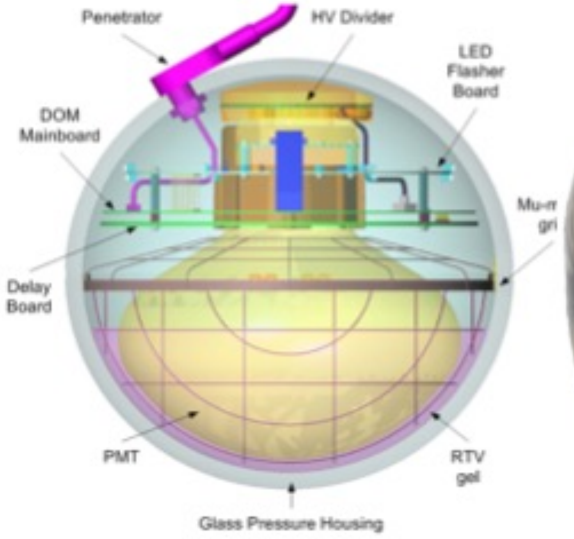
Multi-PMT elongated sensors in ppc



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Performance studies for a next-generation optical sensor for IceCube-Gen2

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We present performance studies of a segmented optical module for the IceCube-Gen2 detector. Based on the experience gained in sensor development for the IceCube Upgrade, the new sensor will consist of up to eighteen 4 inch PMTs housed in a transparent pressure vessel, providing homogeneous angular coverage. The use of custom molded optical 'gel pads' around the PMTs enhances the photon capture rate via total internal reflection at the gel-air interface. This contribution presents simulation studies of various sensor, PMT, and gel pad geometries aimed at optimizing the sensitivity of the optical module in the face of confined space and harsh environmental conditions at the South Pole.

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Table 1: Information on the various optical modules

Name	PMT diameter [inch]	Number of PMTs	Glass diameter [mm]	Glass height [mm]
Gen1 DOM	10	1	330	330
mDOM	3.15	24	356	411
D-Egg	8	2	300	534
mEgg	4	14	300	534
LOM−16	4	16	313	444
LOM−18	4	18	305	540

(a) Gen1 DOM (b) mDOM (c) D-Egg (d) mEgg (e) LOM−18

Figure 1: Schematic view of the optical modules. Gen-1 DOMs are used for the IceCube array, and mDOM and D-Eggs will be deployed in the IceCube-Upgrade holes. mEgg and LOM−18 are two designs for IceCube Gen2 studied here.

Table 2: Effective area of optical modules (preliminary)

Name	Effective area (400 nm) [cm²]	Cherenkov-averaged effective area * [Ratio to Gen-1 DOM]
Gen1 DOM	34 – 37*	1
mDOM	108	3.5 – 4.0
D-Egg	94	2.8 – 3.2
mEgg †	103	3.2 – 3.6
LOM−16†	105	3.2 – 3.7
LOM−18†	118	3.6 – 4.2

∗ Variation comes from a difference of the treatment of the detection efficiency of PMTs.
† If high quantum efficiency PMT is available, these improve by 30%.

Configuration files: om.conf

```
# name  module  area    beta    Rr      Rz      num     dir       cable
Default -1      12.88   0.5     0.1651  0.1651  1       180 0     90
mDOM    40      51.32   1       0.178   0.2055  24      33 0      45
                                                        33 90
                                                        33 180
                                                        33 270
                                                        72 22.5
                                                        72 67.5
                                                        72 112.5
                                                        72 157.5
                                                        72 202.5
                                                        72 247.5
                                                        72 292.5
                                                        72 337.5
                                                        108 22.5
                                                        108 67.5
                                                        108 112.5
                                                        108 157.5
                                                        108 202.5
                                                        108 247.5
                                                        108 292.5
                                                        108 337.5
                                                        147 0
                                                        147 90
                                                        147 180
                                                        147 270
DEgg    120     41.08   0.5     0.150   0.267   2       180 0
                                                        0 0
```

Modules area assumed spheroids (single-axis ellipsoids) specified with *Rr* and *Rz.* Pancake oversizing strategy is enabled when oversize>1

TODO: Add cylindrical shape
(enabled with negative Rz)

DONE: Enable sensor rotation

TODO: is the module structure already in GCD (or elsewhere)? I found PMT coordinates replicated for each optical module in global detector coordinates. Is this optimal?

Default describes IceCube/IceTop/PDOM sensors
can split into separate entries

requires entry for "Default" because areas are relative to "Default", since the number of photons per m of bare muon track is currently hardcoded for DOM

areas here taken from talk by Nobuhiro Shimizu (Consideration of the effective areas of optical modules for ICRC 2021 contribution)

areas are Cherenkov-weighted and solid-angle-averaged (integrated would be ok too) – prefer this to minimize effects of errors in angular and wavelength acceptance curves (think Liouville theorem)

beta describes a single-parameter angular sensitivity behavior of a single PMT (same for all PMTs but can be changed to define per-PMT if needed)
need this per PMT (not per module)

Configuration files: dx.dat, om.map and om.dirs

```
1 1 111.11 0.24184
1 2 19.228 0.160527
1 3 85.746 0.199882
1 4 65.143 0.347785
1 5 132.931 0.379851
...
1122 76 45 -1
1122 77 45 -1
1122 78 45 -1
1122 79 45 -1
1122 80 45 -1
```

dx.dat table of azimuthal directions to cable

om.map Specifies sensor types (can also be read from GCD)

Wavelength dependence is specified in files wv.dat and wv.rde for nominal and high-QE DOMs. Chosen via “type” specified along with an RDE value in file eff-f2k.

TODO: add more wavelength dependence tables as needed.
I think these should be Cherenkov-waited and normalized to 1,
overall impact being expressed via the “area” in map.conf

TODO: add support for reading all new files from GCD (need it to contain meaningful area), and an additional radius parameter (so, *area*, *Rr*, and *Rz*). Also need a parameter that specifies wavelength dependence table, unless it can be expressed as a combination of nominal/high-QE and module type

OM.dirs table of uniform directions on a sphere

Need this for initialization (to find the maximum value of angular sensitivity)

```
1 1 20
1 2 20
1 3 20
1 4 20
1 5 20
1 6 20
1 7 20
1 8 20
1 9 20
1 10 20
...
93 105 40
93 106 120
93 107 120
93 108 40
93 109 110
93 110 120
93 111 40
93 112 40
93 113 200
93 114 220
```

```
0 -1 0 0
1 -0.990439 -0.137952 0
2 -0.990439 0.137952 0
3 -0.987688 -0.0822425 -0.133071
4 -0.987688 -0.0822425 0.133071
5 -0.987688 0.0822425 -0.133071
6 -0.987688 0.0822425 0.133071
7 -0.966393 -0.220117 -0.132792
8 -0.966393 -0.220117 0.132792
9 -0.966393 0.220117 -0.132792
10 -0.966393 0.220117 0.132792
...
632 0.966393 -0.220117 0.132792
633 0.966393 0.220117 -0.132792
634 0.966393 0.220117 0.132792
635 0.987688 -0.0822425 -0.133071
636 0.987688 -0.0822425 0.133071
637 0.987688 0.0822425 -0.133071
638 0.987688 0.0822425 0.133071
639 0.990439 -0.137952 0
640 0.990439 0.137952 0
641 1 0 0
```

