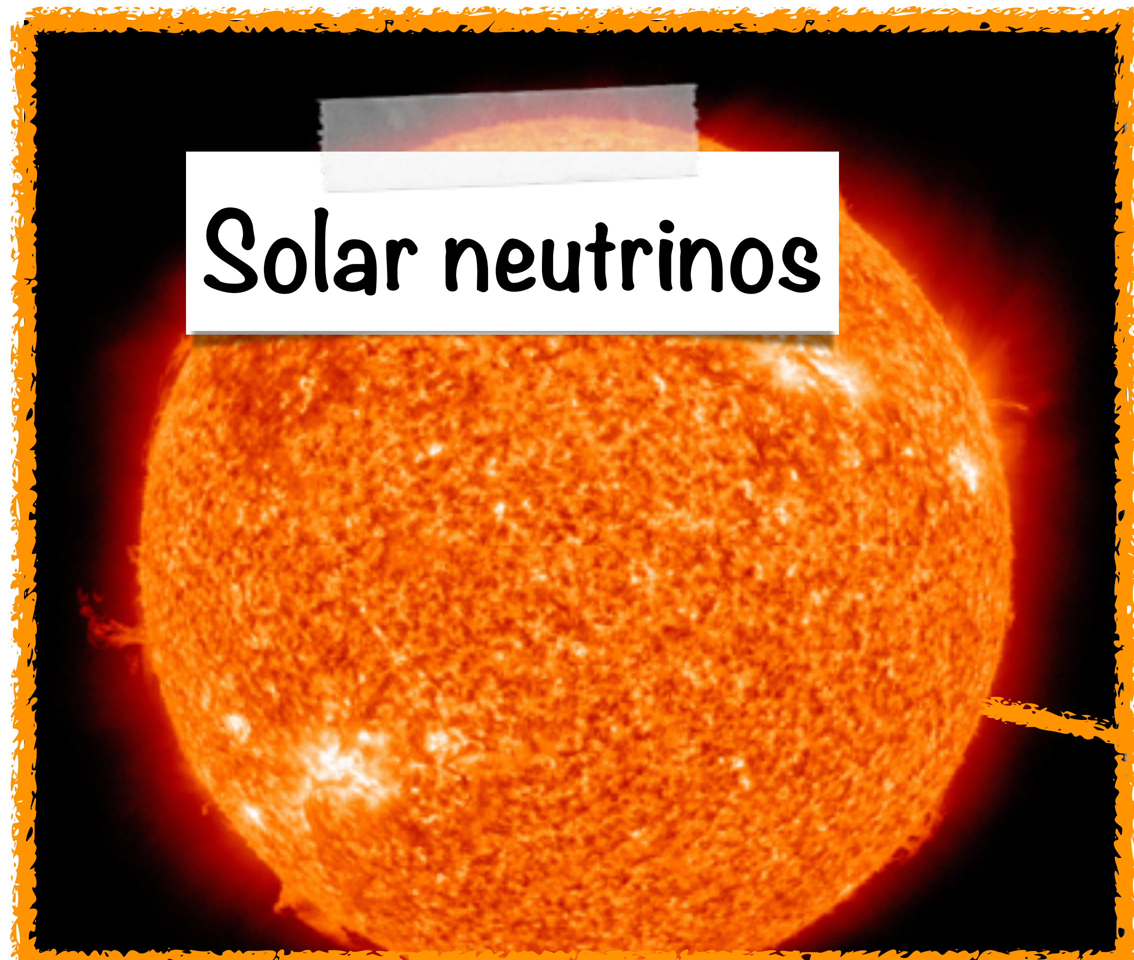
Status of the Hyper-Kamiokande far detector and timing system

Mathieu Guigue on behalf of the Hyper-Kamiokande collaboration

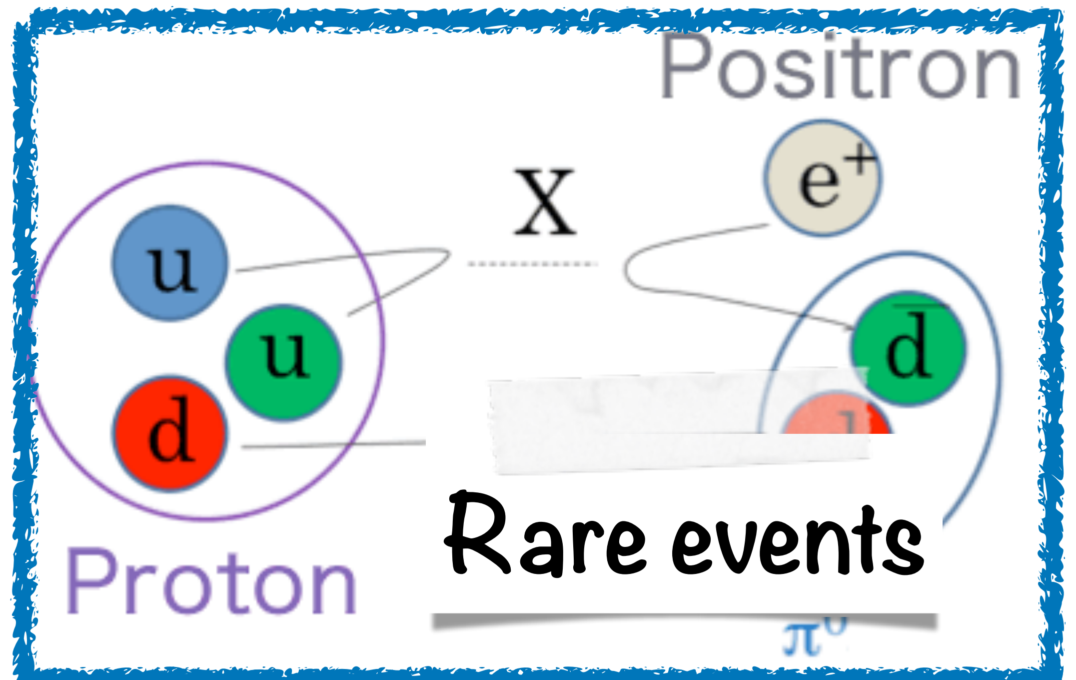
EPS HEP July 2025

Hyper-Kamiokande in a nutshell



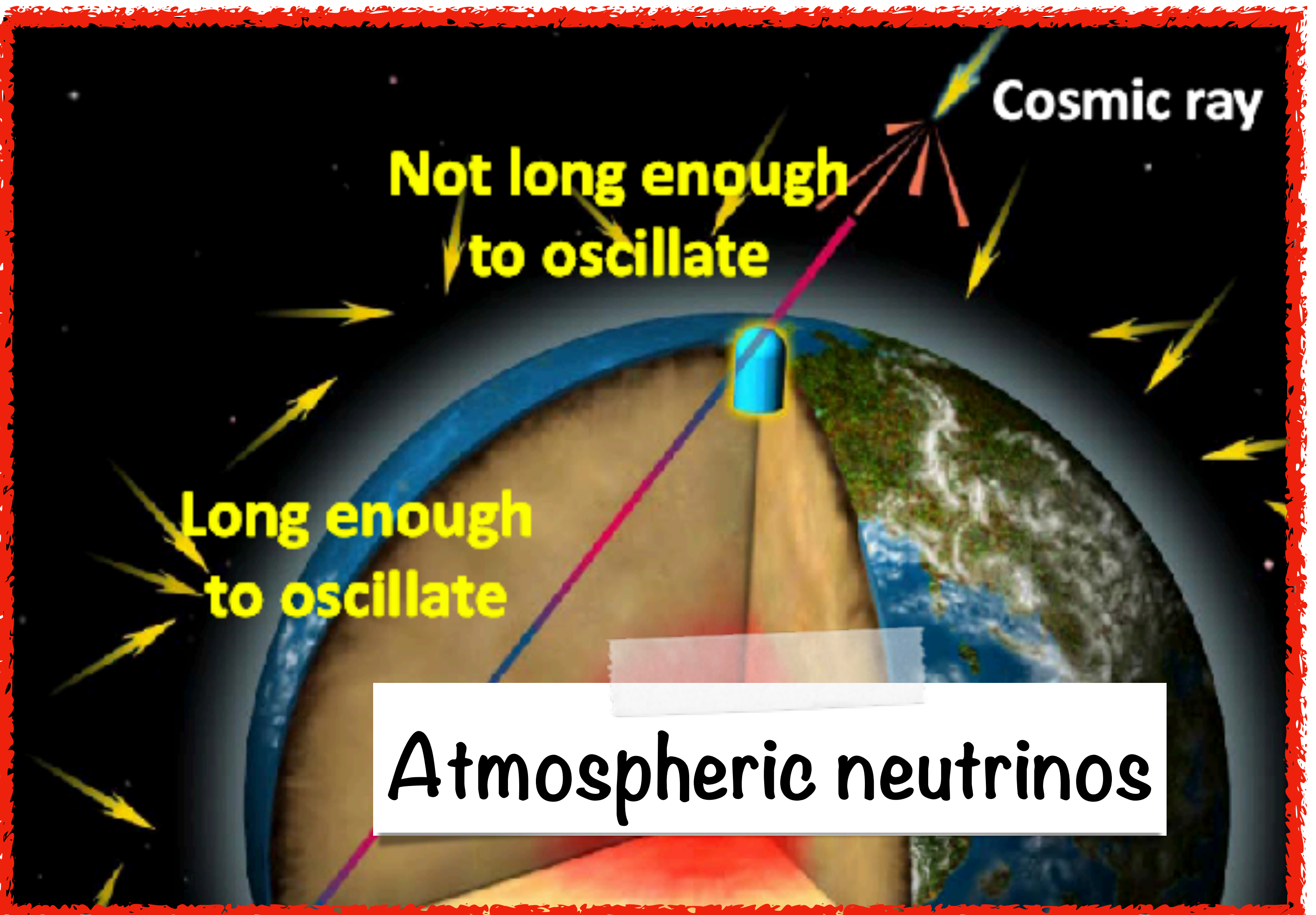
- MSW effect
- Non-standard interactions

ν_e

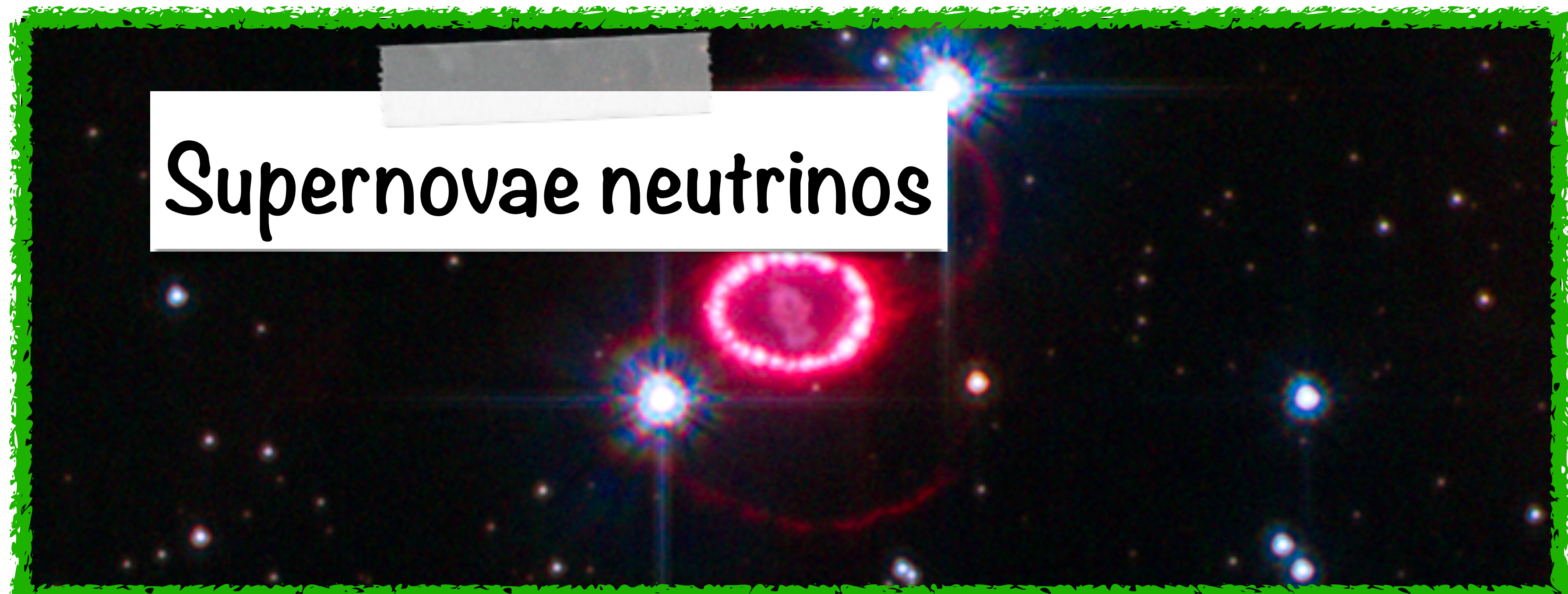


- Probe Grand Unified Theories via p-decay or $n - \bar{n}$ oscillation

ν_e ν_e ν_μ $\bar{\nu}_\mu$

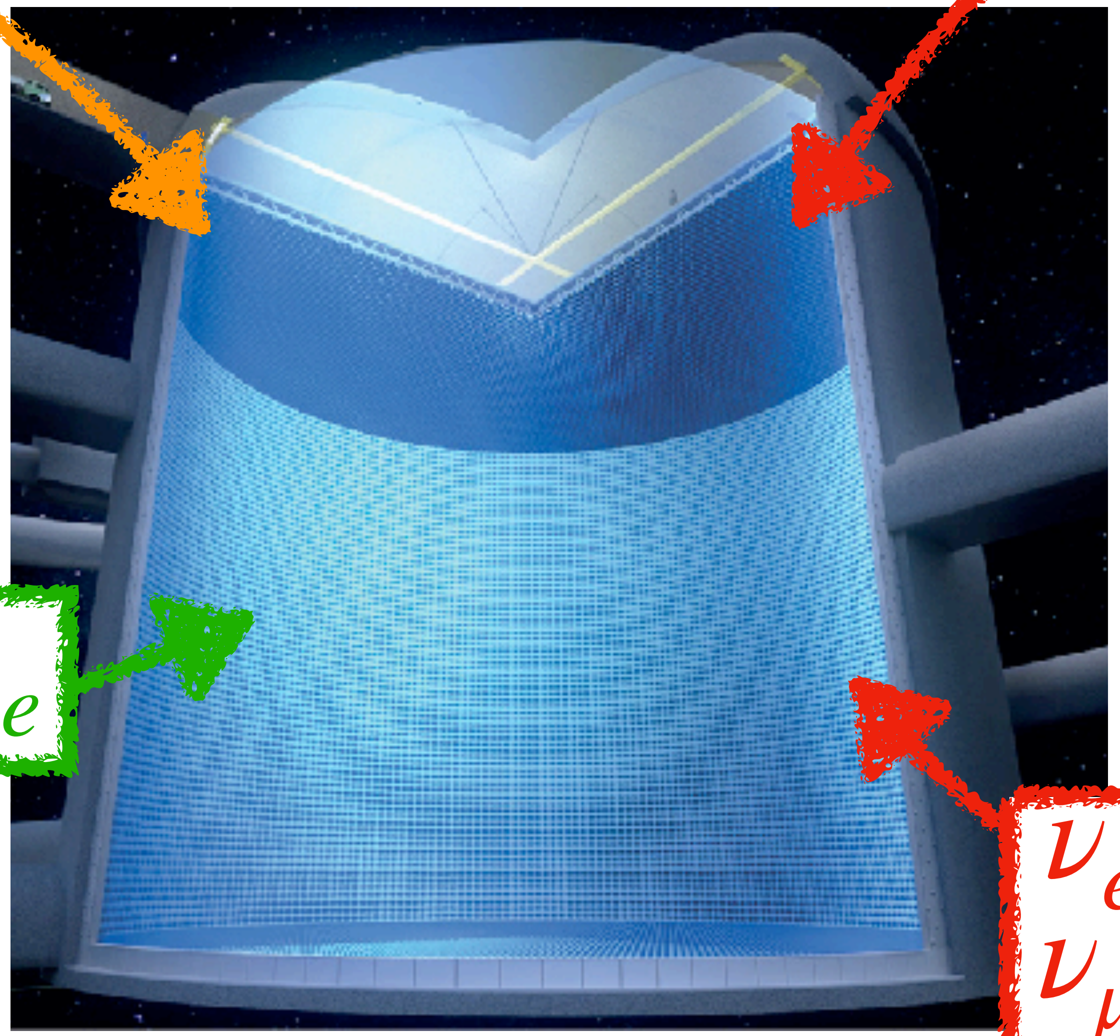


- Observe CP violation for leptons at 5σ
- Precise measurement of $\delta_{\rm CP}$
- High sensitivity to ν mass ordering

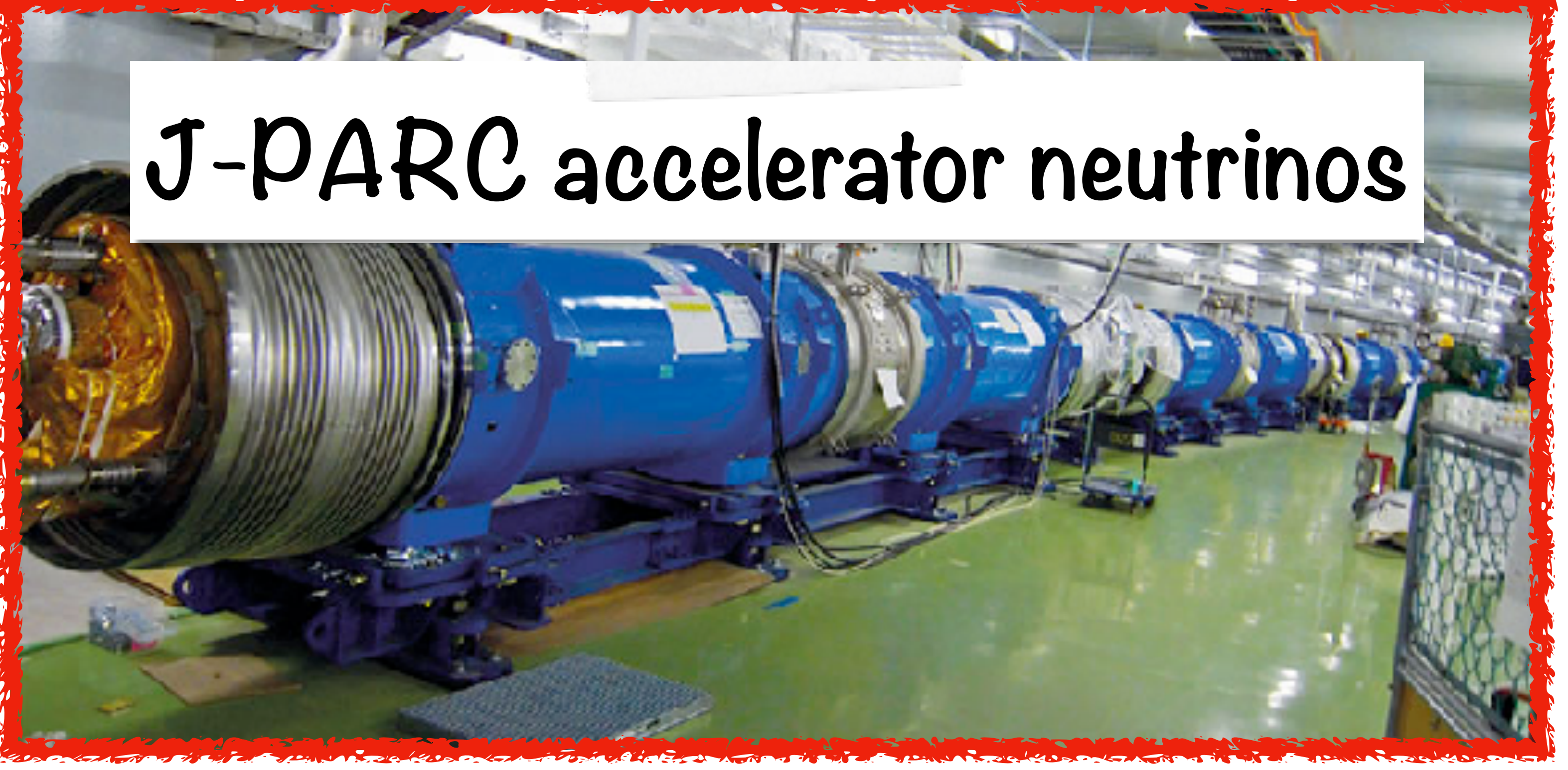


- Transient SN ν: constrain SN profile models
- Relic SN ν: constrain cosmic star formation

