Hyper-Kamiokande

# Status of Hyper-Kamiokande

Benjamin Quilain (LLR - CNRS/Ecole polytechnique)

on behalf of HK-France

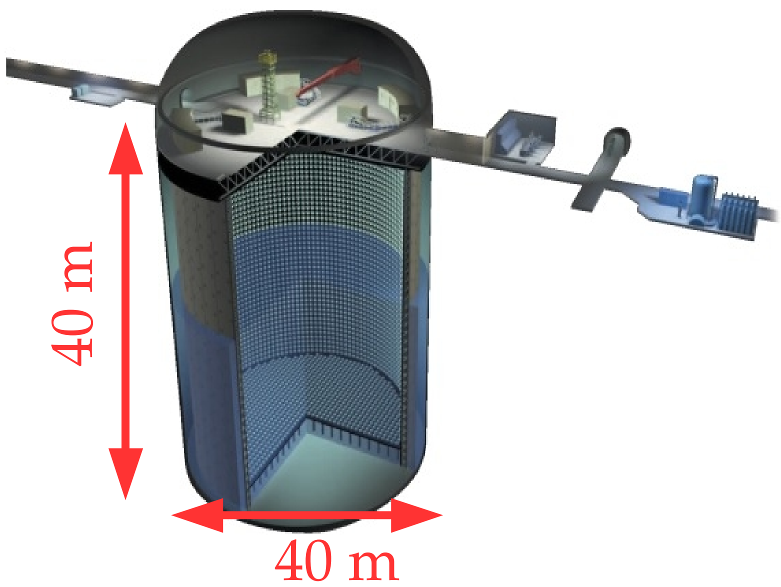
IRN neutrino, IJC lab, 2022/11/17

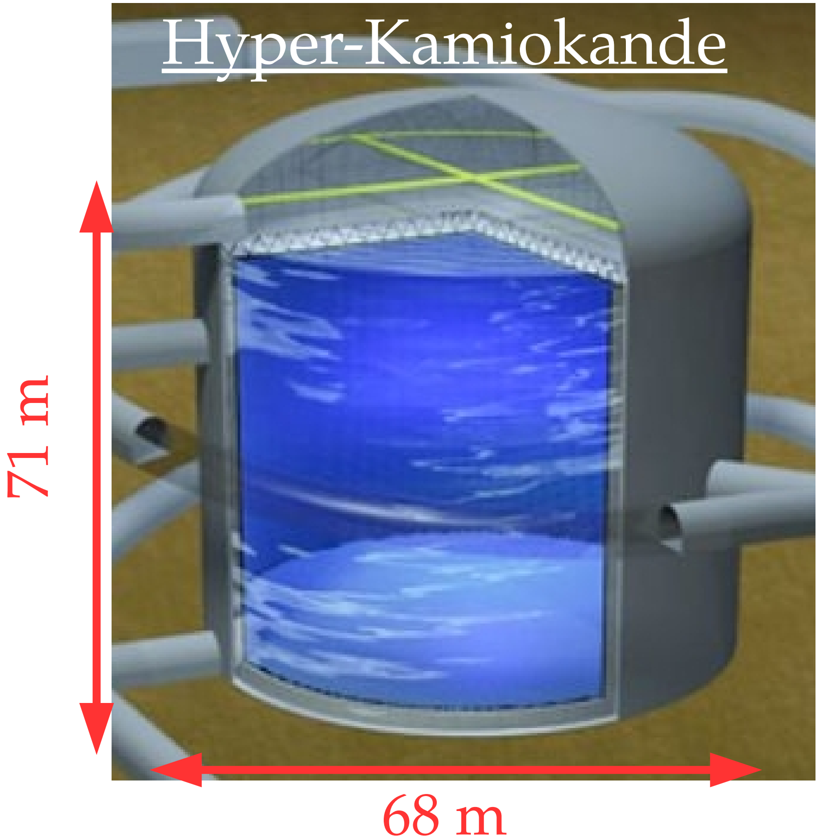
# Reminder : what is Hyper-K ?

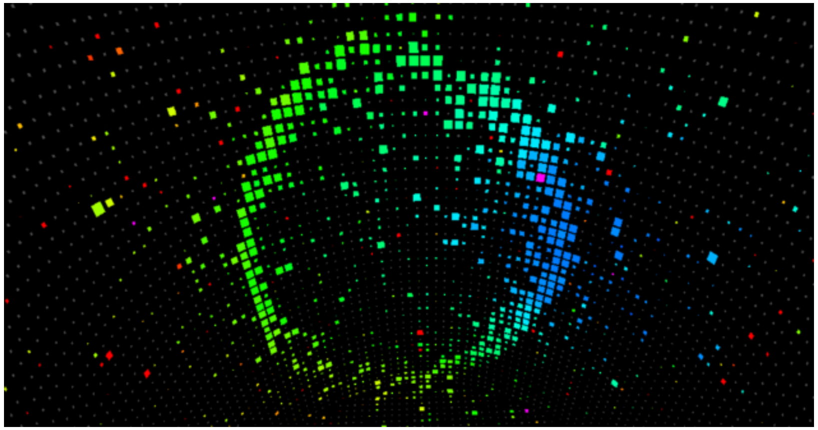
- Next generation of neutrino observatory in Japan→ construction 2020-27

→ A 260 kton water Cherenkov detector → Fiducial Mass ~ 8 x SK.

Super-Kamiokande



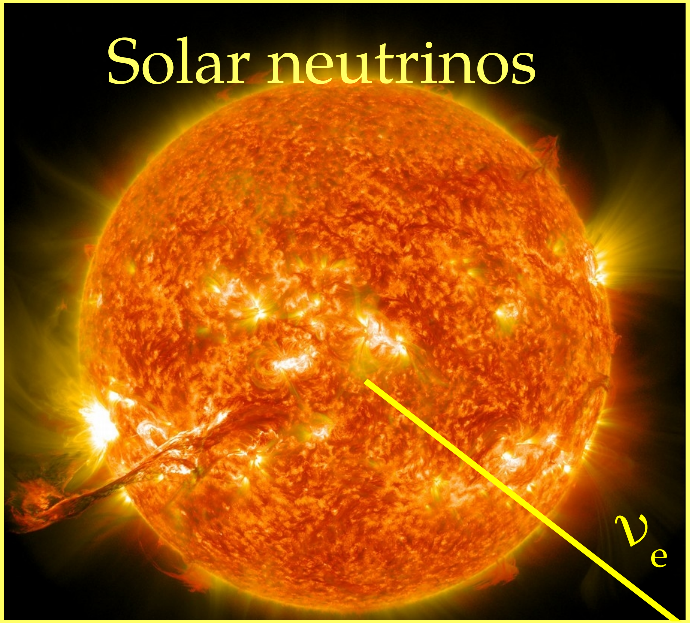



| | Super-K | Hyper-K (1st tank) |
|---|---|---|
| Site | Mozumi | Tochibora |
| Number of ID PMTs | **11,129** | **20,000** |
| Photo-coverage | 40% | 20 %(x2 sensitivity) |
| Mass / Fiducial Mass | 50 kton / **22.5 kton** | 260 kton / **187 kton** |

# Physics case

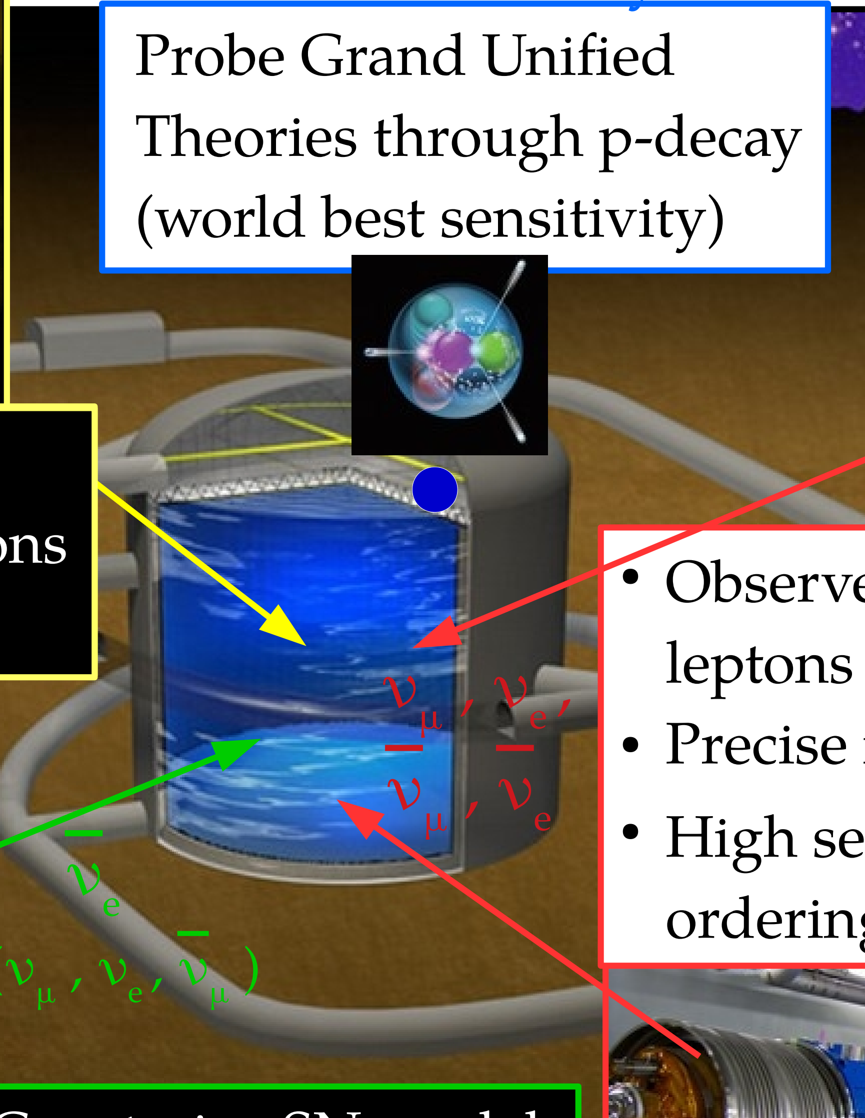
## Solar neutrinos



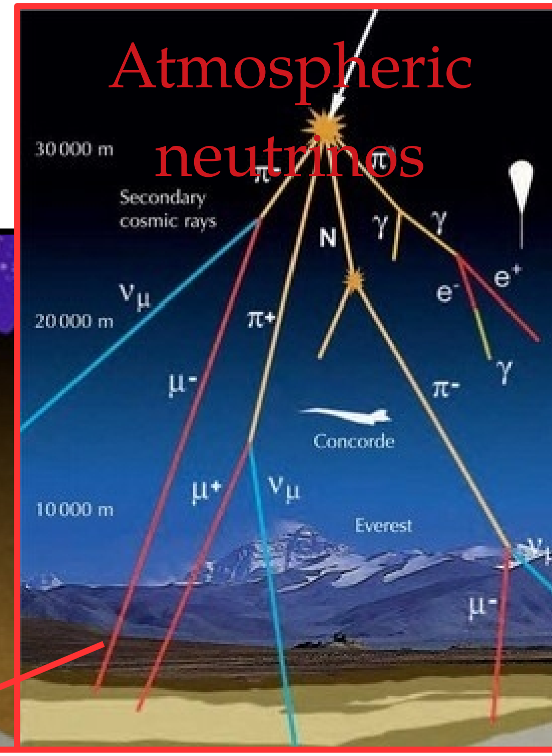

- MSW effect in the Sun
- Non-standard interactions in the Sun.

## Proton decay

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

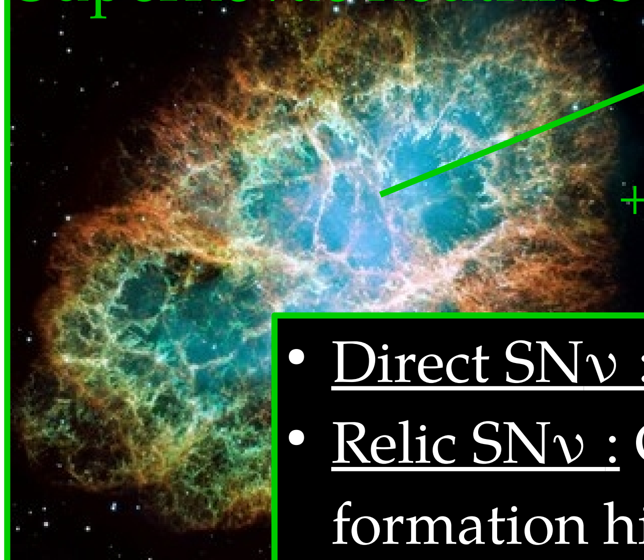



## Atmospheric neutrinos




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

## Supernovae neutrinos

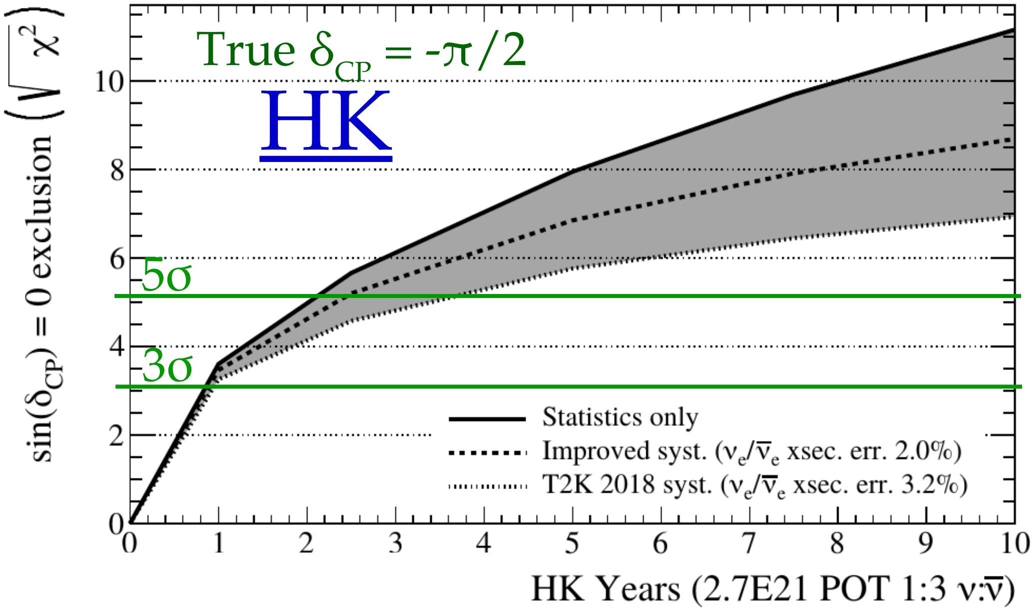


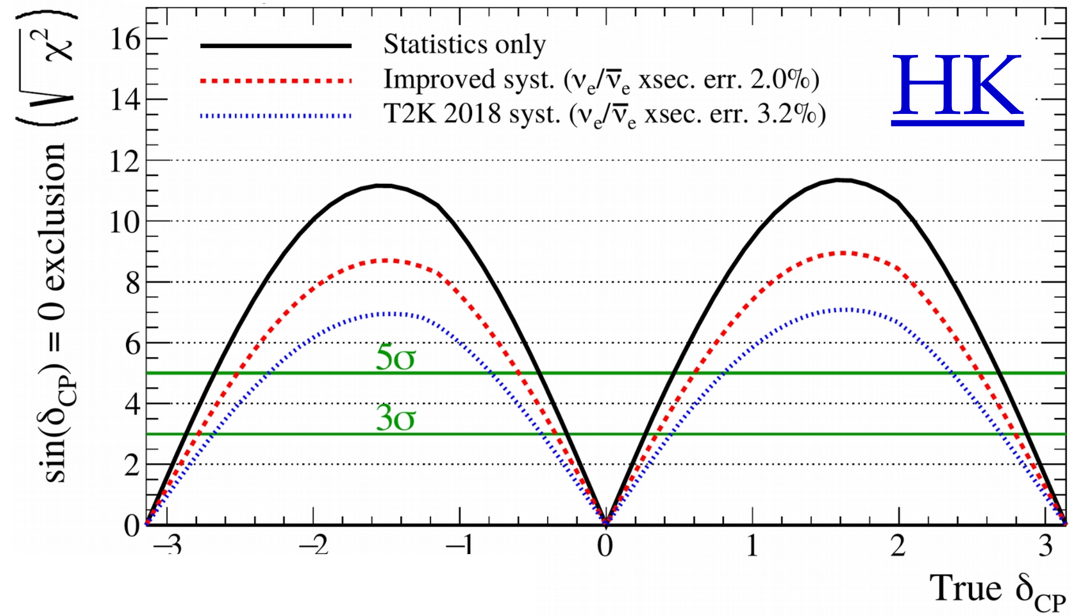
- Direct SNν : Constrains SN models.
- Relic SNν : Constrains cosmic star formation history

JPARC accelerator neutrinos

# Sensitivity to CP violation

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




- $\delta_{CP}$ = -π/2: 5σ after 2-3 years of data taking : known in 2029-2030 !
  → Independent from ↓ systematic uncertainties.

