Multi-PMT Optical Module Designs for IceCube-Gen2

ERLANGEN CENTRE
FOR ASTROPARTICLE
PHYSICS

Alexander Kappes
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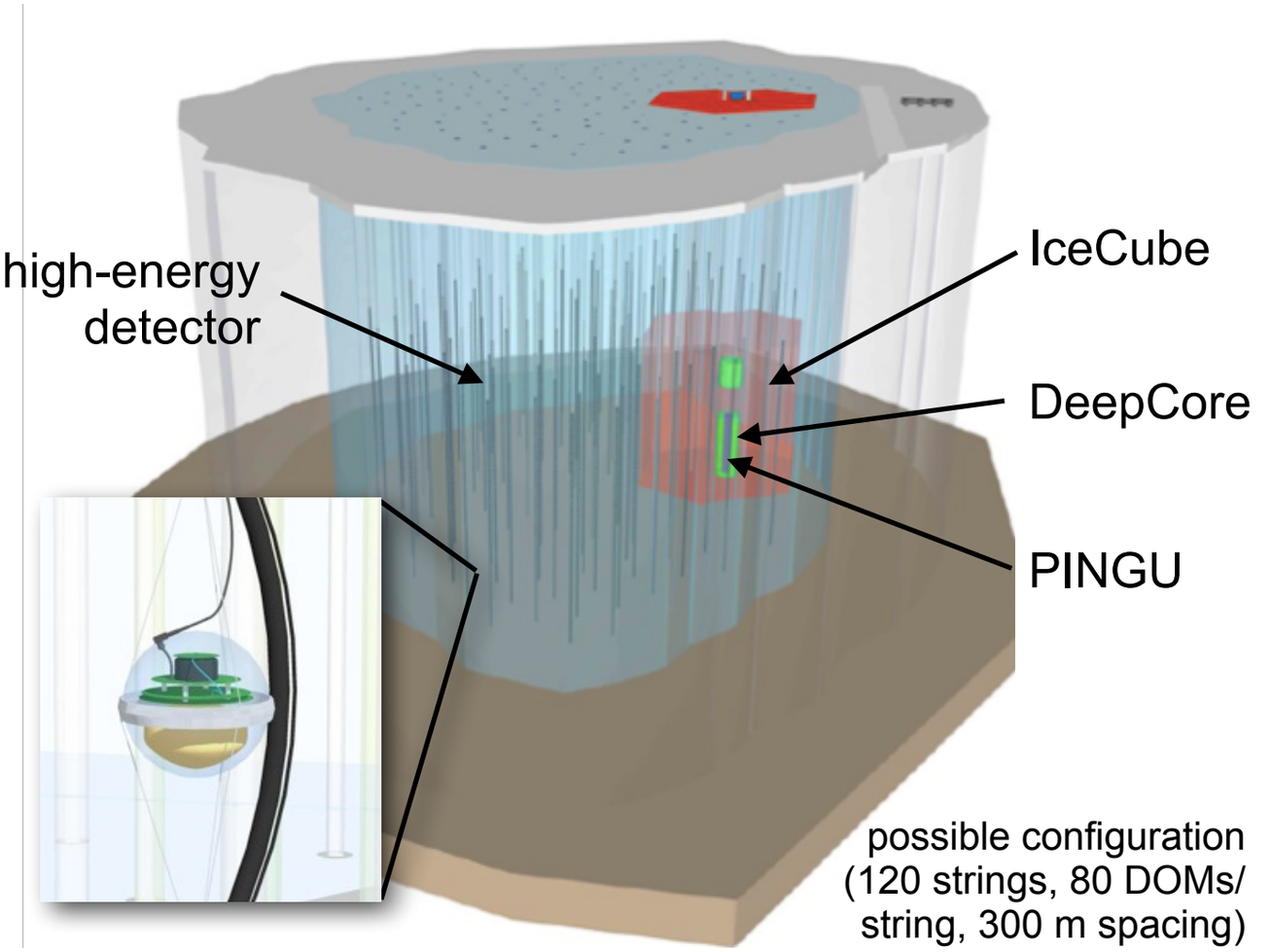
IceCube-Gen2

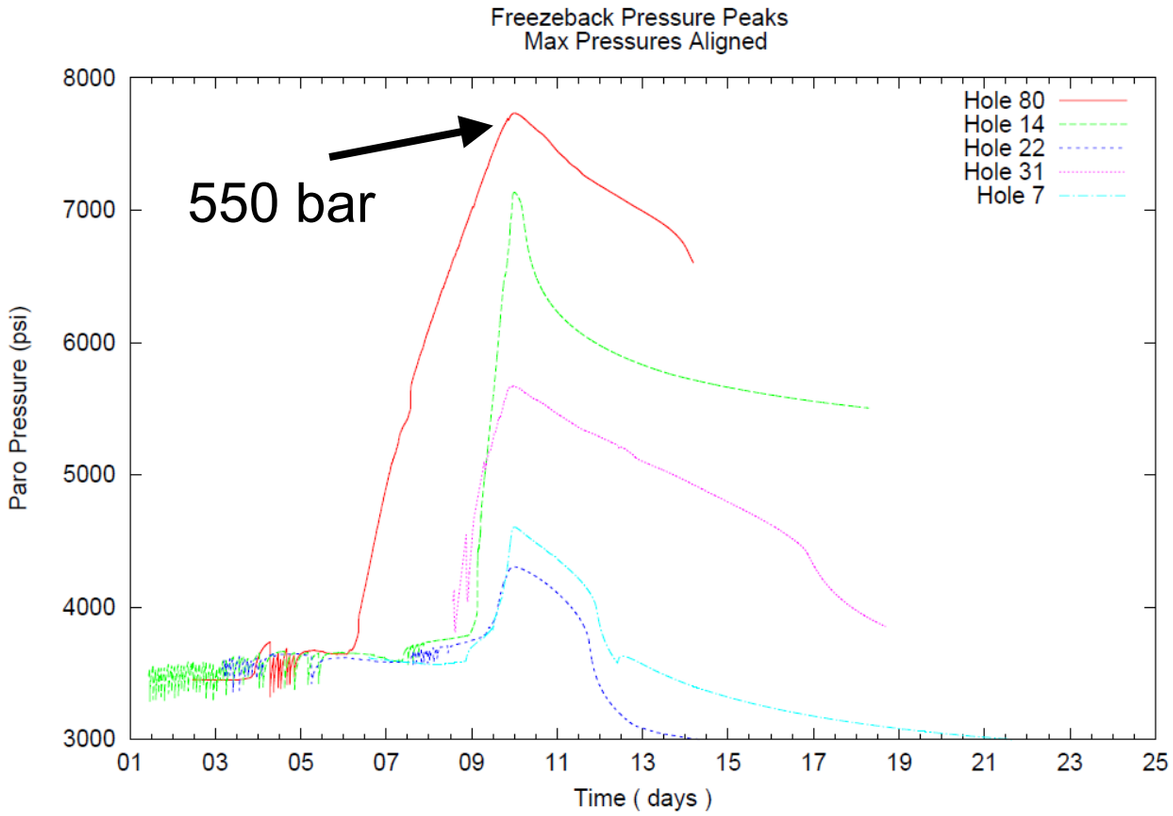
- Next-generation neutrino telescope at South Pole
- Physics goals:
  - neutrino astronomy (high-energy detector)
  - neutrino mass hierarchy (PINGU)
- Instrumentation
  - ~10,000 optical sensors on $\mathcal{O}(140)$ strings
  - $\mathcal{O}(500)$ m^2 photocathode area
  - 5–10 km^3 instrumented volume



IceCube-Gen2

Ambient conditions

- Temperature down to -45 ºC
- Pressure up to 550 bar (freeze-in)
- Optical modules limited to ⌀ ~14 inch
- Low ambient optical noise