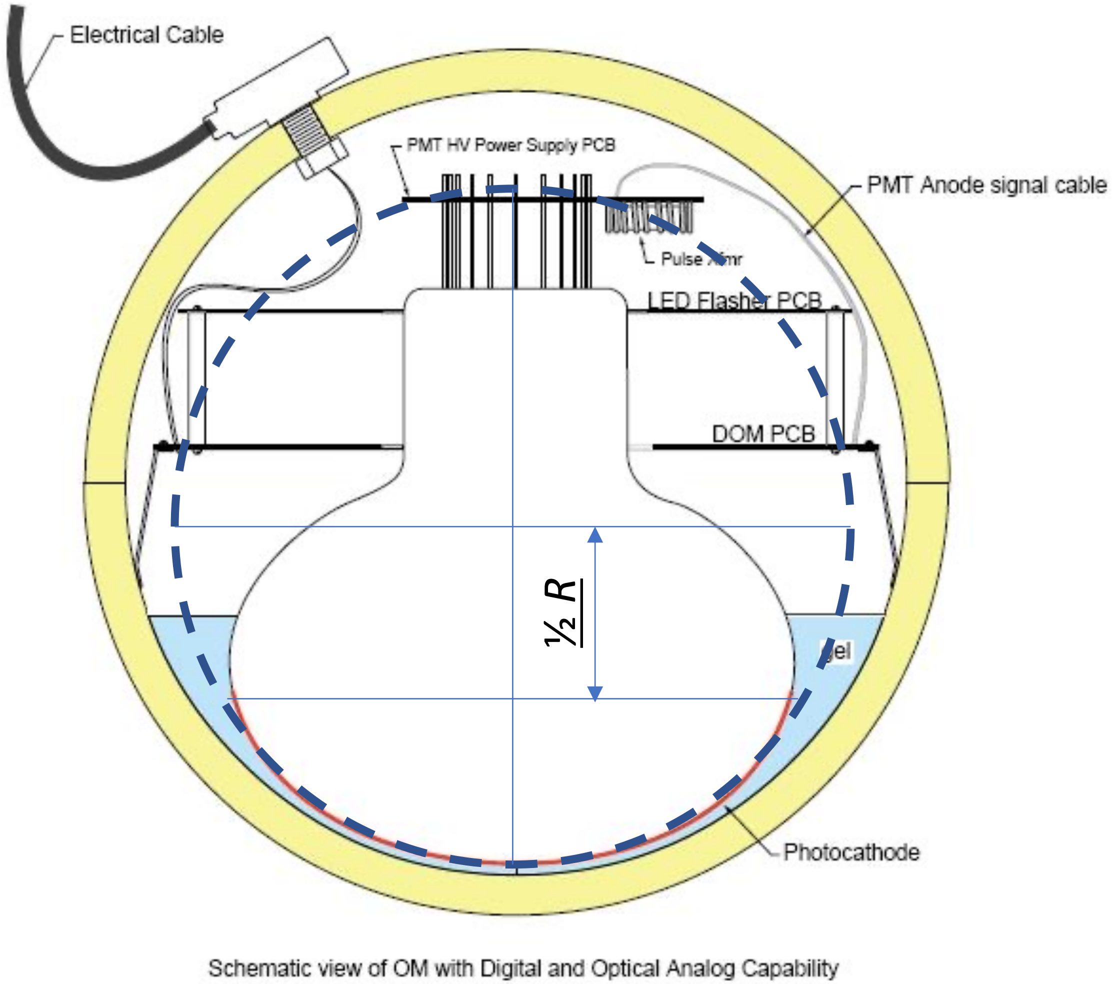
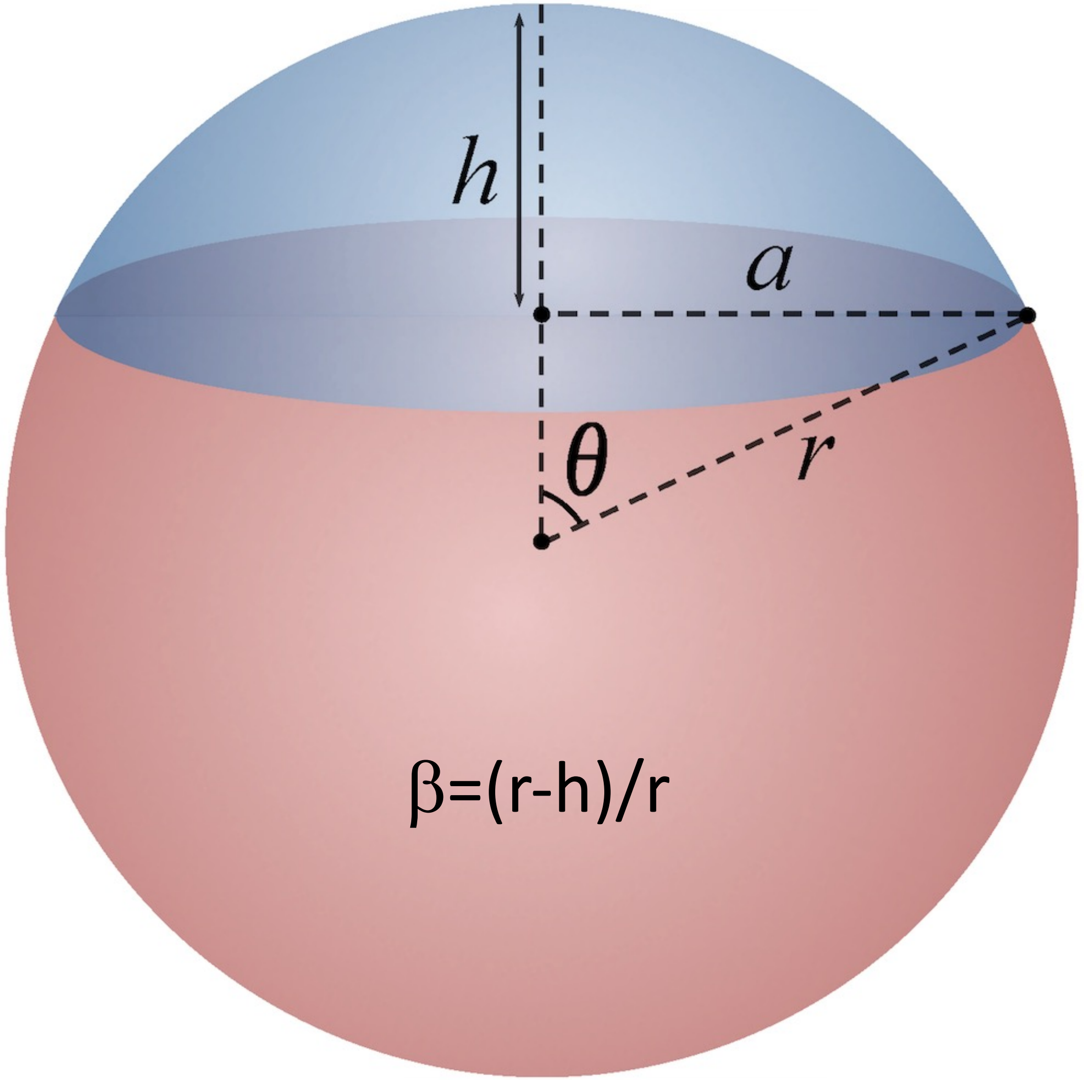
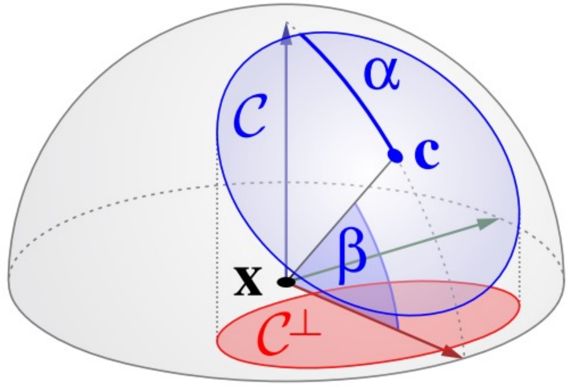
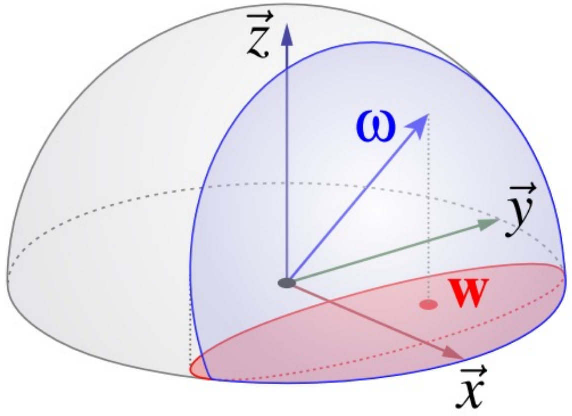
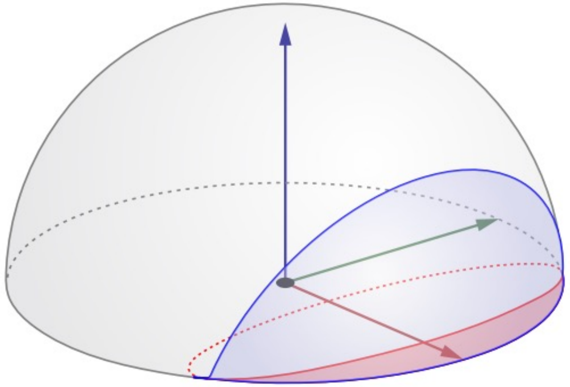


