WWU
MÜNSTER

IceCube Gen2OM prototyping & performance studies

Astroparticle School 2022 Obertrubach-Bärnfels
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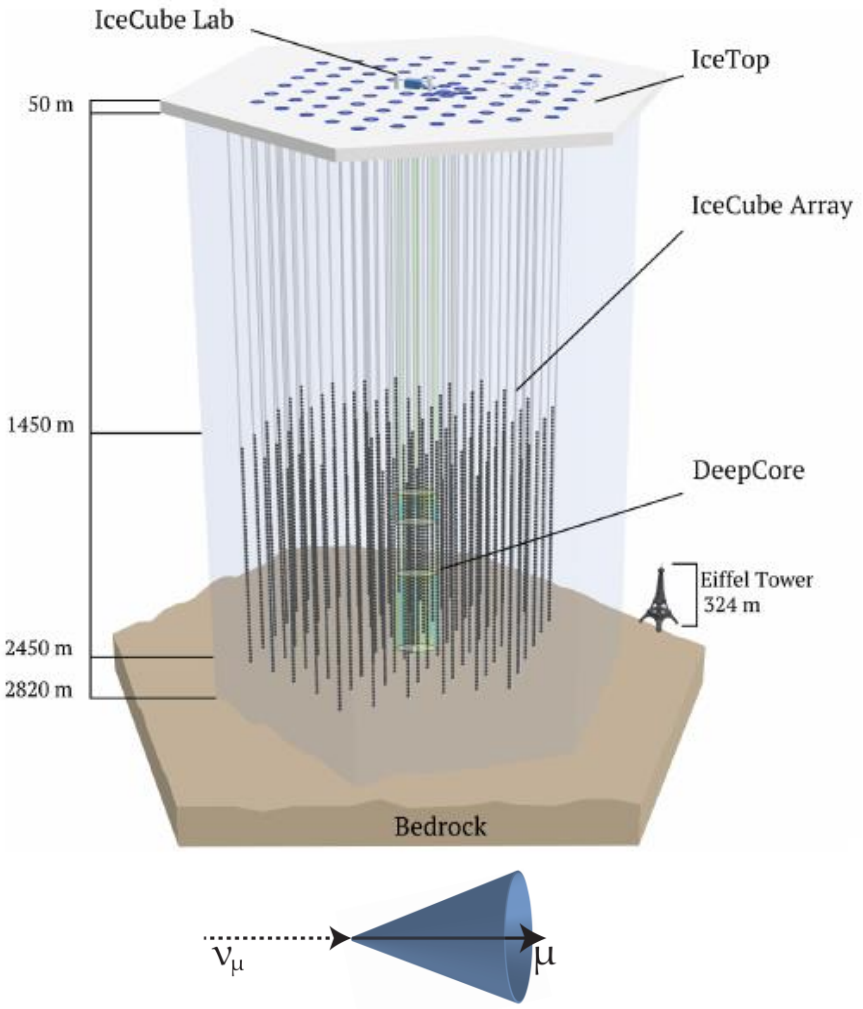
living.knowledge

IceCube introduction

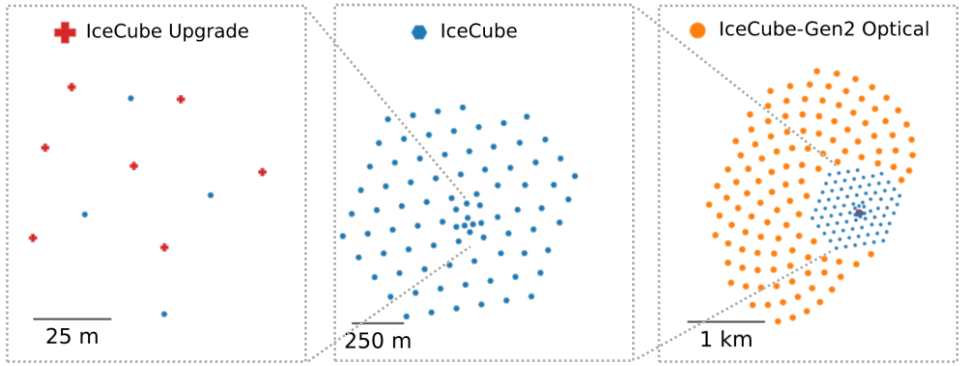


Information

- Module positions
- Number of photons
- Arrival time

Reconstruction

- Energy
- Direction
- (Flavor)



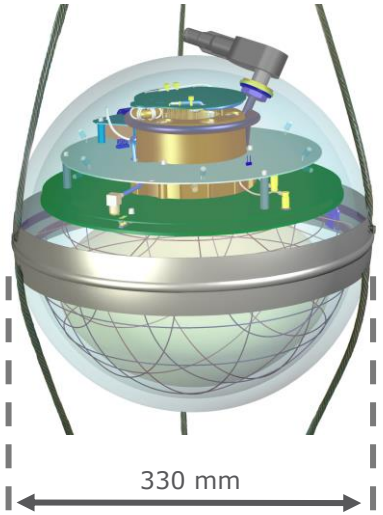
Optimized for neutrino energy:

GeV — TeV — PeV

Optical module history

IceCube

Digital **O**ptical **M**odule
(DOM)



1 x 10″ PMT

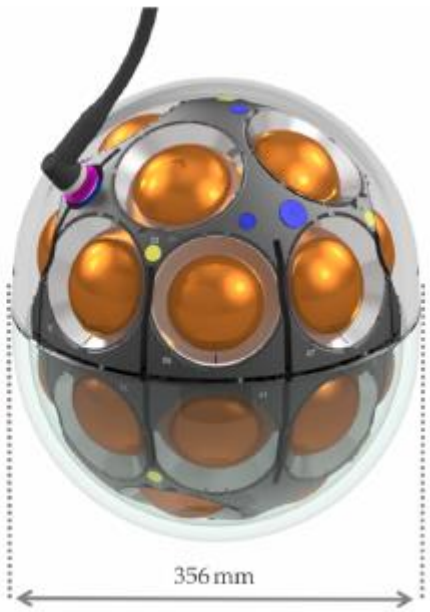
mDOM & DEGG improve upon Gen1 DOM

IceCube Upgrade

dual … **E**llipsoidal **G**lass …
(**dEGG**)

2 x 8″ PMT

Multi-PMT **D**igital **O**ptical **M**odule
(**mDOM**)

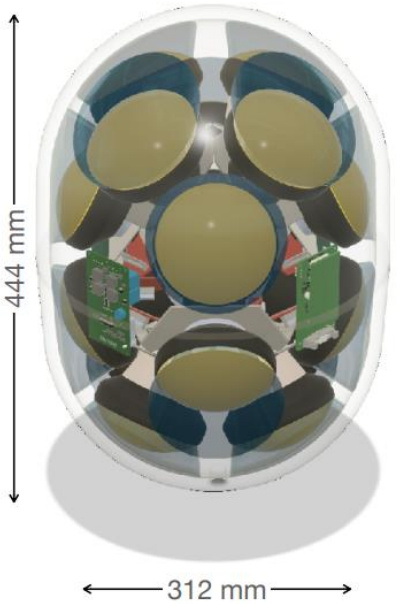


24 x 3″ PMT

Combine mDOM & DEGG knowledge for Gen2OM

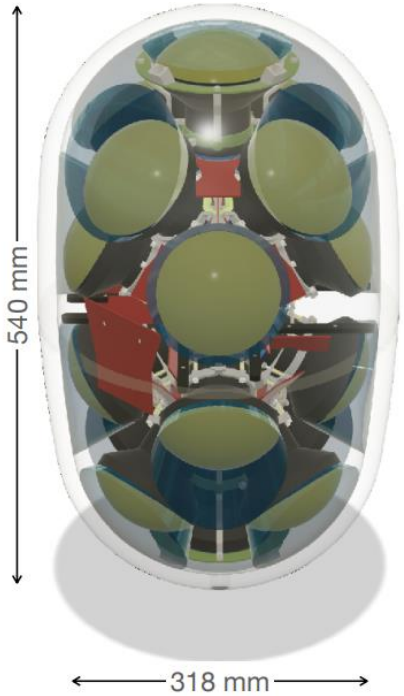
IceCube Gen2

Long **O**ptical **M**odule
(**LOM16**)



16 x 4″ PMT

Long **O**ptical **M**odule
(**LOM18**)



18 x 4″ PMT

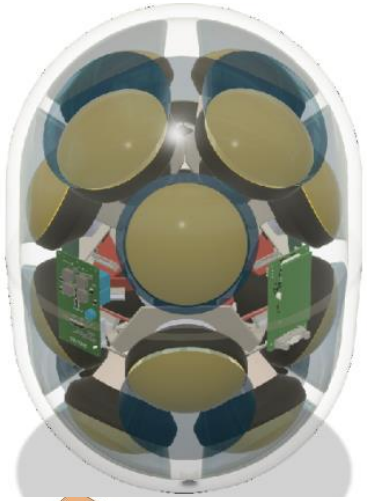
A single module (combination) will be implemented in Gen2 ⇝ Gen2OM

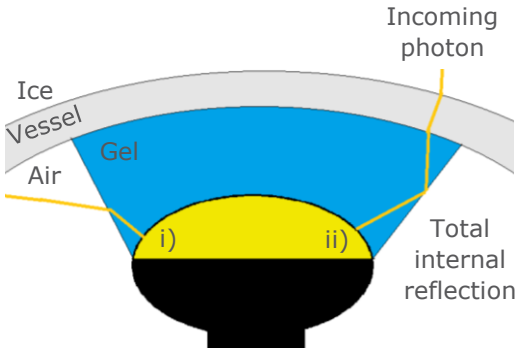
Topic I: Module prototyping - Gelpads

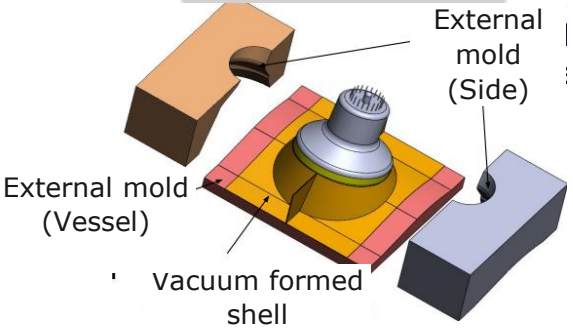
Why? How? What?

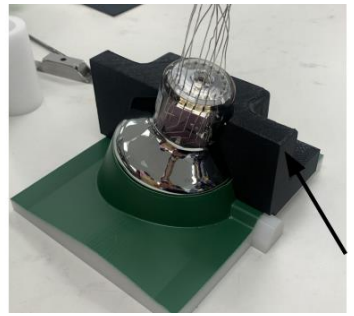
Gelpads!

- Gel acts as optical coupling between vessel & PMT
- Novel concept to enhance photon capture
- Shape comes from PMT glass envelope, inner vessel surface and is constricted by an opening angle
- Preproduce instead of pouring gel into an assembly
- Gelpads are a key component for the performance and integrity









During Prototyping

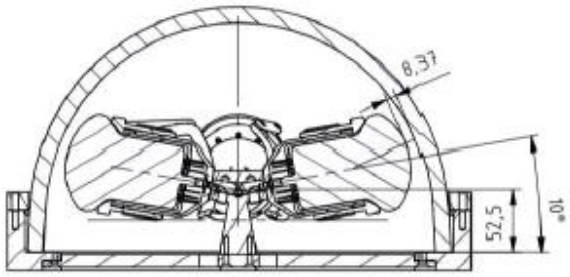
- External 3D-printed molds for shape and vacuum formed polymere sheets for surface smoothness
- Push gelpads (after curing to PMTs) towards inner vessel surface via spring loaded mechanism

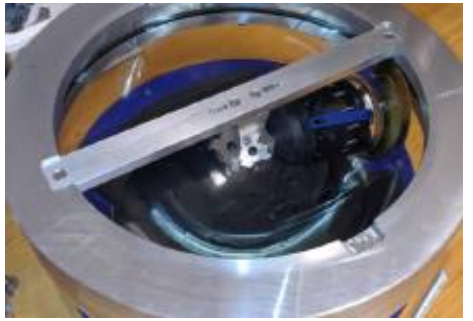
Topic I: Module prototyping

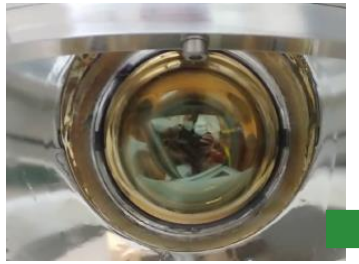
Gelpads quality needs to be a consistent!

Testing items

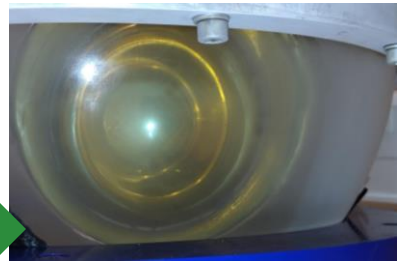
- Quality control: Transparency/surface smoothness after demolding
- Module assembly: Adhesion to vessel surface after curing to PMTs
- Module environment tests: Observe possible delamination in Freezer + underpressure
- Mechanical tests: How much force can gelpads withstand?
- Optical tests: Measurable increase in photon detection
- Prototype tests (2023): Vibration, Mechanical shock, thermal shock, pressure test

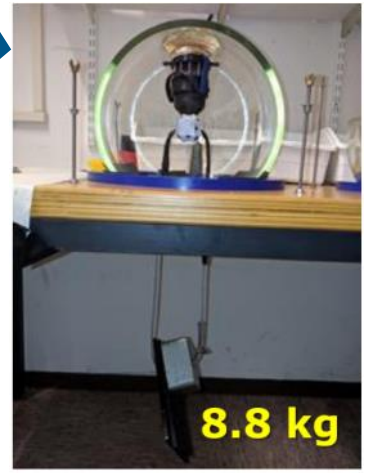






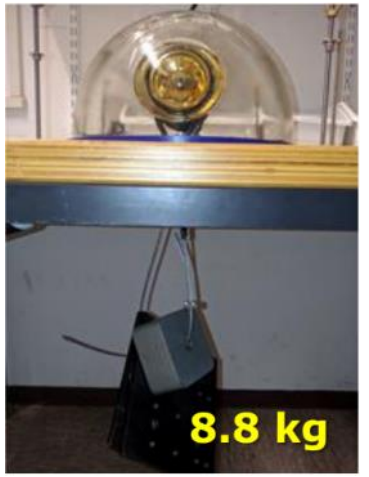
No delaminations/ bubble formation @-45°C after 7 days





Gelpads survive close to 10kg.