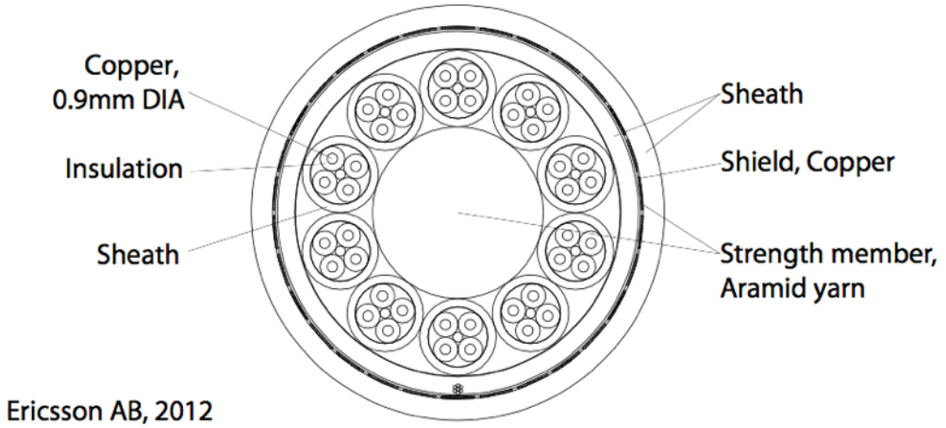
Connection to surface

- Power + communication through copper wires

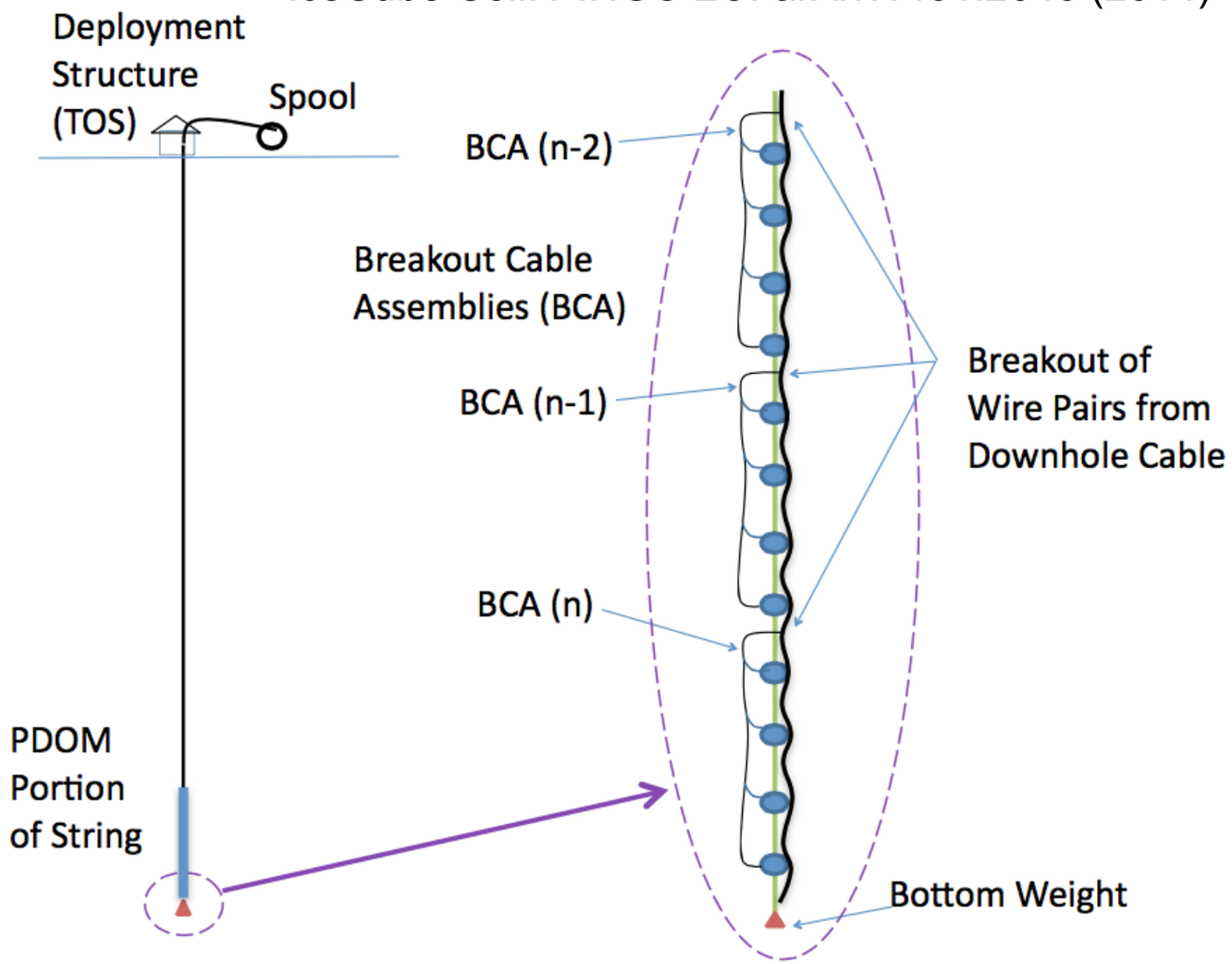
  DOM power usage limited by voltage drop from surface to -2500 m

  4 DOMs per pair: ≲ 2.3 W per DOM
  3 DOMs per pair: ≲ 3.2 W for DOM

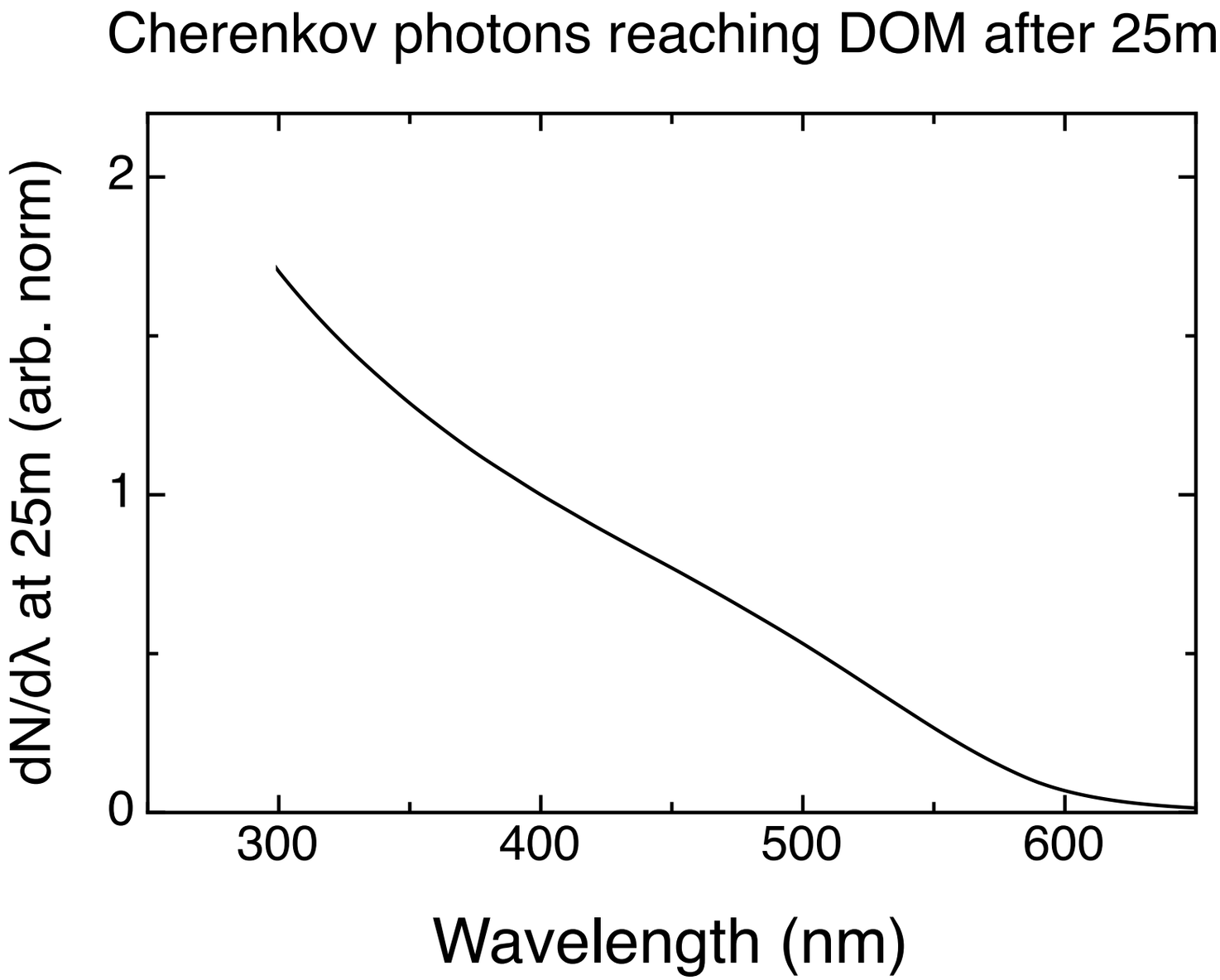
- Available bandwidth per module ~1 Mbit/s



IceCube Coll. *PINGU LOI* arXiv:1401.2046 (2014)



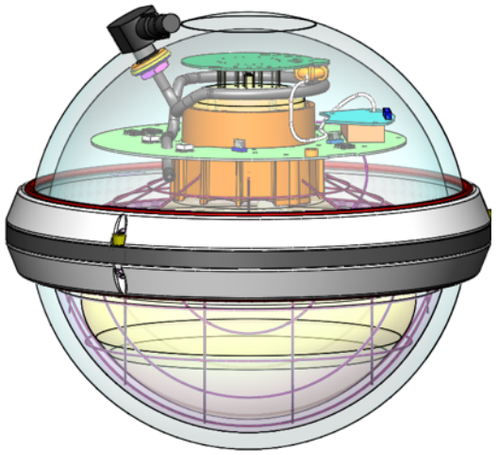
Cherenkov photon spectrum



Attenuation length
Λ_a=160m at 400nm
(scaled with standard
wavelength dependence)

(New) photosensor concepts for IceCube-Gen2

Gen2 DOM
(baseline)



DOM
Digital **O**ptical **M**odule

D-Egg

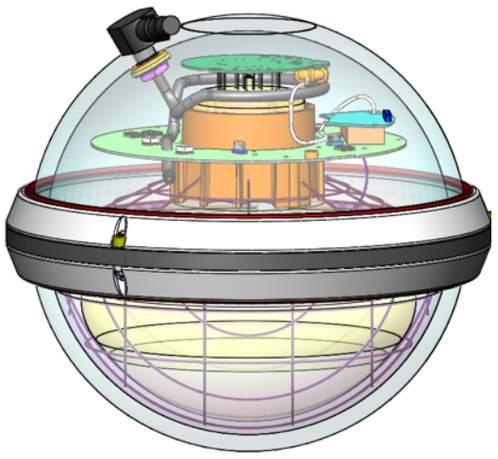
mDOM

WOM

- Baseline concept modernizes/simplifies proven IceCube design
- Alternative sensors for some portion of detector under investigation

(New) photosensor concepts for IceCube-Gen2

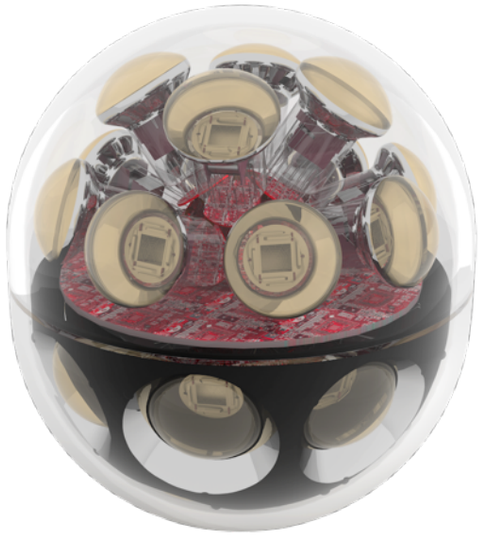
Gen2 DOM
(baseline)



DOM
Digital **O**ptical **M**odule

D-Egg

mDOM



Focus of this talk

WOM

Later talk
(Dustin Hebecker)

- Baseline concept modernizes/simplifies proven IceCube design
- Alternative sensors for some portion of detector under investigation

