D-Egg

The next-gen optical module for the deep in-ice neutrino detector

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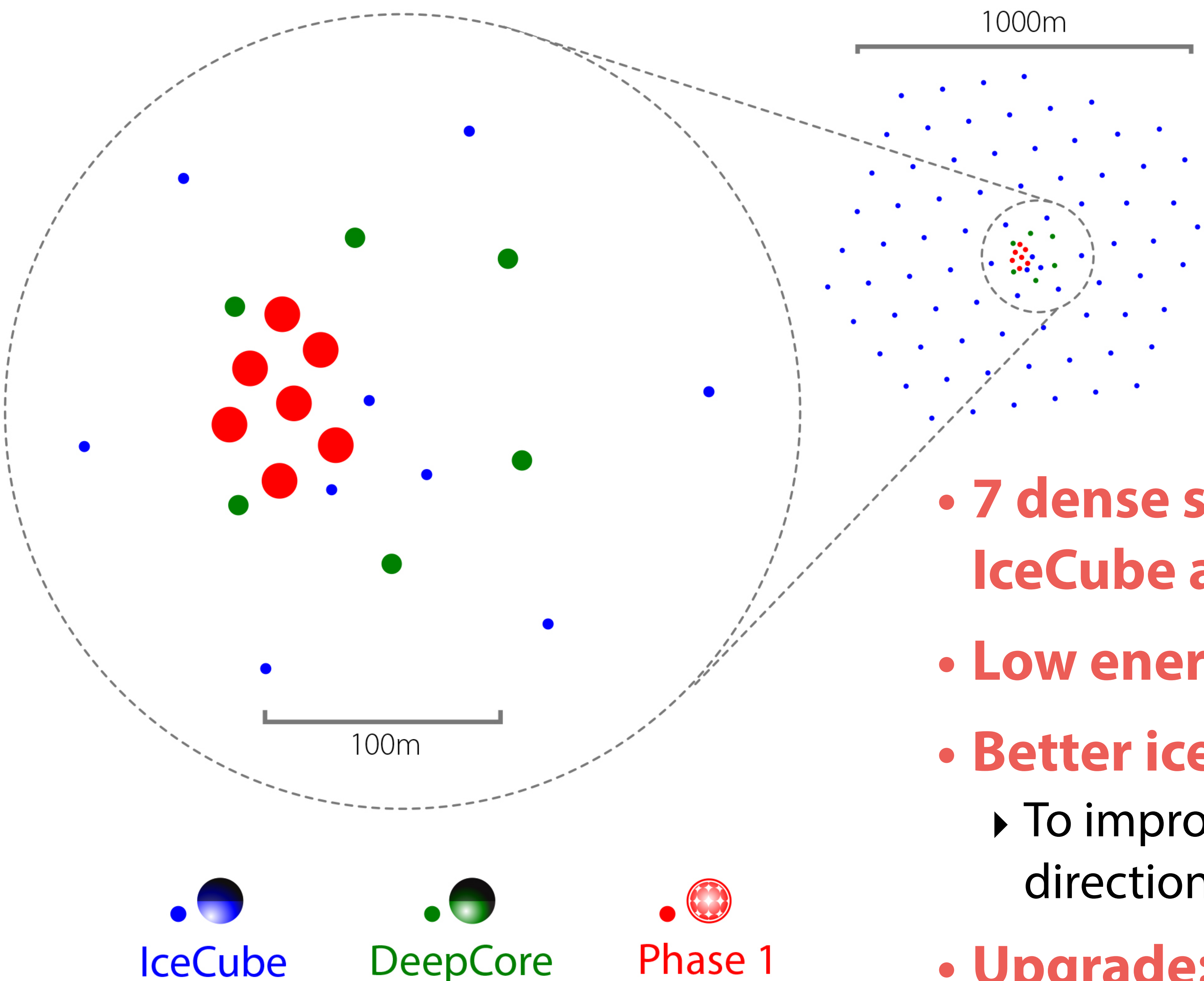
VLVnT 2018 @ Dubna, Russia

ICECUBE GEN2

CHIBA UNIVERSITY

IceCube Upgrade



- **7 dense strings inside the existing IceCube array**
- **Low energy / Oscillation physics**
- **Better ice characterization**
  - To improve IceCube analysis (e.g Cascade direction)
- **Upgrade: Step toward IceCube-Gen2**
  - Deployment in 2022/23
  - Prove new OM technologies

Next-Gen Optical Module?

IceCube DOM

- 1 x 10" PMT in the pressure glass vessel (optical gel in between)
- Waveform measurement (300MSPS at max.)
- Module diameter: 33 cm
- Works very well over a decade

Next-Gen OM

Next-Gen Optical Module?

IceCube DOM

Only 1 PMT seeing downward?

Modest UV transparencies…

- 1 x 10″ PMT in the pressure glass vessel (optical gel in between)
- Waveform measurement (300MSPS at max.)
- Module diameter: 33 cm
- Works very well over a decade

Drilling cost can be reduced if slim design

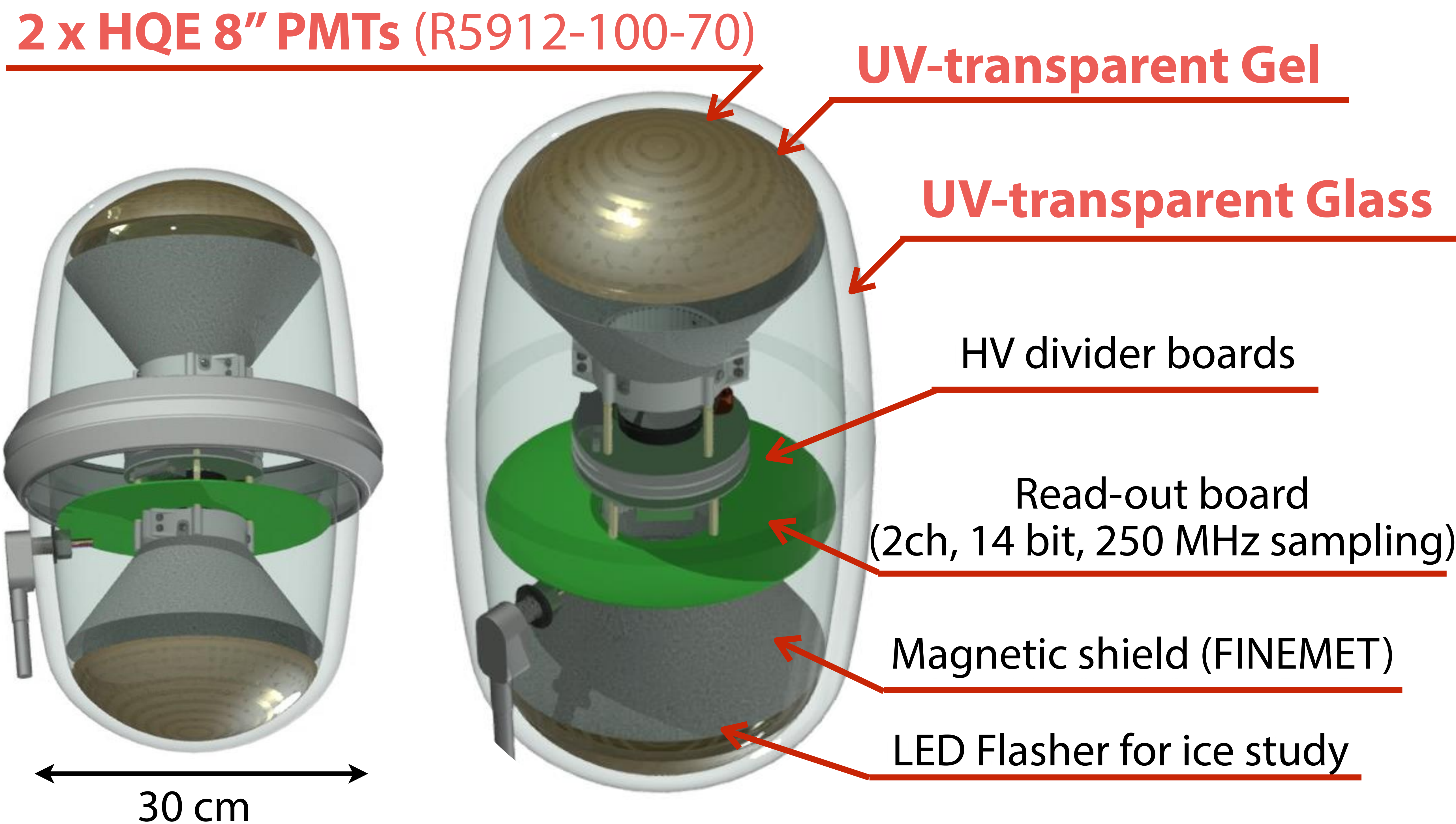
GOOD!!

Next-Gen OM

Idea

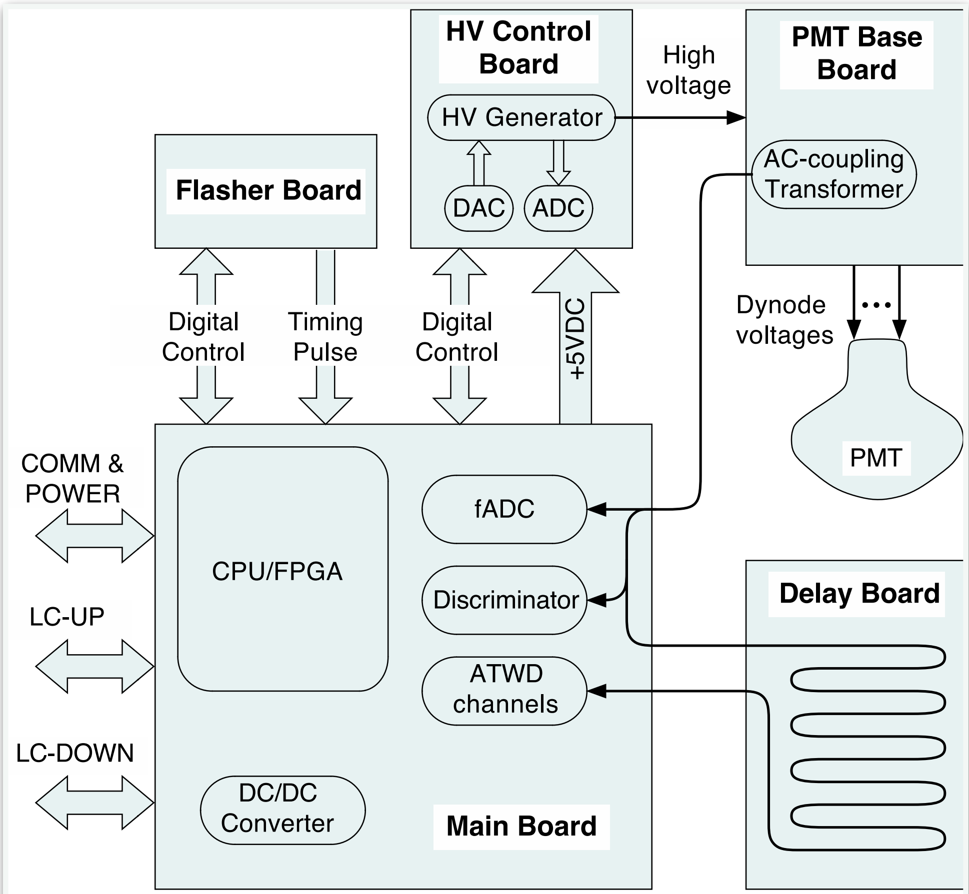
- **Inherit the basic design of DOM**
- **Segmented sensors**
- **High UV transparencies of glass & gel**
- **Slim design for reducing drilling cost**

D-Egg


2 x HQE 8" PMTs (R5912-100-70)
UV-transparent Gel
UV-transparent Glass
HV divider boards
Read-out board
(2ch, 14 bit, 250 MHz sampling)
Magnetic shield (FINEMET)
LED Flasher for ice study
30 cm

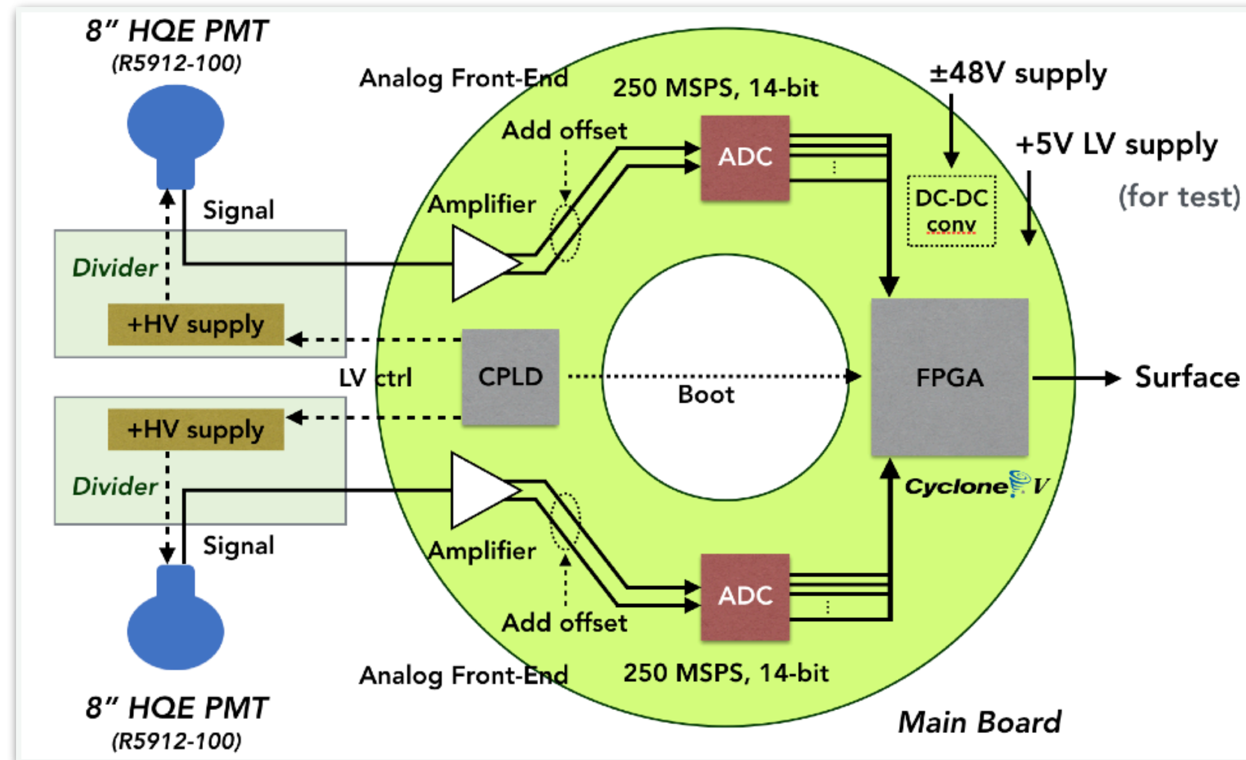
Changes on the read-out system

IceCube DOM Main board



- 1 PMT
- Multiple ADC channels / PMT
  - Fast ADCs (10-bit, 427 ns time window, 300 MSPS, 3 diff. gains)
  - Slow ADC(10-bit, 6.4 us time window, 40 MSPS)
- Needs tigger to start waveform read-out -> delay board is required

D-Egg Main board



- 2 PMTs
- Single ADC channel / PMT
  - 14-bit, 250 MSPS
  - Waveform length: Firmware adjustable
- Possibly pulse extraction inside FPGA
- Continuous digitizing (Zero dead-time)

