Hyper-Kamiokande

Our proposal to contribute to Hyper-K

Benjamin Quilain (LLR - CNRS/Ecole polytechnique)
on behalf of HK-IN2P3 in close collaboration with CEA-IRFU

ILANCE
International Laboratory for Astrophysics, Neutrino and Cosmology Experiments

cnrs dépasser les frontières
IN2P3 Les deux infinis

OMEGA Microelectronics

LLR

l'X École Polytechnique
IP Paris

LPNHE Paris

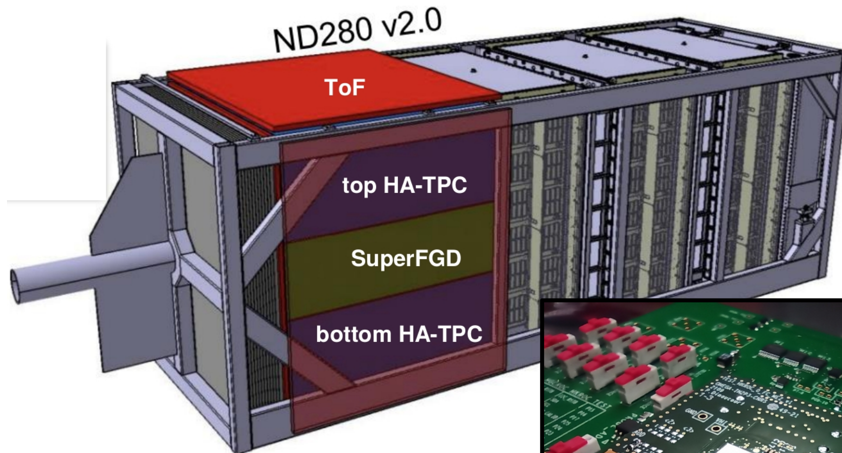
Sciences Sorbonne Université

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

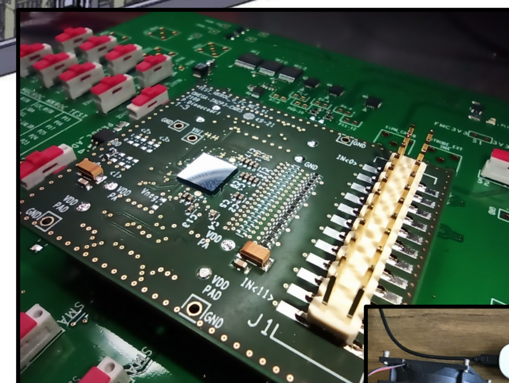
Summary of proposed contributions

<u>One year ago, IN2P3-HK groups made the following proposal @CS :</u>

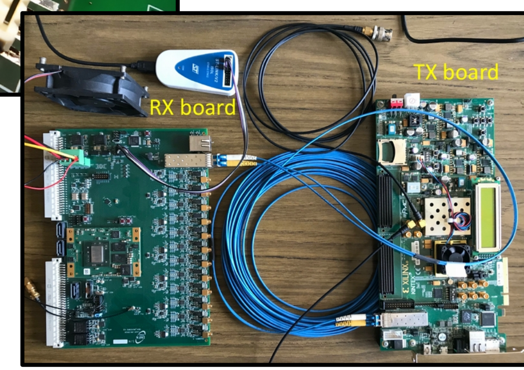
- The ND280-upgrade.



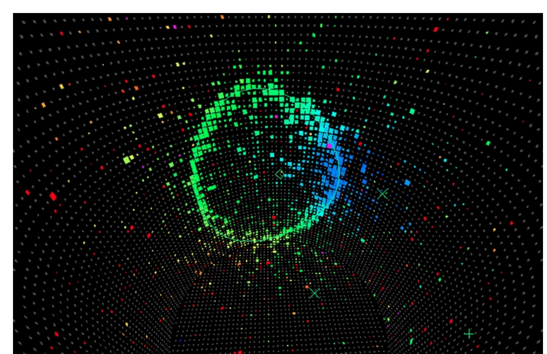
- PMT digitizer for the Far Detector.



- Time generation & clock distribution at Far Detector.



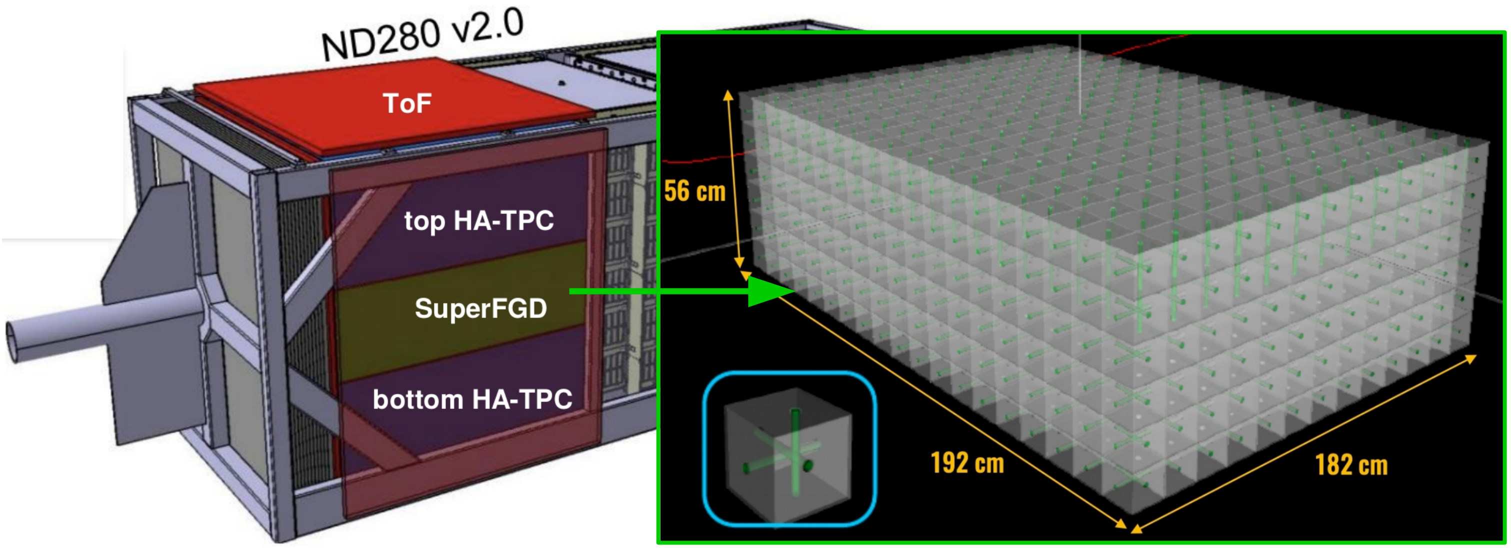
- <u>CC-IN2P3 :</u> HK Tier 1 computing site.



- Shared-item cost & assembly.

I. The ND280-upgrade

The ND280-upgrade : super-FGD



super-FGD :

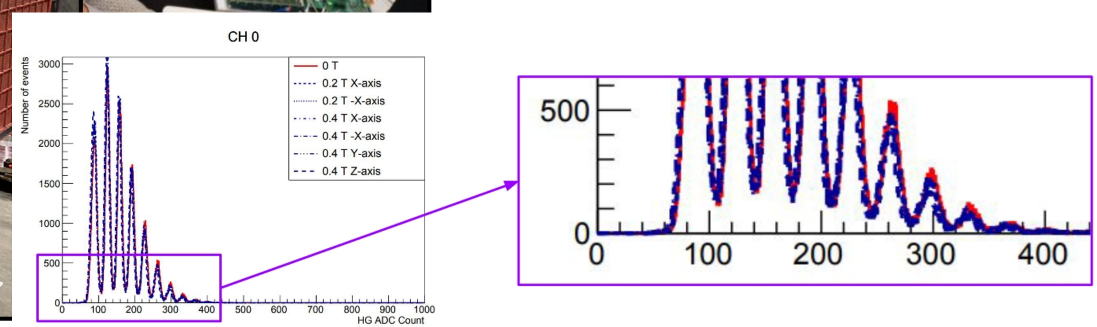
- A massive target (2t).
- A high granularity tracker : 2 millions scintillating cubes of 1 cm-side.

2 million cubes @JPARC

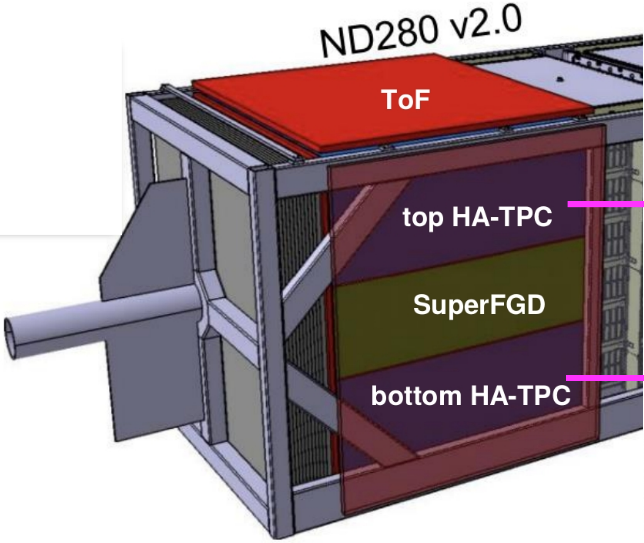
Front-end electronics

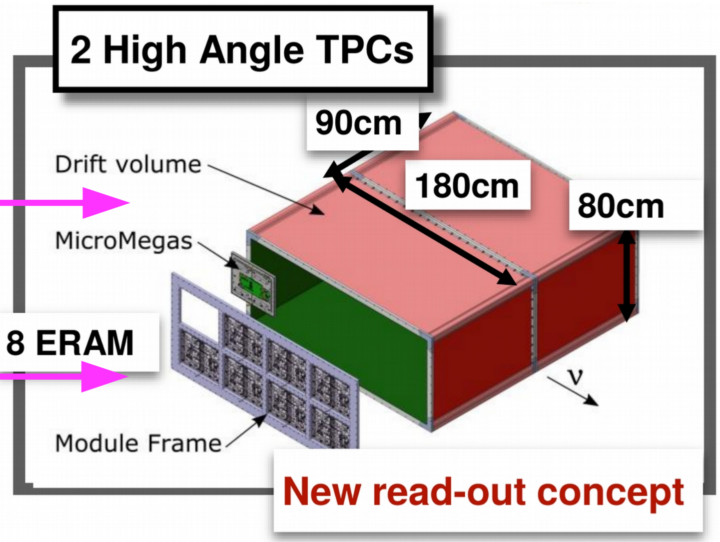
- Front-end final prototype validated.

- Fron-end now in (pre-) production
  → Ready for assembly in spring 2023



The ND280-upgrade : high-angle TPCs



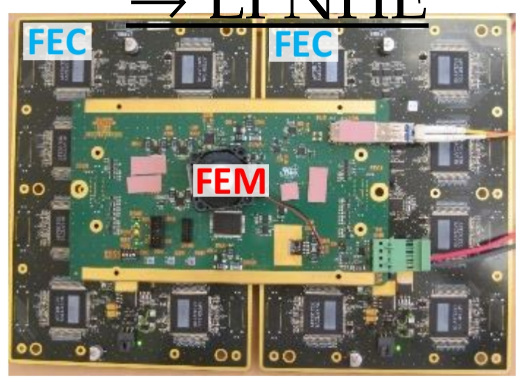


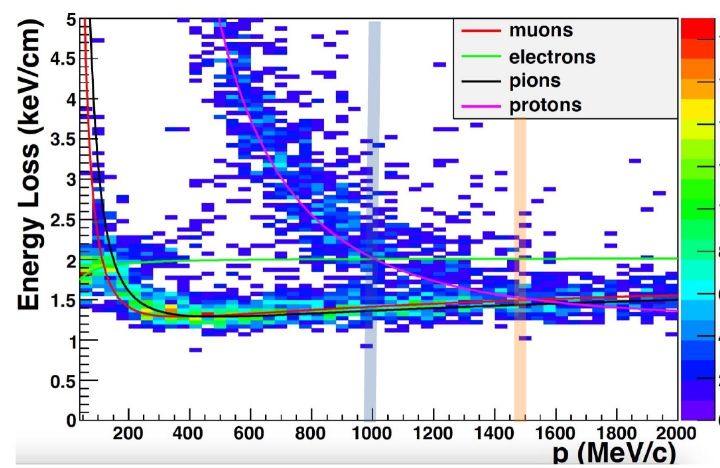
High-angle TPCs :

- Allow an almost 4π PID & momentum reco. for μ & π.
- ~same acceptance as HK → Constrain systematics on whole phase space.

Test beam at CERN

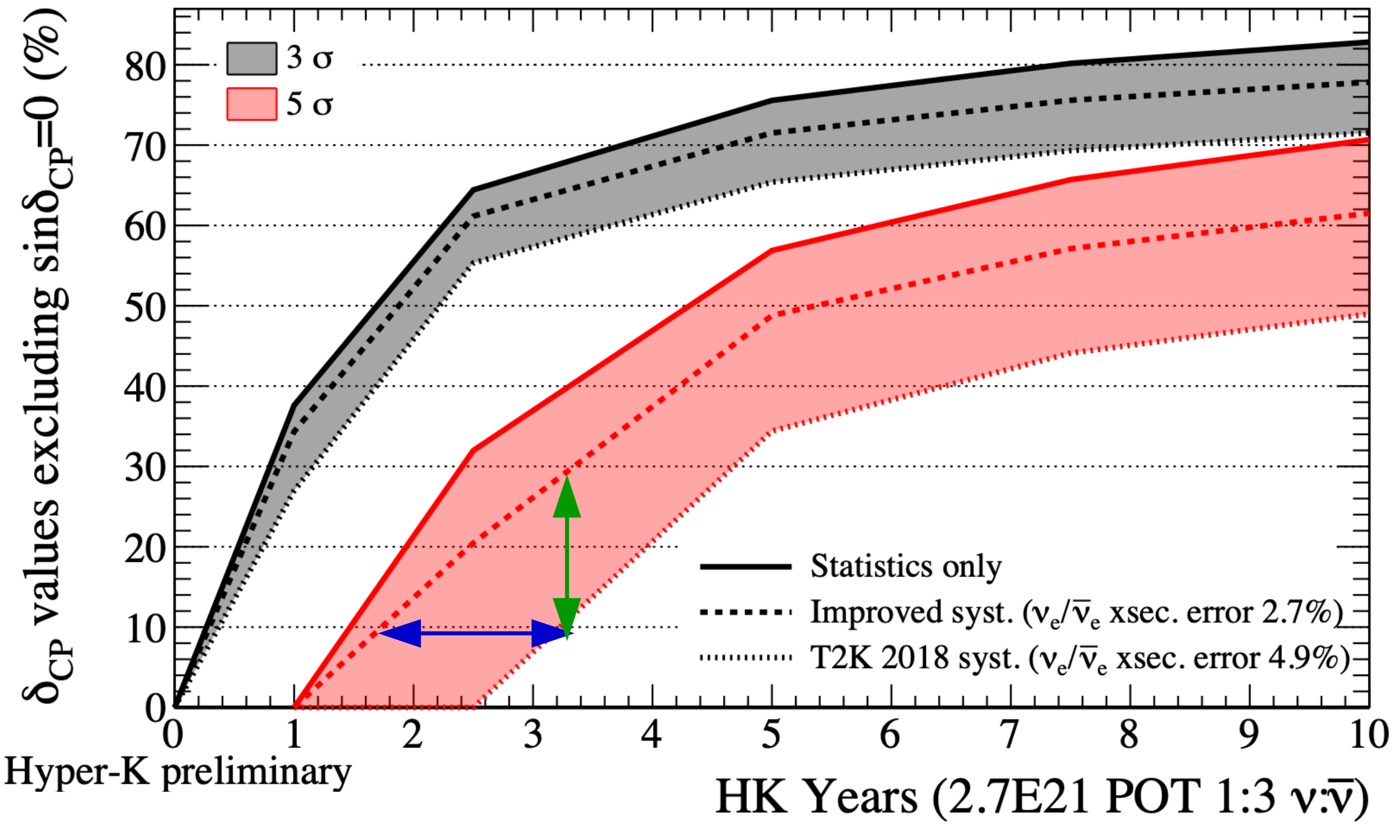
Front-end electronics → LPNHE





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

How ND280-upgrade is critical for HK ?



With the ND280 upgrade (mainly true in first years of HK):

- If CPV maximal : gain up to 1-1.5 year on CP violation discovery.
- Otherwise : gain up to +10-20 % on 5σ exclusion contours at given time.

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

→ IN2P3 has a central contribution in this project thanks to the work of IN2P3 teams & large support from the institute.

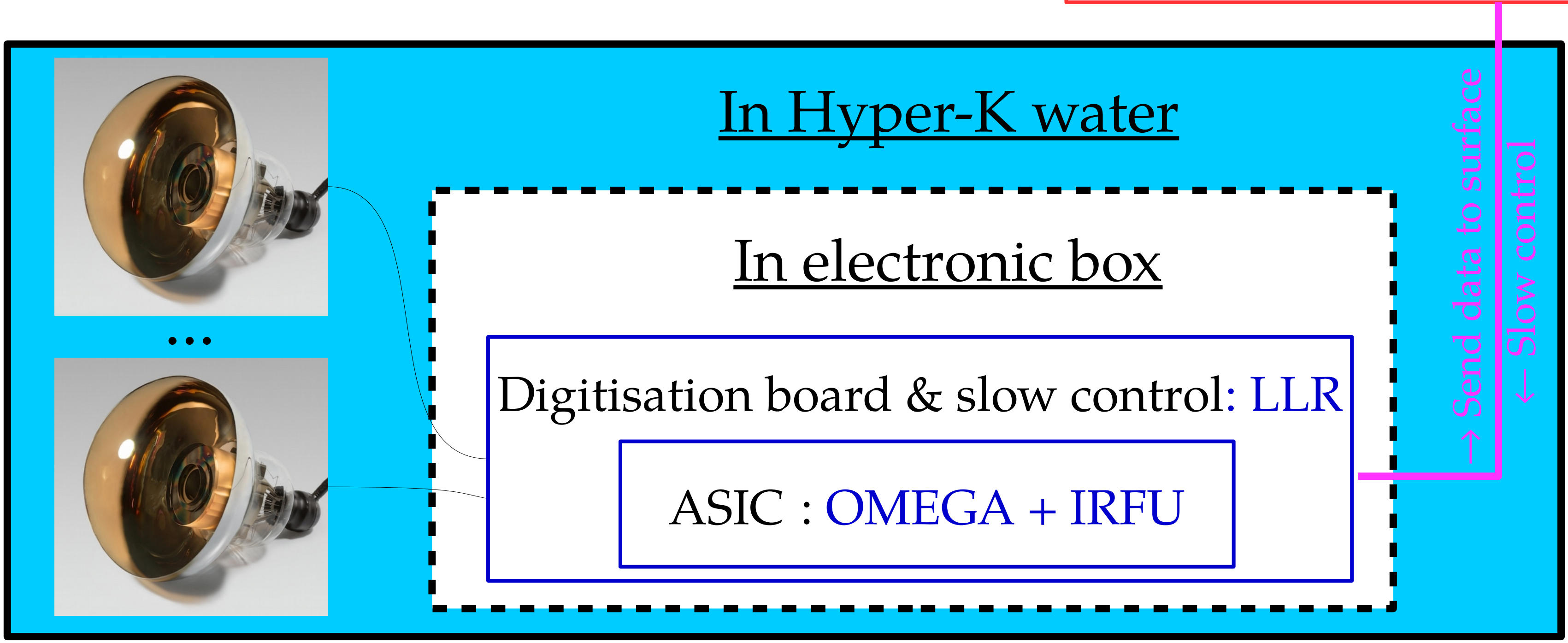
II. The far detector electronics

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.

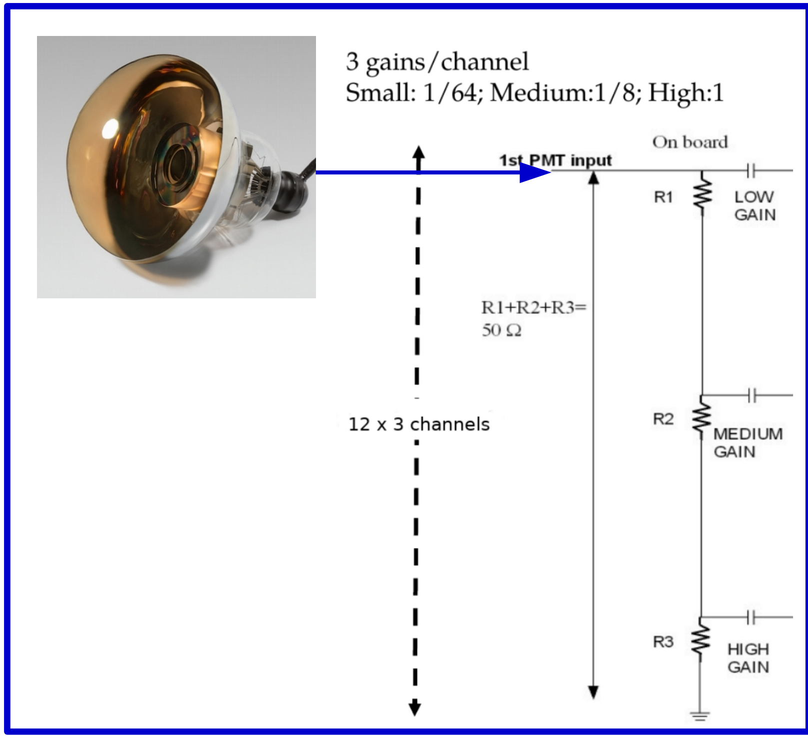


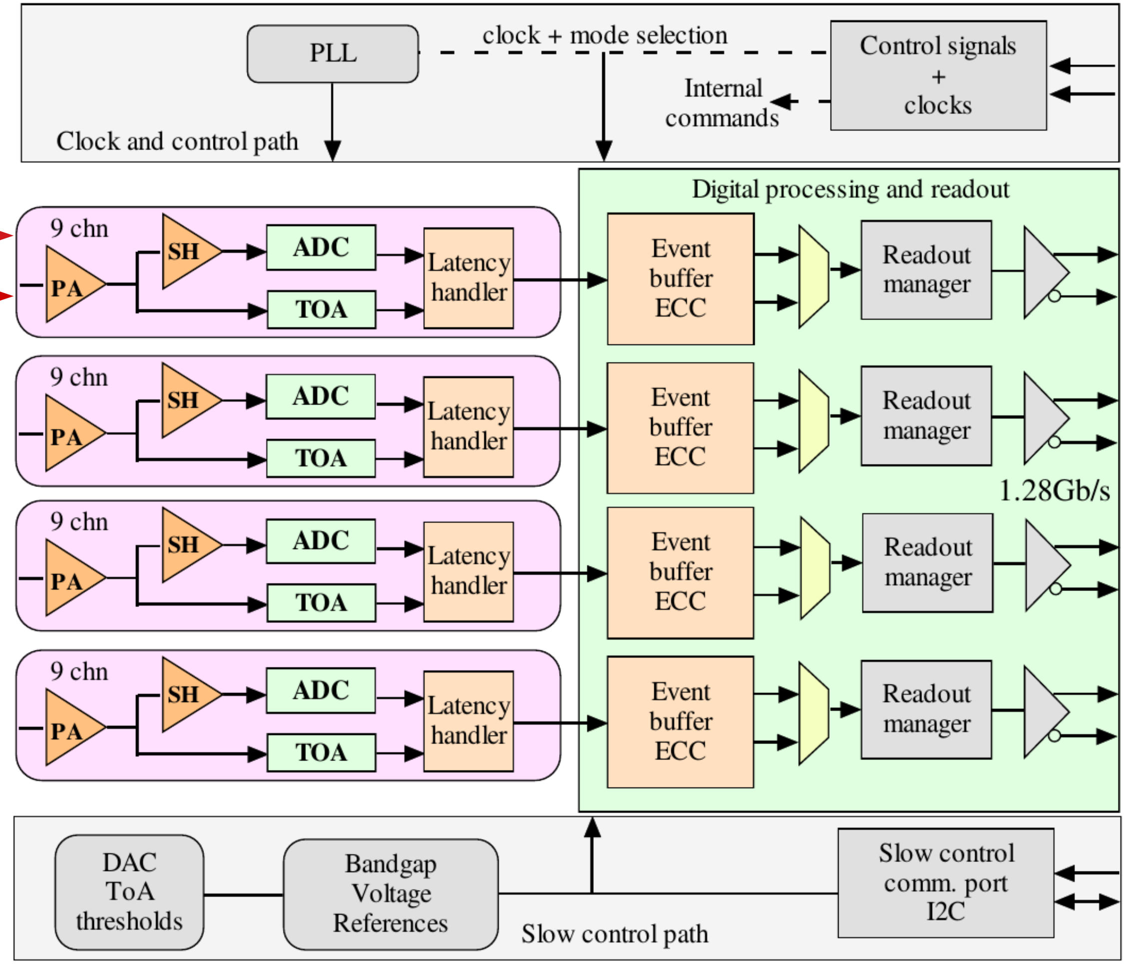
France's proposal : develop the whole PMT charge & time digitization & time synchonization systems

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

The HKROC digitizer

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



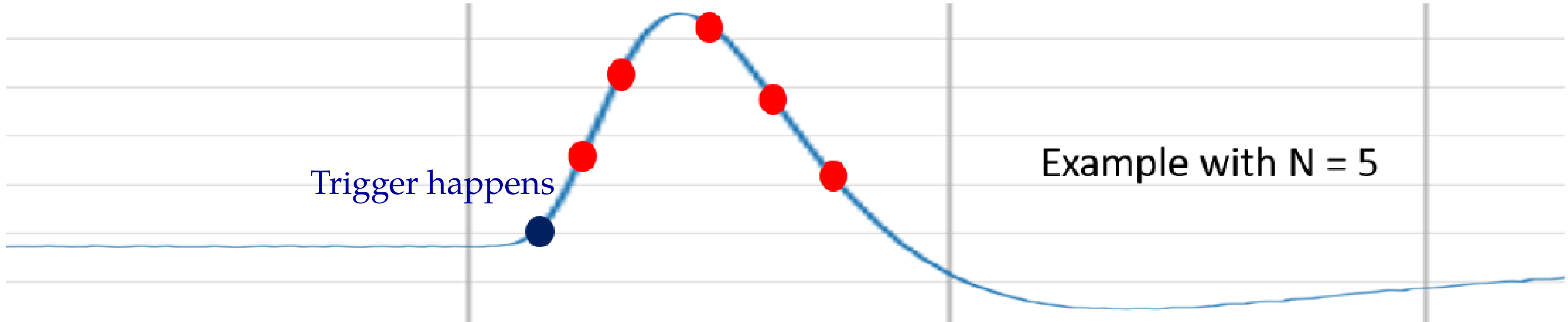


- TSMC CMOS 130nm etching.
- Dynamic range from 0 – 2500 pC : 3 gains / channel.
- 4 readout / ASIC @1.28 Gb/s : 1 readout ↔ 3 PMTs.
- If 1 PMT trigger : read all 3 PMTs of 1 readout.

Overview of the HKROC digitizer

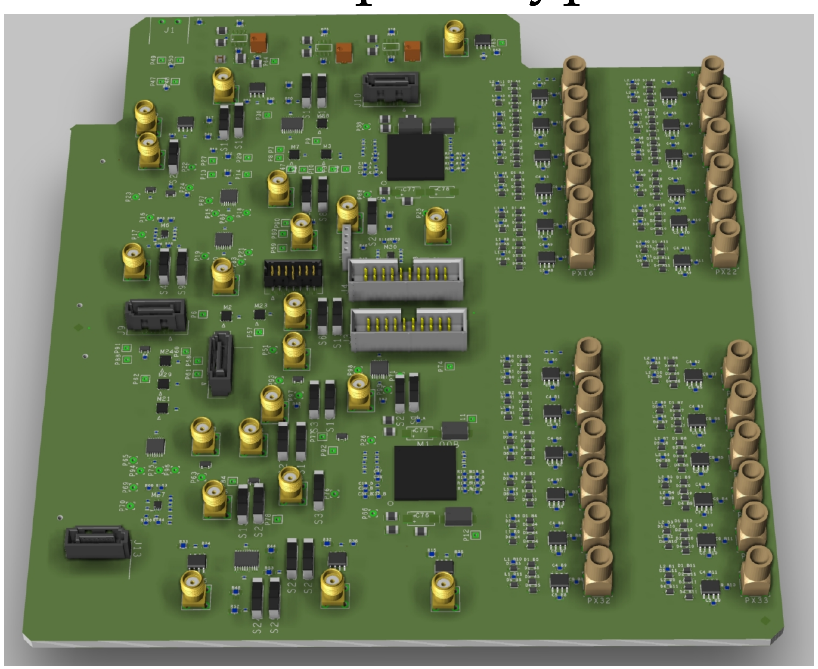
- HKROC is a waveform-like digitiser @40 MHz→ 1 point every 25 ns.

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



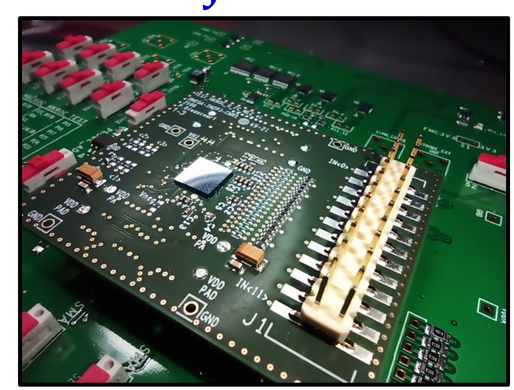
- HKROC digitizer : 24 PMT channels readout by 2 HKROC ASIC.

HKROC prototype v1



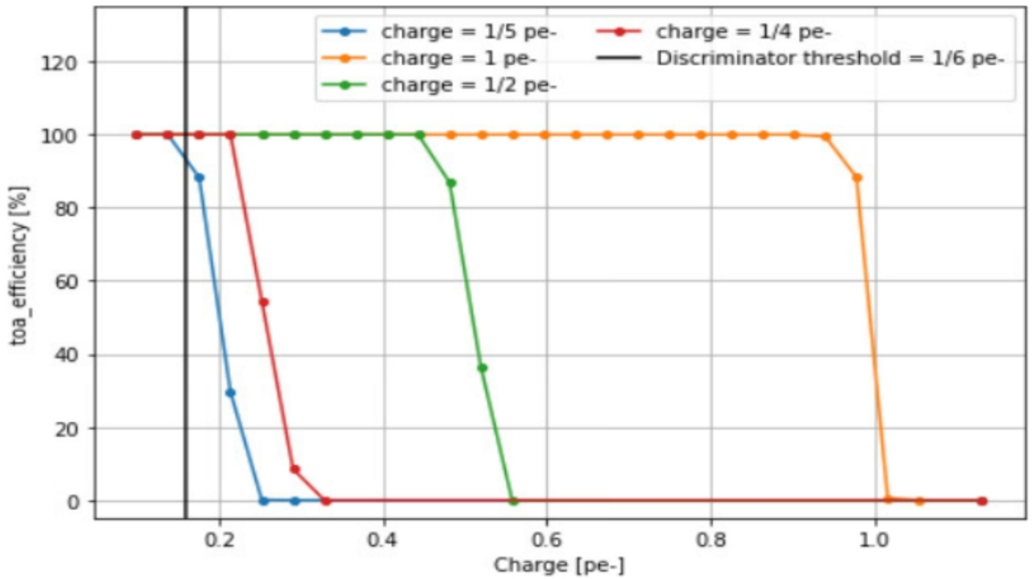
- Started R&D in summer 2020 : Make a chip in 2 years → Challenging schedule :
  1. Receive chip in Dec. 2021.
  2. Provide tested chip by end of June 2022.

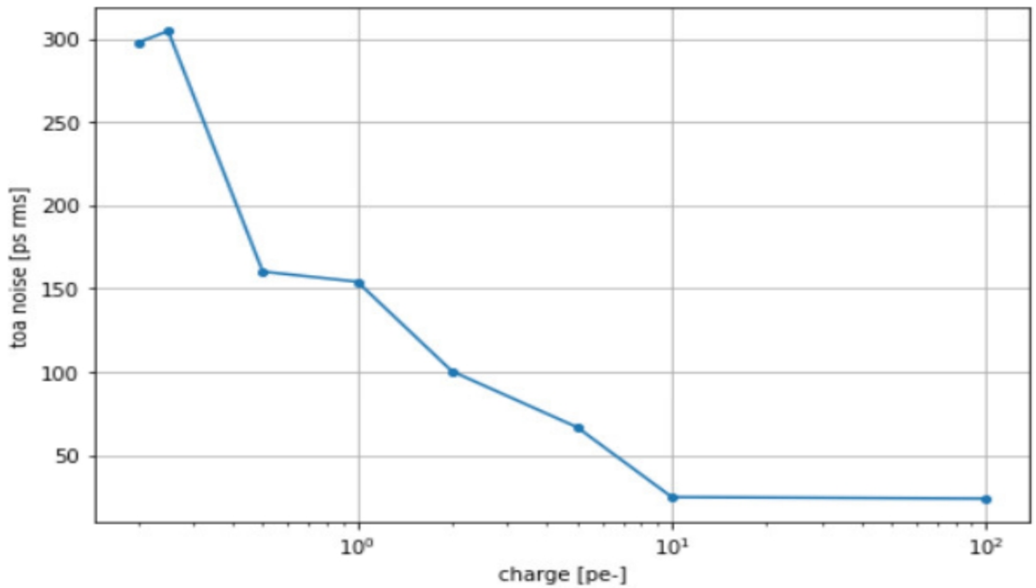
- No delay in 2 years :
  → Chip came back in Jan. 2022 (pandemic).
  → Worked hard to finalize tests for June.



