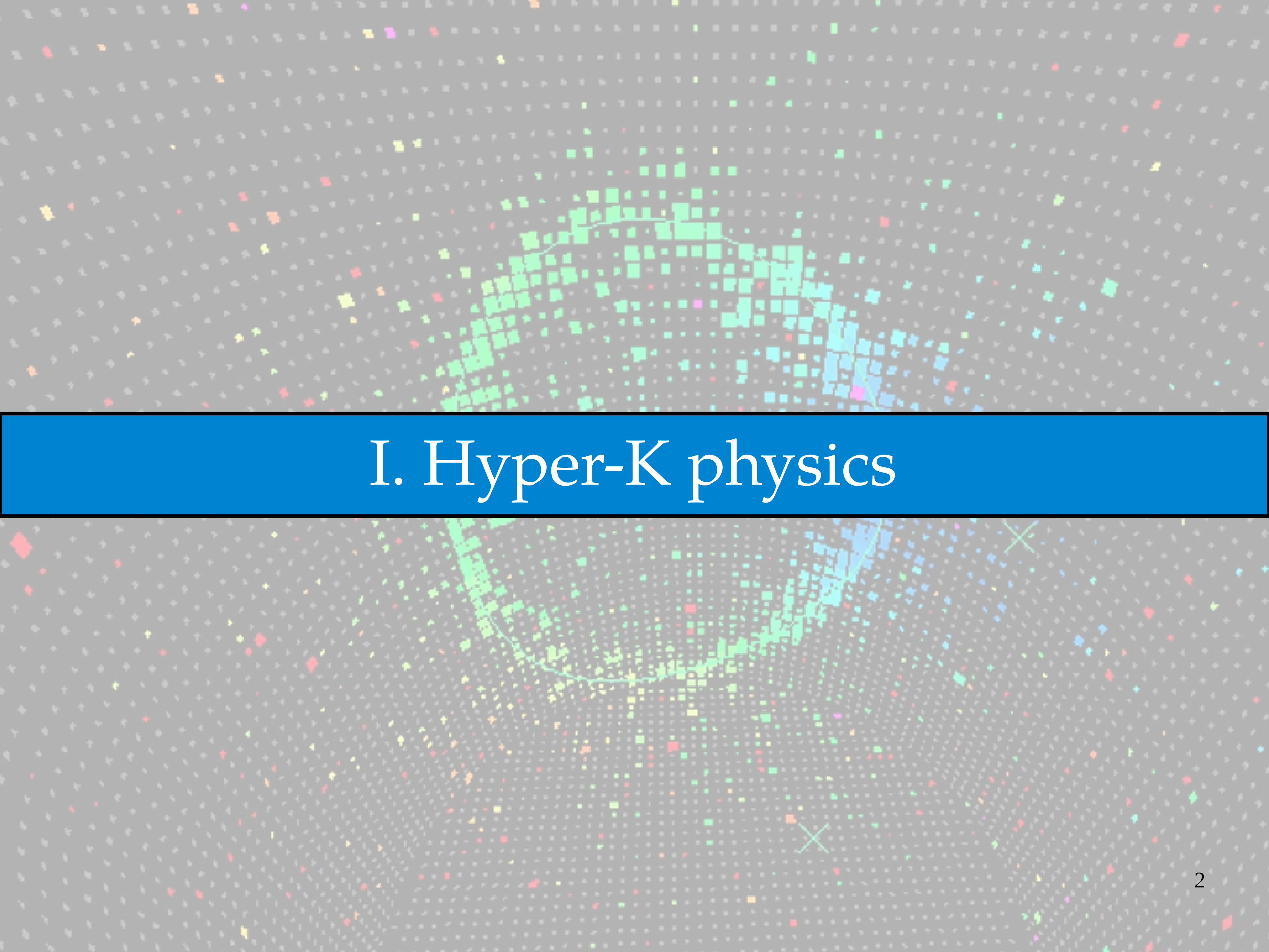
The Hyper-Kamiokande experiment at LLR

Benjamin Quilain representing the LLR neutrino group

& Jerome, Franck, Amine, Mark, Remi, Lorenzo.

Conseil Scientifique du LLR, 2022/10/20



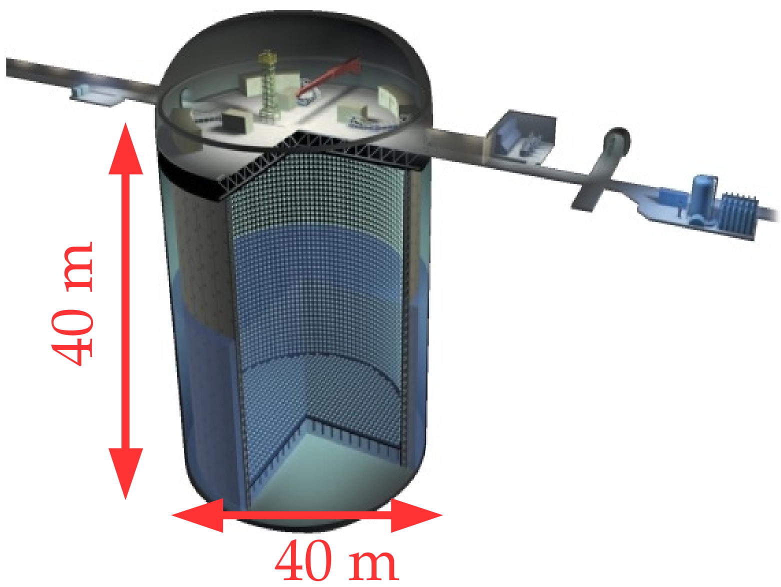
I. Hyper-K physics

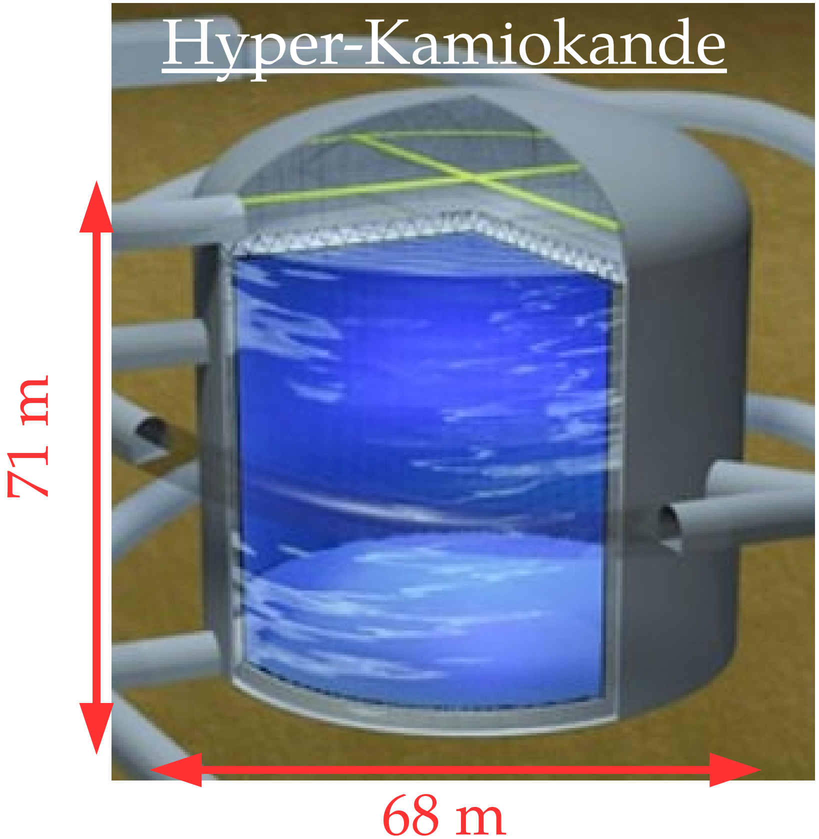
Reminder : what is Hyper-K ?

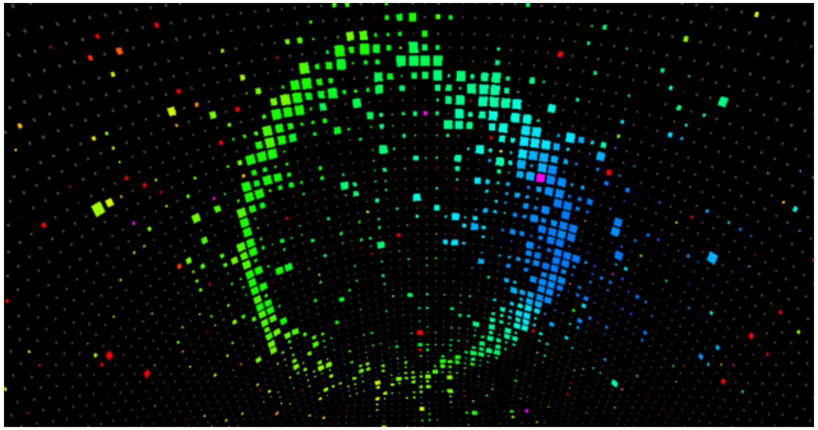
- Next generation of neutrino observatory in Japan→ construction 2020-27

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

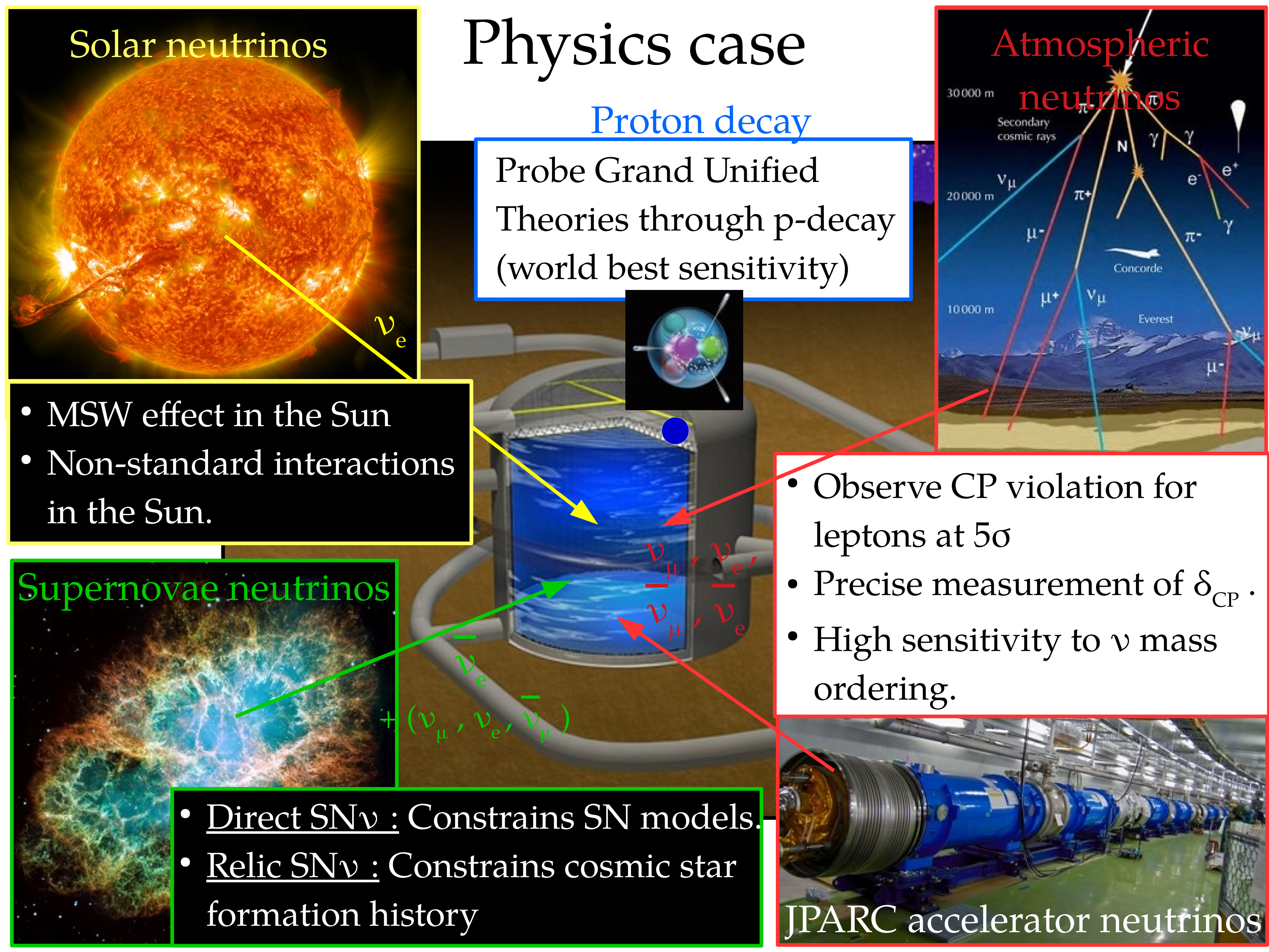
Super-Kamiokande





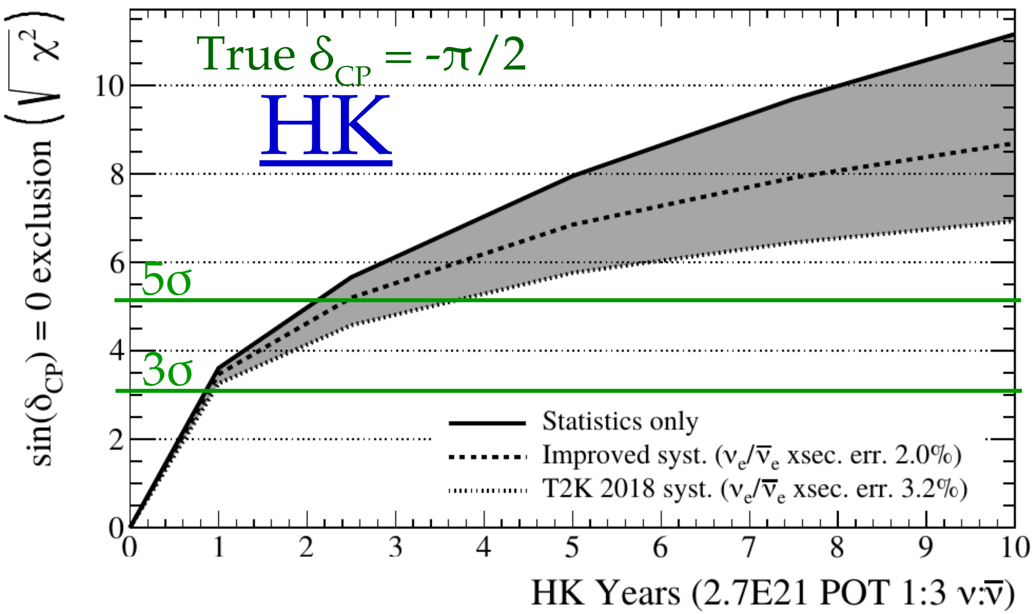


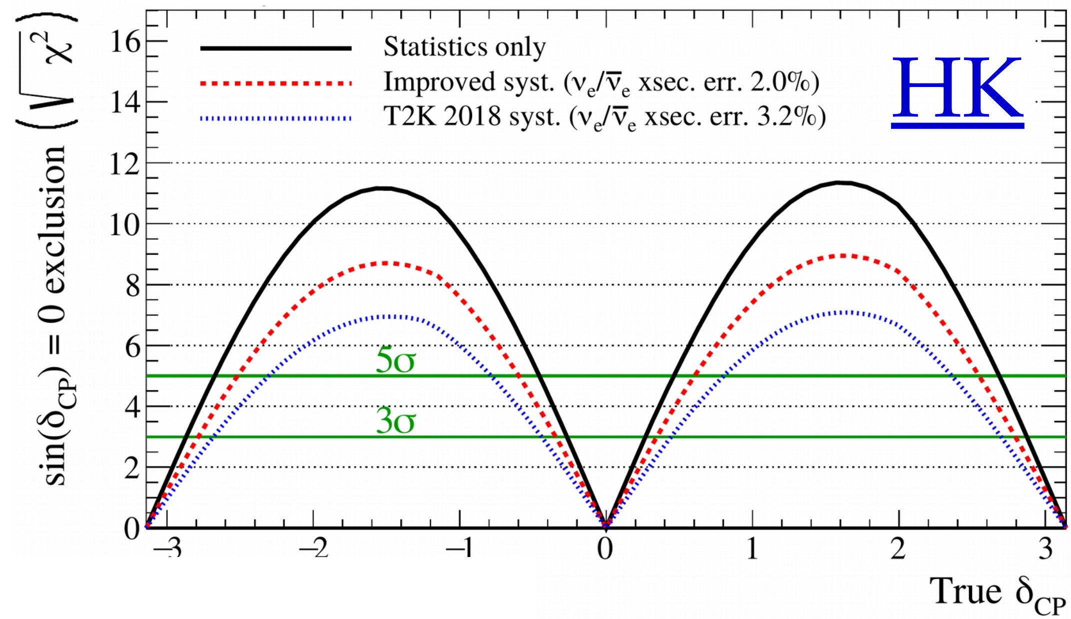
	Super-K	Hyper-K (1st tank)
Site	Mozumi	Tochibora
Number of ID PMTs	**11,129**	**20,000**
Photo-coverage	40%	20 %(×2 sensitivity)
Mass / Fiducial Mass	50 kton / **22.5 kton**	260 kton / **187 kton**


Physics case
Solar neutrinos
ν_e
• 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
30 000 m
20 000 m
10 000 m
Secondary cosmic rays
Concorde
Everest
• Observe CP violation for leptons at 5σ
• Precise measurement of δ_{CP} .
• High sensitivity to ν mass ordering.
ν_μ, ν_e, $\bar{\nu}_\mu$, $\bar{\nu}_e$
Supernovae neutrinos
$\bar{\nu}_e$
+ (ν_μ , ν_e, $\bar{\nu}_\mu$)
• Direct SNν : Constrains SN models.
• Relic SNν : Constrains cosmic star formation history
JPARC accelerator neutrinos

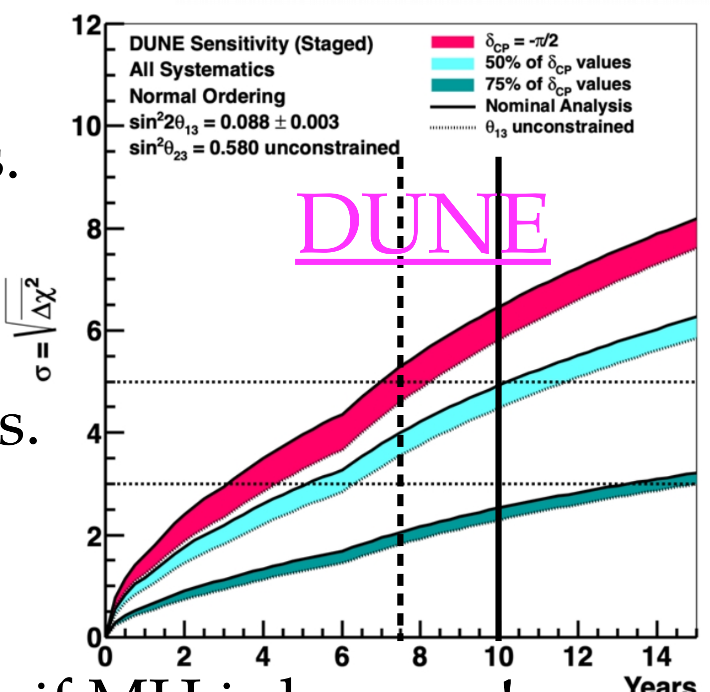
Sensitivity to CP violation

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





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

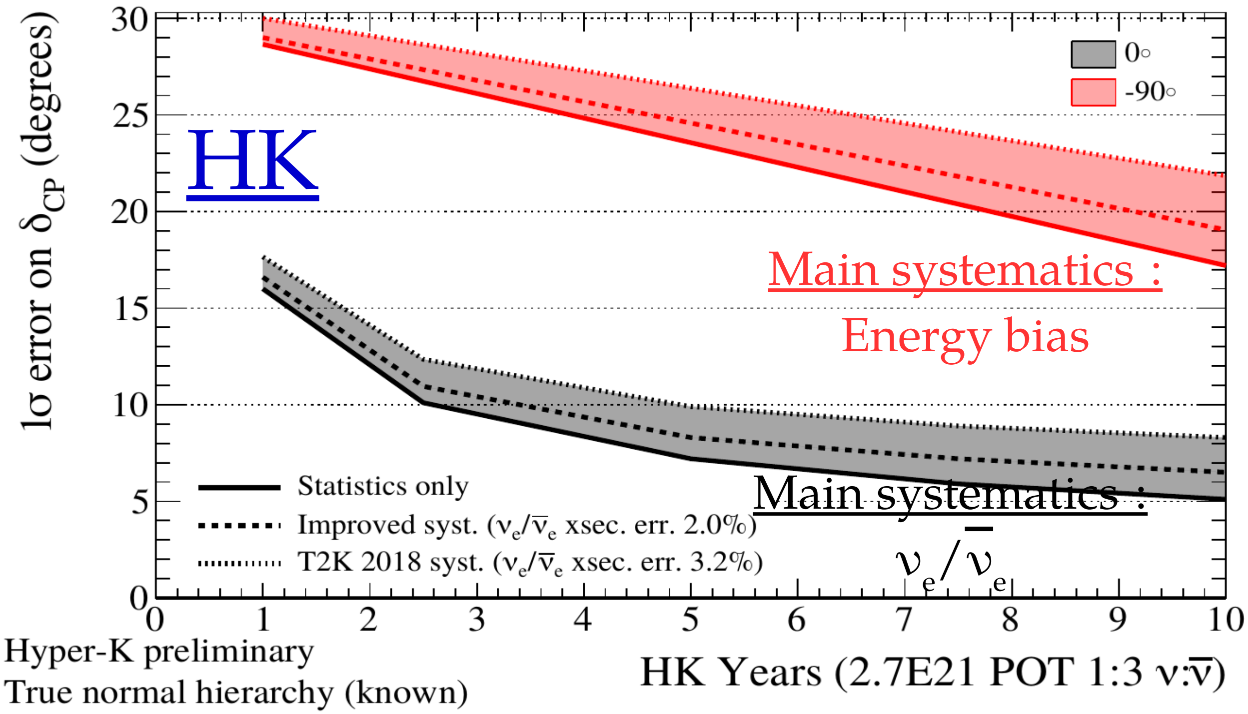


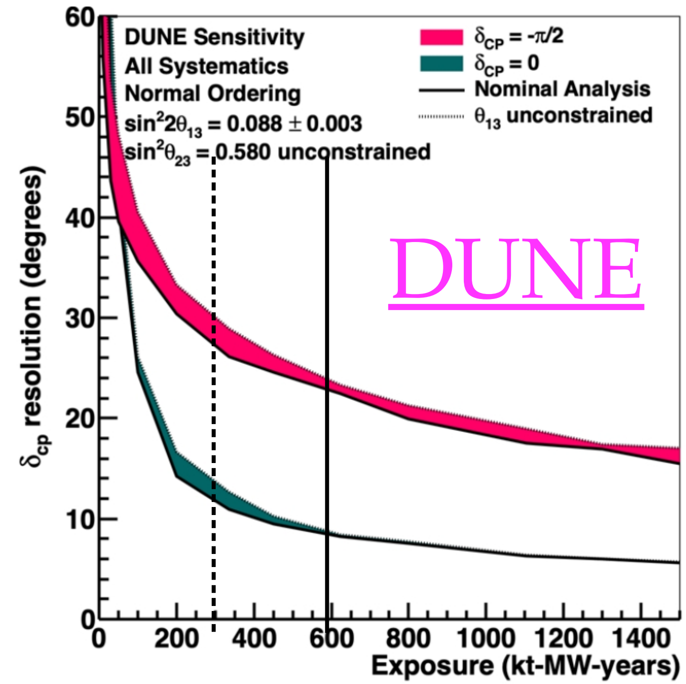
- HK 10 years : 5σ sensitivity on 60% of δ_{CP} values.
  → DUNE : 5σ sensitivity on 40%
- HK has world-best sensitivity to CP violation … if MH is known !

