Examining Ice Anisotropy with Downgoing Muons

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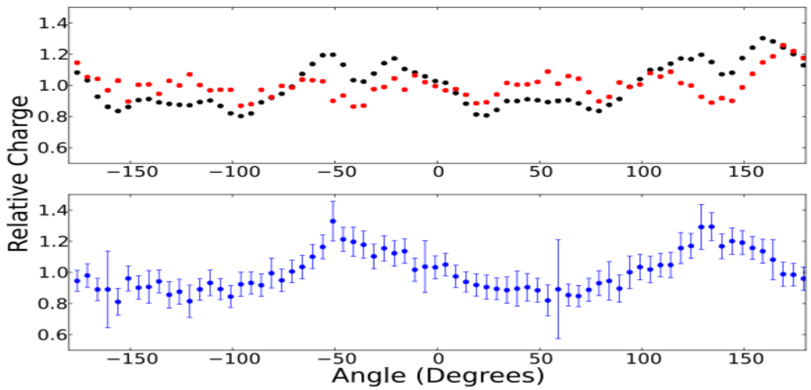
Calibration Workshop 8/1/17

Introduction

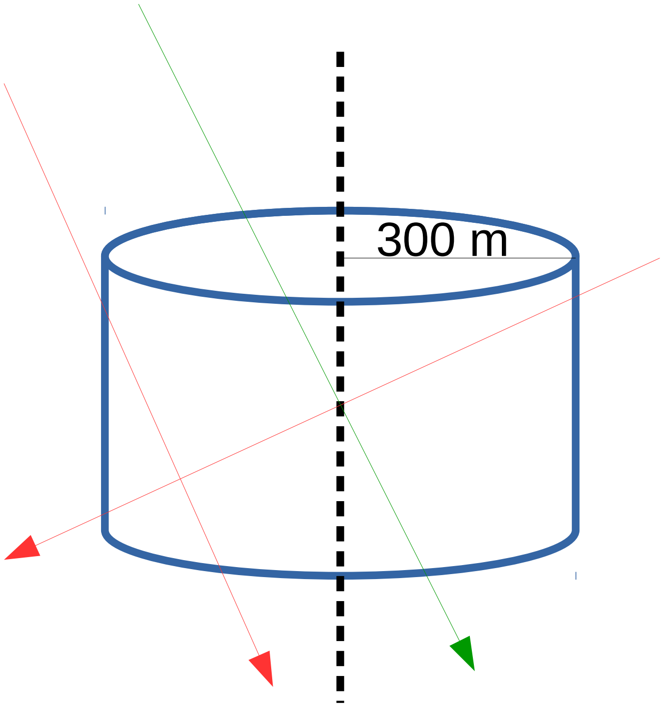
- Muons are bright and numerous, making them attractive candidates as light sources for studying the detector ice
- Previous study done by Kyle Jero showed evidence of anisotropy when comparing simulation with no anisotropy (SpiceMie) to experimental data
- This method has since been used on SpiceLea, and is currently being used on Spice3.2
  - Allows a comparison between SpiceLea (with an anisotropy value of 8%) and Spice3.2 (with an anisotropy value of 10.6%).
- Mostly useful for verification or comparison between two ice models/anisotropy values. A scan over anisotropy values would be computationally infeasible



Source: Evidence of optical anisotropy of the South Pole ice: http://www.cbpf.br/~icrc2013/papers/icrc2013-0580.pdf

Review of SpiceLea Study

- Use Spice-Lea simulation sets
  - 11808 and 11937 used for SpiceLea study
  - Combined energy range of 600 GeV-1e11 GeV
- Compare with data: 2012 IC86 level2 data with deep-core removed
- Examine anisotropy in 50m distance bins (can also do depth bins instead/in addition)
- Use SRTInIcePulses. Select muon tracks with:
  - Passed MuonFilter_12
  - Zenith < 30 degrees
  - Within 300m of the center of the detector at both top and bottom of track
- Make plot of $Q(\phi)/Q_{avg}$ for both experiment and simulation, where:
  - $Q(\phi)$ is the average charge seen by a DOM for a track with position of closest approach at angle ϕ
  - Q_{avg} is the charge seen by DOMs, averaged across all azimuthal angular bins
  - Charges and angles are measured for *every* DOM, so each track gives 4680 datapoints (78 strings*60 DOMs per string)



Example tracks. The green track passes the cut, the red tracks do not.

*Can find more details and results of this study on the wiki page: https://wiki.icecube.wisc.edu/index.php/Ice_Anisotropy_With_Muons

Spice3.2

- Spice3.2 analysis previously put on hold due to lack of full detector Spice3.2 simulation
- Simulation now available (12359), courtesy of Sebastian Sanchez
- Do similar event selection as the SpiceLea study:
  - ~~Passed MuonFilter_12~~ Passed FilterMinBias_13
    - Easier to get better statistics with MinBias (~factor of 10 improvement). Data seems otherwise unaffected
  - Zenith < 30 degrees
  - Within 300m of the center of the detector at both top and bottom of track
  - $Q_{tot} > 16$ pe and $Q_{tot} < 50$ pe

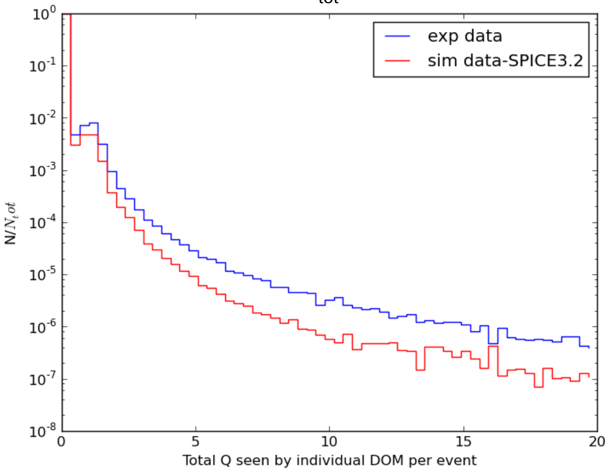
	Spice-Lea	Spice3.2
Direction of major anisotropy axis	126^o	130^o
Major anisotropy coefficient k_1	-0.08	-0.106
Minor anisotropy coefficient k_2	0.04	0.053

(+some other small differences)

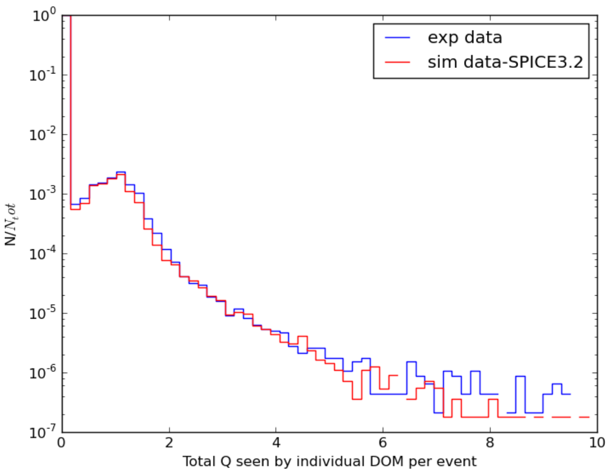
Spice3.2: Q_{tot} Cut

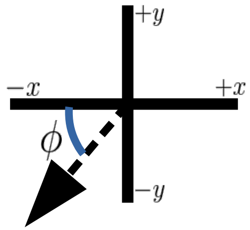
- With no cuts on Q_{tot}, see mismatch between experiment and simulation for amount of charge seen by individual DOMs
- Spice3.2 simulation only covers energy range 600GeV < Eprim < 1e5GeV
  - No current plans for a higher energy extension (1e5 GeV-1e11 GeV)
- Solution: Make cut on Q_{tot} to attempt to filter out the extra high energy events in the experimental data
  - Use full energy range Spice-Lea (11808+11937) simulation to determine where to place the cut
  - It looks like the optimal cut is Q_{tot} > 16 pe and Q_{tot} < 50 pe

