# Signal Digitization in IceCube

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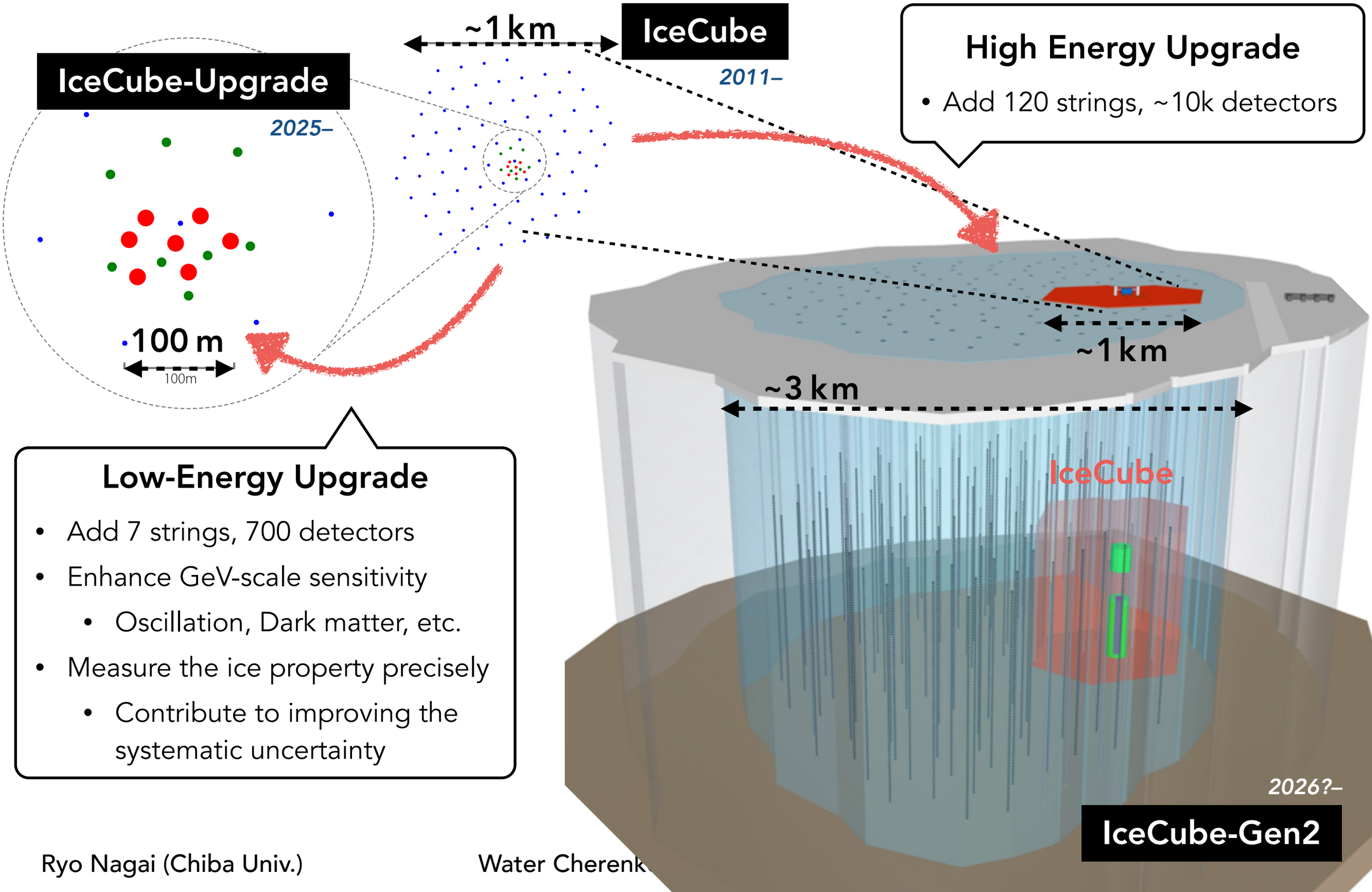
*On behalf of the IceCube Collaboration*

# IceCube / -Upgrade / -Gen2




**High Energy Upgrade**

- Add 120 strings, ~10k detectors

**Low-Energy Upgrade**

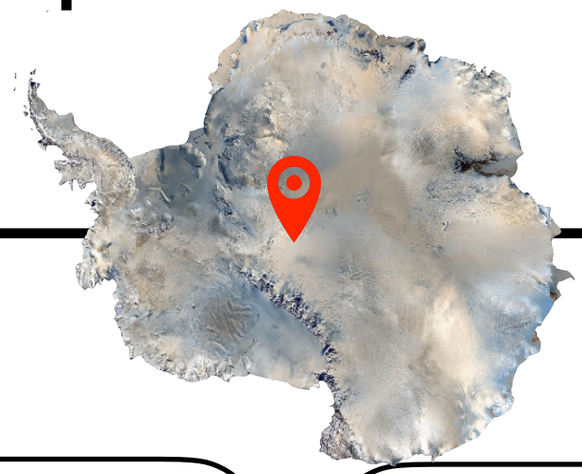
- Add 7 strings, 700 detectors
- Enhance GeV-scale sensitivity
  - Oscillation, Dark matter, etc.
- Measure the ice property precisely
  - Contribute to improving the systematic uncertainty



Water Cherenk

# Constraints on in-situ digitization

## In deep ice at Antarctica



### Need in-situ digitization

- Should cover wide energy range (GeV–PeV)
- Record precise timing

### Enough effective area

- Large PMT
- Multi-PMT solution

### Wide working Temperature

- −55℃ to the room temperature

### Not abundant power

- Limit the sampling frequency
- Limit the number of ADCs

### Cost (Drilling, Components)

Limit the physical space

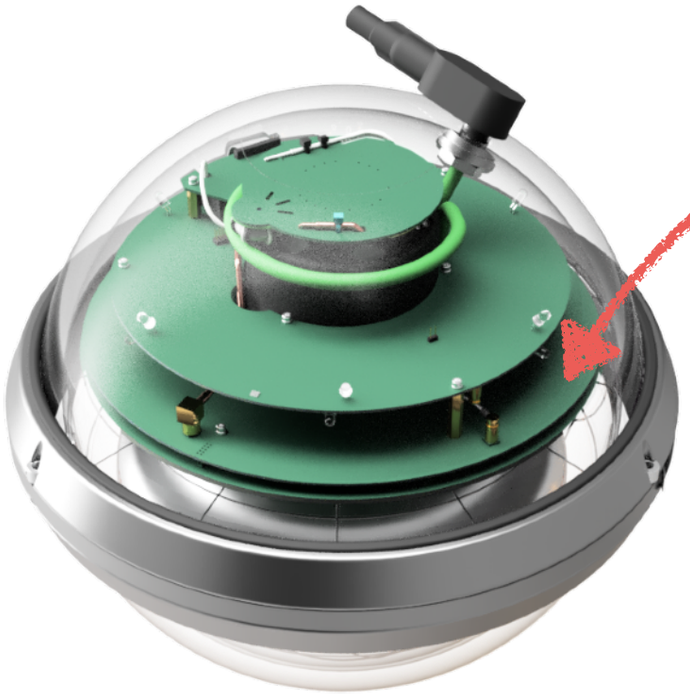
### Durability (nonexchangeable)

