Hyper-Kamiokande

# IN2P3 contributions to Hyper-Kamiokande

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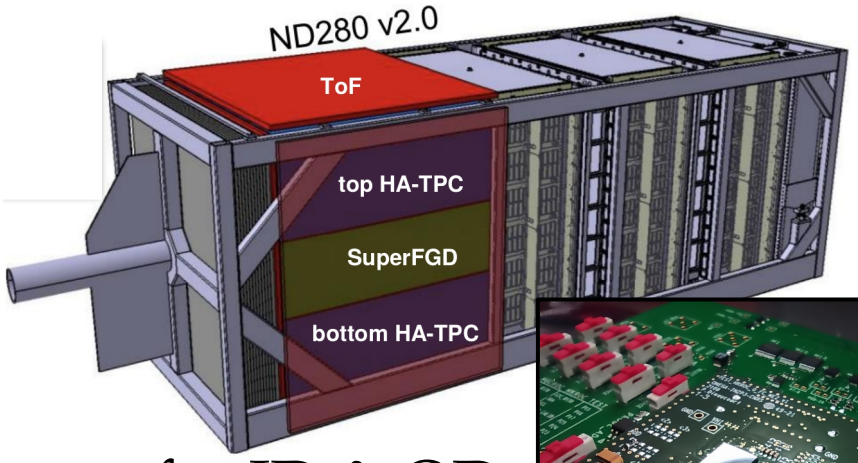
on behalf of HK-France

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

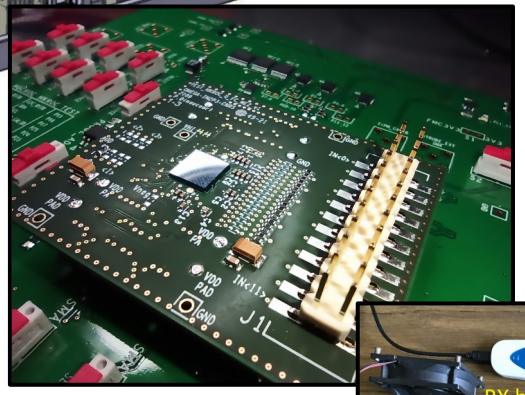
# Summary of proposed contributions

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

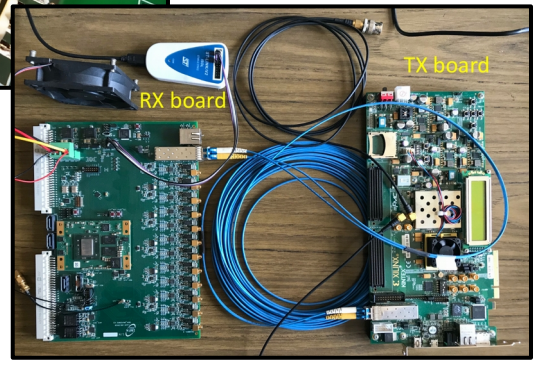
- The ND280-upgrade.



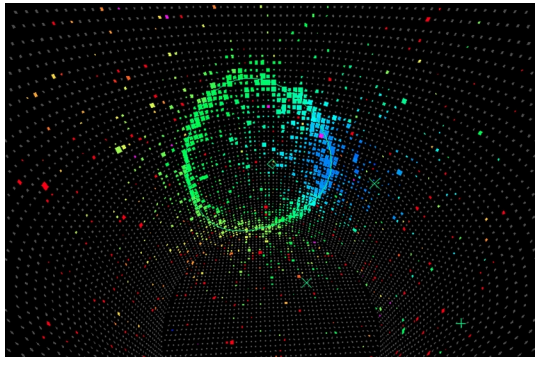

- HKROC complete digitizer for ID & OD.



- Time generation & clock distribution at Far Detector.



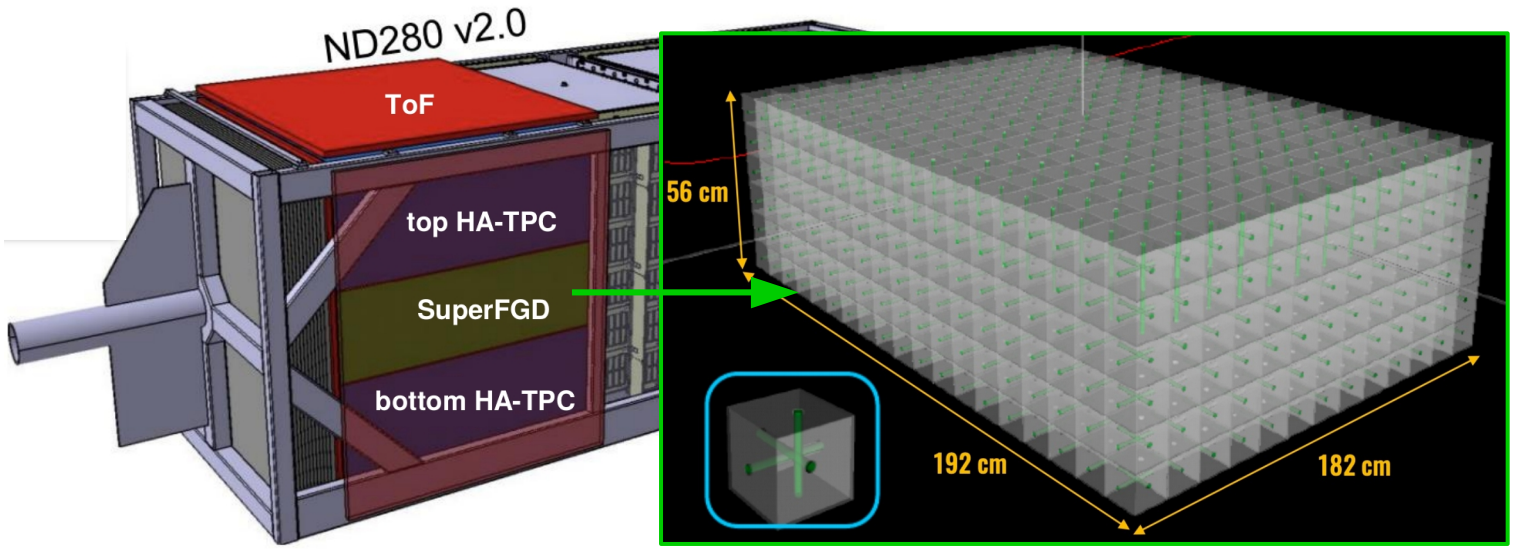

- Shared-item cost & assembly.



- CC-IN2P3 : HK Tier 1 computing system.

# I. The ND280-upgrade

# The ND280-upgrade : super-FGD




super-FGD :

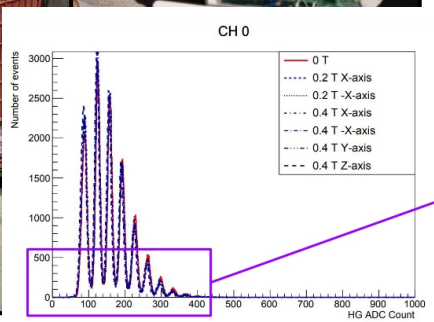
- A massive target (2t).
- A high granularity tracker : 2 millions scintillating cubes of 1 cm-side.

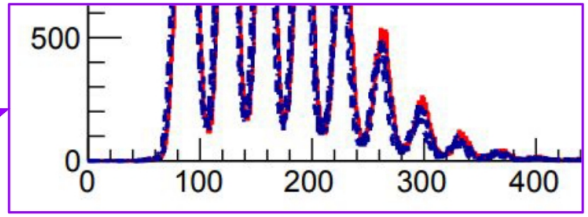
## 2 million cubes @JPARC (July 2022)

## Front-end electronics

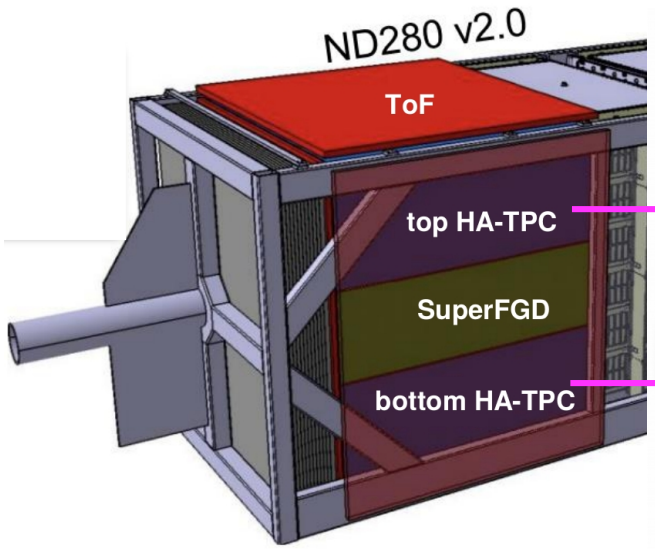

- Front-end final prototype validated.
- Vertical slice tests: → Winter 2022
- Installation&commissioning : spring 2022.

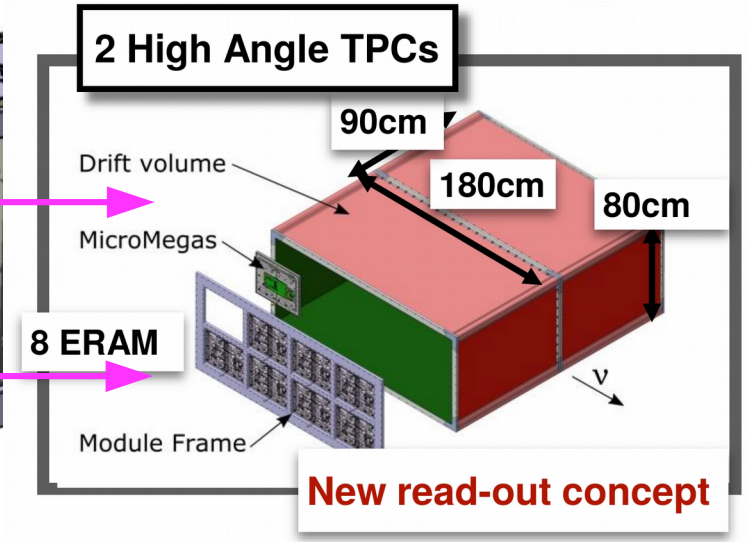
## Cube box @ CERN → Sent to Japan



# The ND280-upgrade : high-angle TPCs



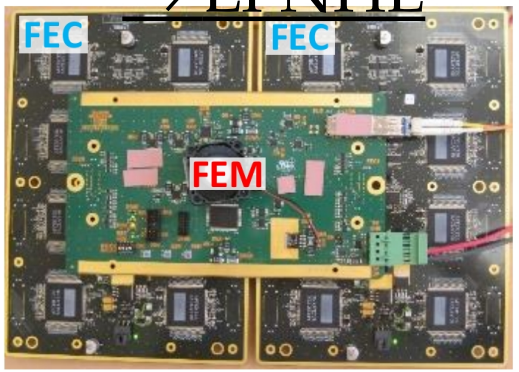



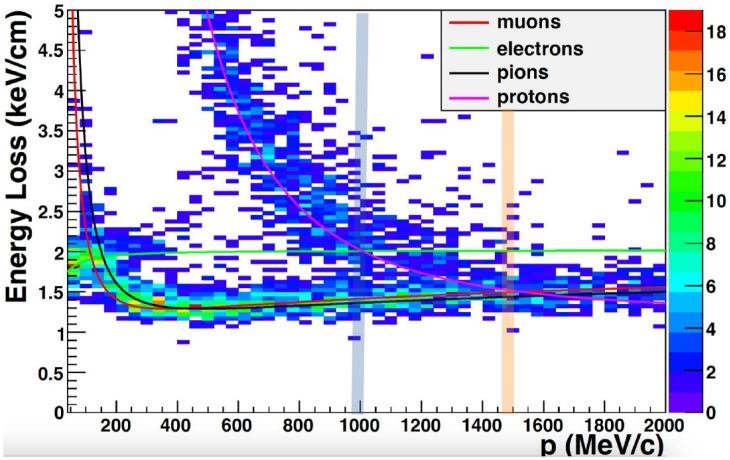

High-angle TPCs :

- Allow an almost 4π PID & momentum reconstruction for μ & π.

## Test beam at CERN

## Front-end electronics → LPNHE



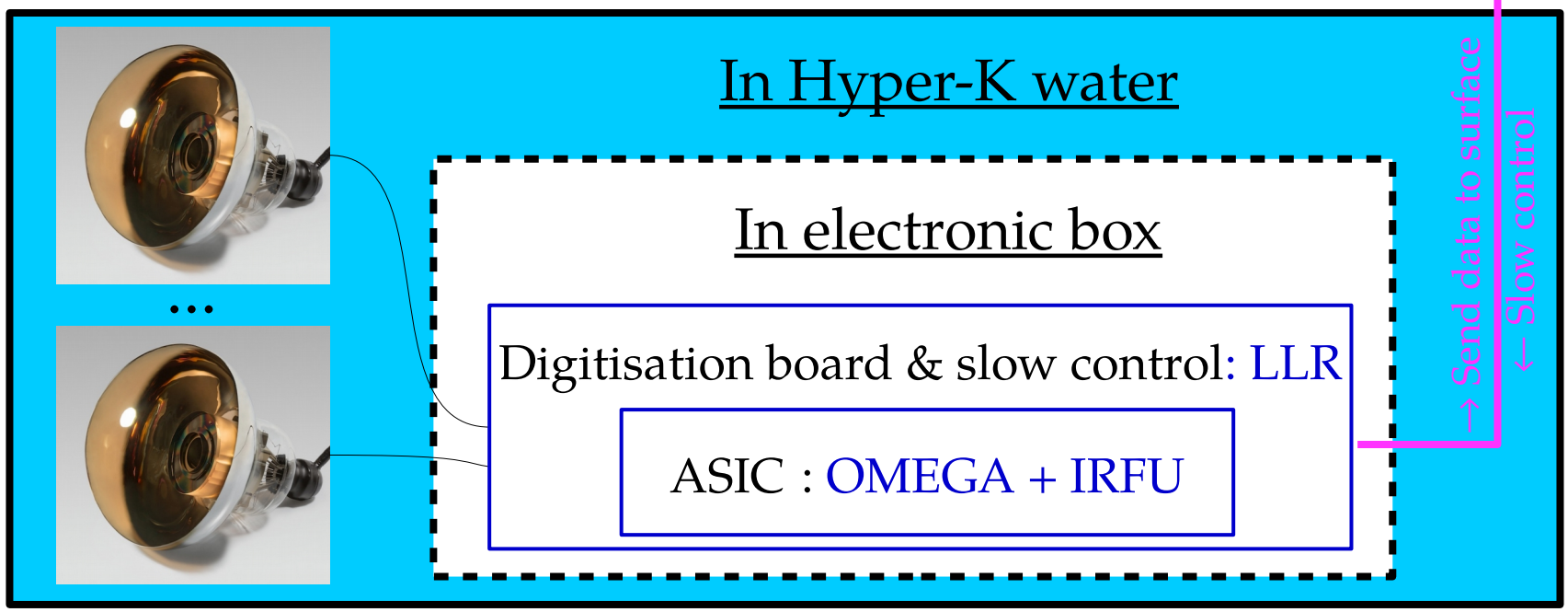

- Full upgrade : operating from 2023 at T2K → When HK starts :
  - Upgrade + INGRID (IN2P3) : only near detectors in HK !
  - HK will benefit of years of data taking to constrain the systematics.

# 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.

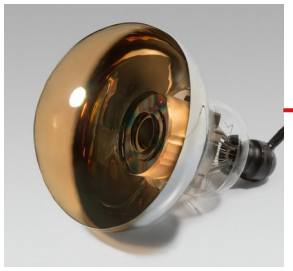


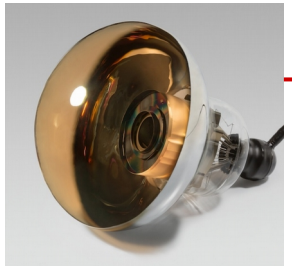

France's proposal : develop the whole PMT read-out digitization & synchonization systems

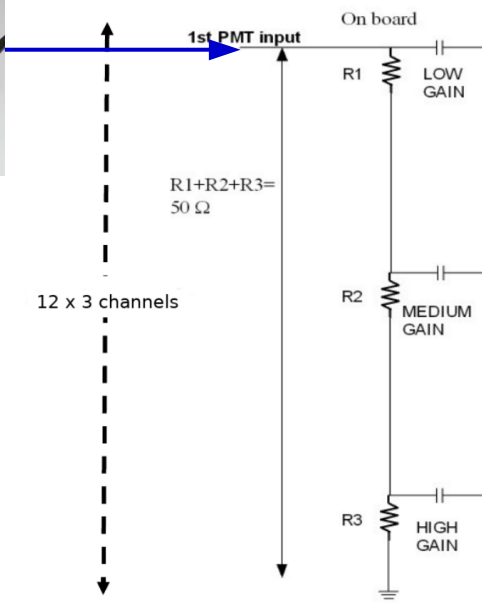
→ Absolutely central role in HK & synergy IN2P3-IRFU.

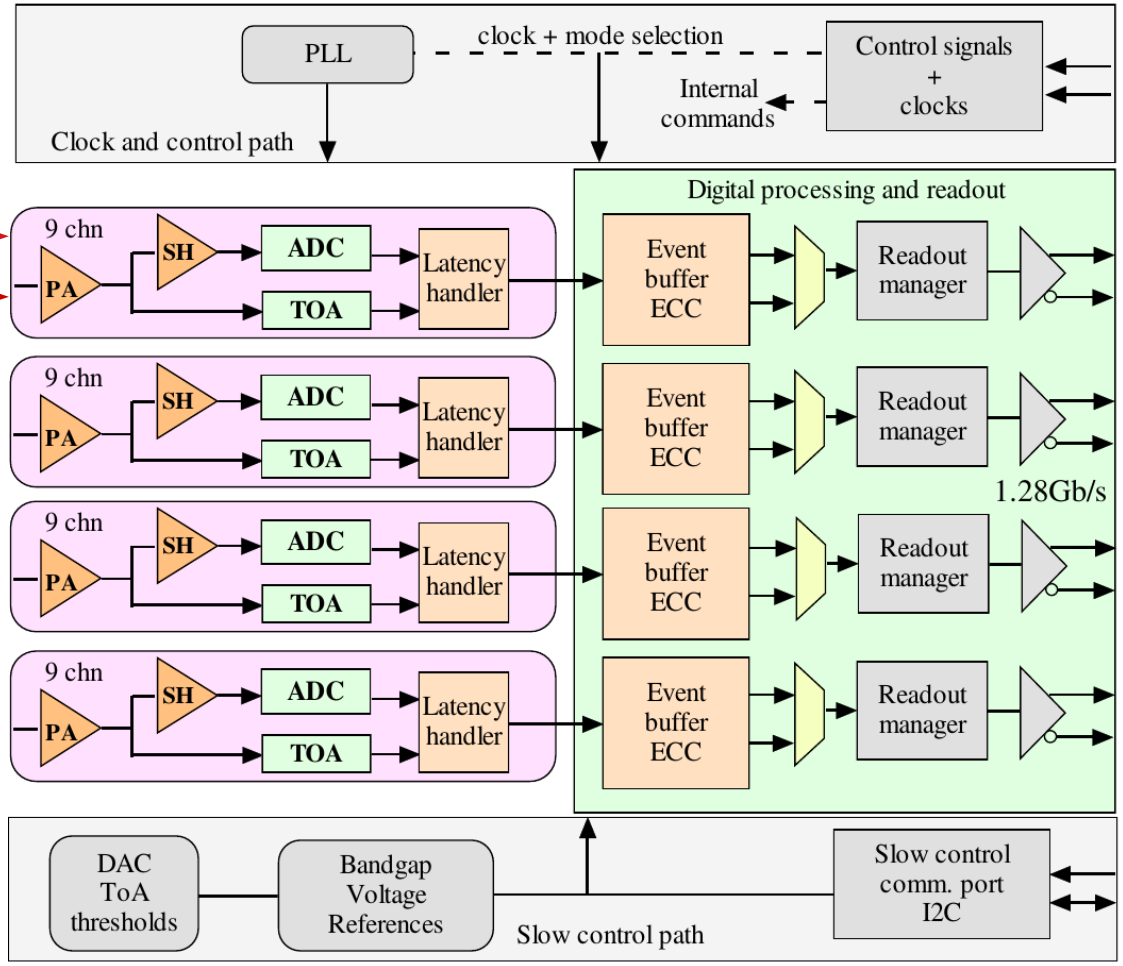
# The HKROC digitizer

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







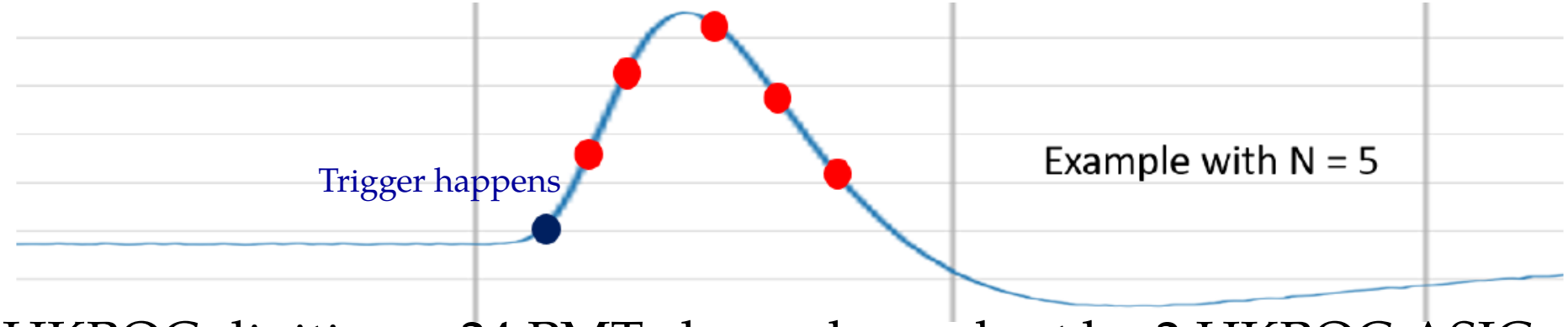




- TSMC CMOS 130nm etching.
- Dynamic range from 0 – 2500 pC : 3 gains / channel.
- 4 readout / ASIC @1.28 Gb/s : 1 readout ↔ 3 PMTs.
- If 1 PMT trigger : read all 3 PMTs of 1 readout.