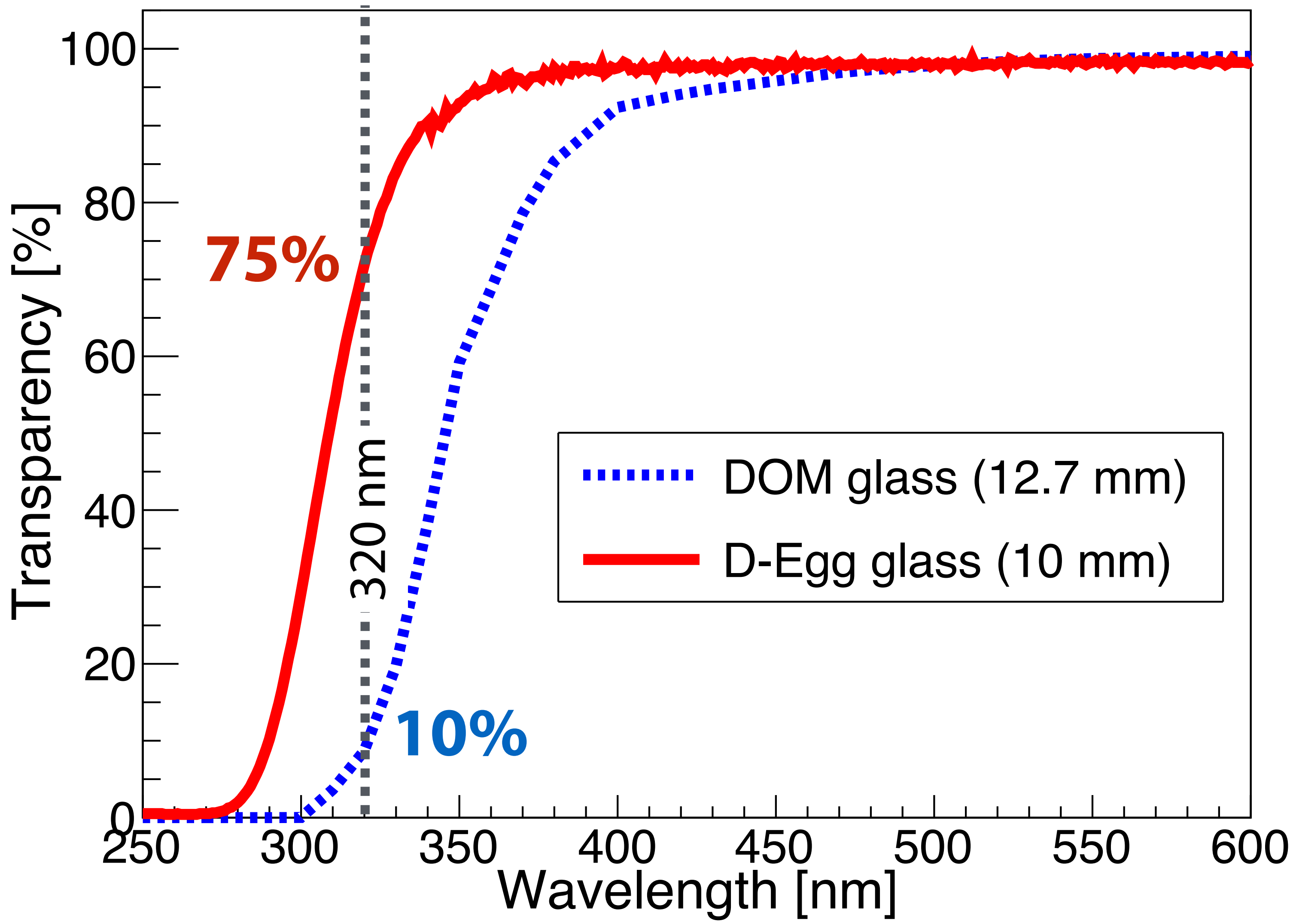
=> R&D ongoing. Final version by Apr. 2019

Current Status

- **Chiba Group is responsible for 300 D-Eggs**
  - Production by Sep. 2021
- **To be deployed in 2022/23**
- **Pressure vessel + Sensors + Analogue circuit are mostly final model**
- **Currently testing with 14 prototype half-modules (Rev.3)**

This talk: Verify the improved capability of Cherenkov photon detection compared to DOM using the prototype modules

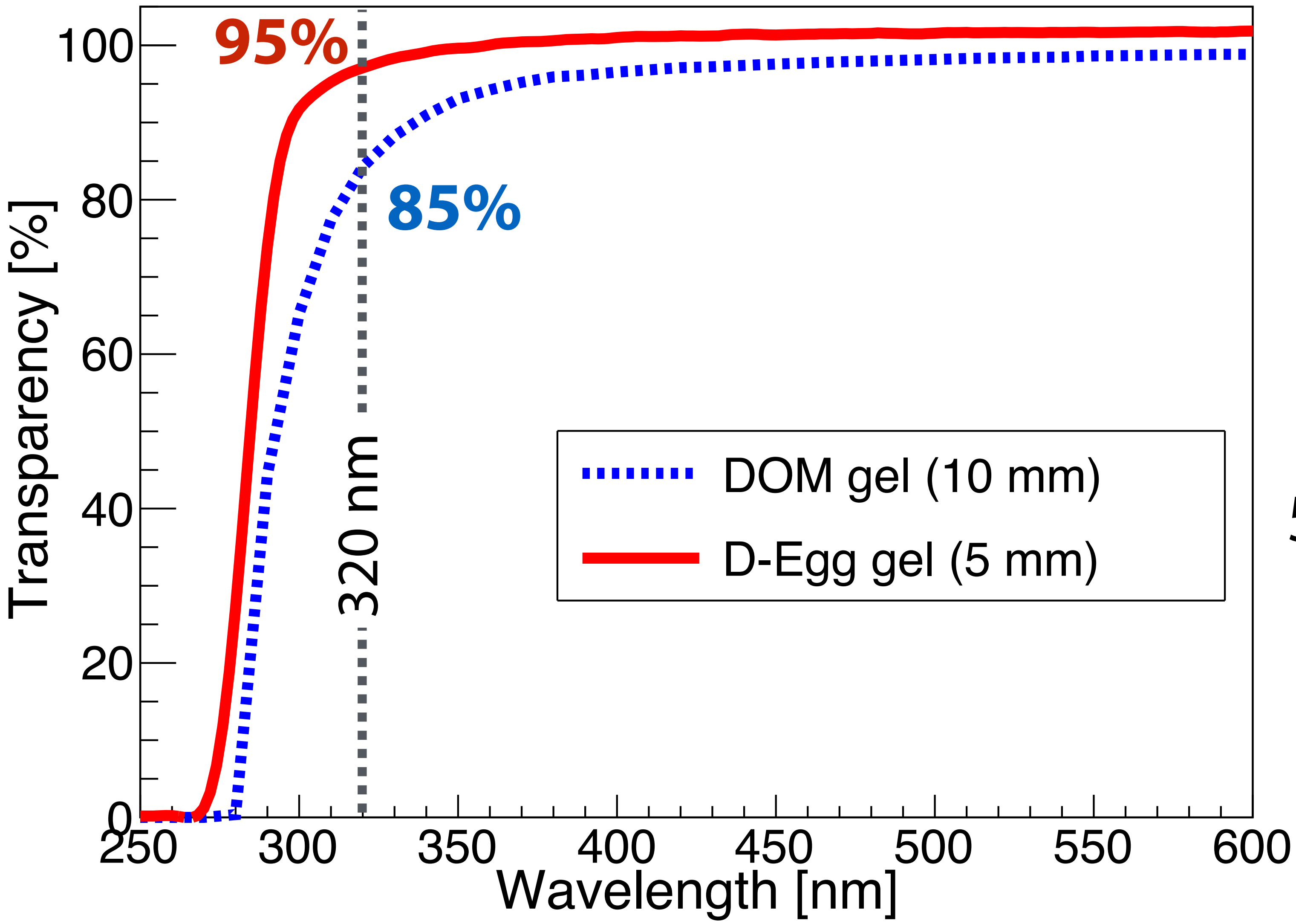
Better Glass For More Photons

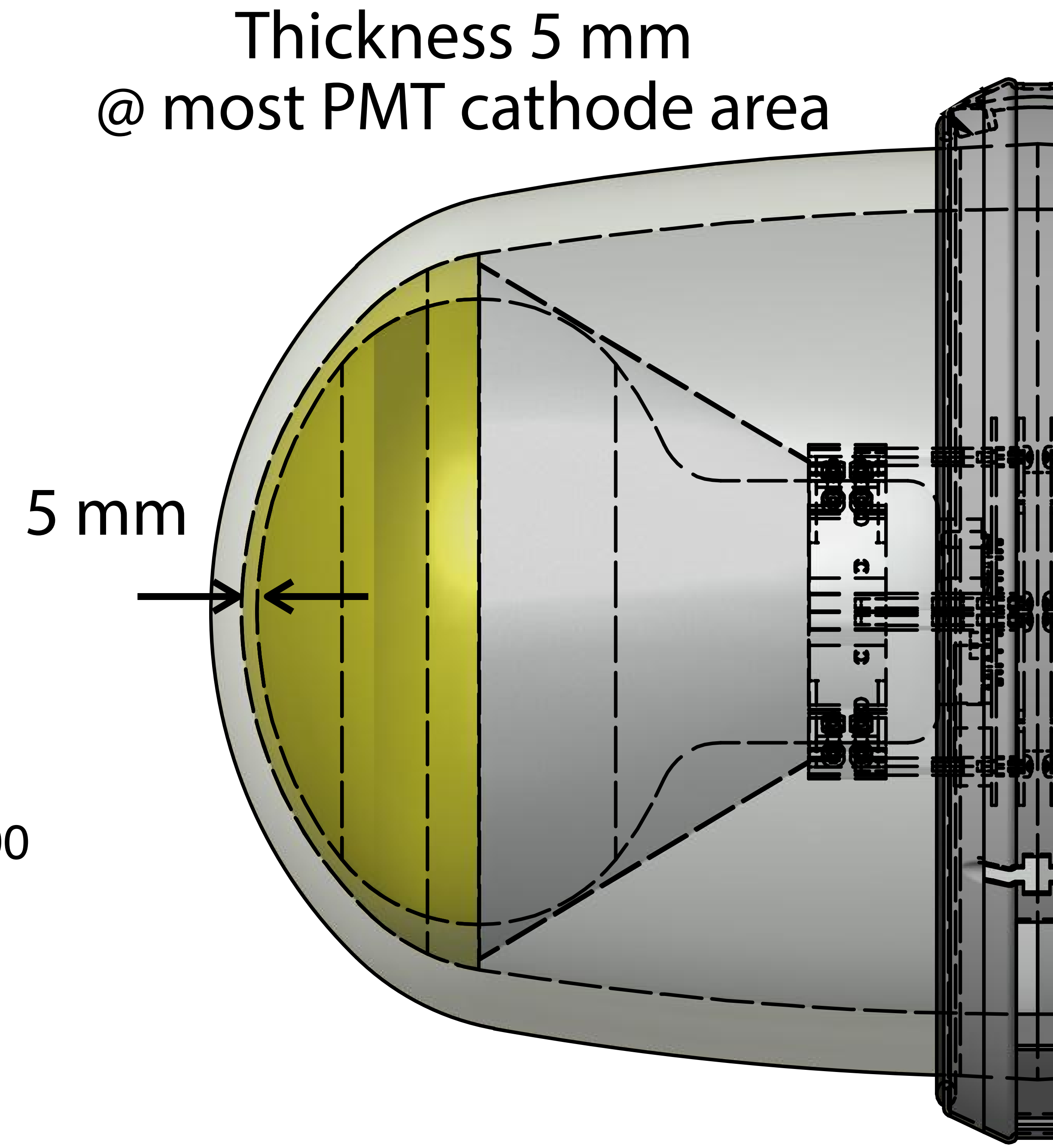


Thickness 10 mm @ bottom
(DOM glass : 12.7 mm)

- **Developed with Okamoto Glass**
- **Reduced Fe content for UV-transparency (<0.008 % by weight)**
- **Shows significantly improved transmittance at UV region**
  - 75% (D-Egg glass) and 10% (DOM glass) @ 320 nm

