# LUCiD Physics Implementations

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# Physics Motivation

- Big goal for HK is studying CP violation in neutrinos
  - Poor understanding of systematics pose big problem in reaching $5\sigma$ discovery potential
  - Can improve systematics via near detectors & reducing data/MC disagreement
  - Near detector still needs to be built and I am not an engineer
  - But I CAN work on the data/MC disagreement problem!

- Can use LUCiD to develop simulation which implements all relevant physics
  - Position dependent water transparency (can incorporate x, y, and z dependencies)
  - Raman scattering, Rayleigh scattering, Mie scattering, absorption
  - QE variation by PMT
  - Reflection on PMT glass & black sheet
  - Internal PMT magnetic field
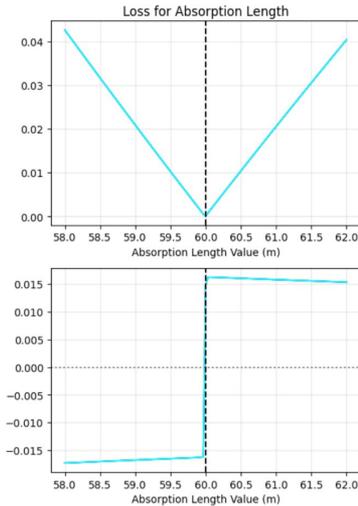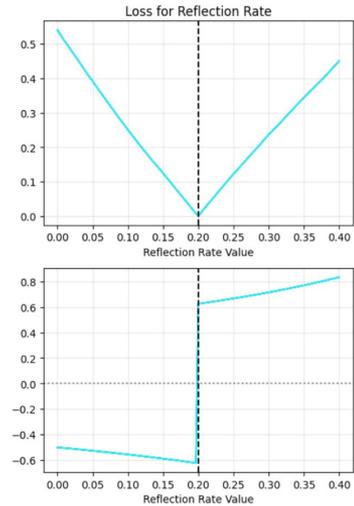  - PMT shifting during water filling

# First steps

Implement correct SK geometry in LUCiD
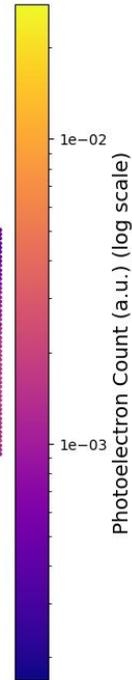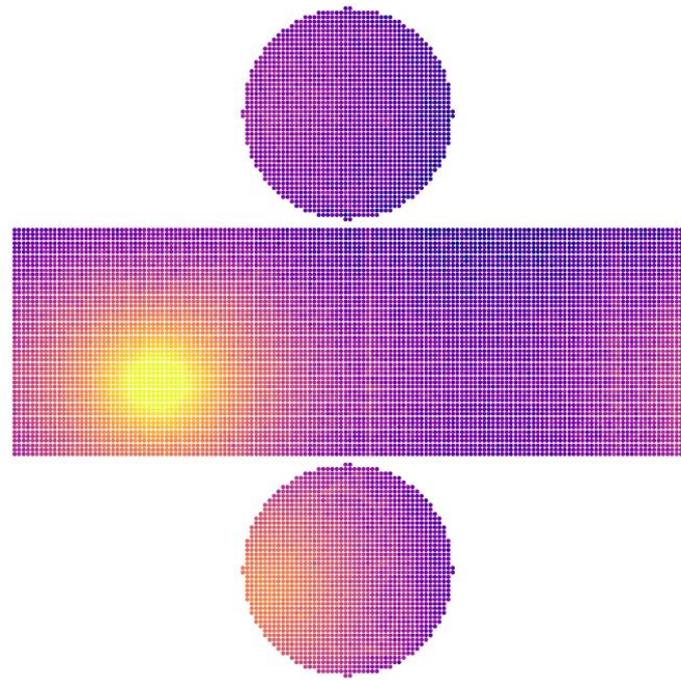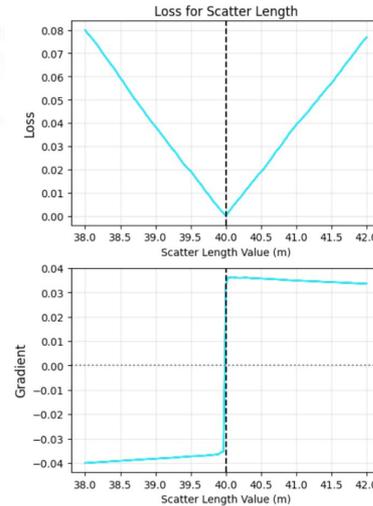
# SKG4