# Overview of the HKROC digitizer

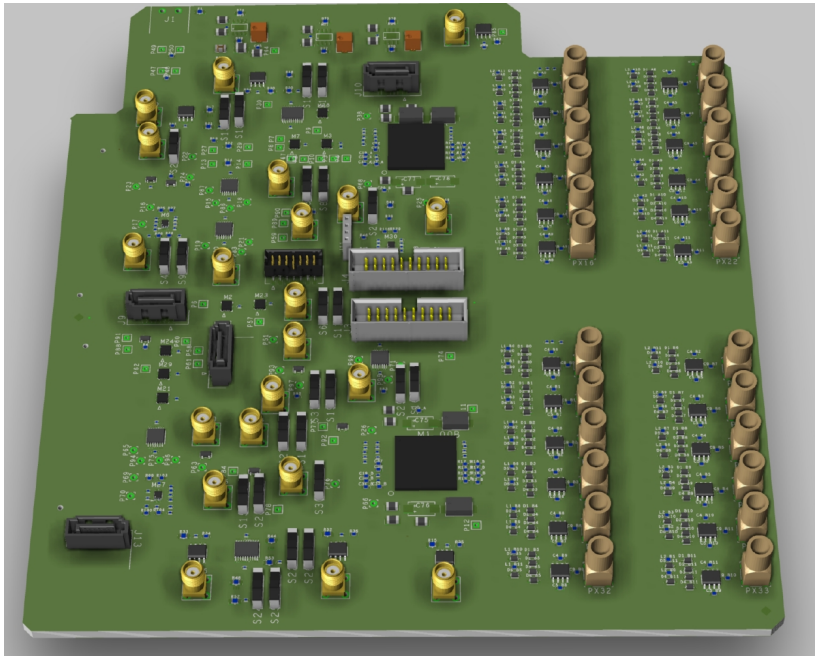
- HKROC is a waveform-like digitiser @40 MHz→ 1 point every 25 ns.

→ Charge digitized by N = 1 → 7 points (chosen by slow-control).

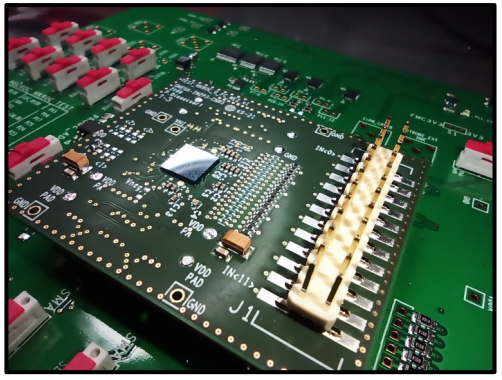



- HKROC digitizer : 24 PMT channels readout by 2 HKROC ASIC.

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.



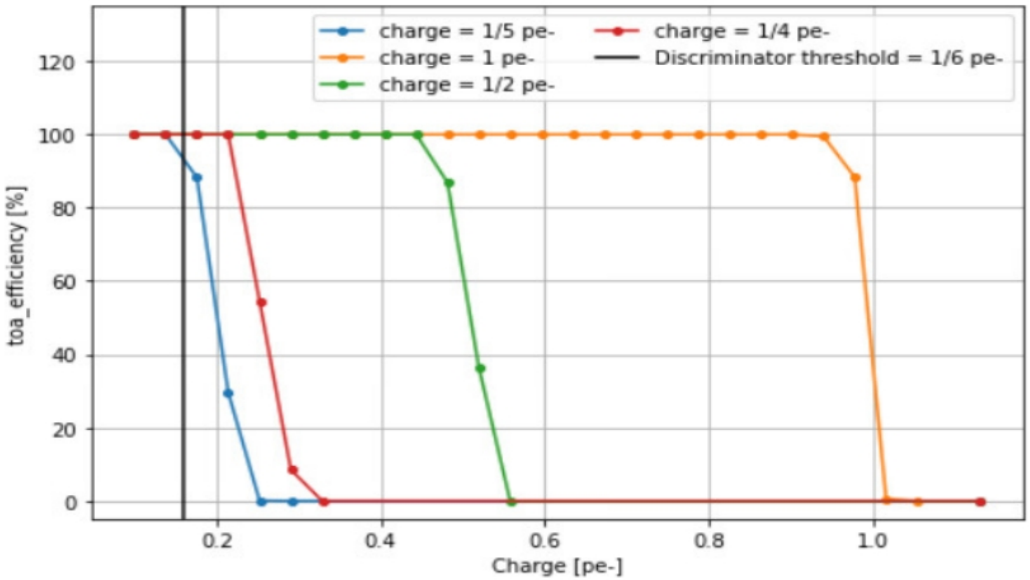
- No delay in 2 years :

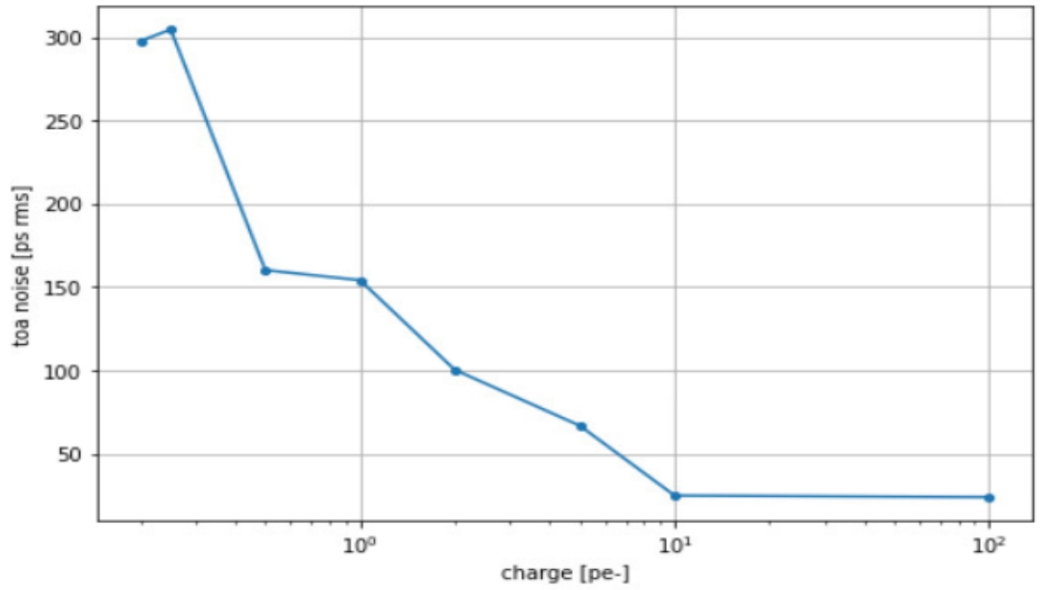
→ Chip came back in Jan. 2022 (pandemic).

→ 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.

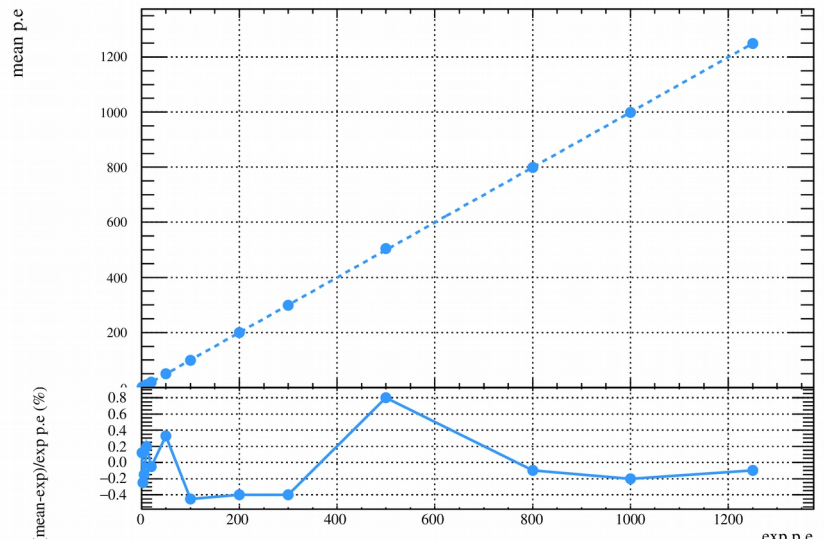
- Hit efficiency :
  90 % for 1/5 p.e events
  ~100 % if ≥ 1/4 p.e

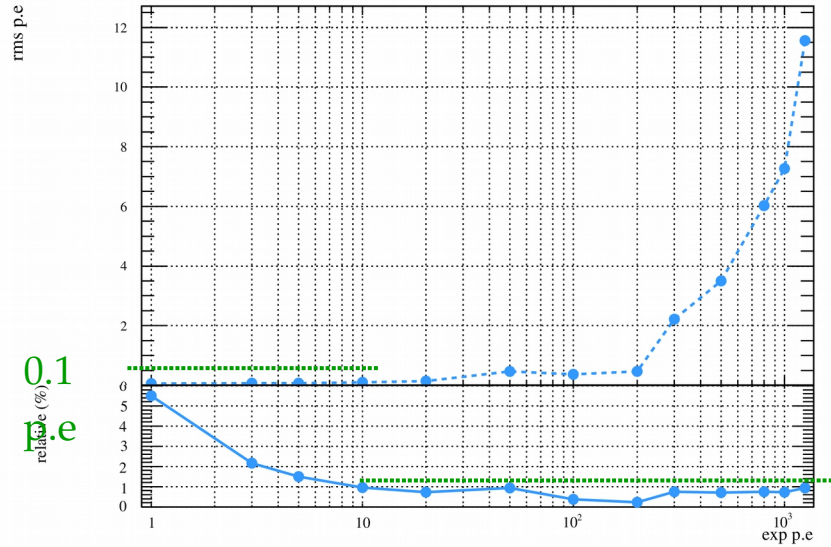
- Very low noise : < 1 Hz.

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

→ Excellent agreement with HK requirements.

# HKROC digitizer - Charge results




0.1 p.e

1 %

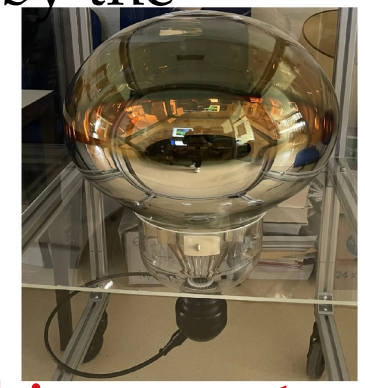
- Charge linearity < ±1% [1 to 1250 p.e.]

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

→ All characteristics fulfill HK requirements & confirmed w/ PMT.

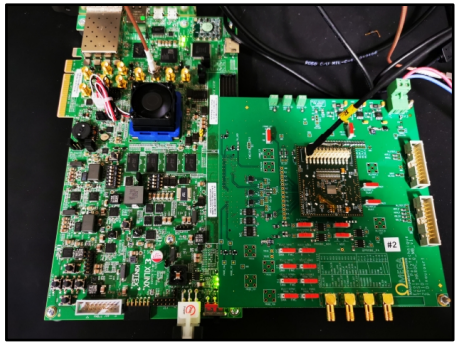
→ Large improvements w/ HKROC much beyond requirements by the collaboration

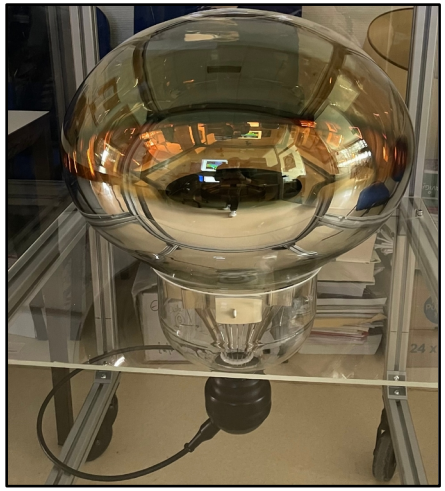
→ Ex: dead-time ↓ **from 1 µs → 30 ns**.



- 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



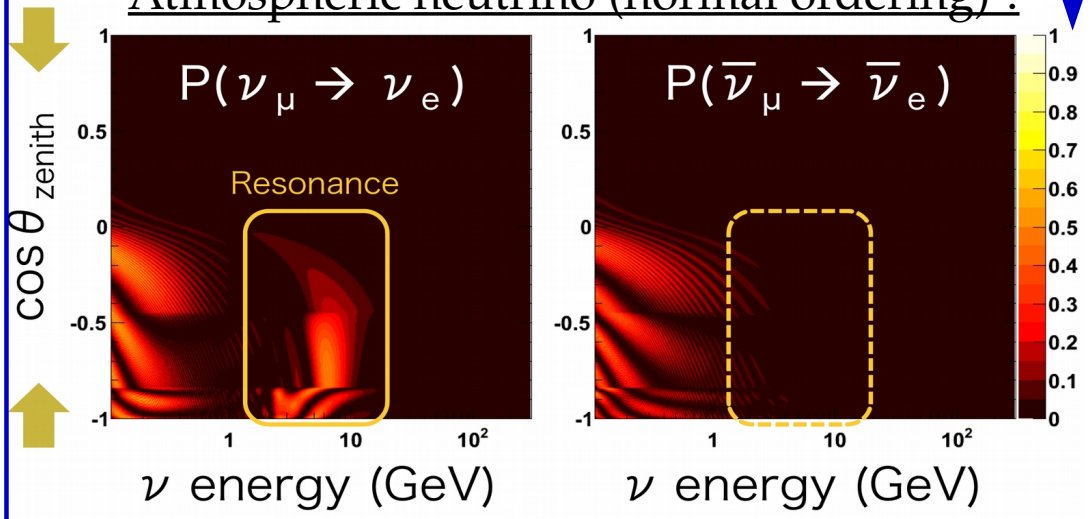


| Item measured | Performances | |
|---|---|---|
| Trigger efficiency at 1/6 p.e. | $> 90\%$ for 1/5 p.e signals<br>100% for $\geq 1/4$ p.e signals | ✓ |
| Trigger noise at 1/6 p.e. | $< 1$ Hz (No trigger observed in 10 s) | ✓ |
| TDC resolution | 150 ps at 1 p.e, 70 ps at 5 p.e, 25 ps $> 10$ p.e<br>Validated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

# HKROC digitizer - Impact on physics

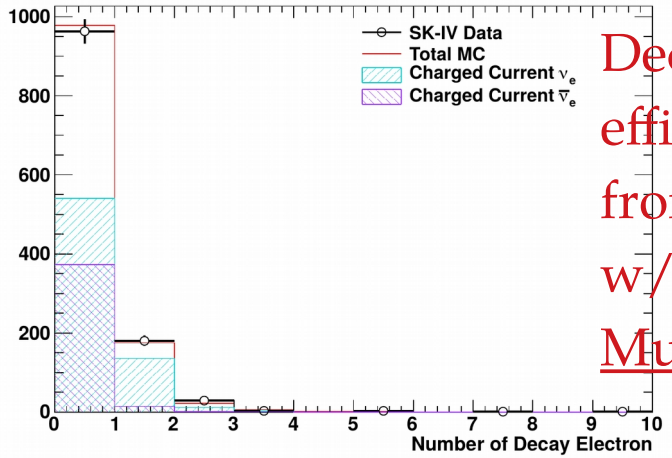
- Large impact on physics : ν mass ordering & Supernova ν.

Atmospheric neutrino (normal ordering) :

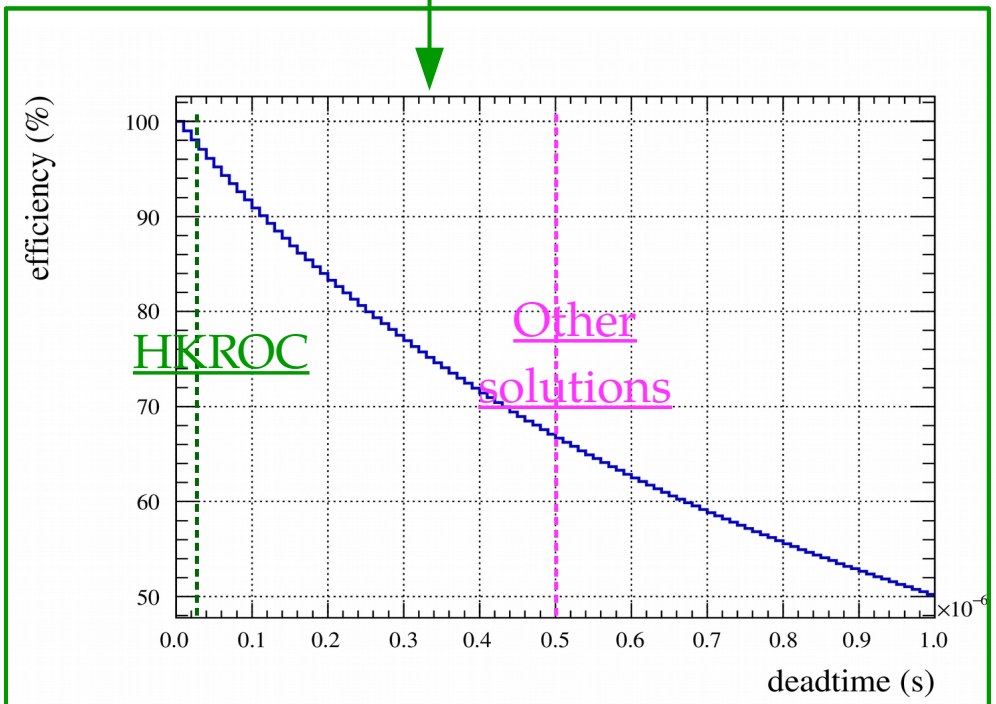



- Normal hierarchy : ↑ $\nu_\mu \rightarrow \nu_e$ .
- Inverted hierarchy : ↑ $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ .

→ 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

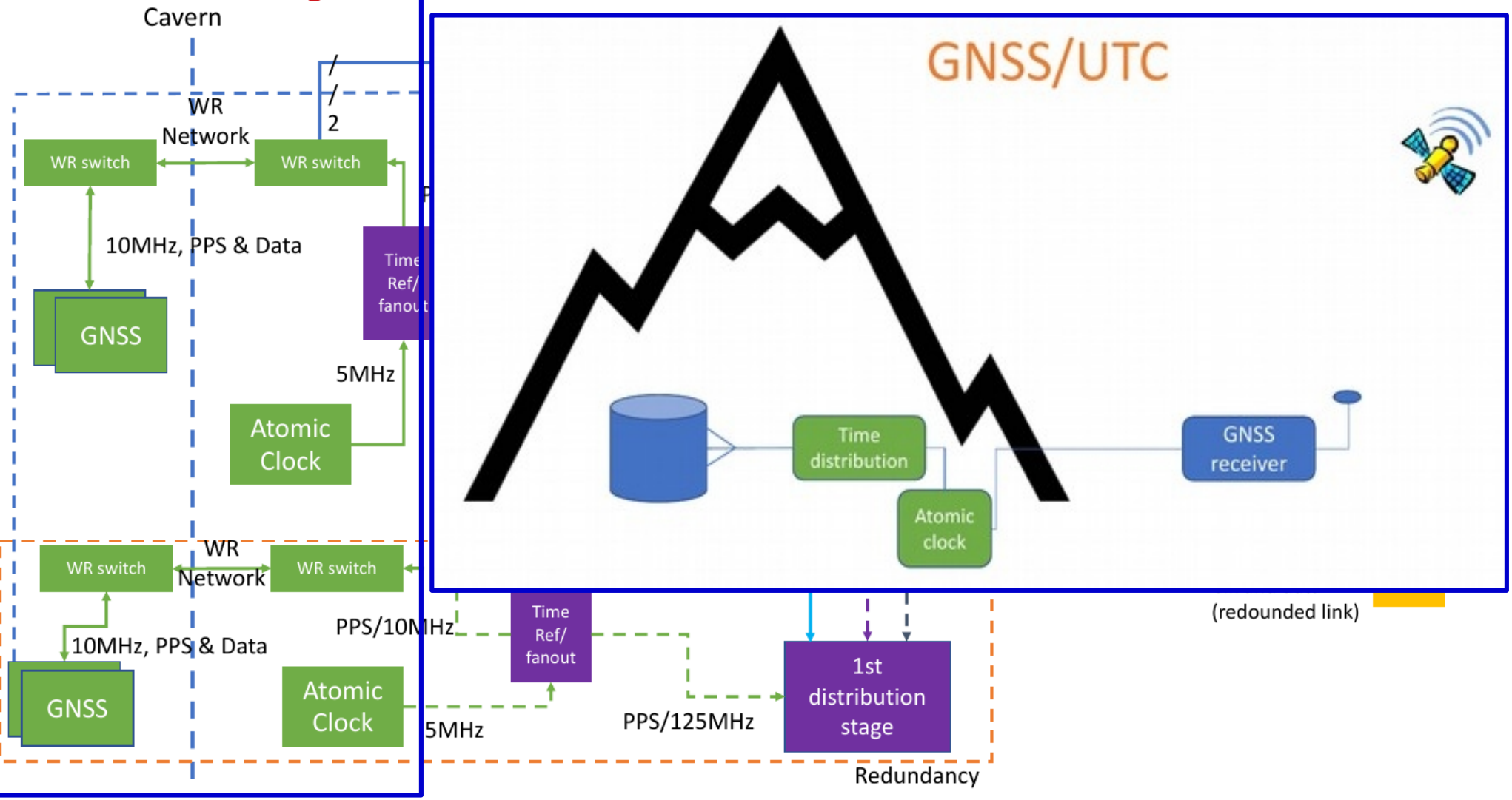



- For 1MHz [Betelgeuse] : HKROC allows to significantly increase efficiency from 67 % to 92.5 % compared to other solutions.