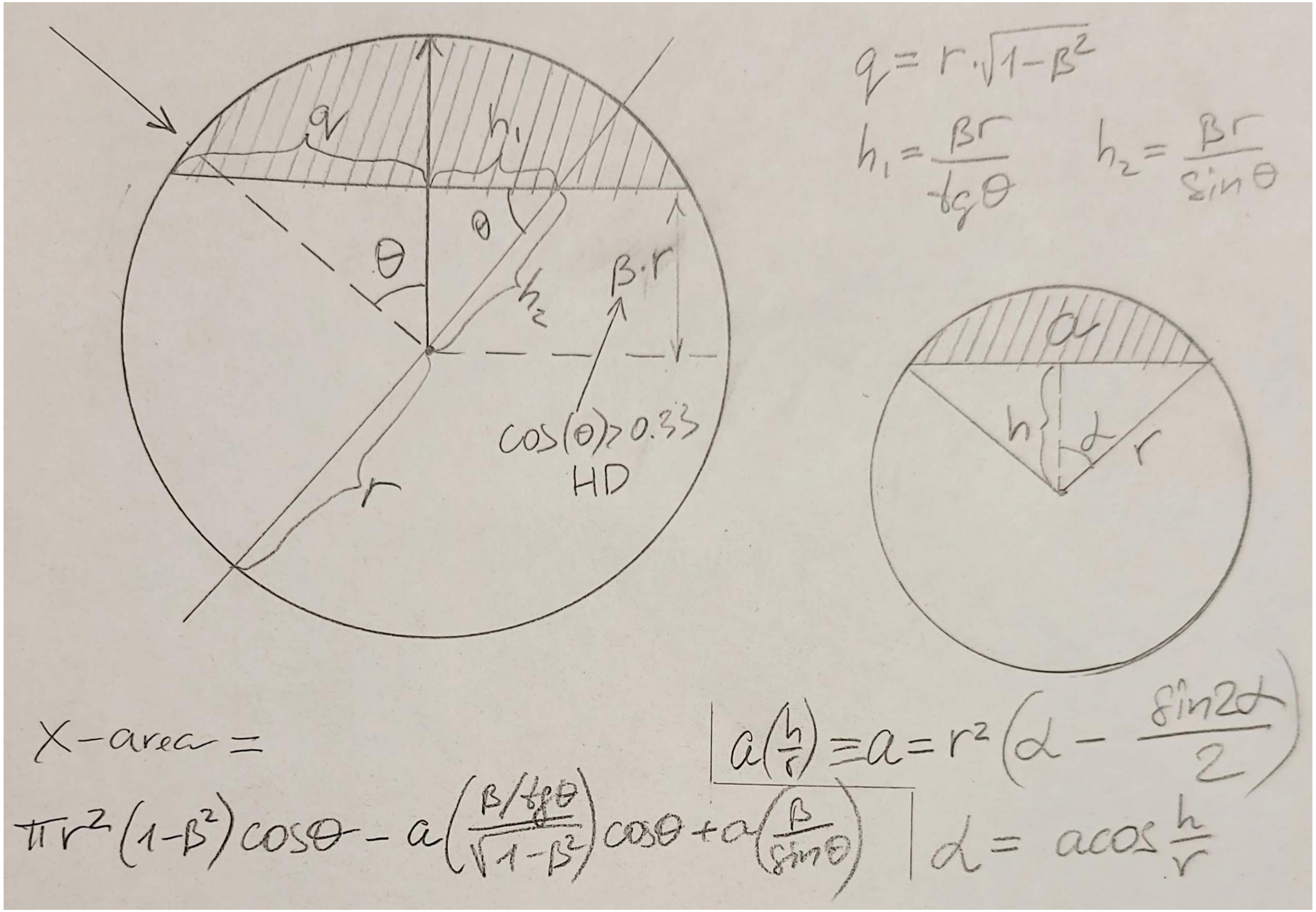
Figure 62: Schematic profile view of a generic Digital Optical Module, showing pressure sphere, optical coupling gel, PMT, signal processing electronics board, LED flasher board, PMT base, and electrical penetrator.

