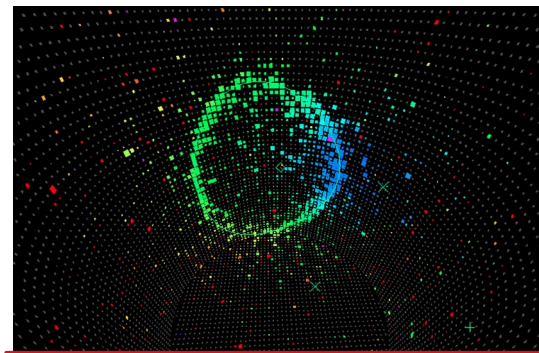


III. The computing system

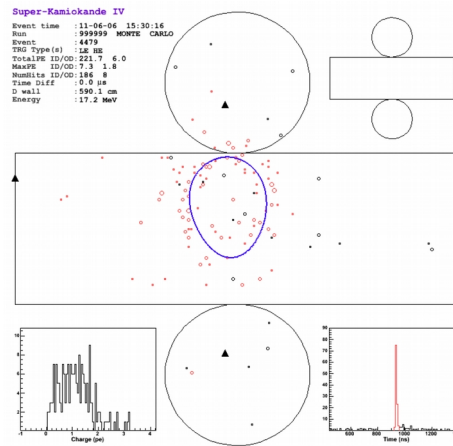
The HK computing strategy

Data & simulation storage

CPU resources



Trigger happens



Raw data

Copy of raw data
Simulated raw events

Simulation

Calibration

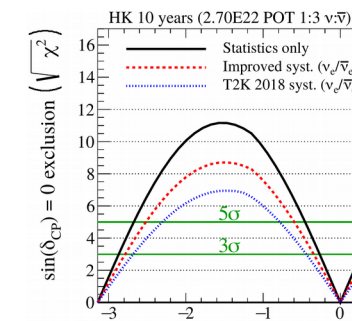
Calibrated data
Calibrated simulation

Reconstruction

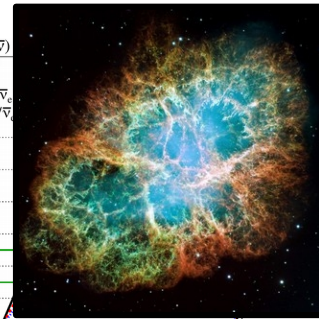
Reconstructed
data & simulation

Physics
analyses

ν oscillation, DSNB search, GUT



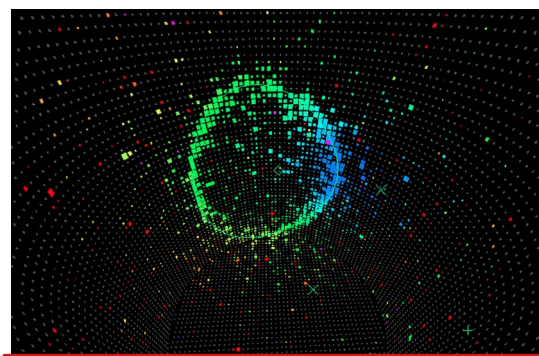
Hyper-K preliminary
True normal hierarchy (known)
 $\sin^2(\theta_{13}) = 0.0218$ $\sin^2(\theta_{23}) = 0.528$ $|m_{21}^2| = 2.509\text{E-}3$



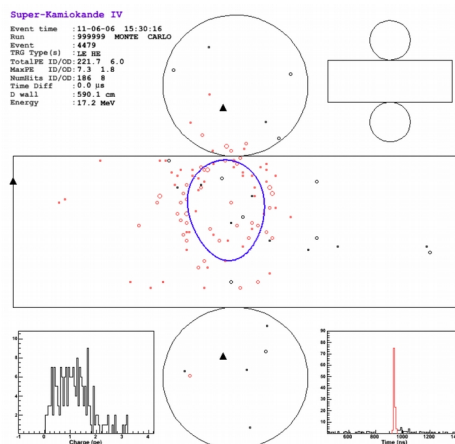
The HK computing strategy

Data & simulation storage

CPU resources



Trigger happens



Raw data

Tier 0

Copy of raw data
Simulated raw events

Tier 1

Calibrated data
Calibrated simulation

Reconstructed
data & simulation

ν oscillation, DSNB search, GUT

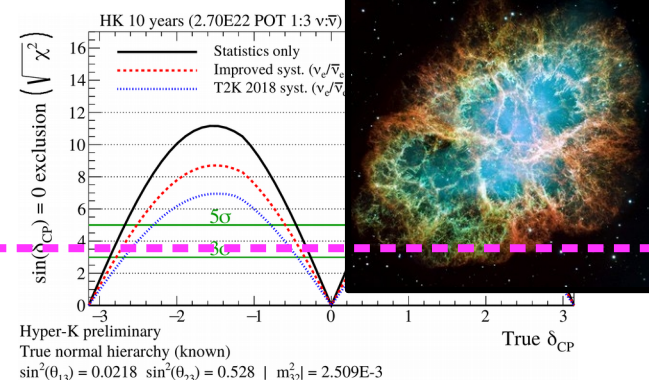
Simulation

Tier 2

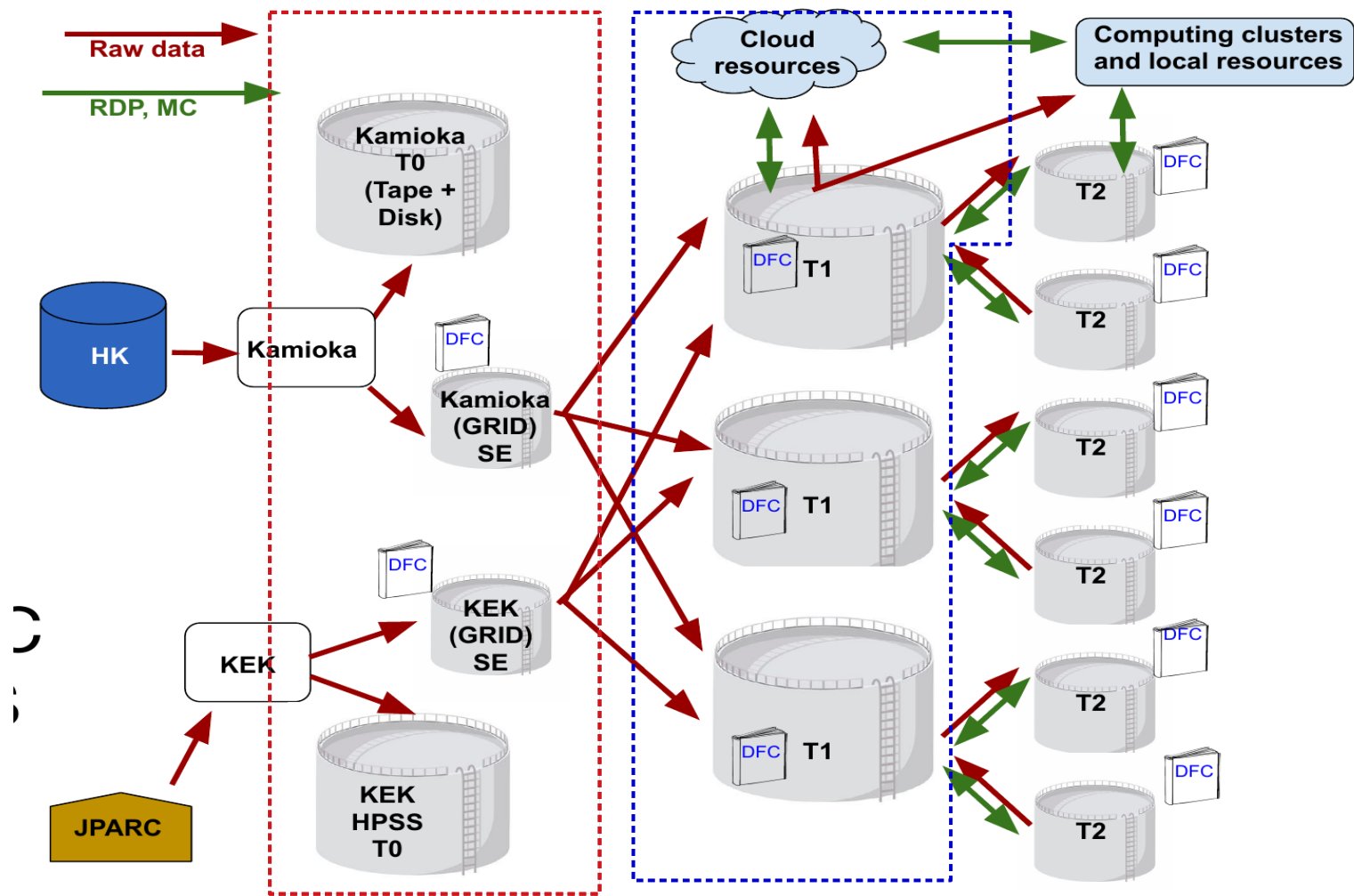
Calibration

Reconstruction

Physics
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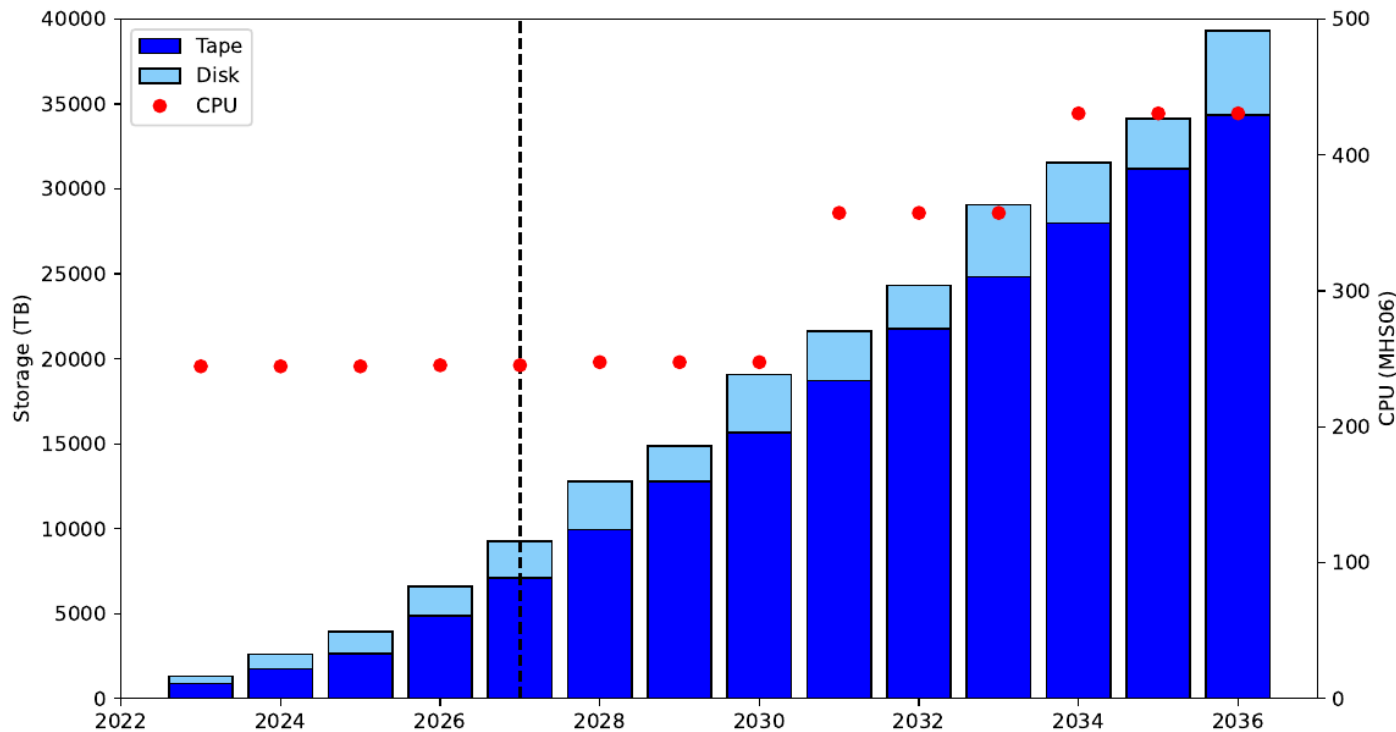
The HK computing strategy



- Each single data file & MC file → Copied on ≥ 2 Tier 1 sites.
- MC productions run on Tier 1.
 - The Tier 1 site contains a copy of each data & simulation file !
 - Offers a central visibility .

The IN2P3 teams computing proposal

- Make CC-IN2P3 a **Tier-1** site to host all HK data.



- Pros :

1. No other group has announced the capacity of a full Tier 1 so far.
2. Having all data in France offers an unparalleled visibility.
3. Full synergy with our goal to lead the analyses in both low and high energy sectors.
4. CC-IN2P3 is already Tier-1 for T2K INGRID & ND280 data & Host the Hyper-K data base since 2022 (synergy with KM3NeT).²⁵
→ Smooth transition & preparation until 2027.

Resources to host a Tier 1 at CC-IN2P3

- How much resources are required to store all HK data ?

→ Overall over 15 years : driven by the Far Detector

Name	Distance along beam	Angle wrt. beam	Expected data rate
INGRID	280 m	0°	78 GB/day
ND280	280 m	2.5°	214 GB/day
IWCD	2 km	0° – 4°	170 GB/day
Far detector	295 km	2.5°	5 TB/day

→ 2 PB / year for HK : Belle-II = 100 PB / year, DUNE = 30 PB/year.

- Full data storage & CPU requested

Detector	Data and MC Storage (TB)	MC (HS06 CPU.h)
INGRID	226	0.51M
ND280	6,891	384M
IWCD	1,460	6700M
Far detector	27,3630	2,004M
Total	35,715	9,138M

→ Corresponds to
~4600 CPU available
at all time for whole
HK (not CC-IN2P3).

→ Require CC-IN2P3 to have 3000 CPU available in average for HK.

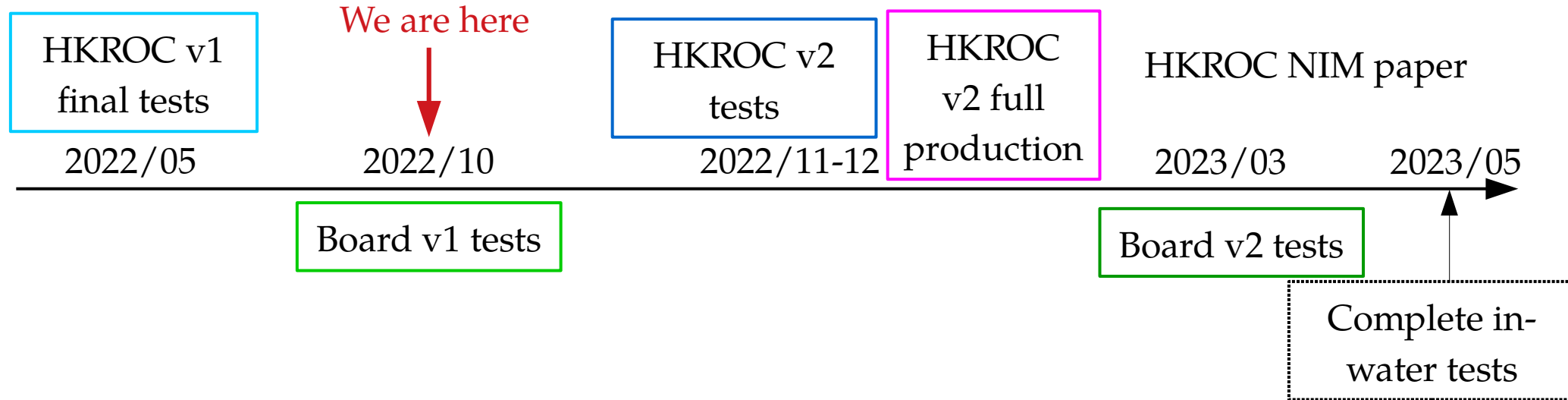


III. Incoming steps & timeline

Prospects for the HKROC digitizer

- 2 other digitizers were competing for HK : QTC (Japan), discrete (Italy).
→ Unfortunately, HKROC not chosen as primary solution for HK.
- Summary of the review:
 1. All 3 solutions for HK digitization are suitable both in terms of minimal requirements & schedule.
 2. The HKROC team has clearly shown the large advantages for physics.
 3. The HK management preferred an already finalized solution with less impact on physics compared to HKROC which will be finalized in 8 months → The main reason we were not selected was that we did not had an on-shelf solution ready (others had).
- HKROC has been built to be a waveform digitizer for any PMT-based experiment for the next 10-15 years.
→ We will finalize the HKROC development all the way to a modular front-end board.