# Overall view of the timing system

## Time-generation :

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



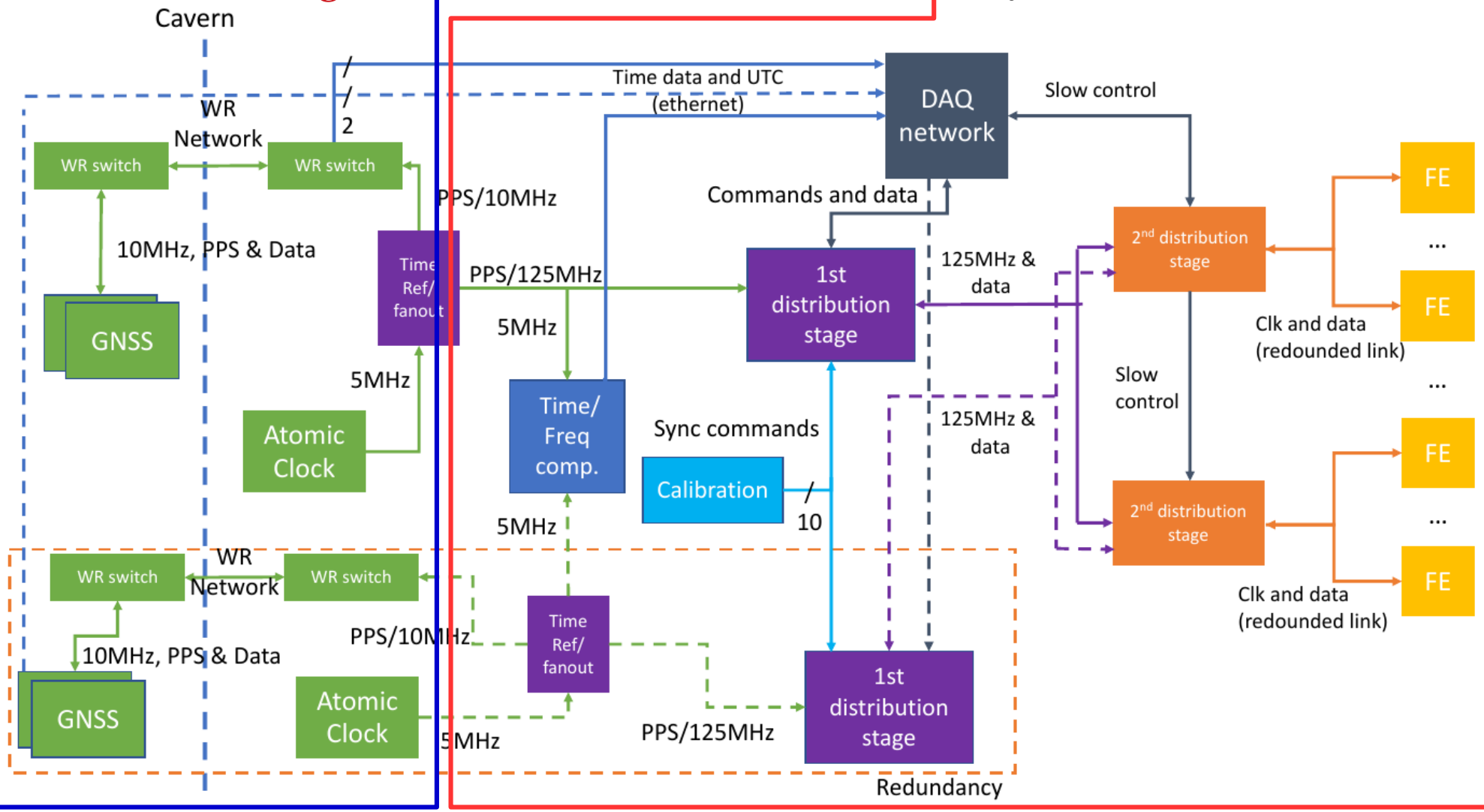
# Overall view of the timing system

## Time-generation :

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

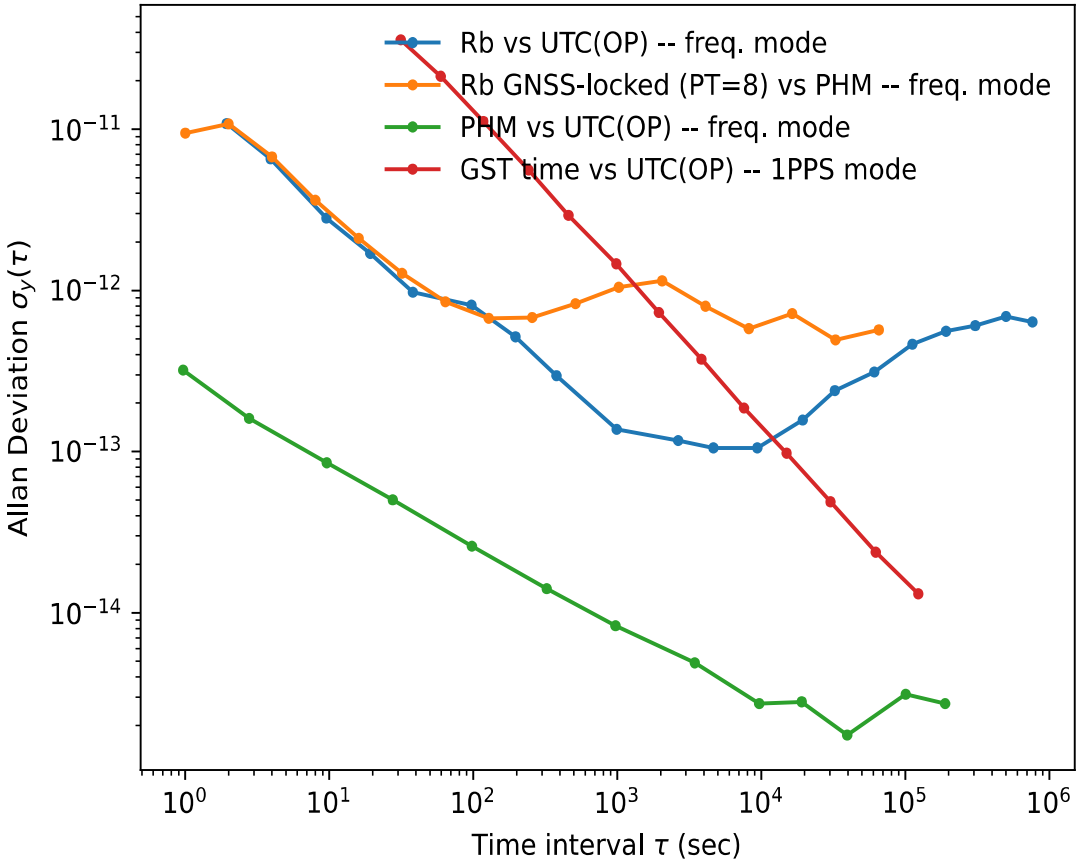
## Time-distribution :

- 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 which provide the French National time.




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

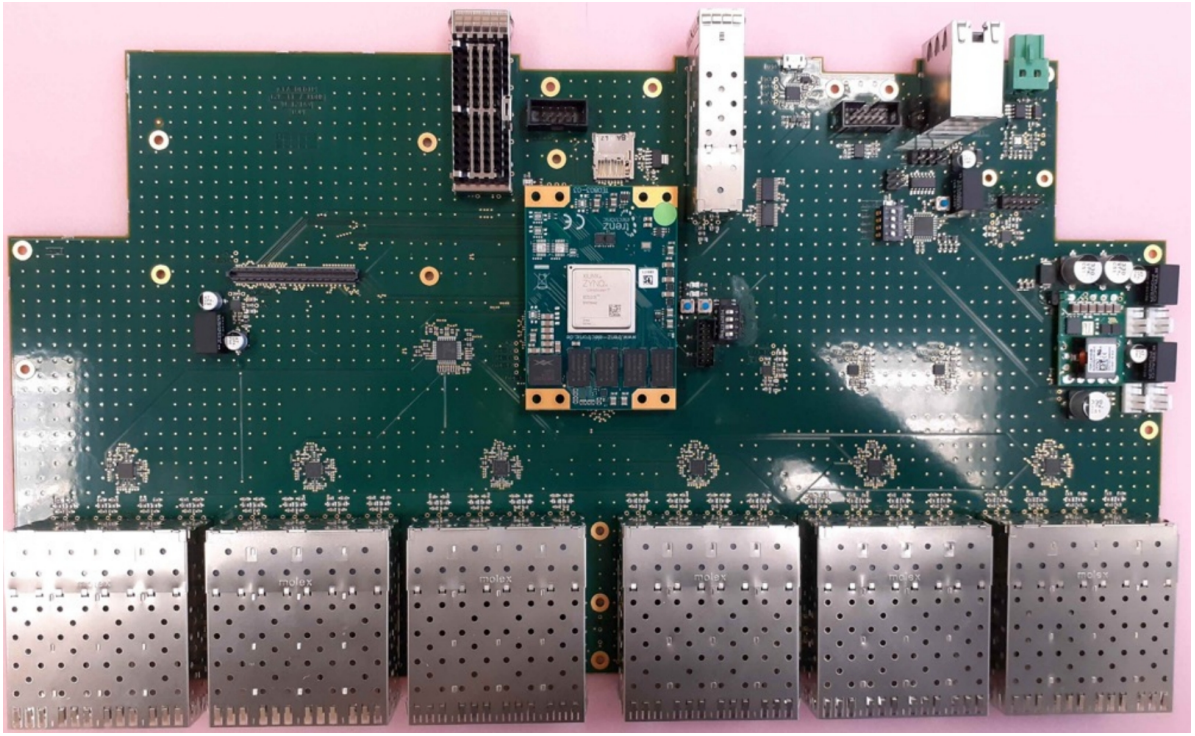
→ Reach $10^{-12}$ s w/ corrections. ✓

# 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.

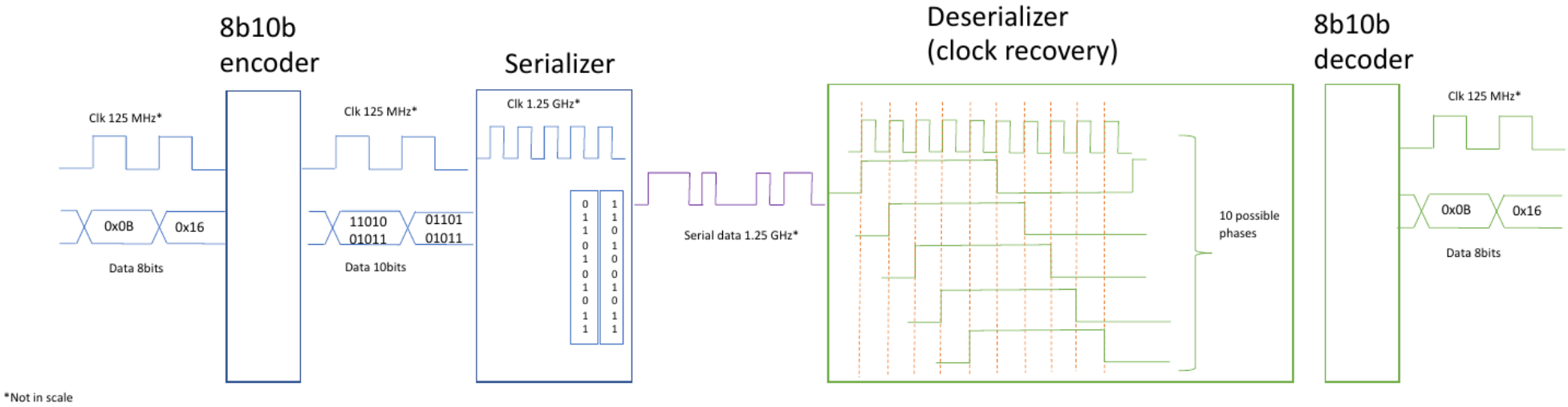


- The board has been received in April.
- Most of the tests are finalized.

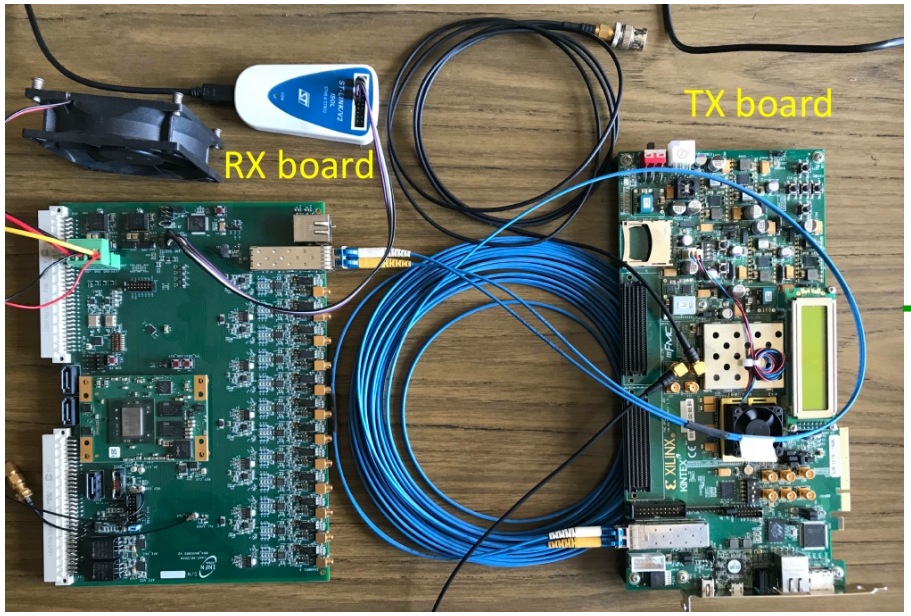
# Second stage distribution

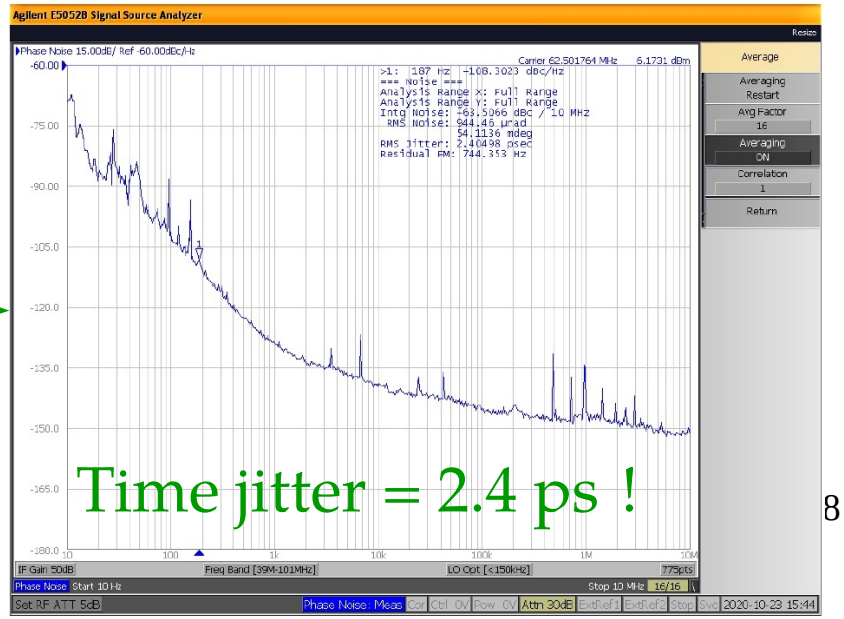
- Second stage at surface & in water vessel :

  → Encodes, sends, & decodes the clock.



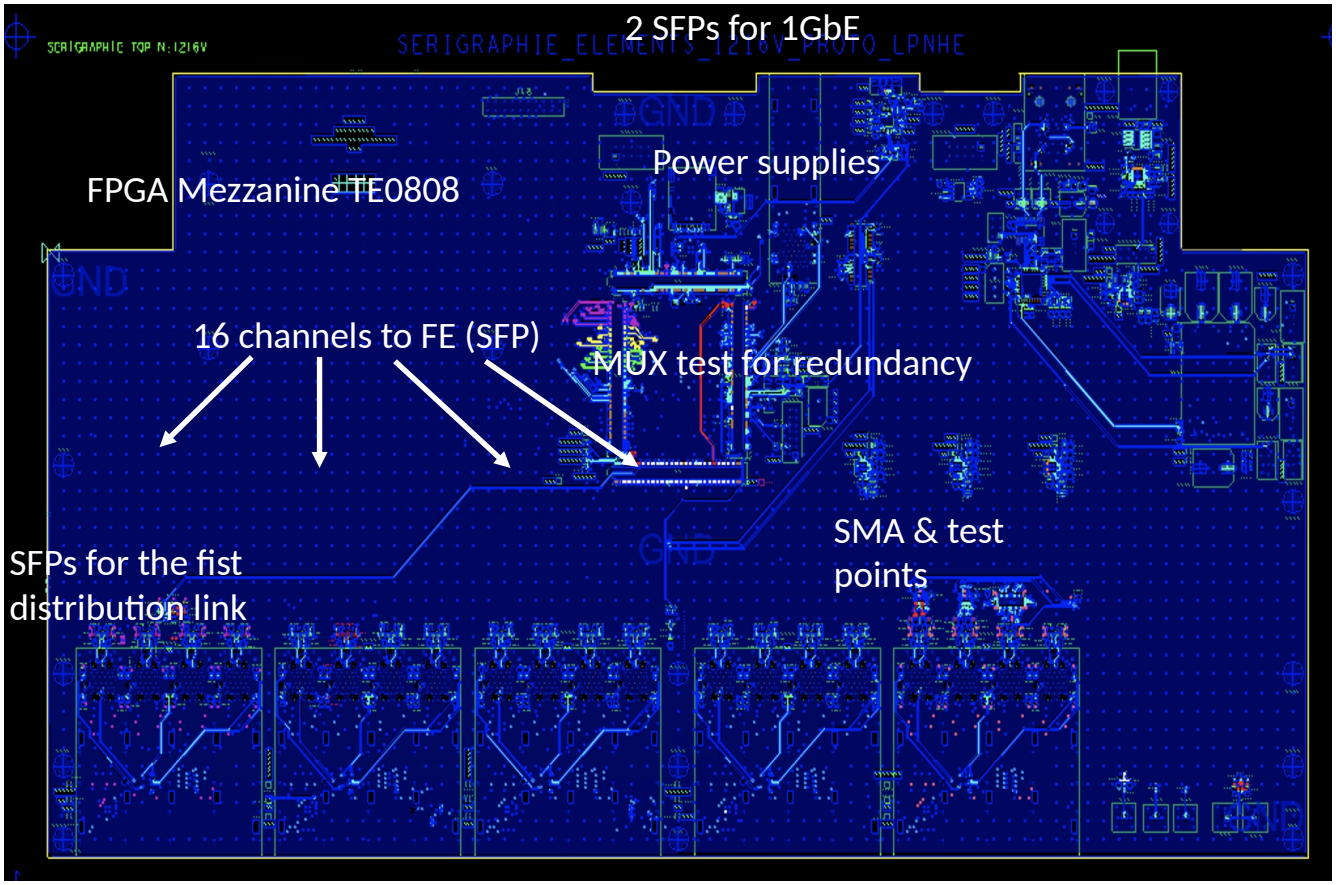

- Concept tested at LPNHE :



# Second stage distribution

- Second stage prototype board : design finalized & send to fabrication.




- Firmware : under development using the same mezzanine (TE0808) and a motherboard EBV

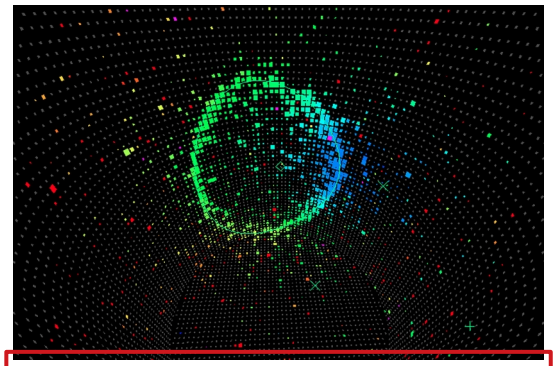
- Software : Embedded under dev. Linux OS already installed and tested. Most peripherals control's sw already written.

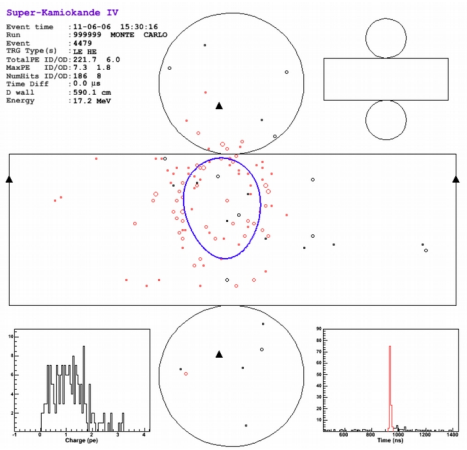
# III. The computing system

# The HK computing strategy

## Data & simulation storage

## CPU resources






Trigger happens

Raw data

Copy of raw data
Simulated raw events

Calibrated data
Calibrated simulation

Reconstructed
data & simulation

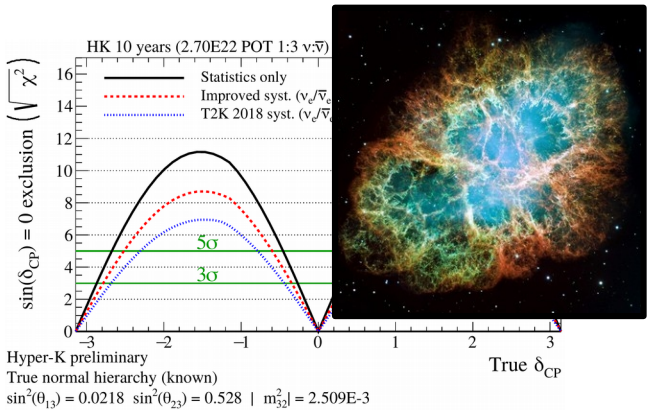
Simulation

Calibration

Reconstruction

Physics analyses

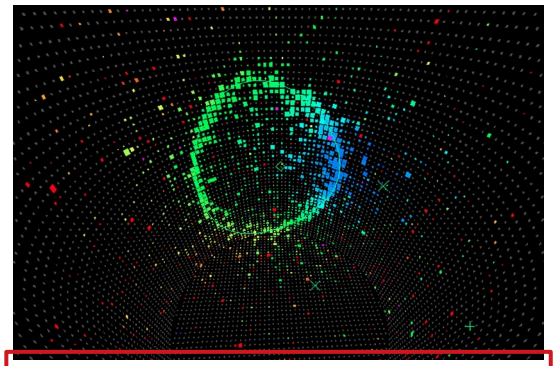
ν oscillation, DSNB search, GUT ….

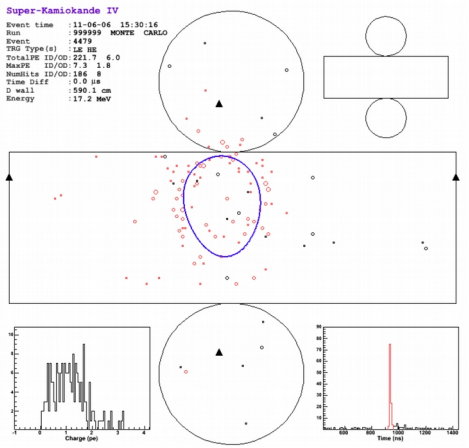


# The HK computing strategy

## Data & simulation storage

## CPU resources






Trigger happens

Raw data

Tier 0

Tier 1 & 2

Copy of raw data
Simulated raw events

Calibrated data
Calibrated simulation

Reconstructed
data & simulation

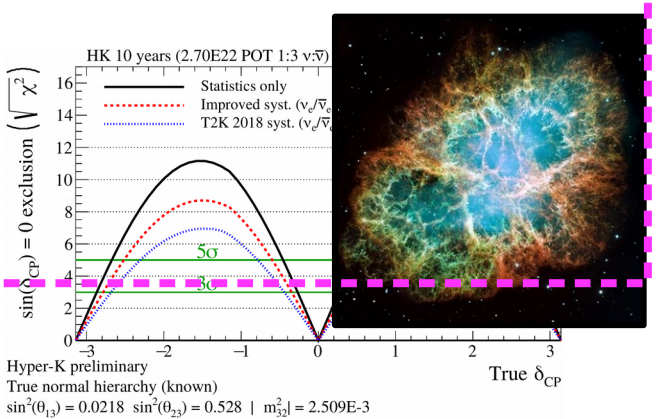
Simulation

Calibration

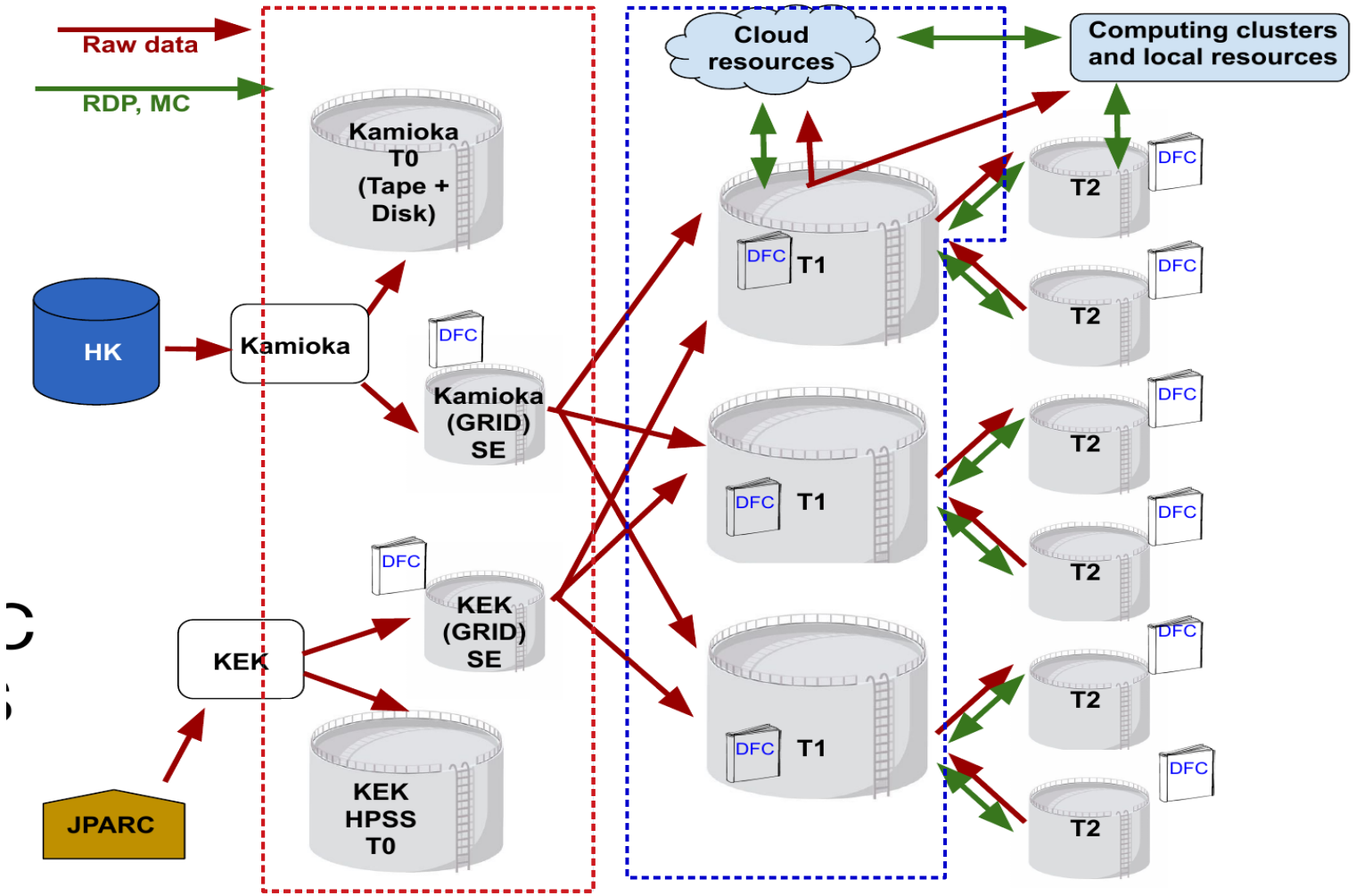
Reconstruction

Physics analyses

ν oscillation, DSNB search, GUT ….