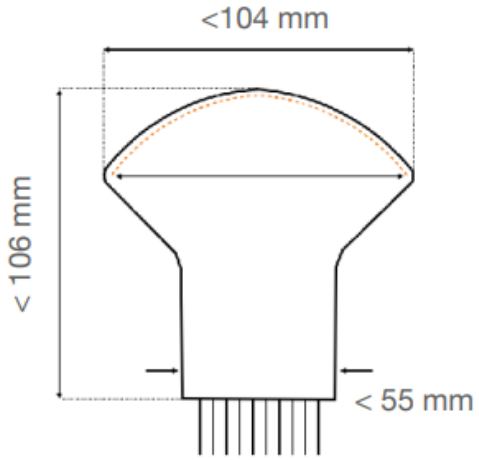
Within the module, much less force will be acting upon gelpads.



Topic II: PMT characterization

Two vendors (Hamamatsu & NNVT) are developing new 4″ PMT models for us

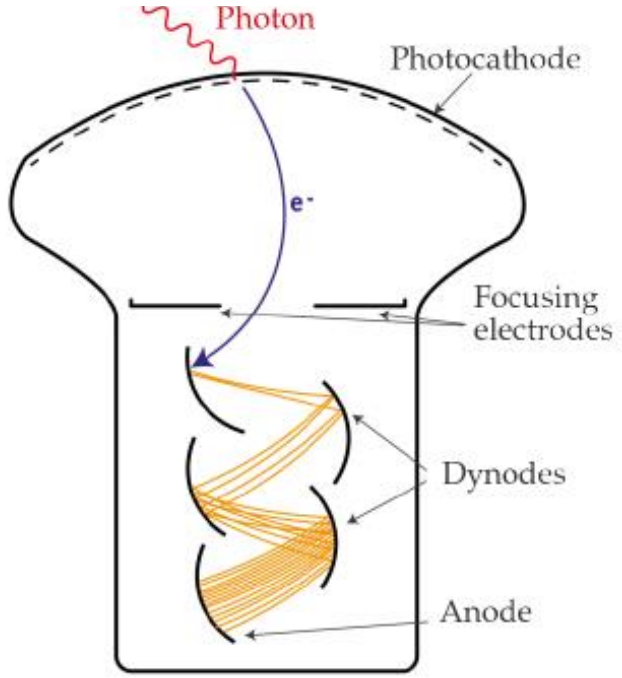
- **Our requirement**: As short as possible with minimum compromise in performance
- Our feedback influences their development



Some selection criteria/PMT specs:

Total length	< 106 mm
Glass envelope diameter	4″ (< 104 mm)
Nominal voltage (5e6 Gain)	< 1500 V
Transit Time Spread (σ)	< 3.4 ns
Rise Time	< 5 ns
Peak to Valley ratio	> 2.0
Quantum Efficiency	> 25% at 400 nm
Dark rate	as low as possible
Afterpulsing	< 15%

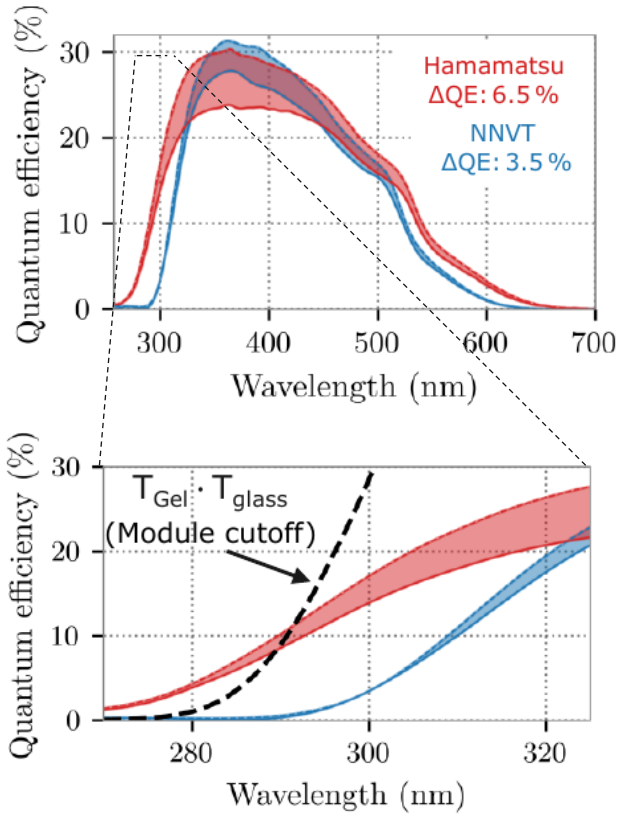
(You don't need to read all of that.
Detection efficiency and time resolution are most important for reconstruction)



Each PMT characteristic is further wavelength and temperature dependant as well as influenced by magnetic fields…

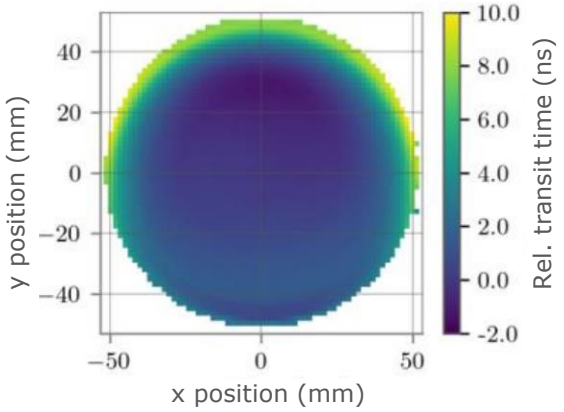
Topic II: PMT characterization

Quantum efficiency

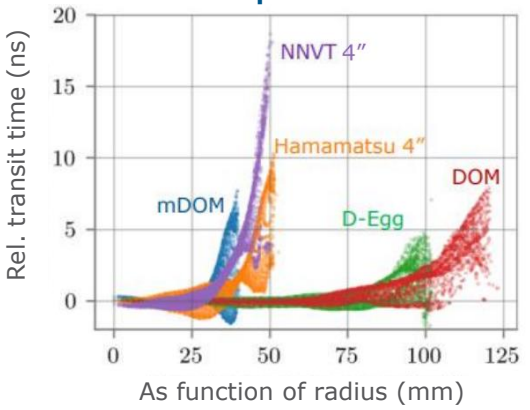


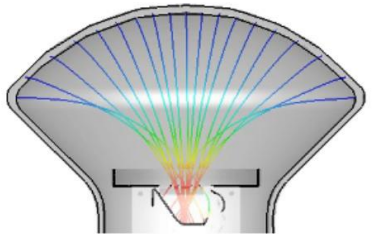
Transit time

Hamamatsu 4″



Comparison

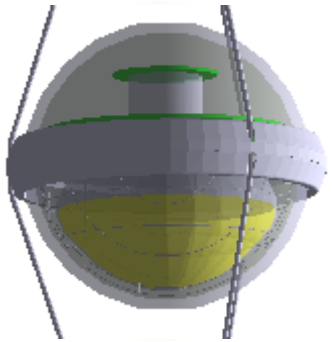




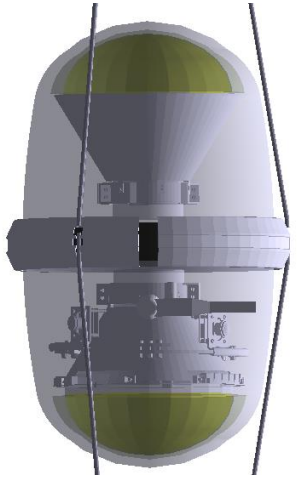
PMT characteristics go into detector simulation used for reconstruction

Topic III: Simulation studies

Geant4 (Monte Carlo based) simulation includes geometry, particle interaction, absorption lengths, refractive indices, …



DOM



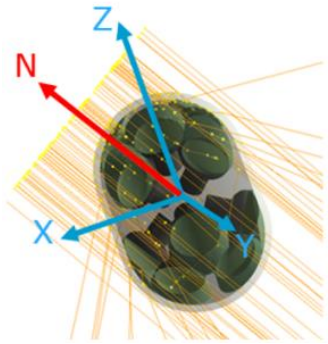
DEgg

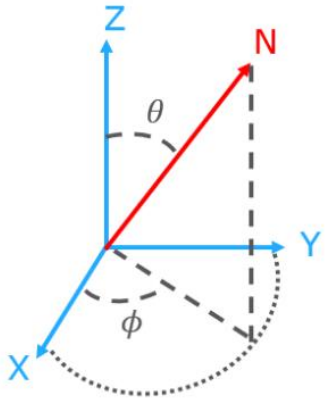
mDOM

LOM16

LOM18

Effective area (cm²) is our measure of module performance

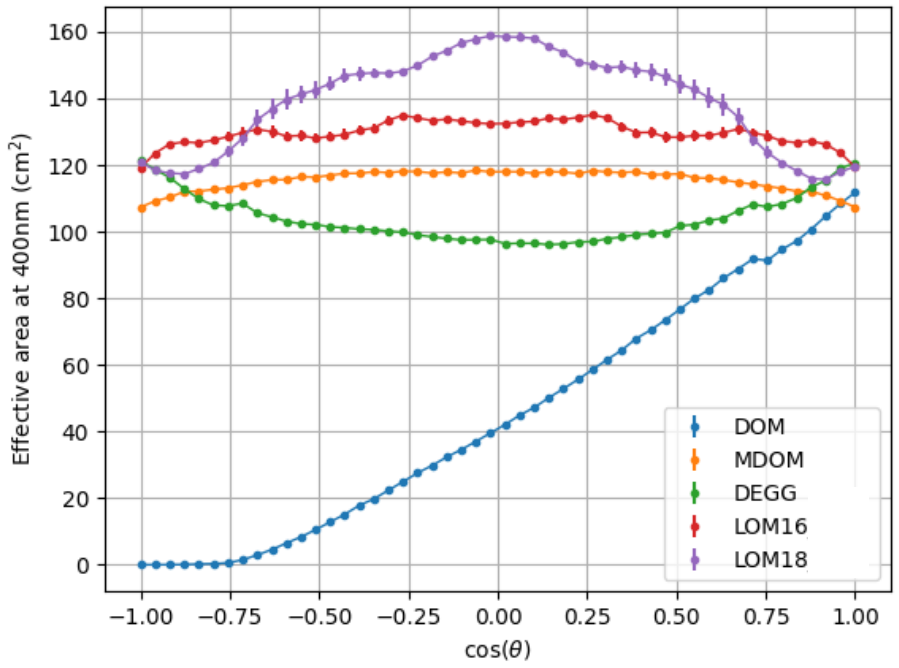




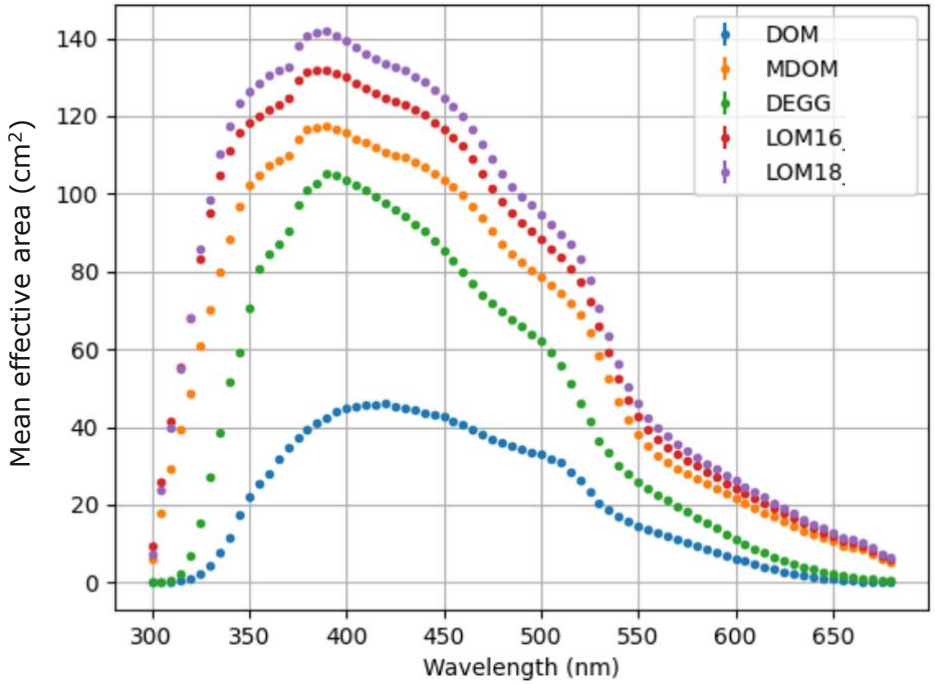
$$A_{\text{eff}}(\theta,\phi) = \frac{N_{\text{det}}(\theta,\phi)}{N_{\text{emit}}} \cdot A_{\text{beam}}$$

Topic III: Simulation studies

Effective Area vs zenith angle (@400nm)



Mean effective Area vs wavelength



- Reminder: DOM (IceCube) dEGG/mDOM (Upgrade) LOM16/LOM18 (Gen2)
- Study optimal PMT positions & angles, opening angles of pads… ➞ check if real life implementation is possible

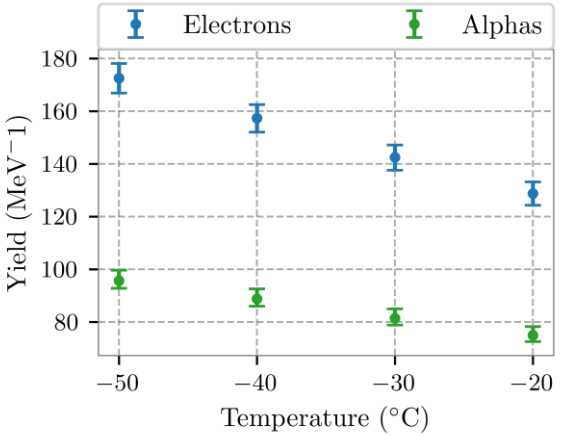
Topic IV: Module background estimation

- The pressure vessel is made from borosilicate glass (>10kg)
- Trace amounts of isotopes
  ⟶ radioactive scintillation
- Temperature dependant (thermal quenching)
- This is IceCubes dominant background source!