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

- HK has world-best sensitivity to CP violation for the coming generation.

# Matter/antimatter asymetry

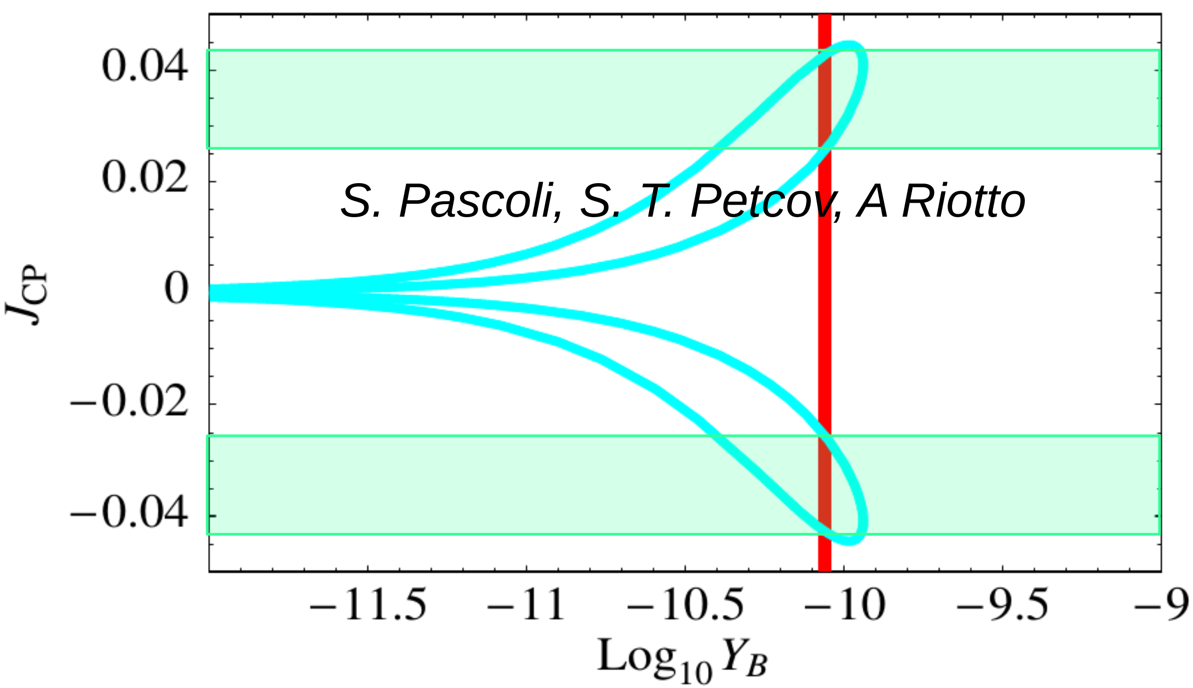
- <u>$\nu$ CP violation at low E maybe the key to matter/antimatter asymetry</u>

  → Class of theories directly link low E $\delta_{CP}$ to matter/antimat. asymetry.


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

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

- First step is to actually measure if CP is violated…




Precision on sin $\delta_{CP}$

↔ Precision on leptogenesis models

<u>Lower limit for leptogenesis :</u>

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

→ $|\sin \delta| \geq 0.78$

# Flavour symetries

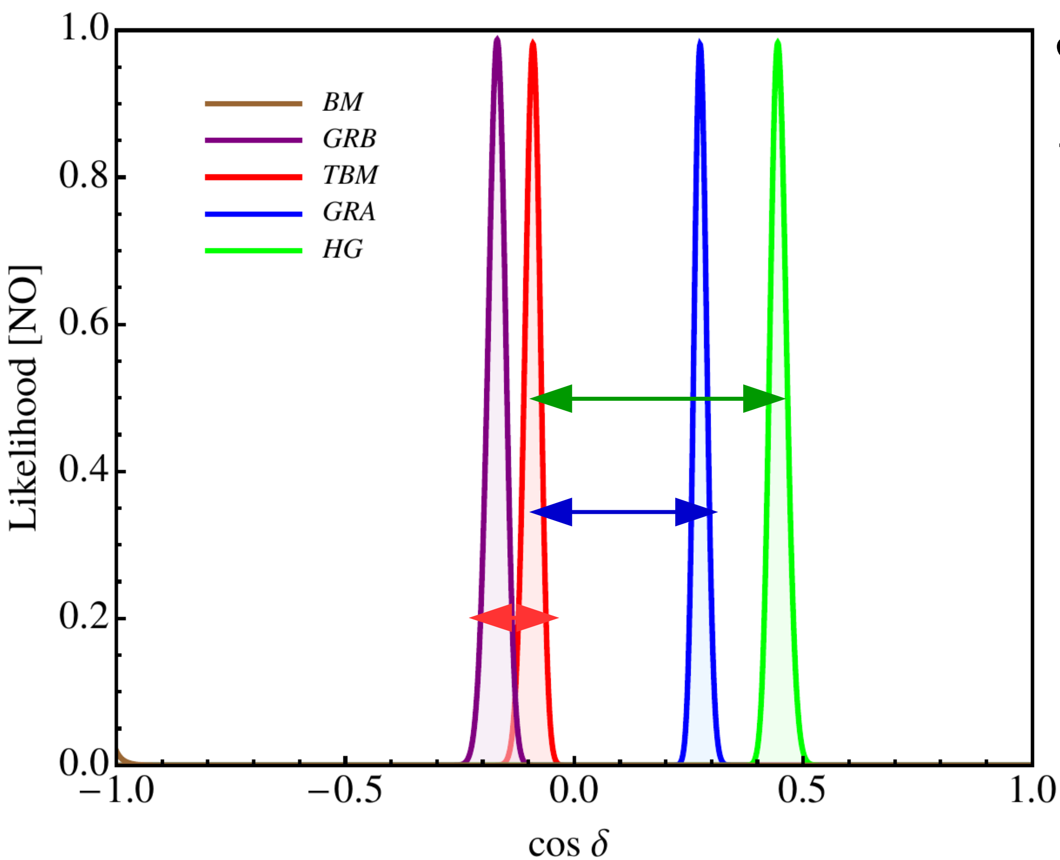
- <u>Models of lepton flavour symetries could be also tested</u>

$e \leftrightarrow \mu \leftrightarrow \tau$

$\nu_e \leftrightarrow \nu_\mu \leftrightarrow \nu_\tau$

**Lepton generation symetric models** → **Links PMNS parameters**

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




$\delta_{CP}$ = less well-known parameter

→ Limits the model constraints.

<u>Model separation requires :</u>

First separation : $\delta\,[\delta_{CP}] < 30°$

Good separation : $\delta\,[\delta_{CP}] < 23°$

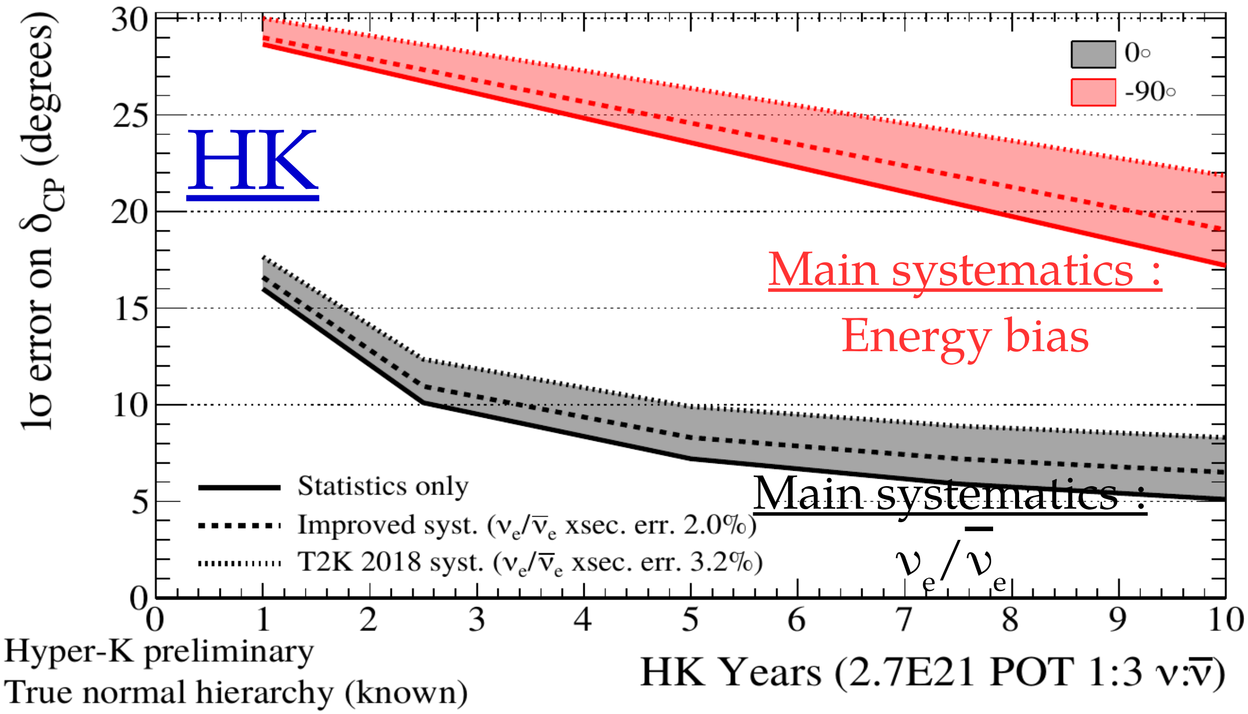
Great separation : $\delta\,[\delta_{CP}] < 5°$

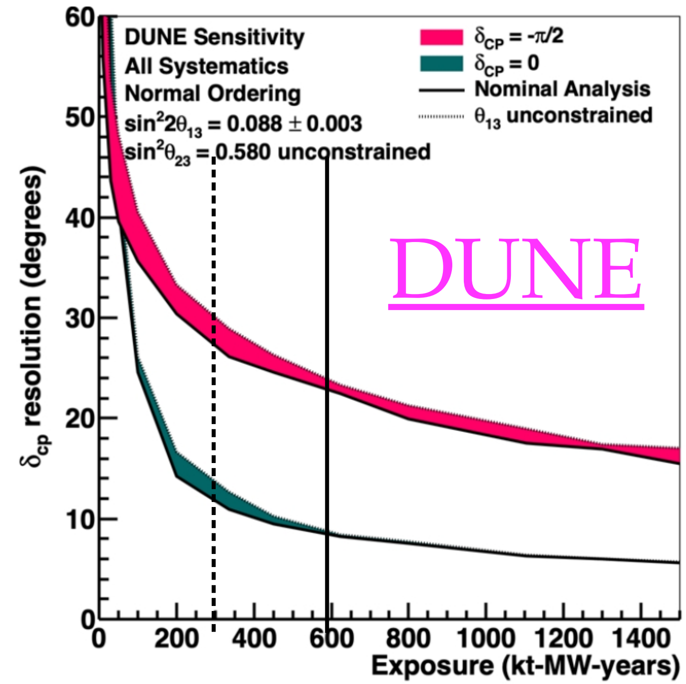
→ Precision of our experiments ?

# Precise measurement of $\delta_{CP}$

- 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° |

- Need both HK&DUNE to reach the best & reliable measurement of $\delta_{CP}$

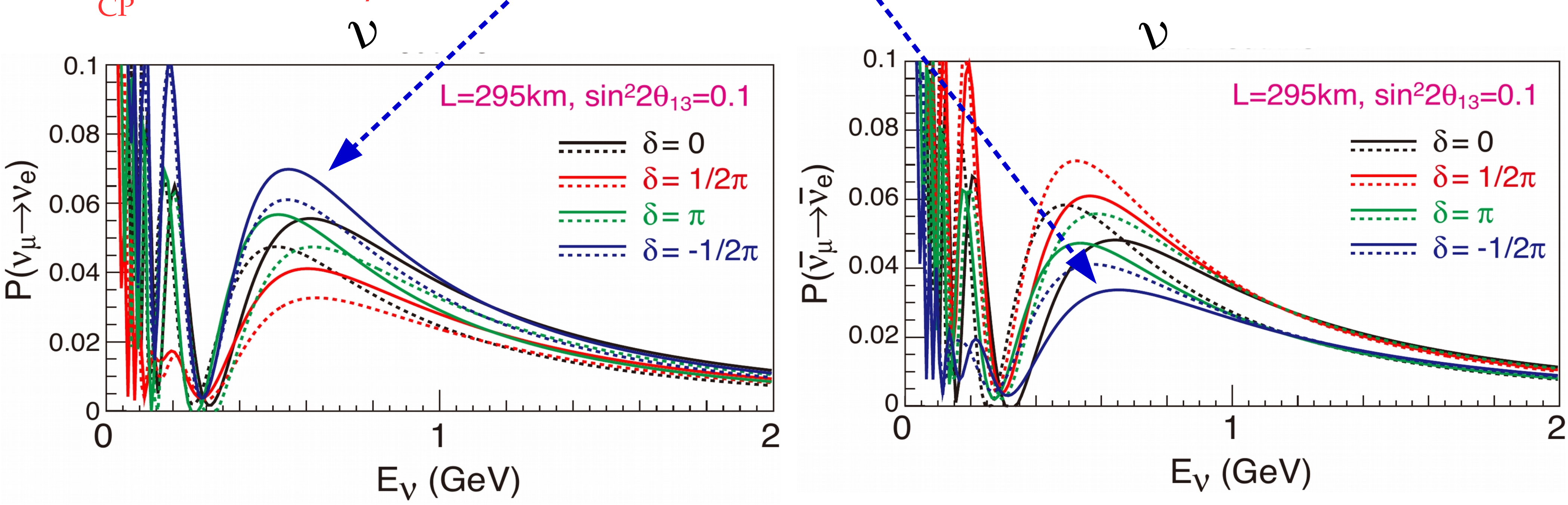
  → And in each, an excellent control of our systematics !