- Keep function for >10 years

🤔

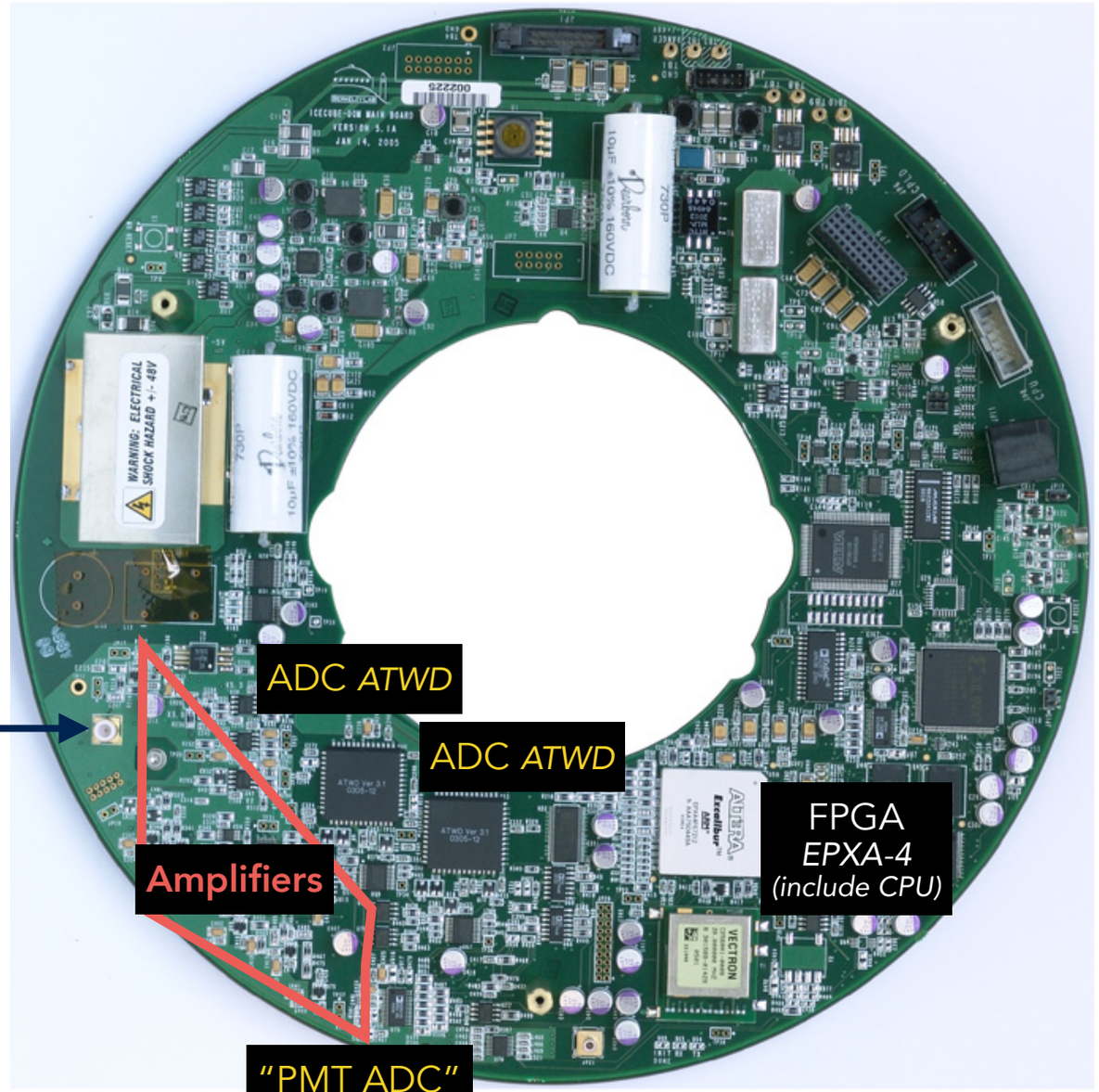
# IceCube DOM Digitization

## DOM: Digital Optical Module



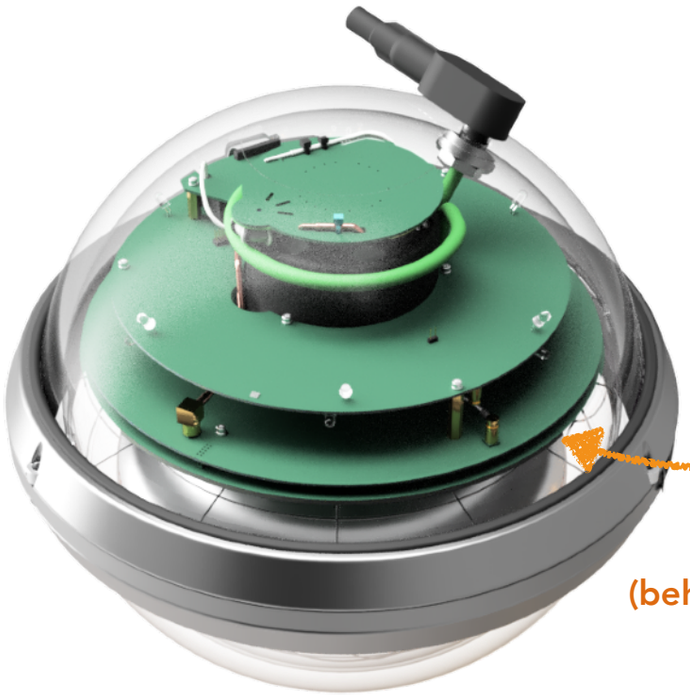
- A 10” PMT facing downwards
- 5160 DOMs are installed in the ice
- 99% are still working for >10 years

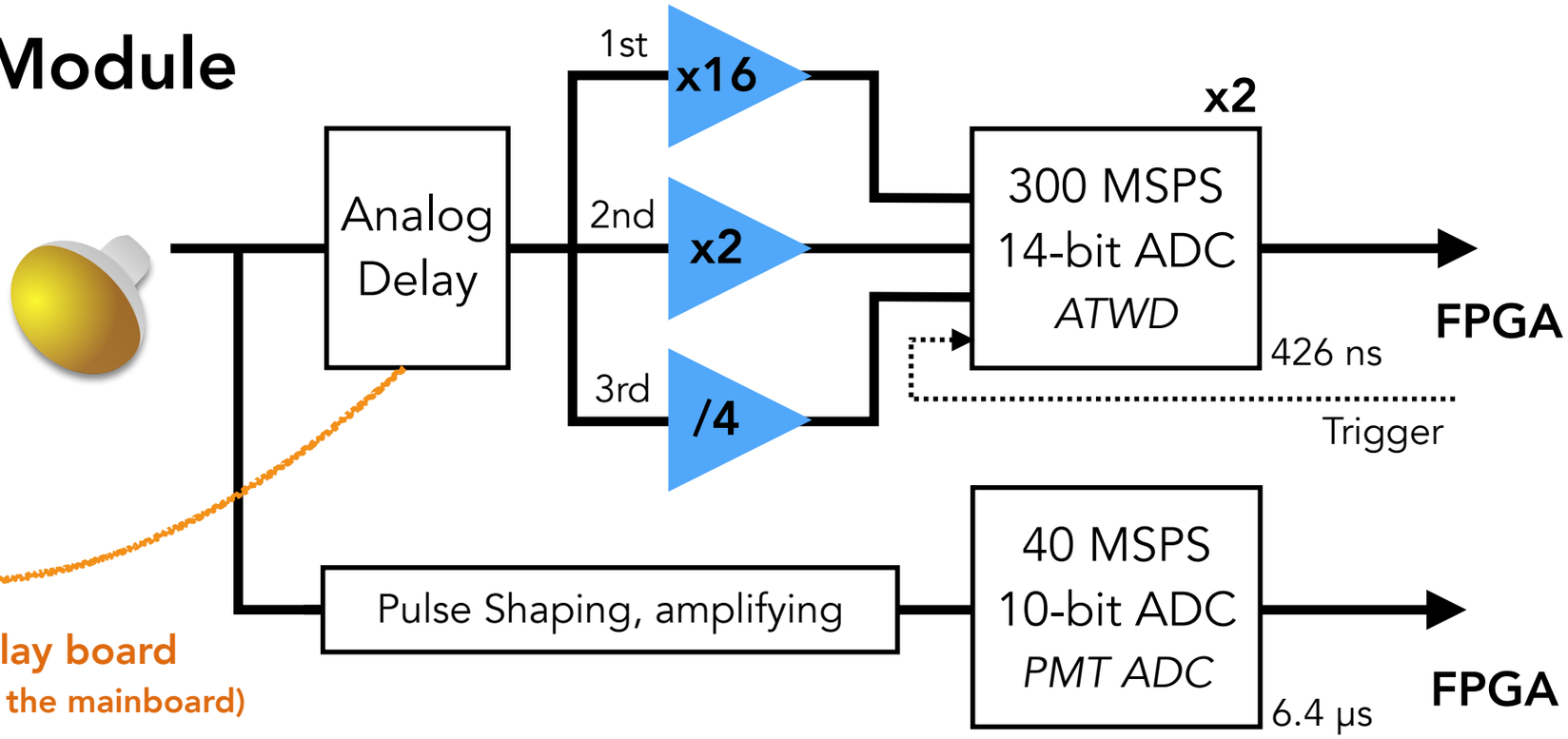
## Front-end DAQ board (Mainboard)



# IceCube DOM Digitization

## DOM: Digital Optical Module






**Delay board**
**(behind the mainboard)**

- ATWD is a fast, **custom-made** ASIC, which digitizes with 128 sampling bins with 300 MSPS (~426 ns window) *after receiving the triggers*
- Since ATWD is busy during the digitization (takes 29 μs), there are 2 ATWDs on a mainboard and switch if one is busy, to reduce the dead time
- To expand the dynamic range, 3 different amplifier outputs into ATWD
- In parallel, PMT ADC is a bit slow, but longer waveform can be digitized