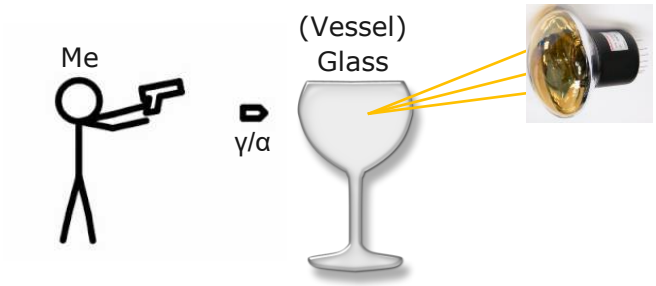
Isotope concentration (how often/what)

Decay	Specific activity (Bq/kg)
^{40}K	60.98 ± 0.86
^{238}U-Chain	4.61 ± 0.07
^{235}U-Chain	0.59 ± 0.05
^{232}Th-Chain	1.28 ± 0.05

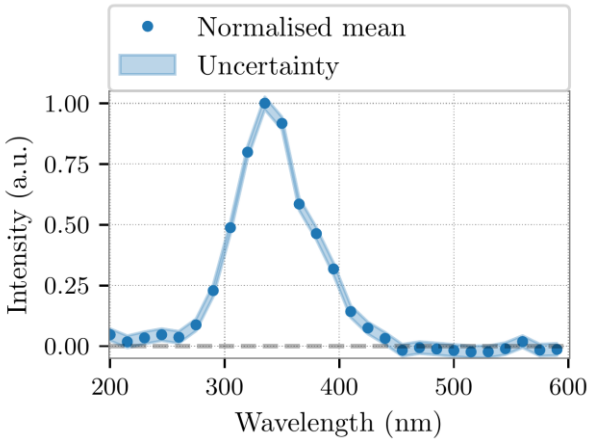
Yield (how many)



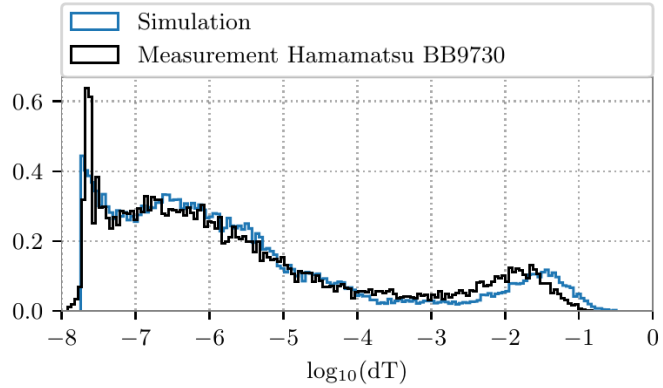
Characterization by γ-spectroscopy shooting γ- & α-particles at glass samples of the vessel, thus deducing 4 parameters



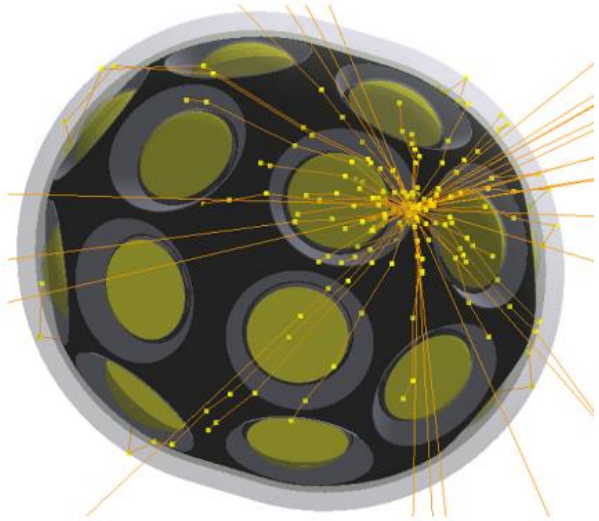
Spectrum (which)



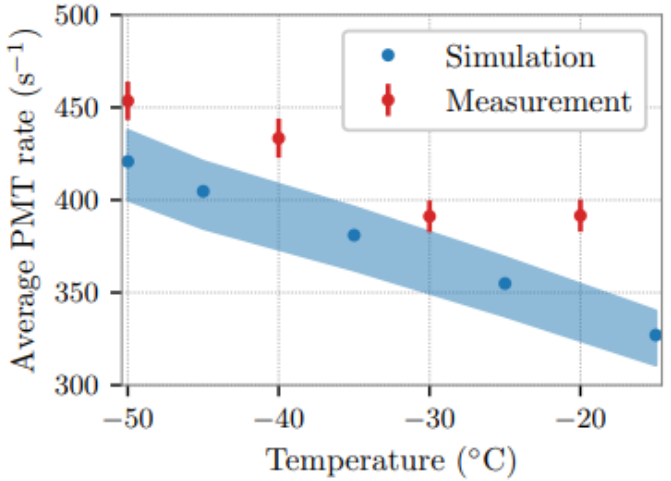
Lifetime (when)



Topic IV: Module background estimation



Measurement is not corrected for intrinsic PMT dark rate (~30 s^{-1}), so it matches better than shown below



Two viable manufacturers for the pressure vessel (Nautilus & Okamoto)

To do:

- Measure spectrum in dependence of temperature for both glass types
- Measure borosilicate components

These results are also used in the detector simulation, go into power consumption calculations and much more.

*Pictures shown here are from my Masterthesis (mDOM) – LOM values (that can be shared) are still in the making

Summary & outlook

Prototyping

Gelpads
- Adhesion & surface quality from different mold materials
- Coupling to vessel
- Optical quality

Module level
- Assembly
- Module enviroment & shock tests
- Scaling to mass production

PMTs

Mechanical
- Dimensions
- Glass quality
- Reflectivity

Characteristics
- Timing
- Efficiency
- Dark rate
- Pulse types
- …

Simulated module performance

Effective Area
- Wavelength dependance
- Photocathode homogenity

Performance studies
- PMT positioning
- Gel pad opening angle
- Gel pad axis tilt

Simulated module background

Scintillation parameters
- Yield
- Spectrum
- Time distribution
- Specific activity

Rate estimation
- Glass suppliers
- PMT dark rate
- Module selection

LOM timeline

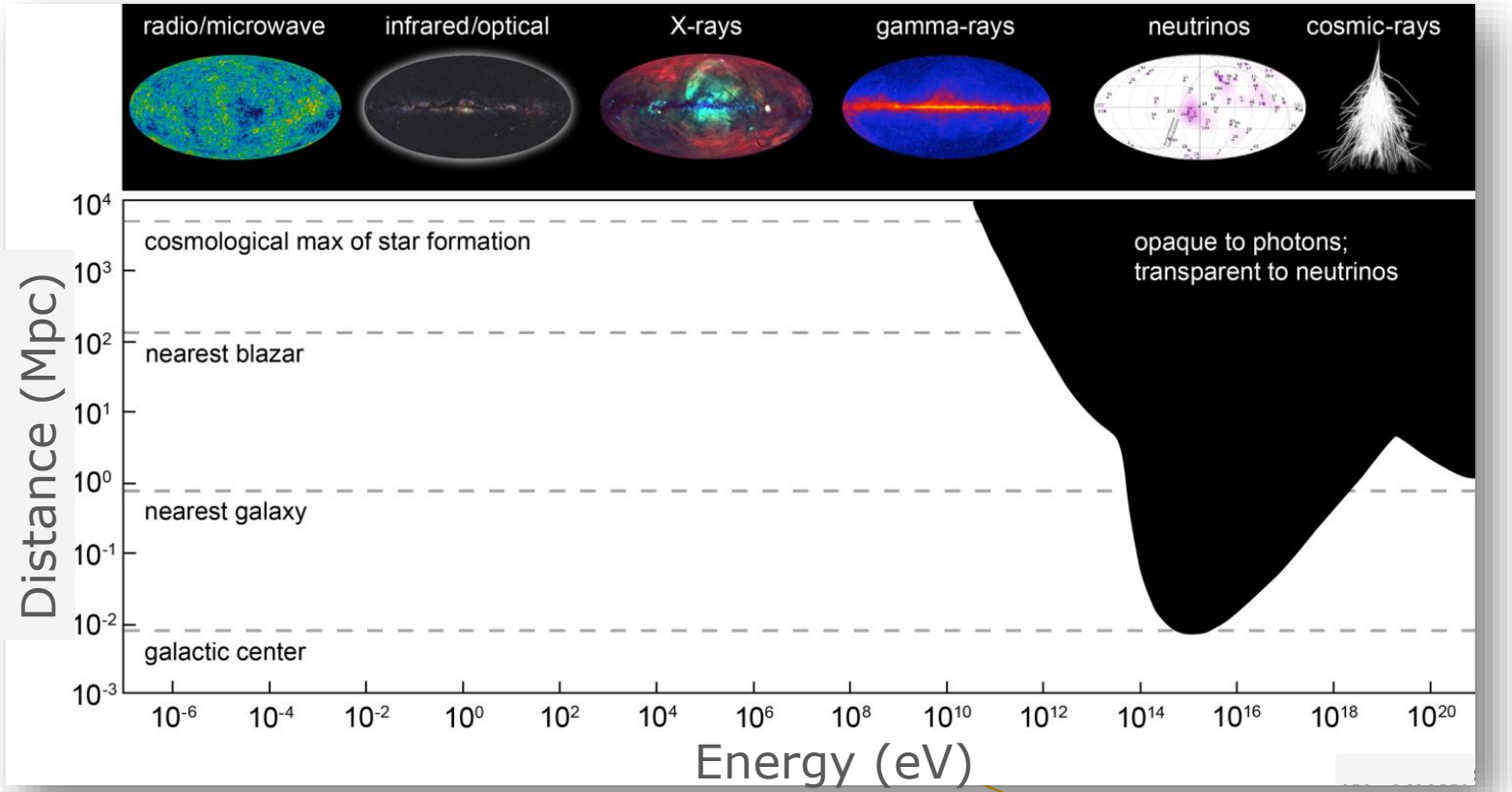
- 2023 Spring: Design Verification Testing (DVT) for IceCube Upgrade
- 2023 Winter: IceCube Upgrade LOM Final Design Review (FDR)
- 2025/26: Deploy 12 LOMs (+2 spare ones) in IceCube Upgrade

Backup

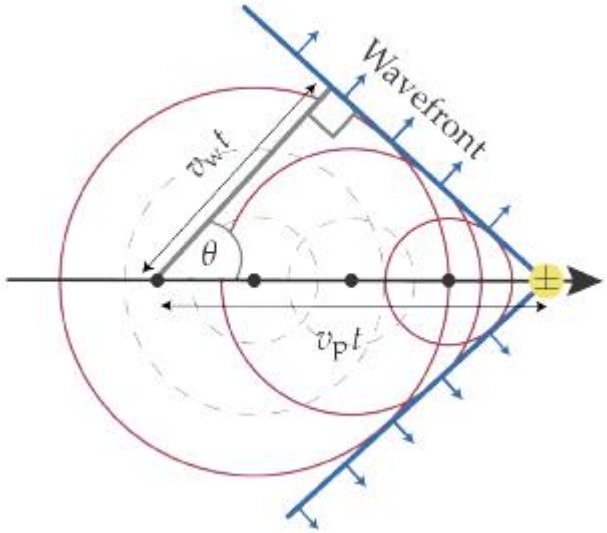
Theory section

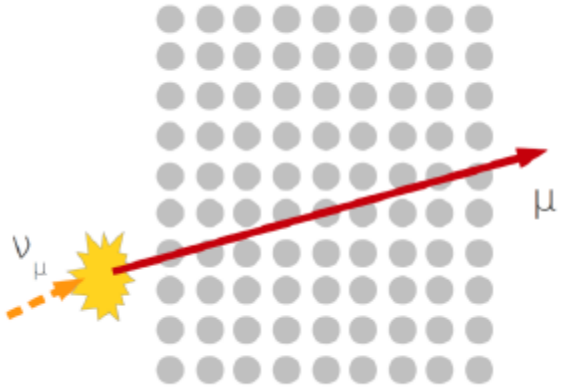
Why neutrinos...?

