The Hyper-Kamiokande experiment at LLR

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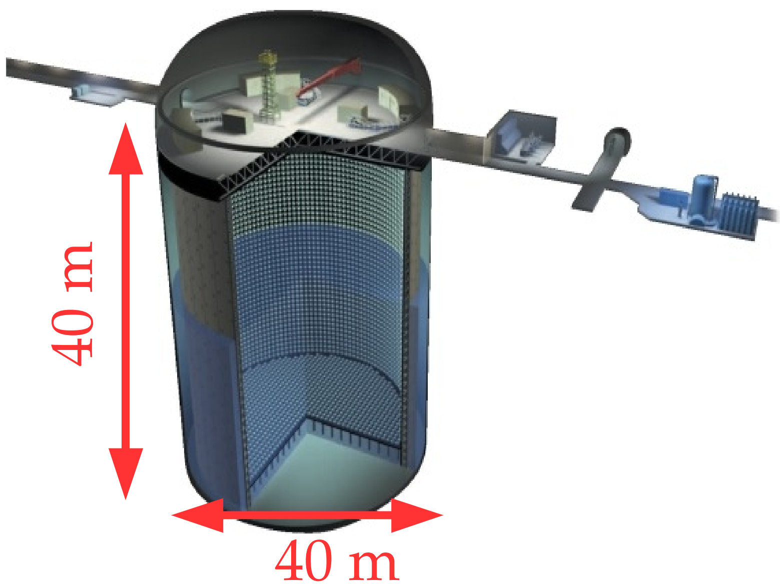
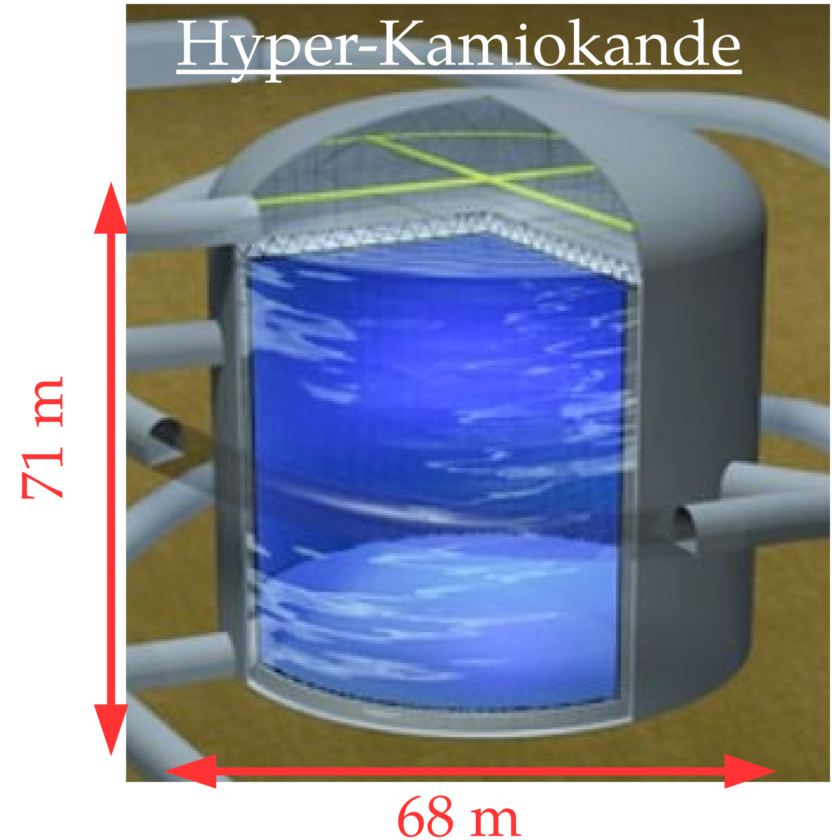
I. Hyper-K physics

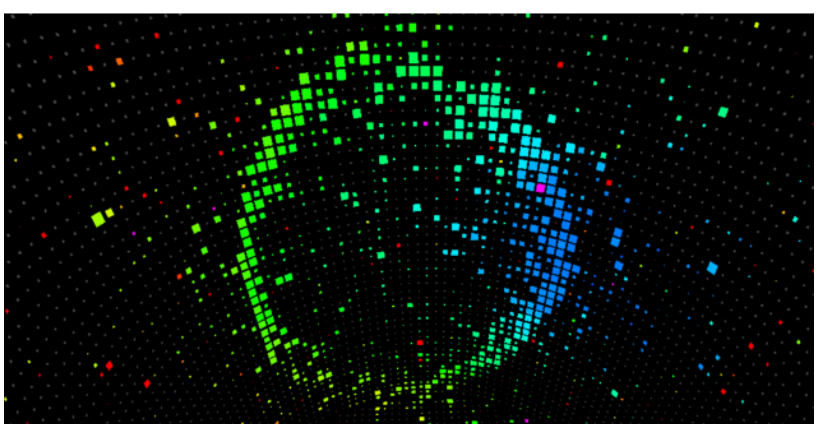
Reminder : what is Hyper-K ?

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

<u>Super-Kamiokande</u>

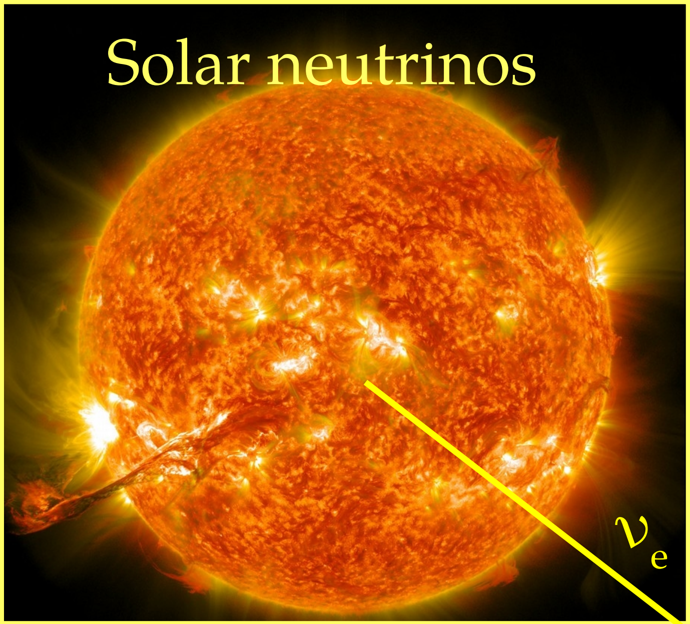




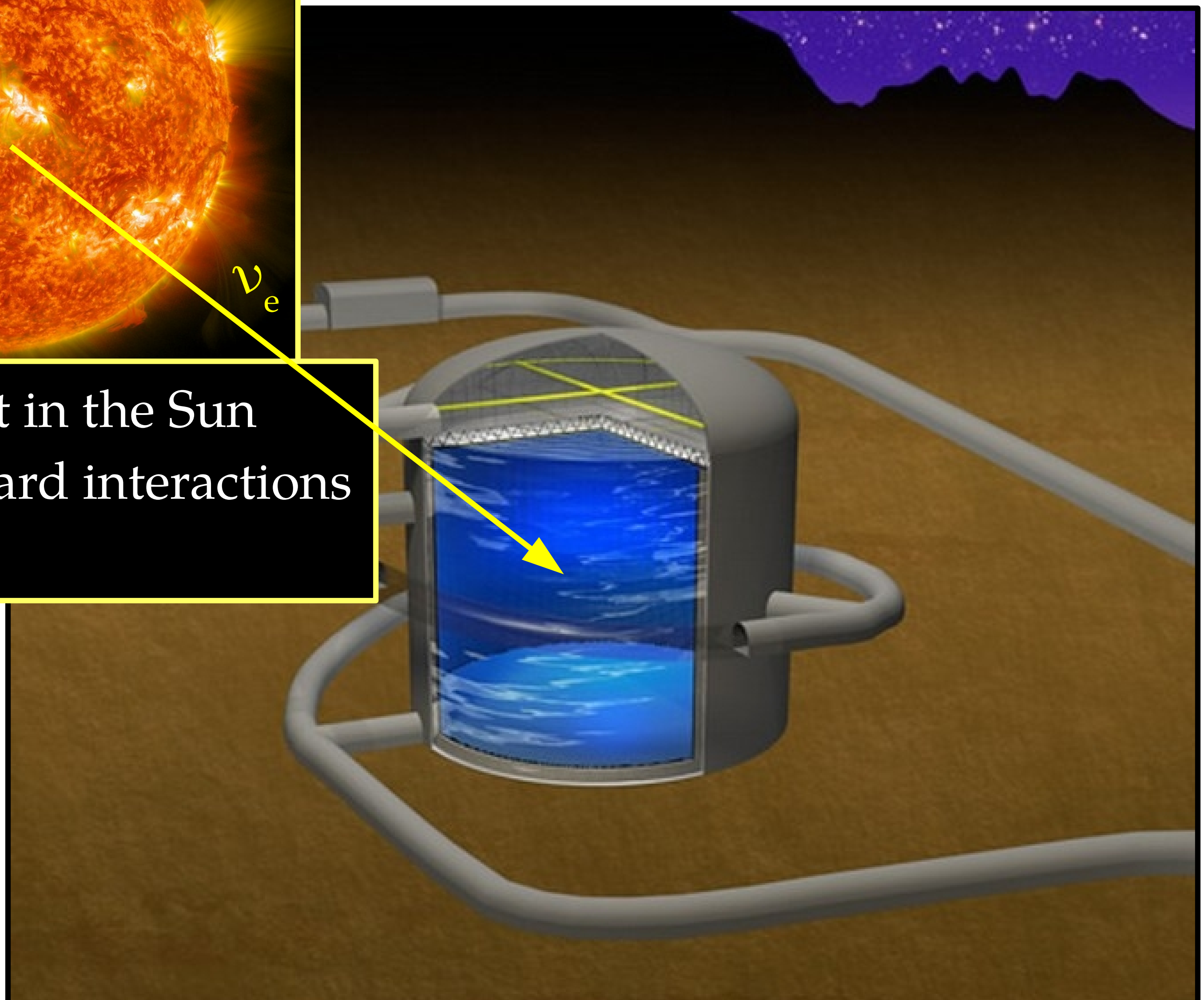


	Super-K	Hyper-K (1st tank)
Site	Mozumi	Tochibora
Number of ID PMTs	**11,129**	**40,000**
Photo-coverage	40%	40% (**×2 sensitivity**)
Mass / Fiducial Mass	50 kton / **22.5 kton**	260 kton / **187 kton**

Physics case

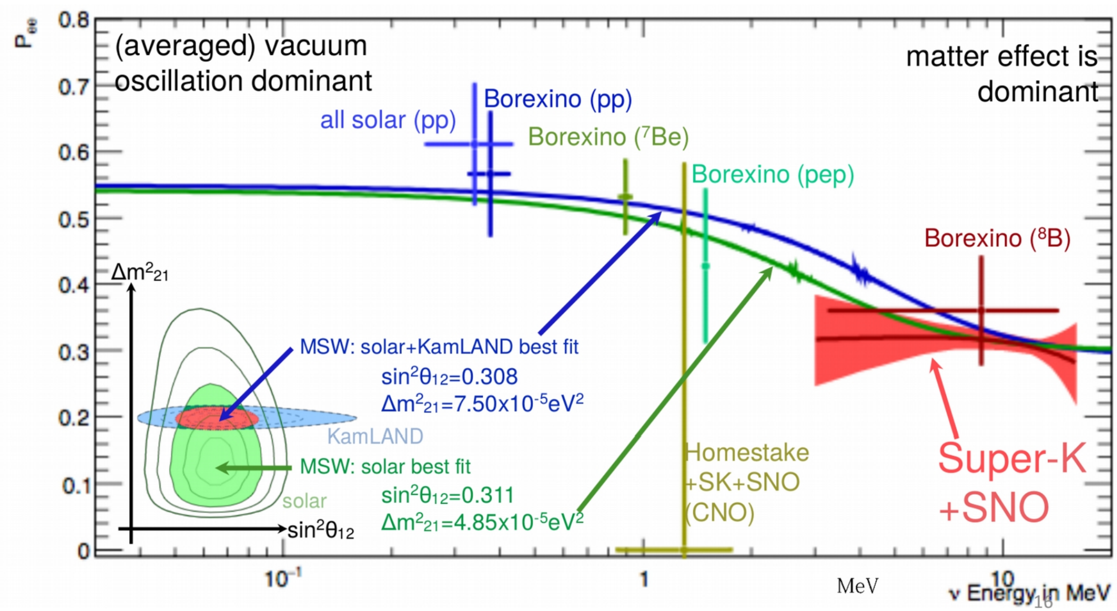


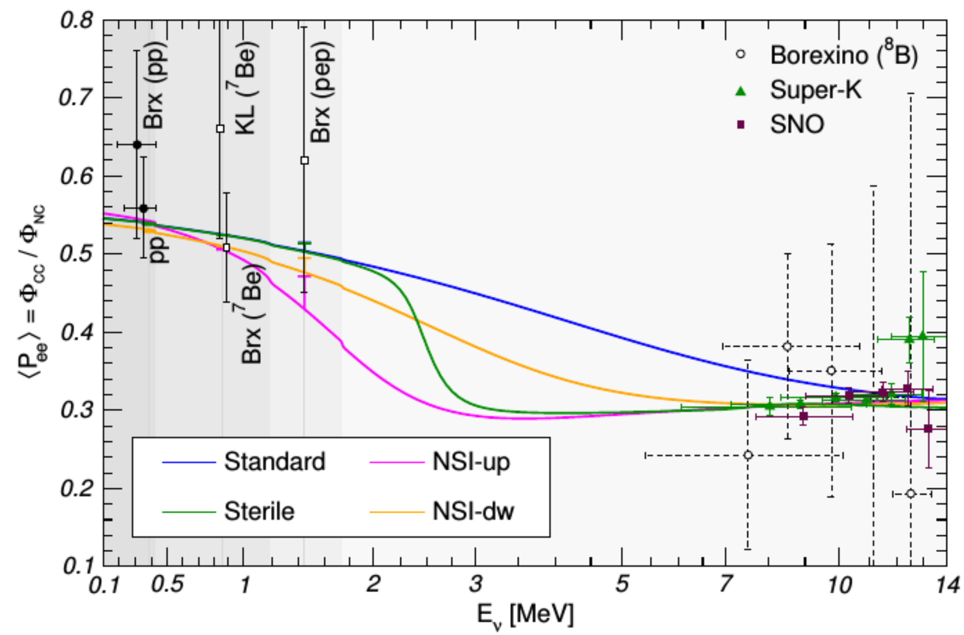
- MSW effect in the Sun
- Non-standard interactions in the Sun.



Solar neutrinos : upturn

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

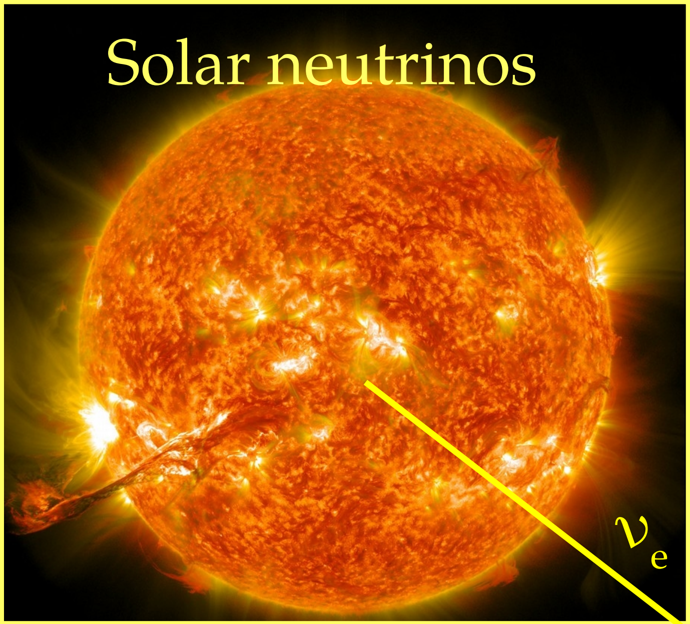




- SK deviates from standard upturn scenario > 2σ.

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

Physics case



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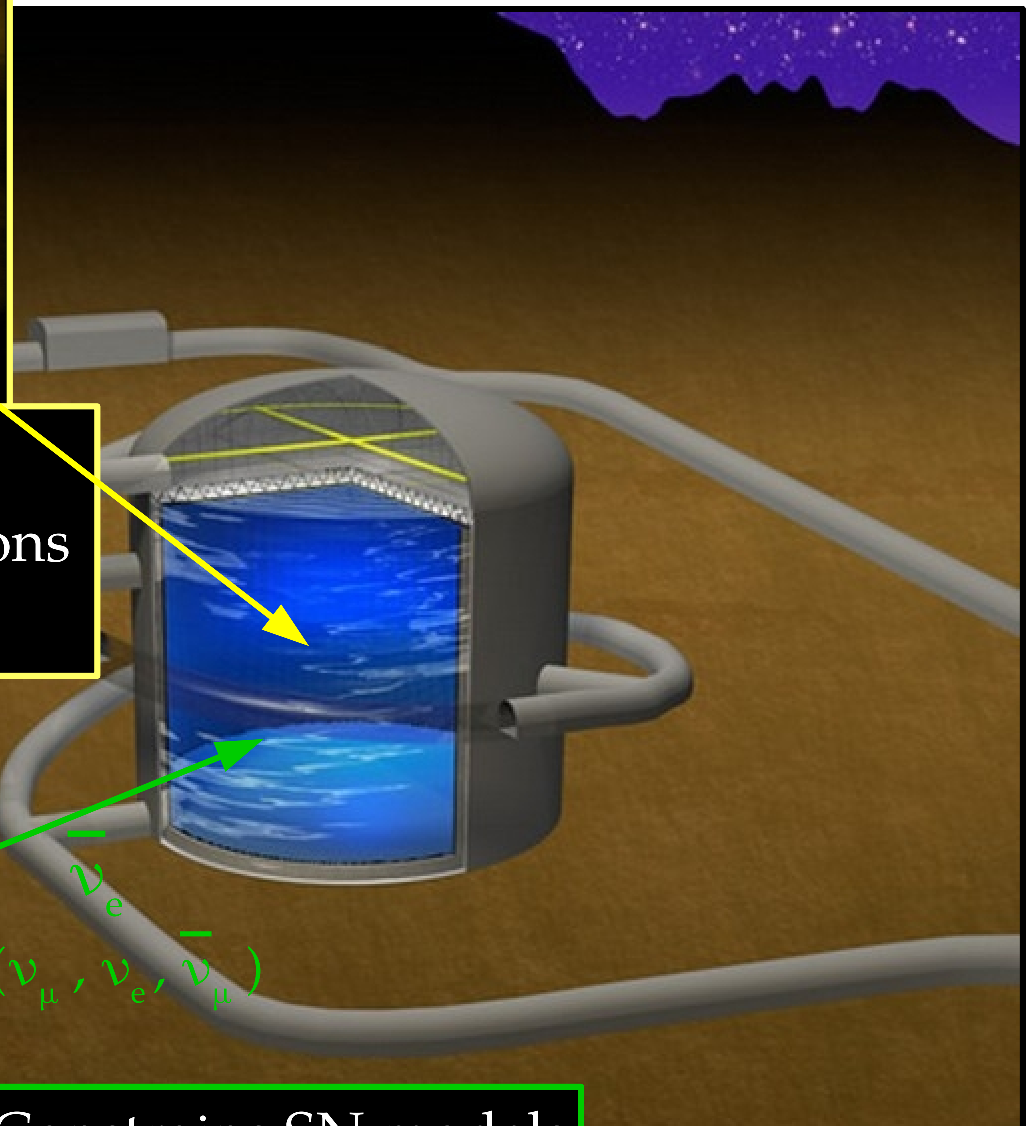
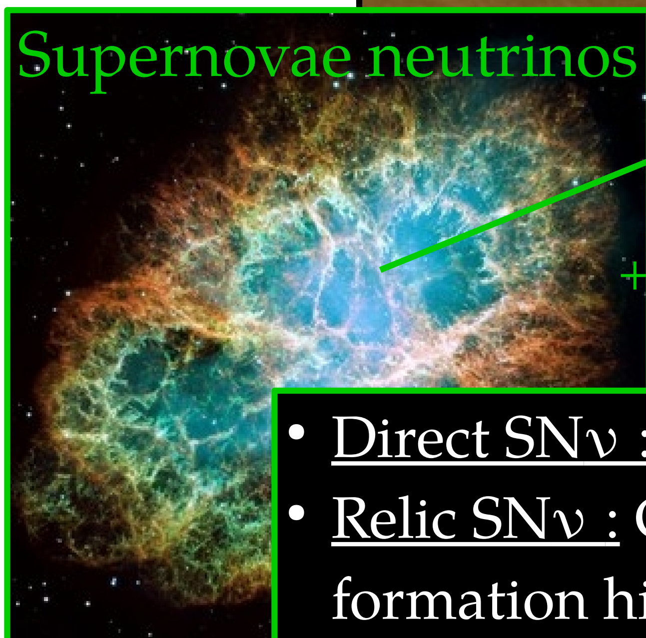
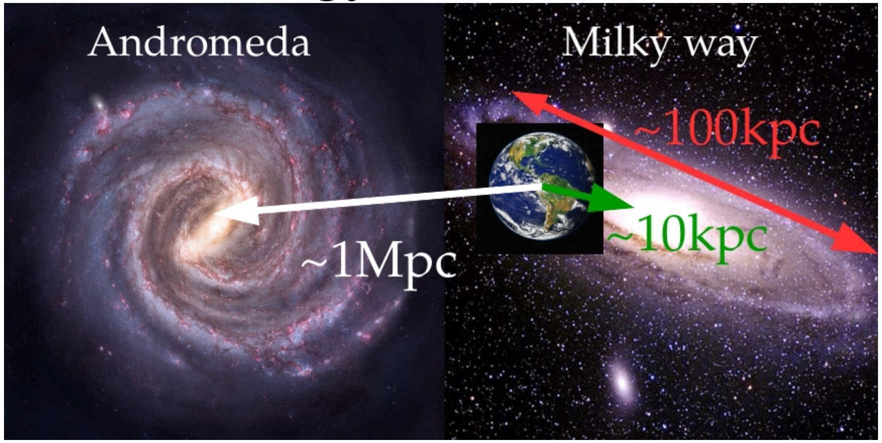