$\bar{\nu}_e$



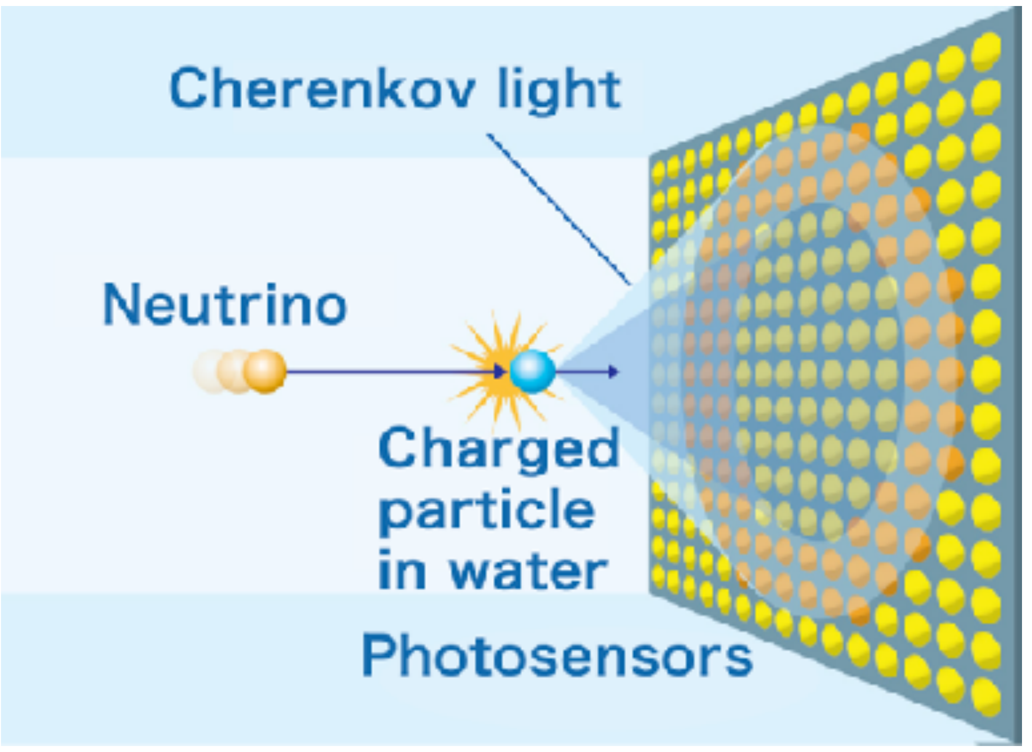
ν_e ν_e ν_μ $\bar{\nu}_\mu$

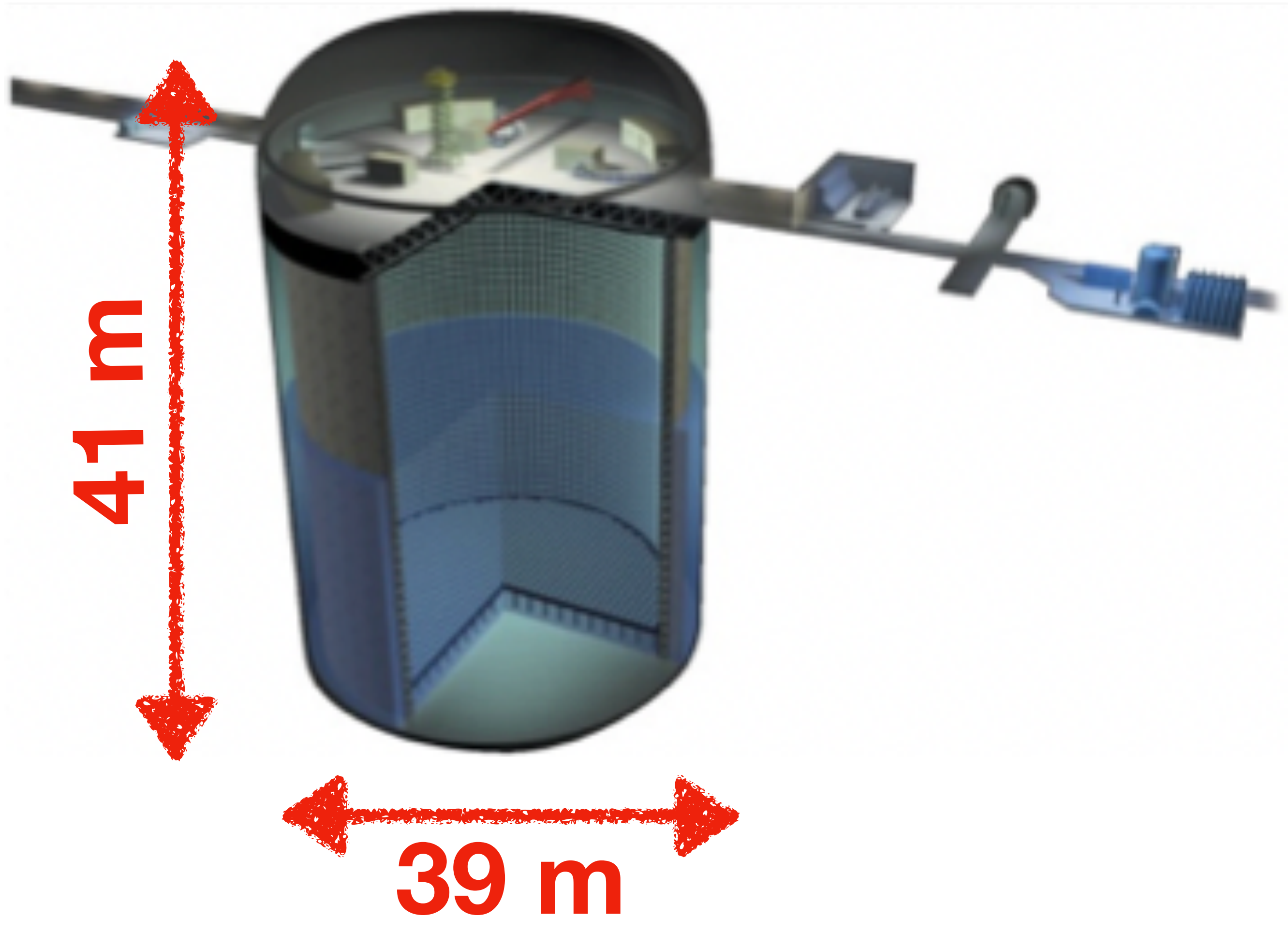


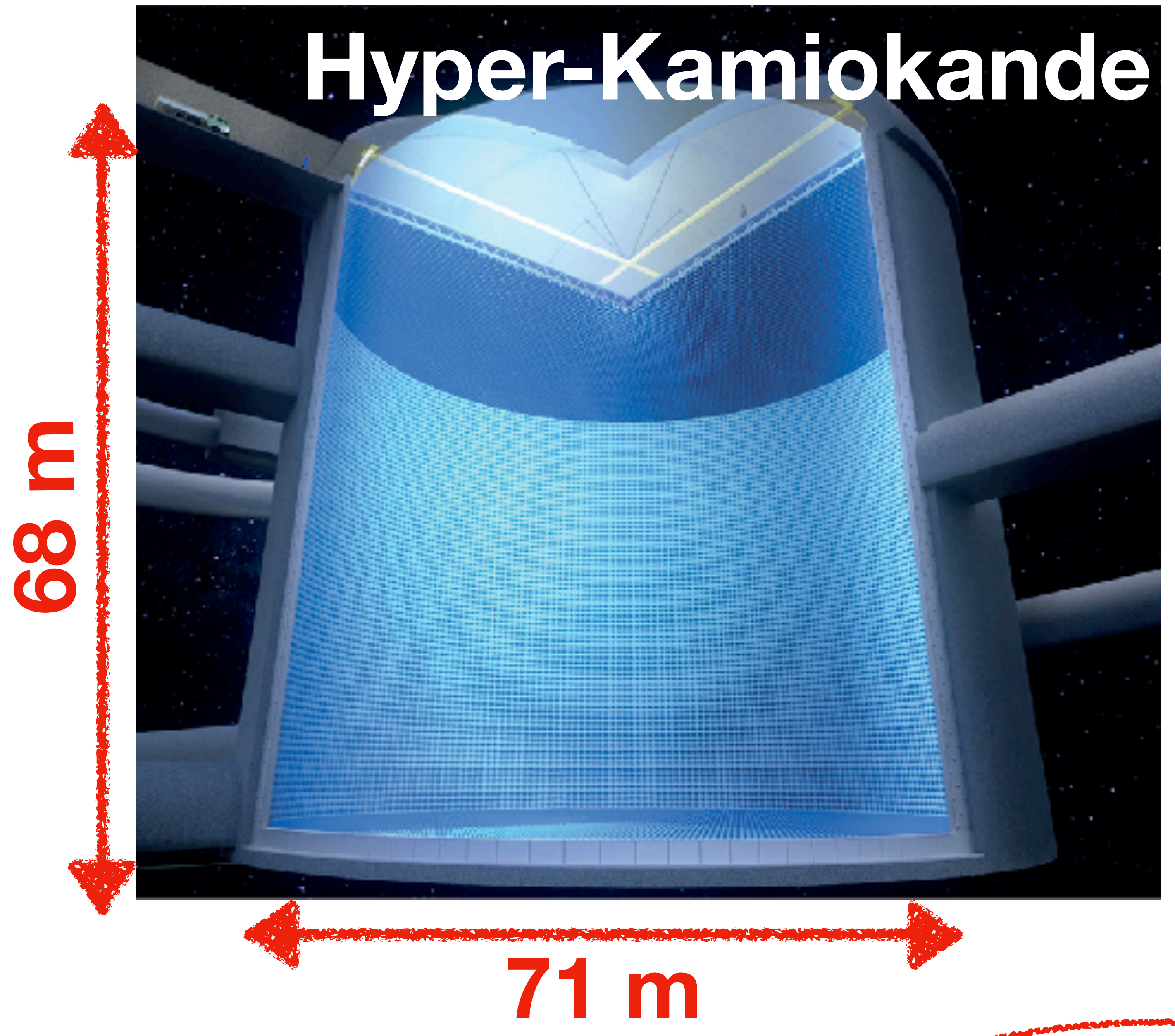
Justyna's talk

Claire's talk

The Hyper-Kamiokande detector





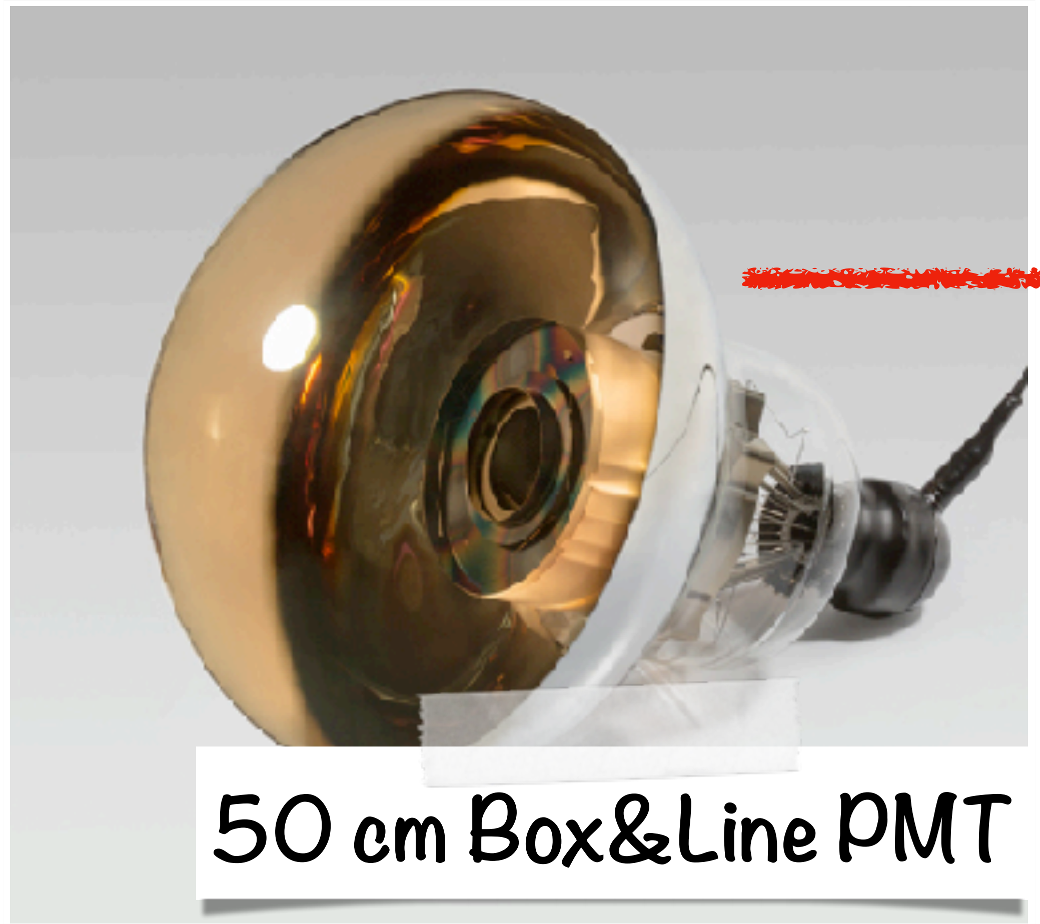


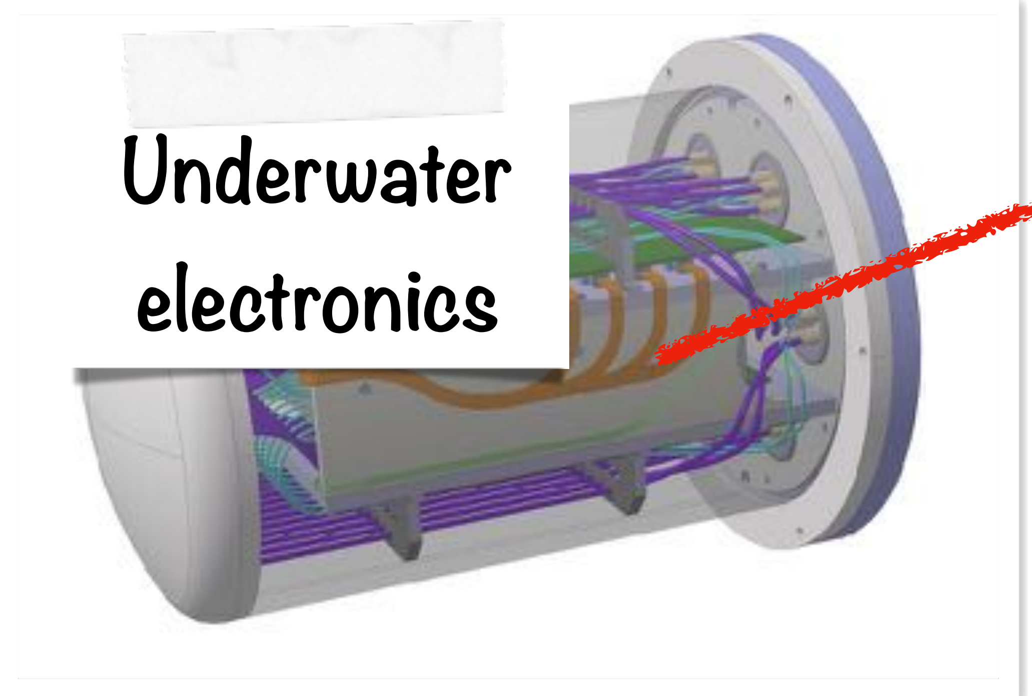
	Super Kamiokande	Hyper Kamiokande
Site	Mozumi	Tochibora
Number of ID 50-cm PMTs	11,129	~20,000
Photo-coverage	40 %	>=20%
Single-photon efficiency/PMT	~12%	~24%
Dark rate/PMT	~4 kHz	~4kHz
Time resolution of 1 photon	~3 ns	~1.5 ns
Total/fiducial mass (kton)	50 / **22.5**	260 / **188**

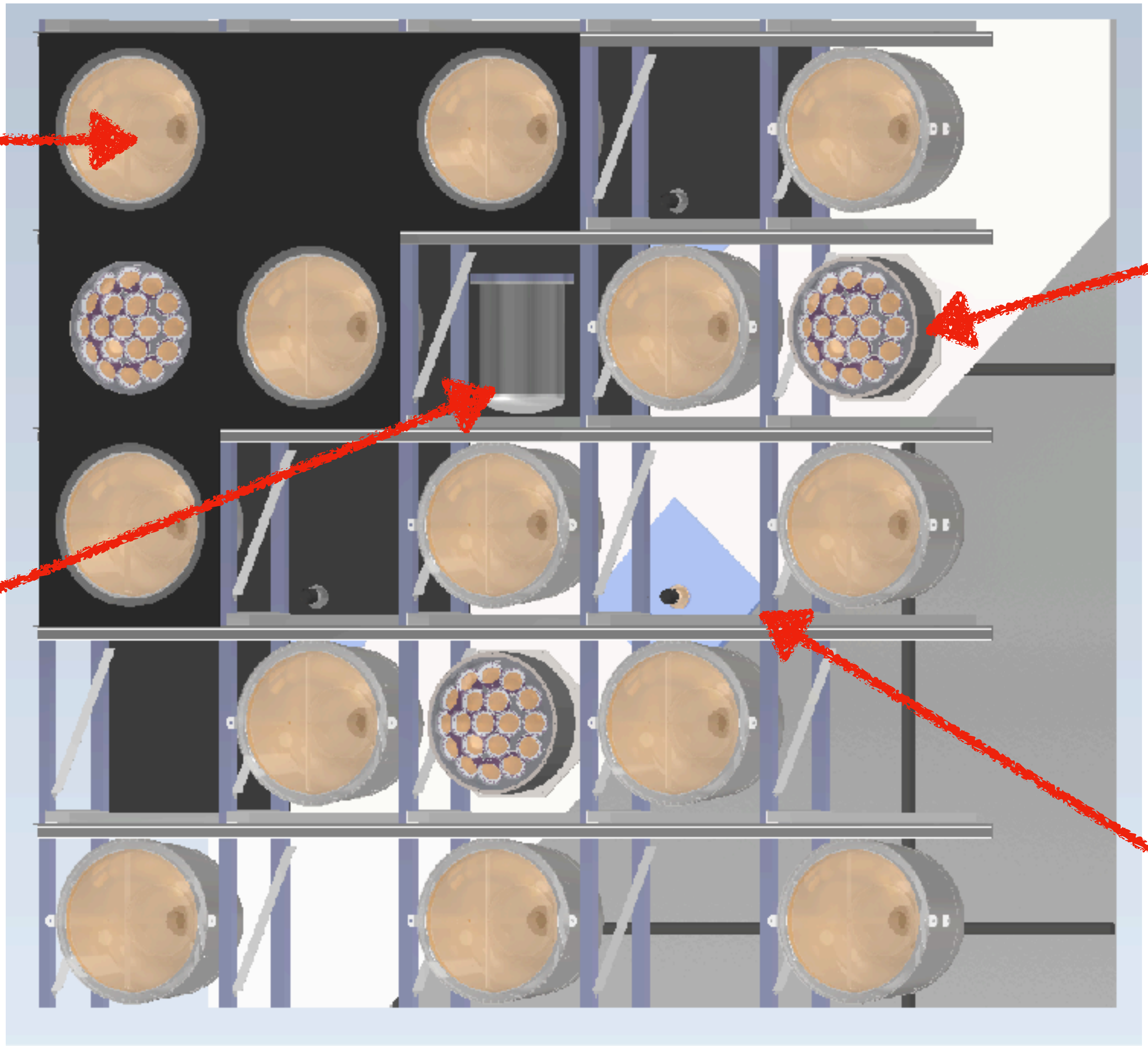
Fiducial volume x8
→ non-beam ν physics

Beam neutrino event rate x 20
→ beam ν physics

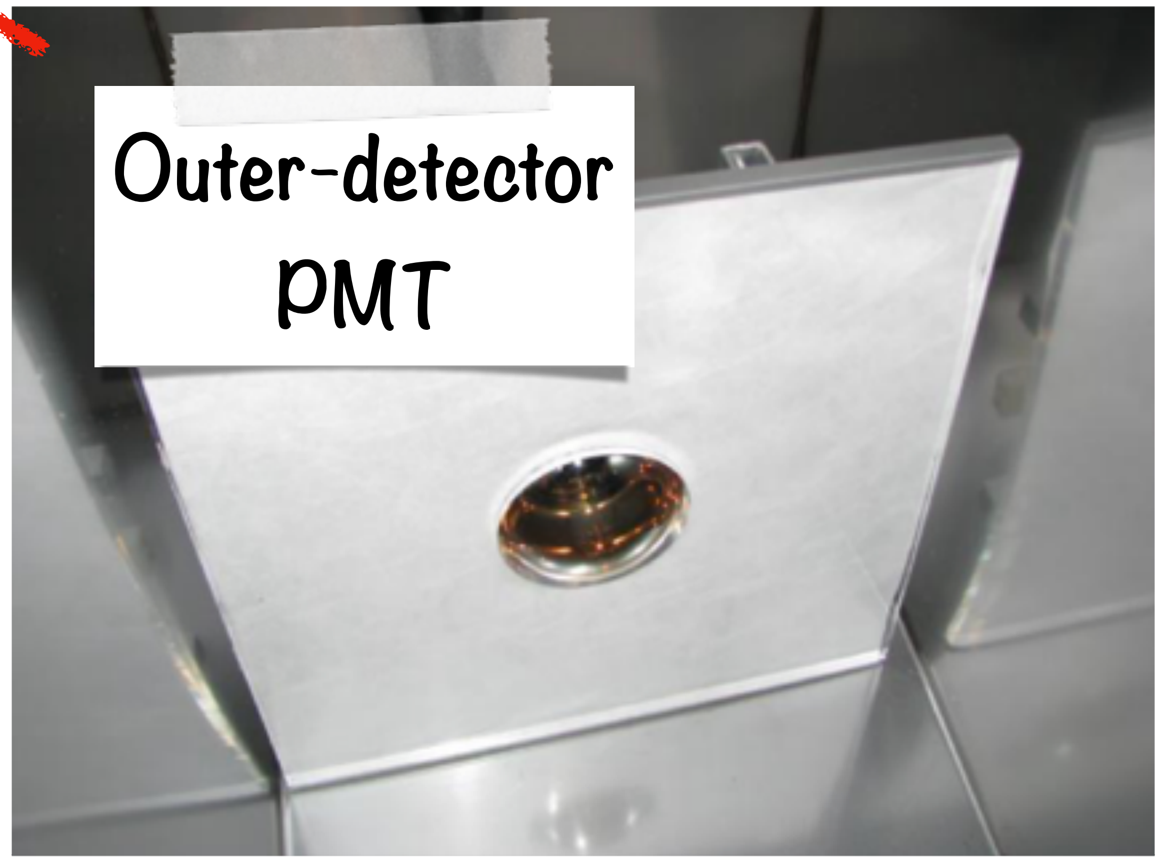
50-cm PMTs, mPMTs and readout







19 x 8 cm PMT



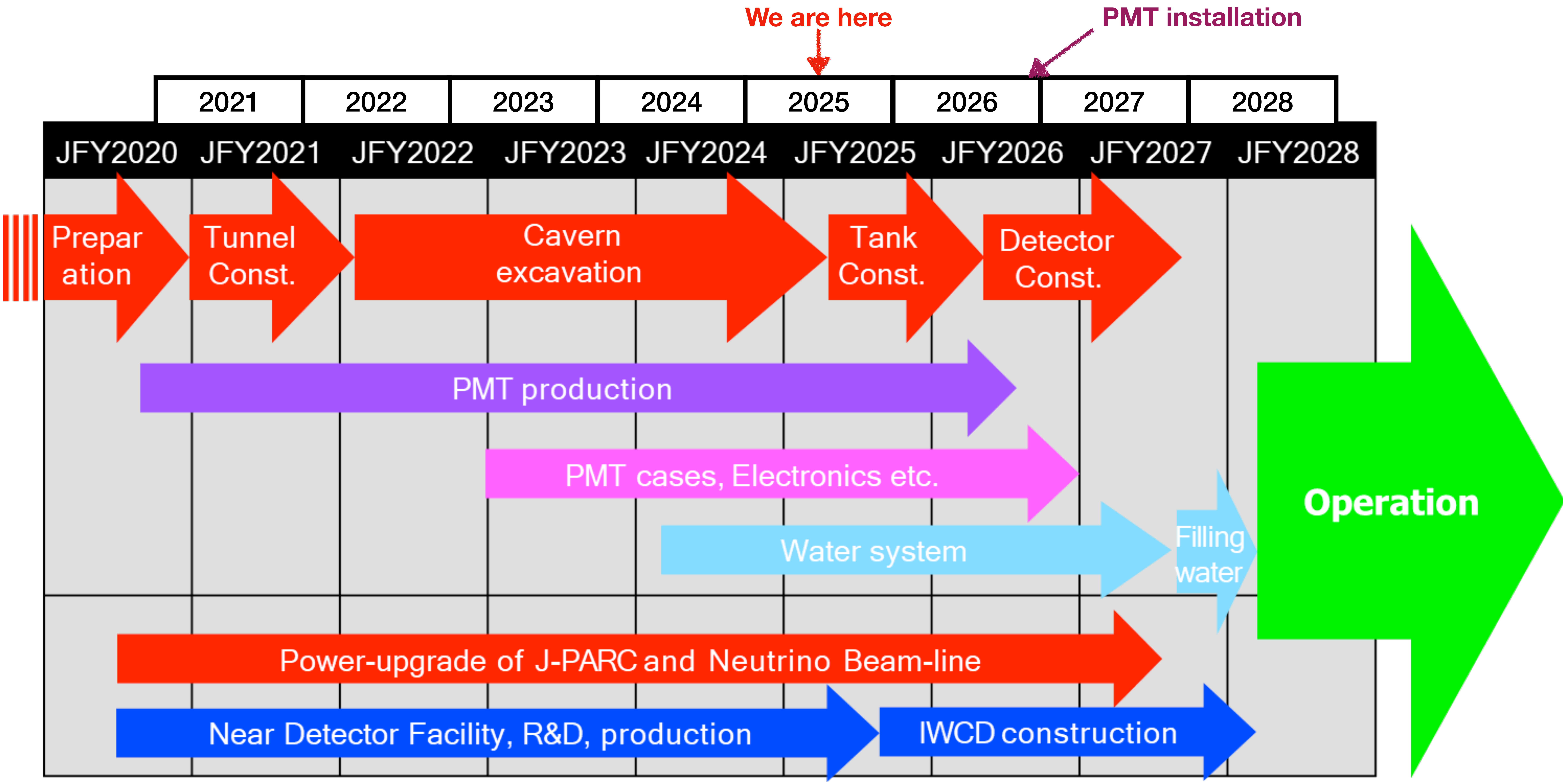
Inner detector:

- ~20k 50-cm PMTs (Hamamatsu R12860)
- ~800 mPMTs (19 8-cm R14374 PMT) → Better SNR, directionality, timing

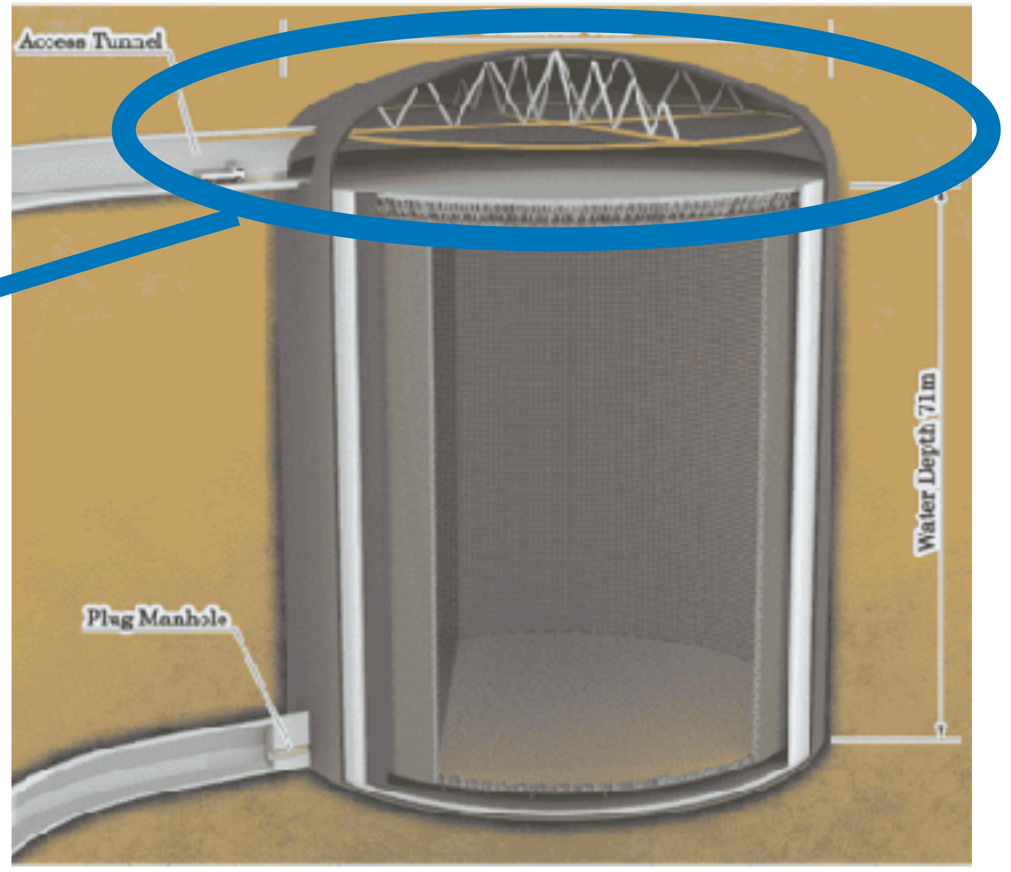
Outer detector: ~3.6k 8-cm PMTs inserted in WLS plates

Optical insulation using Tyvek sheets

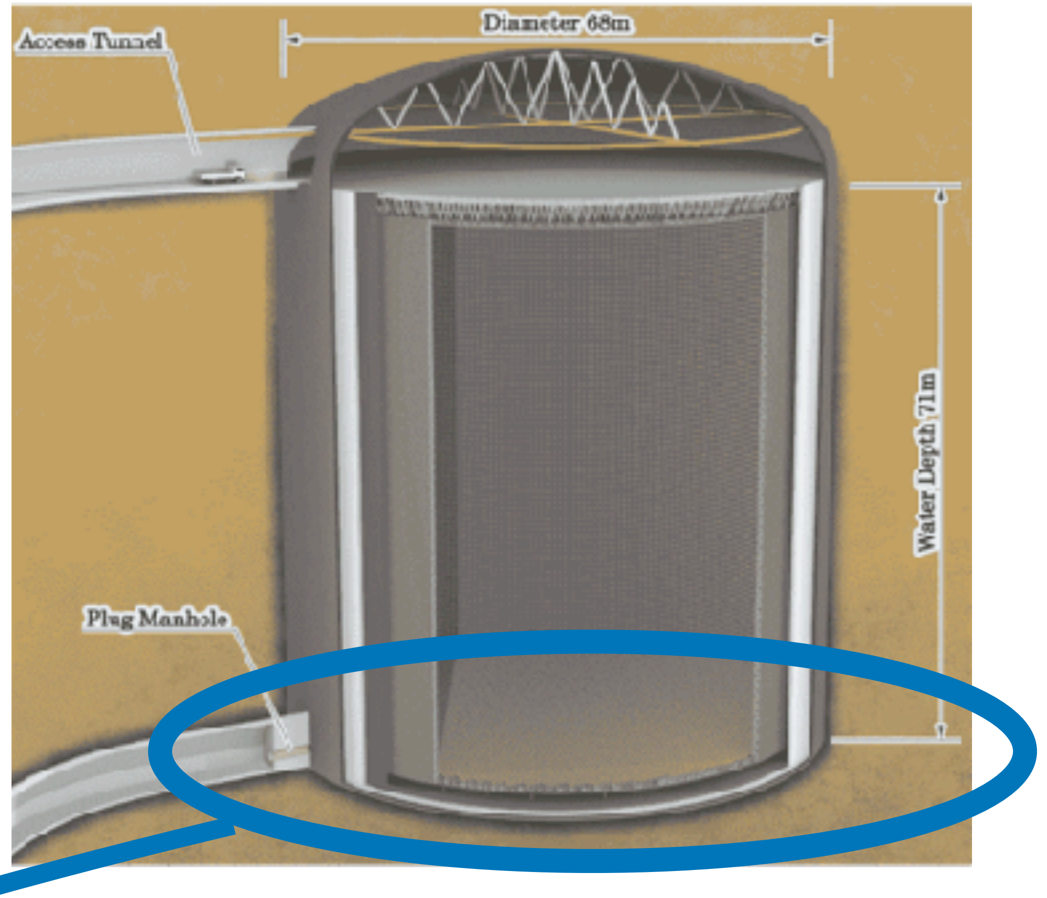
Construction schedule



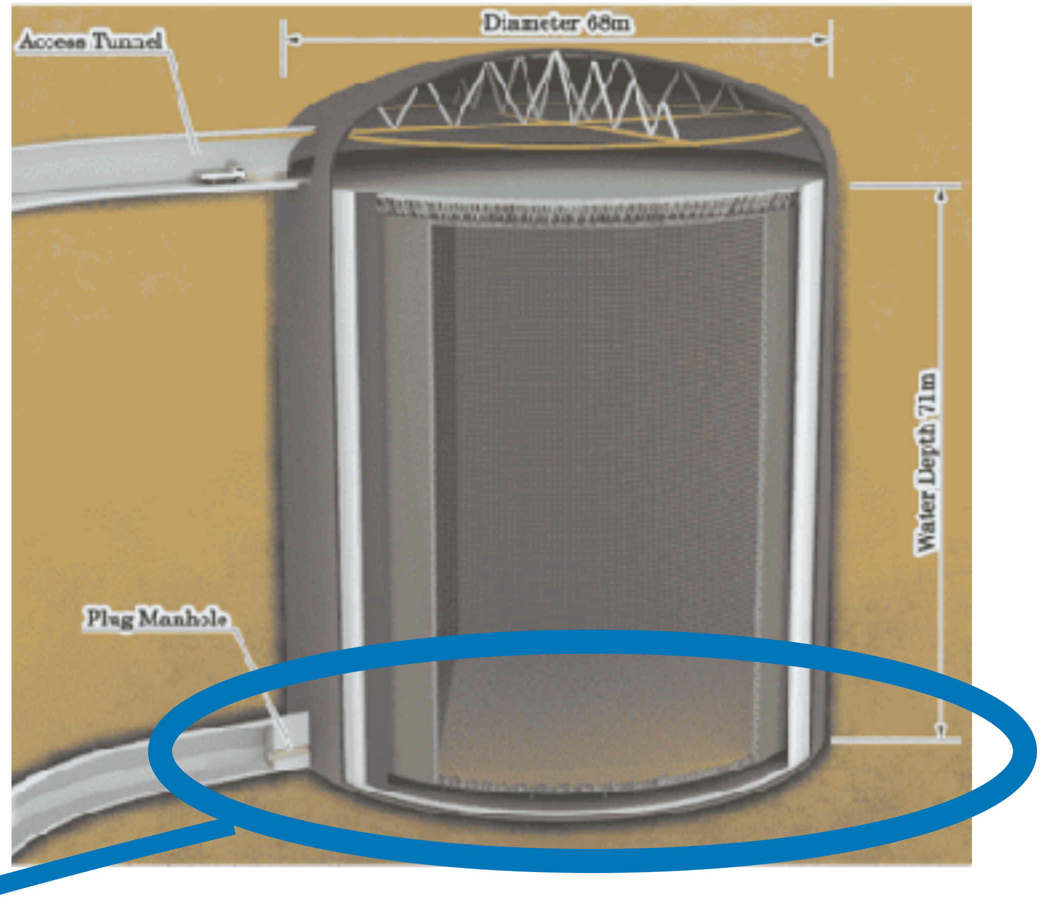
Excavation status



Excavation status



Excavation status



Excavation is about to be completed!

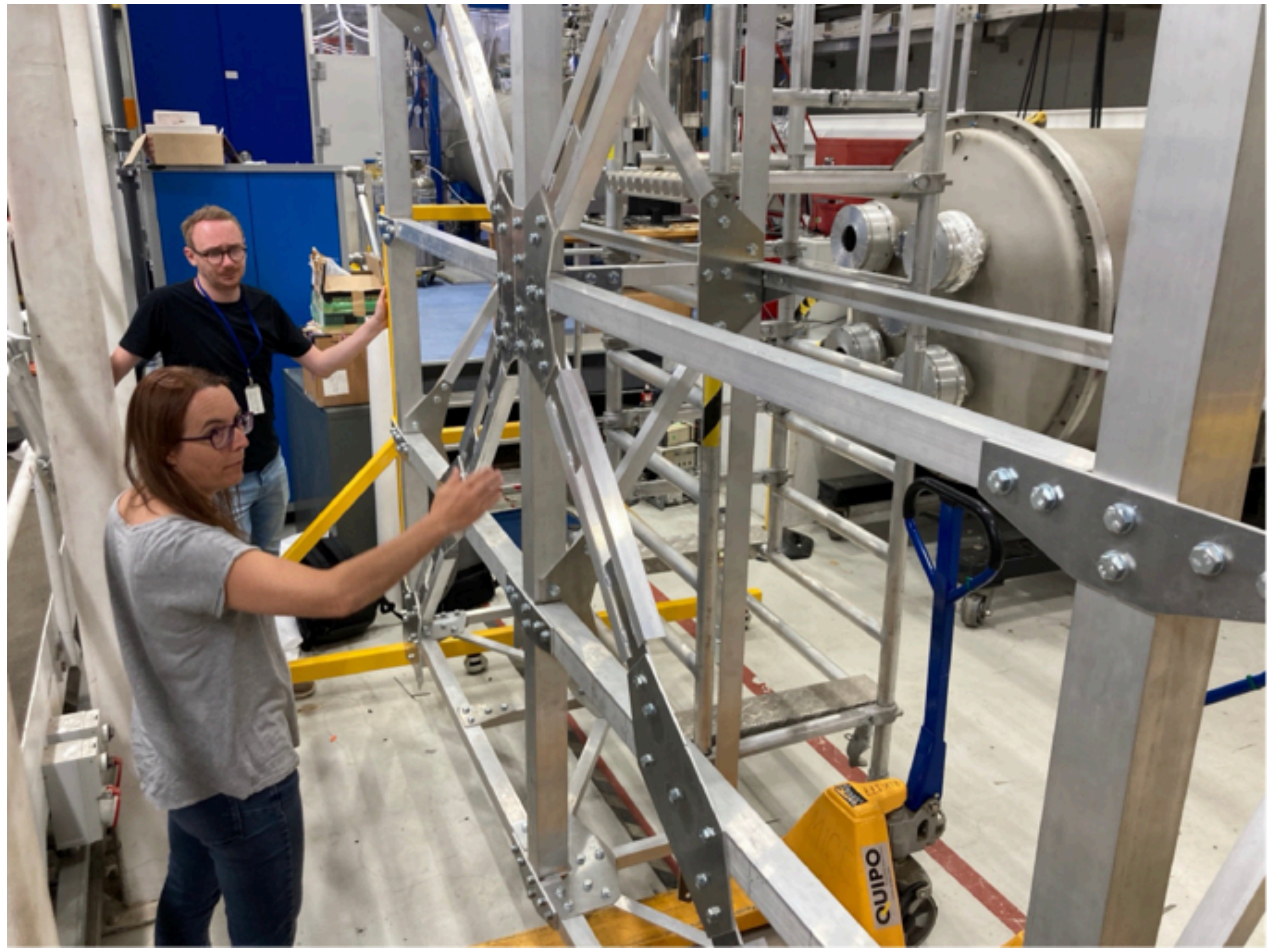
Start of the tank and support structure construction in the coming weeks

Stay tuned!

Mock-ups and installation procedure

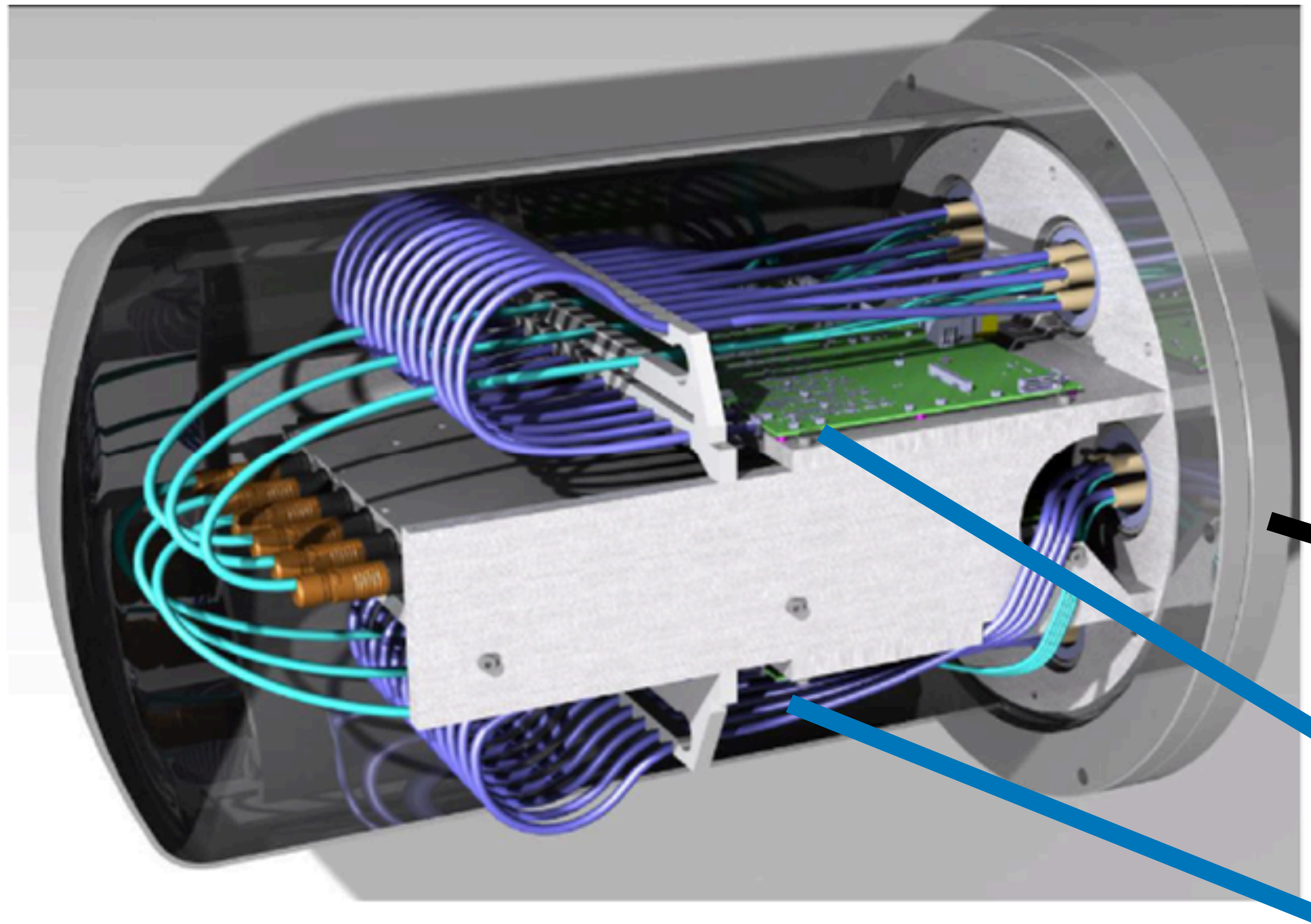
Mock-up in Kamioka

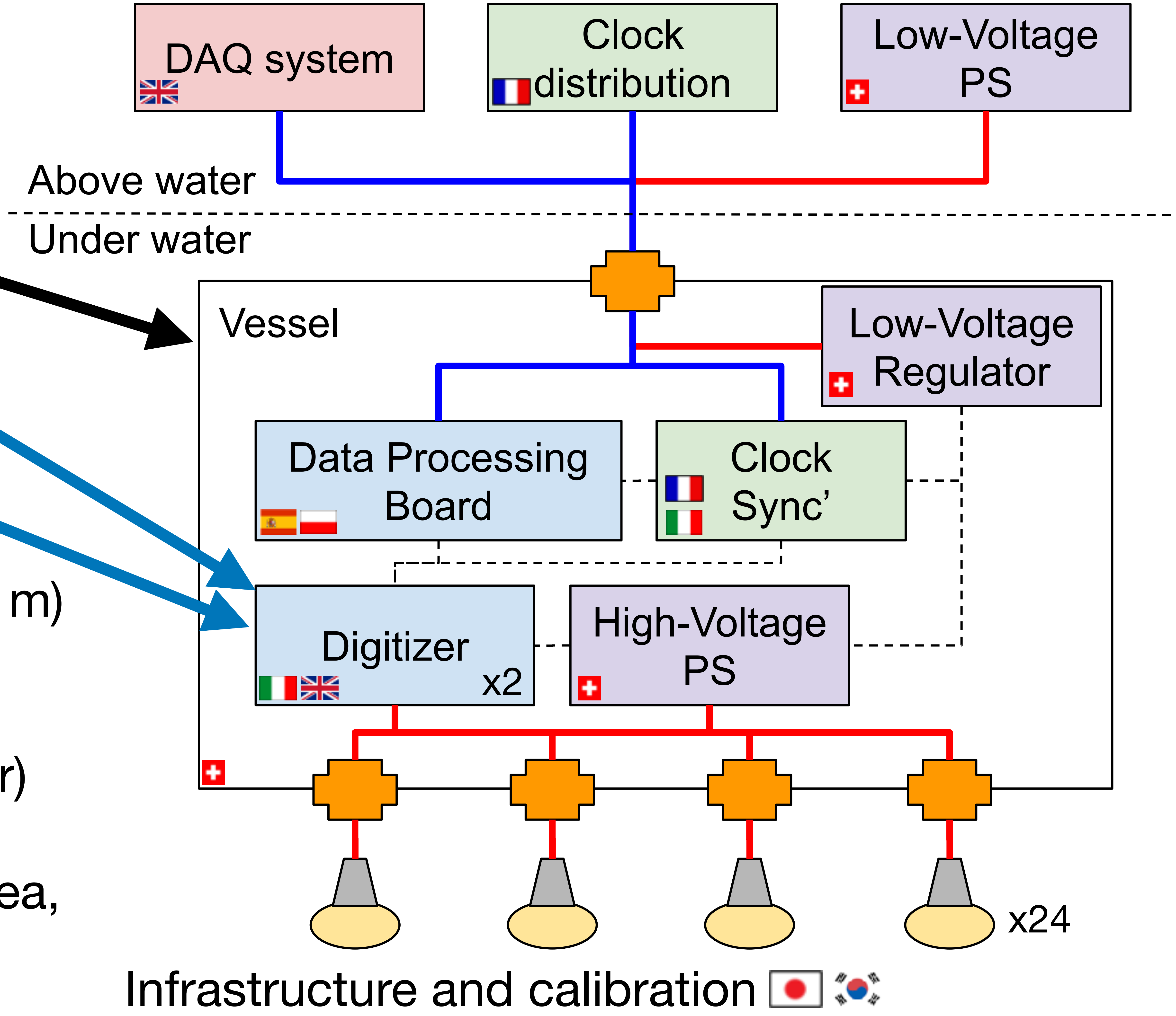
Installation frames in Kamioka and RAL (UK)
→ Finalisation of installation procedure definition
→ Tests/training with Japanese construction company