# Precise measurement of $\delta_{CP}$

$$P(\nu_\mu \to \nu_e) = 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\Delta_{31}$$
$$+8c_{13}^2 s_{12}s_{13}s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23})\cos\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$
$$-8c_{13}^2 c_{12}c_{23}s_{12}s_{13}s_{23}\sin\delta\sin\Delta_{32}\sin\Delta_{31}\sin\Delta_{21} \quad + \ldots$$

sinδ :

- CP-odd : opposite effect for $\nu$ / $\bar{\nu}$ .
- Derivative ≈ 0 for $\delta_{CP}$ ~-π/2
  → Weak sensitivity to $\delta_{CP}$ around -π/2

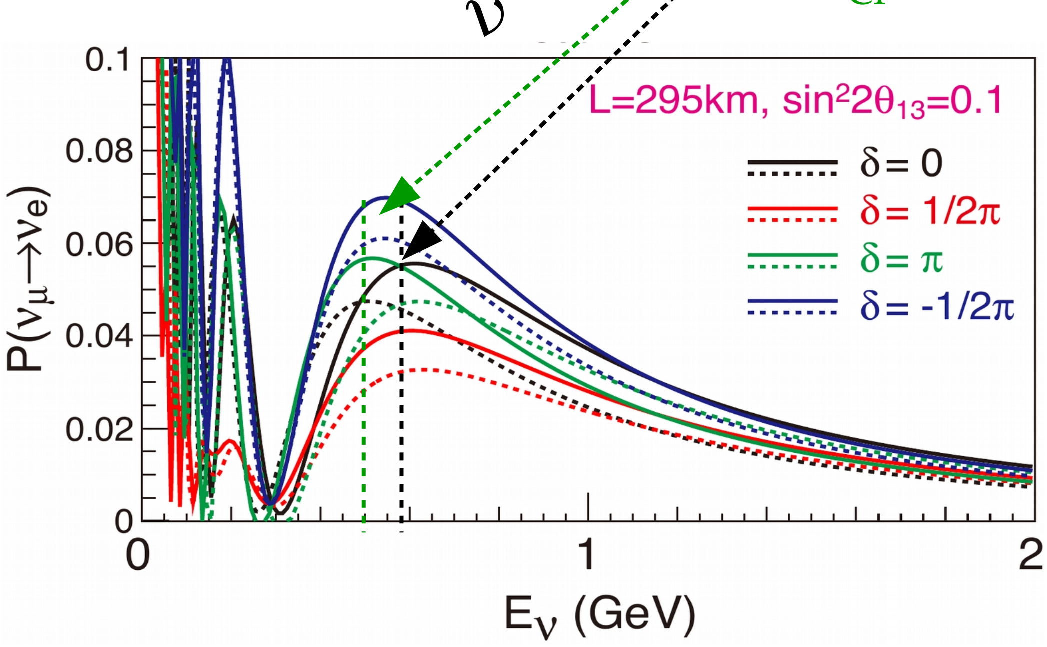


# Precise measurement of $\delta_{CP}$

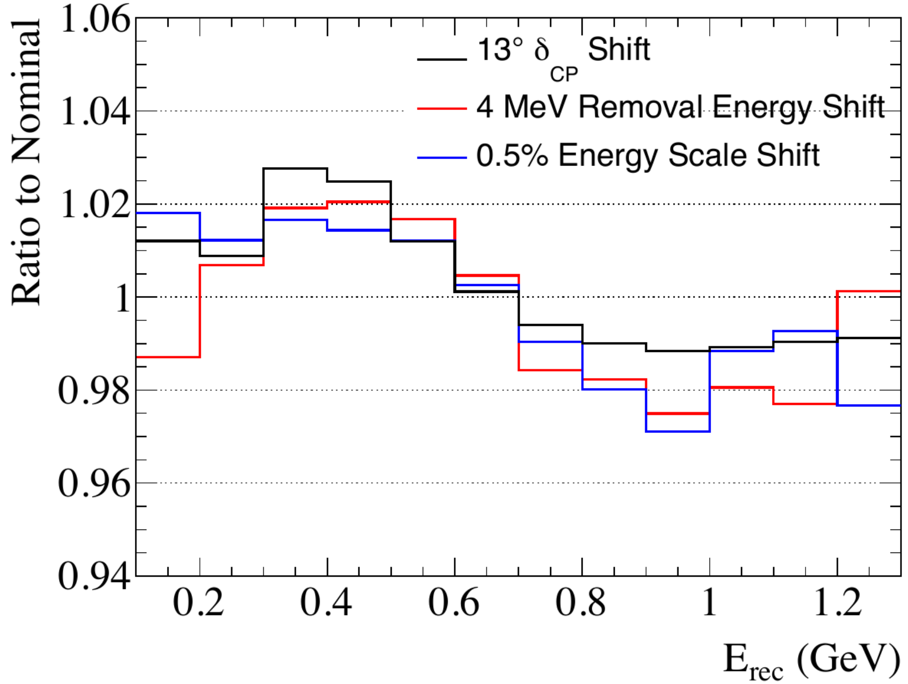
$$P(\nu_\mu \to \nu_e) = 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\Delta_{31}$$
$$+8c_{13}^2 s_{12}s_{13}s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23})\cos\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$
$$-8c_{13}^2 c_{12}c_{23}s_{12}s_{13}s_{23}\sin\delta\sin\Delta_{32}\sin\Delta_{31}\sin\Delta_{21} \quad + \ldots$$

cosδ :

- CP-event : same effect for ν / $\bar{\nu}$ .
- Large derivative for $\delta_{CP}$ ~-π /2
  - → Large sensitivity to $\delta_{CP}$ .
  - → Ideal term to measure $\delta_{CP}$ .




cos δ ≈ E spectrum shift (L fixed).



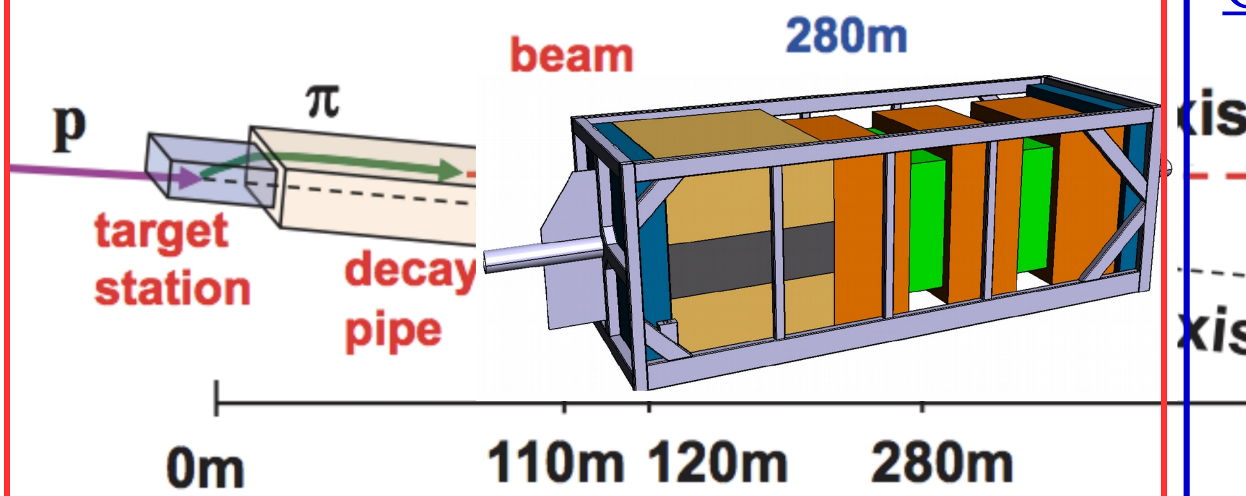

- Need to step-up in spectrum systematics control
  → New complex of near detectors to reach these accuracies.

# Updated systematic uncertainties

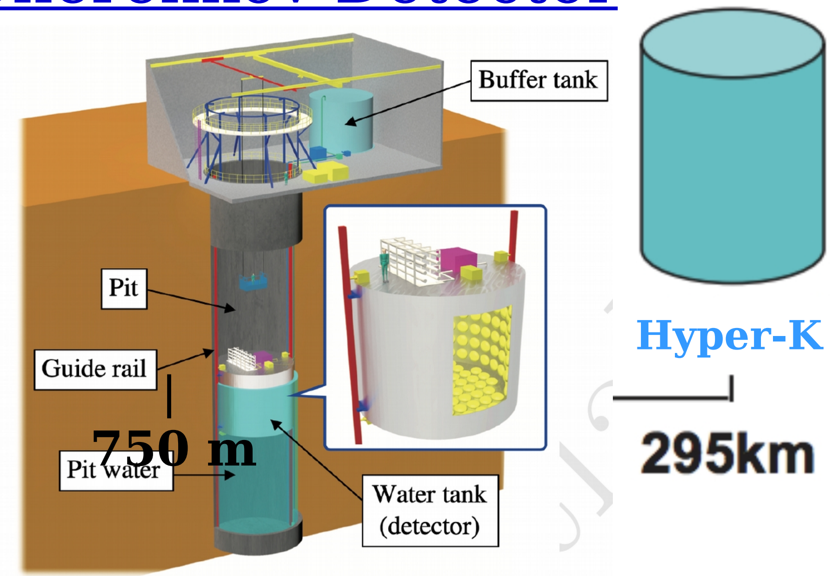
- 2 very complementary near detectors :

New

## Upgraded ND280




## Intermediate Water Cherenkov Detector




### Ideal to measure cross-section

- Very low E-threshold.

→ CC0π, CC1π, CCNπ separation.

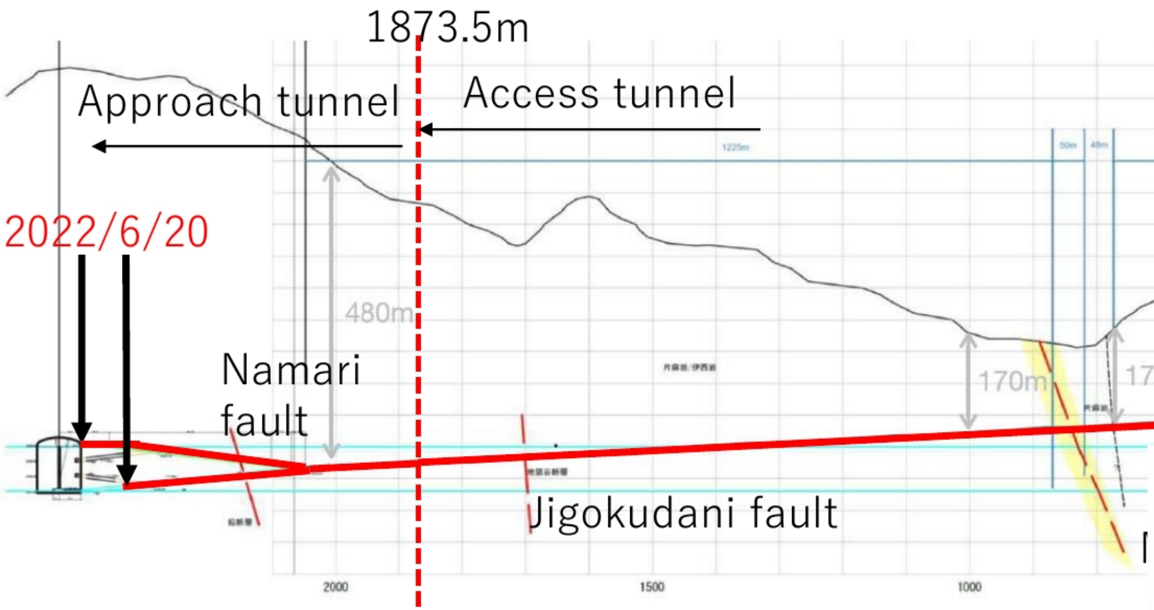
→ Measure of hadronic effects.

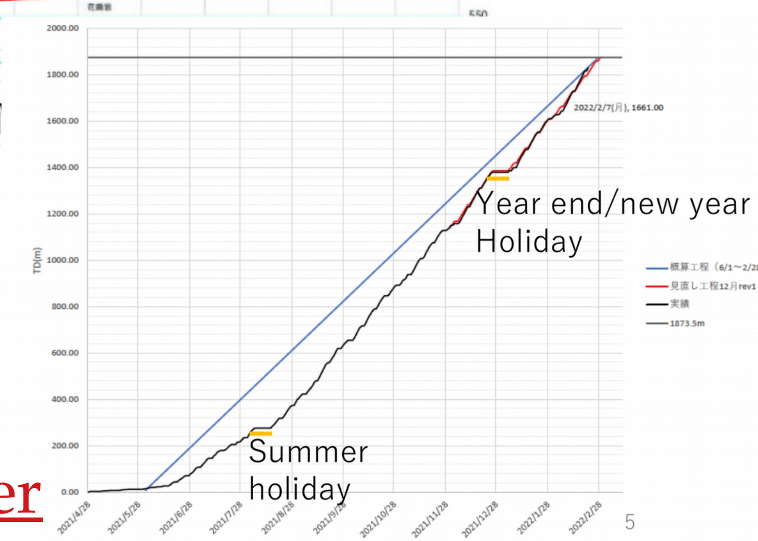
- Here from 2023
  - → Great control from day 1 of HK
- IN2P3 & CEA have leading roles

### Target & acceptance ~ far detector.

- Cancel detector uncertainties & precise measurement of $\nu_e$ / $\nu_\mu$
- Here from 2028.
- Contributions still open
  - → Great opportunity to join HK & synergy with far detector.

# Hyper-K excavation

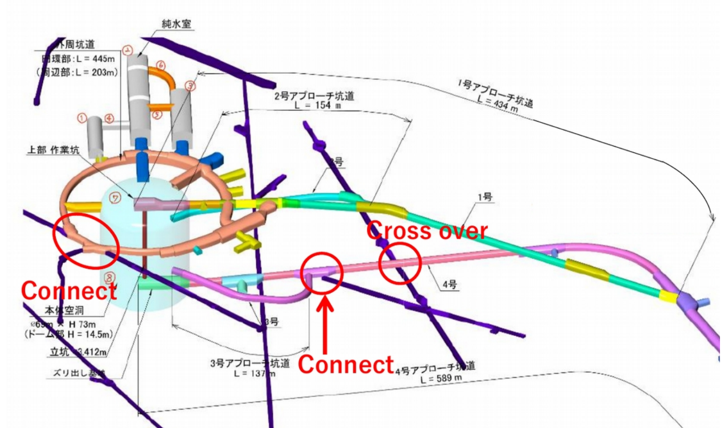



- <u>Excavation of the access tunnel (2 km) is over</u> finished the 25/02/22 → In-time !

- <u>Approach & circular tunnel excavation are over</u>

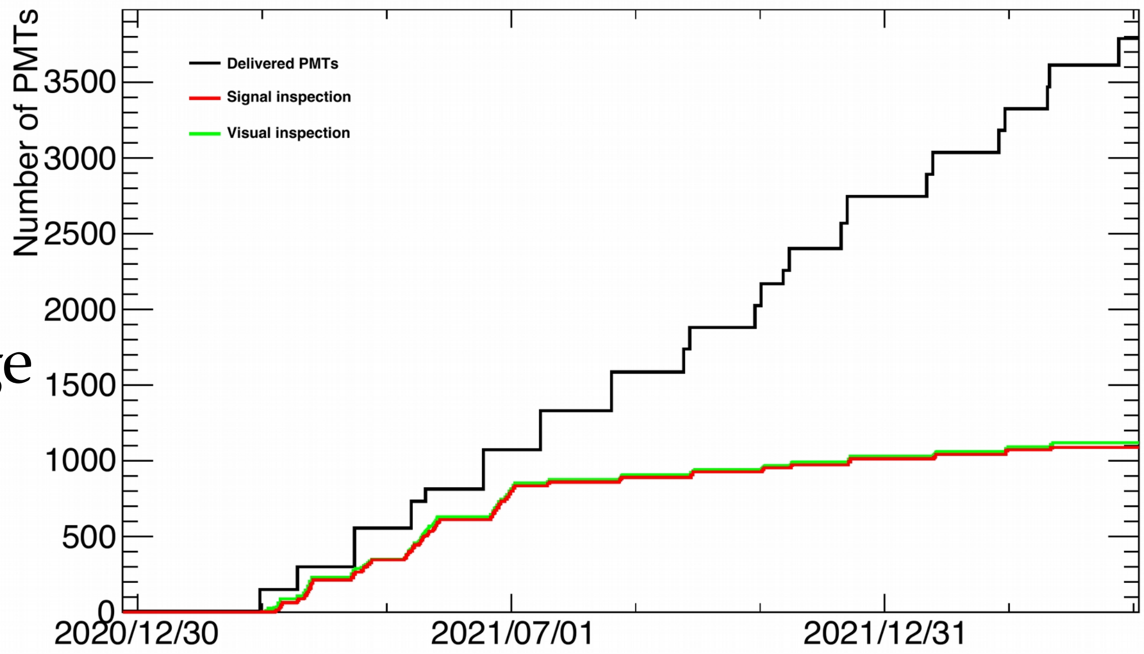
- We have started the dome excavation ! <u>→ No delay in excavation.</u>



# PMT production & delivery

- <u>The delivery of the 20k PMTs of the experiment is on-going :</u>

- <u>~10 % of PMTs checked :</u>
  → PMT quality does not change wrt time & check production issues.
  → 3 inspections :
  1. Visual (detect cracks…).
  2. Mesurements (high dark rate, impedance issue…)
  3. Long-term measurements.