HKROC digitizer timeline



- We propose to keep our R&D original schedule :
→ **First complete digitizer board in spring 2023.**
- Several papers are prepared for a publication at the end of spring 2023.
→ Based on HKROC v2 & prototype board v1.
→ One NIM + others.

Status & timeline for the clock

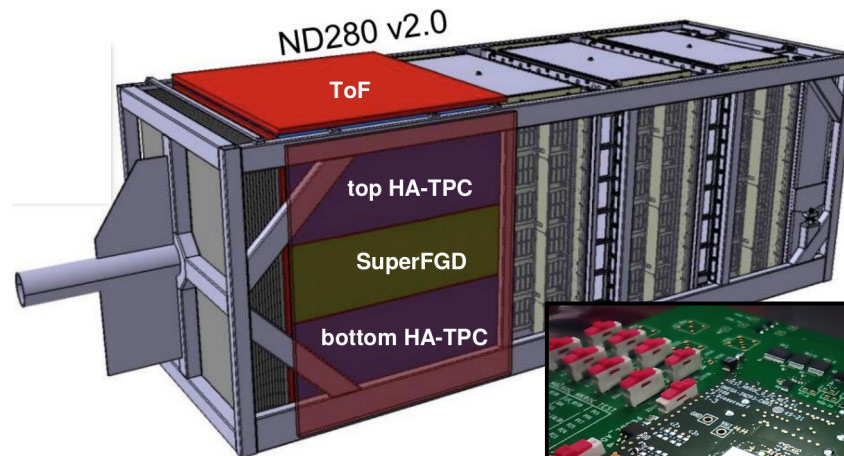
- Final time generation & distribution scheme presented and **validated by the HK electronics group.**
- The timing system technical **note has been submitted and is under technical evaluation.**

→ *Thanks to the incredible work from LPNHE/IRFU & financial support provided by IN2P3 so far, the HK Steering&Resource board **recognized that the IN2P3-CEA-INFN joint group is responsible for building the clock distribution & time synchronization system** for the HK detector.*

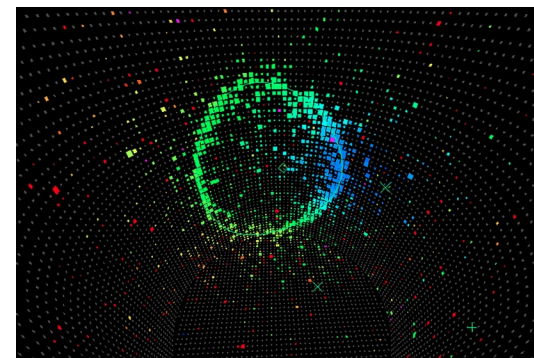
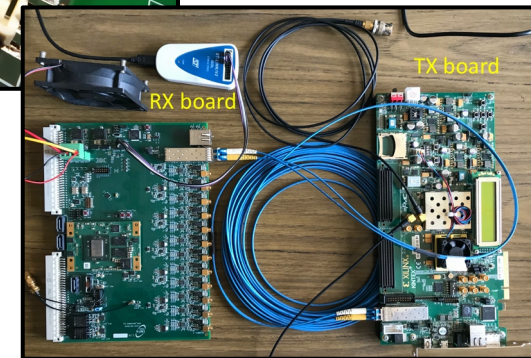
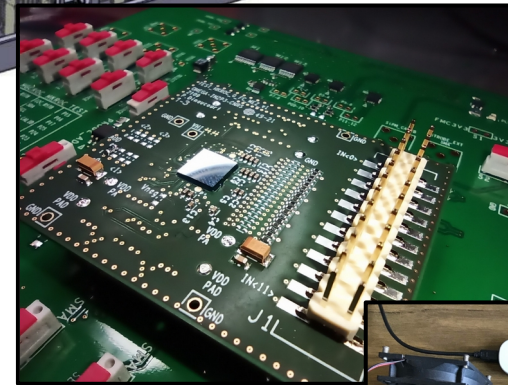
- **Significant progresses on-going** : ahead of official schedule
 - The development is going **perfectly well & on-time !**
 - Ordering components for the final production has started (plan 80 boards for the second distribution stage).
- **As for the digitizer** : the time-generation & clock distribution systems have been developed to be **generic & usable for other experiments.**
 - **NIM paper publication in 2023.**

Summary of proposed contributions

Our updated proposal @CS :



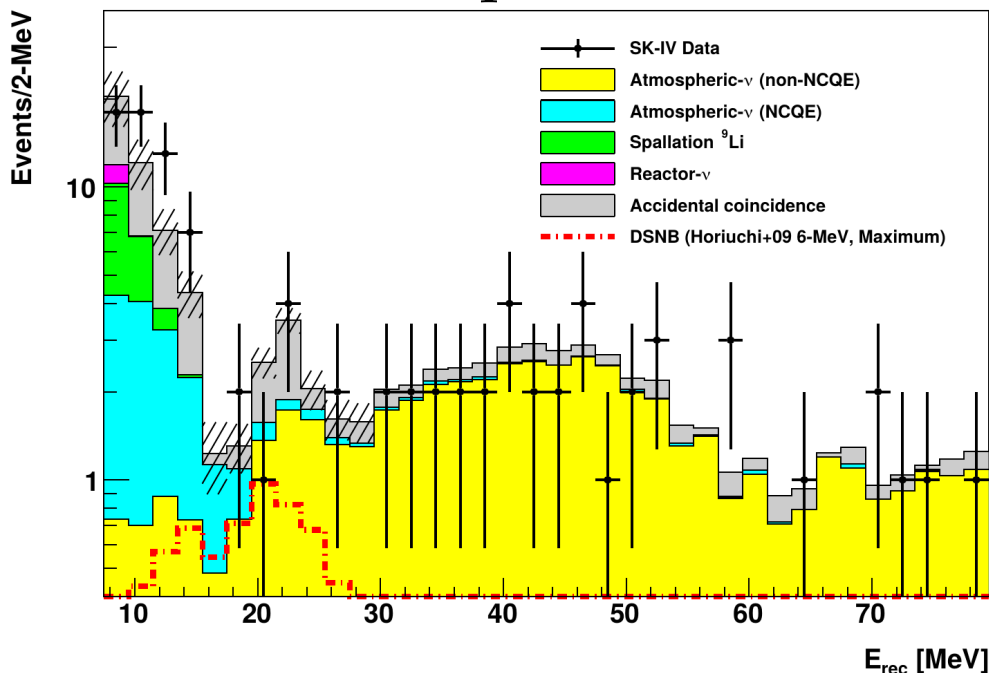
- The ND280-upgrade.
- ~~HKROC complete digitizer for ID & OD.~~
- Time generation & clock distribution at Far Detector.
- Shared-item cost & assembly.
- CC-IN2P3 : HK Tier 1 computing system.



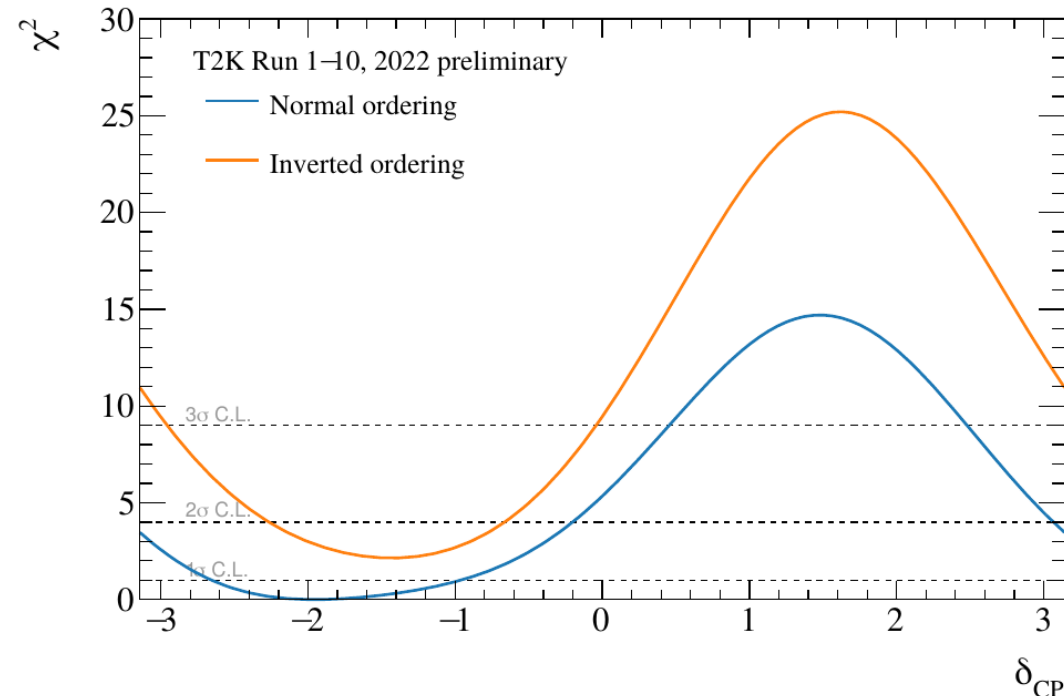
Physics & analyses in T2K-SK era

- IN2P3-groups have central roles in T2K & Super-Kamiokande physics.
 - Near-detector physics : upgrade & cross-section conveners @IN2P3
 - ν oscillation analysis : convener @IN2P3.
 - Leader of the SK DSNB ν analyses in 2018-2022 @IN2P3

DSNB ν @Super-Kamiokande



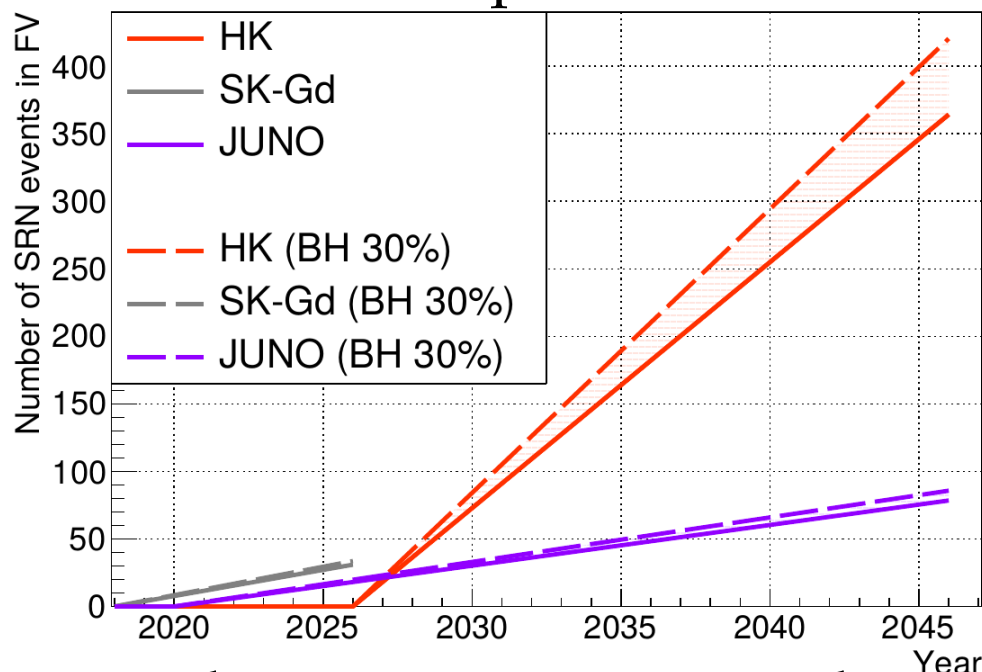
CP violation @T2K



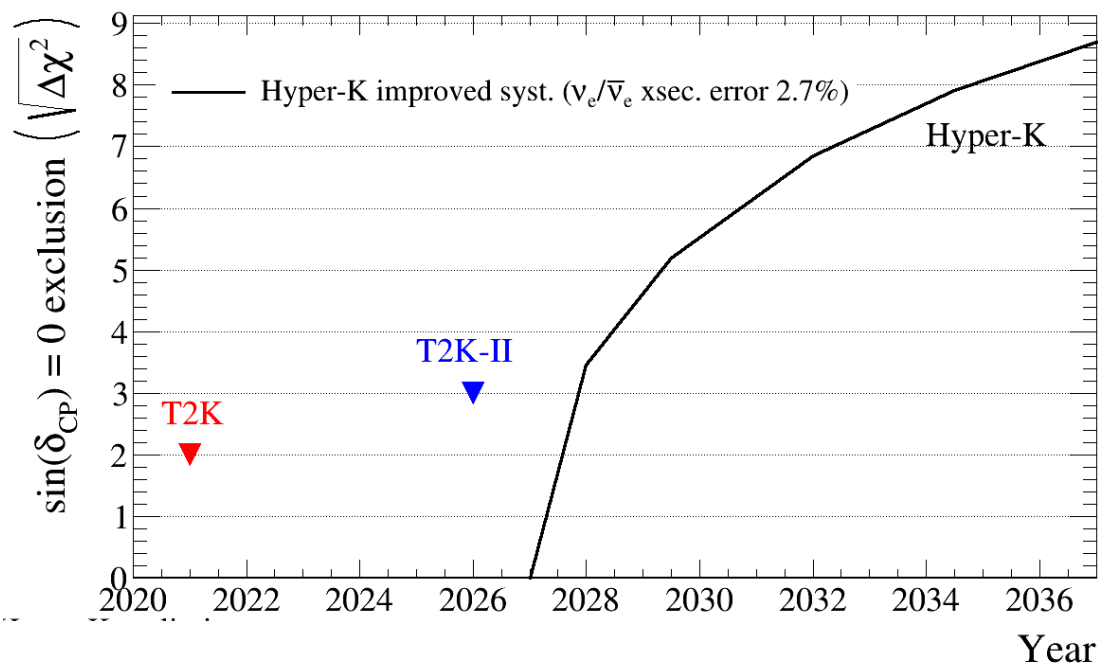
- Our goal : Lead the future Hyper-K analyses from 2027 !
 - Most of existing softwares on SK ≥ 15 years-old : already starts to be outdated & **cannot be scaled to Hyper-K** !

Step-up towards HK era

DSNB ν @Super-Kamiokande



CP violation @T2K



- Need new reconstruction algorithms to extract HK physics potential !
→ And there are still vacant seats to lead these aspects.
- At IN2P3 : have the unique chance to test them on 10-20 years of Super-K & T2K data before HK start & reach major physics milestones
→ Discover the DSNB @SK-Gd, CP violation and mass ordering at 3σ ...
→ To prepare this major task in parallel of T2K/SK and build-on this strengths, we need new members in our groups.