# The HK computing strategy




- 1 data file → Copied on ≥ 2 Tier 1 sites.
- MC productions run on Tier 1 → Then, 1 MC file : copied on 1 T1 + ≥ 1 T2

  → The Tier 1 site contains a copy of each data & simulation file !

  → Offers a central visibility & priviledged access to data !

# Resources to host a Tier 1

- 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.

  → Large request, but relatively small wrt to other experiments.

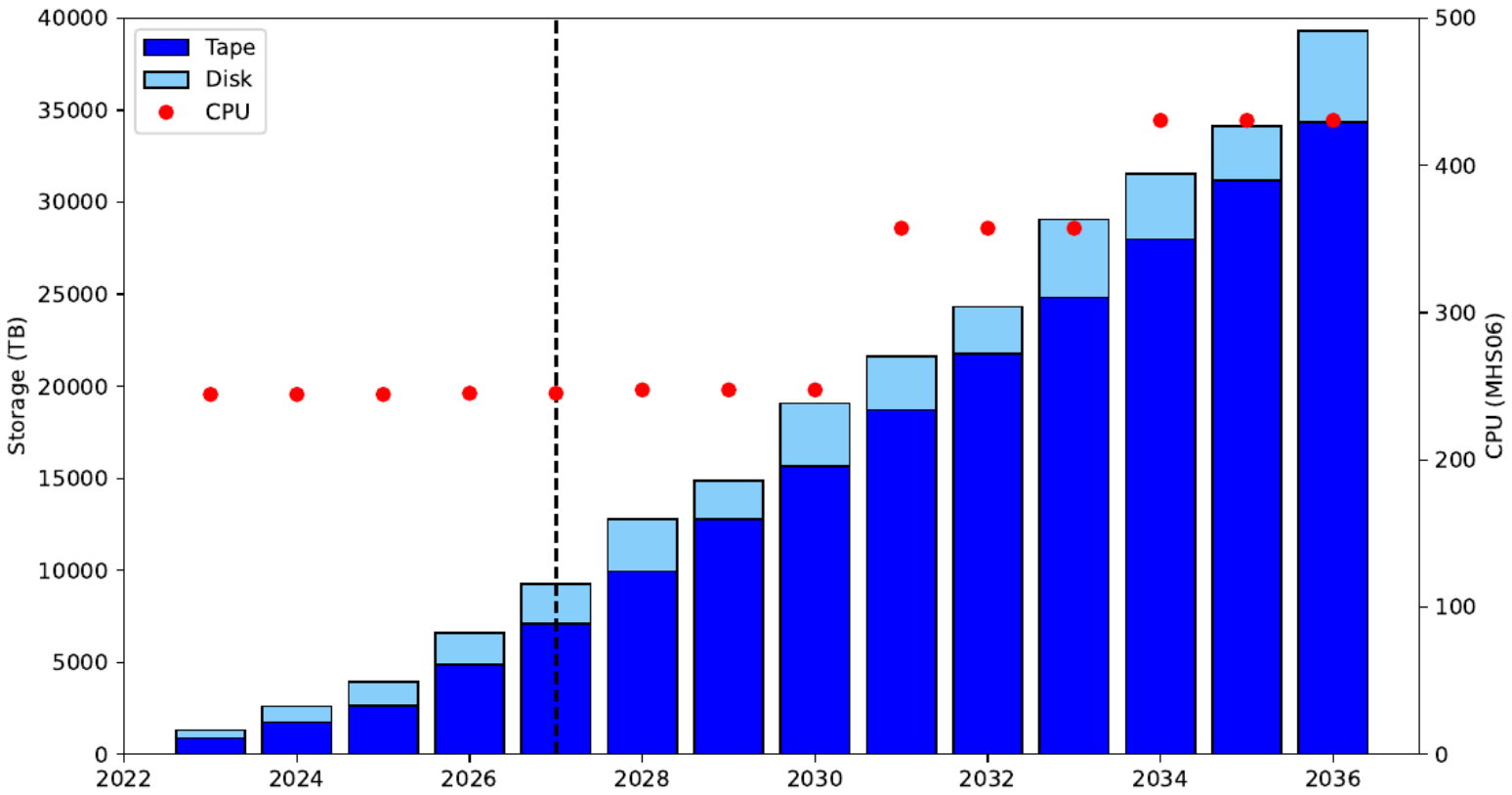
- Full data storage & CPU requested

| 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 |

→ About 9 x $10^9$ HS06 CPU.h over 15 years.

# The IN2P3 teams computing proposal

- Make CC-IN2P3 a **complete Tier-1** for 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. Complete 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

→ Smooth transition & preparation until 2027.

# III. Incoming steps & timeline

# Prospects for the HKROC digitizer

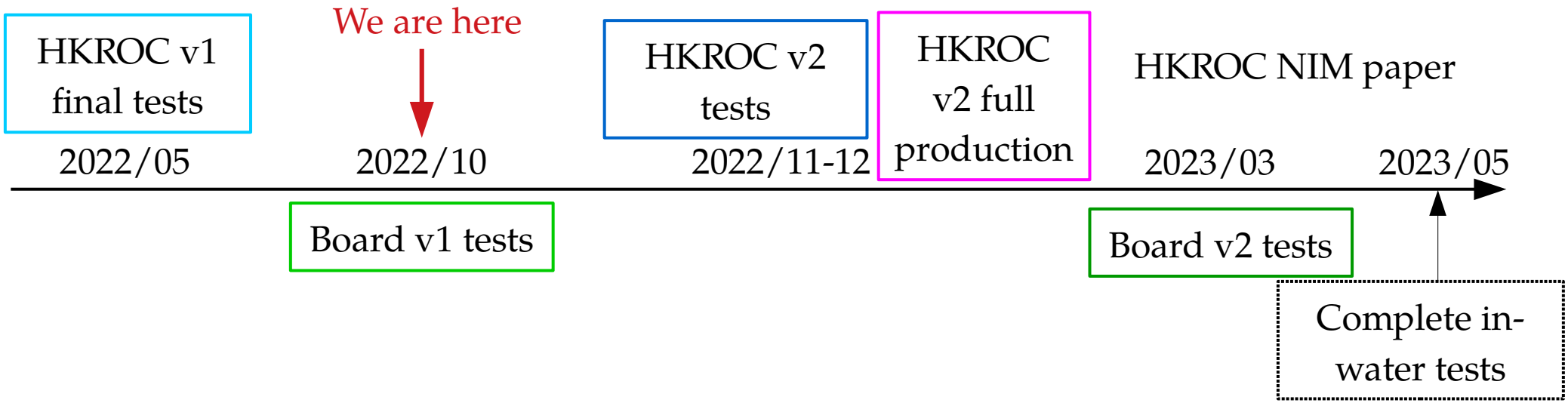
- 2 other digitizers were competing for HK : QTC (Japan), discrete (Italy).
  → Unfortunately, HKROC not chosen as primary solution for HK.

- 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 **prefered an already final 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 a on-shelves solution ready (others had).**

- HKROC has been built to be a **waveform digitizer for any PMT-based experiment in 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

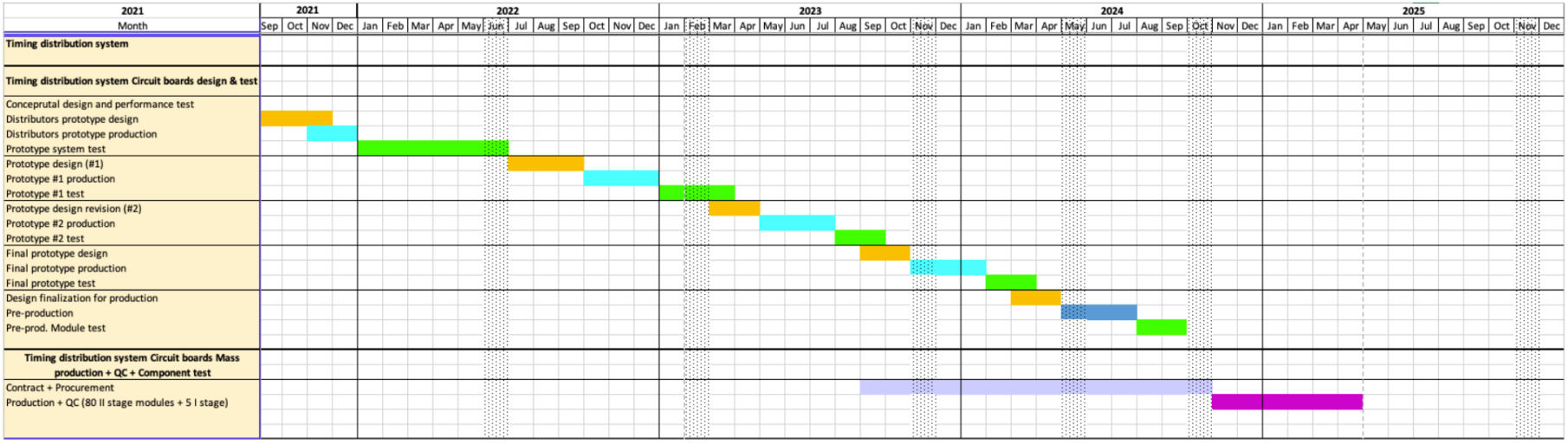
- Final time generation & distribution scheme presented and **validated by the HK electronics group.**
- The timing system technical **note has been submitted and is under technical evaluation**.

→ *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 !**

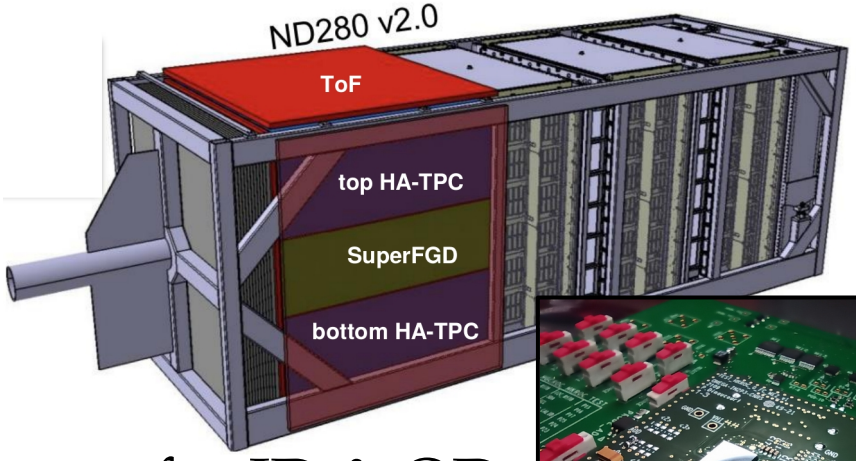
→ Ordering components for the final production has started.



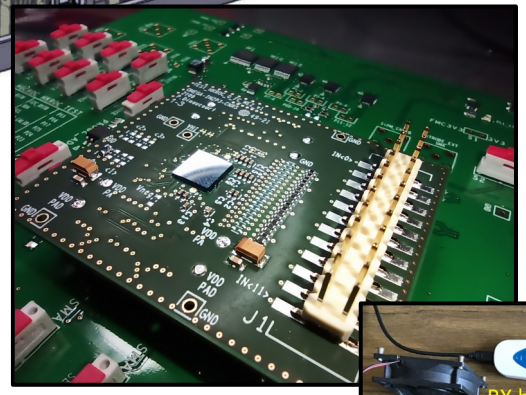
# Summary of proposed contributions

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

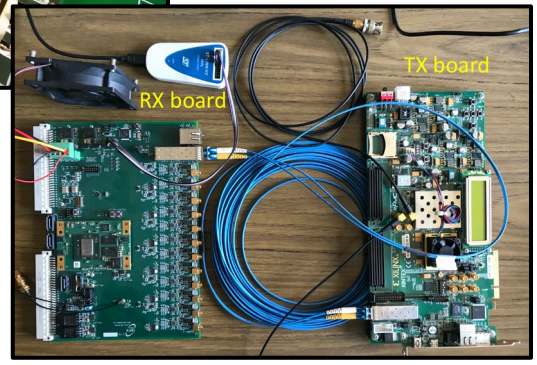
- The ND280-upgrade.



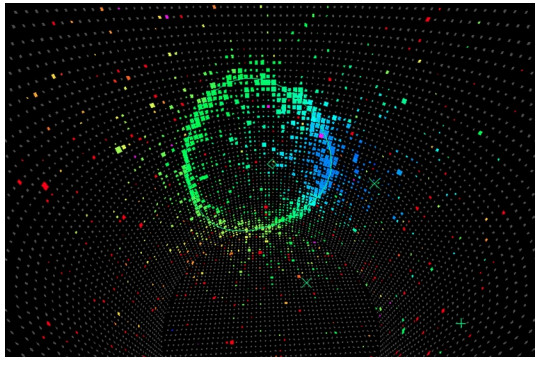

- ~~HKROC complete digitizer for ID & OD.~~



- Time generation & clock distribution at Far Detector.



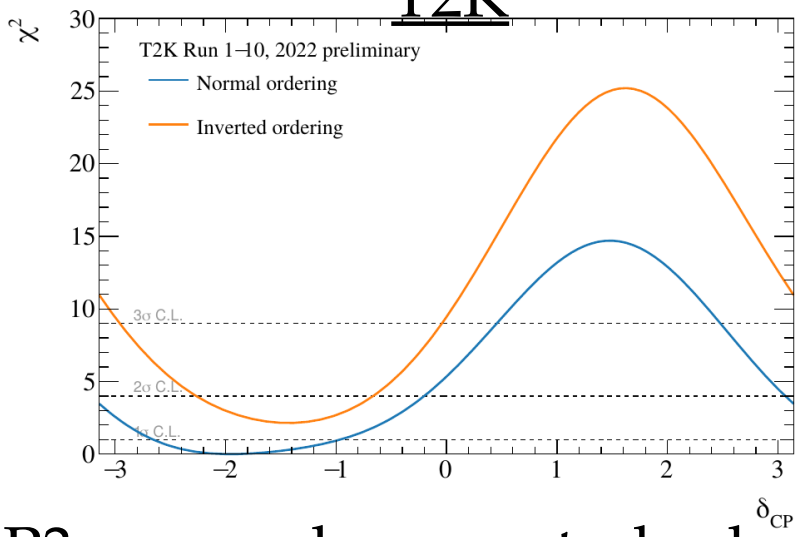

- Shared-item cost & assembly.



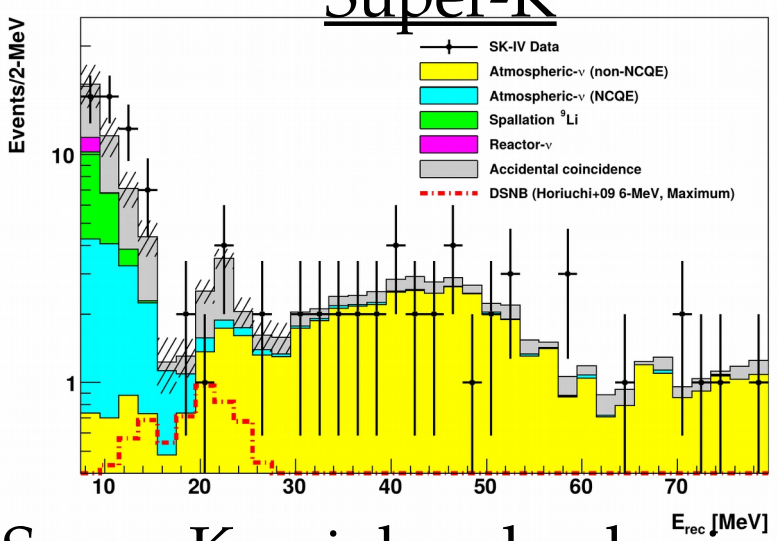
- CC-IN2P3 : HK Tier 1 computing system.

# Let's talk about physics & analyses

T2K




Super-K




- <u>IN2P3-groups have central roles in T2K & Super-Kamiokande physics.</u>
  → Near-detector physics, T2K ν oscillation analysis, SK DSNB.

- <u>Goal :</u> Lead the future Hyper-K analyses from 2027 !
  → Need new reconstruction algorithms to update 20 years-old SK ones.
  → Have the unique chance to apply them 1st on Super-K & T2K data before HK start to : find DSNB, CP violation and mass ordering at 3σ …

- For this purpose, we wish Hyper-K to become an IN2P3 master-project & Need new members in our groups to move from SK/T2K → HK.

# Conclusions

- Hyper-K will be the world-leading experiment in many aspects of neutrino physics for the next 20 years.

- RD4HK only started in January 2022, but tremendous progresses have been 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 %) → To be reduced by a factor of 100 in HKROC v2.

**2. Clock generation & distribution system scheme has been completed :**

→ Time generation system has been validated through measurements.

→ First stage distribution first prototype completely characterized.

→ Second stage distribution first prototype sent to production.



- **Huge technical achievements & success in only 1 year !!**

# 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 accomplish & lead HK physics for 20 years, we need to go beyond RD4HK. And we need it **NOW** :

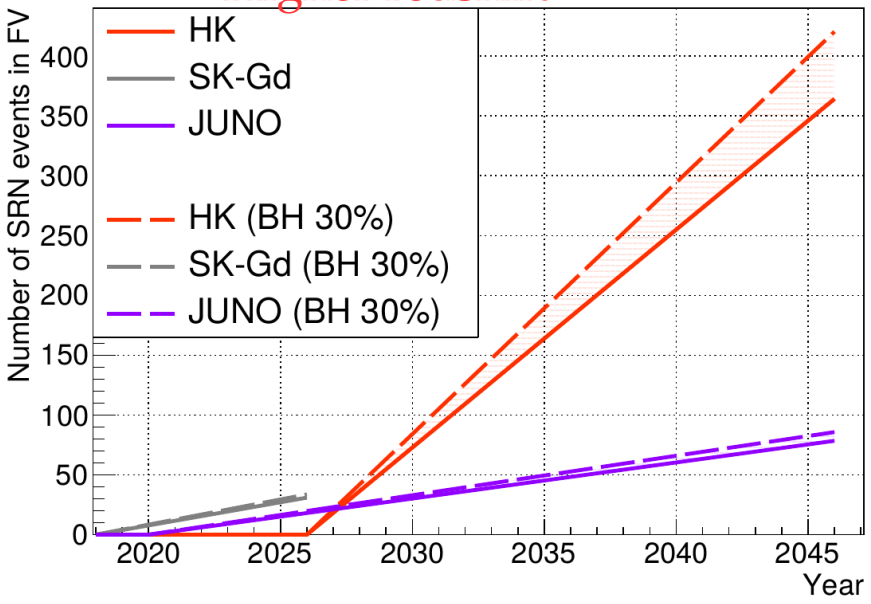
  1. Make CC-IN2P3 a Tier-1 for HK : absolutely central visibility & access to data, at a « relatively small » cost (2 PB/year).

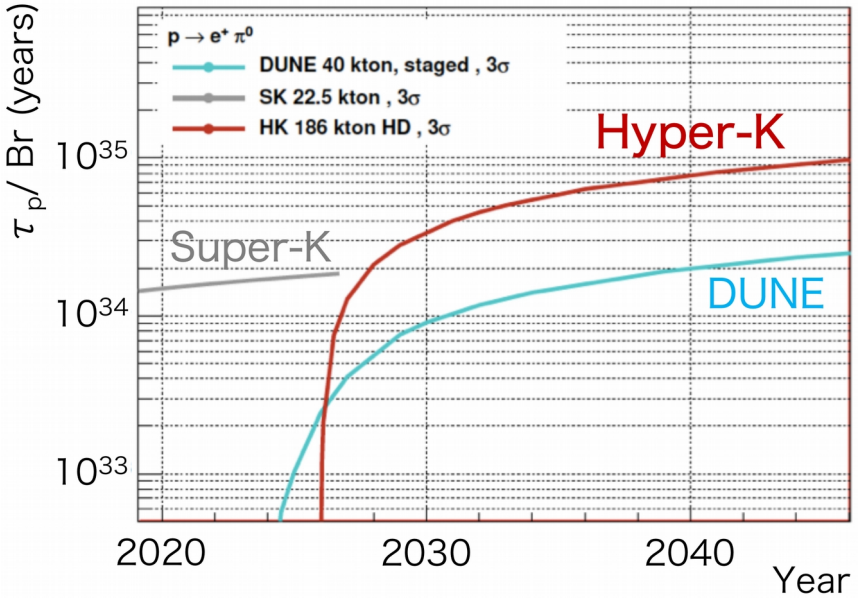
  2. Build on our leaderships & expertize in T2K / Super-Kamiokande (acquired after 15 years of continuous work & investment by IN2P3) to lead the future HK low & high energy analyses.