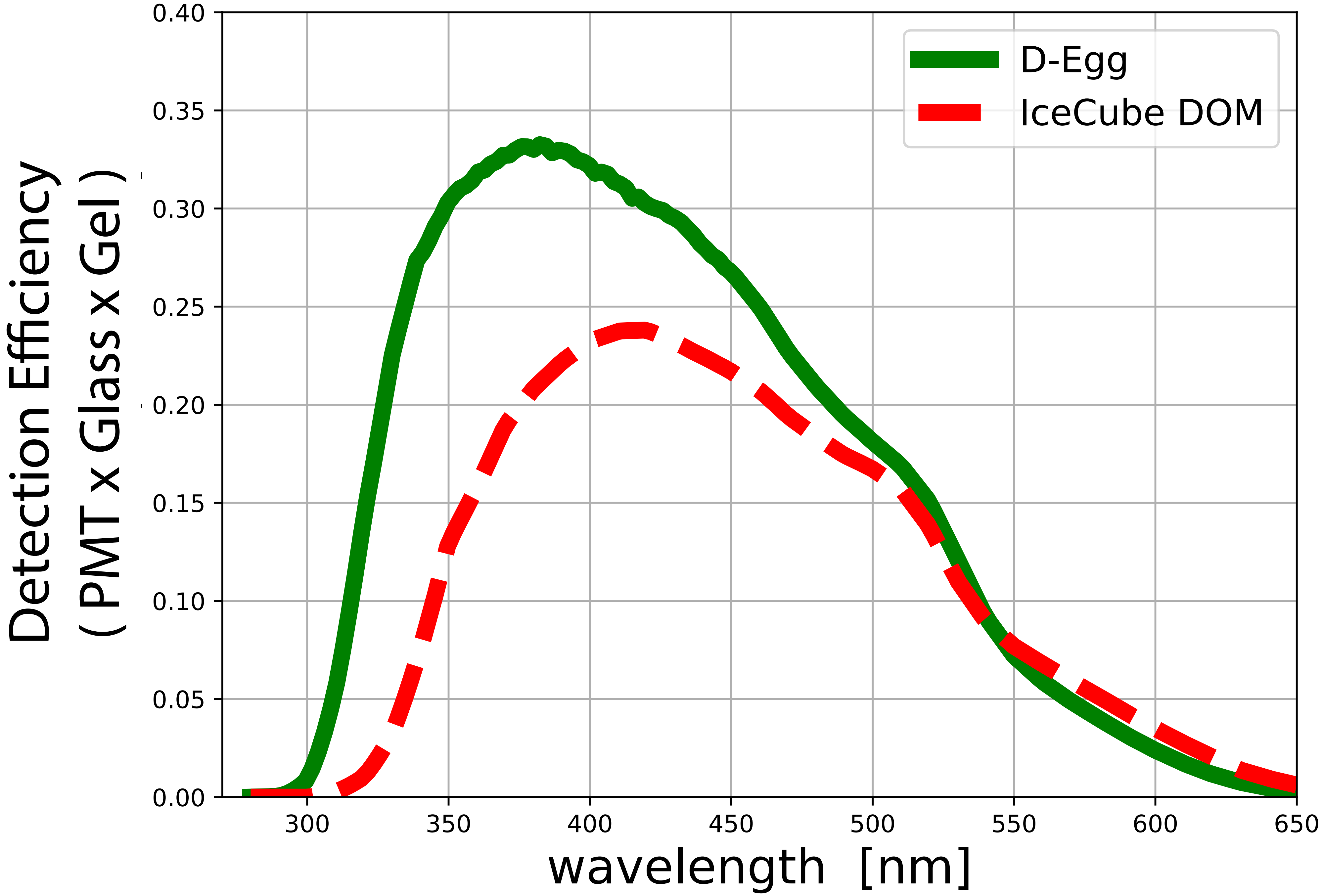
Optical-Coupling Gel





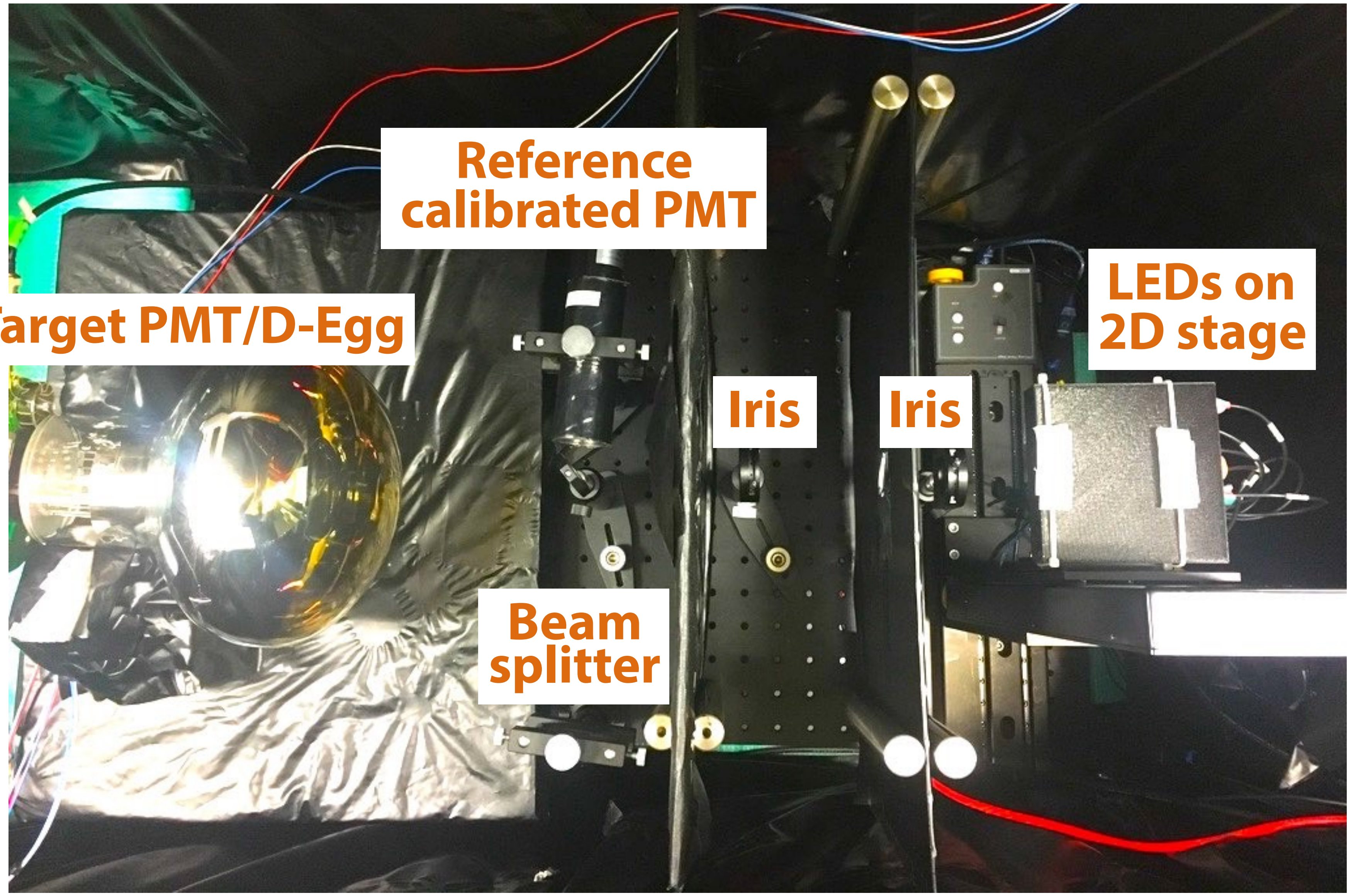
- **Developed by Shin-Etsu**
- **Thickness optimized to 5 mm at the bottom**
- **95% of transparency at 320 nm**

D-Egg v.s. IceCube DOM



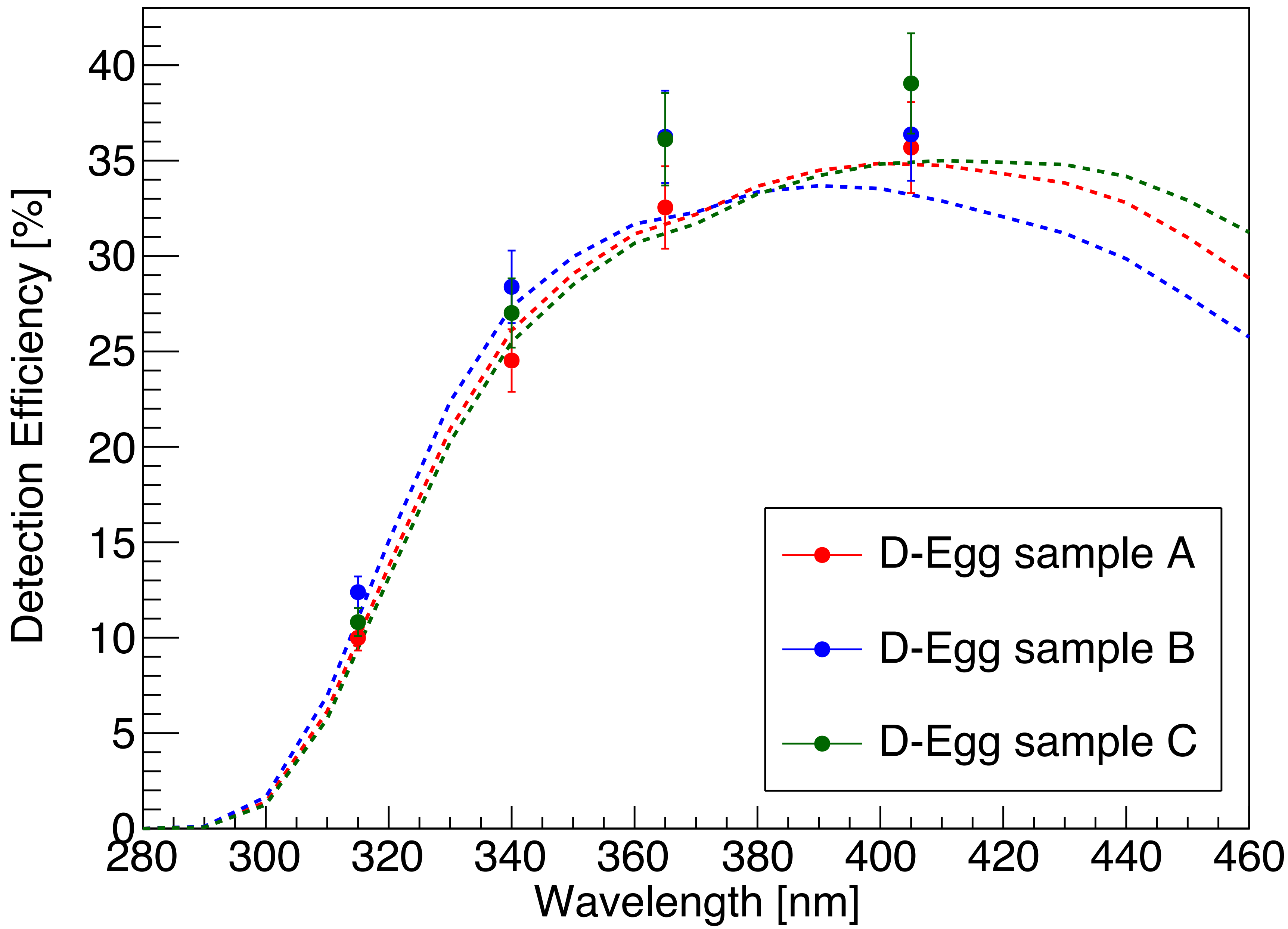
Significant improvement of the sensitivity at the UV region is expected

D-Egg Detection Efficiency (λ dep.)



- **Multi-λ detection efficiency measurement @ Chiba**
  - λ=315, 340, 365, 405, 420, 520, and 572nm
- **Major systematics comes from (Reflection/Transmission) ratio at the beam splitter**
  - Currently 5% is assigned as a systematic error

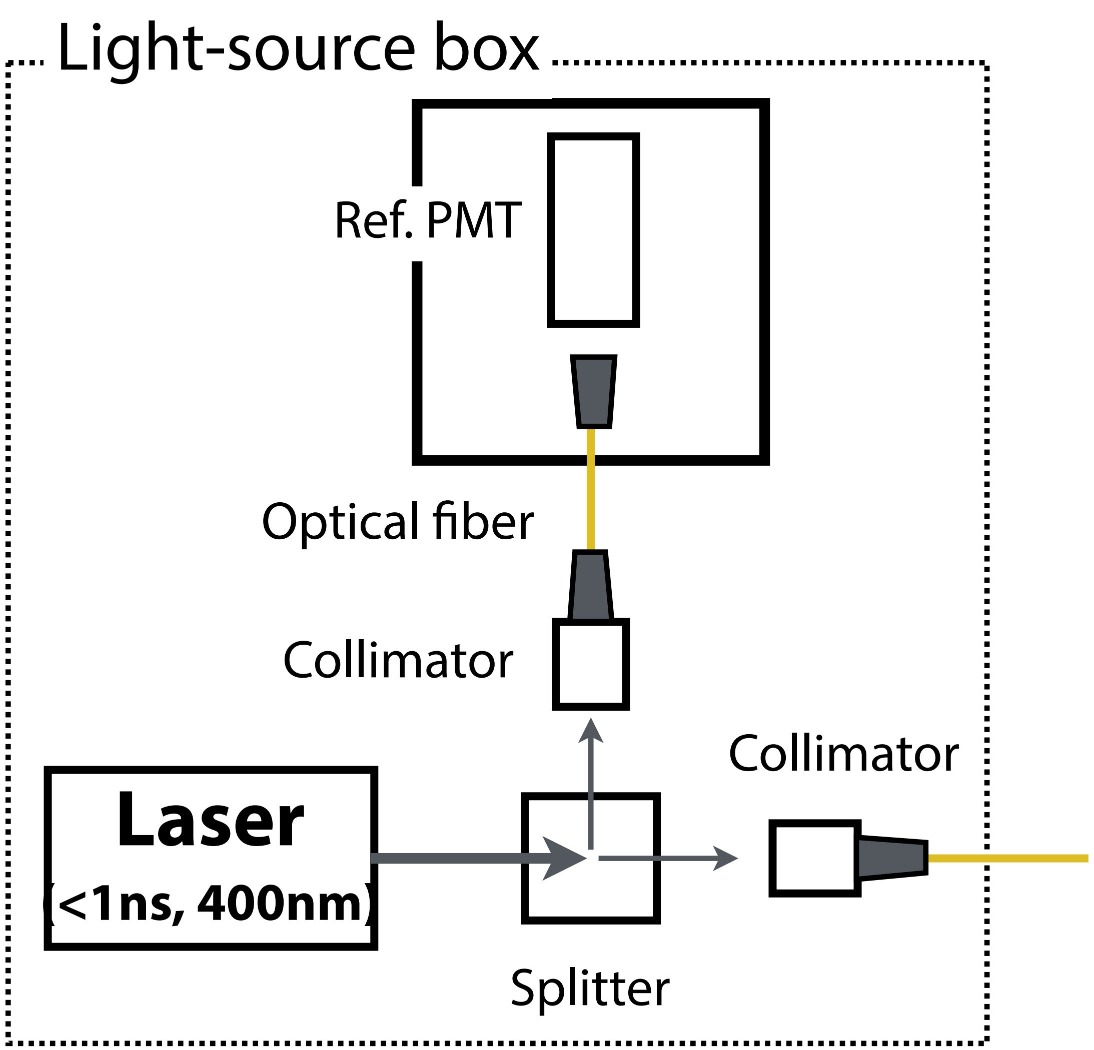
D-Egg Detection Efficiency (λ dep.)



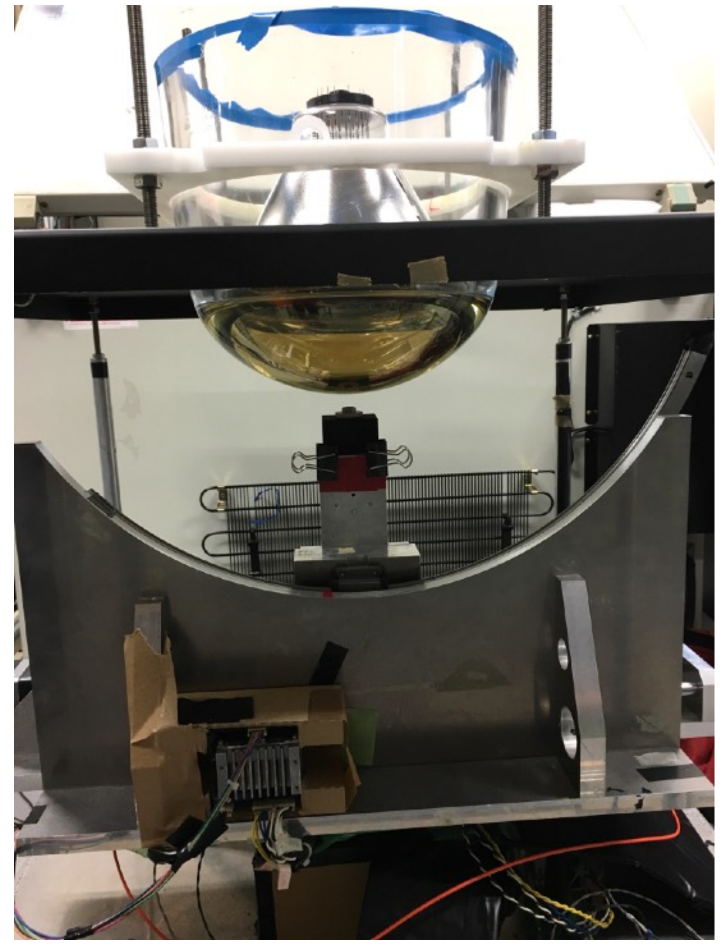
*) Includes reflection at the glass surface

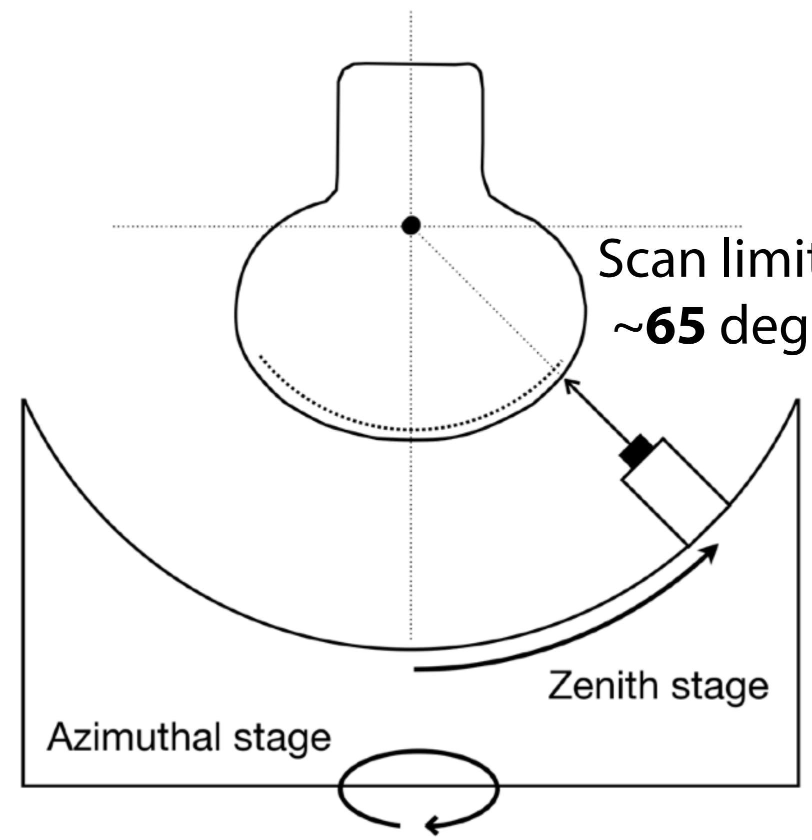
- **Confirmed high detection efficiency of D-Egg at UV region**
  - Confirmed high UV-transparency of glass+gel & high-QE of 8" PMTs
  - Ave. 26.6% at 340nm

D-Egg Detection Efficiency (angular dep.)