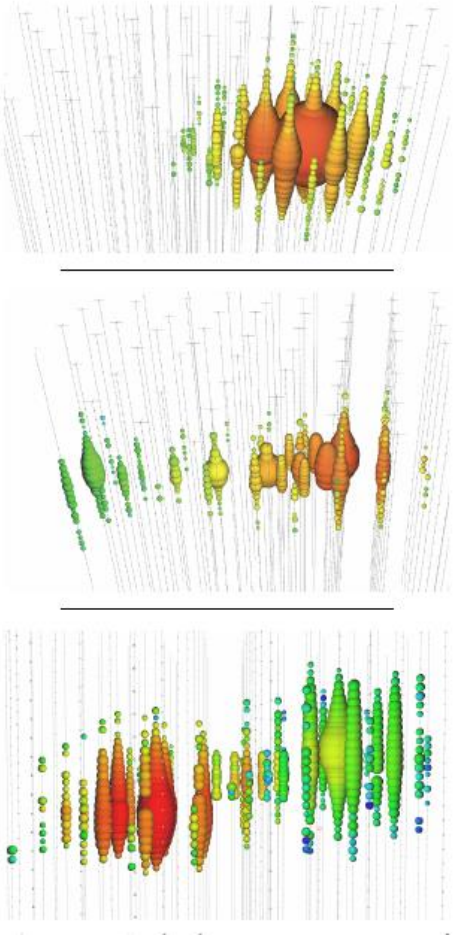
- Cosmic ray sources produce various messengers
- Intergalactic magnetic fields deflect charged particles
- Only gammas or neutrinos point back to source



Cherenkov radiation

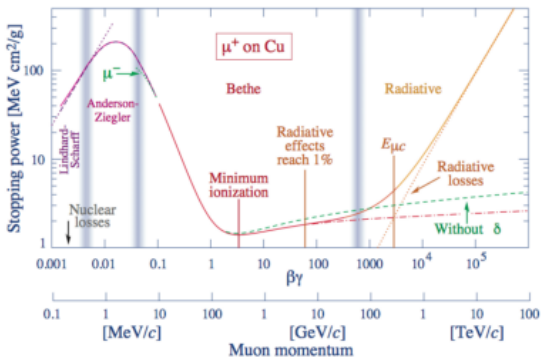


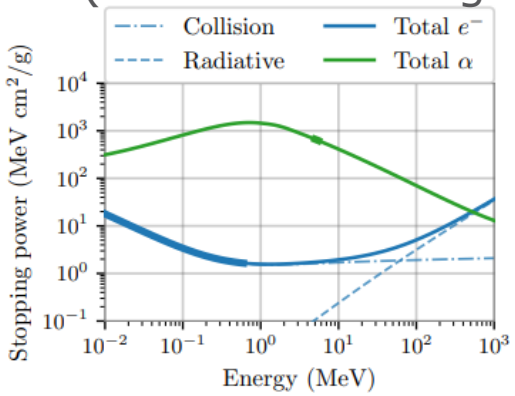




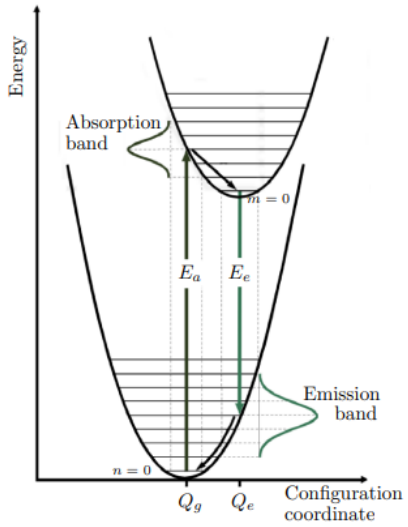
Scintillation theory

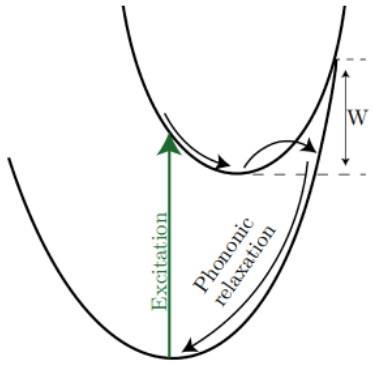
Deposited energy by particles (in boroscilicate glass)



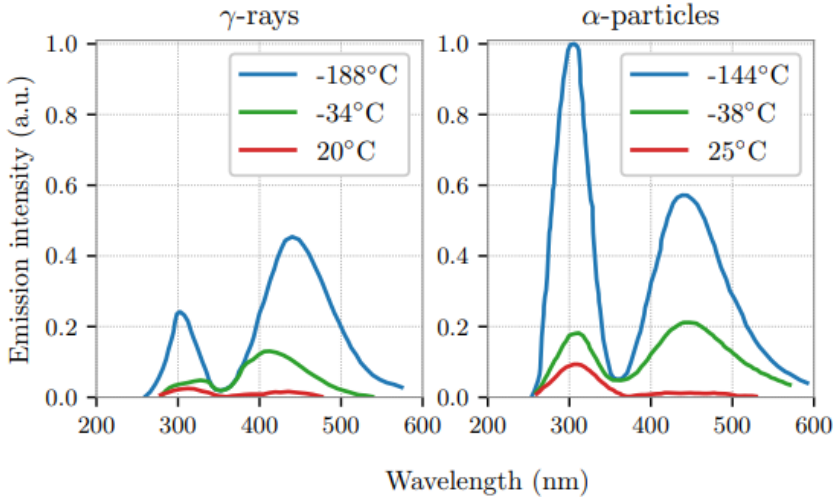


Absorption & emission band model

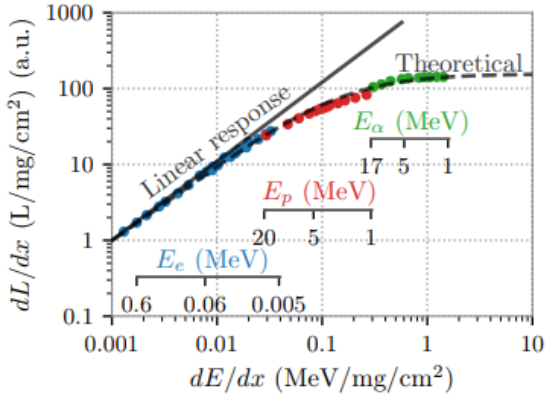




Scintillation spectrum (NaI crystal doped with Tl)



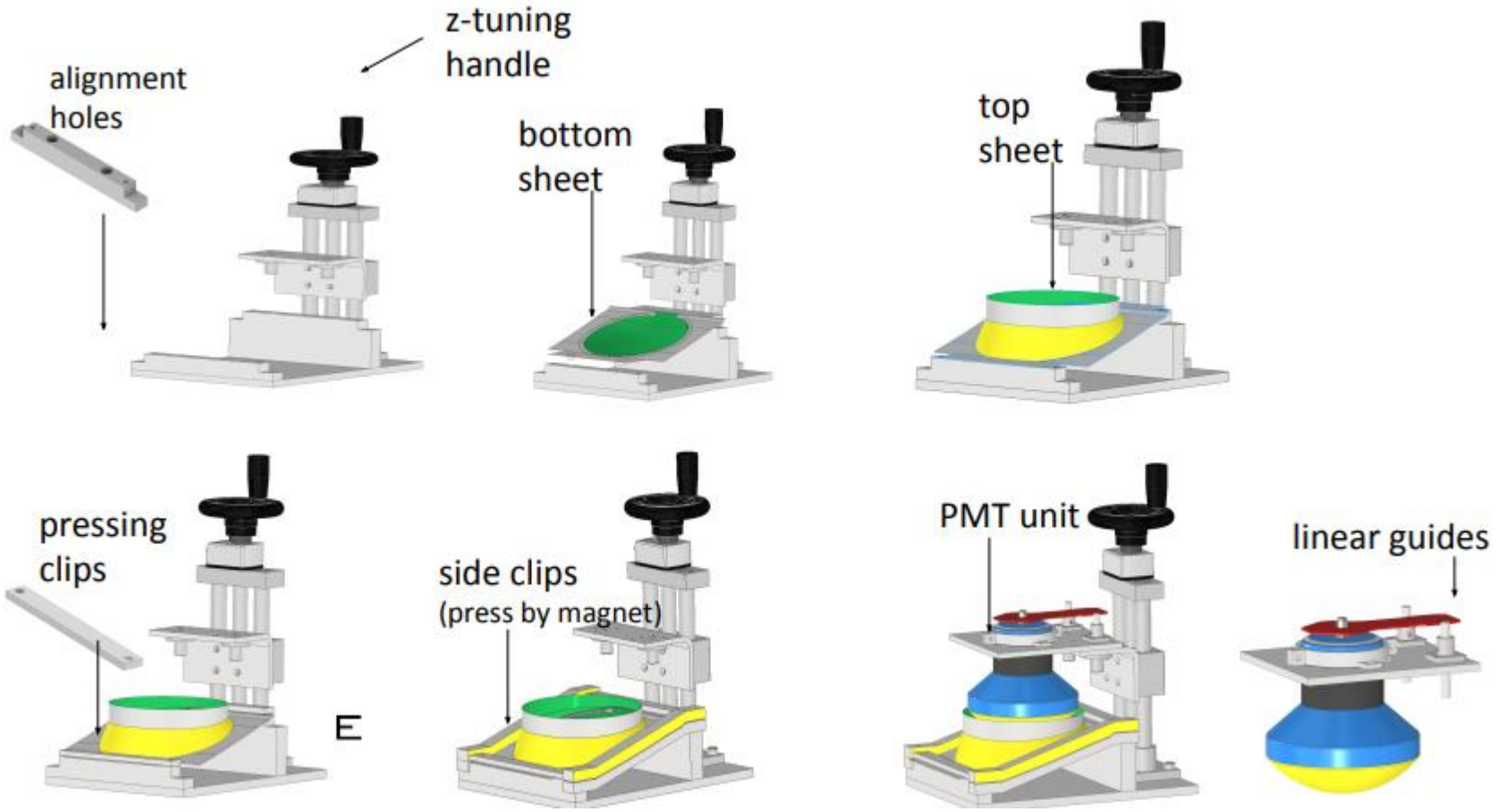
Scintillation Yield



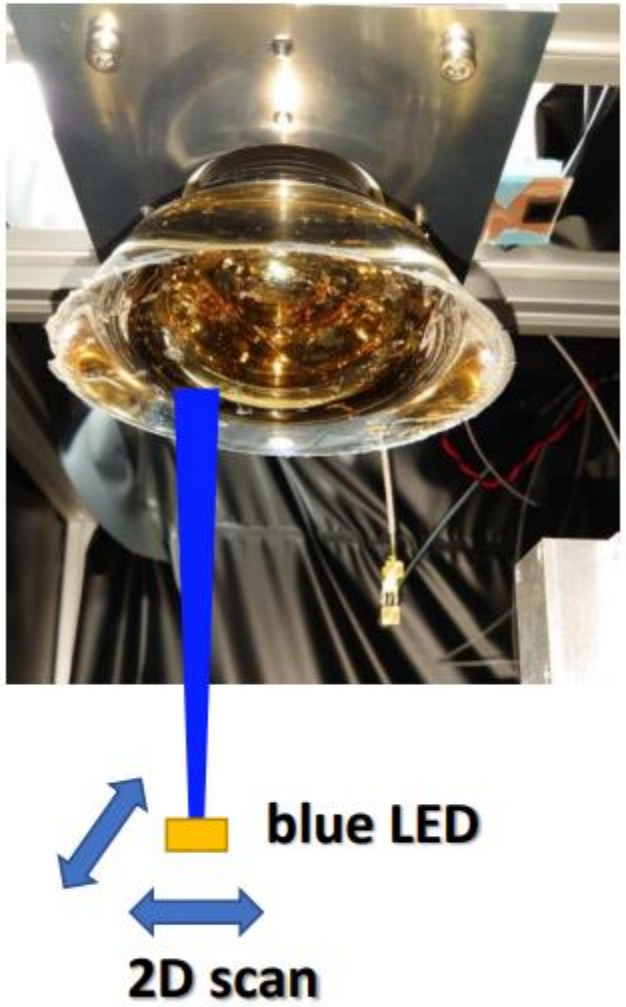
Gelpad section

Gelpad jig

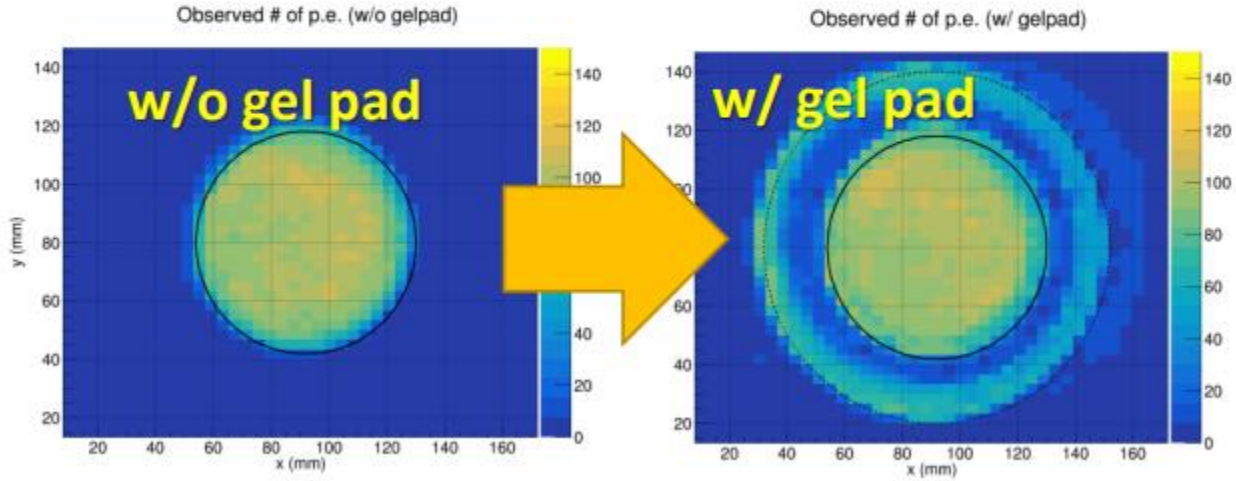
(This one is from Chiba which has the nicest explanation. The one from Madison and mine are different. We all went for independant designs to explore which of the multiple option works best. For mass production the design will be changed to injection molded parts with clip/snap features)