RAL mock-up

Underwater electronics vessel

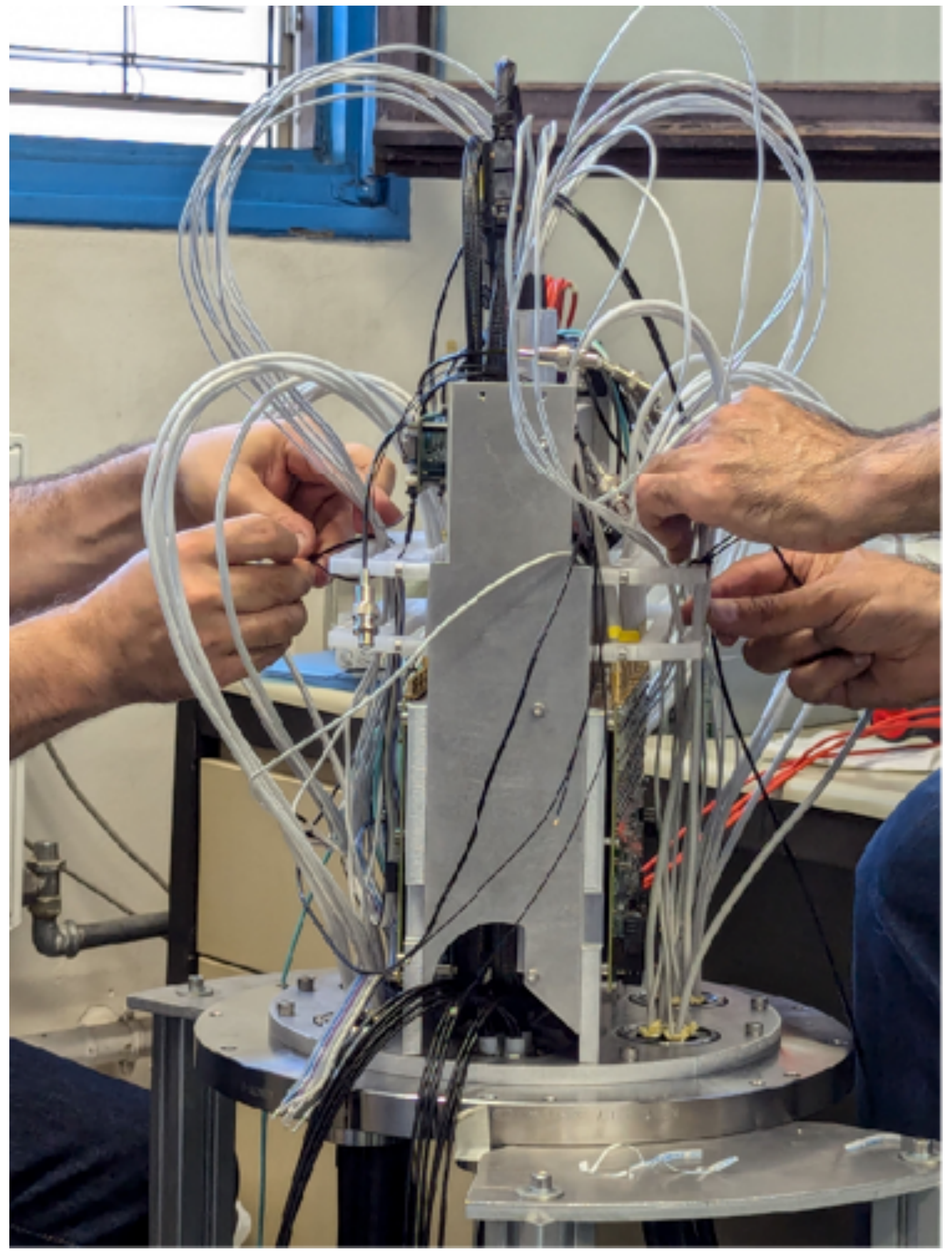




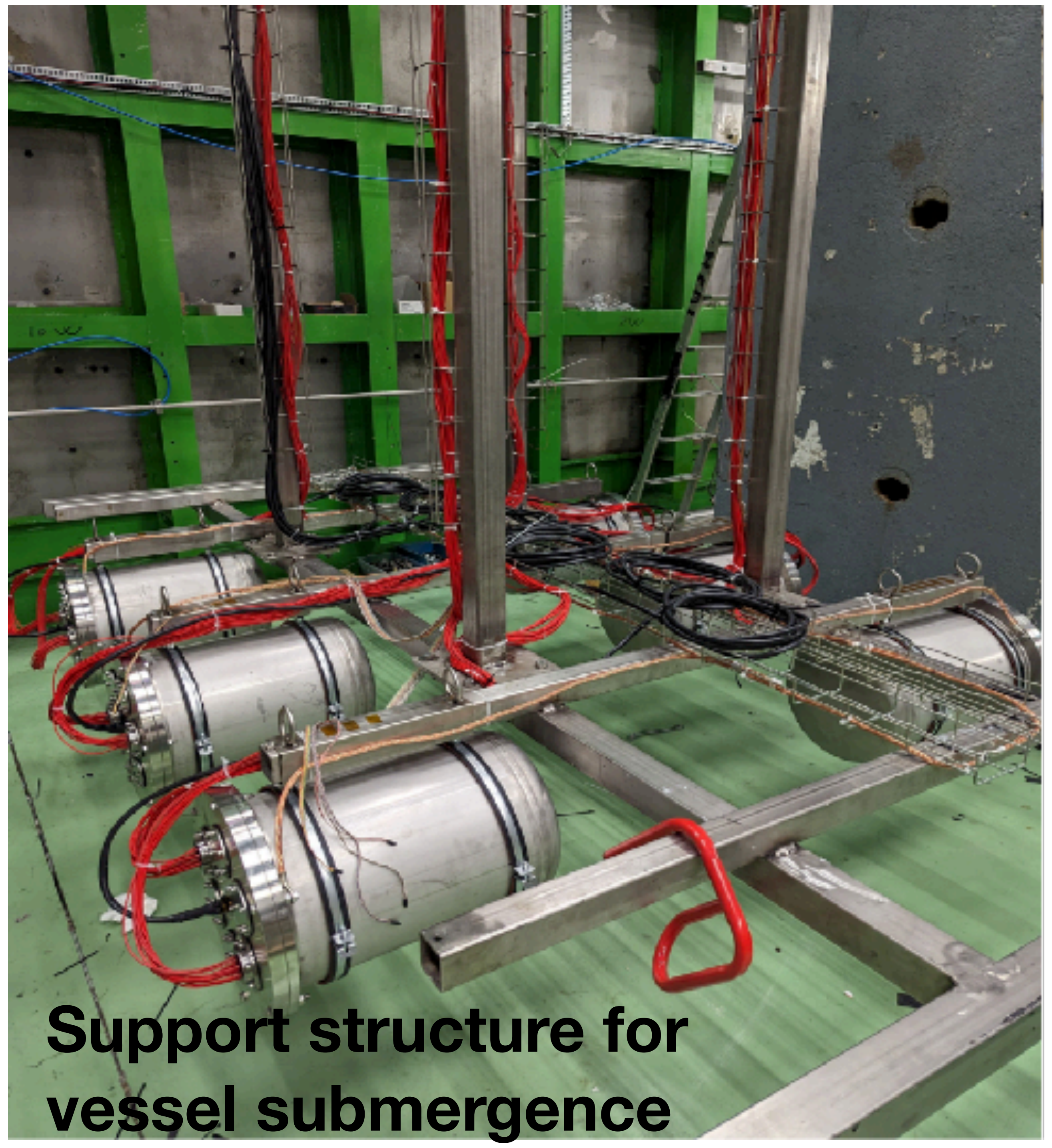
Underwater digitisation electronics
- Short distance between PMT and electronics (<20 m)
- All signals must be brought to vessel
- Data sent back to DAQ (out of water)
- Different from Super-Kamiokande (smaller detector)

<u>International collaboration:</u> France, Italy, Japan, Korea, Poland, Spain, Switzerland, UK

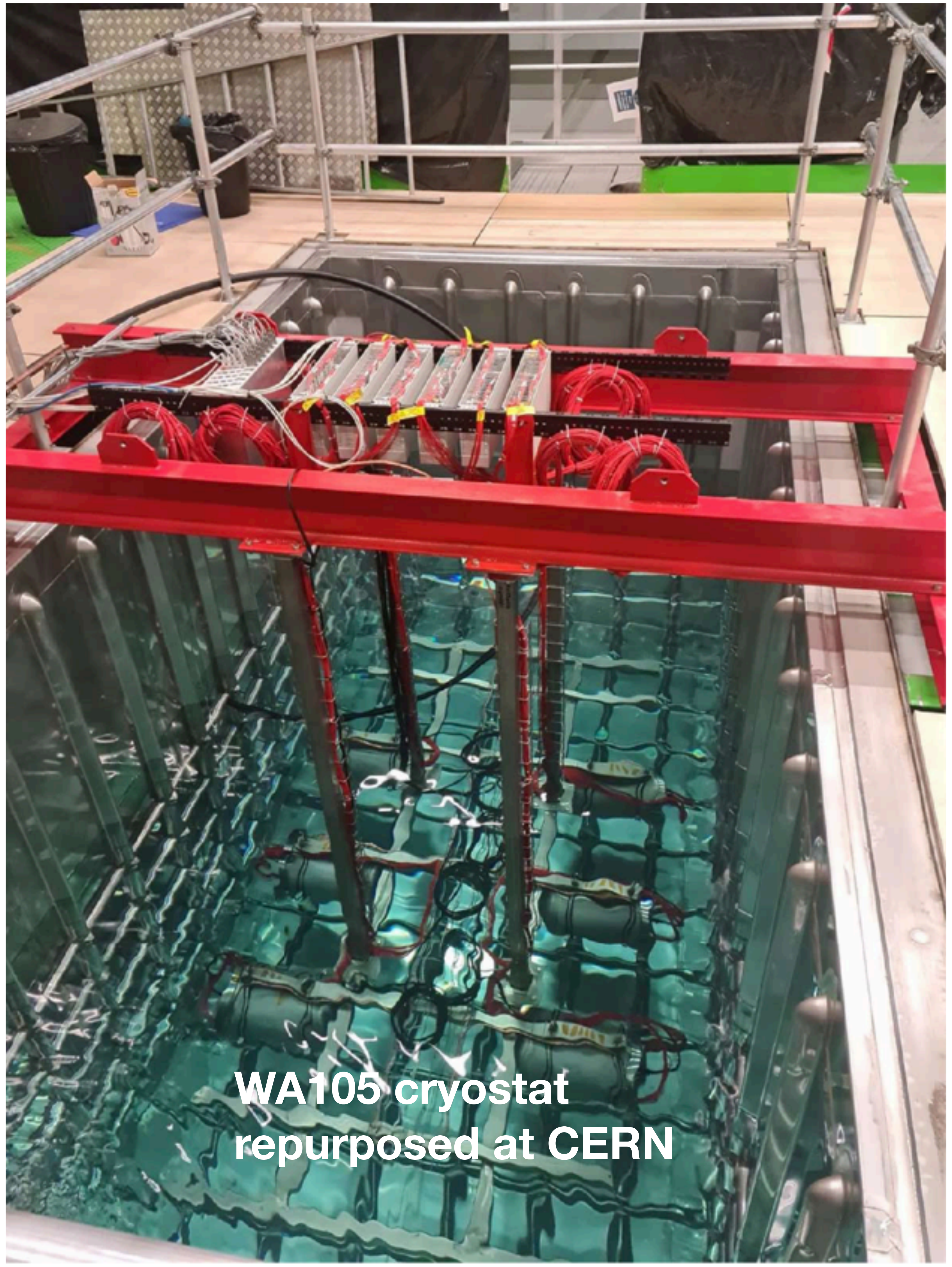
Underwater tests and assembly at CERN



Assembly test-stand



Support structure for vessel submergence

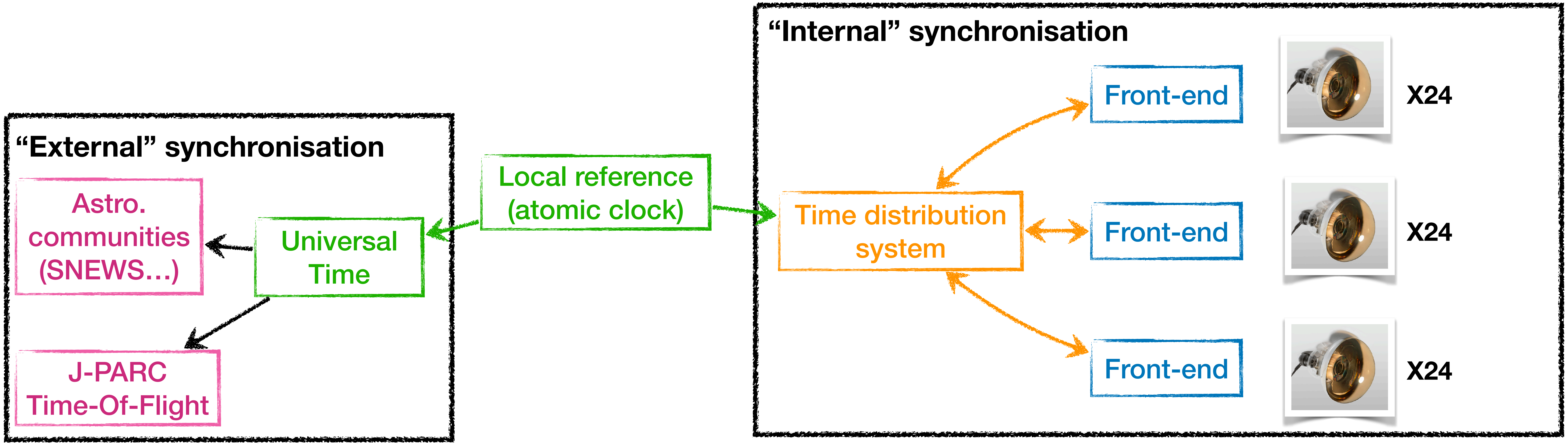


WA105 cryostat repurposed at CERN

Hosted at CERN Neutrino Platform (NP08)
- Vertical test-stand (integration tests of all components)
- Assembly tests on mock-ups
- Assembly and calibration of 1000 vessels
- Storage before shipment to Japan

→ **Vessels assembly and calibration planned for 2nd half of 2026**

Clock and timing requirements



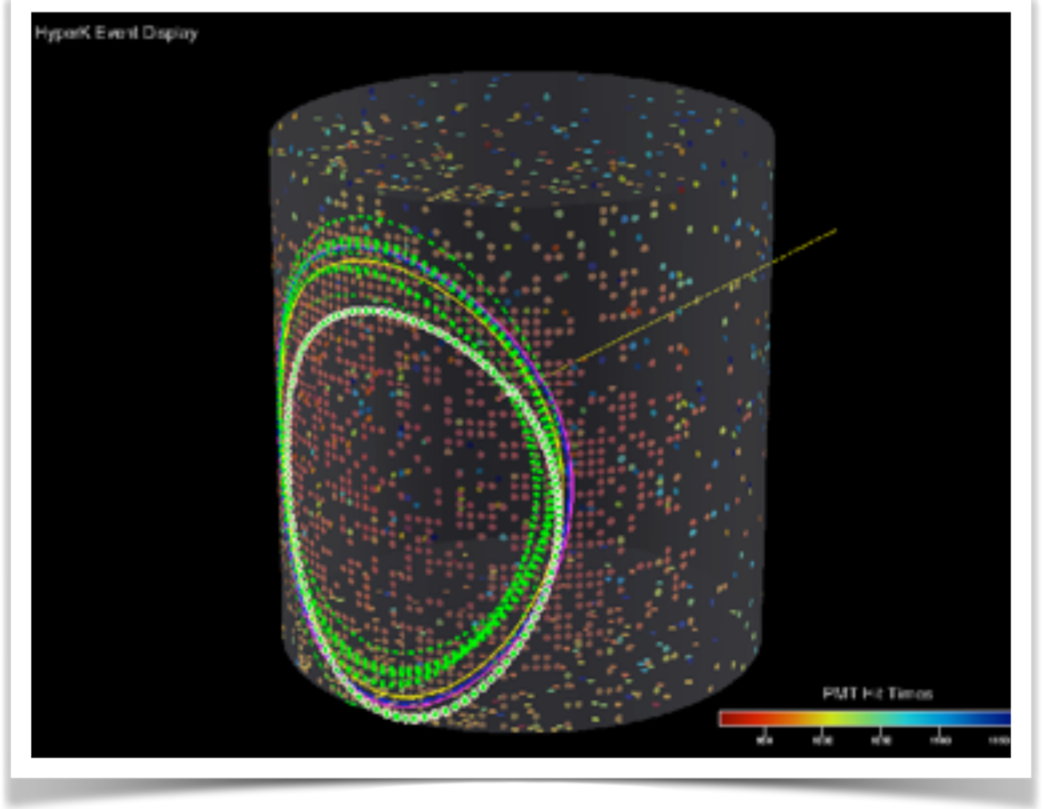
Correlation with external experiments (J-PARC Time-Of-Flight, Supernovae…)