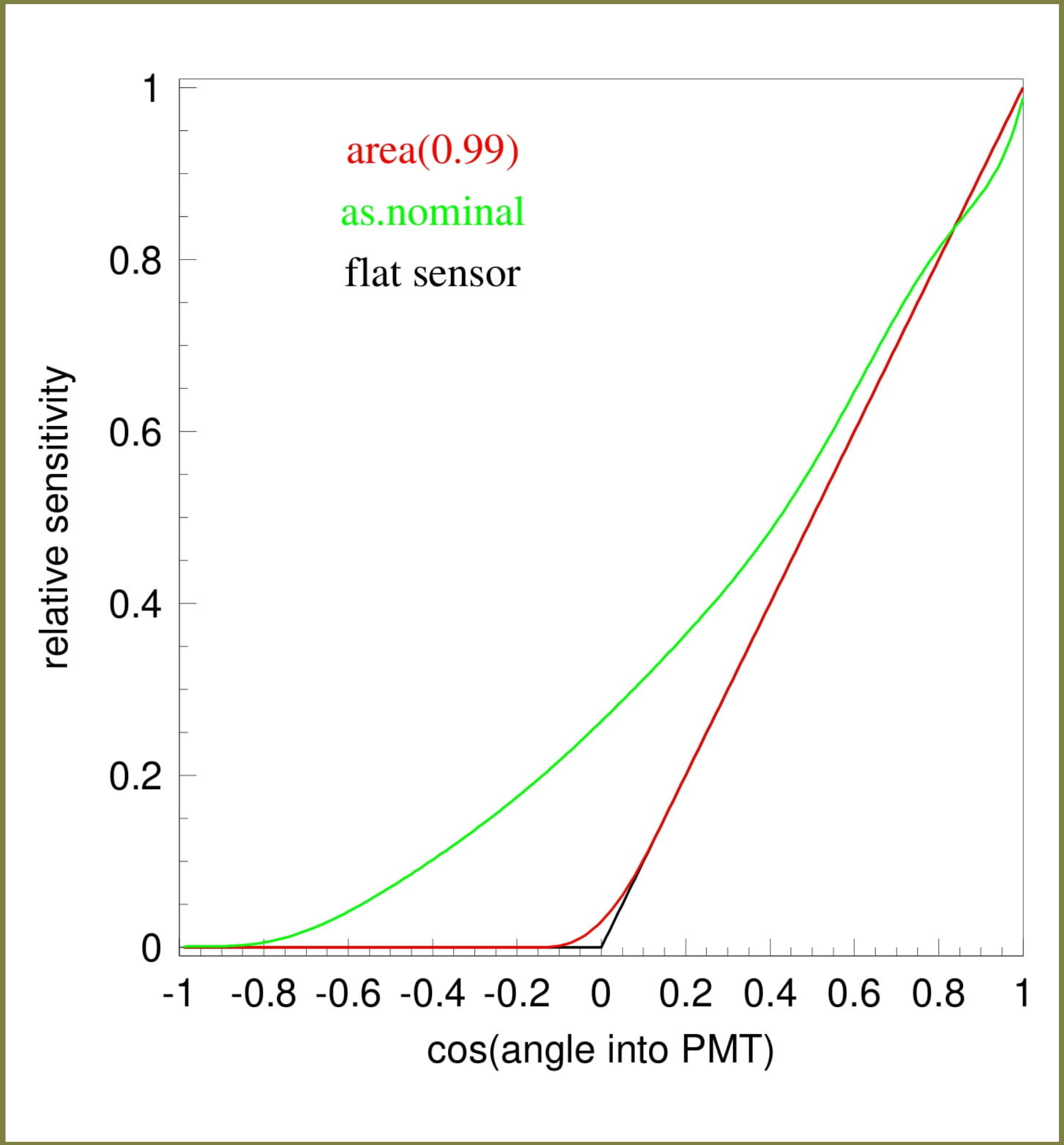


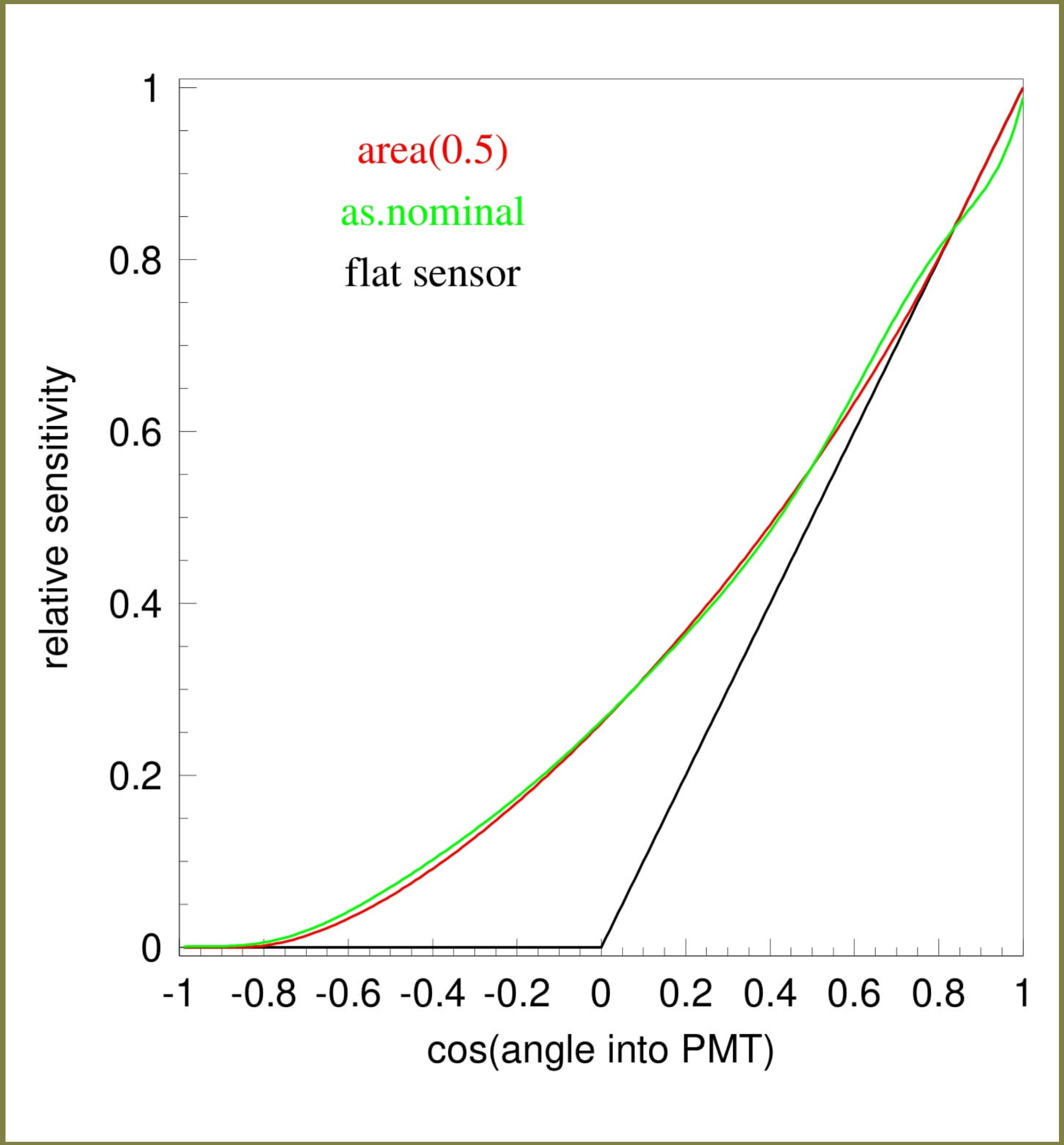

α
C
c
β
x
C⊥


z
ω
y
w
x

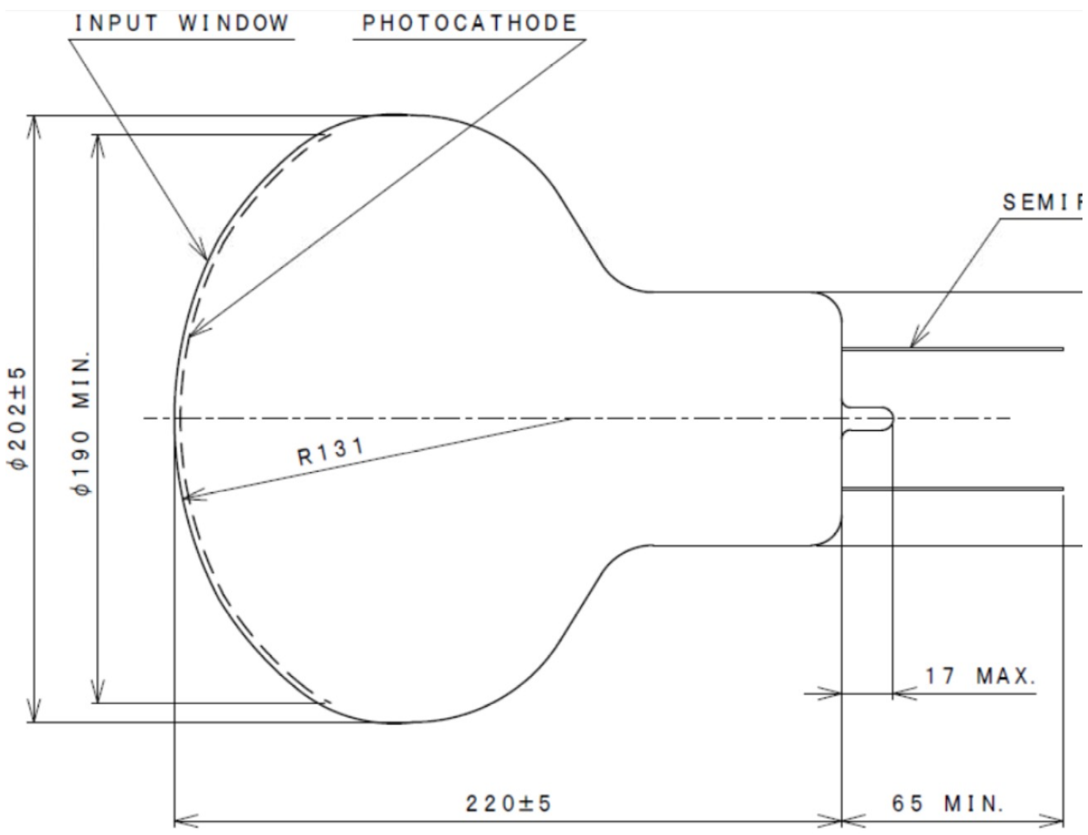



q = r·√(1−β²)
h1 = βr / tgθ
h2 = βr / sinθ
q
h1
θ
θ
h2
β·r
cos(θ)>0.33
HD
r
α
h
α
r
X-area =
πr²(1−β²)cosθ − a((β/tgθ) / √(1−β²)) cosθ + a(β / sinθ)
a(h/r) ≡ a = r²(α − sin2α / 2)
α = acos h/r


area(0.99)
as.nominal
flat sensor
relative sensitivity
cos(angle into PMT)
0
0.2
0.4
0.6
0.8
1
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1

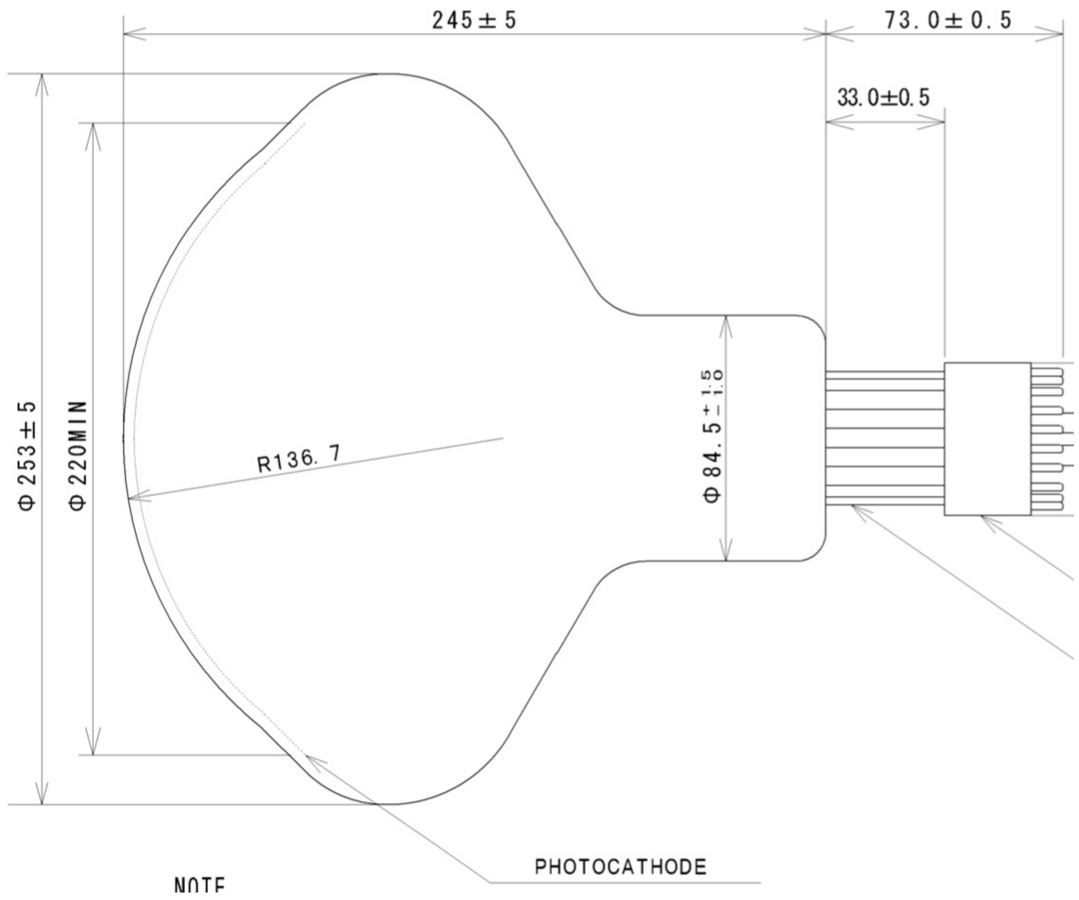

area(0.5)
as.nominal
flat sensor
relative sensitivity
cos(angle into PMT)
0
0.2
0.4
0.6
0.8
1
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1