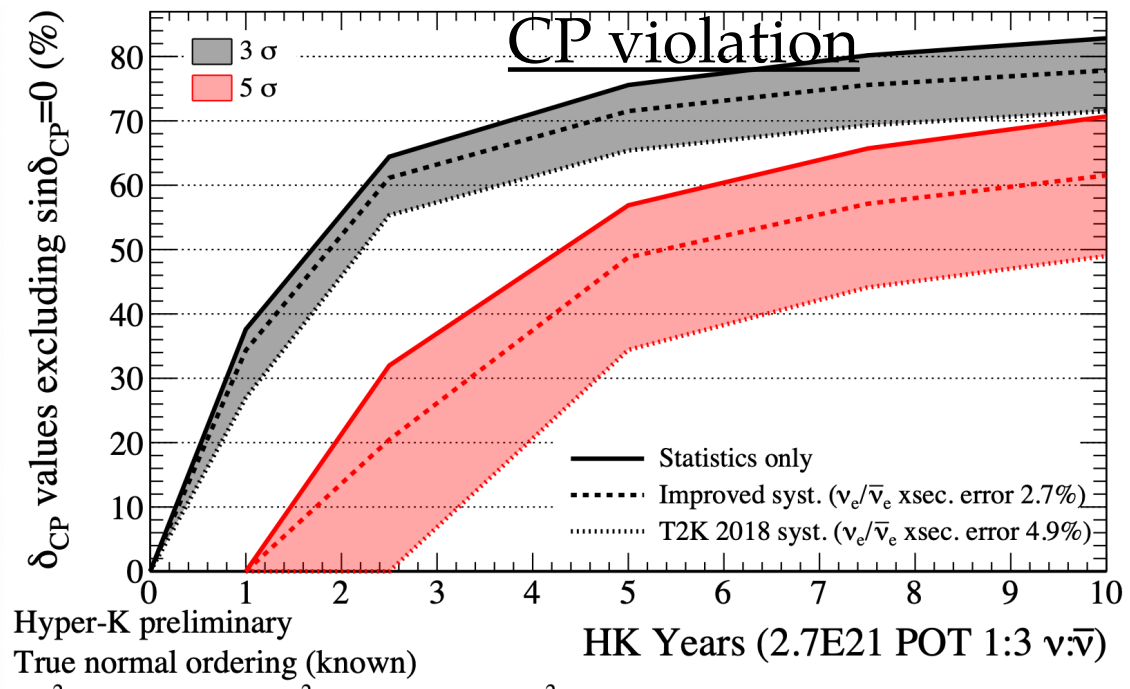
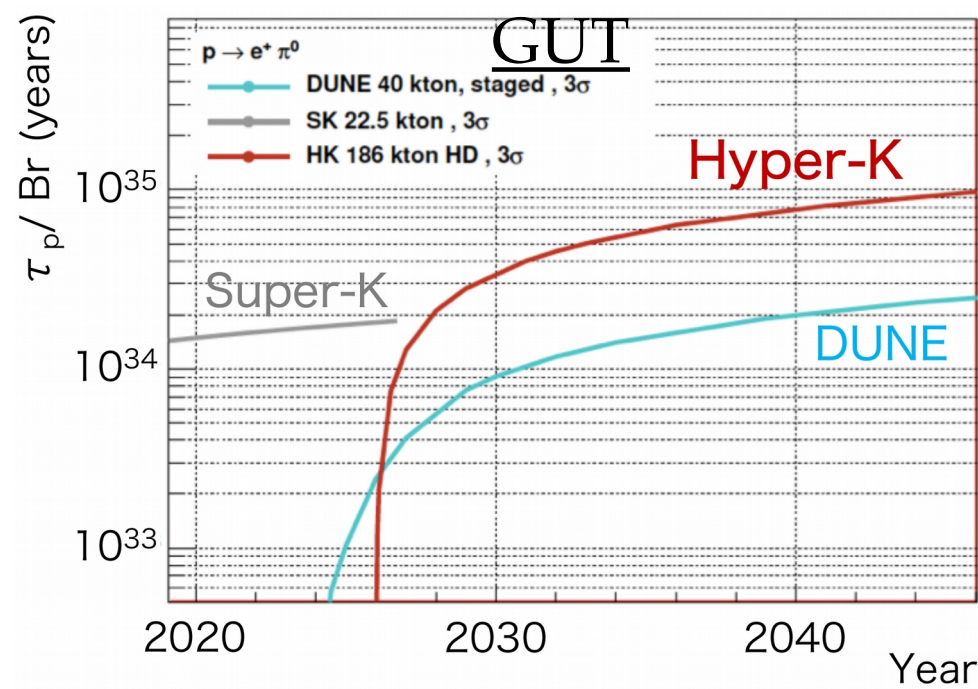
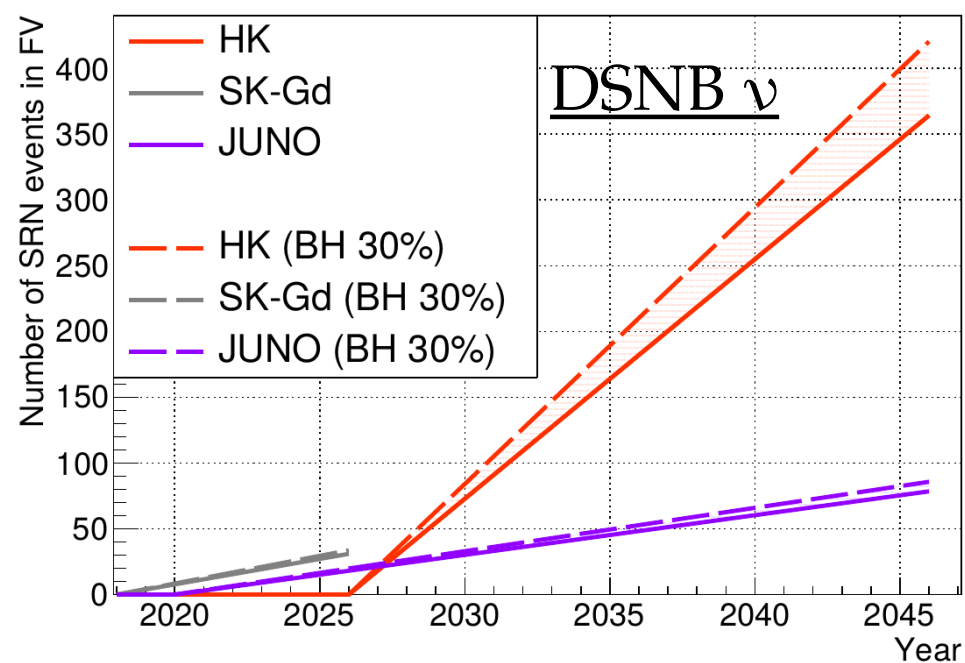
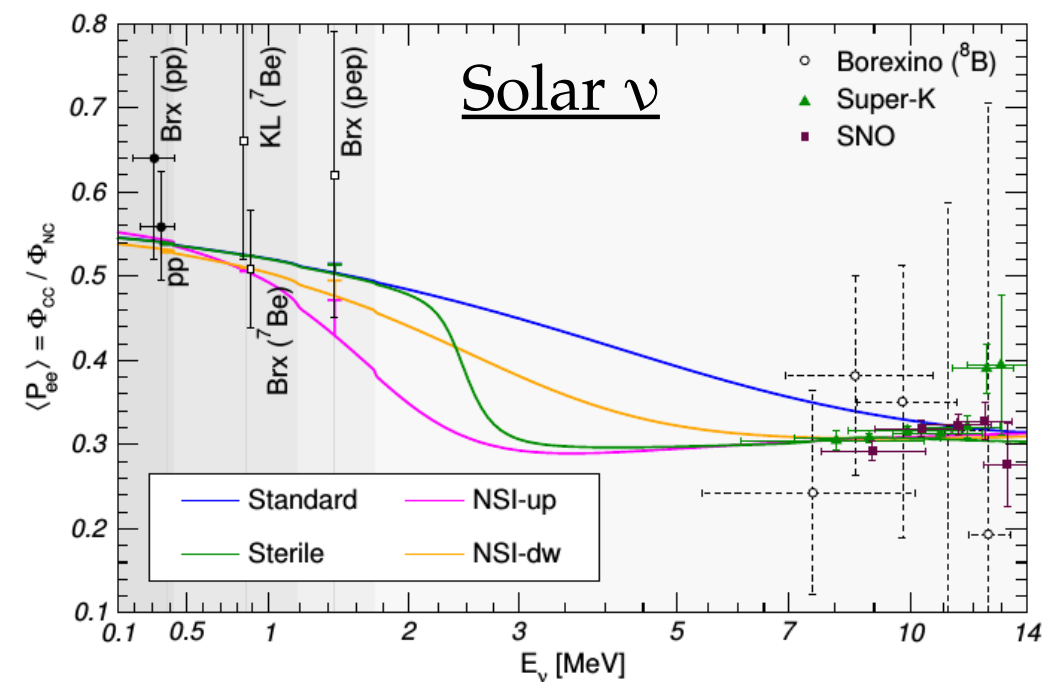
Conclusions

- Hyper-K will be the world-leading experiment in many aspects of neutrino physics for the next 20 years.
- RD4HK only started in 2022, but tremendous progresses were made :
 1. The HKROC ASIC has been received and completely characterized
 - Excellent agreement with expectations, though this is very 1st version.
 - Largely surpass existing CATIROC & other solutions in Hyper-K.
 - Very very small cross-talk found (0.02 %) → ↓ by 100 in HKROC v2.
 2. Clock generation & distribution system scheme has been completed :
 - Time generation system has been validated through measurements.
 - First stage distribution 1st prototype completely characterized.
 - Second stage distribution 1st prototype to be received in 2 weeks !
- Huge technical achievements & success in only 1 year !!
 - Great collaboration between the LLR, LPNHE, OMEGA & IRFU₃₄
 - + financial support from IN2P3.

Conclusions

- HKROC digitizer & clock system development will continue in 2023.
 - Final production-ready digitizer for HKROC : ready by summer 2023
 - Timing : All the way to production !
- To build & lead HK physics for next 20 years, we need to build on RD4HK to go beyond **NOW** :
 1. Make CC-IN2P3 a Tier-1 site for HK :
 - Absolutely central visibility & acces to data at a cost of 2 PB/year.
 - Worked to make CC a Tier 1 for ND280 & host HK data base.
 2. Build on our leaderships & expertize in T2K / Super-K (acquired after 15 years of continuous work & investment by IN2P3) to lead the future HK low & high energy analyses.
- **This is the time to transform this project into a master project !**

Conclusions





Additional slides

HKROC digitizer - Impact on physics

- Conclusion de la revue: malheureusement, HKROC n'a pas ete selectionne en premiere position par Hyper-K.

Item	HKROC	QTC	Discrete	Weight
Basic requirements	4	4,857143	4,8571429	30,00%
Comparison of technical performance beyond basic requirements	4,428571	2,428571	3	15,00%
Proposed schedule and risks	3,071429	4,714286	4,7142857	25,00%
Resources	4,857143	4,428571	4,2142857	15,00%
Reliability	4,142857	4,214286	4,1428571	15,00%
TOTAL	3,982143	4,296429	4,3392857	

- En resume :

1. Les 3 solutions ont ete retenue comme parfaitement viable pour HK.
2. Le cross-talk de l'ASIC a impacte les « basic requirements & schedule. »
3. L'equipe HKROC a su demontre ses larges avantages sur la physique.
4. Le management a clairement prefere une solution déjà finale moins ambitieuse a une solution optimale mais qui sera finale dans 8 mois.

→ Nous avons **decide de proposer un projet alternatif permettant de maintenir ne visibilite forte pour l'IN2P3 et l'IRFU** : plusieurs options sont en cours d'evaluation/negociation.

Rappels de l'organisation RD4HK

Responsable national : B. Quilain

HKROC

F. Dulucq (OMEGA)

Digitiseur

J. Nanni (LLR)

Generation horloge

M. Guigue (LPNHE)

Distribution horloge

S. Russo (LPNHE)

OMEGA

S. Callier (IR)
S. Conforti (IR)
C. De la Taille (IR)
P. Dinaucourt (AI)
F. Dulucq (IR)
A. Mghazli (IR/CDD)
L. Raux (IR)
→ 1.3 FTE / an IR

LLR

A. Afiri (IR/CDD)
L. Bernardi (IR)
F. Gastaldi (IR)
J. Nanni (IR)
→ 1.2 FTE / an IR
A. Beauchene (PhD)
M. Buizza-Avanzini (CR)
O. Drapier (DR)
T. Mueller (CR)
P. Paganini (DR)
B. Quilain (CR)
→ 1.8 FTE / an phys.

LPNHE

E. Pierre (IR)
S. Russo (IR)
V. Voisin (IR)
→ 1.3 FTE / an IR
M. Guigue (MdC)
C. Giganti (CR)
L. Meller (PhD)
B. Popov (DR)
M. Zito (DR)
→ 1.2 FTE / an phys.

ILANCE

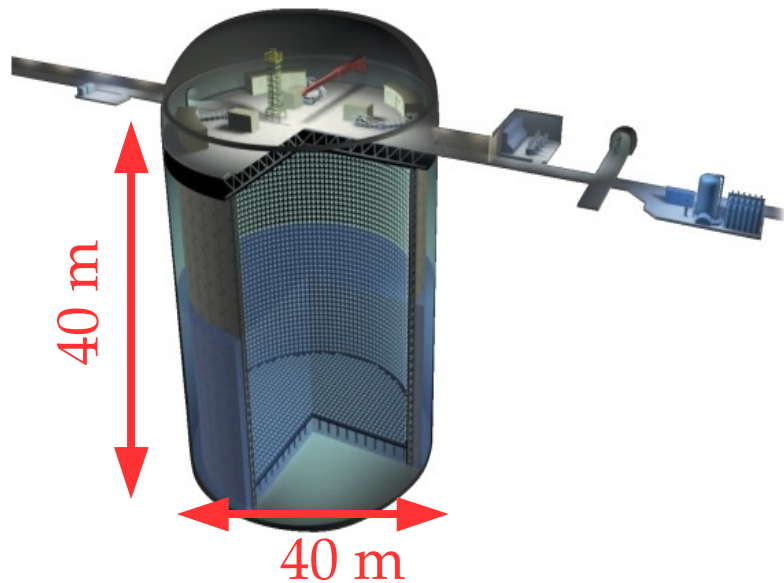
M. Gonin (DR)
G. Pronost (Posdoc)
→ 1.2 FTE / an phys.

**FTE moyens calculés
sur 4 ans 50
(01/2022-12/2025)**

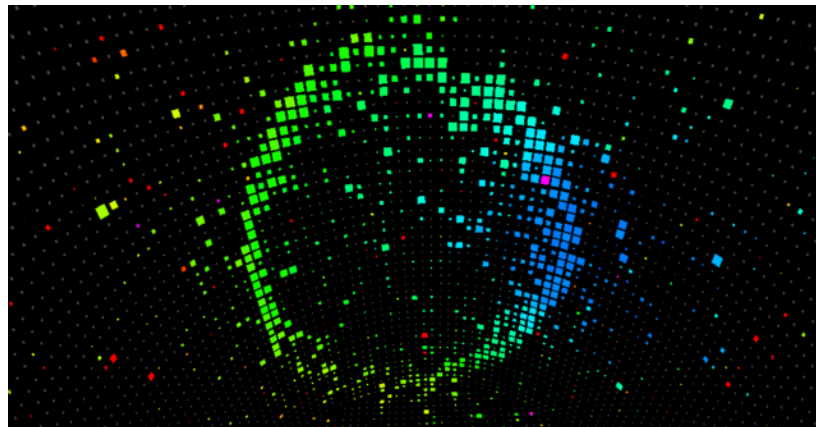
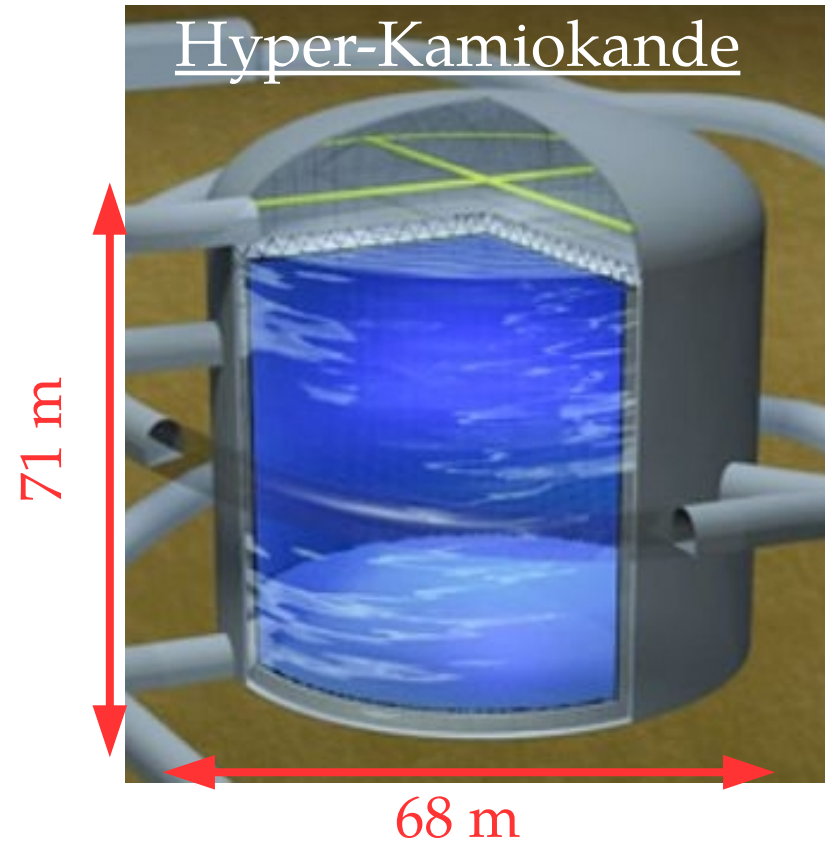
Reminder : what is Hyper-K ?