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 …



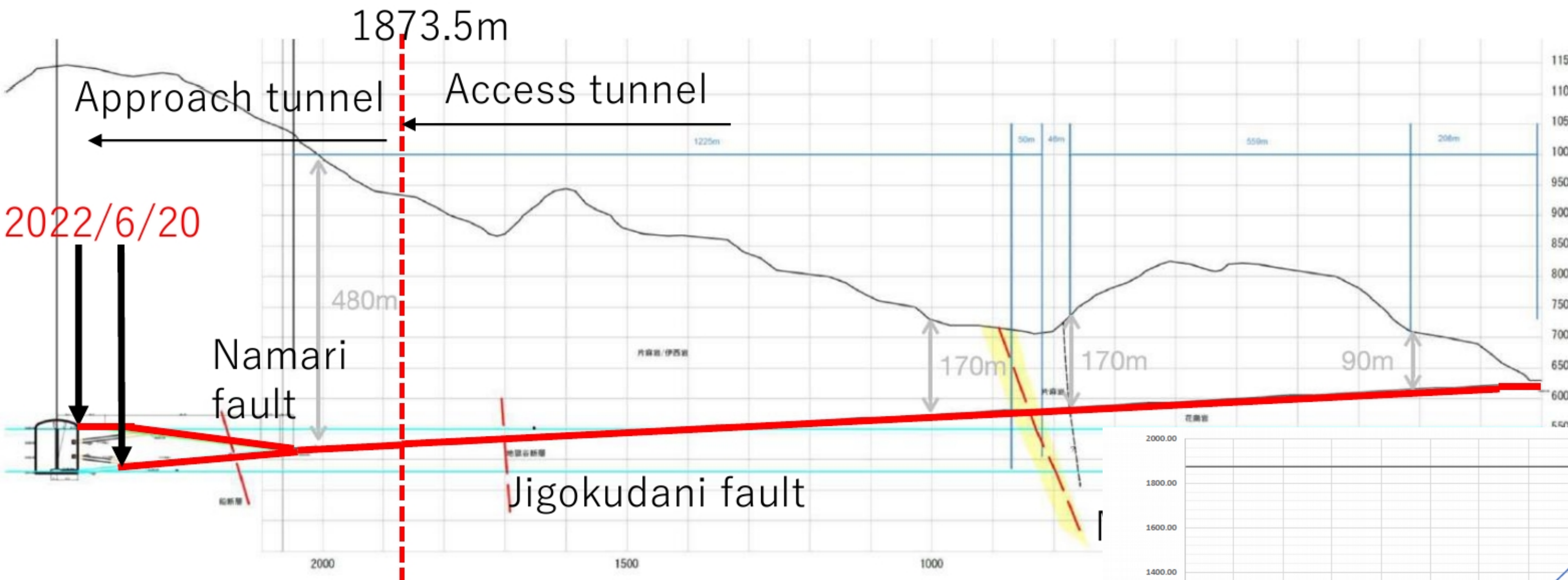


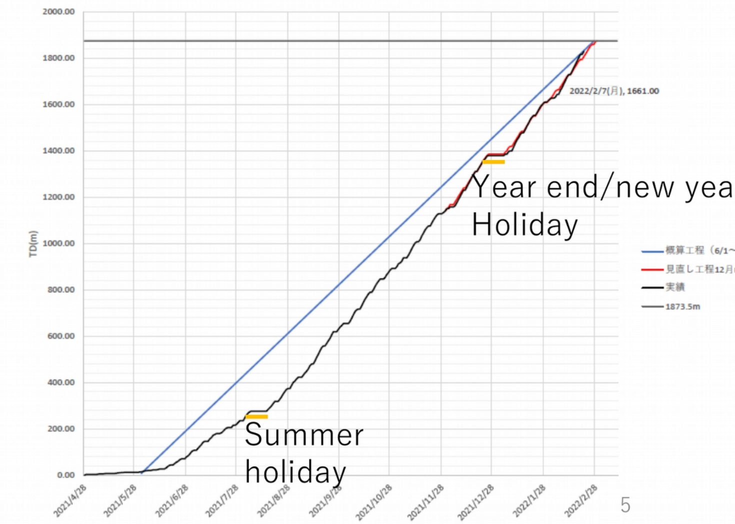
	5 years [HK & DUNE]	10 years [HK & DUNE]
CP conserved $\delta_{CP} = 0$	8° & 13°	6° & 9°
$\delta_{CP} = -\pi/2$	25° & 29°	19° & 24°

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

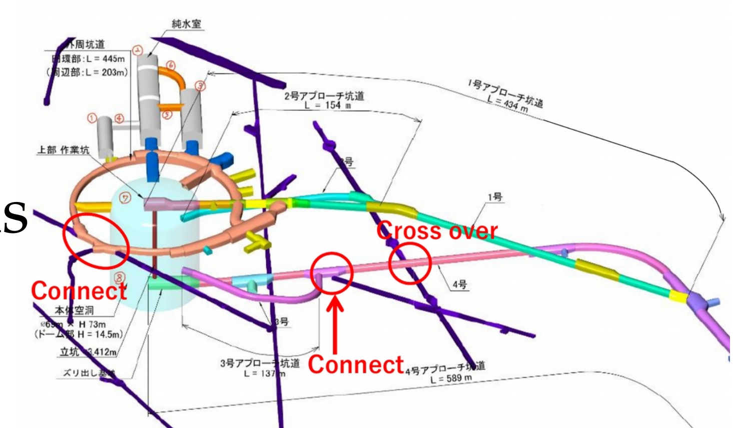
II. Updates on HK project

Hyper-K excavation



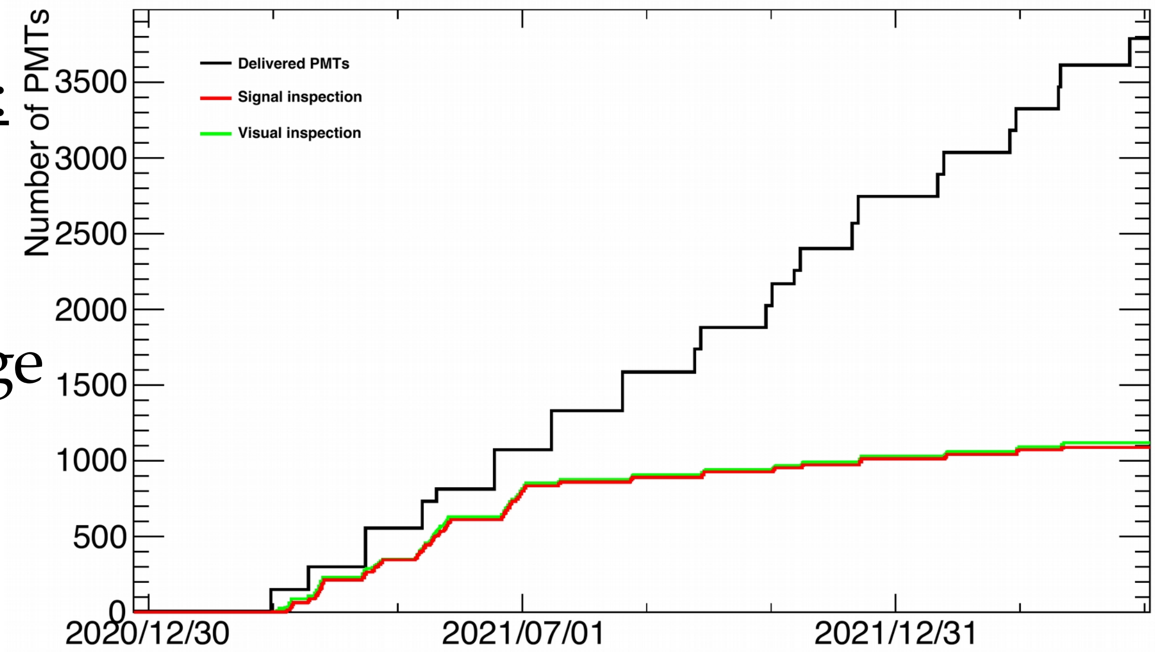


- <u>Excavation of the access tunnel (2 km) is over</u> finished the 25/02/22 → In-time !
- <u>Excavation of approach tunnels is over</u> → > 400 m. We reached the dome region.
- We are currently excavating the circular tunnels around the dome. <u>→ No delay in excavation.</u>



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.

III. Our proposal for contribution

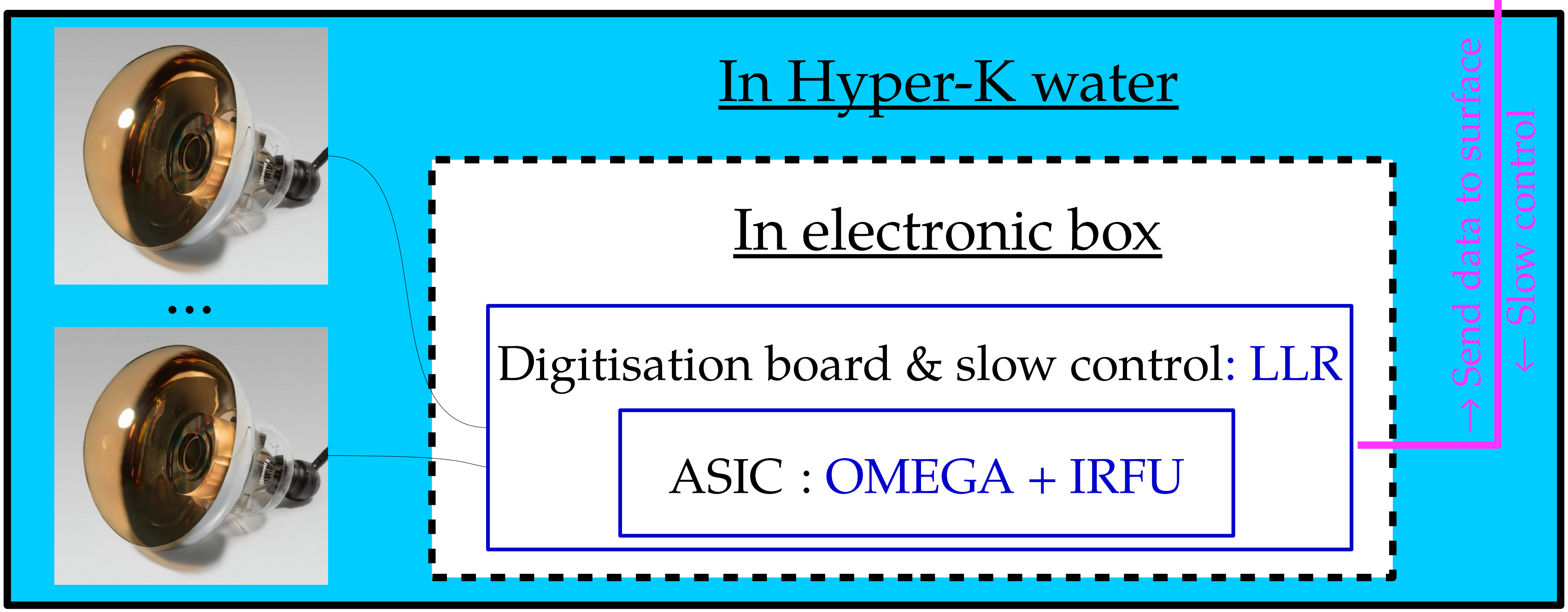
HK far detector electronics

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

- PMT signal to be readout by electronics under water :

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

Clock generation & distribution
LPNHE + IRFU



LLR proposal : develop the whole PMT Q & T digitization system

→ Absolutely central role in HK !

HKROC organigram

Leader : B. Quilain

PI : S. Bolognesi, O. Drapier

ASIC coordinator : F. Dulucq

Board coordinator : J. Nanni

CEA/IRFU
F. Bouyjou (Engineer)
E. Molina (Engineer)
E. Delagnes (Engineer)
S. Bolognesi (Phys)
D. Carabadjac (PhD)
S. Emery (Phys)
S. Hassani (Phys)
G. Vasseur (Phys)

ILANCE
M. Gonin (Phys)
G. Pronost (Postdoc)

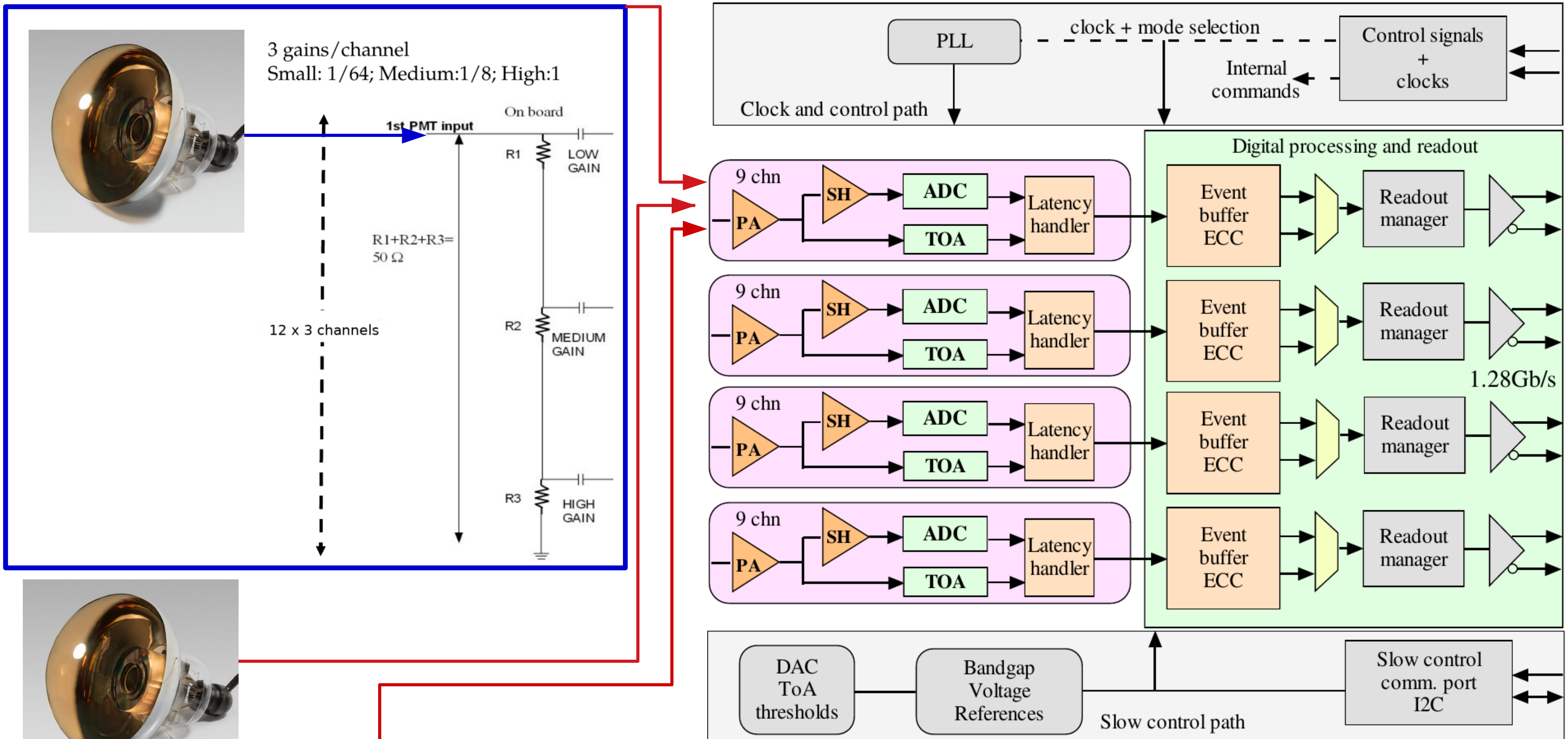
OMEGA
S. Callier (Engineer)
S. Conforti (Engineer)
C. De la Taille (Engineer)
P. Dinaucourt (Engineer)
F. Dulucq (Engineer)
C. de la Taille (Engineer)
A. Mghazli (Engineer)
L. Raux (Engineer)

LLR
A. Afiri (Engineer) → Firmware
L. Bernardi (Engineer) → DAQ & test bench
F. Gastaldi (Engineer) → Supervision & protection circuit
J. Nanni (Engineer) → Leader, supervision, schematics
M. Louzir (Engineer) → Layout
A. Beauchene (PhD)
Confidential (Postdoc)
M. Buizza-Avanzini (Phys)
O. Drapier (Phys)
T. Mueller (Phys)
P. Paganini (Phys)
B. Quilain (Phys)

+ R. Guillaumat (Engineer) → Layout

The HKROC digitizer

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

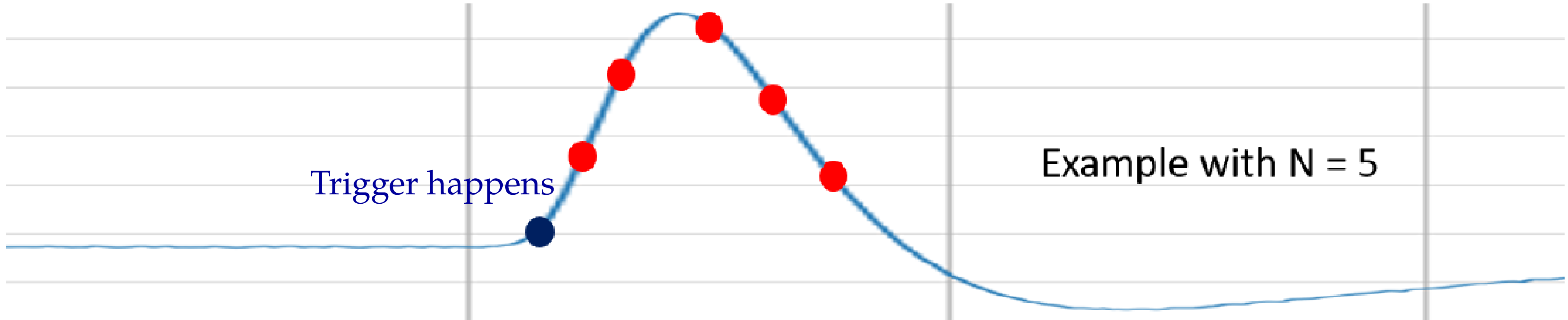


- TSMC CMOS 130nm etching.
- Dynamic range from 0 – 2500 pC : 3 gains / channel.
- 4 readout / ASIC @1.28 Gb/s : 1 readout ↔ 3 PMTs.
- <u>If 1 PMT trigger :</u> read all 3 PMTs of 1 readout.

Overview of the HKROC digitizer

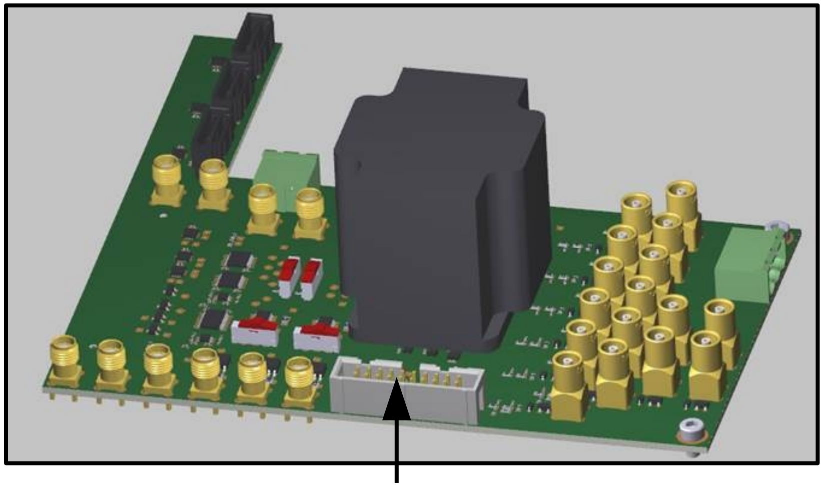
- HKROC is a waveform-like digitiser @40 MHz→ 1 point every 25 ns.

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



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

HKROC prototype v1



Board schematics : F. Gastaldi, J. Nanni.

Firmware : A. Afiri.

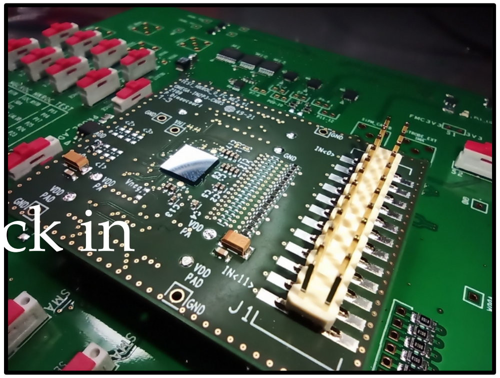
Board layout : R. Guillaumat, M. Louzir

- 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 :

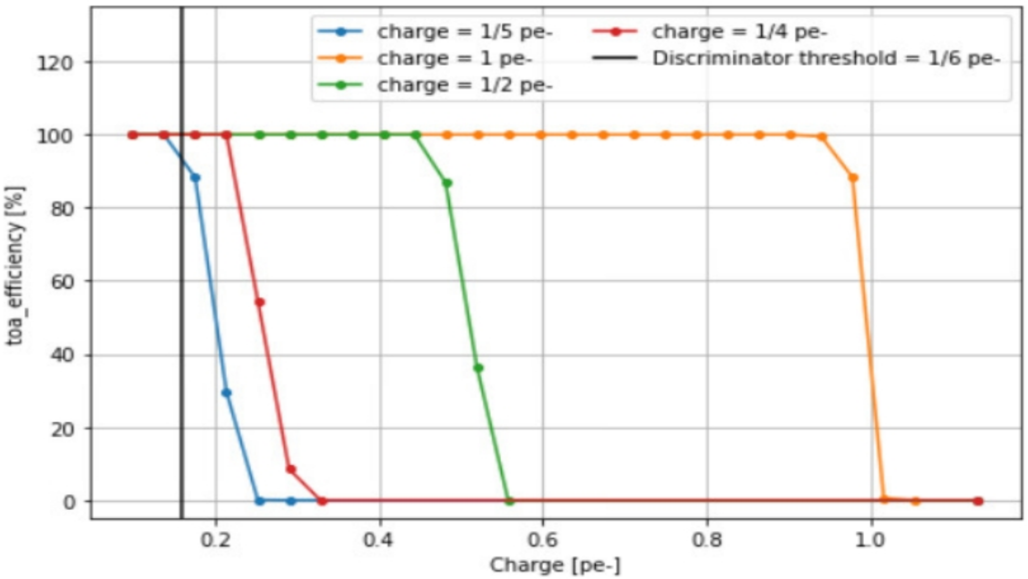
  → Chip & board came back in Jan. 2022 (pandemic).