D-Egg

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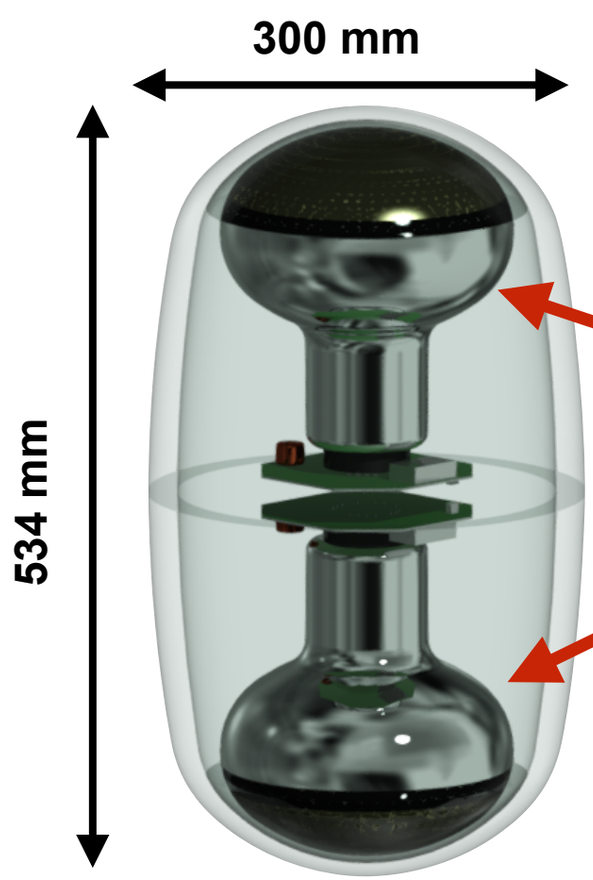
Chiba University

D-Egg concept

- Goals
  - increase sensitivity in particular @ low wavelengths (UV)
  - improve uniformity of acceptance
- Basic features:
  - 2x 8” Hamamatsu R5912-100 HQE (up-down symmetry)
  - Elliptical pressure vessel (⌀30cm)



Hamamatsu R5912-100 HQE

Pressure tests

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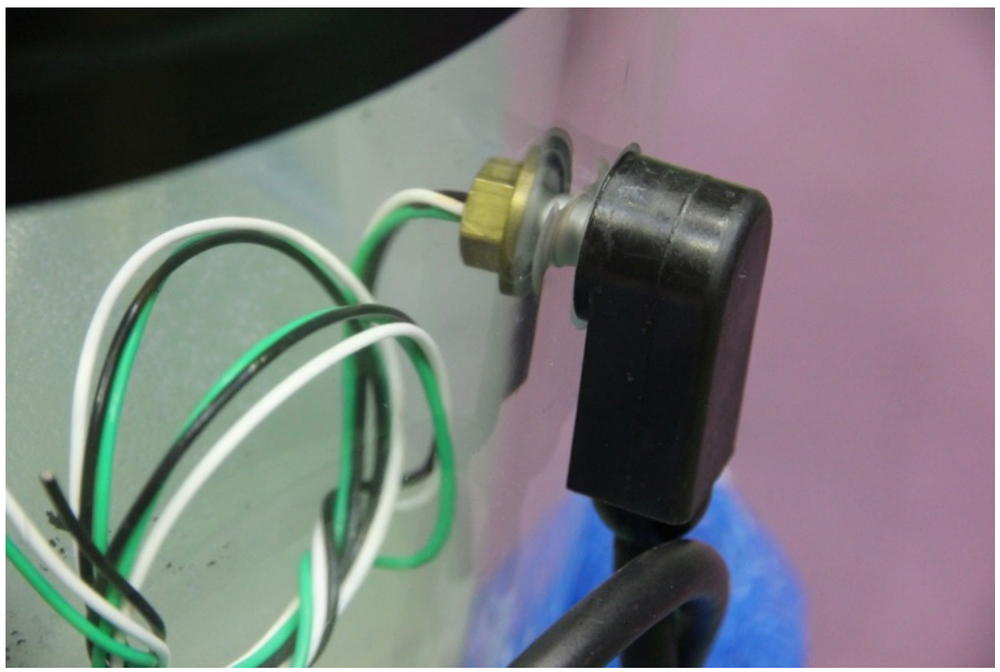
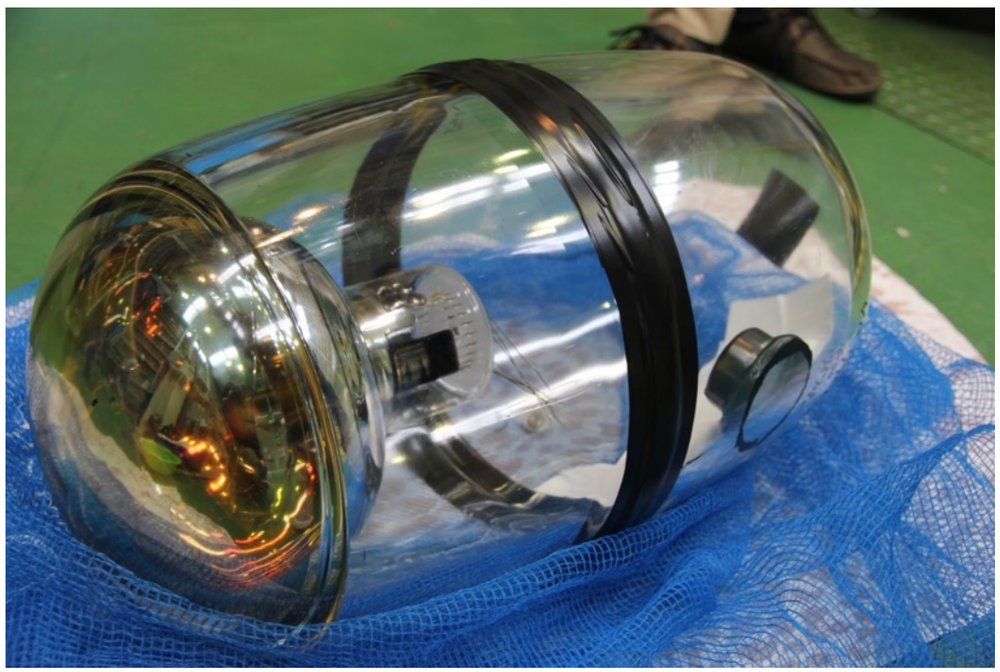
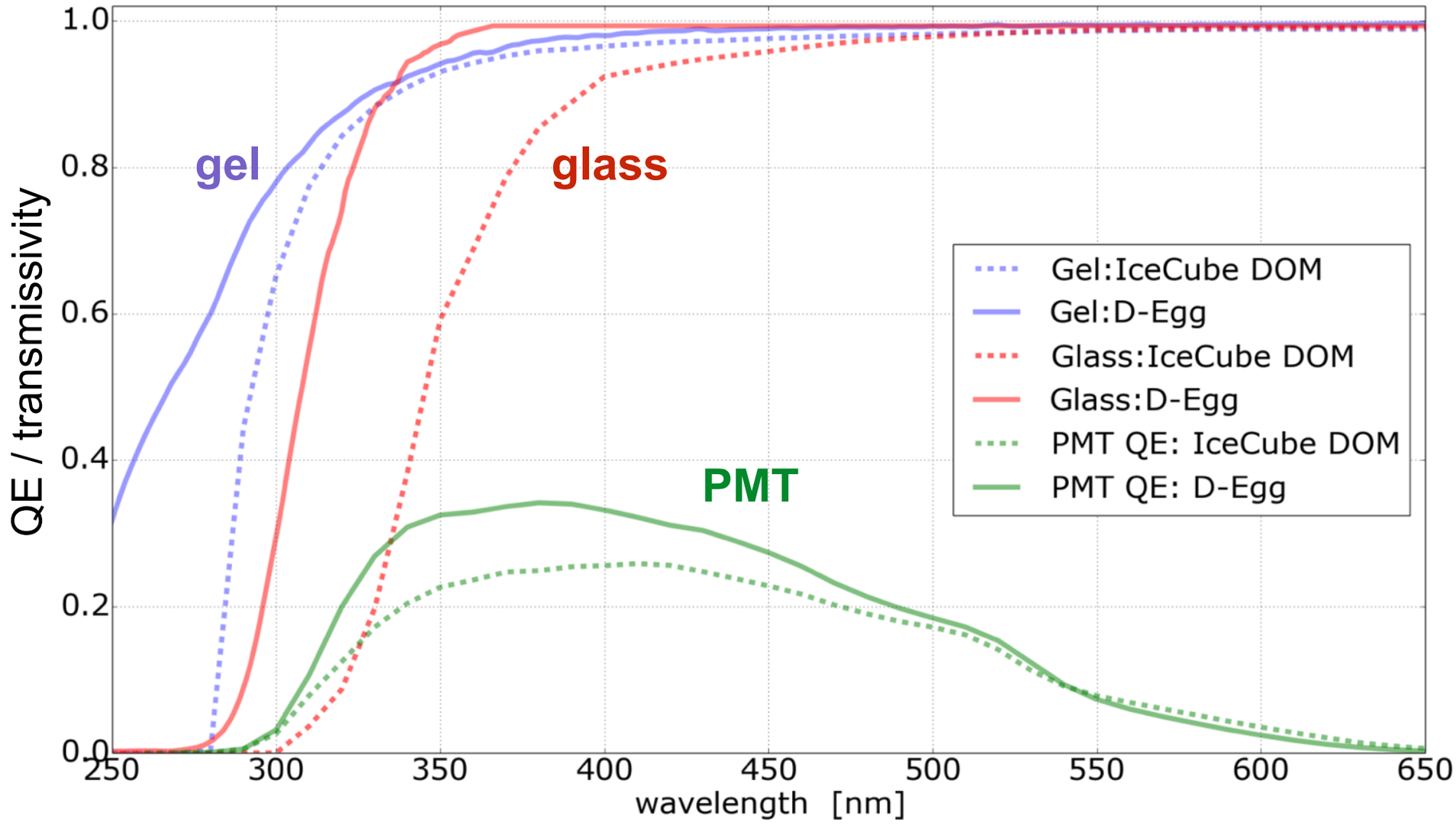
Chiba University

- pressure tests @ 70 MPa (700 bar)
- included penetrator + dummy PMT + gel
- penetrator & PMT OK, gel created bubbles (under investigation)