HKROC digitizer - trigger & timing results

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





- Set threshold at 1/6 p.e.

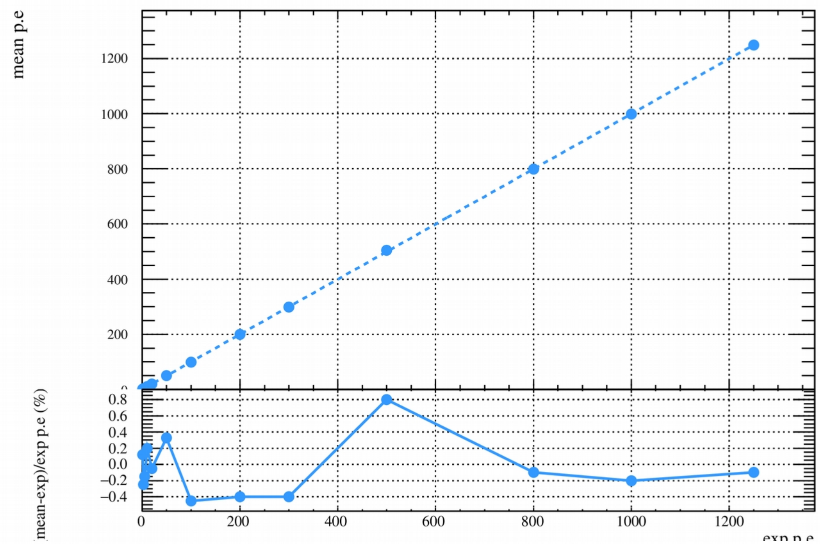
- Hit efficiency :
  90 % for 1/5 p.e events
  ~100 % if ≥ 1/4 p.e

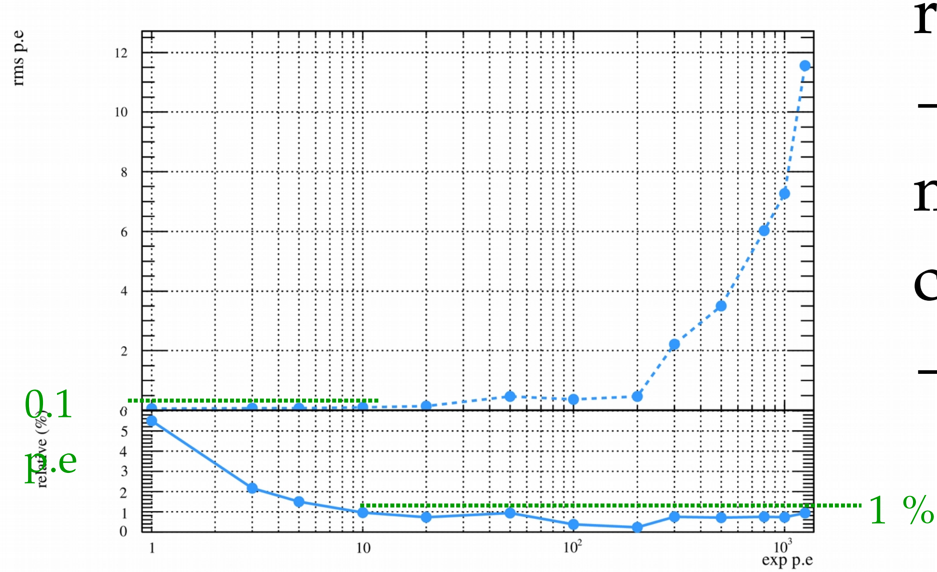
- Very low noise : < 1 Hz.

- 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





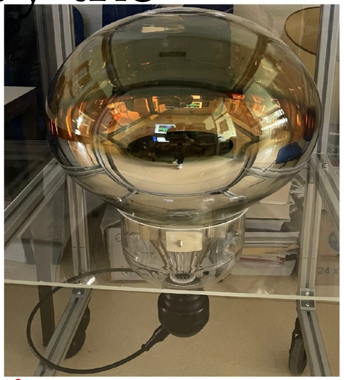
- <u>Charge linearity < ±1%</u> [1 to 1250 p.e.]

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

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

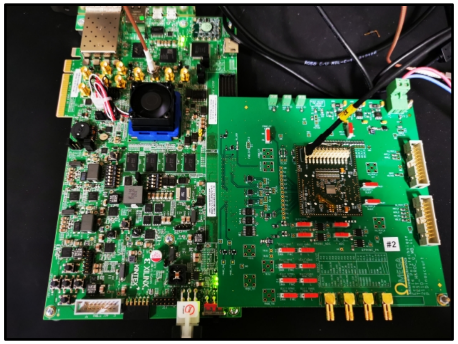
→ Large improvements w/ HKROC much beyond requirements by the collaboration

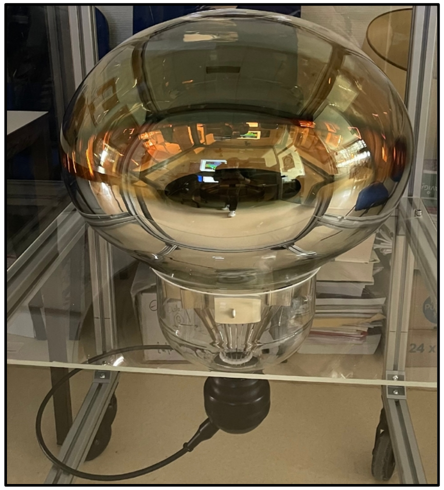
→ <u>Ex:</u> dead-time ↓ **from 1 µs → 30 ns**.



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

Summary of the digitizer measurements



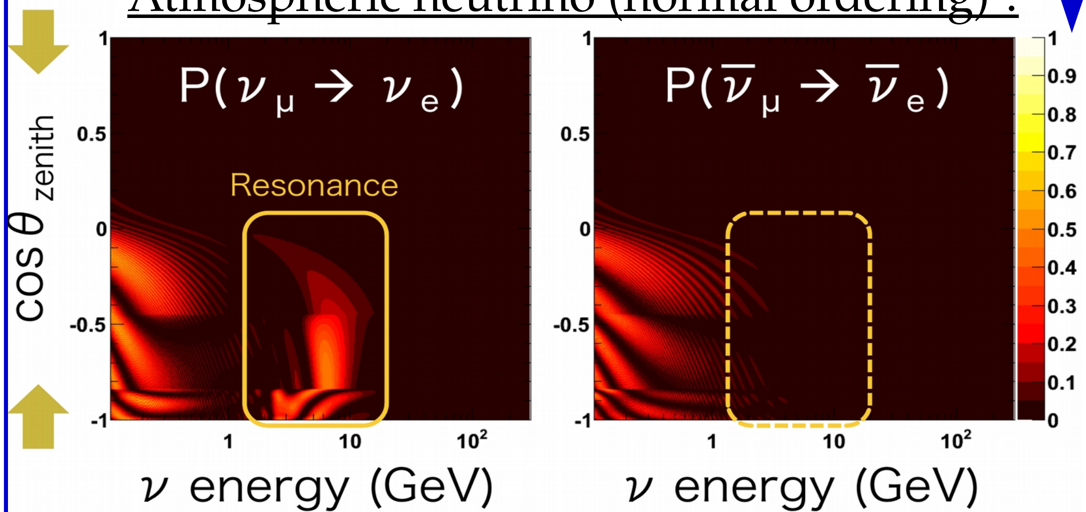


Item measured	Performances
Trigger efficiency at 1/6 p.e.	$>$ 90% for 1/5 p.e signals 100% for $\geq$ 1/4 p.e signals
Trigger noise at 1/6 p.e.	$<$ 1 Hz (No trigger observed in 10 s)
TDC resolution	150 ps at 1 p.e, 70 ps at 5 p.e, 25 ps $>$ 10 p.e Validated with PMT
Charge linearity	$<$ 0.5% in high & 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	$\leq$ 30 ns for two signals of same amplitude $\leq$ 30 ns for a prompt $\leq$ 5 p.e and secondary of 1 p.e $<$ 1 μs for a prompt signal $\leq$ 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% *Note that cross-talk found at ASIC level, but cut* *by FPGA. Identified and will be removed in ASIC v2.*
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/°C gain variation $\Delta Q = 0.05\%$/°C (no correction)
Resistance to HV	Unprotected ASIC received 10^8 5V injection without any impact on performances

HKROC digitizer - Impact on physics

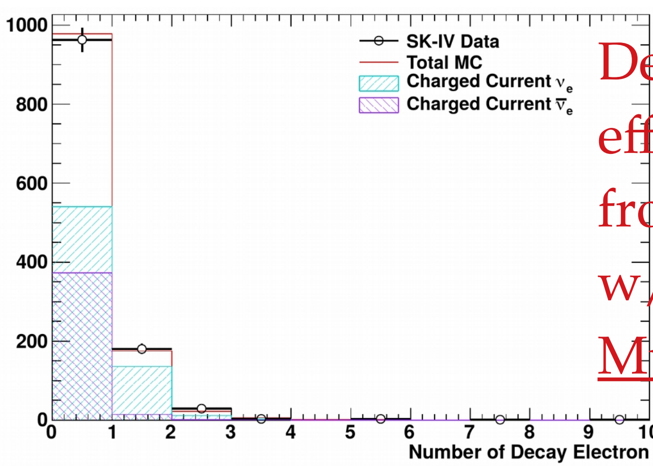
- Large impact on physics : ν mass ordering & Supernova ν.

Atmospheric neutrino (normal ordering) :

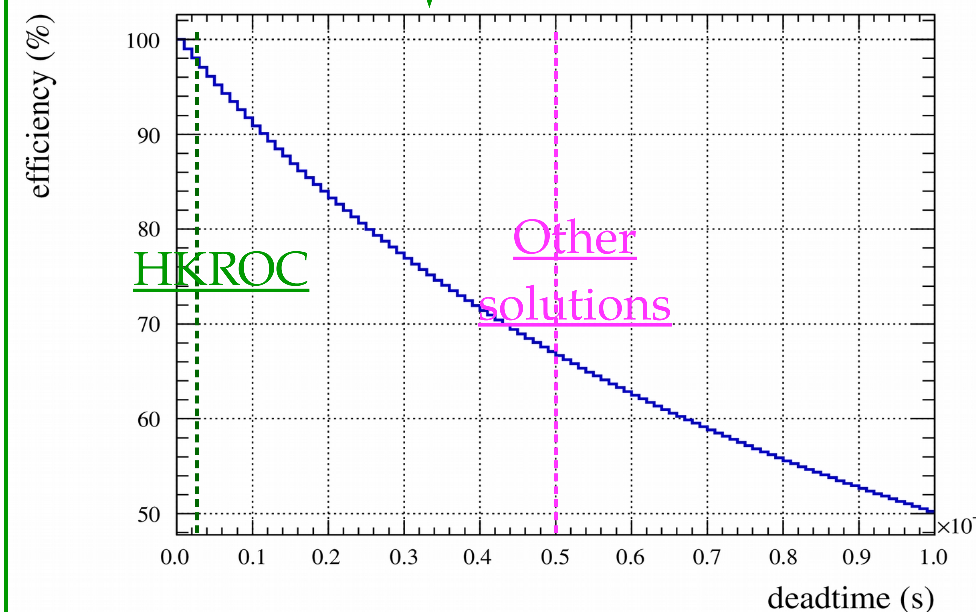


- Normal hierarchy : $\uparrow \nu_\mu \rightarrow \nu_e$.
- Inverted hierarchy : $\uparrow \bar{\nu}_\mu \rightarrow \bar{\nu}_e$.

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



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

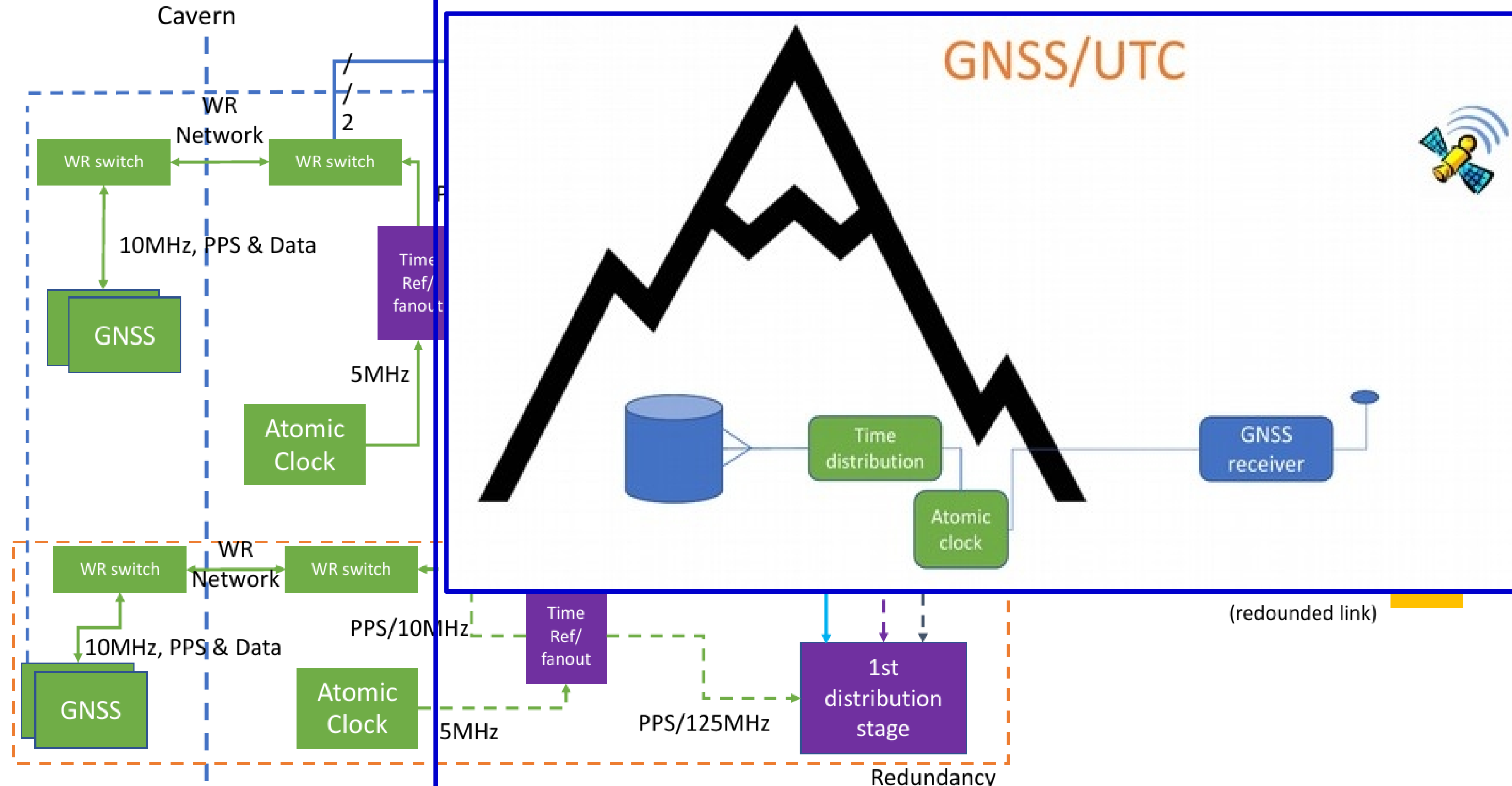


- For 1MHz [Betelgeuse] : HKROC allows to significantly increase efficiency from 67 % to 92.5 % compared to other solutions.

Overall view of the timing system

Time-generation :

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



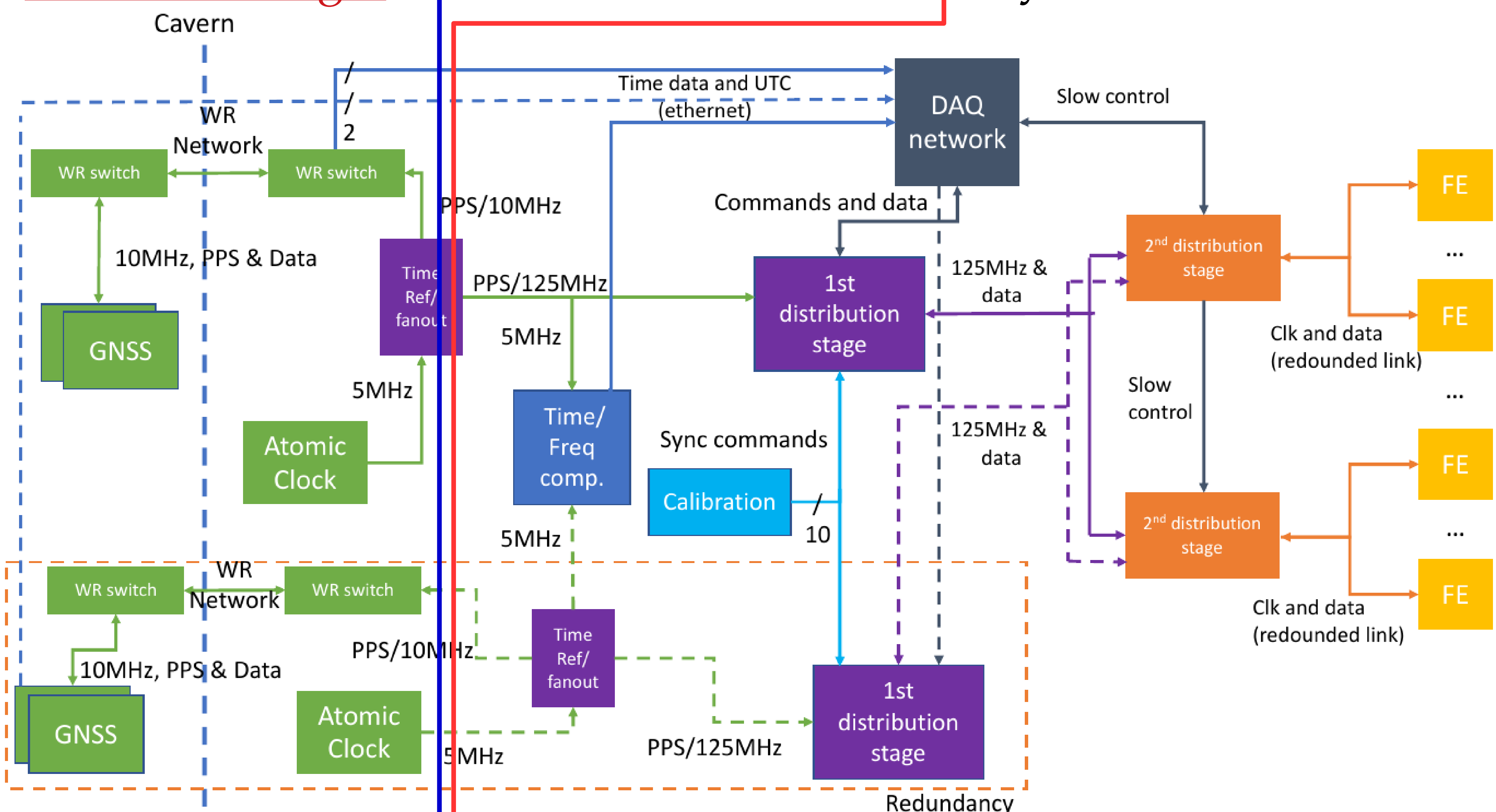
Overall view of the timing system

Time-generation :

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

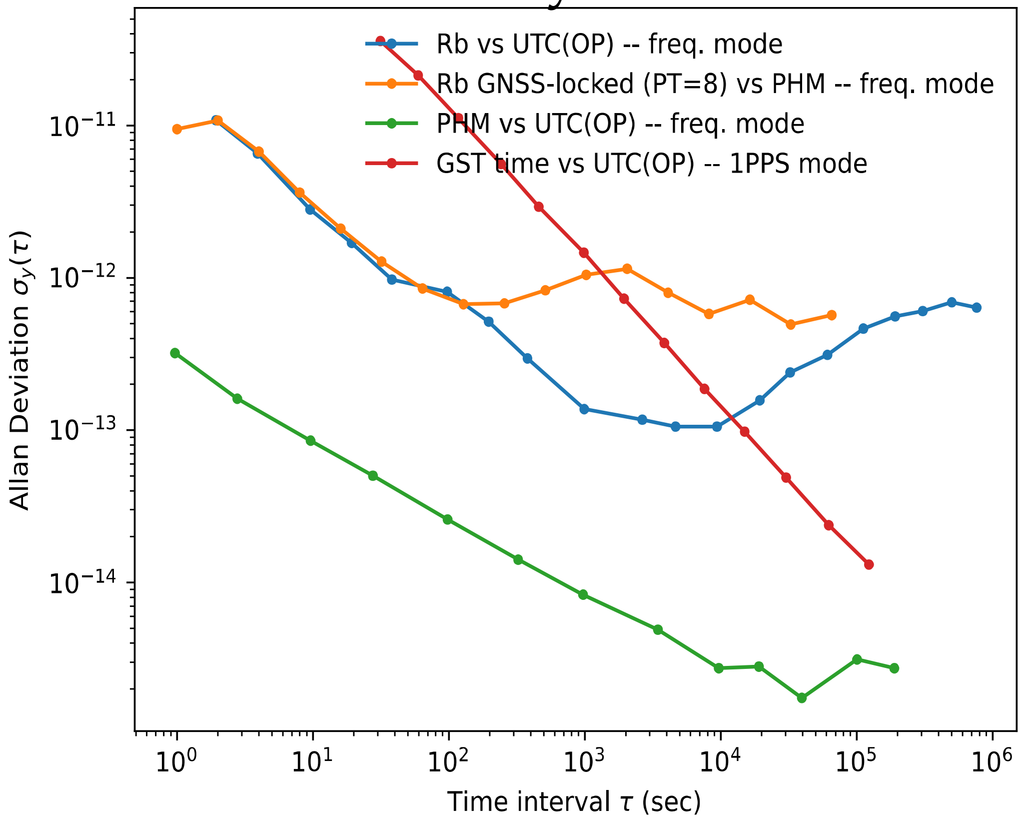
Time-distribution :

- 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 (→ 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 **< 10 ns.** ✓

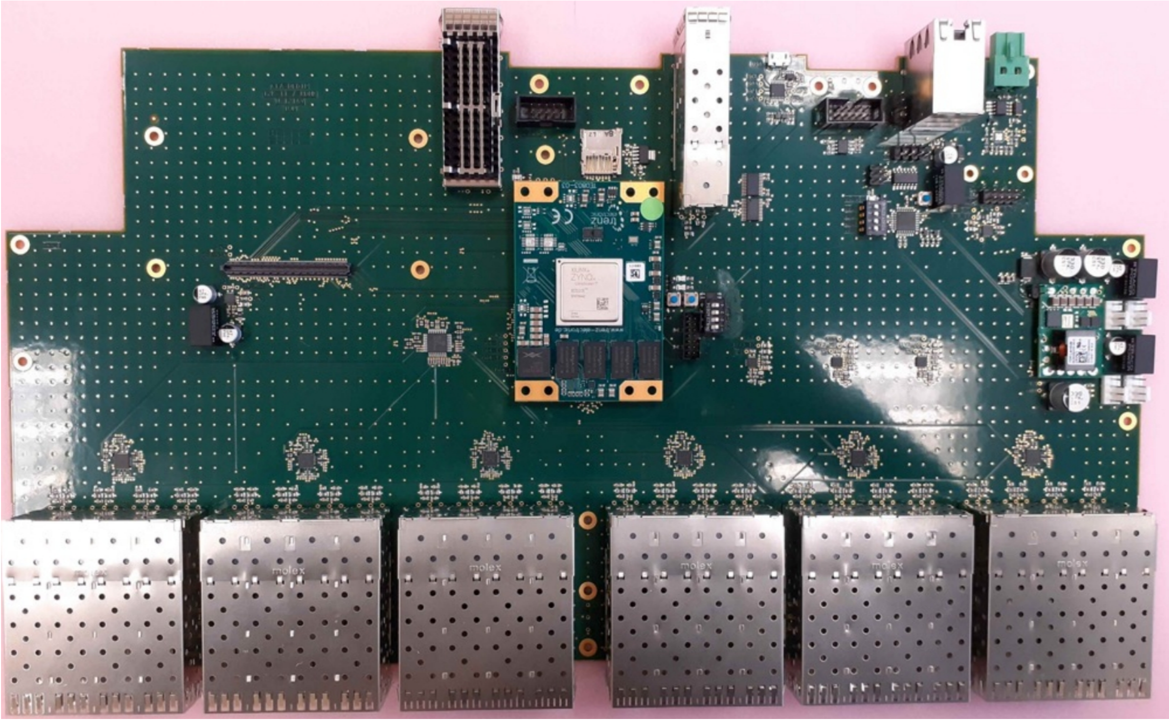
  → Precision on timestamps wrt UTC dominated by time transfer w/ GNSS receivers.

- Wish ↑ accuracy in future (ν mass measurements etc.) ✓

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.

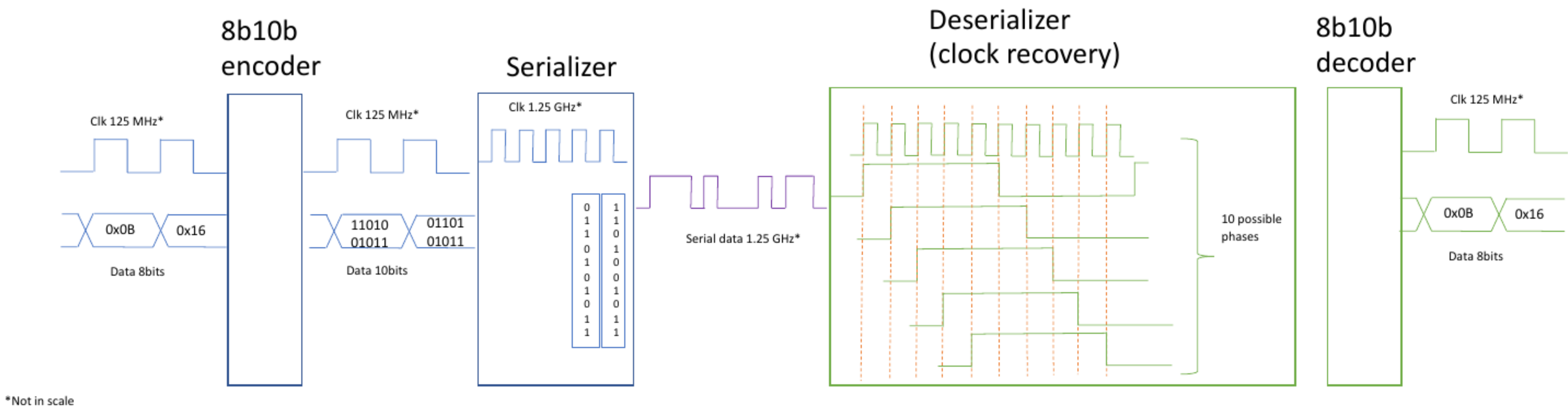
- CEA-IRFU has realized the 1st distribution stage very first prototype.



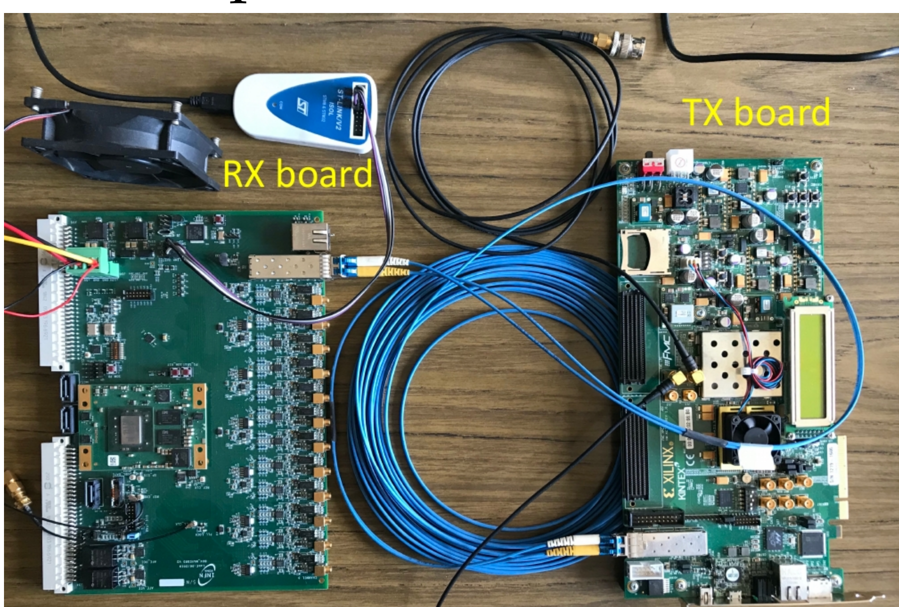
- The board has been received in April 2022.
- Most of the tests are finalized.
- Design of this card also used as starting point for the design of the 2nd stage board.