DEgg PMT



β=0.69   A(head-on)=284 cm^2 A(curved)=336 cm^2

DOM PMT



β=0.59   A(head-on)=380 cm^2 A(curved)=477 cm^2

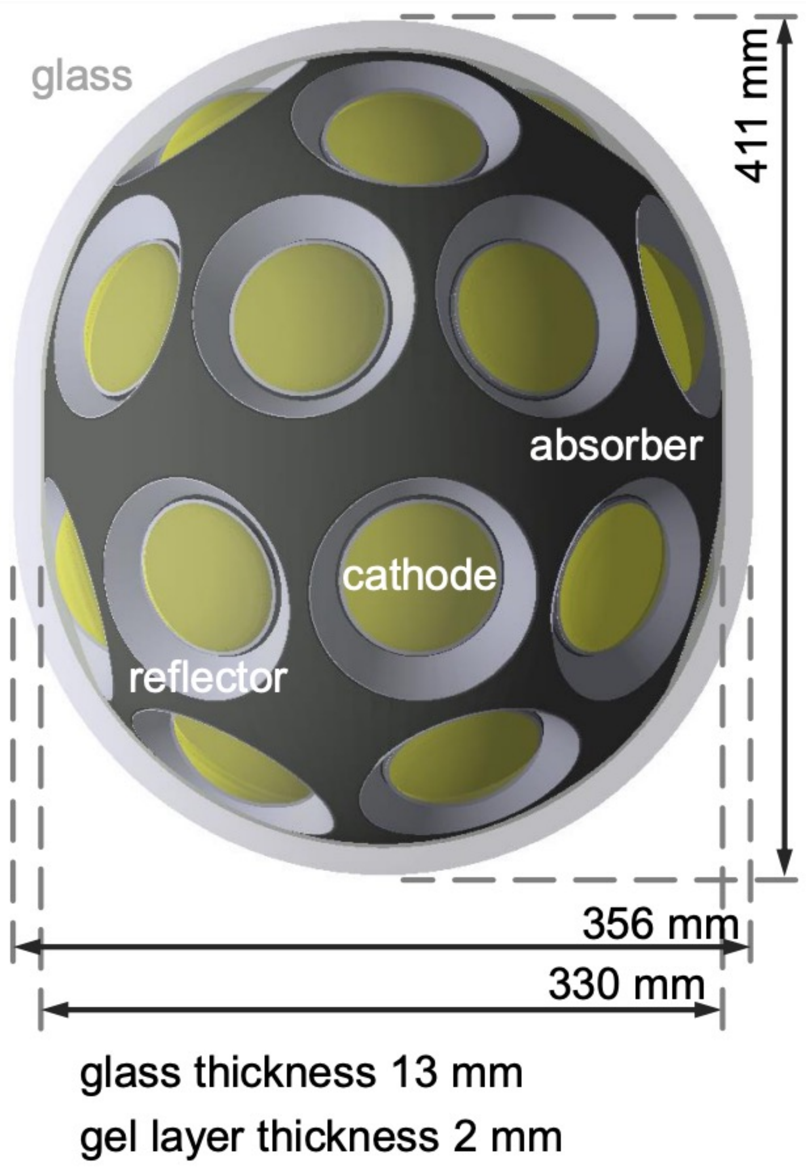
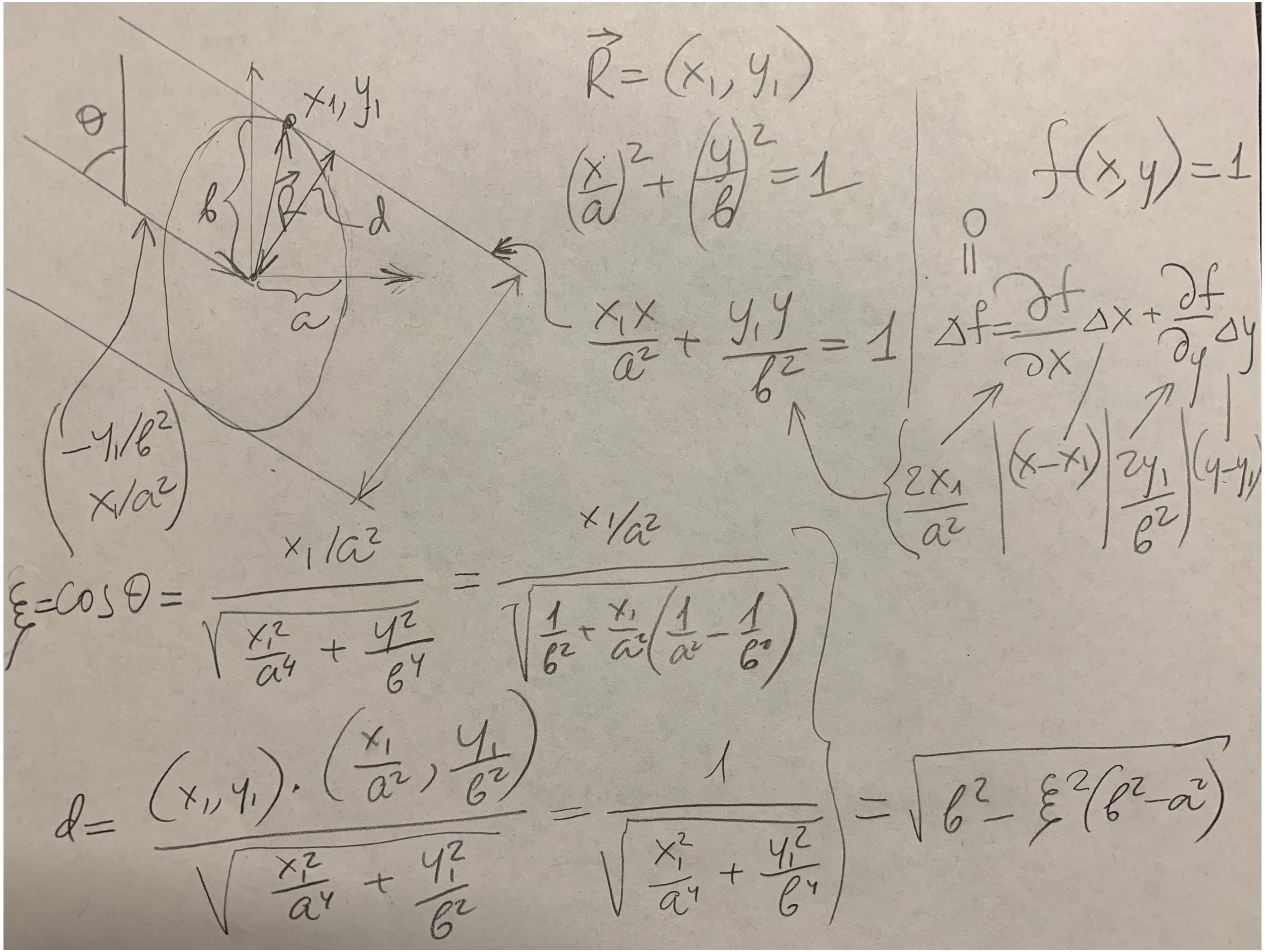


Figure 1: The shape of D-Egg. The height of the glass is 534 mm and the diameter at the equator is 300 mm.



To calculate acceptance chance for a photon that lands on the spheroid sensor we need the sum of all visible cross-sections of PMTs divided by the cross-sectional area of the sensor for that direction.