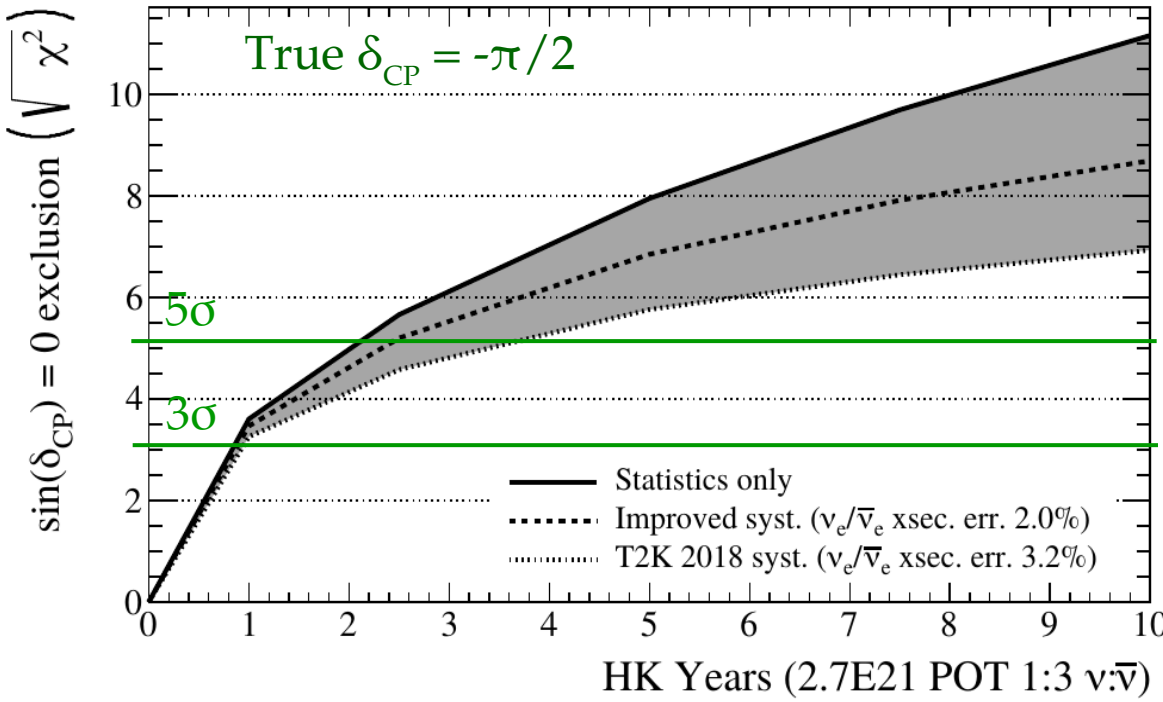
- This is the time to transform this project into a master project !
  → And to ride the last train to prepare analysis tools.

# Conclusions

Higher redshift




$\underline{\delta_{CP} = -\pi/2}$: 5σ after 2-4 years of data taking

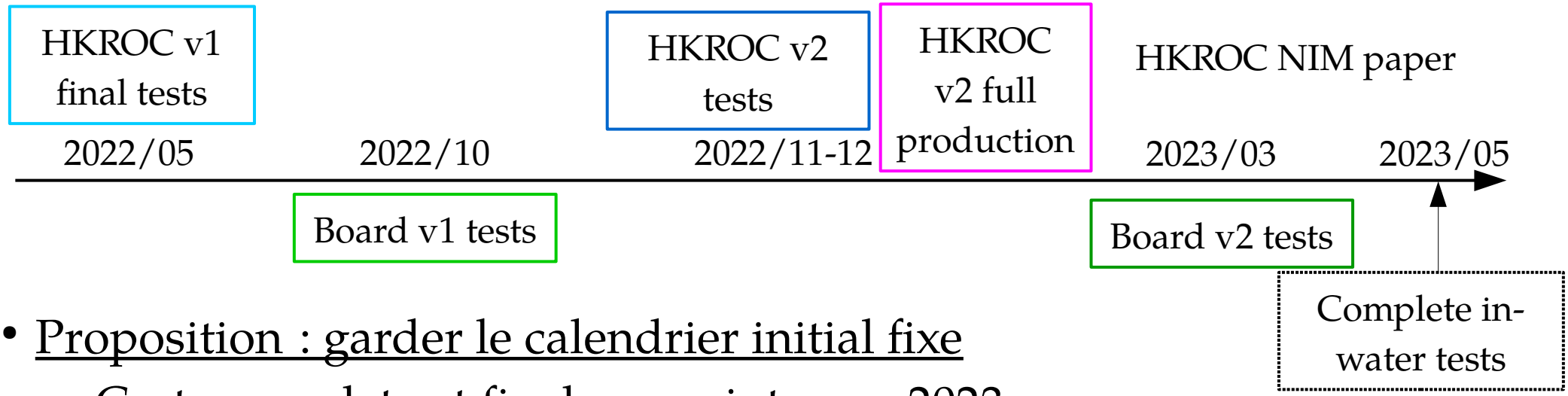
→ Independent from ↓ systematic uncertainties.

→ DUNE will require 7-8 years.

# Additional slides

# HKROC digitizer - Impact on physics

Le groupe HKROC propose de finaliser la R&D ASIC + carte :




- Proposition : garder le calendrier initial fixe
  → Carte complete et finale au printemps 2023.
  → Demande budgetaire additionnelle : prod. de quelques cartes v2.

- Papier NIM : Preparation pour publication fin printemps 2023.
  → Base sur HKROC v2 & carte proto v1 : tests finalises en Fevrier 2023.

- Hiver 2022 : contact avec d'autres manip utilisant des PMTs (IceCube gen2…), upgrade HK eventuel, HK outer-Detector etc.

# 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** | |
| | | | | |

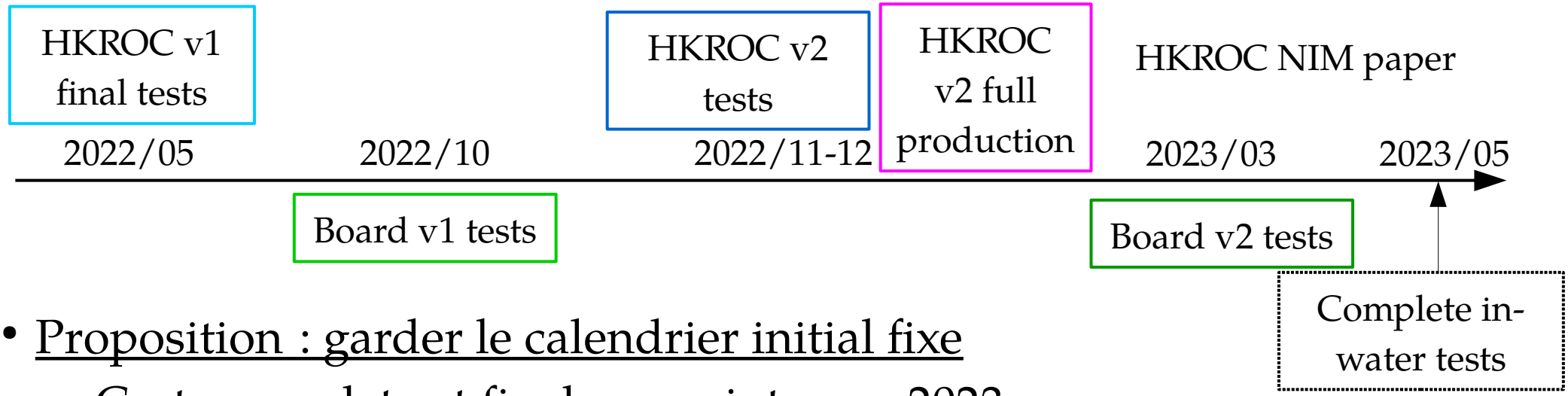
- En resume :

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.

# HKROC digitizer - Impact on physics

Le groupe HKROC propose de finaliser la R&D ASIC + carte :

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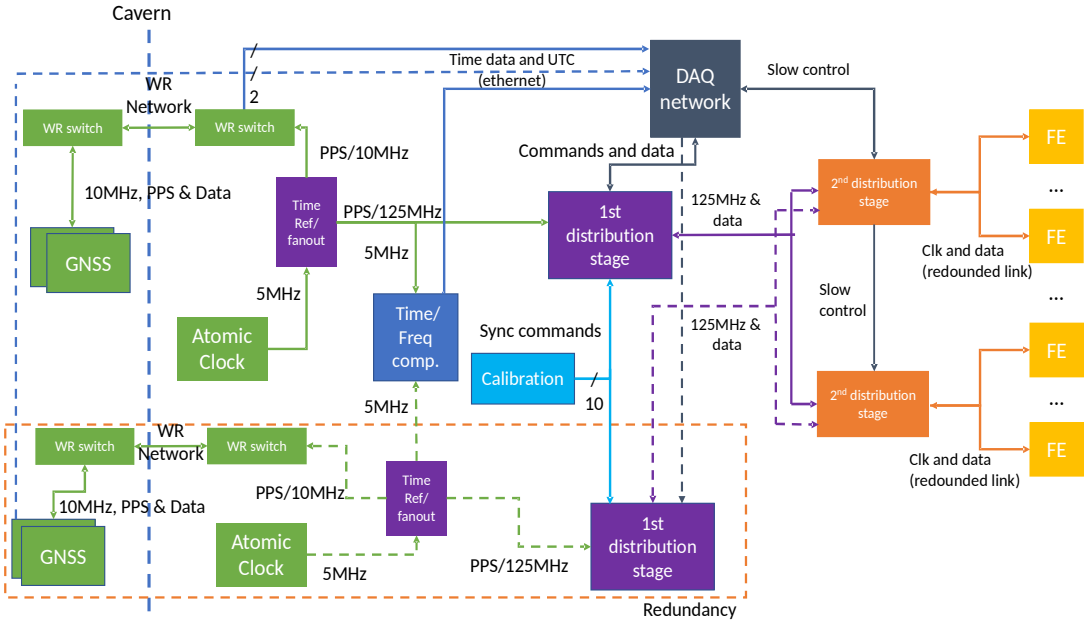
# Faits marquants 2022 - Electronique

- Final time distribution scheme presented and validated by the HK electronics group.
- The time distribution subsystem technical **note has been submited and is under evaluation** (delayed due to digitiser choice)

→ It should be highlighted that there is no alternative solution in HK !




- Significant progresses on-going : ahead of official schedule

**→ The development is going perfectly well & on-time !**

- Ordering components for the final production via PUMA procedure. Anticipation on the 2024 spending

# Rappels de l'organisation RD4HK

Responsable national : B. Quilain

| HKROC | Digitiseur | Generation horloge | Distribution horloge |
|---|---|---|---|
| F. Dulucq (OMEGA) | J. Nanni (LLR) | M. Guigue (LPNHE) | 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

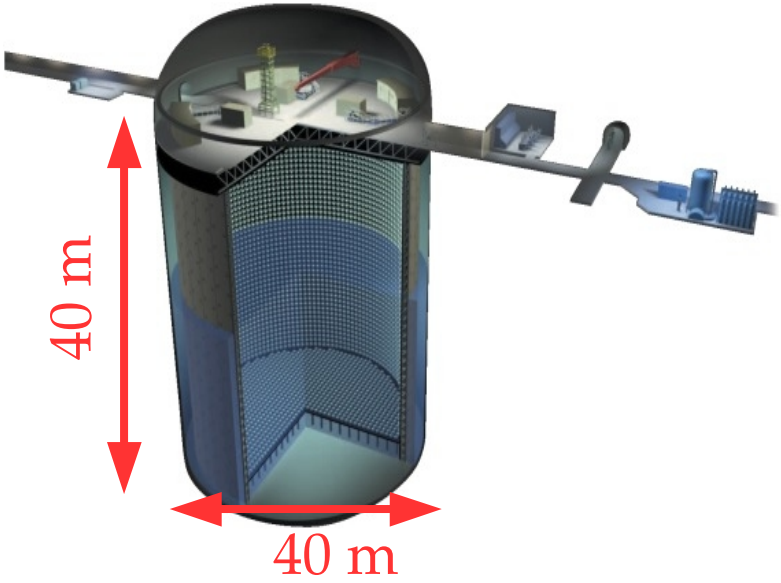
M. Gonin (DR)
G. Pronost (Posdoc)
**→ 1.2 FTE / an phys.**

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

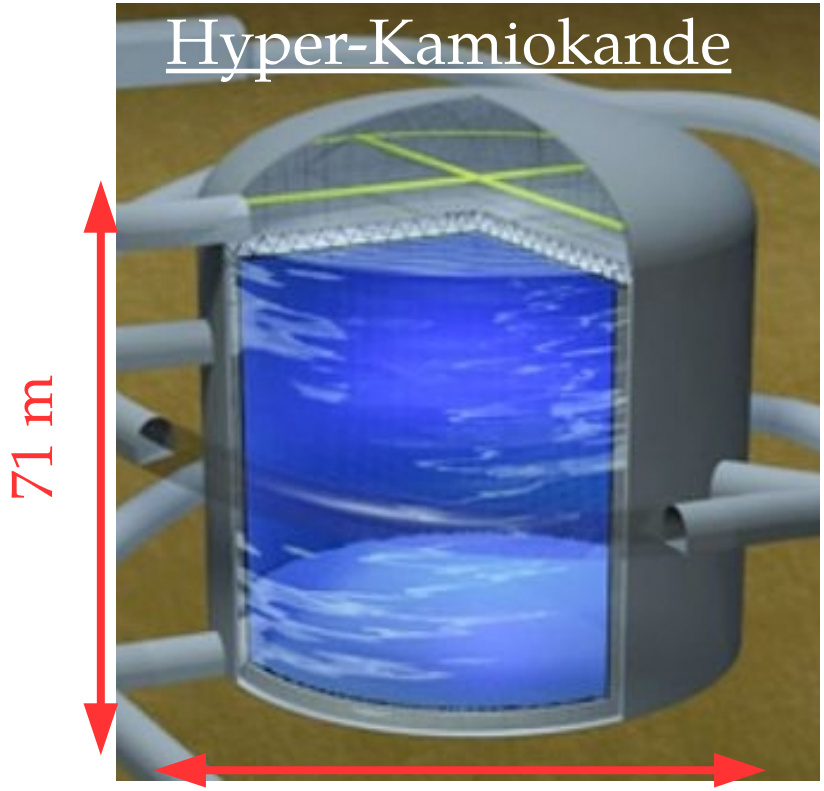
# Reminder : what is Hyper-K ?

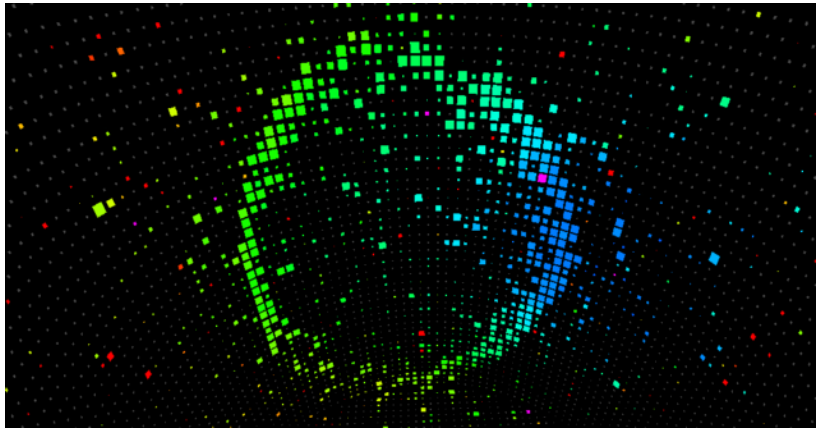
- Next generation of neutrino observatory in Japan→ construction 2020-27
  → A 260 kton water Cherenkov detector → Fiducial Mass ~ 8 x SK.

Super-Kamiokande



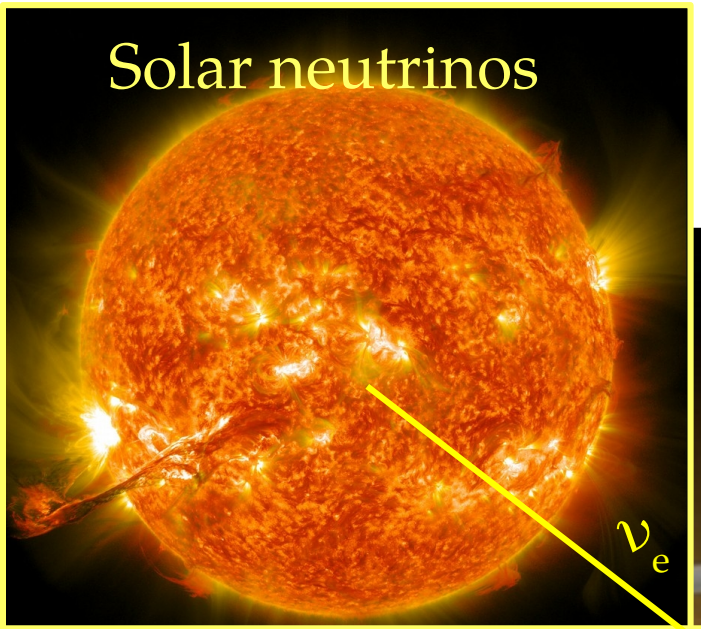

Hyper-Kamiokande



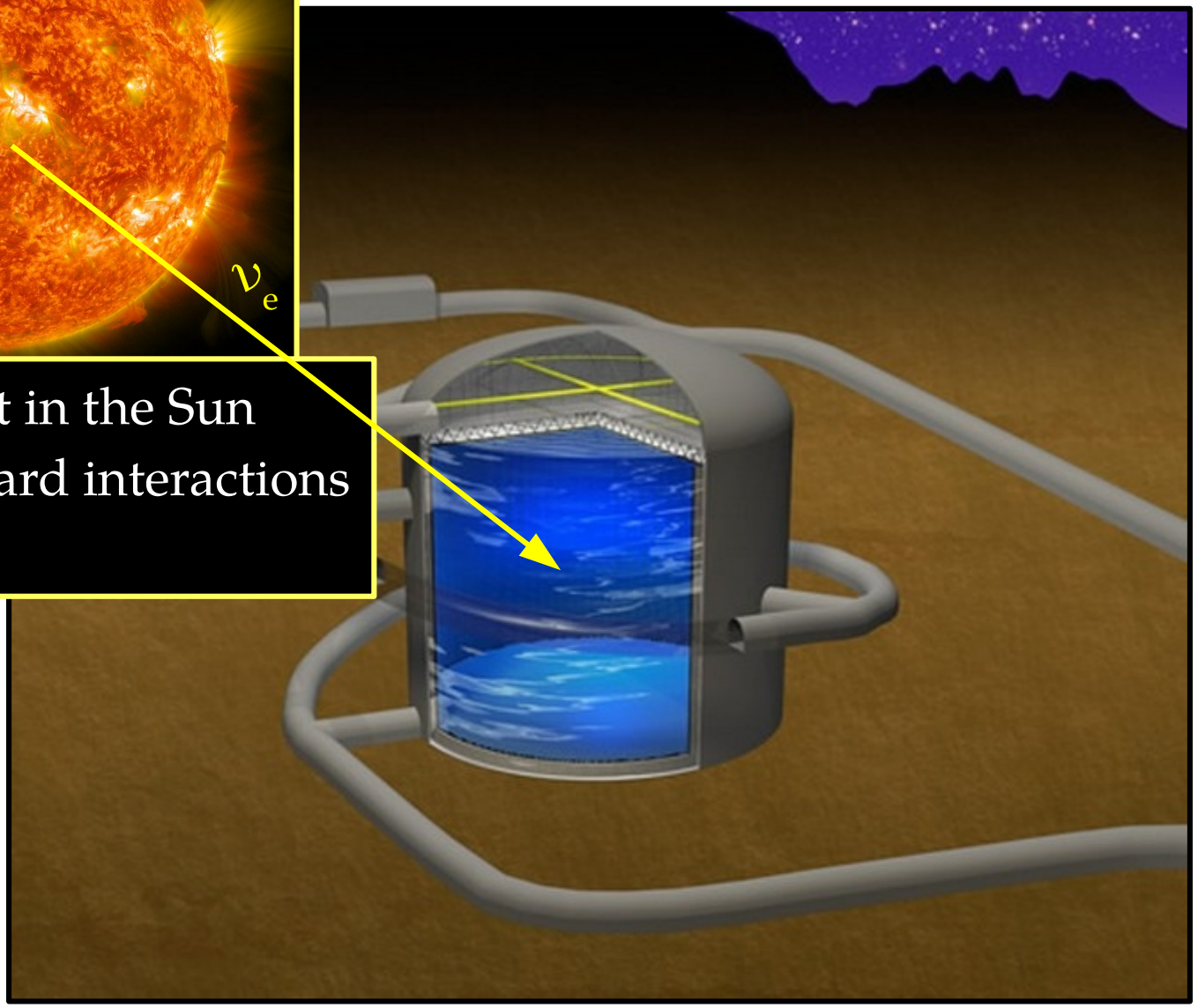



| | Super-K | Hyper-K (1st tank) |
|---|---|---|
| Site | Mozumi | Tochibora |
| Number of ID PMTs | 11,129 | 40,000 |
| Photo-coverage | 40% | 40% (×2 sensitivity) |
| Mass / Fiducial Mass | 50 kton / 22.5 kton | 260 kton / 187 kton |

# Physics case

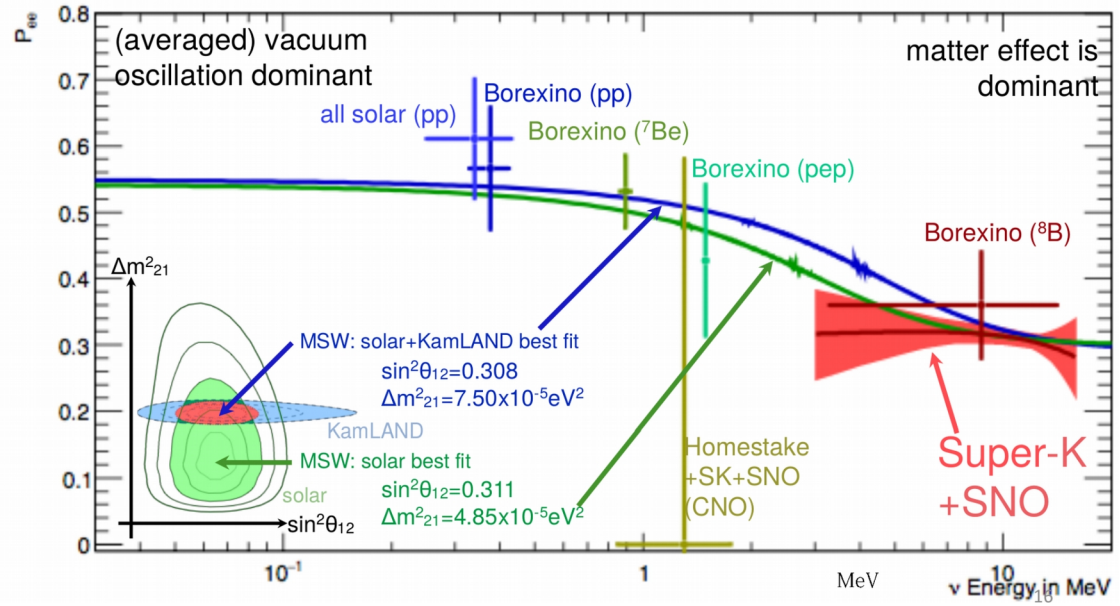


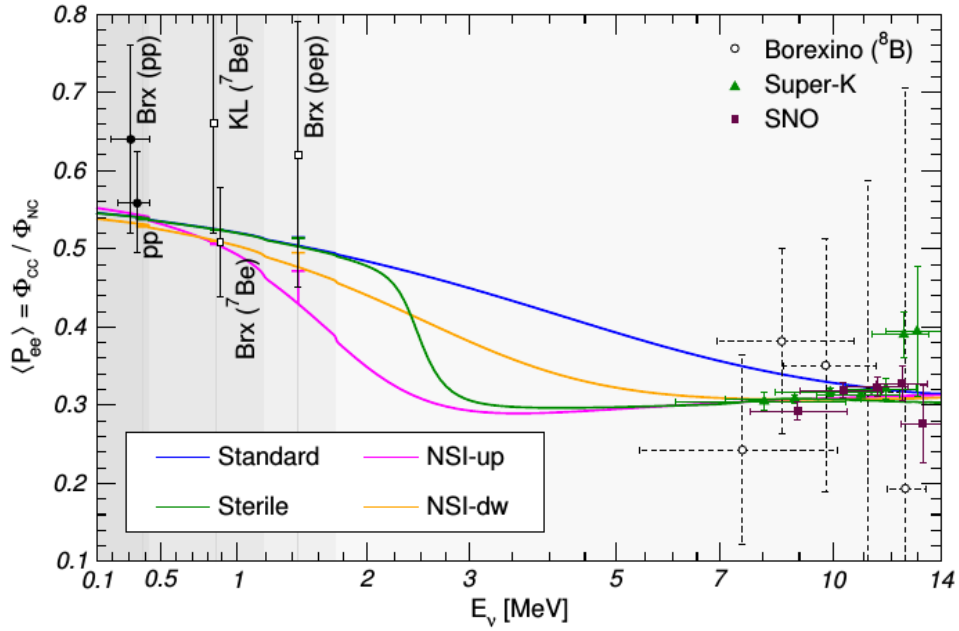

- MSW effect in the Sun
- Non-standard interactions in the Sun.