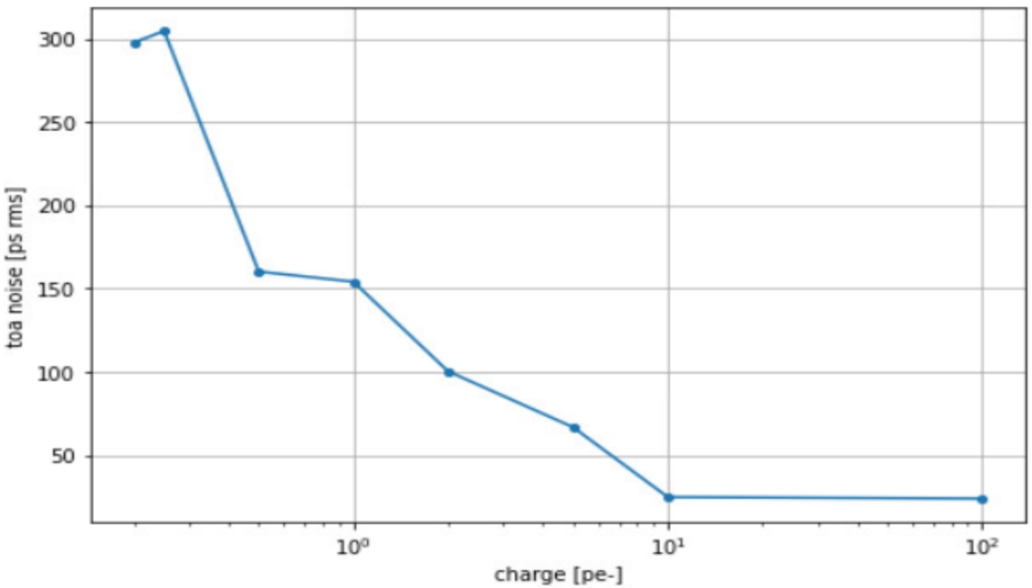
  → Worked hard to finalize tests for June.



HKROC digitizer - trigger & timing results

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





- Set threshold at 1/6 p.e.

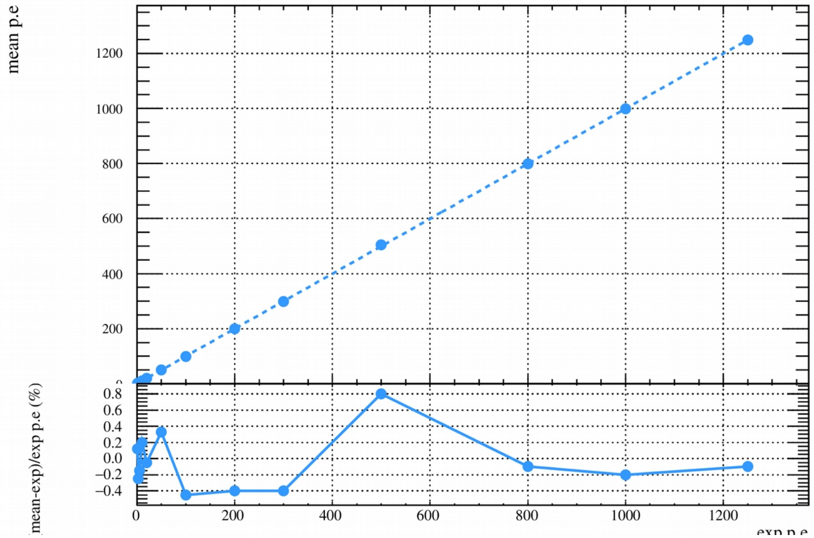
- Hit efficiency :
  90 % for 1/5 p.e events
  ~100 % if ≥ 1/4 p.e

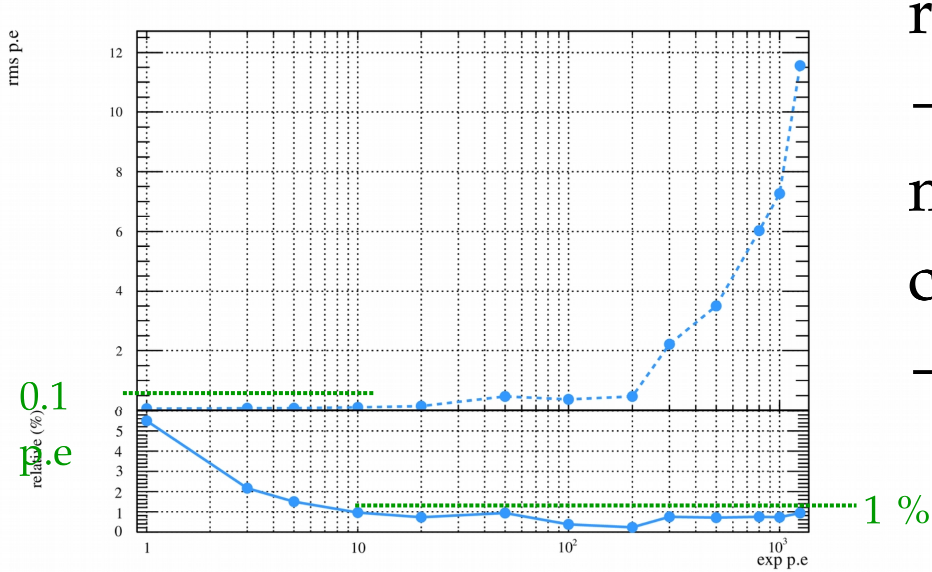
- Very low noise : < 1 Hz.

- 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

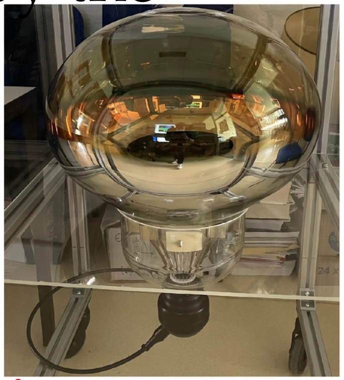




- <u>Charge linearity < ±1%</u> [1 to 1250 p.e.]

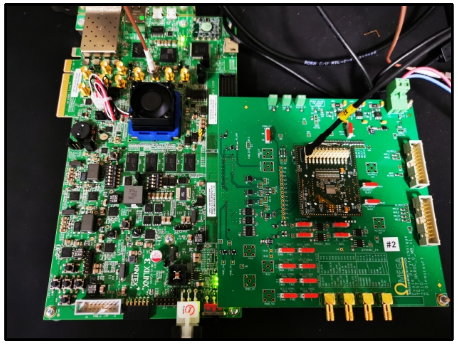
- <u>Charge resolution :</u>
  < 0.1 p.e @≤ 10 p.e, < 1 % otherwise.

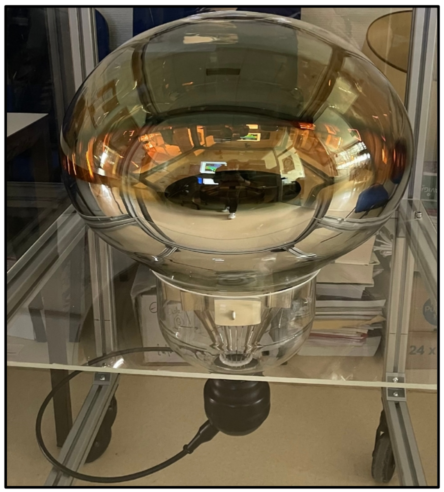
→ All characteristics fulfill HK requirements & confirmed w/ PMT.
→ Large improvements w/ HKROC much beyond requirements by the collaboration
→ <u>Ex:</u> dead-time ↓ **from 1 µs → 30 ns.**



- 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

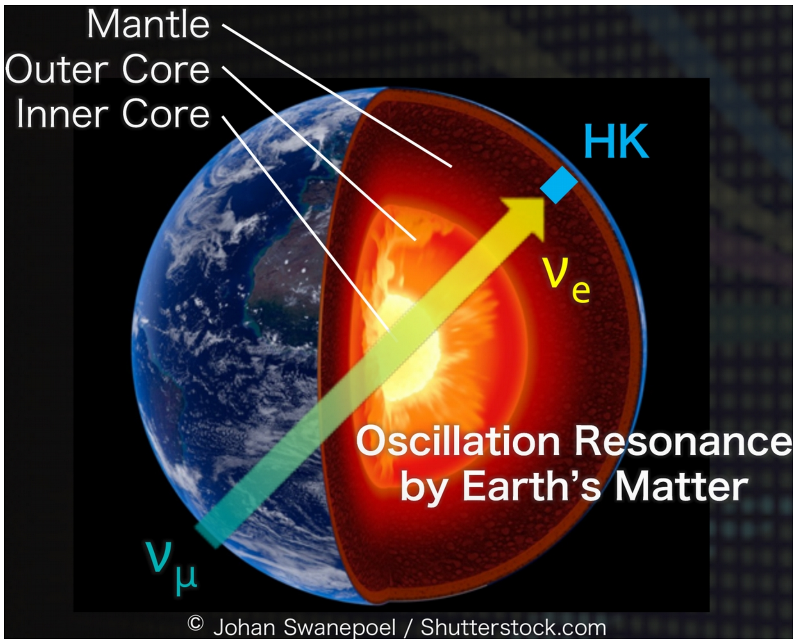




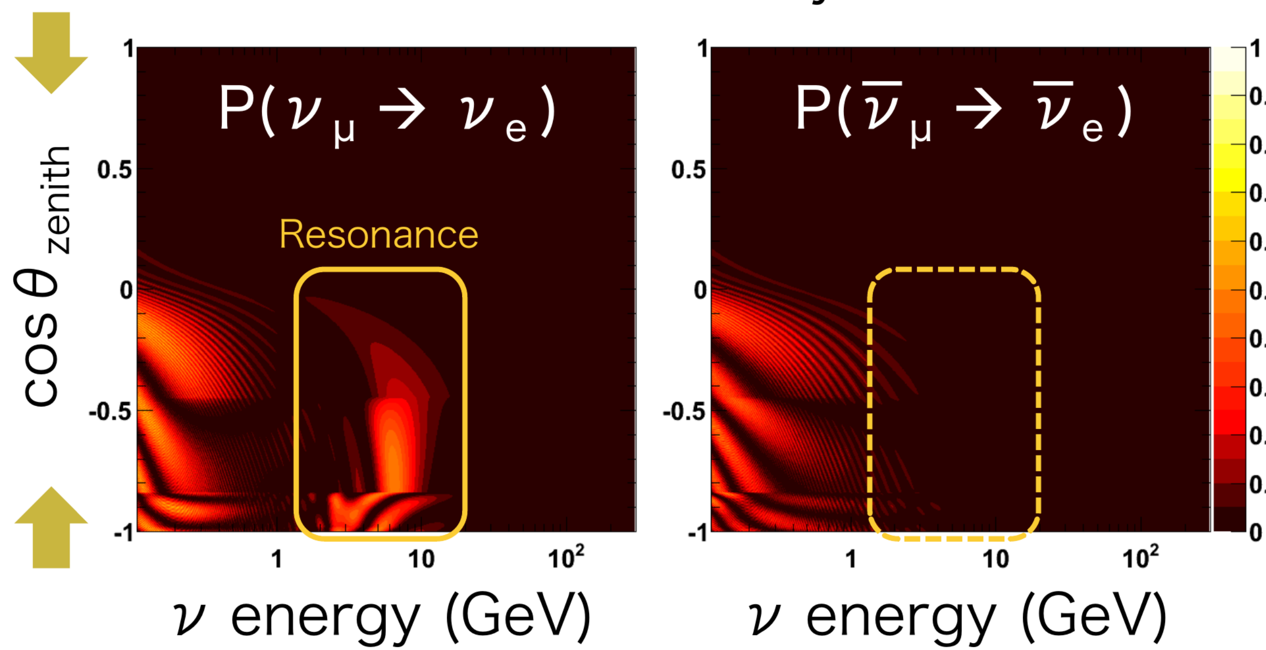
Item measured	Performances	
Trigger efficiency at 1/6 p.e.	$>90\%$ for 1/5 p.e signals 100% for $\geq 1/4$ p.e signals	✓
Trigger noise at 1/6 p.e.	<1 Hz (No trigger observed in 10 s)	✓
TDC resolution	150 ps at 1 p.e, 70 ps at 5 p.e, 25 ps >10 p.e Validated with PMT	✓
Charge linearity	$<0.5\%$ in high & 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	≤ 30 ns for two signals of same amplitude ≤ 30 ns for a prompt ≤ 5 p.e and secondary of 1 p.e <1 μs for a prompt signal ≤ 850 p.e and secondary 1 p.e	✓
Maximal hit-rate w/ 100% eff.	415 kHz in normal mode 950 kHz in SN-mode Potential extension beyond to be studied.	✓
Cross-talk	Hit probability in neighbouring channel of a 1250 p.e signal is $<0.1\%$ *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	✓

Impact on neutrino mass-ordering

Detection of decay-electrons plays a key-role in atmospheric & beam physics → **Example of Mass Hierarchy, key physics goal of HK.**

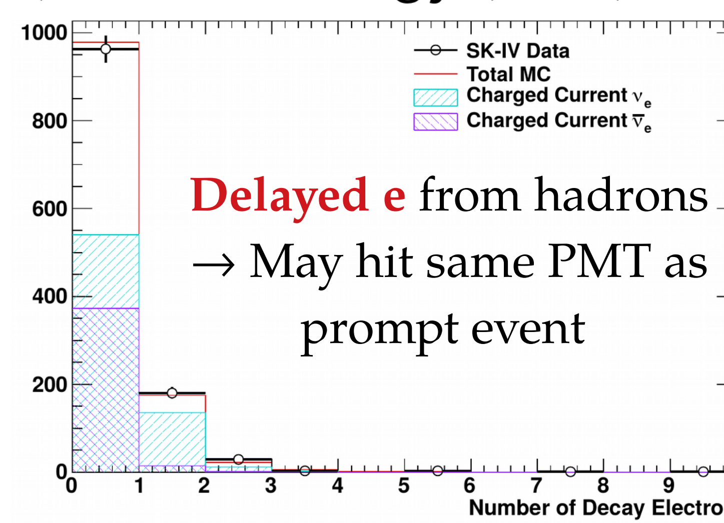


Normal Hierarchy case



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

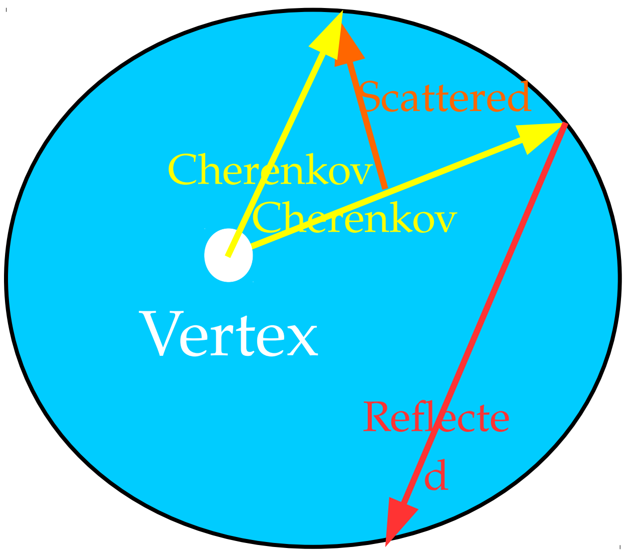
  → Decay-e are central to separate ν_e / $\bar{\nu}_e$.
- Decay-e hit efficiency increased from 68 % → 98 % w/ HKROC !!

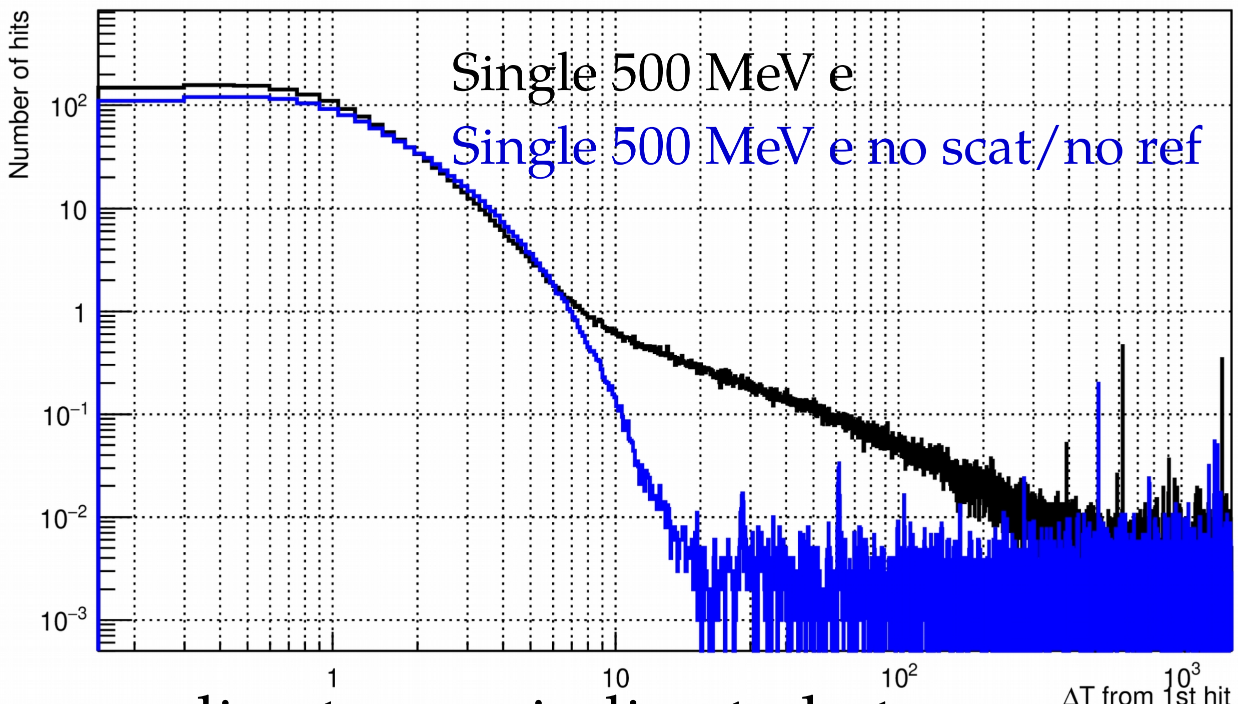


Impact on scattering & reflection

- **<u>Separation of direct & indirect light</u>** has an important impact on high-energy events in SK & HK.
  → Impact reconstruction algorithm, key question in calibration etc.
  → HKROC low dead-time offers unique possibility to separate direct & indirect photons hitting same PMT.

<u>ΔT between hits :</u>





- Half of the PMT are hit by one direct + one indirect photon.
- 65 % of PMT hit by 2 photons w/ Δ T ≥ 10 ns.
- 30 % of PMT hit by 2 photons w/ Δ T ≥ 30 ns.

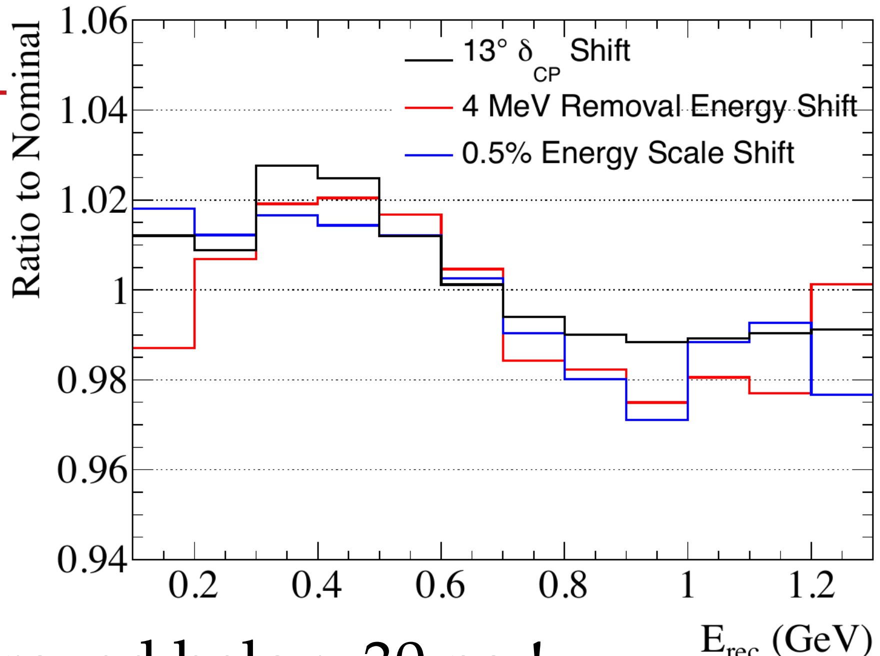
Impact on scattering & reflection

- If HKROC can separate > 2 hits @30 ns :

→ Avoid bias for 30 % of the hit (compared to other solutions).

→ This can bring a decisive improvement to E-reconstruction :

1. Large contribution wrt our ~5 % momentum resolution.
2. Can bring significant contribution to minimize E-scale calibration & uncertainty :



→ **Need to bring E-scale uncertainty < 0.5 %** (>2 % in SK) to maximize constraints on δ_{CP}.

- Bonus : HKROC deadtime could be improved below 30 ns !

Impact on Supernovae

- If Betelgeuse explodes : 1 hit / µs for each PMT in HK.

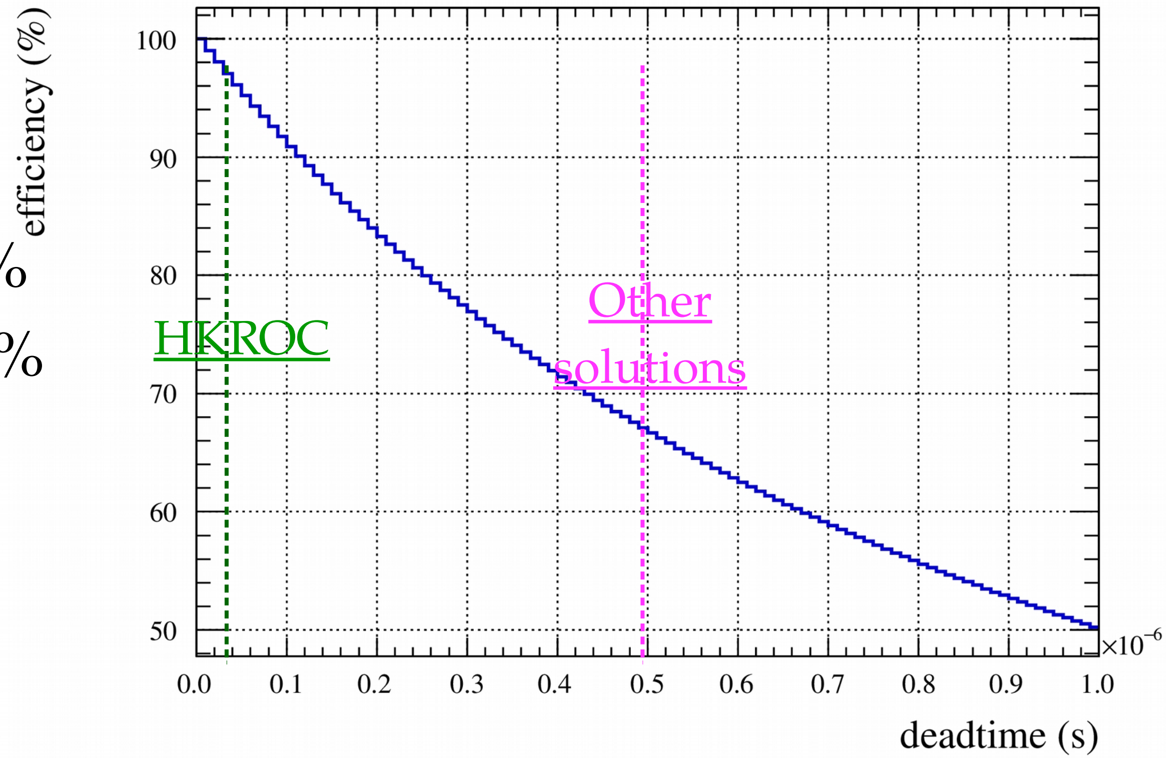
-

- Of course, not a continuous rate at 1 MHz : random distribution of time with an average of 1 MHz → Dead-time plays a crucial rôle

- For 1MHz SN, efficiency is :

→ For Dead-time of 500 ns : 67 %

→ For Dead-time of 30 ns : 92.5 %



- @1 MHz : HKROC allows to significantly increase efficiency from 67 % to 92.5 % compared to other solutions.