Maximum of ratio of PMT area sum to sensor area determines the "surface efficiency" of the sensor, and the photons are simulated to uniformly cover the area of the sensor. The angular sensitivity is applied thereafter.

The solid-angle averaged and "flat" areas are easily related to each other at initialization. Still, recommend using average effective sensor area as input (to minimize errors due to angular sensitivity interpretation and simulation)

```
Configuring in "/data/user/dima/I3/ice-full/"
Configuring icemodel in "/data/user/dima/I3/ice-full/"
Configuring tiltmodel in "/data/user/dima/I3/ice-full/"
Configuring holeice from "/data/user/dima/I3/ice-full/as.dat"
Using oversize as set with OVSZ=1
Configured: xR=1 eff=1 sf=0.35 g=0.9
With hole ice: xH=0.5 sca=0.03 (0.35,0.9) abs=100
Ice anisotropy is k(130)=1,1,1
New Ice anisotropy is 1.82212,0.740818,0.740818
Renorm. NI anisotropy 1.69545,0.689318,0.689318
Ice absorption anisotropy scaling is 0
Initialized BFR diffusion patterns; s_eff=0.00246854 m^-1
Loaded 2 angsens coefficients
Configured 642 test directions
 OM Type -1 with 1 PMTs added (x1)
 OM Type 40 with 24 PMTs added (x1.10952)
 OM Type 120 with 2 PMTs added (x1.93195)
Loaded 131072 random multipliers
Using fixed positions of hole ice columns from str-f2k!
Loaded 14843 cable positions
 Found 5160 OMs of type -1
 Found 9760 OMs of type 40
Warning: string 71 too close to cell boundary
Loaded 14920 DOMs (21x19)
Loaded 80x110 2d dust layer points
Ice layer thickness: UNIFORM
Loaded 42 wavelenth points
Loaded 171 ice layers
Air bubble parameters: 11.7 1350 1400
```

Hole ice → With hole ice line

SPICE BFRv2 (Ice anisotropy … Initialized BFR diffusion patterns)

om.conf (Configured 642 test directions … OM Type 120)

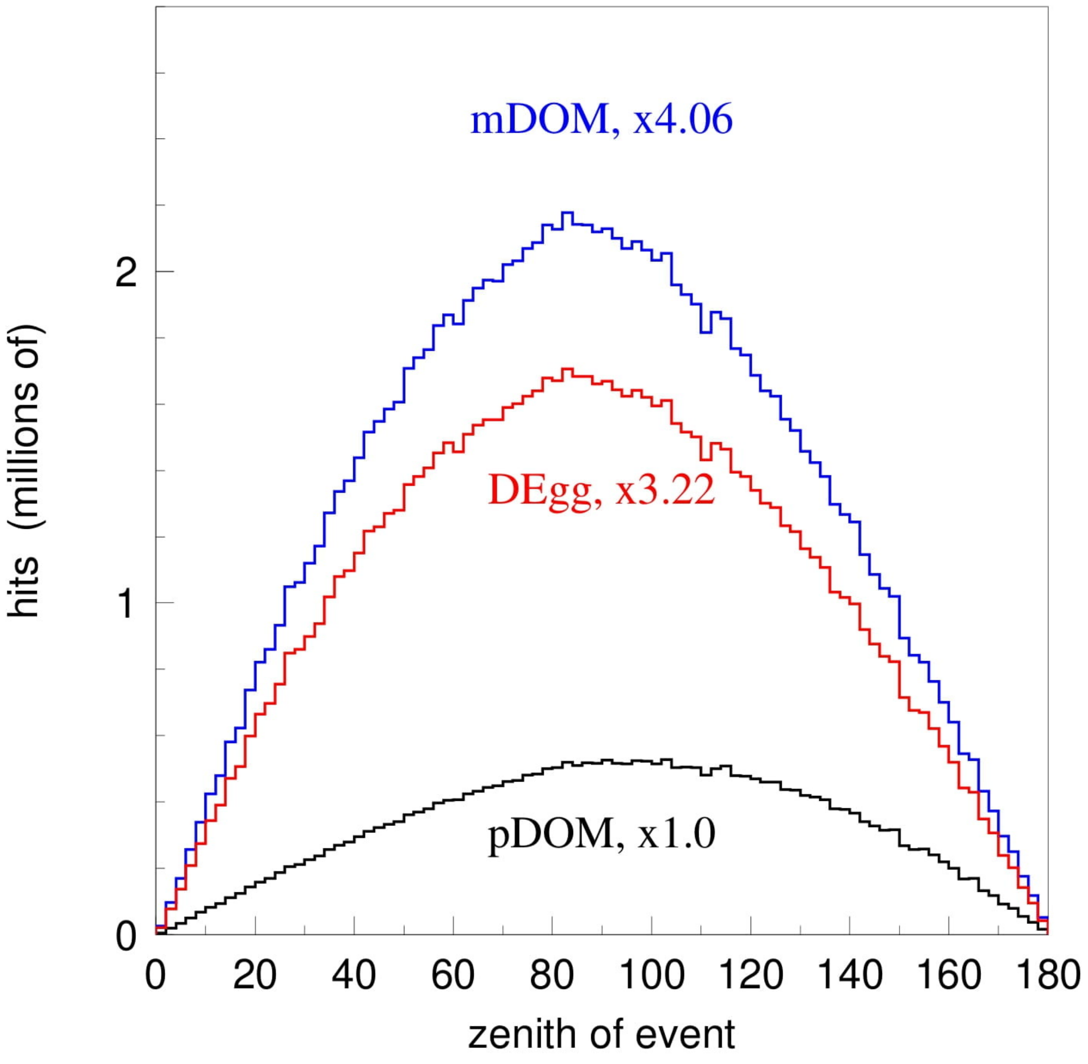
relative max surface density of sensor (max over all possible directions)

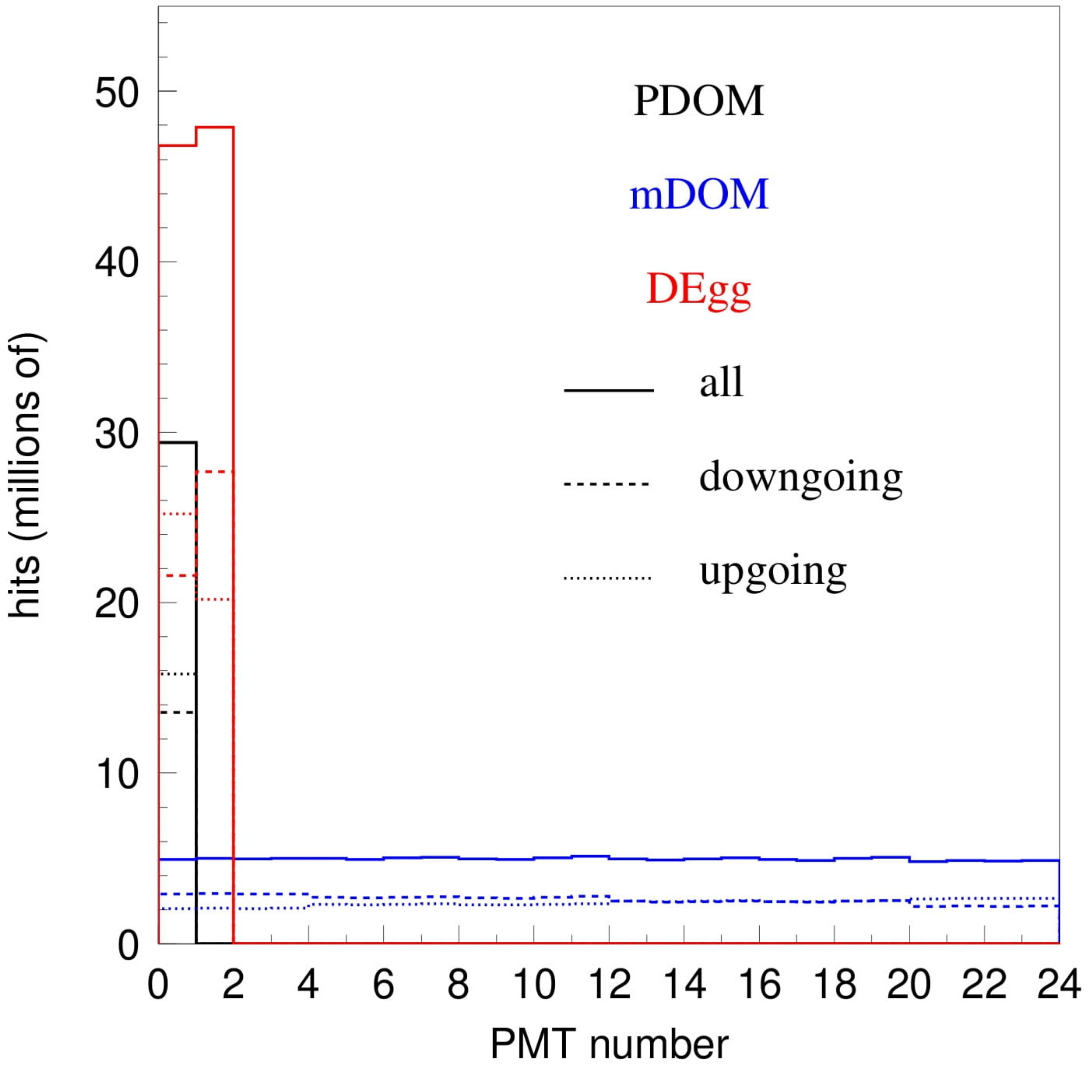
cables → Loaded 14843 cable positions

om.map (or GCD) (Found … OMs of type …)