- Next generation of neutrino observatory in Japan → construction 2020-27
→ A 260 kton water Cherenkov detector → Fiducial Mass ~ 8 x SK.

Super-Kamiokande



Hyper-Kamiokande



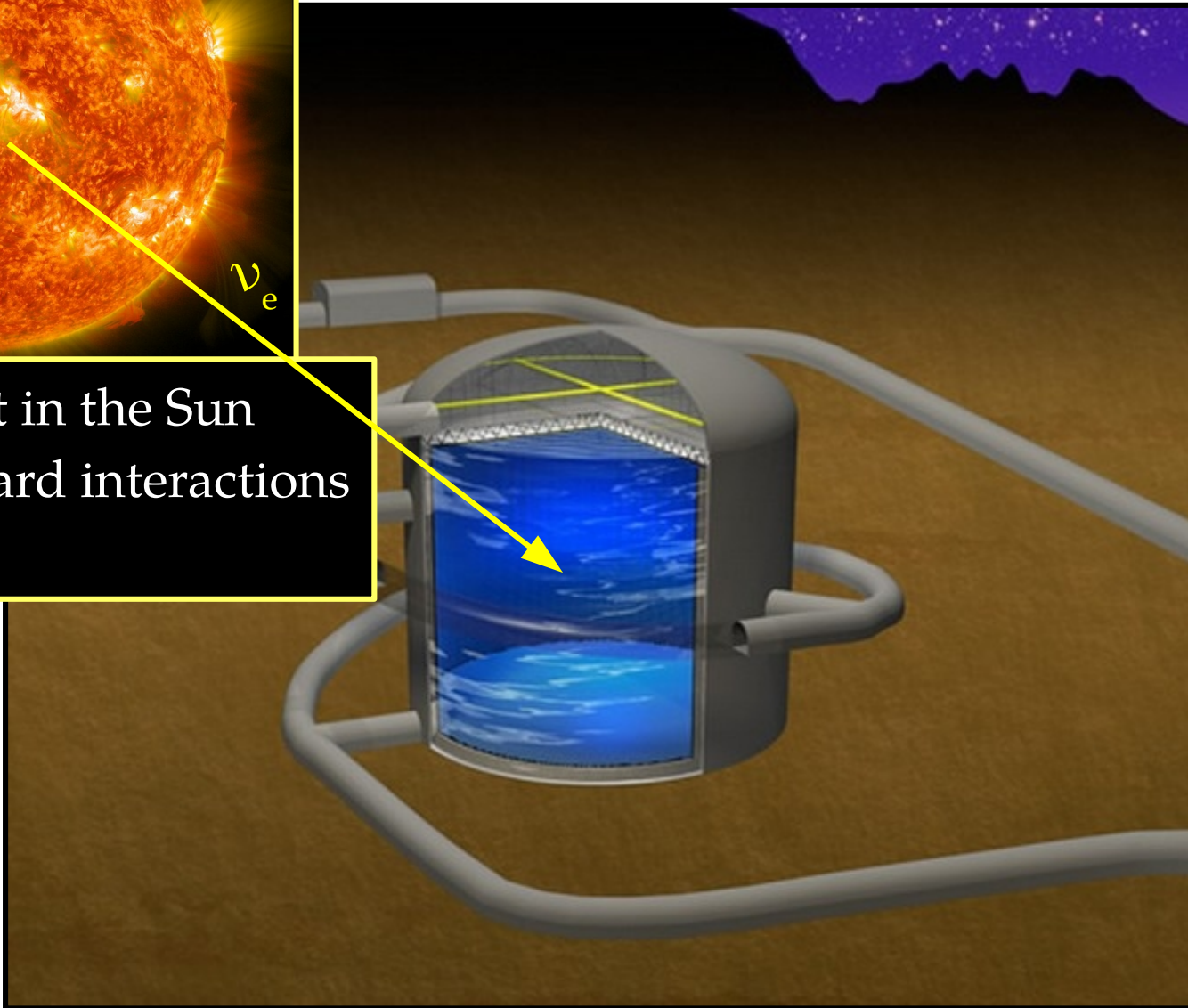
	Super-K	Hyper-K (1st tank)
Site	Mozumi	Tochibora
Number of ID PMTs	11,129	40,000
Photo-coverage	40%	40% (x2 sensitivity)
Mass / Fiducial Mass	50 kton / 22.5 kton	260 kton / 187 kton

Solar neutrinos

Physics case

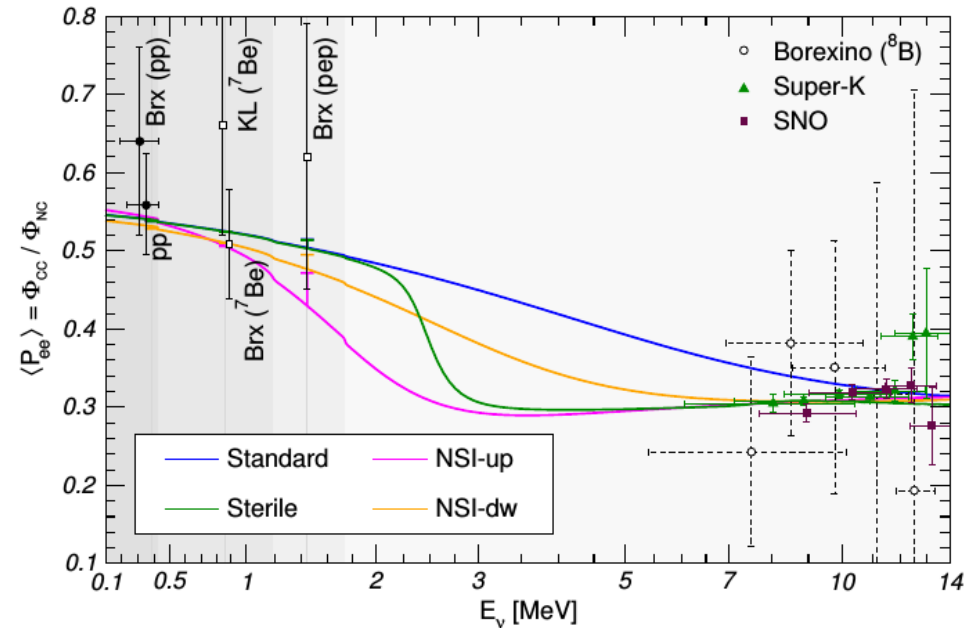
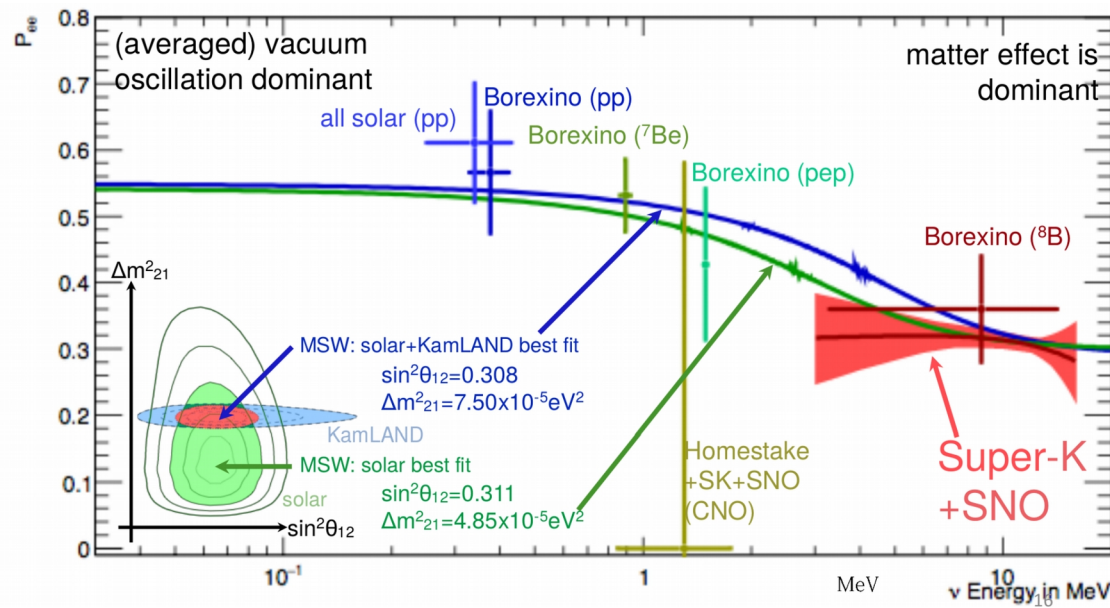
- MSW effect in the Sun
- Non-standard interactions in the Sun.

ν_e



Solar neutrinos : upturn

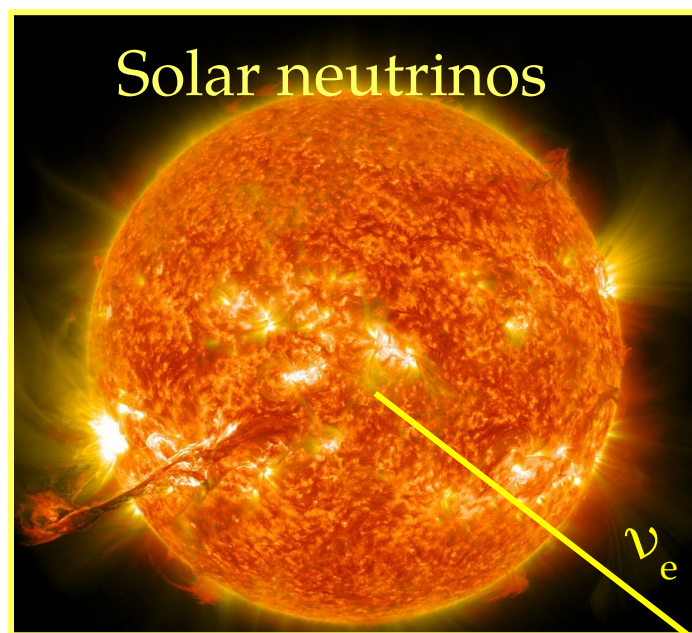
- Probe solar ν : SK/SNO found a high matter effect in the Sun
 $\leftrightarrow$ Solar upturn shifted to lower energies



- SK deviates from standard upturn scenario $> 2\sigma$.
- Displacement of the upturn can be explained by :
 - Statistical fluctuation ?
 - Light sterile neutrino ?
 - Non Standard Interaction in the dense Sun ?

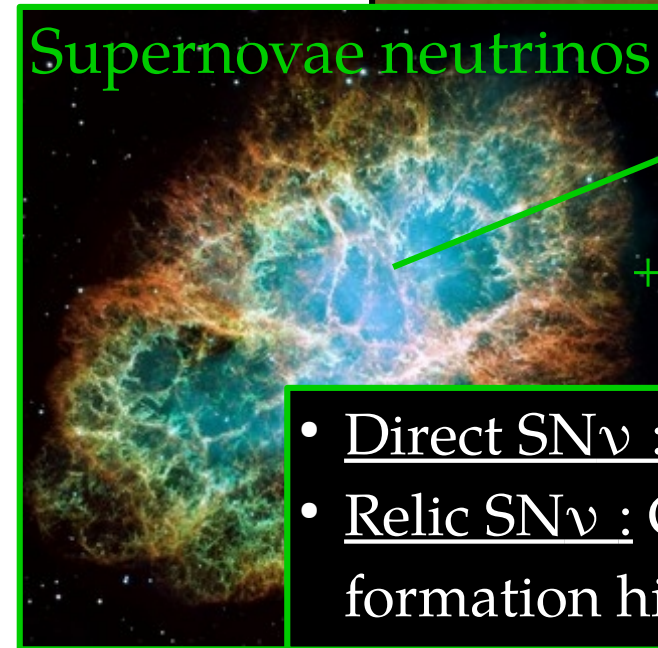
Physics case

Solar neutrinos

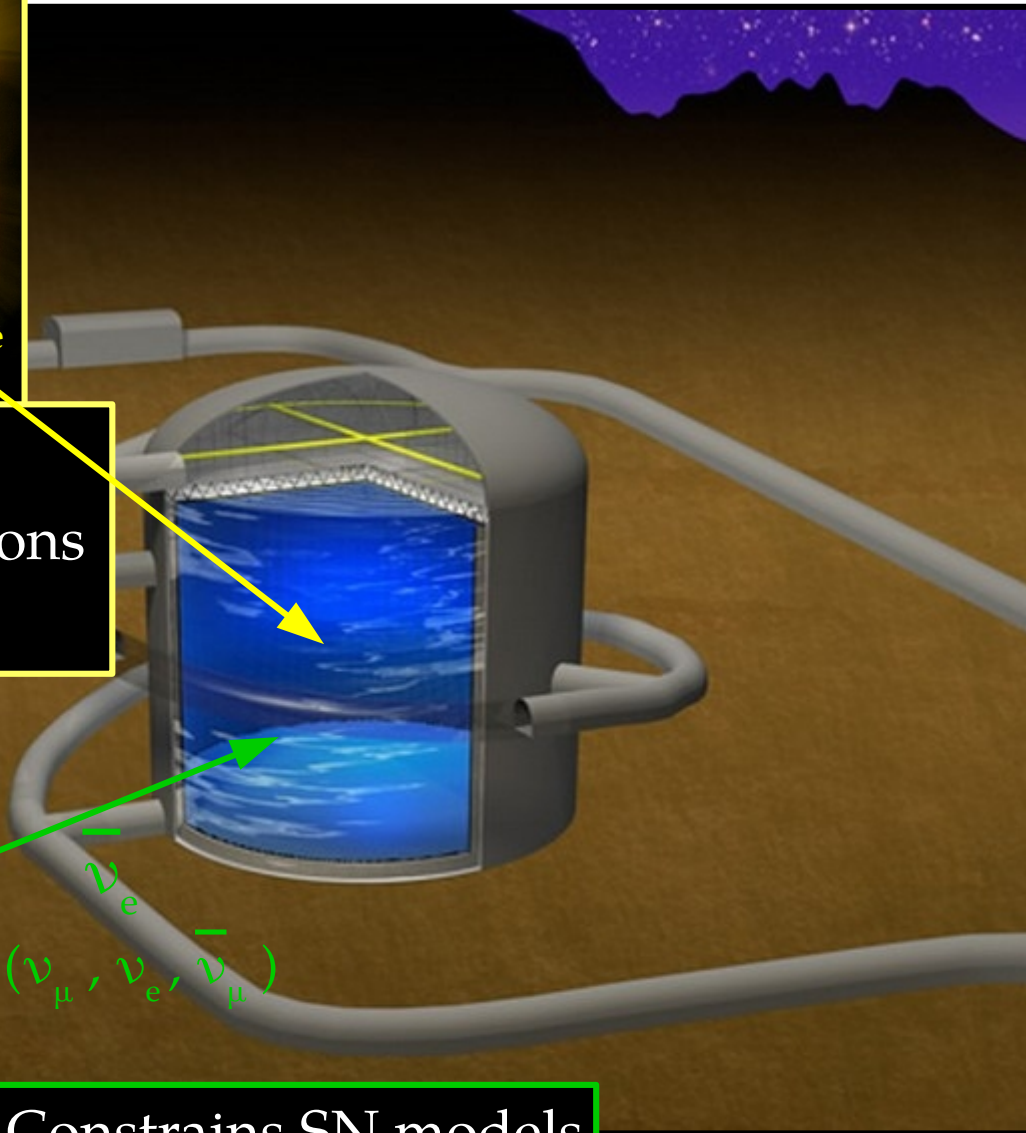


- MSW effect in the Sun
- Non-standard interactions in the Sun.