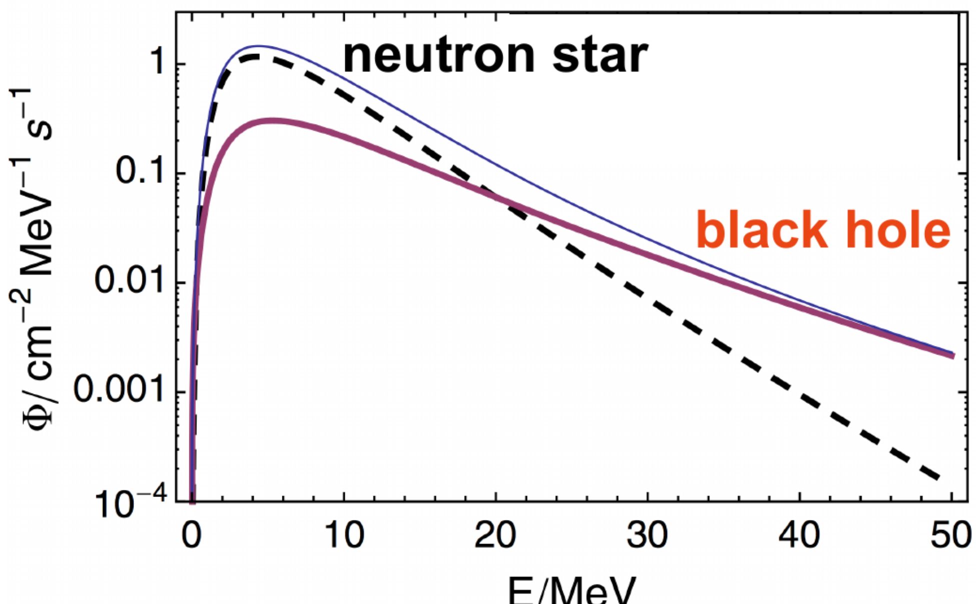
- <u>Direct SNν :</u> Constrains SN models.
- <u>Relic SNν :</u> Constrains cosmic star formation history

Supernovae neutrinos

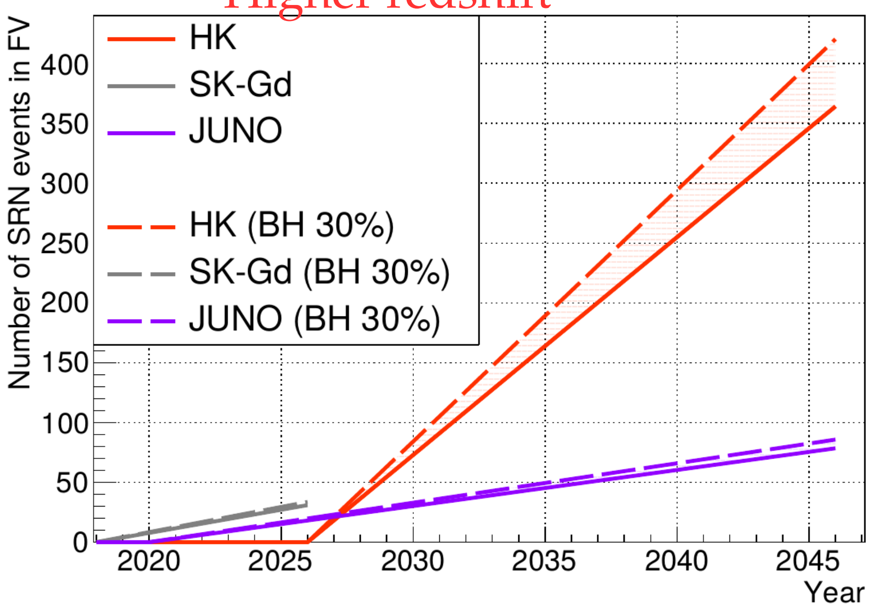
- Unique probe for supernovae ν : 99 % of SN energy → ν.
  - But direct ν detection very rare.
  - HK also sensitive to extra-galactic SNν from Andromeda !



- 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



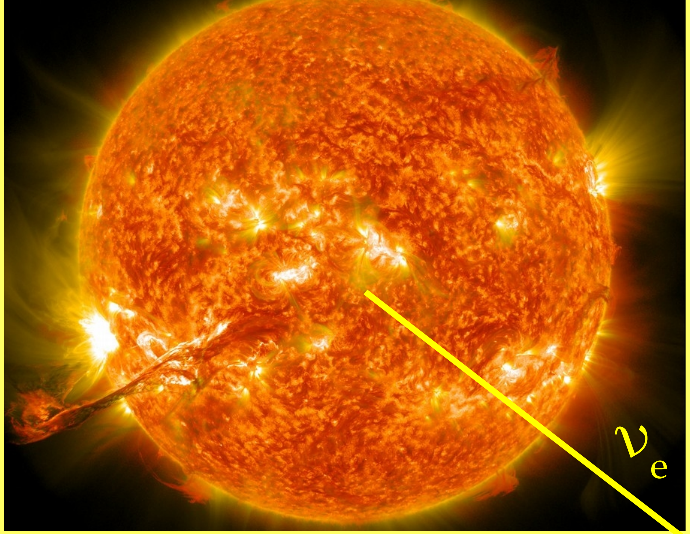
Higher redshift



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

Physics case

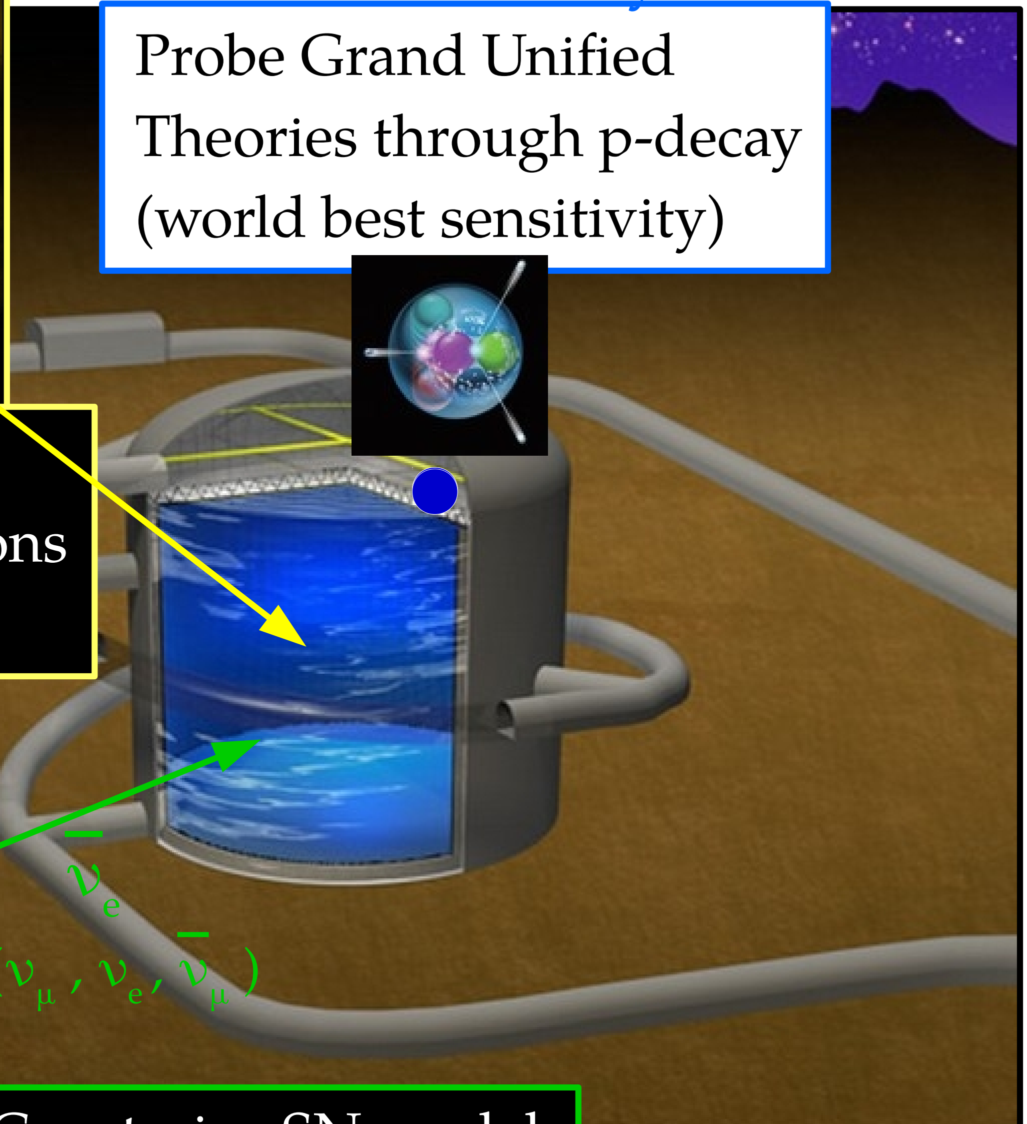
Solar neutrinos



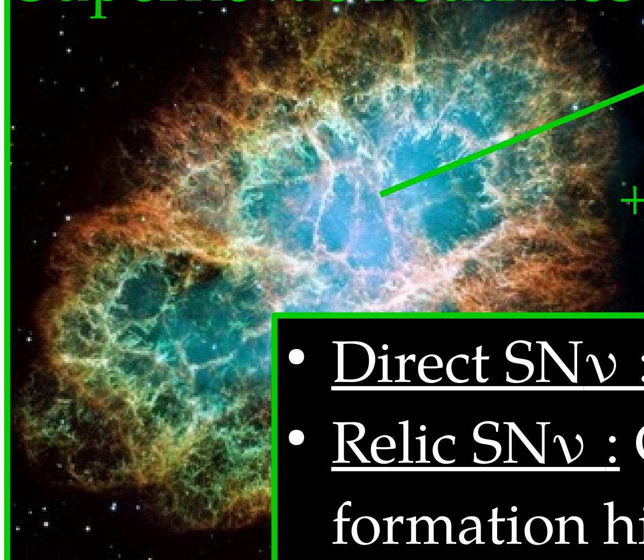
- MSW effect in the Sun
- Non-standard interactions in the Sun.

Proton decay

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



Supernovae neutrinos

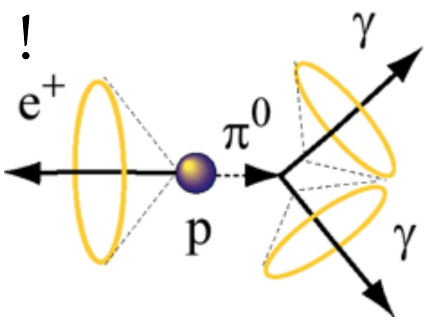


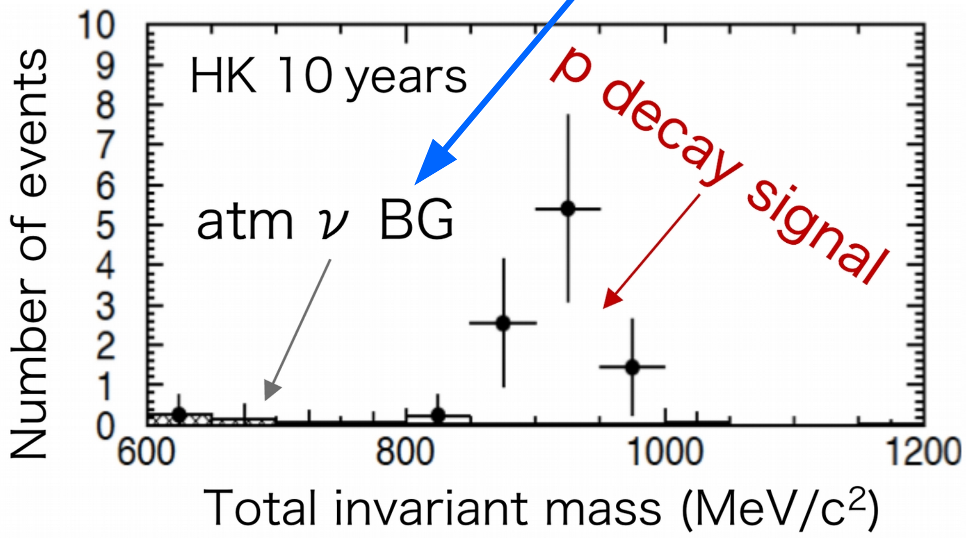
- <u>Direct SNν :</u> Constrains SN models.
- <u>Relic SNν :</u> Constrains cosmic star formation history

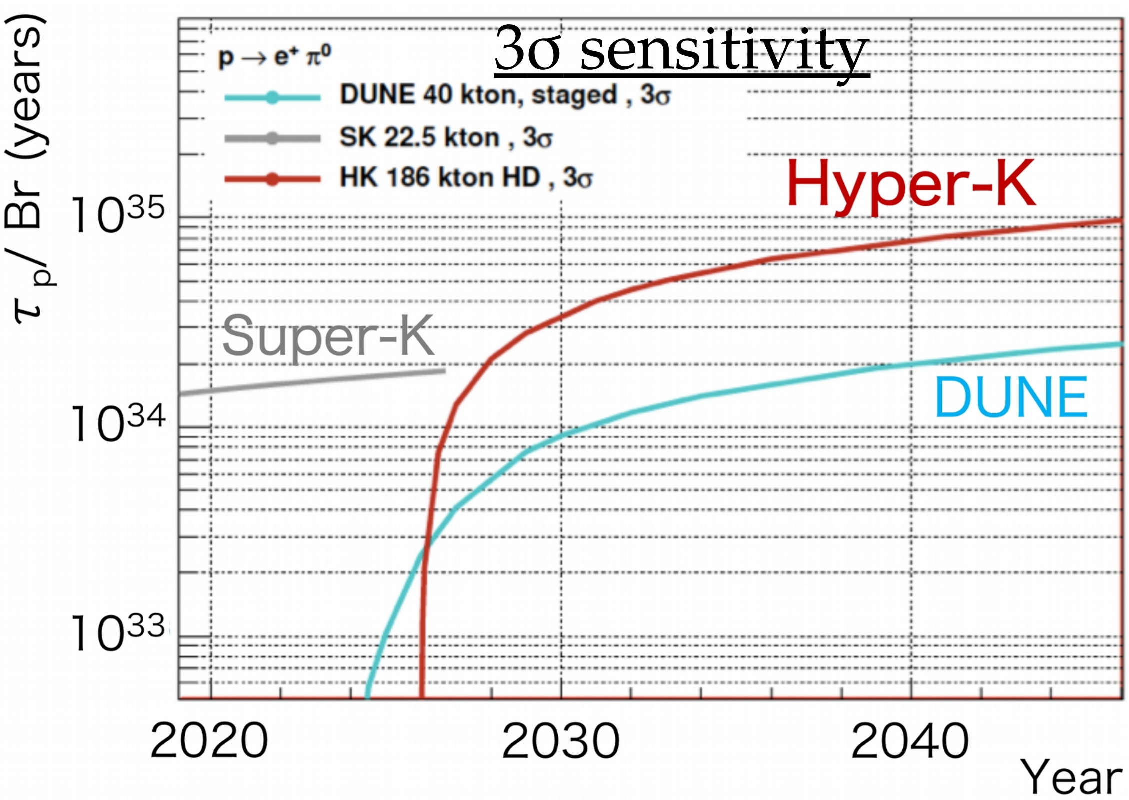
GUT and proton decay

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

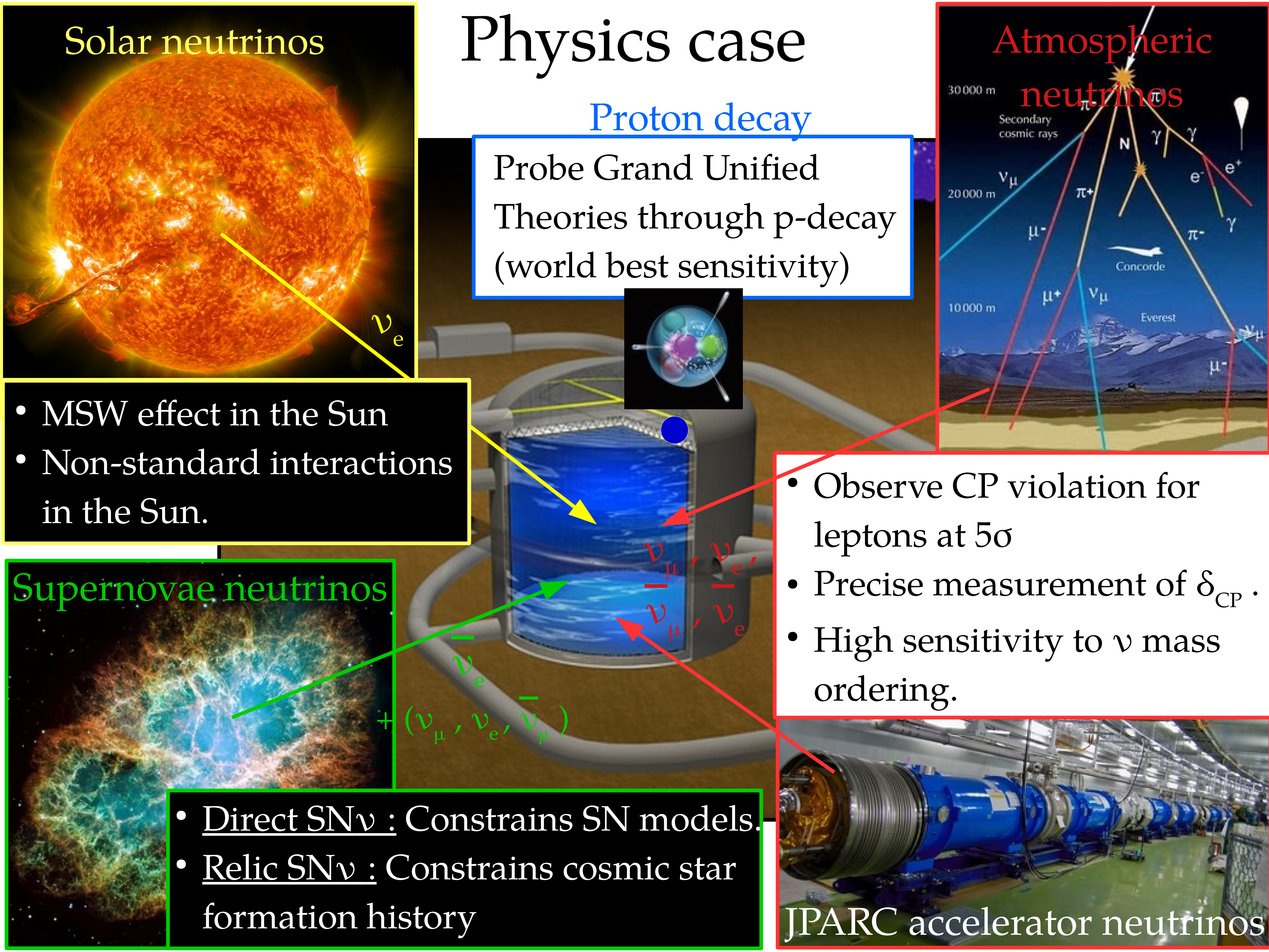
- <u>Golden channel :</u> $p \to e^+ + \pi^0 \to$ Almost background free !
  $\to$ Requires 2γ & reconstructed energy = Invariant M_P
  $\to$ <u>Bkg :</u> Atmospheric ν producing e.g. a π^0.







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


Physics case
Solar neutrinos
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
N
ν_μ
π^+
π^-
μ^-
μ^+
e^-
e^+
γ
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

Focus on CP violation

- CP violation search essentially based on accelerator ν : T2HK

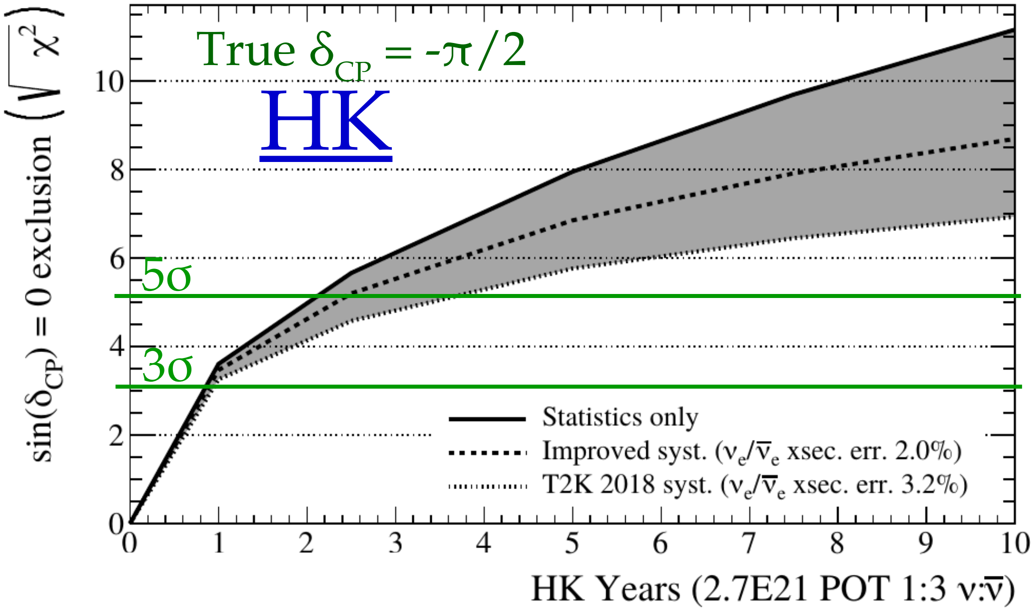
- ν_e appearance in a ν_μ beam and ν_μ disappearance & $\bar{\nu}$ equivalents.
- Detector technologies, calibration, analyses well-proven by T2K&SK.