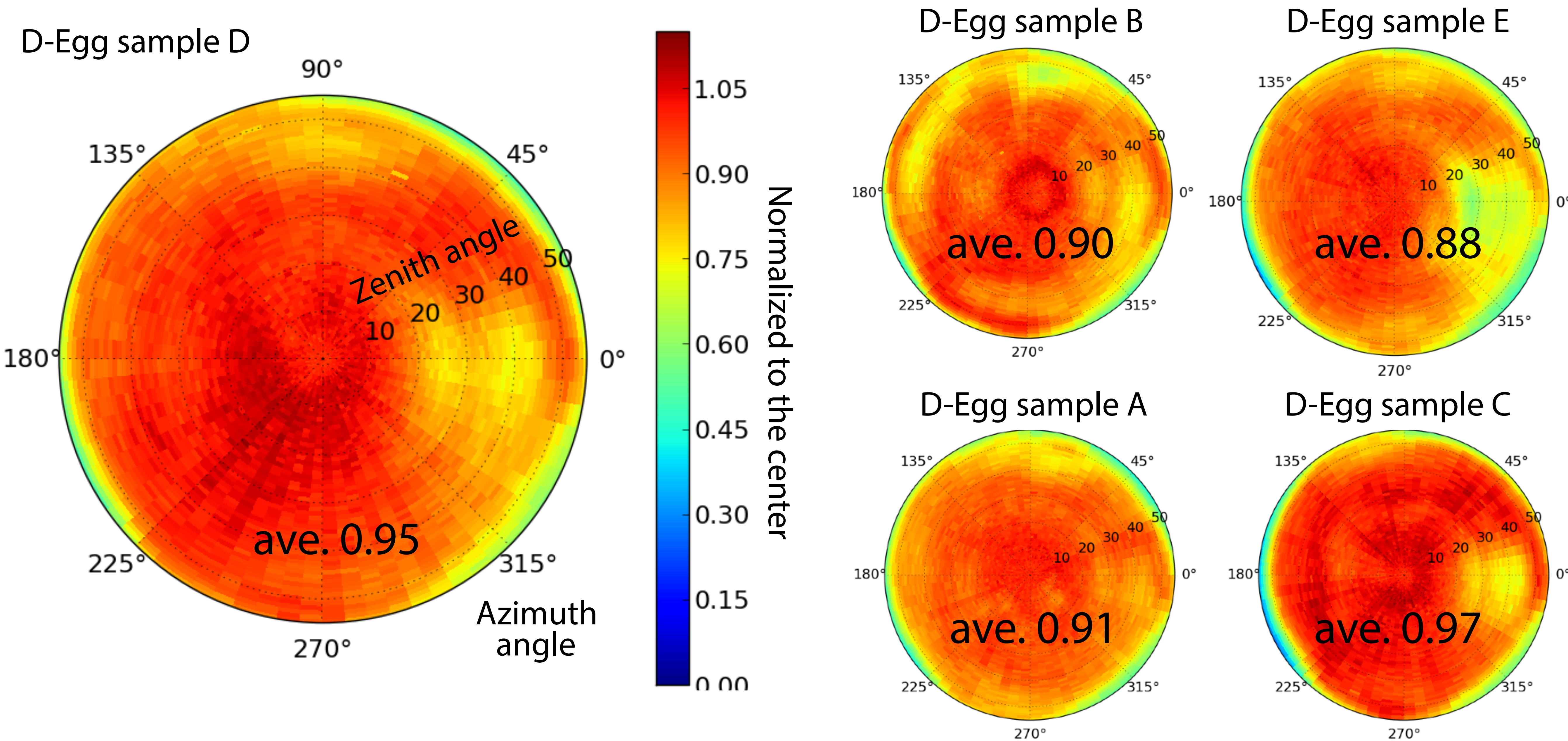
Scan system





- **Test bench for 8" PMT / D-Egg cathode uniformity measurement**
  - Fast laser (pulse width < 1ns, λ=400 nm)
  - Sampling pitch : zenith 1°& azimuth 5° => ~5000 points over the cathode
  - 1 half D-Egg / day

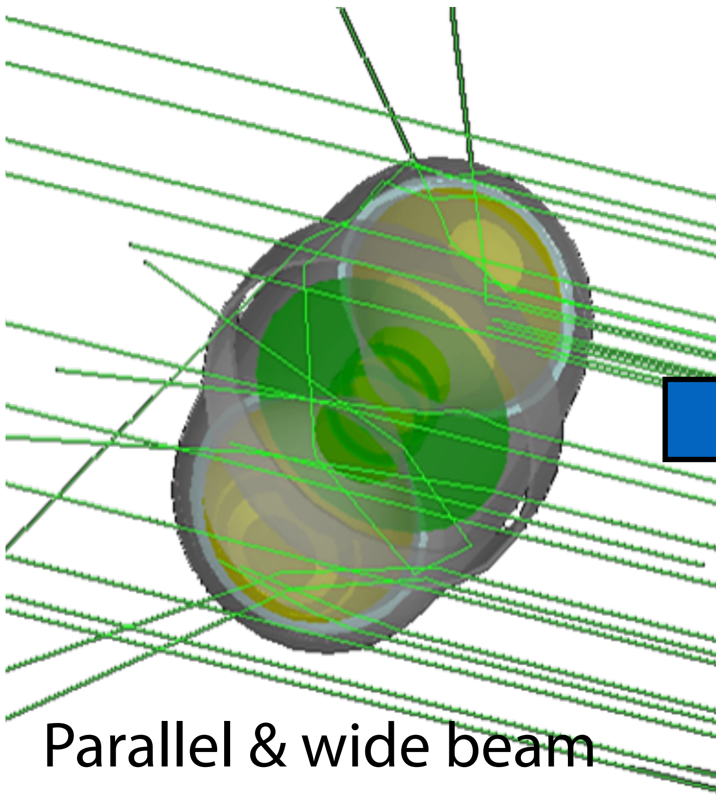
D-Egg Detection Efficiency (angular dep.)



- **High efficiency up to 50 degree**
- **Confirmed uniform responses, but also a local minimum**
  - Due to the dynode structure of the 8″ PMT (varied largely depending on PMTs)

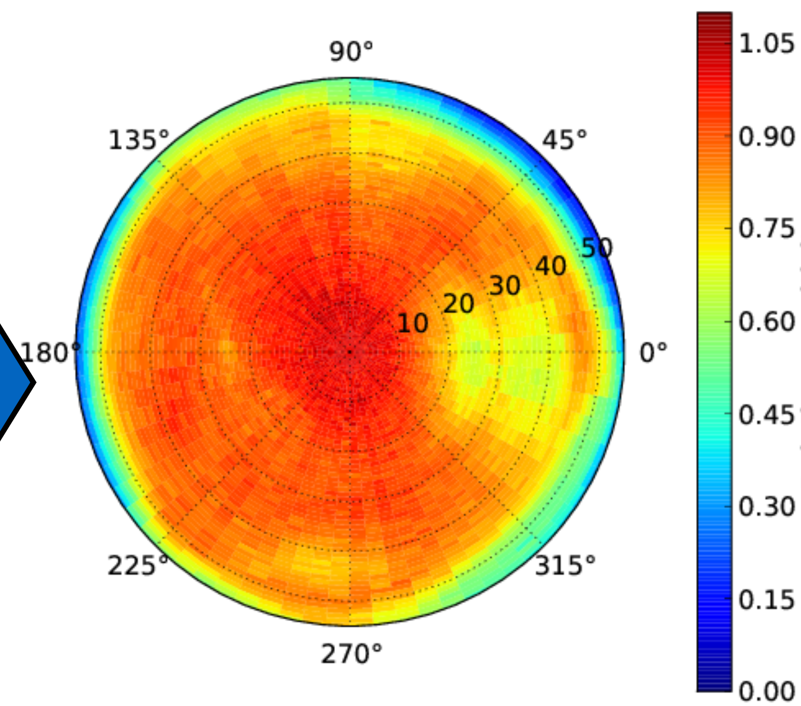
Effective Area Calculation

Photon propagation in the glass & gel

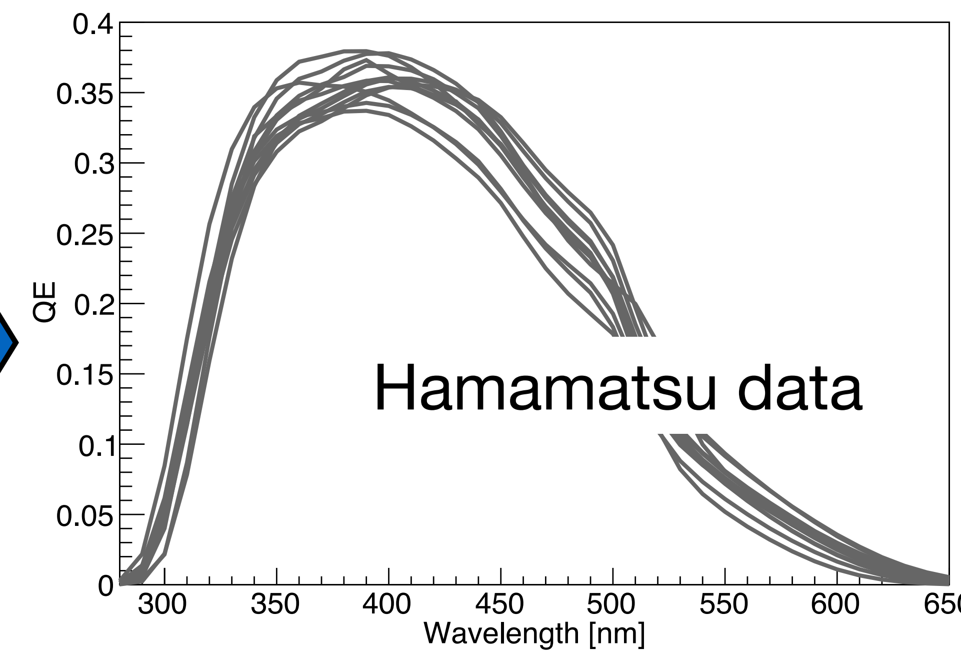


Parallel & wide beam

Cathode uniformity



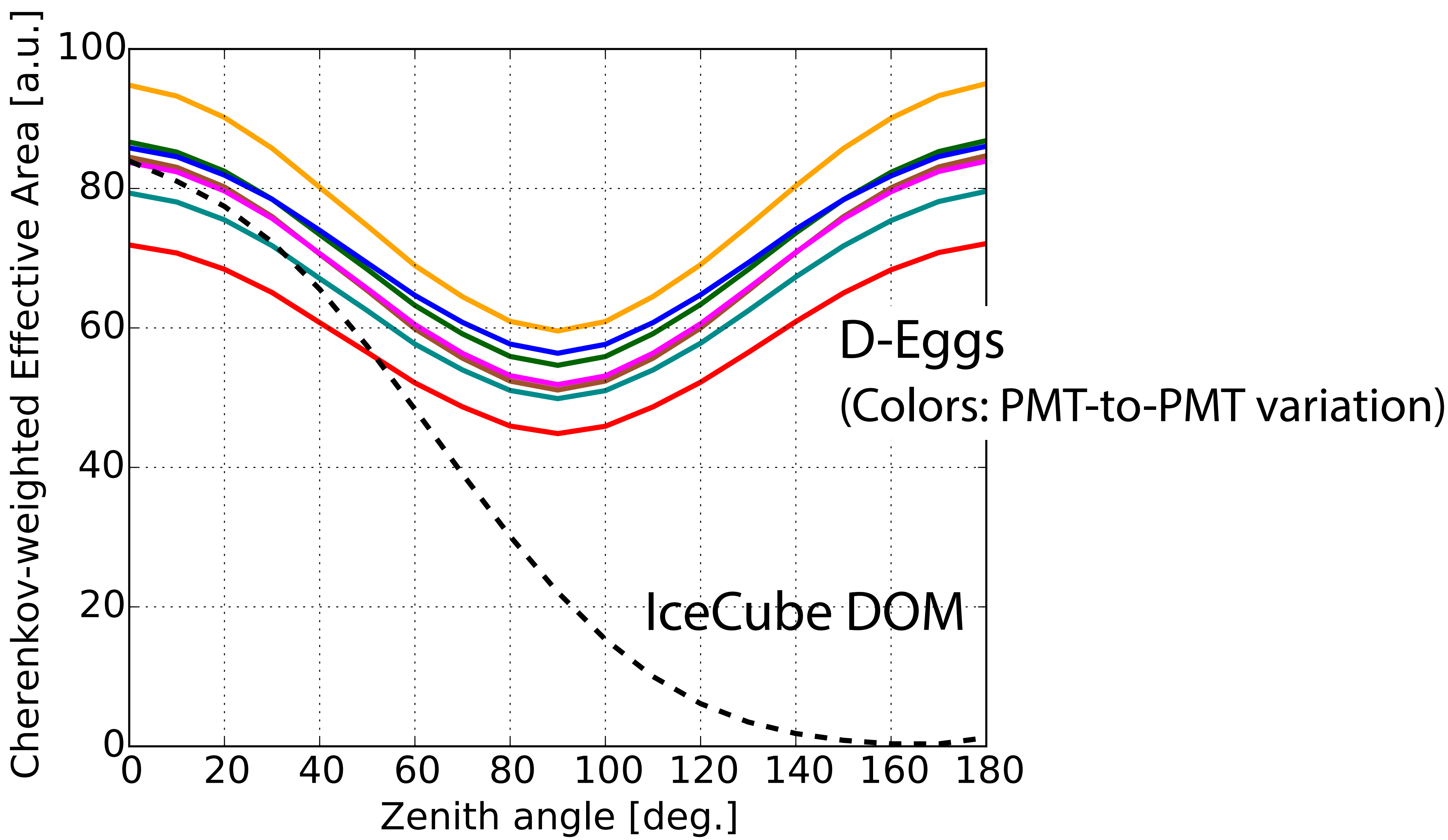
Quantum Efficiency



Geant4 simulation + **Measured for each PMT**

Effective area calculation based on the measured PMT responses

Performance of D-Egg



- **Horizontal direction is NOT blind angle for D-Egg (60% of vertical sens.)**
- **Expected sensitivity of D-Egg is twice as that of IceCube DOM**
  - D-Egg is a slim OM, but has two high-QE PMTs and UV-transparent glass & gel

Beyond Dual-PMT System

Lots of spaces available on the sides…
-> Put more detectors!

WLS Fibers in D-Egg

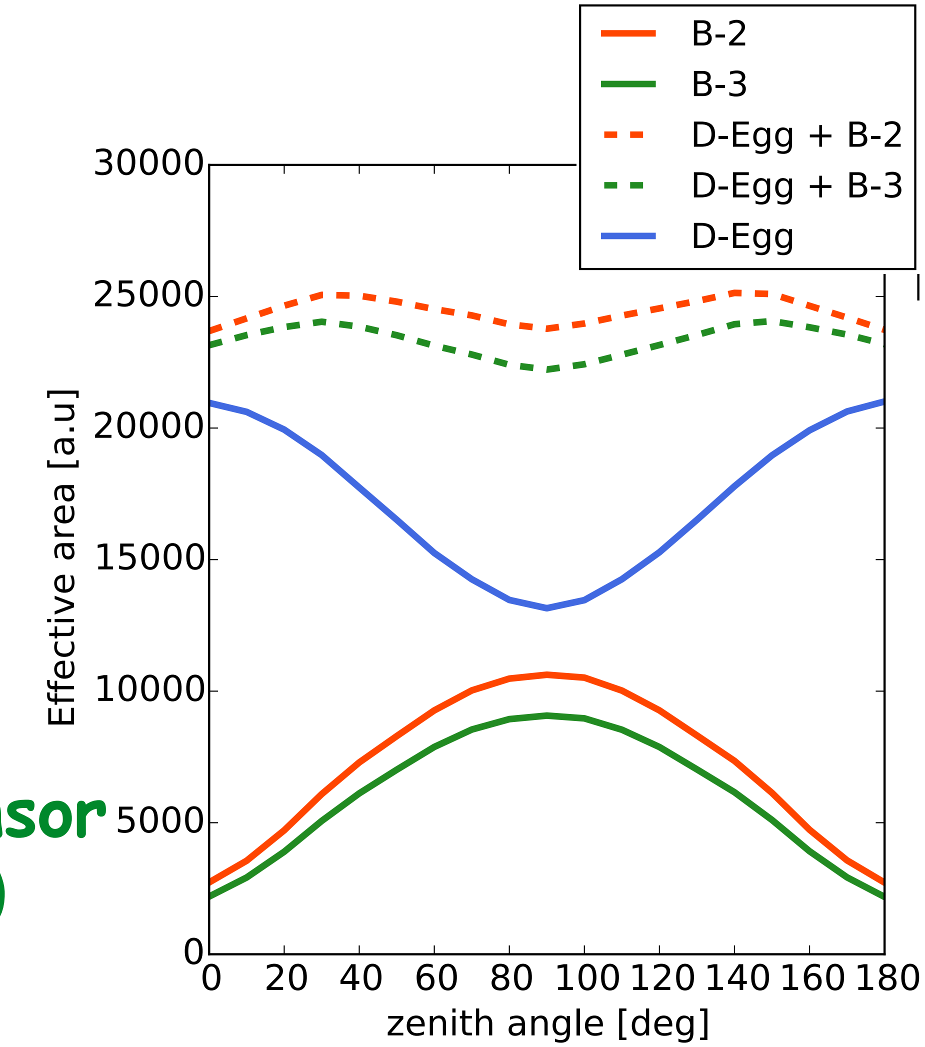
Geant4 simulation

↓

WLSF response table

↓

QE of photosensor (e.g. MPPC)