No Q_{tot} Cuts

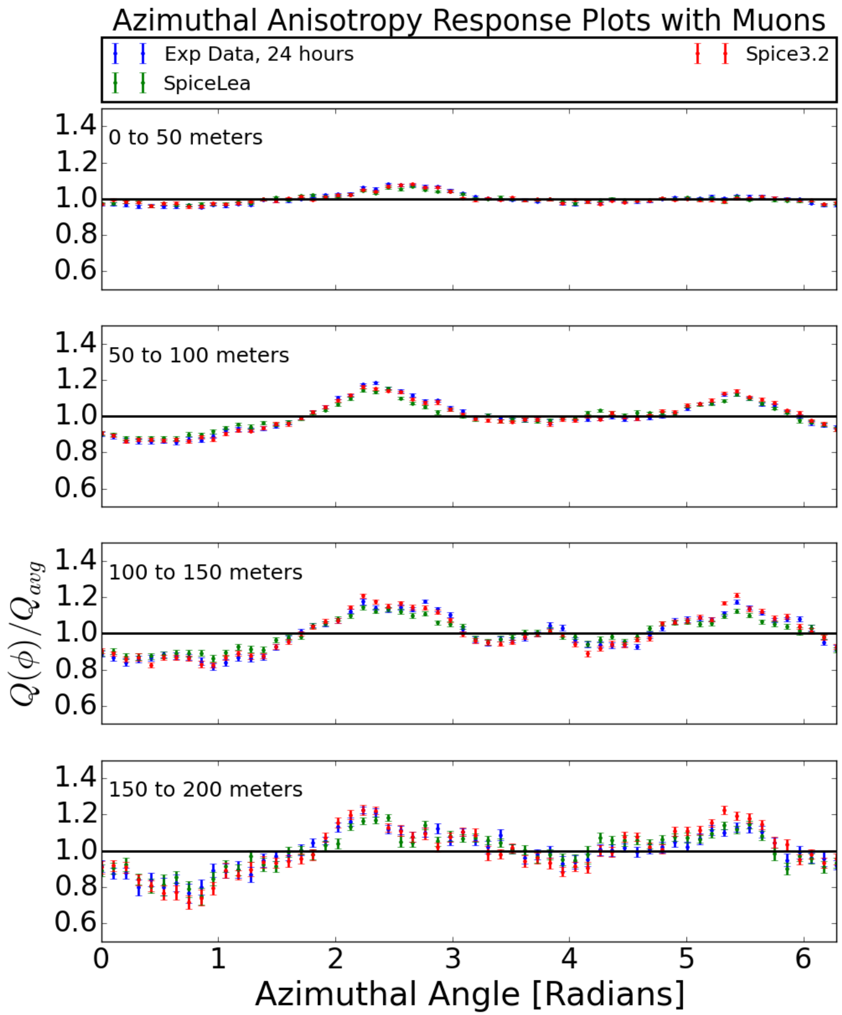


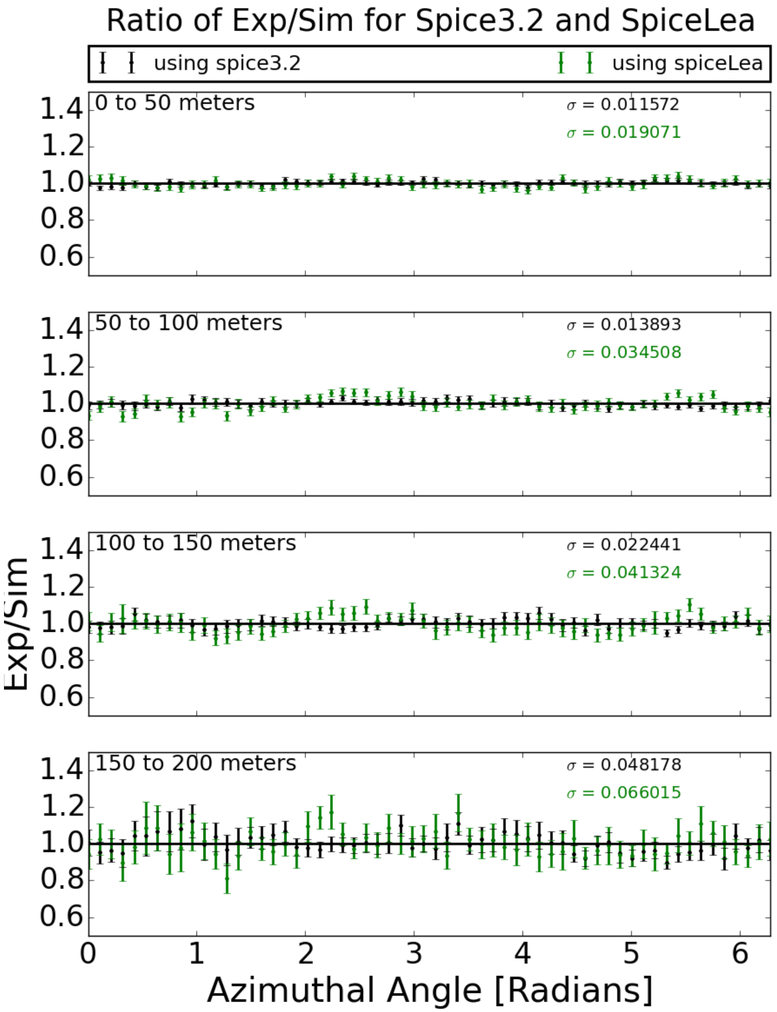
16 pe < Q_{tot} < 50 pe





Spice3.2: Results





→ How can we describe how well each model describes the anisotropy?

Quantifying Anisotropy in Spice3.2

- How can we quantify how well these different ice models describe the anisotropy specifically?
  - Standard deviation (previous plots) is insufficient
- Ideally, the method we choose should be able to able to pick out the anisotropy from other possible existing effects
  - Especially important when comparing models with differences other than just anisotropy values.
- Try a fourier analysis based approach
  - We know the anisotropy has a frequency of $\omega=2$, use fourier analysis to pick out this frequency from the others
  - Use the magnitude of the $\omega=2$ fourier coefficient to quantify the performance of a particular ice model (with respect to anisotropy)
  - Other frequencies may correspond to other effects ($\omega=6$?)
  - Can also do fits, either of sine waves or higher order fits by including more terms in the inverse transform

Quantifying Anisotropy: A Fourier Approach

- Take discrete fourier transform (DFT) of the exp/sim plots, as defined by numpyp.fft.fft() with N=60:

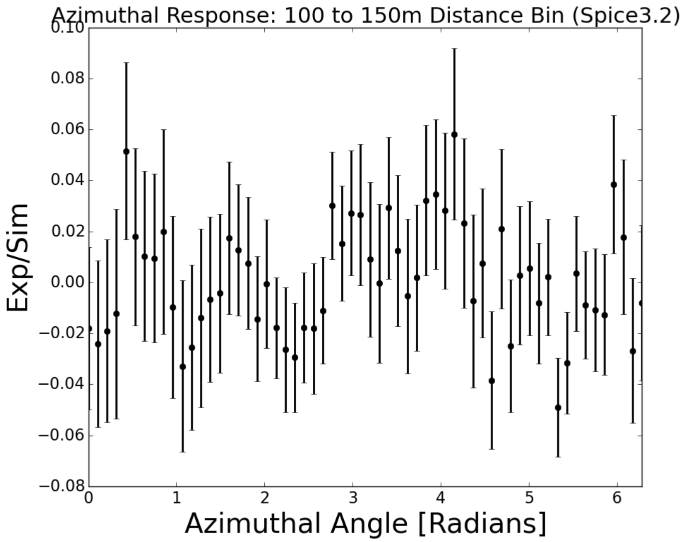
$$A_\omega = \sum_{\theta_n} y(\theta_n)\exp(-i\omega\theta_n)$$