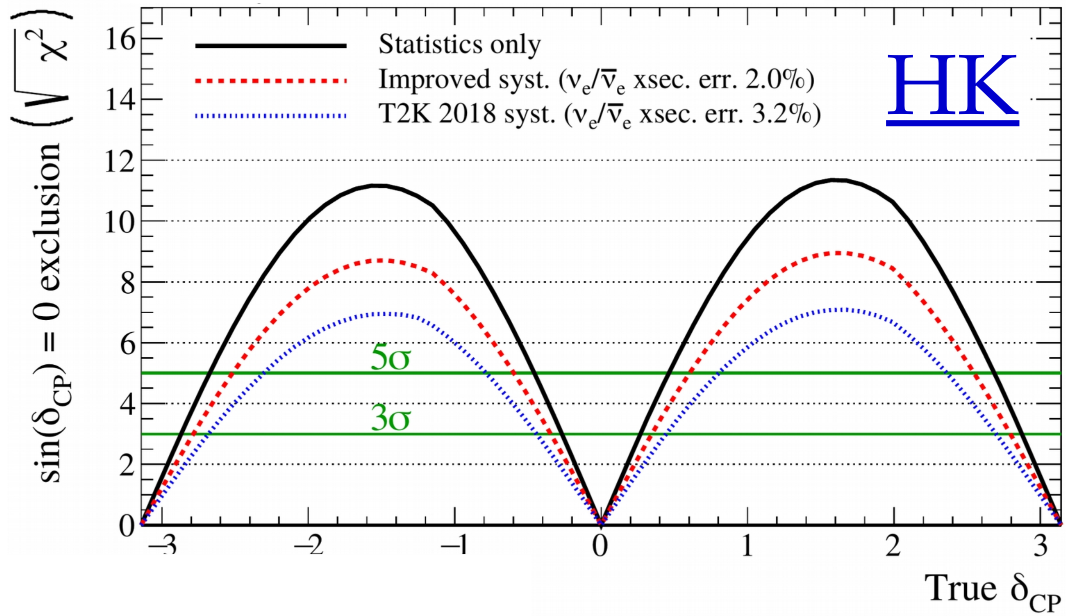
$\Longrightarrow$ Quick start ! Which relies on 2 milestones :

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).

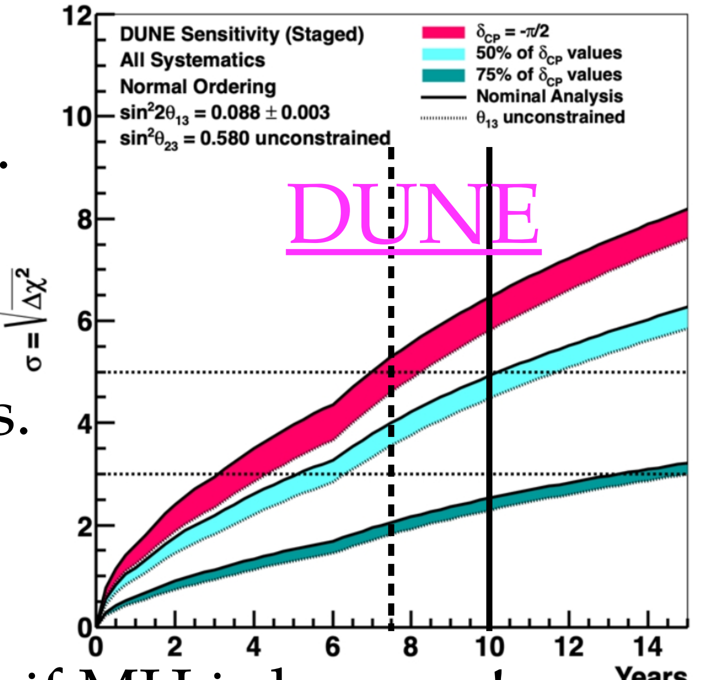




- $\delta_{CP} = -\pi/2$: 5σ after 2-4 years of data taking

  → Independent from ↓ systematic uncertainties.

  → DUNE will require 7-8 years.



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

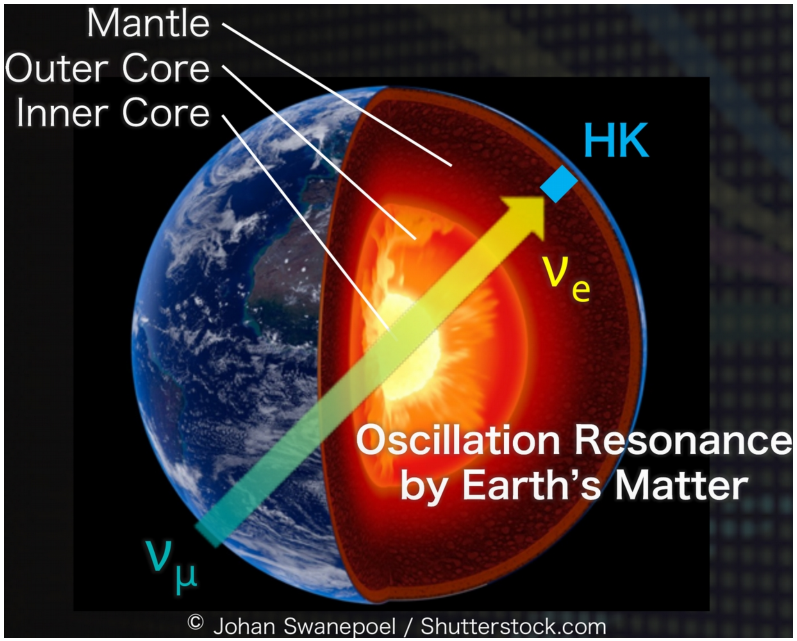
  → DUNE : 5σ sensitivity on 40%

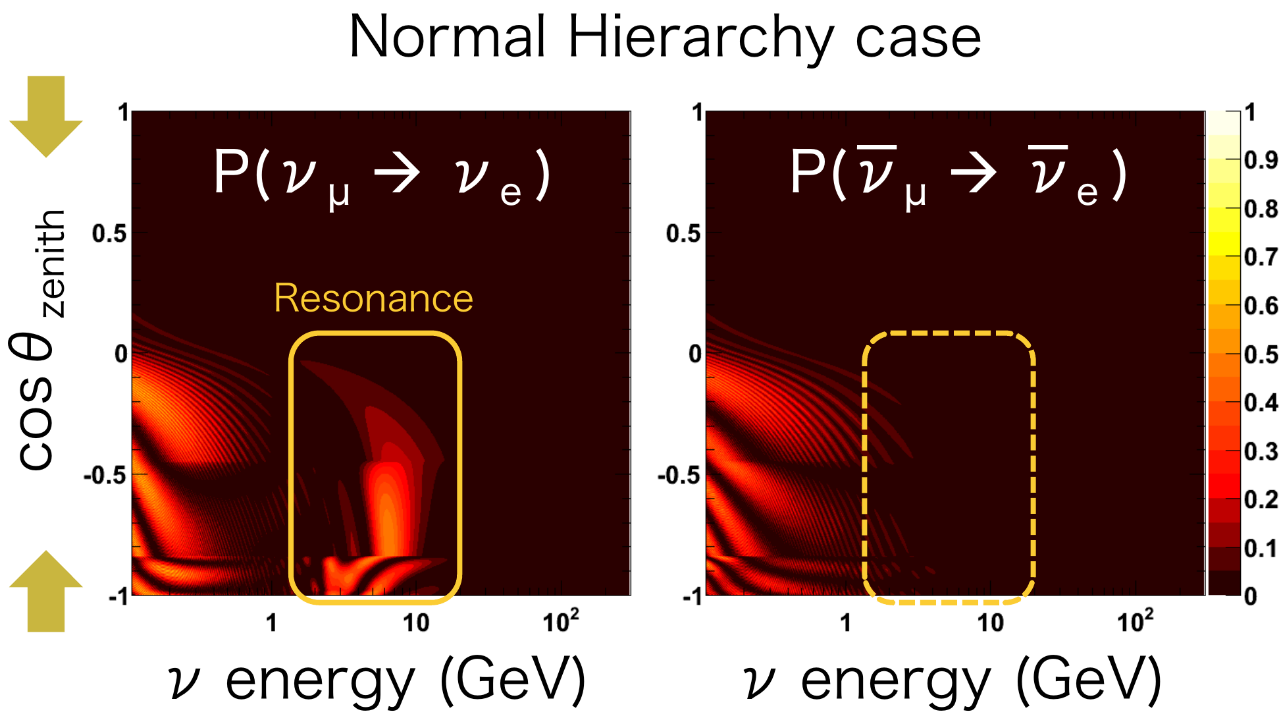
- HK has world-best sensitivity to CP violation … if MH is known !

Atmospheric neutrinos

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

  $\rightarrow$ The longer the baseline, the higher the effects





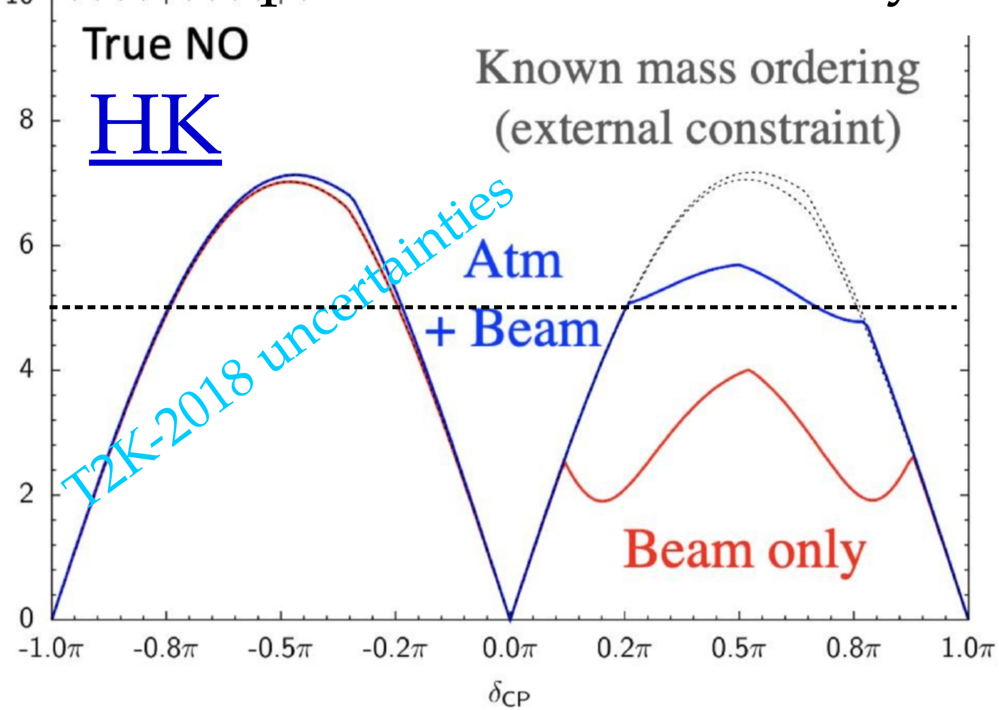
- Mass hierarchy determined with upward-going multi-GeV ν_e sample :

atm. baseline ≤ 13000 km ≫ 295 km accelerator baseline

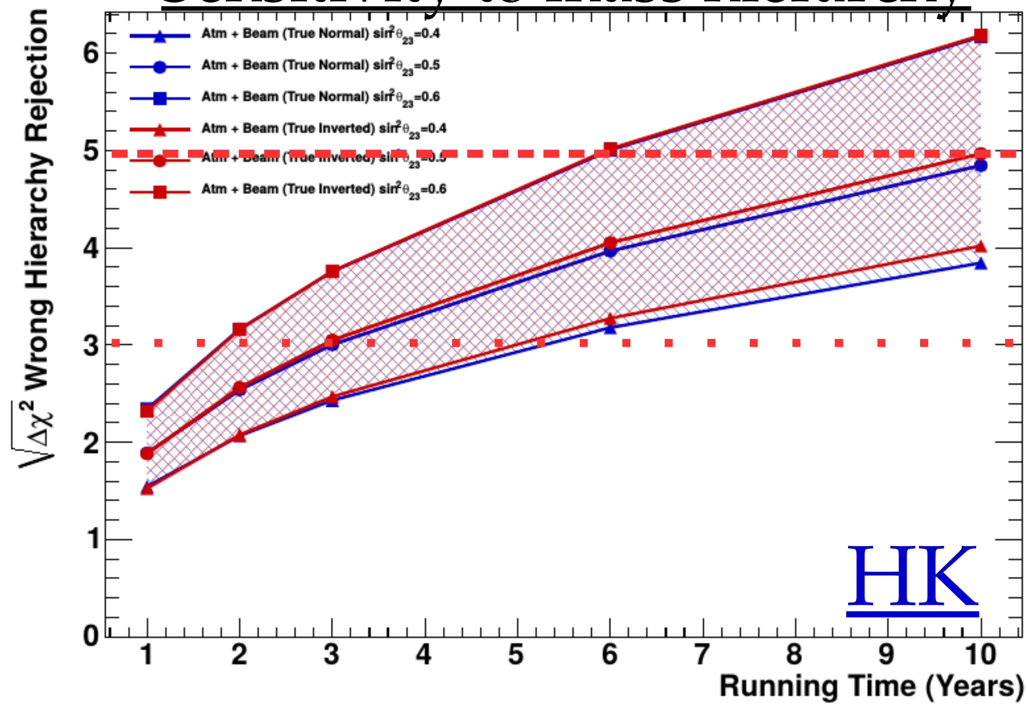
  - <u>Normal hierarchy :</u> enhancement of $\nu_\mu \rightarrow \nu_e$.
  - <u>Inverted hierarchy :</u> enhancement of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$.

Combination of atmospheric + beam ν

Impact on CPV sensitivity

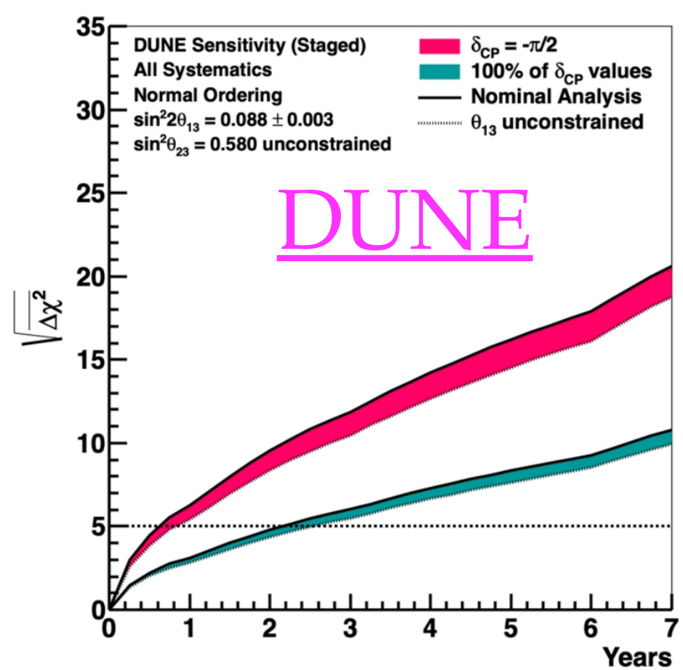


Sensitivity to mass hierarchy



- 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 :

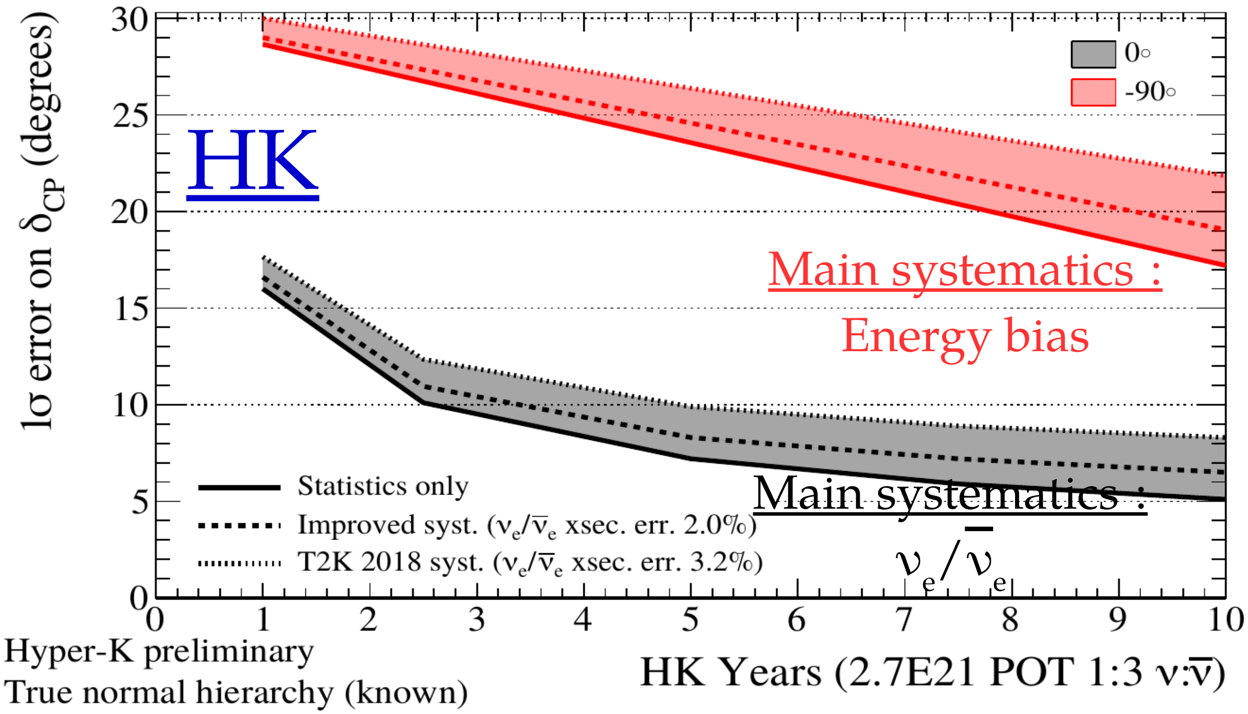
  → HK after ≥ 6-10 years via atmospheric.

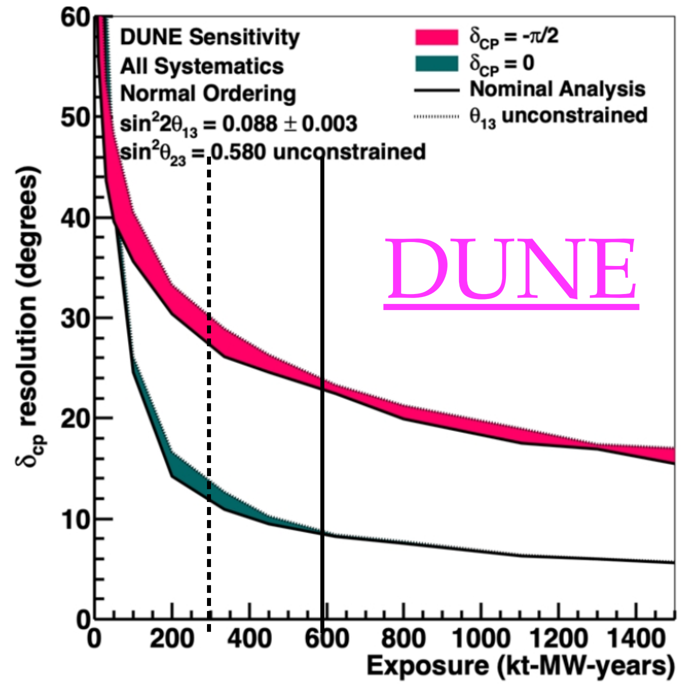
  → DUNE : after 1-2 years.