→ event time-tagging < 100 ns using GNSS receivers

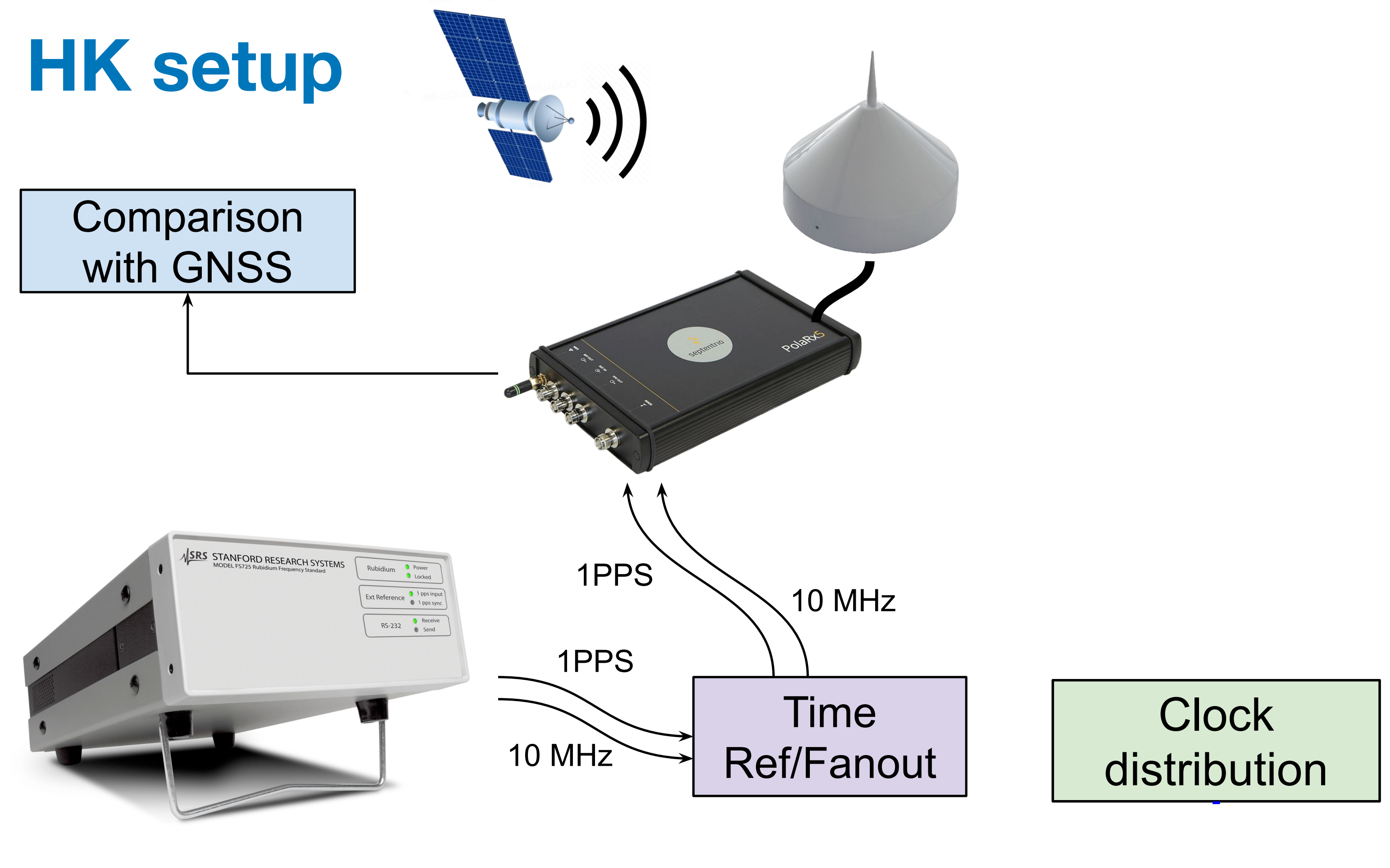
Rings reconstruction by coincidence

→ time difference between PMTs < 100 ps

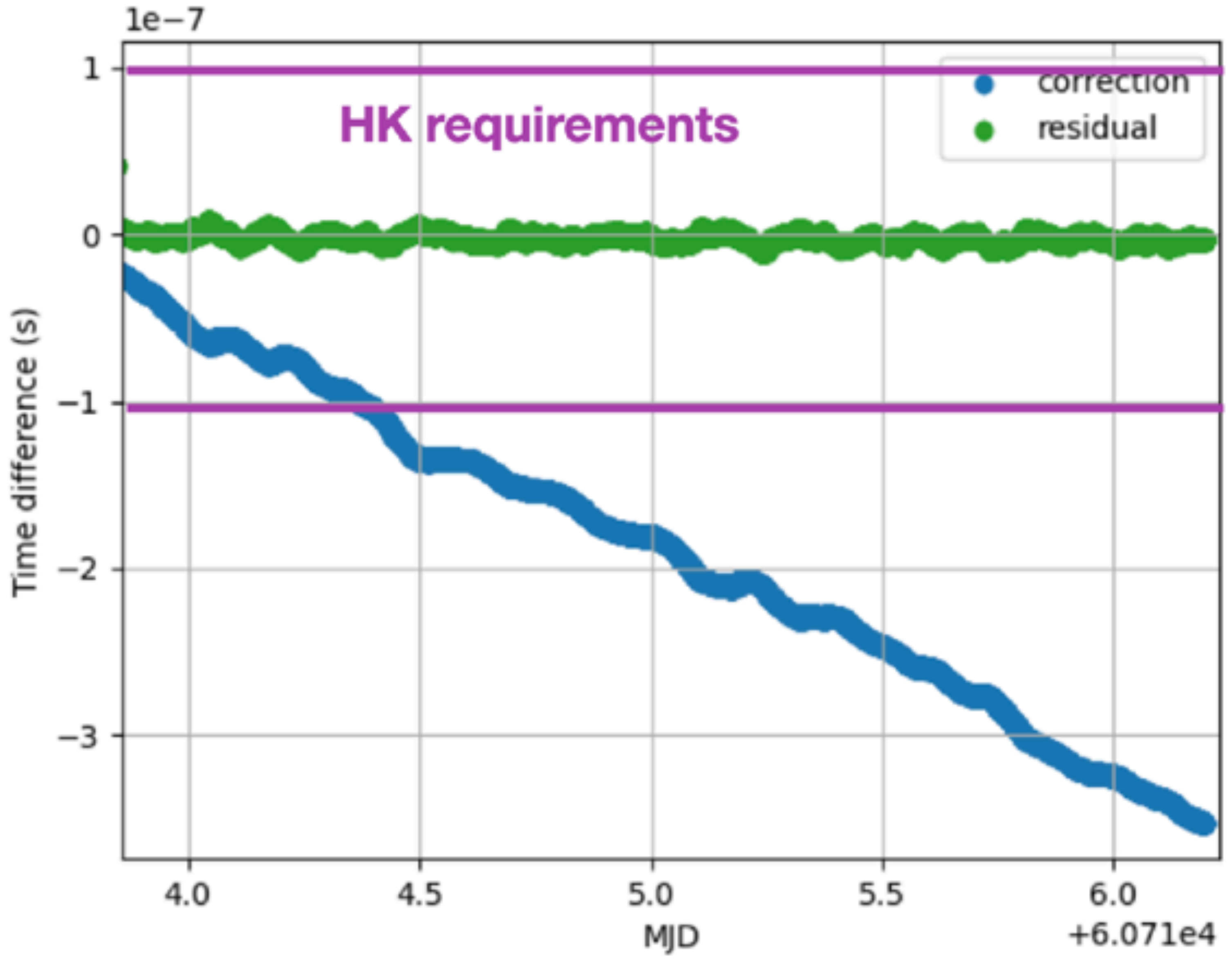
→ constant skew after reset

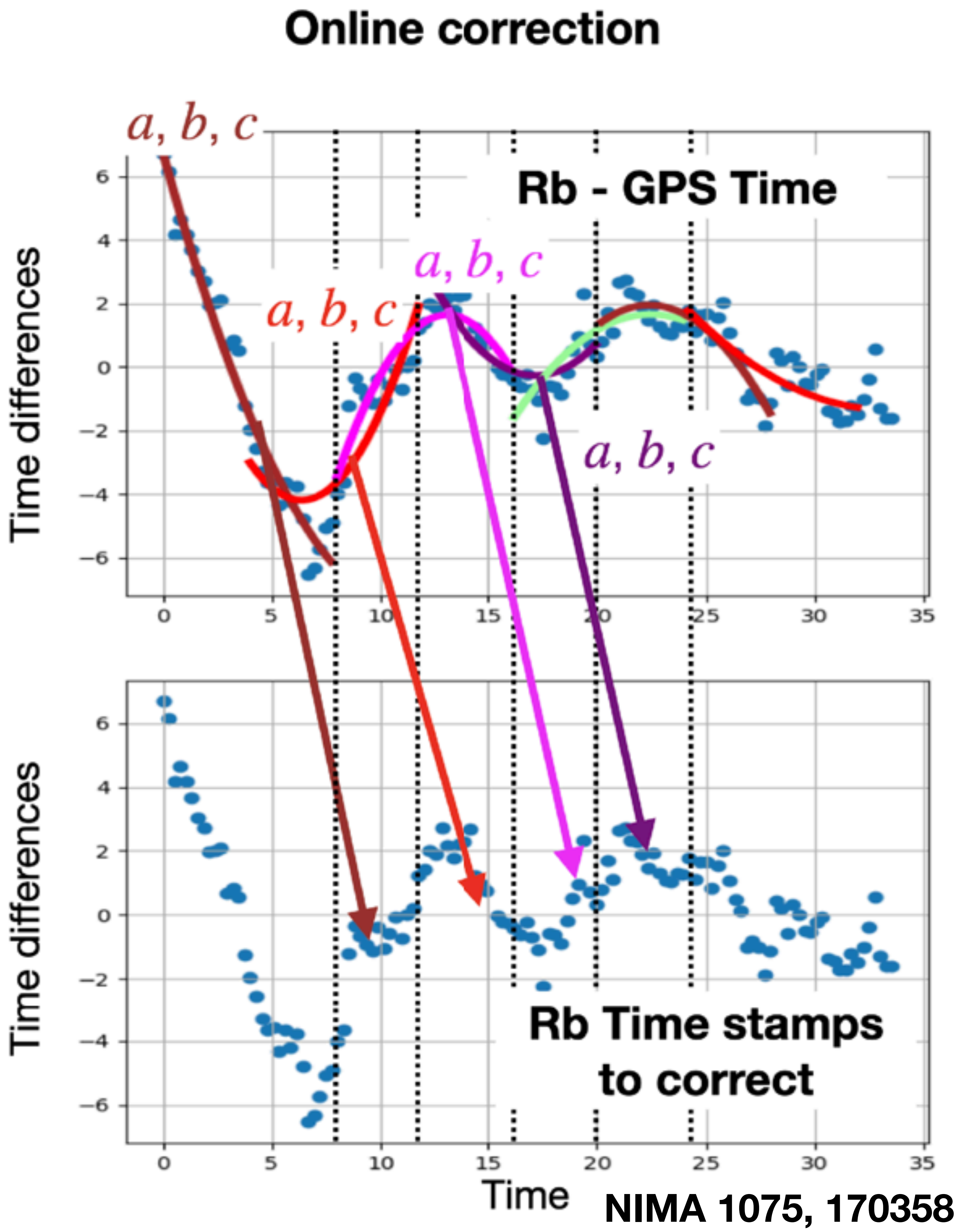


Time synchronisation and clock correction



Free-running clock and GNSS-in comparison





NIMA 1075, 170358

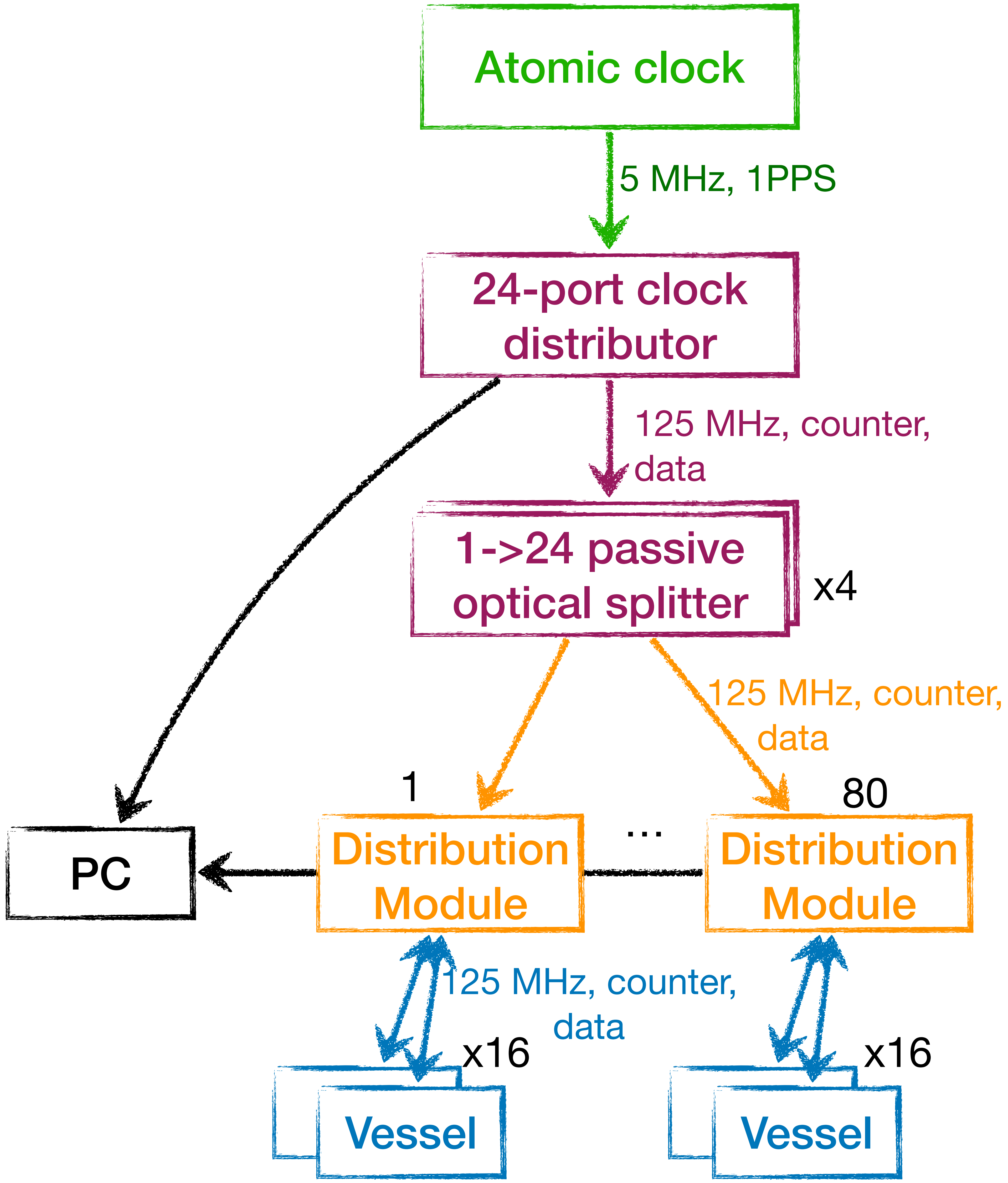
Measure clock 1PPS drift with GPS receiver to correct/predict drift
- Very precise: few ns precision — NIMA 1075, 170358 (2025)
- Insensitive to dilution of precision (bad satellites sky distribution)
- Long-term clock drift corrected by steering clock (software control)

→ Results in agreement with simulation

→ Validation using a test-stand in Paris — UTC(OP) via White-Rabbit

→ Investigating more stable clocks like Cs clock

Clock distribution status



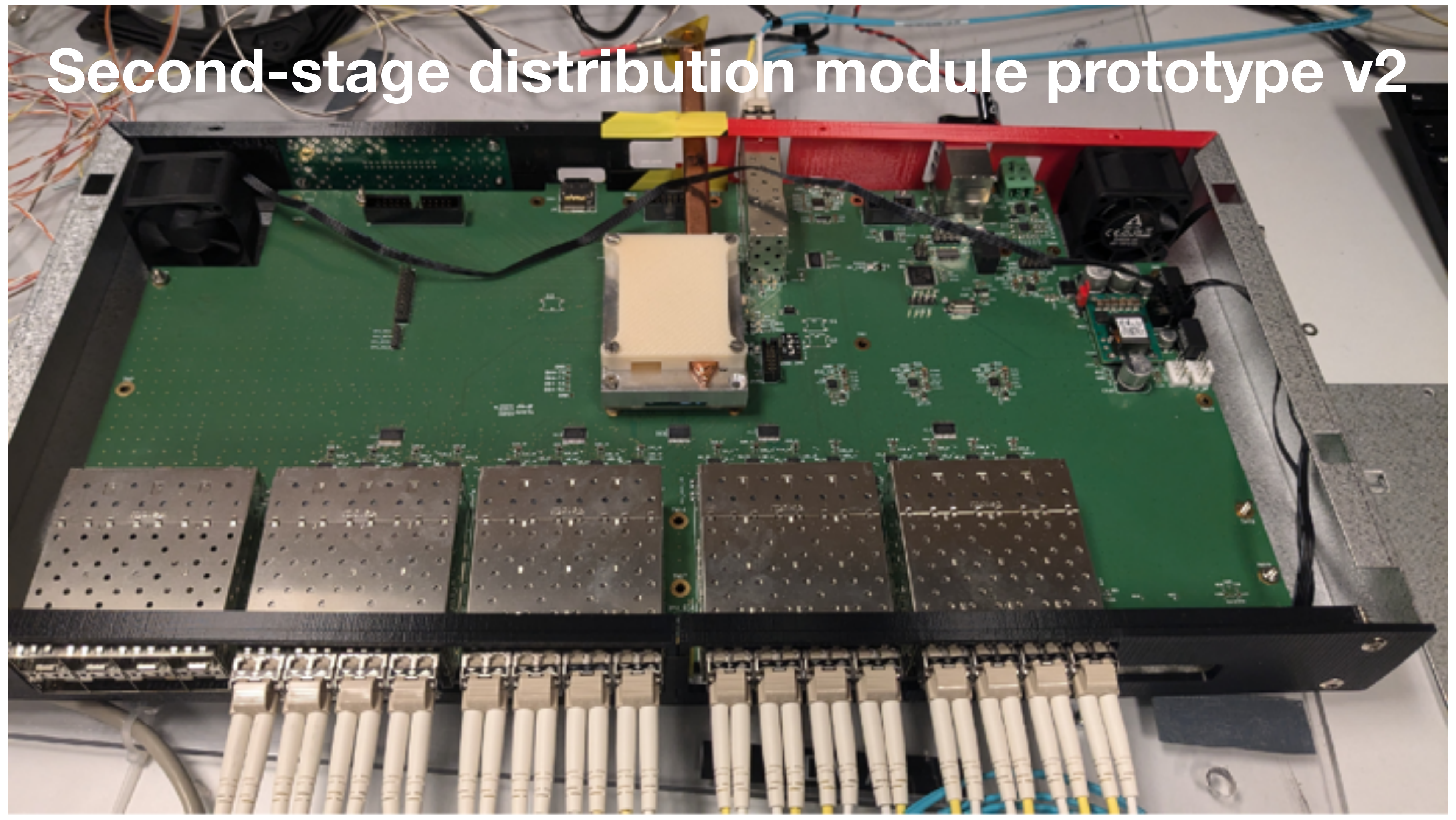
Two-stages distribution system

- Distribute/multiply atomic clock signals to 1000 vessels
- Propagate synchronous data to all vessels
- Based on Clock-in-Data-Recovery (CDR)

Full timing synchronisation test using function generator

- Realistic signal through digitiser, DPB
- < 300 ps resolution, consistent with TDC resolution

→ **Final production started — Ready by mid 2026**



Conclusions and prospects

Hyper-Kamiokande construction is under way
- Excavation almost completed and tank and support structure installation will start soon
- Photo-detectors and electronics installation in 2027

Electronics production is on-going
- Challenging because digitisation happening underwater
- International efforts
- CERN as a centralised place for electronics assembly, calibration and transportation

Significant efforts on the timing system to reach requirements and beyond
- Design (free running Rb clock and GNSS comparison) fully validated
- Investigating more stable clocks to improve system stability
- Production of the distribution boards in 2025-2026

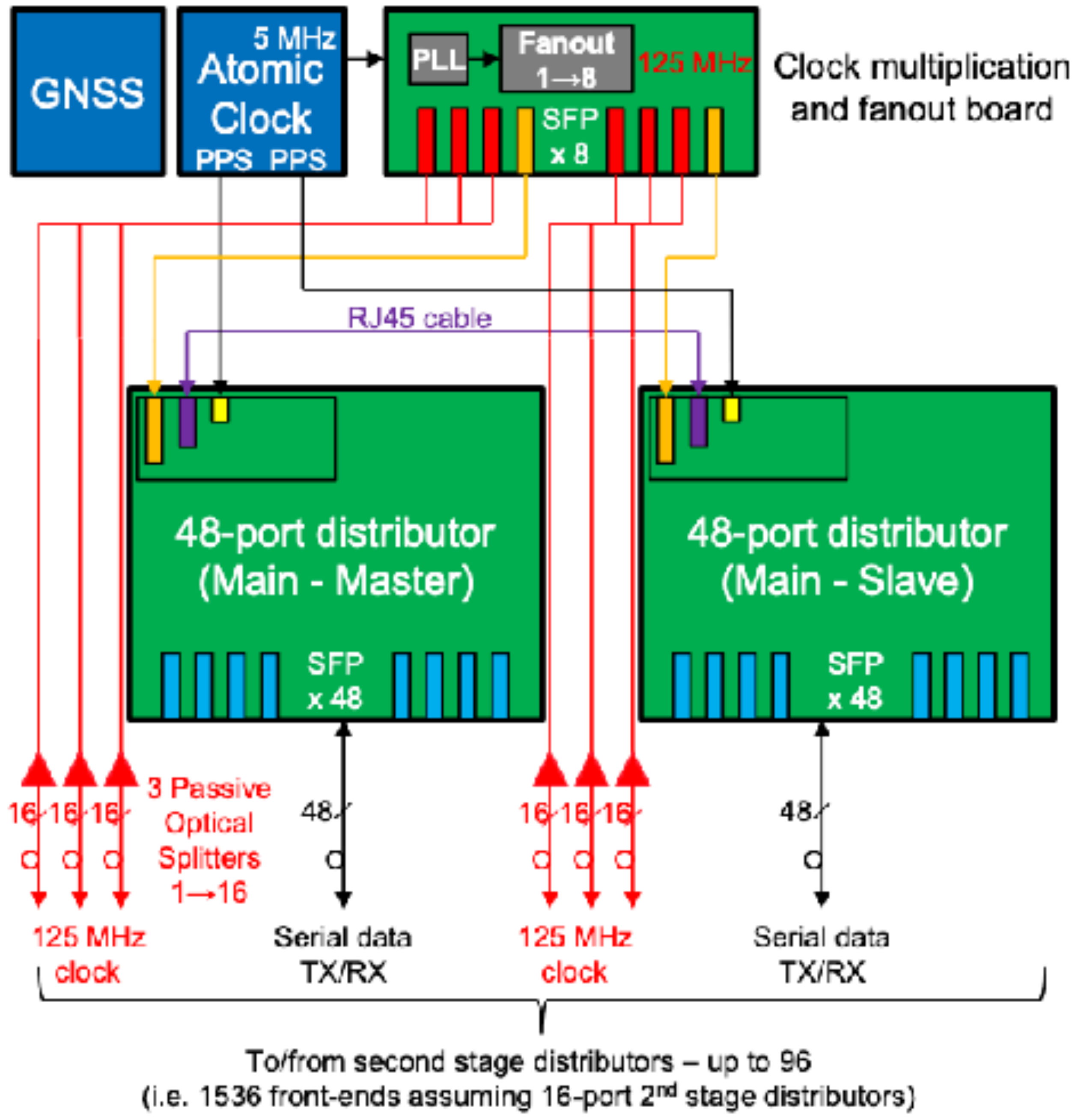
Water filling and commissioning until mid-2028 (7 months!)
Data taking start foreseen mid-2028!

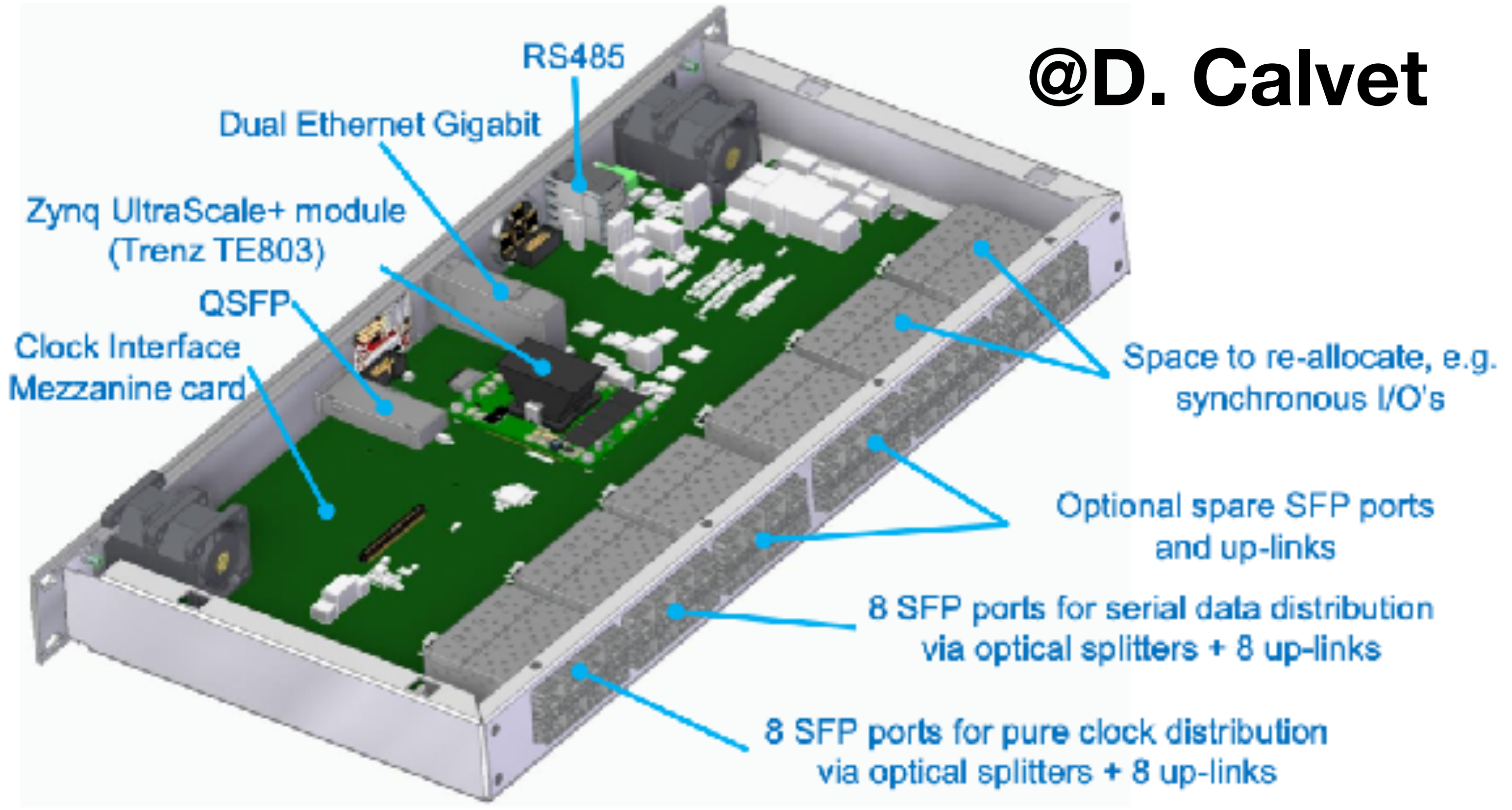
Stay tuned!