2D Tilt → Loaded 80x110 2d dust layer points

Response to isotropic flux of muons and electron cascades, IceCube with all sensors replaced





Sensor eff. area ratios (to pDOM):
3.19 (DEgg), 3.98 (mDOM)

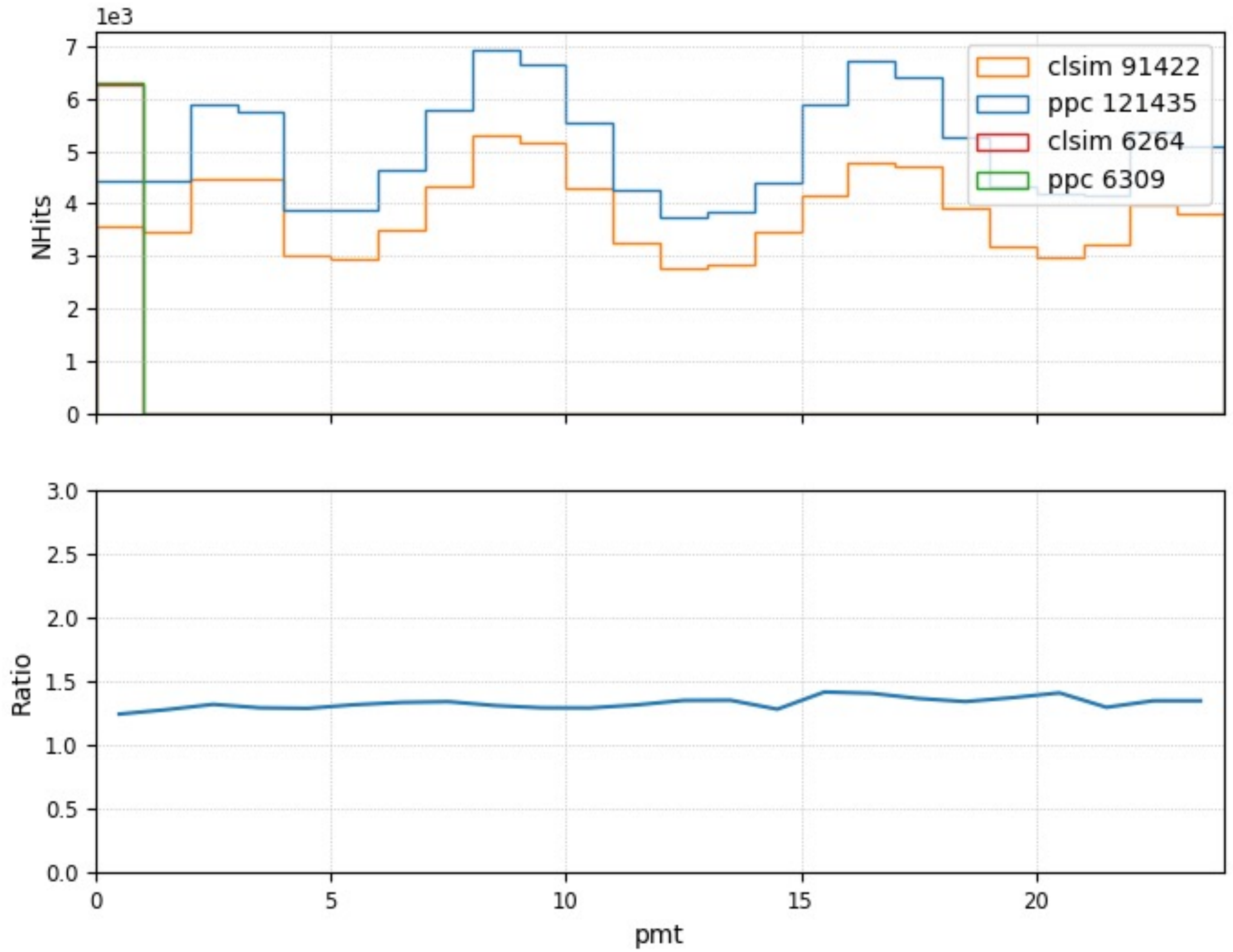
Simulation of Sunflower_240m_v3.2.2 (Tianlu)

ppc simulation with

SPICE BFRv2
Direct Hole Ice
2d Tilt Maps
Cable Shadow

mDOMs/pDOM areas of 3.98 from N. Shimizu
cf. 2.24(?) in clsim sim.

```
if sensor == I3OMGeo.OMType.PDOM:
    return 29.2*I3Units.cm2
elif sensor == I3OMGeo.OMType.DEgg:
    return 43.3*I3Units.cm2
elif sensor == I3OMGeo.OMType.mDOM:
    return 65.4*I3Units.cm2
```



- Elongated and/or multi-PMT sensor treatment has been added to ppc (on git)

- Some TODO items to be resolved in the next few weeks, but should be possible to use now with external configuration files (in resources/ice/gen2 – copy these into your PPCTABLESDIR directory)

- Collecting info for configuration of sensors within icetray: geometry of sensor (incl. PMT configuration), wavelength sampling tables, space-angle-averages areas, and angular sensitivity curves

- The sensor data for the above need to come from dedicated studies including internal sensor structure, glass/gel transmission, quantum efficiencies, etc. (Nobuhiro or Kotoyo?)

1) # of Cherenkov photons in $d\lambda$ is $\frac{dN_e}{d\lambda} \cdot d\lambda$
(emitted per meter of bare muon track)

2) ice propagation results in a loss (fraction) function that adds time delay component (t) and arrival direction $(\vec{n})$ and landing coordinates $(\vec{r})$ on a OM sensor: $F(\vec{n}, \vec{r}, t)$

3) Quantum efficiency, PMT acceptance, and losses due to glass and gel transmission are all together another fraction $Q(\vec{n}, \vec{r})$

All of these depend on wavelength λ, but since photons do not change wavelength, we have:

$$\underline{\text{Total \# of pulses per } \Delta\lambda, \Delta\vec{n}, \Delta\vec{r}, \Delta t} = Q(\vec{n}, \vec{r}) \cdot F(\vec{n}, \vec{r}, t) \cdot \frac{dN_e}{d\lambda} =$$

$$= \underbrace{F(\vec{n}, \vec{r}, t)}_{\text{ice propagation}} \cdot \frac{d \int_{\lambda_0}^{\lambda} Q(\vec{n}, \vec{r}, \lambda') \cdot \frac{dN}{dX} dX}{d\lambda}$$

} cherenkov-convolved acceptance

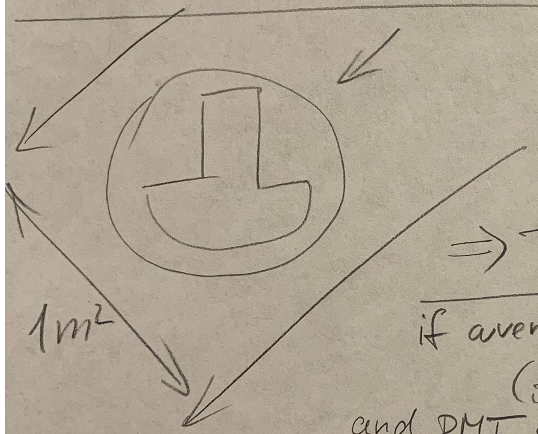
photon sampling function

Frank-Tamm formula
(# of Cherenkov photons emitted by bare muon track)

$$\frac{d^2E}{dx\, d\omega} = \frac{e^2}{c^2}\left(1 - \frac{1}{\beta^2 n^2}\right) \omega\, d\omega$$