Gel pads

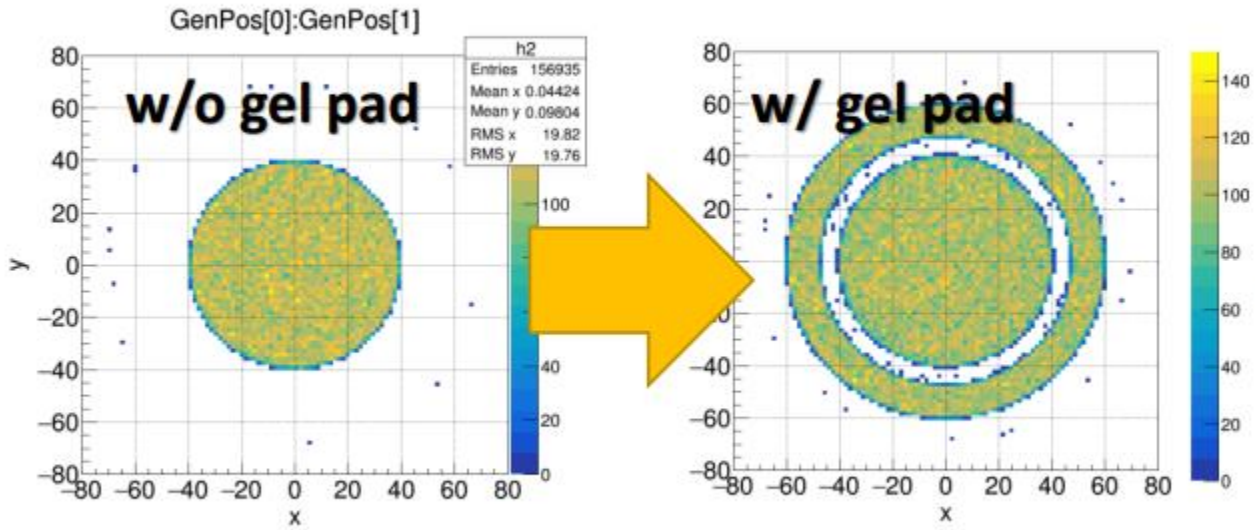


Experiment



+67%

MC (GEANT4 optical simulation)

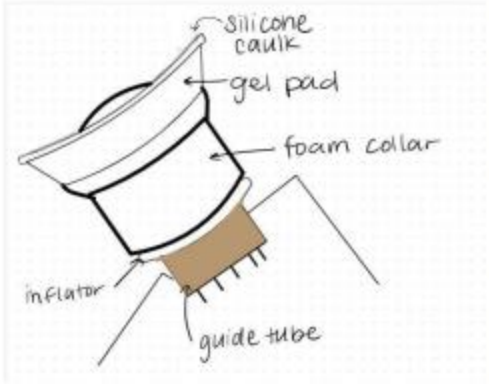


+75%

PMT guide and pushing mechanism

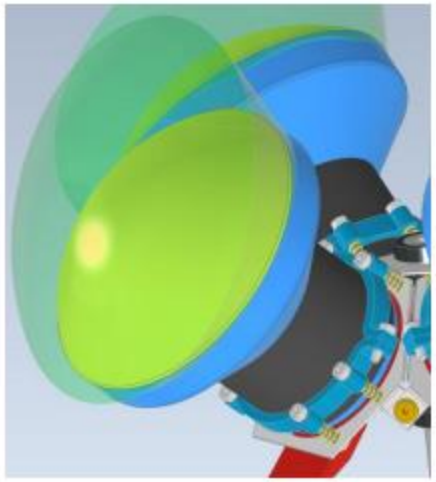
◆PMT supports need

① to push PMT + gel pads for the gluing
② to accommodate a few mm shrinkage of housing glass @70 MPa
③ to be flexible to the heat shrinkage @ -45C



➢ **UW/PSL**

- a form collar to accommodate the shrinkage
- inflator bag to actively push the gel pads



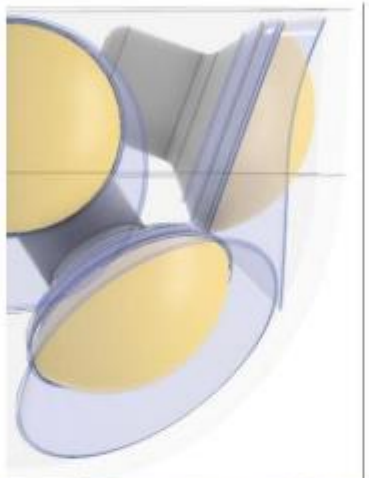
➢ **Chiba**

- springs to push and support
- plastic collar holder

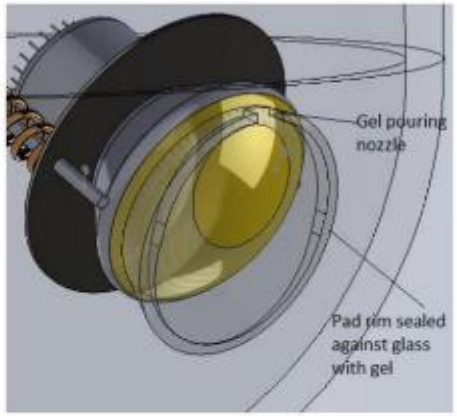
Gel pad casting approaches

Precasting

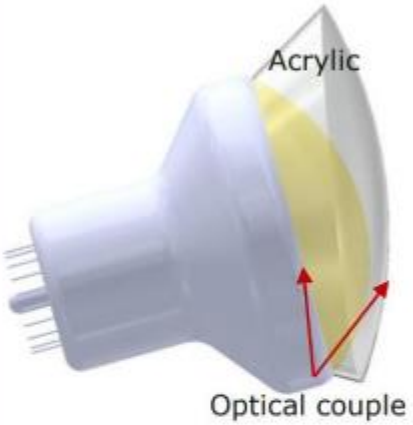
In-Situ

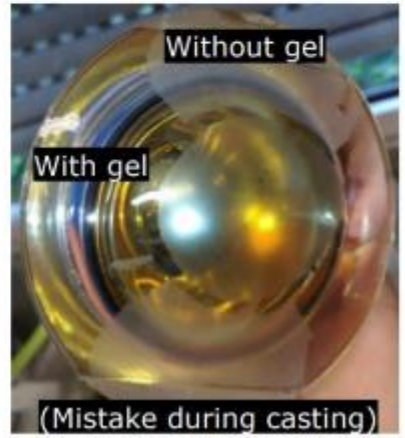


Hybrid



Acrylic pads

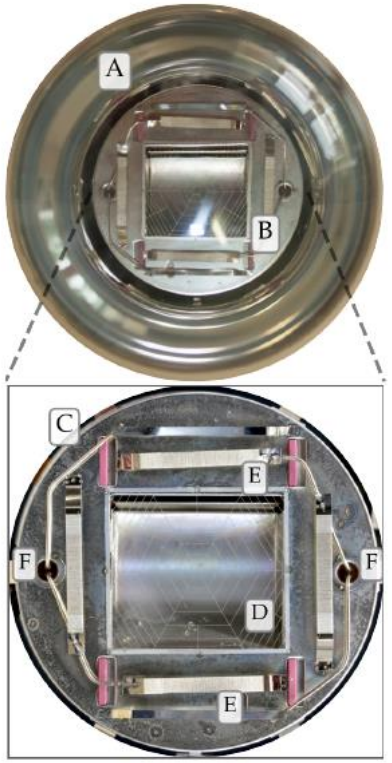


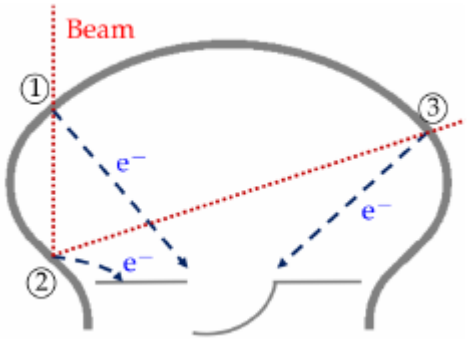


PMT section

Hamamatsu R16293-01

NNVT N2041





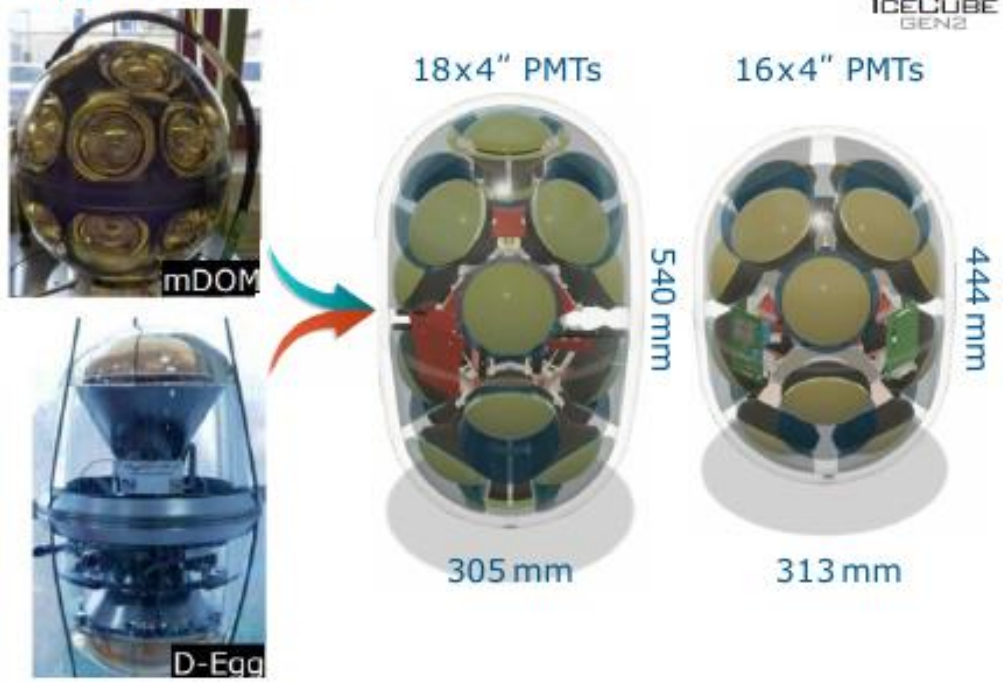
Preface

PMT Requirements

Total length	< 106 mm
Glass envelope diameter	4″ (< 104 mm)
Nominal voltage (5e6 Gain)	< 1500 V
Transit Time Spread (σ)	< 3.4 ns
Rise Time	< 5 ns
Peak to Valley ratio	> 2.0
Quantum Efficiency	> 25% at 400 nm
Dark rate	as low as possible
Afterpulsing	< 15%

- Hamamatsu & NNVT are developing new 4″ PMT models
- **Should be designed as compact as possible**
- We are in close communication with them regarding mechanical and performance specifications

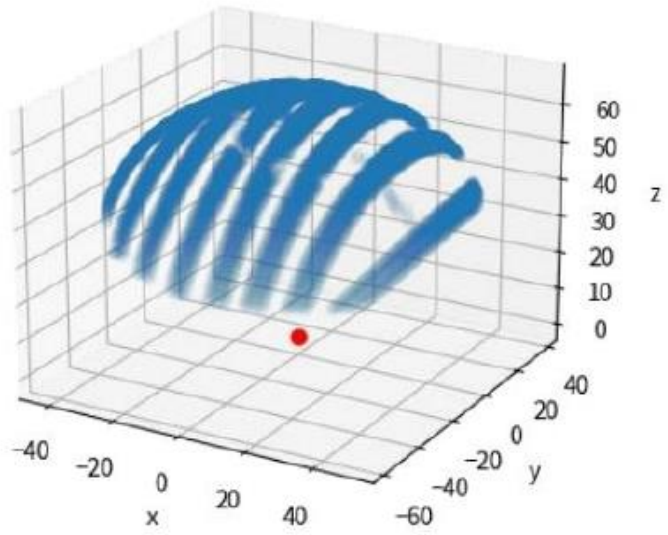
Main Upgrade modules



Hamamatsu R16293 (4 inch)

NNVT N2041 (4 inch)