- **More sensitivity for the horizontal direction?**
  - Wavelength Shifting (WLS) fiber detector can improve the sensitivity from the horizontal direction
- **Start discussion with Kuraray**
- **Mainly aims Gen2, but possibly install some prototypes in Upgrade**

Summary

- **D-Egg as a next-gen optical module for the deep in-ice neutrino detector**
- **IceCube Chiba Group will produce 300 D-Eggs by Sept. 2021**
- **Performance studies using multiple prototype D-Egg modules verified:**
  - Detection efficiency at 340 nm is 26.6%
  - Geant4 based simulation indicates that the sensitivity of D-Egg is 2 x IceCube DOM
- **Mass production will start from Oct. 2019**
- **R&D of optional sensors for D-Egg is on going for further sensitivity**

Backup

Schedule

Sep. 2018- Apr. 2019	Jun. 2019	Oct. 2019	Sep. 2021	2022-23
Preliminary Reviews for each component	Final Design Review	D-Egg Assembling Starts & Dedicated Tests	Shipping Start	Deployment

Noise Sources in D-Egg…

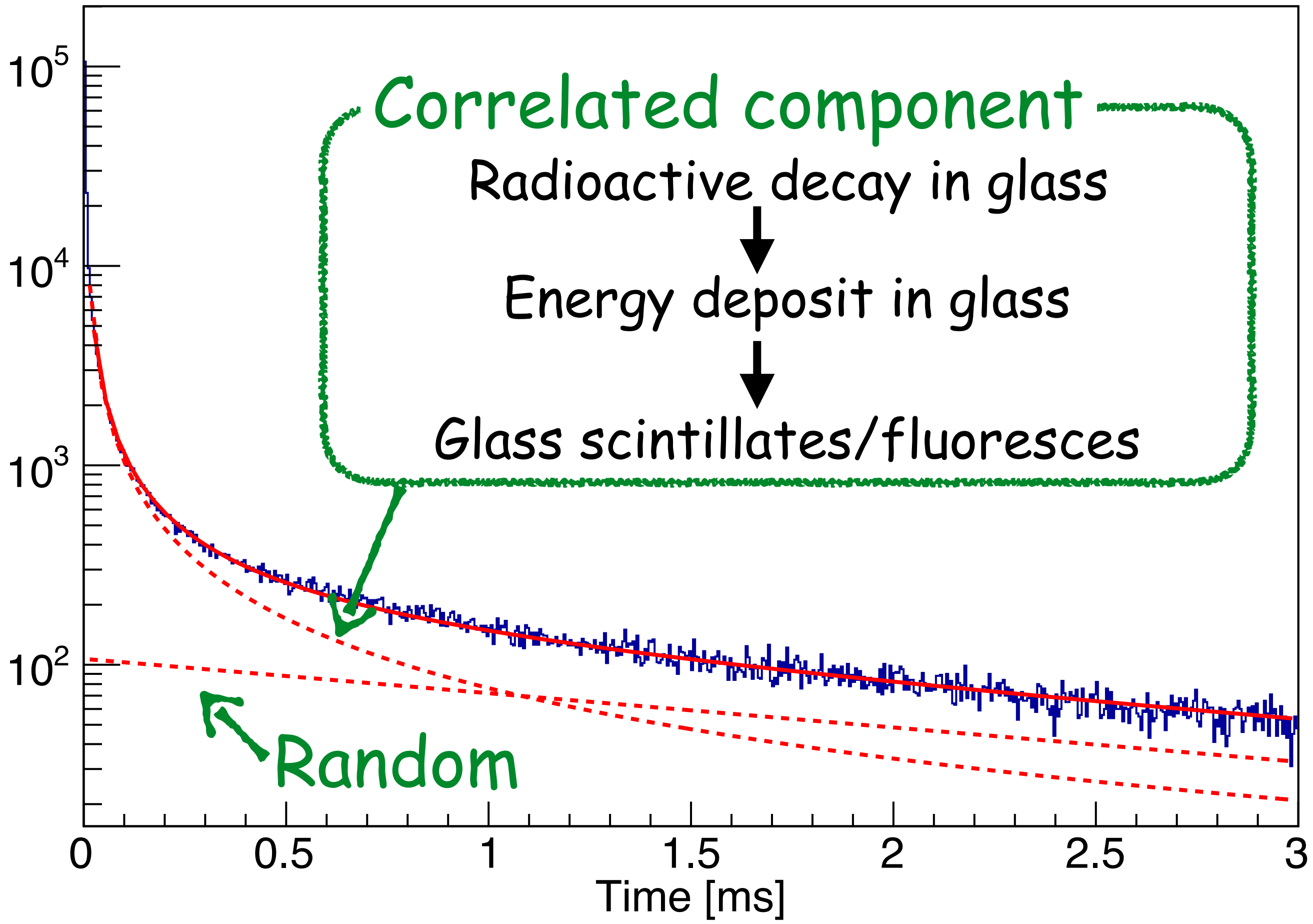
8” PMT

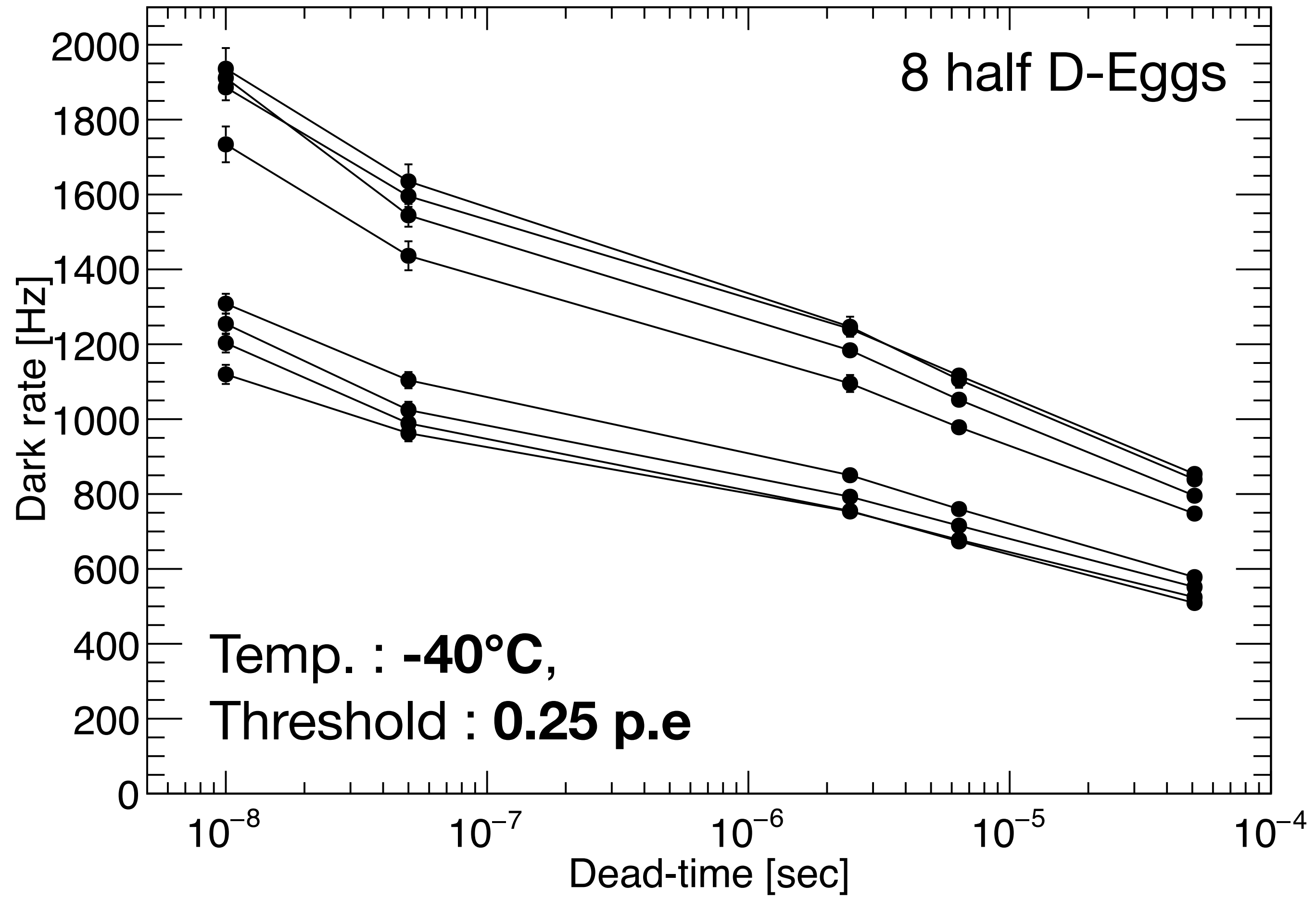
- Dark rates get at low temperature (-20℃ – -40℃)
- Need to accept high dark rate due to high QE

Glass

- Very important at low temperature
- ^{40}K contamination in a glass is know to a noise source
- Developed ^{40}K-reduced glass sphere
  - 0.0163 % by weight (0.03% for IceCube)
  - 4 Bq/Kg (beta), 0.7 Bq/Kg (gamma)
- Glass is UV-transparent for noises too!

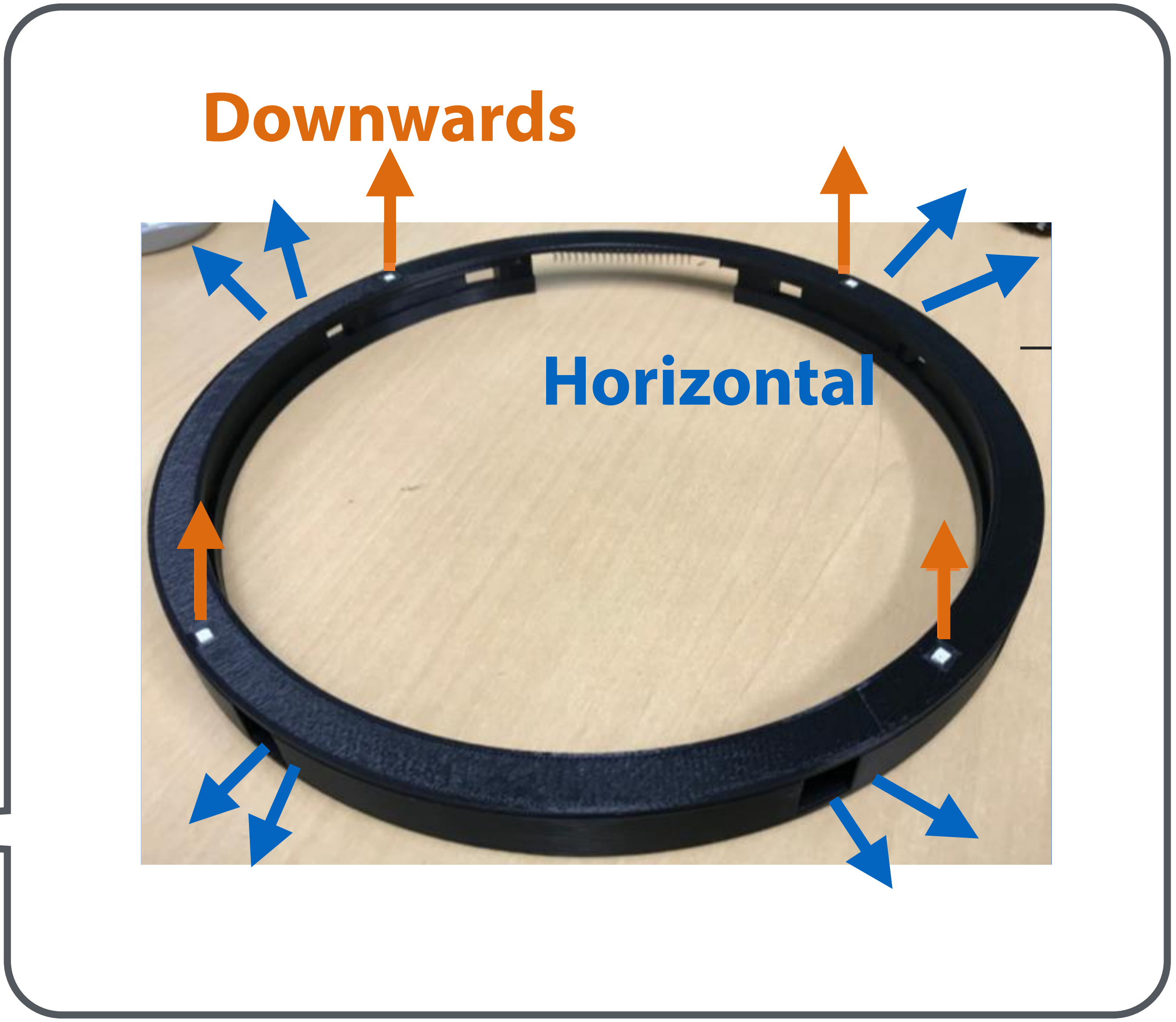
Dark Rates At Low Temperature





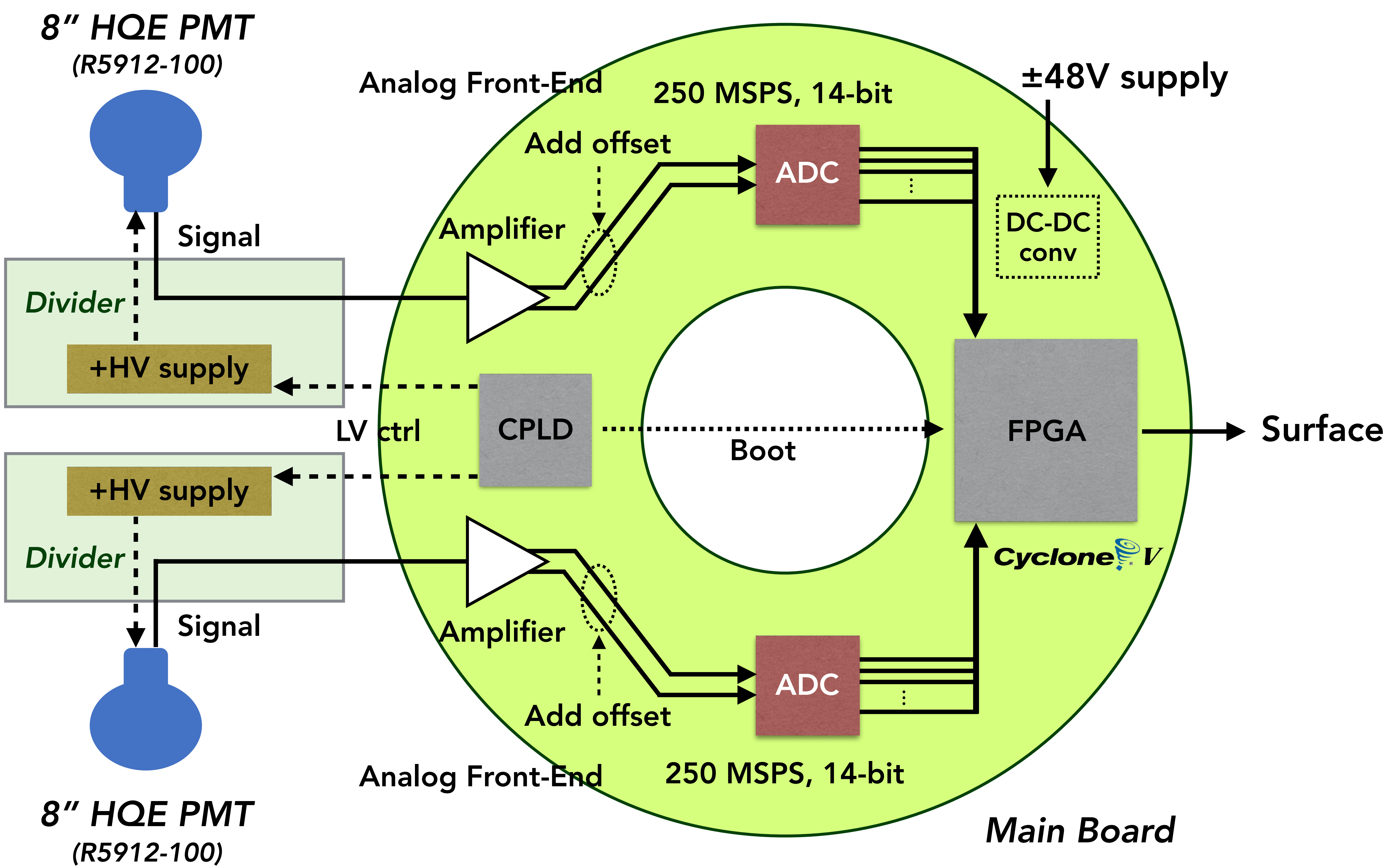
- **Correlated component (dt < ms) is important at low temperature**
  - Time interval distribution follows the IceCube model
- **Obtained dark rates of D-Egg: 800–1200 Hz @ -40℃, 2.45 us dead-time**
  - Contribution from PMT : 450Hz (with small fluctuation)
  - Same level as IceCube DOM's by the laboratory measurements
- **Continue glass studies to reduce dark rates for the Gen2 array**