# Solar neutrinos : upturn

- <u>Probe solar ν :</u> SK/SNO found a high matter effect in the Sun
  ↔ Solar upturn shifted to lower energies

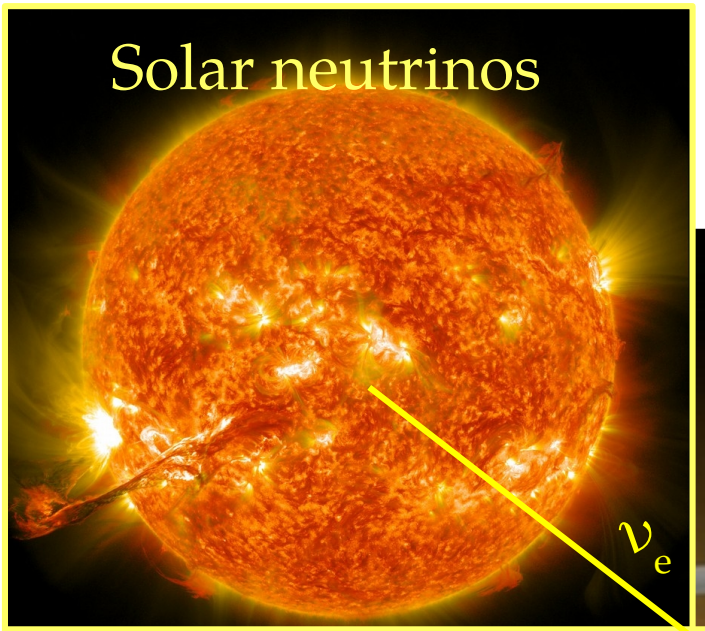



- SK deviates from standard upturn scenario > 2σ.

- <u>Displacement of the upturn can be explained by :</u>
  - Statistical fluctuation ?
  - Light sterile neutrino ?
  - Non Standard Interaction in the dense Sun ?

# Physics case

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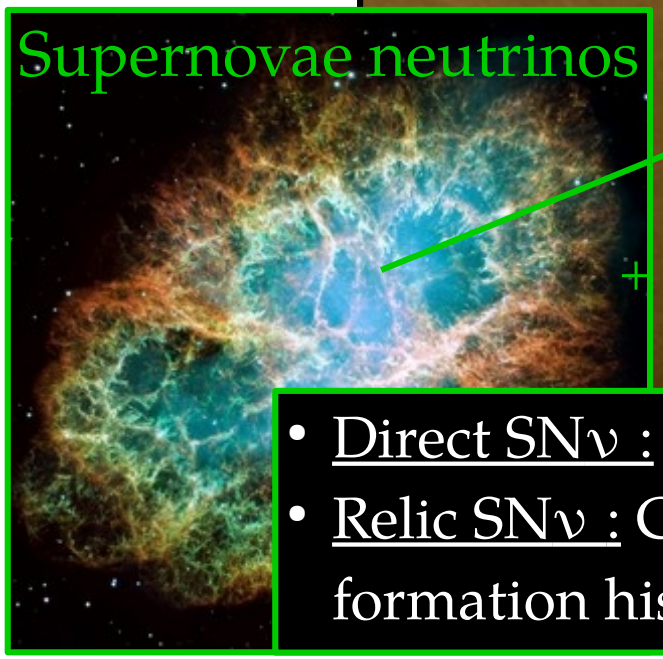
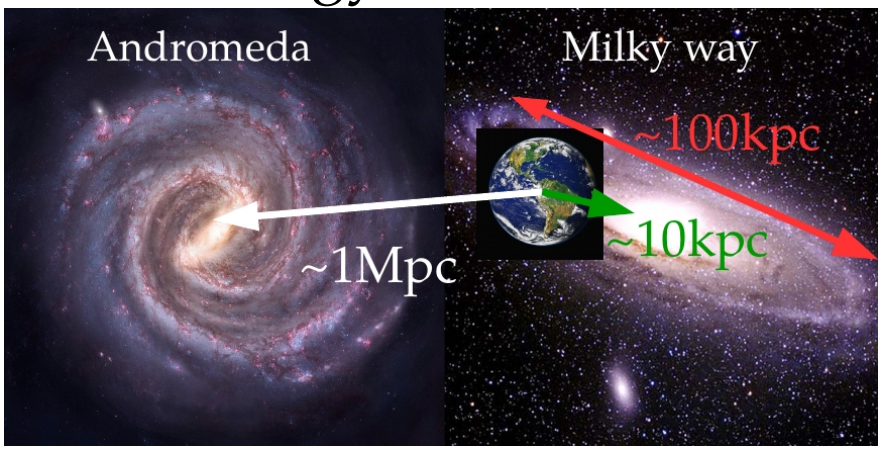



$\bar{\nu}_e + (\nu_\mu, \nu_e, \bar{\nu}_\mu)$

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

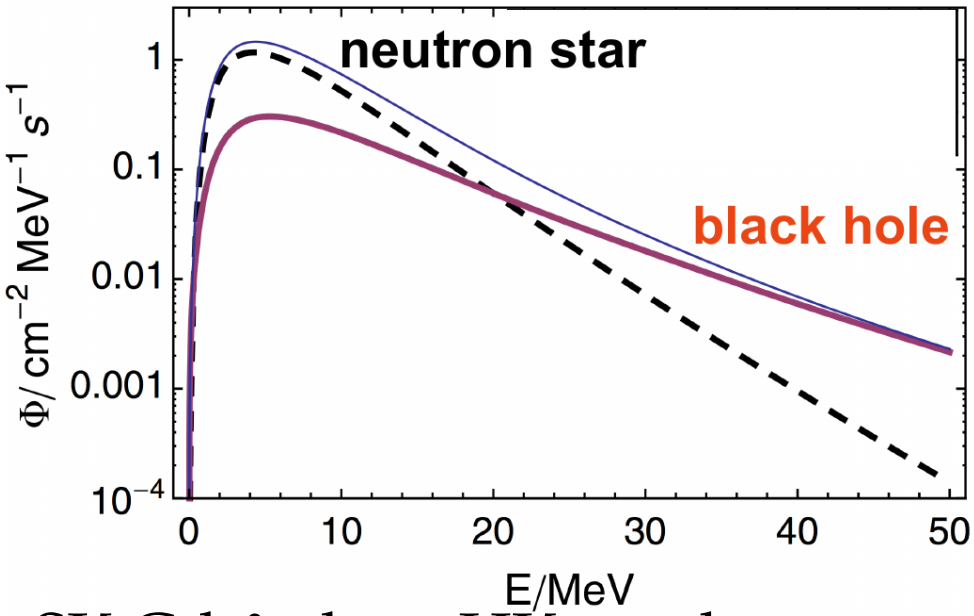
# Supernovae neutrinos

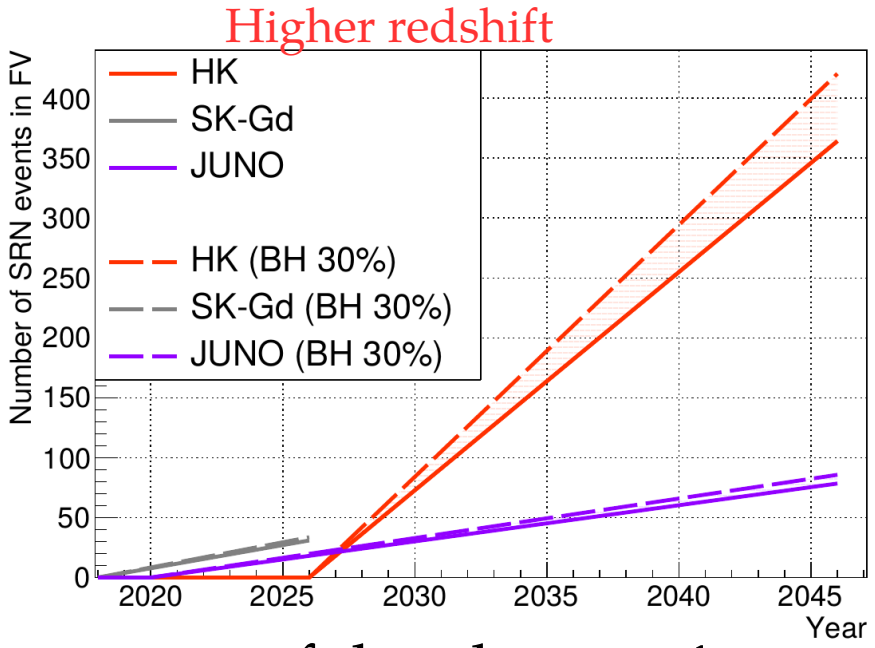
- Unique probe for supernovae ν : 99 % of SN energy → ν.
  - But direct ν detection very rare.
  - HK also sensitive to extra-galactic SNν from Andromeda !




- SN-relic neutrino → new constraints on cosmic star history → May be first detected in SK-Gd.

  → But spectrum determined by HK : Low energy ↔ Probe older stars

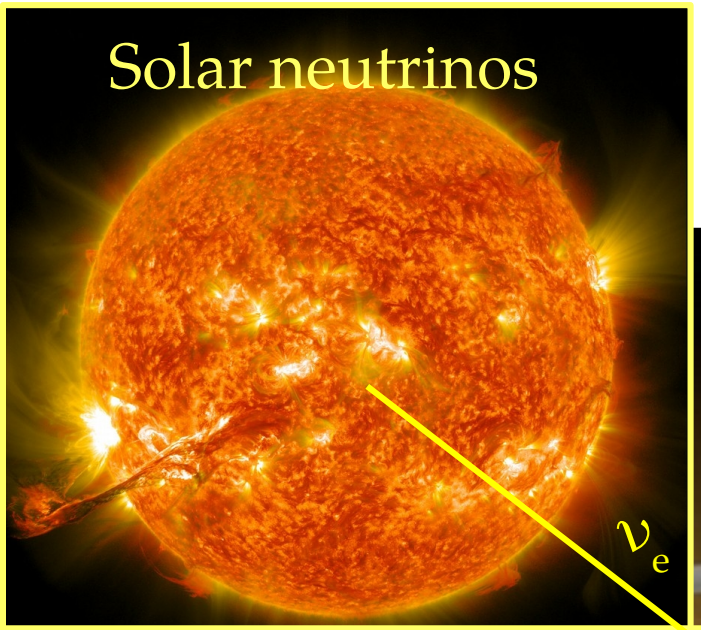



- SK-Gd & then, HK are the pioneer experiments of this domain !

# Physics case

## Solar neutrinos



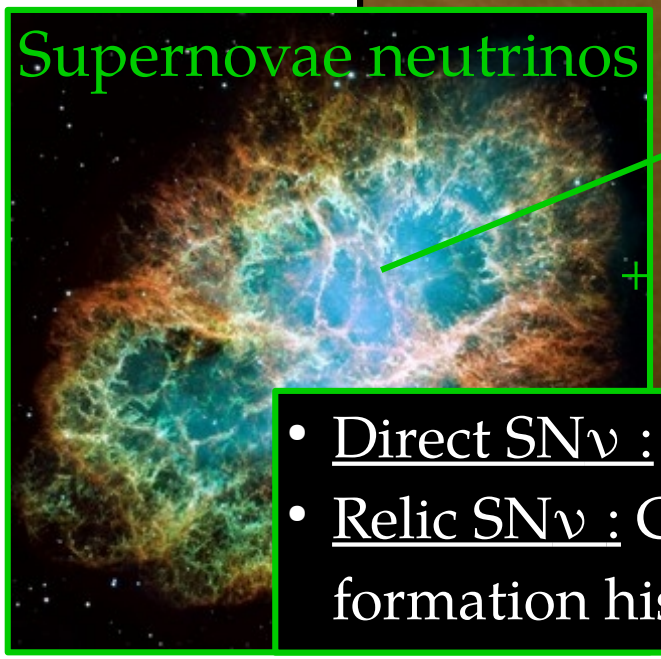

- MSW effect in the Sun
- Non-standard interactions in the Sun.

## Proton decay

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



## Supernovae neutrinos

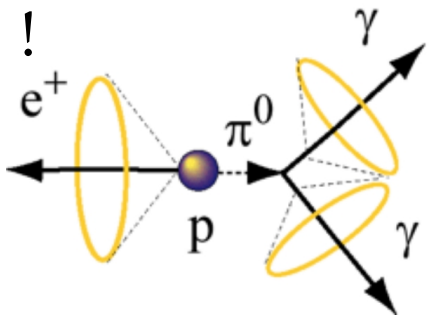


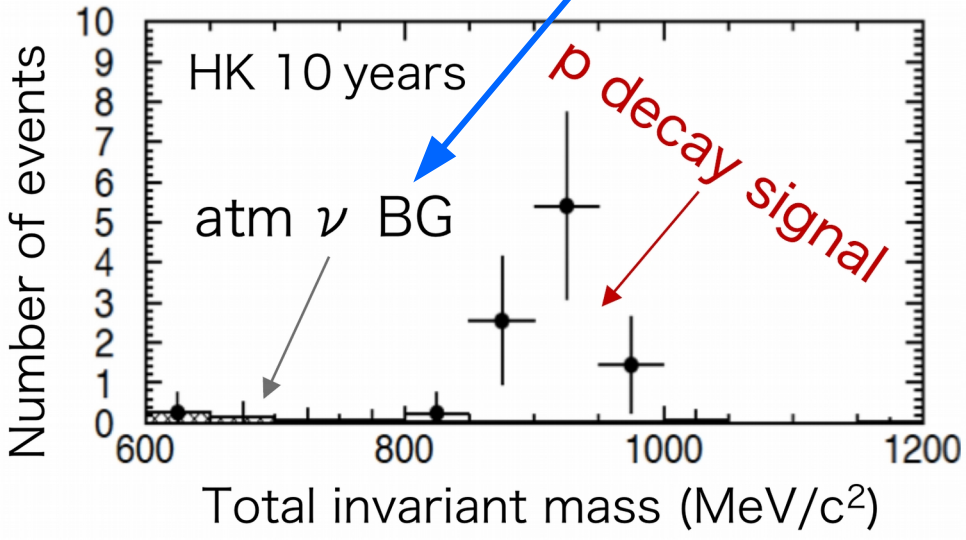

- <u>Direct SNν :</u> Constrains SN models.
- <u>Relic SNν :</u> Constrains cosmic star formation history

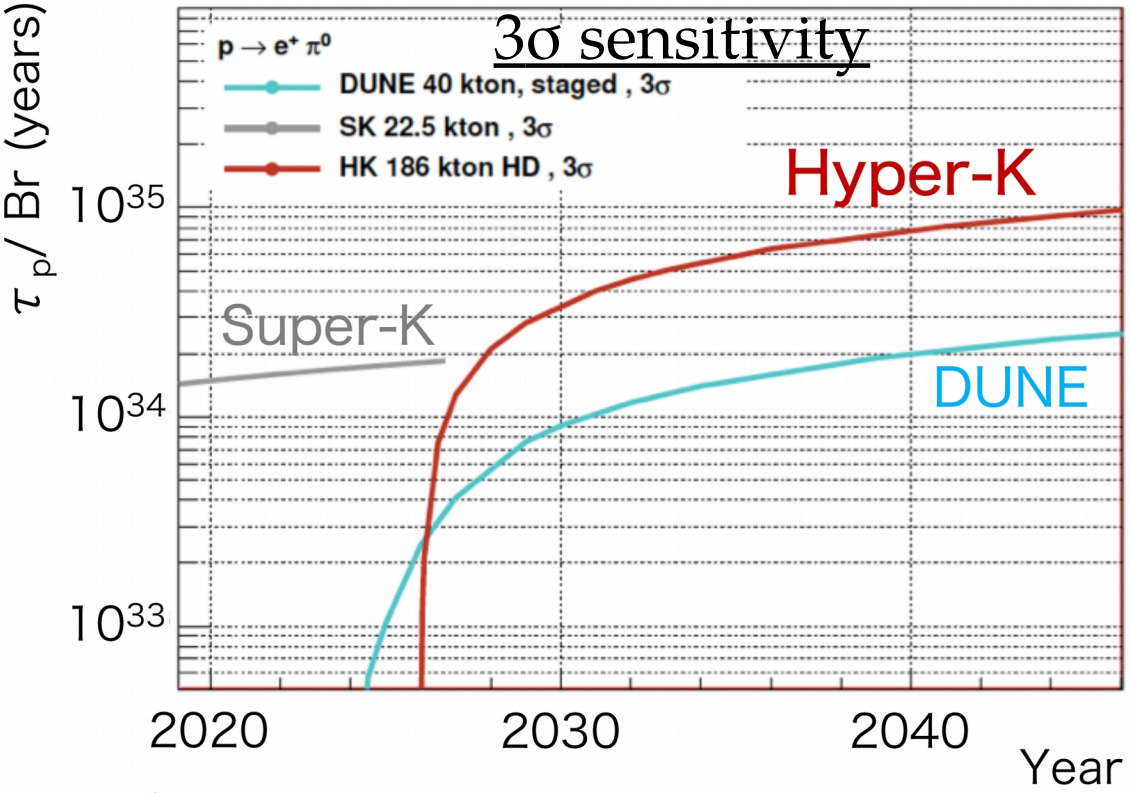
# GUT and proton decay

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

- Golden channel : $p \rightarrow e^+ + \pi^0 \rightarrow$ Almost background free !
  $\rightarrow$ Requires $2\gamma$ & reconstructed energy = Invariant $M_P$
  $\rightarrow$ Bkg : Atmospheric $\nu$ producing e.g. a $\pi^0$.



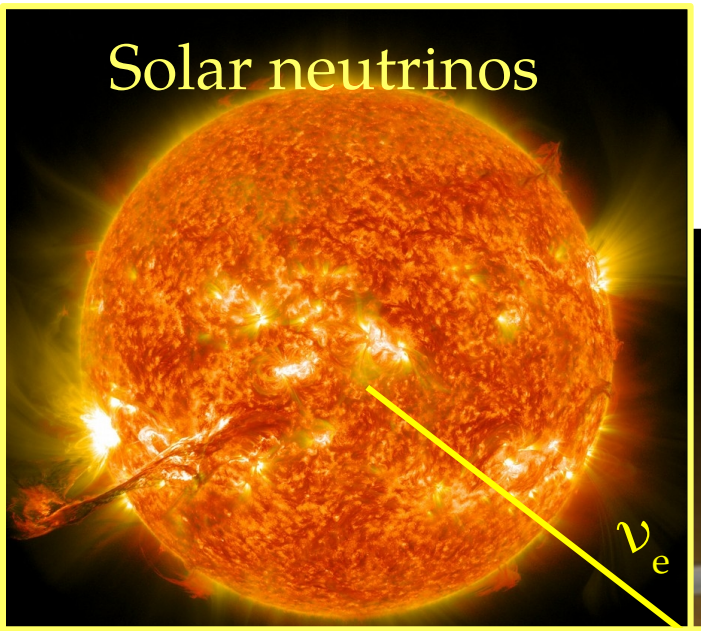




- 3σ sensitivity reach $\tau_P$ /Br = $10^{35}$ years $\rightarrow$ 1 order of magnitude beyond SK or DUNE

# Physics case

## Solar neutrinos

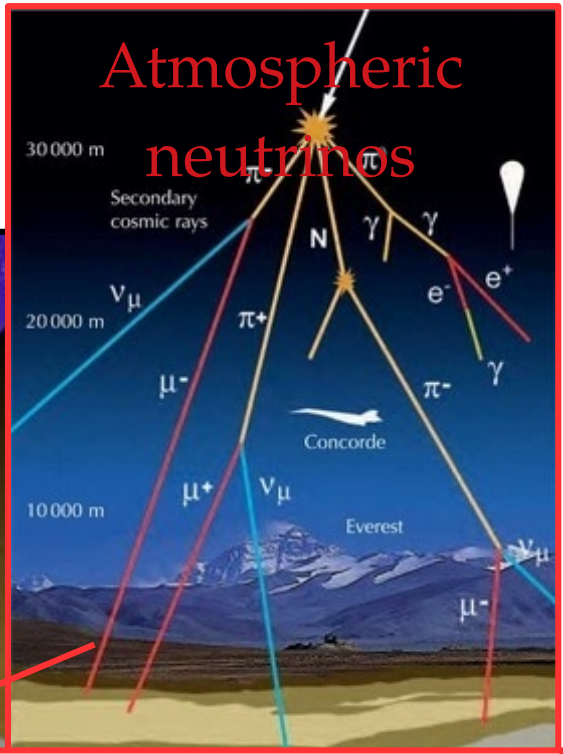



- MSW effect in the Sun
- Non-standard interactions in the Sun.