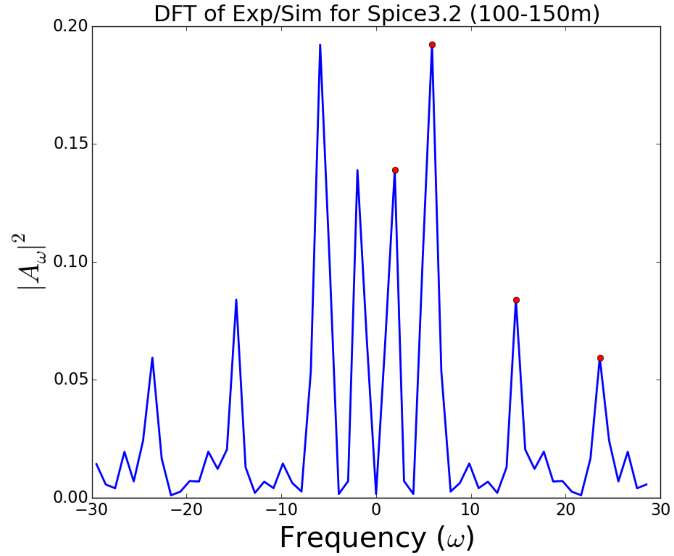
$$\theta_n = \frac{2\pi n}{N} \qquad n = 0, 1, 2, ..., N$$

$$\omega = -\frac{N}{2}, -\frac{N}{2}+1, ..., \frac{N}{2}$$

- With the inverse transform:

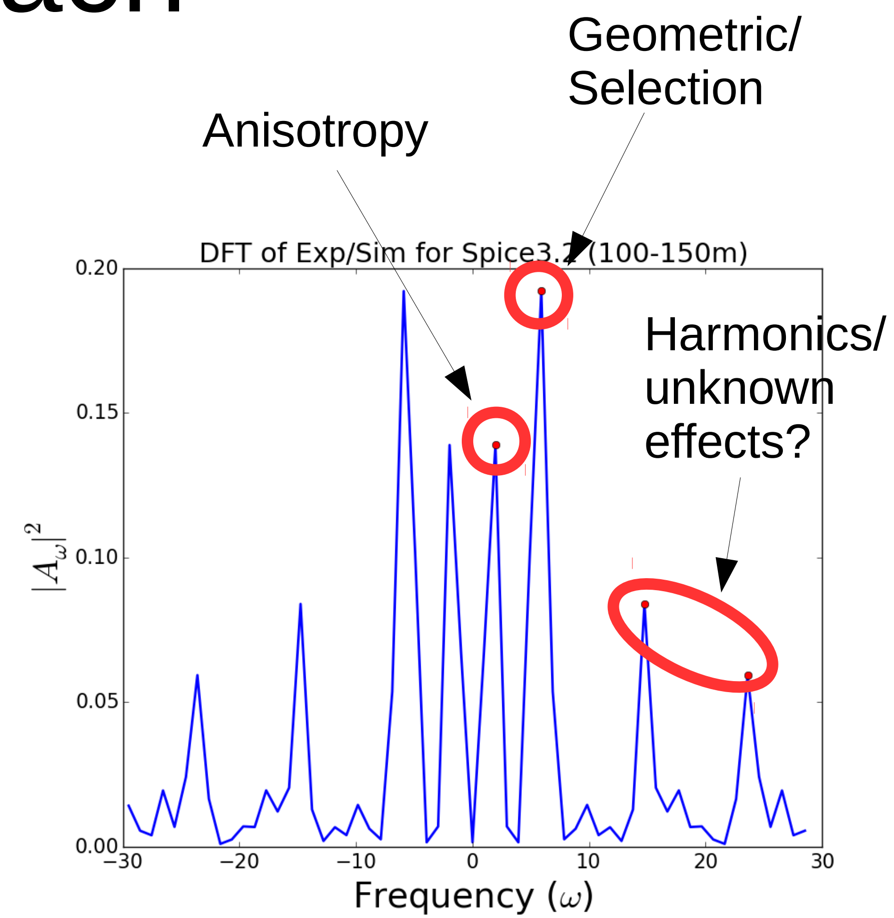
$$y(\theta_n) = \frac{1}{N}\sum_{\omega} A_\omega \exp(i\omega\theta_n)$$





Quantifying Anisotropy: A Fourier Approach

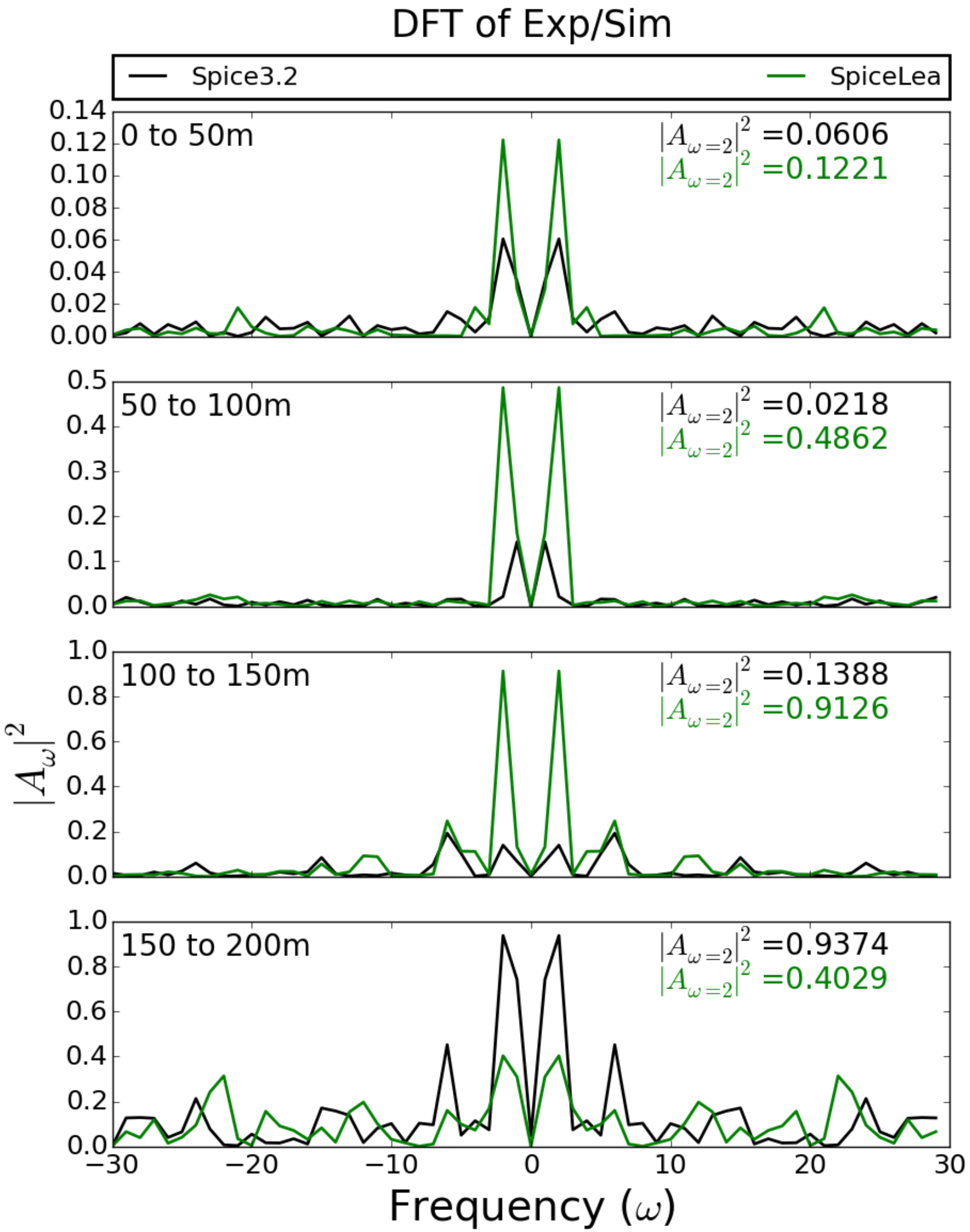
- Can use this method to pick out the frequency associated with the anisotropy: ω=2
  - The smaller A_2 is, the better the ice model matches the actual anisotropy value*
- Other effects present as well:
  - ω=6 geometric/selection effect
  - Even higher frequency effects at ω=15, 24