LED Flasher in D-Egg



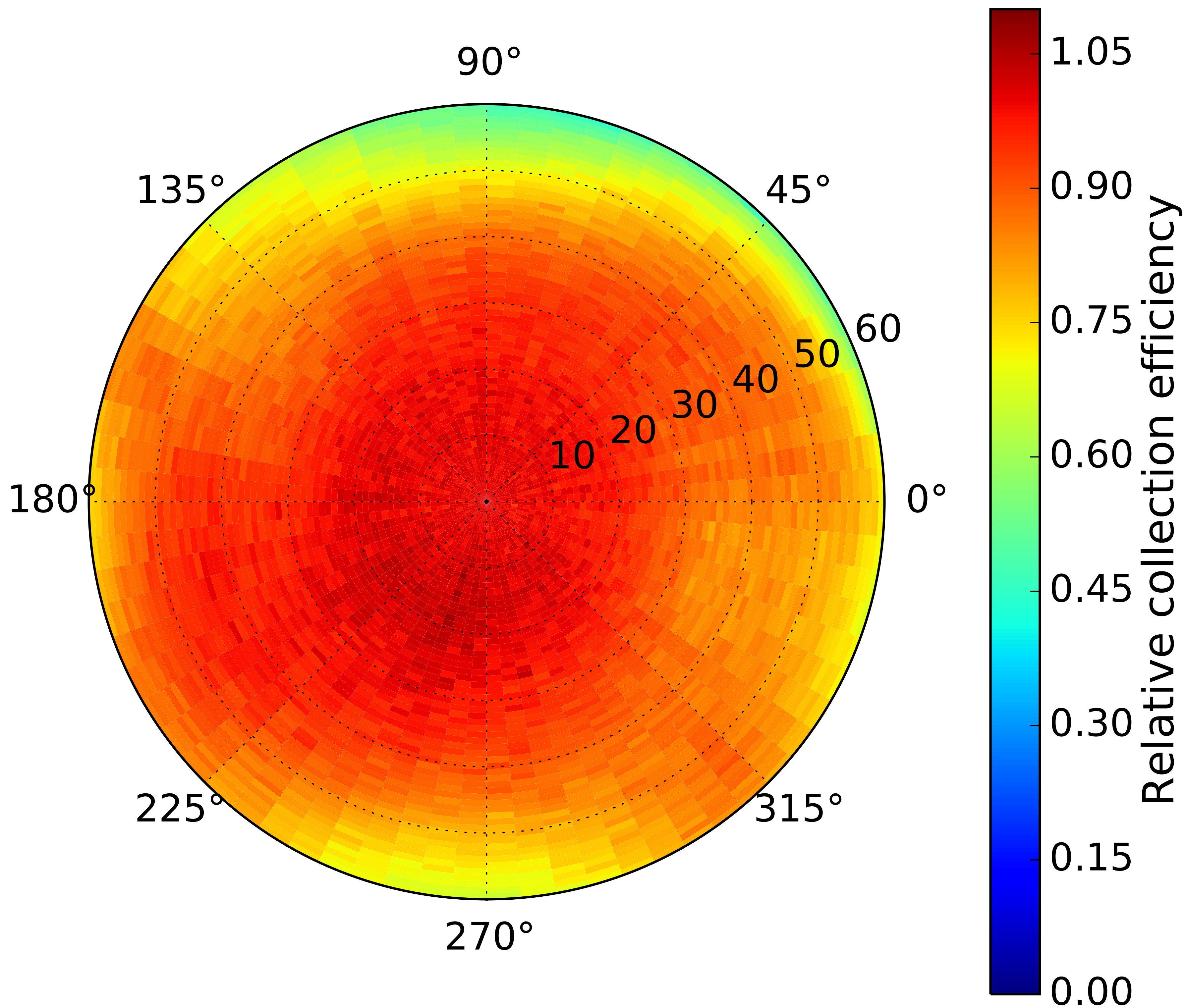
- **D-Egg stores a LED Flasher ring surrounding the bottom PMT**
  - 4 x downward (3-colored) LEDs & 8 x horizontal LEDs
  - LEDs will be optically coupled to gel & glass
- **Simulation studies are ongoing to optimize LED Flasher specs**

Schematics



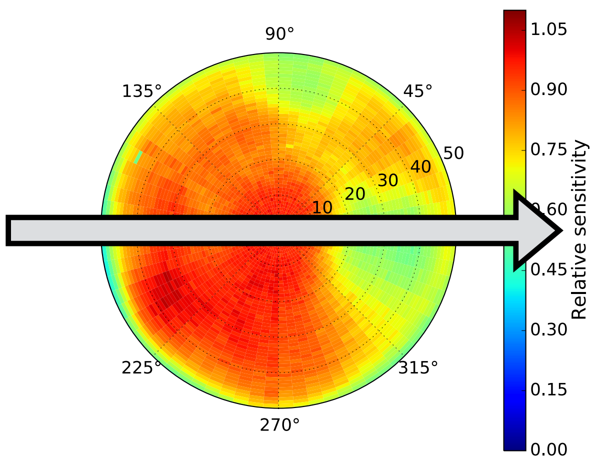
8″ HQE PMT
(R5912-100)
Analog Front-End
250 MSPS, 14-bit
±48V supply
Add offset
ADC
DC-DC
conv
Amplifier
Signal
Divider
+HV supply
LV ctrl
CPLD
Boot
FPGA
Surface
+HV supply
Divider
Cyclone V
Signal
Amplifier
ADC
Add offset
Analog Front-End
250 MSPS, 14-bit
8″ HQE PMT
(R5912-100)
Main Board

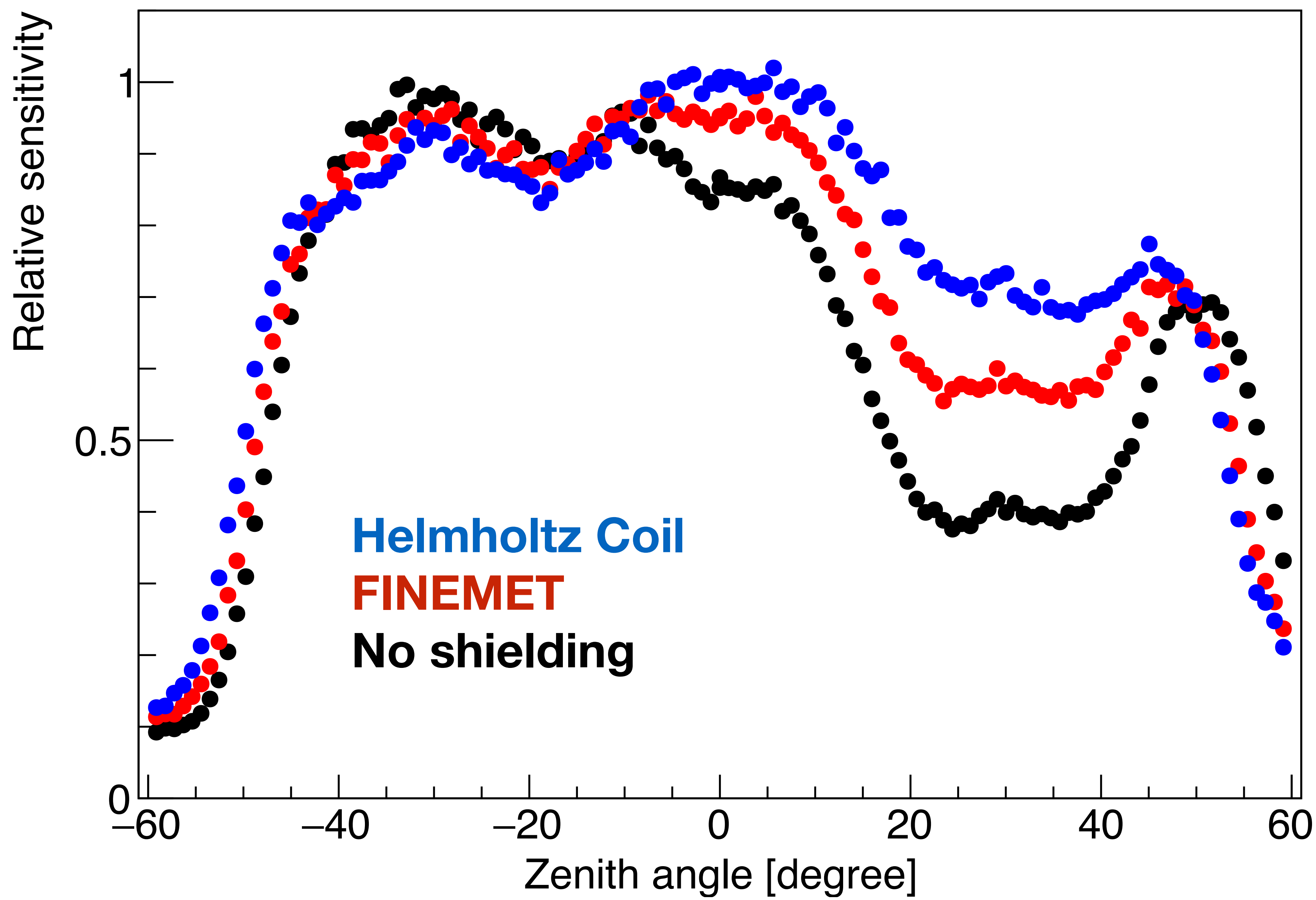
Bare 10" PMT Uniformity



TA1552 with a IceCube HV base (1.6 kV)