IV. Result of the review & incoming steps

Prospects for the HKROC digitizer

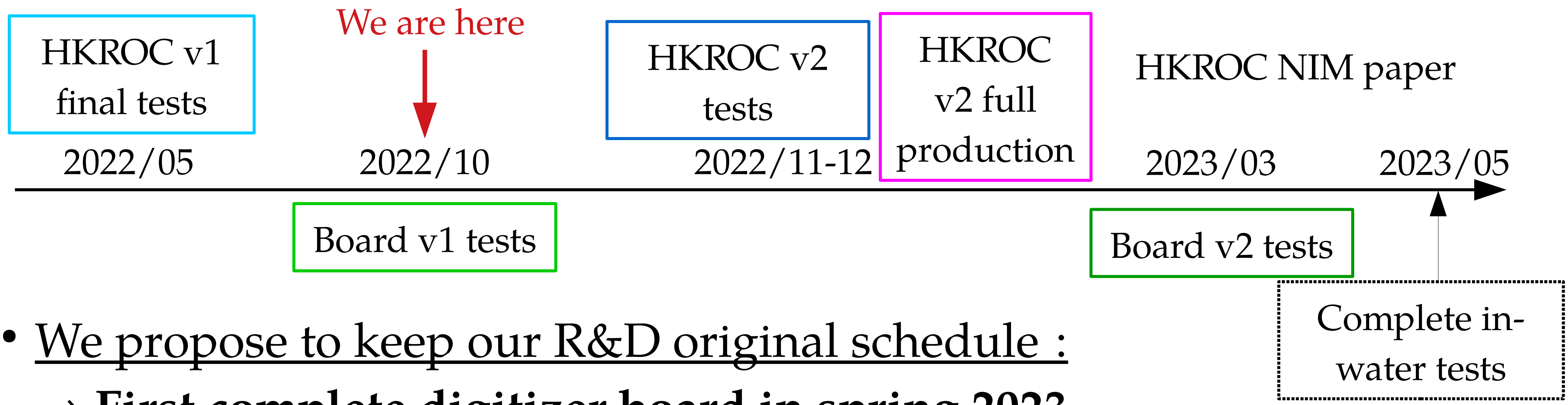
- 2 other digitizers were competing for HK : QTC (Japan), discrete (Italy).
  → Unfortunately, HKROC not chosen as primary solution for HK.

- 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



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

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

- From now : 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.).

Conclusions

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

- The HKROC project started in 2020/06 (Budget X). In 2 years, we have :
  1. An HKROC ASIC designed, completely characterized and which works as expected (though this is very 1st version !).
  → A very very small cross talk (0.02%) has been found : to be reduced by a factor 100 in HKROC v2 (coming in November).
  2. A prototype board v0 tested, an incoming board v1 coming this month, and a v2 coming in spring !

→ **Huge technical achievements & success** that shows the **top-class expertize of our engineers at LLR, OMEGA & IRFU.**

→ Incredible team work of **Amine (firmware), Franck (overall & protection circuit), Mark (Layout), Remi (Layout), Lorenzo (DAQ & test bench)…. and Jerome (basically all).**

Conclusions

- We should finalize the HKROC digitizer development until end of summer 2023.
  → Final production-ready digitizer for HKROC.
  → Could be used for IceCube gen2, IWCD, Hyper-K upgrade…
  → A generic board to treat waveform digitization for all future OMEGA ASICs (SiPM version etc.).
  → There is a possibility to test it in situ at CERN from start of 2024 (Water Cherenkov Test Experiment) : **do physics & test HKROC.**

- For HK : many alternative options has been discussed in the last weeks (see next slides).
  → Our proposal : keep the door open for HKROC in case it can be used (IWCD, HK…) → **To be re-discussed in one year**.
  → And focus our efforts on leading the analyses tools & computing : host all Tier 1 data of HK at CC-Lyon : central visibility for LLR & built on our expertize in SK/T2K (oscillation analysis, DSNB software…).

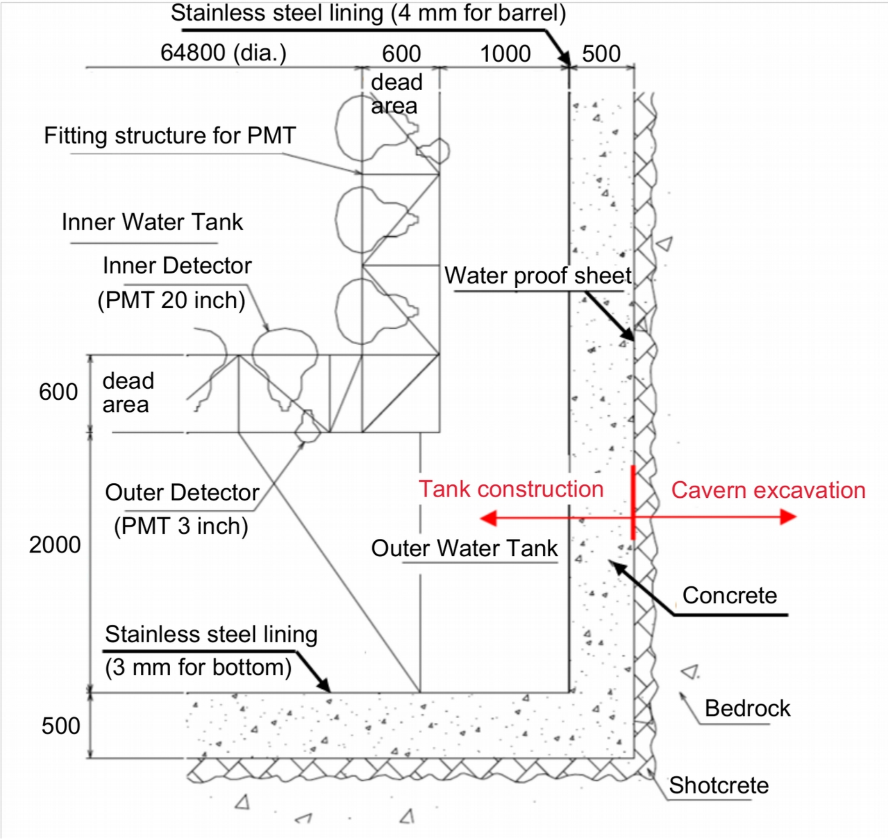
The HKROC team at work

Option 1 : Outer-detector of HK

Option 1 : Use HKROC for the OD

Pros :

1. Good visibility for our engineers & R&I
2. Rely on our HKROC board
→ Control all aspects to ensure it will work for HK.
3. Less risk overall for the collaboration as we share FTE & fundings.



→ We probed management : they prefer not.

→ We probed INFN colleagues : they do not wish, they have the manpower & money to use discrete.

→ Conclusions : Not possible.

Options investigated

Option 2 : Have a role in the hardware/firmware of the discrete solution :

a. The calibration circuit.

b. Data packaging & processing → Done on the spanish board (discrete FPGA is too small), so we will have to comply to Spain rules and choices.

c. Take care of a part of slow control → But same issue as b.

Pros :

1. Be part of the front-end digitizer.
2. We have found some items matching our engineers expertize.

Cons :

1. Limited role as ultimately, Spain & Italy will decide → No leadership..
2. Lots of coordination between groups : loss of time & frustration.
3. Should start now → Not compatible w/ HKROC schedule.

Conclusions : No

Options investigated

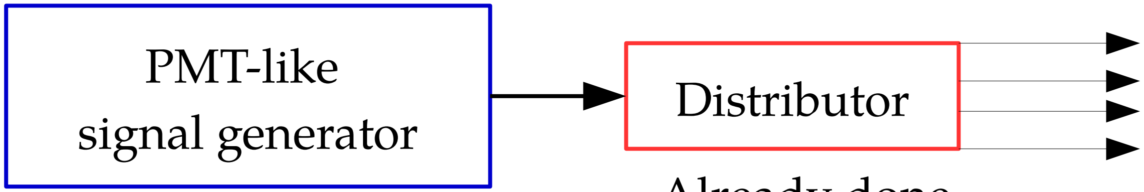
Option 3 : Leading role in the testing, calibration and integration.

→ Proposed by HK management.

a. Build a test bench to test the assembled vessels at CERN.

b. Supervise/do the tests.

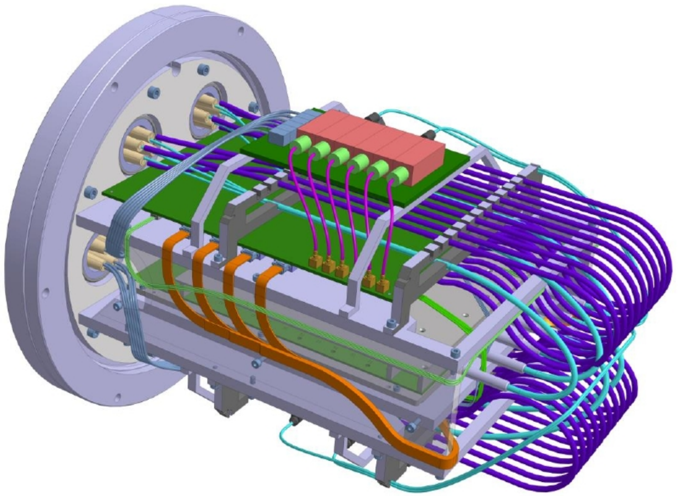
c. This is a leading role in the mass production tests. **We do not test the Italian discrete digitizer during R&D phase.**



-Designed at LLR (same as HKROC calibrator) ?

-Commercial generator ?

-Already done in Korea



When : Need the system for start of 2024.

Options investigated

Option 3 : Leading role in the testing, calibration and integration.

Pros :

-…. ? we still have a rôle in HK front-end ?

-Directly connected to physics.

Cons :

-No real hardware rôle in HK, only temporary using a test bench : limited visibility.

-Korea is also part of this « testing leadership » : we would really do this just for CERN test bench → Even more limited visibility.

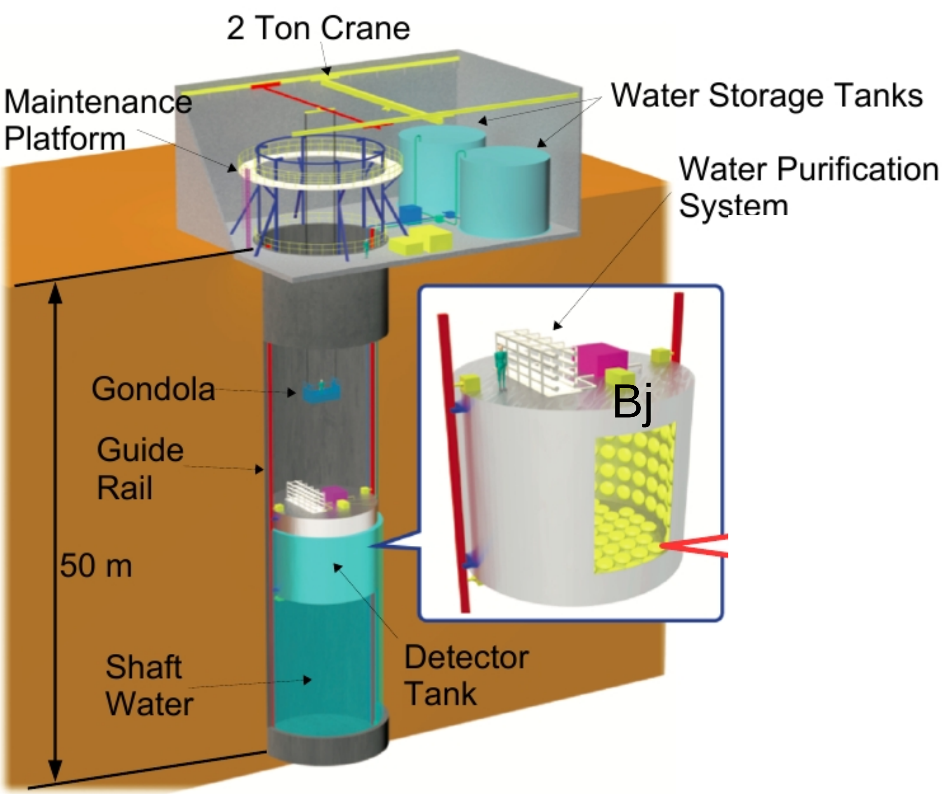
-Would mean to spend important time at CERN helping on the tests.

Conclusions : No.

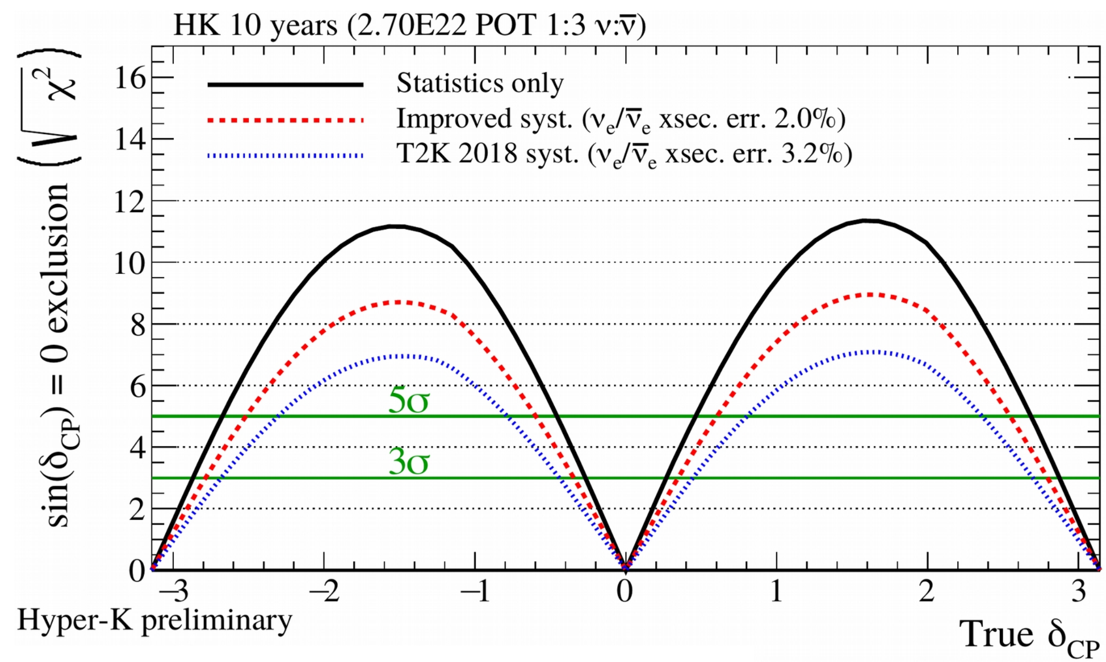
Options investigated

Option 4 : Use HKROC as a digitizer in the IWCD experiment.

→ IWCD : a Water Cerenkov near detector located 800 m from the neutrino production point.



HK



→ A crucial detector for HK precision measurement :

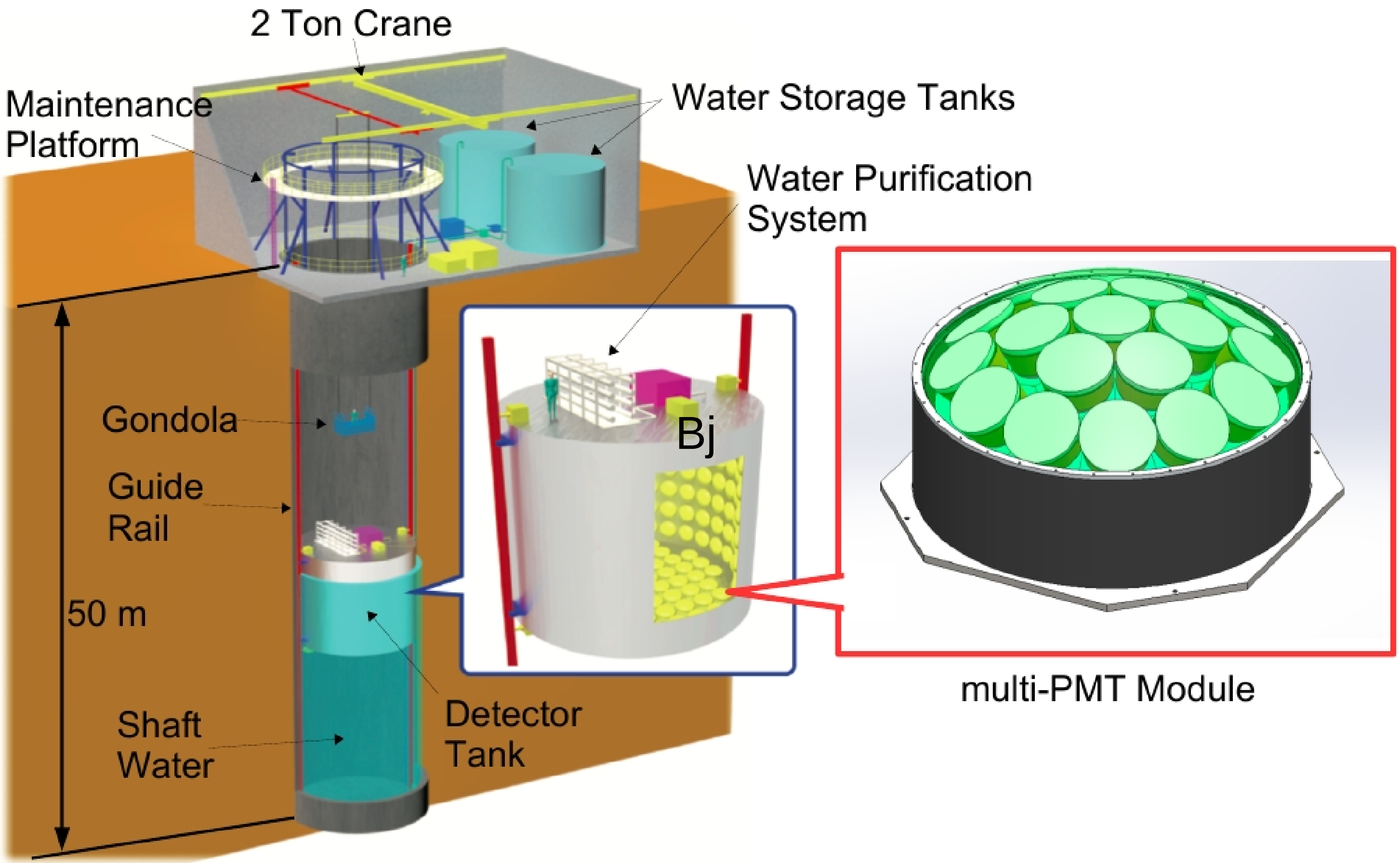
- Impact the CP violation search if CP is not maximally violated.
- Impact the resolution on δ_{CP} measurement.

Options investigated

- Inner-detector based on multi-PMTs :

→ Already has a Canada/Poland electronics based on 125 MHz flash ADC. But, basically, this is not working as expected for now…

→ HKROC is also a waveform digitizer, and could probably be used !



- Outer-detector : would be single 3'' PMTs

→ No electronics for now, so HKROC would be perfect.

Options investigated

- Option 4a : we do both ID & OD IWCD electronics.
  Option 4b : we do only OD IWCD electronics.

Pros :

-[All] Can use HKROC on HK.

-[4a] Very good visibility & use full waveform digitization potential.

Cons :

-[All] IWCD schedule is delayed (start in 2030) and uncertain.

-[All] It may clash with work on Far Detector & ND280-upgrade if our group does not expand → Need more French collaborators to join IWCD.

-[4b] Limited visibility, and a bit of a shame to use HKROC only for OD.

Options investigated

<u>Conclusions :</u>

-4b would have been ok if package w/ FD-OD → INFN said no for FD-OD so 4b is not a good option anymore.

-4a is interesting : but this should not be our priority given the uncertainty on IWCD schedule.

→ Finalize the HKROC development and discuss afterwards.

→ This should not be our priority for now.

→ Wait to have more IN2P3 groups in the IWCD to exploit physics.

→ It matches the IWCD calendar relatively well, as final decision may happen only by end of 2023.

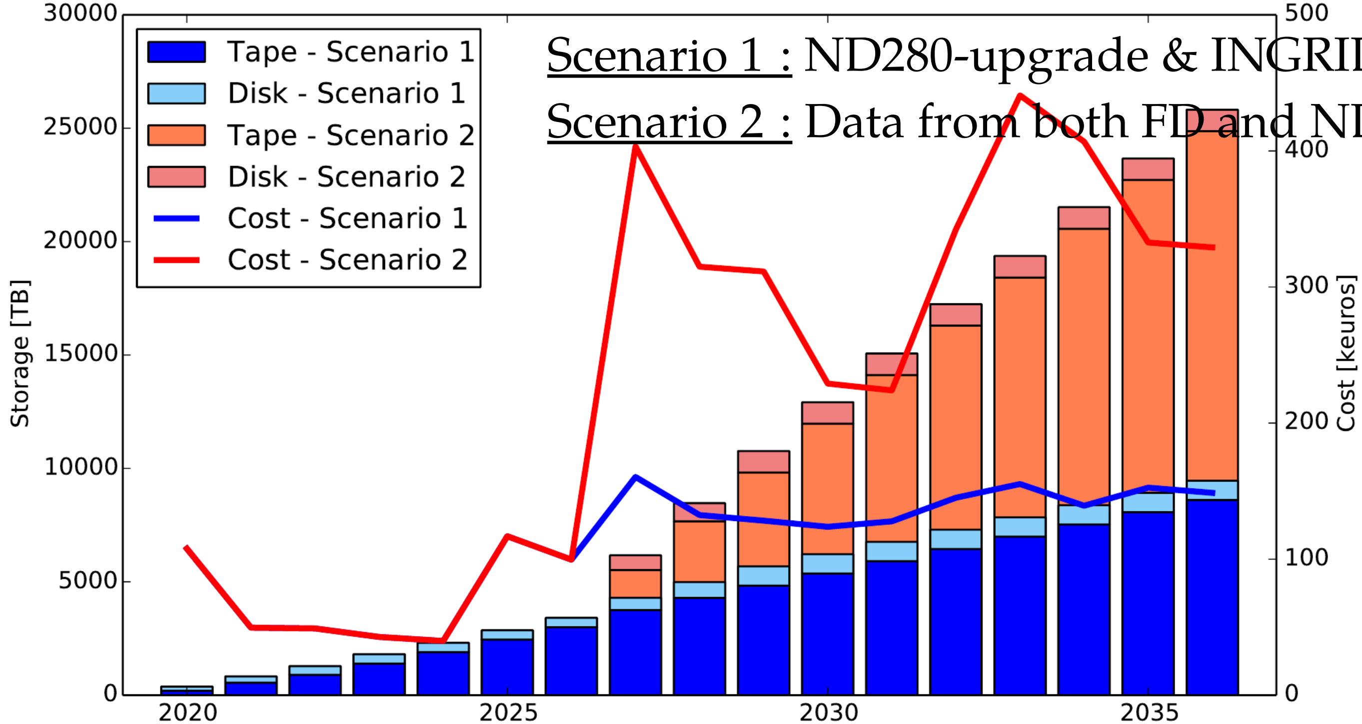
The computing proposal

- <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.