Supernovae neutrinos



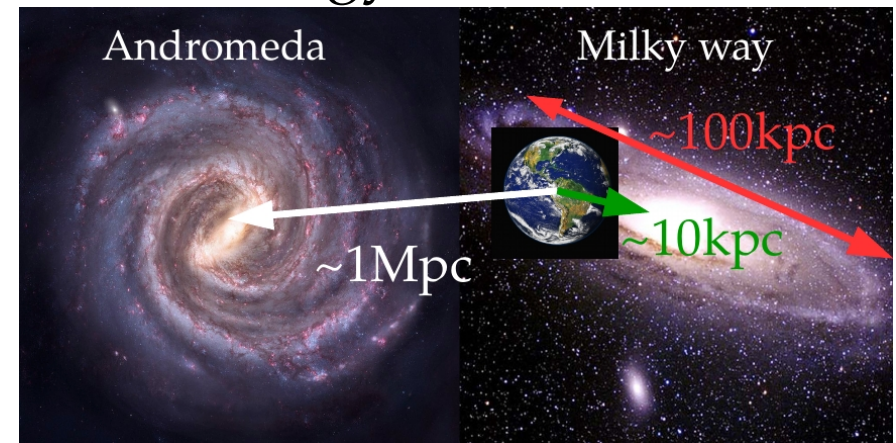
- Direct SN ν : Constrains SN models.
- Relic SN ν : Constrains cosmic star formation history



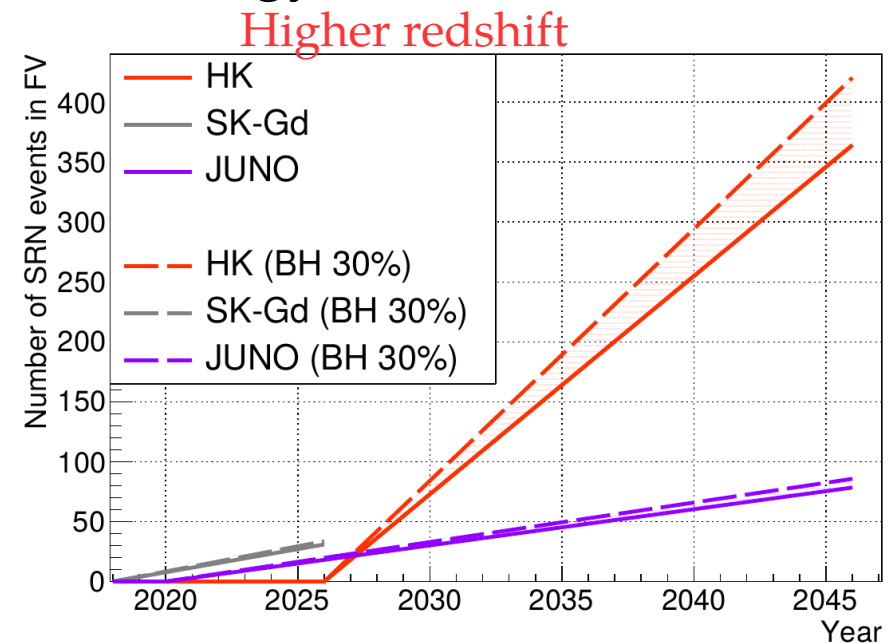
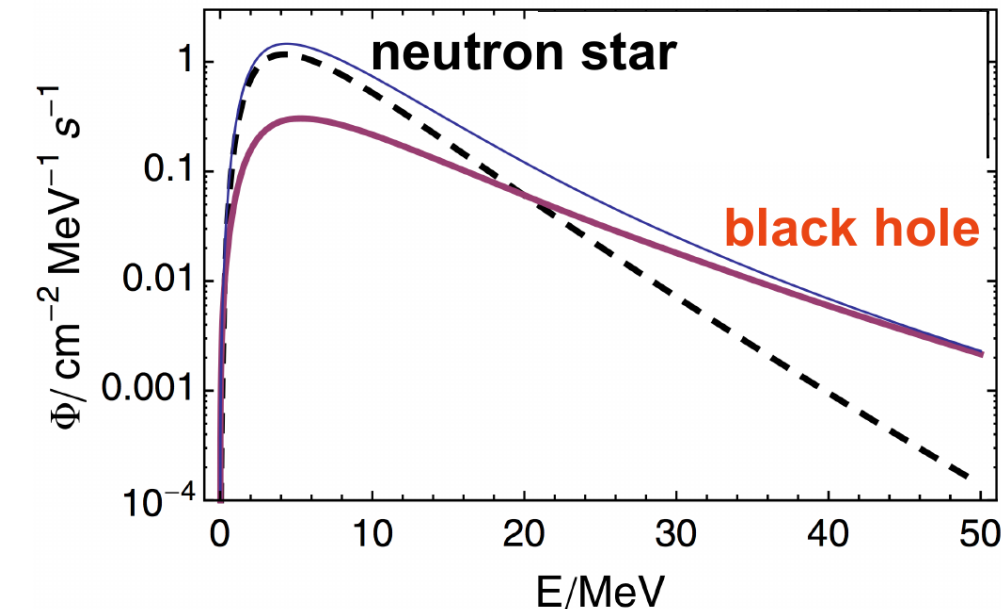
Supernovae neutrinos

- Unique probe for supernovae ν : 99 % of SN energy $\rightarrow \nu$.

- But direct ν detection very rare.
- HK also sensitive to extra-galactic SN ν from Andromeda !



- SN-relic neutrino $\rightarrow$ new constraints on cosmic star history $\rightarrow$ May be first detected in SK-Gd.
 $\rightarrow$ But spectrum determined by HK : Low energy $\leftrightarrow$ Probe older stars



- SK-Gd & then, HK are the pioneer experiments of this domain !

Solar neutrinos

Physics case

Proton decay

Probe Grand Unified Theories through p-decay (world best sensitivity)

- MSW effect in the Sun
- Non-standard interactions in the Sun.

Supernovae neutrinos

- Direct SN ν : Constrains SN models.
- Relic SN ν : Constrains cosmic star formation history

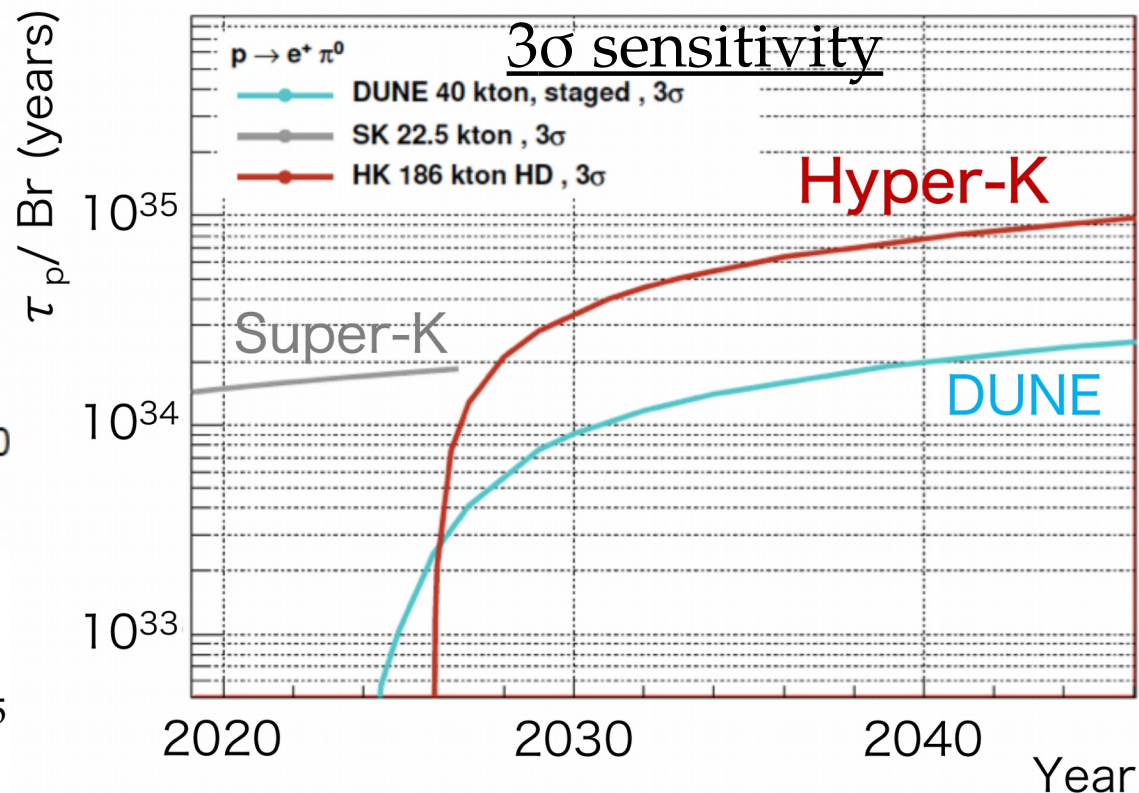
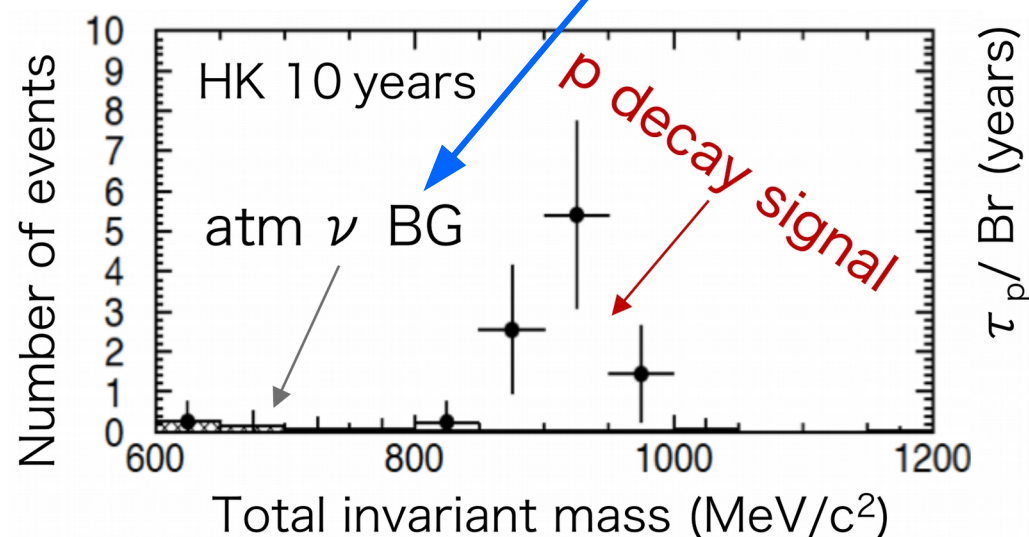
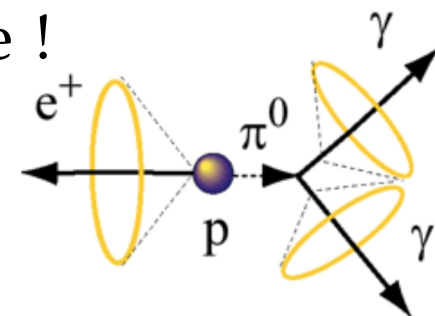
GUT and proton decay

- Probe Grand Unified Theories at a new scale through proton decay.

- Golden channel : $p \rightarrow e^+ + \pi^0 \rightarrow$ Almost background free !

→ Requires 2γ & reconstructed energy = Invariant M_p

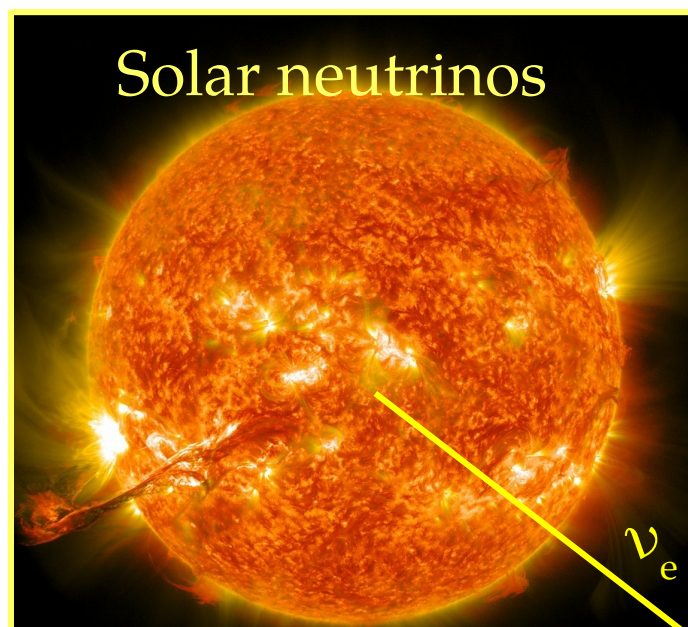
→ Bkg : Atmospheric ν producing e.g. a π^0 .



- 3σ sensitivity reach $\tau_p / \text{Br} = 10^{35}$

years → 1 order of magnitude beyond SK or DUNE

Solar neutrinos



- MSW effect in the Sun
- Non-standard interactions in the Sun.

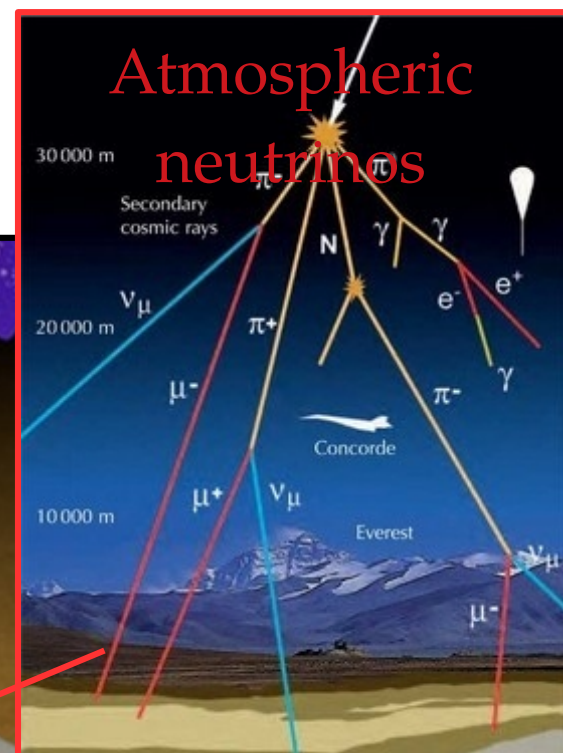
Physics case

Proton decay

Probe Grand Unified Theories through p-decay (world best sensitivity)

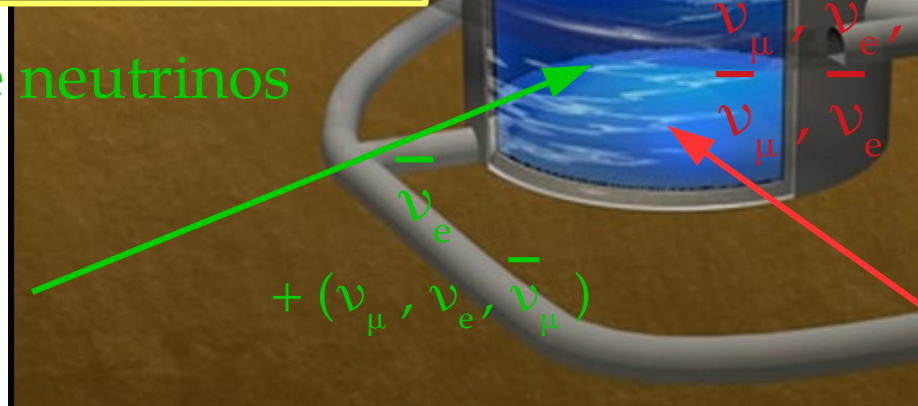


Atmospheric neutrinos



- Observe CP violation for leptons at 5σ
- Precise measurement of δ_{CP} .
- High sensitivity to ν mass ordering.