- Current physics models being used by SK

- Want to use these models in LUCiD to confirm results and make it easier to convince SK people that this work matters

- SKG4 manual completely in Japanese!!!
  - Thank you Claude

# SKG4 Implementations of Relevant Physics - Scattering

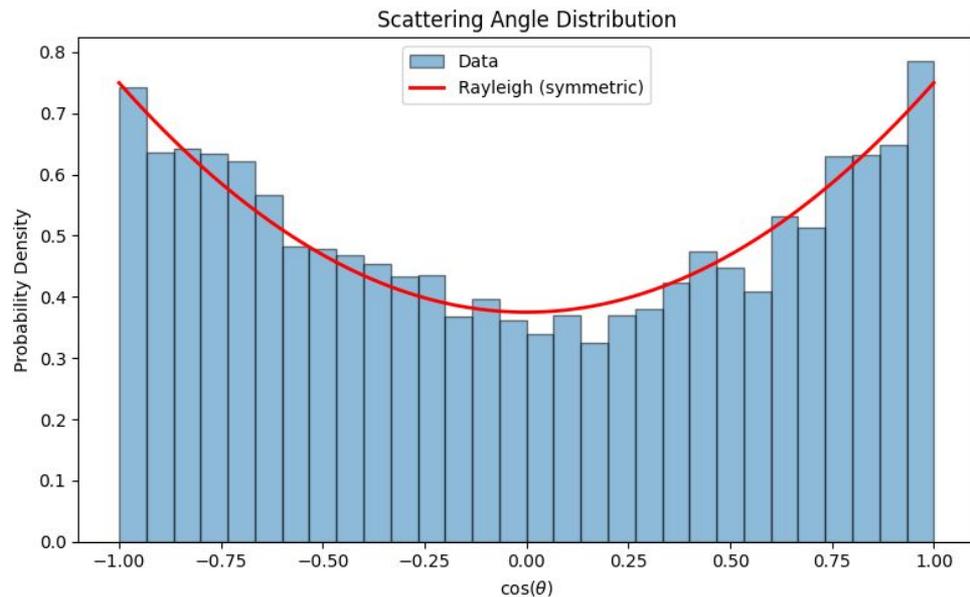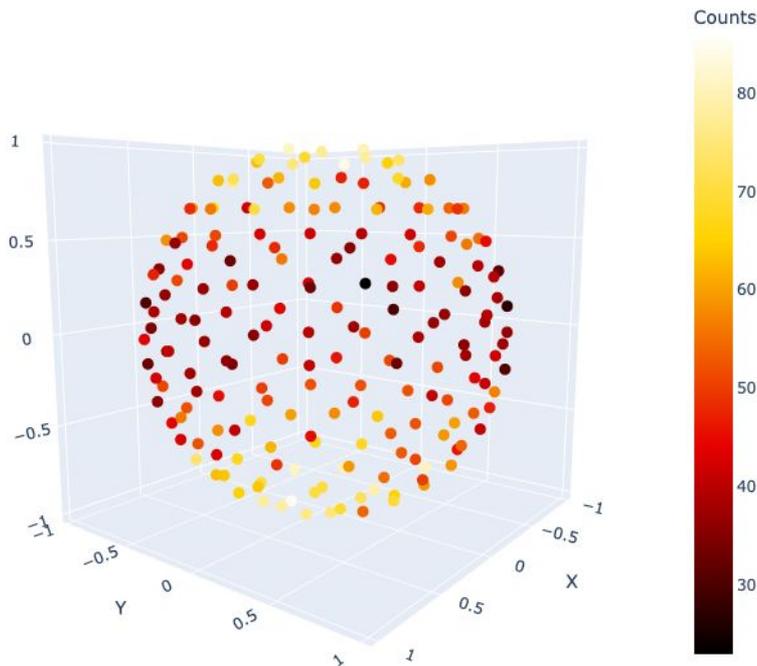* All scattering based off of Geant4 (not specific to SKG4)

Rayleigh Scattering

- Elastic scattering off density fluctuations in water
- Scattering length read directly from data file (table of mean free paths) as function of wavelength
- Samples exponential path length from mean free path & generates new direction following Rayleigh phase function ($\propto 1+\cos^2\Theta$) when scatter occurs

# Current LUCiD Implementation of Rayleigh Scattering

- Uses Rayleigh phase function & solves inverse CDF analytically using Cardano's formula

# SKG4 Implementations of Relevant Physics - Scattering

* All scattering based off of Geant4 (not specific to SKG4)

Mie Scattering

$$P(\cos\theta) = \frac{1 - g^2}{(1 + g^2 - 2g\cos\theta)^{3/2}}$$

- Geant4 uses Henyey-Greenstein phase function parametrized by forward asymmetry g, backward asymmetry g, and forward-to-backward ratio
    - g = 1 means perfectly forward, g = 0 means perfectly backwards
    - Different from calibration paper!!! (calibration paper assumes P(cos) ~ cos)

- Parameters come from data file where Mie scattering is assumed to be all forward-directed (i.e. g=0.666666)
    - But this means Mie acts as mostly forward scattering according to the SKG4 manual???