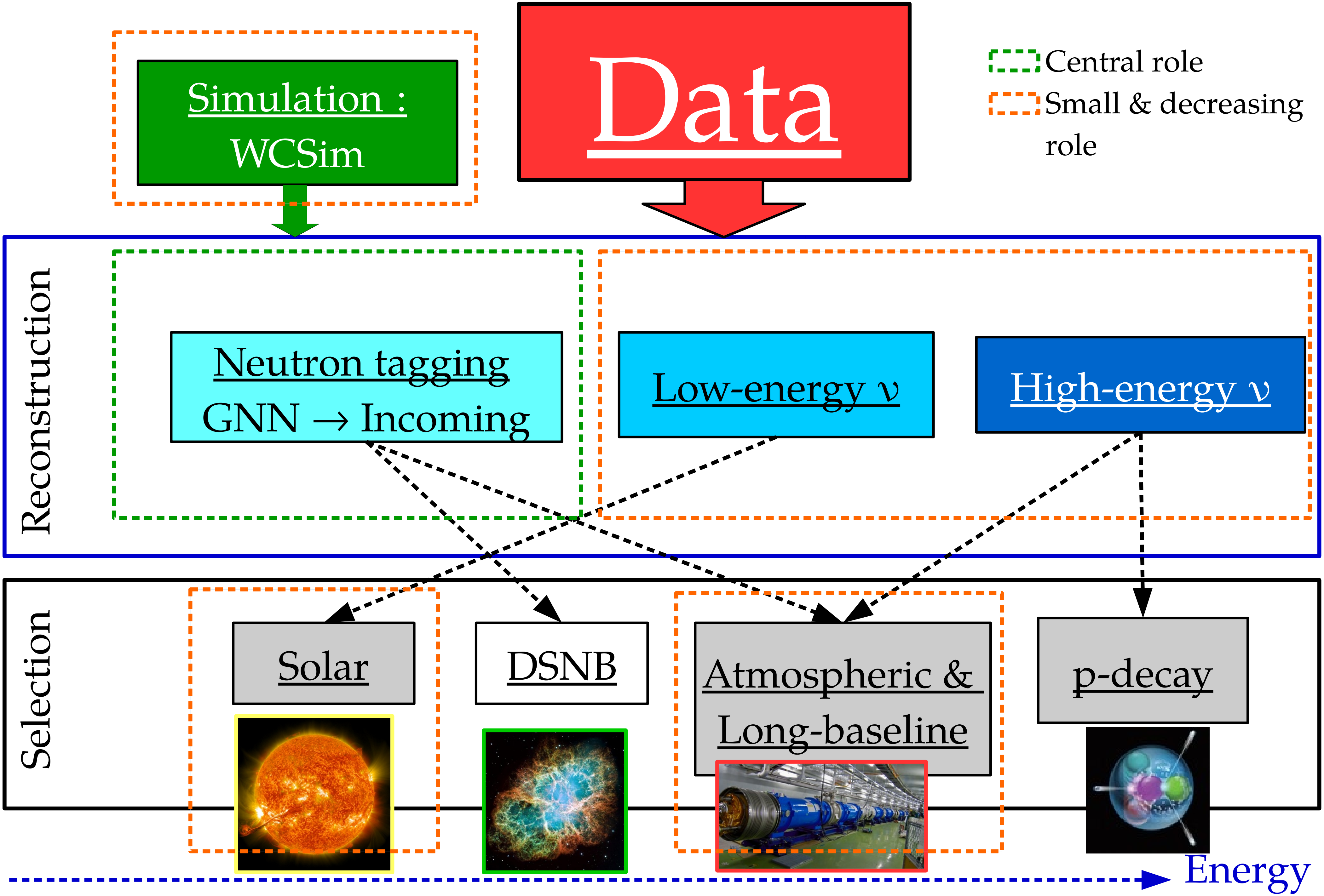


- <u>Pros :</u>

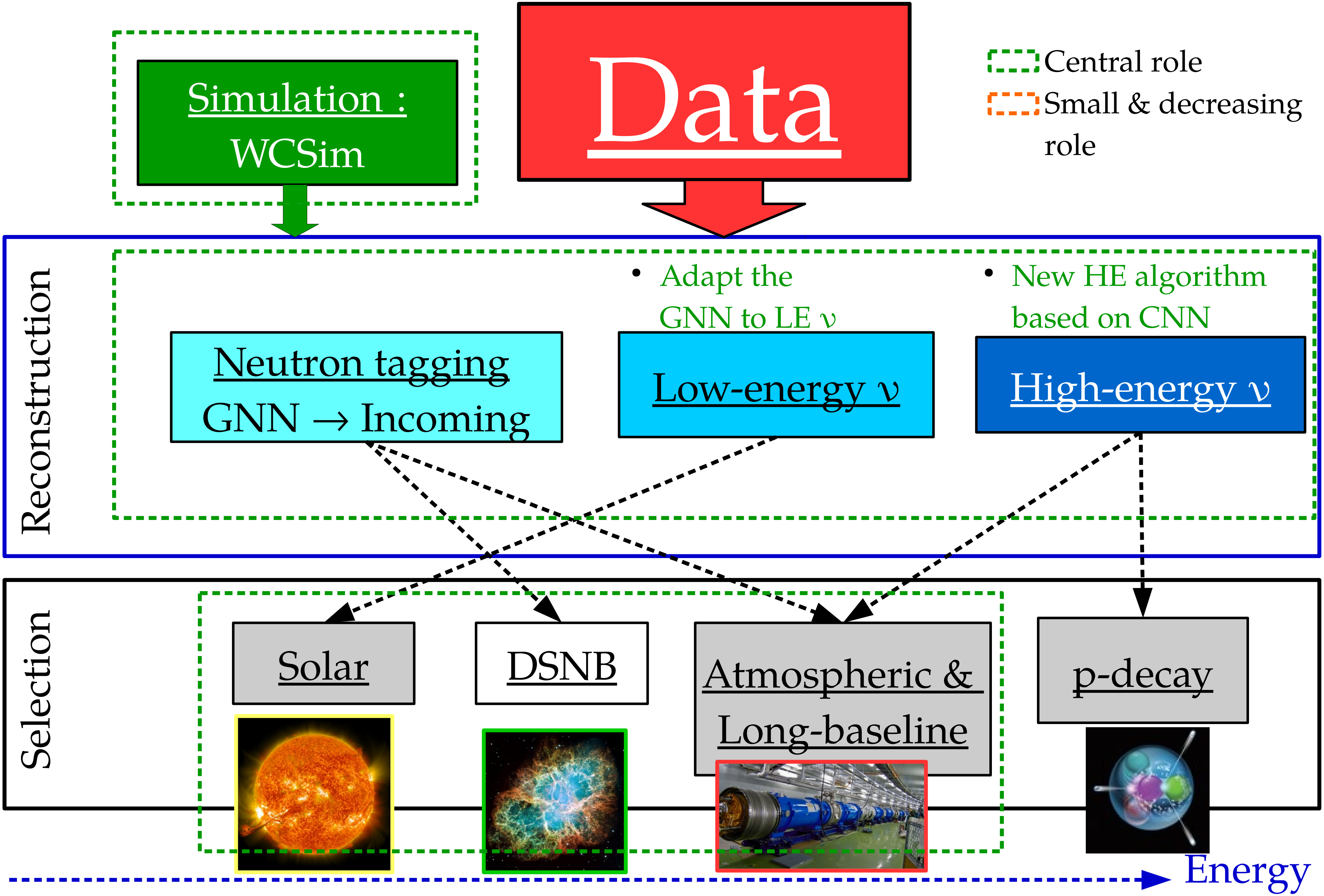
1. No other group has announced the capacity of a full Tier 1 so far.
2. Having all data in France offers a great visibility.
3. Complete synergy with our goal to lead the analyses in both low and high energy sectors.

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

Computing & analysis: situation now

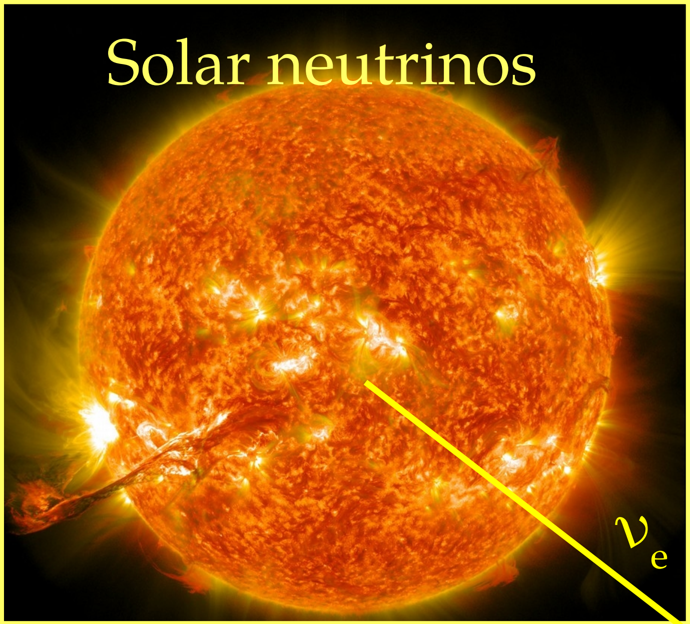


Situation + 1 permanent

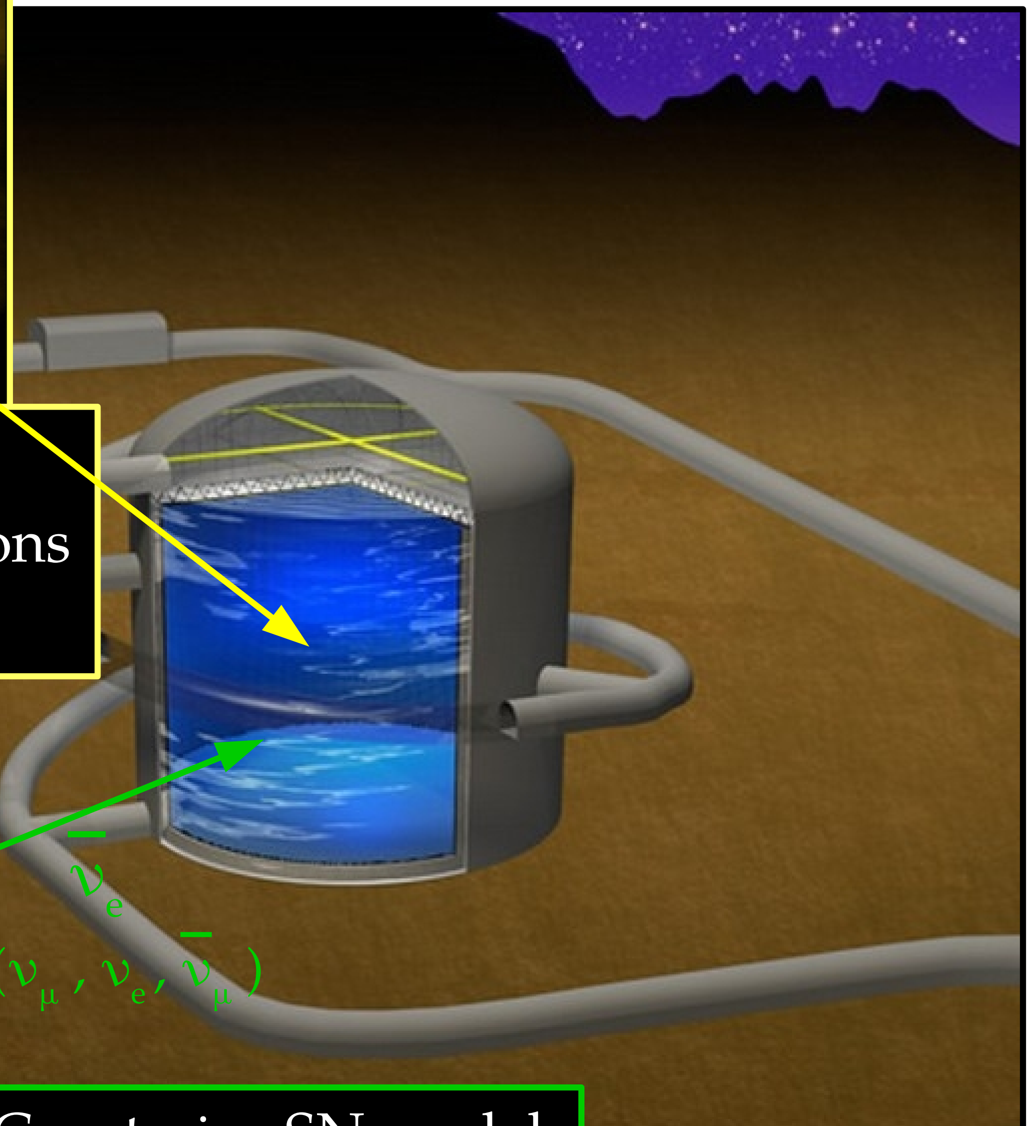


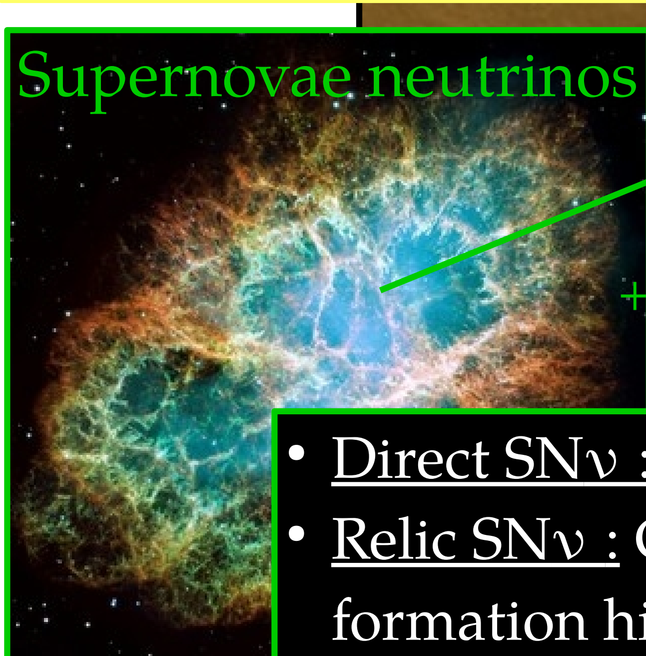
Additional slides

Physics case



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

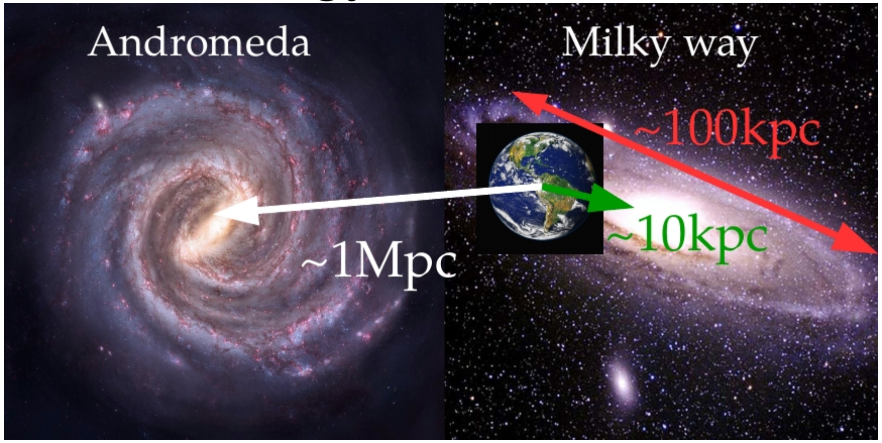




- Direct SNν : Constrains SN models.
- Relic SNν : Constrains cosmic star formation history

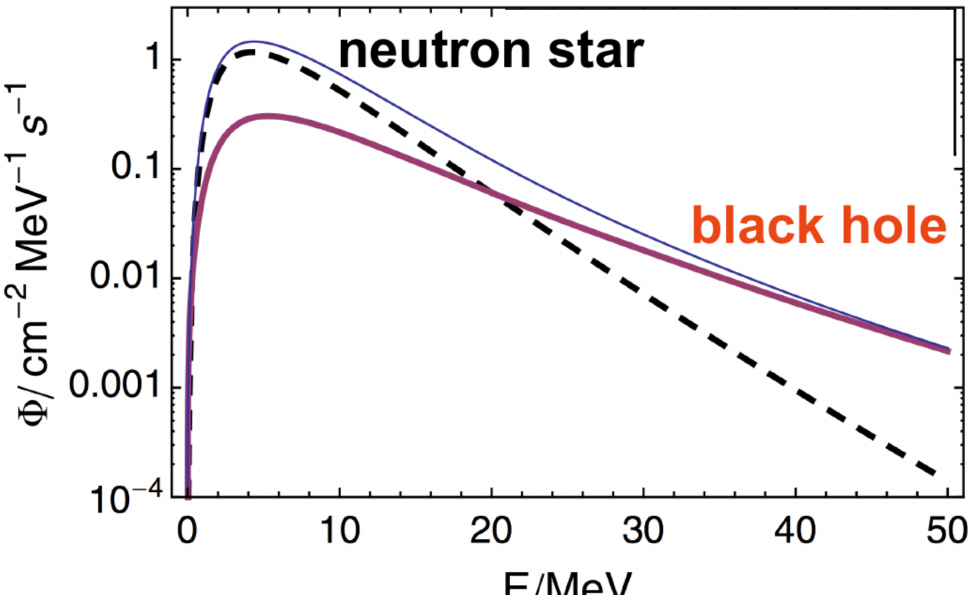
Supernovae neutrinos

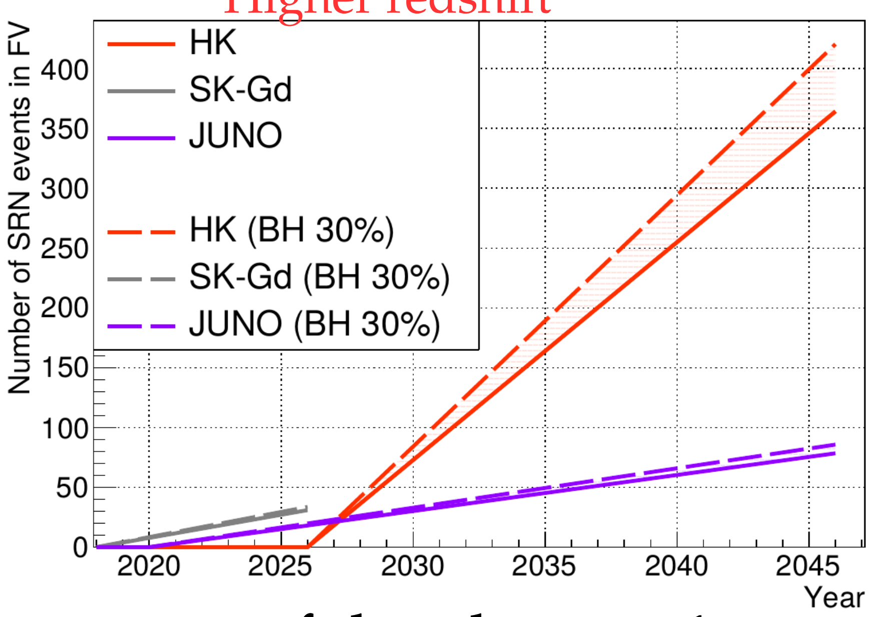
- Unique probe for supernovae ν : 99 % of SN energy → ν.
  - But direct ν detection very rare.
  - HK also sensitive to extra-galactic SNν from Andromeda !



- 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

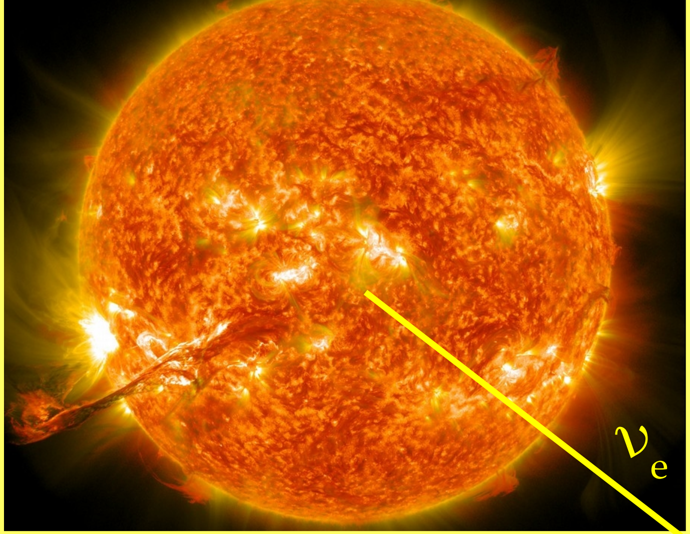




- SK-Gd & then, HK are the pioneer experiments of this domain !