$E = N \cdot \hbar\omega \qquad \omega = \frac{2\pi c}{\lambda} \qquad \alpha = \frac{e^2}{\hbar c}$

$$\Rightarrow d\left(\frac{dN}{dx}\right) = 2\pi\alpha \left(1 - \frac{1}{\beta^2 n^2}\right) \frac{d\lambda}{\lambda^2}$$



fraction f results in pulses (incl sub-threshold)

$\Rightarrow$ Then $f \cdot 1m^2$ = eff. area

if average eff. area (over solid angle) is known,
and PMT ang. sens. is known
and PMT geometry inside OM is known
$\Rightarrow$ can calculate eff. area for given direction

OM is simulated as a shape (e.g., spheroid) cross-sectional area of which is $A(\theta)$

Then: # of Cherenkov pulses is $d\left(\frac{dN}{dx}\right) \cdot \underbrace{\frac{\text{Eff. Area}(\theta)}{A(\theta)}}_{\text{acceptance}}$

Since $A(\theta)$ does not depend on λ, recommend "Cherenkov-weighted eff. area" + wavelength dependence curve

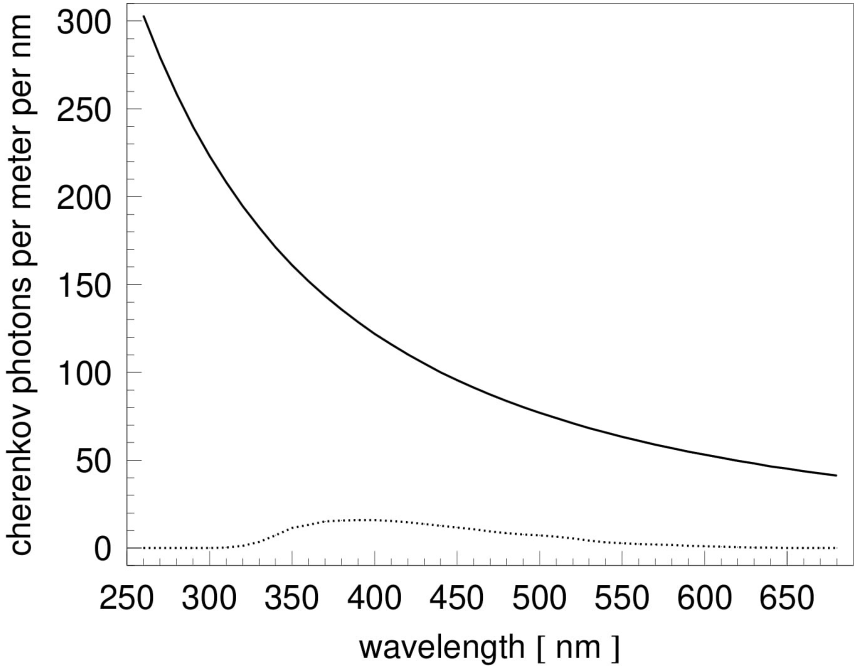
$\hookrightarrow \int d\left(\frac{dN}{dx}\right) \cdot \text{EffArea} \Big/ \int d\left(\frac{dN}{dx}\right)$

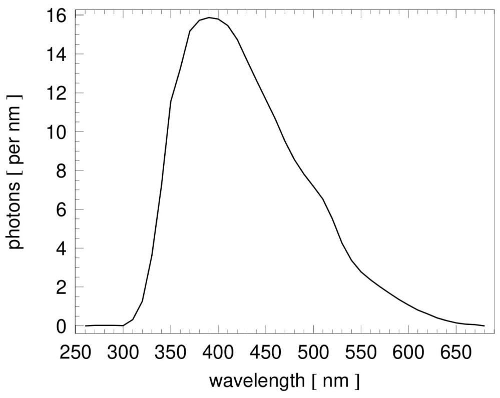
The direction of propagation of the Cherenkov light does not need correction, but the velocity does. Using an extensive table of data [5] and interpolating linearly in $\log \lambda$ for phase refractive index for ice, we generated a polynomial (with wavelength λ in micrometers)

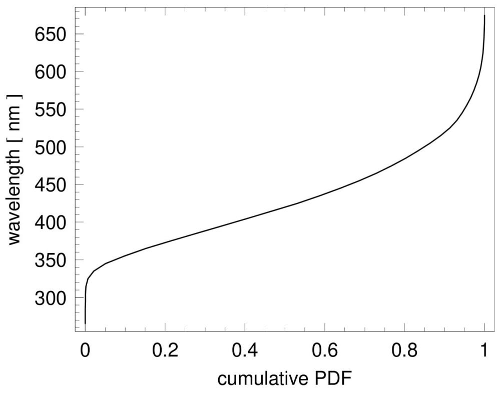
$$n(\lambda) = 1.55749 - 1.57988\lambda + 3.99993\lambda^2 - 4.68271\lambda^3 + 2.09354\lambda^4 \quad (3)$$

in the region 0.3 μm to 0.6 μm for which Cherenkov light contributes to the signal of a muon. For group refractive index, we generated a polynomial for the fractional increase

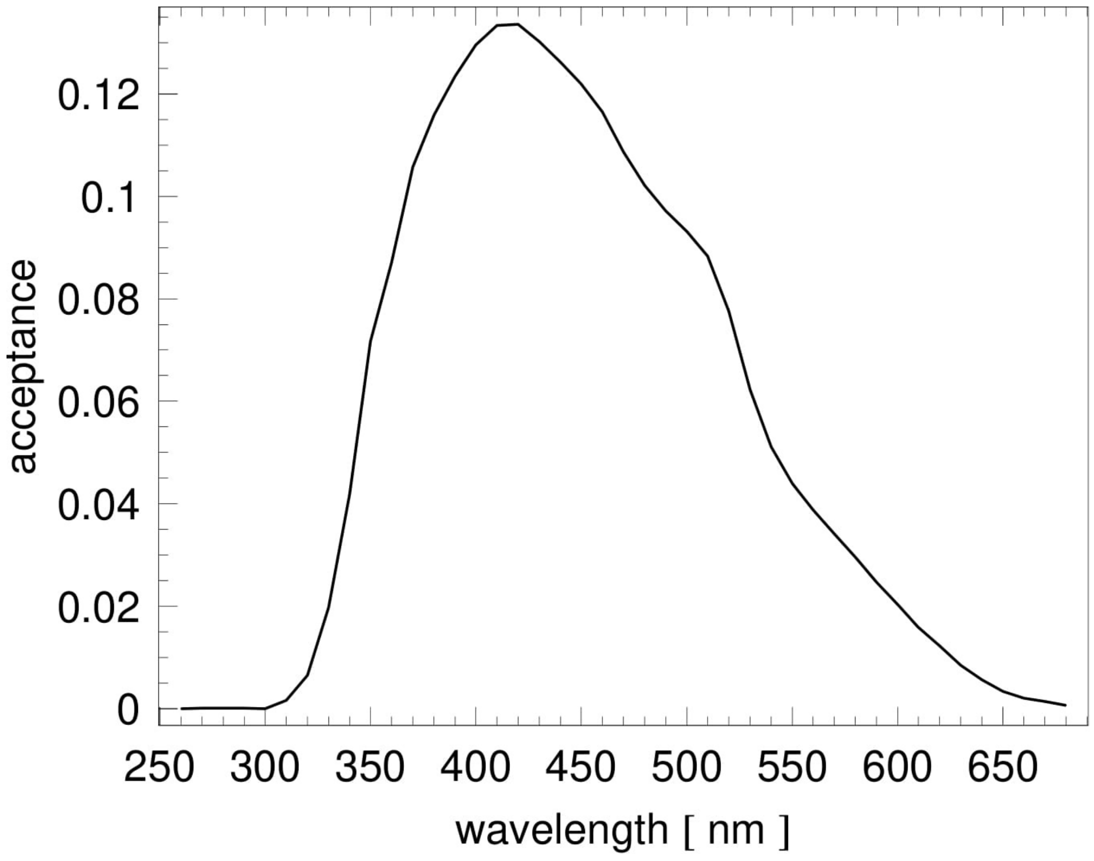
$$\frac{n_g - n}{n} = \frac{\lambda}{n}\left|\frac{\mathrm{d}n}{\mathrm{d}\lambda}\right| = 0.227106 - 0.954648\lambda + 1.42568\lambda^2 - 0.711832\lambda^3 \quad (4)$$







Calculated for a spherical DOM with radius 16.51 cm



This fraction of photons crossing the DOM sphere result in PMT pulses (incl. sub-threshold pulses)