Backup

Clock distribution prototypes

First-stage distributor prototype

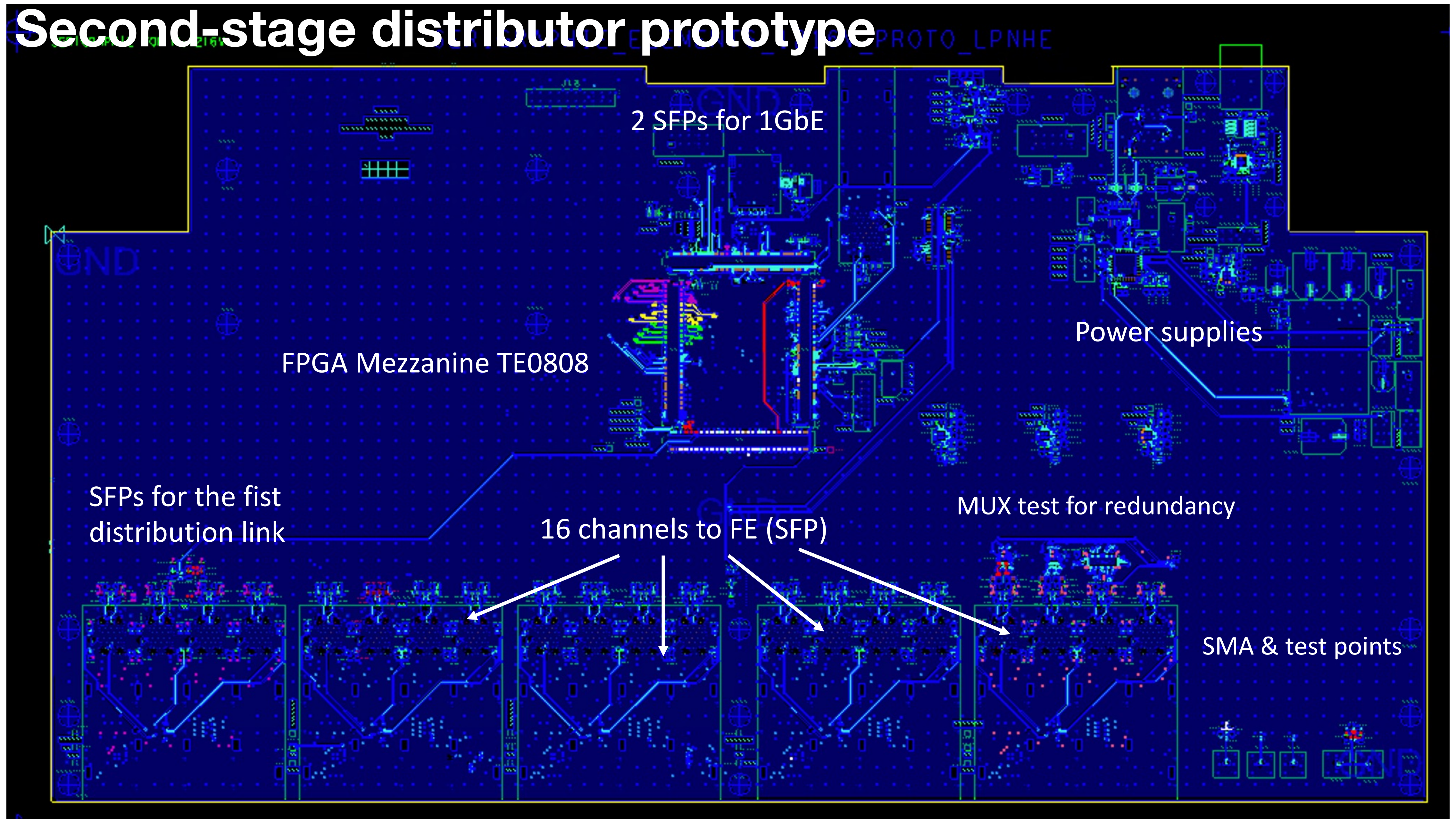




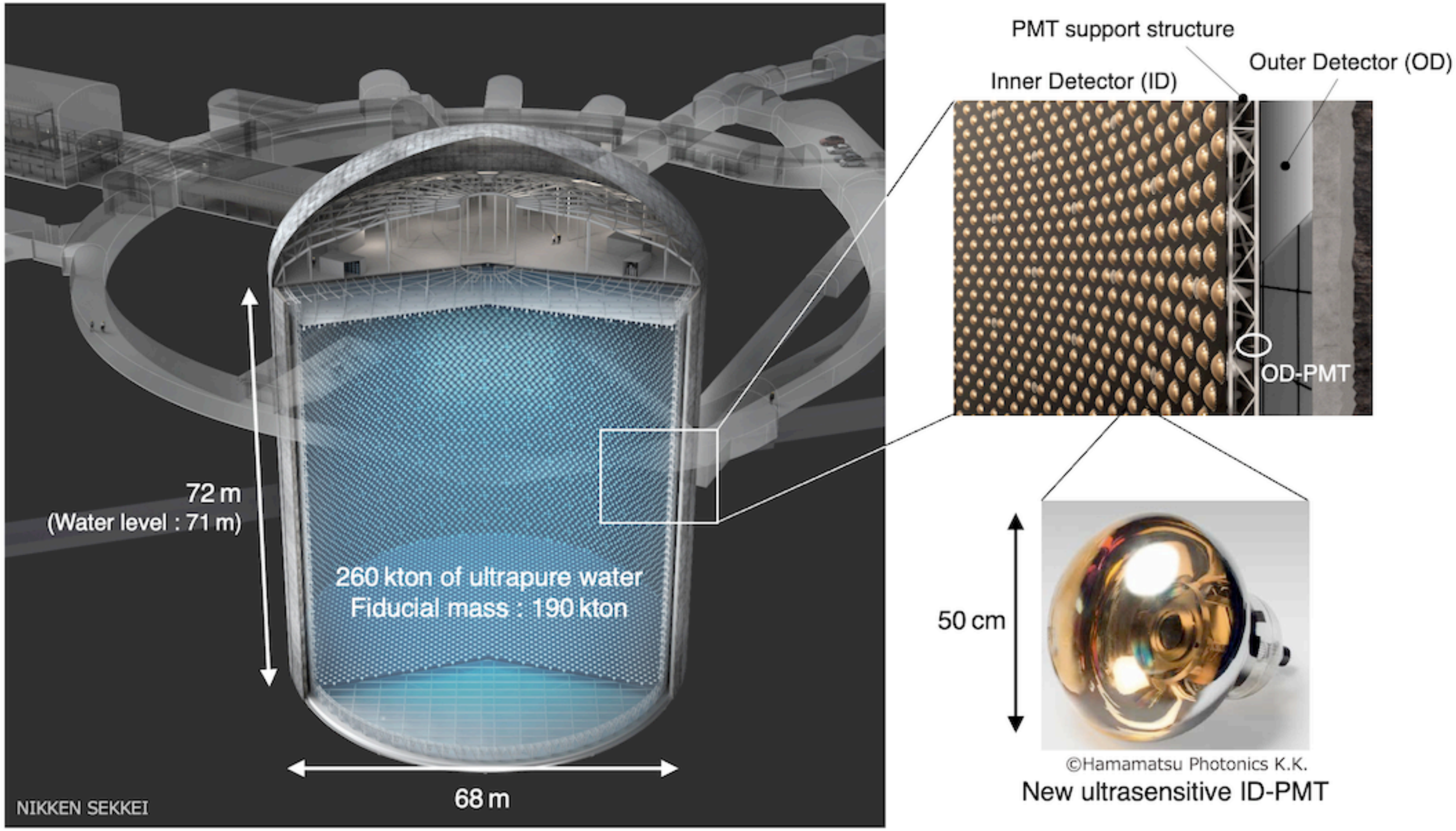
@D. Calvet

First- and second-stage distributors based on similar design
- Xilinx Zynq UltraScale+ (2 multi-core processors + FPGA)
- 48 or 32 SFP optical transceivers (half for redundancy)
- 2 GbEth links for external control and display

First prototypes being built/received and characterized



Zoom-in HK detector



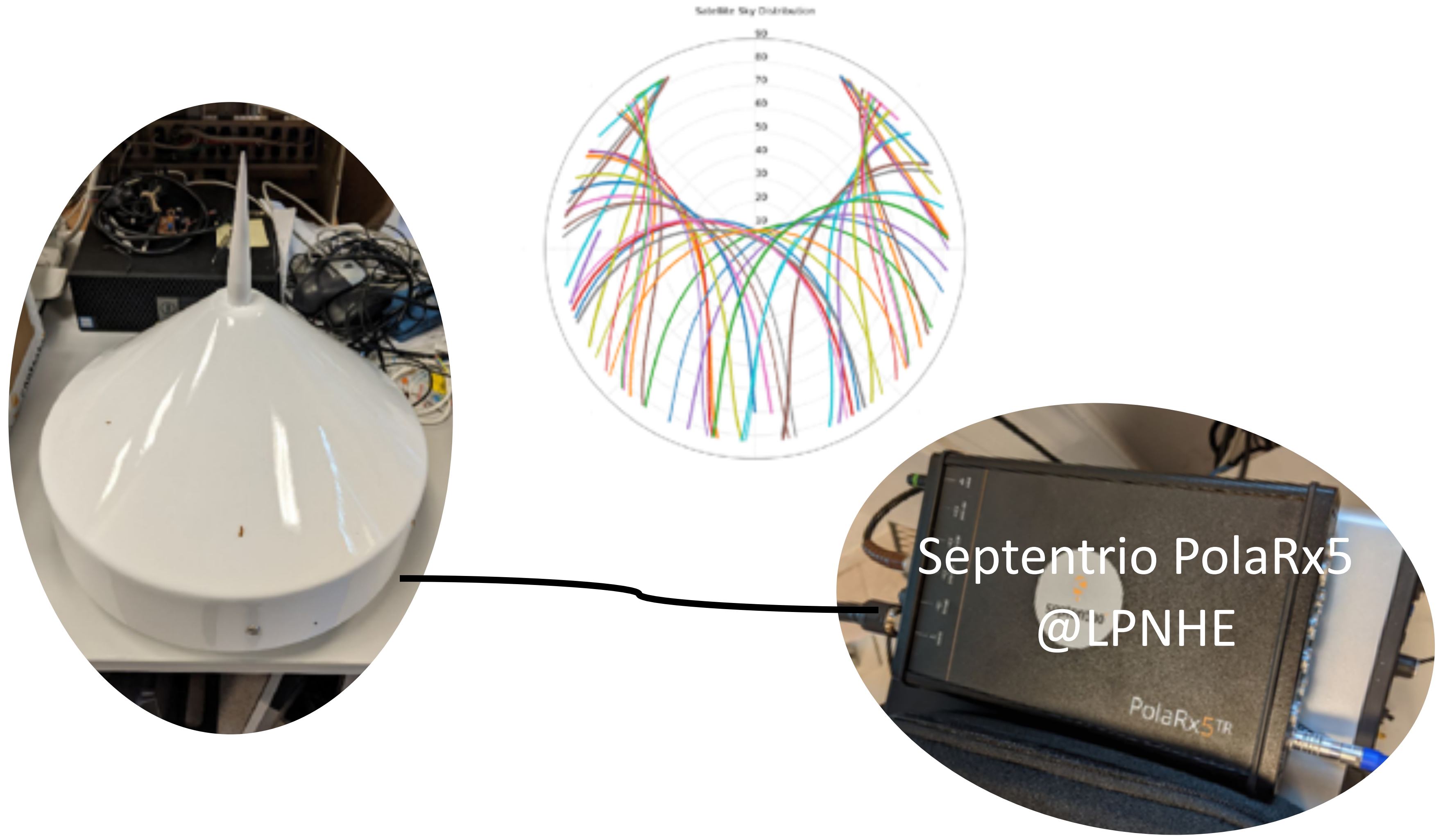
New ultrasensitive ID-PMT

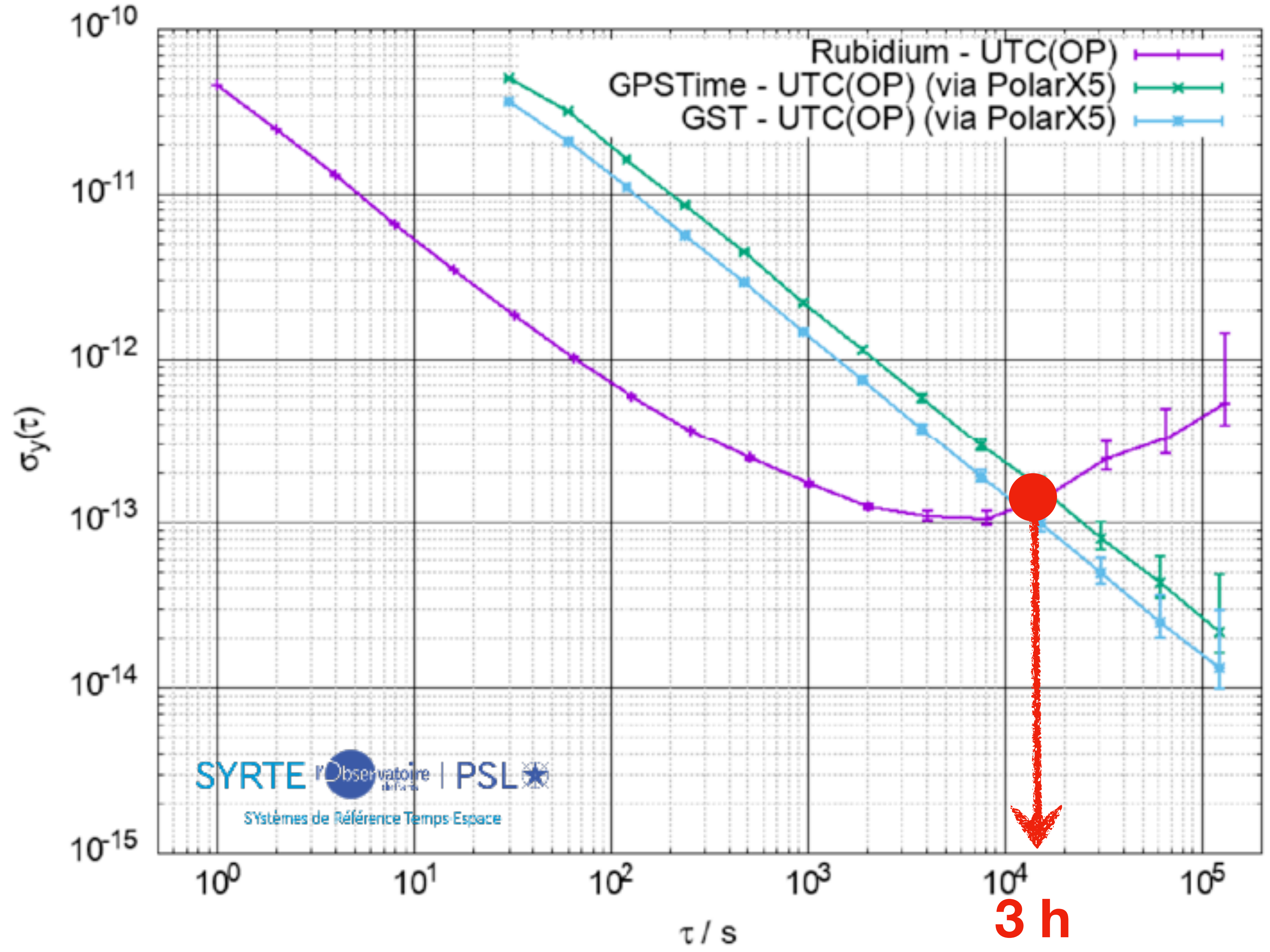
Time synchronization: GNSS

Correlation local time ↔ UTC using data stream coming from Global Navigation Satellite System (GNSS)

Short-term: Rb clock more stable than GNSS
Long-term: frequency of Rb clock changes (random walk) correctable using GNSS

→ Combine free-running atomic clock and offline time correction issued by GNSS receiver
→ Corrections every ~3 hours



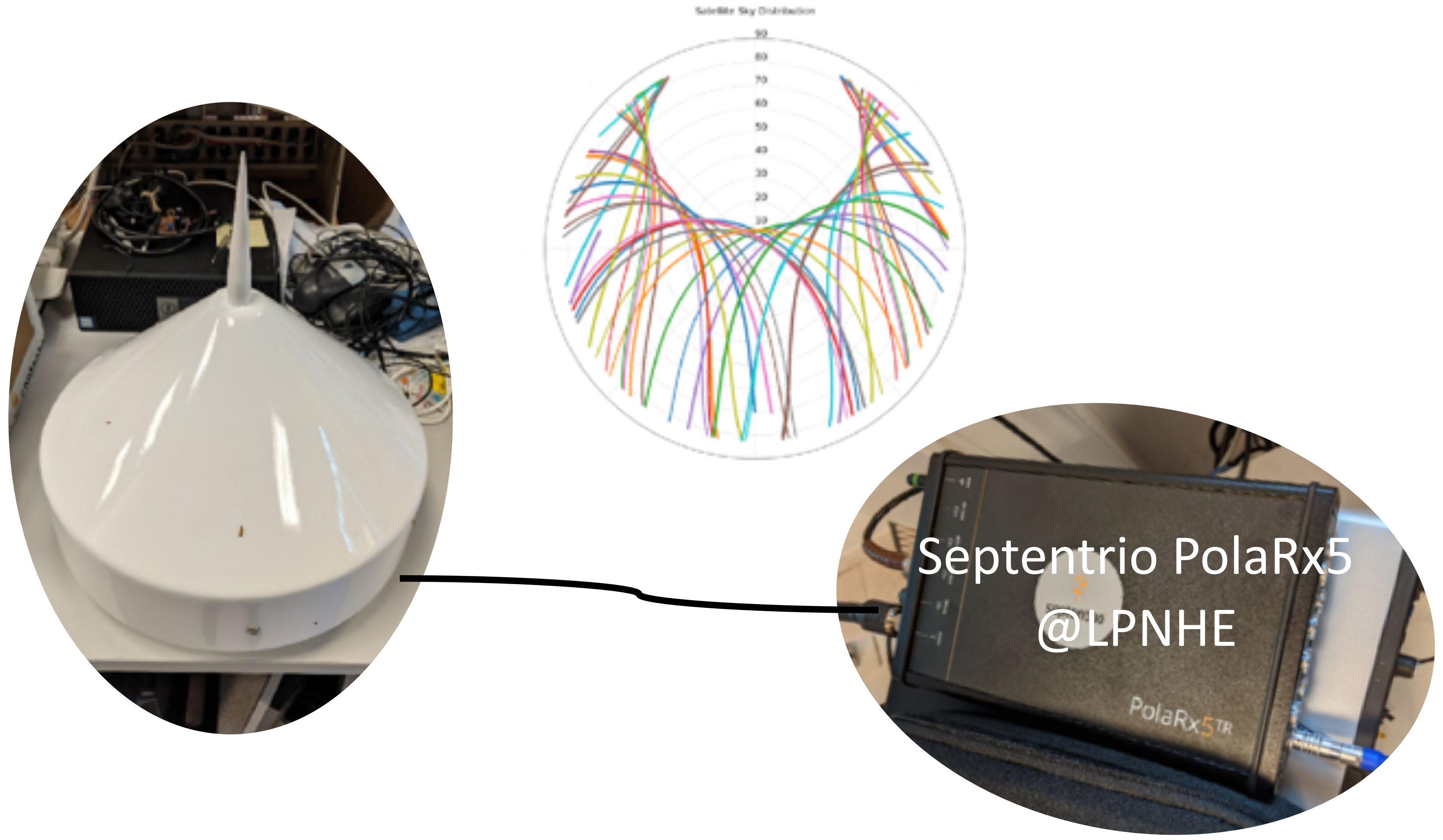


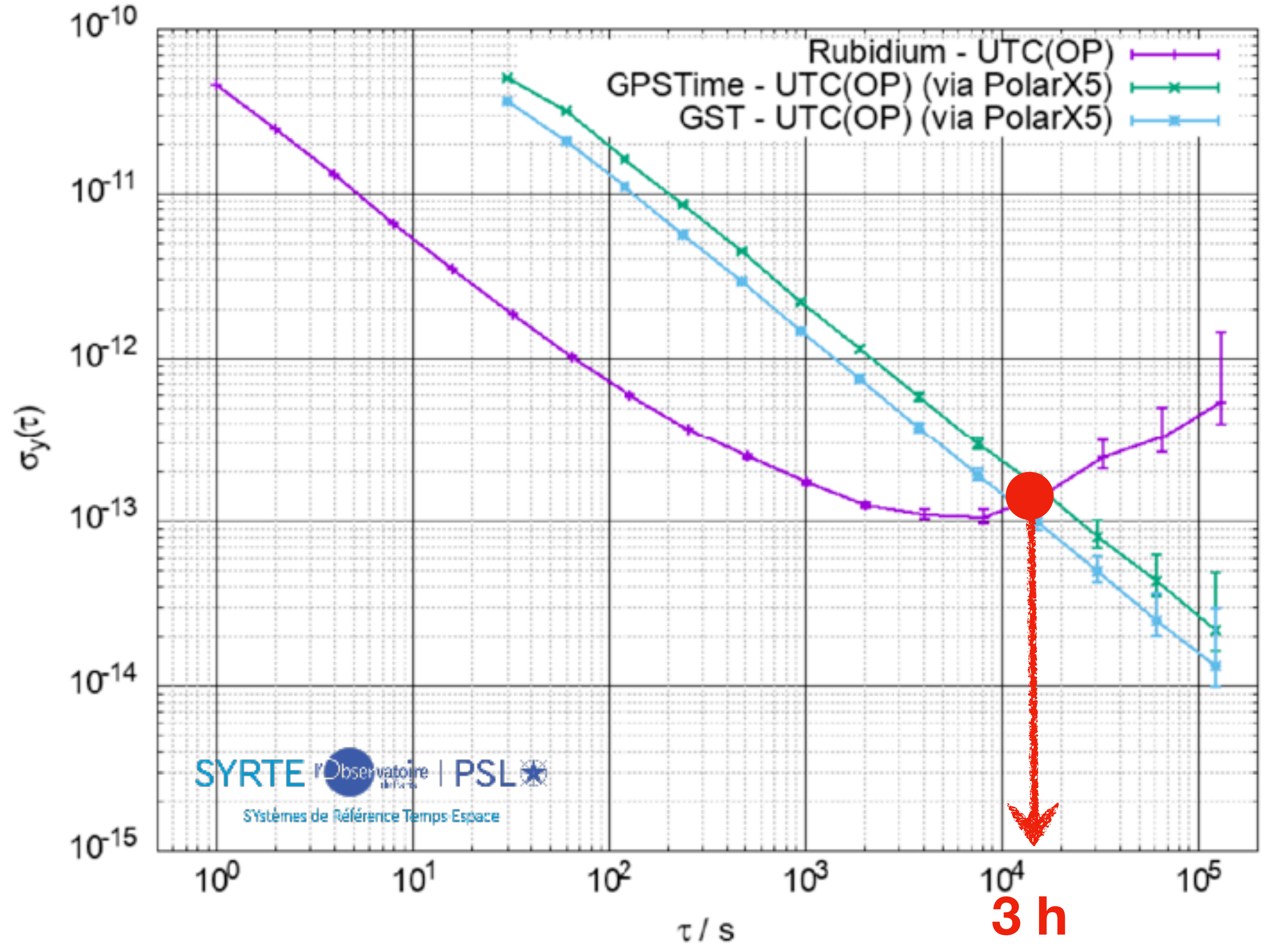
Time synchronization: GNSS

Correlation local time ↔ UTC using data stream coming from Global Navigation Satellite System (GNSS)