Physics case

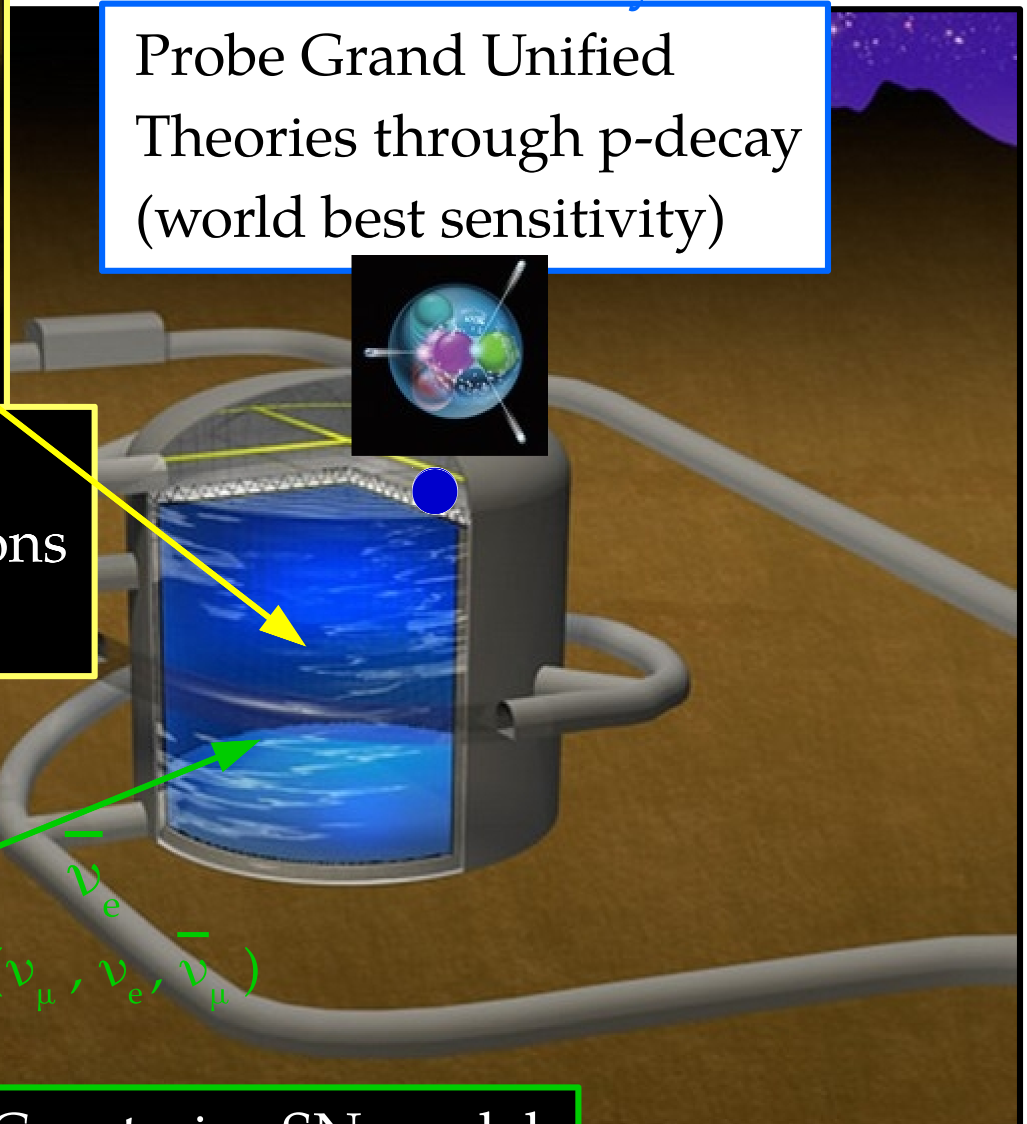
Solar neutrinos



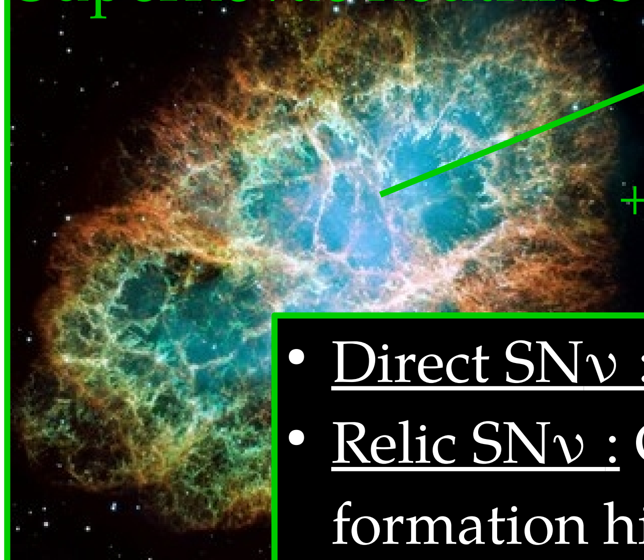
- MSW effect in the Sun
- Non-standard interactions in the Sun.

Proton decay

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



Supernovae neutrinos

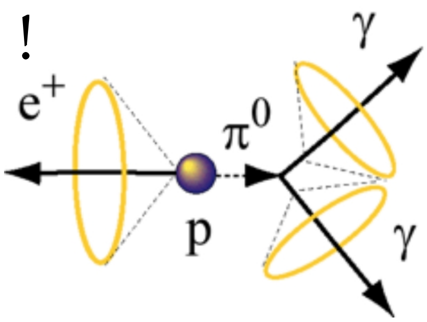


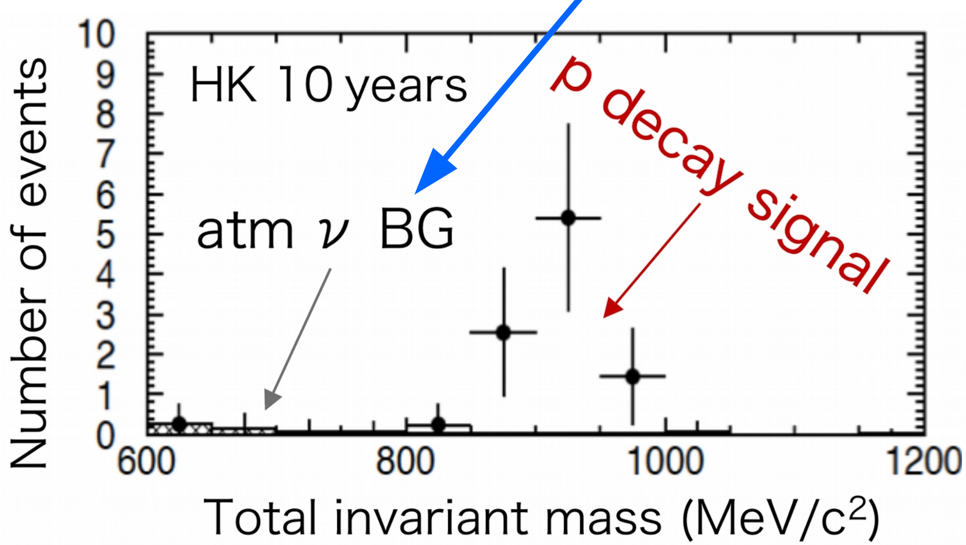
- Direct SNν : Constrains SN models.
- Relic SNν : Constrains cosmic star formation history

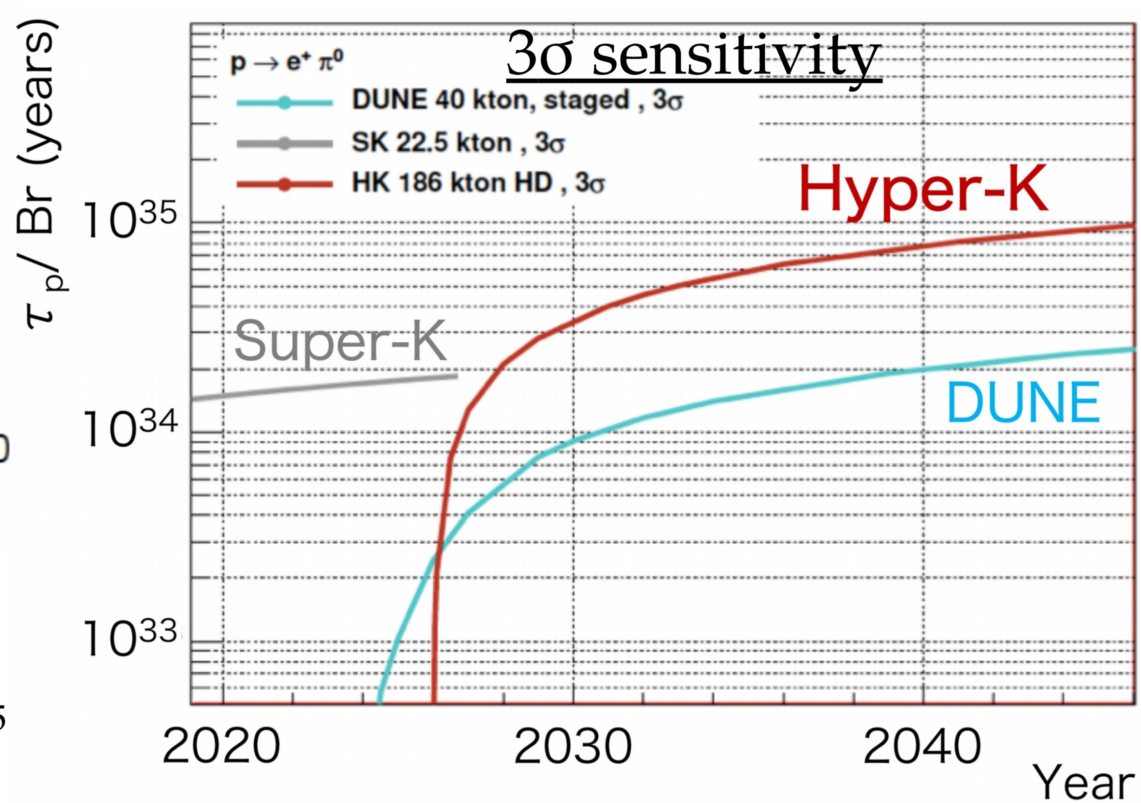
GUT and proton decay

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

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





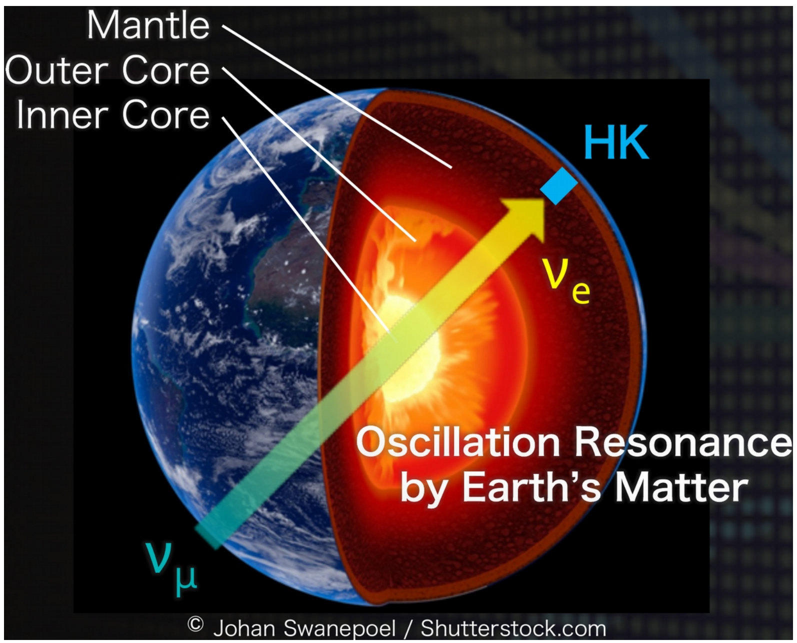


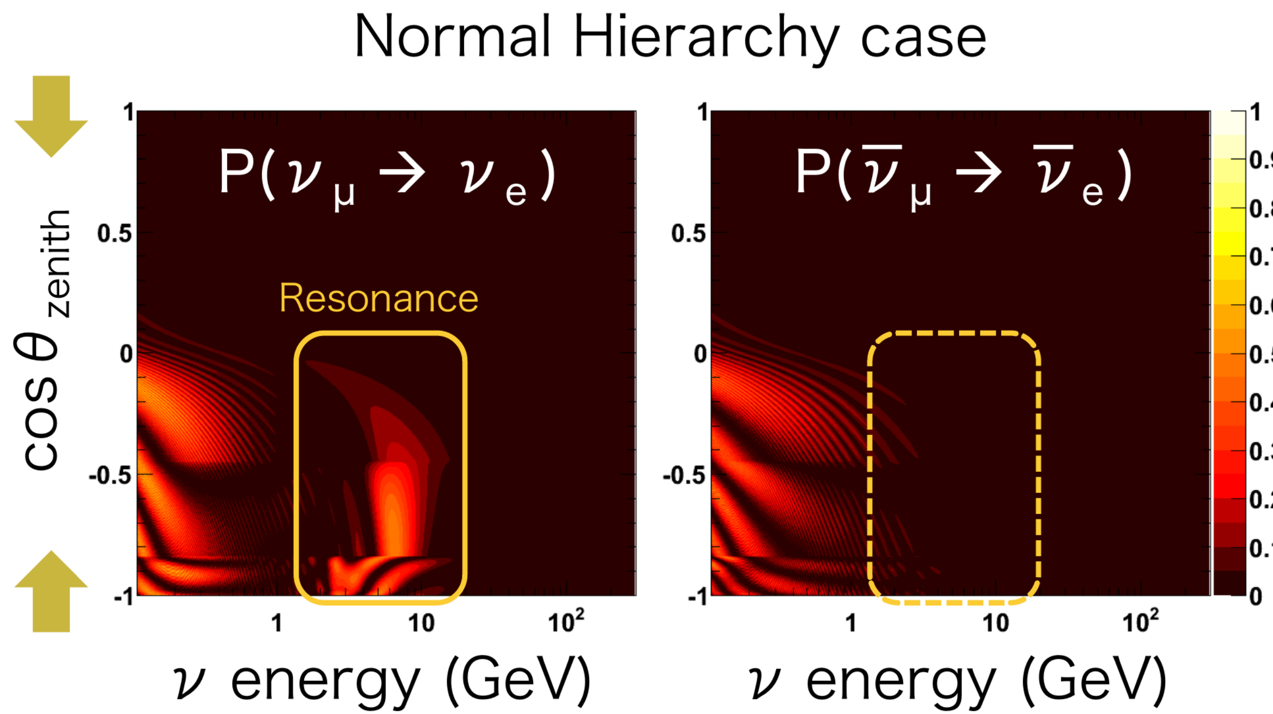
- 3σ sensitivity reach τ_P /Br = 10^{35} years → 1 order of magnitude beyond SK or DUNE

Atmospheric neutrinos

- <u>Mass-hierarchy can be accessd through matter effects</u>

  → The longer the baseline, the higher the effects





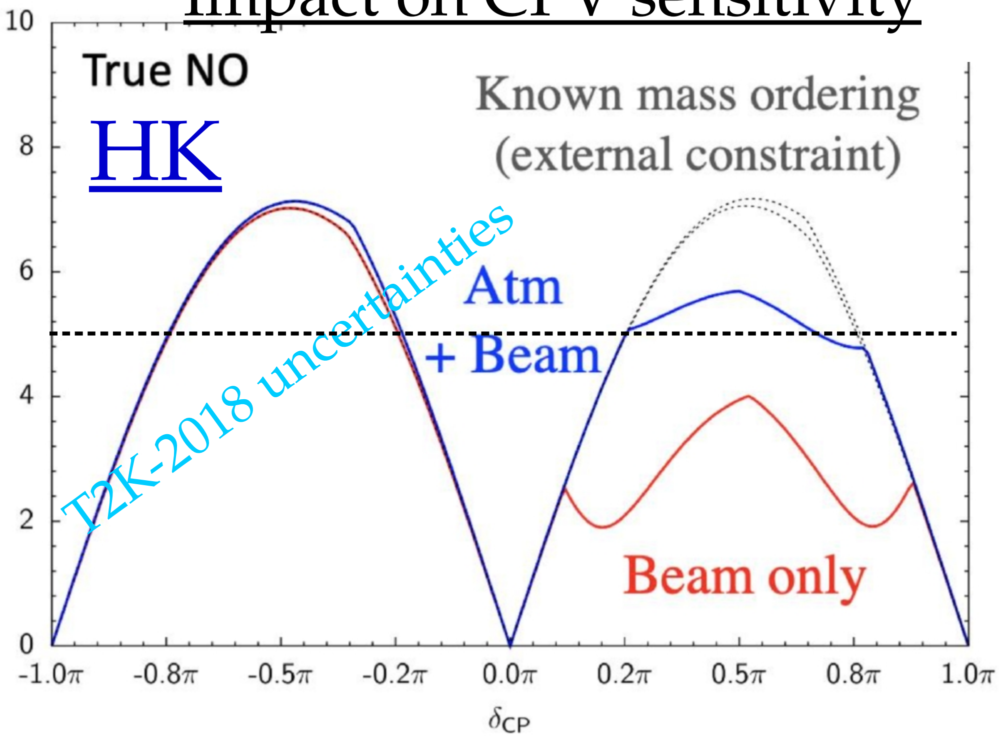
- Mass hierarchy determined with upward-going multi-GeV ν_e sample :

atm. baseline ≤ 13000 km ≫ 295 km accelerator baseline

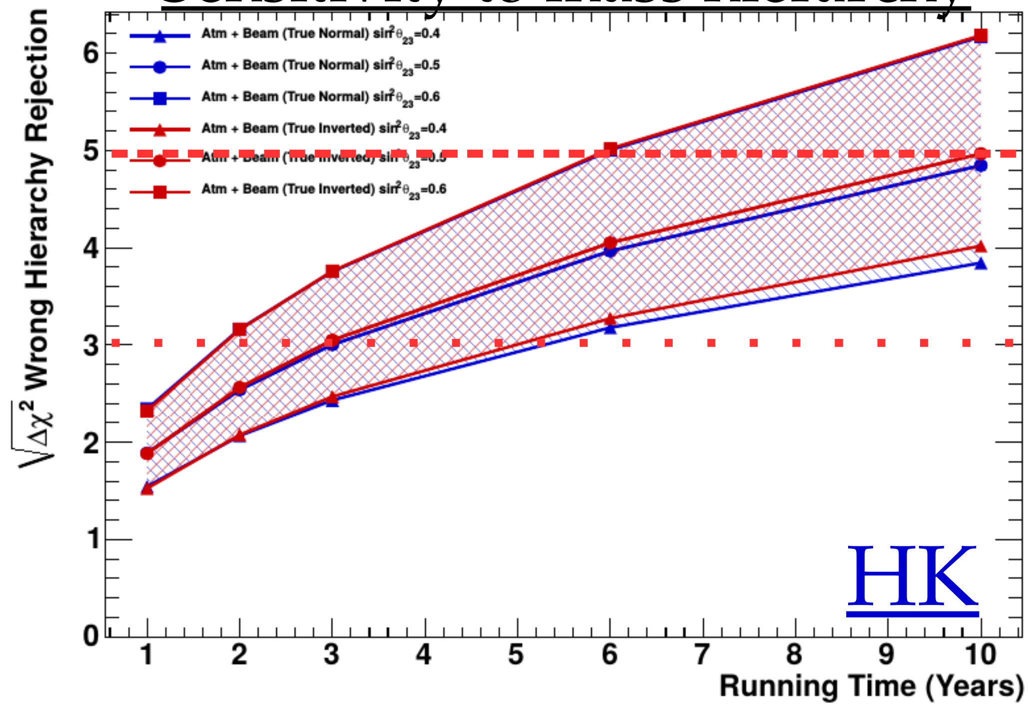
- <u>Normal hierarchy :</u> enhancement of $\nu_\mu \rightarrow \nu_e$.
- <u>Inverted hierarchy :</u> enhancement of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$.

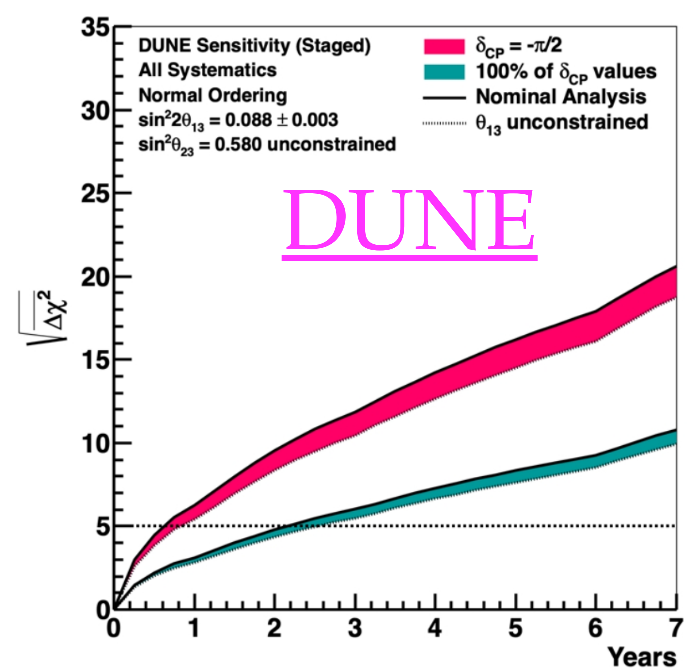
Combination of atmospheric + beam ν

Impact on CPV sensitivity



Sensitivity to mass hierarchy





- Even if MH is not known when HK starts

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

- MH would be determined by :

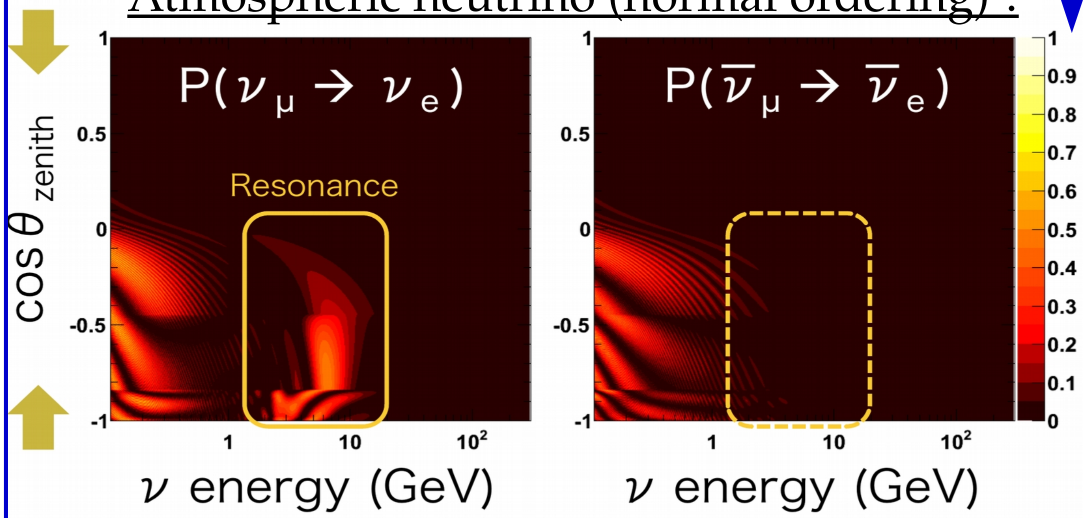
  → HK after ≥ 6-10 years via atmospheric.

  → DUNE : after 1-2 years.

HKROC digitizer - Impact on physics

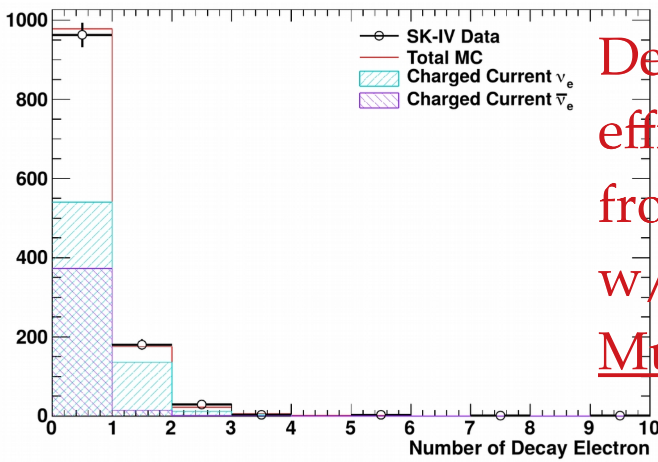
- Large impact on physics : ν mass ordering & Supernova ν.