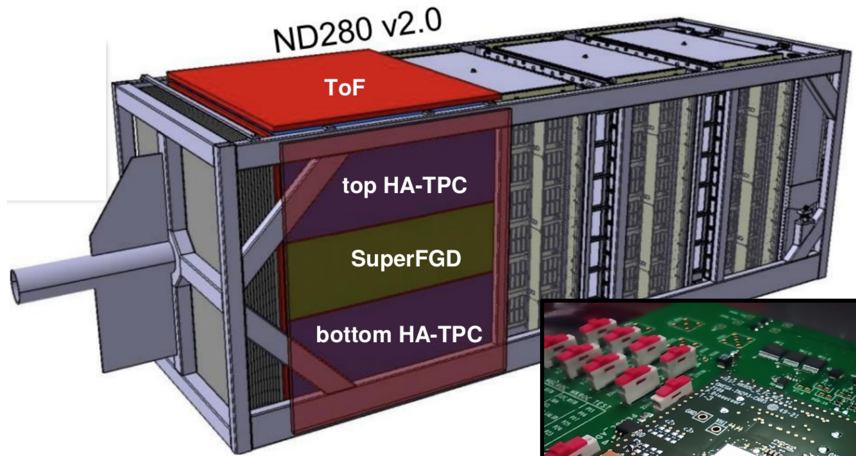




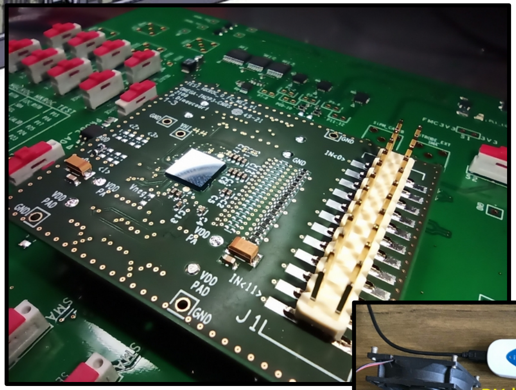
- **<u>Minor issues identified et solved with Hamamatsu :</u>** the production is on-going as expected, <u>no delay until now</u>.
  **→ The detector will take its first data in 2027.**

# Summary of proposed contributions

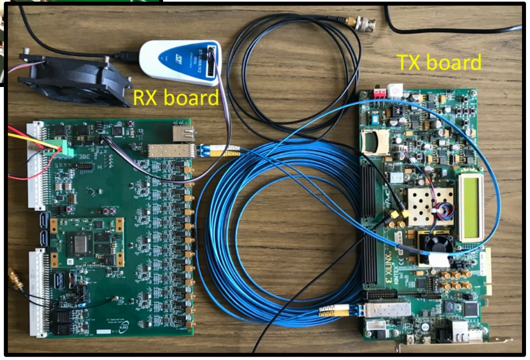
<u>HK presented at 2021/10 IN2P3 scientific council :</u>




- The ND280-upgrade.

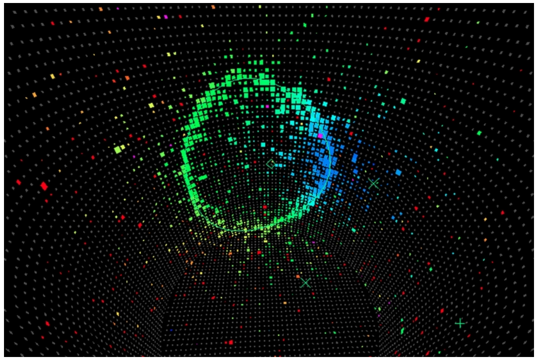


- PMT digitizer for the Far Detector.




- Time generation & clock distribution at Far Detector.
  → See Lucile's talk at 2022/06 IRN.

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



# Summary of proposed contributions

From 2022/03 : HK became an IN2P3 R&T master project. New

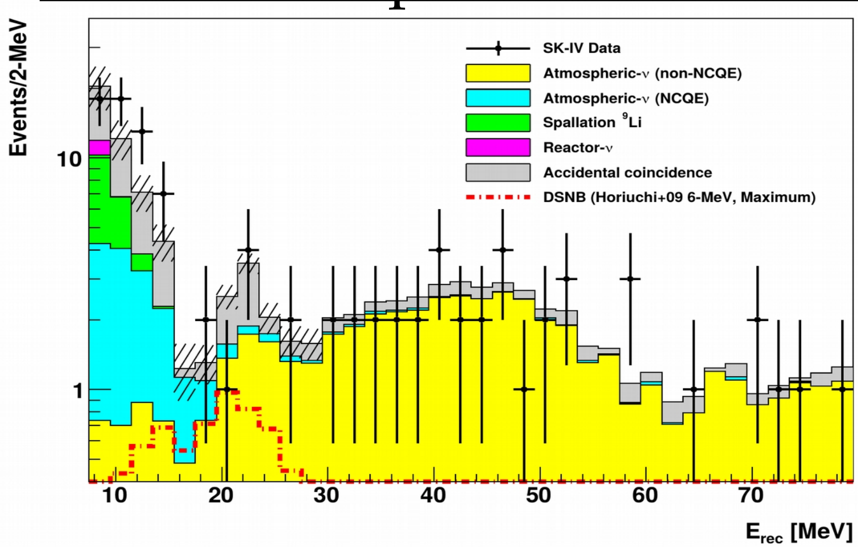
2022/10 : HK presented again to IN2P3 CS « pour avis » : New

- The ND280-upgrade.
- ~~PMT digitizer for the Far Detector.~~

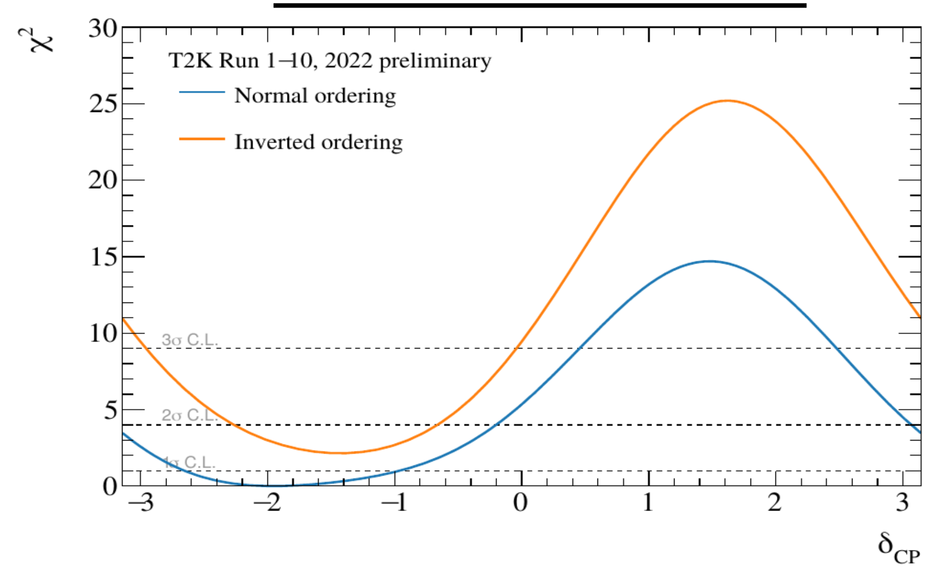
  → Collaboration chose an alternative (INFN) solution. See : CSIN2P3-2023
- Time generation & clock distribution at Far Detector.
- CC-IN2P3 : HK Tier 1 computing site.

**& export our leadership in low and high E sectors from SK/T2K → HK**

DSNBν @Super-Kamiokande

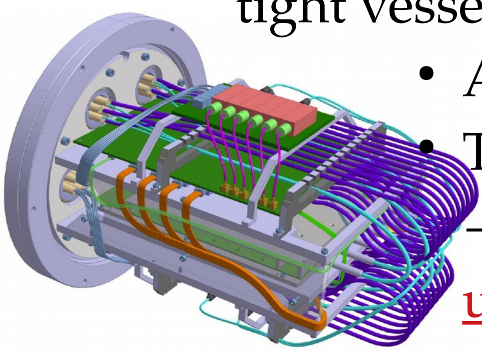



CP violation @T2K

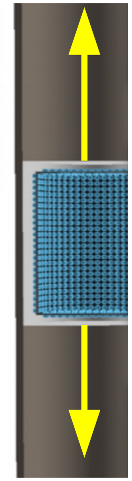


# Some proposed contributions

## Readout electronics assembly & test @CERN



- Read-out electronics in water-tight vessel under water.
  - Assembly at CERN.
  - Test bench & tests
  
  → Can raise hand until spring 2023.

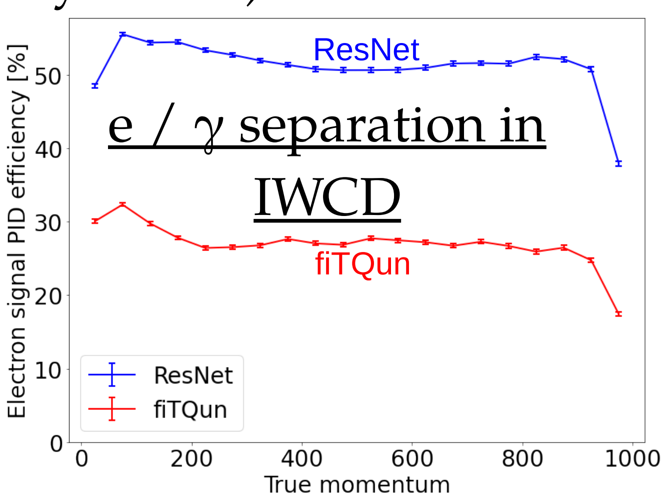


- **IWCD**
  - Outer detector photosensors.
  - Outer detector digitizer.
  - Elevation mechanical system
  
  → Can raise hand until end of 2023.

## Reconstruction algorithms

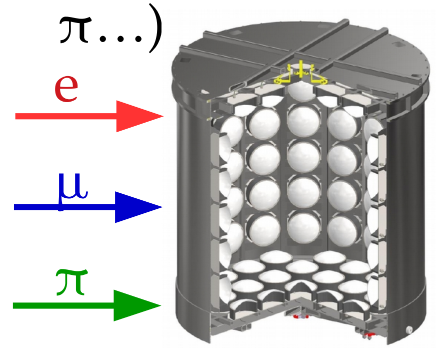
- Upgrade algorithms from SK (< 15 year old) to HK

e / γ separation in IWCD




## Water Cherenkov Test Experiment

- A 4m x 4m Water Cherenkov @CERN.
- Precision measurement of Cherenkov profile w/ known particle beam (e, μ, π…)




→ Crucial to syst. uncertainties in SK & tomorrow in HK.

- Commissioning from early 2024.

ND280 Upgrade++, FD multi-PMT electronics …

# Conclusions

- Hyper-K will be the world-leading experiment in many aspects of neutrino physics for the next 20 years.
  → Today we solely focused on CPV and $\delta_{CP}$.

- Construction & production are on-time, no delay since the start
  **→ HK will take its first data in 2027.**

- **IN2P3 & IRFU teams plans to have a leading role**, building on their years of expertize in SK/T2K & hardware contributions.

- Other groups/collaborators inIN2P3/IRFU are welcome to participate to this extremely exciting experiment
  → Hardware : there are still some seats to be taken, before full production start in 2024-2025.
  → Software : we plan to host whole HK data at CC-Lyon : unique chance to also lead the development of reconstruction algorithm.

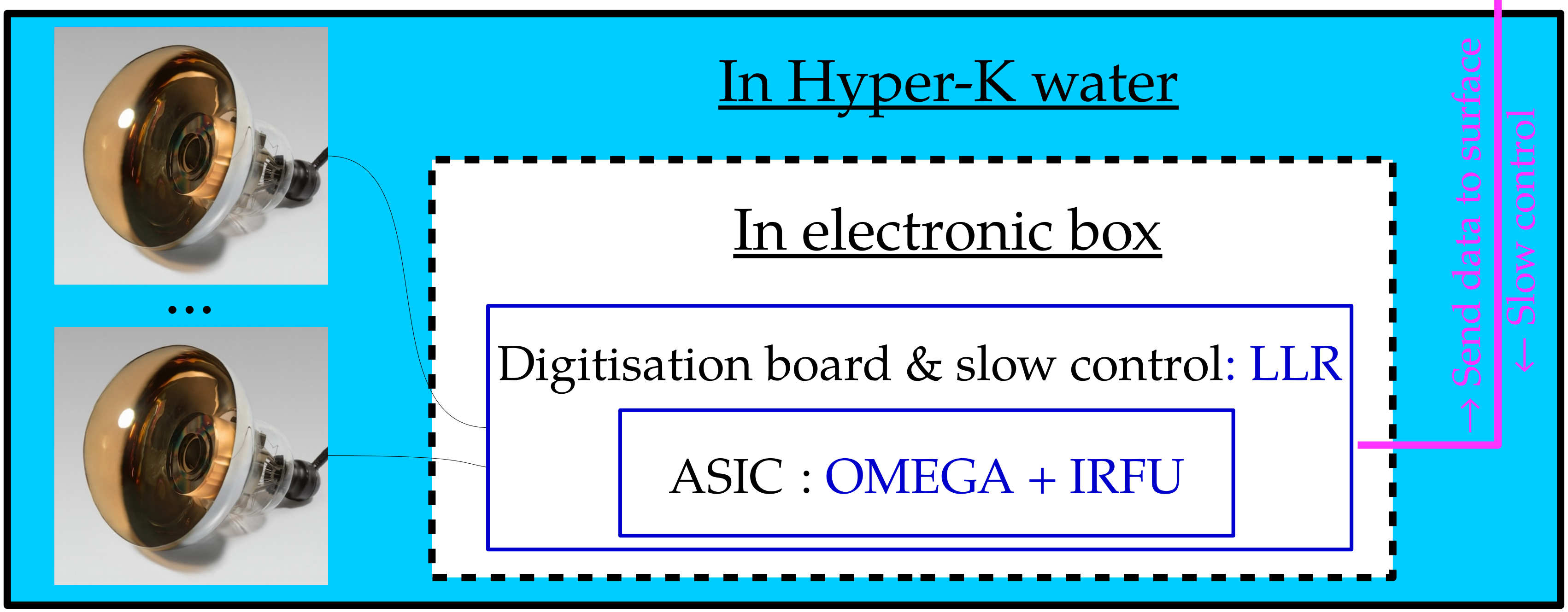
# Additional slides

# HK far detector electronics

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

- <u>PMT signal to be readout by electronics under water :</u>

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



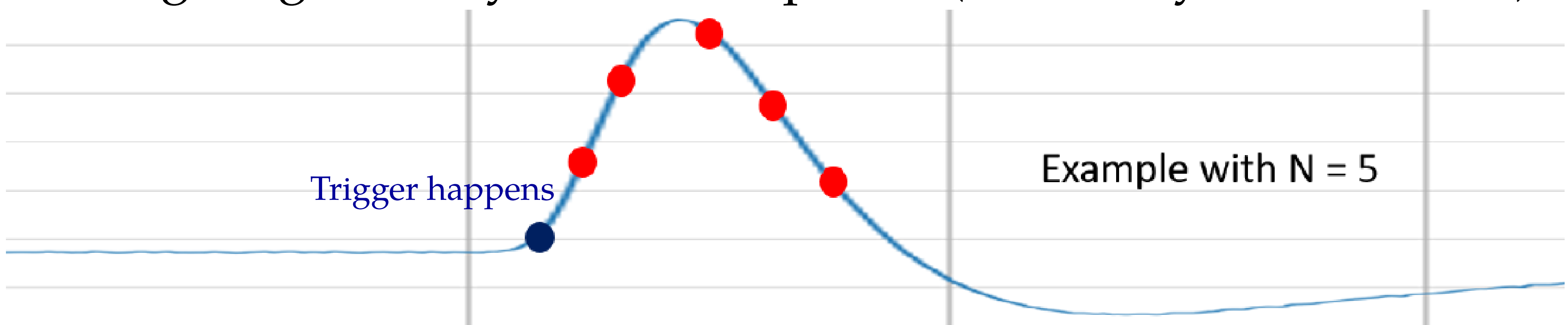

<u>LLR proposal :</u> develop the whole PMT Q & T digitization system

→ Absolutely central role in HK !