## Proton decay

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

## Atmospheric neutrinos




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

## Supernovae neutrinos

$\bar{\nu}_e$

$+ (\nu_\mu, \nu_e, \bar{\nu}_\mu)$

$\nu_\mu, \nu_e$

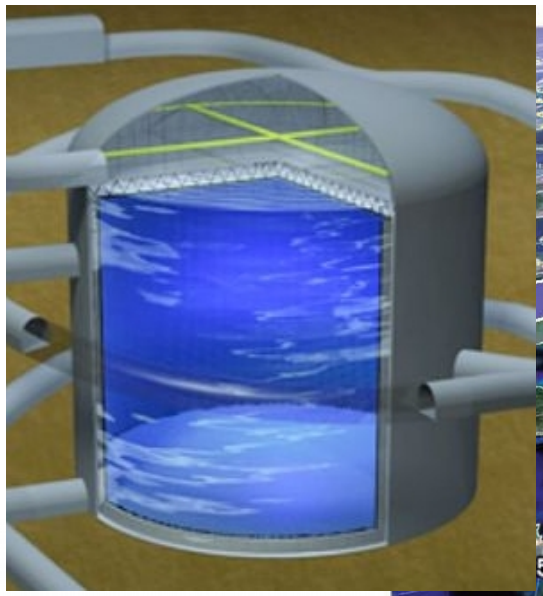
$\bar{\nu}_\mu, \bar{\nu}_e$

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

# Focus on CP violation

- CP violation search essentially based on accelerator $\nu$ : T2HK

Hyper-Kamiokande



Detect

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

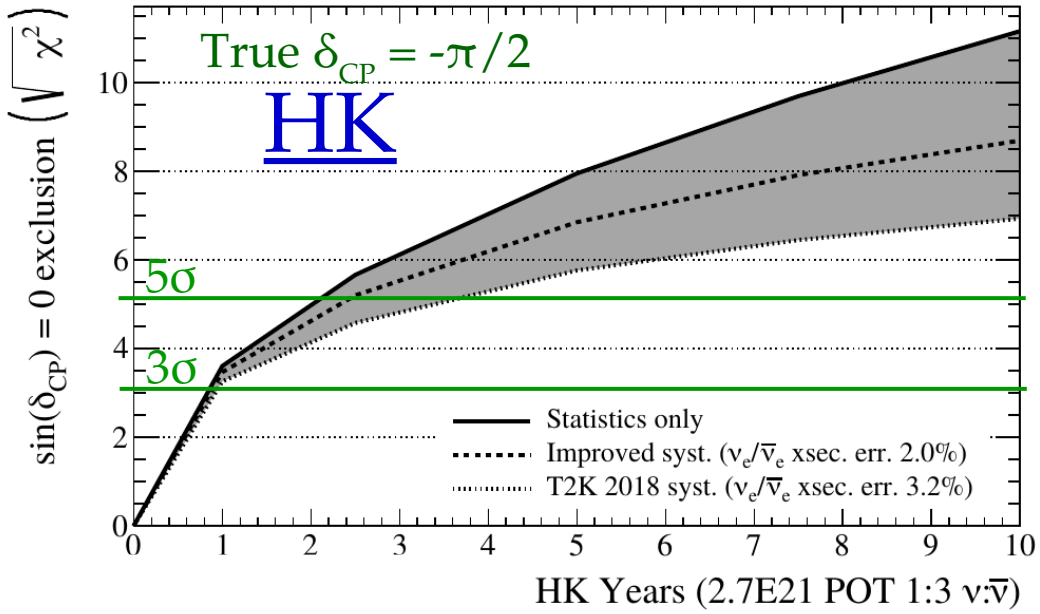

- $\nu_e$ appearance in a $\nu_\mu$ beam and $\nu_\mu$ disappearance & $\bar{\nu}$ equivalents.
- Detector technologies, calibration, analyses well-proven by T2K&SK.

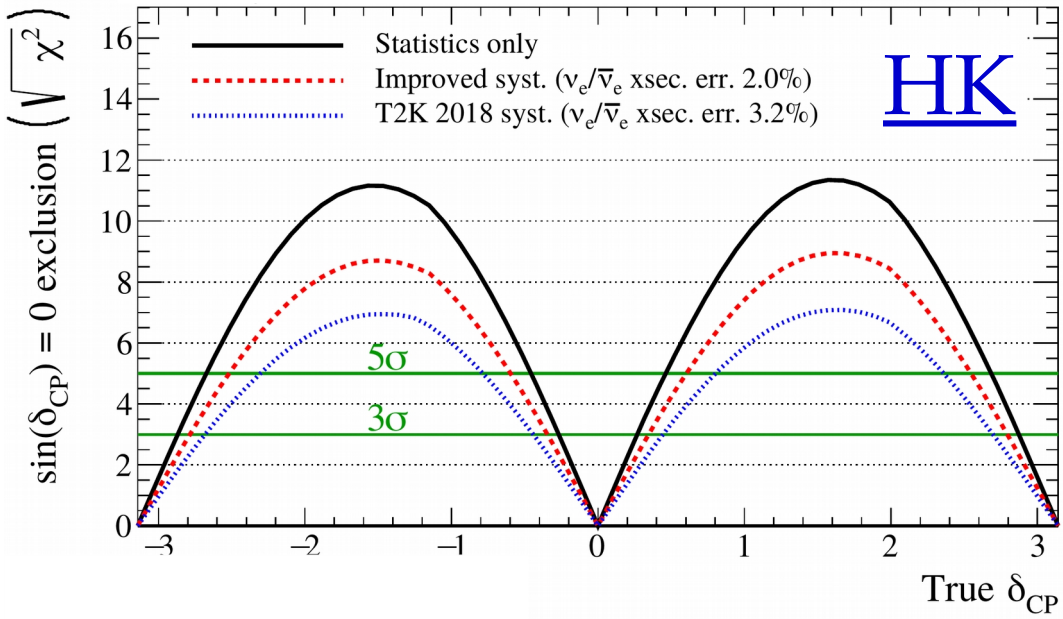
⟹ Quick start ! Which relies on 2 milestones :

1. ↓ time to accumulate statistics → Beam upgrade.
2. ↓ systematic uncertainties → Constrains $\nu_\mu$ &$\nu_e$ flux before oscillation

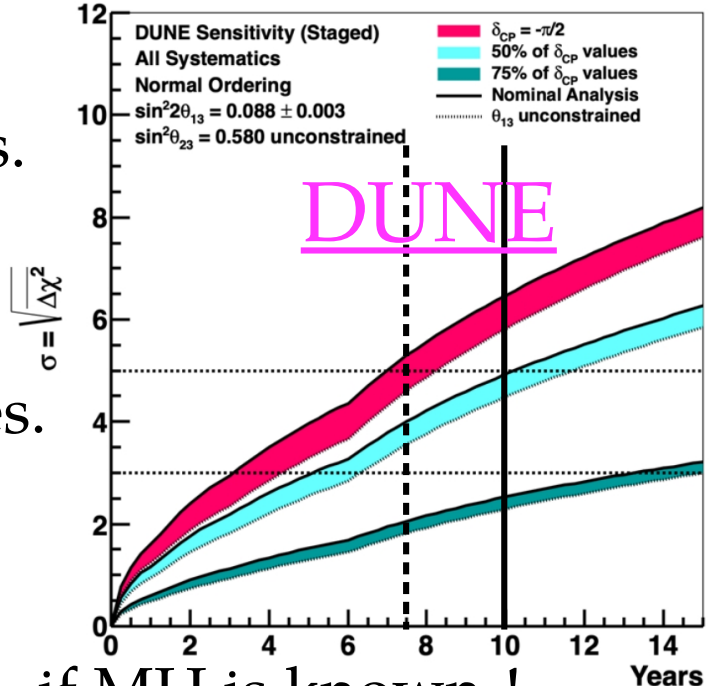
# Sensitivity to CP violation

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




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

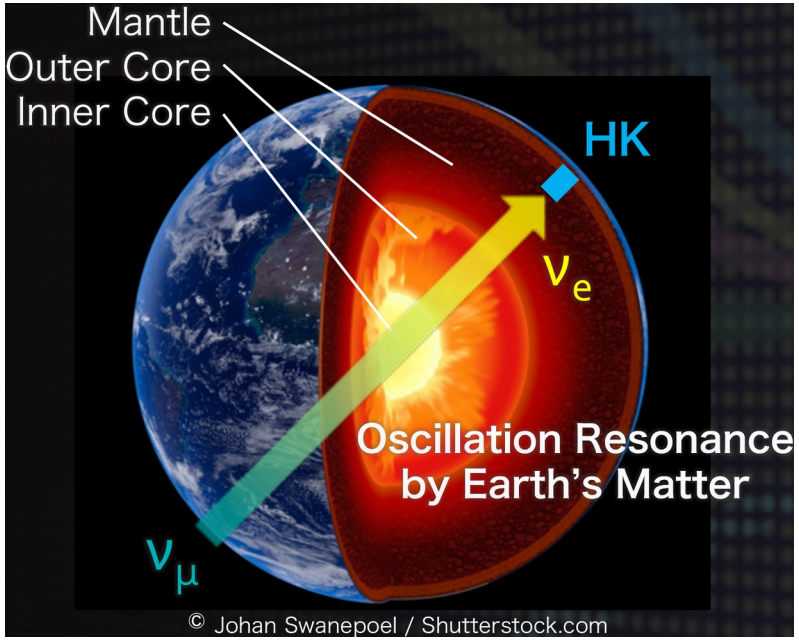



- HK 10 years : 5σ sensitivity on 60% of $\delta_{CP}$ values.
  → DUNE : 5σ sensitivity on 40%

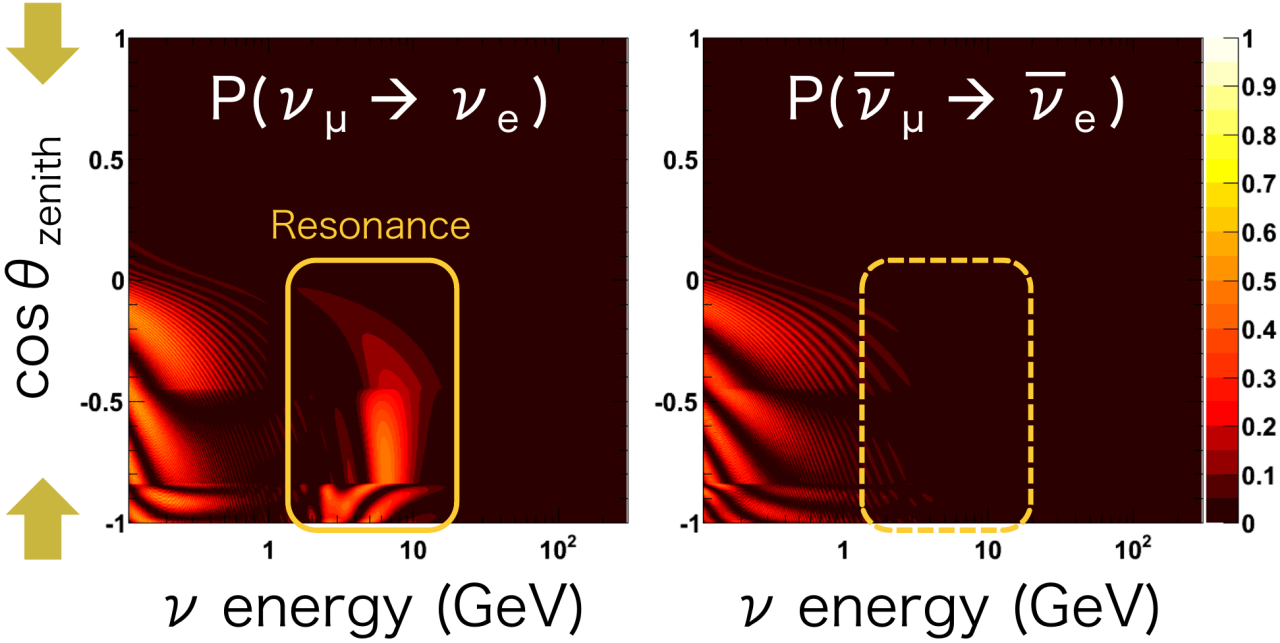
- HK has world-best sensitivity to CP violation … if MH is known !

# Atmospheric neutrinos

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




Normal Hierarchy case



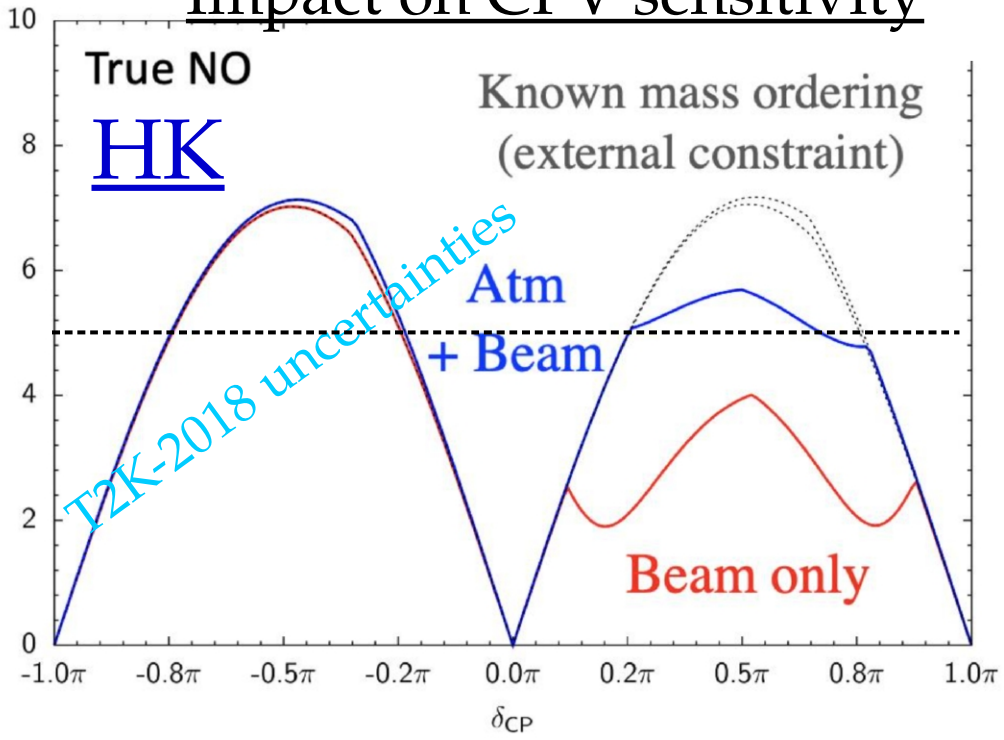

- Mass hierarchy determined with upward-going multi-GeV $\nu_e$ sample :

atm. baseline ≤ 13000 km ≫ 295 km accelerator baseline

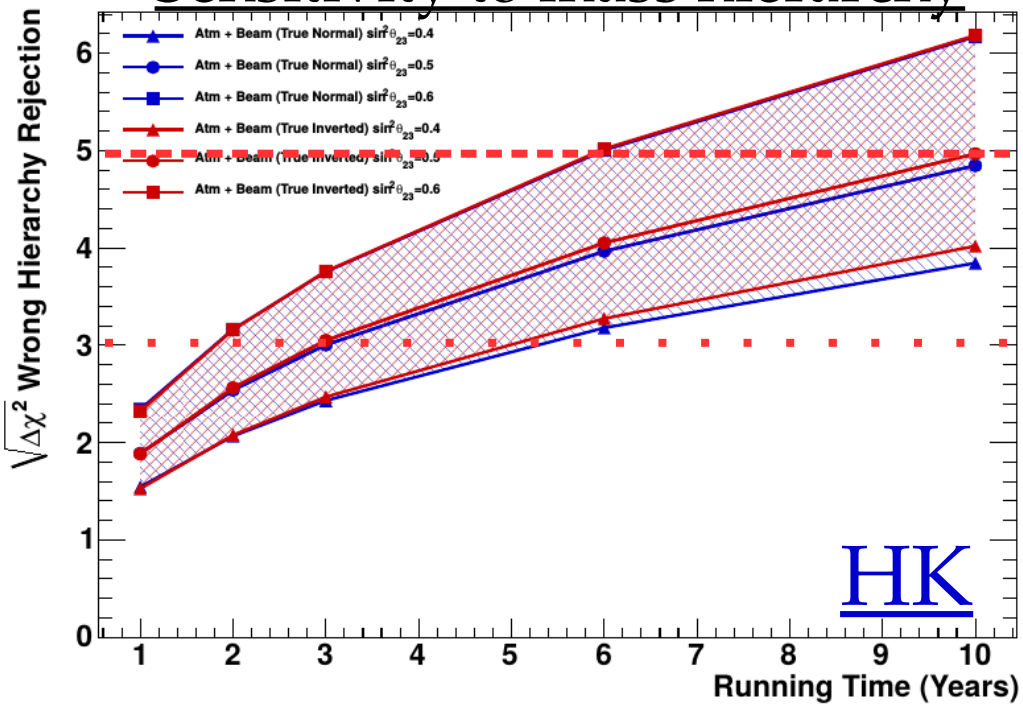
- Normal hierarchy : enhancement of $\nu_\mu \rightarrow \nu_e$ .
- Inverted hierarchy : enhancement of $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ .

# Combination of atmospheric + beam ν

## Impact on CPV sensitivity




## Sensitivity to mass hierarchy



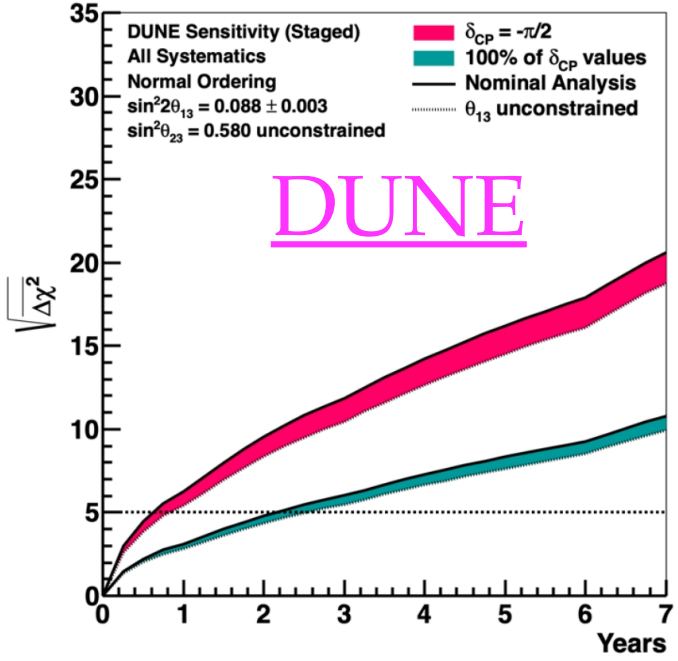

- Even if MH is not known when HK starts

→ Sensitivity to CPV is little affected if we add atmospheric ν.

- MH would be determined by :

  → HK after ≥ 6-10 years via atmospheric.

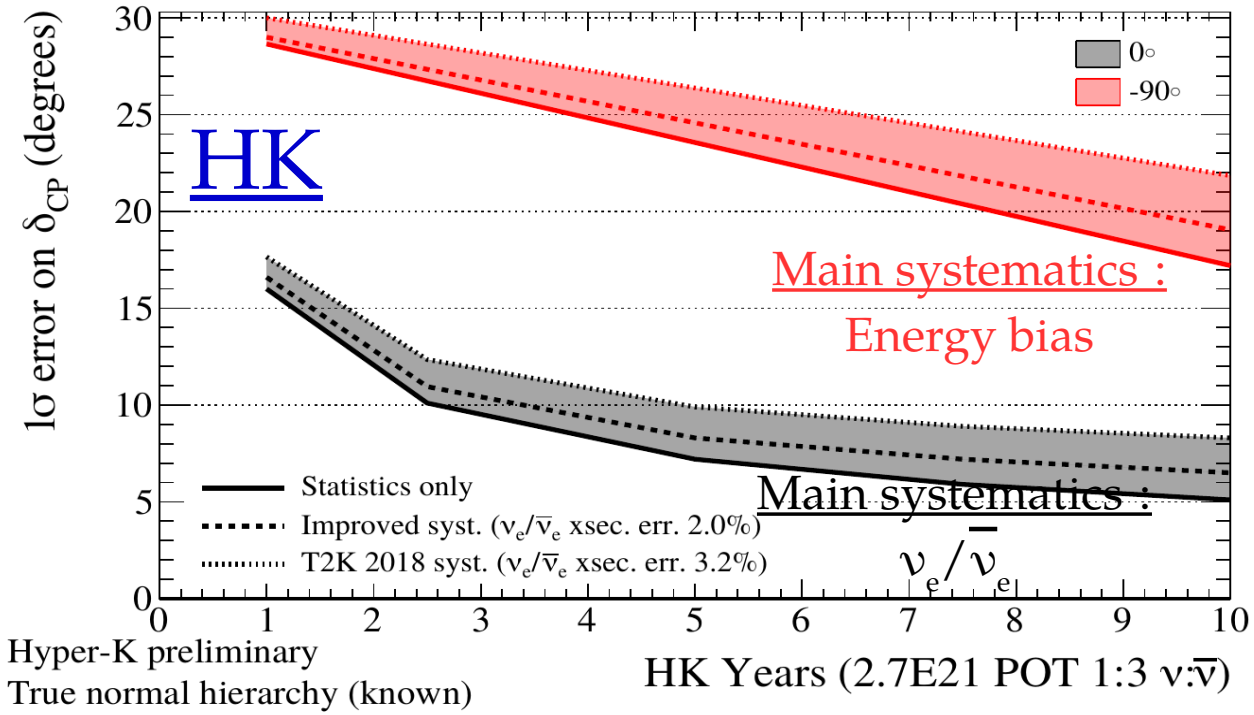
  → DUNE : after 1-2 years.

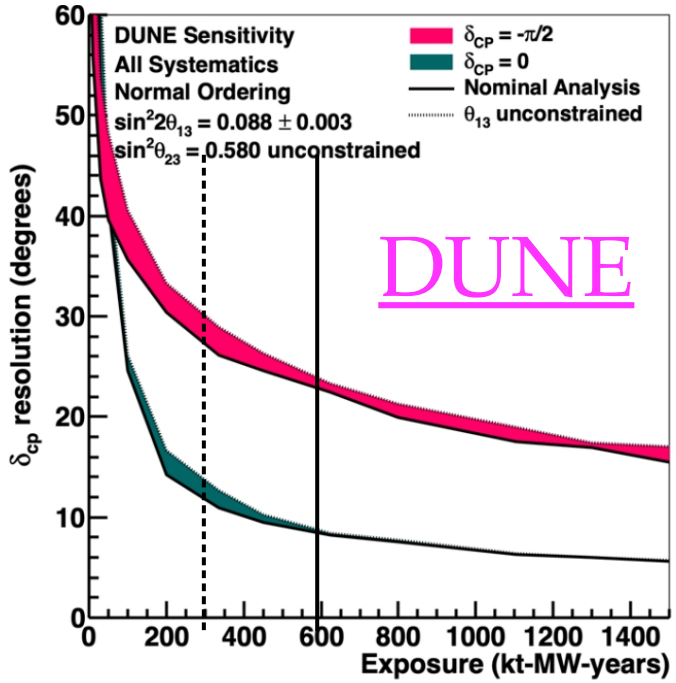


# Precision of $\delta_{CP}$ measurement

- After CPV is determined, accurate measurement of $\delta_{CP}$ will be crucial

  → Maximal CPV, leptogenesis, symetries of lepton's generations ...