# DOM Problem for Upgrade era

*Already 20 years passed since the development…*

- ATWD system limits the time window & (would) have large dead-time
  — we don't want to miss rare events / waveforms
- Many components (especially FPGA) are already obsolete
  — we can't produce the same board any longer

*Also, technology has been much grown…*

**Time to Redesign it!**

**Simple scheme**

**Complicated solution**

# Family of Digital Optical Modules

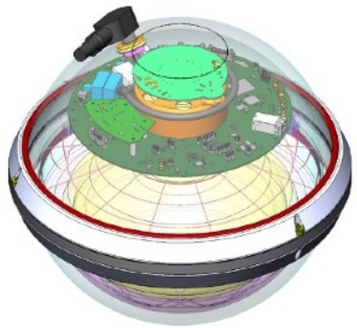
## IceCube

DOM

Simple scheme

## IceCube-Upgrade

Production ongoing

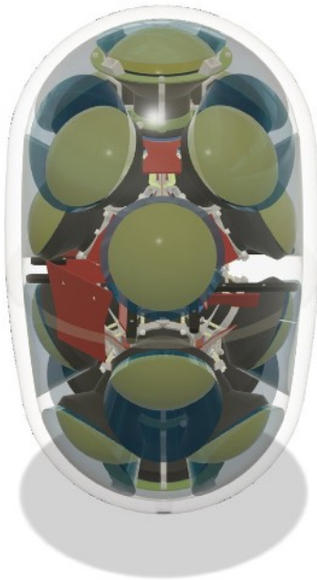


PDOM

Production completed!

D-Egg

## IceCube-Gen2



LOM

Under development

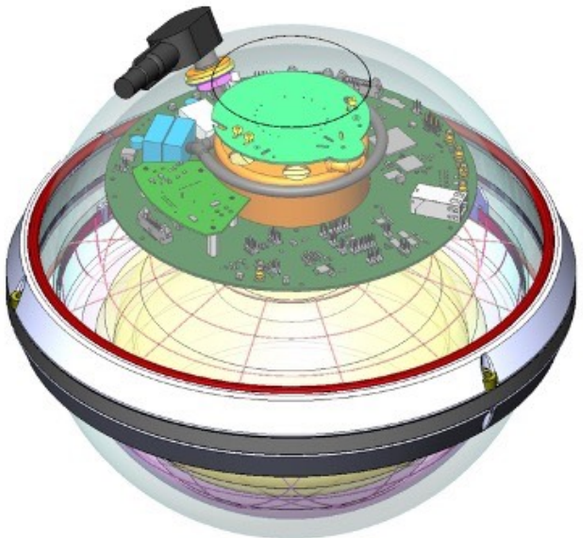
mDOM

Production ongoing

Complicated solution

# Upgrade Digitization-1: Simple Scheme

PDOM



Update only the electronics
from the DOM

D-Egg

Share the electronics

- Difference between them: **# PMTs** (channels)
- Analog front-end circuit & FPGA function are **identical**
  - The board shape, layout, etc. are different