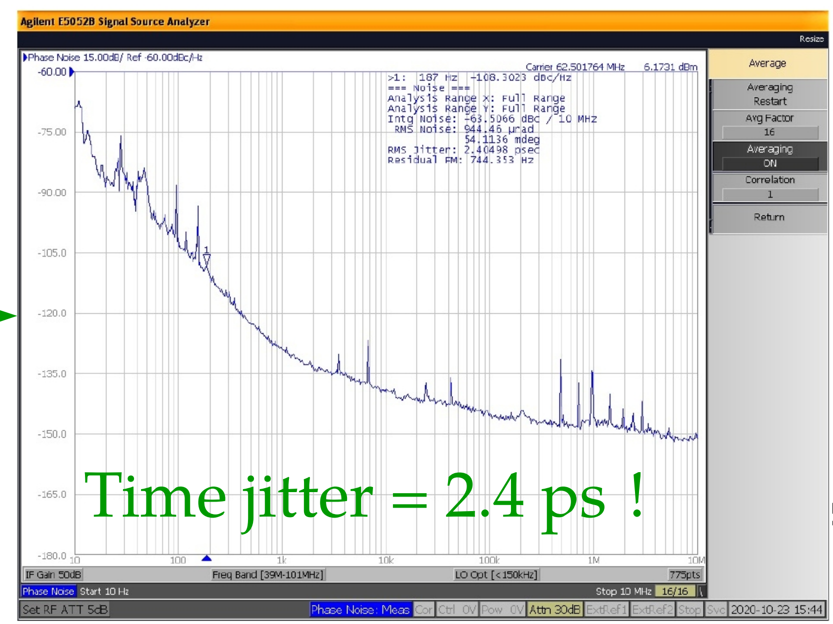
Second stage distribution

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



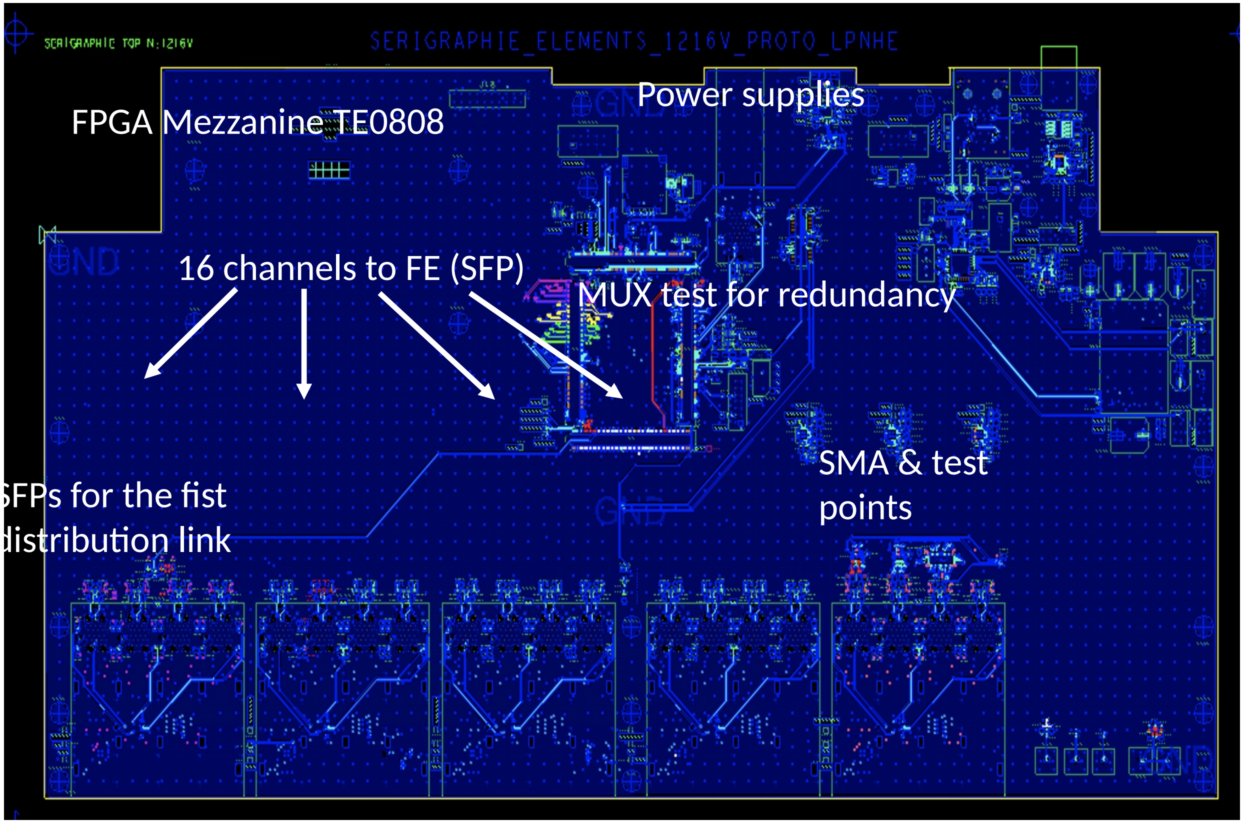
- Concept tested at LPNHE :





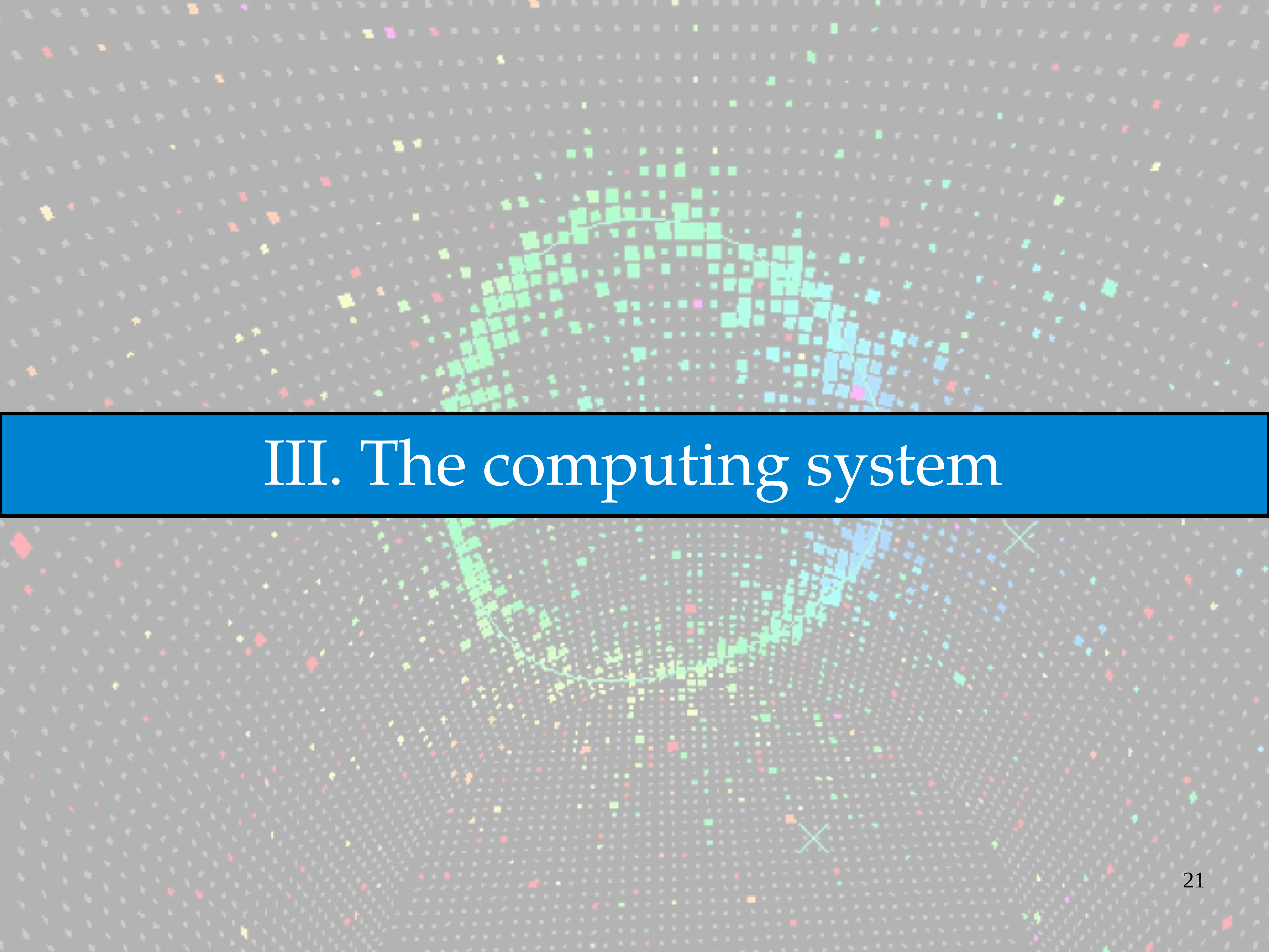
Second stage distribution

- 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.

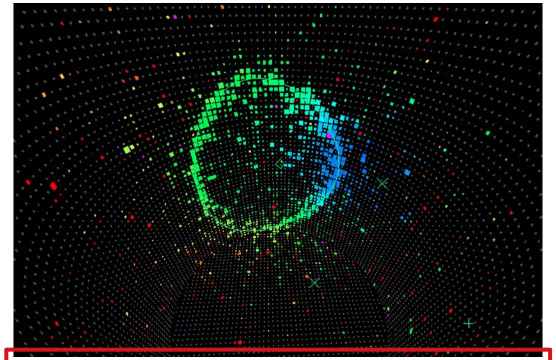


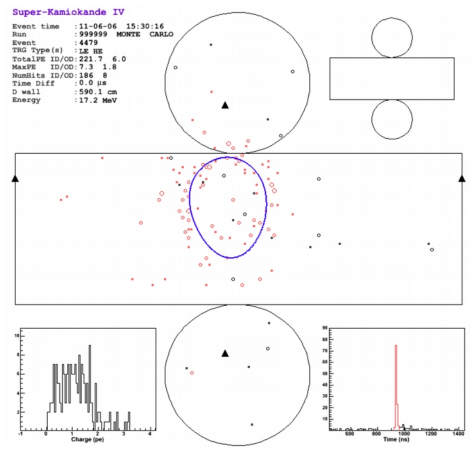
III. The computing system

The HK computing strategy

Data & simulation storage

CPU resources





Trigger happens

Raw data

Tier 0

Copy of raw data
Simulated raw events

Calibrated data
Calibrated simulation

Reconstructed
data & simulation

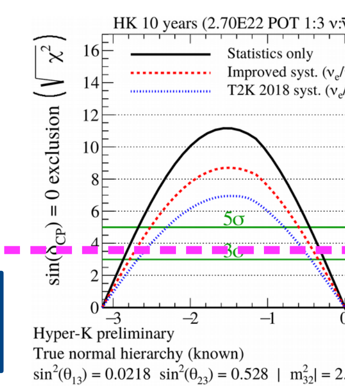
Tier 1
→ Contains all data.
→ Do whole physics analyses

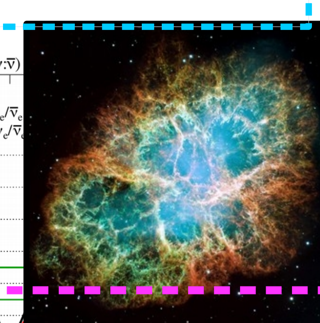
Simulation

Tier 2

Calibration

Reconstruction





Physics analyses

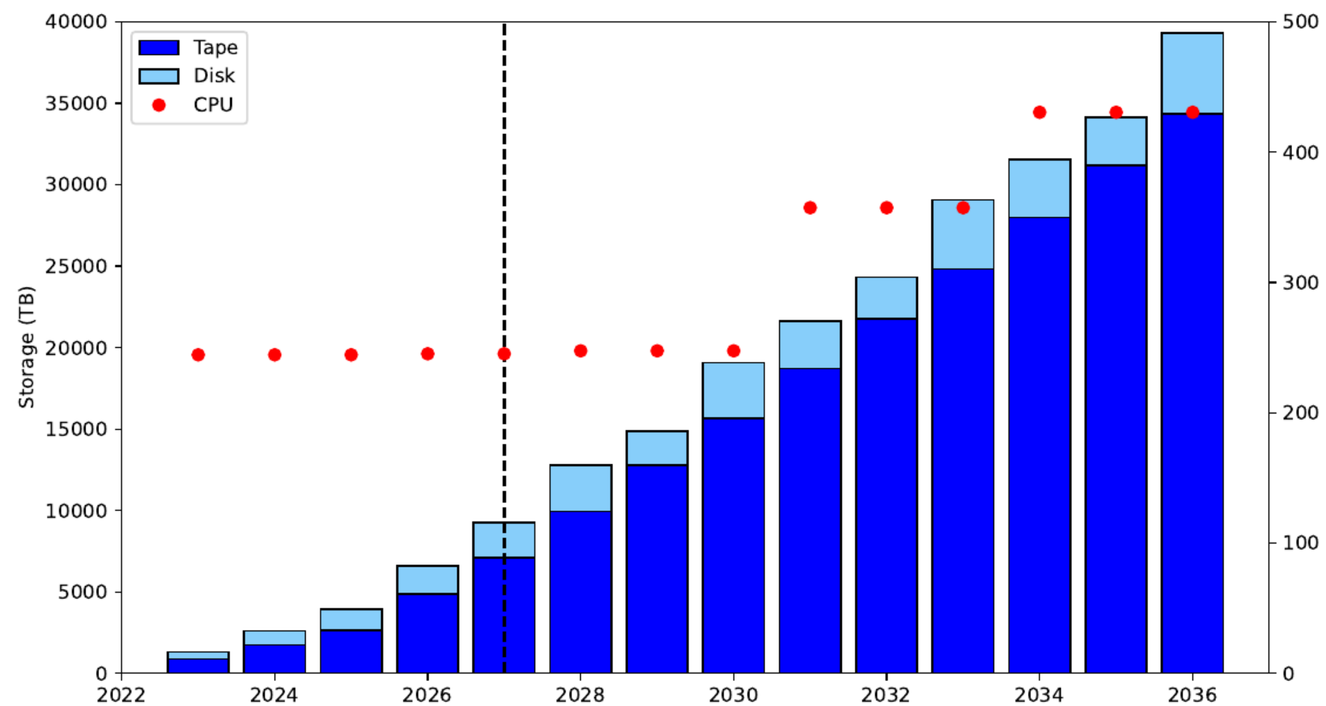
ν oscillation, DSNB search, GUT ….

The IN2P3 teams computing proposal

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

- Pros :

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



Resources to host a Tier 1 at CC-IN2P3

- 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.

- 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.

IV. Incoming steps & timeline

Prospects for the HKROC digitizer

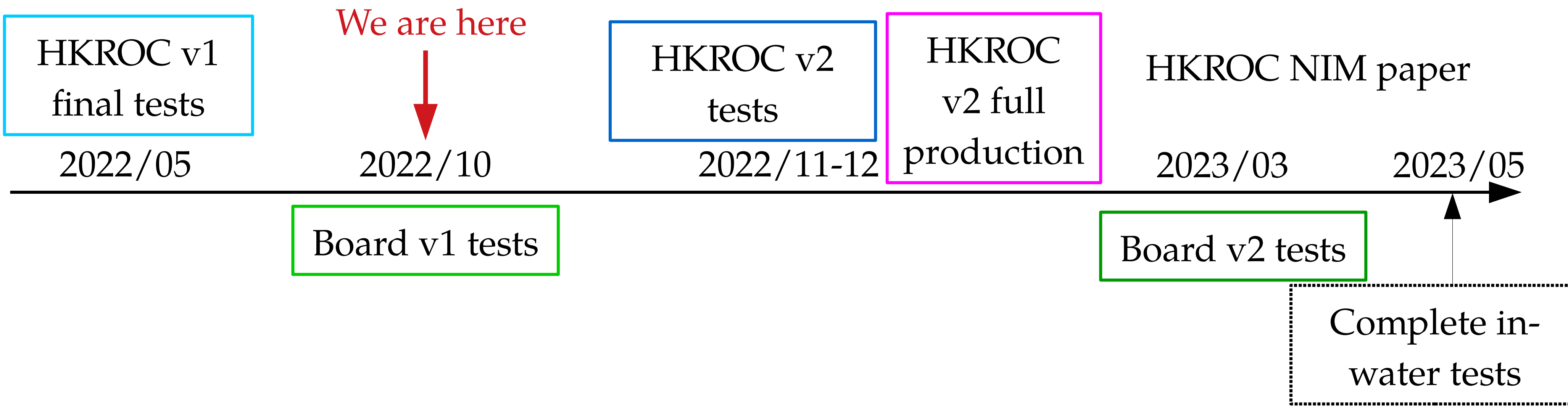
- 2 other digitizers were competing for HK : QTC (Japan), discrete (Italy).
  → Unfortunately, HKROC not chosen as primary solution for HK.

- 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).

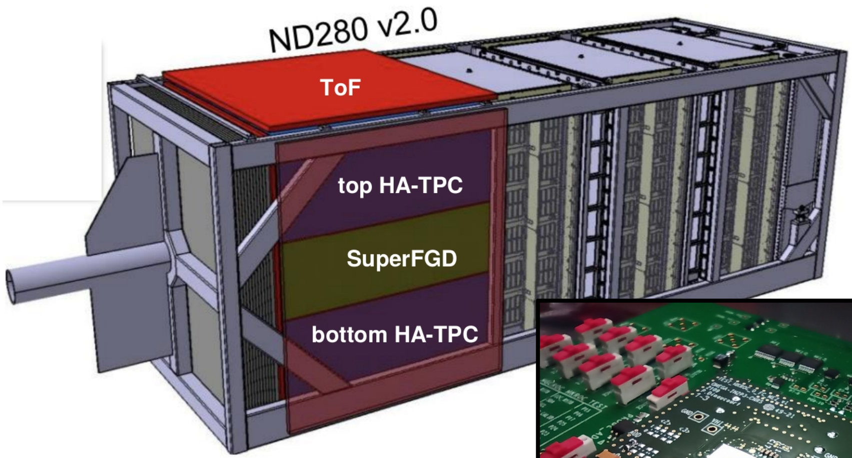
- As for the digitizer : the time-generation & clock distribution systems have been developed to be **generic & usable for other experiments**.

  → NIM paper publication in 2023.

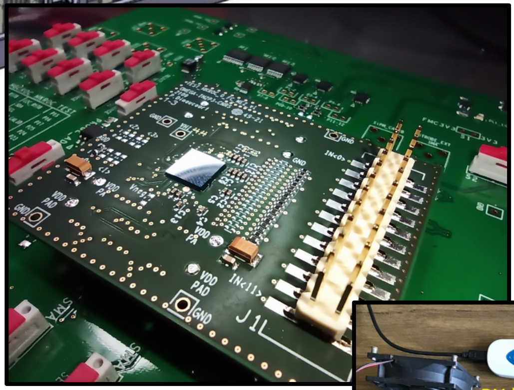
Summary of proposed contributions

<u>Our updated proposal @CS :</u>

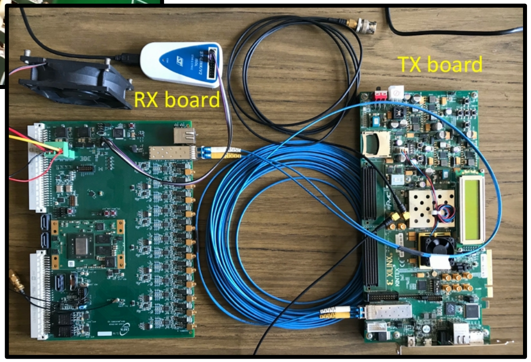
- The ND280-upgrade.



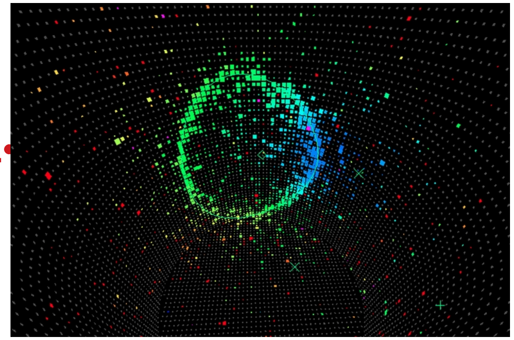
- ~~PMT digitizer for the Far Detector.~~



- Time generation & clock distribution at Far Detector.



- <u>CC-IN2P3 :</u> HK Tier 1 computing site.
  <u>**& lead analyses in both low and high energy sectors.**</u>



- Shared-item cost & assembly.

Physics & analyses in T2K-SK era

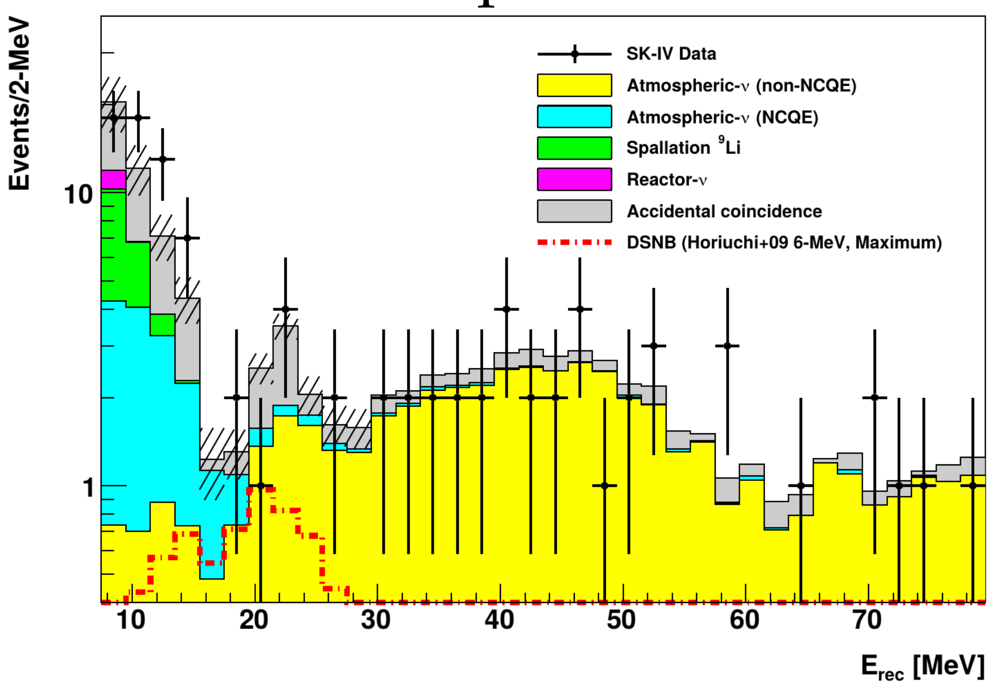
- <u>IN2P3-groups have central roles in T2K & Super-Kamiokande physics.</u>

  → Near-detector physics : upgrade & cross-section conveners @IN2P3

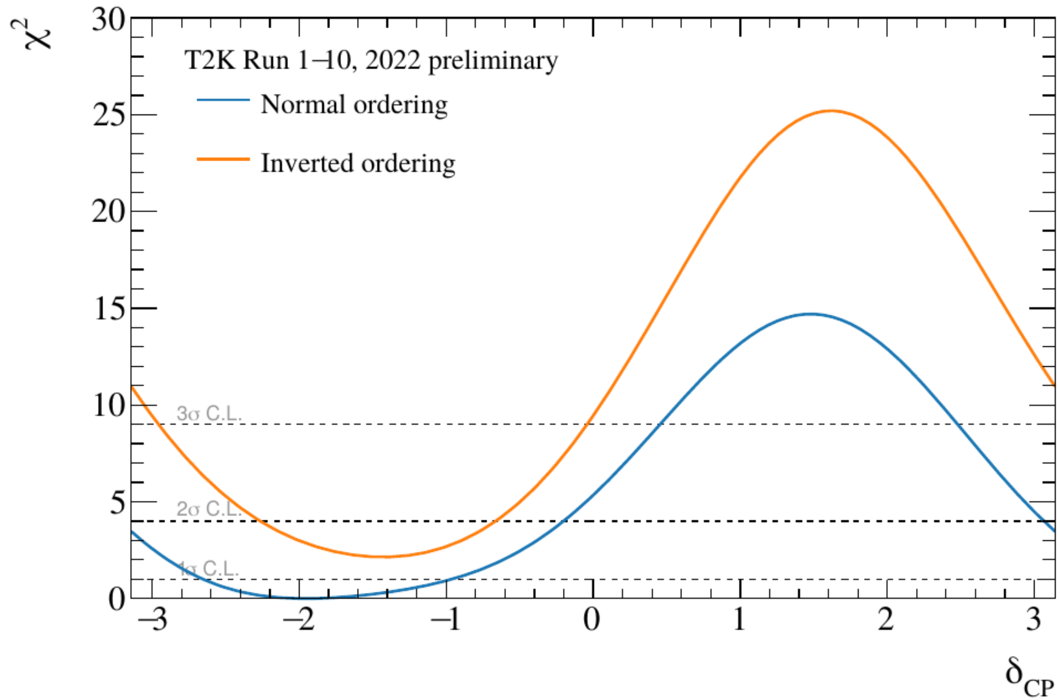
  → ν oscillation analysis : convener @IN2P3.

  → Leader of the SK DSNBν analyses in 2018-2022 @IN2P3

<u>DSNBν @Super-Kamiokande</u>



<u>CP violation @T2K</u>

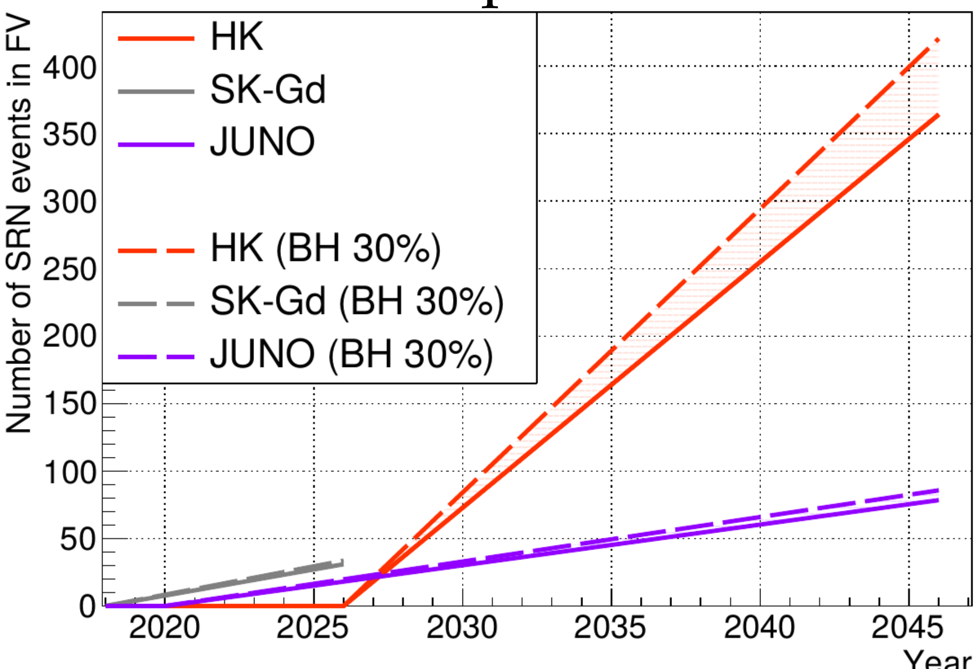


- <u>Our goal :</u> Lead the future Hyper-K analyses from 2027 !

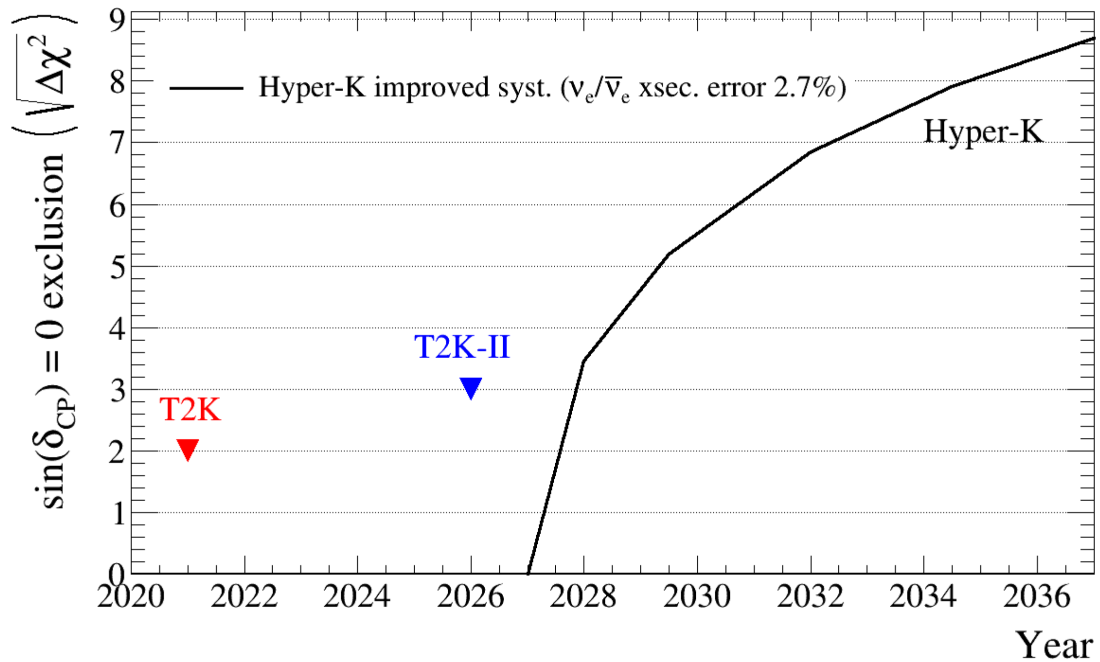
  → Most of existing softwares on SK ≥ 15 years-old : already starts to be outdated & **<u>cannot be scaled to Hyper-K</u>** !

Step-up towards HK era

DSNBν @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 20 years of Super-K & 10 years of 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 these 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 & IRFU
  + 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 !

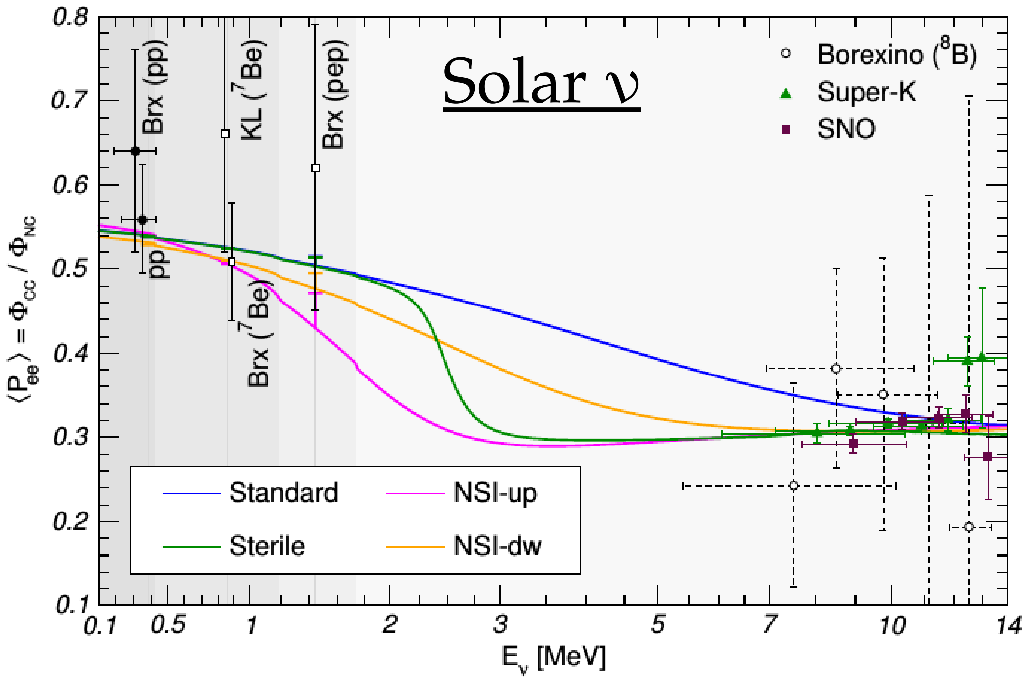
- To build & lead HK physics for next 20 years, we need to build on RD4HK to go beyond **NOW** :

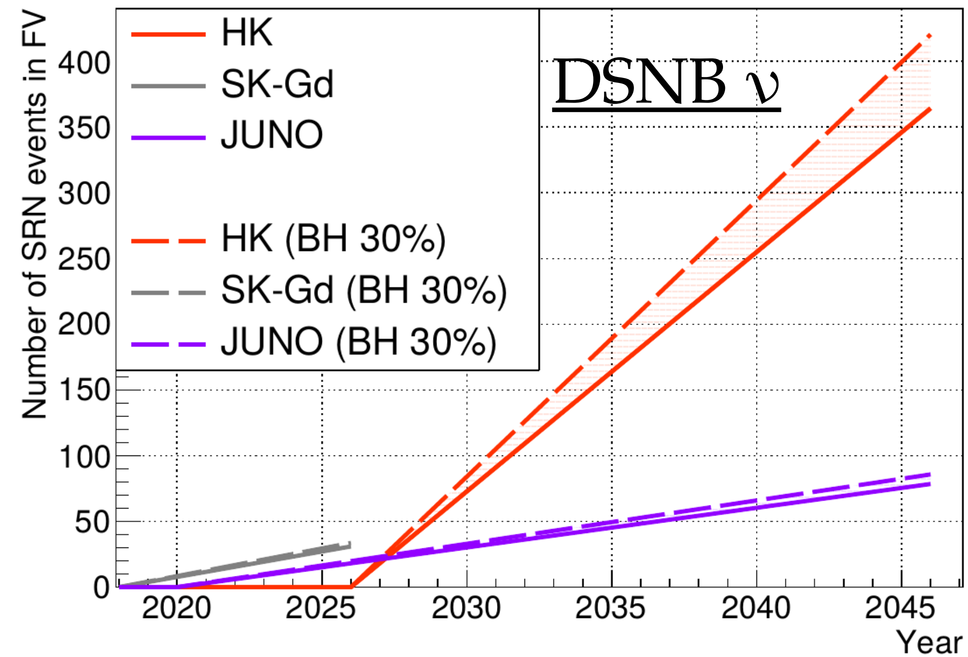
  1. Make CC-IN2P3 a Tier-1 site for HK :
  → Absolutely central visibility & acces to data at a cost of 2 PB/year.
  → Worked to make CC a Tier 1 for ND280 & host HK data base.

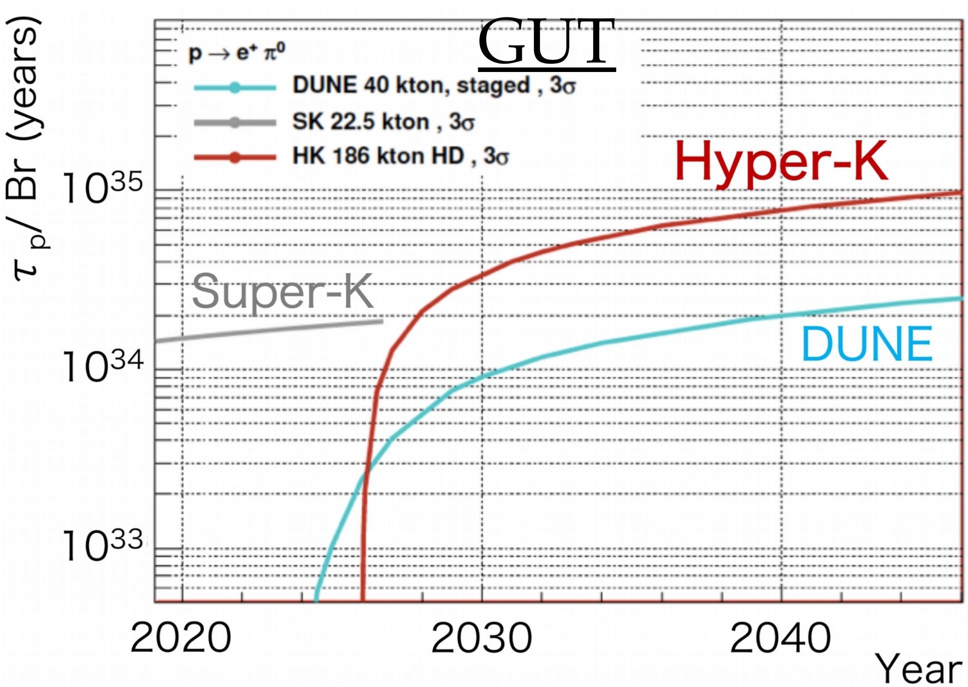
  2. Build on our leaderships & expertize in T2K / Super-K (acquired after 15 years of continuous work & investment by IN2P3) to lead the future HK low & high energy analyses.