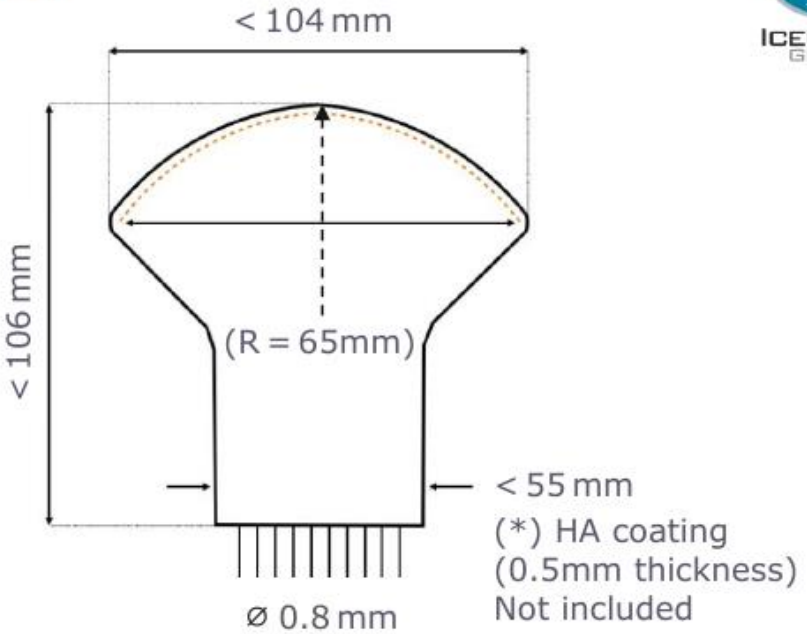
Mechanical inspection



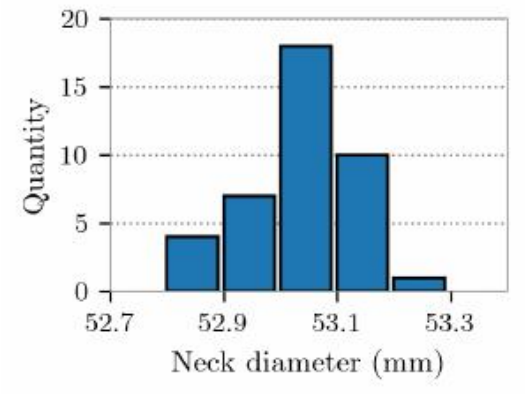
Hamamatsu photocathode radius

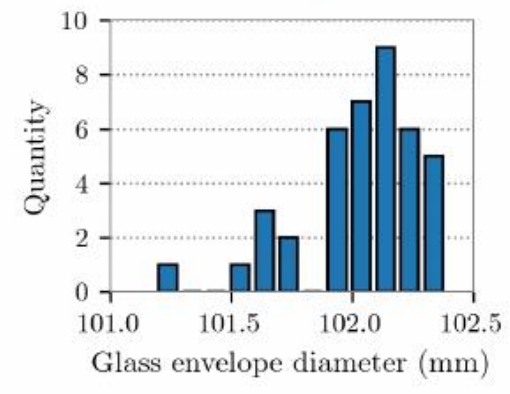
Measured: (65.4 ± 0.3) mm

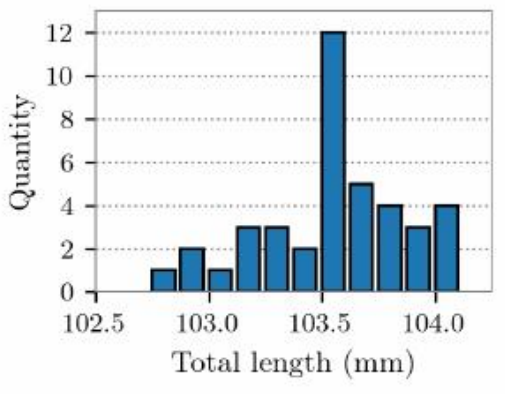
Design: (65.0 ± 2.0) mm



40 Hamamatsu PMTs (with HA coating) delivered in March

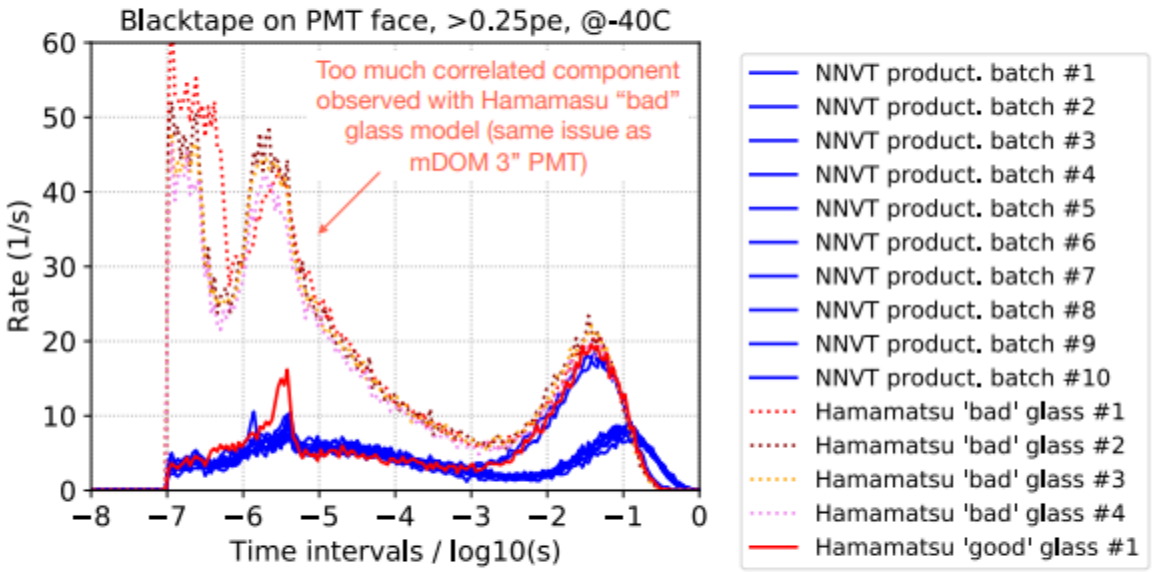






Both vendors satisfy the mechanical requirements - well within stated ±2 mm tolerances

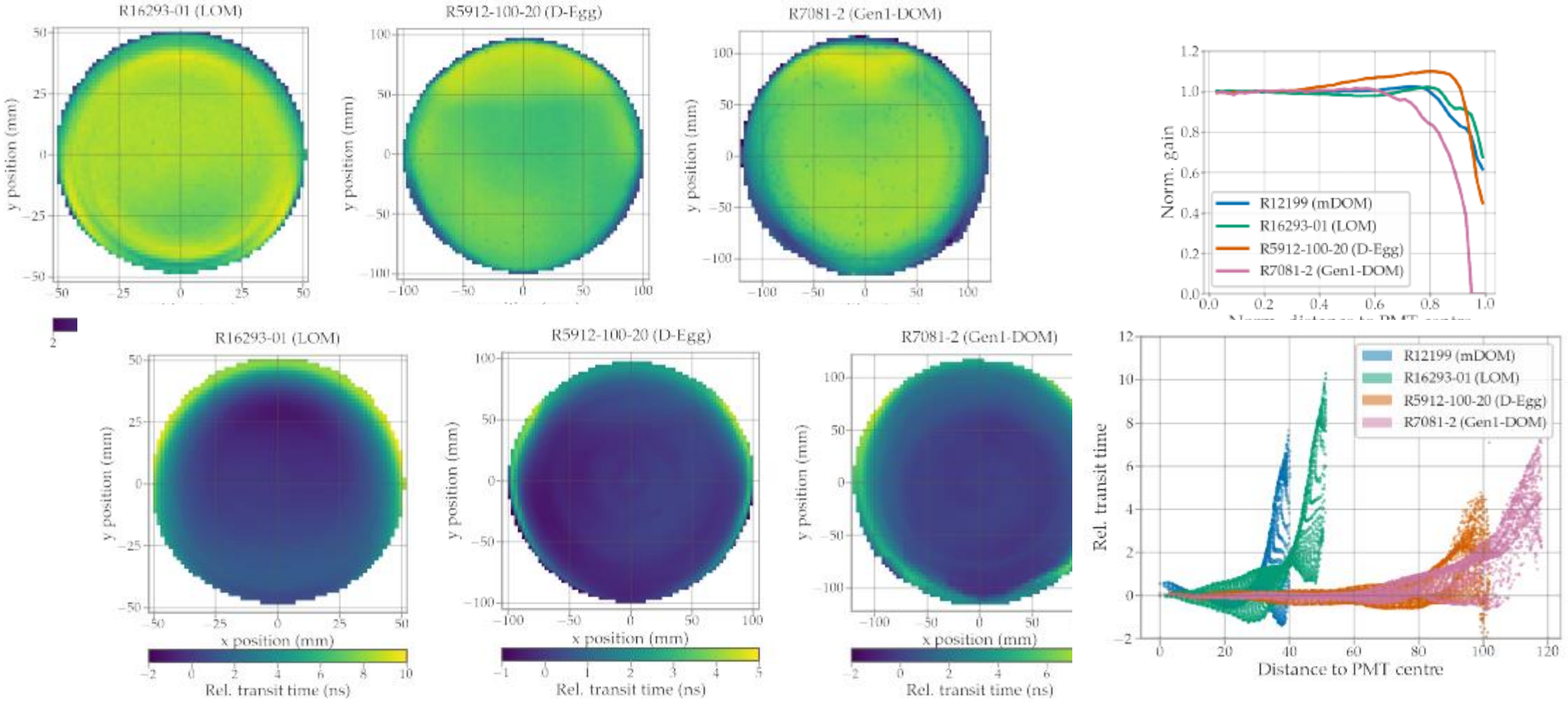
4” PMTs — Dark rate at low temperature



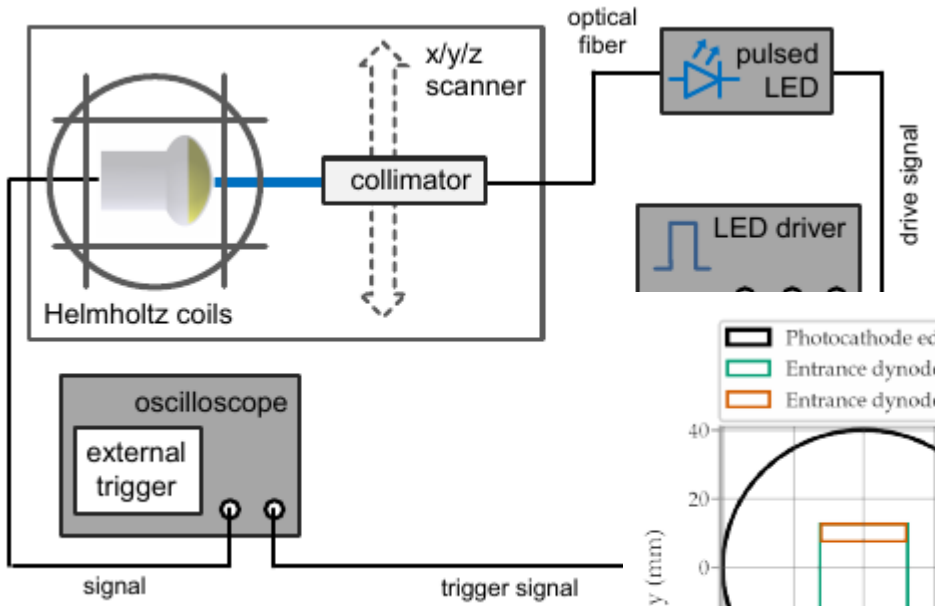
Dark rates
(with 100ns deadtime, >0.25pe, @-40C, black tape on PMT face)

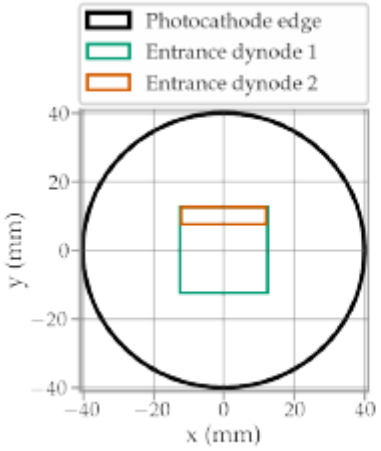
- Hamamatsu “bad” glass model
  - 106-134 [1/s] (4 samples)
- Hamamatsu “good” glass model
  - 44 [1/s] (1 sample)
- NNVT production batch
  - 31.6 [1/s] (10 samples)
  - NNVT said their current glass supplier&method is scalable for Gen2 scale production

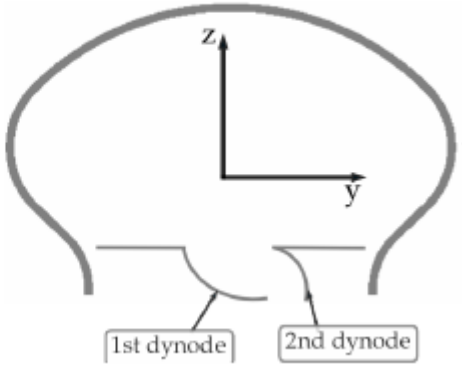
Hamamatsu’s glass-quality situation for Gen2 is hard to predict for now,
but we confirmed that both PMT vendors can produce 4” PMTs with low-enough dark rates at low temperature

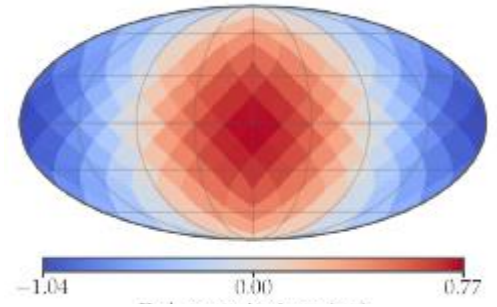

R16293-01 (LOM)
R5912-100-20 (D-Egg)
R7081-2 (Gen1-DOM)
y position (mm)
Norm. gain
R12199 (mDOM)
R16293-01 (LOM)
R5912-100-20 (D-Egg)
R7081-2 (Gen1-DOM)
x position (mm)
Rel. transit time (ns)
Rel. transit time
Distance to PMT centre

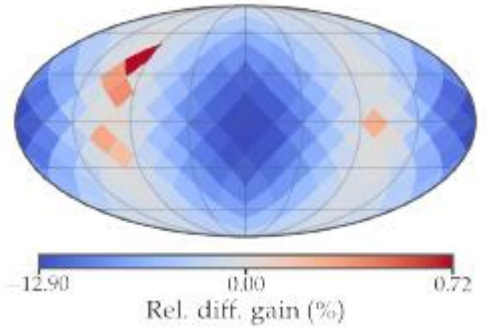
PMT magnetic field dependance











Knowing your PMT is important!