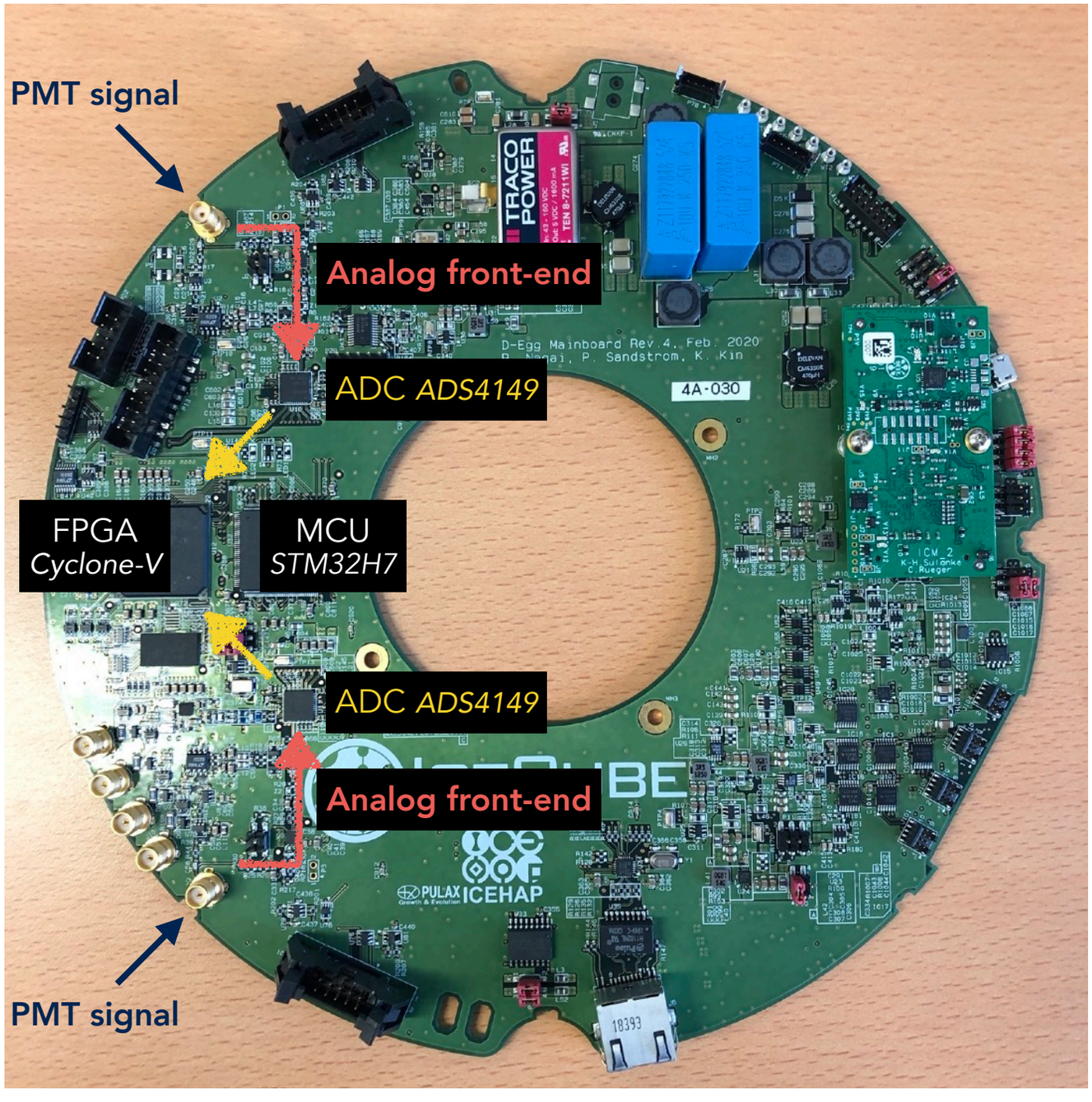
→ *Will show the D-Egg case only*

# Upgrade Digitization-1: Simple Scheme

## D-Egg

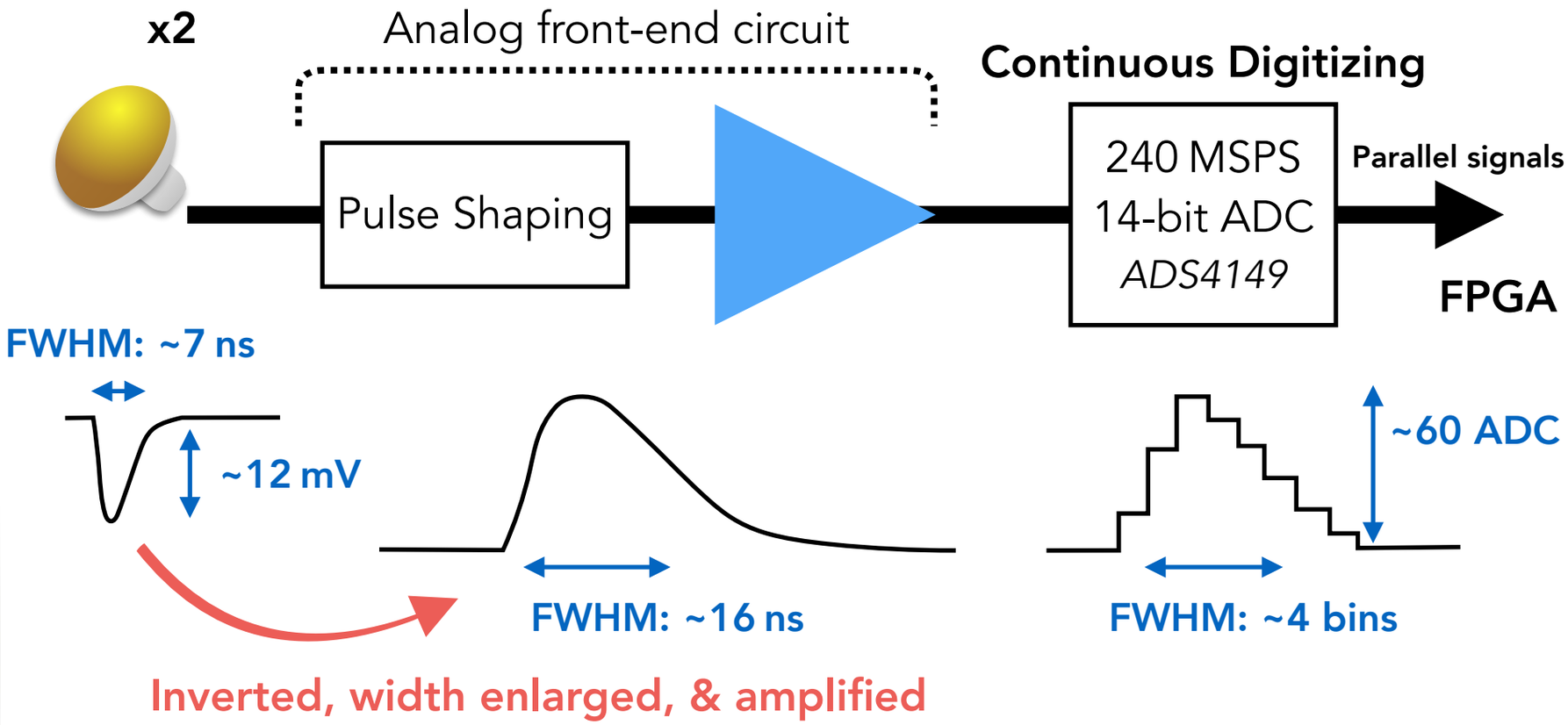
- Two 8″ HQE PMTs
- Horizontally slimmed design
  to reduce the drilling cost…
  (The narrower hole, the faster/cheaper drilling)
- ~300 production **completed** in 2021

## Front-end DAQ board (Mainboard)



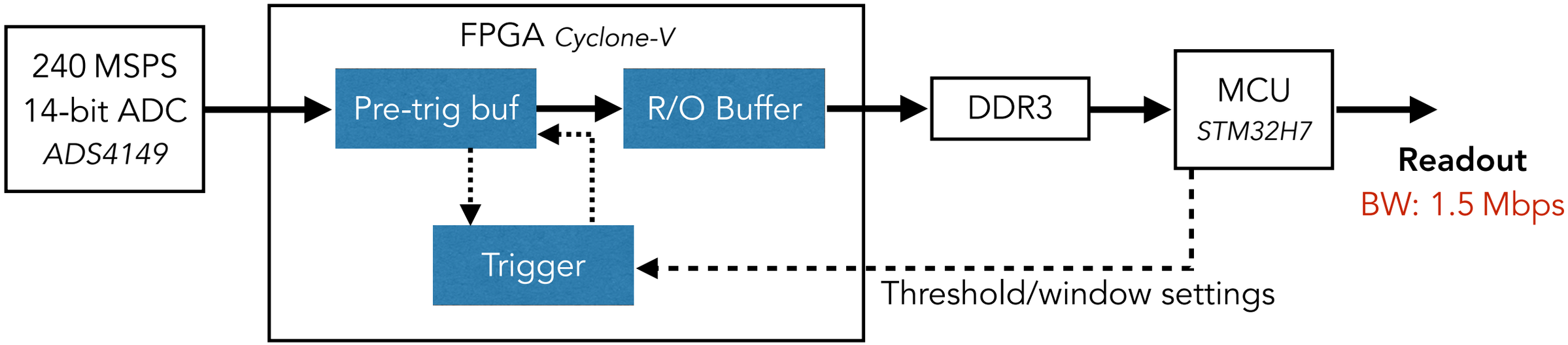
# Upgrade Digitization-1: Simple Scheme

D-Egg

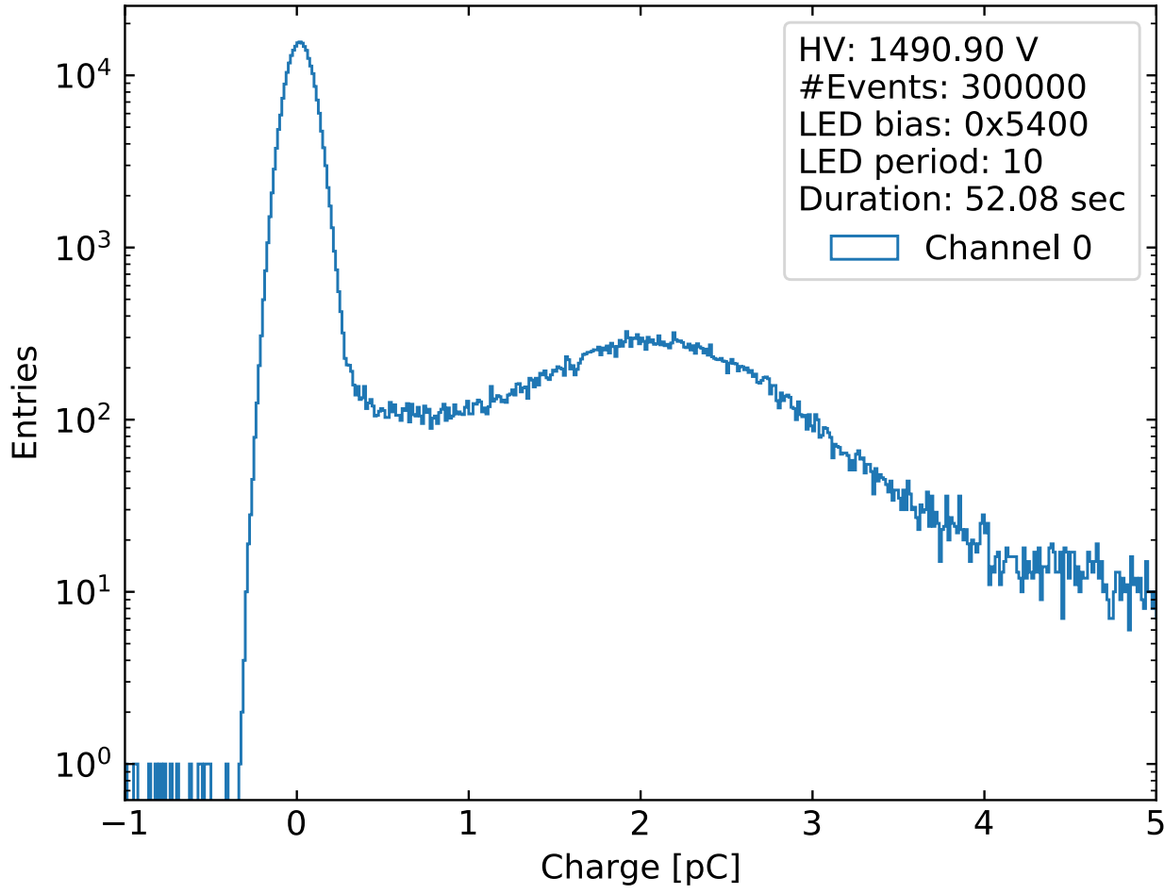



- Very simple scheme makes it possible **to digitize without dead-time**
  - Thanks to the off-the-shelf extremely low power ADC (ADS4149)
- FPGA (Cyclone-V) stores the data to the flash memory only when the trigger signal is published
- Operation power consumption is only **4.5 W (for 2 channels)**