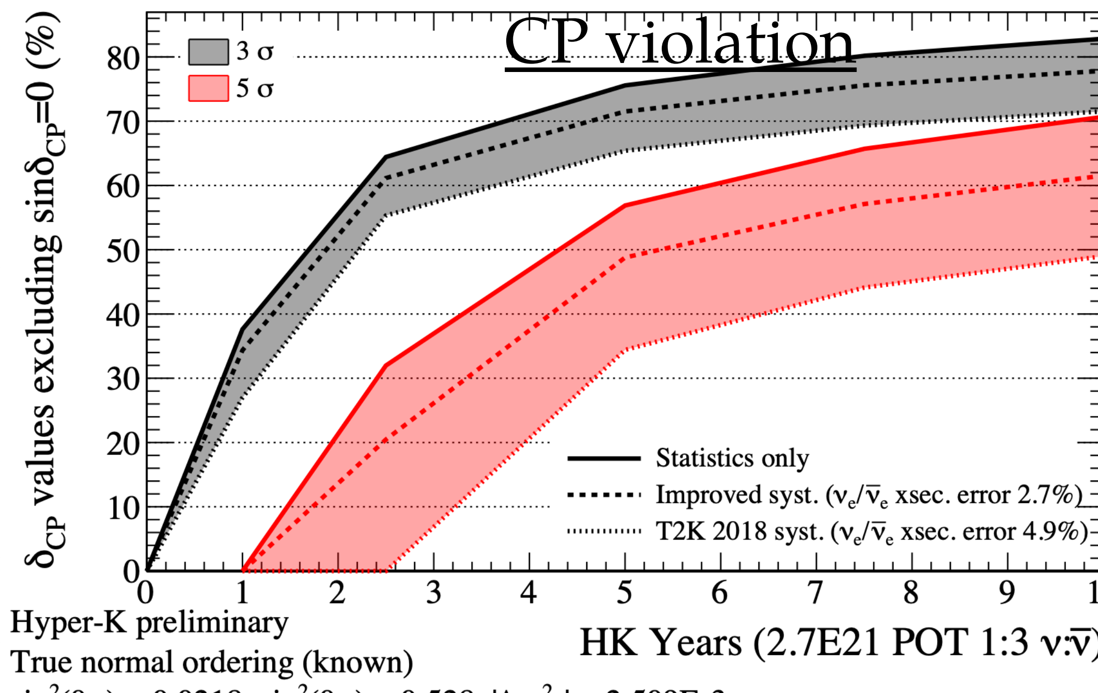
- This is the time to transform this project into a master project !

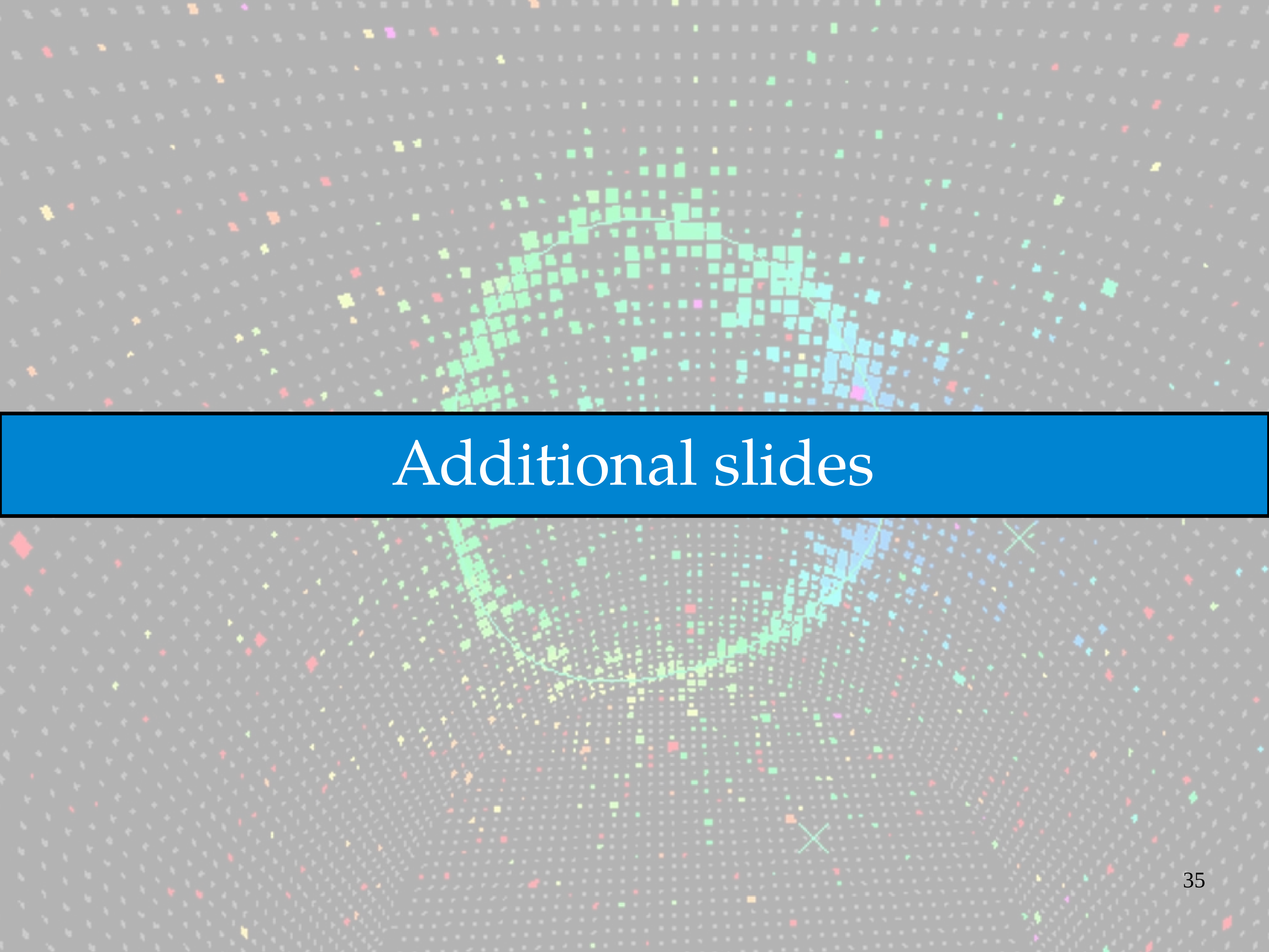
Conclusions











Additional slides

Reminder of the organisation

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 calcules sur 4 ans (01/2022-12/2025)

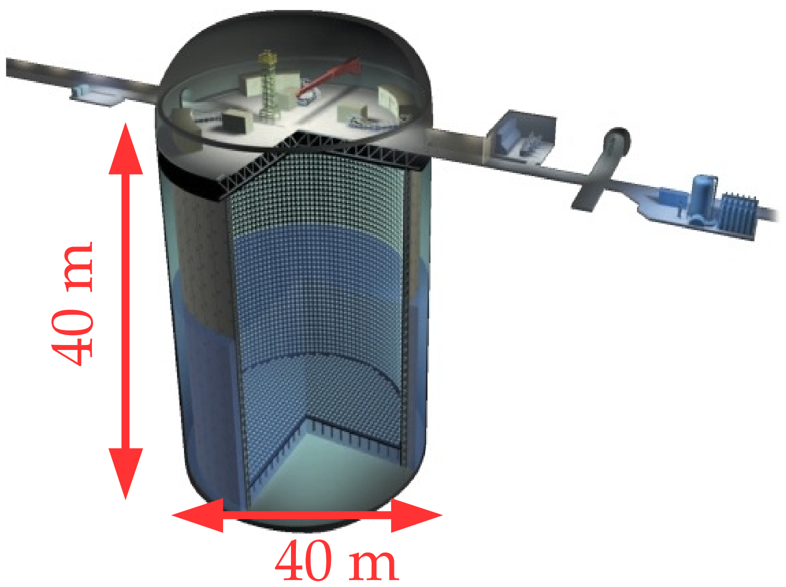
Reminder of the costs required for items

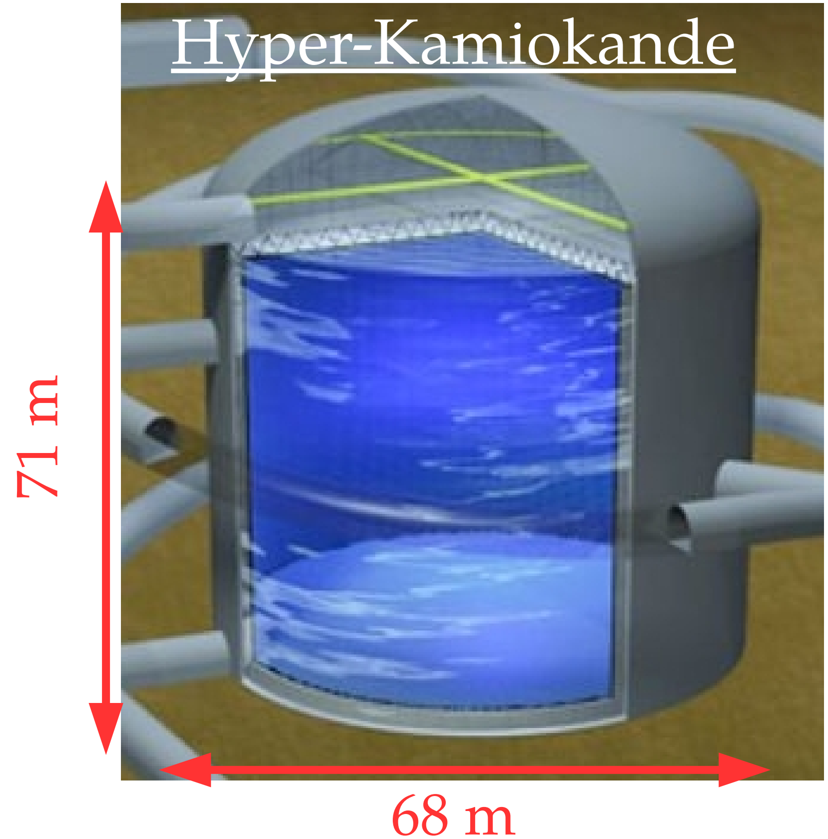
Item	Cost (M)	Partially covered with external fundings	Funding approval	Construction period	Requested fundings (M)
ND280 Upgrade	6	T2K Collaboration	2019	2019 – 2022	0.6 (obtained)
Far detector timing	0.6	ANR - INFN - CEA	2022	2023 – 2026	0.4
Communication cables	2	European countries	2022	2023 – 2026	0.2-0.4
Chip and Front-end	2.5	CEA - INFN	2022	2023 – 2026	1-2.5
Computing (CC-IN2P3)	3.8	CEA	2021	2021 – 2037	3.8
	Note that costs for computing are spread over a much longer period of time (15 years).				
Total	14.9	-	-	-	~6-7.7

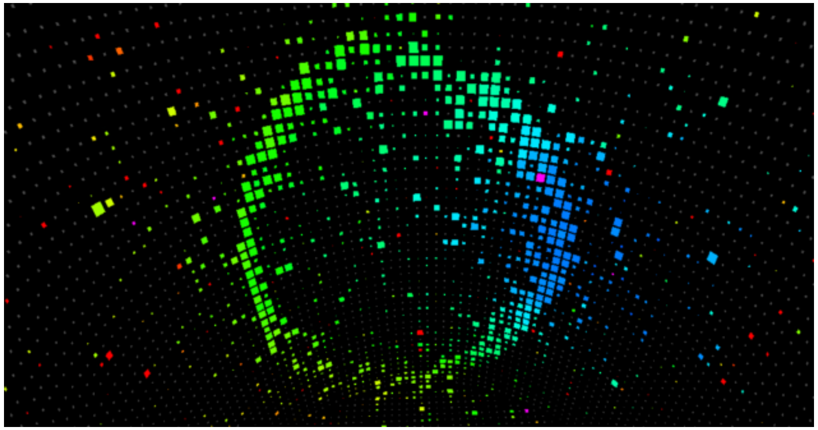
Reminder : what is Hyper-K ?

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

Super-Kamiokande

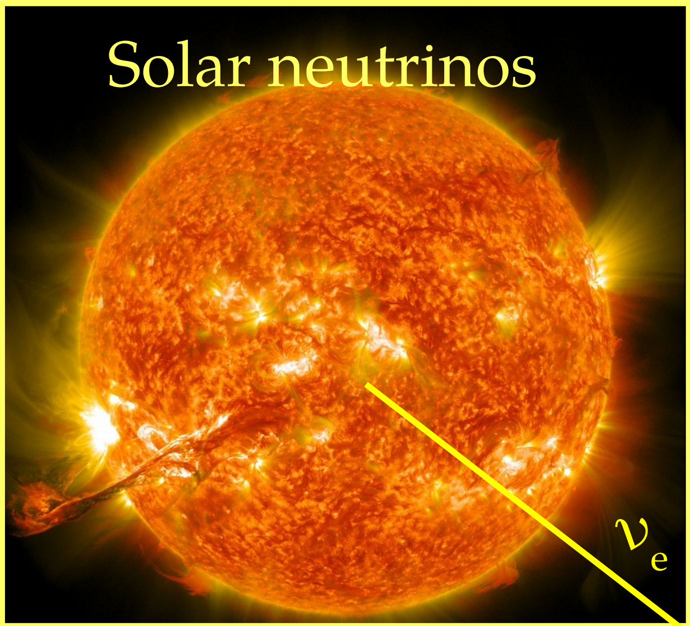




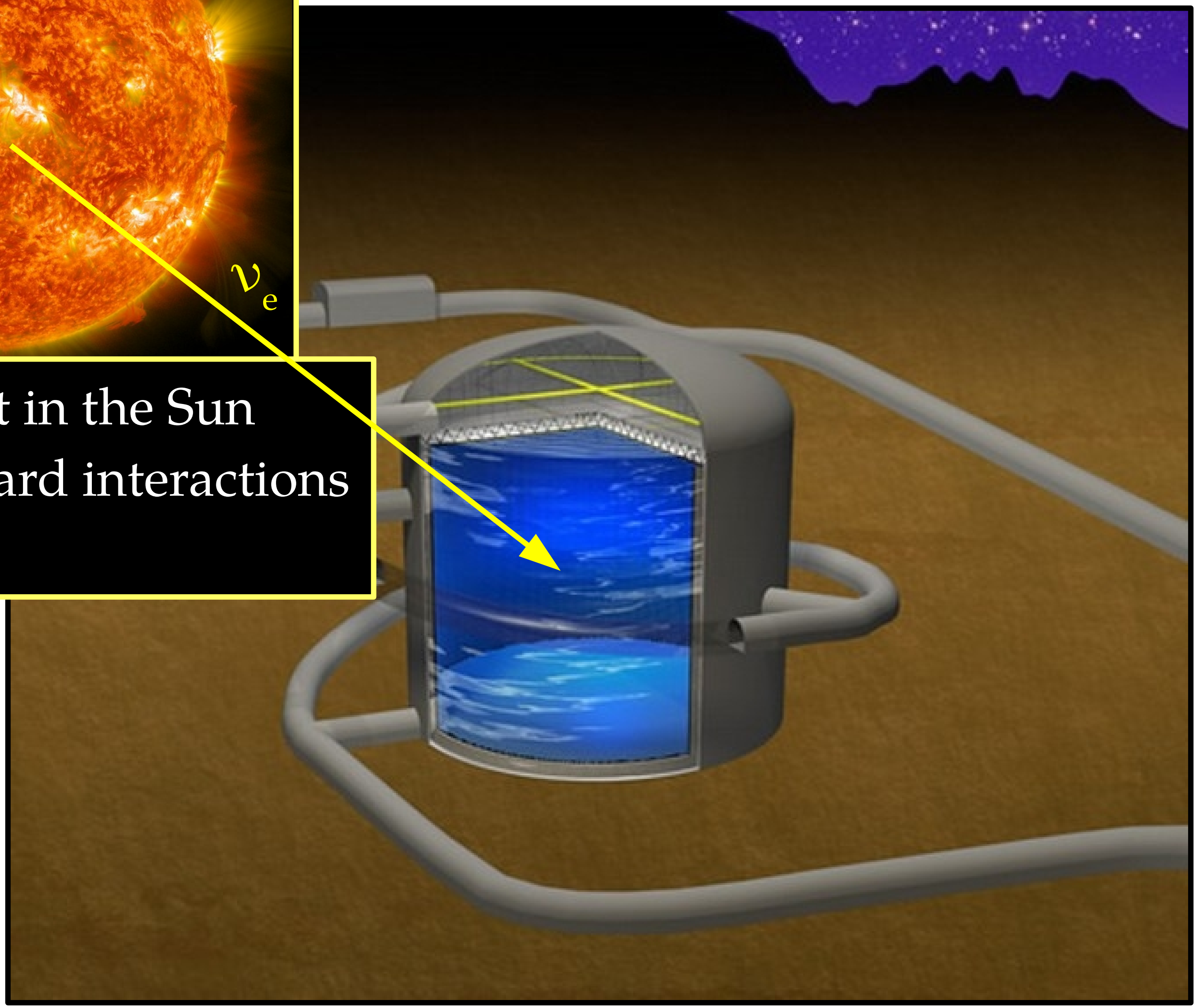


	Super-K	Hyper-K (1st tank)
Site	Mozumi	Tochibora
Number of ID PMTs	**11,129**	**40,000**
Photo-coverage	40%	40% (**×2 sensitivity**)
Mass / Fiducial Mass	50 kton / **22.5 kton**	260 kton / **187 kton**

Physics case

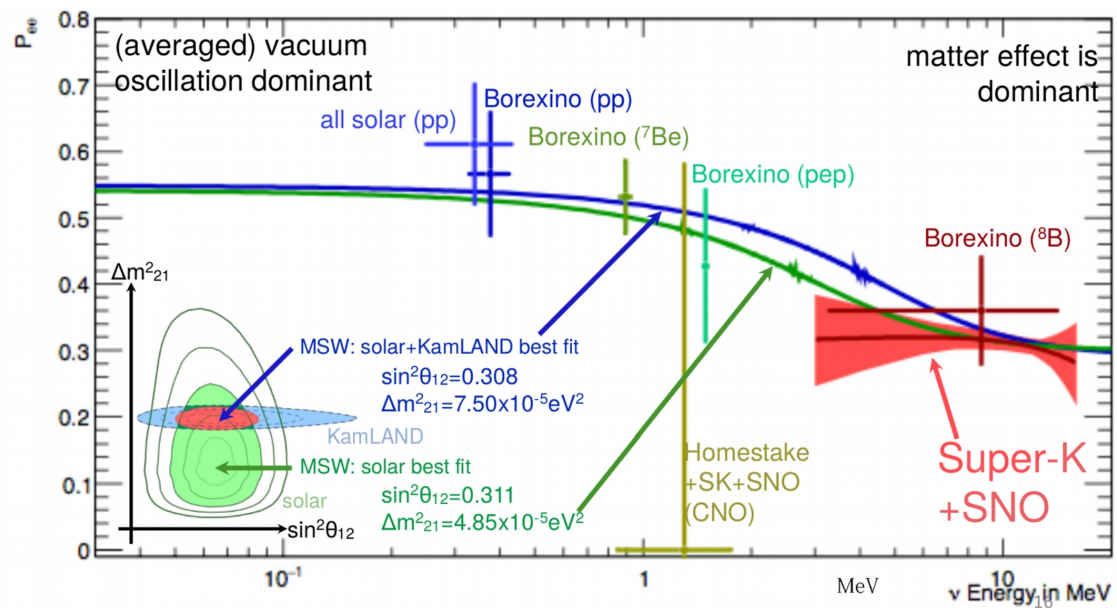


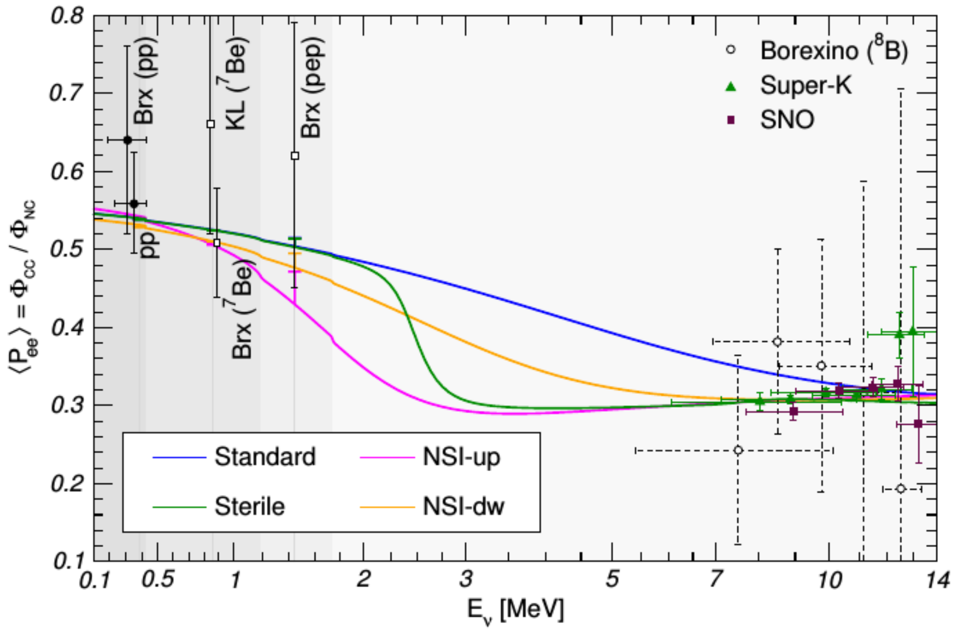
- MSW effect in the Sun
- Non-standard interactions in the Sun.



Solar neutrinos : upturn

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

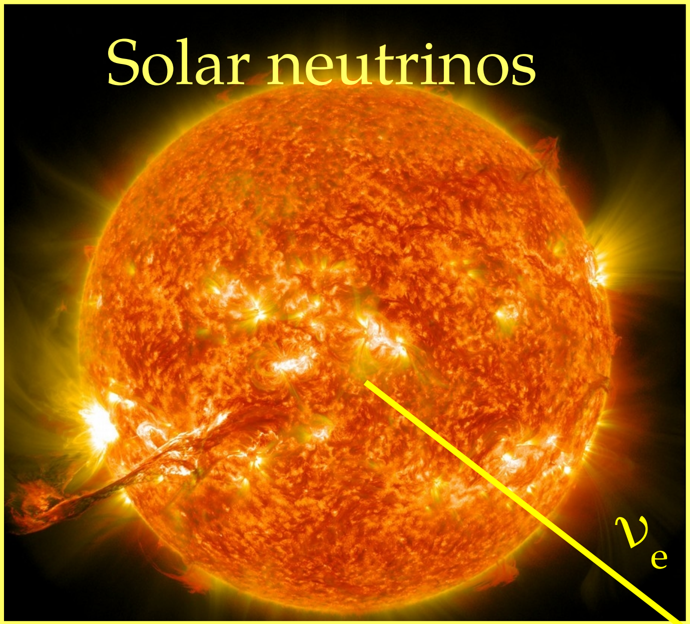




- SK deviates from standard upturn scenario > 2σ.

- <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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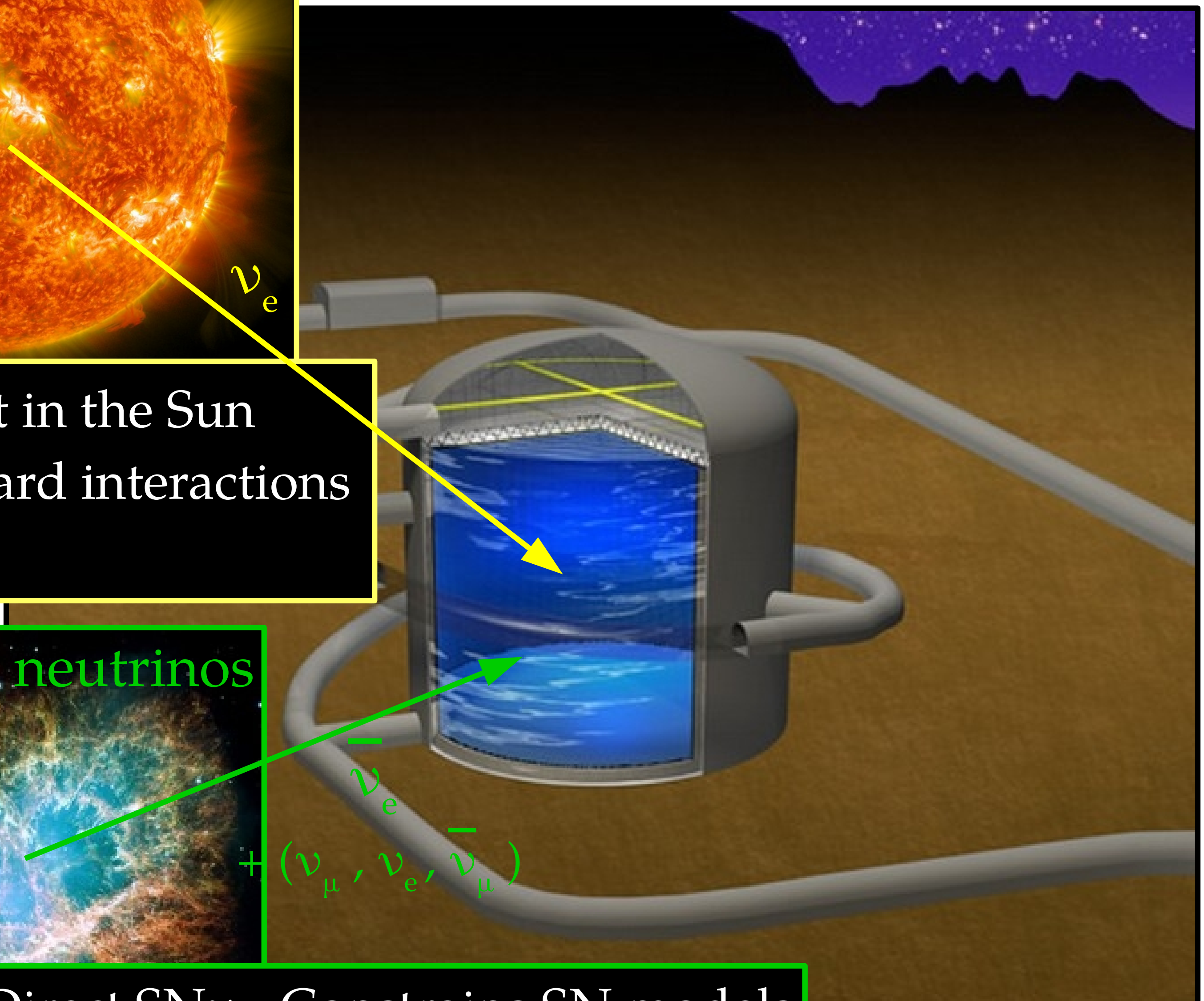
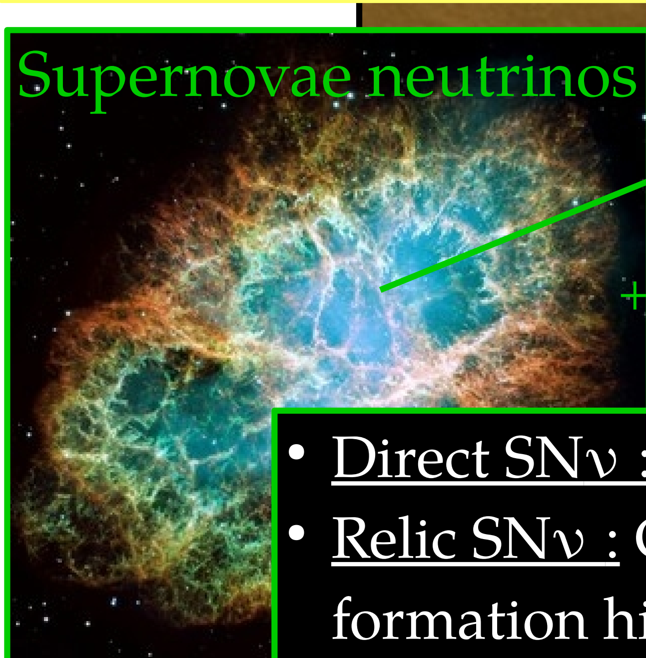
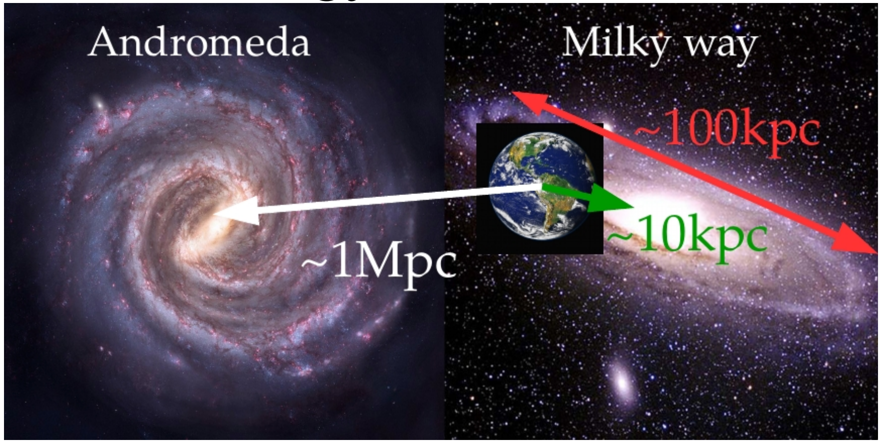




- Direct SNν : Constrains SN models.
- Relic SNν : Constrains cosmic star formation history

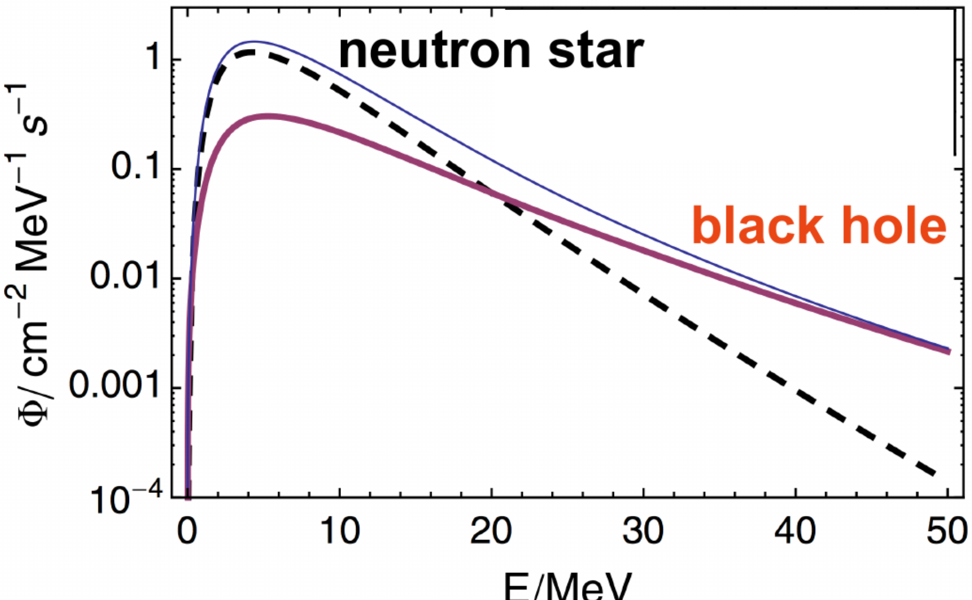
Supernovae neutrinos

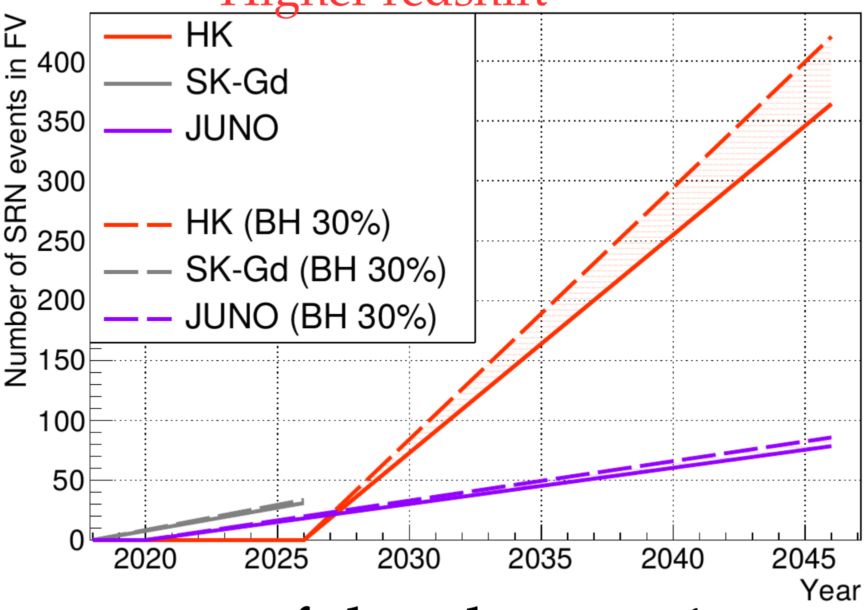
- Unique probe for supernovae ν : 99 % of SN energy → ν.
  - But direct ν detection very rare.
  - HK also sensitive to extra-galactic SNν from Andromeda !