*Assuming that the anisotropy is the only ω=2 effect

Quantifying Anisotropy: A Fourier Approach (All Distance Bins)

- In general, the ω=2 mode is smaller when using Spice3.2
  - Different for 150m < d < 200m, but statistics are worse in this distance bin
- The ω=6 mode becomes much more significant at distances greater than 100m
  - Higher frequency ω=15, 24 modes seem related to the ω=6 mode



Quantifying Anisotropy: A Fourier Approach

- This method allows us to fit cosine waves for the anisotropy
  - 2 degrees of freedom: amplitude and phase

$$y = C\cos(\omega\theta + \phi)$$

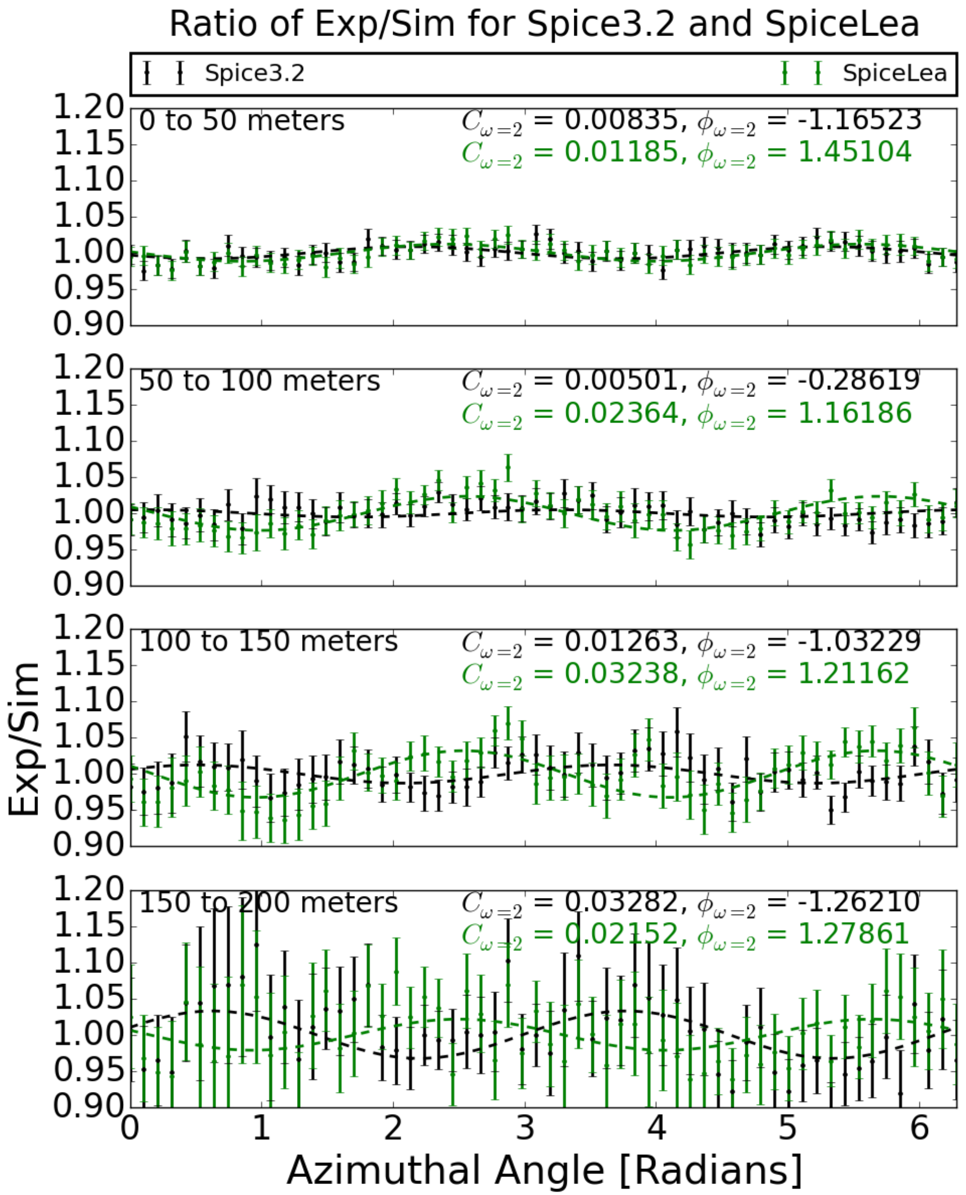
Where:

$$C = \sqrt{a^2 + b^2} \qquad \tan\phi = \frac{b}{a}$$

$$A_\omega = a + bi$$

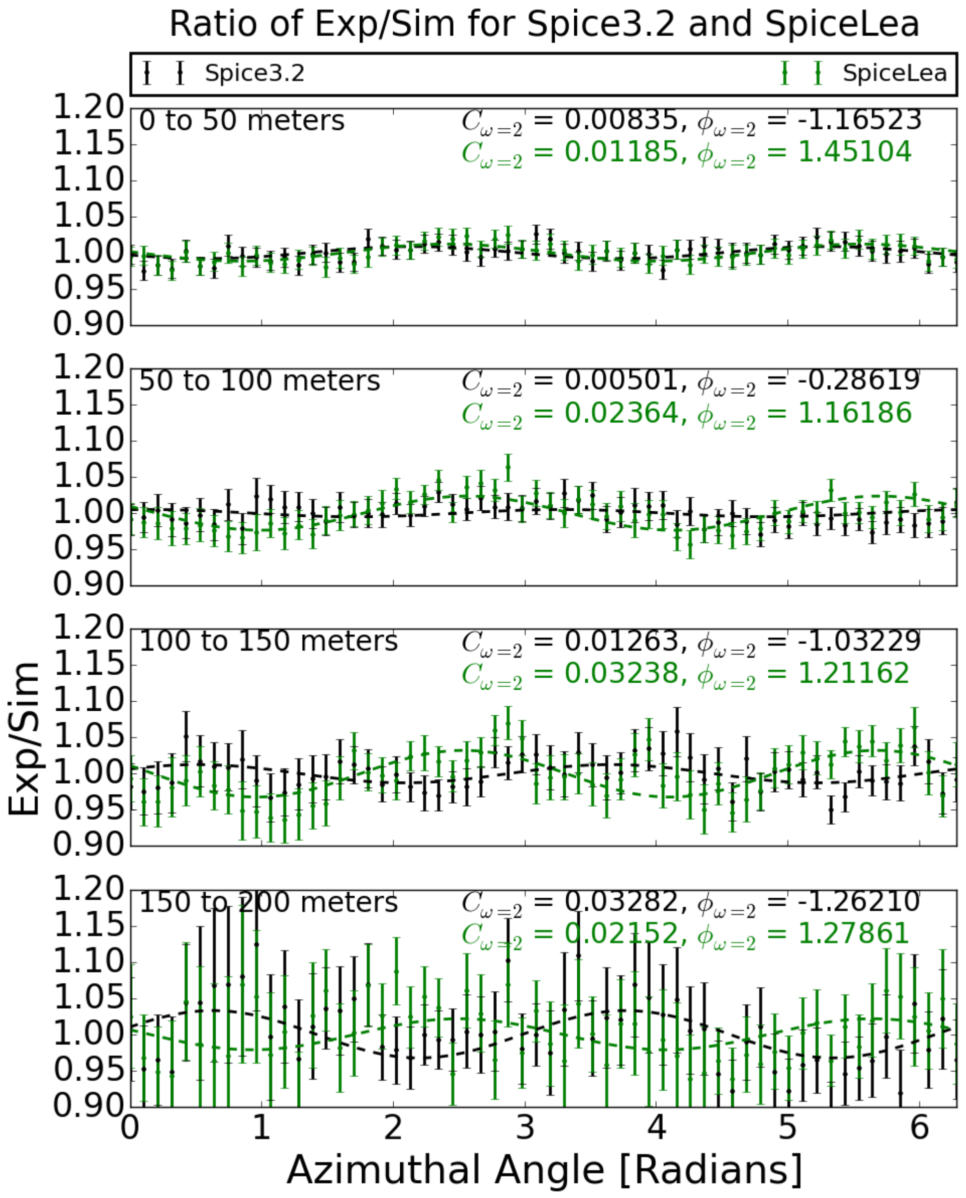
- Can also include higher frequency modes by doing a partial inverse transform:

$$y(\theta_n) = \frac{1}{N}\sum_{\omega=2,6} A_\omega \exp(i\omega\theta_n)$$



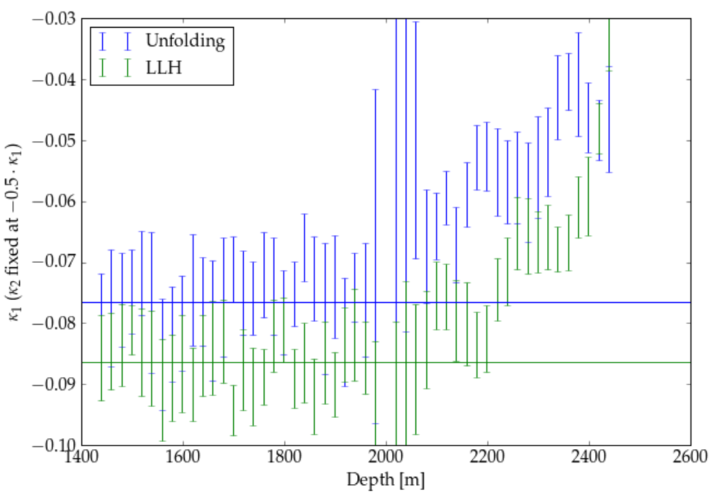
Quantifying Anisotropy: A Fourier Approach

- In general C_2 is smaller for Spice3.2 than for SpiceLea, except in the 150m to 200m distance bin
  - Expected from power spectrum plots
  - Anisotropy value might be closer to the 10.6% value than the 8% value*
- The fits are ~180 degrees out of phase
  - Suggests that Spice3.2 is overmodeling the anisotropy, while SpiceLea is undermodeling the anisotropy



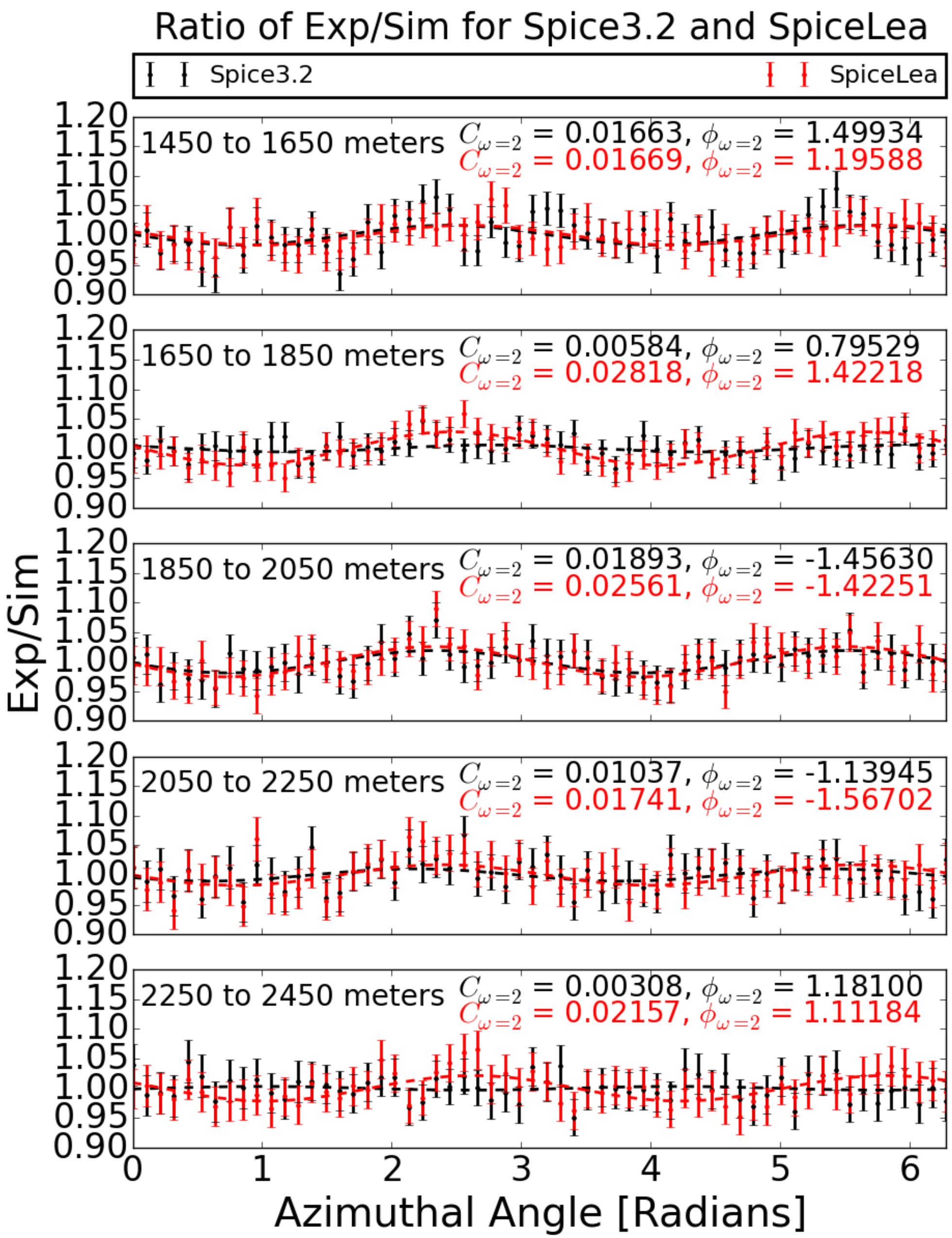
*Assuming that the anisotropy is the only ω=2 effect

Depth Bins



Plot from Martin Rongen’s Calibration Call slides, July 14

- Try binning in depth instead of distance
  - 1 distance bin: 0-100m
  - 5 depth bins (200m each)
- Look for change in C_2 in bottom depth bin
  - No evidence for depth dependence, but depth dependence is a small effect
  - Spice3.2 and SpiceLea are in phase when binned in depth (probably because only considered 0-100m)