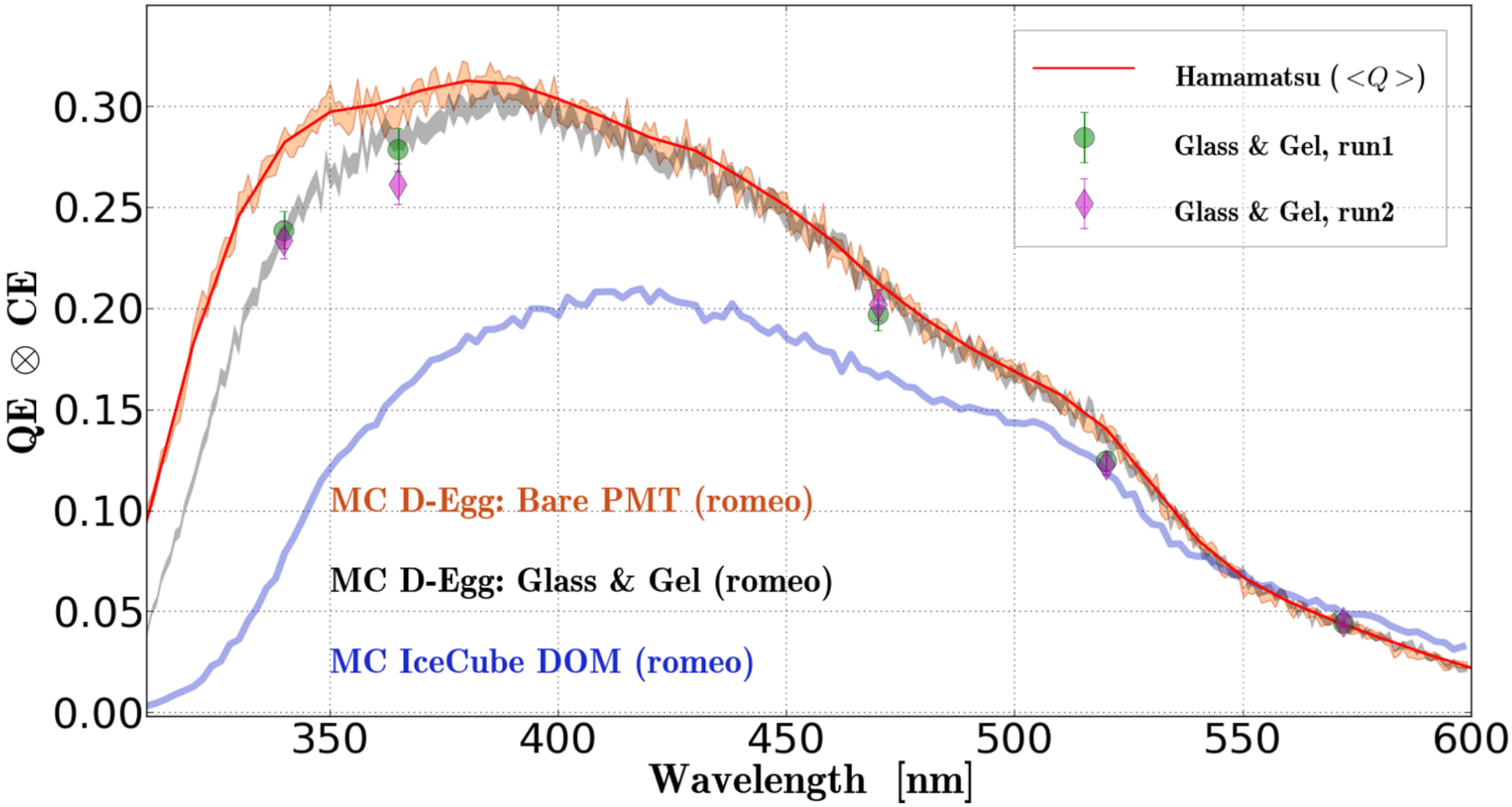
UV sensitivity – limiting factors



- Pressure vessel: borosilicate glass with enhanced UV transparency (reduced Fe_2O_3)
- Gel: new development with enhanced UV transparency

Quantum and collection efficiencies

- 8” Hamamatsu R5912-100 HQE:
  high sensitivity in UV range



Angular acceptance of module

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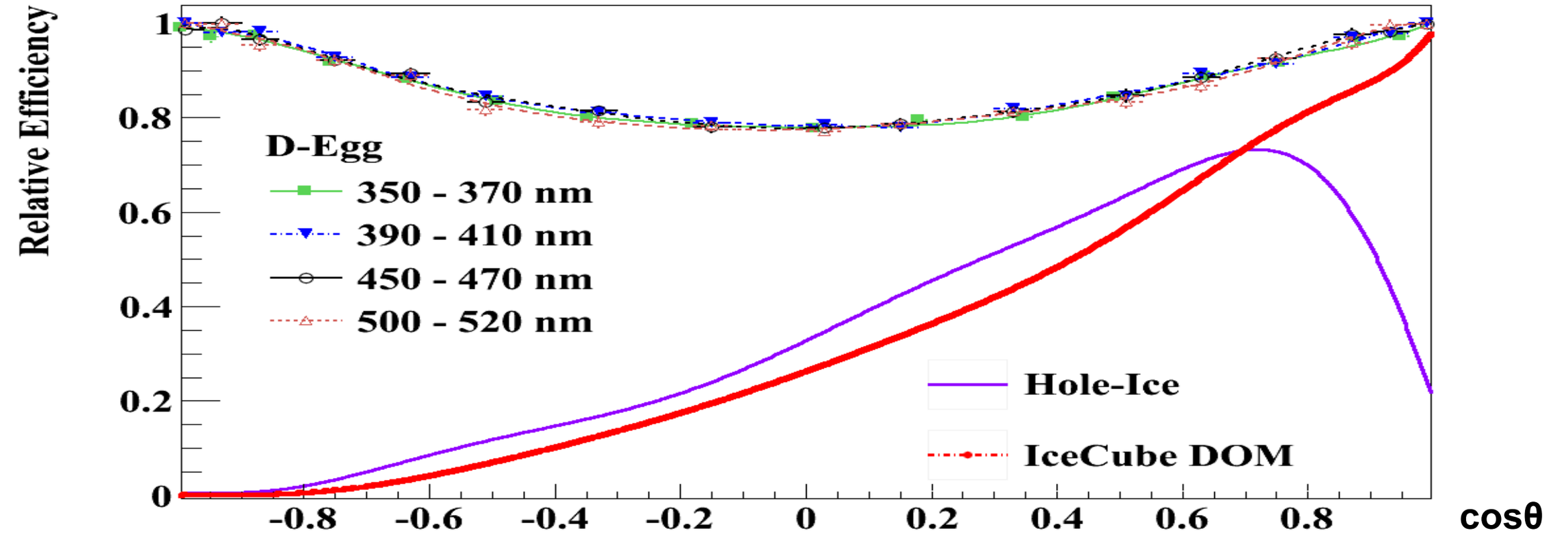