Supernovae neutrinos



- Direct $SN\nu$: Constrains SN models.
- Relic $SN\nu$: Constrains cosmic star formation history

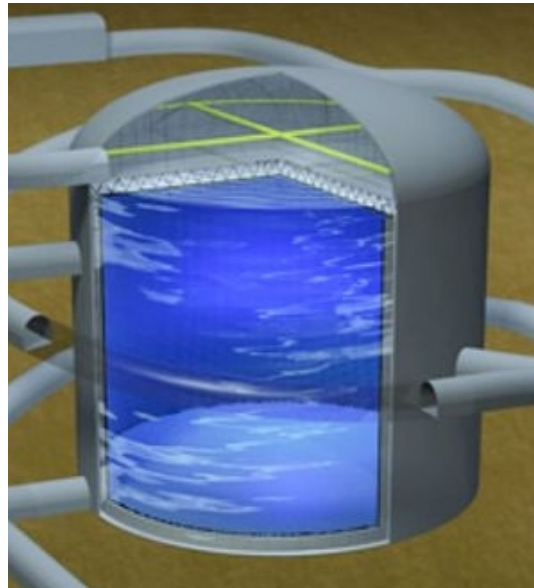


JPARC accelerator neutrinos

Focus on CP violation

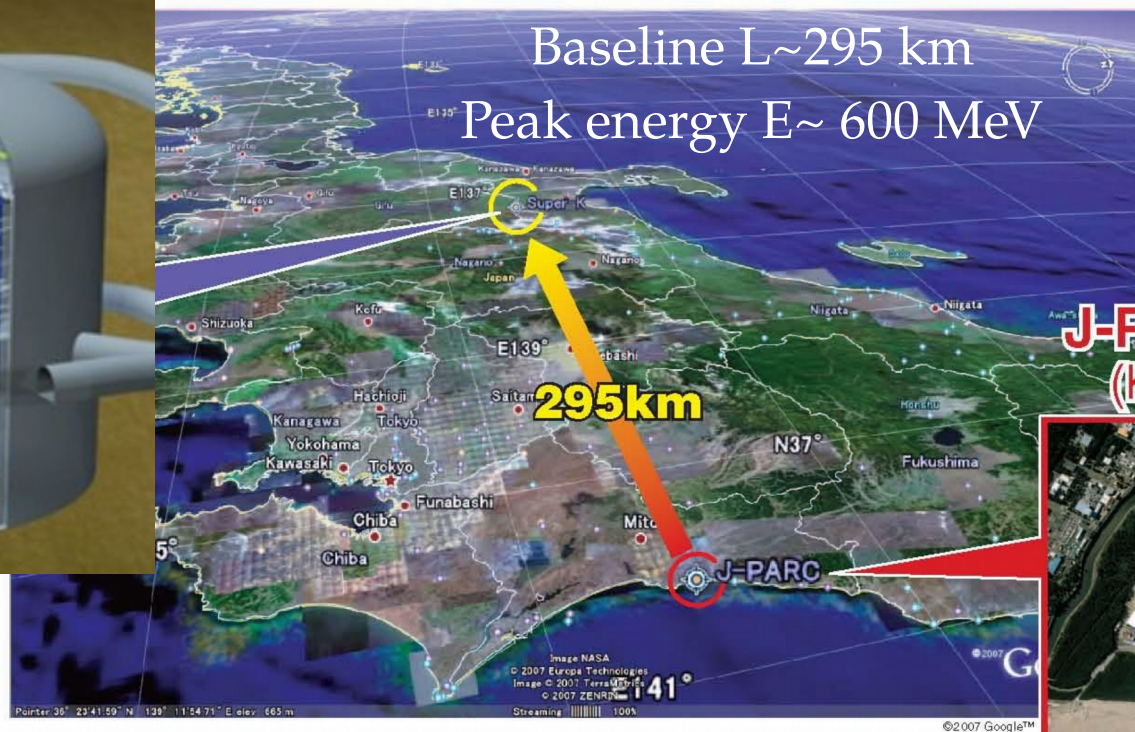
- CP violation search essentially based on accelerator ν : T2HK

Hyper-Kamiokande



Detect

$$\nu_{\mu}, \nu_e / \bar{\nu}_{\mu}, \bar{\nu}_e$$



Produce $\nu_{\mu} / \bar{\nu}_{\mu}$

J-PARC Main Ring
(KEK-JAEA, Tokai)



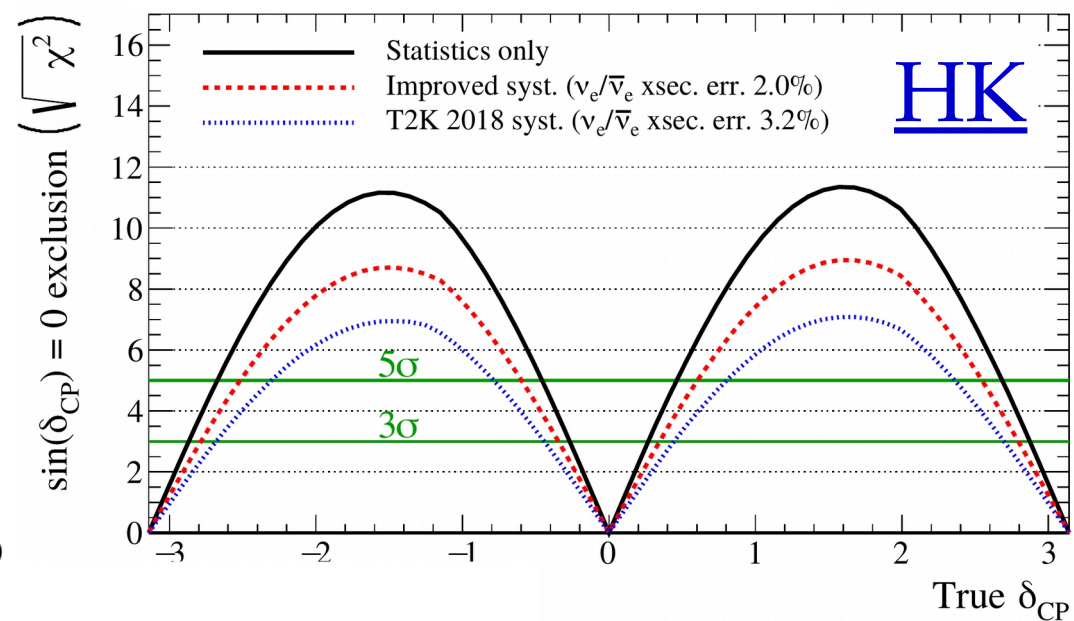
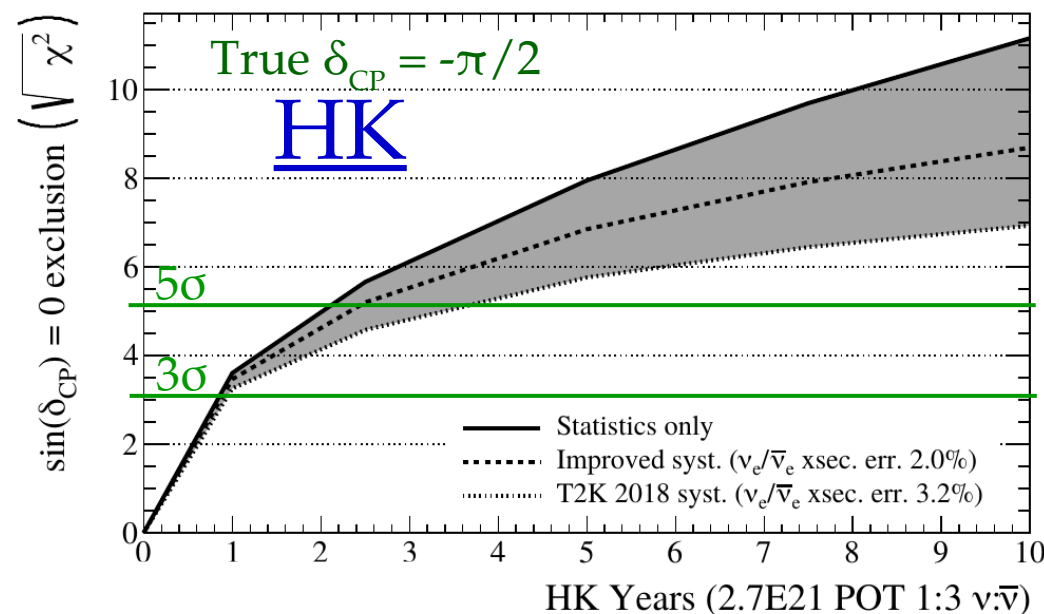
- ν_e appearance in a ν_{μ} beam and ν_{μ} disappearance & $\bar{\nu}$ equivalents.
- Detector technologies, calibration, analyses well-proven by T2K&SK.

$\Rightarrow$ Quick start ! Which relies on 2 milestones :

- ↓ time to accumulate statistics → Beam upgrade.
- ↓ systematic uncertainties → Constrains ν_{μ} & ν_e flux before oscillation

Sensitivity to CP violation

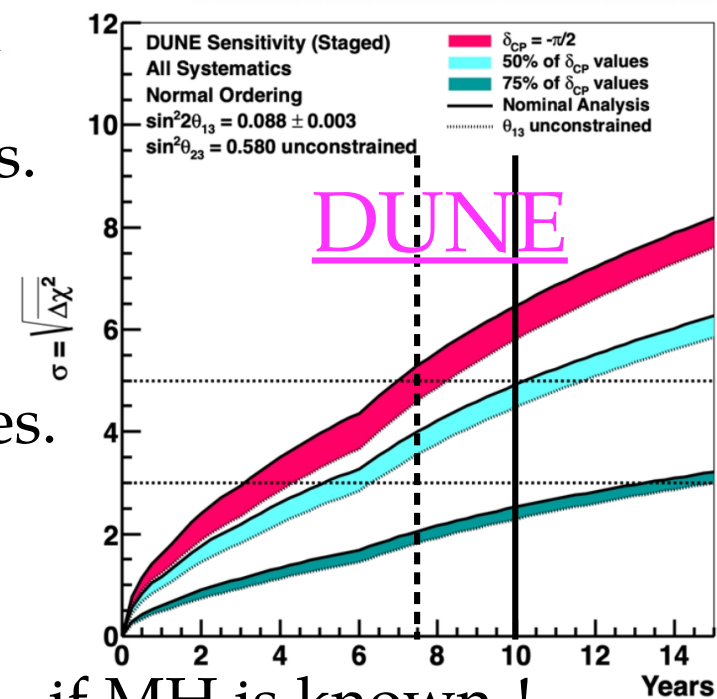
- Assuming a run $\nu:\bar{\nu} = 1:3$ @1.3MW (can be adjusted).



- $\delta_{CP} = -\pi/2$: 5 σ after 2-4 years of data taking
 - Independent from ↓ systematic uncertainties.
 - DUNE will require 7-8 years.

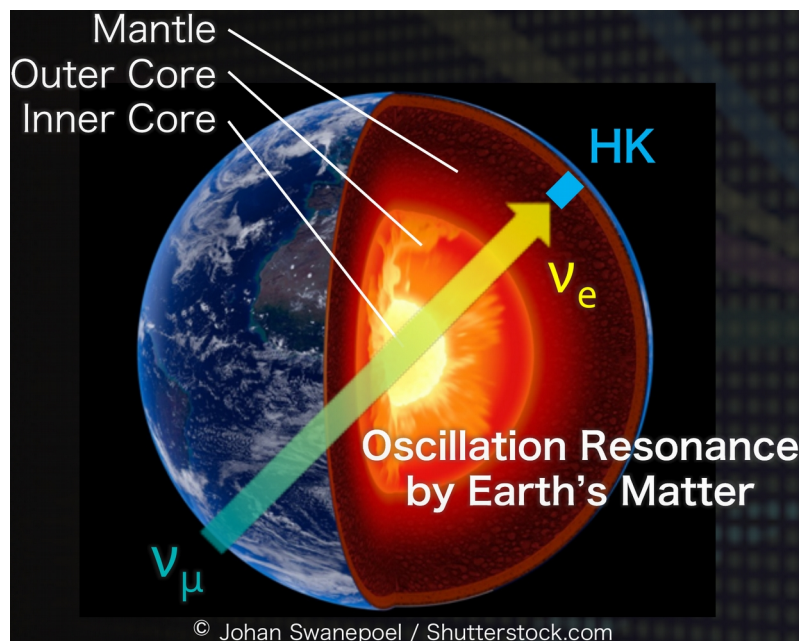
- HK 10 years: 5 σ sensitivity on 60% of δ_{CP} values.
 - DUNE: 5 σ sensitivity on 40%

- HK has world-best sensitivity to CP violation ... if MH is known !

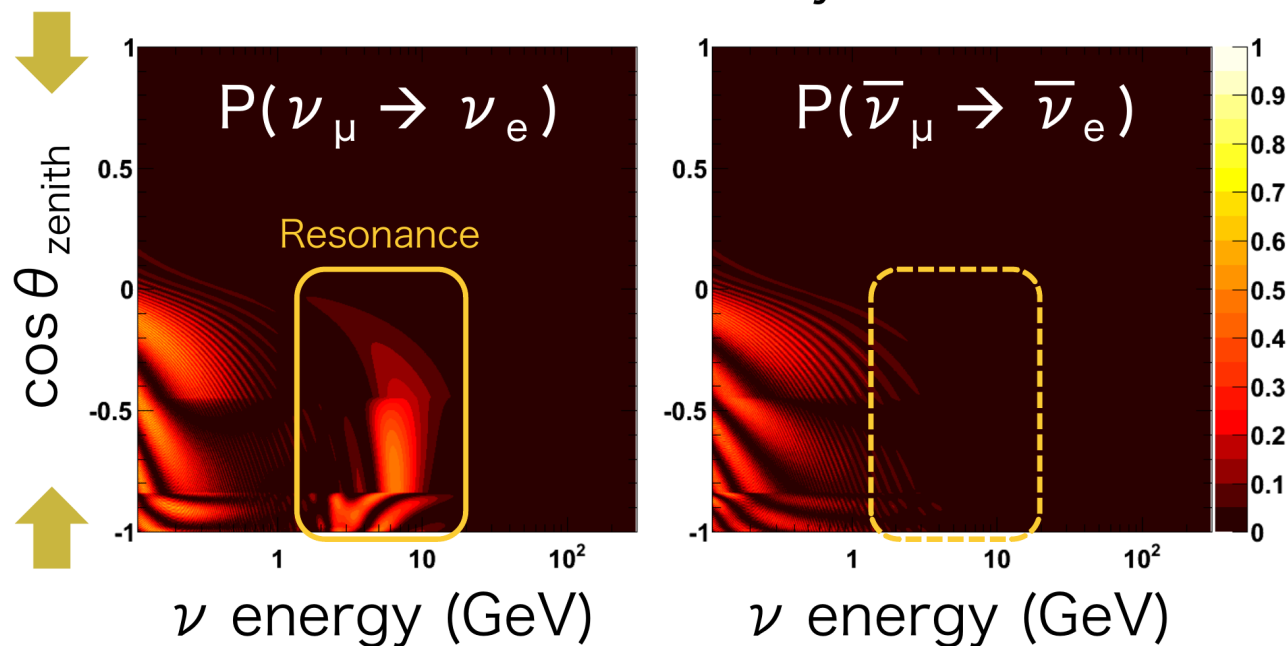


Atmospheric neutrinos

- Mass-hierarchy can be accessed through matter effects
→ The longer the baseline, the higher the effects