- 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

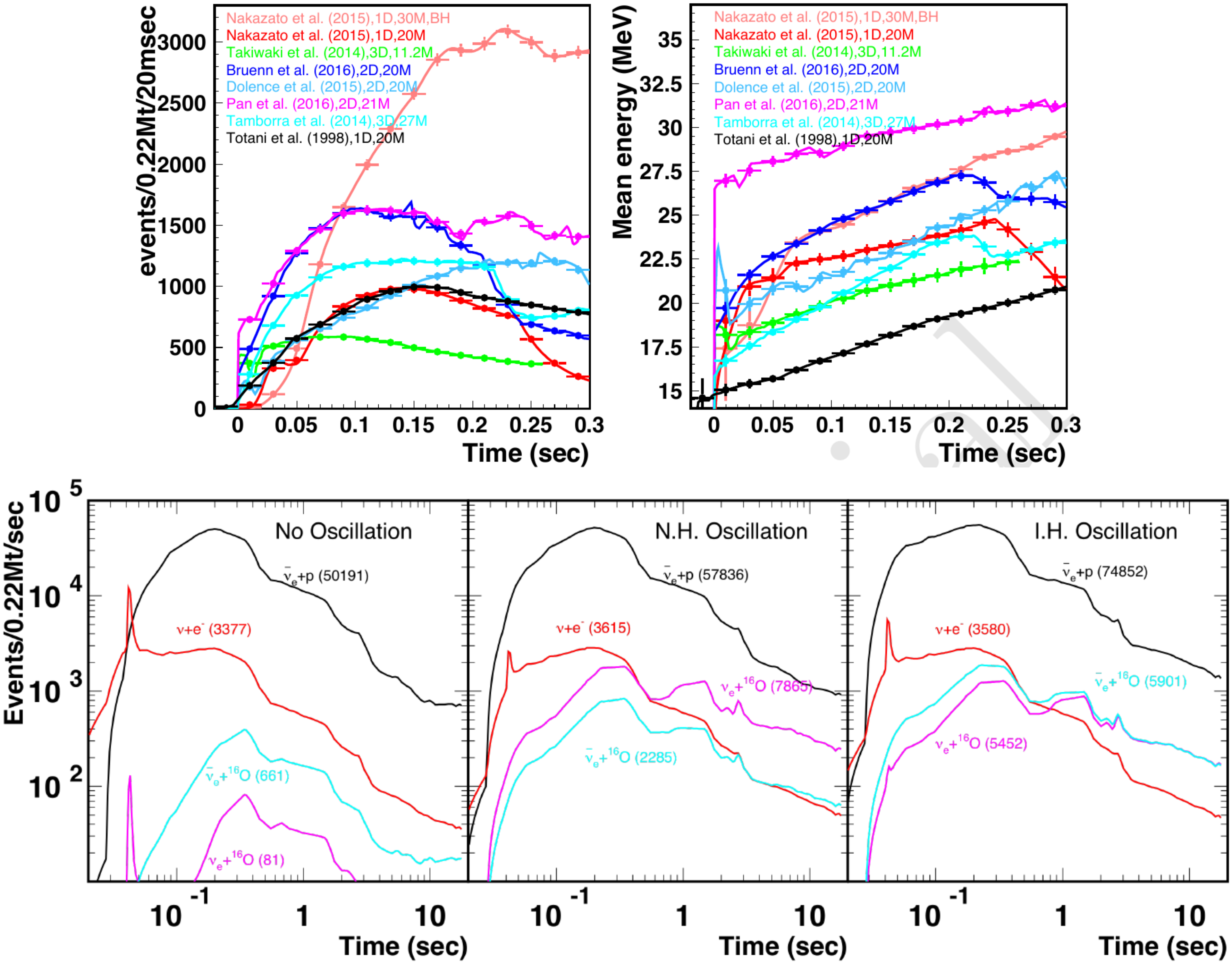
Higher redshift





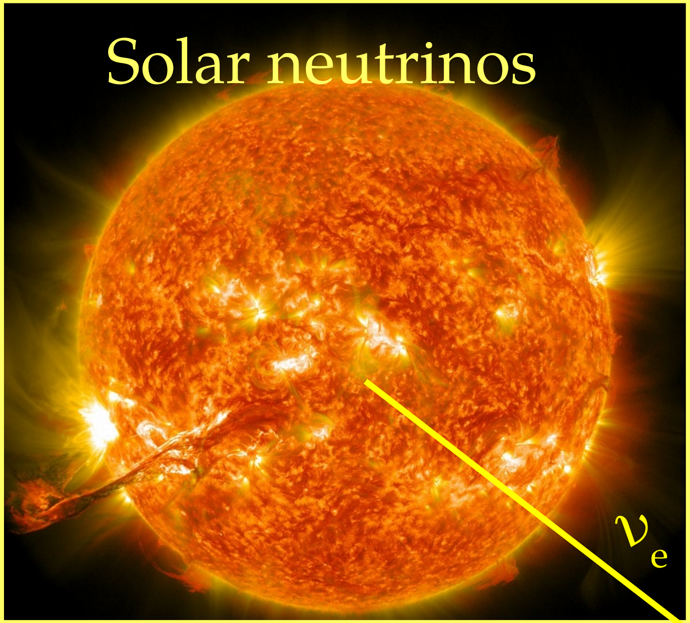
- SK-Gd & then, HK are the pioneer experiments of this domain !

Supernovae neutrinos - burst



Physics case

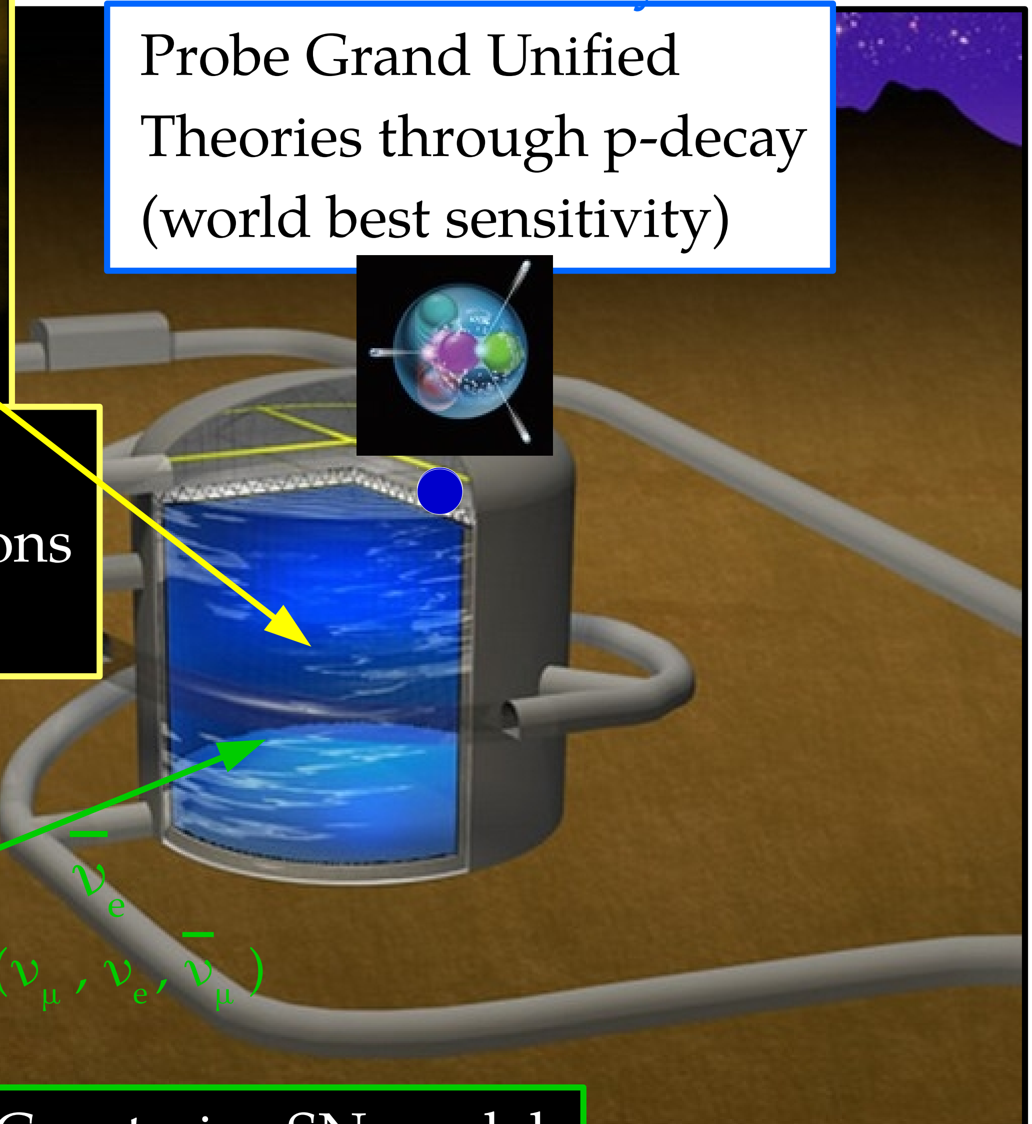
Solar neutrinos



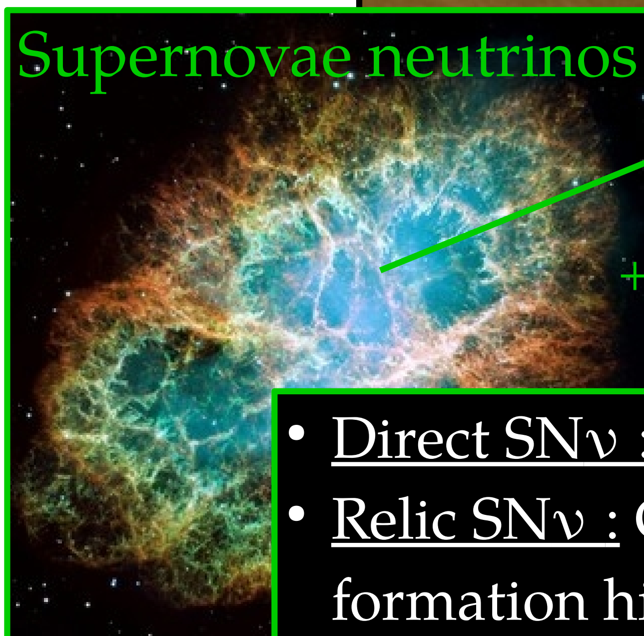
- MSW effect in the Sun
- Non-standard interactions in the Sun.

Proton decay

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



Supernovae neutrinos

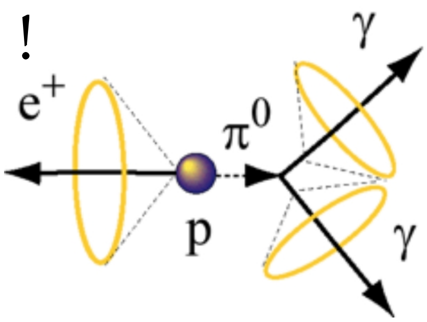


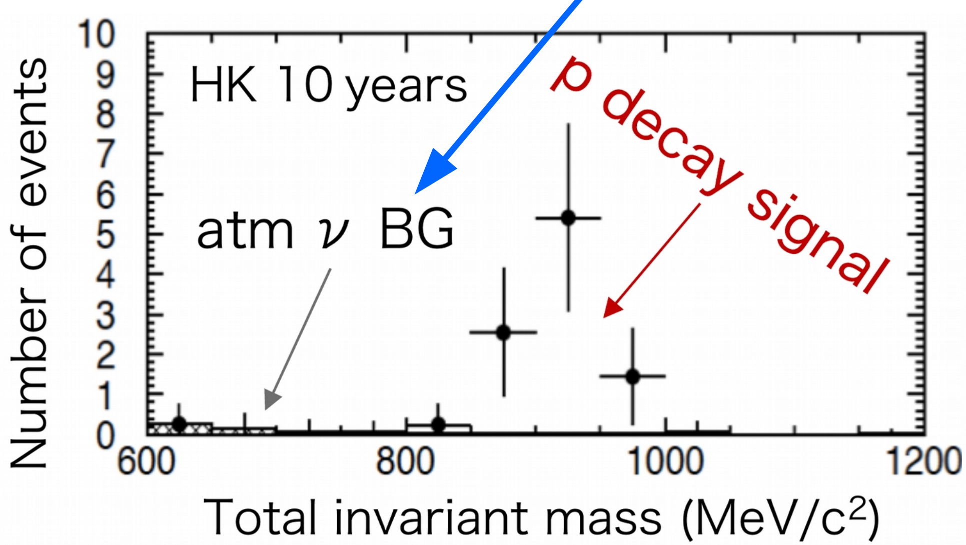
- <u>Direct SNν :</u> Constrains SN models.
- <u>Relic SNν :</u> Constrains cosmic star formation history

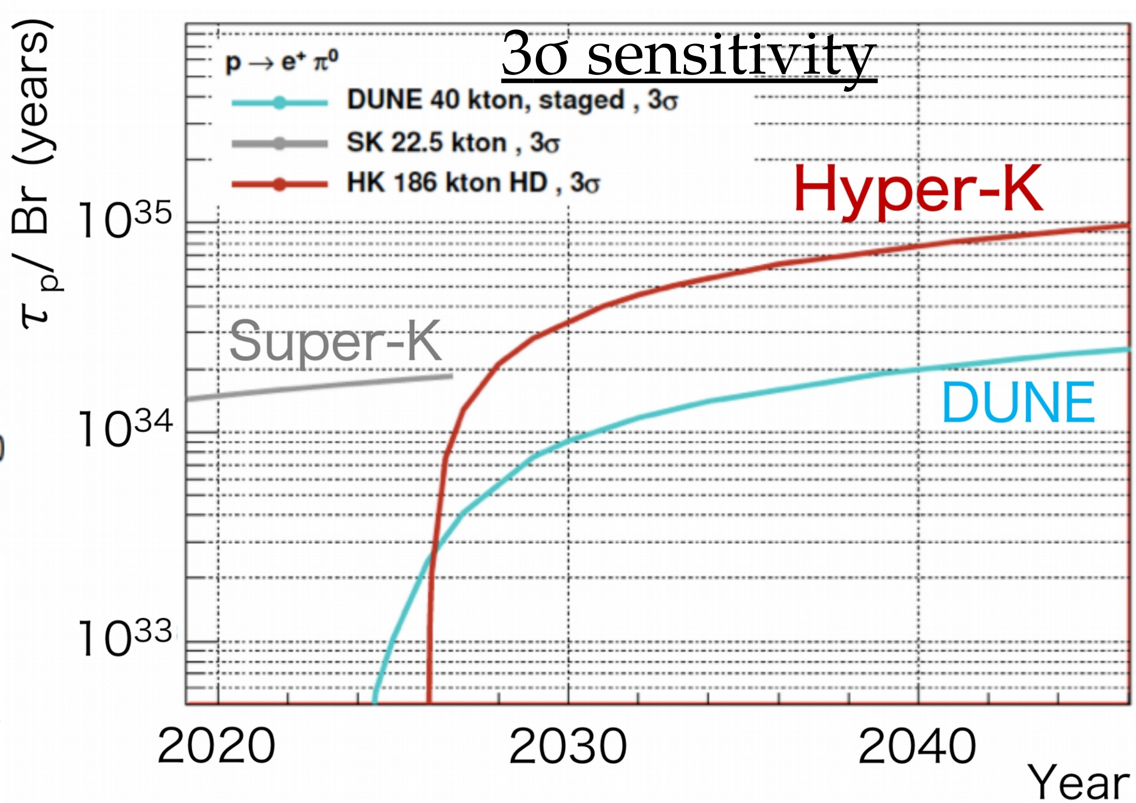
GUT and proton decay

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

- <u>Golden channel :</u> $p \to e^+ + \pi^0 \to$ Almost background free !
  $\to$ Requires 2γ & reconstructed energy = Invariant M_P
  $\to$ <u>Bkg :</u> Atmospheric ν producing e.g. a π^0.



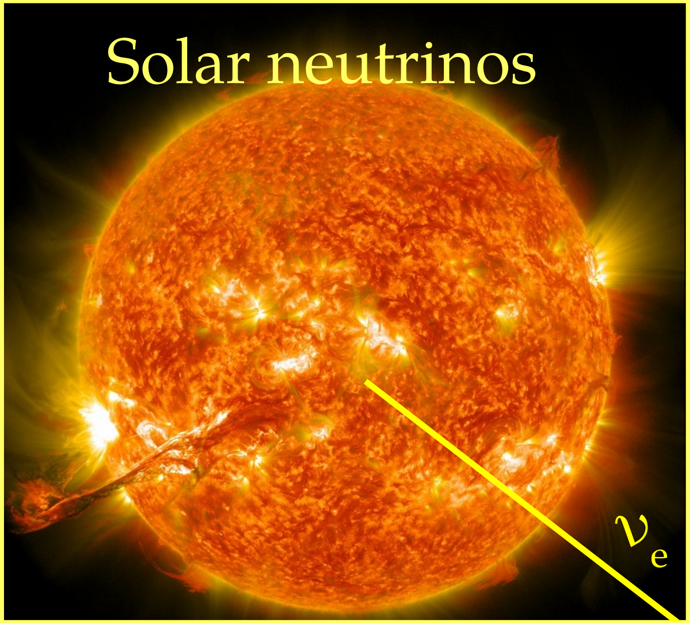




- 3σ sensitivity reach τ_P /Br = 10^{35} years $\to$ 1 order of magnitude beyond SK or DUNE

Physics case

Solar neutrinos



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Proton decay

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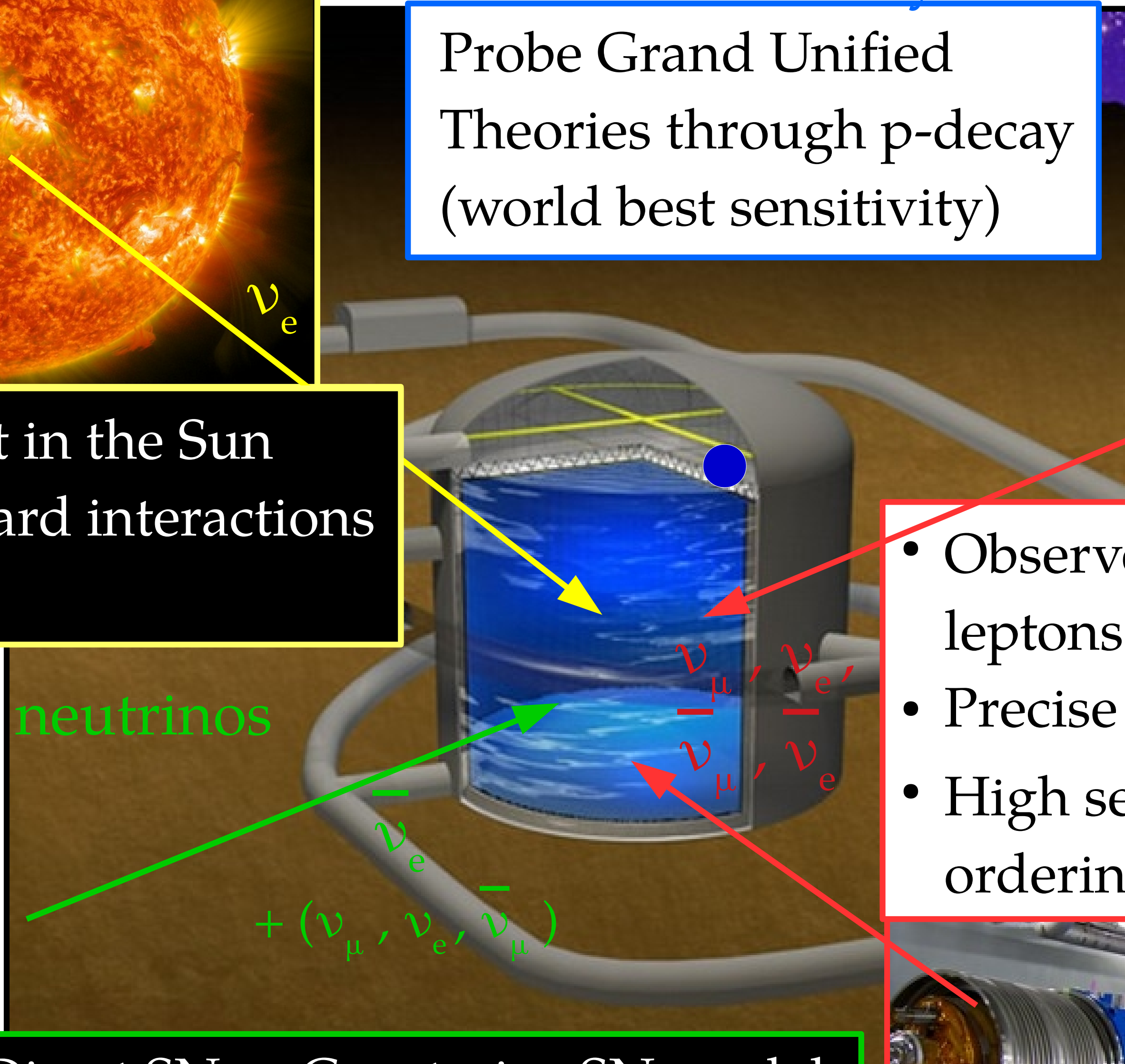
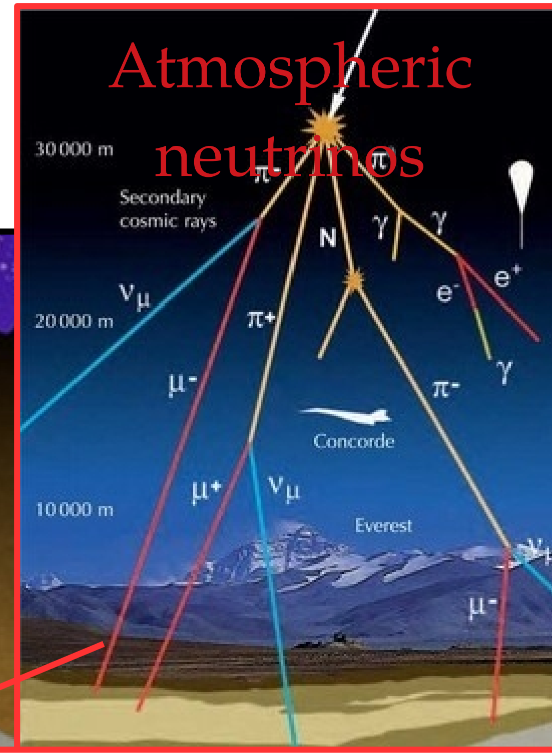


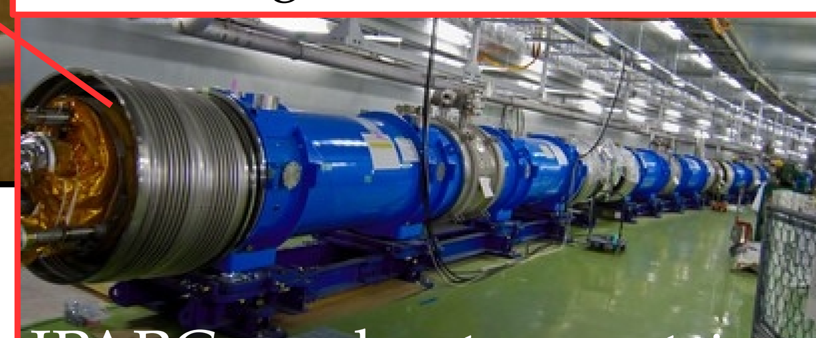
Atmospheric neutrinos



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

Supernovae neutrinos

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

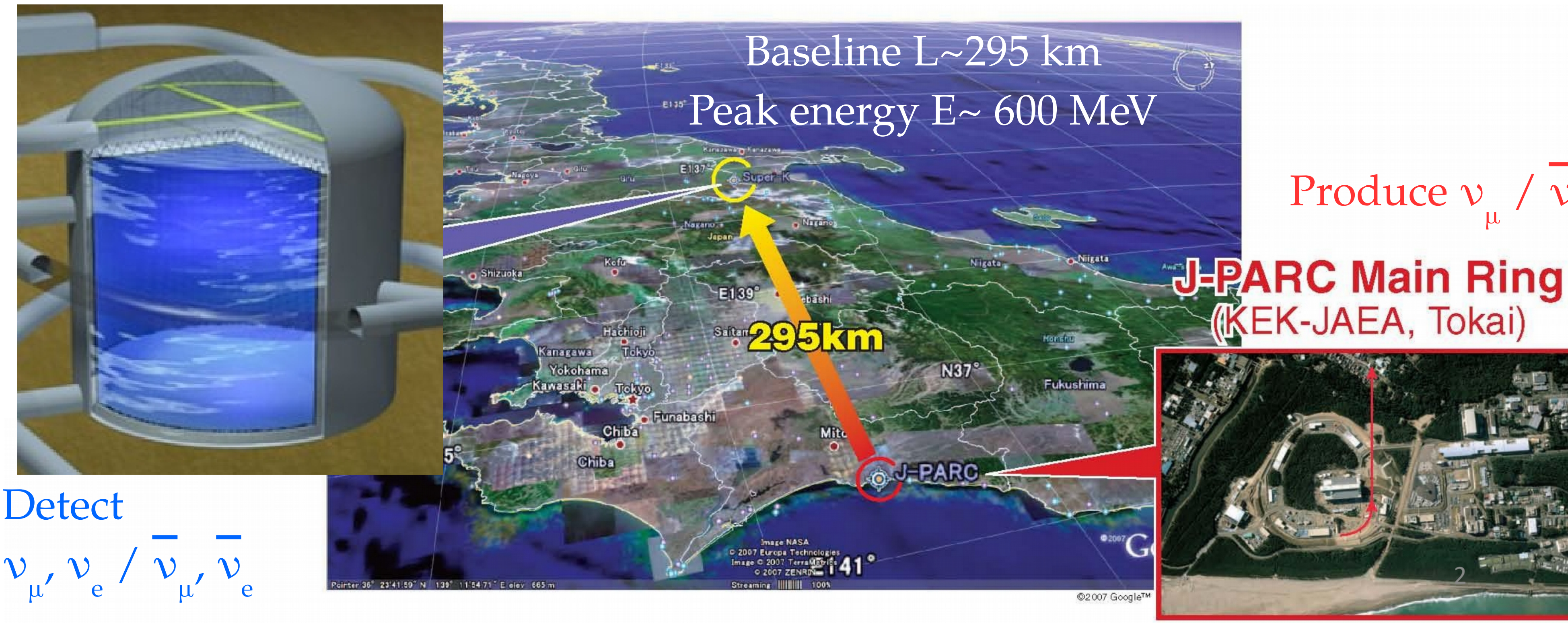


JPARC accelerator neutrinos

Focus on CP violation

- CP violation search essentially based on accelerator ν : T2HK

Hyper-Kamiokande



Detect

ν_μ, ν_e / $\bar{\nu}_\mu, \bar{\nu}_e$

Produce ν_μ / $\bar{\nu}_\mu$

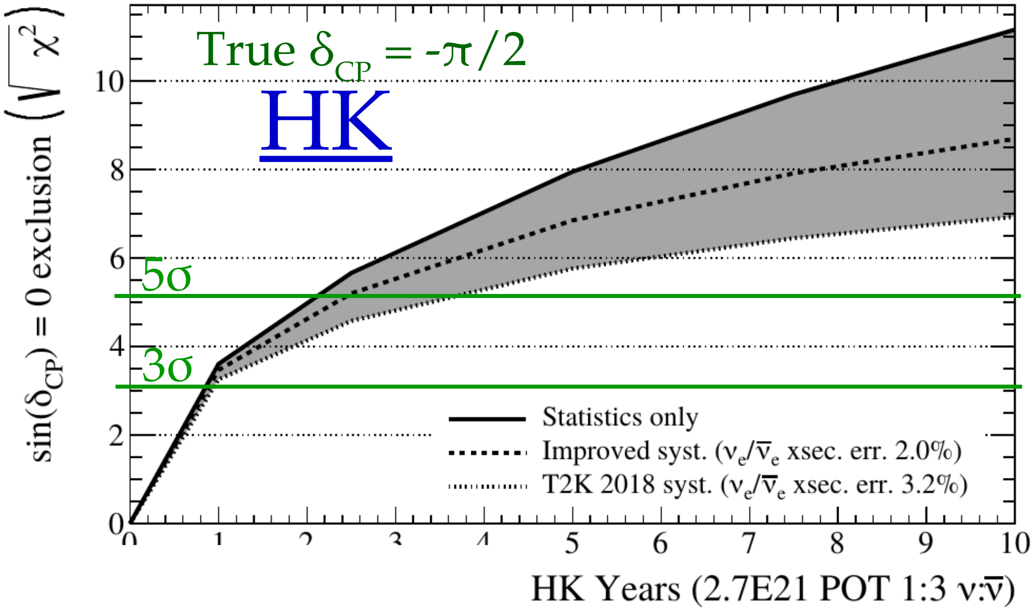
- ν_e appearance in a ν_μ beam and ν_μ disappearance & $\bar{\nu}$ equivalents.
- Detector technologies, calibration, analyses well-proven by T2K&SK.