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°

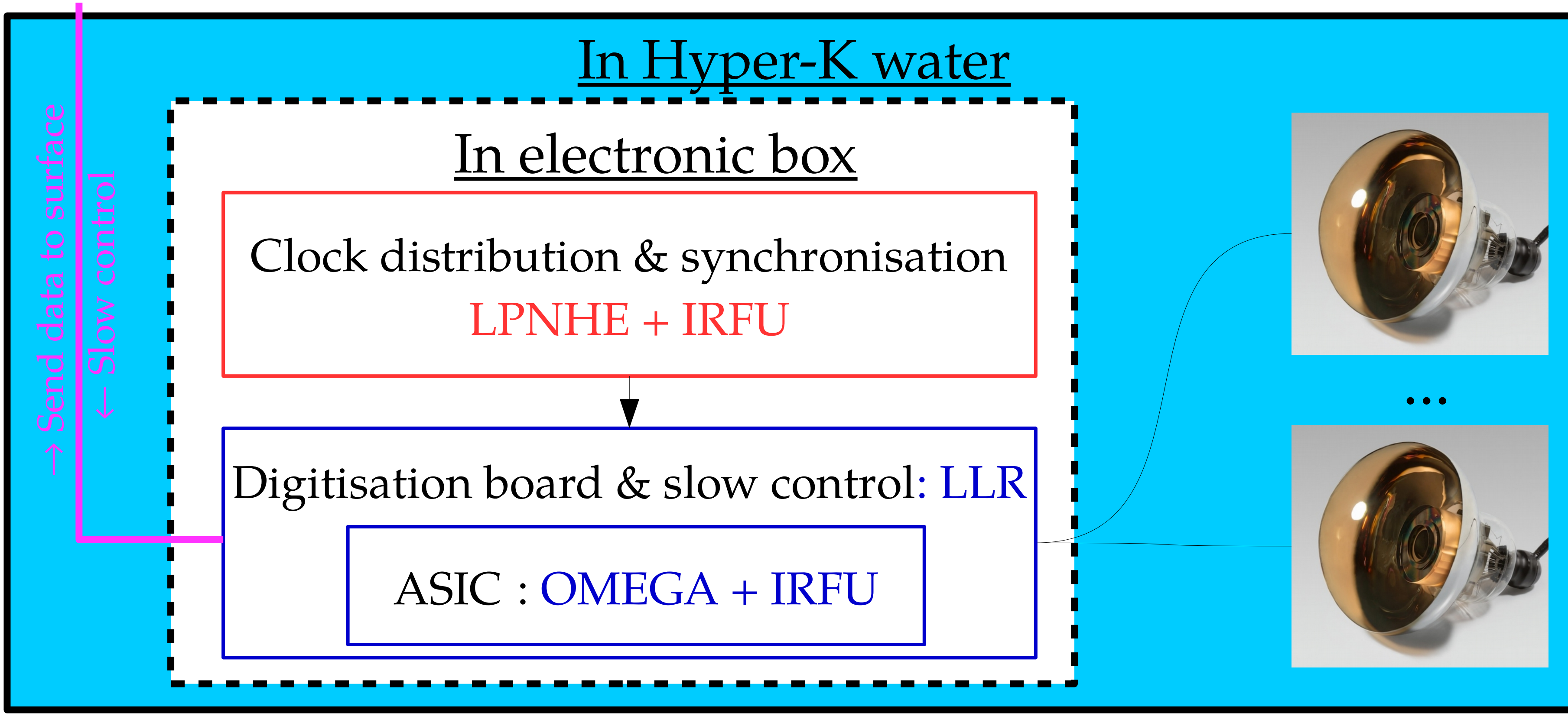
- HK will be the leading experiment for CPV & δ_{CP} measurements in the next 20 years.

II. Electronique de HK et notre proposition

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 would develop the whole PMT read-out (w/o DAQ).
- LLR & OMEGA (+IRFU) : joint project to design the whole 20k PMT time & charge digitization. → Central role in HK!

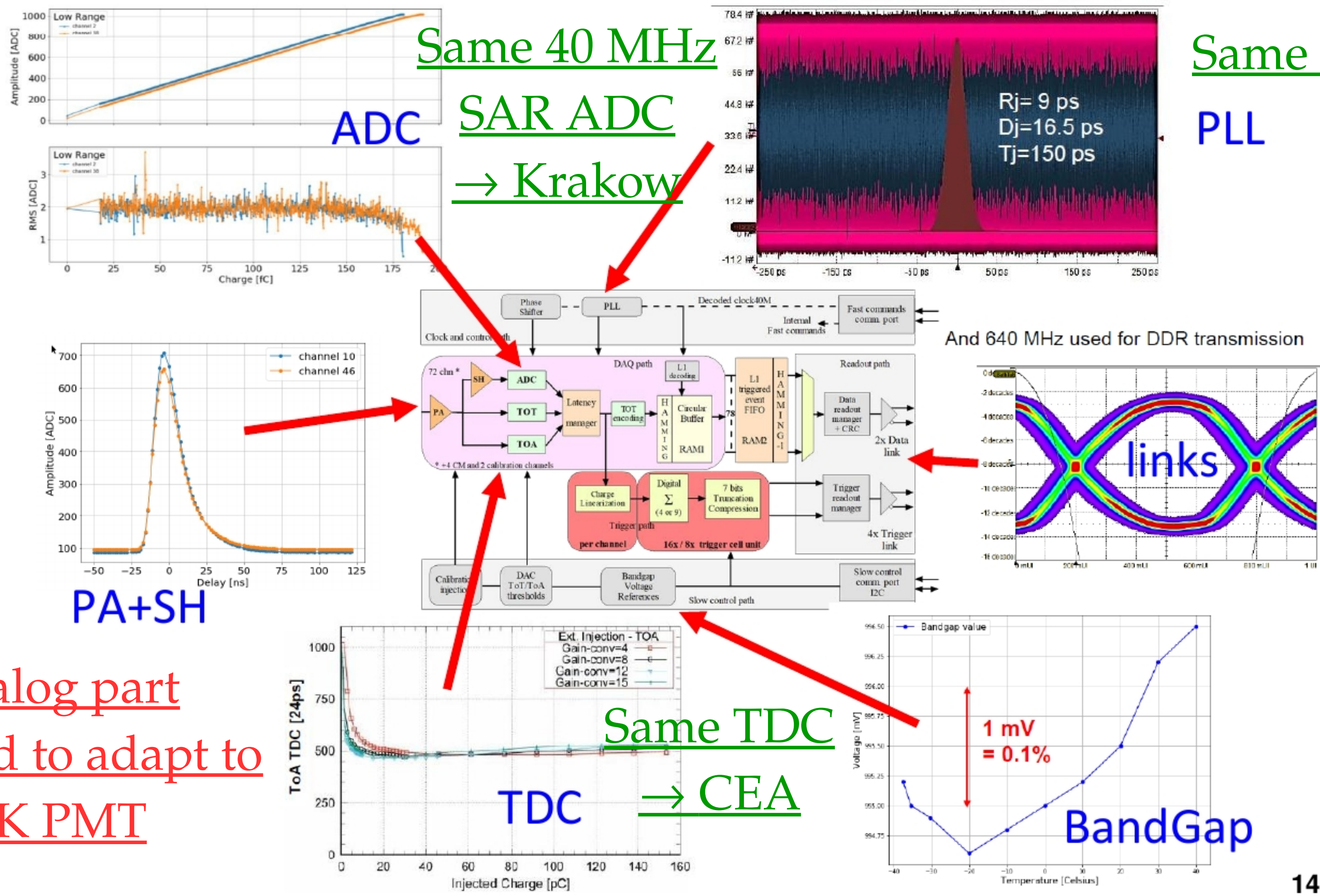
Technical constraints

Physics constraint	**Impact on electronics requirement**
Detect synchronous (beam) & asynchronous (atm., solar, p-decay, SN) events	Self triggering for each channel
Detect close SN (e.g. Beltegeuse) w/ no event loss	Channel dead time < 1 µs
Detection threshold as low as possible (negligible noise compared to PMT one)	Charge threshold < 0.25 p.e.
Excellent detection & no charge ↔ E bias from low (solar, SN) to high energy physics	Charge linearity < 1 % from 0 to 2500 pC (0 to 1250 p.e. for HK)
Excellent charge ↔ E resolution	0.05 p.e. RMS < 25 p.e
Electronics < PMT time resolution (1.3 ns)	Electronics timing RMS < 0.3 ns at 1 p.e.
Low power consumption as under water	1 W/ channel

- Candidate among existing chips : CATIROC for JUNO 8 cm PMT. But :
  → Deadtime of 9 µs > 1 µs.
  → Designed for small PMTs operating w/ gain ~10^6 vs HK PMT ~ 10^7 : operating range 0-300 pC.
  → Use AMS 0.35 µm etching : will be soon stopped.

Origins of the HKROC : the CMS HGCROC

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

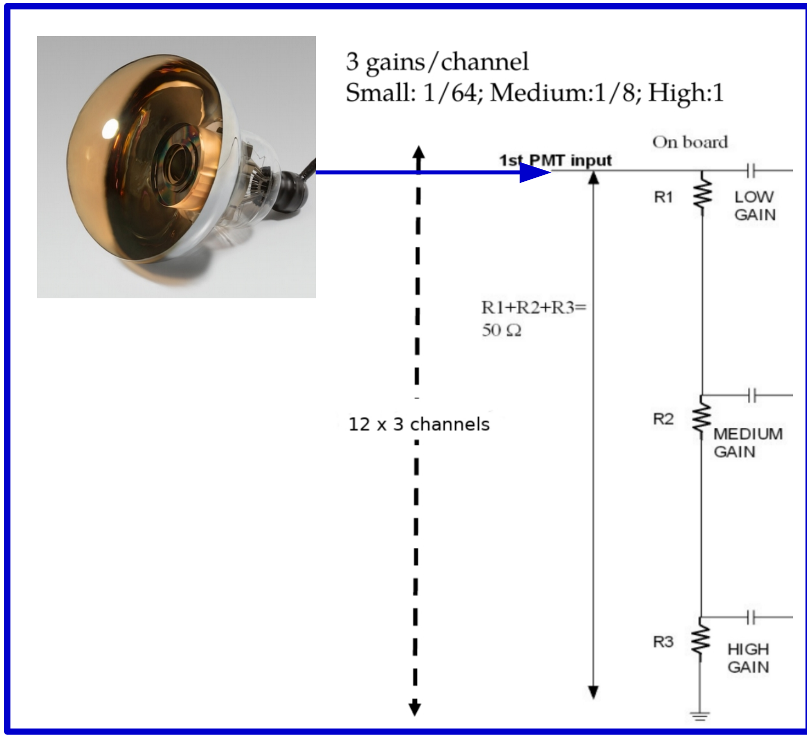


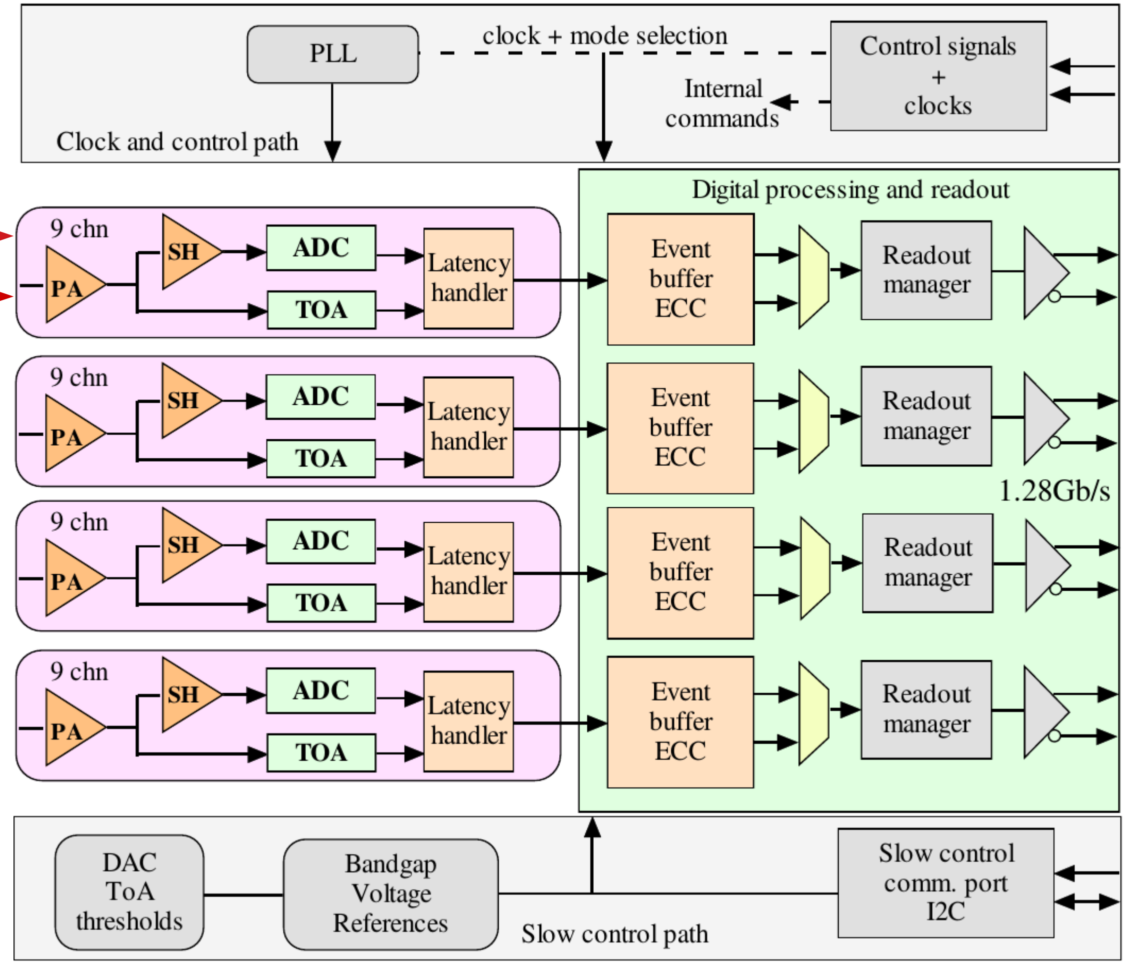
Analog part changed to adapt to HK PMT

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

The HKROC digitizer

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



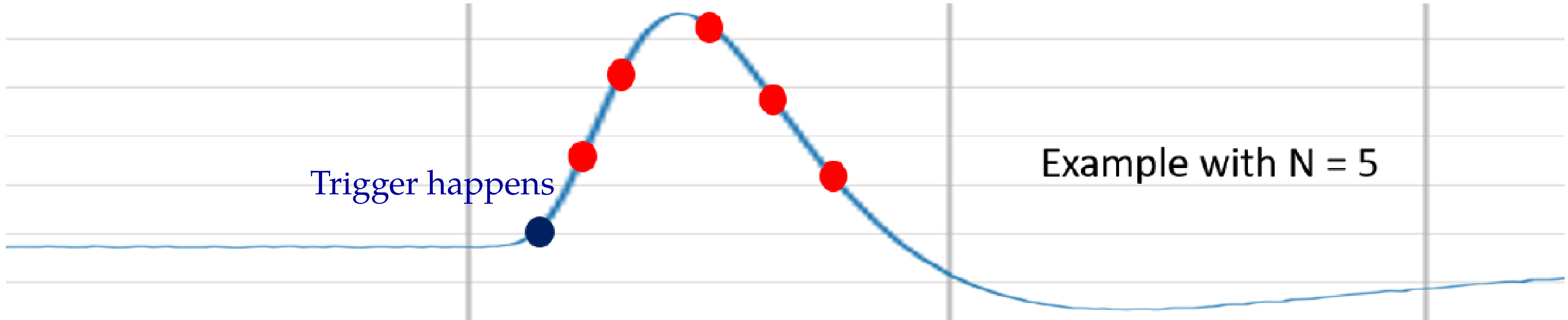


- TSMC CMOS 130nm etching.
- Dynamic range from 0 – 2500 pC : 3 gains / channel.
- 4 readout / ASIC @1.28 Gb/s : 1 readout ↔ 3 PMTs.
- <u>If 1 PMT trigger :</u> read all 3 PMTs of 1 readout.

Overview of the HKROC digitizer

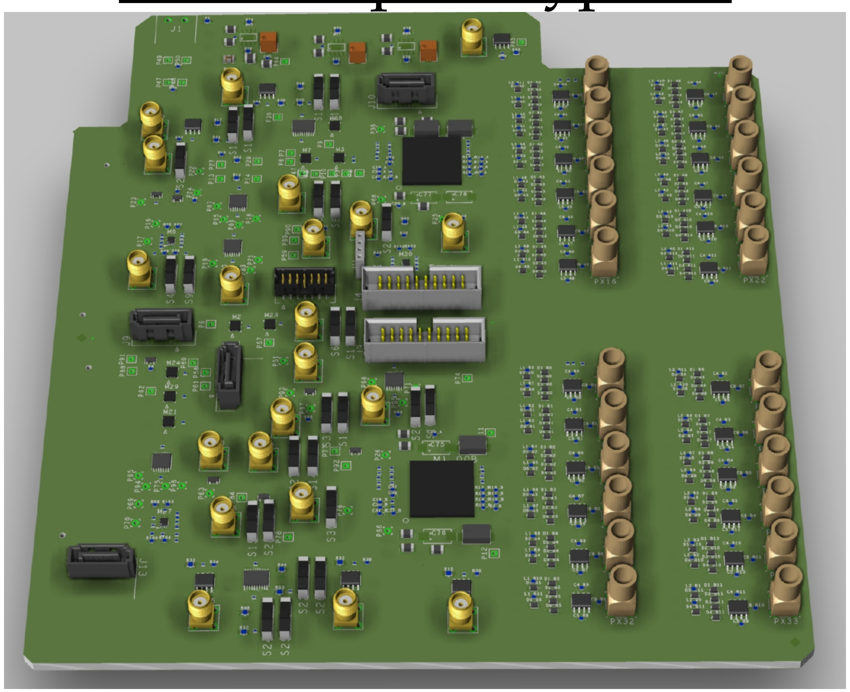
- HKROC is a waveform-like digitiser @40 MHz→ 1 point every 25 ns.

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

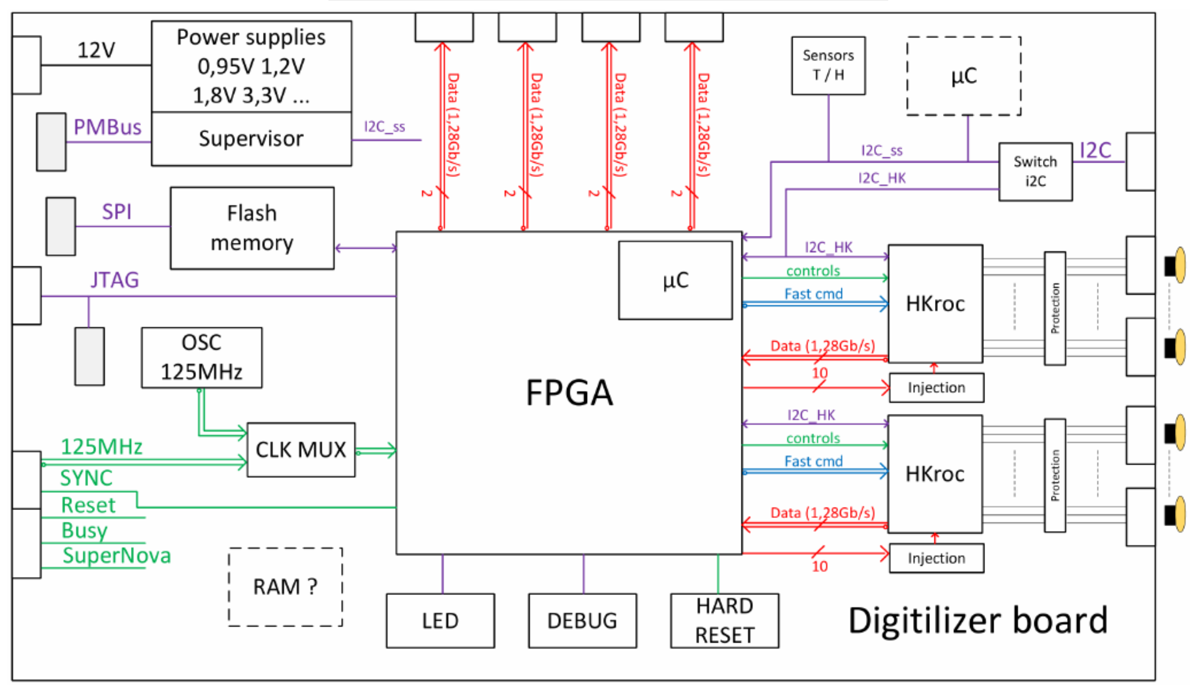


- HKROC digitizer : 24 PMT channels readout by 2 HKROC ASIC.