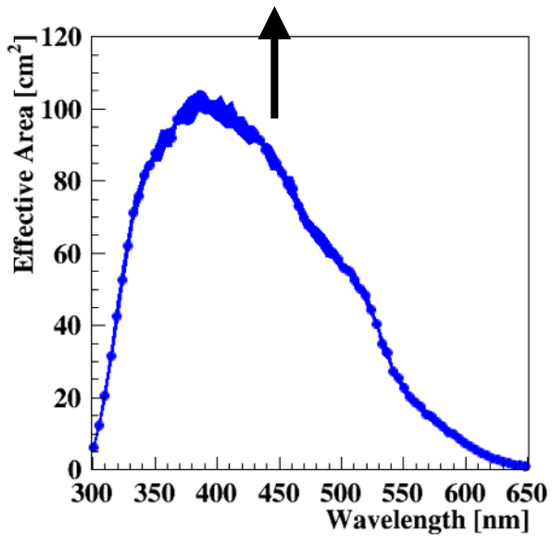

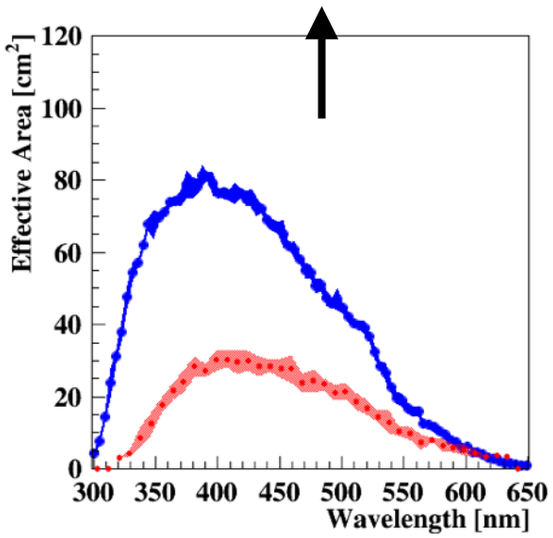

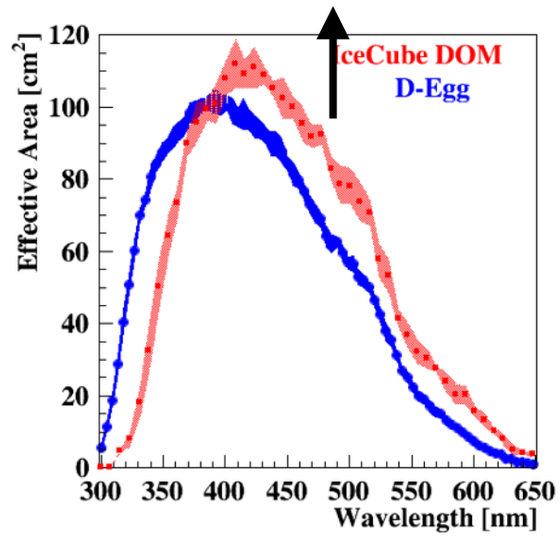

Multi-PMT DOM

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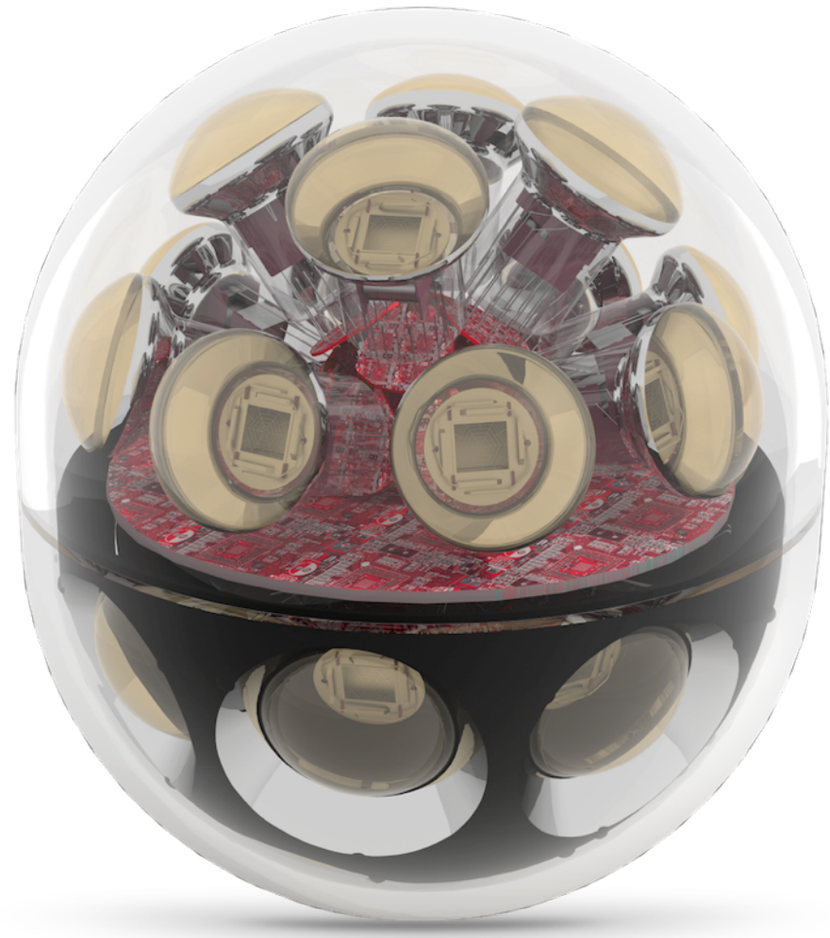
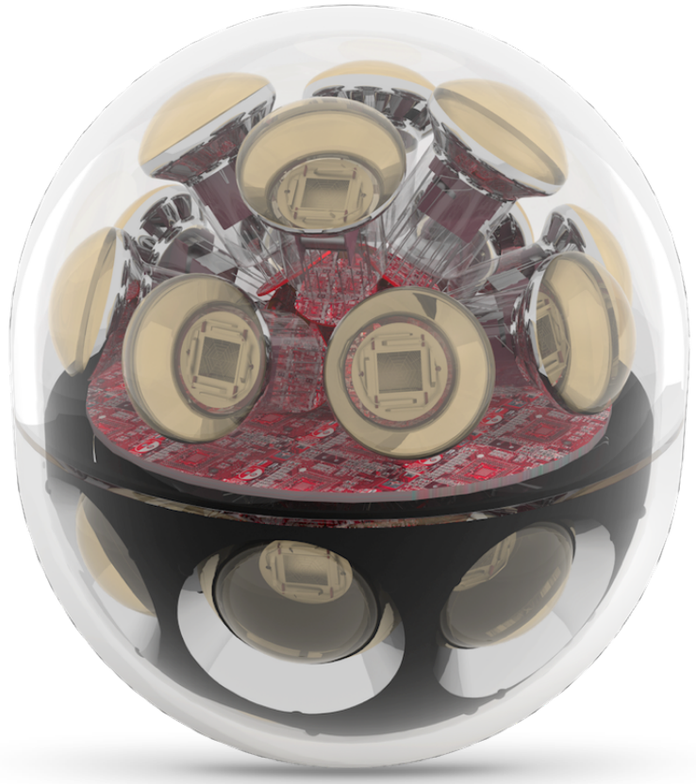
A. Kappes
T. Kittler
M. Tselengidou

A. Bänisch
A. Kölpin
S. Lindner
J. Röber



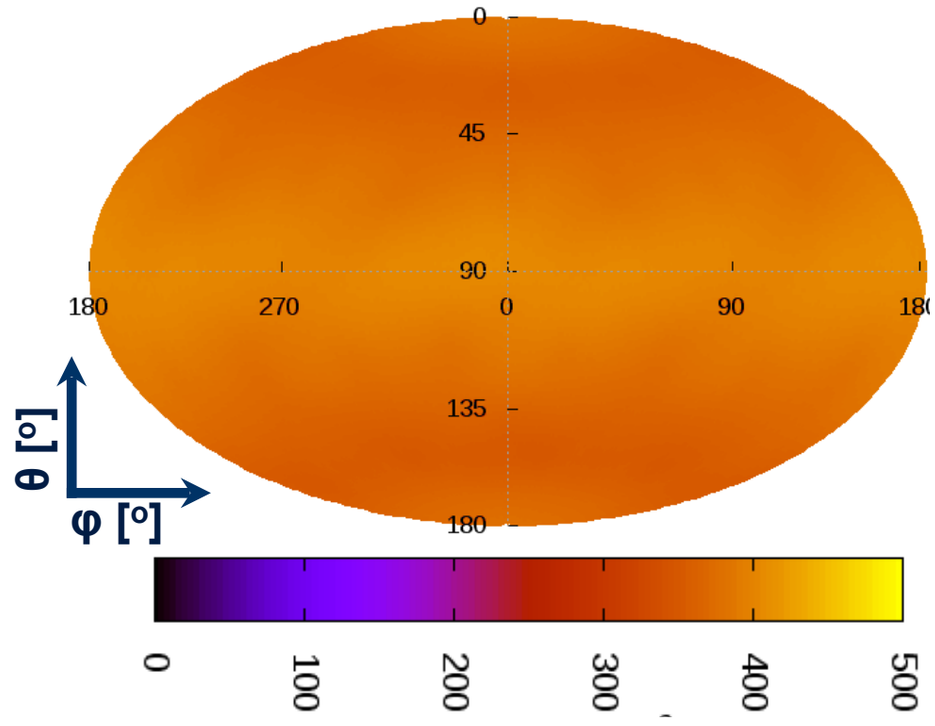
IceCube mDOM

- Diameter: 14 inch
- 24x 3 inch PMTs (Hamamatsu R12199-02)
- Includes full digitization and IceCube-DAQ communication electronics



Advantages compared to IceCube-DOM

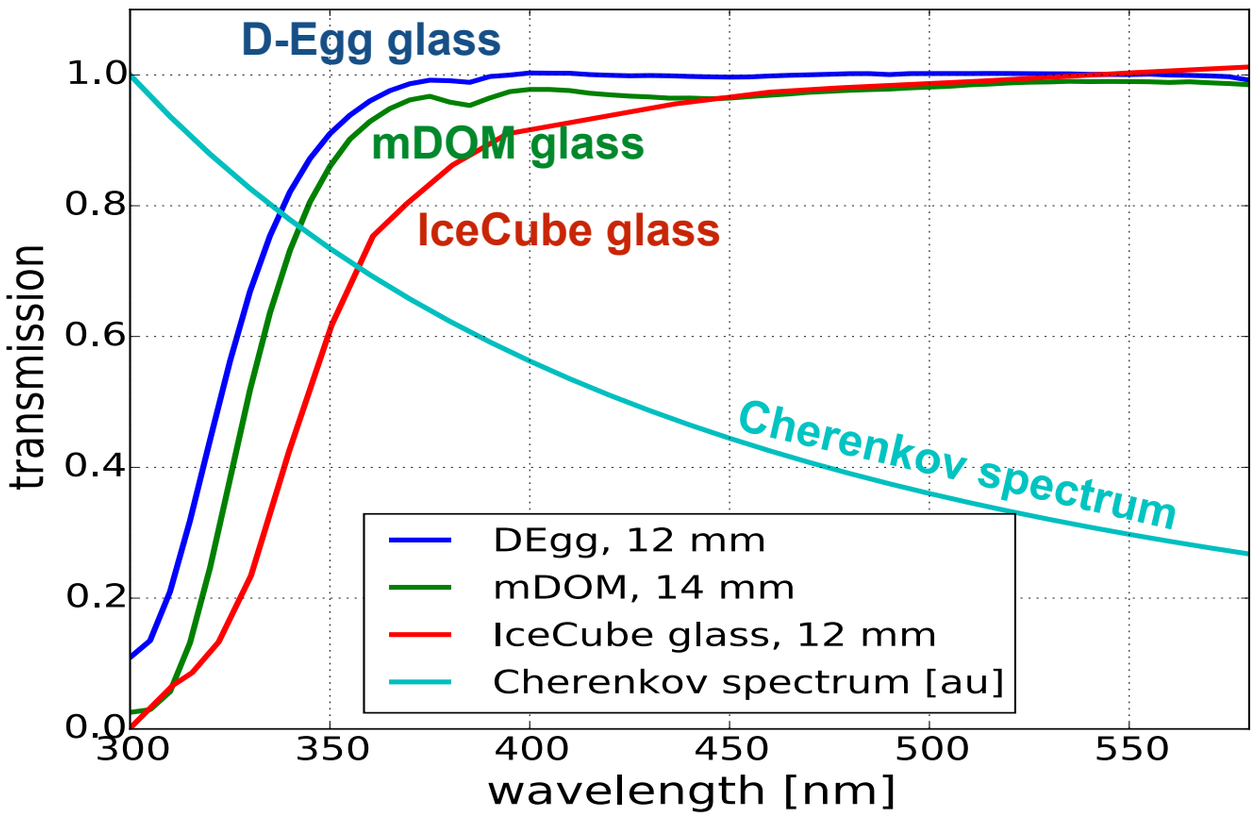
- Doubled effective area
- Uniform 4π angular effective area
- Local coincidences (e.g. for bckg suppression)
- Directional sensitivity
- Higher dynamic range



effective area (cm^2) @ 470 nm (no QE & CE)

Pressure vessel

- Developed in cooperation with Nautilus
  - 14” sphere with cylindrical extension (latter for accommodation of electronics)
  - glass thickness: 14 mm
  - pressure rating: 700 bar (to be tested)
- Production with same technique as “standard” glass spheres → low price
- First prototypes ordered (delivery expected in Oct / Nov)

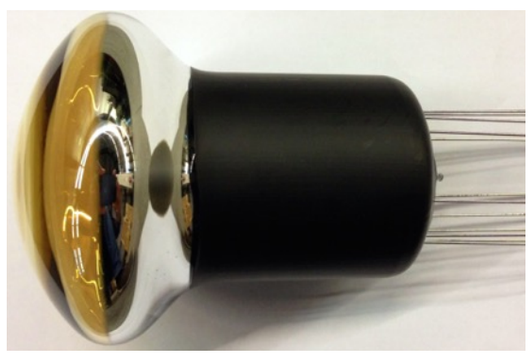


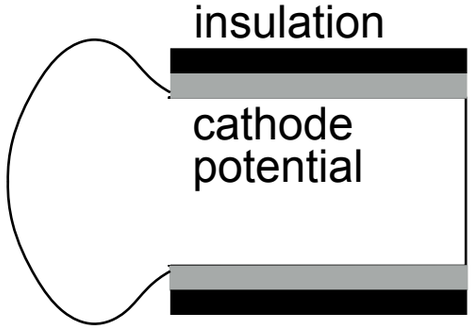
Currently considered PMTs

Hamamatsu R12199-02

- photocathode Ø = 80 mm
- length = 98 mm /
  cylinder Ø = 52 mm
- TTS (FWHM) = ~3.5 ns
- peak-to-valley ratio = ~3.5
- gain ~5×10^6 @ ~1100 V