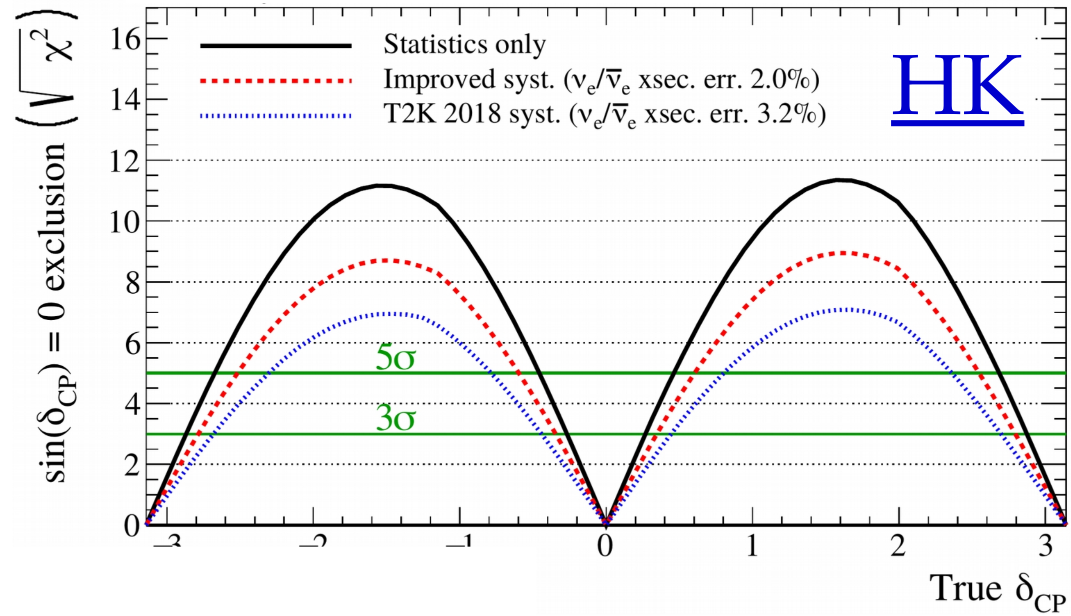
$\Longrightarrow$ Quick start ! Which relies on 2 milestones :

1. $\downarrow$ time to accumulate statistics $\rightarrow$ Beam upgrade.
2. $\downarrow$ systematic uncertainties $\rightarrow$ Constrains ν_μ&ν_e flux before oscillation

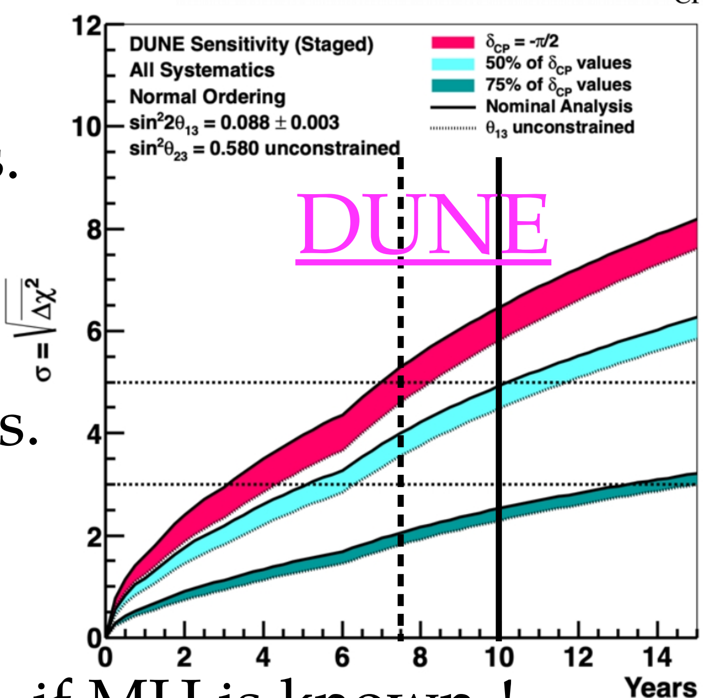
Sensitivity to CP violation

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





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

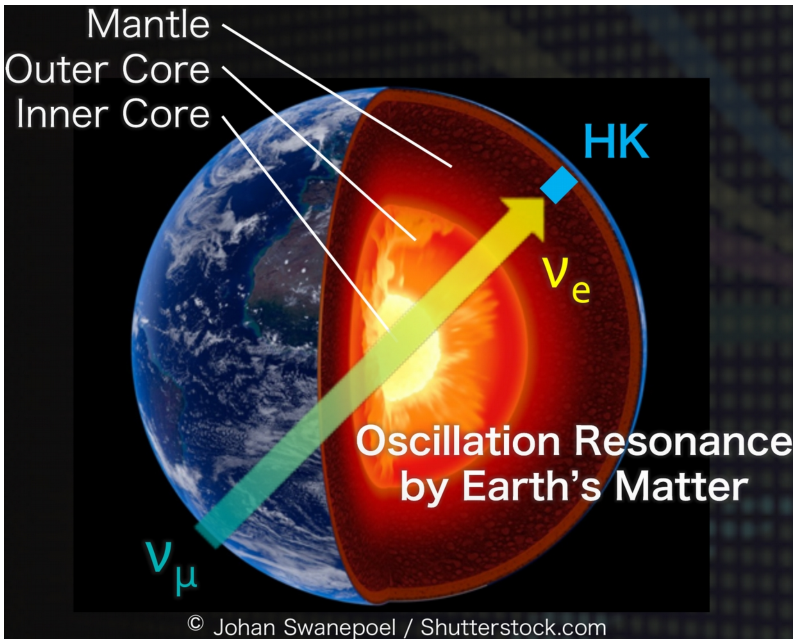


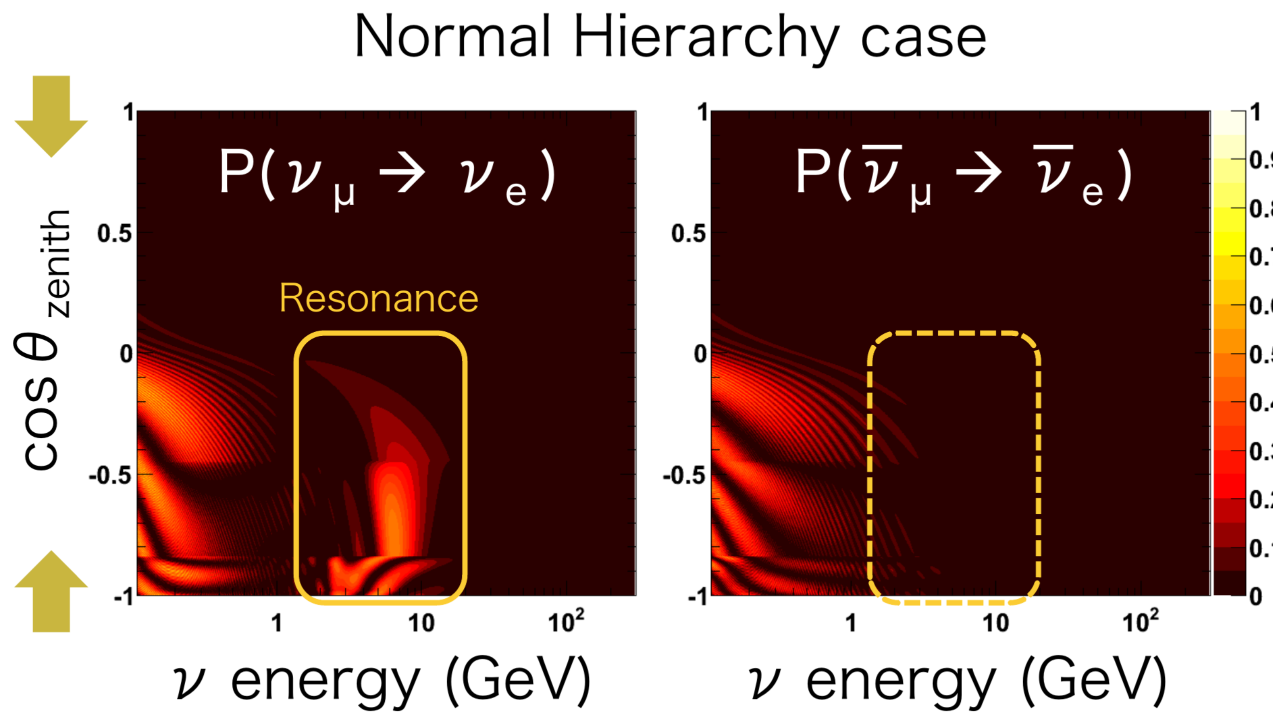
- HK 10 years : 5σ sensitivity on 60% of δ_{CP} values.
  → DUNE : 5σ sensitivity on 40%

- 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





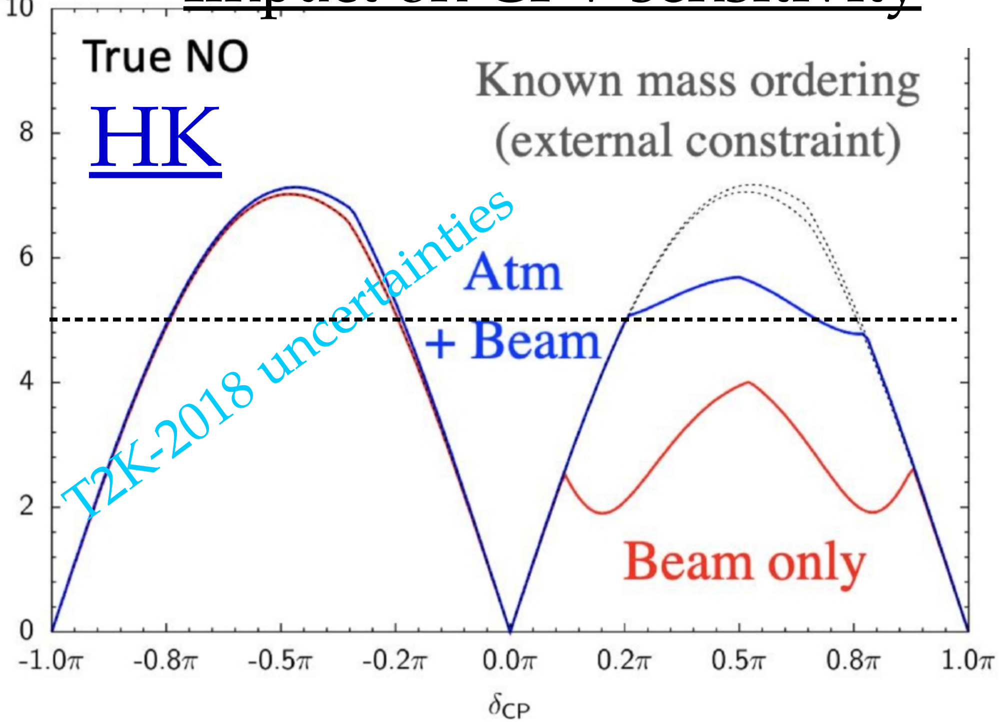
- Mass hierarchy determined with upward-going multi-GeV ν_e sample :

atm. baseline ≤ 13000 km ≫ 295 km accelerator baseline

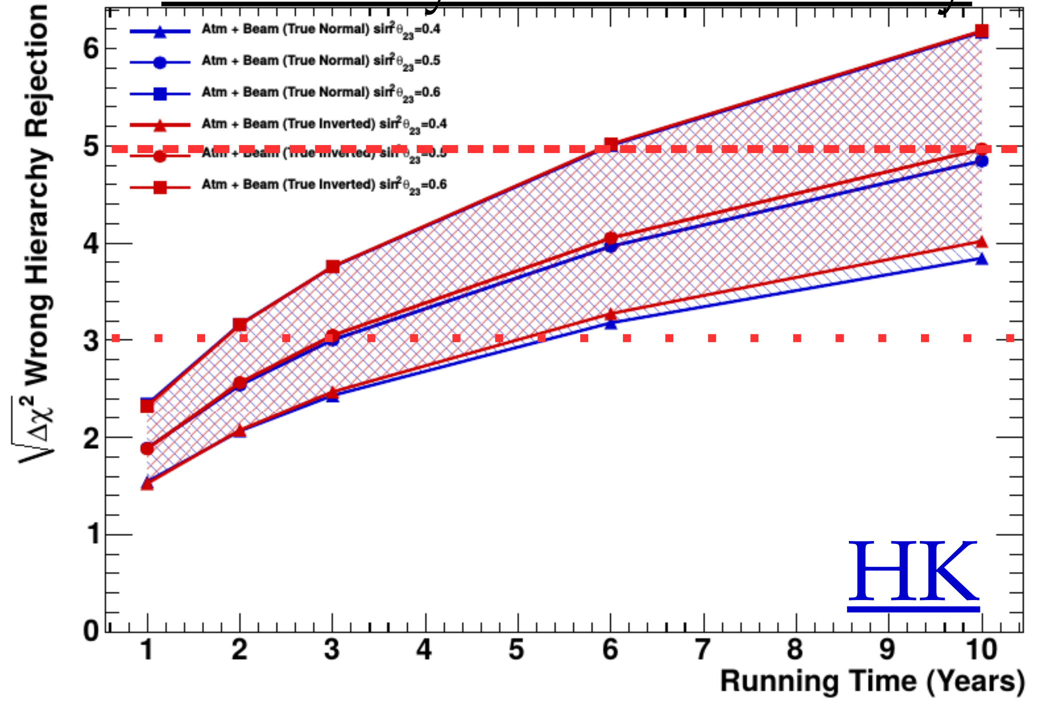
- Normal hierarchy : enhancement of $\nu_\mu \to \nu_e$.
- Inverted hierarchy : enhancement of $\overline{\nu}_\mu \to \overline{\nu}_e$.

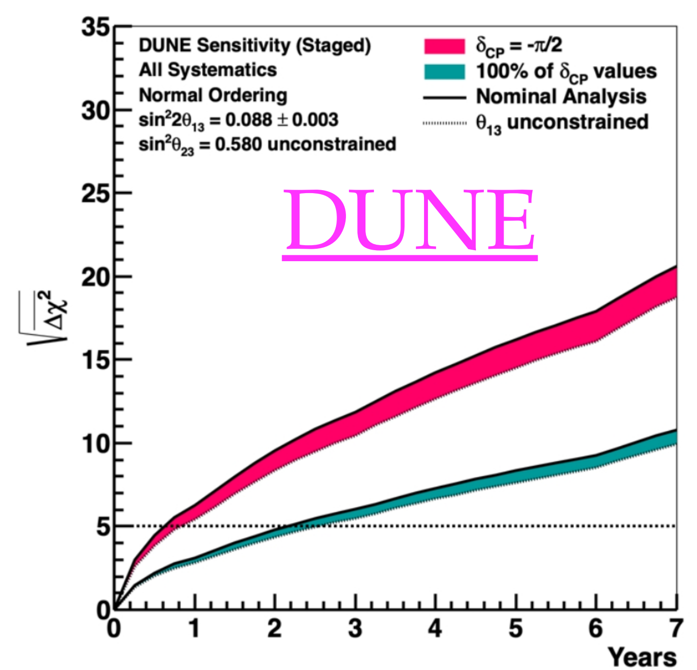
Combination of atmospheric + beam ν

Impact on CPV sensitivity



Sensitivity to mass hierarchy





- Even if MH is not known when HK starts

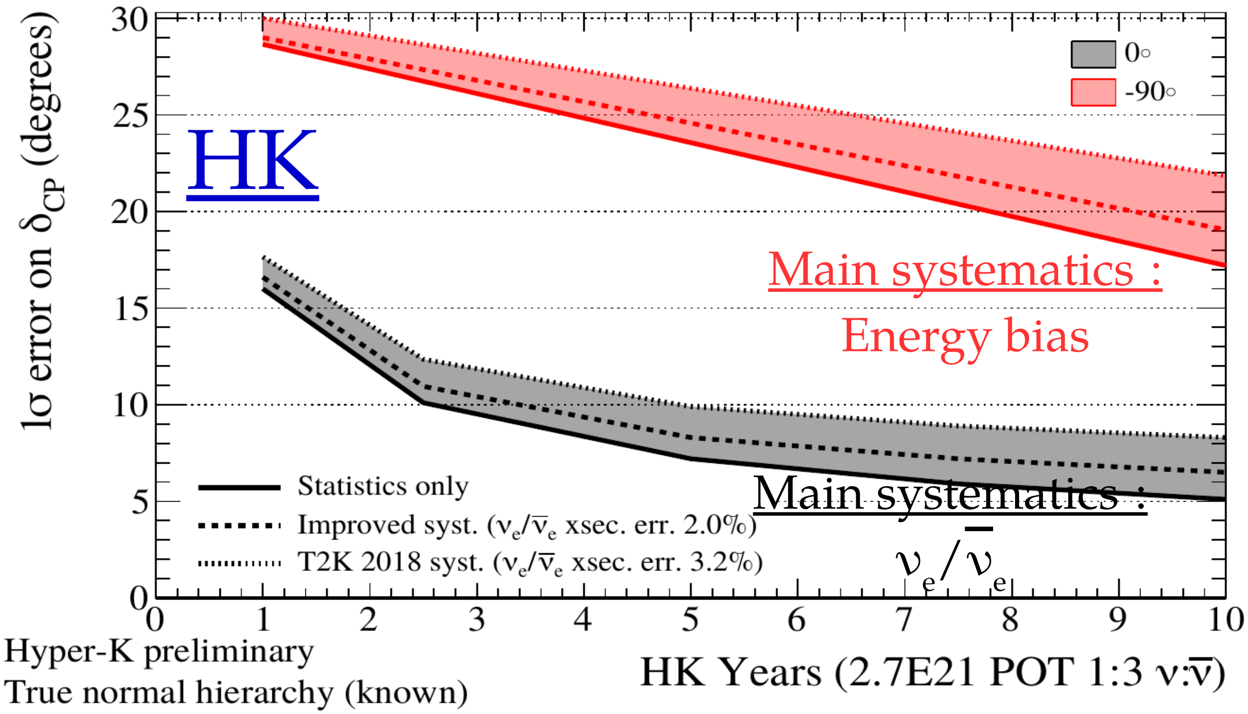
→ Sensitivity to CPV is little affected if we add atmospheric ν.

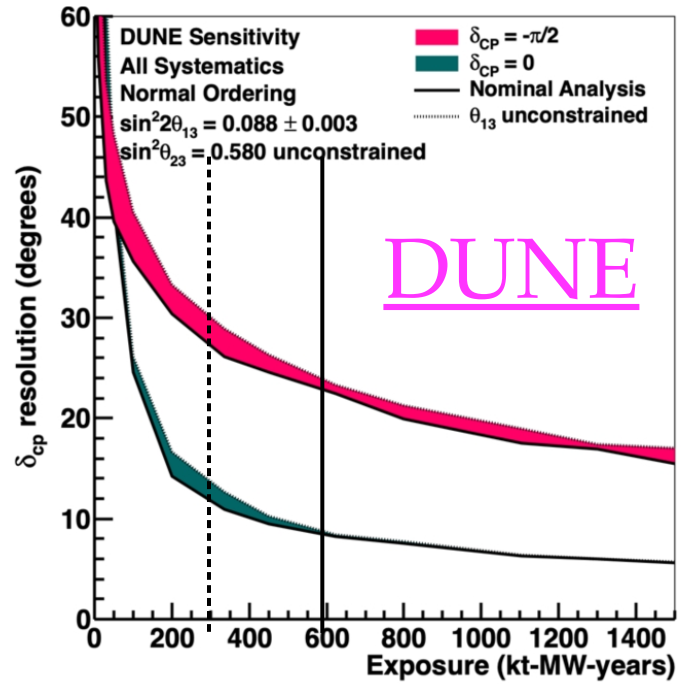
- MH would be determined by :
  - → HK after ≥ 6-10 years via atmospheric.
  - → DUNE : after 1-2 years.

Precision of 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.

L'asymétrie matière / antimatière

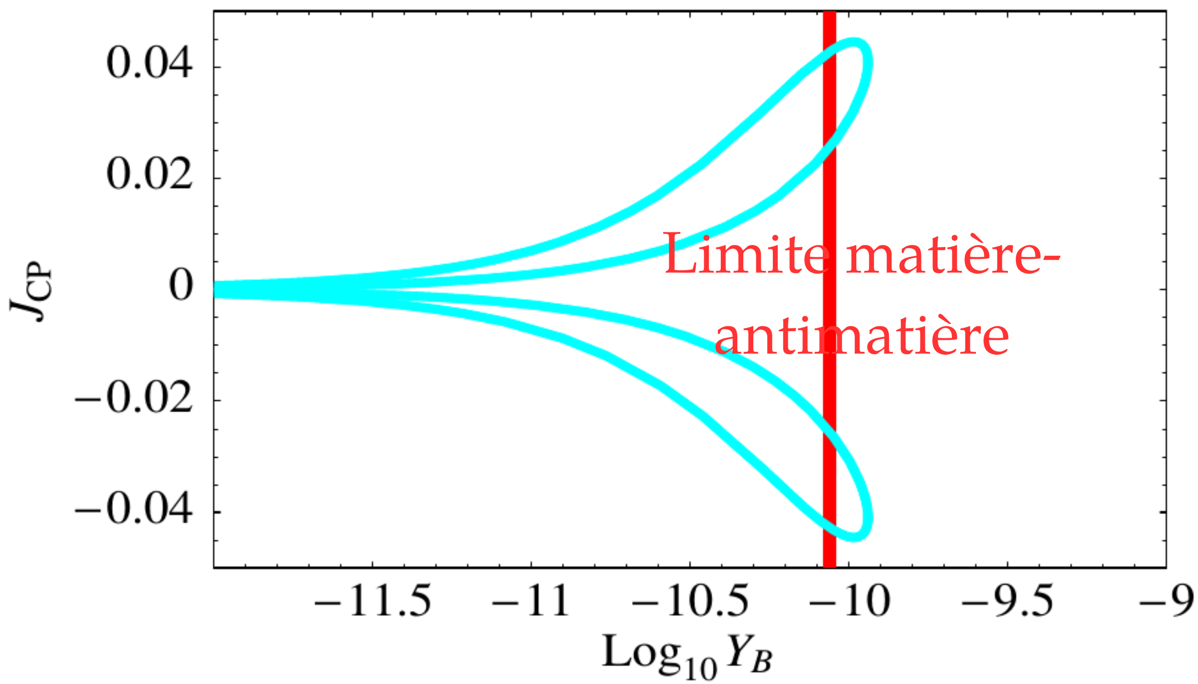
2. Que fait on après la découverte de la CPV > 2030 ?

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

Violation CP des neutrinos de basse E → Leptogénèse → Asymétrie matière et l'antimatière

$$\Delta P = P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e) \propto J_{CP}$$

$$|Y_B| \cong 2.8 \times 10^{-13} \, |\sin \delta| \left(\frac{s_{13}}{0.2}\right) \left(\frac{M_1}{10^9 \text{ GeV}}\right)$$



Précision sur $\sin \delta_{CP}$

↔ Précision de la sonde des modèles de leptogénèse

Limite basse leptogénèse :

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

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

L'asymétrie matière / antimatière

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

a. On mesure avec précision la CPV i.e. sin δ_{CP}.

Violation CP des neutrinos de basse E → Leptogénèse → Asymétrie matière et l'antimatière

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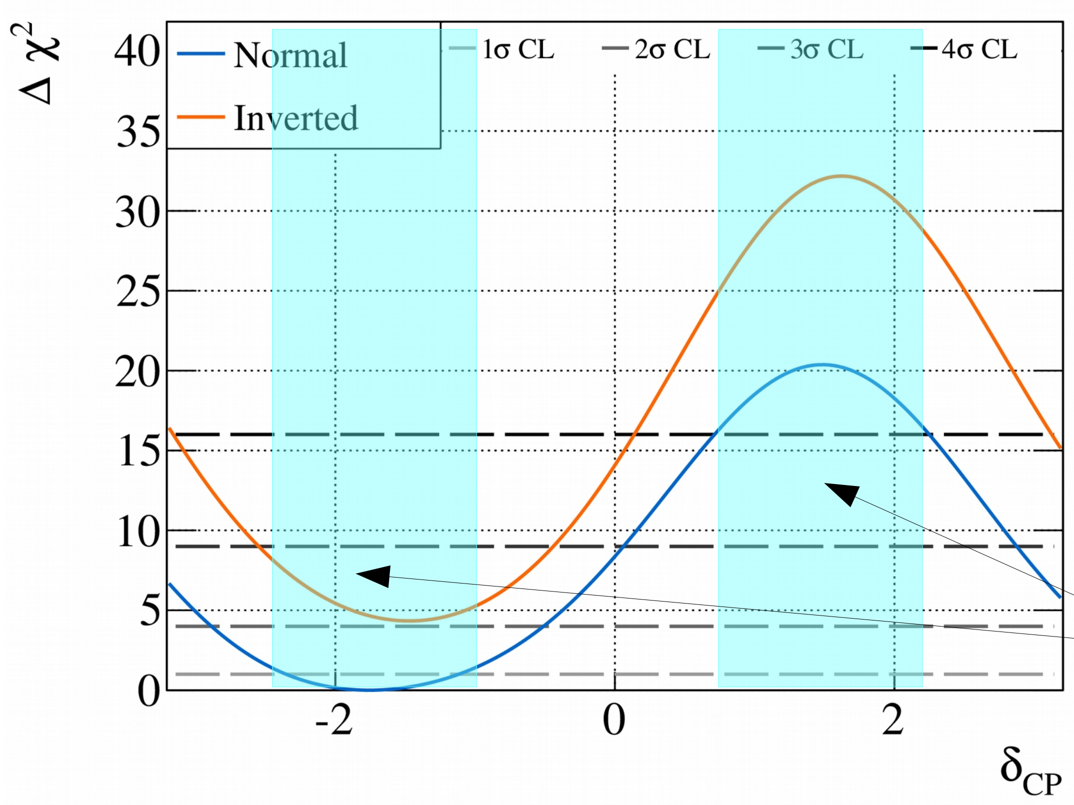


Précision sur sin δ_{CP}

↔ Précision du sondage des modèles de leptogénèse

Limite basse leptogénèse :

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

→ $|\sin\delta| \geq 0.78$

Symétrie de saveurs

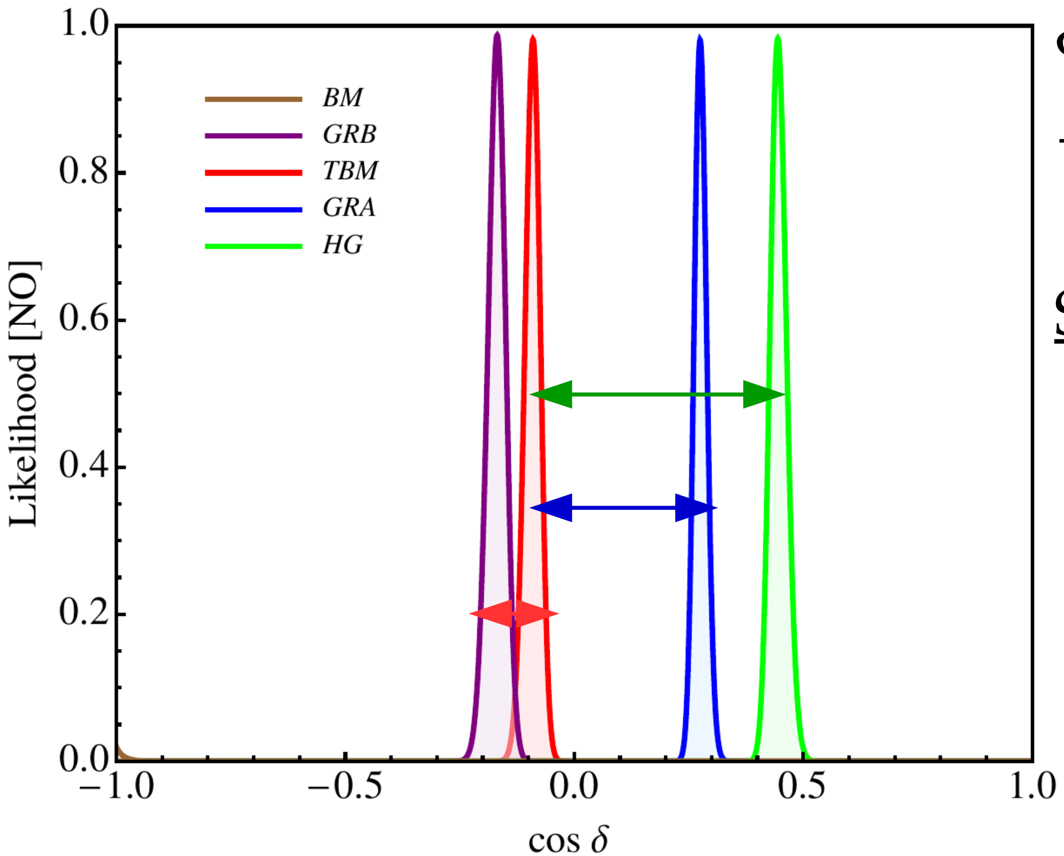
2. Que fait on après la découverte de la CPV > 2030 ?

a. On mesure avec précision la CPV i.e. sin δ_{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 :

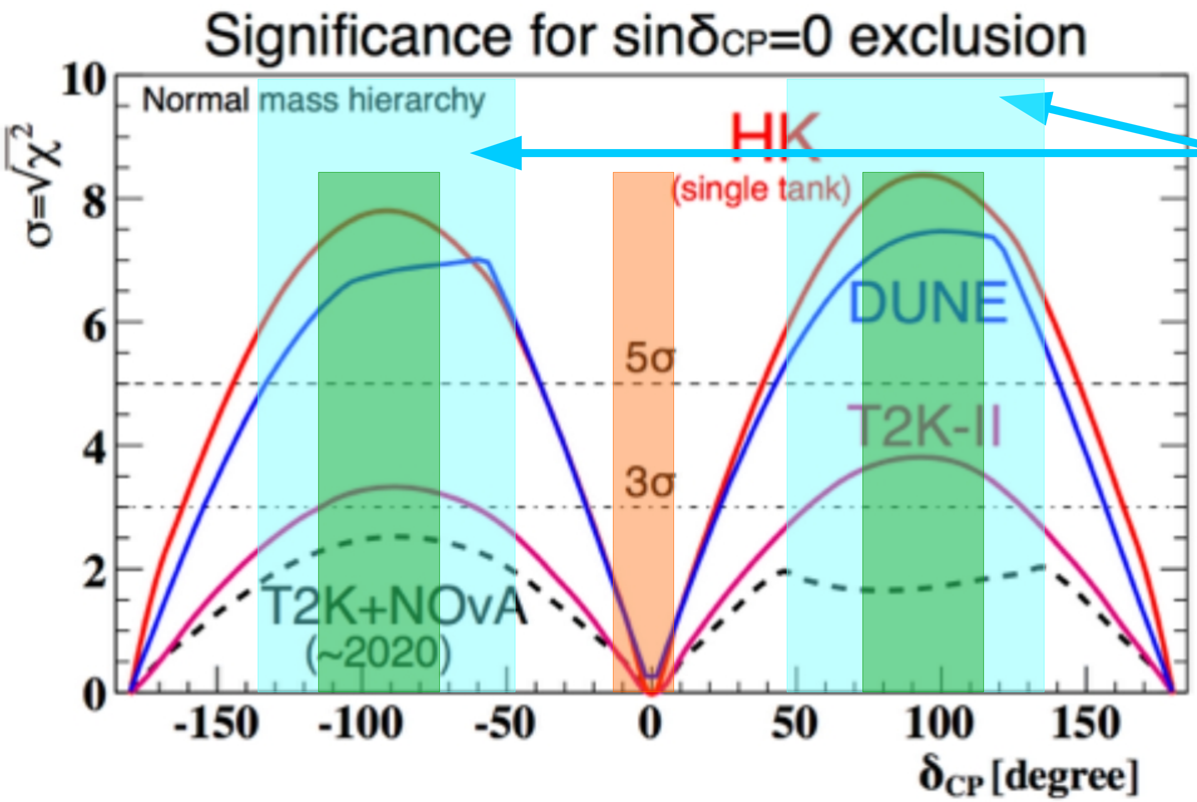
Début de séparation : δ [δ_{CP}] < 30°

Bonne Séparation : δ [δ_{CP}] < 23°

Excellente séparation : δ [δ_{CP}] < 5°

→ Précision HK et DUNE ?

Scénarios de leptogénèse



Limite basse leptogénèse :

| sin δ | ≥ 0.78

Précision HK/DUNE

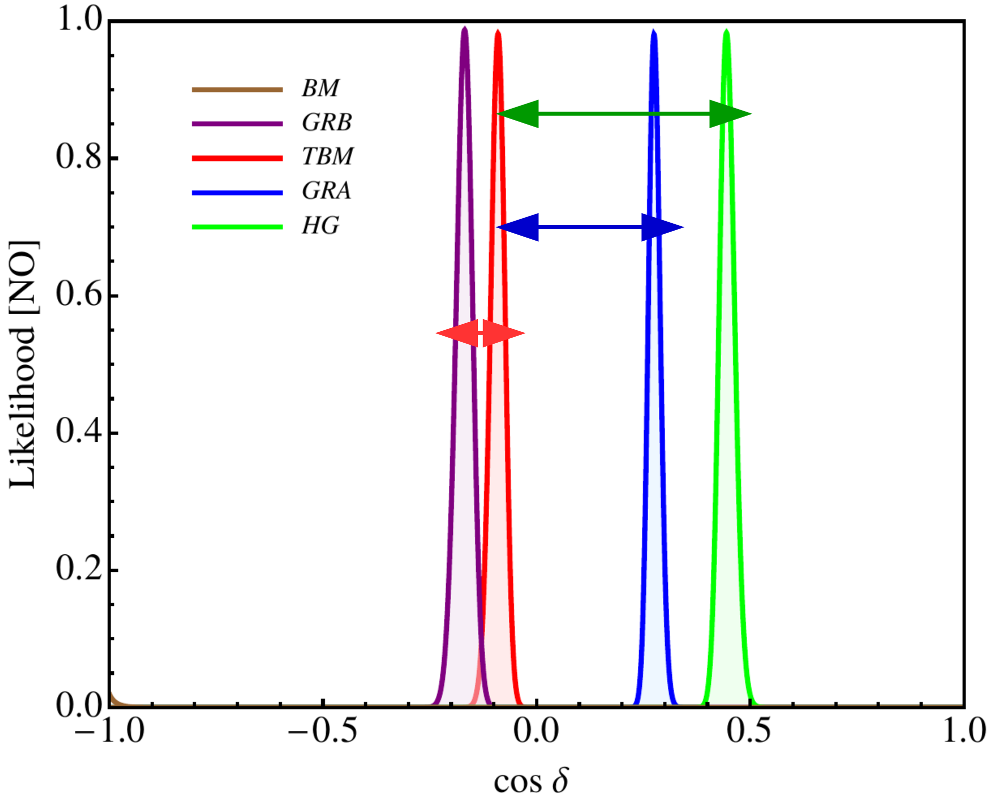
→ Si $\delta_{CP} = 0$

→ 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° → 6°	10° → 8°
$\delta_{CP} = -\pi/2$	22° → 20°	26° → 19°

Scénarios de symétries de saveurs



Séparation des modèles requiert :

Début de séparation : $\delta\,[\delta_{CP}] < 30°$

Bonne Séparation : $\delta\,[\delta_{CP}] < 23°$

Excellente séparation : $\delta\,[\delta_{CP}] < 5°$

- Précisions finales de HK et DUNE seront similaires → Bonnes

- Il n'y aura peut etre pas de génération suivant HK et DUNE :

→ On aura alors deux mesures avec des systématiques complètement ≠

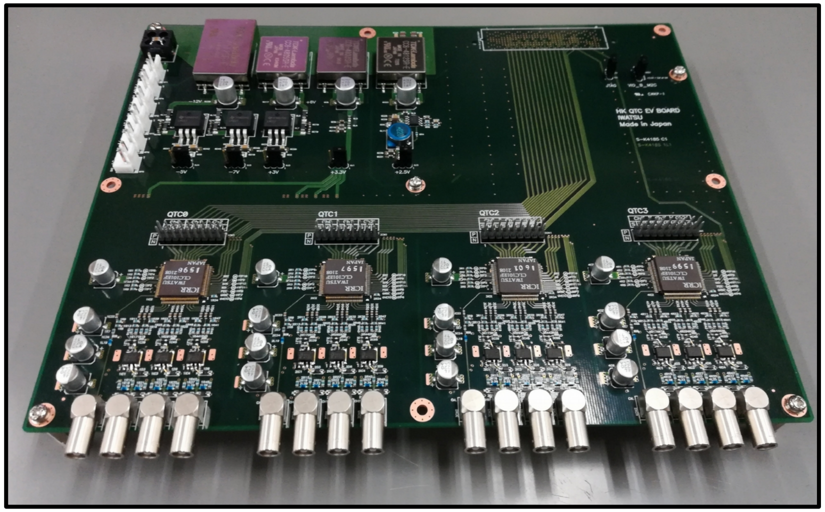
→ Idéal pour un ajustement commun !