Atmospheric neutrino (normal ordering) :

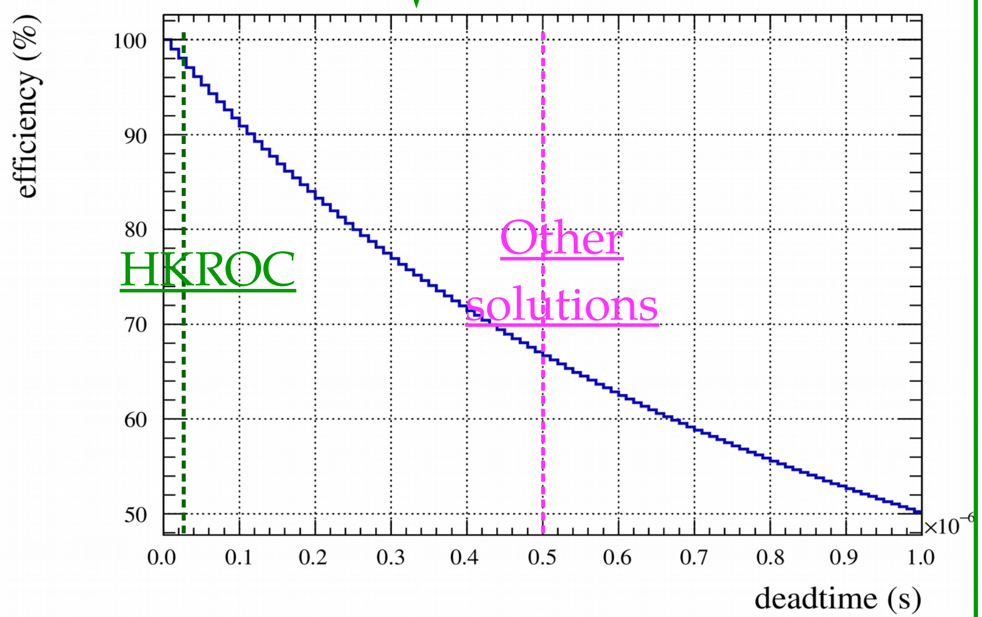


- Normal hierarchy : ↑ $\nu_\mu \rightarrow \nu_e$.
- Inverted hierarchy : ↑ $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$.

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



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



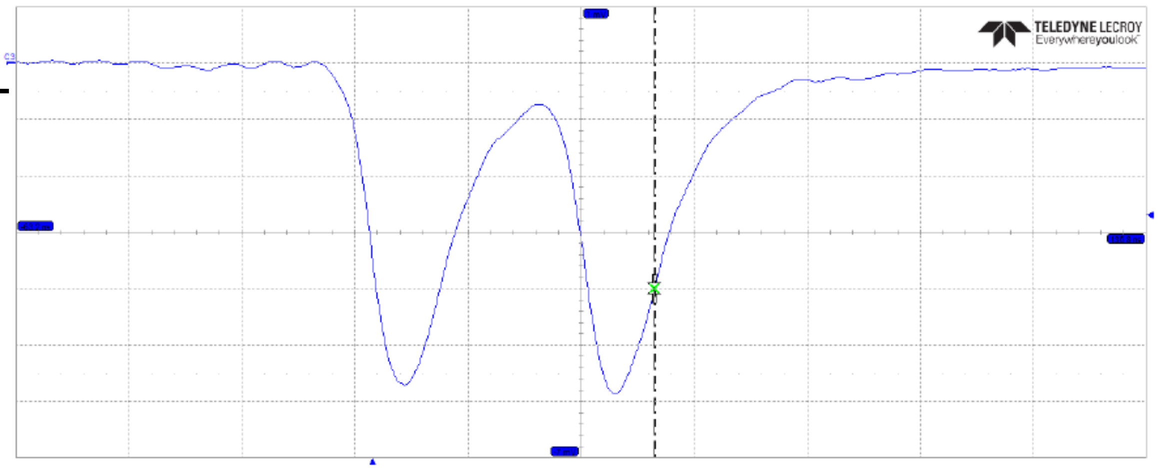
- For 1MHz [Betelgeuse] : HKROC allows to significantly increase efficiency from 67 % to 92.5 % compared to other solutions.

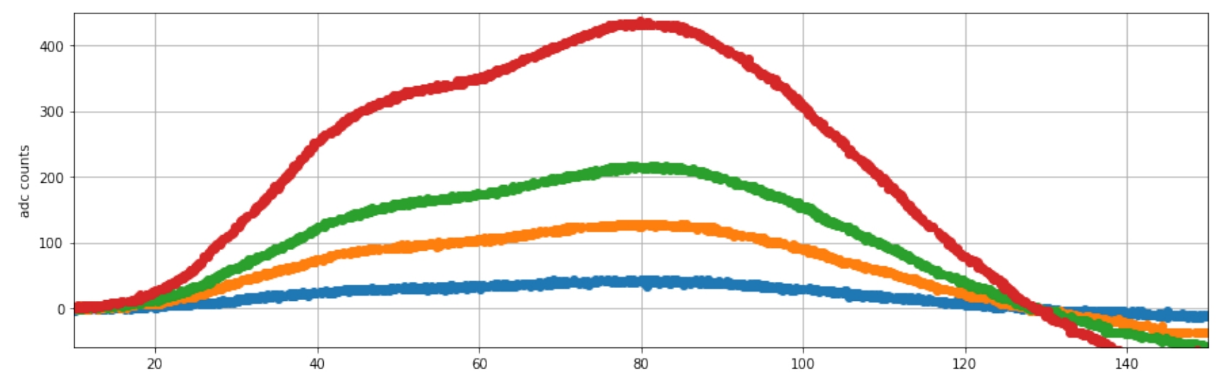
Pile-up & dead-time

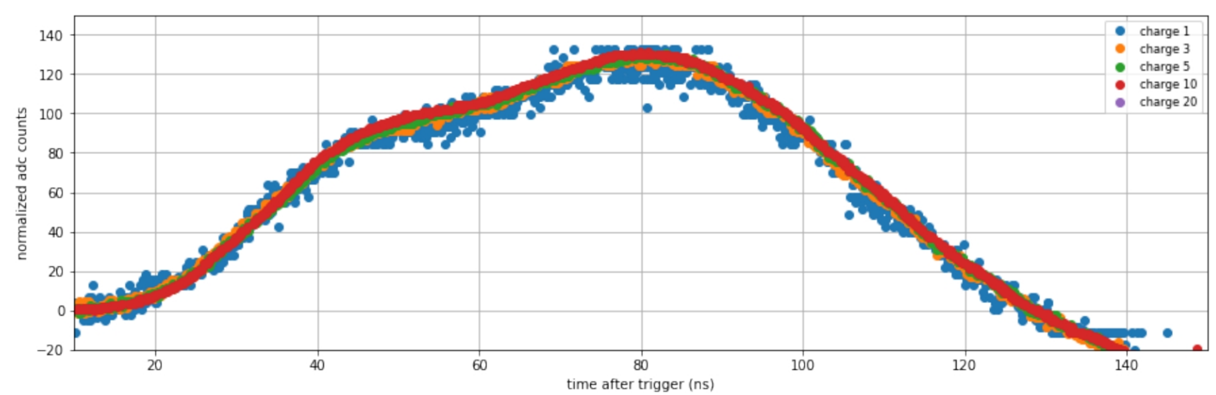
- Can we go beyond this 1 μs dead-time using HKROC ?

- <u>We tested & measured 2 peaks separated by Δt = 30 ns.</u>

- <u>Eye check :</u>
  → Event separation is not trivial !
  → Good linearity, even for pile-up event.
  → Apply charge reco. w/ 2 peaks at fixed trigger times.



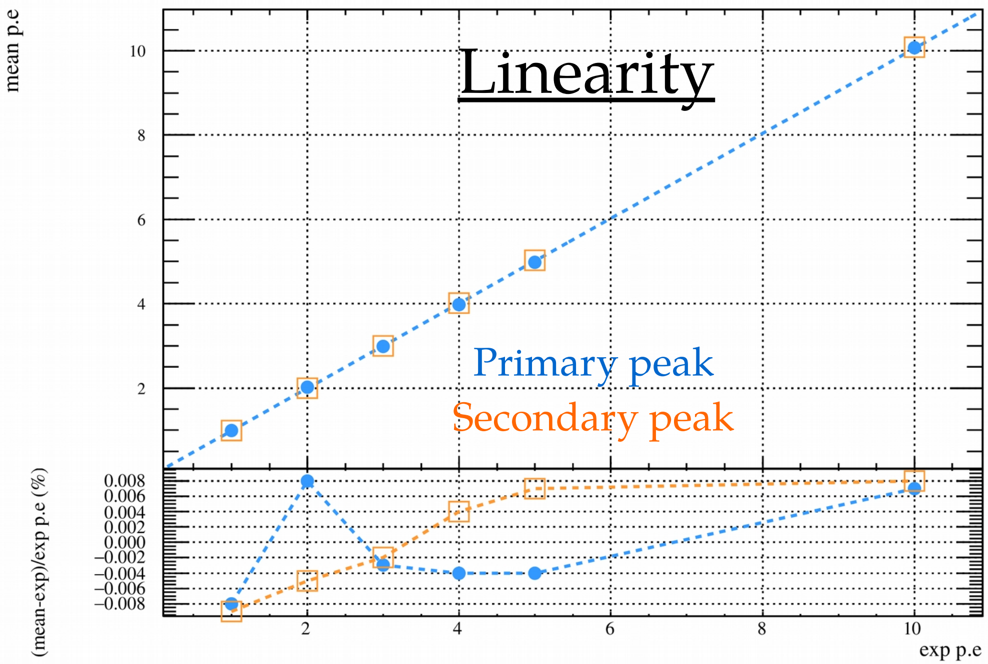


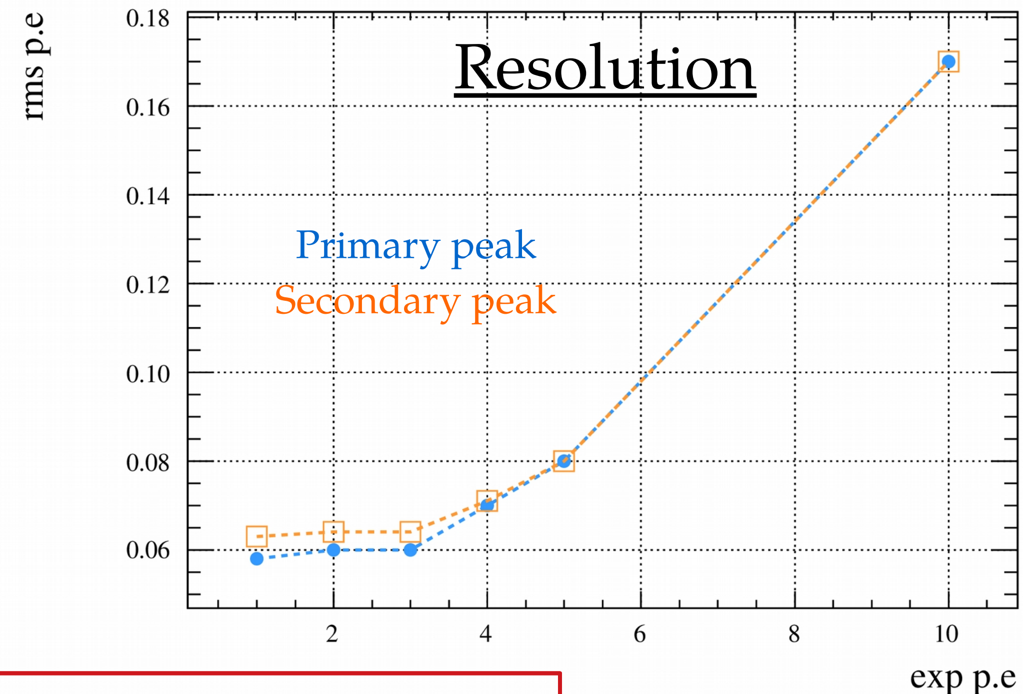


Pile-up & dead-time

- For 2 peaks of same amplitude separated by **Δt = 30 ns** :

→ Considerable improvements compared to requirements.





→ Charge linearity ≤ 1 % & charge resolution < 0.1 p.e

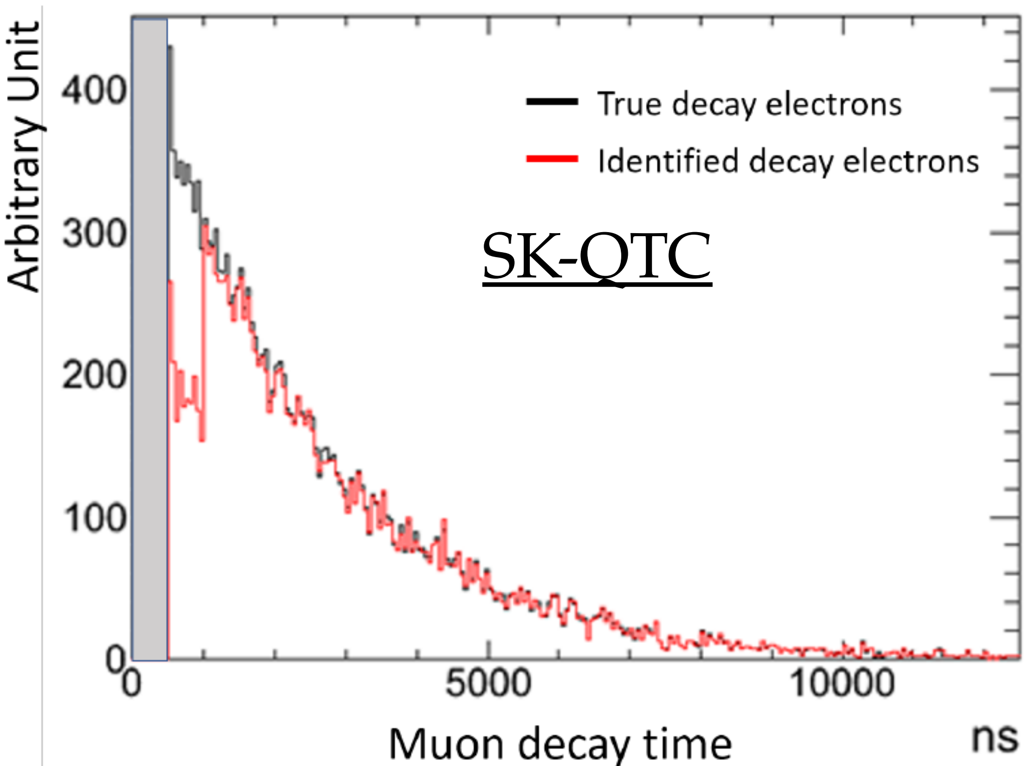
[except @10 p.e : 0.16 p.e → To be improved w/ incoming algorithm]

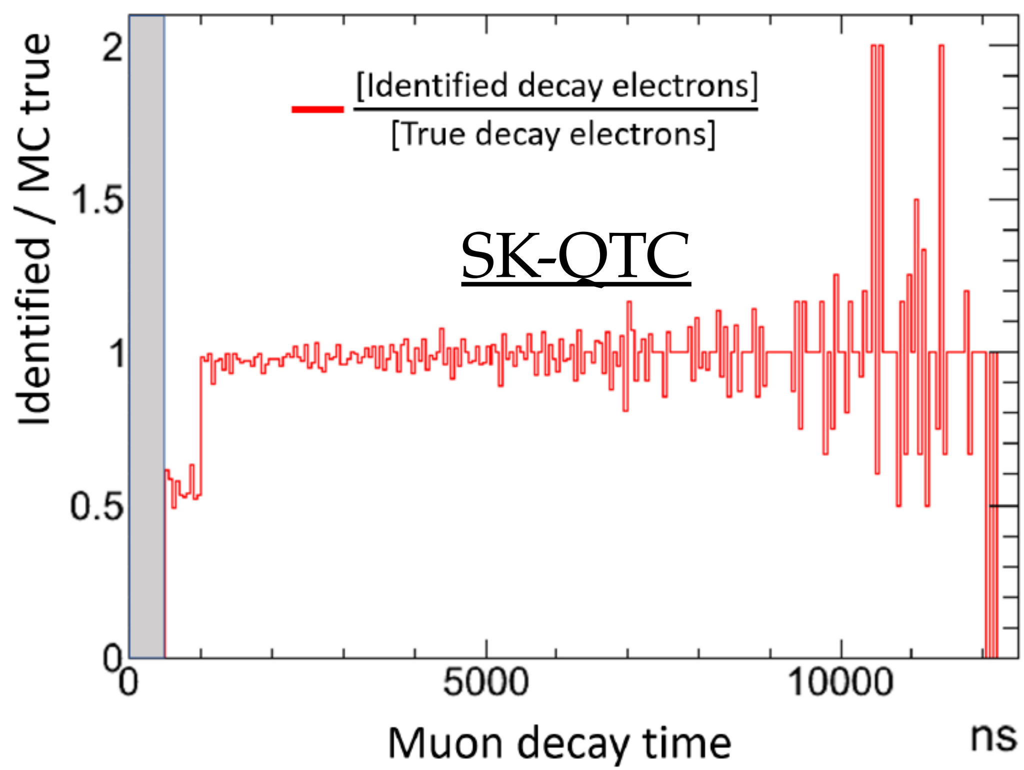
→ Q reco. almost perfect for 2 peaks of same amplitude down to **Δt = 30ns**

→ Key question : How much does it impacts physics ?

Impact on decay-electron

- <u>Decay-e :</u> plots from SK-QTC from WG4 document.





- <u>Decay-e efficiency is 68 %</u> with an SK-like electronics.
  → What will be the efficiency with HKROC in Hyper-K?
  → <u>Careful :</u> HKROC dead-time depends on primary hit charge.
  → Rely on a simulation of 2k atmospheric neutrinos in HK to check decay-e hit efficiency.

Impact on decay-electron

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

→ Crucial impact mass-ordering : $\bar{\nu}_e$ / ν_e !

→ Important impact on long-baseline physics (CP violation), especially in multi-ring channels → See back-up

High-hit rate tolerance

- 2 modes: Normal & Supernova (Used for very close SN (Betelgeuse)).
  → SN-mode = only High Gain channel (≤ 35 p.e).

- Maximal averaged hit rate per PMT (Poisonnian) :

	Normal mode	SN mode
Maximal hit rate	415 kHz	950 kHz

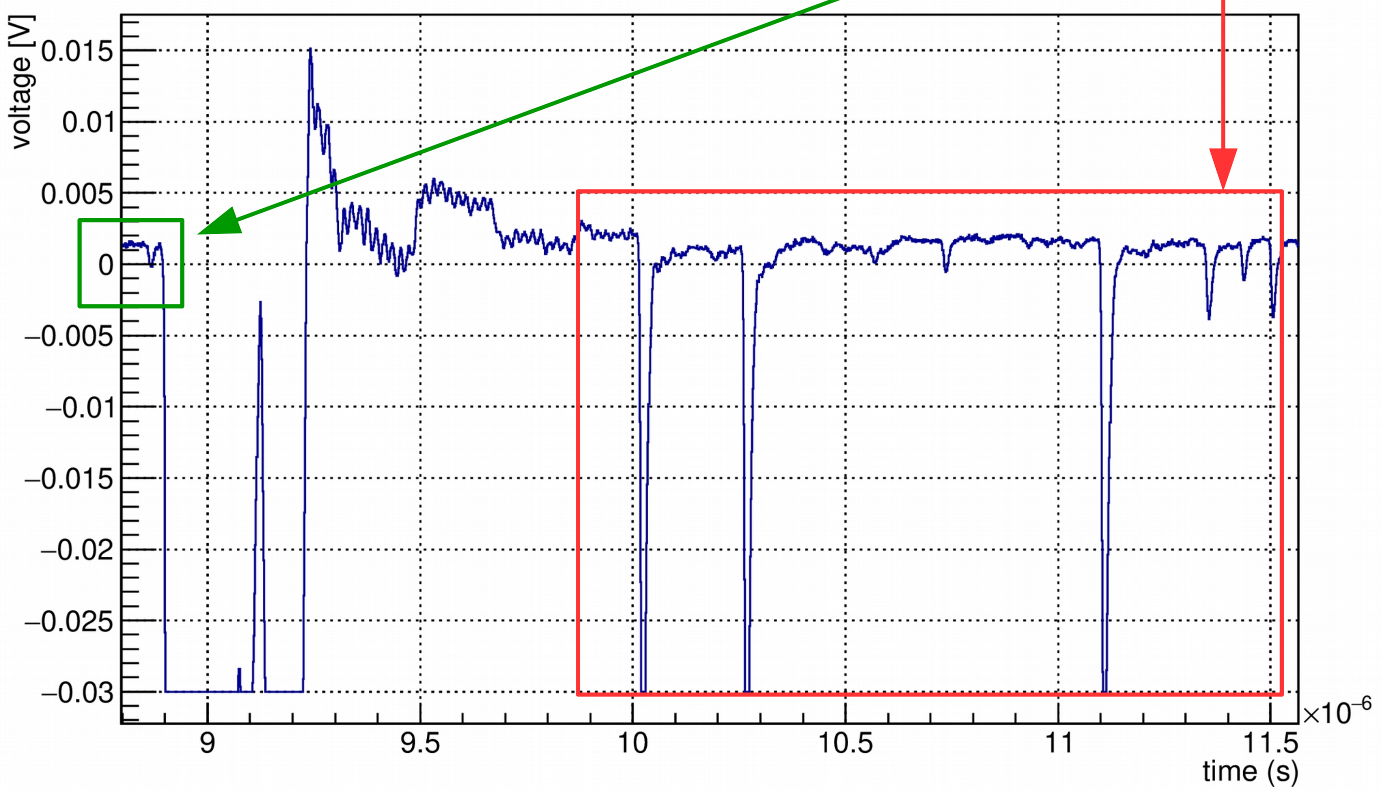
- The bottleneck comes from HKROC ASIC memory depth

→ Bottleneck happens when memory filling speed > read-out speed.

- Instantaneous max. hit rate : **30 MHz** for ≤ 11 events.