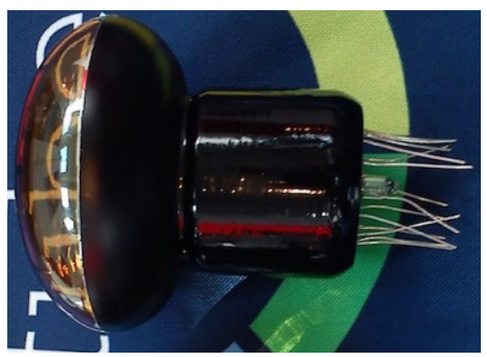
Hamamatsu R12199-02 HA





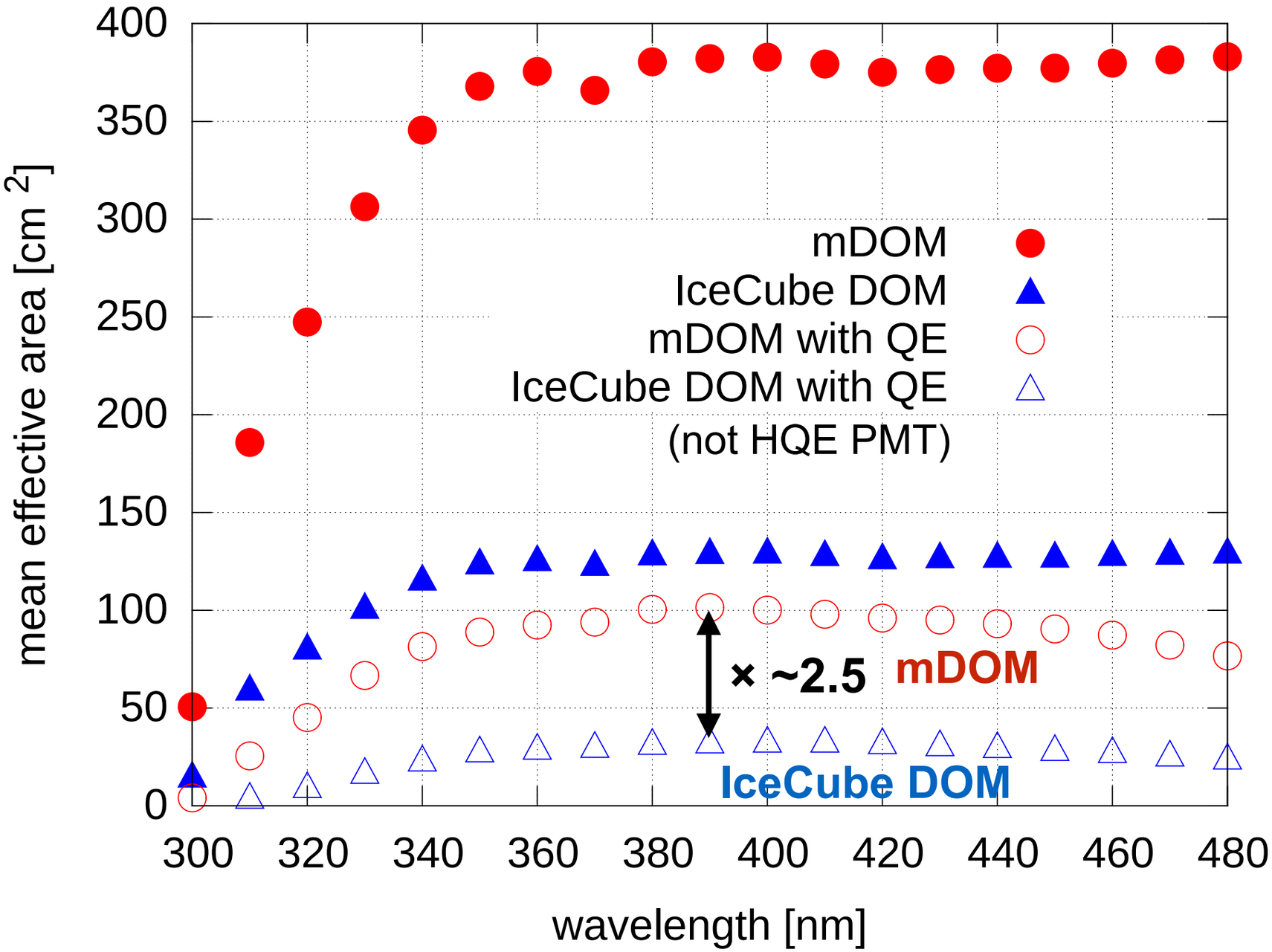
should help to keep dark count
under control if cathode @ −HV

ETEL 9320 KFL



- photocathode Ø = 87 mm
- length = 95 mm /
  cylinder Ø = 52 mm
- characteristics under
  investigation

Effective area from GEANT4 simulation



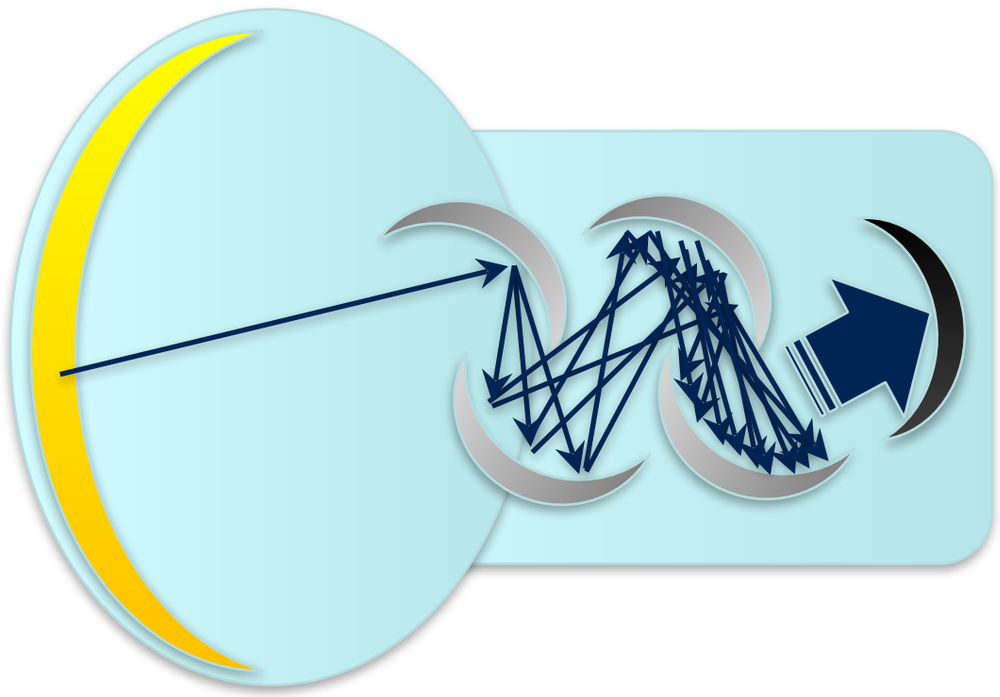
Dark-count rates

Glacial ice very radioactive clean

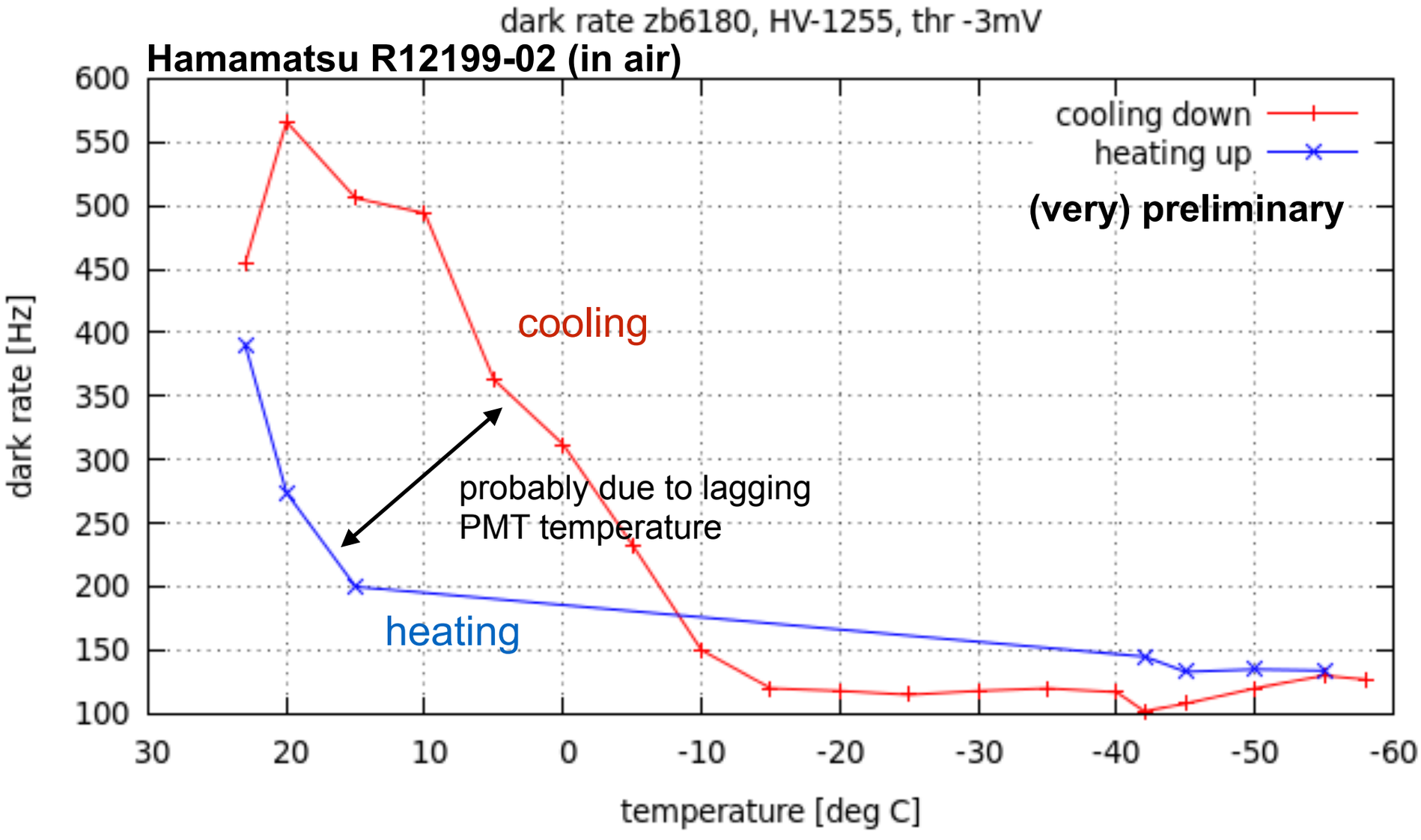
→ module itself dominant background source