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

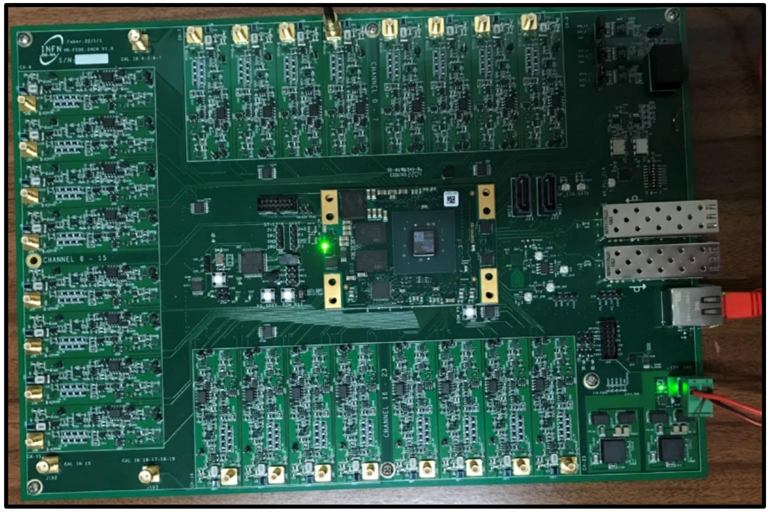
The Hyper-K candidate digitizers

- 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.

HKROC digitizer - Impact on physics

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

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**	

- <u>En resume :</u>

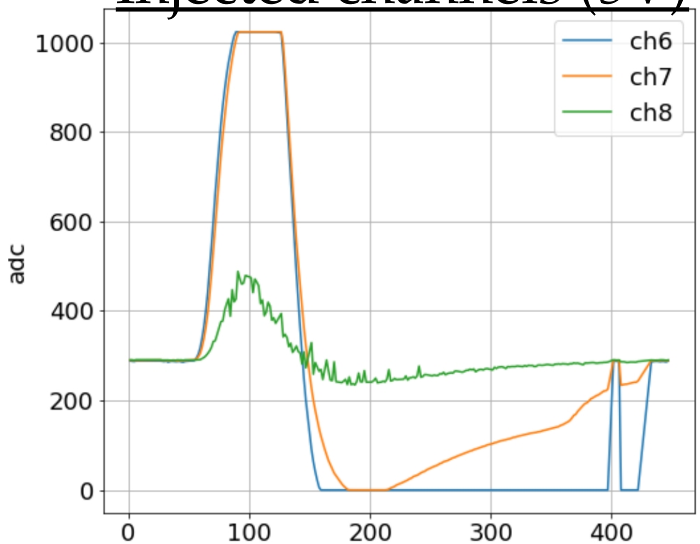
1. Les 3 solutions ont ete retenue comme parfaitement viable pour HK.
2. Le cross-talk de l'ASIC a impacte les « basic requirements & schedule. »
3. L'equipe HKROC a su demontre ses larges avantages sur la physique.
4. Le management a clairement <u>prefere une solution déjà finale moins ambitieuse a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

→ 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.

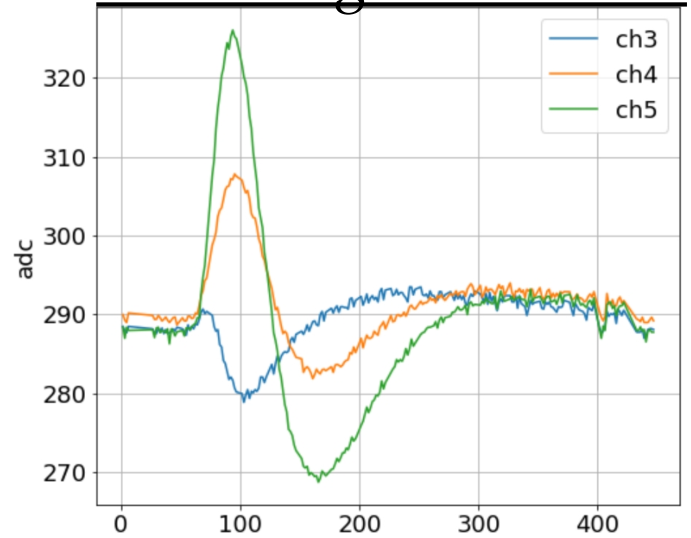
Cross-talk measurements

- <u>Full cross-talk measurements :</u>

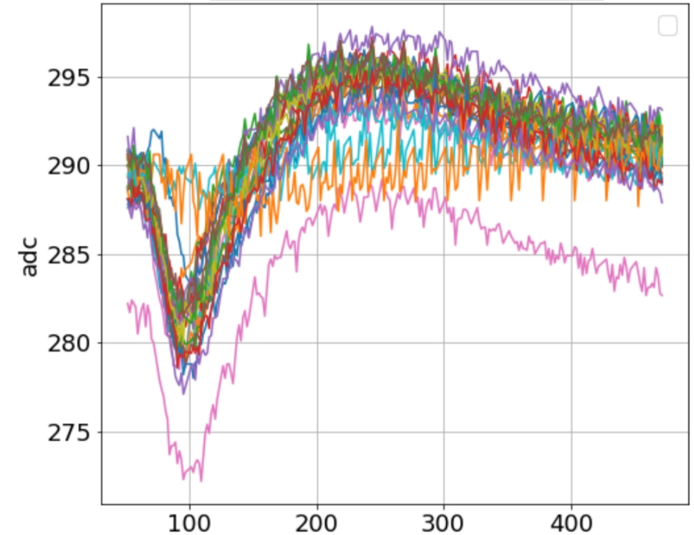
<u>Injected channels (5V)</u>



<u>Close neighbour chans</u>



<u>All other chans</u>



- <u>Found 2 sources of cross-talk :</u>

<u>1. Close : Only on 2 neighbour (as a function of distance</u>

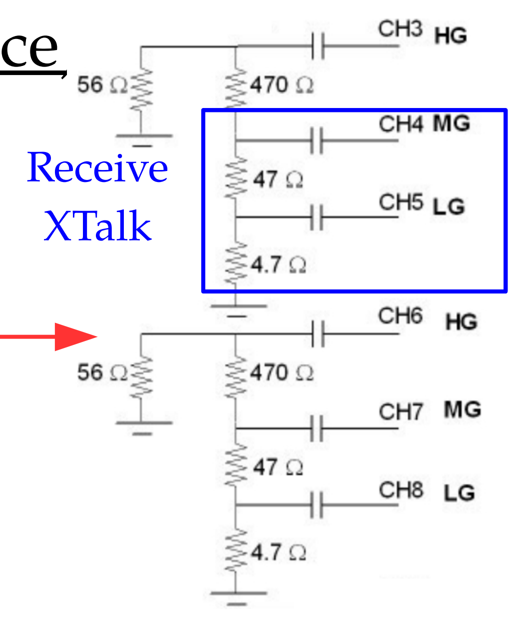
→ Receive ~ 100 p.e on LG, 5 p.e on MG, 0 on HG.

<u>2. Diffuse cross-talk :</u>

→ Receive 1/5 p.e on all channels : close to detection threshold.

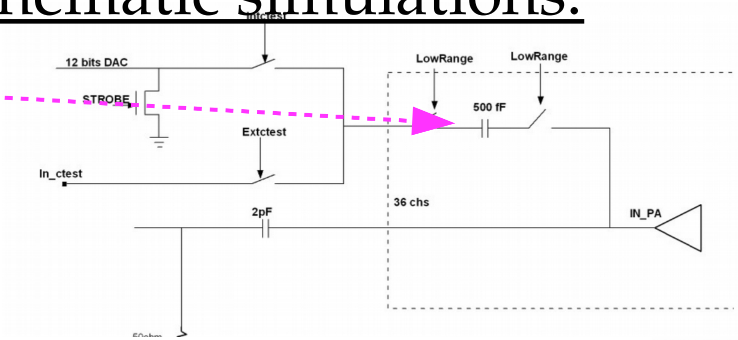
→ Smaller but much more worrysome for physics.

Injection

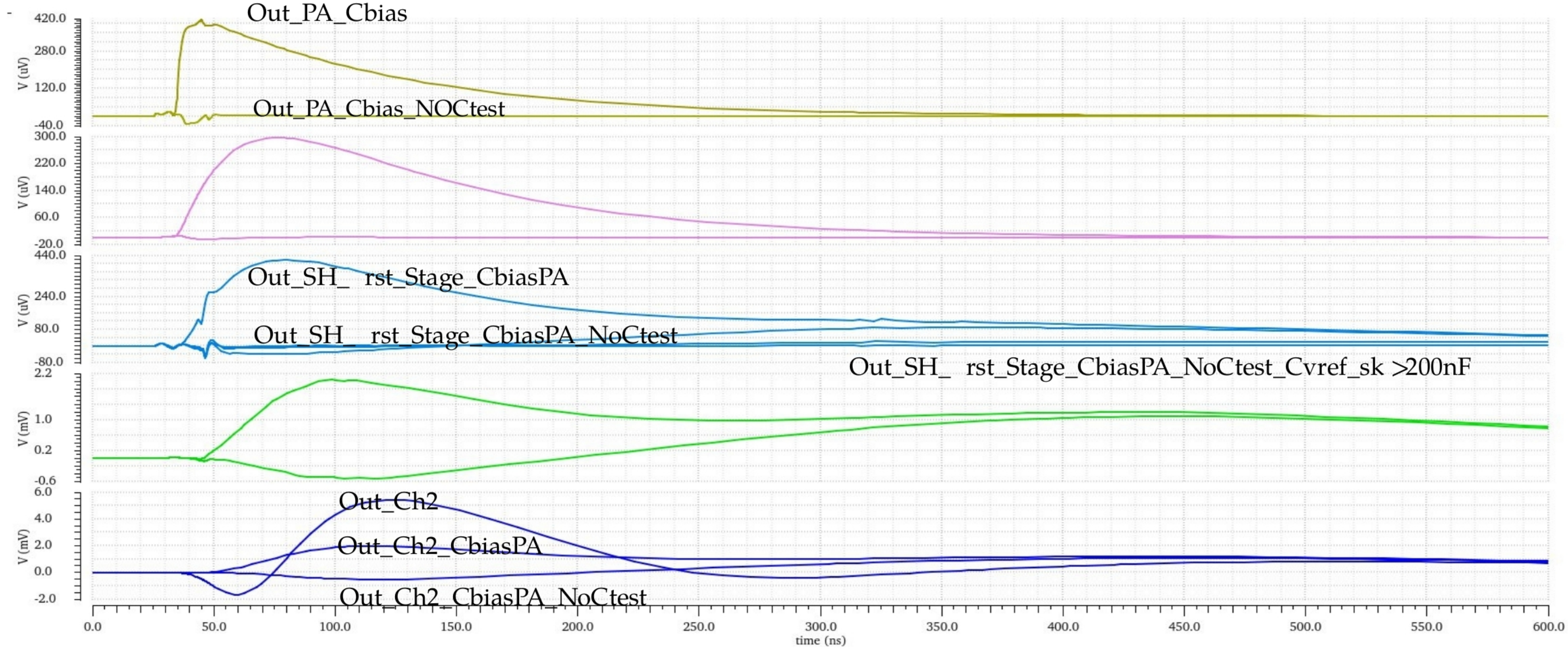


Source & fix of the diffuse cross-talk

- <u>The diffuse cross-talk has been observed in schematic simulations.</u>
  → Comes from PA bias voltage, and CTest.



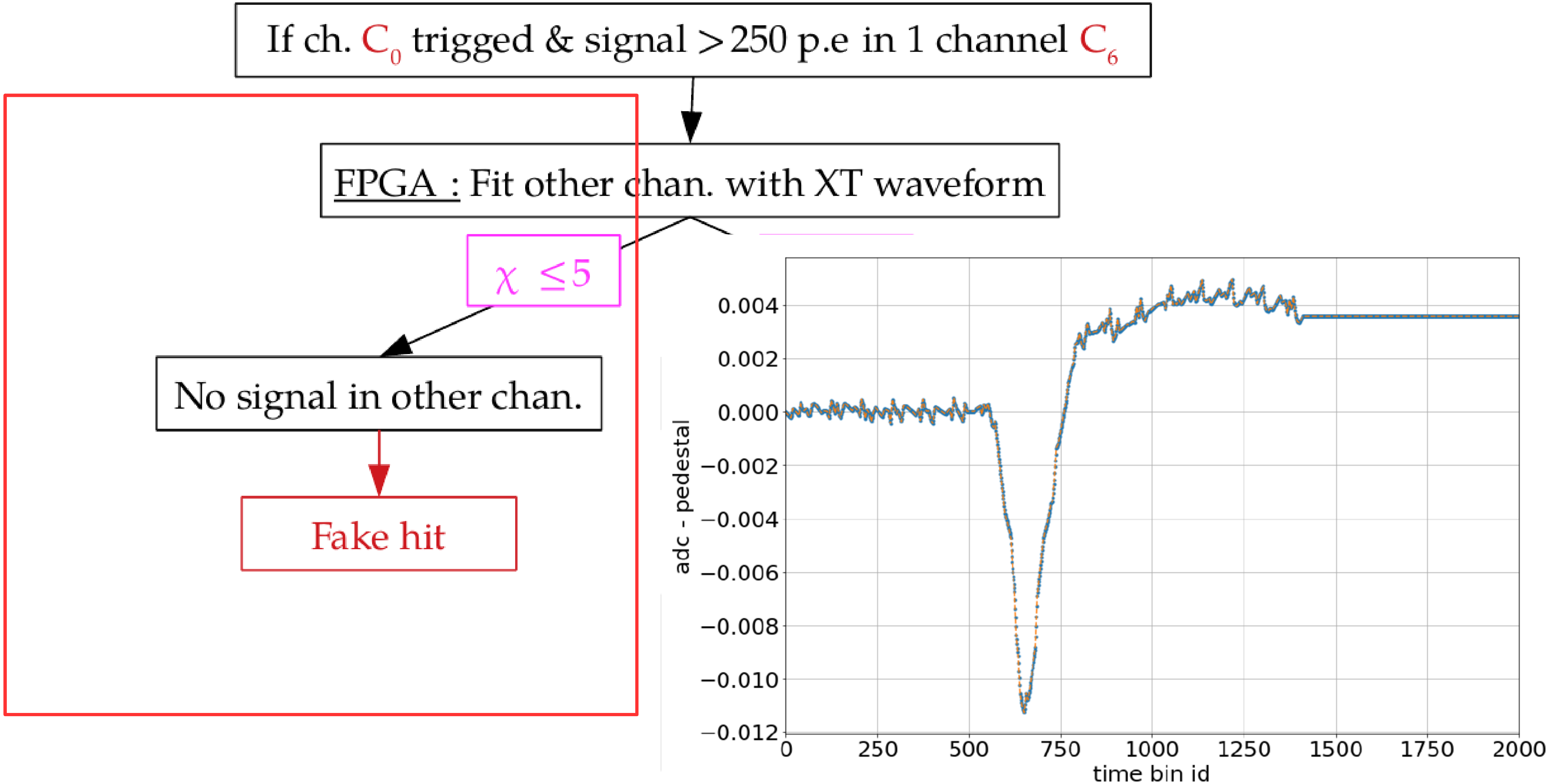
- <u>Added decoupling C=100 nF to PA bias V :</u>



- The cross-talk is completely identified & removed at all level (PA → Trigger and shaper → Charge) : implemented in HKROC v2 (Dec.).

Fake signals and diffuse cross-talk

- <u>Step 2 : during data-taking :</u>



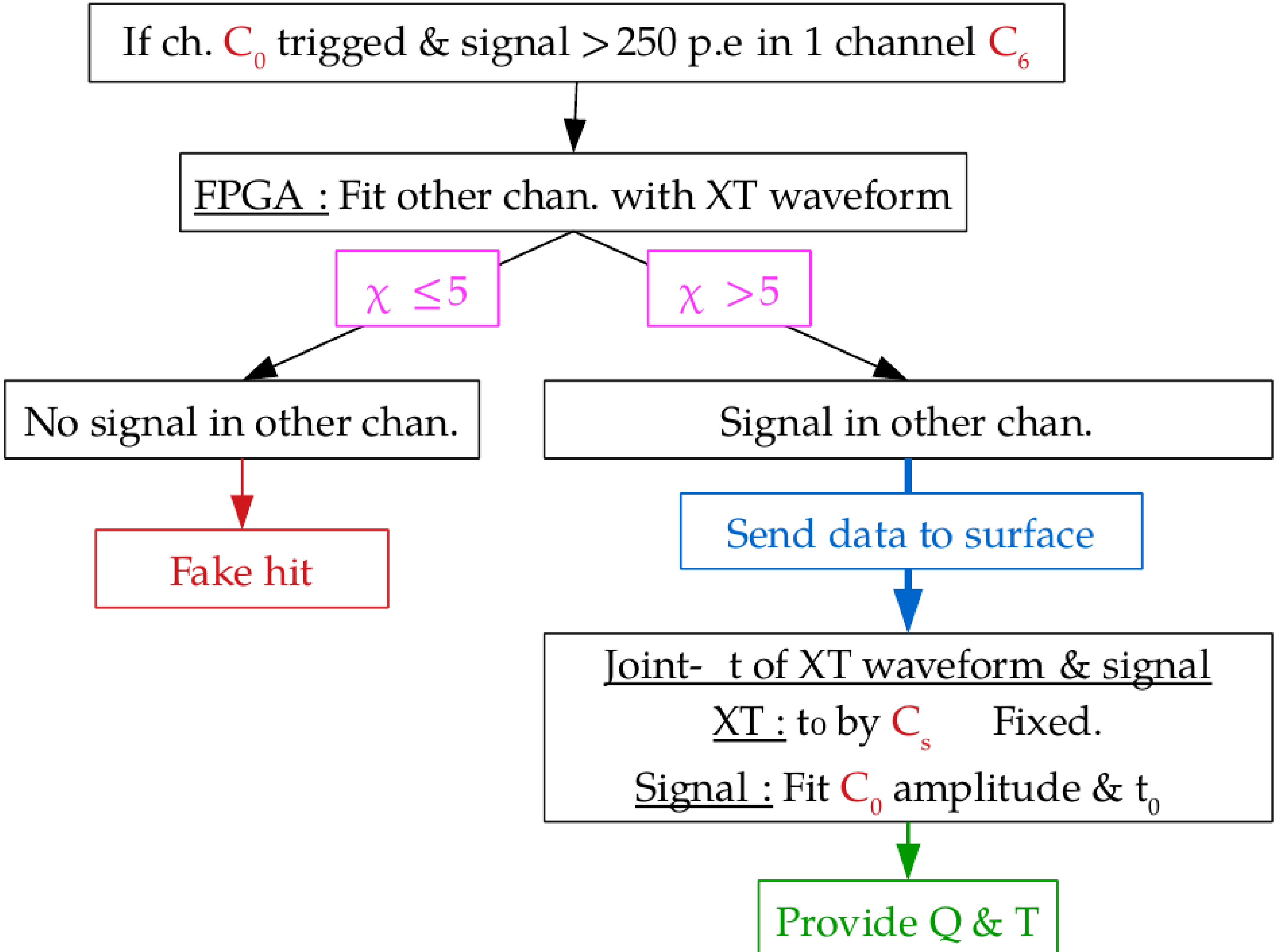
→ All cross-talk hits were removed by this cut in our measurements.

Conclusions : close and diffuse cross-talk do not create any fake hit !

→ Satisfies requirements in HK table, but not enough !

Simulatenous event & diffuse cross-talk

- Solution : Relies on the same method used to reject fake hits :



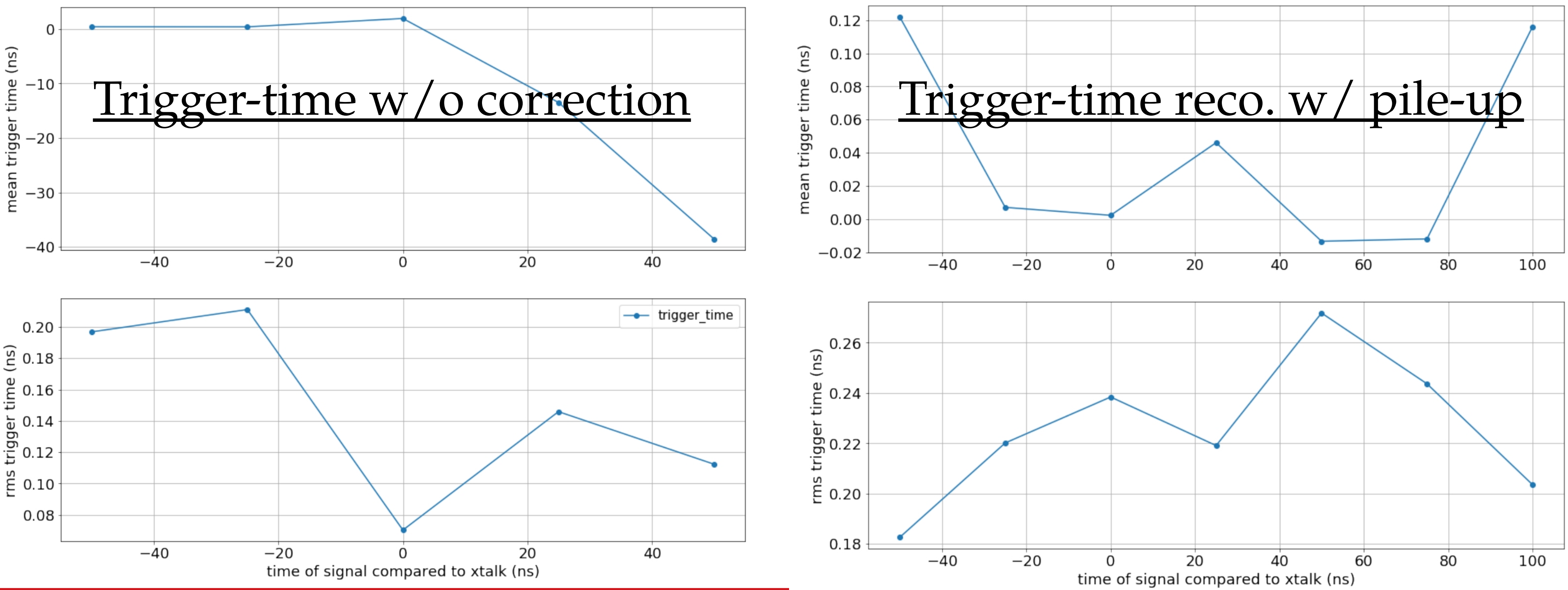
→ Try to reconstruct the 1 p.e event trigger time using the pile-up reconstruction : could in theory correct the baseline shift. In reality ?

Simulatenous event & diffuse cross-talk

- <u>To be complete :</u> 1 and 850 p.e event trigger time ≠ was varied :

$\Delta t = t_{1pe} - t_{850pe}$	-50 ns	-25 ns	0 ns	25 ns	50 ns	75 ns	100 ns

- <u>Results on the trigger time reconstructed :</u>

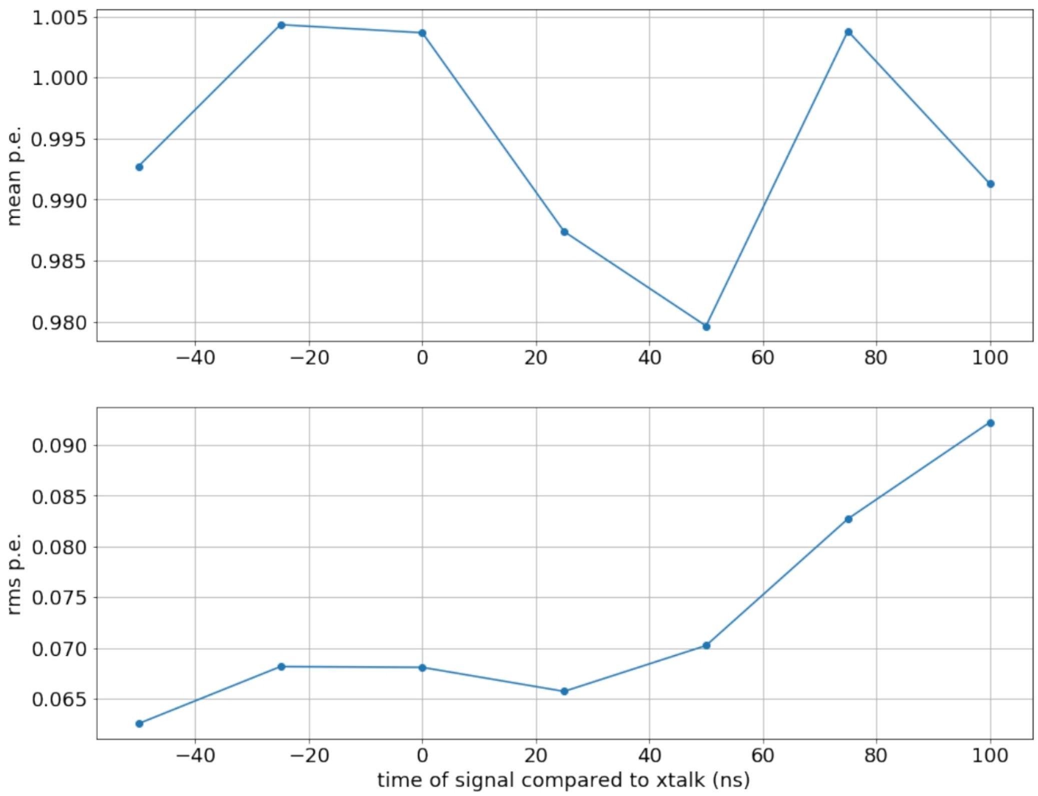


1. Clear shift of 1 p.e trigger time (up to 40 ns) if XT happens before.
2. Completely corrected through the pile-up reconstruction.

→ RMS ≤ 260 ps : of course worse than HKROC nominal capabilities (150

Simulatenous event & diffuse cross-talk

- Charge reconstruction done simulatenously with trigger time :



- Average charge reco. ≤ 1 % !
  → Except for 2 points, which are simply due to few outliers that we are checking now : issue of our very raw/new algorithm
  → Solved tomorrow.

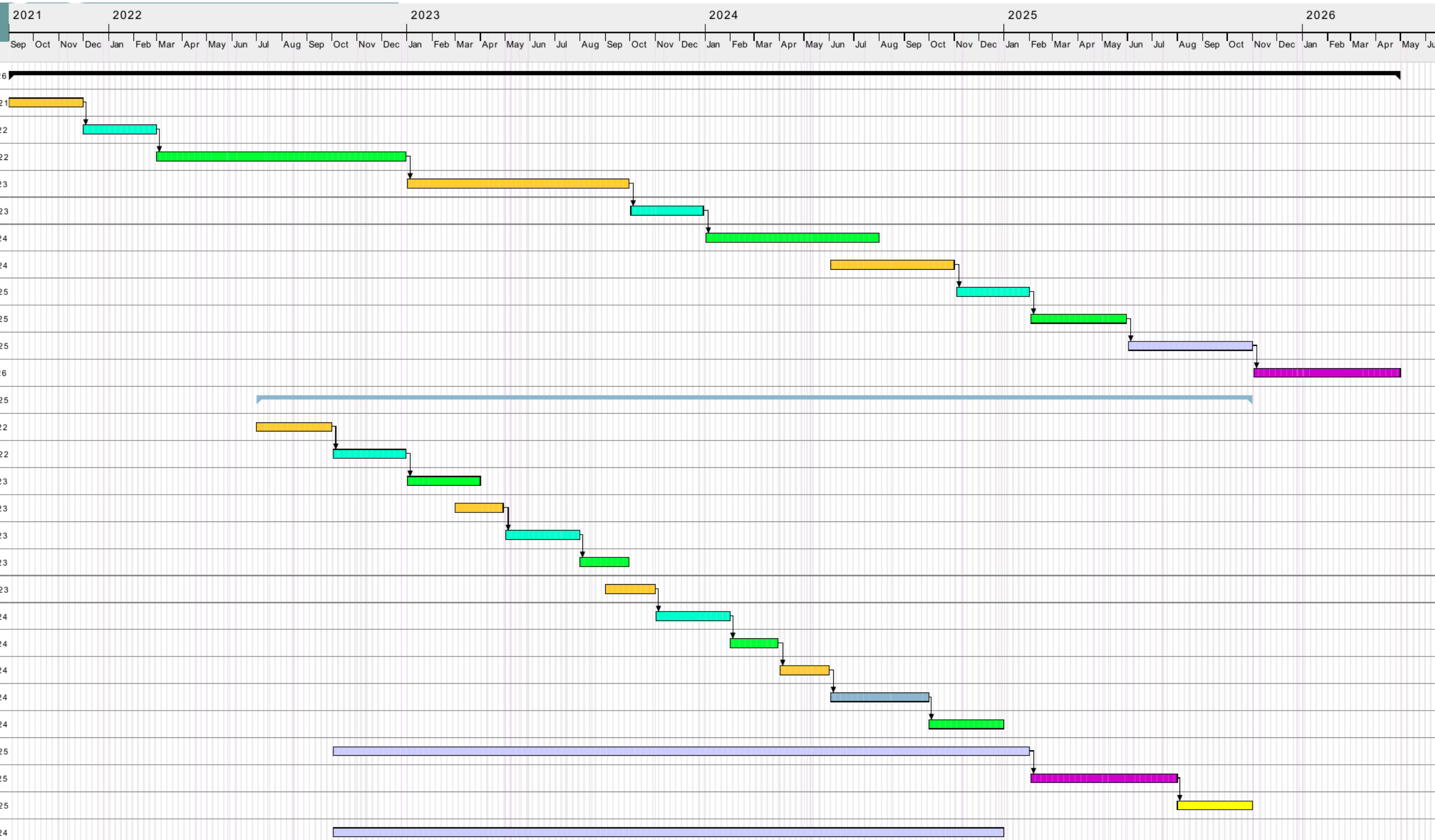
- Charge reconstructed RMS < 0.1 p.e !

- The method developed here is far from optimal :

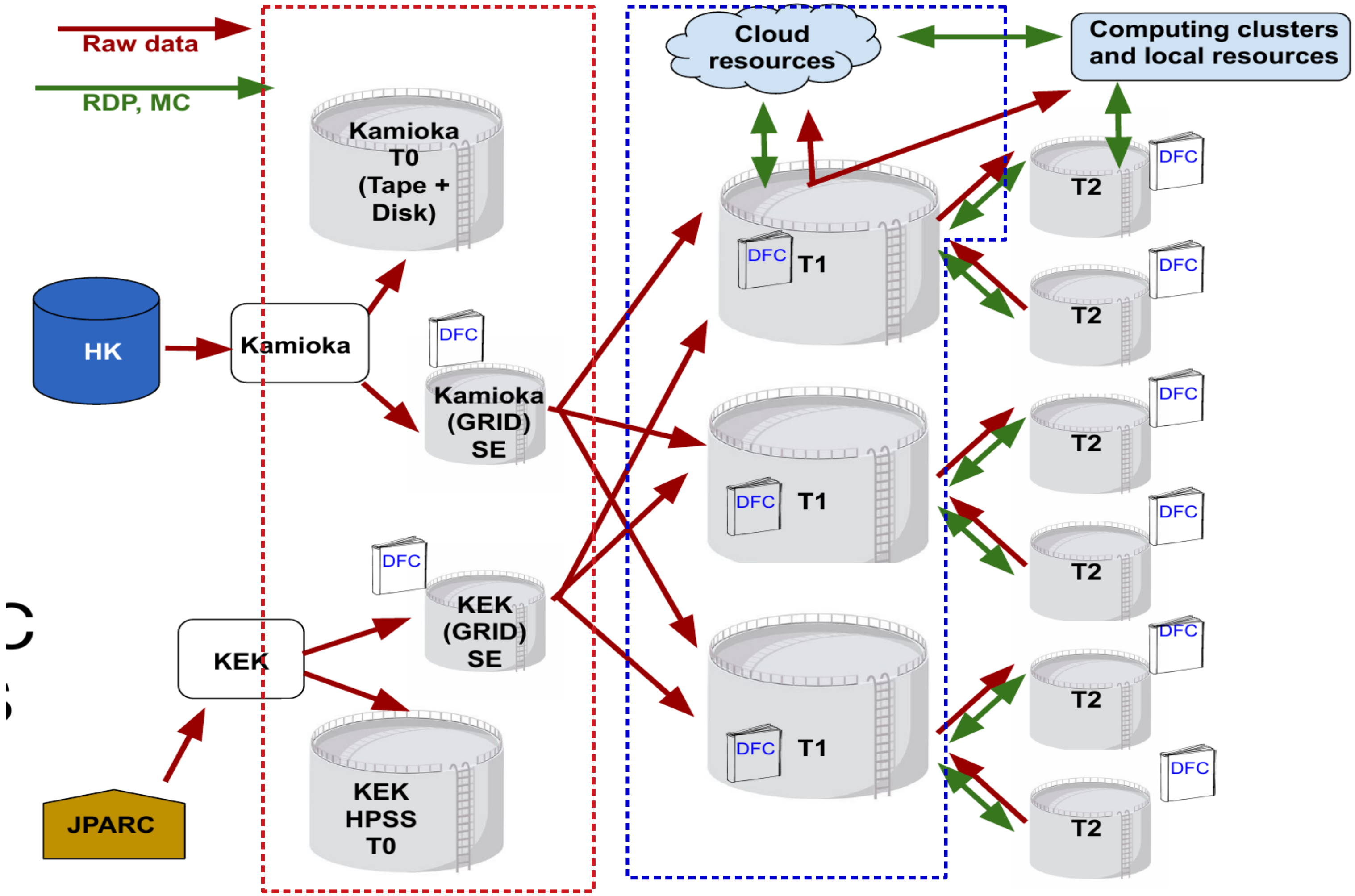
→ But have shown there is a close to negligible impact on the trigger rate, time and charge reconstruction of a 1 p.e peak.