HKROC prototype v1

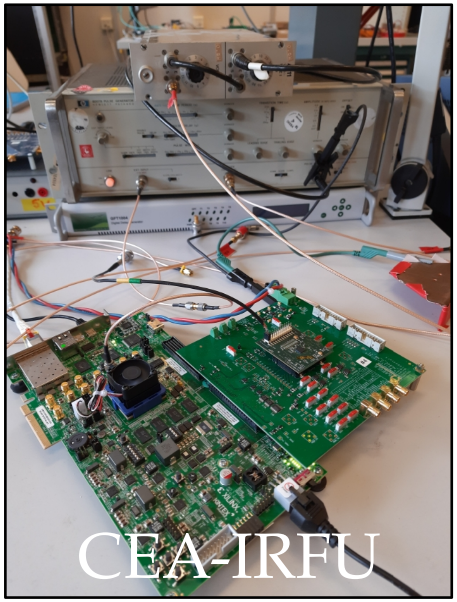


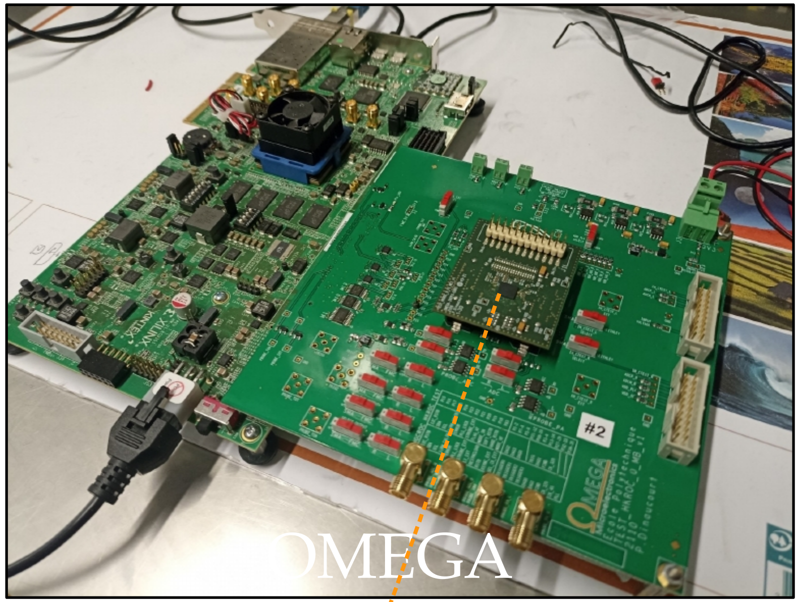
HKROC final board

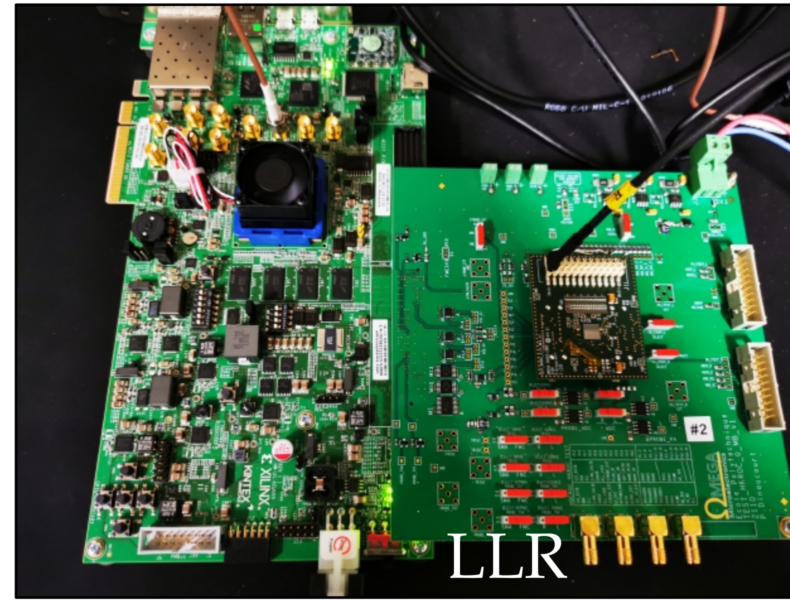


Performances of the HKROC digitizer

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



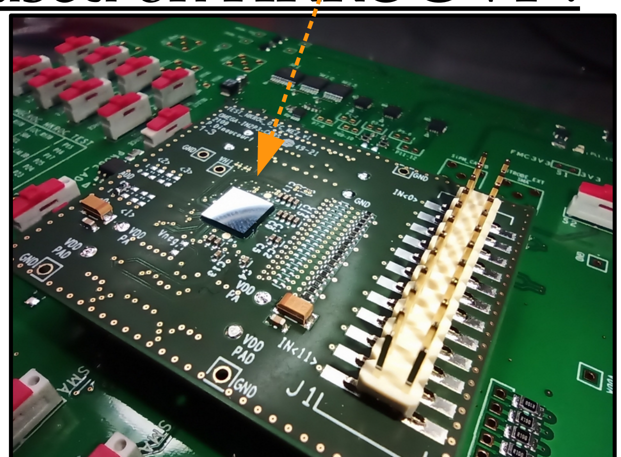


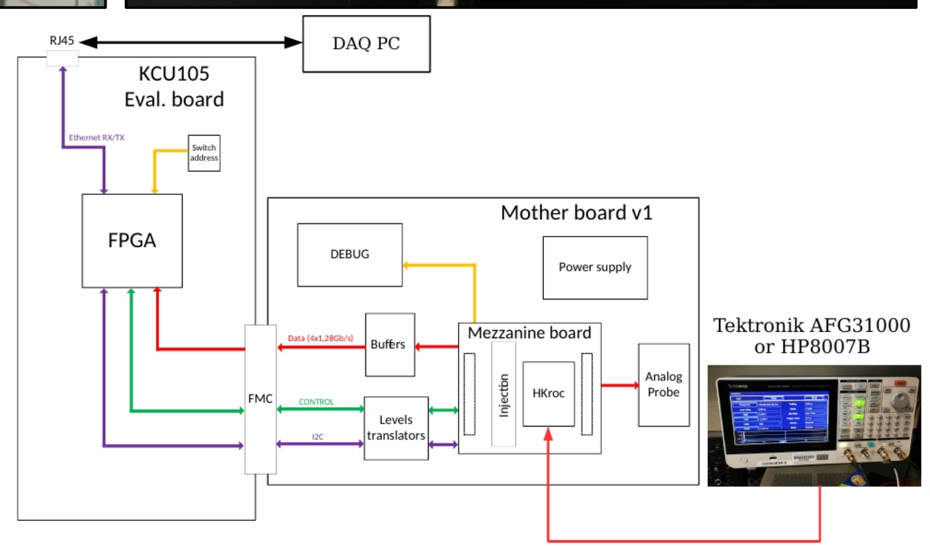


- <u>Measurements based on HKROC v1 :</u>

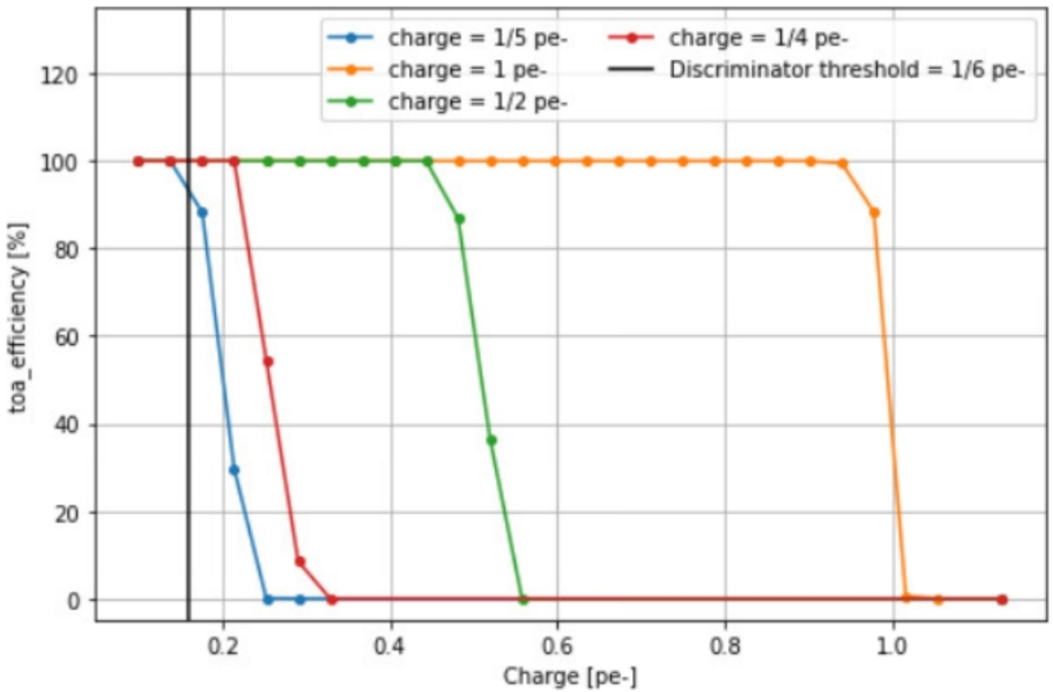
→ Back fom prod. on 01/28.

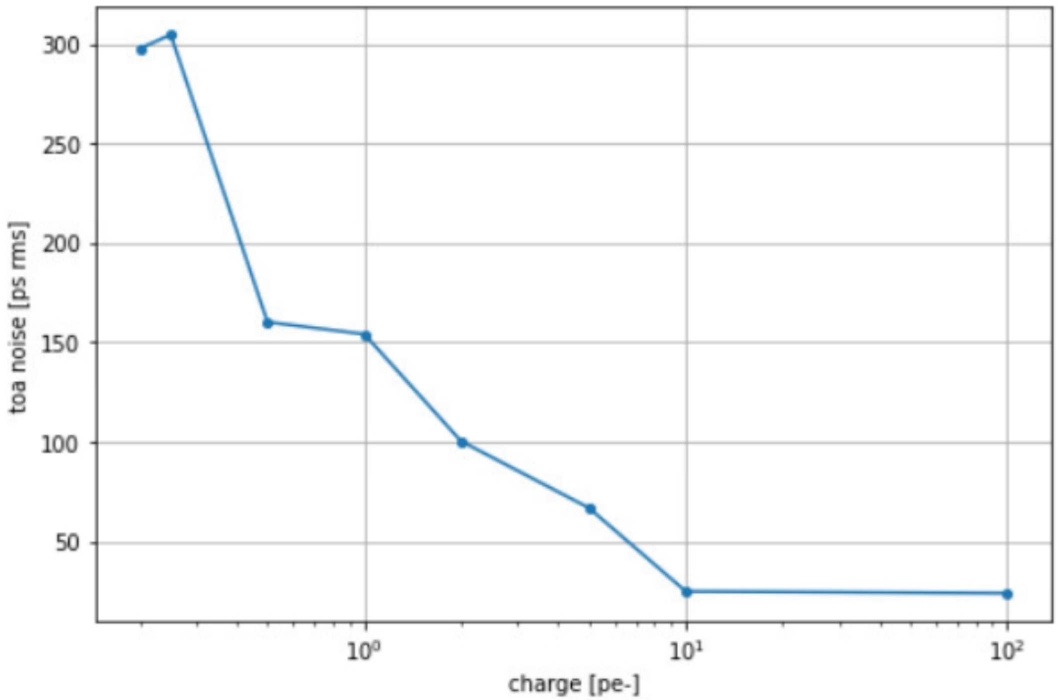
→ <u>Chip size :</u> 5 mm x 5 mm [Ultra-compact]





Trigger rate and time resolution





- <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

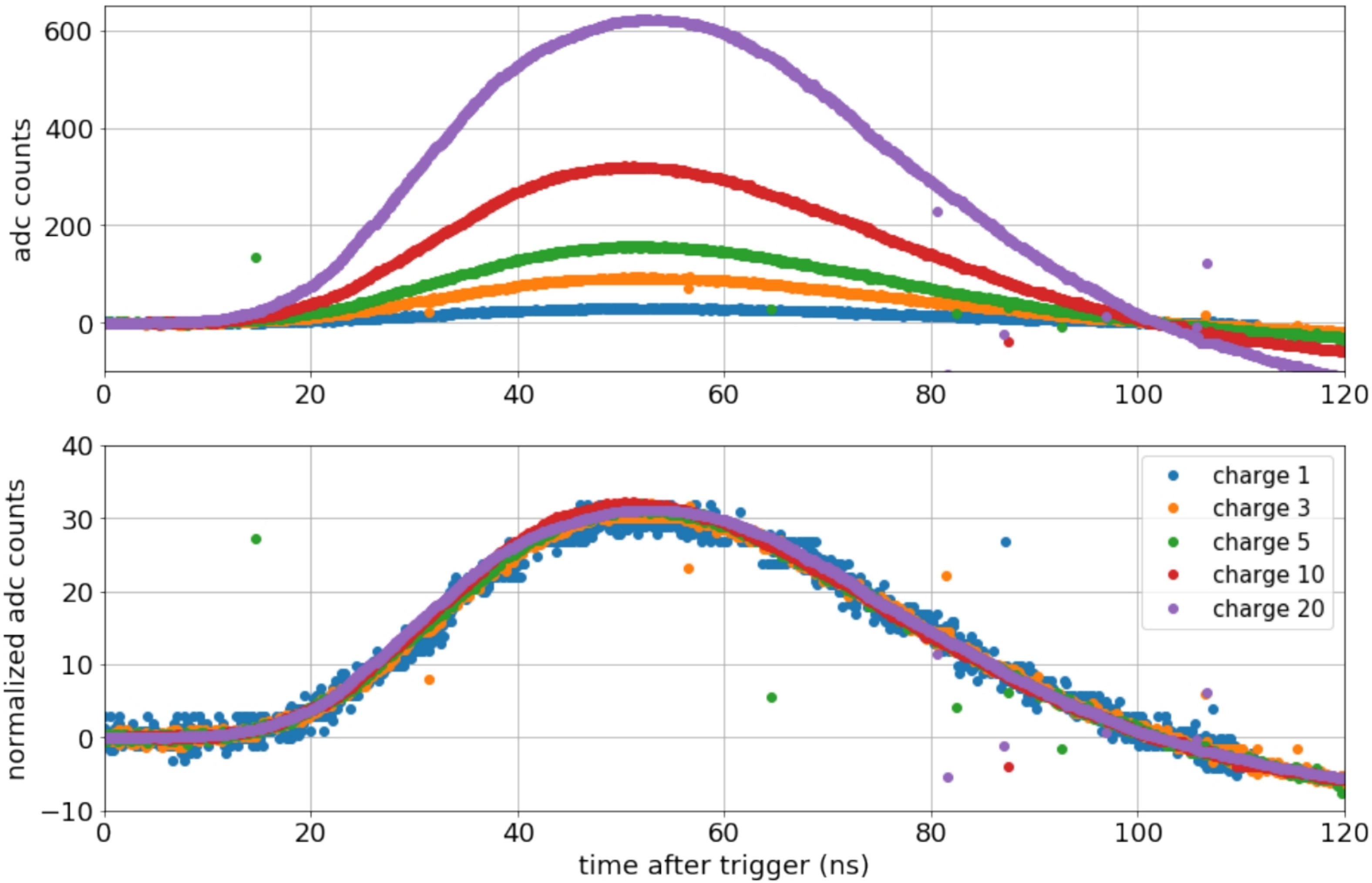
- <u>Very low noise :</u> < 1 Hz (0 noise hit in 10s)

- <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.

Charge reconstruction

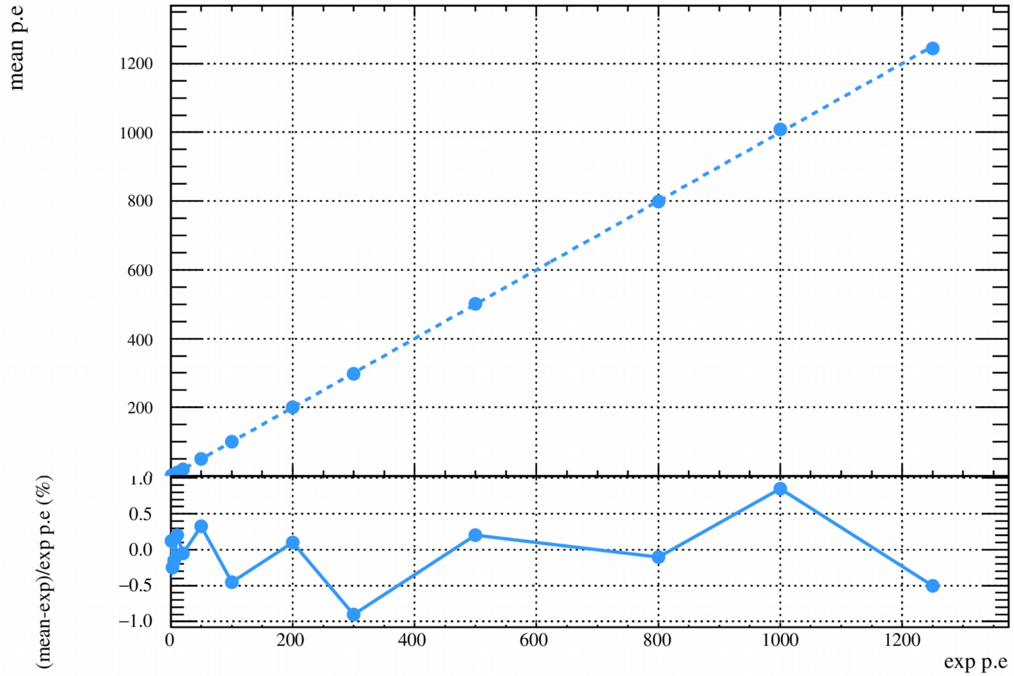
- <u>200 events taken. For each event, 6 points/snapshots are taken :</u>

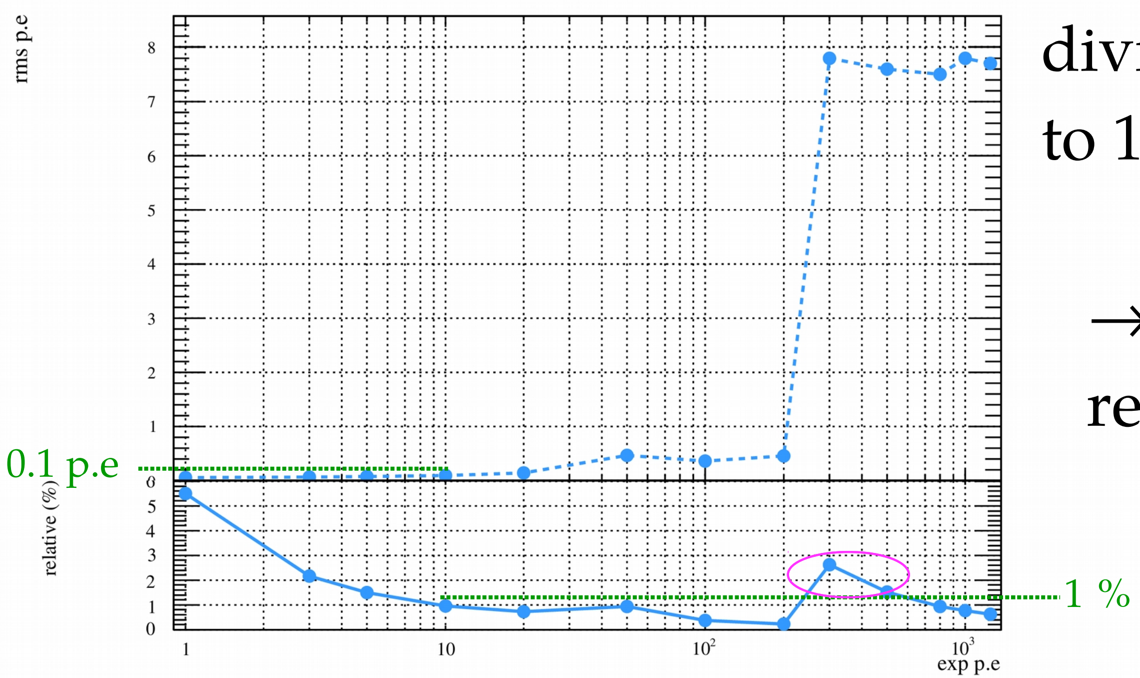


<u>→ Eye check :</u> Normalized distributions in good agreement → Good linearity ?

→ All results in next slides are done using only 3 points per waveform.

Charge reconstruction





- **<u>Charge linearity < ±1%</u>** from 1 to 1250 p.e

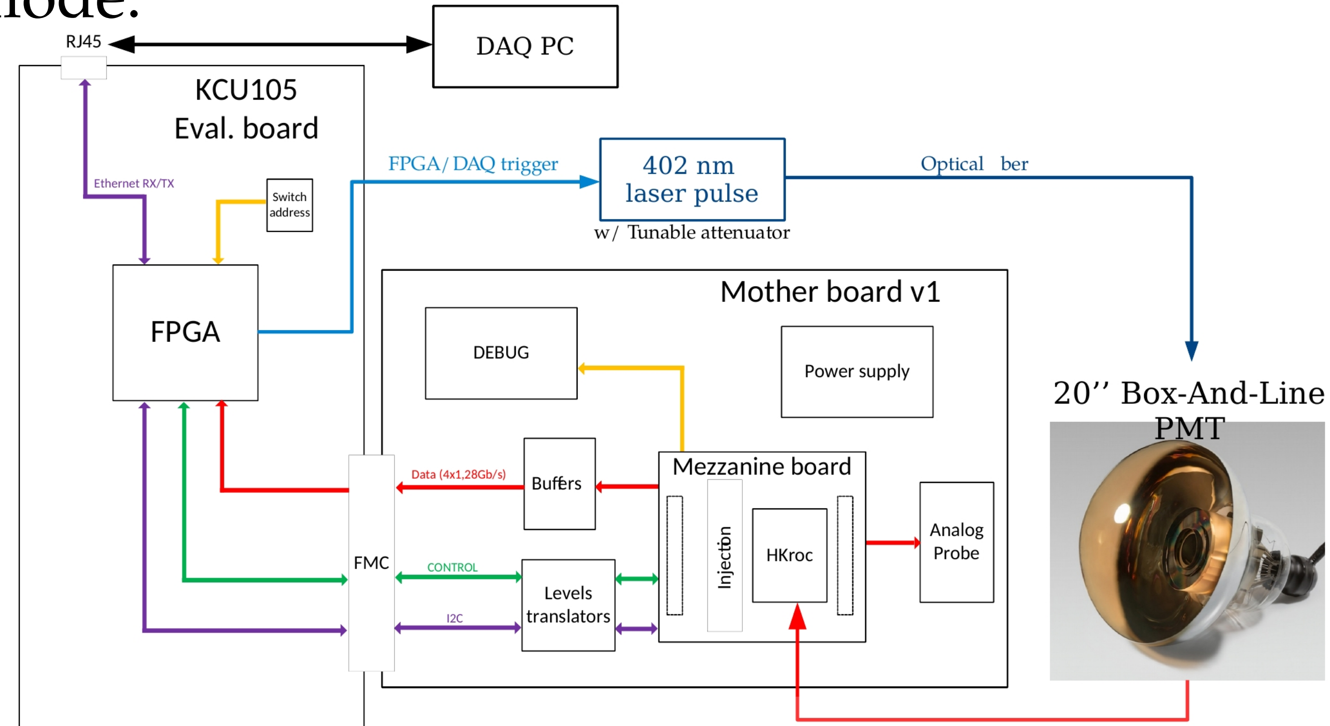
- **<u>Charge resolution :</u>**
  < 0.1 p.e @≤ 10 p.e
  < 1 % otherwise.