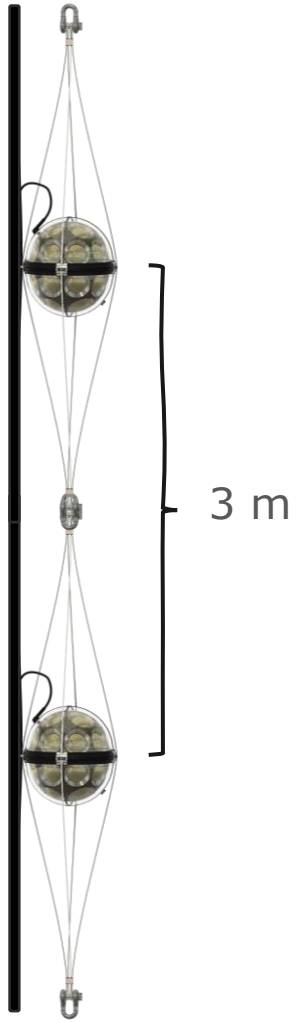
Timing:

- 1 ns ≙ ~15 cm photon travel distance
- Time systematics translate into track misreconstructions!
- Time *budget* for Upgrade 5 ns

Gain and efficiency:

- Energy reconstruction depends on number of photons
- Uncertainty in efficiency directly translate to uncertainty on number of detected photons
- Estimate for number of detected photons:

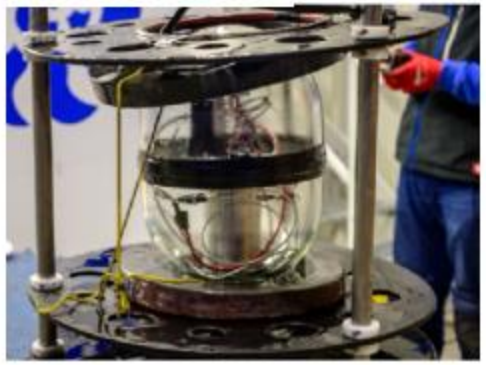
  # detected photons = pulse charge / mean charge



Module section

Component Status (1/2)

Pressure Vessel

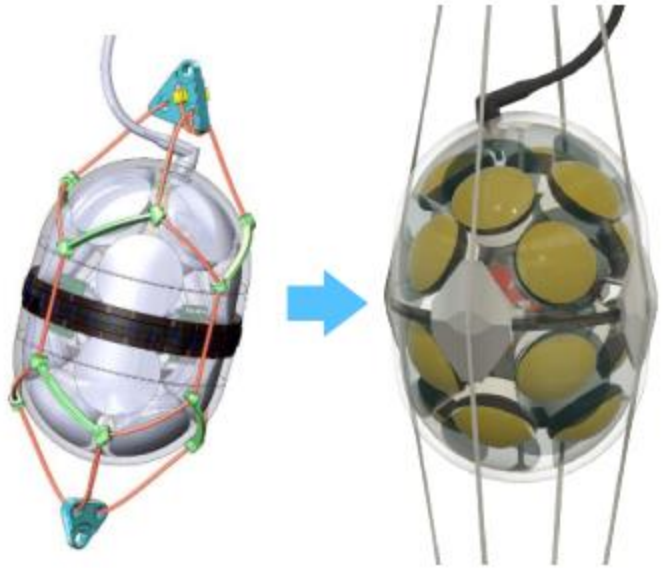


- Custom designed for the 16/18 PMT designs
- Same optical properties as mDOM/D-Egg
- 70 MPa rating confirmed & observed deformation at 70 MPa consistent with simulations

Penetrator Cable Assembly

- Same as other Upgrade MMB host modules
- Ready for Upgrade
- Need a new company for Gen2

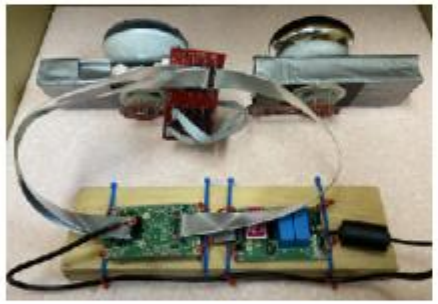
Harness



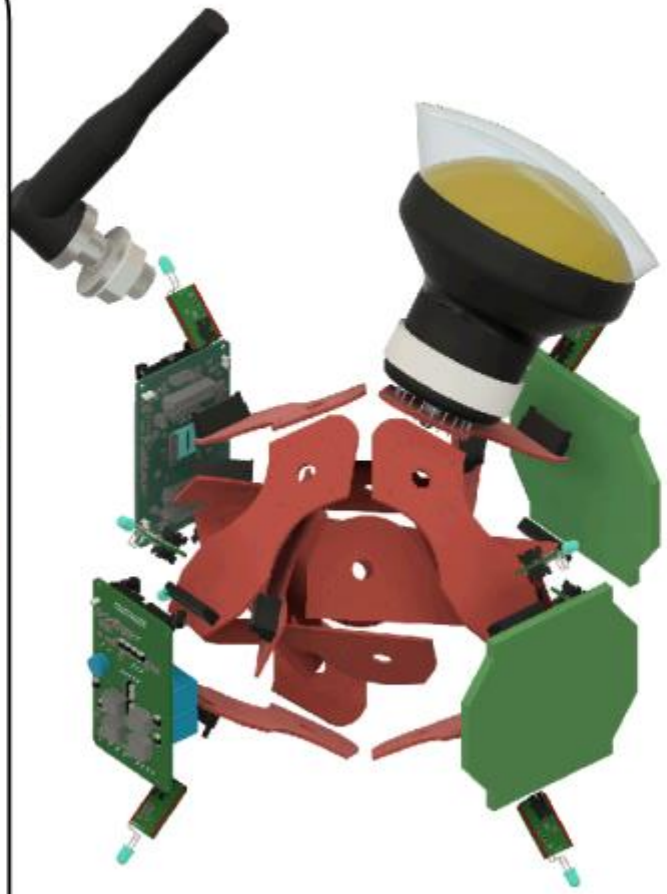
- Fishnet style (@ Brussels Meeting) -> mDOM style harness
- Aim (Upgrade) PDR this year
- **Delaney's talk for more details**

Component Status (2/2)

Electronics

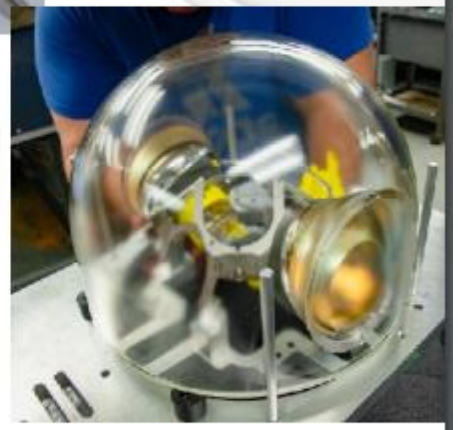


- Prototypes available for all of wuBase, Fanout, and MMB
- Solved parts procurement issues for Upgrade modules
- **More details in Sean's talk**



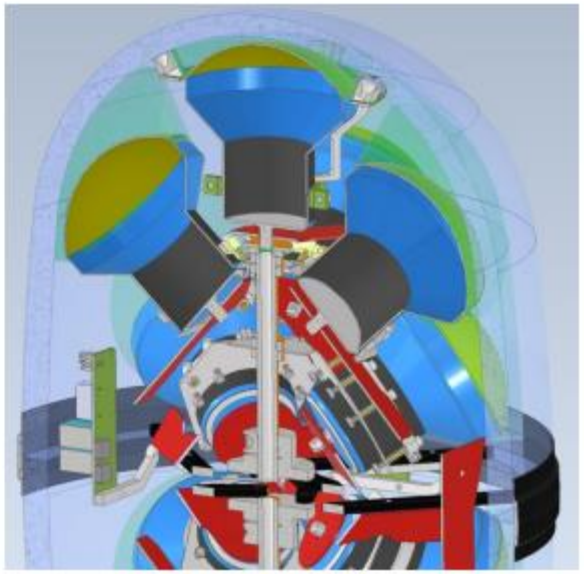
…How about 4" PMTs?

"Gelpad" & Internal structure



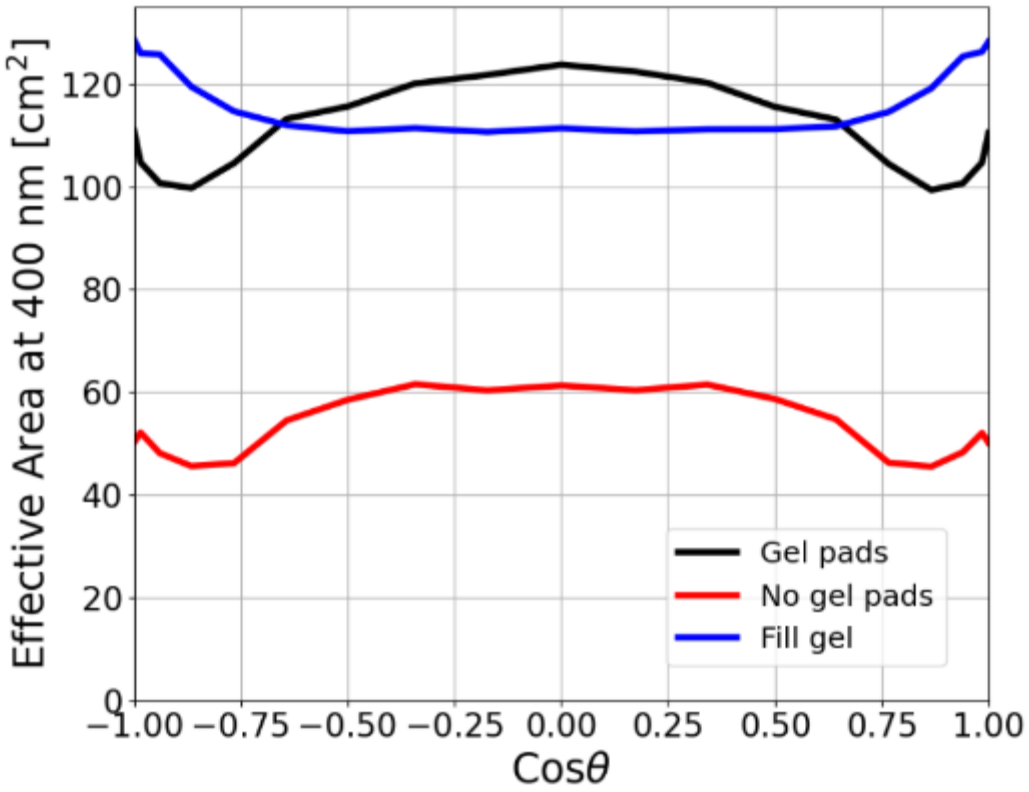
- Have explored lots of ideas & Converged to "cavity method" after Brussel meeting
- Vacuum forming machines at each group for fast iterations of the mold development
- **Vedant's talk for more details**

Internal structure



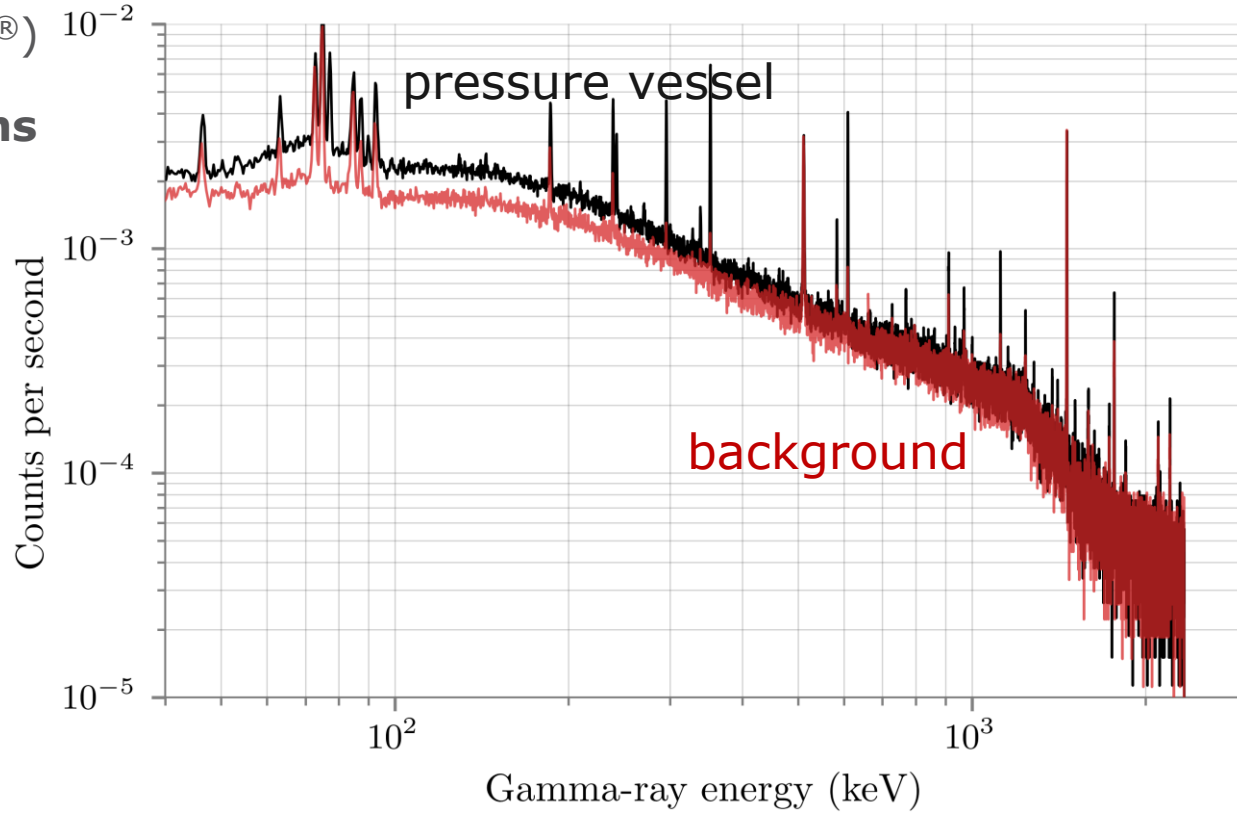
- Very densely packed module!
- Both designs use
  center shafts and **metal sheet frames**
  (for the 18-PMT design,
  the polar PMT is pushed by the center shaft)
- Recently, a skeleton mockup of LOM-18 was assembled at Chiba.
  → As we assemble components in 3D CAD,
  we could do.