Normal Hierarchy case



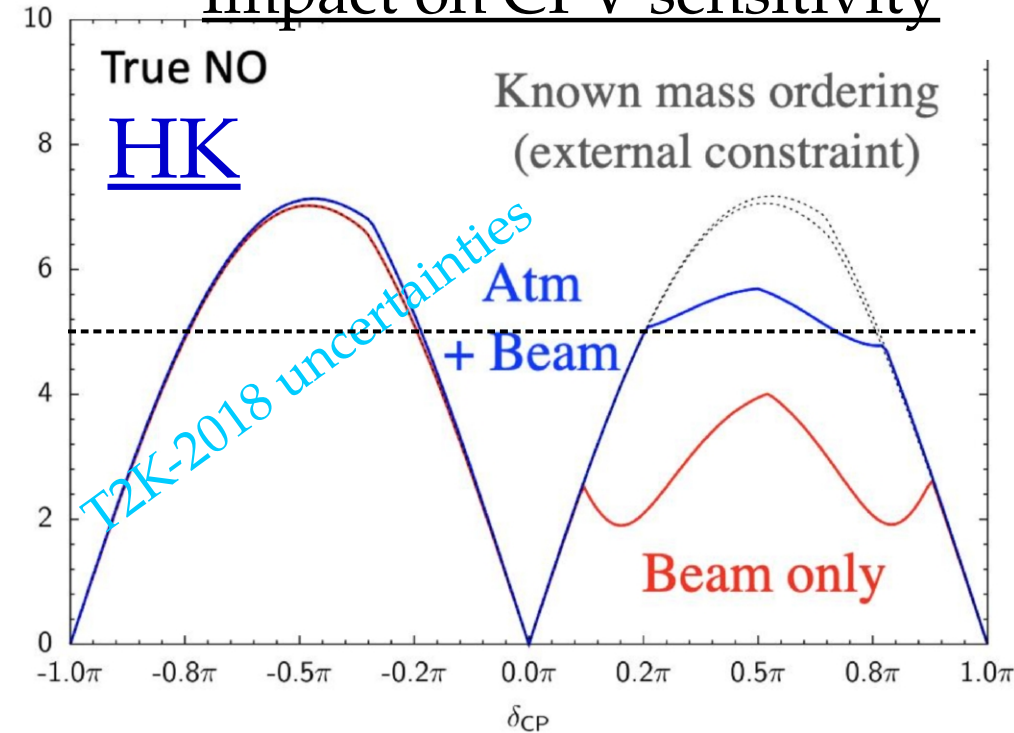
- Mass hierarchy determined with upward-going multi-GeV ν_e sample :

atm. baseline ≤ 13000 km $\gg$ 295 km accelerator baseline

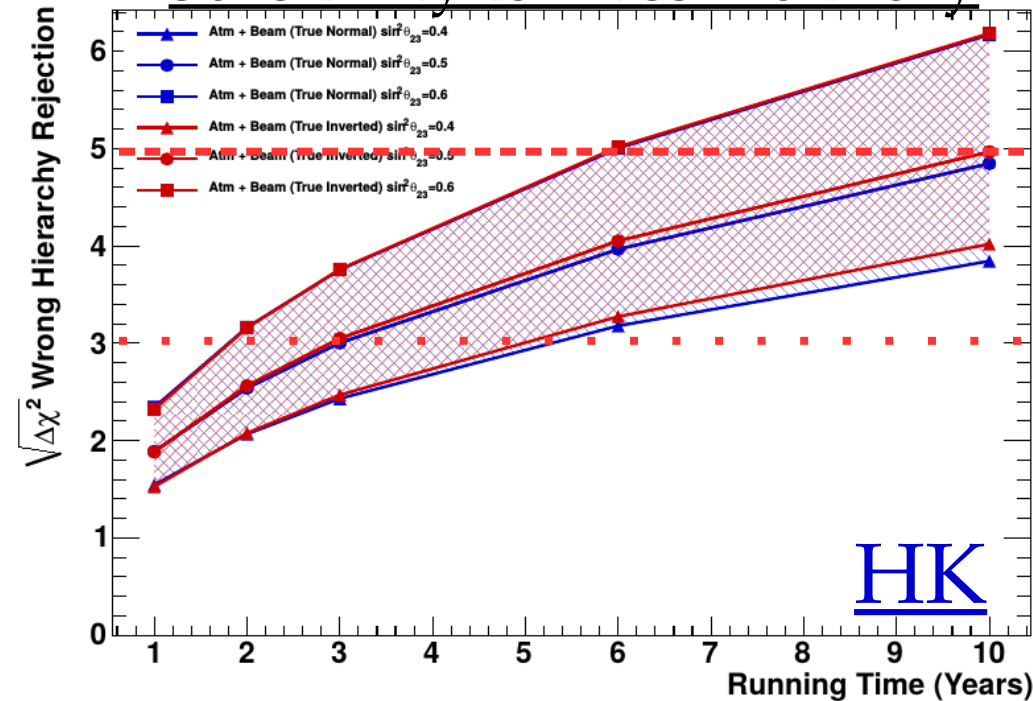
- Normal hierarchy : enhancement of $\nu_\mu \rightarrow \nu_e$.
- Inverted hierarchy : enhancement of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$.

Combination of atmospheric + beam ν

Impact on CPV sensitivity

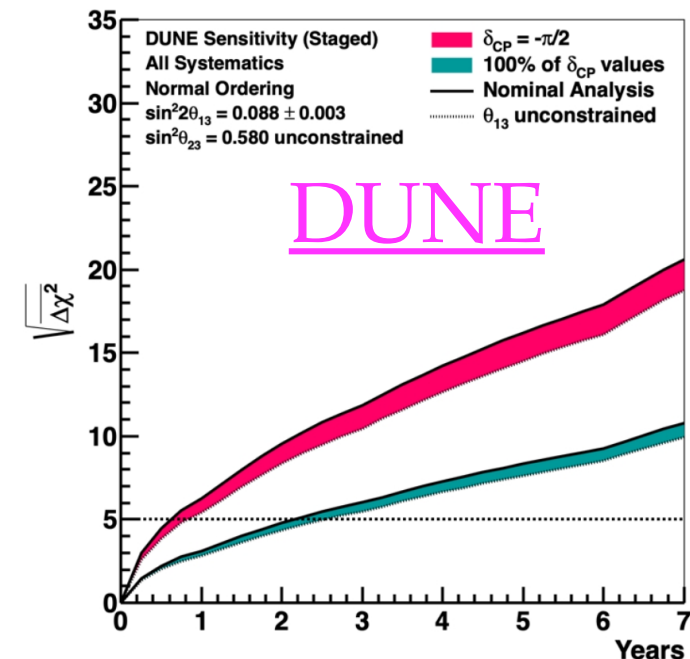


Sensitivity to mass hierarchy



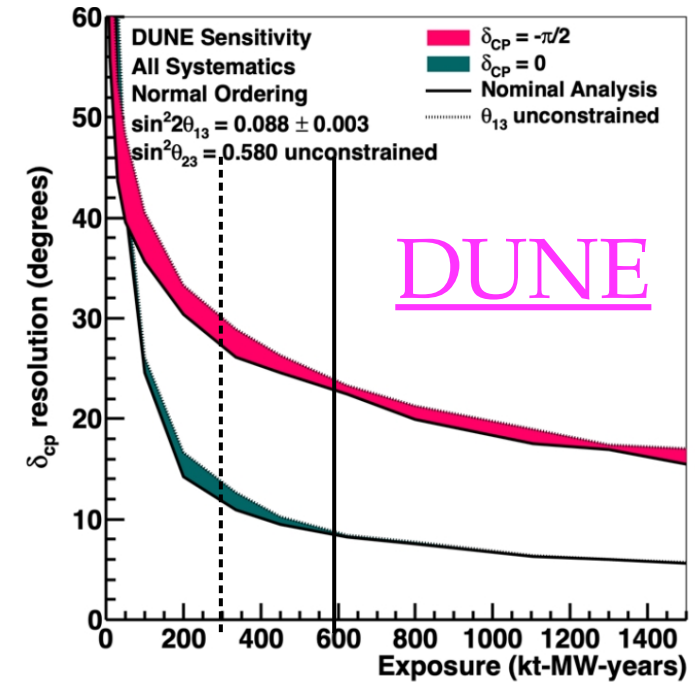
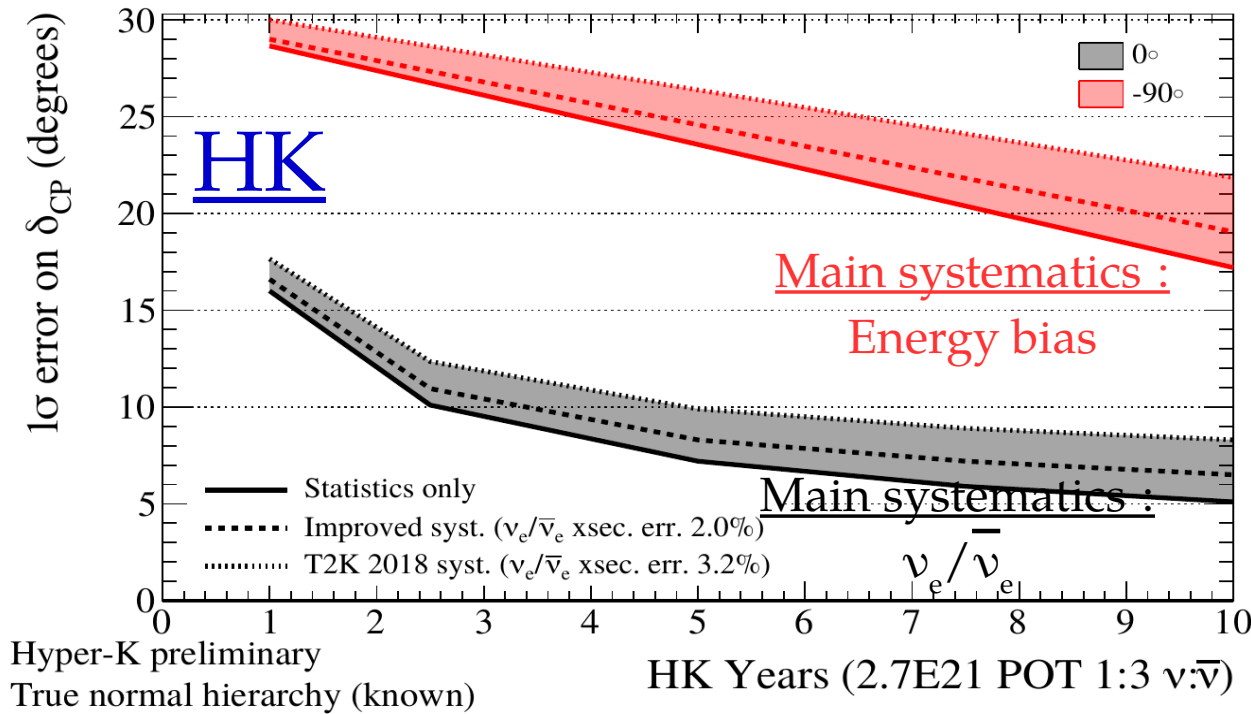
- Even if MH is not known when HK starts
→ Sensitivity to CPV is little affected if we add atmospheric ν .

- MH would be determined by :
→ HK after $\geq 6-10$ years via atmospheric.
→ DUNE : after 1-2 years.



Precision of δ_{CP} measurement

- After CPV is determined, accurate measurement of δ_{CP} will be crucial
 → Maximal CPV, leptogenesis, symetries of lepton's generations ...



	5 years [HK & DUNE]	10 years [HK & DUNE]
CP conserved $\delta_{CP} = 0$	8° & 13°	6° & 9°
$\delta_{CP} = -\pi/2$	25° & 29°	19° & 24°

- HK will be the leading experiment for CPV & δ_{CP} measurements in the next 20 years.

2. Que fait on après la découverte de la CPV > 2030 ?

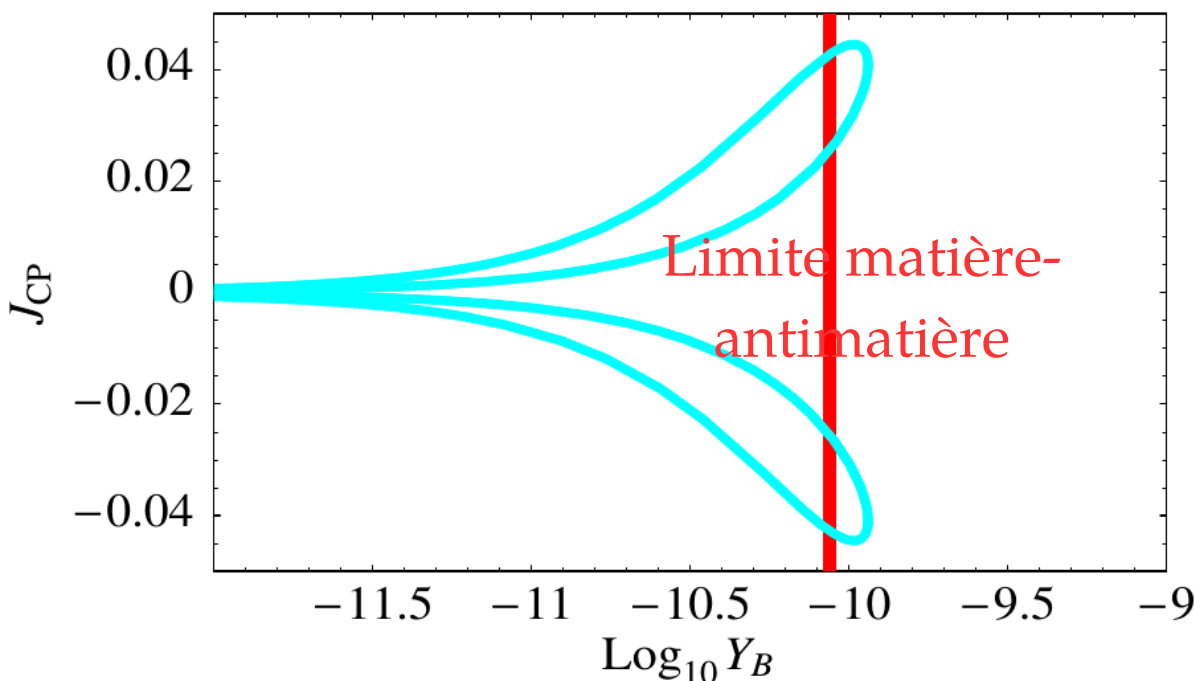
a. On mesure avec précision la CPV i.e. $\sin \delta_{\text{CP}}$.

Violation CP des
neutrinos de basse E

Leptogénèse

Asymétrie matière et
l'antimatière

$$\Delta P = P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \propto J_{\text{CP}} \quad |Y_B| \cong 2.8 \times 10^{-13} |\sin \delta| \left(\frac{s_{13}}{0.2} \right) \left(\frac{M_1}{10^9 \text{ GeV}} \right)$$



Précision sur $\sin \delta_{\text{CP}}$

↔ Précision de la sonde des
modèles de leptogénèse

Limite basse leptogénèse :

$$|\sin \theta_{13} \sin \delta \delta_{\text{CP}}| \geq 0.11$$

$$\rightarrow |\sin \delta| \geq 0.78$$

2. Que fait on après la découverte de la CPV > 2030 ?

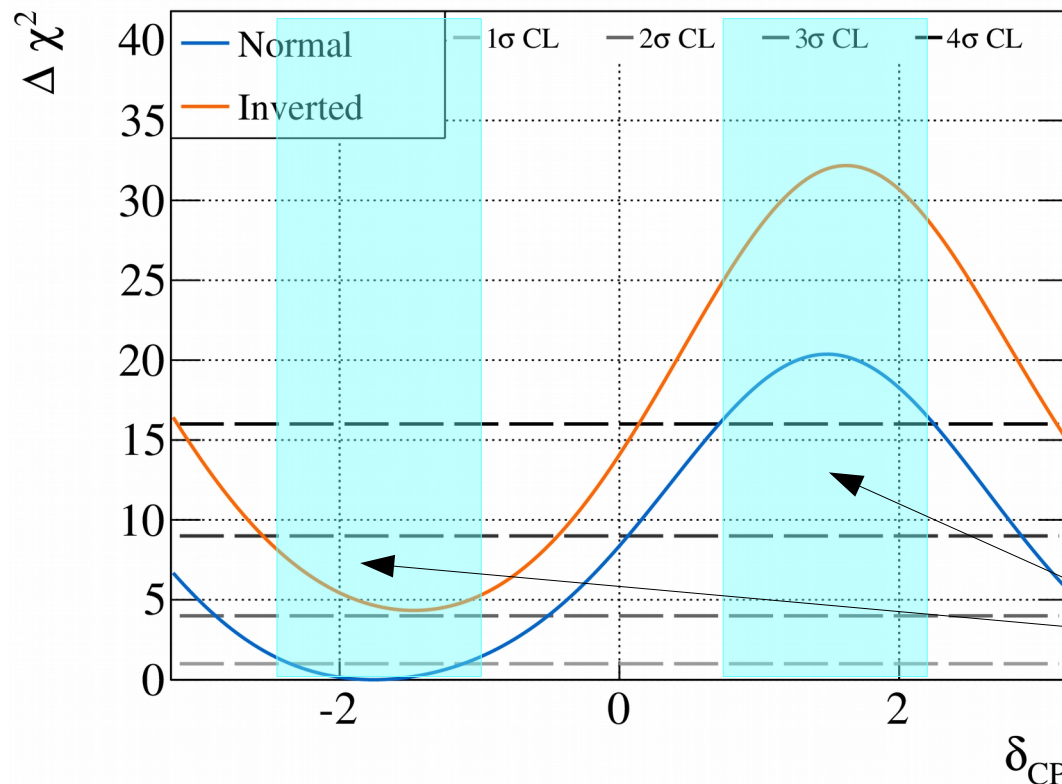
a. On mesure avec précision la CPV i.e. $\sin \delta_{\text{CP}}$.