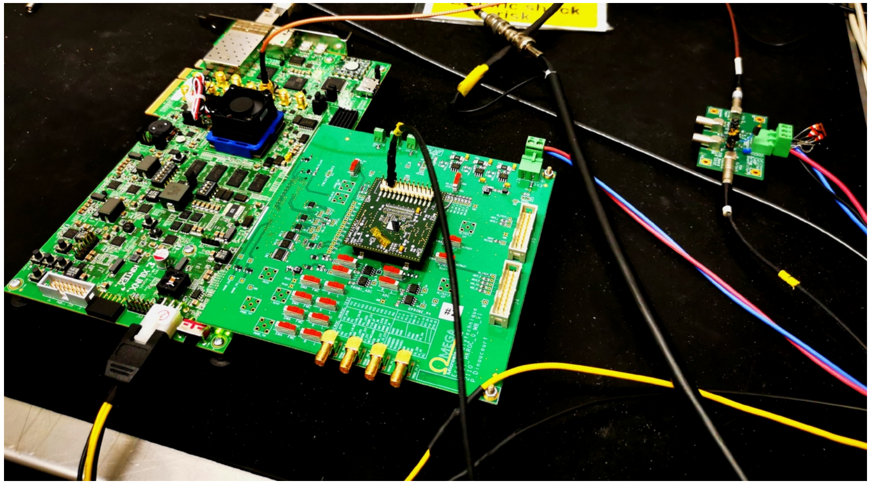
→ <u>Except for two points :</u> will be solved by changing the voltage divider on the board from 1:10:1000 to 1:9:45.

→ Excellent agreement with HK requirements.

Measurements with the PMT

- <u>Connected Hamamatsu R12680 PMT to HKROC :</u> illuminated by a PILAS 402 nm laser diode:

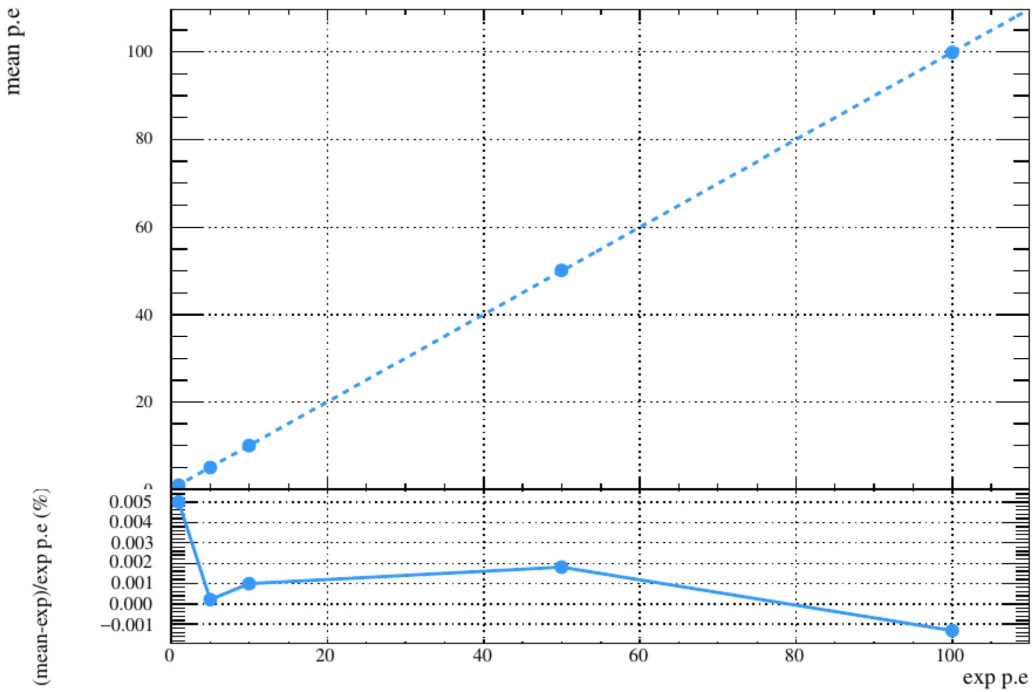




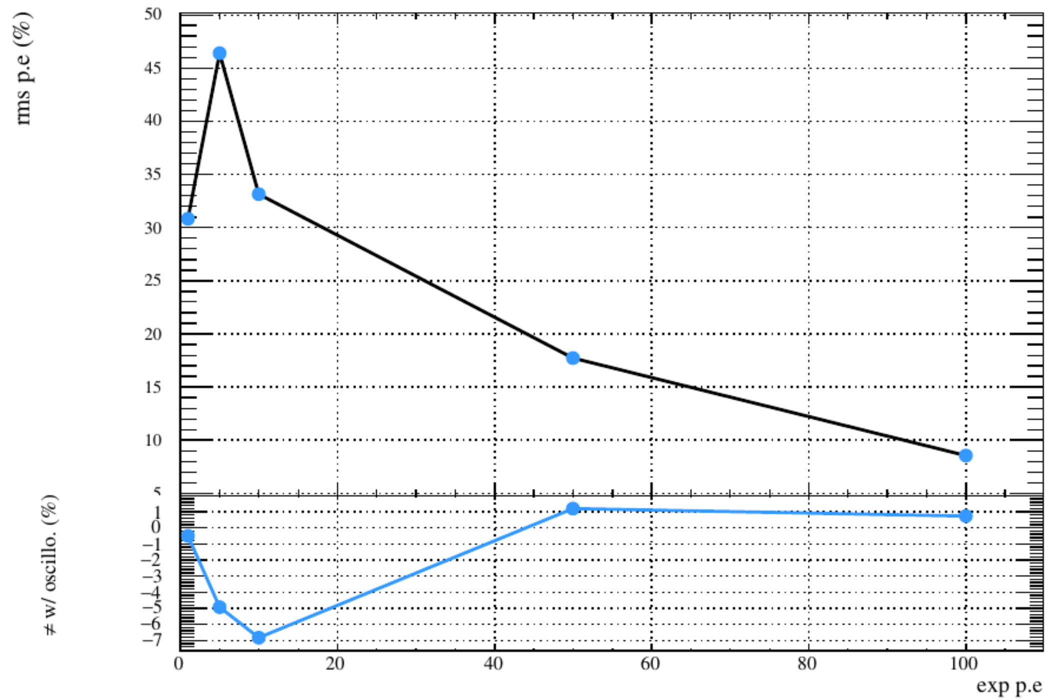
→ Substantial amount of time spent to finely characterize the PMT charge & time.

Charge measurements with the PMT

Linearity measurements :



Resolution measurements :



- The charge linearity is ≤ ±1%

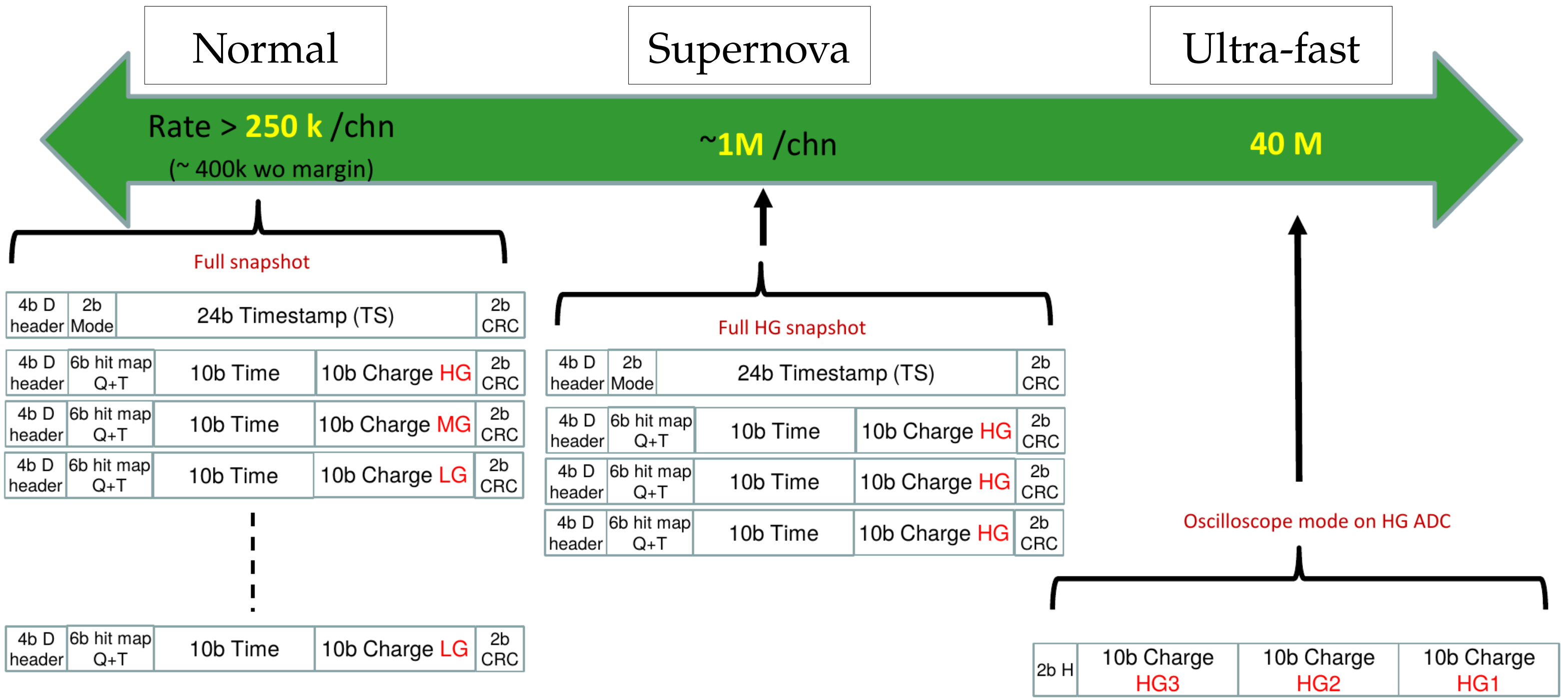
→ Exact same behaviour than with the function generator.

- The charge resolution is almost unchanged (max 7%) wrt the PMT resolution.

- Time resolution = 2.8 ns → Same as PMT w/o digitizer

High-hit rate tolerance

- <u>2 modes cope-up w/ high hit-rate :</u> Normal (≤ 400 kHz) & Supernova (≤ 950 kHz) → Used for very close SN (Beltegeuse).
  → <u>Dynamic change between 2 modes</u> w/ « almost full » memory pin.
  → « Almost full » when > 10 events happen consecutively ≥ 400 kHz.

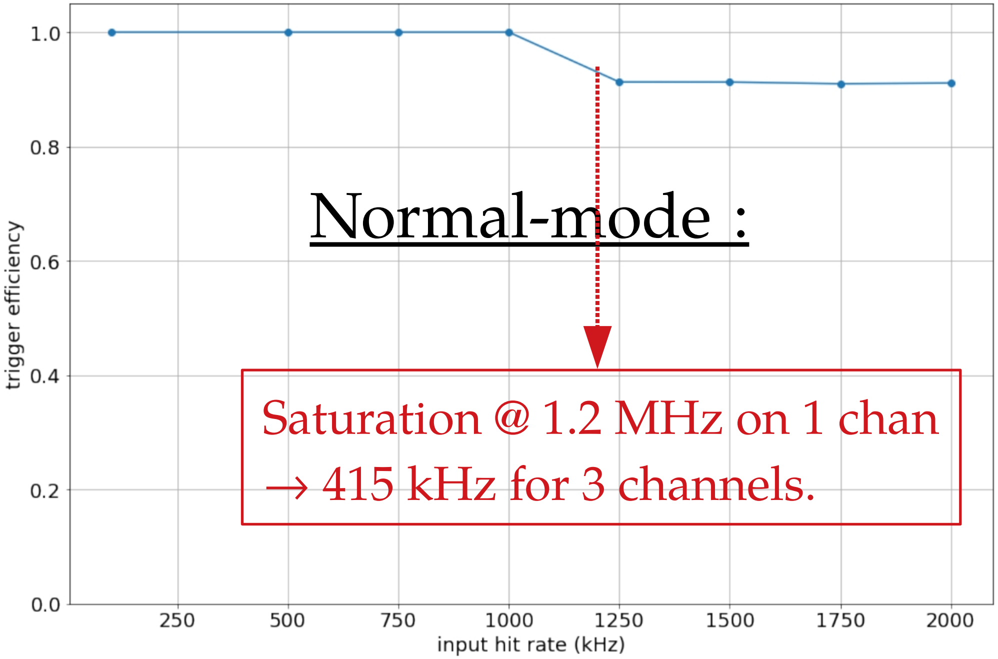


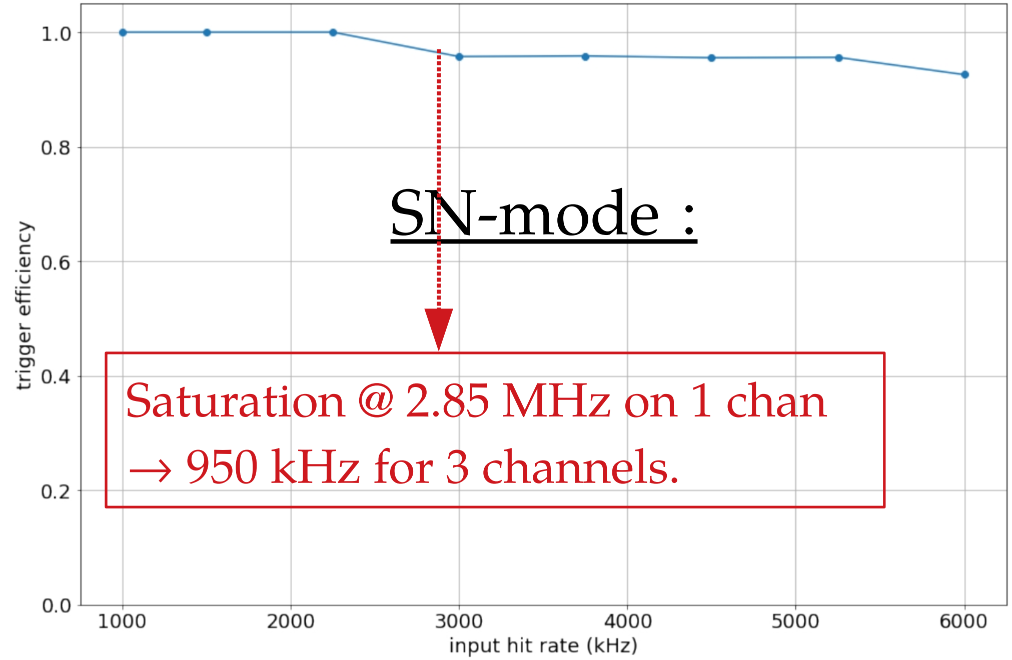
- <u>SN-mode :</u> same as normal mode, but only HG channel (≤ 35 p.e).

- One ASIC readout link (one memory buffer) ↔ 3 PMT channels
  <u>→ To test saturation :</u> inject up to 1 MHz on 3 consecutive channels.

High-hit rate tolerance

- Inject 3 times higher rate on one channels (Simpler technically)
  → Confirmed w/ analog probe saturation happens at same point.

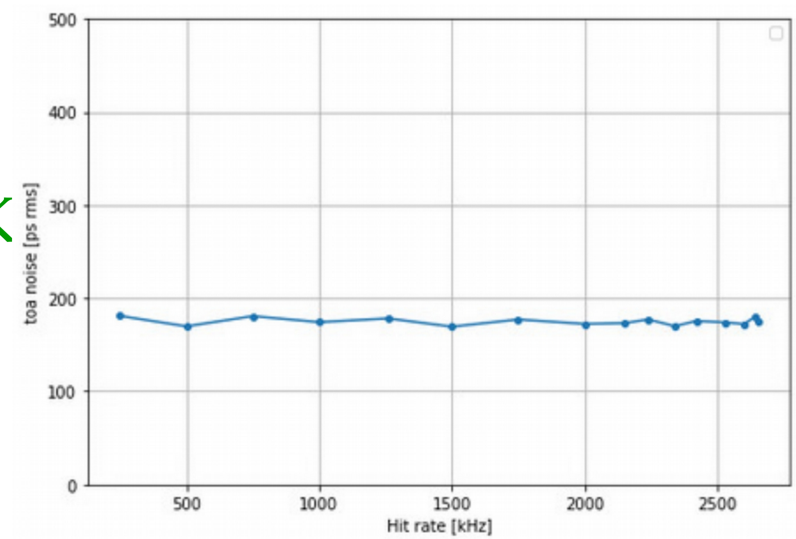




- SN-mode works exactly as in simulation !

- Q/T perf. not affected & compatible w/ HK

- Confirmed « almost full-flag » is working exactly as expected.

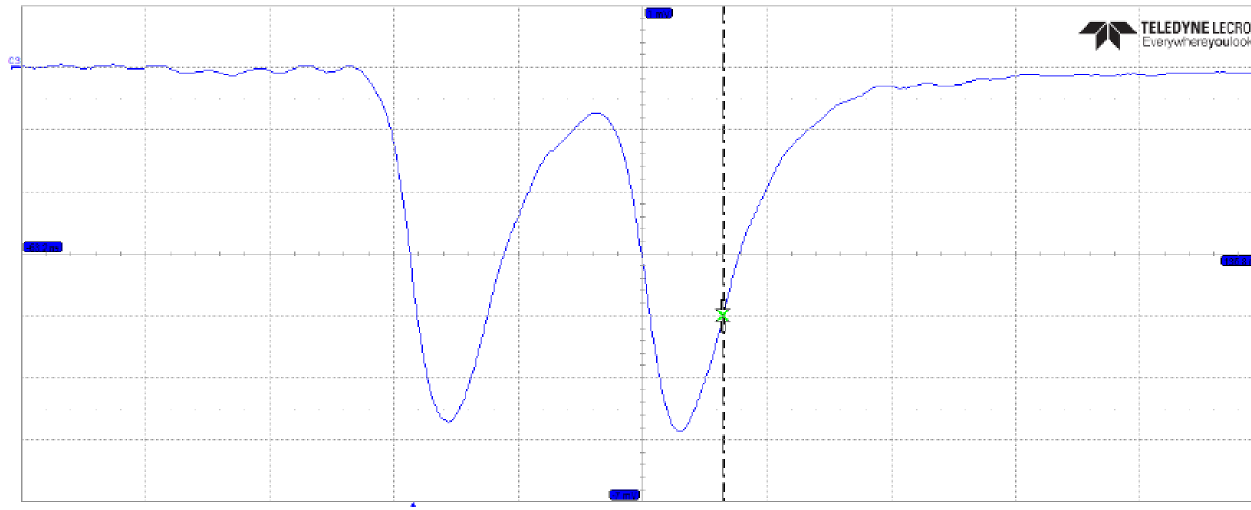


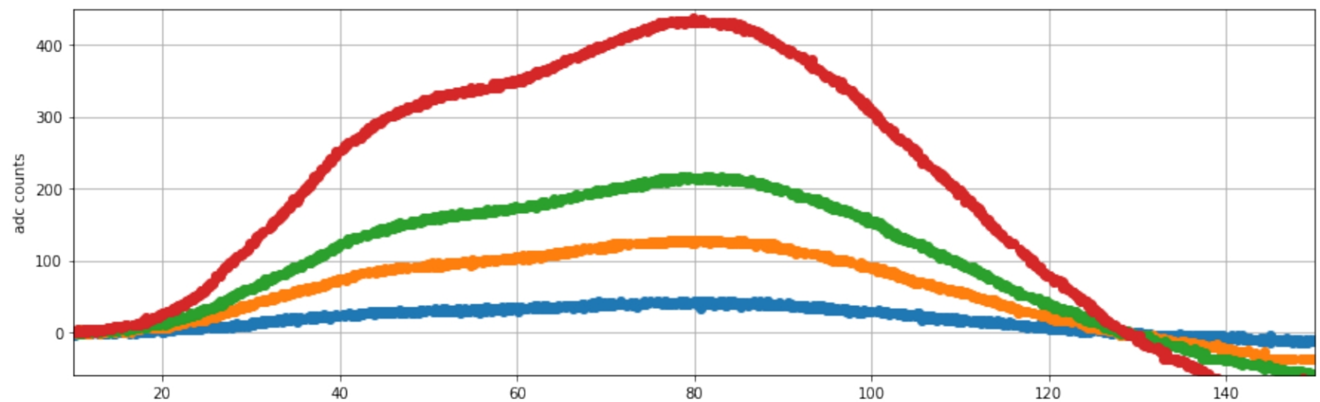
Pile-up measurements

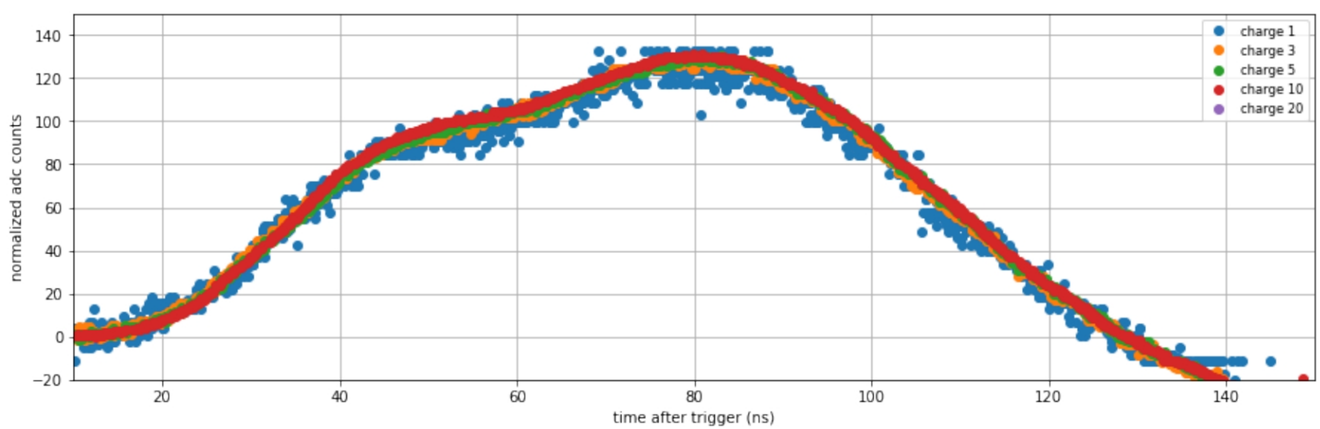
- 2 events w/ same charge separated by $\Delta t = 30$ ns.