# Overview of the HKROC digitizer

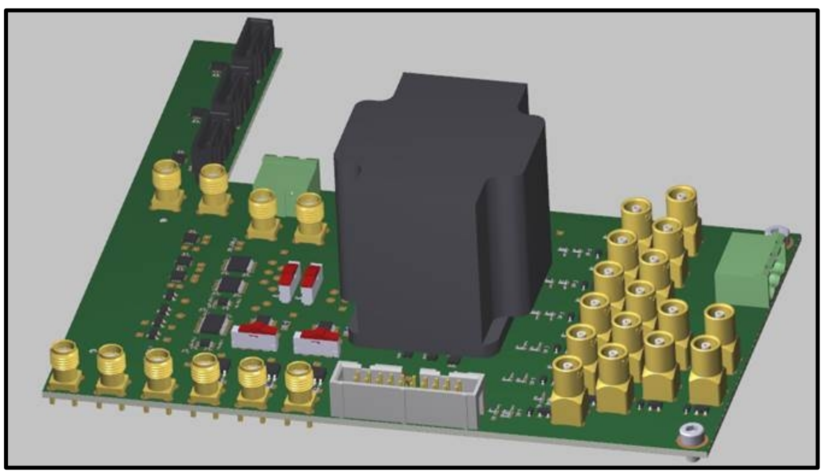
- HKROC is a waveform-like digitiser @40 MHz→ 1 point every 25 ns.

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




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

HKROC prototype v1

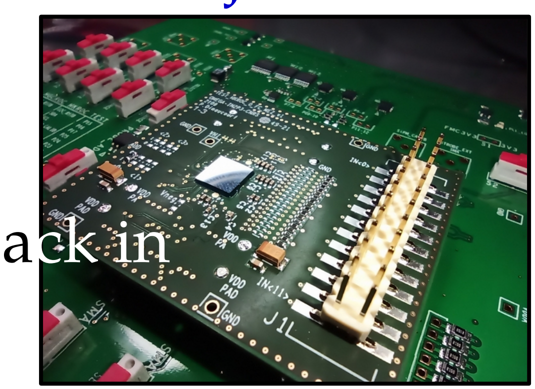


- Started R&D in summer 2020 : Make a chip in 2 years → Challenging schedule :
  1. Receive chip in Dec. 2021.
  2. Provide tested chip by end of June 2022.

- No delay in 2 years :

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

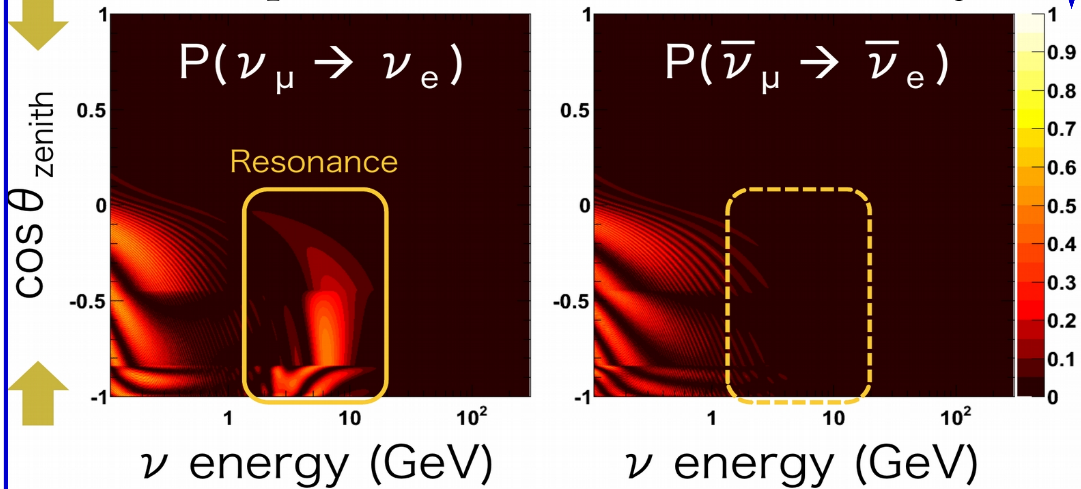
  → Worked hard to finalize tests for June.



# HKROC digitizer - Impact on physics

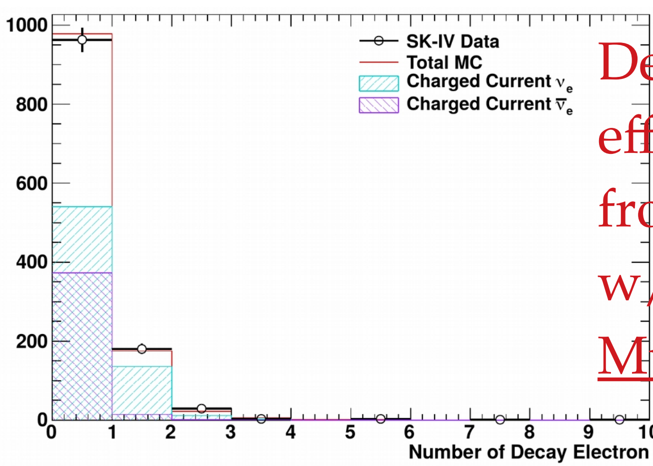
- Large impact on physics : ν mass ordering & Supernova ν.

Atmospheric neutrino (normal ordering) :

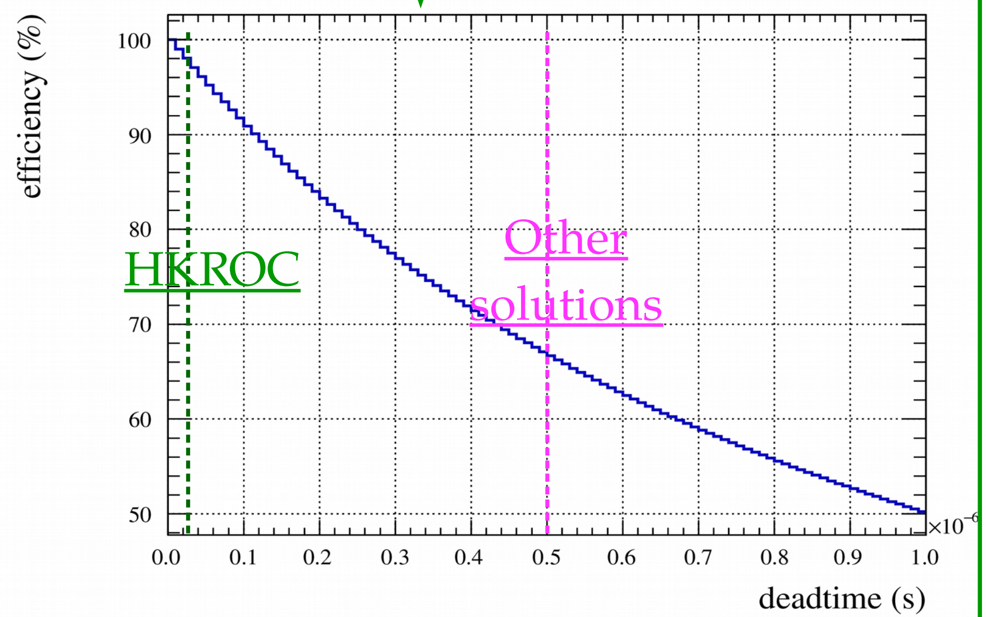



- Normal hierarchy : ↑ $\nu_\mu \rightarrow \nu_e$ .
- Inverted hierarchy : ↑ $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ .

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



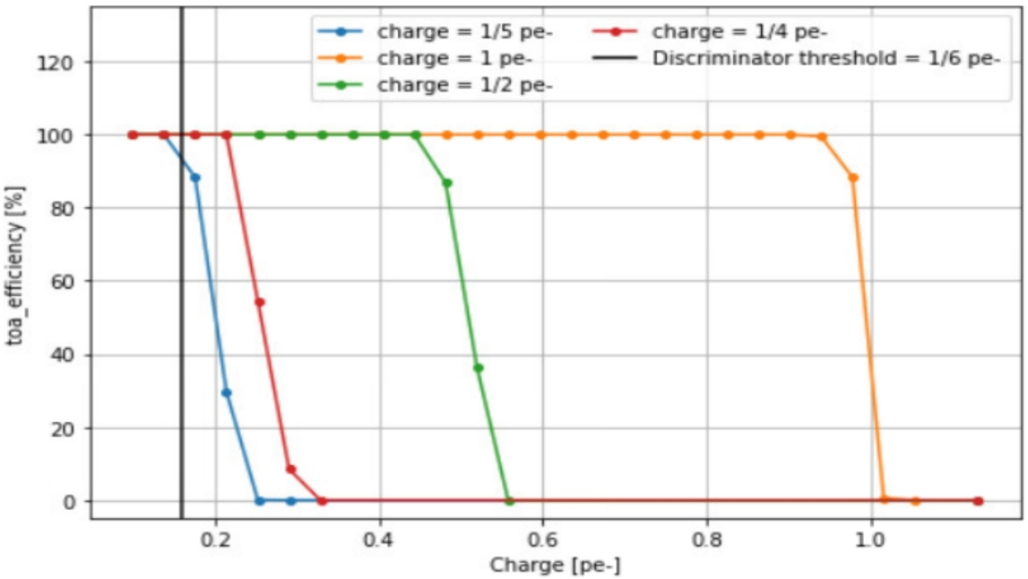

Decay-e hit efficiency increased from 68 % → 98 % w/ HKROC for Multi-GeV events

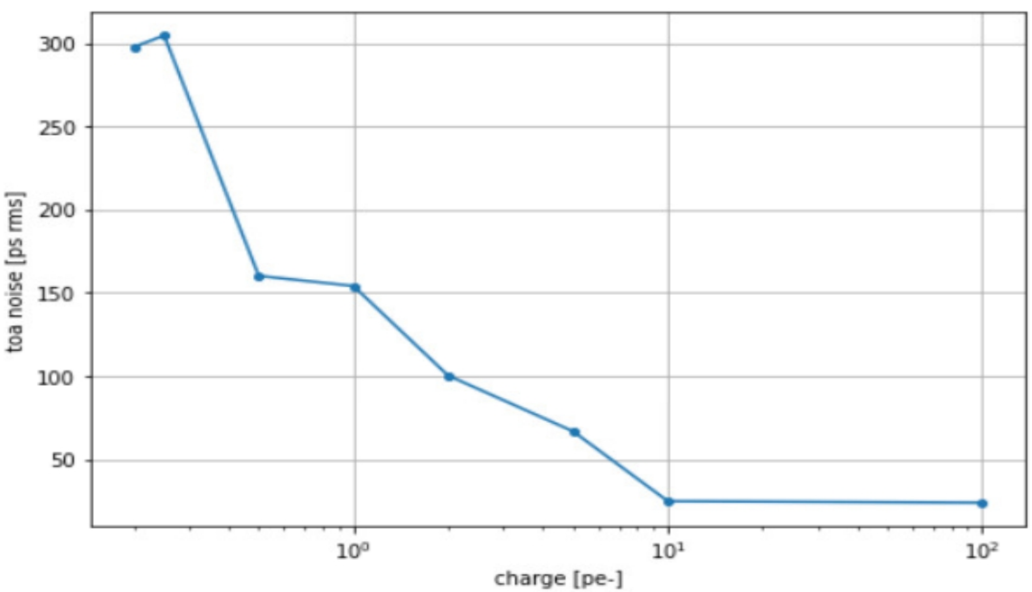



- For 1MHz [Betelgeuse] : HKROC allows to significantly increase efficiency from 67 % to 92.5 % compared to other solutions.

# HKROC digitizer - trigger & timing results

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




- <u>Set threshold at 1/6 p.e.</u>

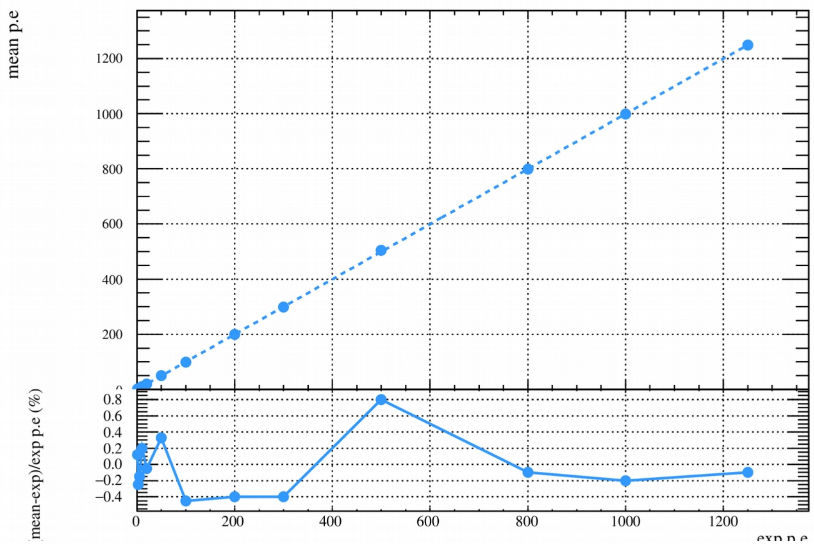
- <u>Hit efficiency :</u>
  90 % for 1/5 p.e events
  ~100 % if ≥ 1/4 p.e

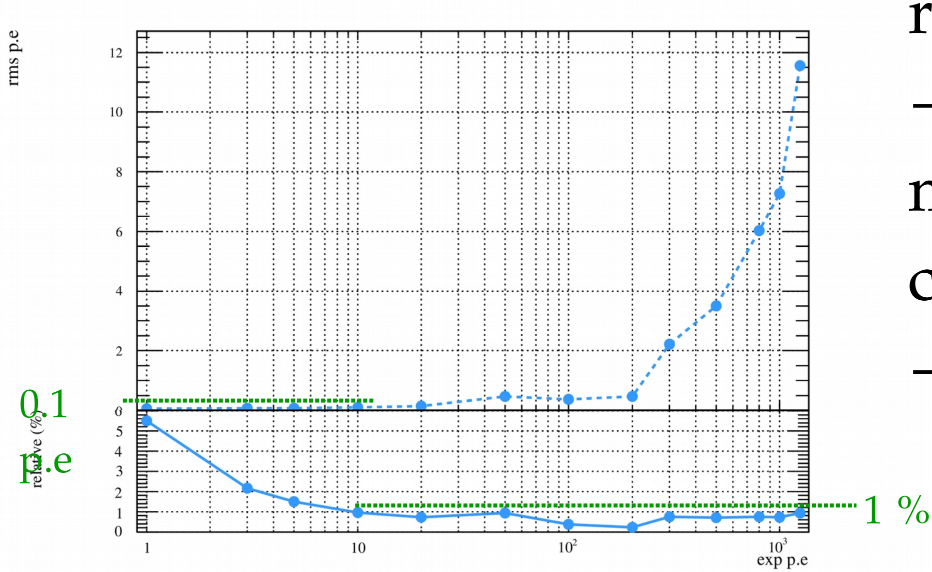
- <u>Very low noise :</u> < 1 Hz.

- <u>TDC resolution :</u>
  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

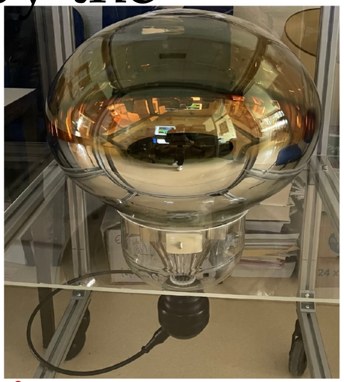



- <u>Charge linearity < ±1%</u> [1 to 1250 p.e.]

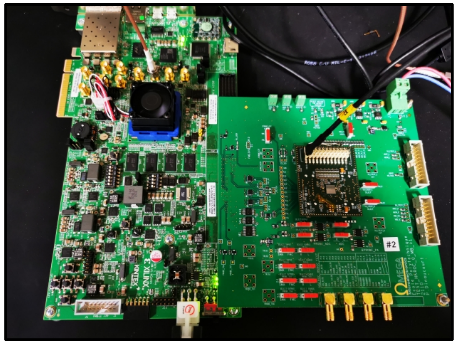
- <u>Charge resolution :</u>
  < 0.1 p.e @≤ 10 p.e, < 1 % otherwise.

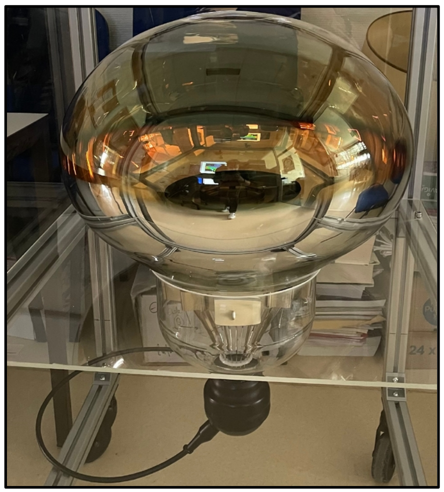
→ All characteristics fulfill HK requirements & confirmed w/ PMT.
→ Large improvements w/ HKROC much beyond requirements by the collaboration
→ <u>Ex:</u> dead-time ↓ **from 1 µs → 30 ns**.