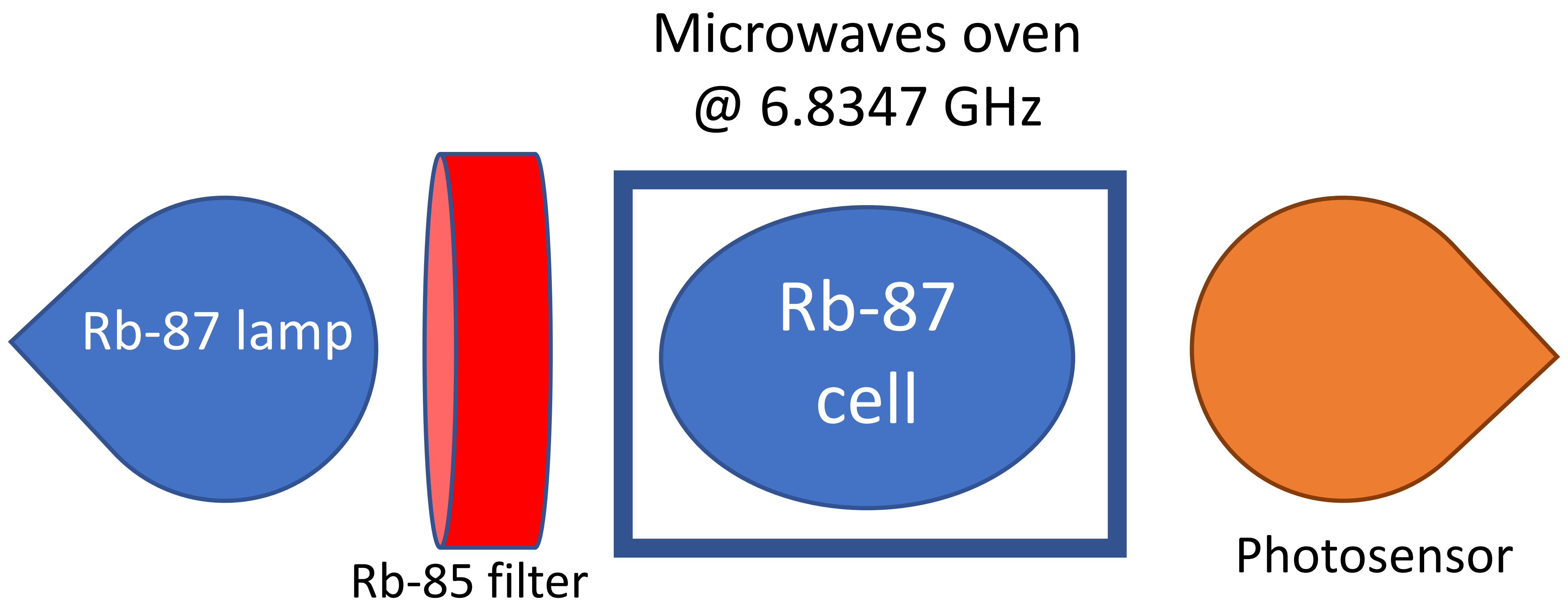
✓ Calibration of antenna, cables & electronics in collaboration with SYRTE (Obs. Paris) against time standard (precision sub-ns)

✓ Rb clock+GNSS measurements at LPNHE
- Impact of the number of visible satellites
- Synchronization GNNS-Rb clock via White-Rabbit
- Common view technique performances
- Usage of multi-constellations for better precision

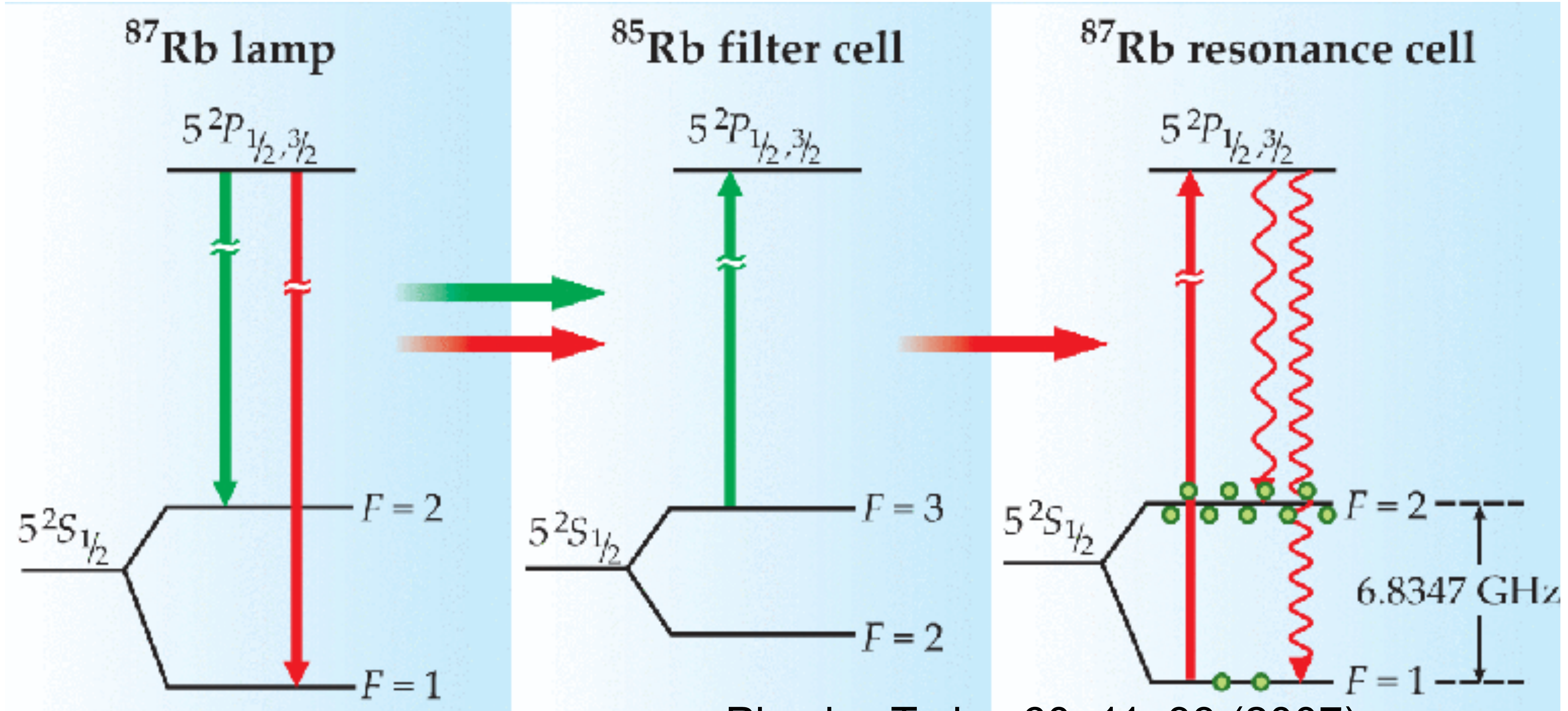




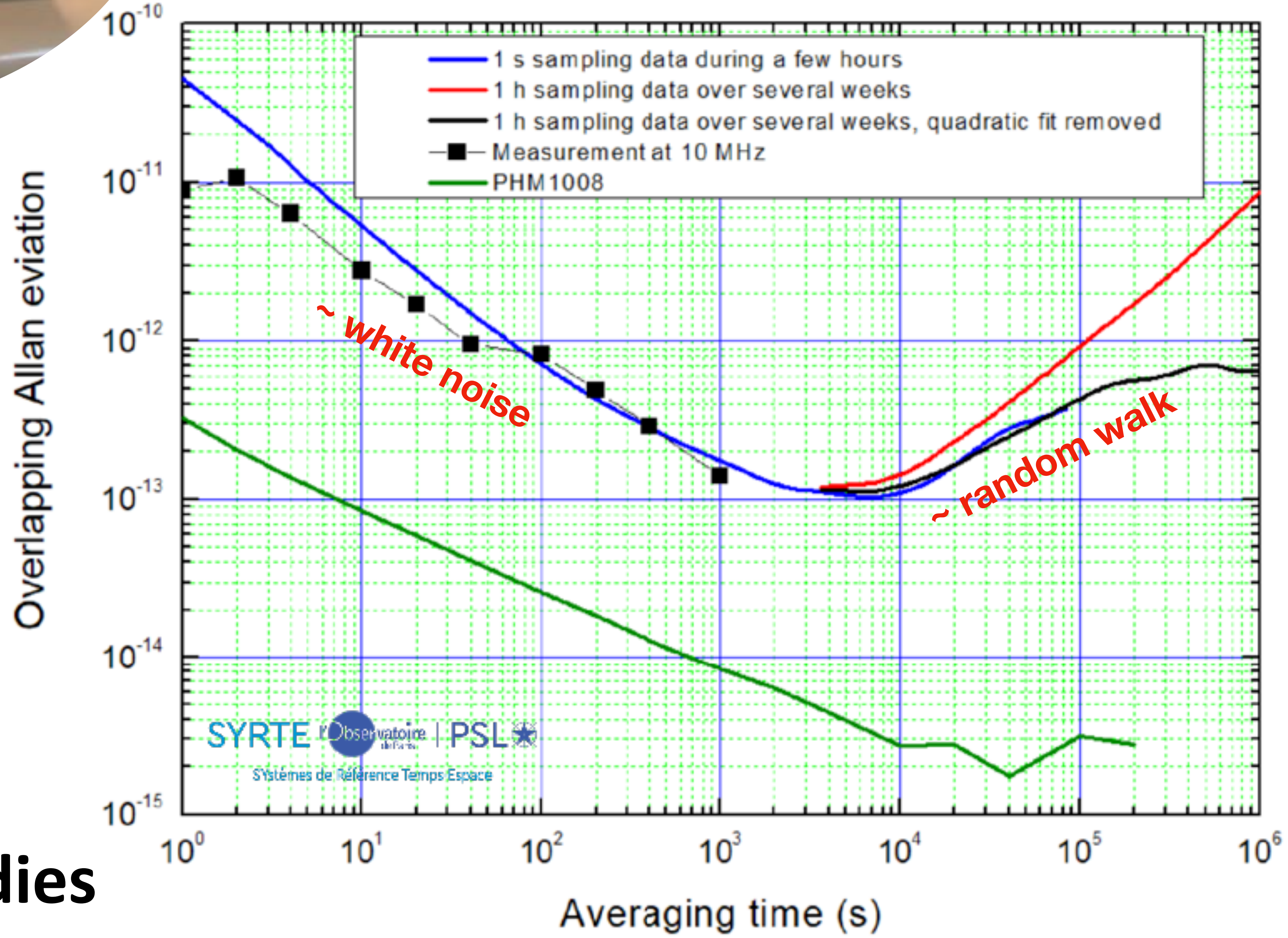
Time generation: Rb atomic clock



Intrinsic white noise
- SRS FS7025: ~40 ps@1 s
- PHM1008: 0.3 ps@1 s



Physics Today 60, 11, 33 (2007)



Allan standard deviation: paper

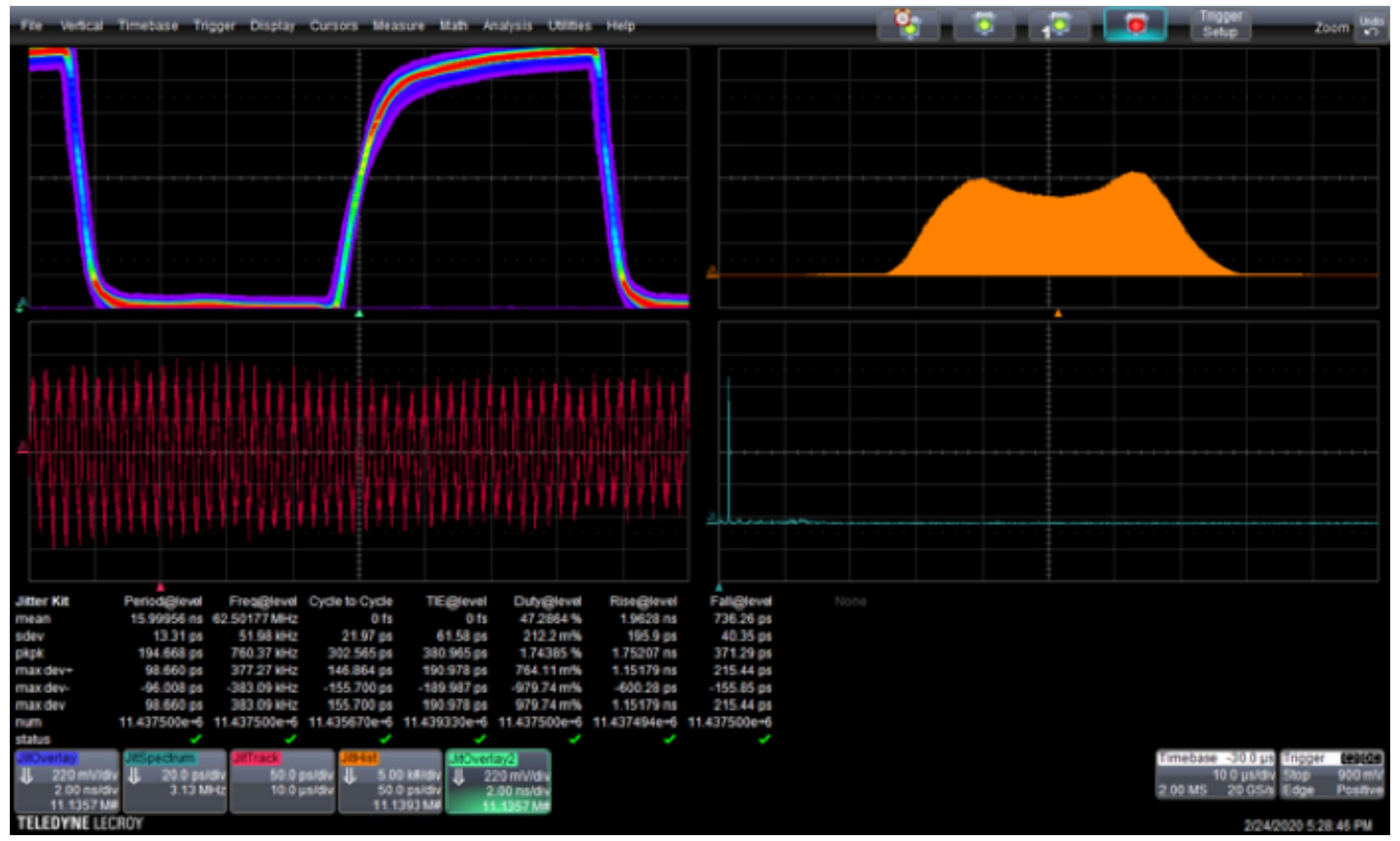
Comparison with time reference at SYRTE → **performances studies**

More stable clocks e.g. Passive Hydrogen Maser (PHM1008)

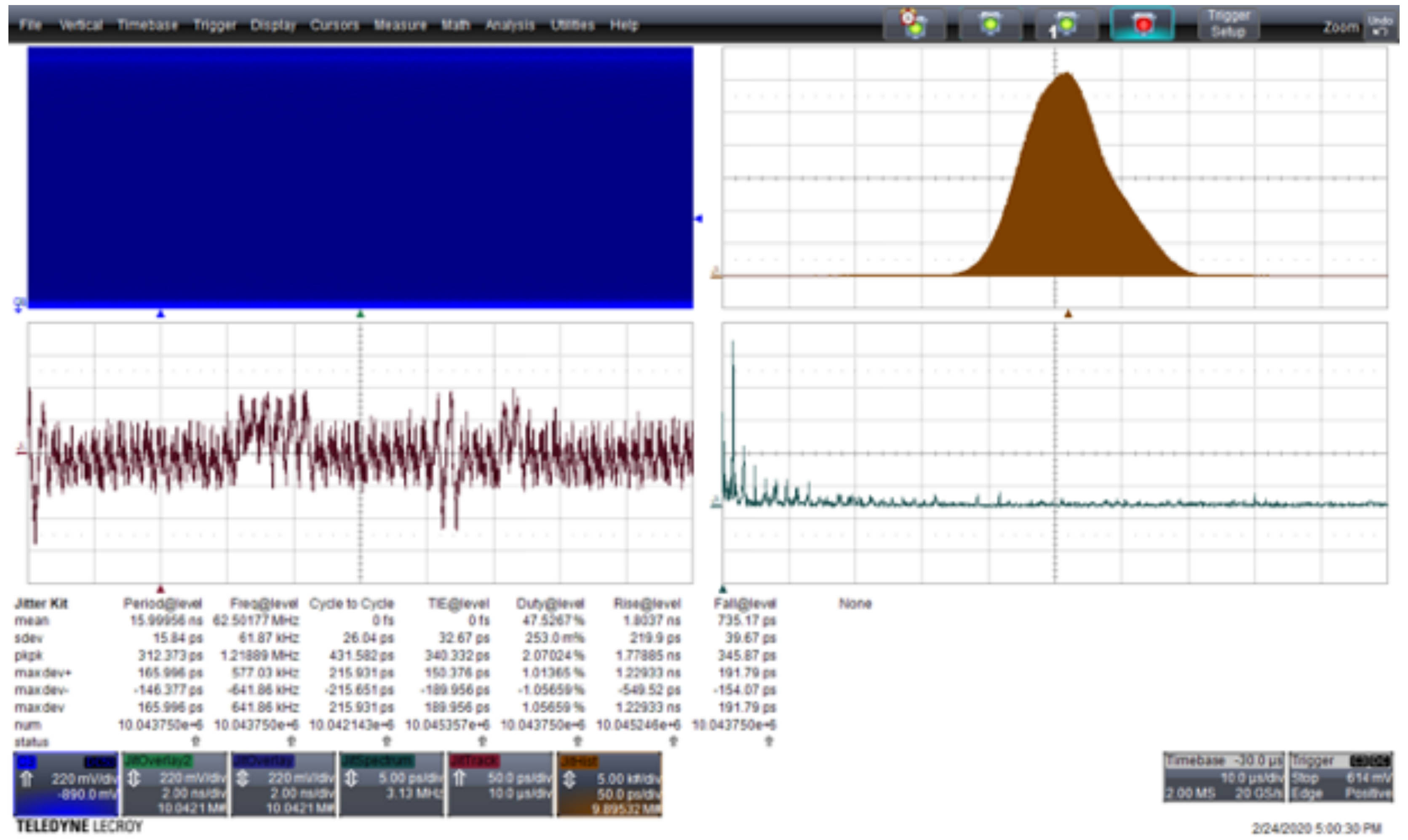
Clock distribution performances

Time domain

Received clock time
using oscilloscope (jitter 50 ps)

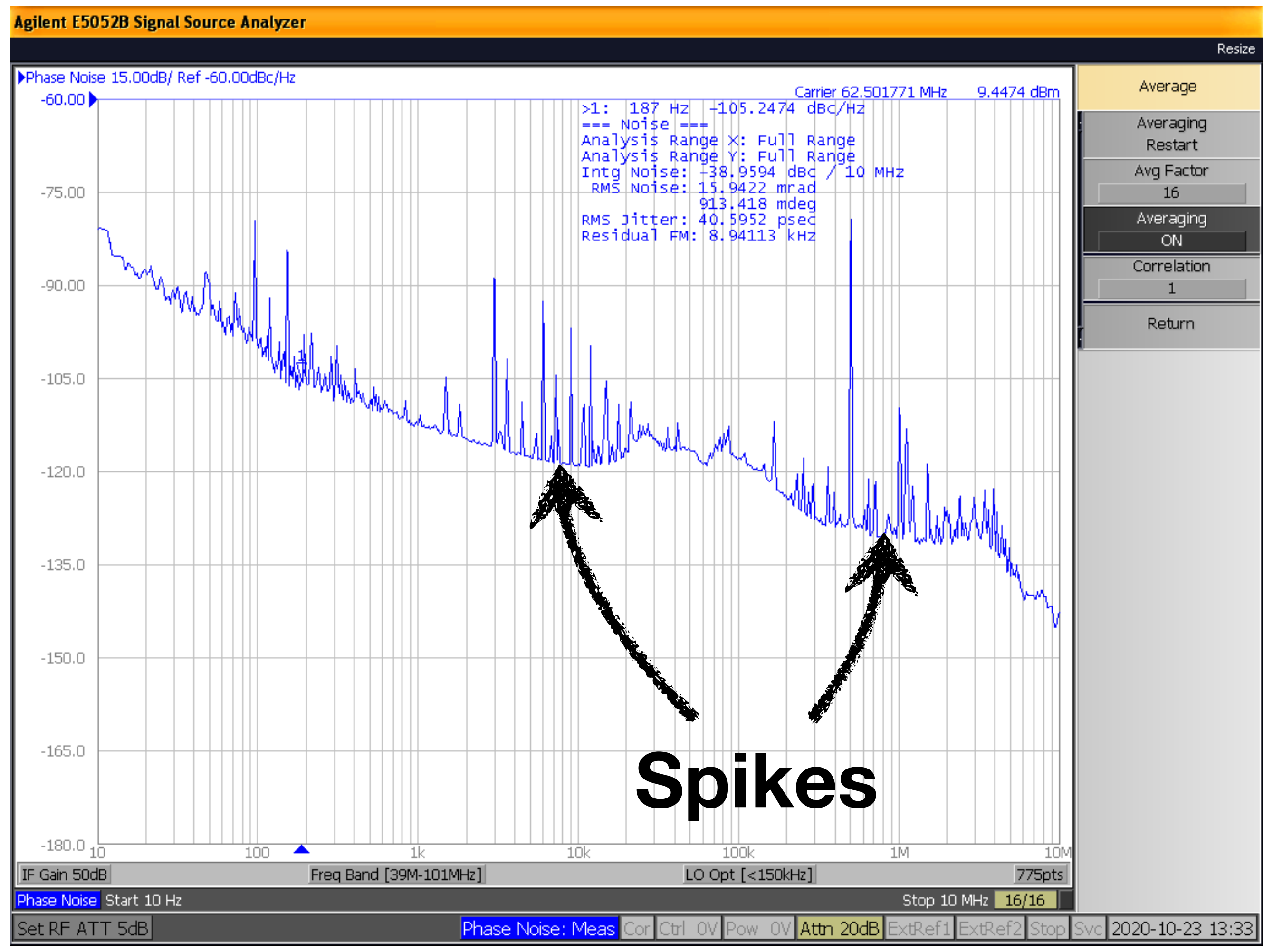


Transmitted clock time
using oscilloscope (jitter 32 ps)