- <u>Can we reconstruct both peaks properly ?</u>
  → Requested dead-time for Hyper-K is 1 μs.

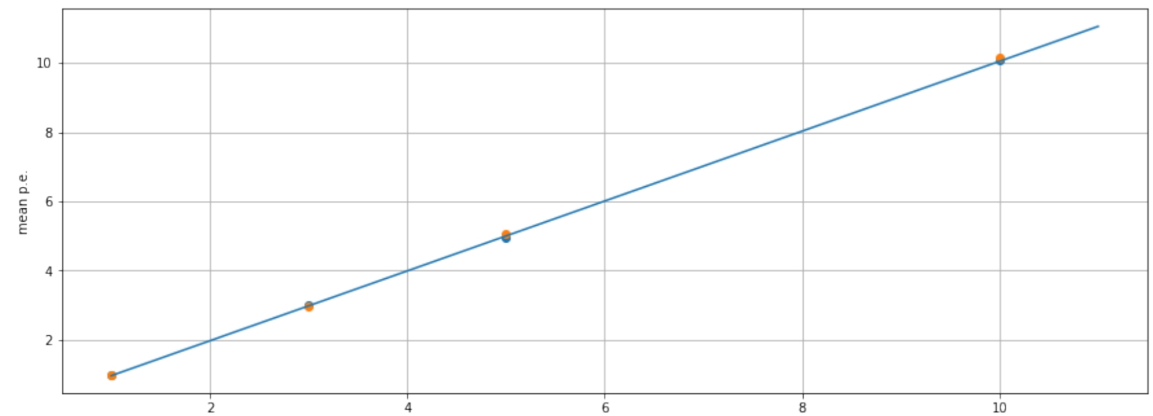
- <u>Eye check :</u>
  → Event separation is not trivial !
  → Good linearity, even for pile-up event.
  → Apply charge reco. w/ 2 peaks at fixed trigger times.

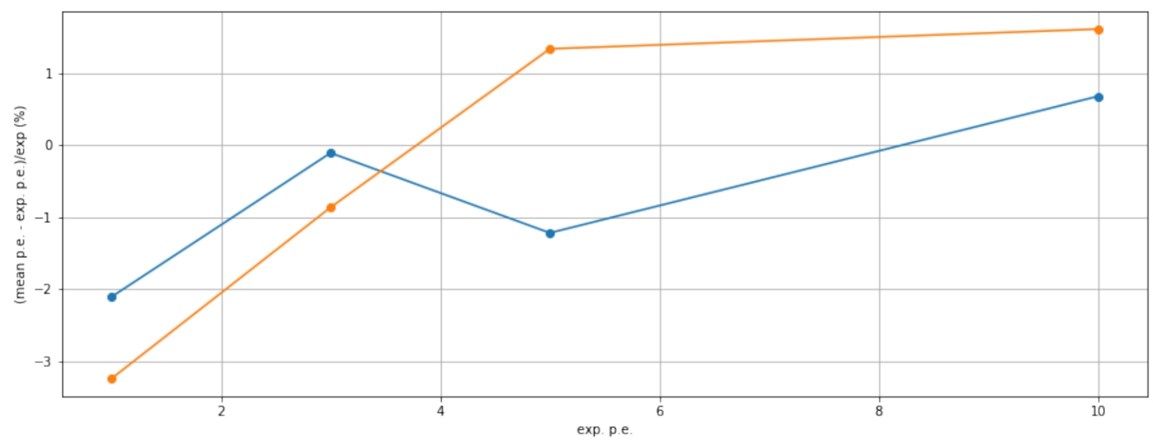


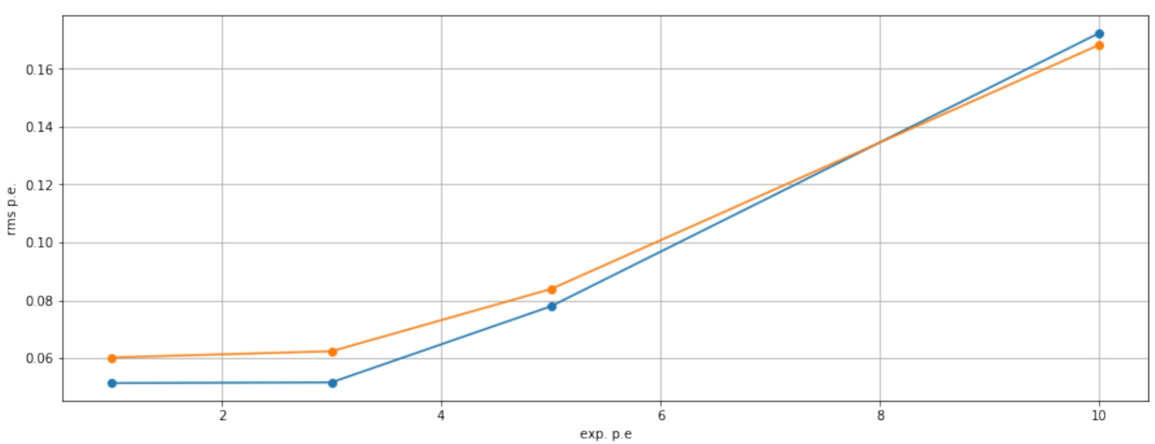




Pile-up measurements







- <u>Charge linearity < ±2-3%.</u>

- <u>Charge resolution :</u>
  < 0.1 p.e ≤ 5 p.e
  < 0.17 at 10 p.e

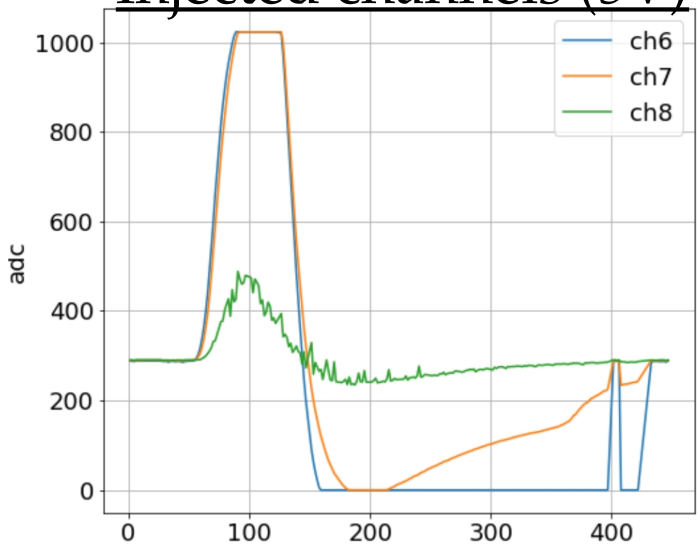
→ Charge reco. almost perfect for 2 peaks of Δt = 30 ns (algorithm to be improved to go below 30 ns).

<u>Potential ↑ impact on physics :</u>
→ Separate of direct & scattered light, μ/π separation, ↑ efficiency of decay-e…
→ To be studied w/ the Physics & software group.

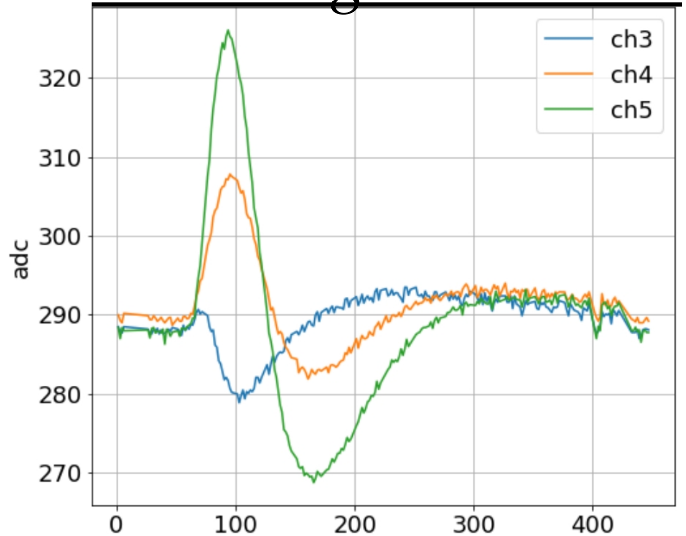
Cross-talk measurements

- Full cross-talk measurements :

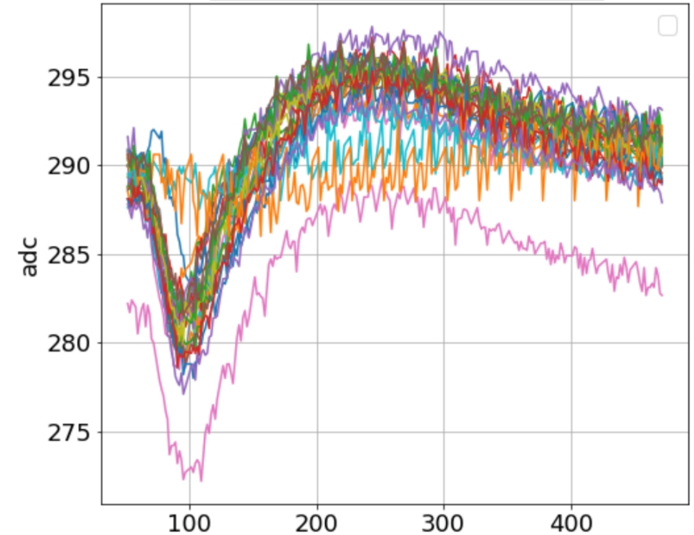
Injected channels (5V)



Close neighbour chans



All other chans



- Found 2 sources of cross-talk :

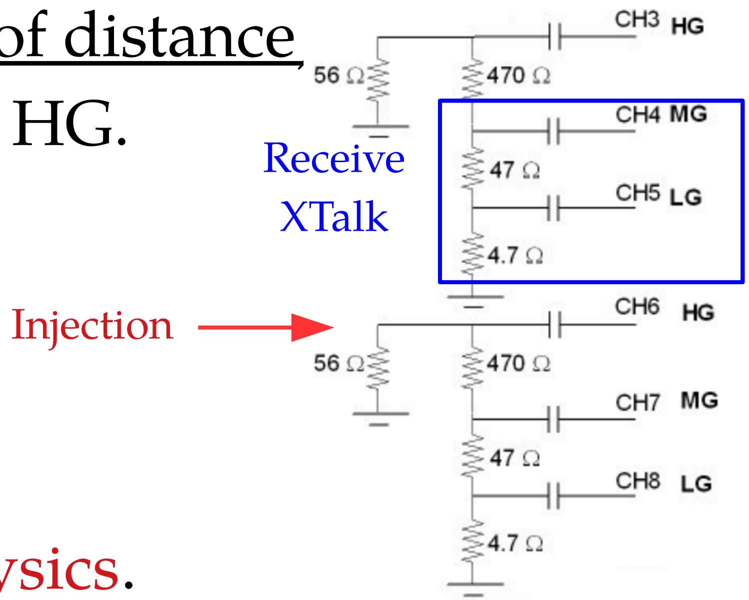
1. Close : Only on 2 neighbour (as a function of distance

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

2. Diffuse cross-talk :

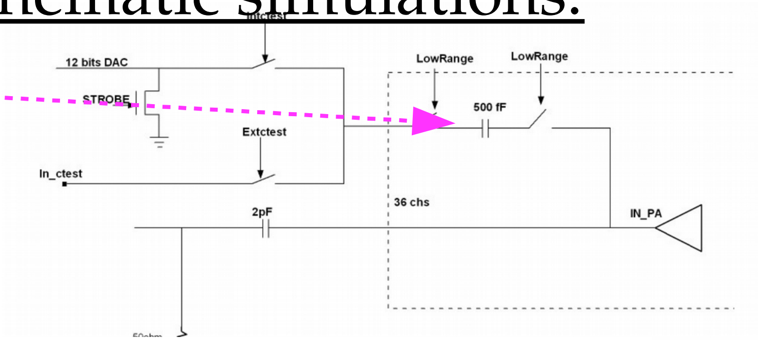
→ Receive 1/5 p.e on all channels : close to detection threshold.

→ Smaller but much more worrysome for physics.

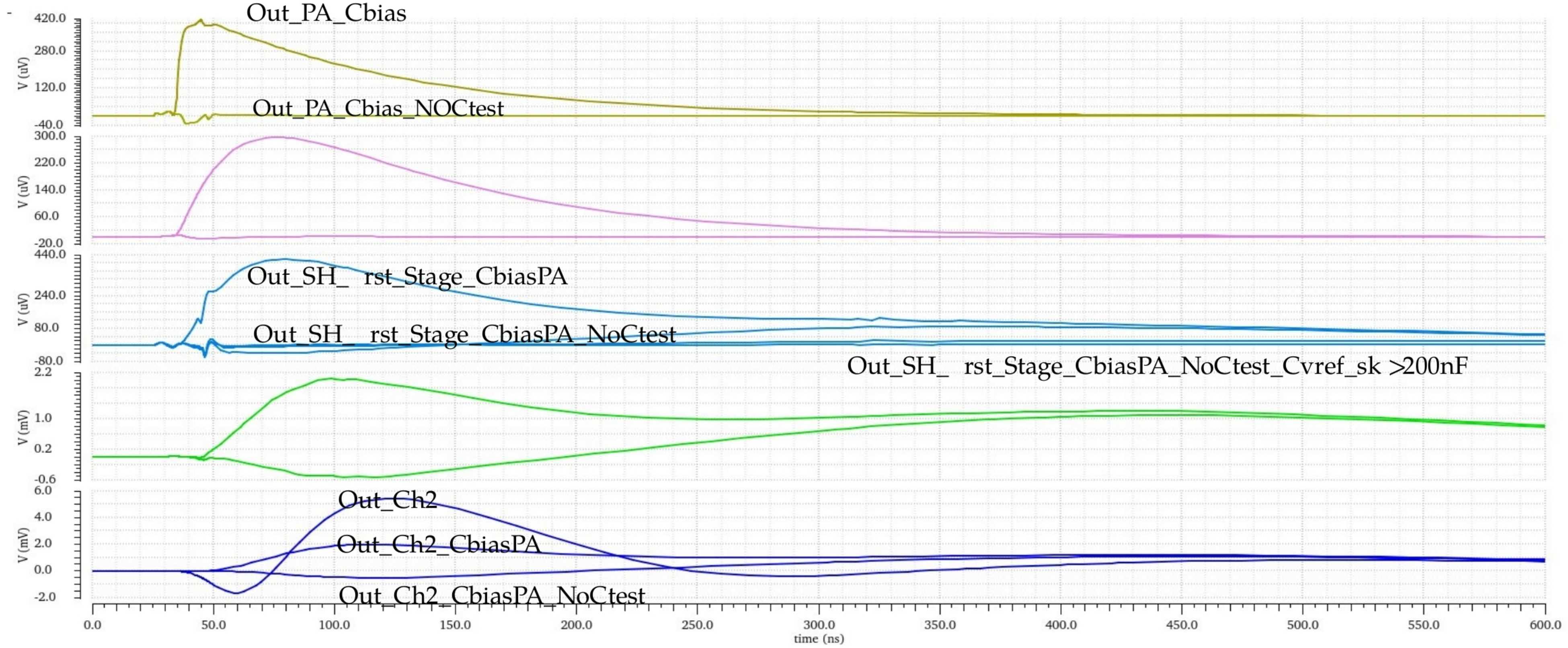


Source & fix of the diffuse cross-talk

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



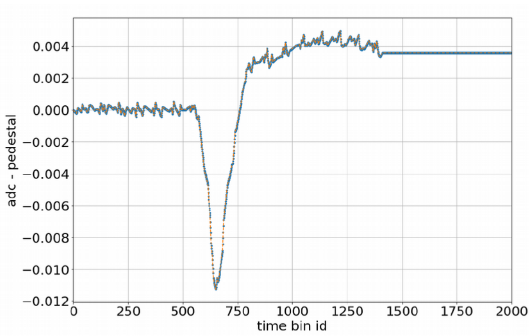
- Added decoupling C=100 nF to PA bias V :



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

What if we were to install HKROC today ?

- Relies on waveform to remove fake hits & fit simulatenous signals.



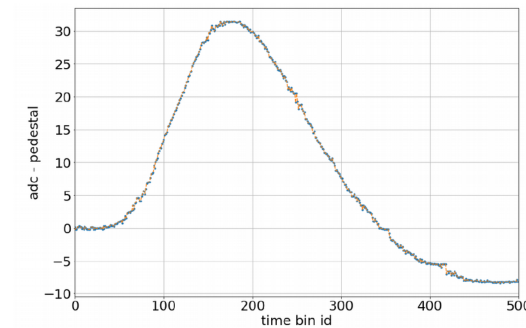
If ch. C_0 trigged & signal > 250 p.e in 1 channel C_6

↓

FPGA : Fit other chan. with XT waveform

- $\chi^2 \leq 5$ → No signal in other chan. → **Fake hit**
- $\chi^2 > 5$ → Signal in other chan. → Send data to surface → Joint- t of XT waveform & signal
  - XT : to by C_s Fixed.
  - Signal : Fit C_0 amplitude & t_0

  → Provide Q & T



Note : cross-talk > 250-300 p.e
→ Not an issue for OD even for HKROC v1.

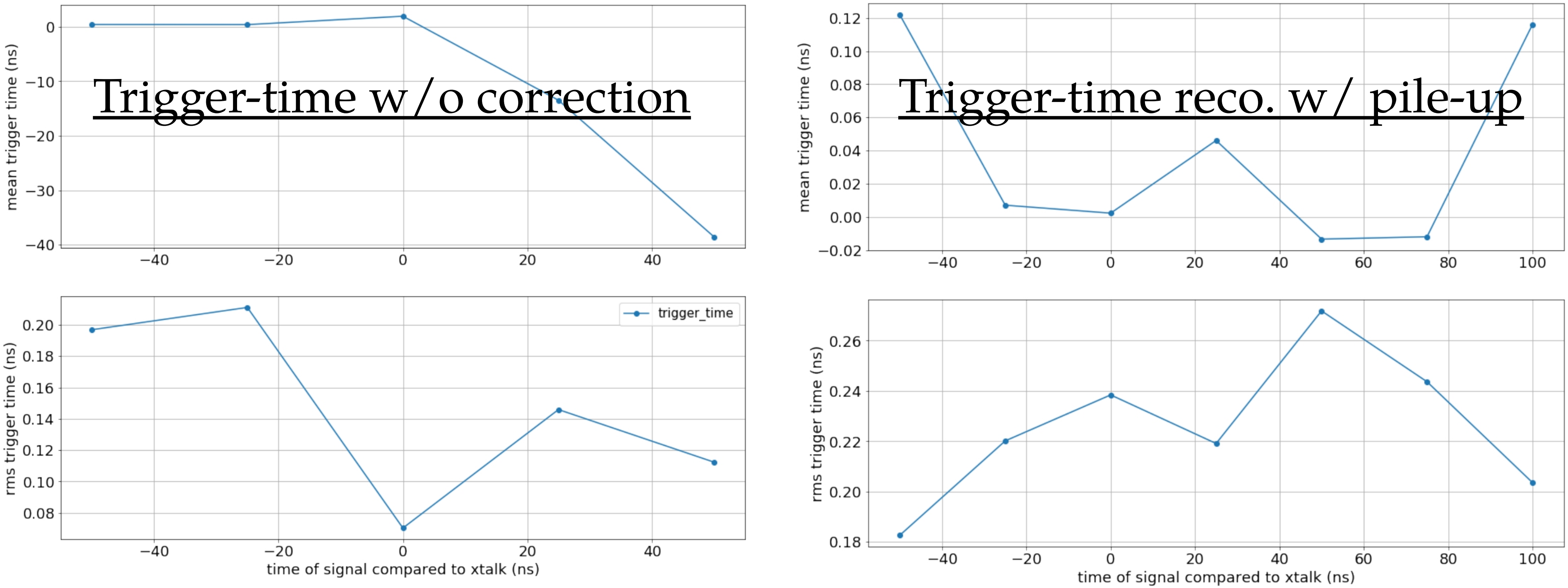
→ Try to reconstruct the 1 p.e event trigger time using the pile-up reconstruction : could in theory correct the baseline shift. In reality ?

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>

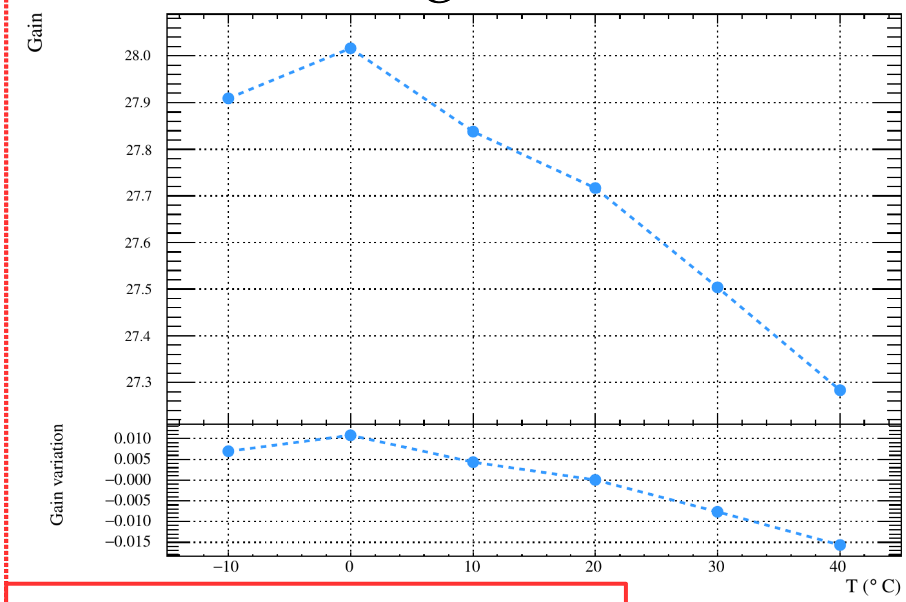


1. Clear shift of 1 p.e trigger time (up to 40 ns) if XT happens before.
2. Completely corrected through the pile-up reconstruction.