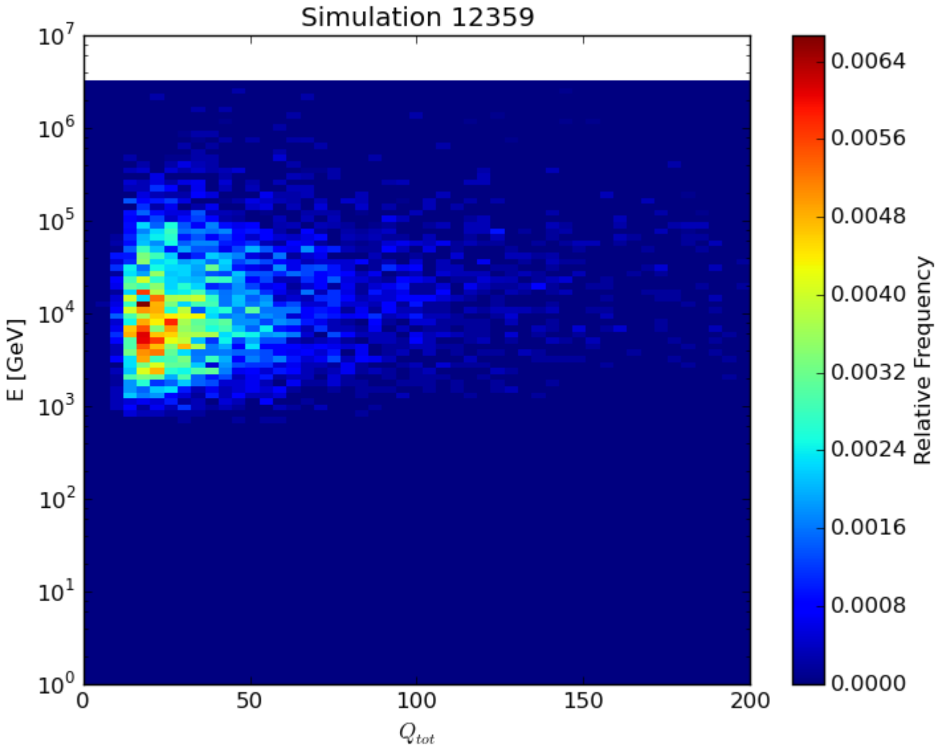


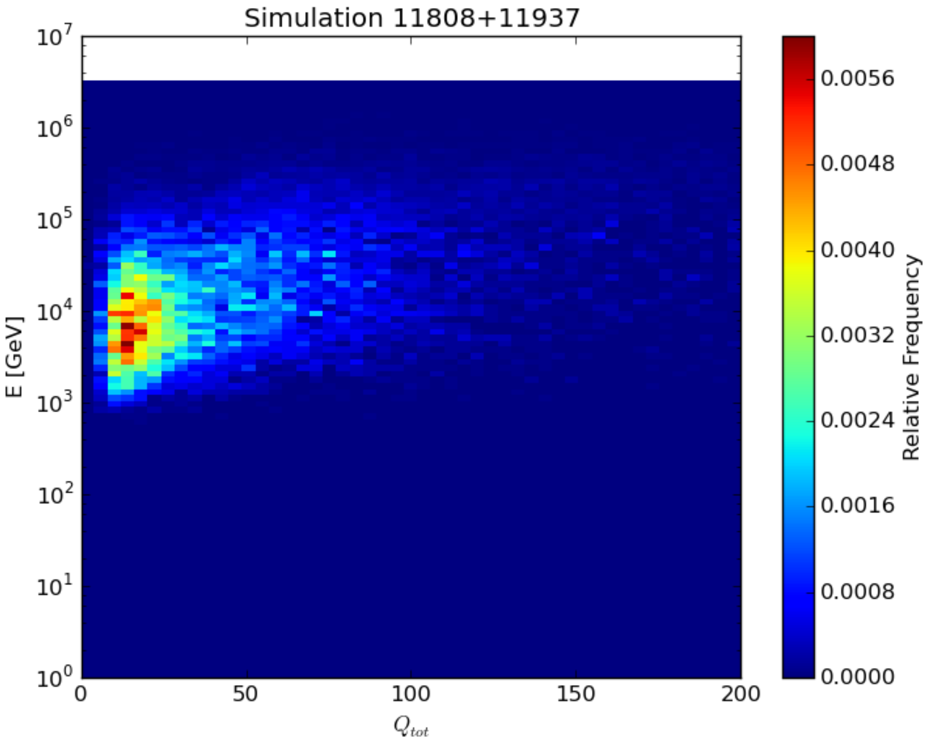
Summary/Status

- Downgoing muons used to examine anisotropy values in SpiceLea and Spice3.2 simulation
  - A fourier analysis reveals that the ω=2 mode is smaller in the power spectrum for Spice3.2.
  - Fits of the ω=2 mode are 180 degrees out of phase for the two ice models
  - If the ω=2 mode is solely due to anisotropy, this suggests that the anisotropy value is between 8% and 10.6%
  - A higher frequency ω=6 mode is apparent at distances greater that 100m, but still only partially understood
  - Currently no evidence for depth dependent anisotropy in this analysis, though it is uncertain whether such an effect would be visible here
- To do:
  - Repeat analysis using horizontal/diagonal muons (such that cherenkov light front hits the DOM at a zenith angle of 90 degrees or more)
  - Do similar analysis with timing information instead of charge information (make plots of $t_{res}(\Phi)/t_{res\ avg}$)
  - Examine ω=6 geometric effect. Why does this affect plots of $Q(\Phi)/Q_{avg}$?
  - Check depth dependence better: finer depth bins? Why are Spice3.2 and SpiceLea in phase when binned in depth, but not when binned in distance? Try larger distance/multiple distance bins with depth bins.
  - Expand distances considered beyond 200m (is this feasible?)
  - Check SpiceMie for ω=2 mode, try finding a way to convert C_2 to an anisotropy value

Backup slides

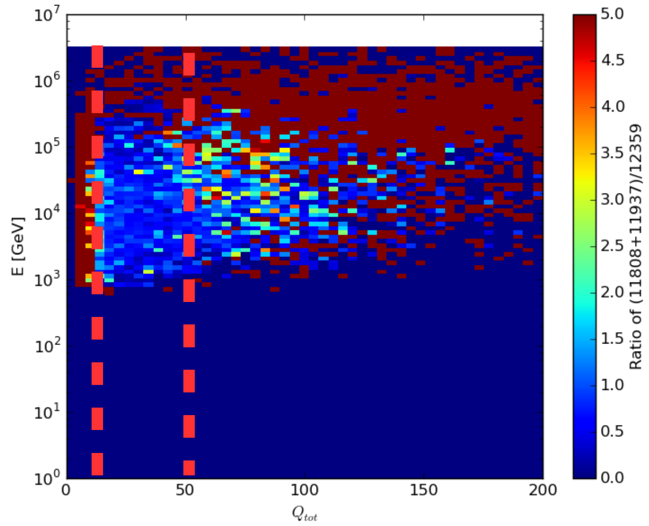
Spice3.2: Q_{tot} Cut

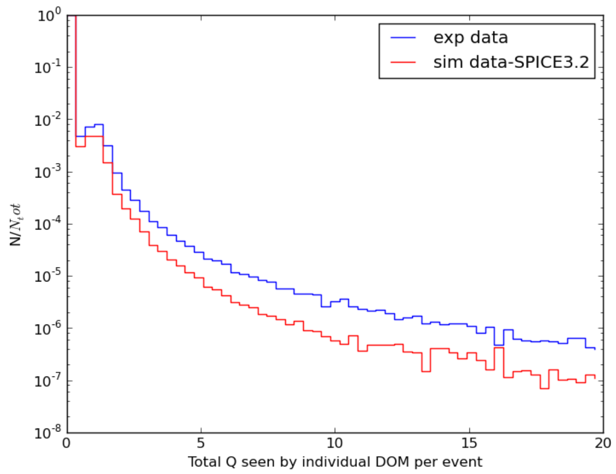


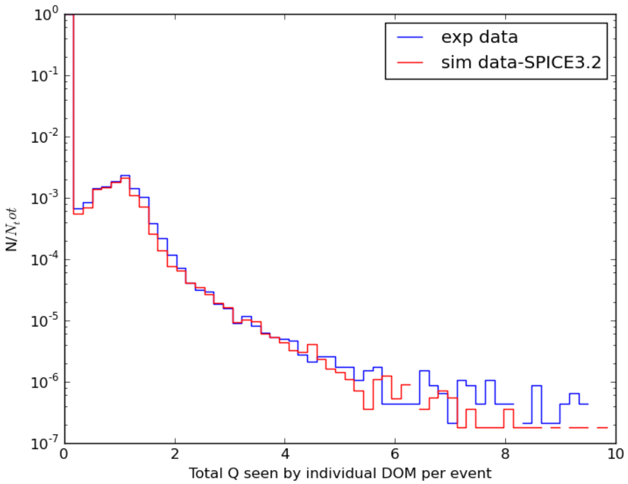


Spice3.2: Q_{tot} Cut

- Pick out region that is roughly similar for both full energy range simulation (11808+11937) and reduced energy range simulation (12359)
  - Apply Q_{tot} cut to both experiment and simulation
- Cuts are then:
  - Passed FilterMinBias_13
  - Zenith < 30 degrees
  - Within 300m of the center of the detector at both top and bottom of track
  - Q_{tot} > 16 pe and Q_{tot} < 50 pe