Sources for dark count rate

- Radioactive decays (e.g. K40)
  (glass of PMT and pressure vessel)
- Field effect emission from PMT electrodes
  → not too high voltages/gains
- Thermal emission from photocathode
  → low temperatures



Dark count rate vs. temperature

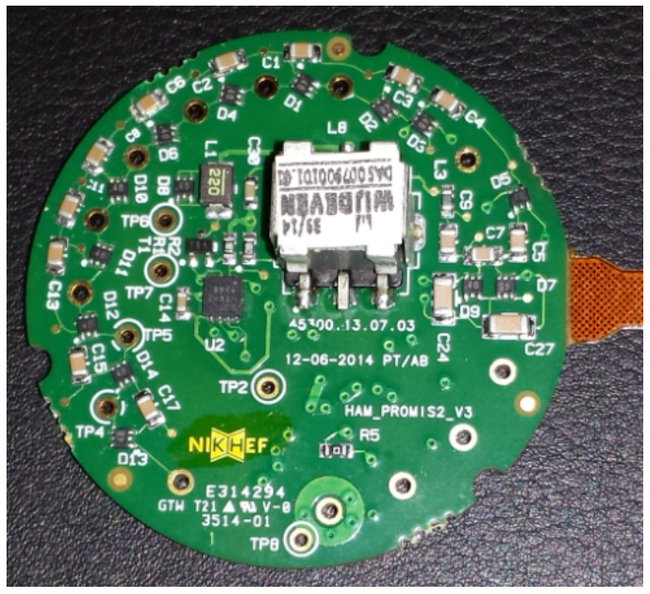


Dark-count rate reduction from ~500 Hz @ 20º C to 100–150 Hz < –30º C (thresh. ~0.3 pe, -HV)

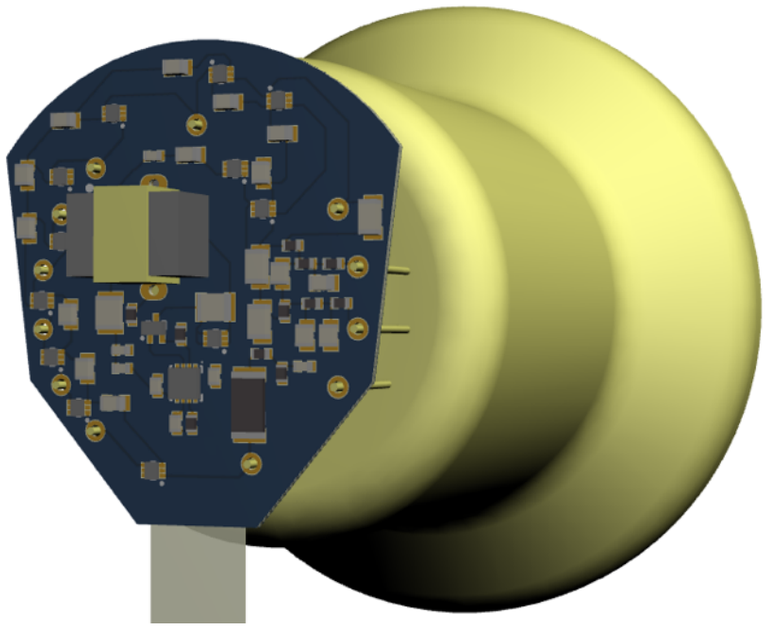
(comparison: standard IceCube 10” PMT: ~300-400 Hz @ 0.25 p.e.)

PMT base

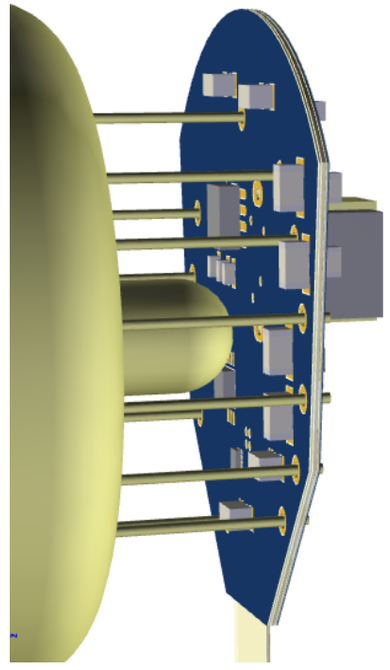
- HV generation on base; copied from KM3NeT (Cockcroft Walton design, Nikhef)
  - low power (3−5 mW)
  - small adaptions due to new board shape
- Front-end electronics for signal processing on backside



KM3NeT: HV generation



New optimized board shape with HV circuitry



Backside with front-end electronics

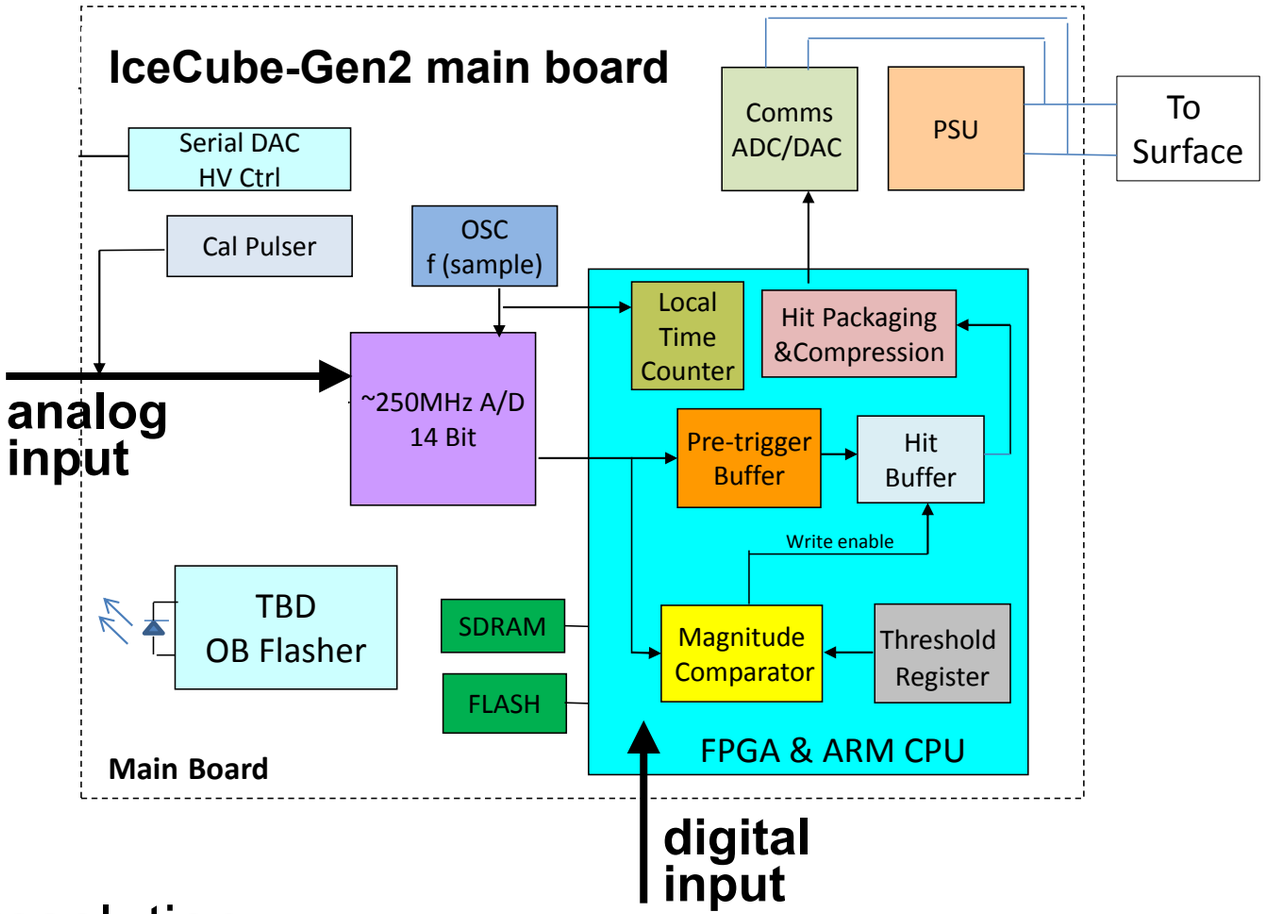
Readout concepts

Based on KM3NeT

- ToT pulse generation on each Base
- Time measurement at FPGA

Additional use of ADC

- Summing of all analog-base-signal and digitization by ADC



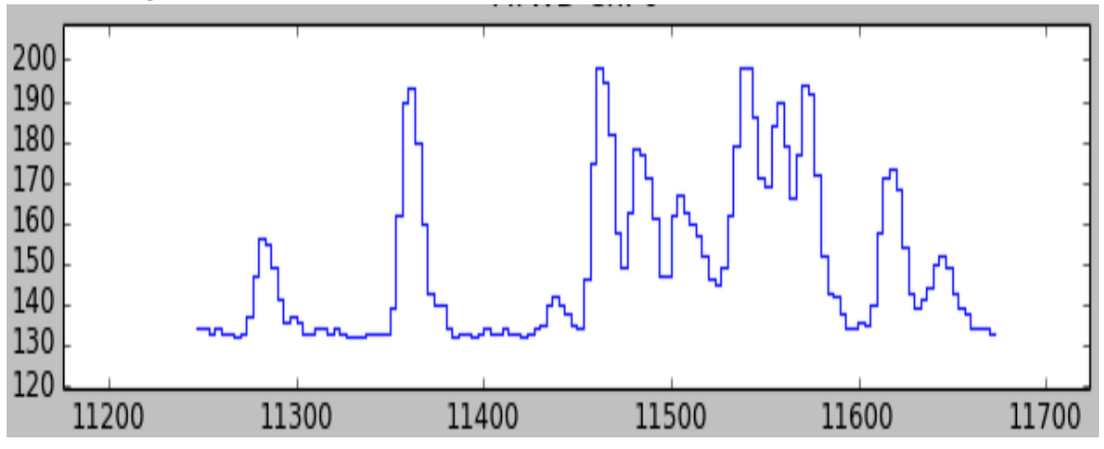
Direct Digitization at each base with low resolution

- Discrete, multiple (4) Comparator design
- ASIC comparator design (8 bit)

Power consumption crucial factor!