# Upgrade Digitization-1: Signal Readout

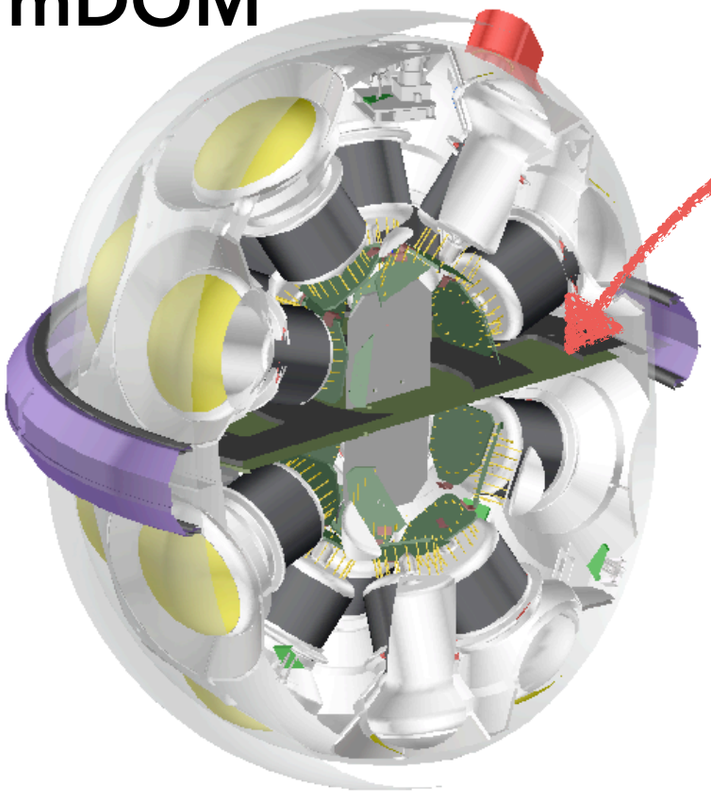



- Waveform readout :
  standard operation for D-Egg DAQ
  - Time window changeable up to ~30 μs
  - But slow readout (~10 Hz)
- Only getting integrated charge & time information
  - So fast readout (>kHz)
  - Use it to check SPE distribution shape