Violation CP des
neutrinos de basse E

Leptogénèse

Asymétrie matière et
l'antimatière

$$\Delta P = P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \propto J_{\text{CP}} \quad |Y_B| \cong 2.8 \times 10^{-13} |\sin \delta| \left(\frac{s_{13}}{0.2} \right) \left(\frac{M_1}{10^9 \text{ GeV}} \right)$$



Précision sur $\sin \delta_{\text{CP}}$

↔ Précision du sondage des
modèles de leptogénèse

Limite basse leptogénèse :

$$|\sin \theta_{13} \sin \delta \delta_{\text{CP}}| \geq 0.11$$

$$\rightarrow |\sin \delta| \geq 0.78$$

Symétrie de saveurs

2. Que fait on après la découverte de la CPV > 2030 ?

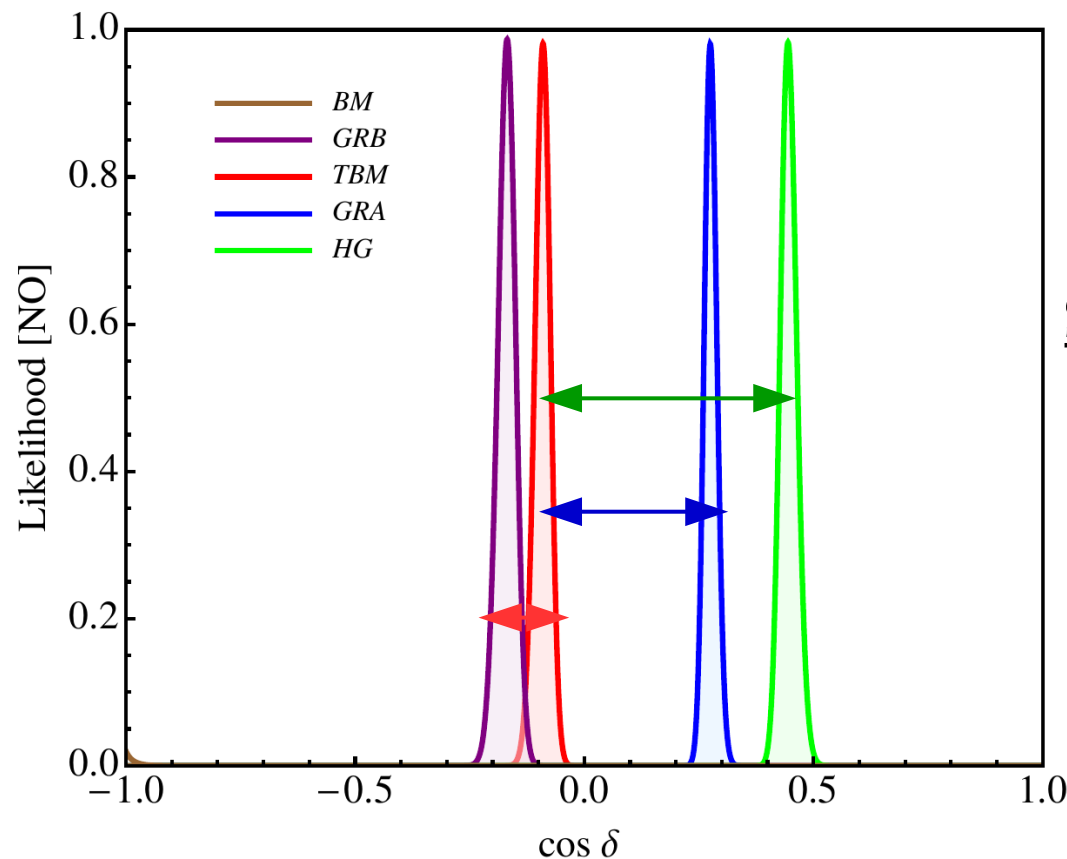
a. On mesure avec précision la CPV i.e. $\sin \delta_{\text{CP}}$.

b. On mesure avec précision δ_{CP} .

$$\cos \delta = \frac{\cos 2\theta_{23} \cos 2\theta_{13}}{\sin 2\theta_{23} \sin \theta_{13} (2 - 3 \sin^2 \theta_{13})^{\frac{1}{2}}}$$

Modèle de symétries de
génération des leptons

Relient les paramètres
de PMNS



δ_{CP} le moins bien connu

→ limite pour contraindre modèles

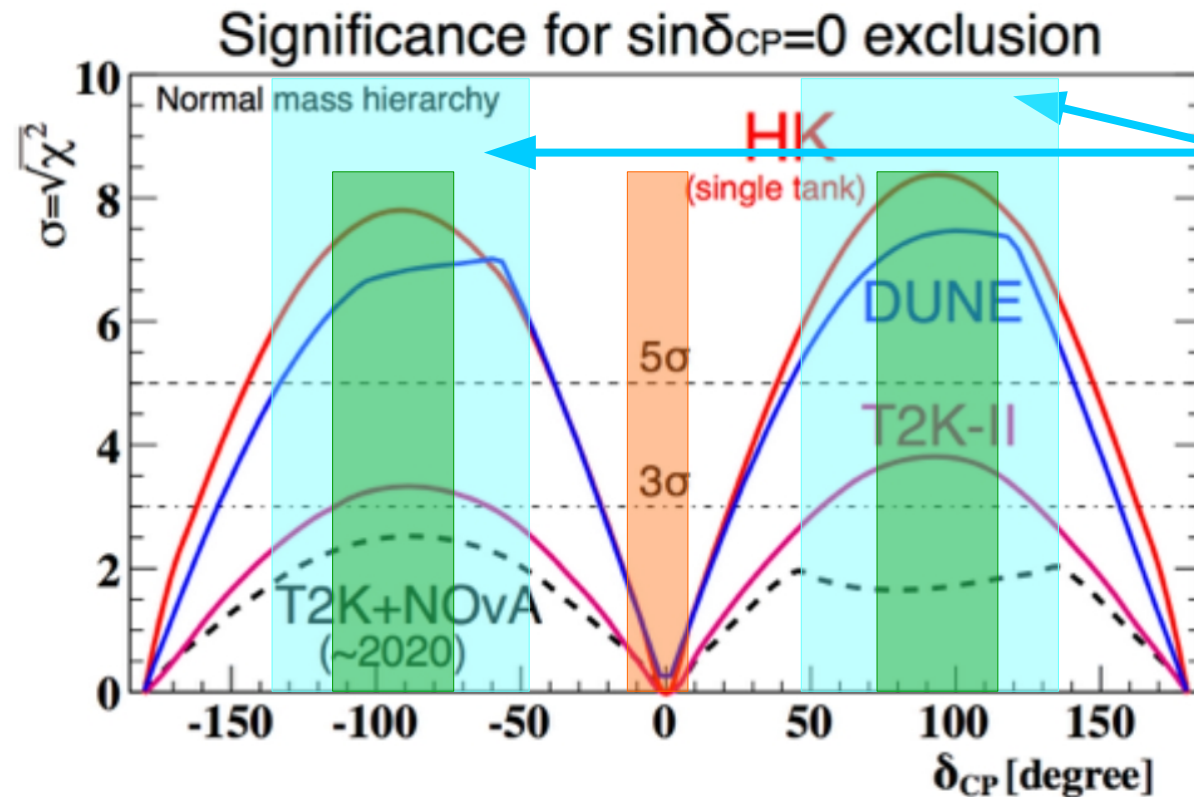
Séparation des modèles requiert :

Début de séparation : $\delta [\delta_{\text{CP}}] < 30^\circ$

Bonne Séparation : $\delta [\delta_{\text{CP}}] < 23^\circ$

Excellente séparation : $\delta [\delta_{\text{CP}}] < 5^\circ$

→ Précision HK et DUNE ?



Limite basse leptogénèse :

$$|\sin \delta| \geq 0.78$$

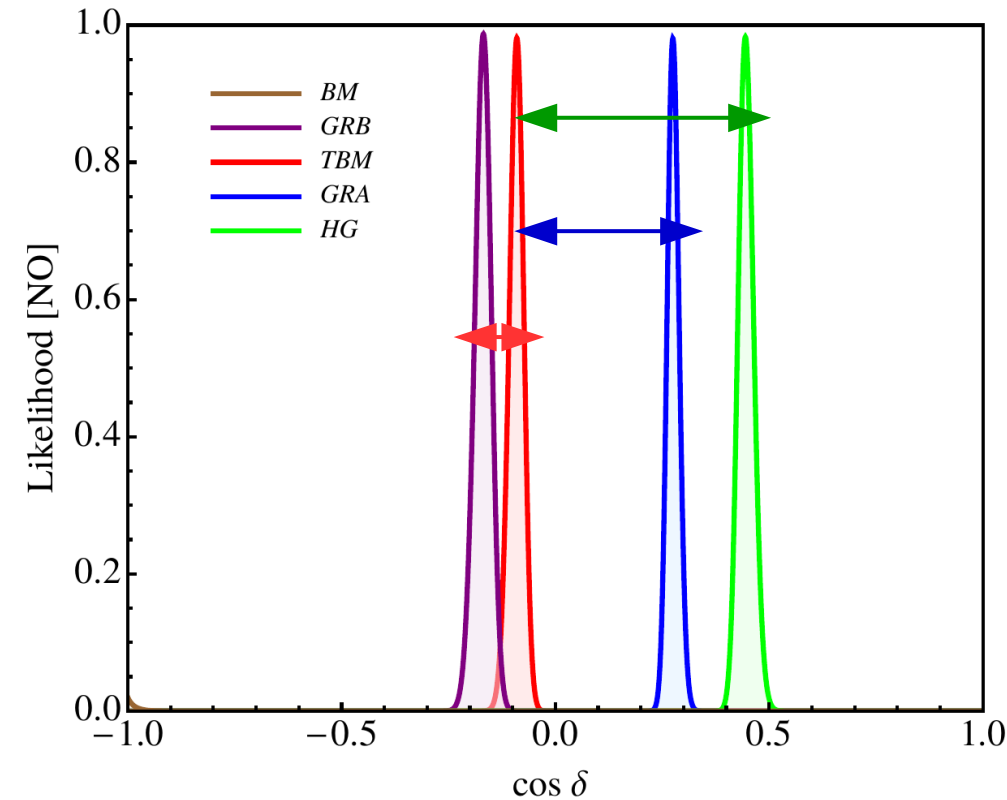
Précision HK/DUNE

$$\rightarrow \text{Si } \delta_{CP} = 0$$

$$\rightarrow \text{Si } \delta_{CP} = -\pi/2$$

- Si pas de CPV (Si $\delta_{CP} = 0$) : Définitive exclusion de toute explication de l'asymétrie mat./antimat. par la CPV de Dirac.
- Si CPV (i.e $\delta_{CP} = -\pi/2$) : Fortes contraintes sur modèles de leptogénèse.

	HK [10 ans → Final]	DUNE [10 ans → Final]
CPV et $\delta_{CP} = 0$	$8^\circ \rightarrow 6^\circ$	$10^\circ \rightarrow 8^\circ$
$\delta_{CP} = -\pi/2$	$22^\circ \rightarrow 20^\circ$	$26^\circ \rightarrow 19^\circ$



Séparation des modèles requiert :

Début de séparation : $\delta [\delta_{CP}] < 30^\circ$

Bonne Séparation : $\delta [\delta_{CP}] < 23^\circ$

Excellente séparation : $\delta [\delta_{CP}] < 5^\circ$

- Précisions finales de HK et DUNE seront similaires → Bonnes

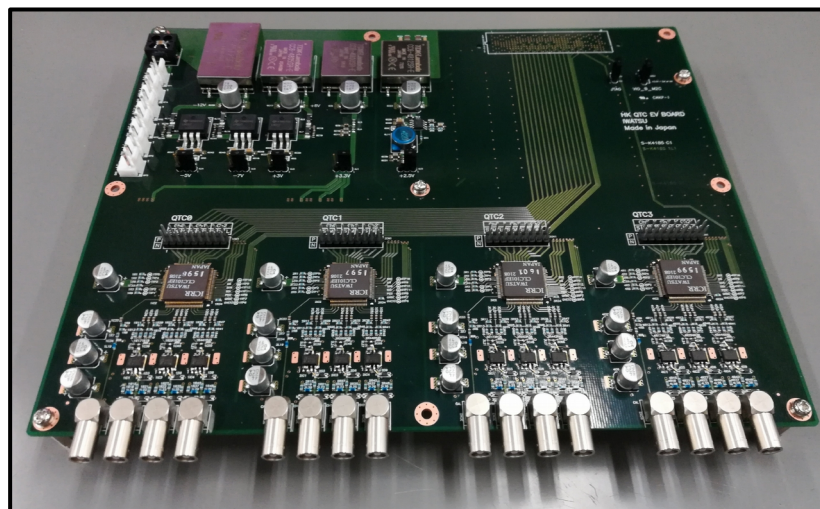
- Il n'y aura peut être pas de génération suivant HK et DUNE :
 - On aura alors deux mesures avec des systématiques complètement $\neq$
 - Idéal pour un ajustement commun !

	HK [10 ans → Final]	DUNE [10 ans → Final]
CPV et $\delta_{CP} = 0$	$8^\circ \rightarrow 6^\circ$	$10^\circ \rightarrow 8^\circ$
$\delta_{CP} = -\pi/2$	$22^\circ \rightarrow 20^\circ$	$26^\circ \rightarrow 19^\circ$

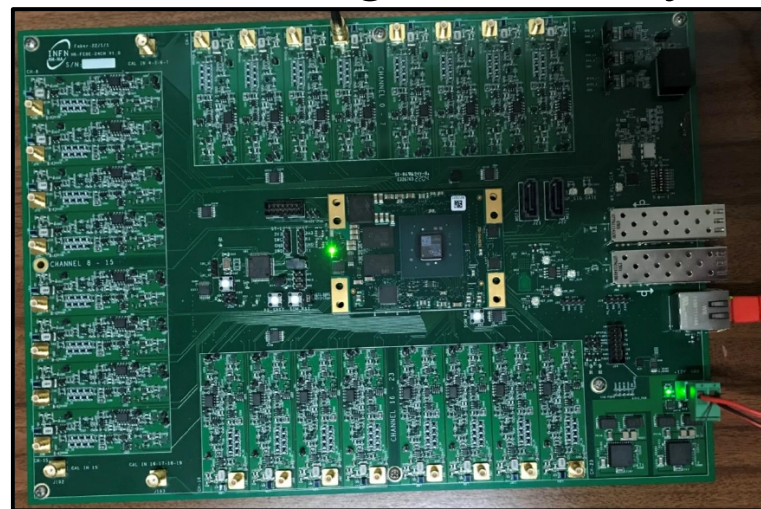
The Hyper-K candidate digitizers

- 3 digitizers considered : all high-specs but explore $\neq$ digitization method

QTC digitizer (Japan)



Discrete digitizer (Italy)



	QTC	Discrete	HKROC
Charge digitizer	ASIC (QTC)	Commercial ADC	ASIC (HKROC)
Digitization method	Charge integration	Charge integration	Waveform digitizer
TDC	On FPGA	Same as QTC	HKROC internal TDC

- All 3 solutions will likely match the specs.
- Internal review will finish next week.
- Collaboration review has started

→ Decision by end of July.