3 DOMs per wire pair → ≲ 60 mW per base

example waveform

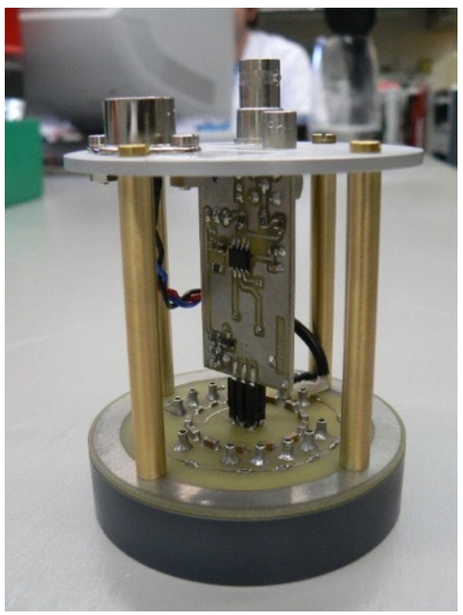


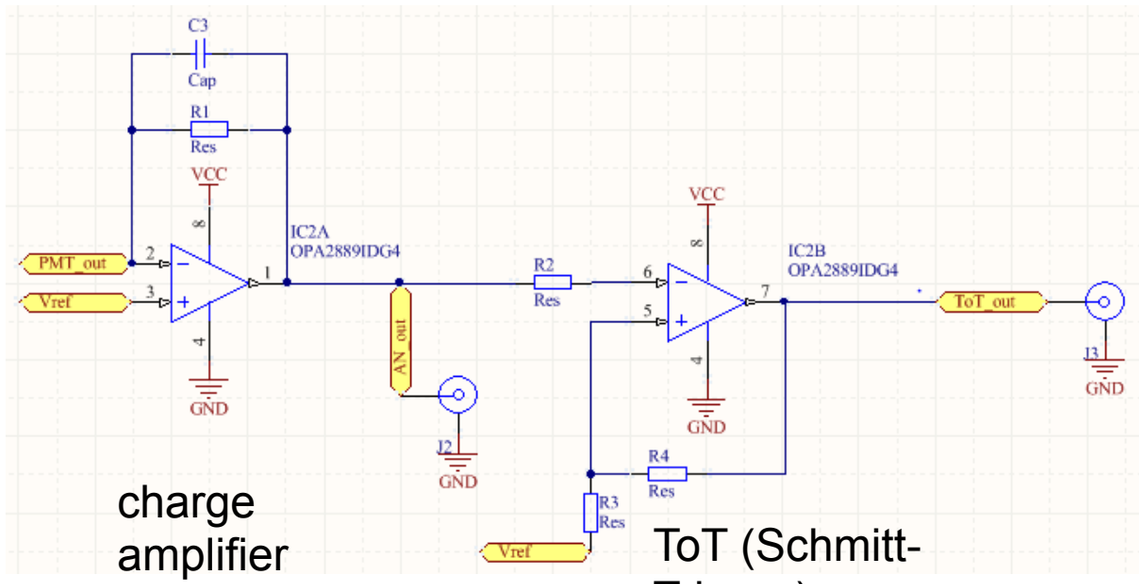
Discrete layout for single ToT readout

- Low power & tiny footprints
- Micro controller
  - Communication
  - Control of DACs (HV, threshold ToT)
  - PMT-Status
  - Calibration
- Low Power Charge Amplifier & Comparator

Load	Consumption
HV generation	*~5 mW*
Microcontroller	*<< 1 mW*
DACs	*~10 µW*
Charge Amplifier	*~5 mW*
ToT	*~5 mW*
Signalling to mainboard	*??*

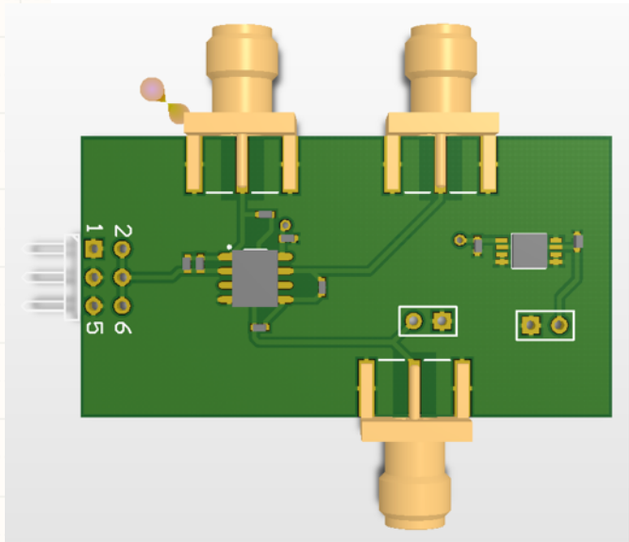
Test setup





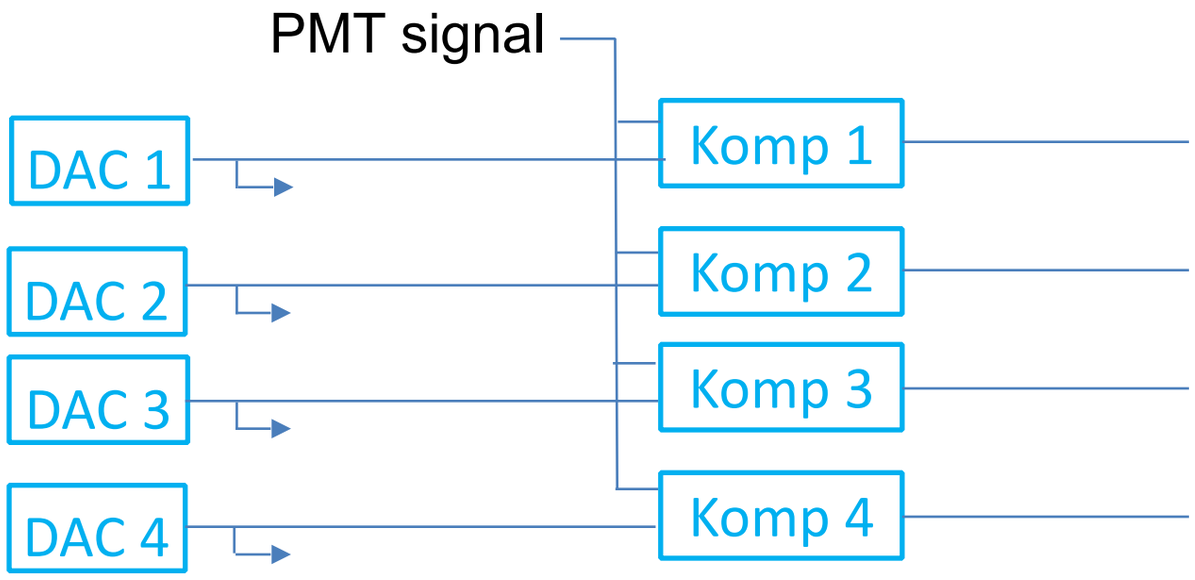
charge amplifier

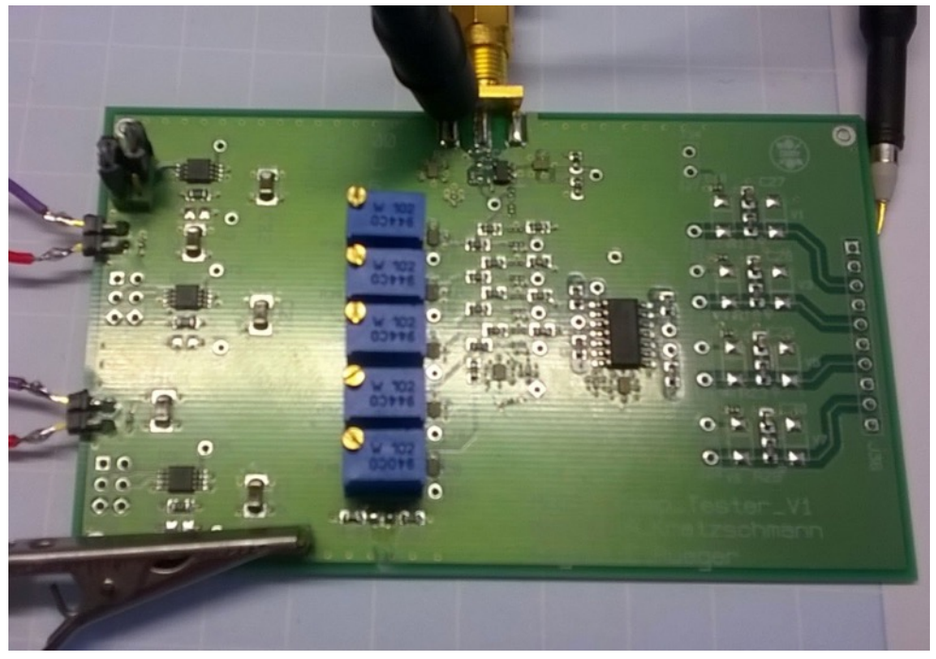
ToT (Schmitt-Trigger)



Discrete, multiple comparator design

- Test setup





- Measured power consumption: ~40 mW per base for 0.001 – 1 MHz toggle rate (expected rates ≲ 0.05 MHz)

Summary

- IceCube-Gen2 next-generation neutrino observatory at the South Pole
- Installation of ~10,000 additional optical modules
- DOM baseline design based on proven IceCube module
  - HQE 10” PMT
  - simplified electronics and DAQ
- Alternative designs (D-Egg, mDOM) with enhanced photon detection concepts under development:

Bundesministerium
für Bildung
und Forschung

Enhanced photon detection concepts

	DOM	D-Egg	mDOM
• Multi-PMT concept			
pros: - more uniform angular acceptance - larger photocathode area - local coincidences - directionality - higher dynamic range	✗	✓	✓✓✓
cons: electronics for large number of readout channels	–	(yes)	yes
• UV transparency			
pros: increased # photons	✗	✓✓	✓
cons: higher price	–	?	no
• High-QE PMTs			
pros: increase # photons	✓	✓	✗(?)
cons: degraded other PMT parameters	no	?	–