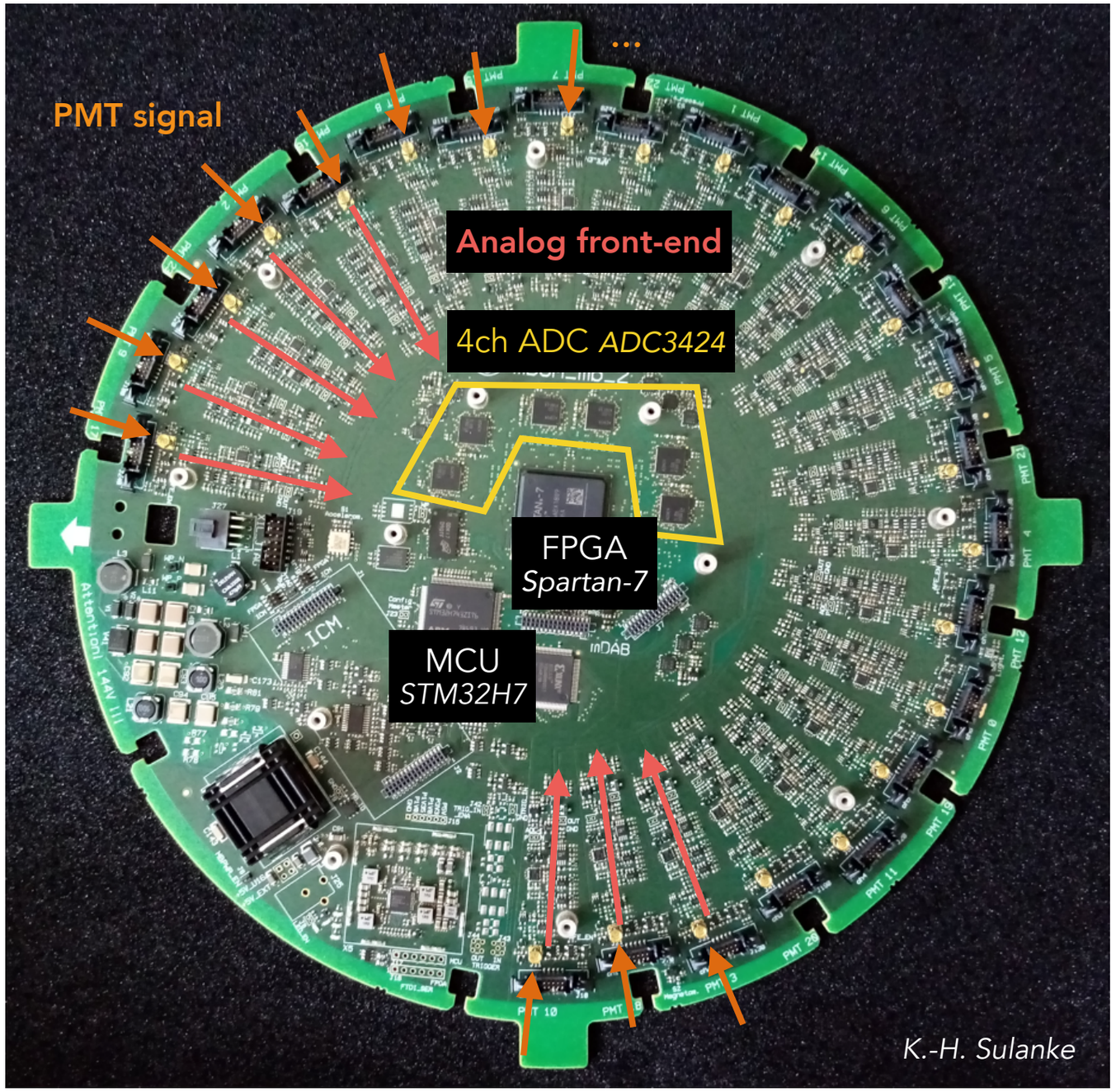
# Upgrade Digitization-2: multi-PMT

mDOM

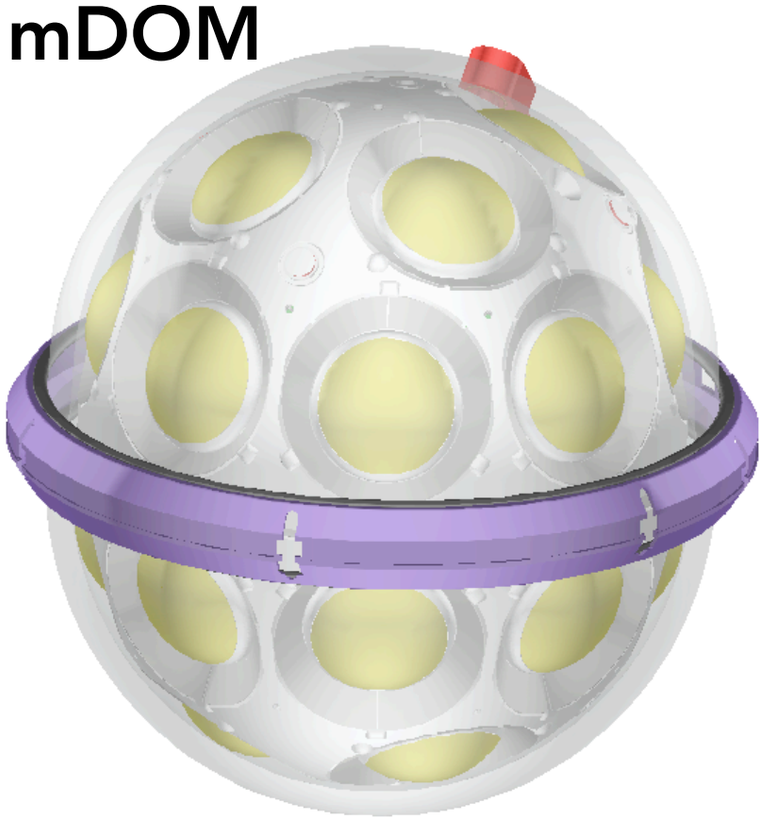


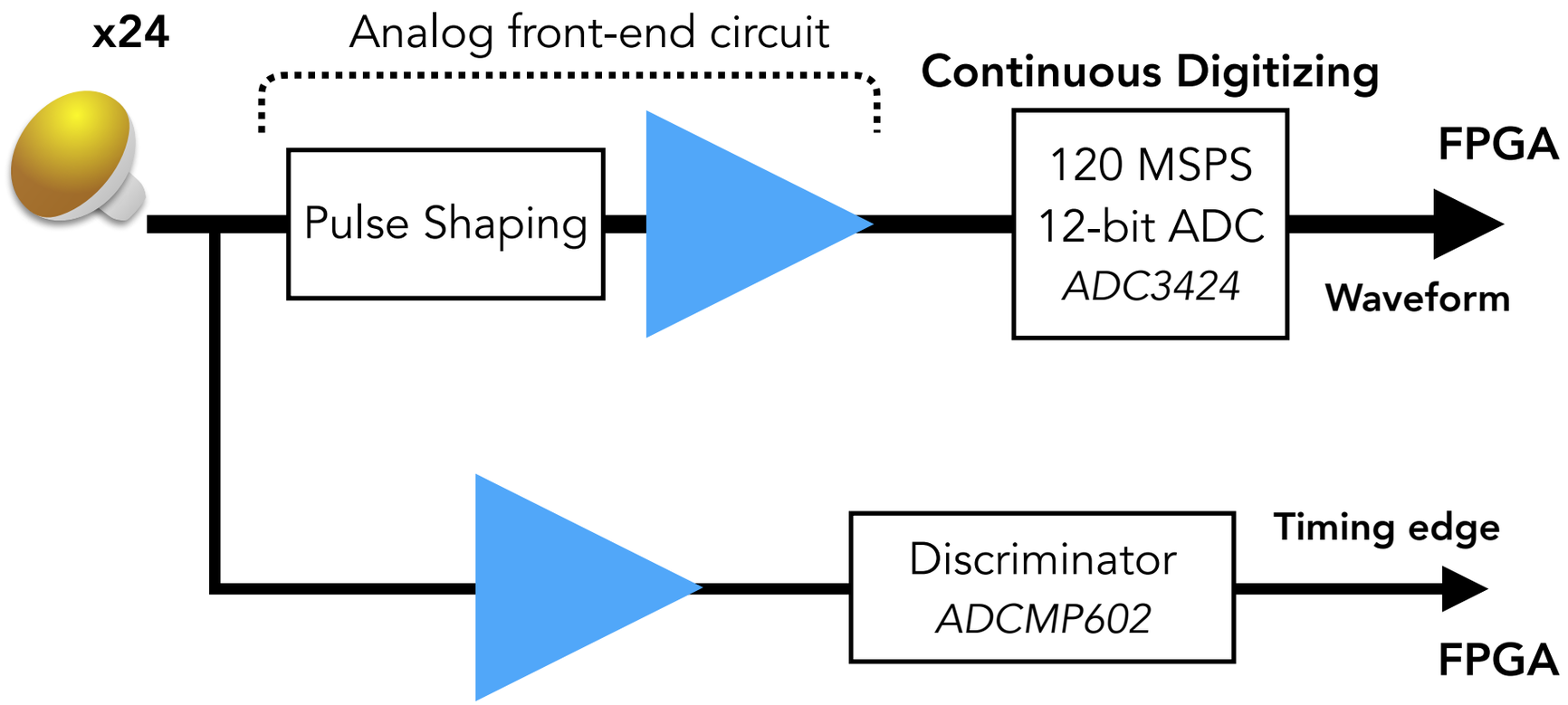
- 24 3″ PMTs
- Photon incident direction information
- ~400 production ongoing
  but some parts are in short supply now…

## Front-end DAQ board (Mainboard)



# Upgrade Digitization-2: multi-PMT

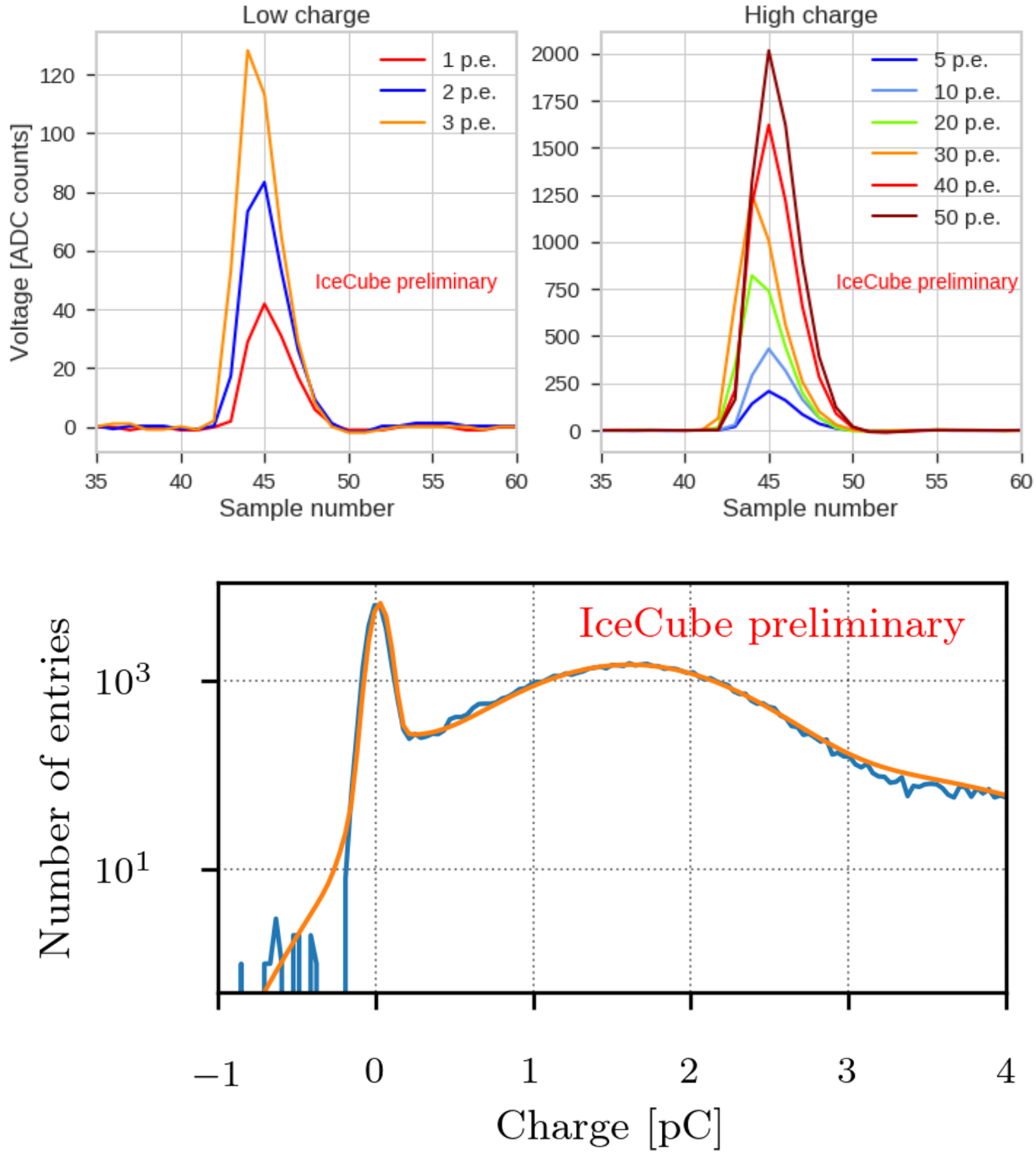



- Similar to the simple scheme, but instead of high frequency ADC, divide 2 signal lines — can keep enough time resolution (**~1 ns**)
  - 120 MHz waveform ADC
  - **960 MHz** timing discriminator
- Operation power consumption is **~10 W**

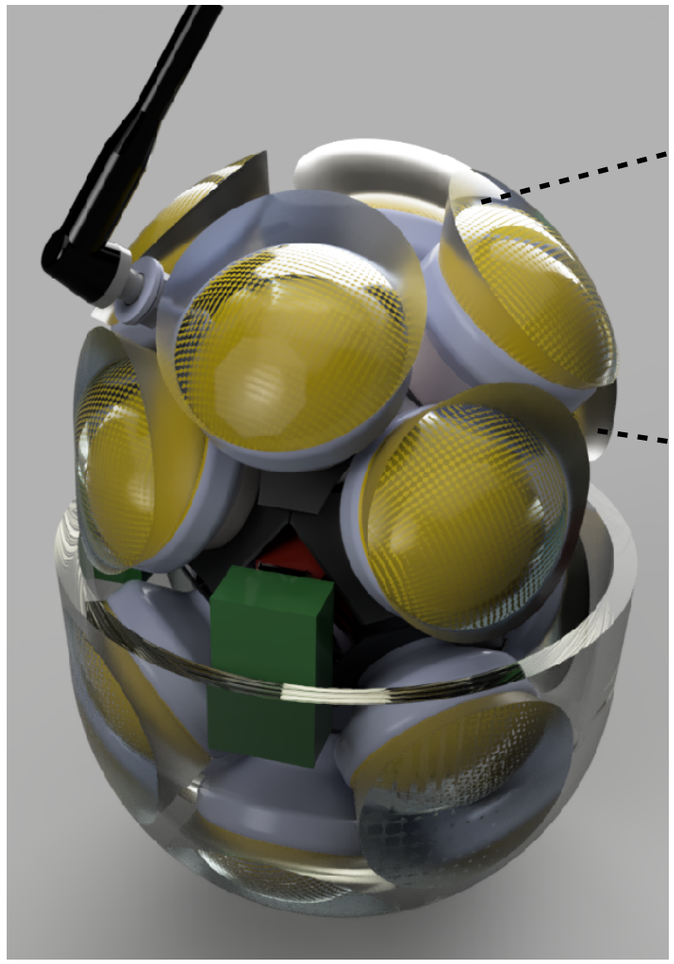
# Upgrade Digitization-2: multi-PMT

- Both waveform / charge-time info readouts are supported
  *(same as PDOM/D-Egg)*
  - Main software is identical to PDOM/D-Egg's
- Clear PMT signal is observed
  - Enough S/N to the SPE
  - Linear response seen for < 50 PE signal
- Charge-time info readout contributes to obtaining clear SPE distribution in a short time