Simulation section


Effective Area at 400 nm [cm^2]
120
100
80
60
40
20
0
−1.00 −0.75 −0.50 −0.25 0.00 0.25 0.50 0.75 1.00
Cosθ
Gel pads
No gel pads
Fill gel

Isotopes in pressure vessel glass

- Pressure vessel **13 kg** borosilicate glass (VITROVEX®)
- Trace amount of isotopes from **natural decay chains** and **^{40}K**
- Gamma spectroscopy measurement results in:
  - ^{238}U chain 4.61 Bq/kg
  - ^{232}Th chain 1.28 Bq/kg
  - ^{235}U chain 0.59 Bq/kg
  - ^{40}K 61 Bq/kg
- ~50 radioactive isotopes, ~3k decays/s per mDOM

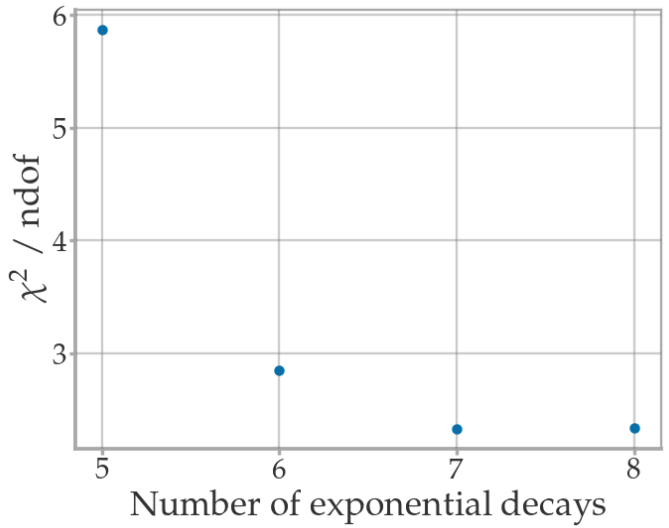


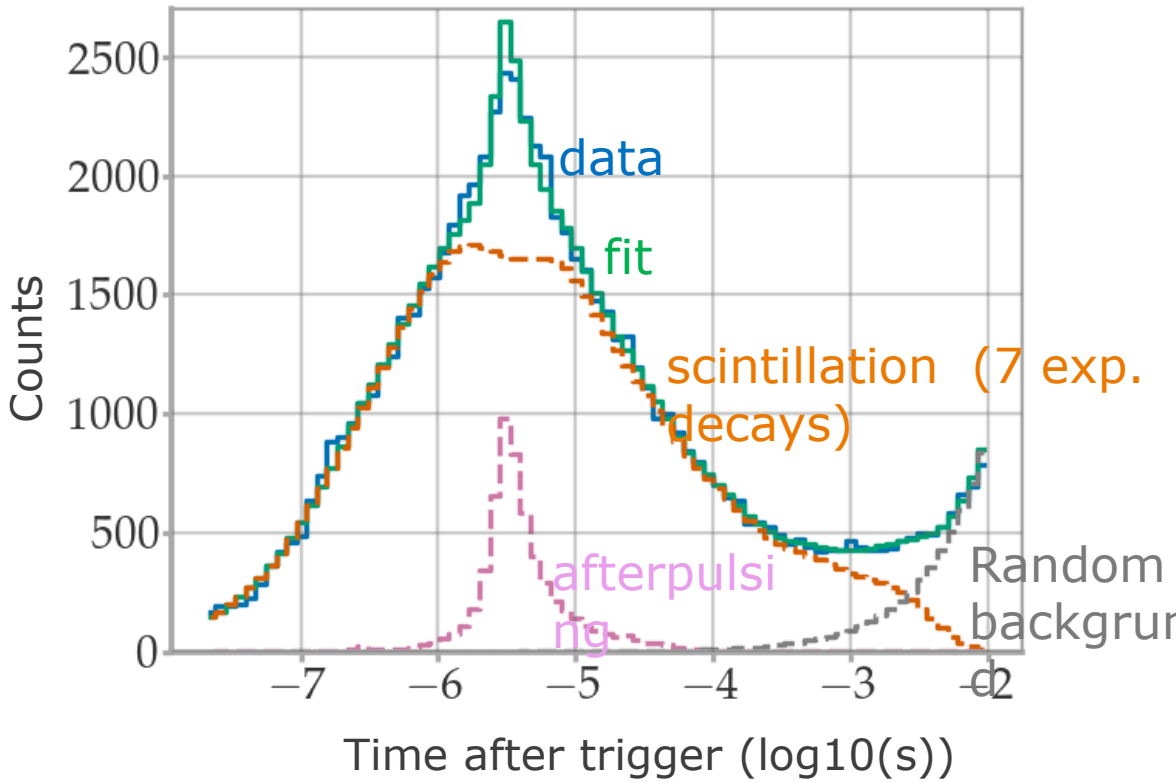
Scintillation time distribution

- Fit distribution with sum of exponential decays

$$f(t) = \sum_{i=1}^{N} h_i e^{-\alpha_i t}$$

- Consider dark rate and correlated background!
- Fit / data agreement stops improving at 7 exponential decays



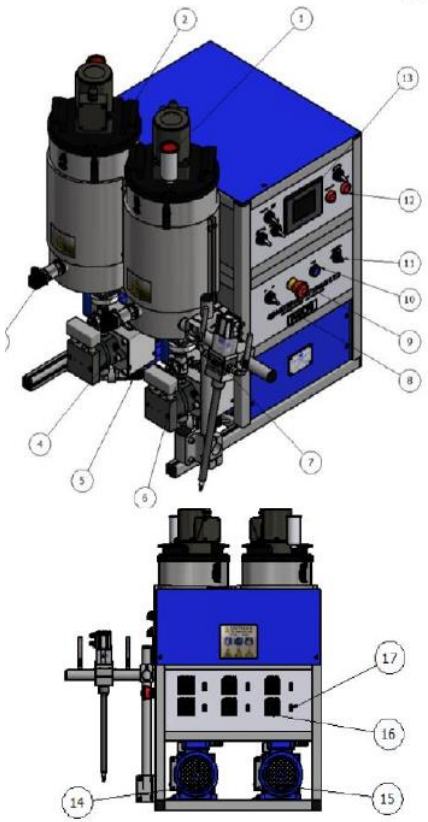


Other

Scaling towards mass production

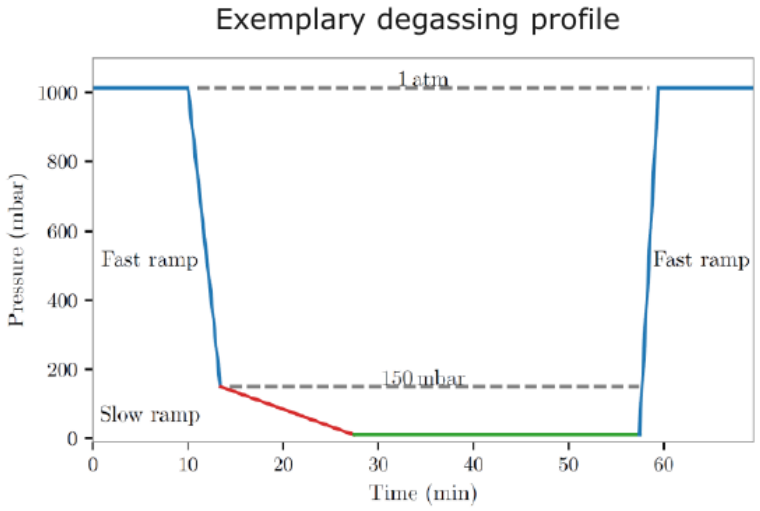
- Manufacture gelpad molds from injection molding -> 4 I.M. dies needed for LOM16 (6 for LOM16)

Gel dispensor



MeterMix Par30 Dosing system

PMTs/Gelpads transported on trays of ~20 to use as a single batch



Curing in controlled environments (12 h @ 50°C vs 48h @ room temp)

Example: E40C-1490-6

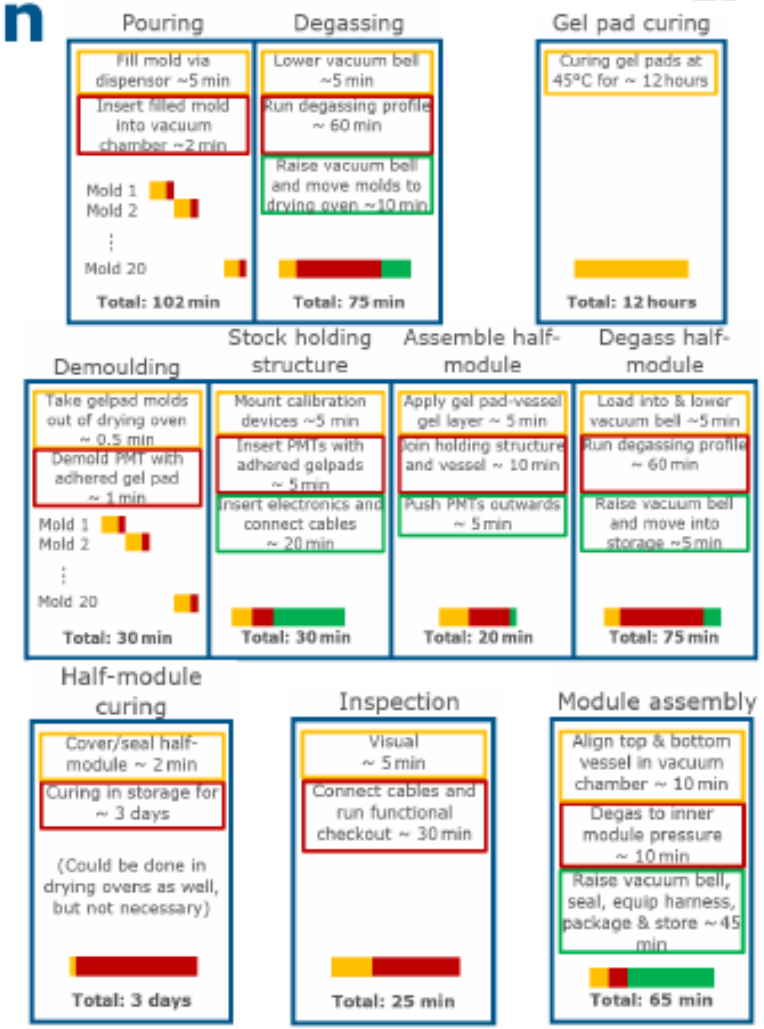
Production schedule estimation

- The number of produced modules per production site is limited by the available space, present equipment and workers
- Processes can be done in parallel during curing & degassing times to maximize usage of equipment (segmented boxes on the right)
- Production sites could focus on different parts and work together
- Gel pad production could be outsourced

Module production requirement:

- Gen2 string deployment peaking at 2200 modules per year (2029 / 2030)
- Total required modules/week (peak) : 42
- Total required modules/week (mean): 32
- Reasonable load per moderate* production site: 9 modules/week
- 5 production sites required, larger sites or produce in advance for 2029/30

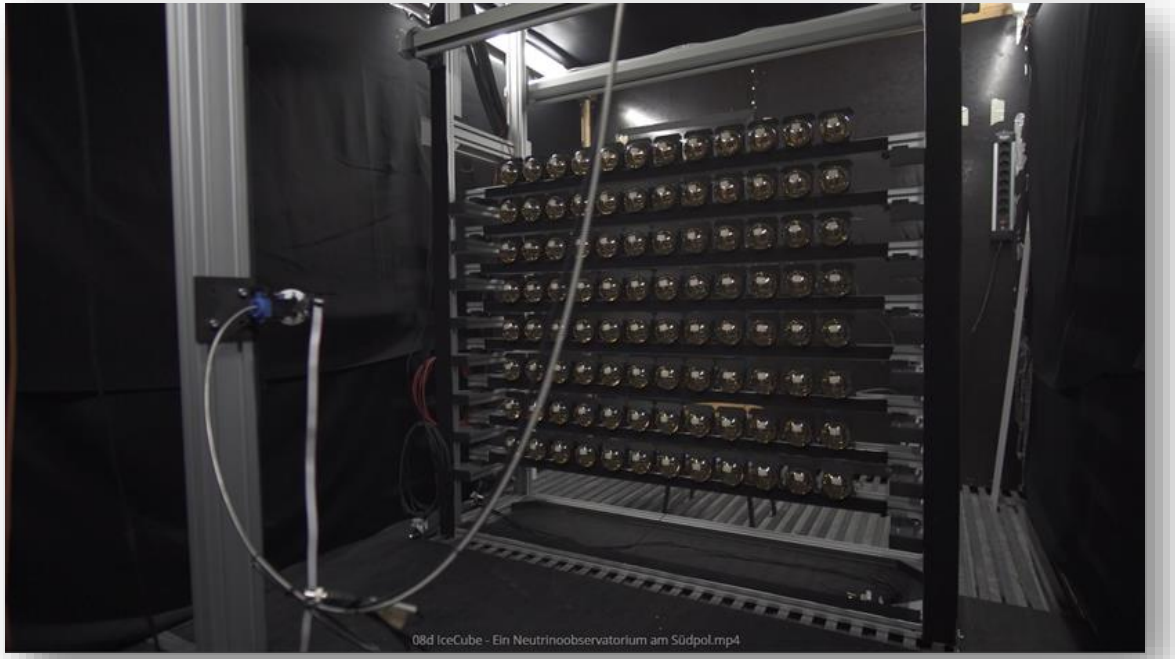
*In small production hall with one of each equipment



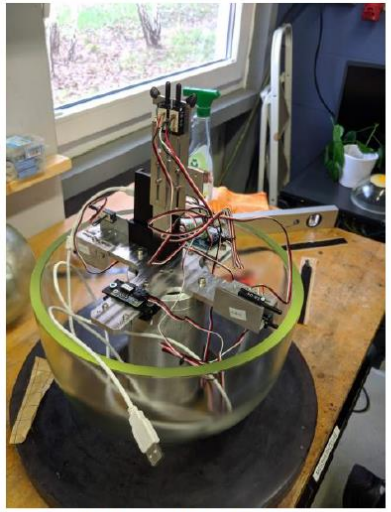
Estimated hands-on time per module: ~8 hours

Acceptance testing of all PMTs (mDOM)

- PMTs tested for requirements in Aachen and Dortmund at –20°C
- Many tests including:
  - Gain calibration
  - Timing
  - Dark rate
  - …



Pressure test



Deformation logger

Rig to secure module

Pressure chamber

View inside pressure chamber