Timing system schedule

Name	Begin date	End date
1st Stage Clock Distributor	9/1/21	4/30/26
48-port clock distributor prototype - design	9/1/21	11/30/21
48-port clock distributor prototype - production	12/1/21	2/28/22
48-port clock distributor prototype - test	3/1/22	12/30/22
1st Stage Clock Distributor prototype - design	1/2/23	9/29/23
1st Stage Clock Distributor prototype - production	10/2/23	12/29/23
1st Stage Clock Distributor prototype - test	1/2/24	7/31/24
1st Stage Clock Distributor final - design	6/3/24	10/31/24
1st Stage Clock Distributor final - production	11/4/24	1/31/25
1st Stage Clock Distributor final - test	2/3/25	5/30/25
Contracting & component procurement	6/2/25	10/31/25
Production (6 units min.)	11/3/25	4/30/26
2nd Stage Clock Distributor	7/1/22	10/31/25
2nd Stage Clock Distributor Prototype #1 design	7/1/22	9/30/22
2nd Stage Clock Distributor Prot...	10/3/22	12/30/22
2nd Stage Clock Distributor Prototype #1 test	1/2/23	3/31/23
2nd Stage Clock Distributor Prot...	3/1/23	4/28/23
2nd Stage Clock Distributor Prot...	5/2/23	7/31/23
2nd Stage Clock Distributor Prot...	8/1/23	9/29/23
2nd Stage Clock Distributor Final Prototype design	9/1/23	10/31/23
2nd Stage Clock Distributor Fina...	11/2/23	1/31/24
2nd Stage Clock Distributor Final Protype test	2/1/24	3/29/24
2nd Stage Clock Distributor design finalization	4/2/24	5/31/24
2nd Stage Clock Distributor Pre-production	6/3/24	9/30/24
2nd Stage Clock Distributor pre-...	10/1/24	12/31/24
2nd Stage Clock Distributor Contract & Procurment	10/3/22	1/31/25
2nd Stage Clock Distributor Mass...	2/3/25	7/31/25
2nd Stage Clock Distributor Mass...	8/1/25	10/31/25
Time Distribution Endpoint procurment	10/3/22	12/31/24



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 .

Systematics : from T2K to Hyper-K

- Need to reduce uncertainties from 5% (T2K) to 3% (HK)

	1-Ring μ		1-Ring e			
Error source	FHC	RHC	FHC	RHC	FHC 1 d.e.	FHC/RHC
SK Detector	2.40	2.01	2.83	3.79	13.16	1.47
SK FSI+SI+PN	2.20	1.98	3.02	2.31	11.44	1.58
Flux + Xsec constrained	2.88	2.68	3.02	2.86	3.82	2.31
E_b	2.43	1.73	7.26	3.66	3.01	3.74
$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	0.00	0.00	2.63	1.46	2.62	3.03
NC1γ	0.00	0.00	1.07	2.58	0.33	1.49
NC Other	0.25	0.25	0.14	0.33	0.99	0.18
Osc	0.03	0.03	3.86	3.60	3.77	0.79
All Systematics	4.91	4.28	8.81	7.03	18.32	5.87
All with osc	4.91	4.28	9.60	7.87	18.65	5.93

- SK detector & FSI/SI/PN : can be reduced using same near/far detector

- Uncertainty on extrapolation of ND280 constraints to SK :
  → Can be reduced using same flux, target, acceptance between near/far.

- $(\nu_e / \nu_\mu) / (\bar{\nu}_e / \bar{\nu}_\mu)$ is crucial for δ_{CP} measurement
  → Detector capable of high ν_e - ν_μ CC, ν_μ NC, γ separation.

Why extrapolation is not straightforward

- Having same near & far detector should suppress all uncertainties ?

$$N_{ND} \sim \Phi_{ND} \cdot \sigma_{ND} \cdot \epsilon_{ND}$$

Goal :

Same fluxes : $\Phi_{FD} \sim \Phi_{ND}$

Same cross-section corrections : $\sigma_{FD} \sim \sigma_{ND}$

Same detector responses : $\varepsilon_{FD} \sim \varepsilon_{ND}$

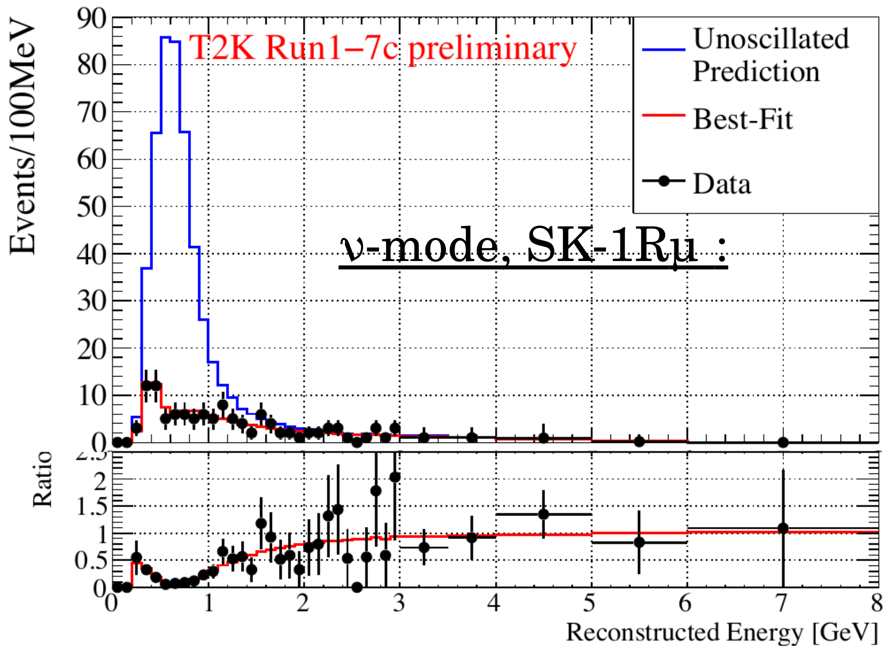
Observable	Flux	Cross section	Detector response	

$$N_{FD} \sim \Phi_{FD} \cdot \sigma_{FD} \cdot \epsilon_{FD} \cdot P_{Osc.}$$

Goal → Find $P_{osc}(E_\nu)$

1. Measure N_{FD}
2. Estimate Φ_{FD}, σ_{FD} & ε_{FD} with models

- **Fluxes are ≠ at near & far detectors :** solid angle + oscillation.



→ Cannot do simple N_{FD}/N_{ND} ratio to extract $P_{osc}(E_\nu)$: convoluted to cross-section & detector model uncertainties.

→ Needs for near detector :

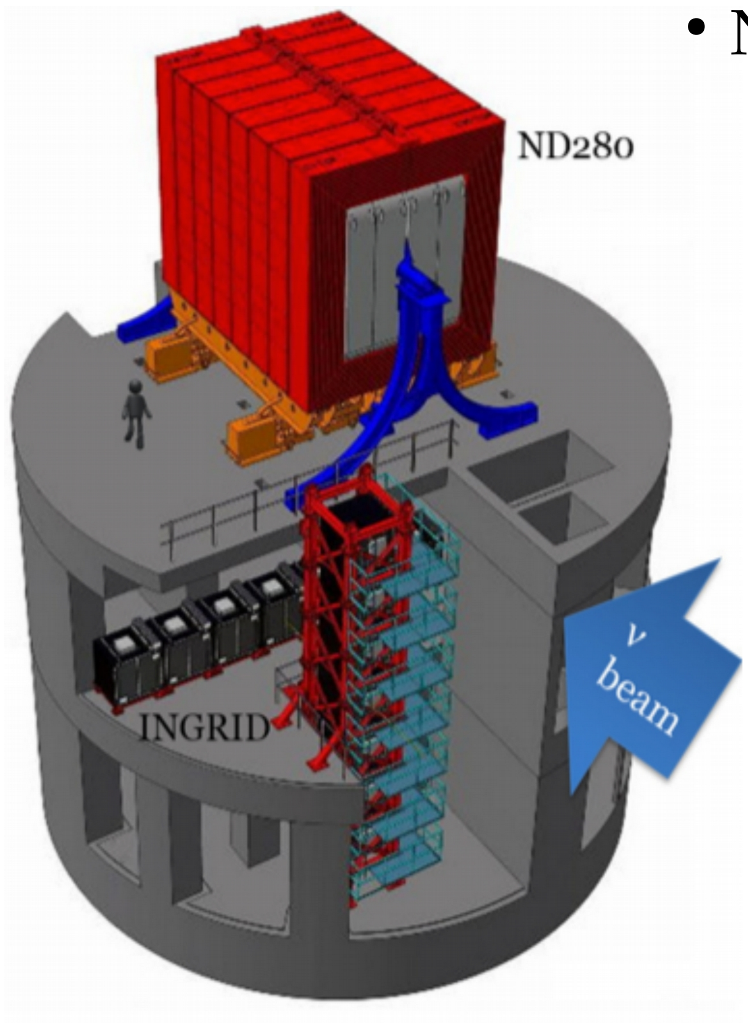
1. Perfect detector to measure cross-section

→ Low hadron threshold : ND280.

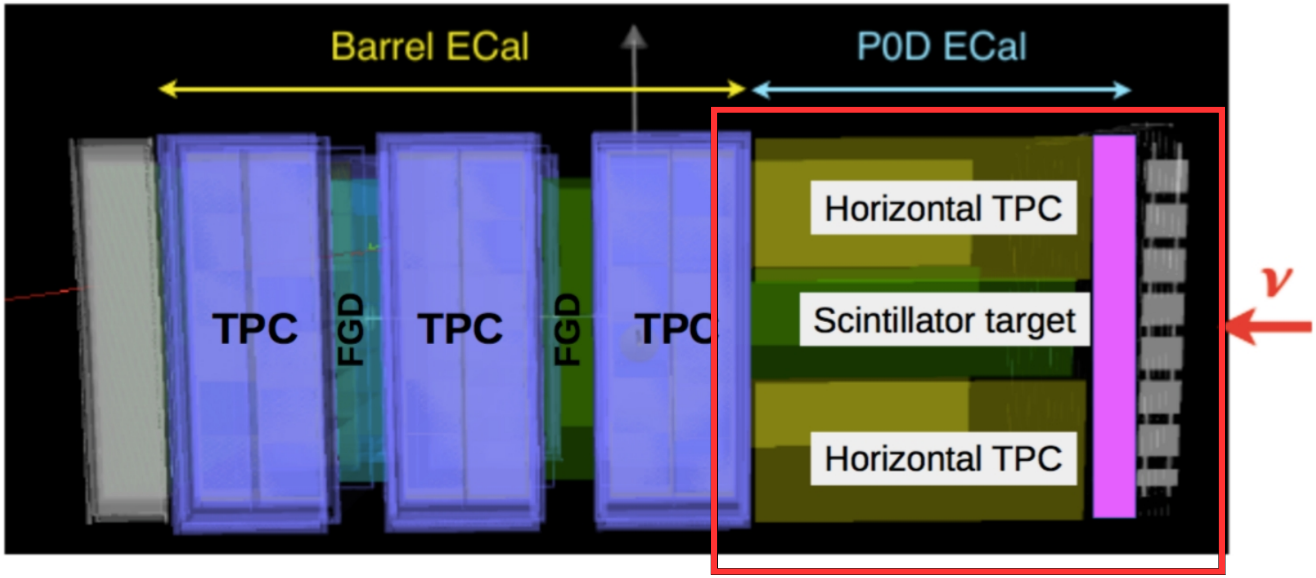
2. Detector w/ target & acceptance as close as possible to far detector : IWCD.

The rôle of ND280-upgrade & INGRID

- <u>Exising near detector complex @280m :</u> ND280 + INGRID



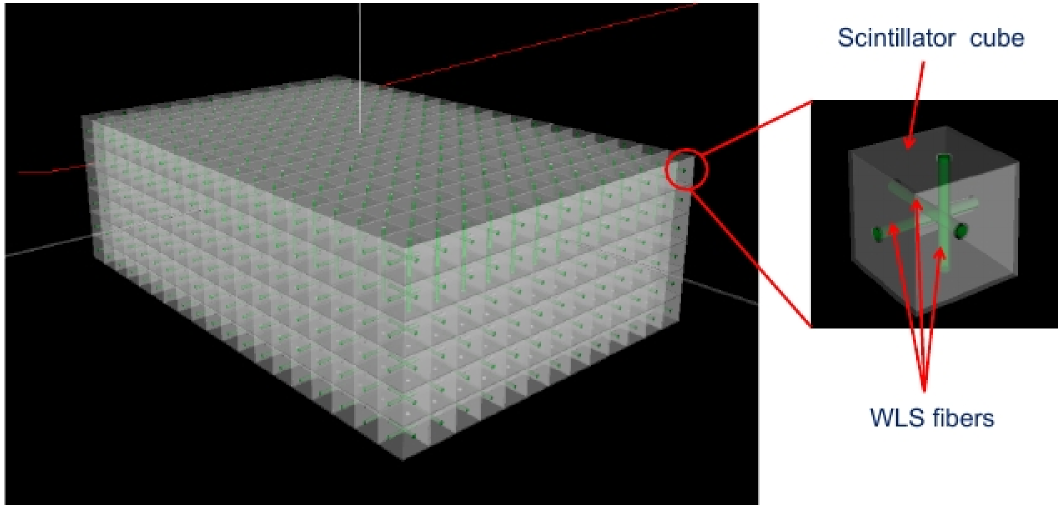
- ND280 is being upgraded now for T2K :



- New horizontal TPCs up / down
  → ~4π acceptance for μ as SK /HK
  => Constrain HK high angle regions with data

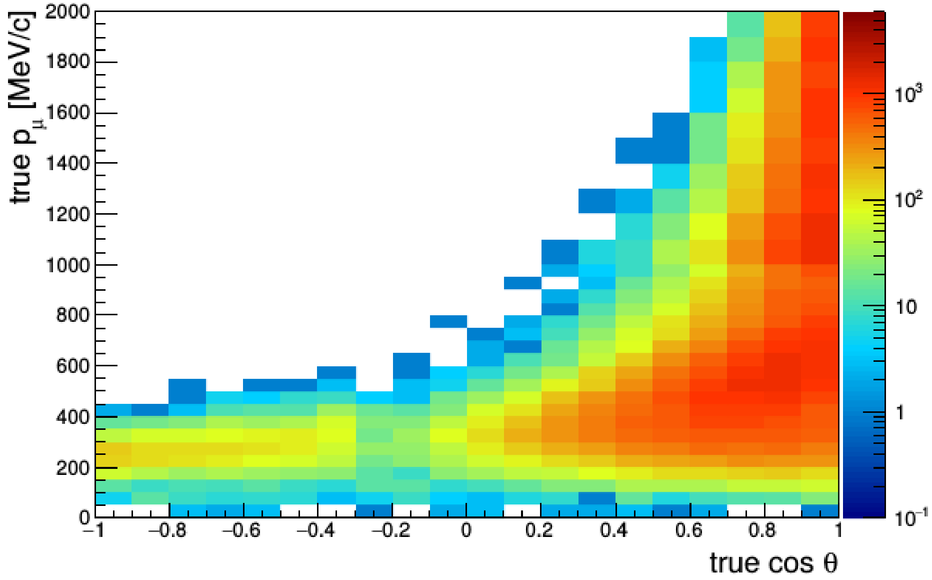
The role of ND280-upgrade & INGRID

Super-FGD tracker

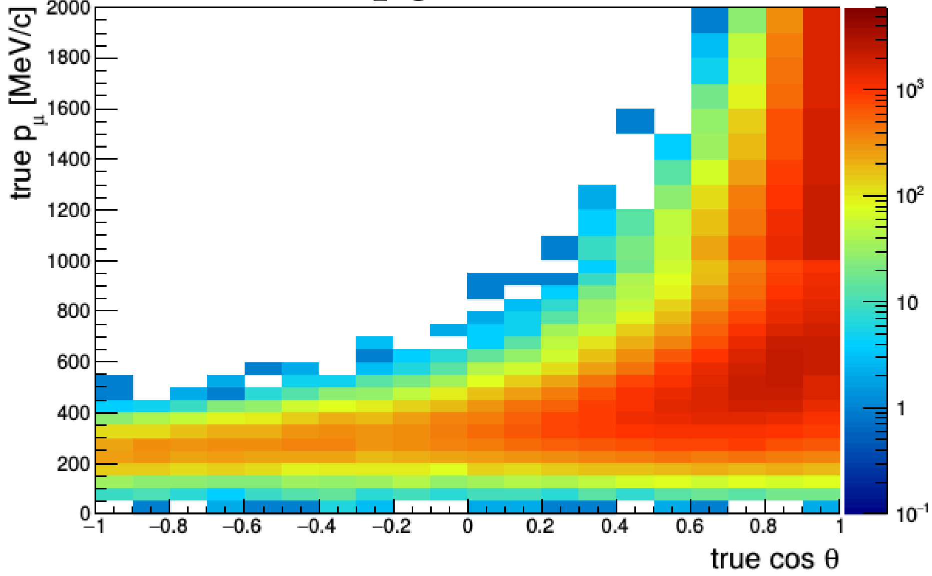


- 1 cm³ scintillating cubes.
- Readout in 3 directions
  → Improved tracking & E-resolution
- Allows a 4π acceptance for π, p & low energy μ.

Current ND280

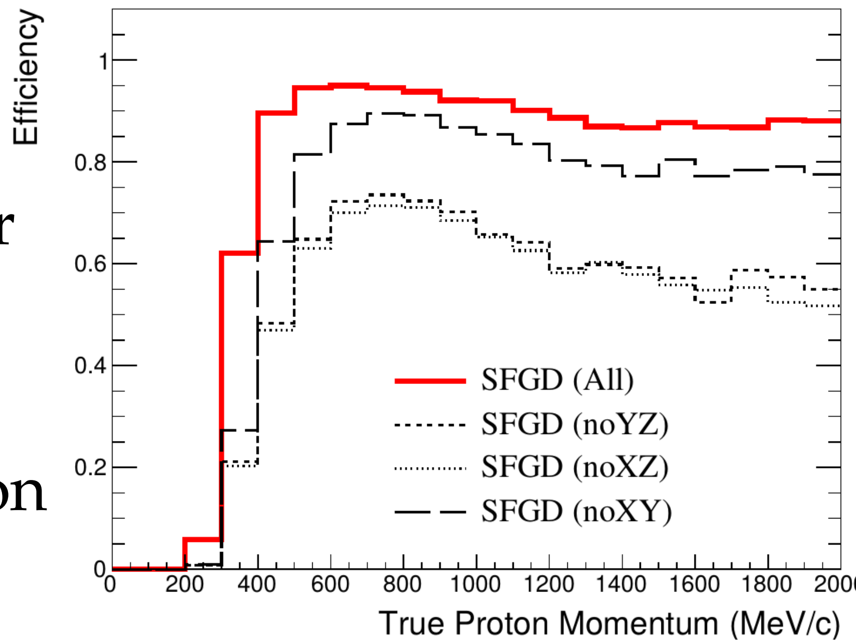


Upgrade

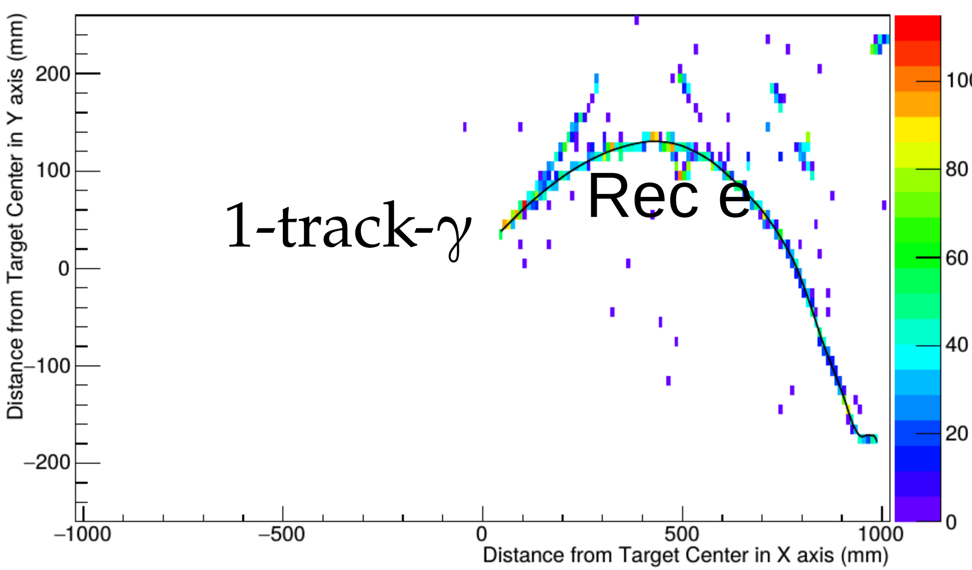


The role of ND280-upgrade & INGRID

- Current ND280 : p-threshold limited to 450 MeV/c
- Upgrade : Improved tracking => Lower hadron threshold.
  p-threshold : 450 → 300 MeV/c
  → Larger ability to identify cross-section models (CCQE, 2p-2h etc.)
  → Lower systematics in rate and E.



- Current ND280 : γ bkg limit ν_e measurements < 1 GeV.
- Upgrade : Improved E-resolution
  => e/1-track-γ separation possible
  → Constraints on $(\nu_e / \nu_\mu) / (\bar{\nu}_e / \bar{\nu}_\mu)$



The role of ND280-upgrade & INGRID

- Need to reduce uncertainties from 5% (T2K) to 3% (HK)

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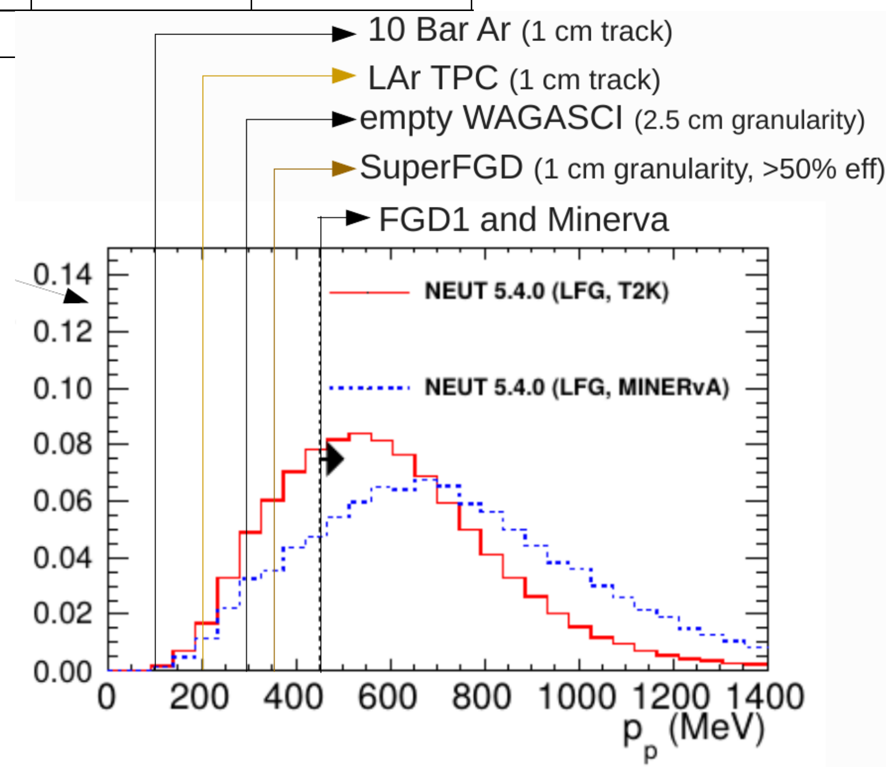
All Systematics	4.91	4.28	8.81	7.03	18.32	5.87
All with osc	4.91	4.28	9.60	7.87		

- Near and far detector are still different
- <u>XS model dependency that might be not represented in this table.</u>

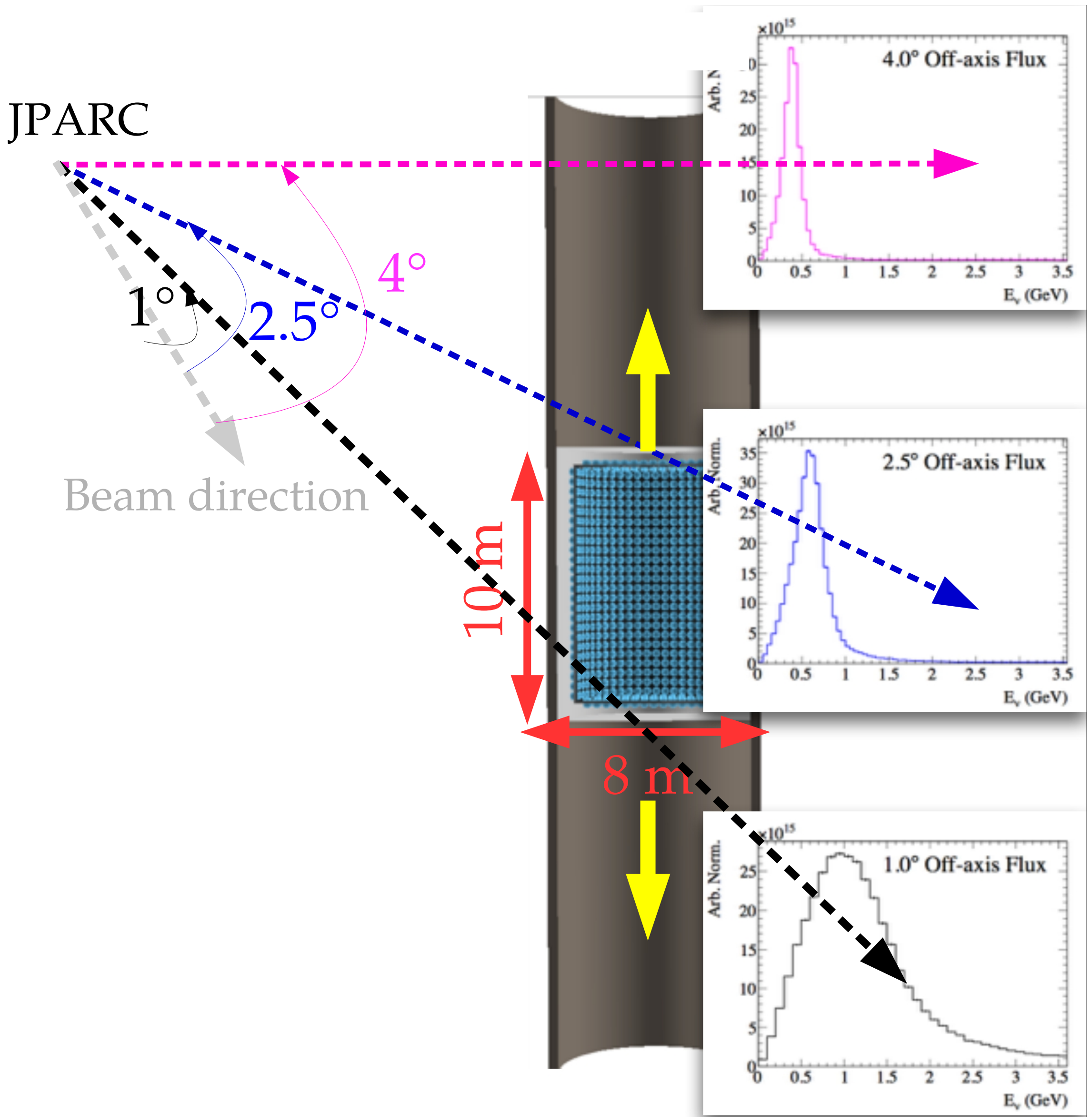
→ Q^2 dependency of the cross-section, 2p2h interactions, Final State Interactions etc.

→ Can we go beyond these limitations ?



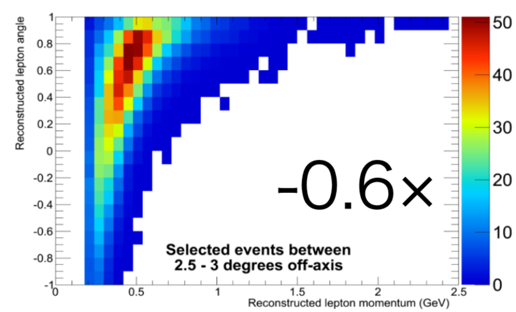
The IWCD

- New Intermediate Water Cherenkov detector (E61):

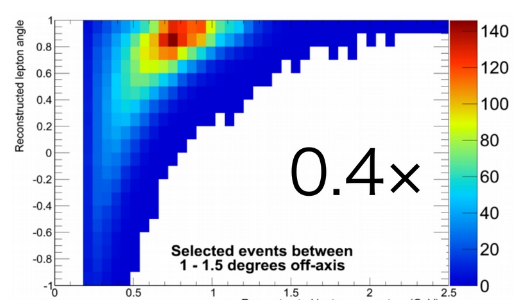


1. HK flux = linear combination of different off-axis angles.

2. Take same combination of reconstructed number of neutrinos (e.g. in p_μ/θ_μ)

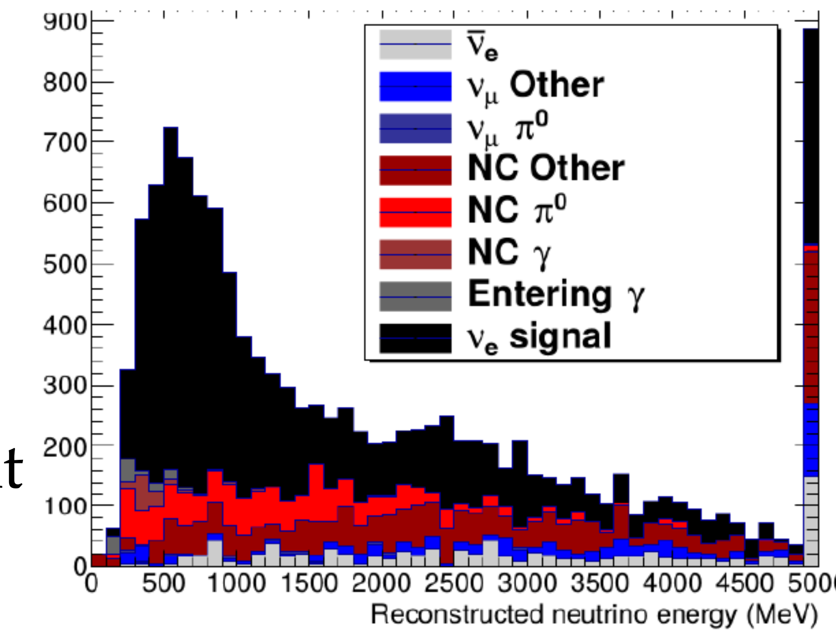


→ Drastically reduce use of cross-section models !



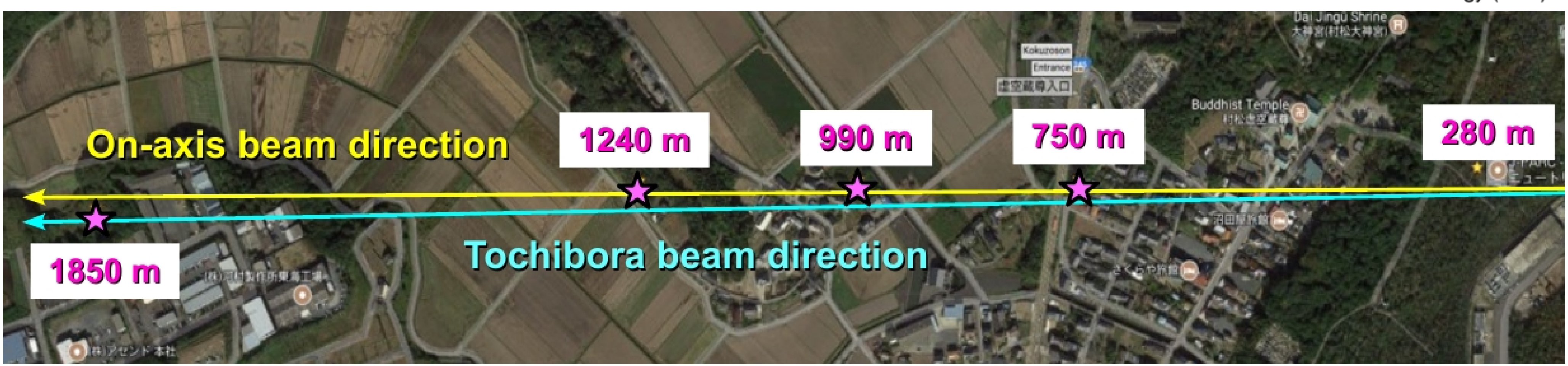
The IWCD

- Water Cherenkov : Excellent ν_e / ν_μ separation
  → Extremely precise measurement o f (ν_e / ν_μ) / ($\bar{\nu}_e$ / $\bar{\nu}_\mu$).



- Loaded with Gd for n-tagging
  → Enhanced $\nu/\bar{\nu}$ separation.
  → Measure n-multiplicy

- Sites under survey (balance between event rate / pile-up vs pit depth)



- ND280 + IWCD totally complementary to reach systematics ≤ 3 %.

The IWCD

- kskssk