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

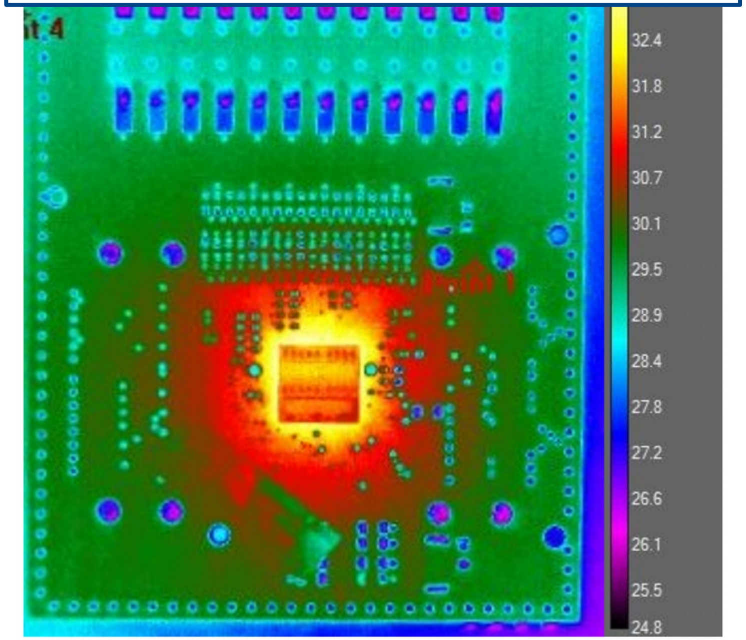
Temperature dependency & Power

Gain/charge measurement :



Measured with HGCROC

HKROC temperature on-board



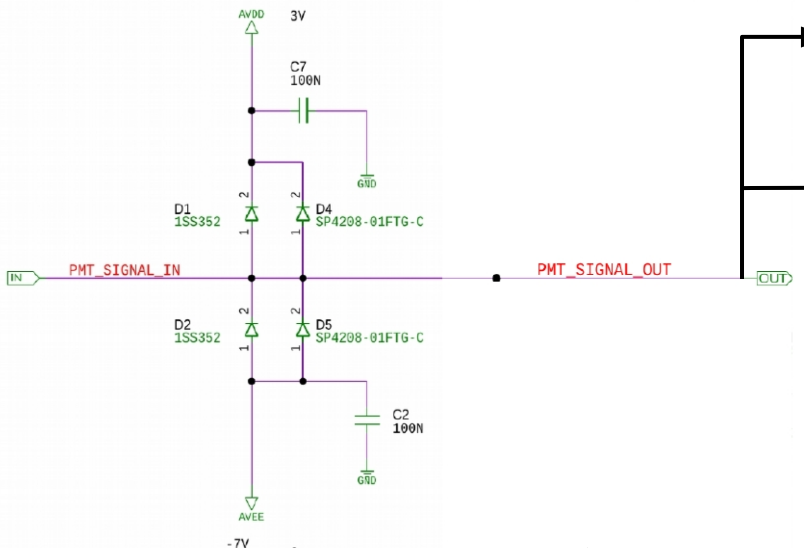
Board power consumption (1 HKROC) :

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		

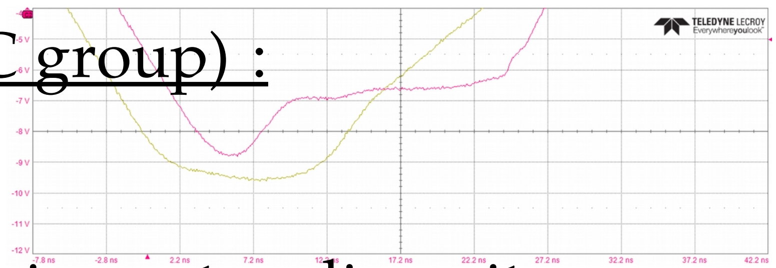
- Δ t = 1ps / °C
- Δ Gain = 0.05 % / °C (w/o corr.).
  → Well within Hyper-K needs.
- Temperature on chip (34°C) is 9°C higher than ambient temperature.
- Power for 2 HKROC < 6.6 W.
  → ≤ 24 W required.

Lifetime : Protection board & MTBF

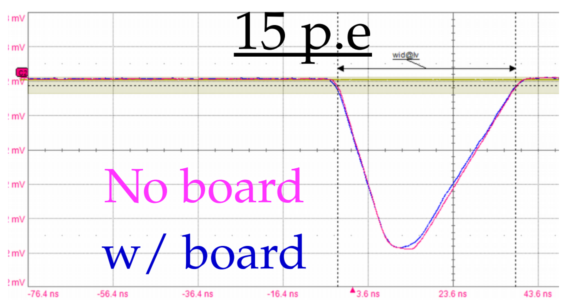
- Protection board added (Many thanks to QTC group) :

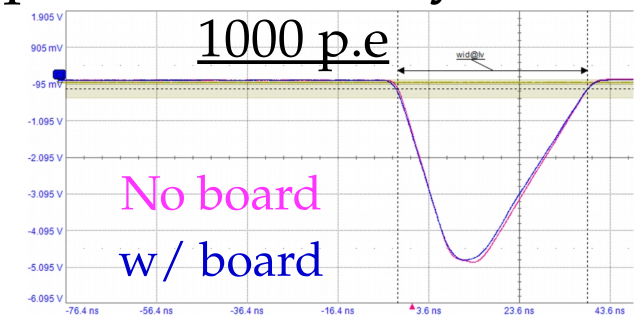


→ Cut signal < -7V



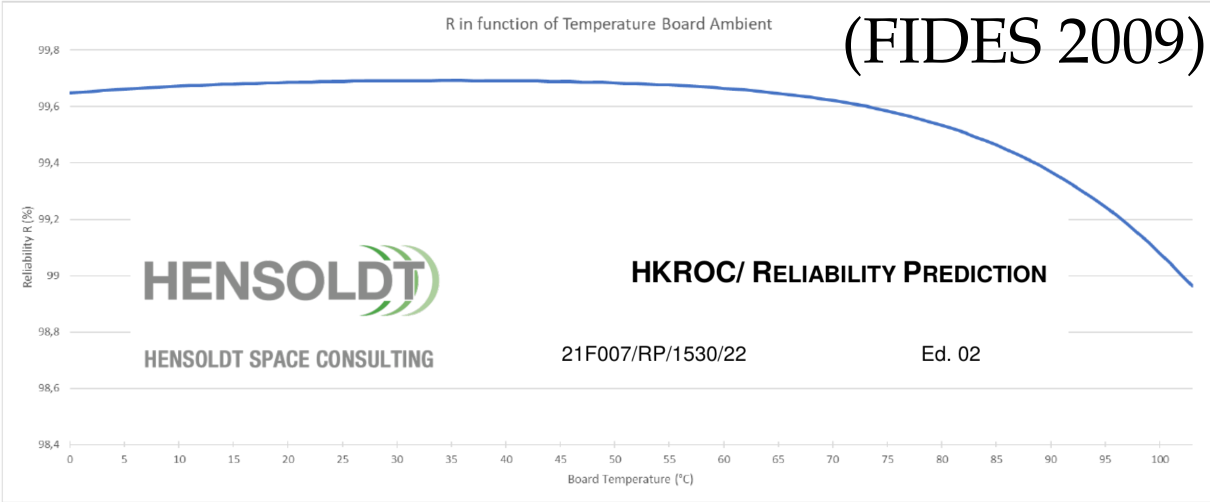
→ Now testing if no impact on linearity





- 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)



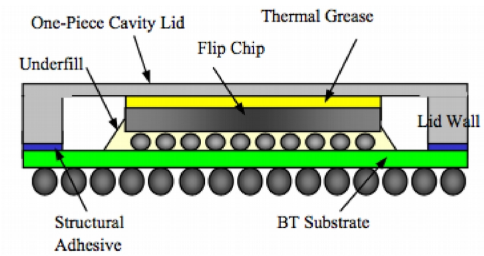
- ≥ 99.7 % survival rate after 10 years (> 99 % required).
- Homeworks : evaluate MTBF of the whole board → On-going.

Summary of the digitizer measurements

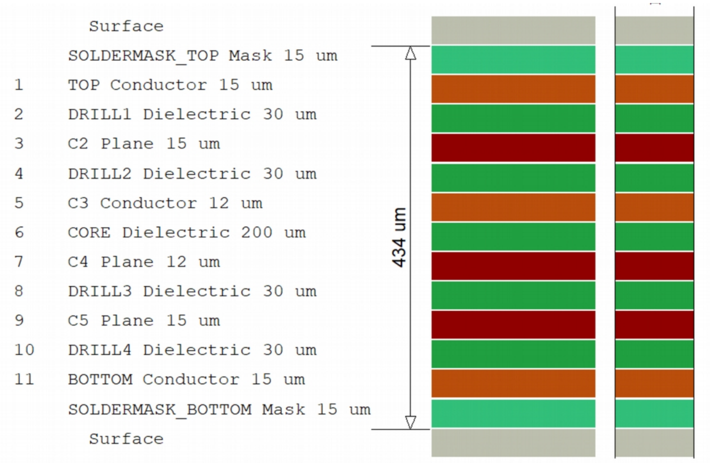
Item measured	Performances
Trigger efficiency at 1/6 p.e.	$> 90\%$ for 1/5 p.e signals 100% for $\geq 1/4$ p.e signals
Trigger noise at 1/6 p.e.	< 1 Hz (No trigger observed in 10 s)
TDC resolution	150 ps at 1 p.e, 70 ps at 5 p.e, 25 ps > 10 p.e Validated with PMT
Charge linearity	$< 0.5\%$ in high & 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

III. Incoming R&D and decision milestones

HKROC digitizer planning : ASIC



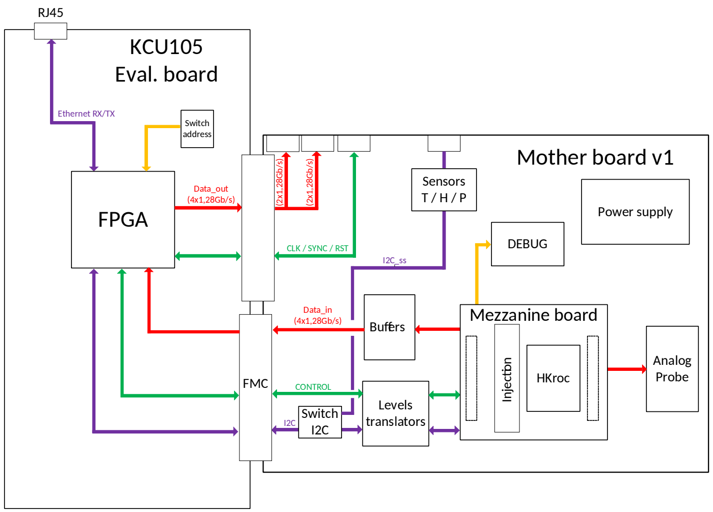
- Current version v1 : mounted on board w/ flip-chip.
- BGA-package for final board : ordered & in prod.
  → To be received in September.

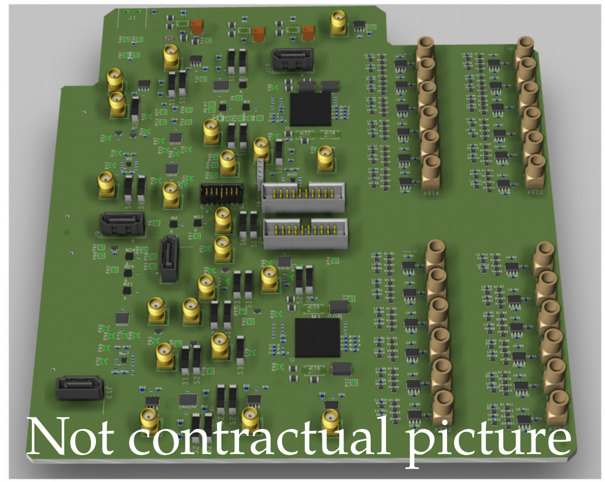


- Version v2 : A TSMC run for OMEGA already scheduled in Dec. 2022.
  → Will use it to fine tune HKROC for HK.
  → Completely remove cross-talk.
  → Likely to submit 2 versions :
    - v2-A : minimal change wrt v1 for safety.
    - v2-B : more aggressive changes to ↑ hit-rate largely beyond our requirements.

HKROC digitizer planning : Board

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





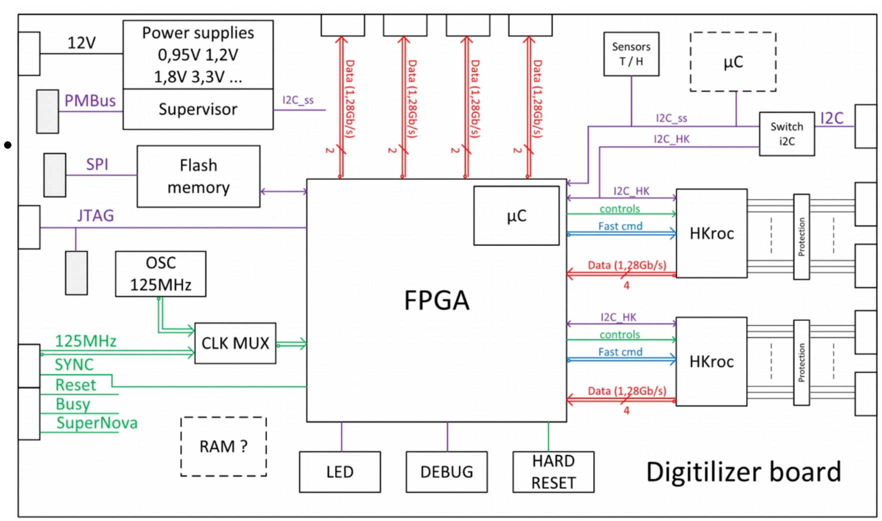
- Test whole circuit from analog to digitized points.
- Test the 2 HKROCs.
- Tests communication with DPB (Curro & al.)

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

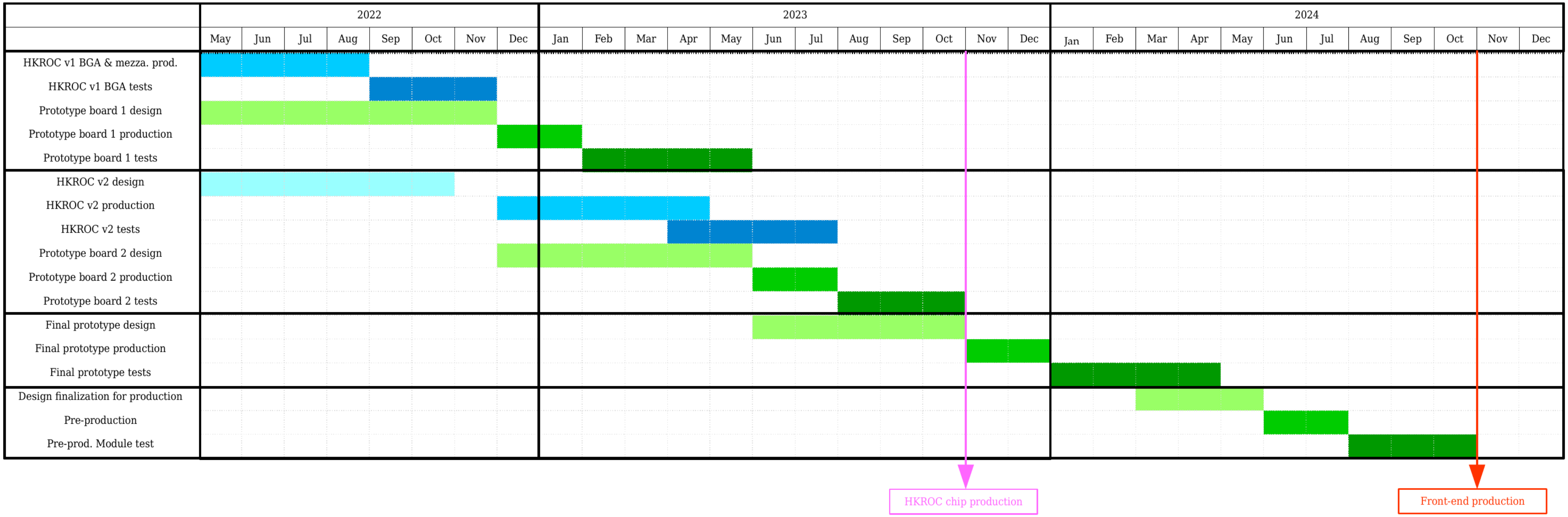
→ 1 HKROC-board in 2022/09, 2 HKROC board in 2023/01.

- Prototype v2 : The final prototype board.

  → To be received in summer 2023.



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).

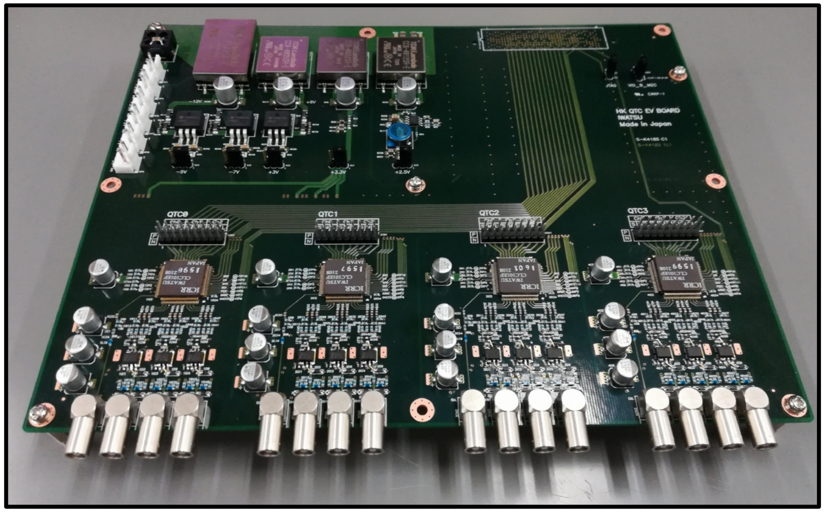
- <u>Board production :</u> from Q4 2024 to mid-2025.

- We are completely on-time !

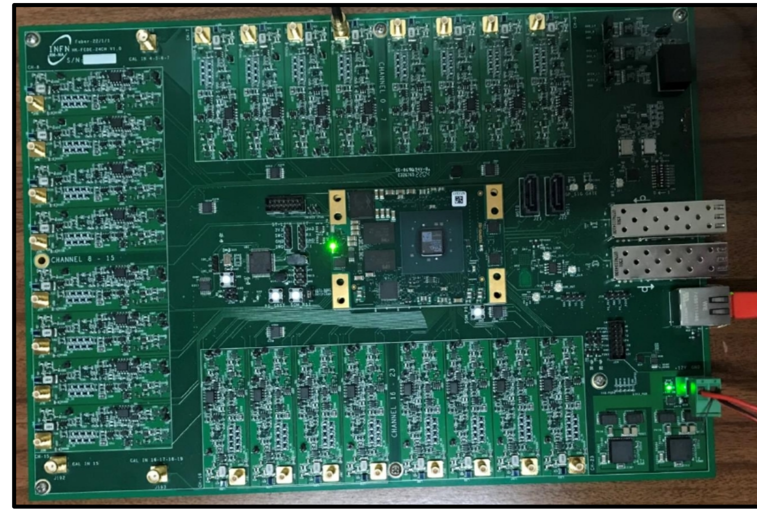
The Hyper-K candidate digitizers

- 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.

Conclusions

- Developed a digitizer based on HKROC ASIC.
  → Compact & based on years of R&D for CMS.

- Massive measurement & characterization campaign started in February
  → First HKROC received on 01/28 !
  → Simultaneous tests at 3 labs by 3 teams allowed to be ready in-time & prepare all test benches for future production tests.
  → Not a single months of delay after 2 years of pandemic => A fantastic team effort : at LLR : Franck, Jerome, Amine, Olivier, Antoine, Marc & Lorenzo. Thank you to them/us for our incredible work & crazy hours !
  → Fascinating project that we managed to clear in-time. Whatever the collaboration decision, we made an incredible ASIC for future WC experiments.

- Some homeworks remaining : Test the signal reflection, tune the protection board etc. → Imperative to clear them quickly to be selected.

Conclusions

- Waveform digitization allows some additional features that can improve physics & hat has been little investigated so far :
  → Separate of direct & scattered light, μ/π separation, ↑ decay-e eff. …
  → Studying possible cons : limited charge range for SN ≤ 35 p.e.
  → To be studied from now w/ the Physics & software group.
  → Any interested person (or idea) is highly welcome.

- We are in best position to have a central rôle in HK as all of us dreamed about 2 years ago.
  → Decision to be taken in the incoming 2 months.
  → We have already started to proceed to the next stage as if we were selected.