# SKG4 Implementations of Relevant Physics - Scattering

* All scattering based off of Geant4 (not specific to SKG4)

Mie Scattering

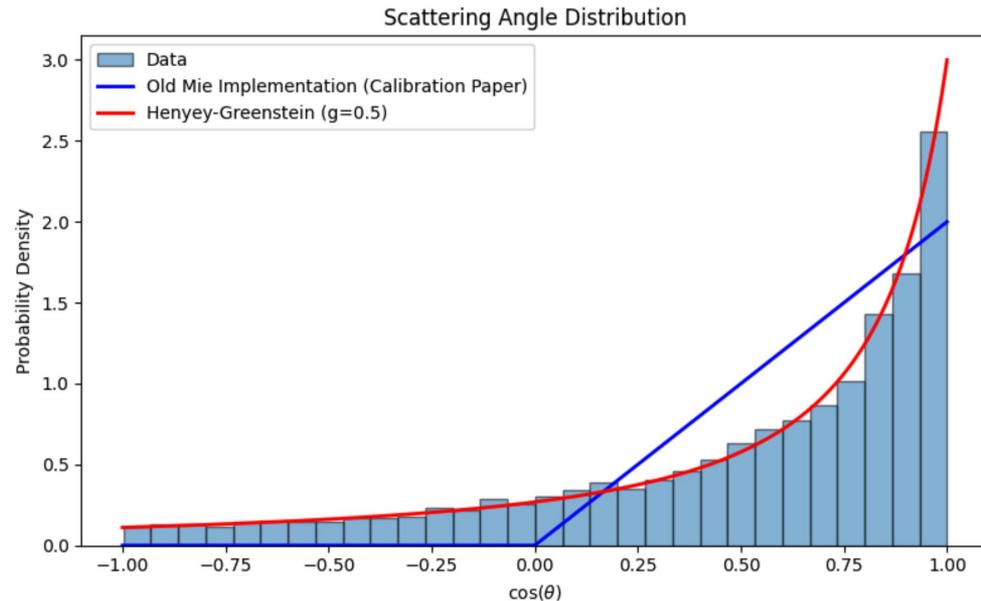- Shown on right is current SKG4 Mie scattering implementation (from my understanding that g=0.666666)
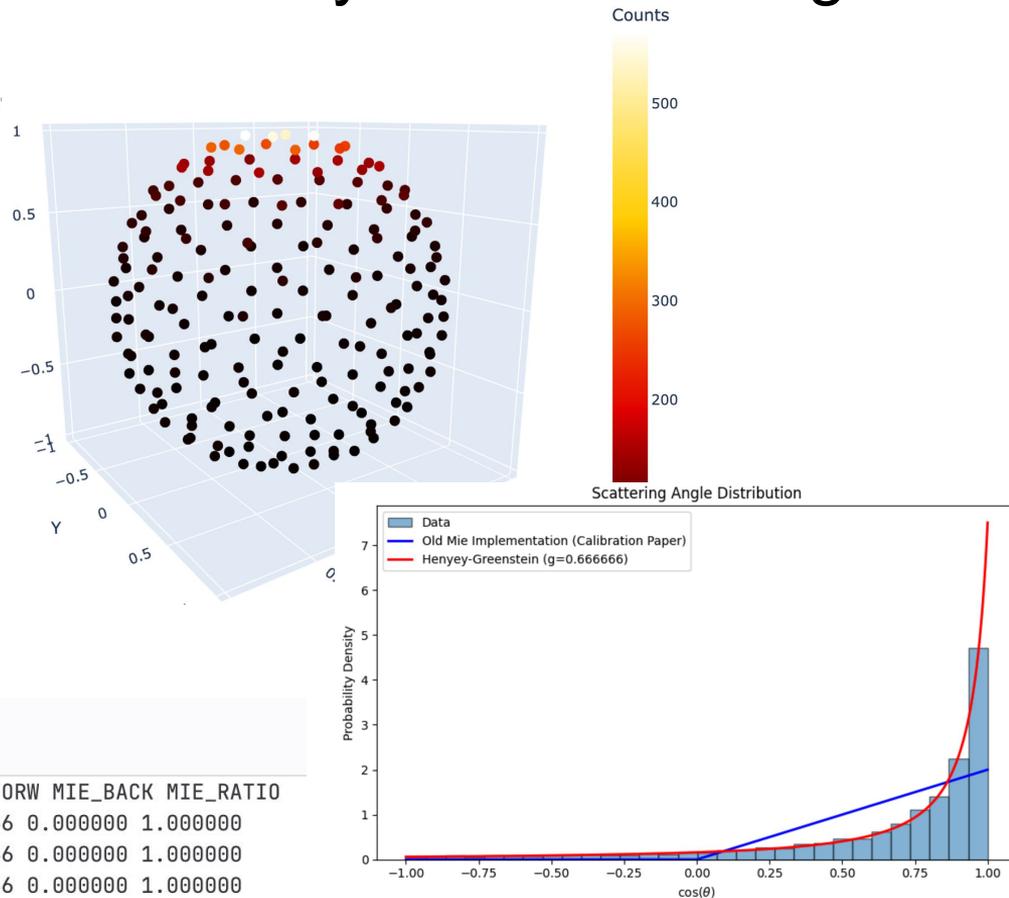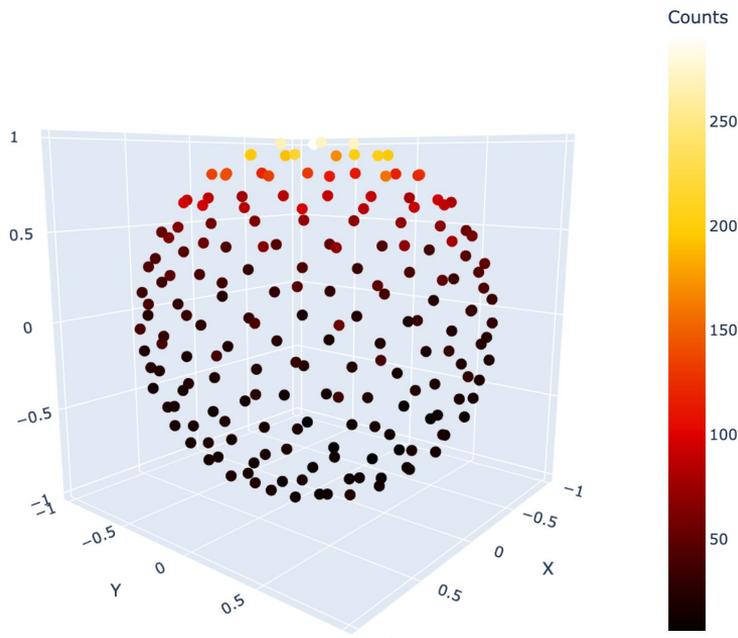