- 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

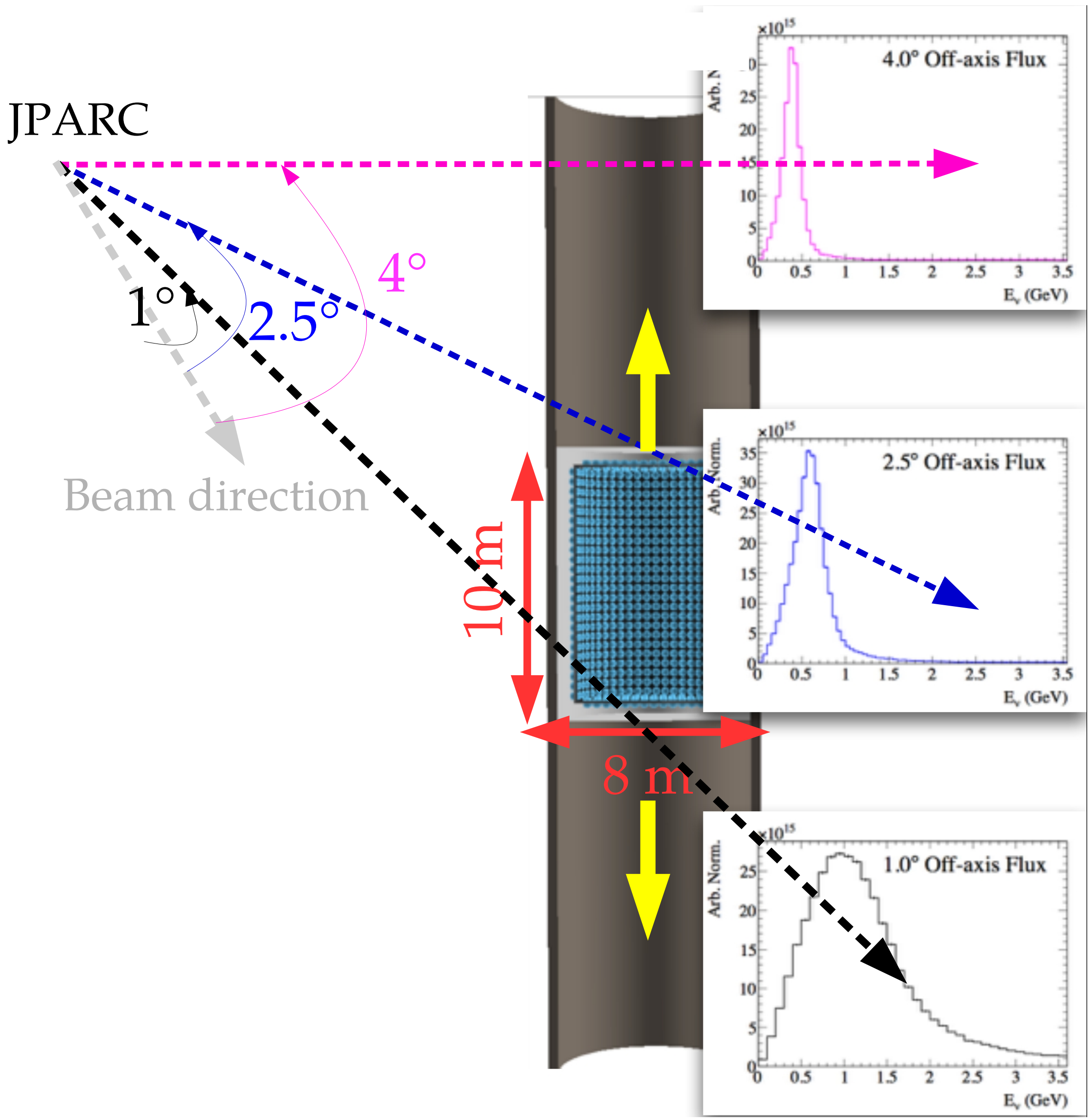




| Item measured | Performances |
|---|---|
| Trigger efficiency at 1/6 p.e. | $>$ 90% for 1/5 p.e signals<br>100% for $\geq$ 1/4 p.e signals |
| Trigger noise at 1/6 p.e. | $<$ 1 Hz (No trigger observed in 10 s) |
| TDC resolution | 150 ps at 1 p.e, 70 ps at 5 p.e, 25 ps $>$ 10 p.e<br>Validated with 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 |

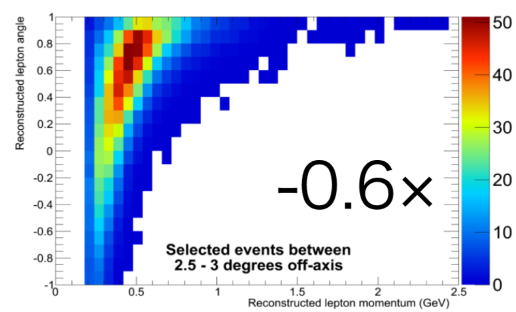
# The IWCD

- New Intermediate Water Cherenkov detector (E61):



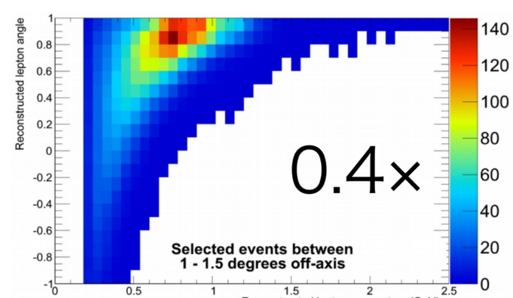

1. HK flux = linear combination of different off-axis angles.

2. Take same combination of




reconstructed number of neutrinos (e.g. in $p_\mu/\theta_\mu$)

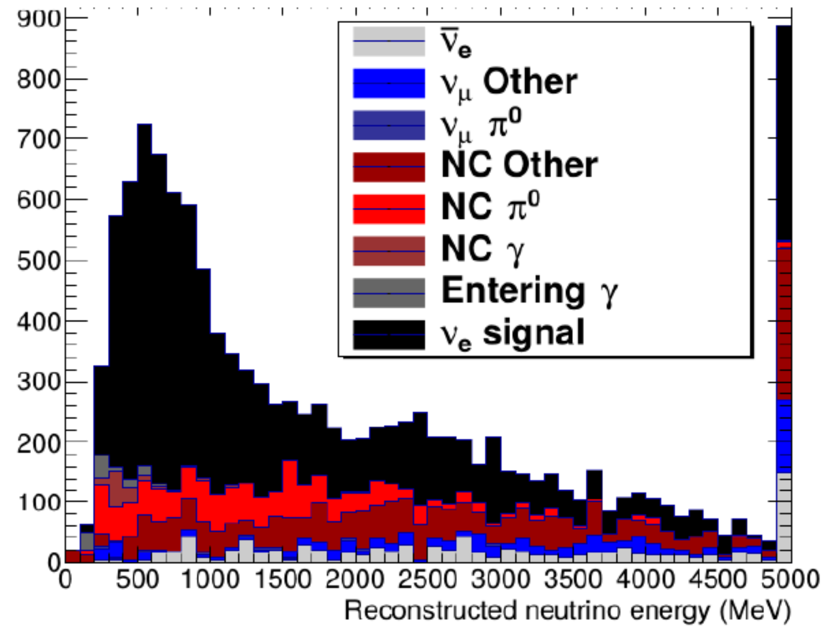
→ Drastically reduce use of cross-section models !



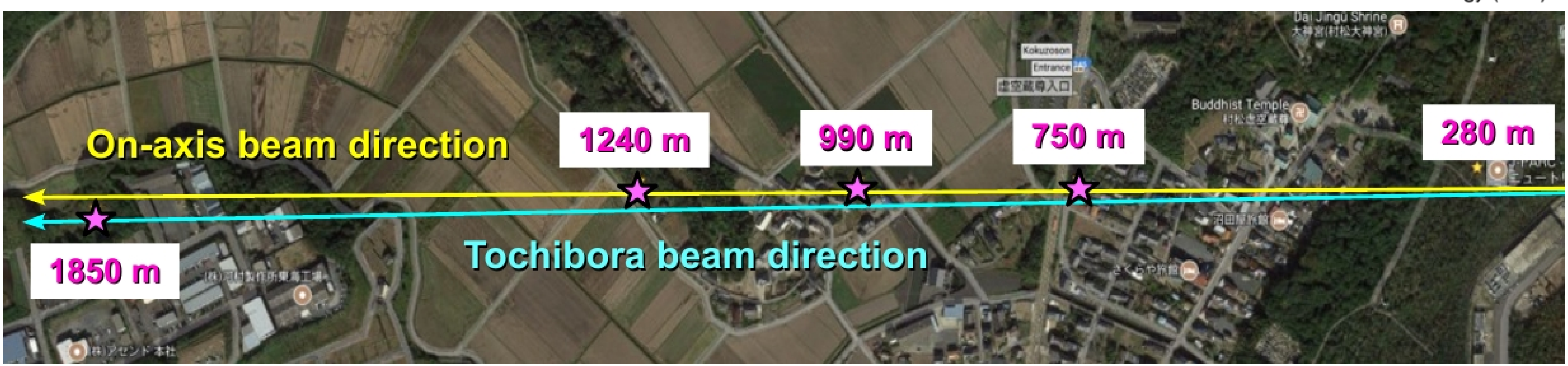
# The IWCD

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

- 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 %.

# 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 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

| 2022/05 | 2022/10 | 2022/11-12 | | 2023/03 | 2023/05 |
|---|---|---|---|---|---|
| HKROC v1 final tests | We are here ↓ | HKROC v2 tests | HKROC v2 full production | HKROC NIM paper | |
| | Board v1 tests | | | Board v2 tests | Complete in-water tests |

- <u>We propose to keep our R&D original schedule :</u>
  → **First complete digitizer board in spring 2023.**

- <u>NIM paper : Being prepared for a publication at the end of spring 2023.</u>
  → Based on HKROC v2 & prototype board v1.

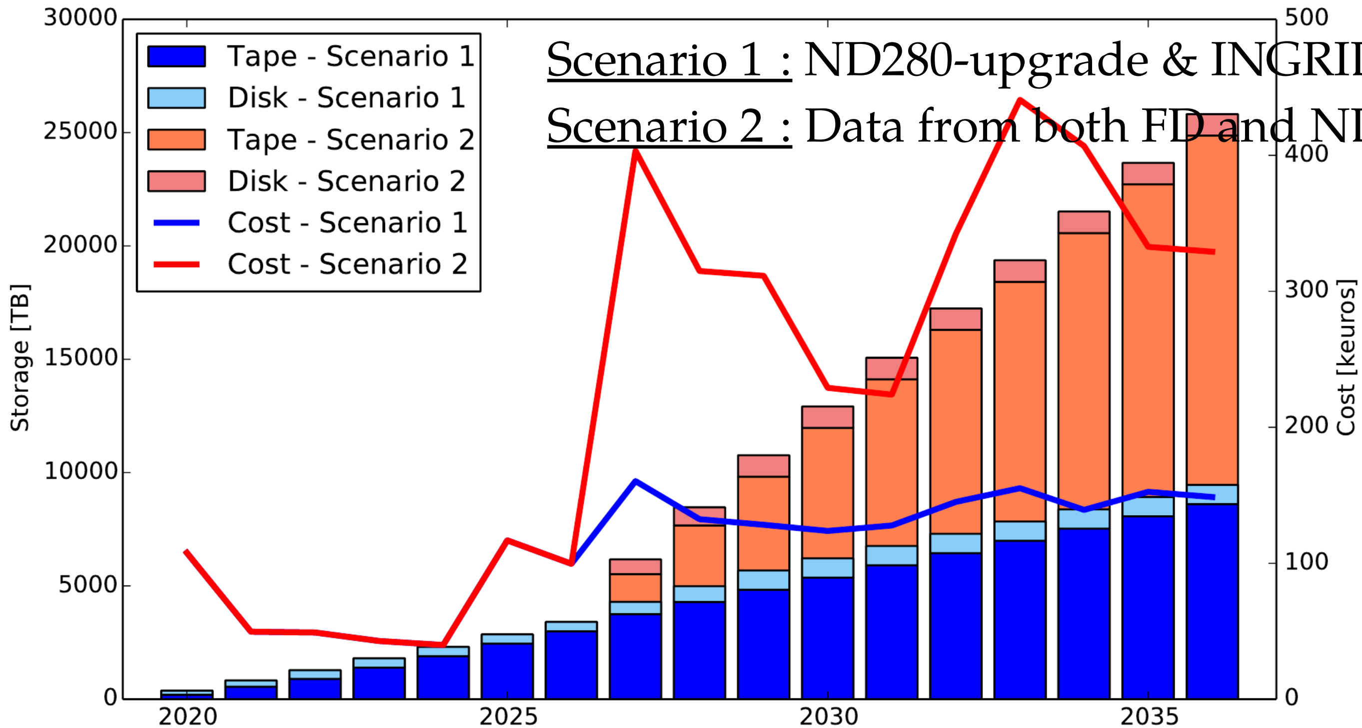
- <u>From now :</u> starts contact with other experiment using PMTs : IceCube gen2, potential HK upgrade, Intermediate Water Cherenkov Detectors.

- Allows the LLR to develop **a board that could be used in future also for all HKROC cousins** (SiPM version etc.).

# The computing proposal

- <u>Option 5 :</u> host a **complete Tier-1** data of HK (scenario 2).

  → And develop all production tools on the cluster.




<u>Scenario 1 :</u> ND280-upgrade & INGRID data.

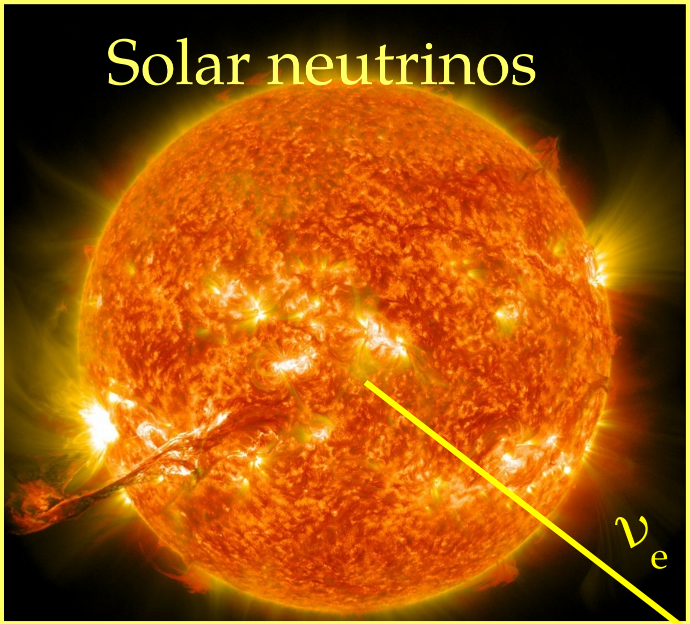
<u>Scenario 2 :</u> Data from both FD and ND.