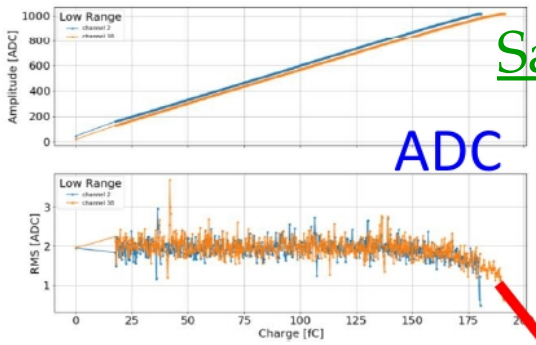




| | 5 years [HK & DUNE] | 10 years [HK & DUNE] |
|---|---|---|
| CP conserved $\delta_{CP} = 0$ | 8° & 13° | 6° & 9° |
| $\delta_{CP} = -\pi/2$ | 25° & 29° | 19° & 24° |

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

# Origins of the HKROC : the CMS HGCROC

- HKROC based on HGCROC : chip developed for CMS-HGCalorimeter
  → Rely on many years of expertize & tests.

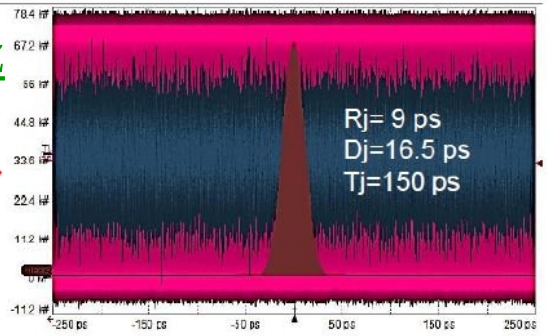



ADC

Same 40 MHz

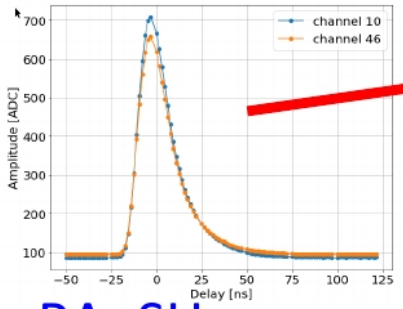
SAR ADC

→ Krakow

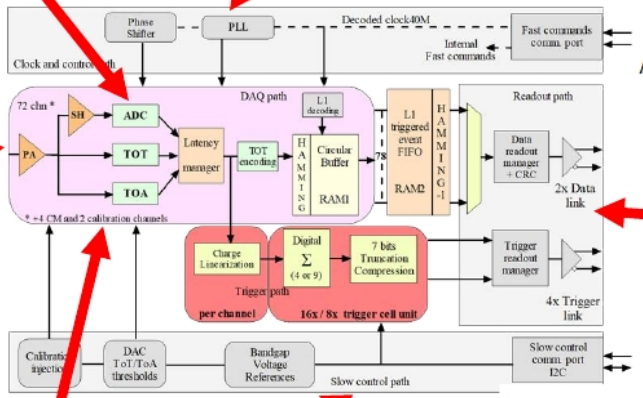



Same PLL

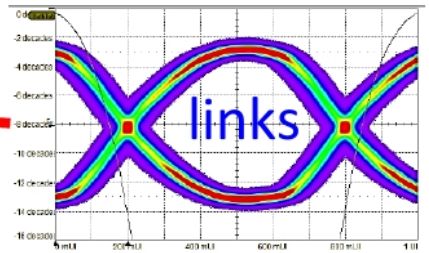
PLL



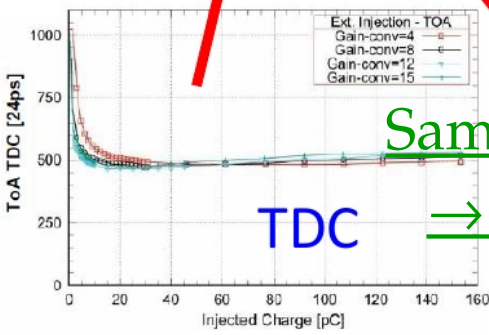

PA+SH




And 640 MHz used for DDR transmission



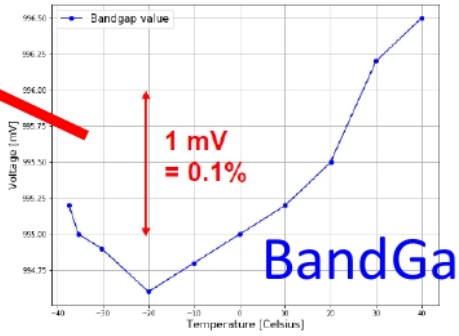

Analog part changed to adapt to HK PMT




Same TDC

→ CEA

TDC



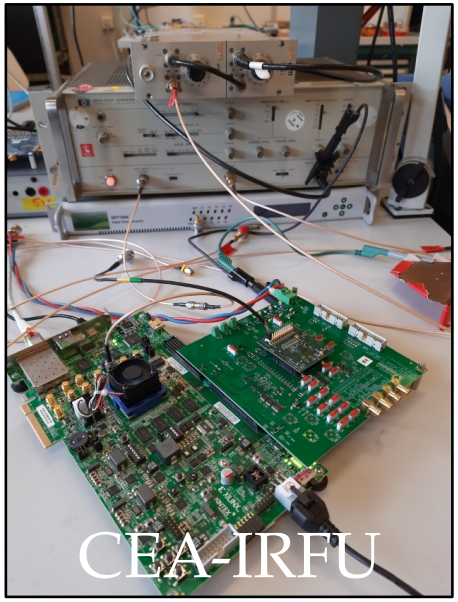

BandGap

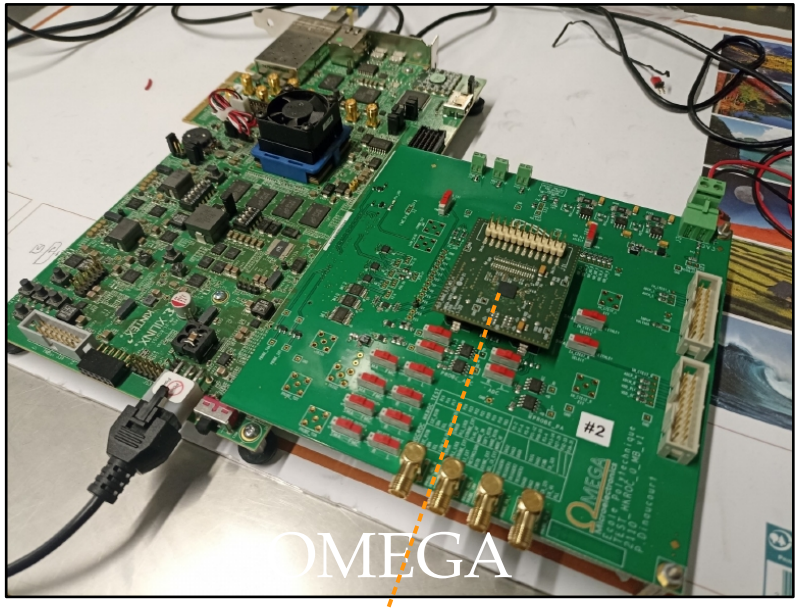
14

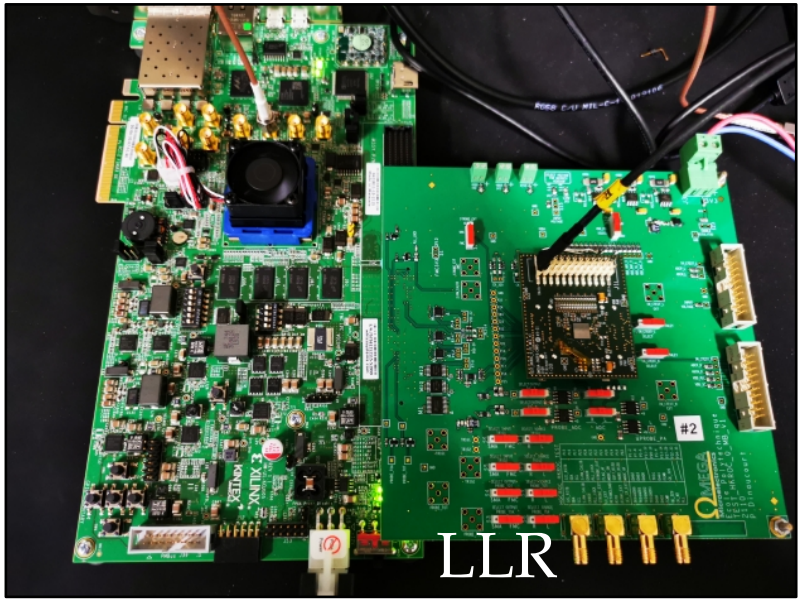
- Same experts have developed the HKROC (OMEGA, CEA, LLR).
  → Great synergy between our projects !

# Performances of the HKROC digitizer

- Measurements @3 test bench/labs in parallel : CEA, OMEGA, LLR.
  → High redundancy to ↓ risk of mistakes.
  → Ready for the pre-production & production tests, also @3 labs.



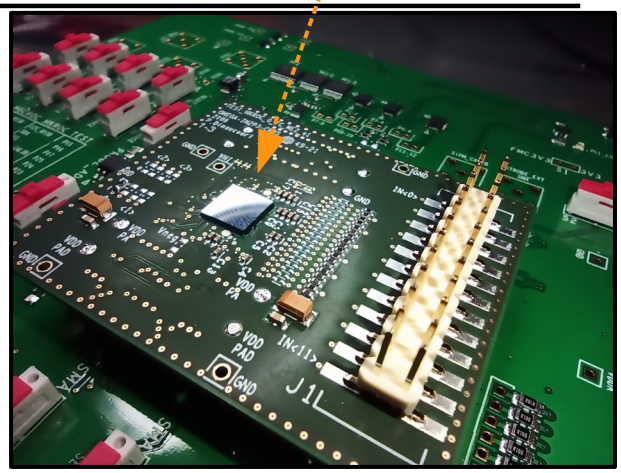



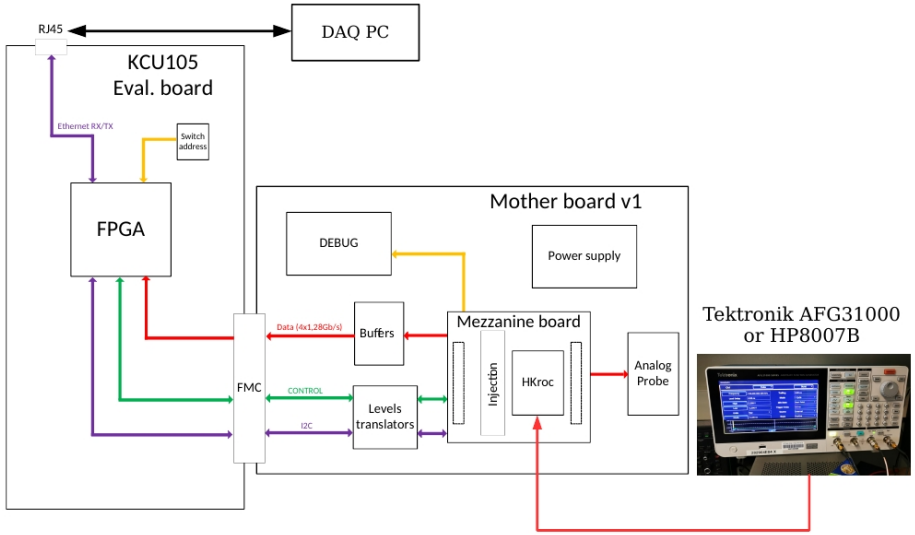

- Measurements based on HKROC v1 :

→ Back fom prod. on 01/28.

→ Chip size :

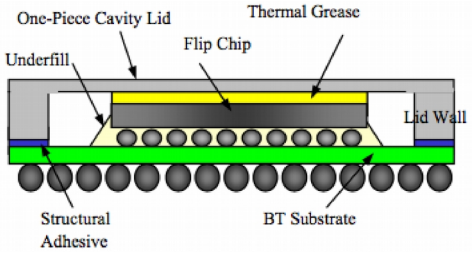
5 mm x 5 mm [Ultra-compact]





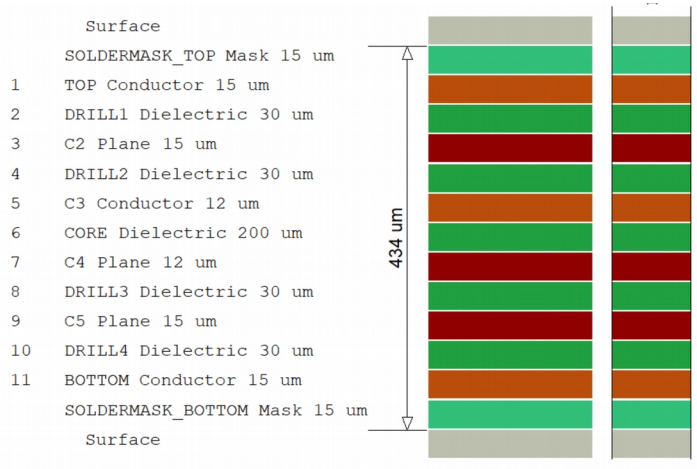
# HKROC digitizer planning : ASIC

- Current version v1 : mounted on board w/ flip-chip.



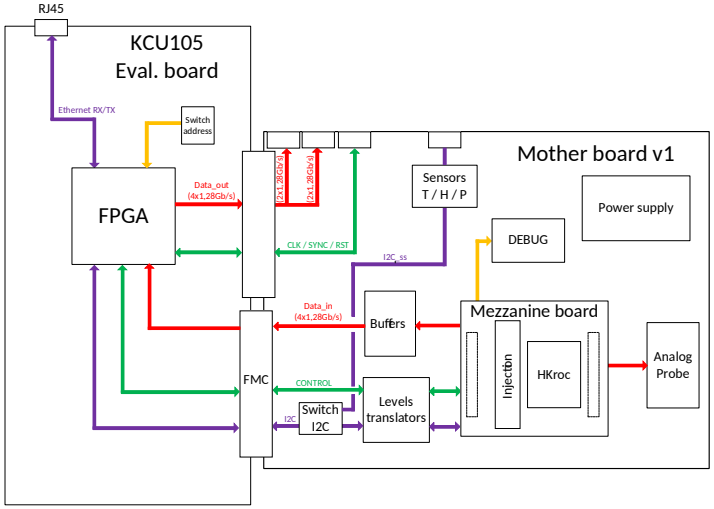

- BGA-package for final board : ordered & in prod.
  → To be received in September.

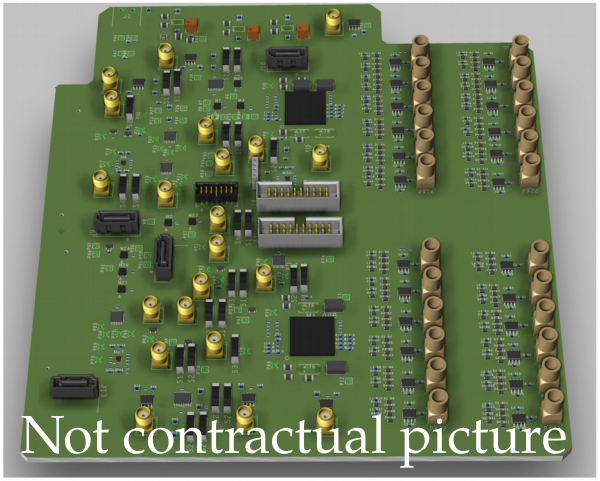
- Version v2 : A TSMC run for OMEGA already scheduled in Dec. 2022.
  → Will use it to fine tune HKROC for HK.
  → Completely remove cross-talk.
  → Likely to submit 2 versions :
  - v2-A : minimal change wrt v1 for safety.
  - v2-B : more aggressive changes to ↑ hit-rate largely beyond our requirements.



# HKROC digitizer planning : Board

- <u>Prototype v1 :</u> Same as final prototype board except for the FPGA & Interface with PC left on the KCU105.



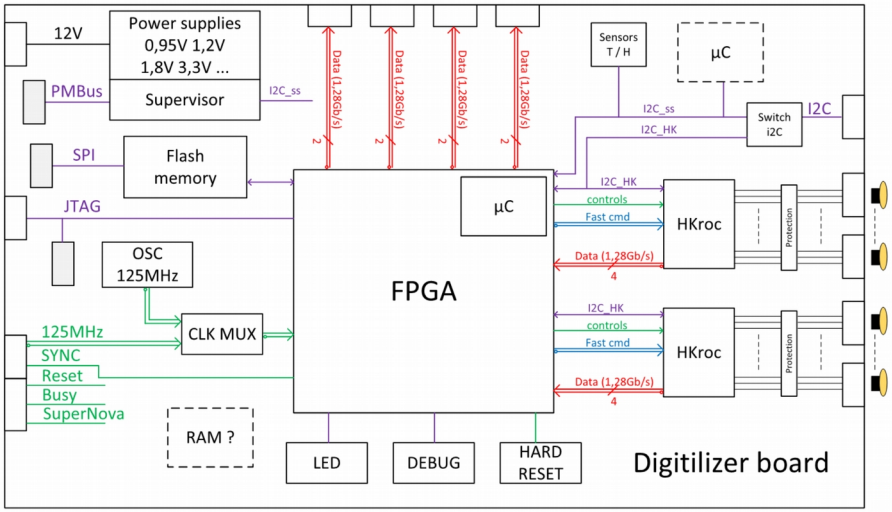




- Test whole circuit from analog to digitized points.
- Test the 2 HKROCs.
- Tests communication with DPB (Curro & al.)

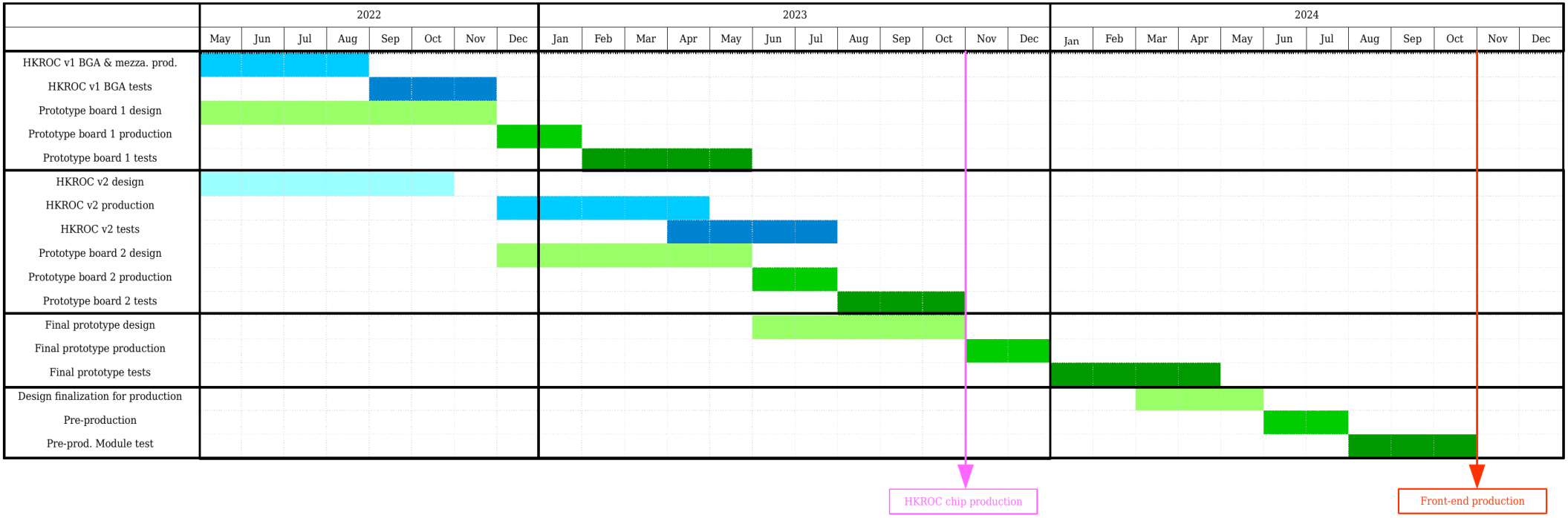
→ Schematics well-advanced (based on current mother board).

→ 1 HKROC-board in 2022/09, 2 HKROC board in 2023/01.

- <u>Prototype v2 :</u> The final prototype board.
  → To be received in summer 2023.



# Updated schedule towards production




- ASIC production could be done in advance : from end of 2023.

  → Have **3 operating ROBOT** to test them at CEA, LLR & OMEGA (used for CMS to test 200,000 HGCROC chips).

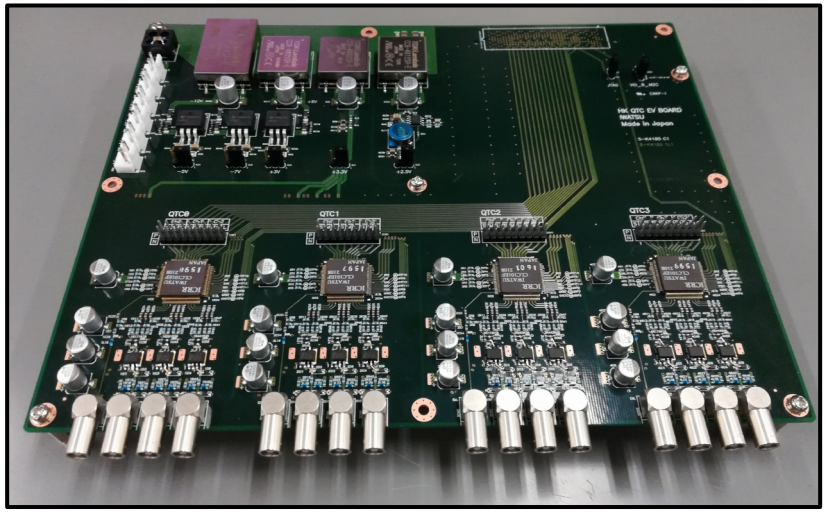
- Board production : from Q4 2024 to mid-2025.

- We are completely on-time !

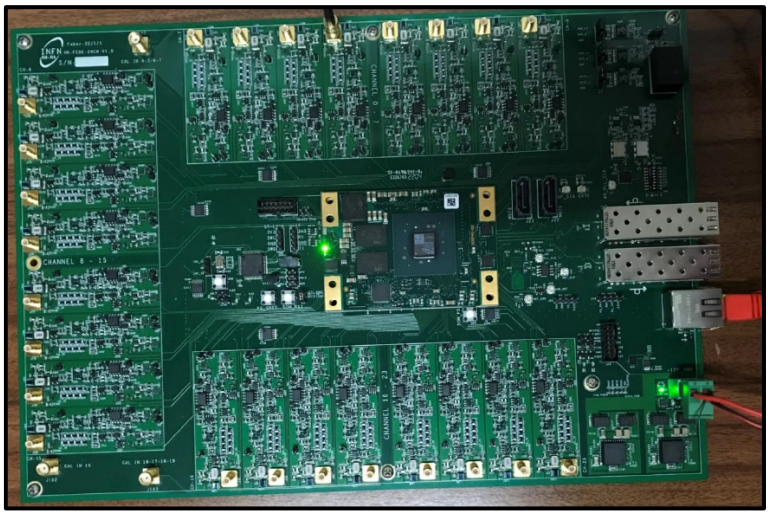
# The Hyper-K candidate digitizers

- 3 digitizers considered : all high-specs but explore ≠ 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.