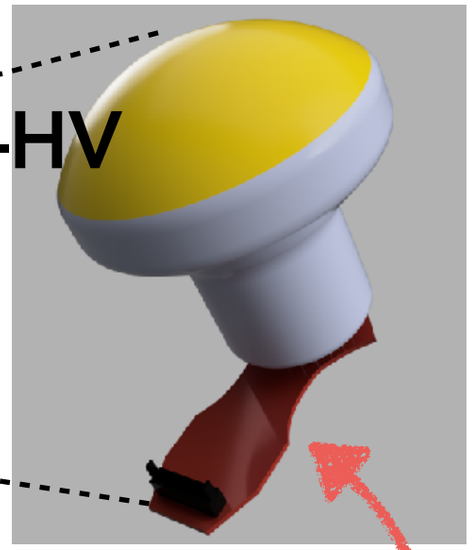



*[1] PoS ICRC2021 (2021) 1070*

# Gen2 Digitization



LOM (16)

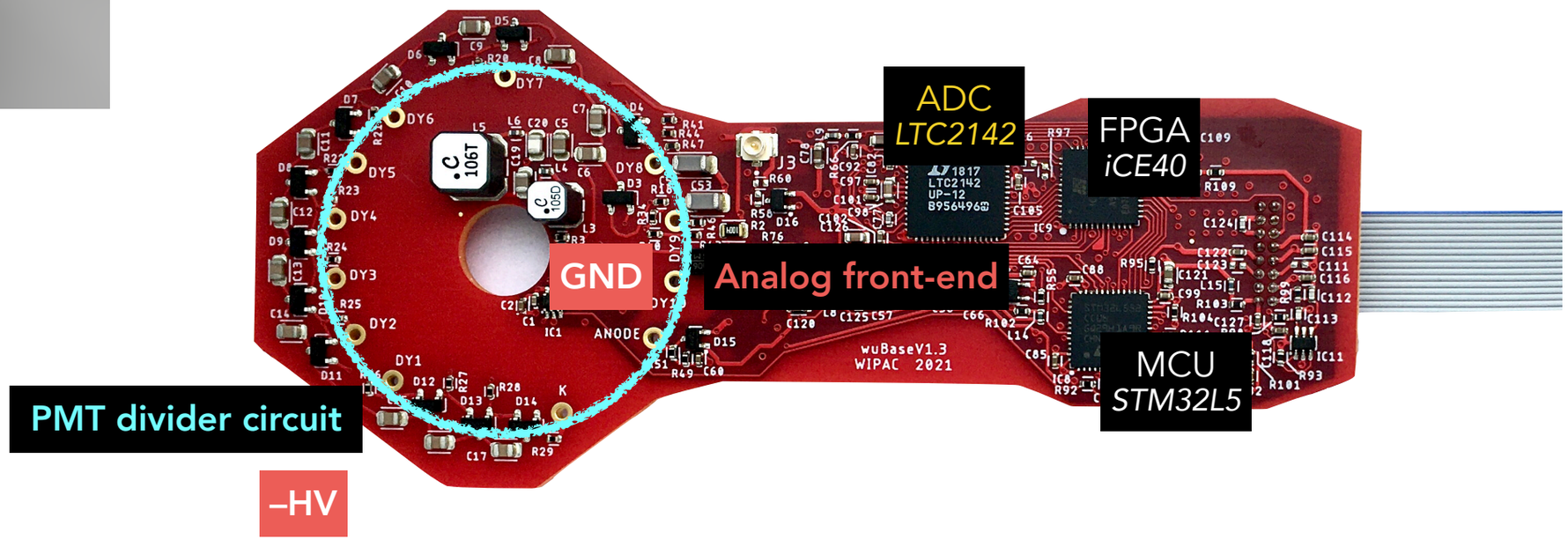



*D-Egg + mDOM concept*

- 16–18 (TBD) 4″ PMTs in a slim glass vessel
- Negative HV applied to the cathode side

## PMT base + Front-end DAQ board

(under development)



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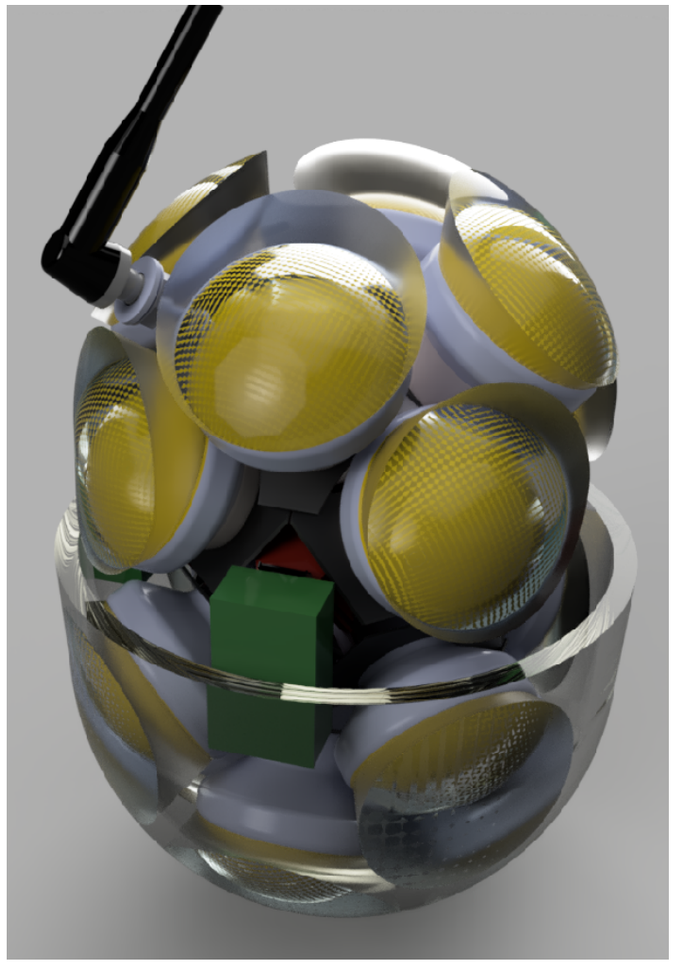