- <u>Pros :</u>

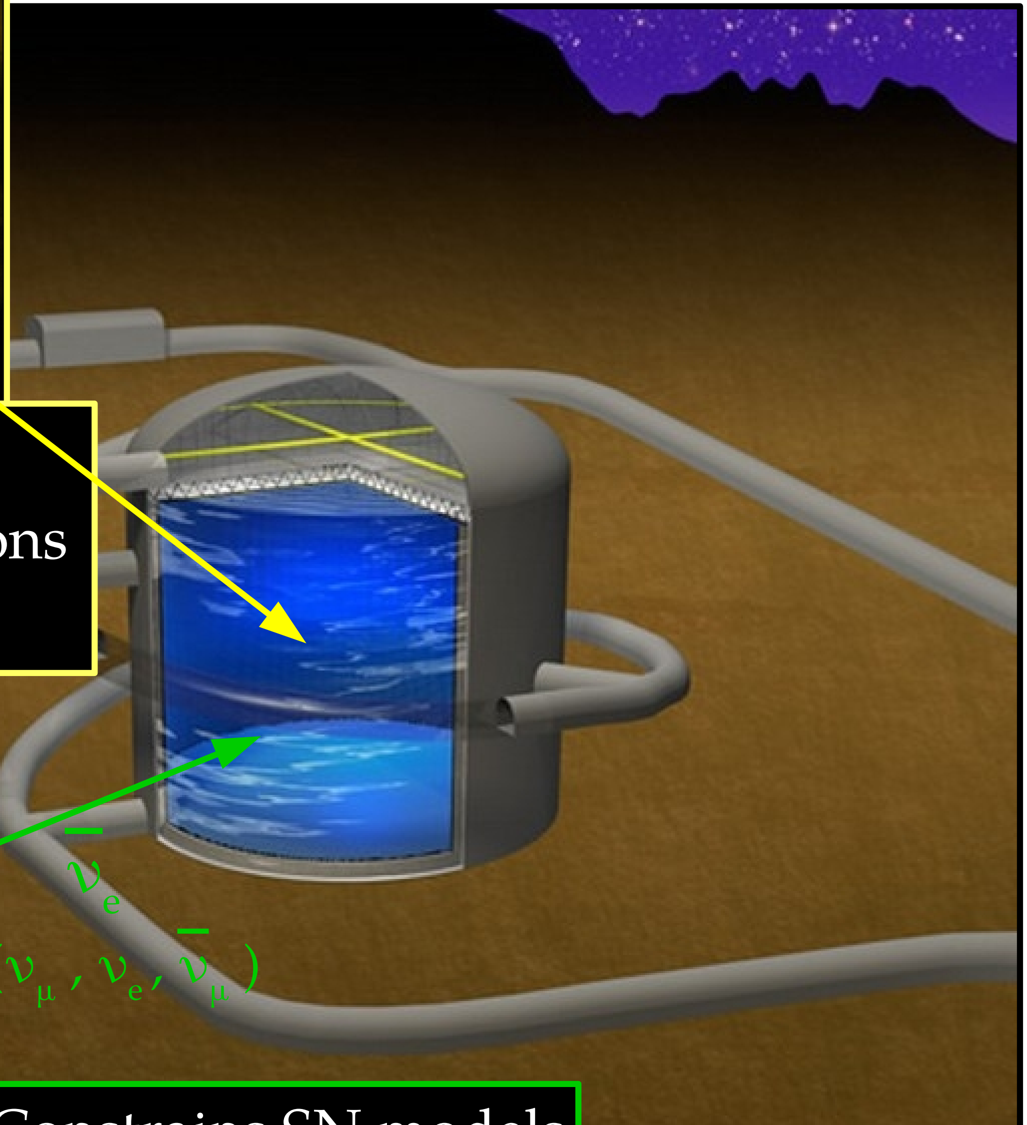
1. No other group has announced the capacity of a full Tier 1 so far.
2. Having all data in France offers a great visibility.
3. Complete synergy with our goal to lead the analyses in both low and high energy sectors.

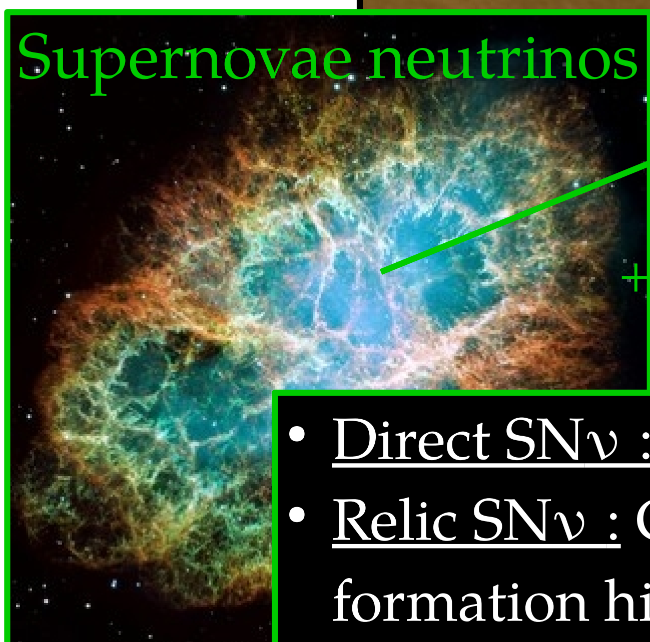
**→ May require fraction of FTE from a software engineer at LLR.**

# Physics case




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

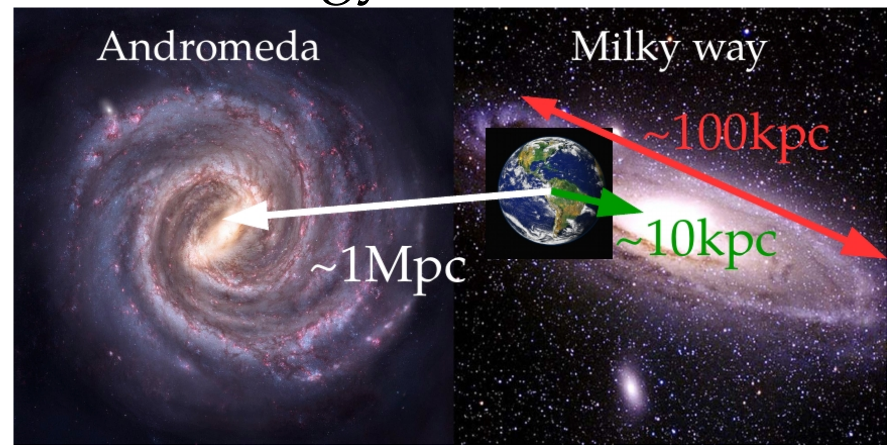



- <u>Direct SNν :</u> Constrains SN models.
- <u>Relic SNν :</u> Constrains cosmic star formation history

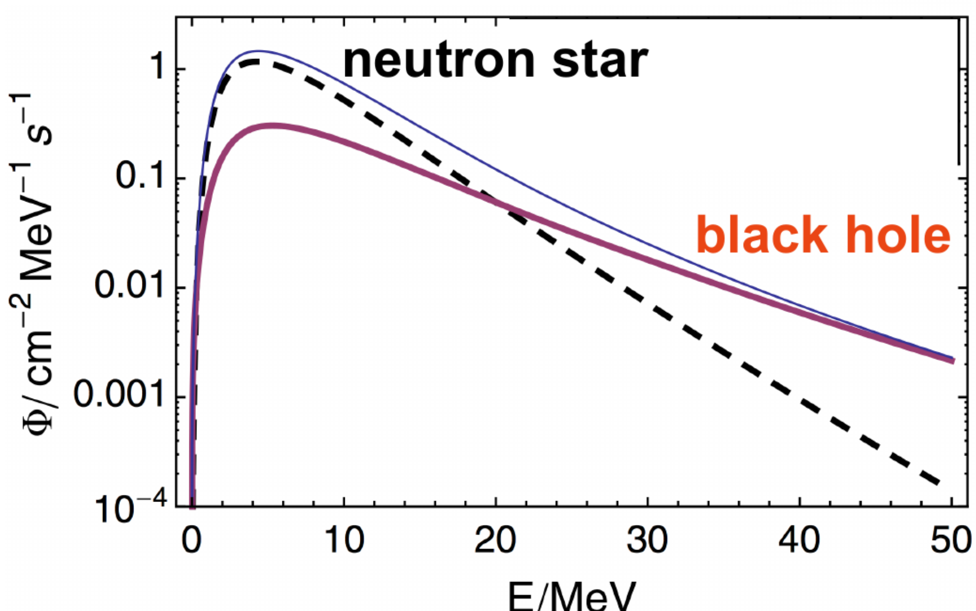
# Supernovae neutrinos

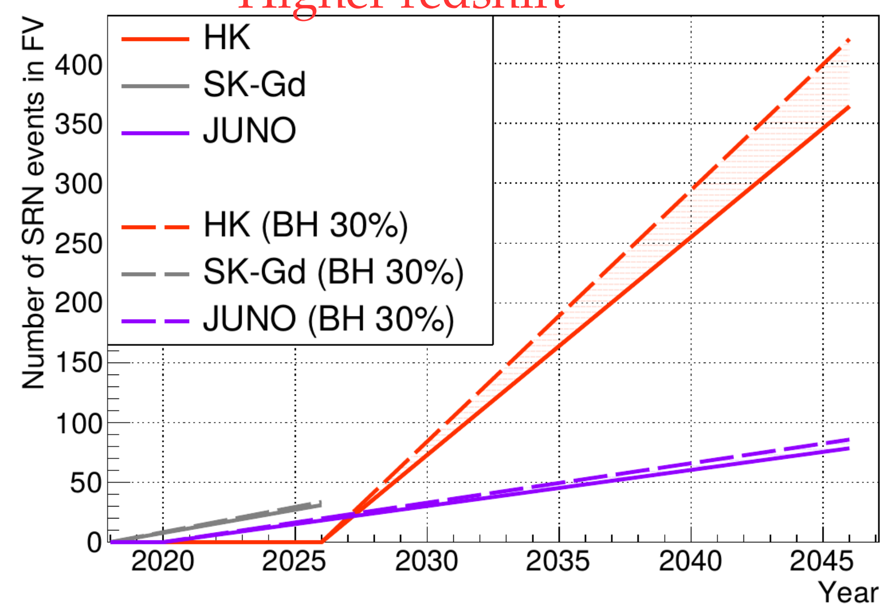
- Unique probe for supernovae ν : 99 % of SN energy → ν.
  - But direct ν detection very rare.
  - HK also sensitive to extra-galactic SNν from Andromeda !




- 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

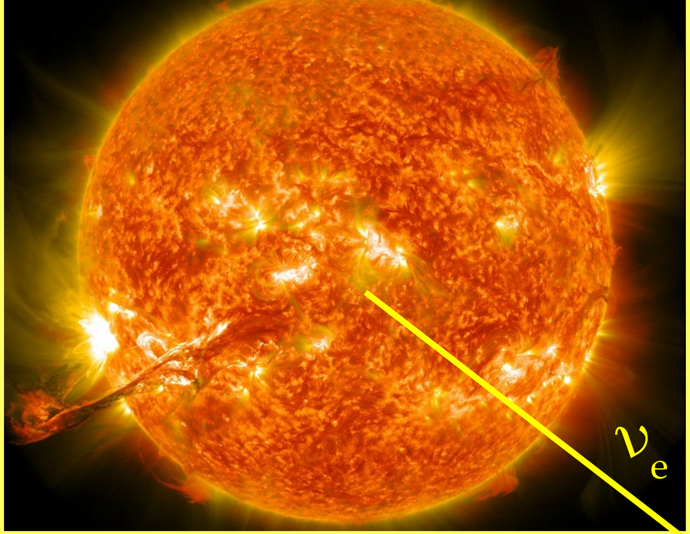



- SK-Gd & then, HK are the pioneer experiments of this domain !

# Physics case

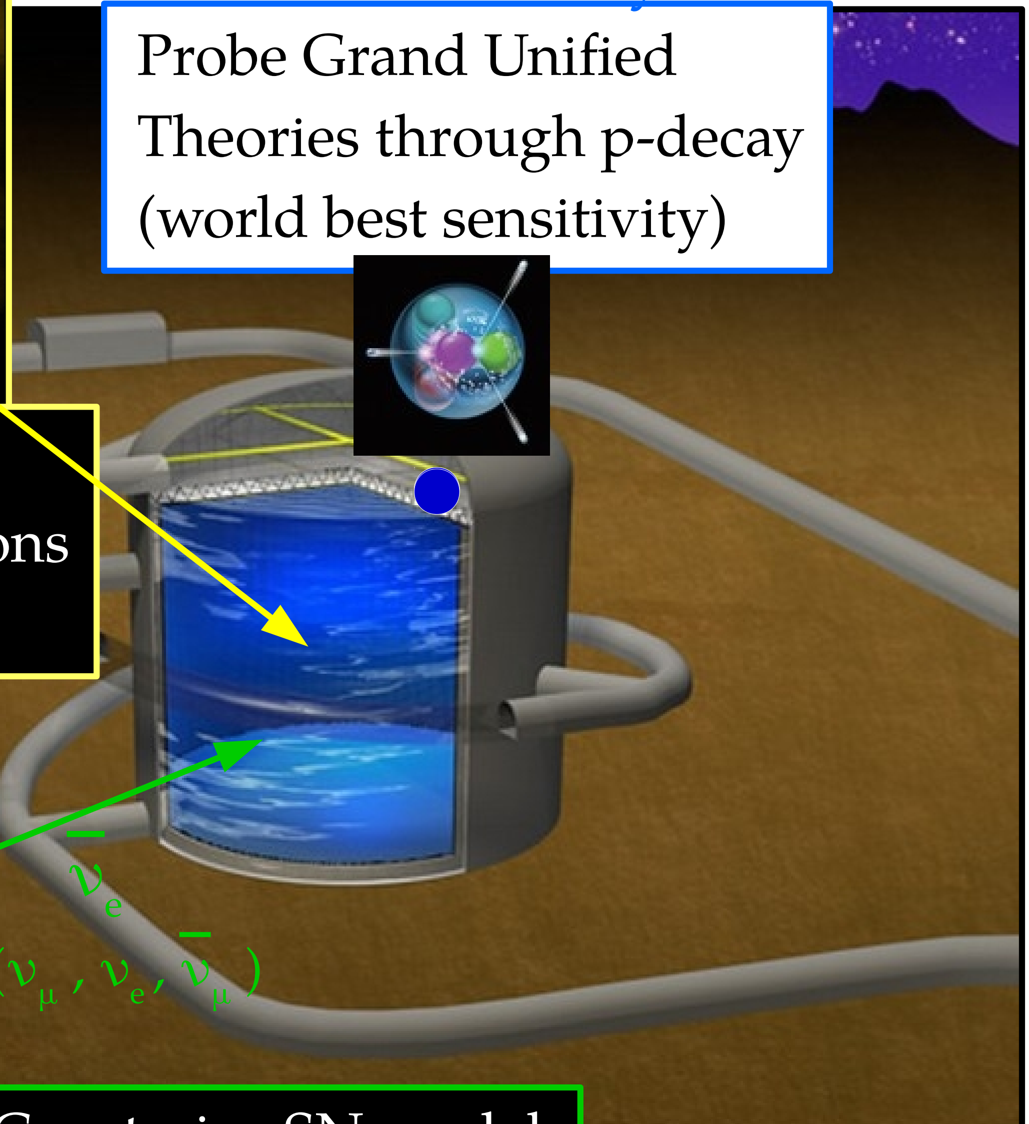
Solar neutrinos



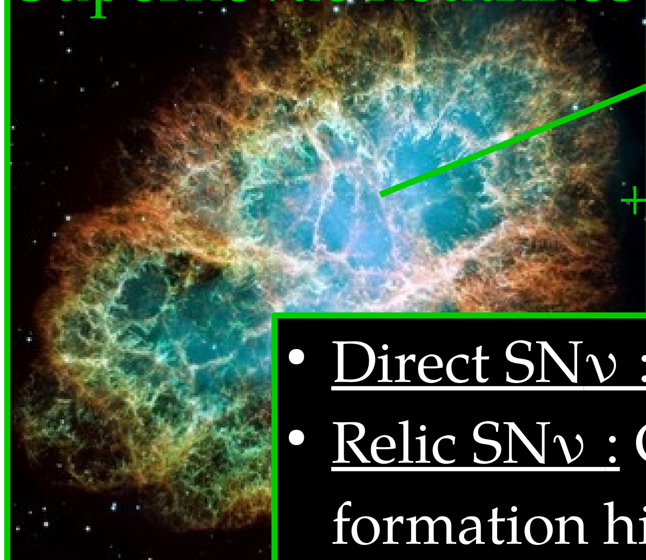

- MSW effect in the Sun
- Non-standard interactions in the Sun.