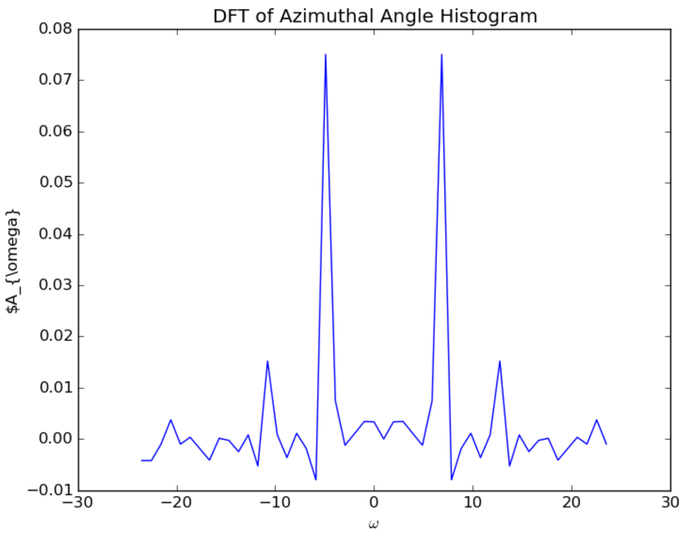


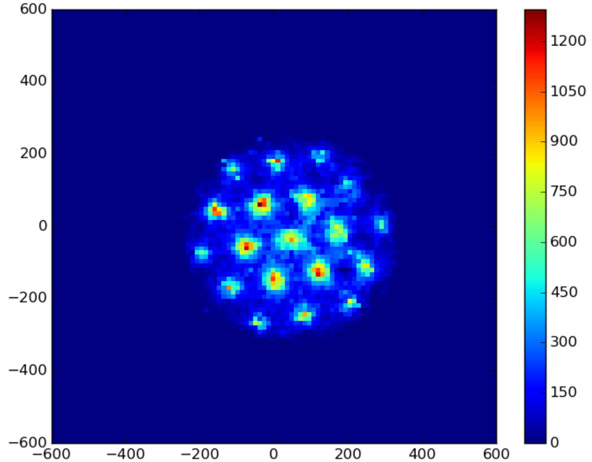


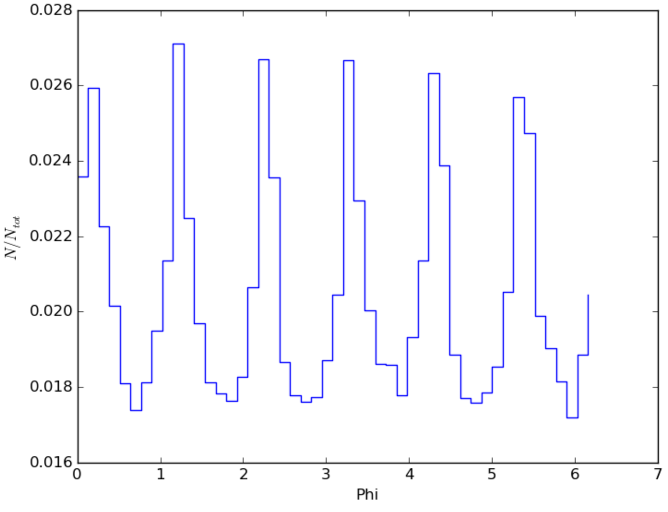


Geometric/Charge Dependent Selection Effects?

- Azimuthal angle histogram shows 6-fold symmetry (some kind of detector effect) in both experiment and simulation
- DFT shows this effect is mostly composed of the ω=6 mode, relatively little ω=2

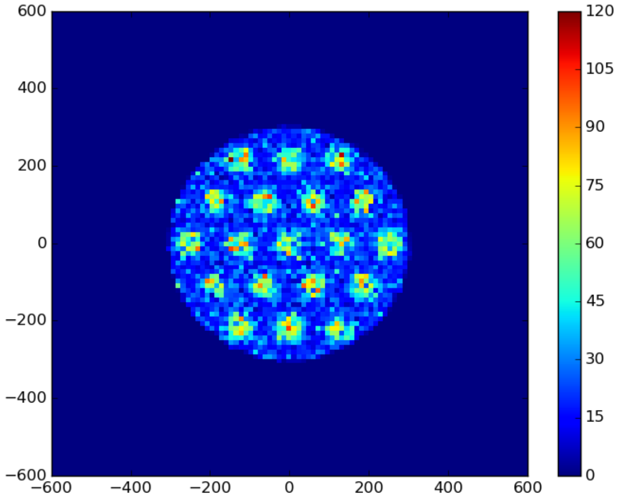


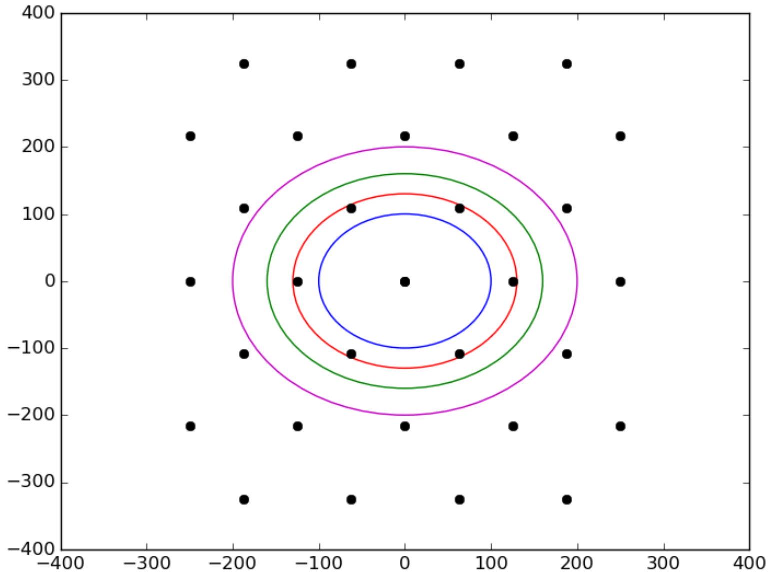


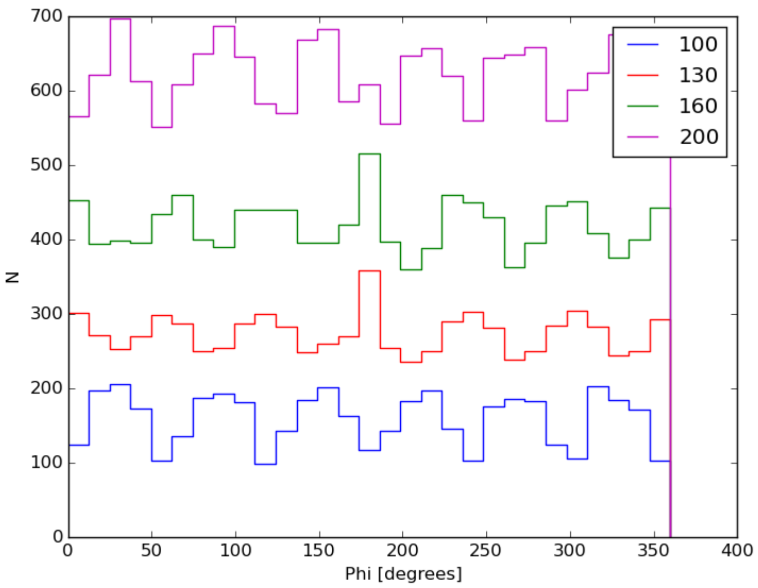


Geometric/Charge Dependent Selection Effects?