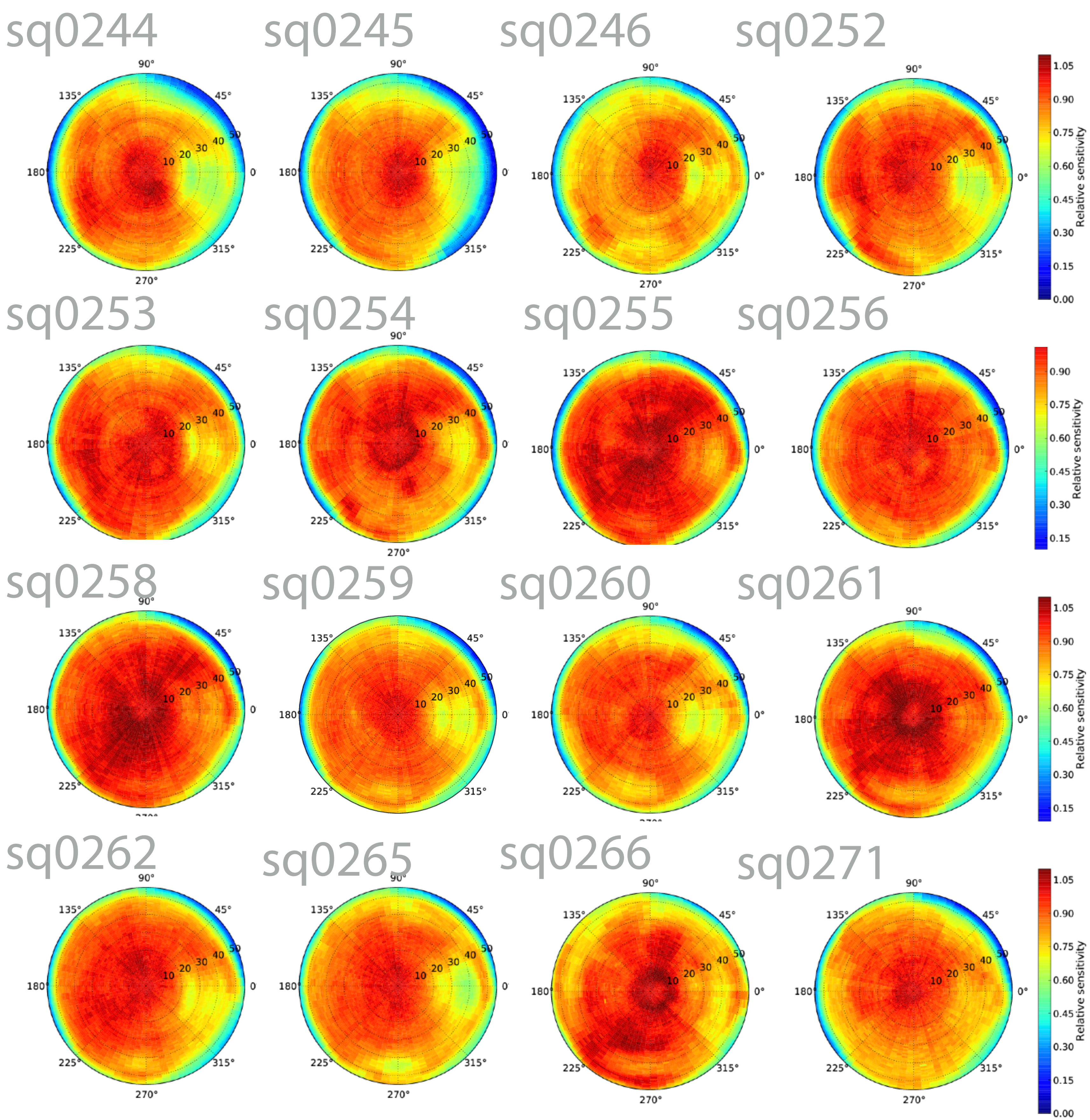
Slicing along the dynode structure

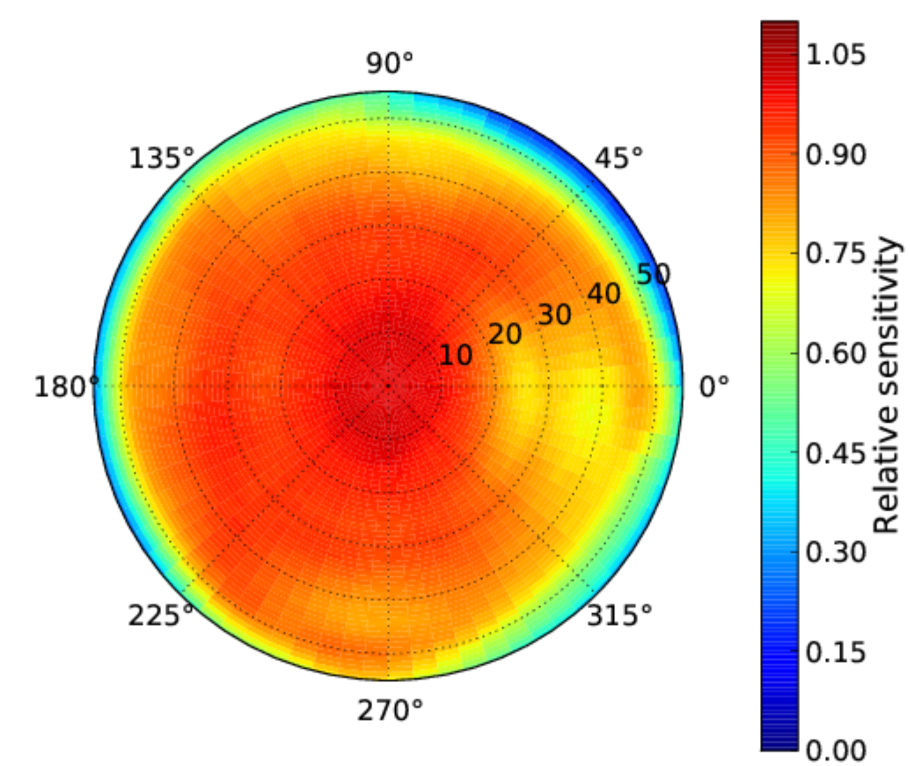




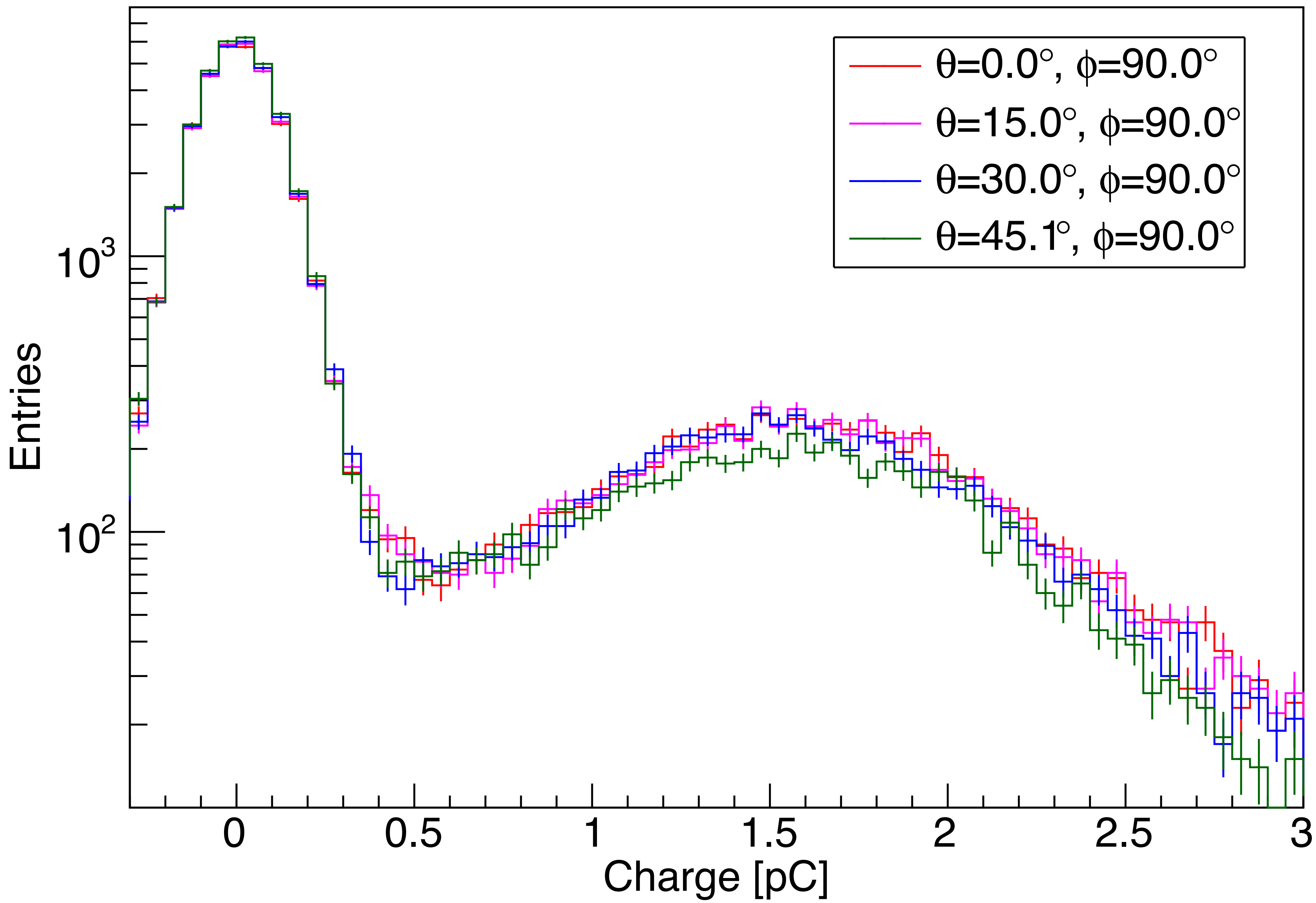
Sensitivity at the local minimum is mostly half compared to the center region (FINEMET option)