Proton decay

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




Supernovae neutrinos

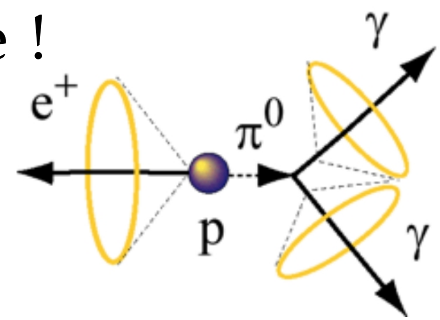


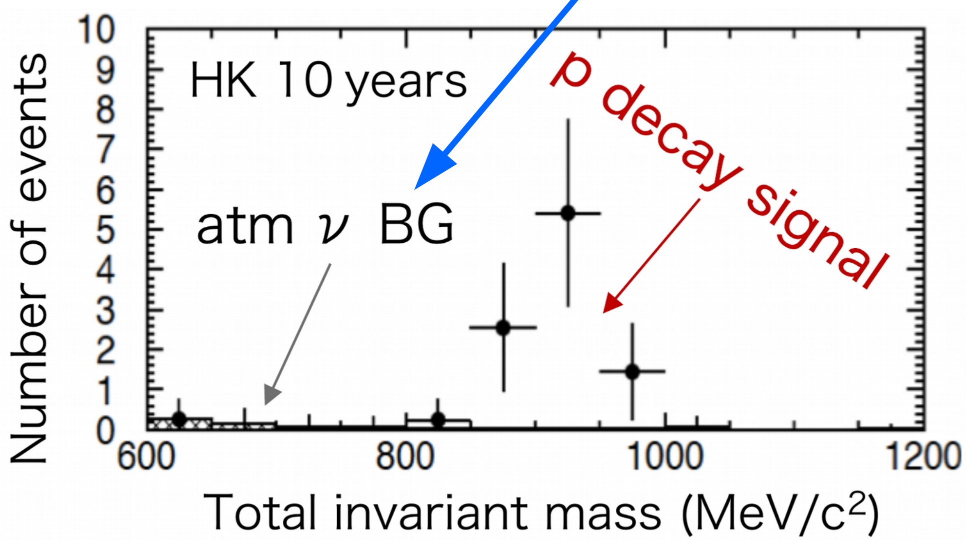
- Direct SNν : Constrains SN models.
- Relic SNν : Constrains cosmic star formation history

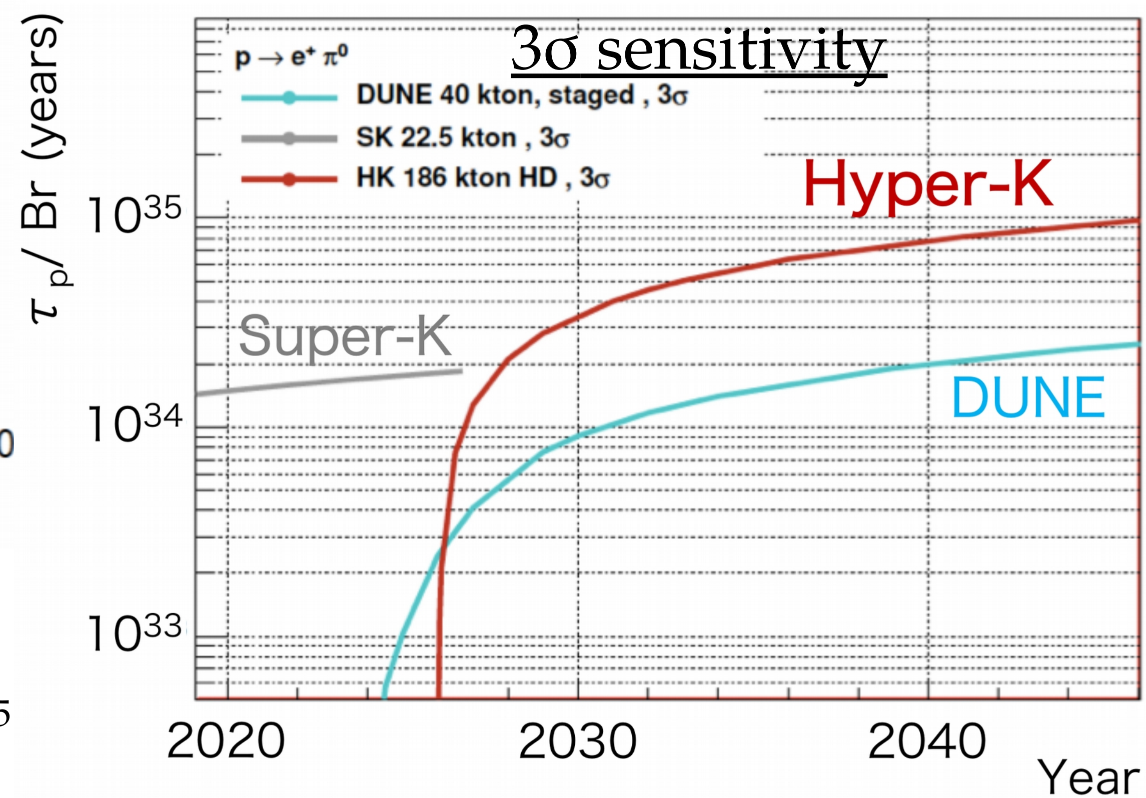
# GUT and proton decay

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

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



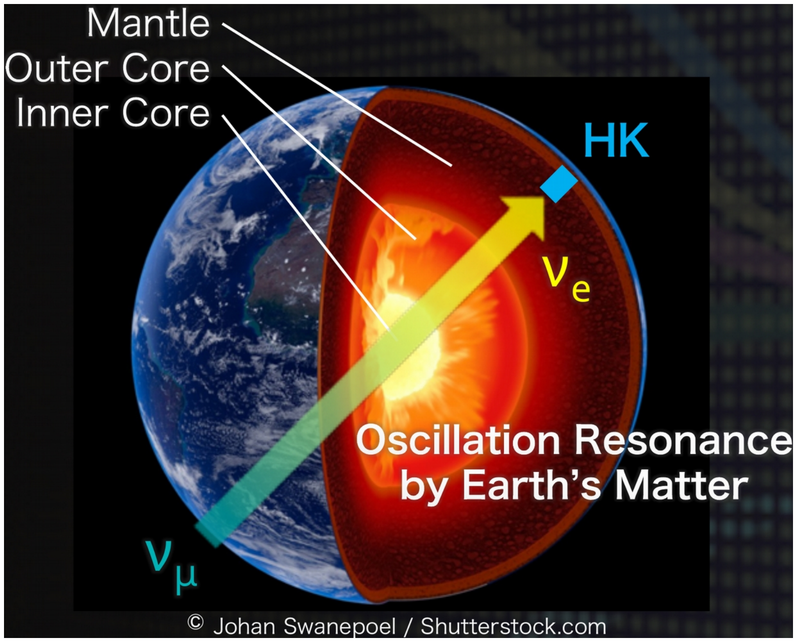



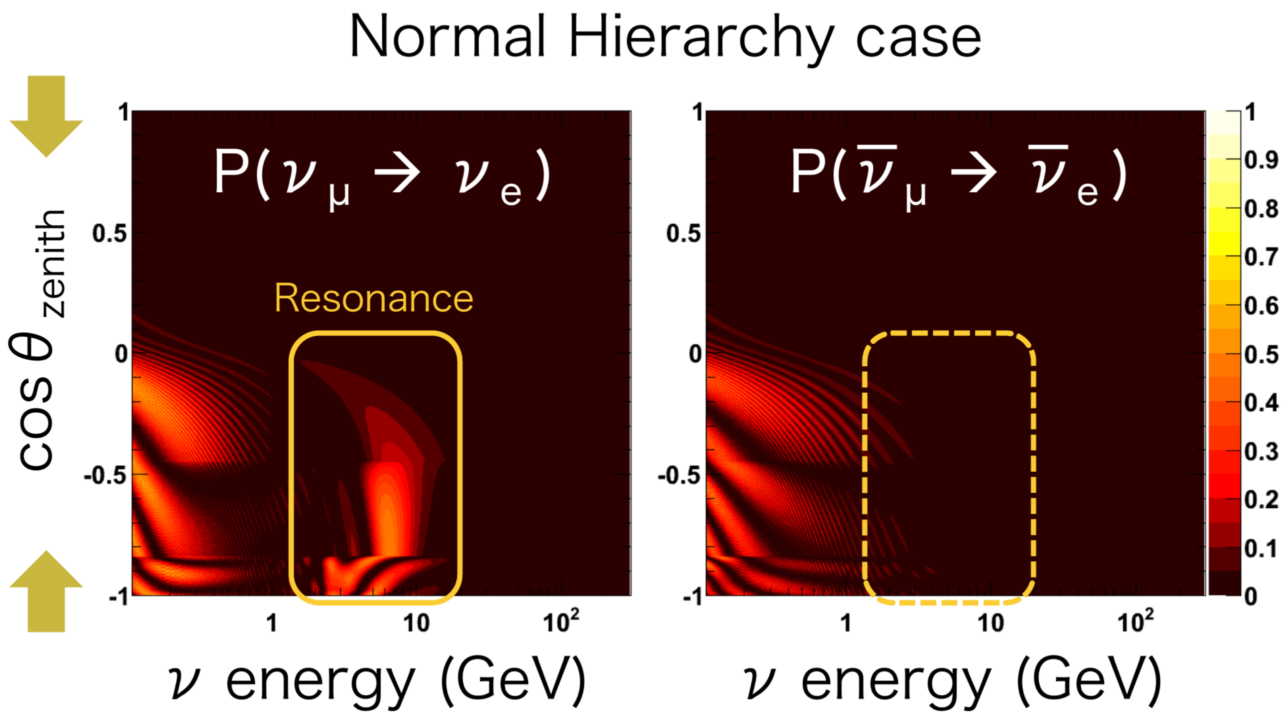

- 3σ sensitivity reach $\tau_P$ /Br = $10^{35}$ years → 1 order of magnitude beyond SK or DUNE

# Atmospheric neutrinos

- Mass-hierarchy can be accessd through matter effects

  → The longer the baseline, the higher the effects



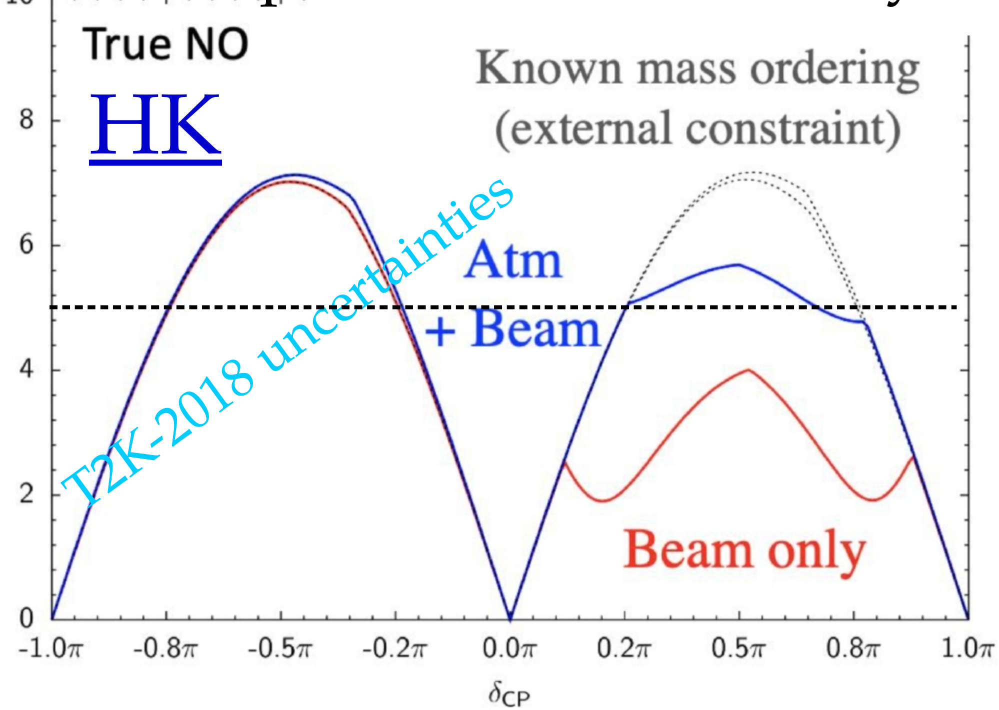

- Mass hierarchy determined with upward-going multi-GeV $\nu_e$ sample :

atm. baseline ≤ 13000 km ≫ 295 km accelerator baseline

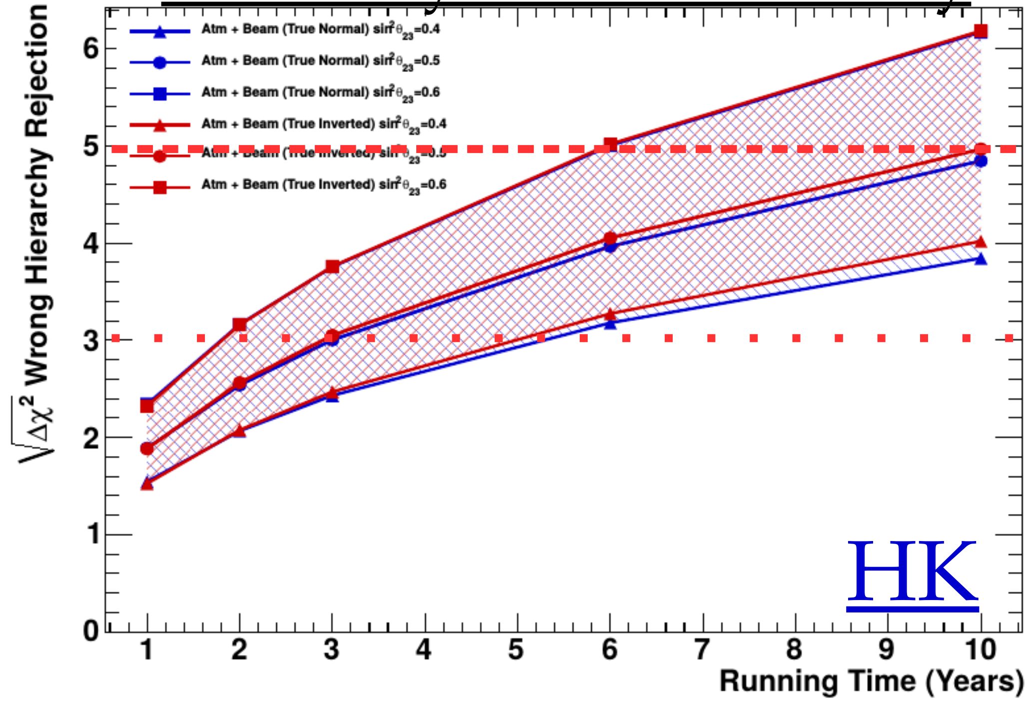
  - Normal hierarchy : enhancement of $\nu_\mu \to \nu_e$ .
  - Inverted hierarchy : enhancement of $\overline{\nu}_\mu \to \overline{\nu}_e$ .

# Combination of atmospheric + beam ν

## Impact on CPV sensitivity

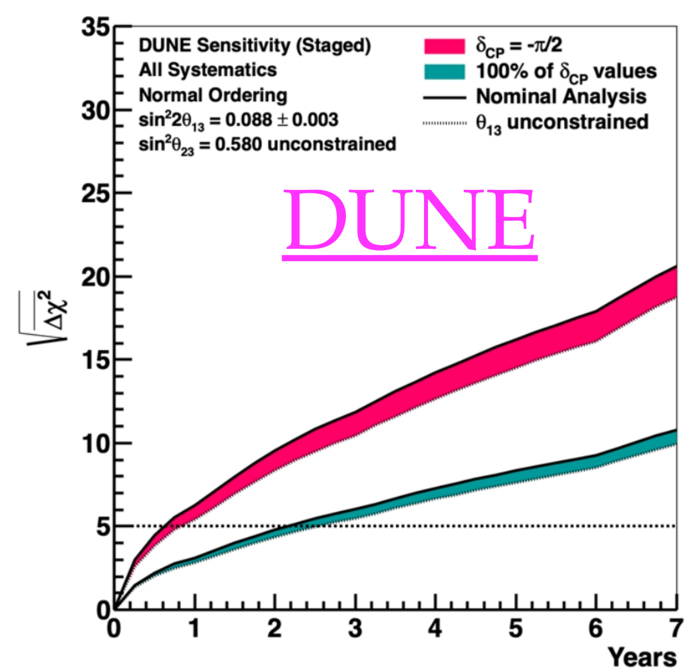



## Sensitivity to mass hierarchy




- 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.