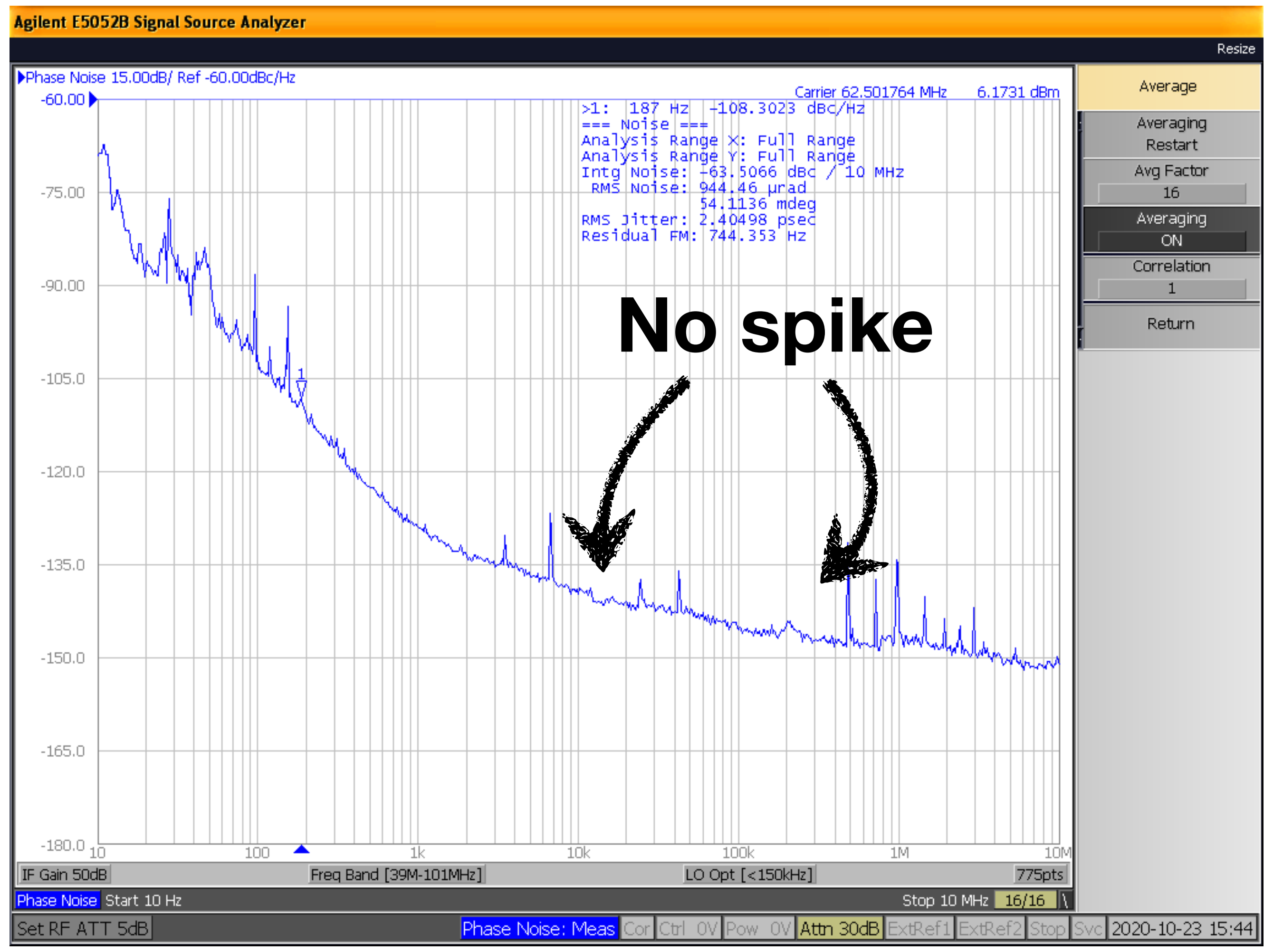


Frequency domain

Received clock (TX→RX) (jitter 40.6 ps)



Cleaned with Phase-Locked Loop (jitter 2.4 ps)



→ Required jitter below 100 ps is achievable with this technology !

Clock and GNSS slow control

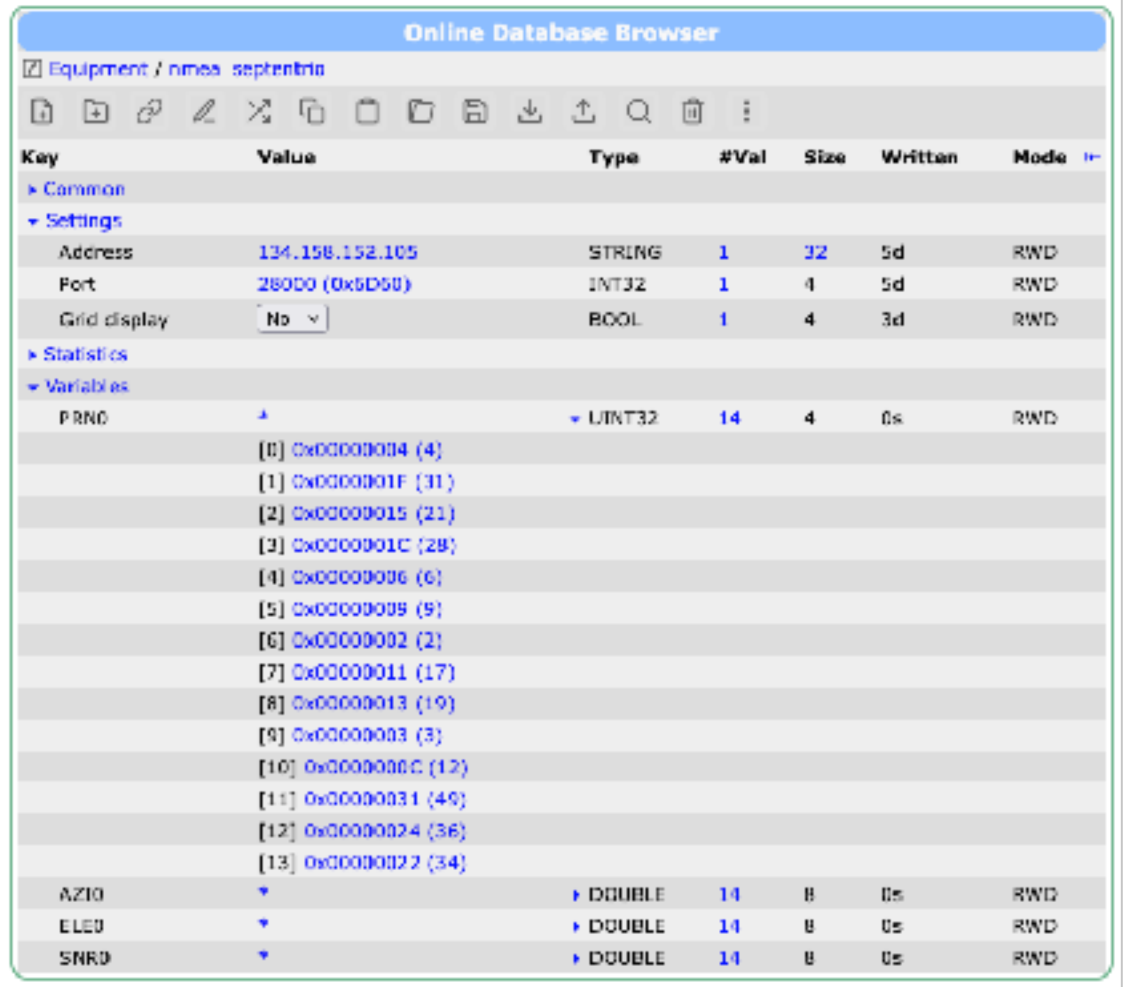
Monitoring of GNSS receivers via NMEA and CGGTTS readout (in addition to SBF files logging)

NMEA (National Marine Electronics Association)
- Instantaneous information about 1 Hz
- can be changed to e.g. 0.1 Hz
- number, elevation, azimuth of satellites in view or used for position fix
- dilution of precision
- proprietary informations like receiver temperature, …
- Useful for monitoring !

CGGTTS:
- aggregation of 13 minutes of 1PPS phase difference with one GNSS constellation
- Used for time transfer and external clock drifting !

NMEA file format

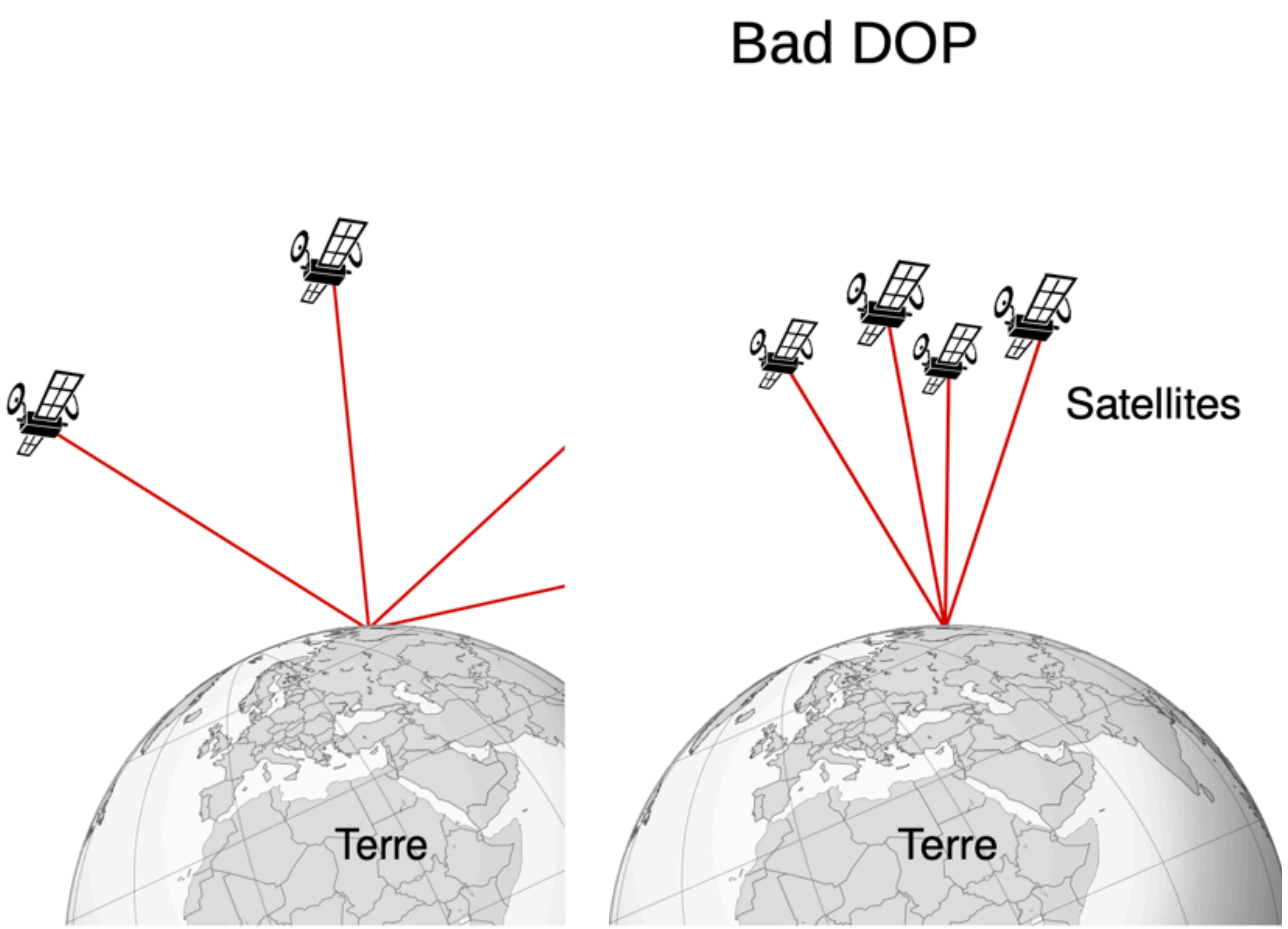
```
$GPGGA,092750.000,5321.6802,N,00630.3372,W,1,8,1.03,61.7,M,55.2,M,,*76
```
→ Fixed position of the receiver (“fix”) (5321.6802° N, 630.3372° W)
```
$GPGSA,A,3,10,07,05,02,29,04,08,13,,,,,1.72,1.03,1.38*0A
```
→ Identification of the satellites used in the fix (A: automatique; 3: fix 3D; satellites: 02, 04, 05, 07, 08, 10, 13, 29…)
```
$GPGSV,3,1,11,10,63,137,17,07,61,098,15,05,59,290,20,08,54,157,30*70
```
→ Coordinates (elevation, azimuthal angle) and signal-to-noise ratio for in view satellites (3,1: 3 pages-1st page)

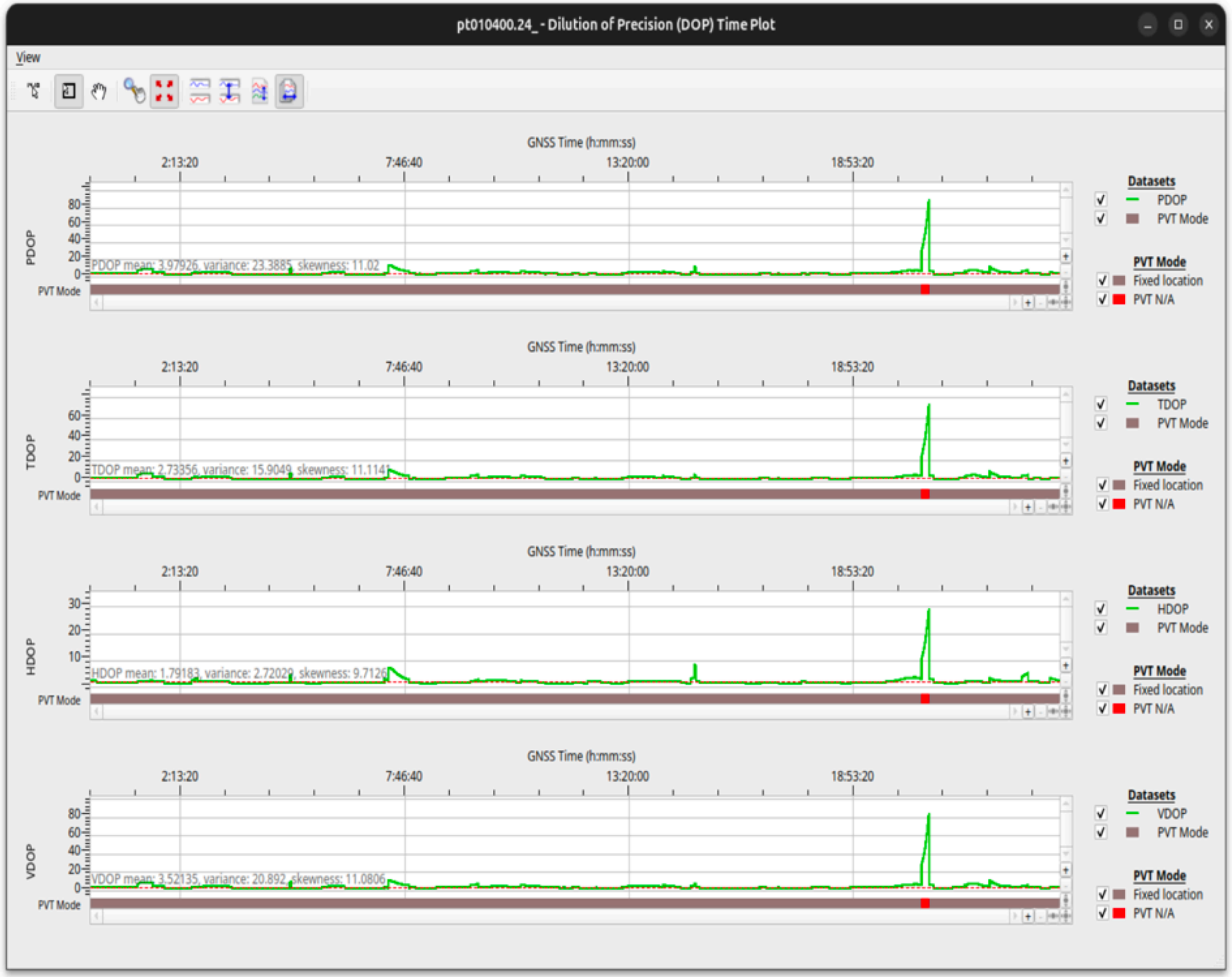


CGGTTS file format

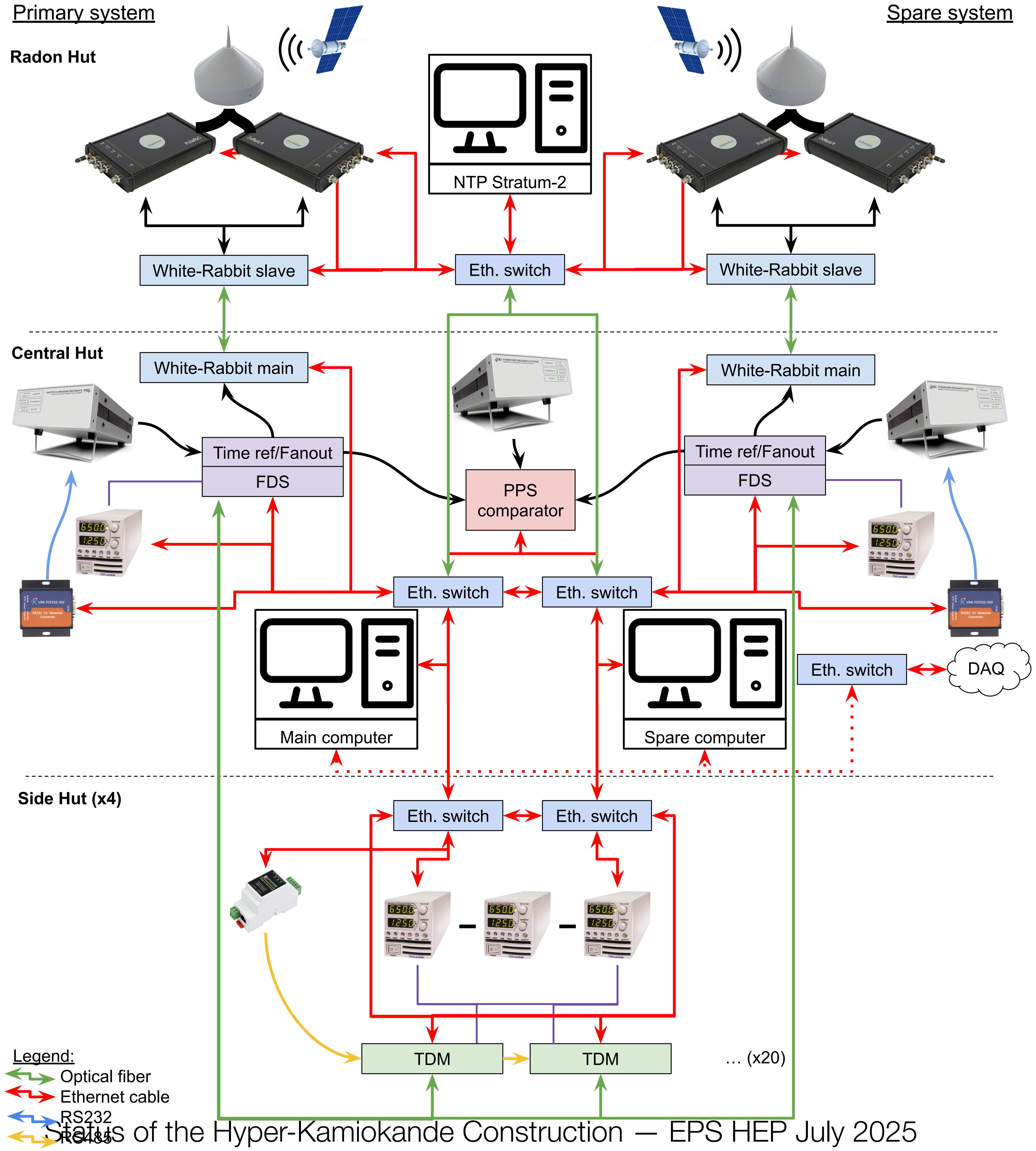
```
SAT CL  MJD  STTIME TRKL ELV AZTH   REFSV      SRSV     REFSYS    SRSYS  DSG IOE MDTR SMDT MDIO SMDI MSIO SMSI ISG FR HC FRC CK
             hhmmss  s  .1dg .1dg    .1ns     .1ps/s     .1ns    .1ps/s .1ns    .1ns.1ps/s.1ns.1ps/s.1ns.1ps/s.1ns
G04 FF 60578 000600  780  44 2940   -3460099   332     1038676    403   56 179  936  563   97 -119   97 -119  36  0  0 L3P EB
G05 FF 60578 000600  780 185  485    2915517   286     1038647    274   45  56  252   14  107   -2  107   -2  35  0  0 L3P 75
G16 FF 60578 000600  780 435 3004    2759627   149     1038651    251   24   7  118  -16   91   21   91   21  18  0  0 L3P 5D
G18 FF 60578 000600  780 677 1196    7590096   269     1038641    249   13  63   88   -2   93   27   93   27   9  0  0 L3P 69
G20 FF 60578 000600  780  42  235   -2664401    72     1038653     68  122  11  973  778  121  172  121  172  85  0  0 L3P 91
G23 FF 60578 000600  780  76 1427   -2236545   359     1038671    442   87  73  592 -439  225 -192  225 -192  66  0  0 L3P 04
G25 FF 60578 000600  780  77 1272   -3957628   435     1038652    435   79   4  588  432  239 -122  239 -122  52  0  0 L3P E1
G26 FF 60578 000600  780 780 2661     325797   419     1038650    332    9  68   83   -1   85  -38   85  -38   7  0  0 L3P 56
G27 FF 60578 000600  780 186 2611    1378816   284     1038666    280   27 113  253  -81  170  -27  170  -27  17  0  0 L3P CD
G28 FF 60578 000600  780 211 1948    5270845   399     1038649    264   27 111  224   73  201   57  201   57  21  0  0 L3P A3
G29 FF 60578 000600  780 331  690    6795390   216     1038650    241   27  12  148   26  108   48  108   48  21  0  0 L3P 7E
G31 FF 60578 000600  780 429 2271    3281370   305     1038656    309   20   8  119   13  119   -5  119   -5  15  0  0 L3P 62
```

Dilution of precision





Overall scheme



Glossary

CGGTTS: CCTF Group on GNSS Time Transfer Standards
NMEA: National Marine Electronics Association
GNSS: Global Navigation Satellite System
GPS: Global Positioning System
FSCD: First Stage Clock Distributor
TDM: Time Distribution Module
iBERT: Integrated Bit Error Ratio Tester