📄 **WaterProperty.dat** 📋 4.65 KiB

```
1   #Energy[eV] RINDEX ABSLENGTH[m] RAYLEIGH[m] MIEHG[m] MIE_FORW MIE_BACK MIE_RATIO
2   1.569620 1.328850 0.000000 3867.912176 3473.560609 0.666666 0.000000 1.000000
3   1.589740 1.329060 0.000000 3661.193605 3473.433042 0.666666 0.000000 1.000000
4   1.610390 1.329270 0.000000 3462.693975 3474.828790 0.666666 0.000000 1.000000
```

# Current LUCiD Implementation of Mie Scattering

- Uses HG function and implements analytical inverse CDF
- Cannot add g as recoverable via gradient descent
    - Current implementation has non-differentiable geometry

$$\cos\theta = \frac{1}{2g}\left[1 + g^2 - \left(\frac{1-g^2}{1-g+2gu}\right)^2\right]$$





Scattering Angle Distribution

Legend:
- Data
- Old Mie Implementation (Calibration Paper)
- Henyey-Greenstein (g=0.5)

# SKG4 Implementations of Relevant Physics - Scattering

\* All scattering based off of Geant4 (not specific to SKG4)

Raman Scattering

- Not implemented in SKG4!
- Main effect is to shift Cherenkov photons to longer wavelengths where QE is lower
- Important for low-energy analyses!!!!

# SKG4 Implementations of Relevant Physics - Scattering

\* All scattering based off of Geant4 (not specific to SKG4)

Determining Scattering Length

- Each scattering process is competing
    - Each scattering independently proposes a step length
- At each step, an interaction length is sampled and the minimum of all proposed step lengths is invoked
- If Rayleigh wins, new dir. generated from Rayleigh phase function, if Mie wins, new dir. generated from HG phase function, if absorption wins photon is killed

# Current LUCiD Implementation of Total Scattering

Determining Scattering Length

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