All measured uniformity maps



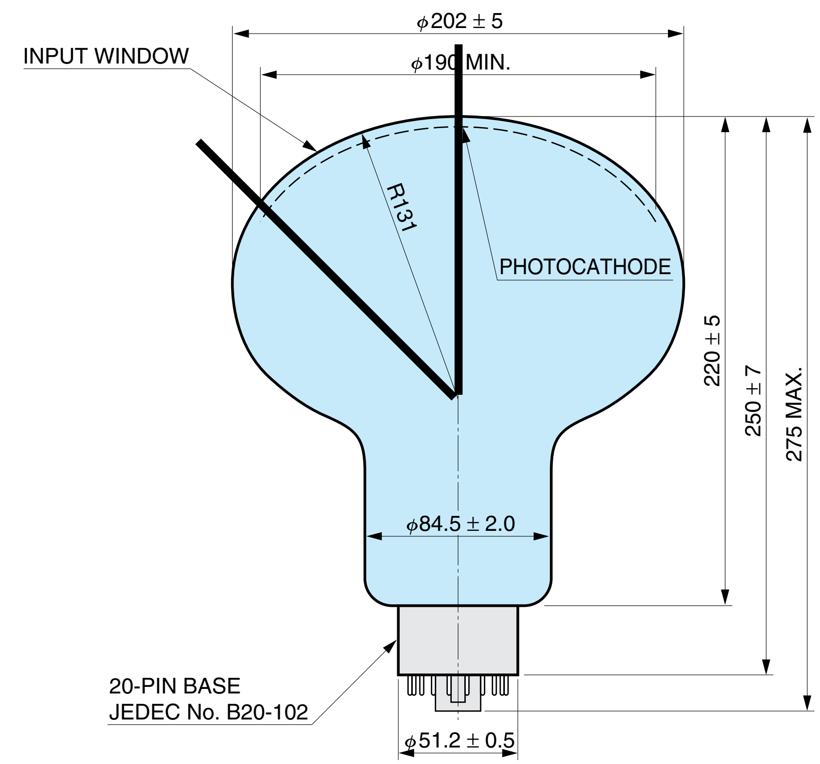


SPE distribution & Zenith angle dependence



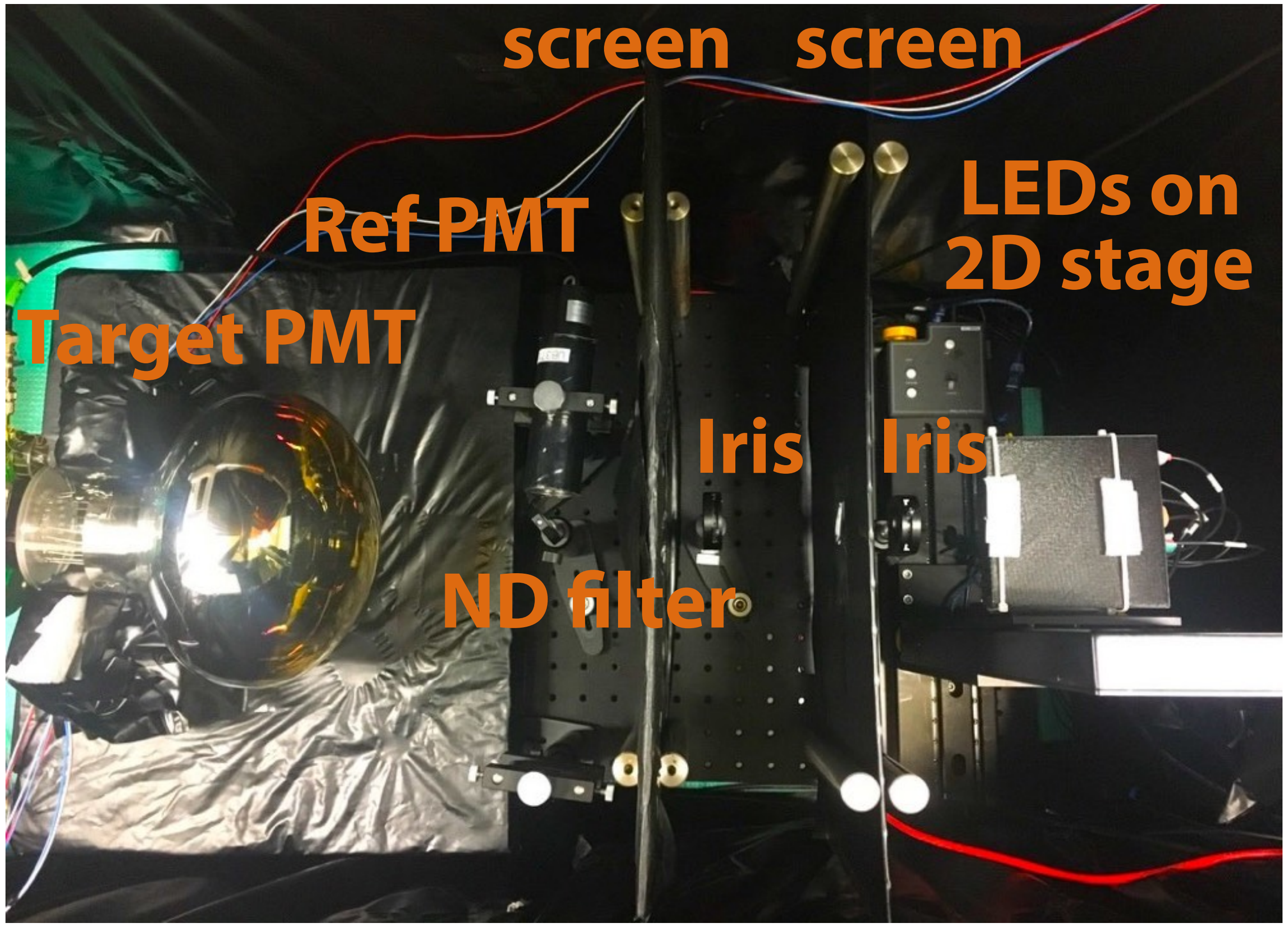
Chiba data

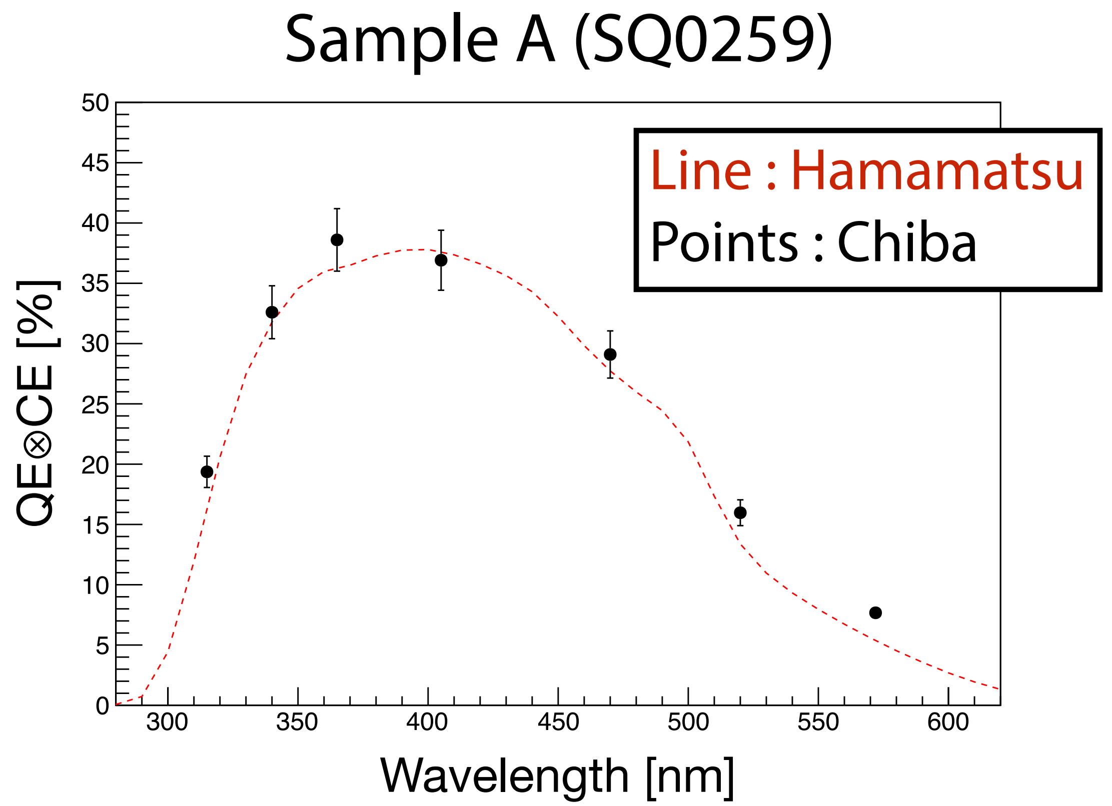
θ_{max}~47°

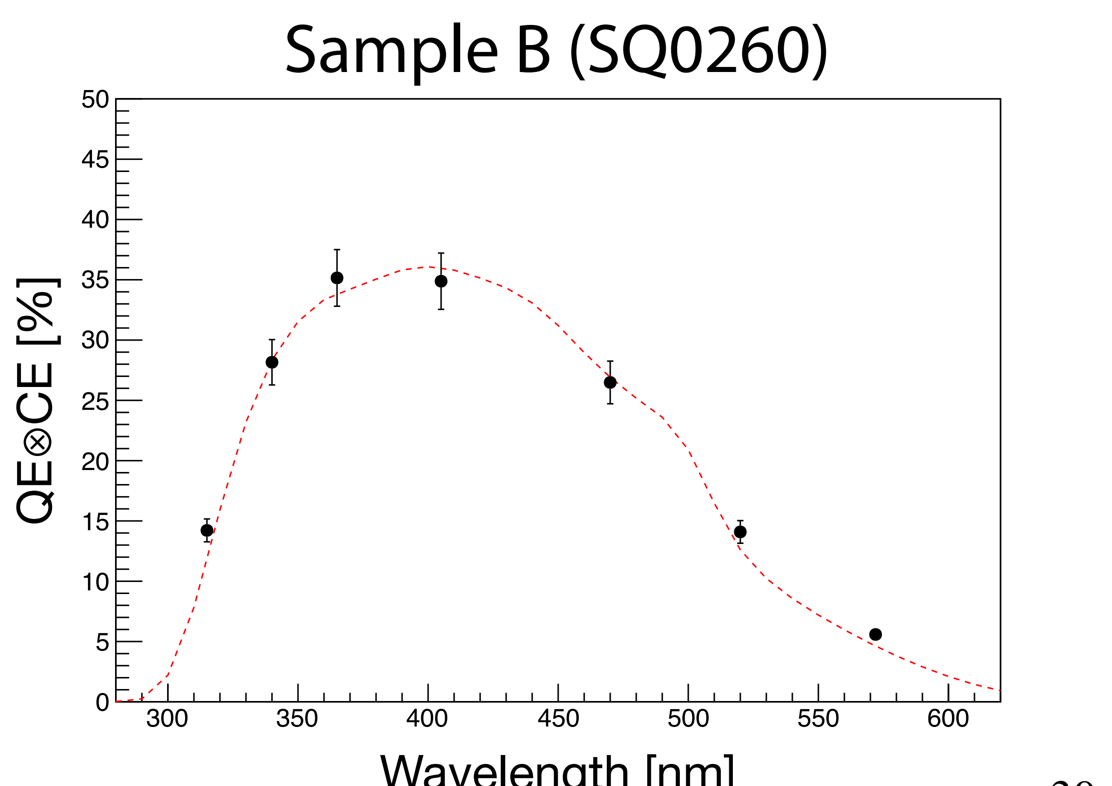


-> Next slide : Gain v.s. Peak to valley ratio

Quantum Efficiency & Spectral Response



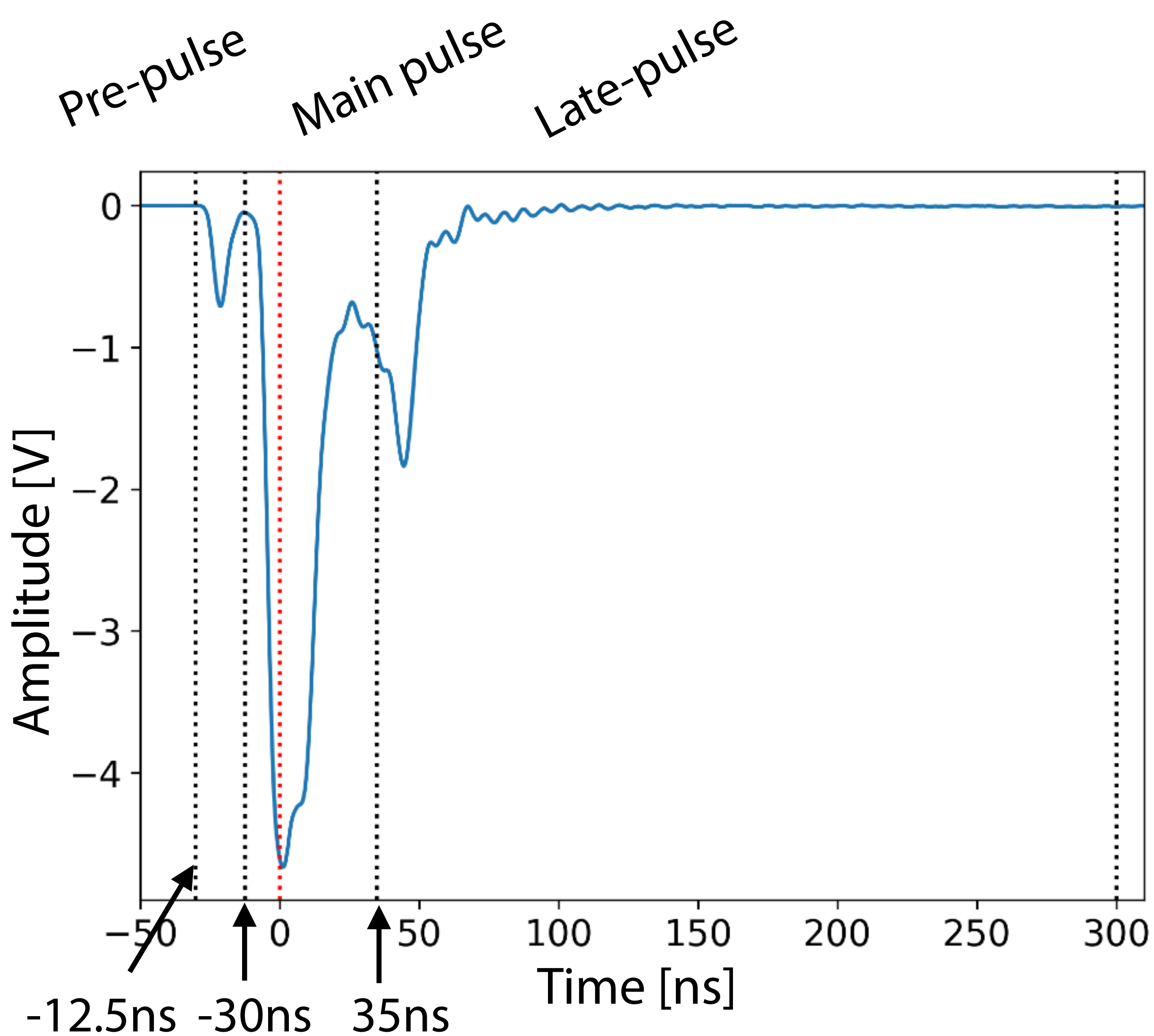


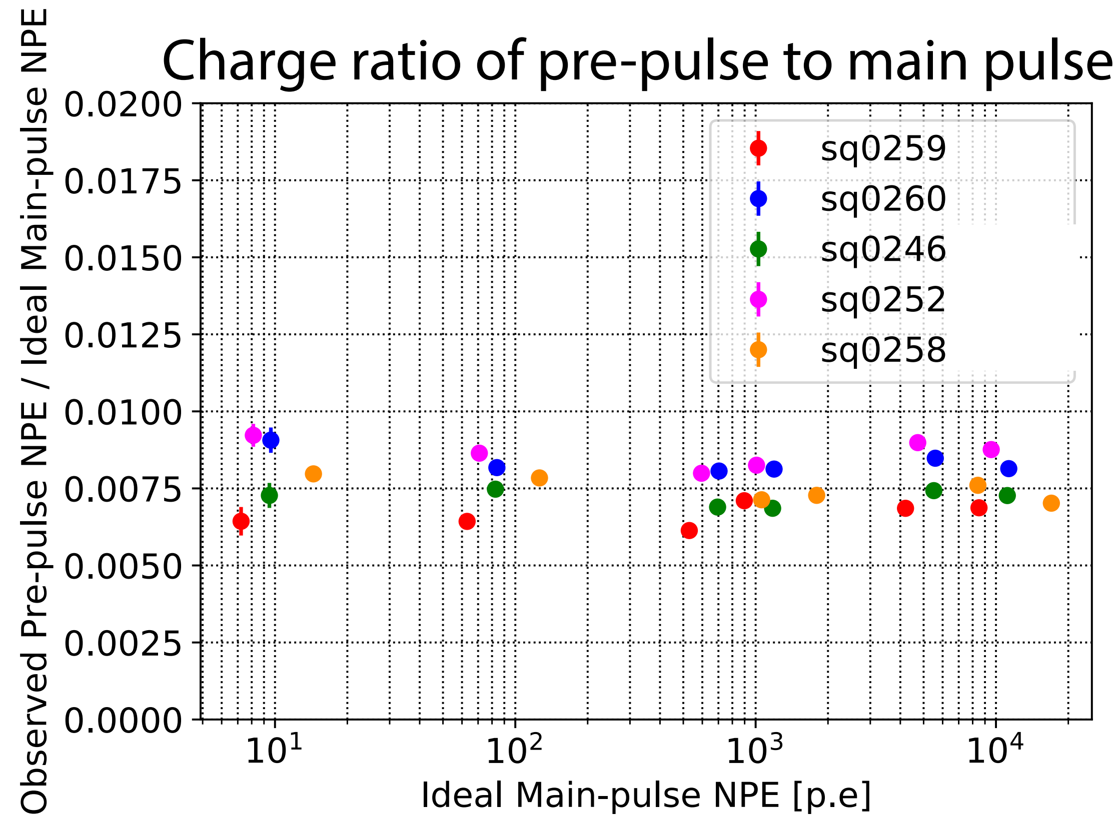


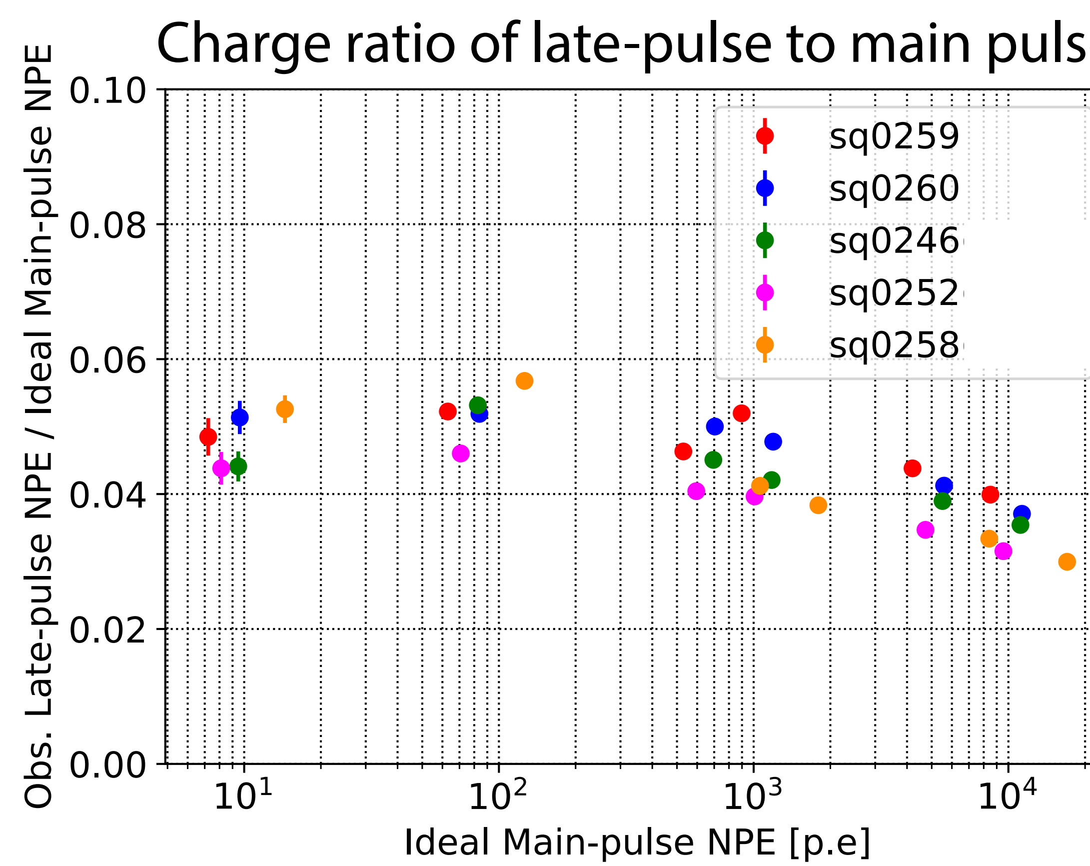
- **Multi-λ QE measurement @ Chiba**
  - λ=315, 340, 365, 405, 420, 520, and 572nm
- **Systematics under investigation**

Pre-pulse & Late-pulse

Chiba data



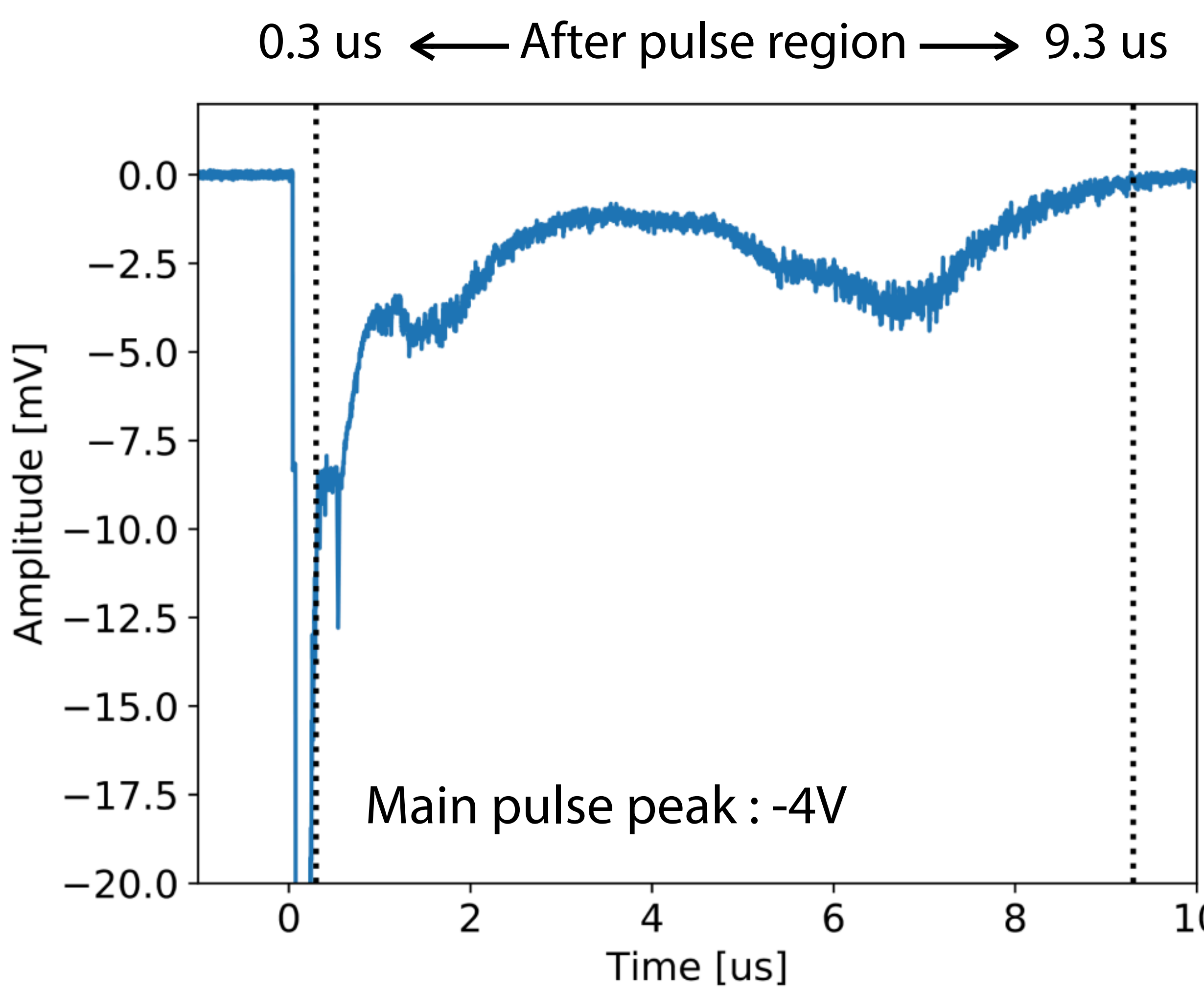


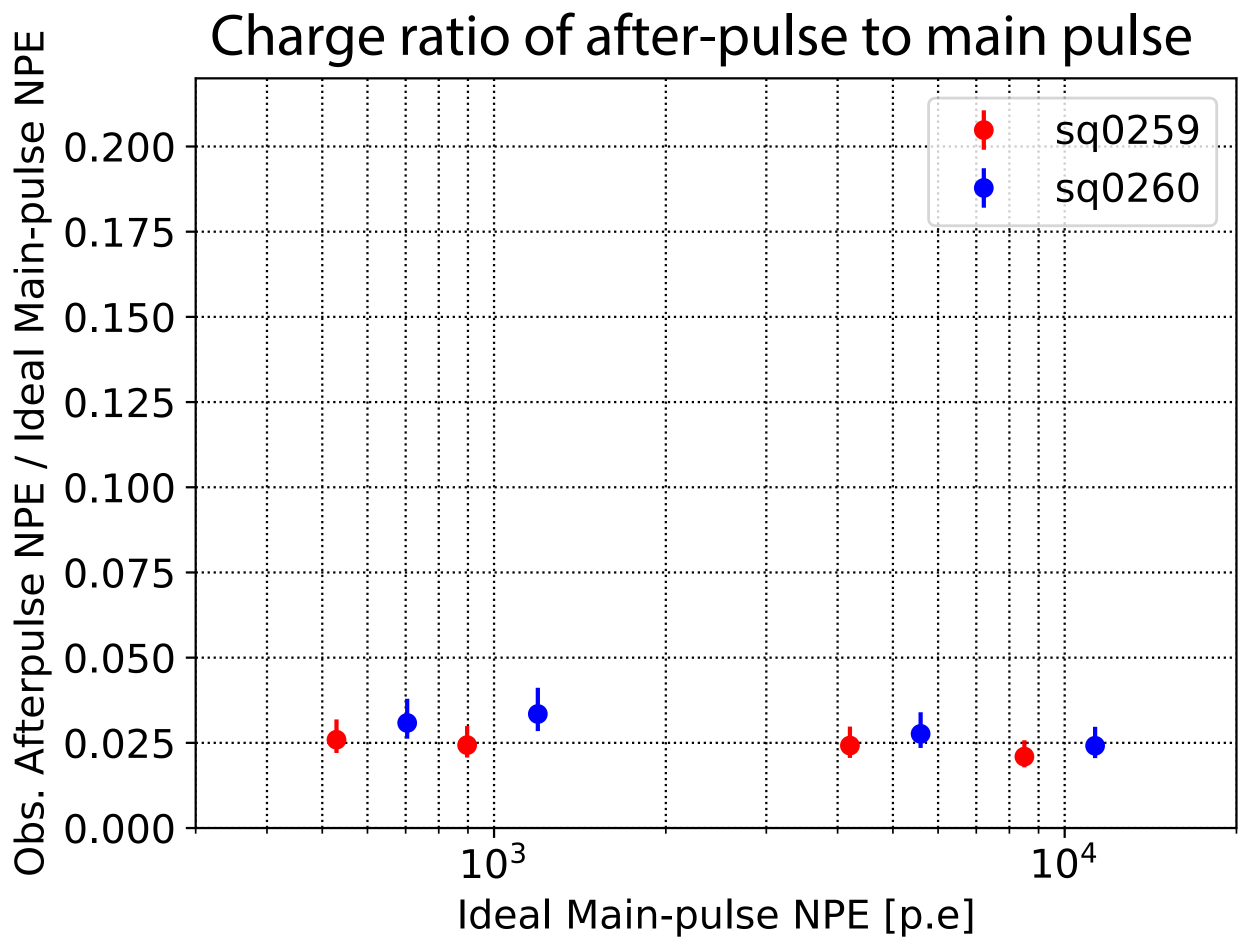


- **Observed pre-pulse ratio is 0.75 %**
- **Observed late-pulse ratio is 5 %**
- **PMT dependences look small**

After-pulse

Chiba data





- **Clear after-pulse peaks in us-scale after the main pulse**
- **Observed after-pulse ratio is 2.5 %**