Impact on pre-pulse & after-pulses

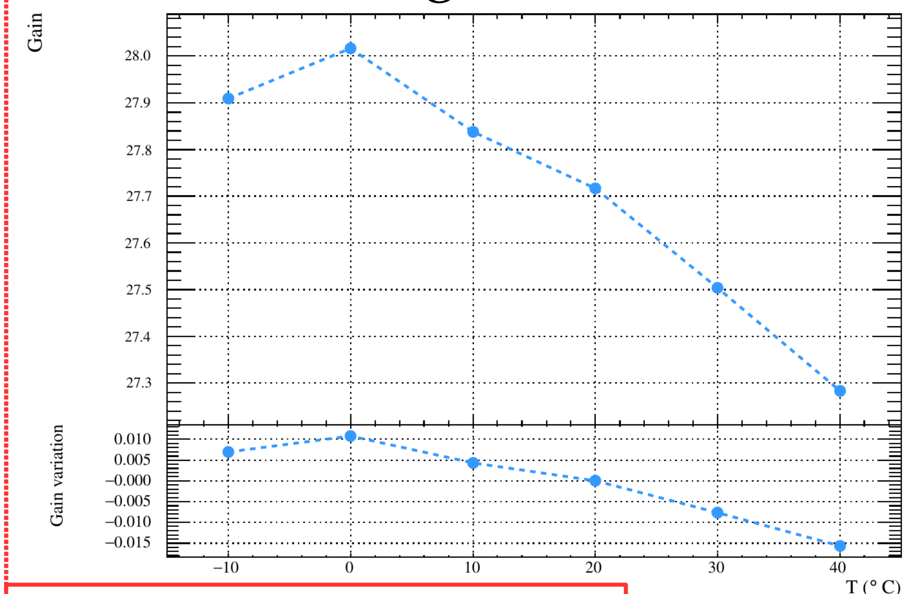
- HK PMTs has a non zero probability of pre- & after-pulses :



- **Pre-pulses (5 % of the time) not separated w/ main peak → Bias the time measurement.**
  → All solutions with 500 ns integration+read-out time will suffer from this : time-over-threshold does not help for events with > 1 p.e !
  → HKROC will reconstruct both the pre-pulse & main-pulse separately for $\Delta t \geq 30$ ns !

Temperature dependency & Power

Gain/charge measurement :

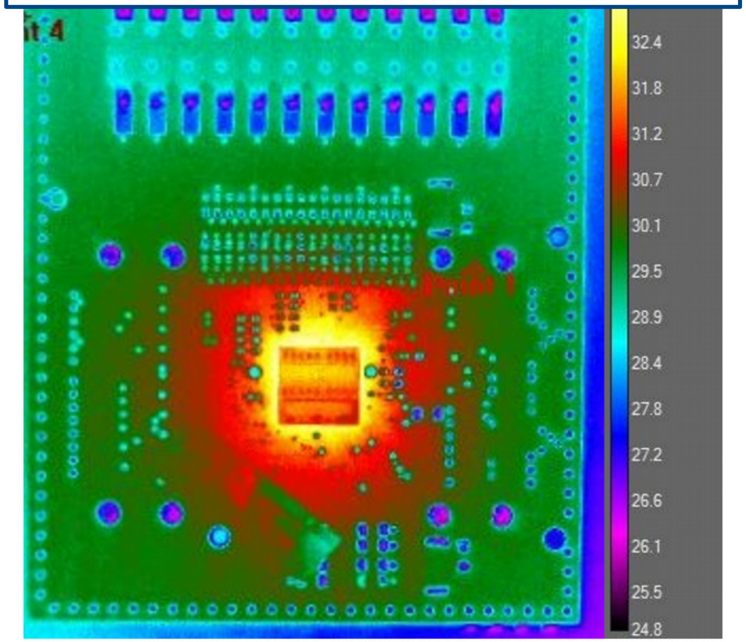


Measured with HGCROC

Board power consumption (1 HKROC) :

Supernova mode			
VCC INT	0.99	0.95	1.04
VCC AUX	0.54	1.80	0.30
VCC BRAM	0.02	0.95	0.03
VCC 1V8	0.02	1.80	0.01
VADJ 1V8	0.16	1.80	0.09
VCC 1V2	0.06	1.20	0.05
HGTAVCC	0.17	1.00	0.17
HGTAVTT	0.18	1.20	0.15
ASIC & Mother board	1.09	3.3	0.330
Total	3.23		

HKROC temperature on-board

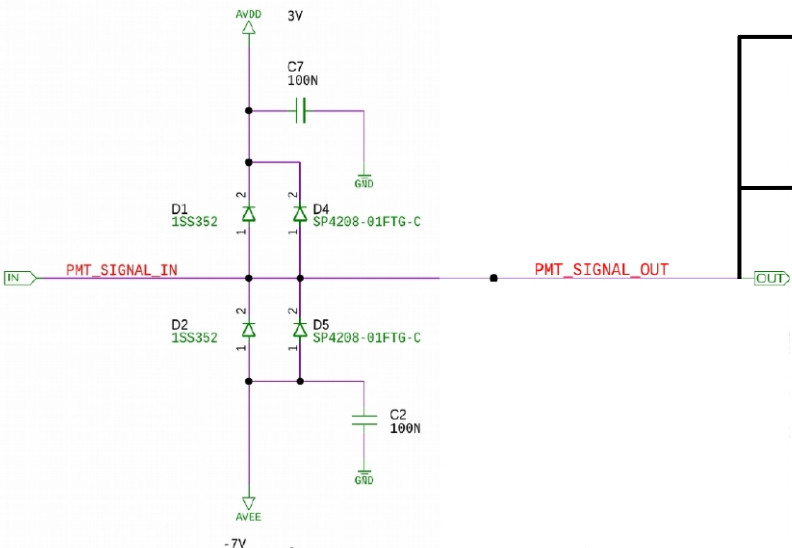


- Δ t = 1ps / °C
- Δ Gain = 0.05 % / °C (w/o corr.).
  → Well within Hyper-K needs.
- Temperature on chip (34°C) is 9°C higher than ambient temperature.

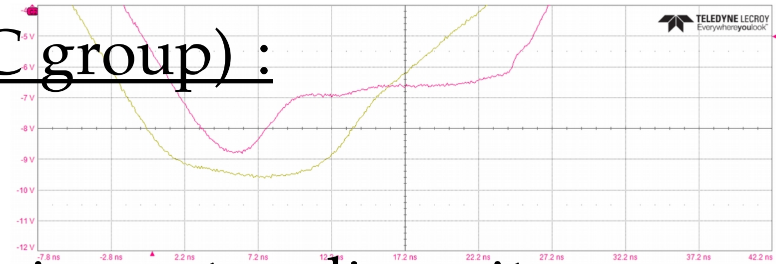
- Power for 2 HKROC < 6.6 W.
  → ≤ 24 W required.

Lifetime : Protection board & MTBF

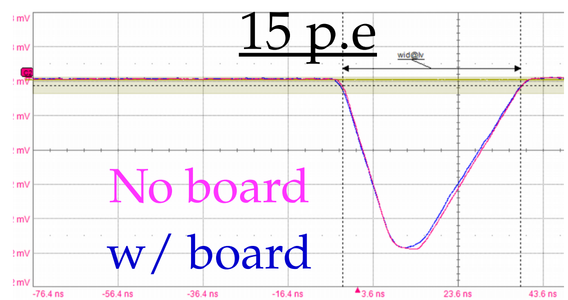
- Protection board added (Many thanks to QTC group) :

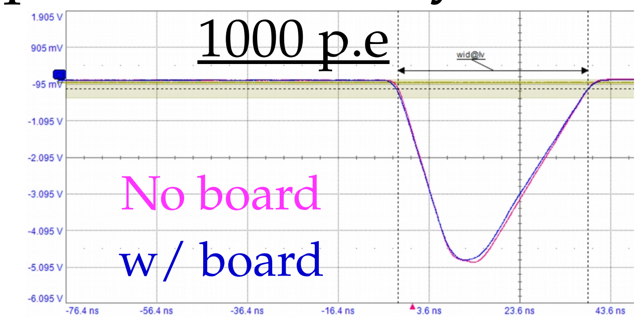


→ Cut signal < -7V



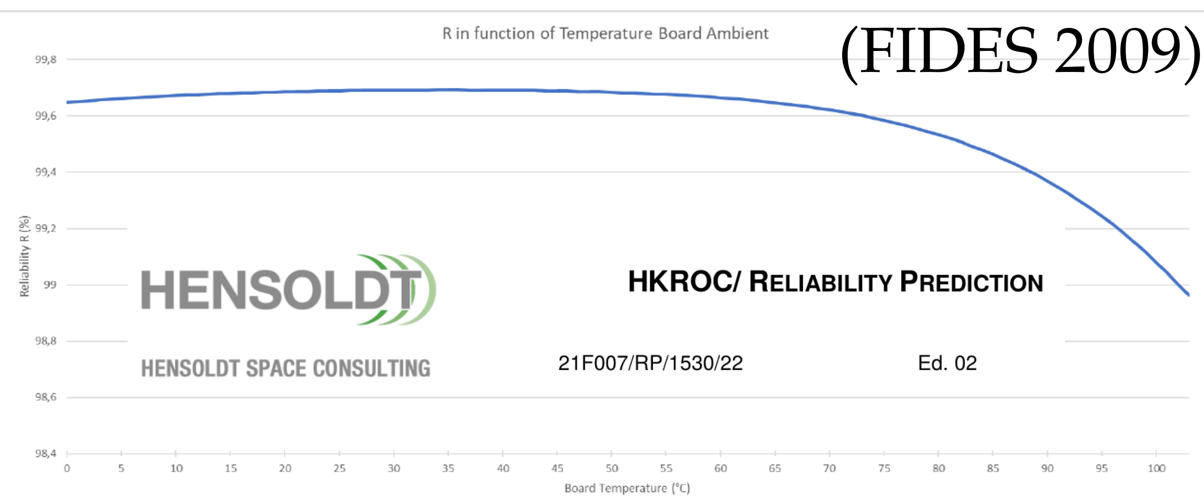
→ Now testing if no impact on linearity





- MTBF of HKROC (10 years): Focused on ASIC since not a commercial component (where we can select appropriate MTBF).
  → Hensoldt SC : specialized in MTBF evaluation for space & deep water components.

(FIDES 2009)

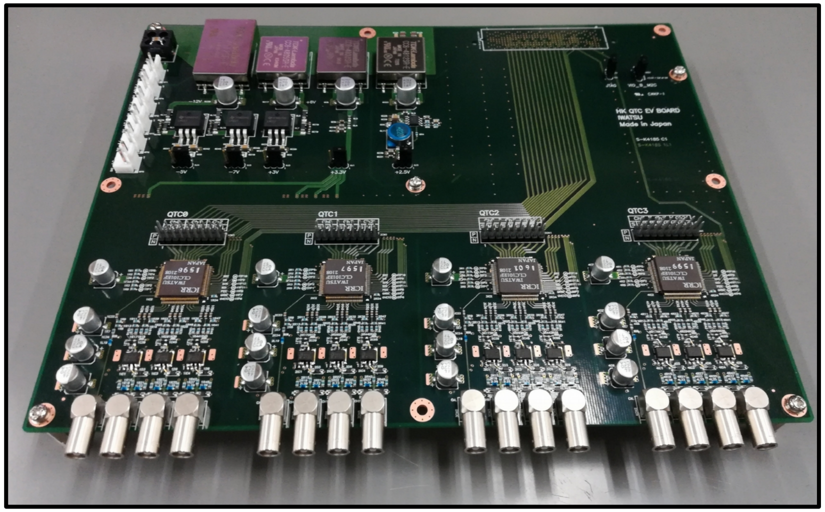


- ≥ 99.7 % survival rate after 10 years (> 99 % required).
- Homeworks : evaluate MTBF of the whole board → On-going.

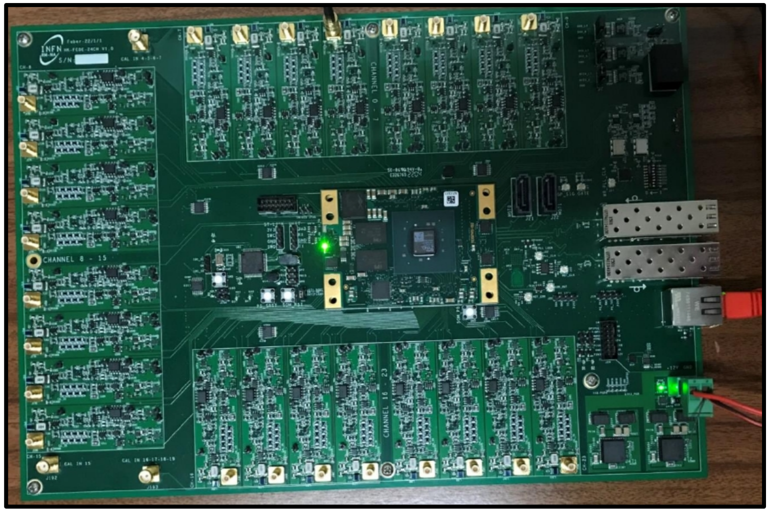
The Hyper-K candidate digitizers

- <u>3 digitizers considered :</u> all high-specs but explore ≠ digitization method

<u>QTC digitizer (Japan)</u>



<u>Discrete digitizer (Italy)</u>

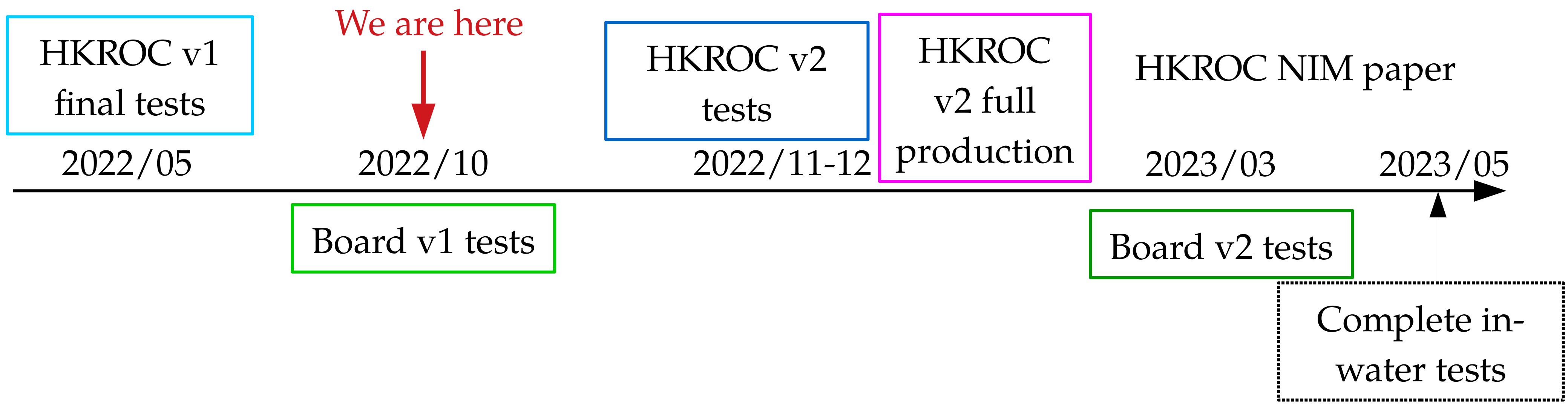


	QTC	Discrete	HKROC
Charge digitizer	ASIC (QTC)	Commercial ADC	ASIC (HKROC)
Digitization method	Charge integration	Charge integration	Waveform digitizer
TDC	On FPGA	Same as QTC	HKROC internal TDC

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

→ Decision by end of July.

Short-time schedule (before May 2023)



- HKROC v1 tests are **final & fulfill HK requirements** (final section).

- Production of **HKROC v2 started on 20th of July** !
  → Tremendous support from CMS experiment and the whole CERN in order to have a last minute spot on this run.
  → Back in **November for pre-production final tests.**

- The complete HKROC production (≥ 3200 ASICs) for whole experiment **scheduled in December** → Funded whatever the collaboration decision.

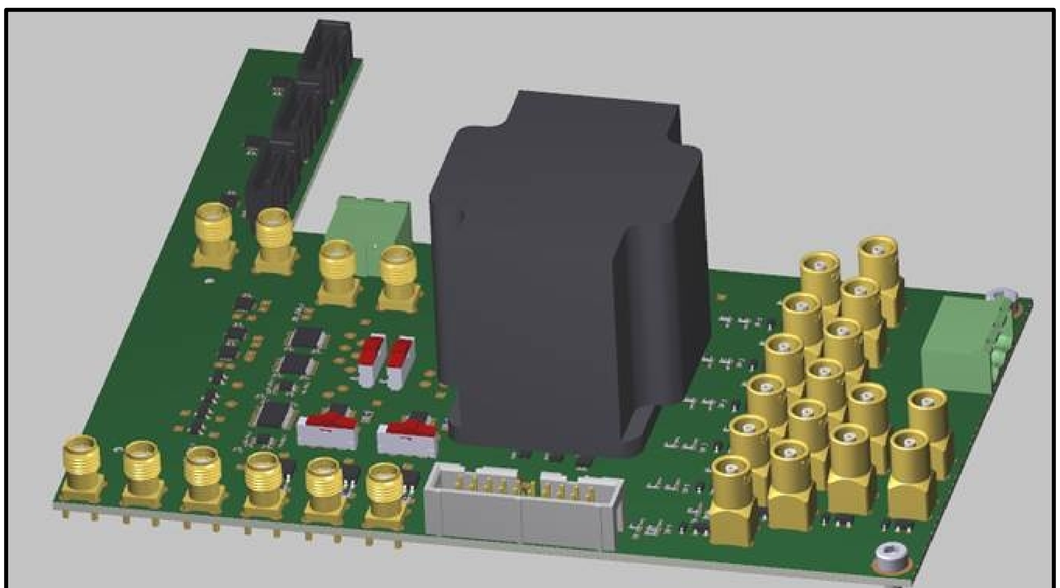
Short-time schedule (before May 2023)

We are here

2022/05	2022/10	2022/11-12		2023/03	2023/05
HKROC v1 final tests	Board v1 tests	HKROC v2 tests	HKROC v2 full production	Board v2 tests	HKROC NIM paper

Complete in-water tests

- <u>HKROC v1 board design is final :</u>



→ Contains protection circuit, the ASIC, internal calibration circuit & all links to other boards : data acquistion & transmission will be completely tested.

→ To be delivered <u>by end of October.</u>

Short-time schedule (before May 2023)

HKROC v1 final tests — 2022/05

We are here — 2022/10

Board v1 tests

HKROC v2 tests — 2022/11-12

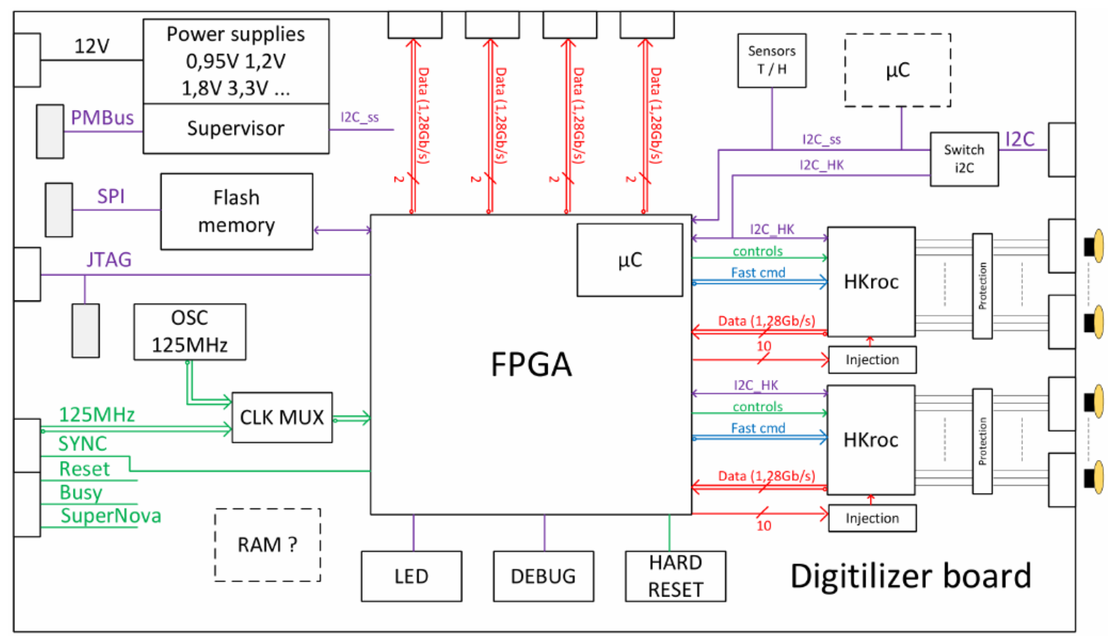
HKROC v2 full production

Board v2 tests — 2023/03

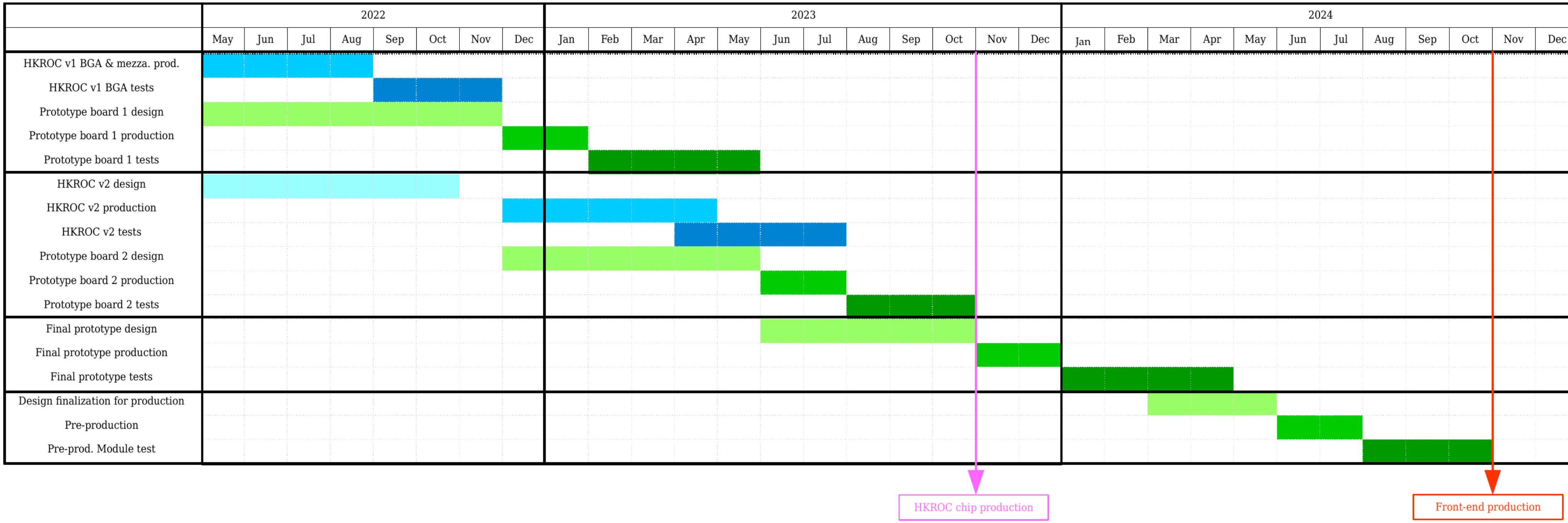
HKROC NIM paper — 2023/05

Complete in-water tests

- <u>v2 design on-going</u>
  → Contains all items (ASIC, FPGA, calibration, protection, link to other boards….)
  → Schematics final : December.
  → Layout : January.
  → To be delivered : end of <u>February 2023.</u>
  → **<u>FPGA already ordered !</u>**



Updated schedule towards production



- <u>ASIC production could be done in advance :</u> from end of 2023.
  → Have **<u>3 operating ROBOT</u>** to test them at CEA, LLR & OMEGA (used for CMS to test 200,000 HGCROC chips).

- <u>Board production :</u> from Q4 2024 to mid-2025.

- We are completely on-time !