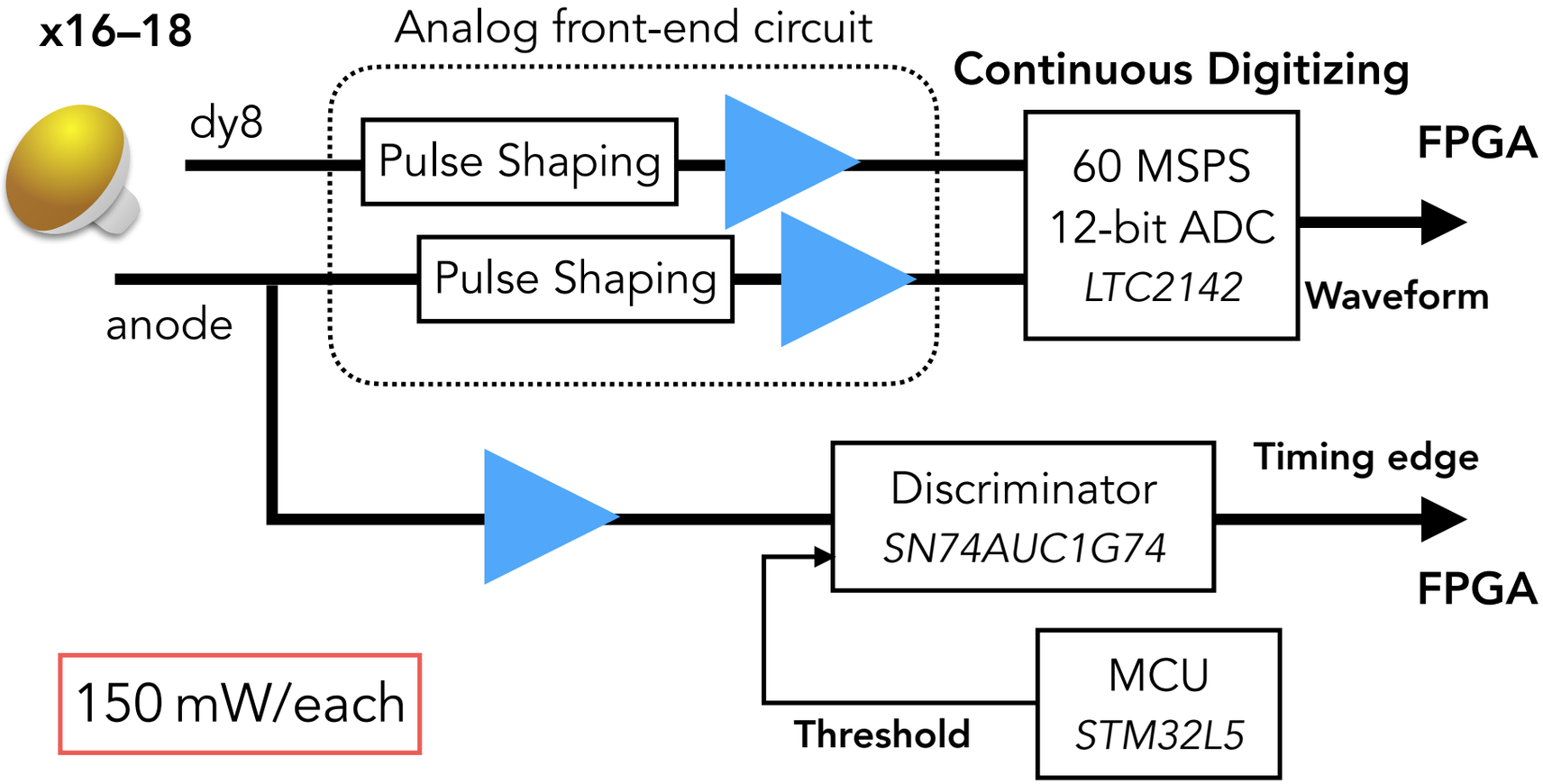


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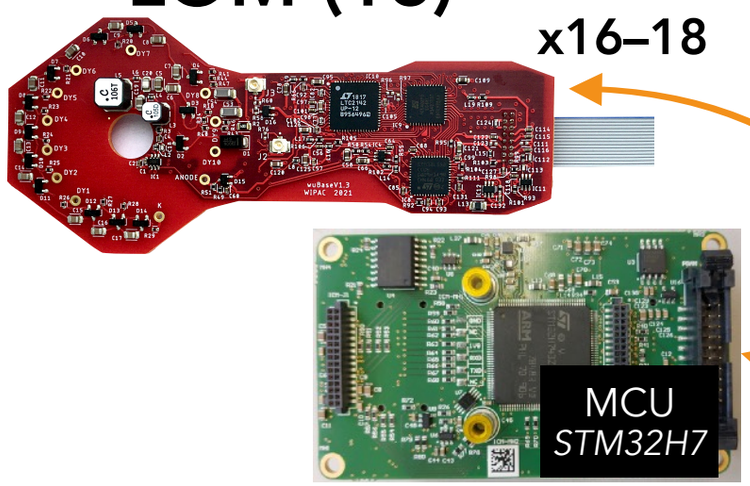
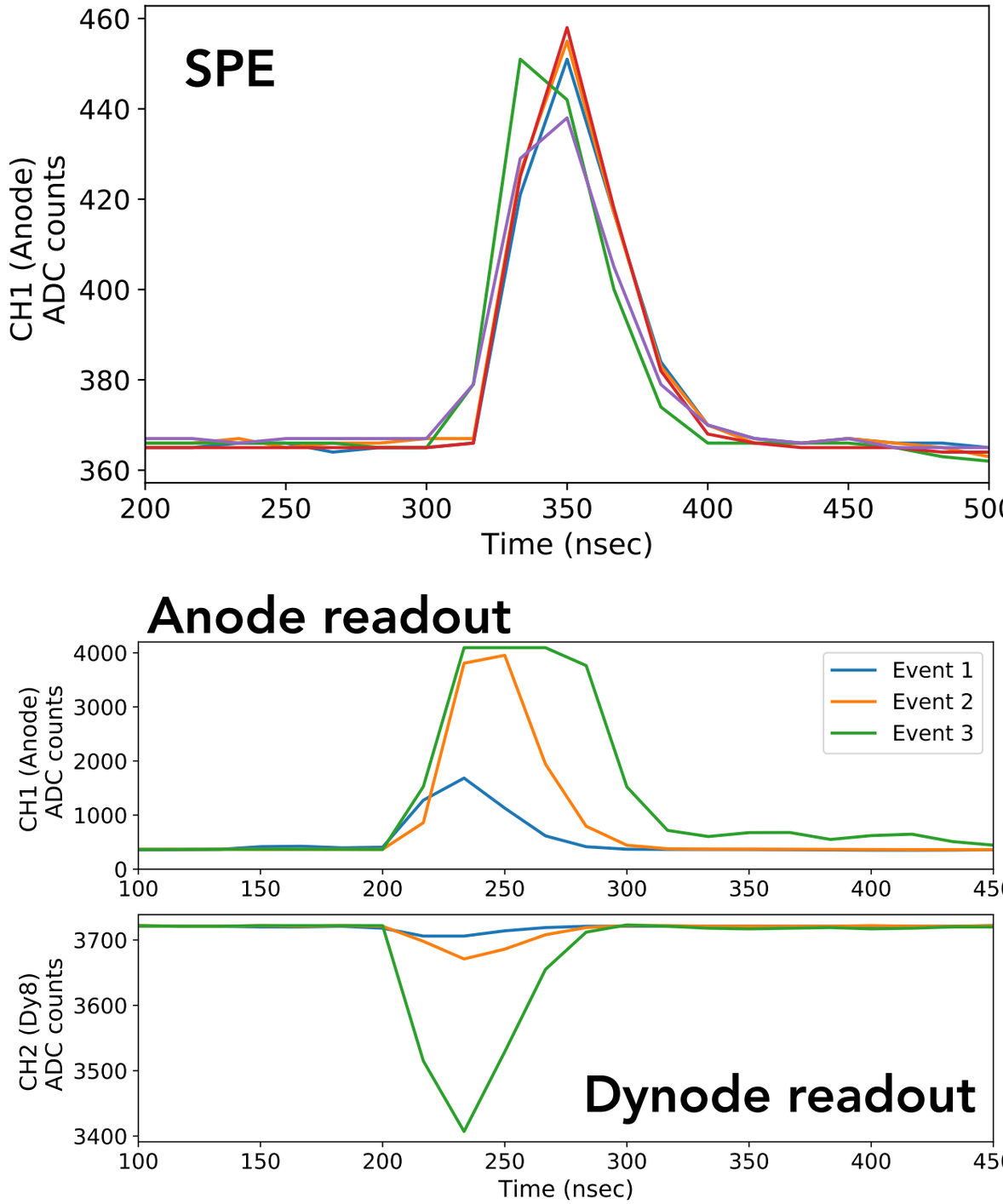



- Very similar to mDOM, but both **anode+dynode signals** are digitized to widen the dynamic range
- Whole digitization processes in each **PMT base + digitization board**
  - Mainboard works only as commander/communicator
- *Another possibility*: build ASIC… (would save power & cost)

# Gen2 Digitization: First test results

- Clear SPE has been observed with the FWHM of ~50 ns
  - Baseline noise ~1 ADC count… **extremely good!**
- **Anode+dynode readout** contribute to expanding the dynamic range…
  - Even if anode side saturated, dynode signal can recover the whole range of the pulse

**Circuit design looks no problem**




*[1] PoS ICRC2021 (2021) 1062*

# Summary

- IceCube detectors are in deep ice, so the in-ice digitization is necessary
- IceCube is now using several in-ice digitization systems with carefully managing the critical limitations:
  - cost, power consumption, …
- Thanks to the technology growing, Upgrade modules can digitize without dead-time
  - D-Egg: Simple scheme, the final testing stage
  - mDOM: Complicated, the production stage
- Gen2 module (LOM) is under development, but its main concept shares with the Upgrade modules and so far looks working well