- Geometric effect definitely present and able to be modeled simply, but somehow coupling to a charge



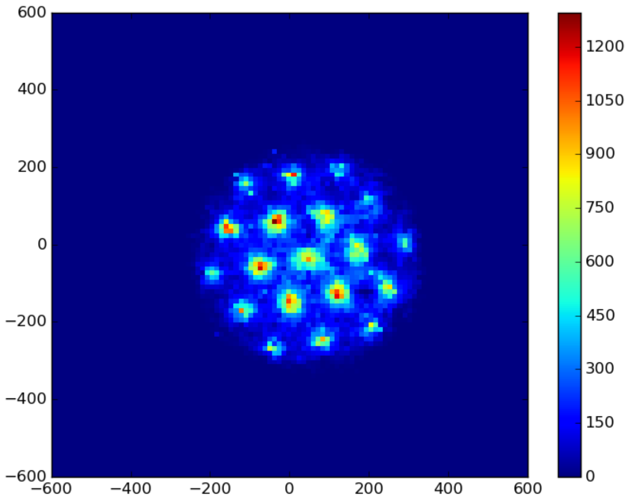


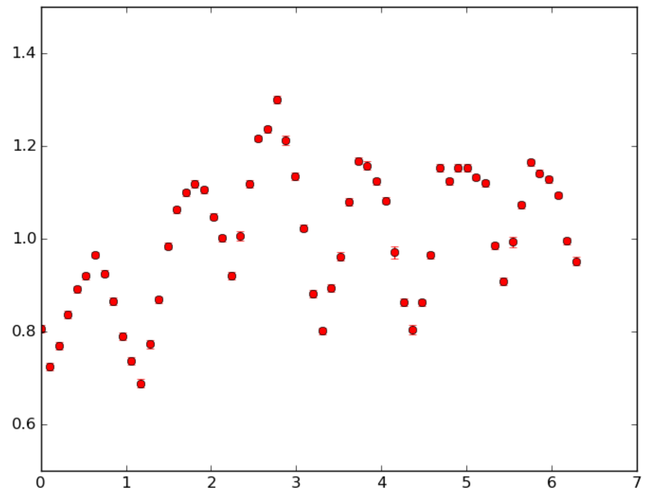


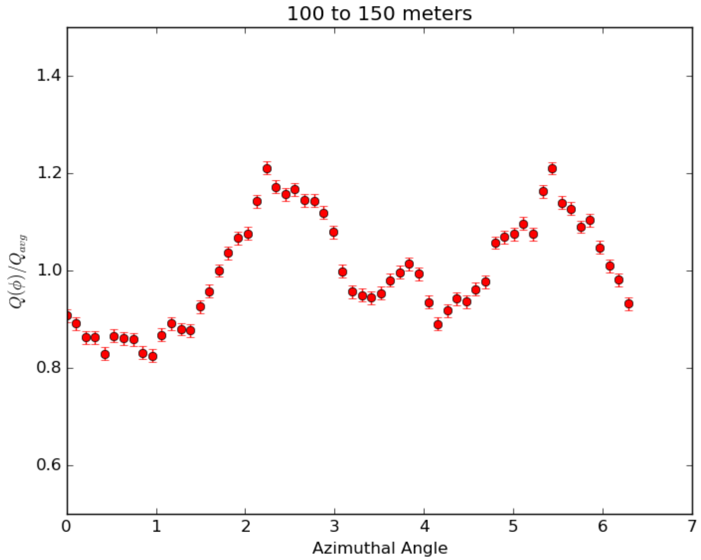
Geometric/Charge Dependent Selection Effects?

Shape of Q/Q_{avg} plots changes with new cuts, but change is reflected in both simulation and experimental data

- Azimuthal angle variations must relate to Q in some manner, could explain ω=6 mode in ratio plots

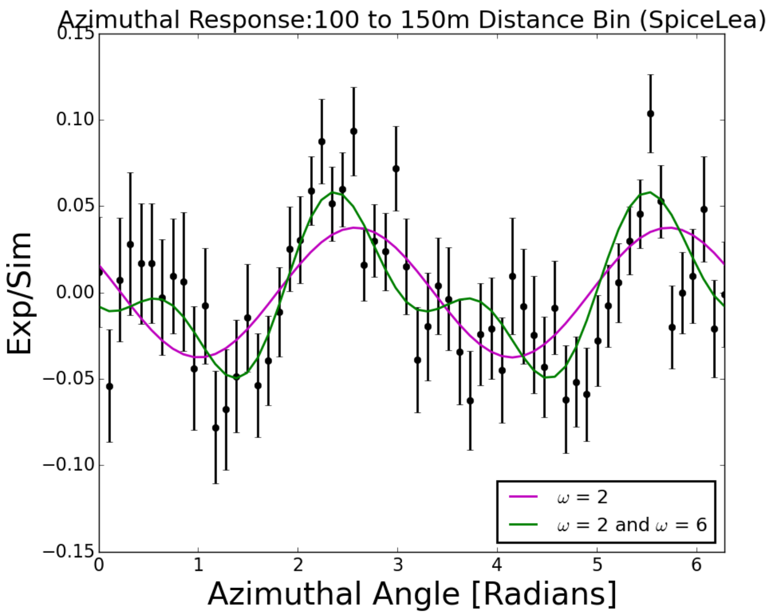


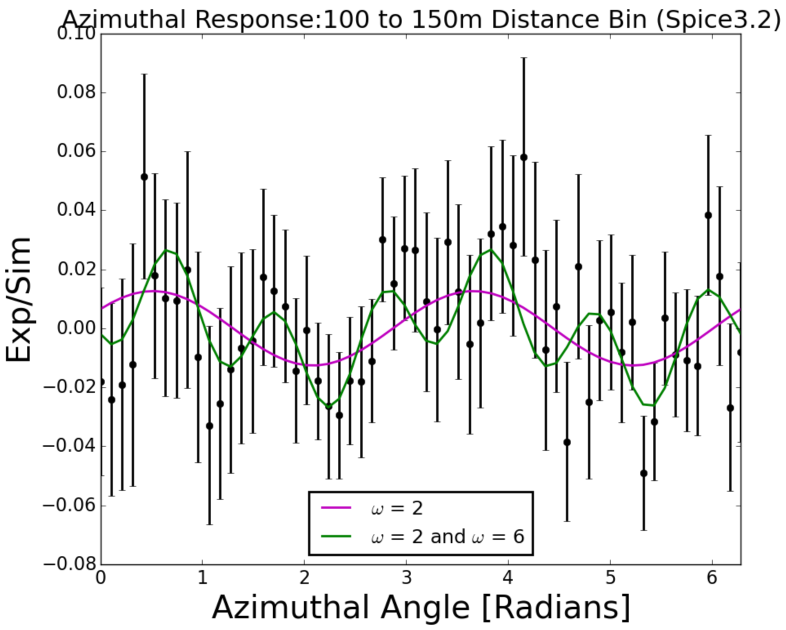




Partial inverse transform fits

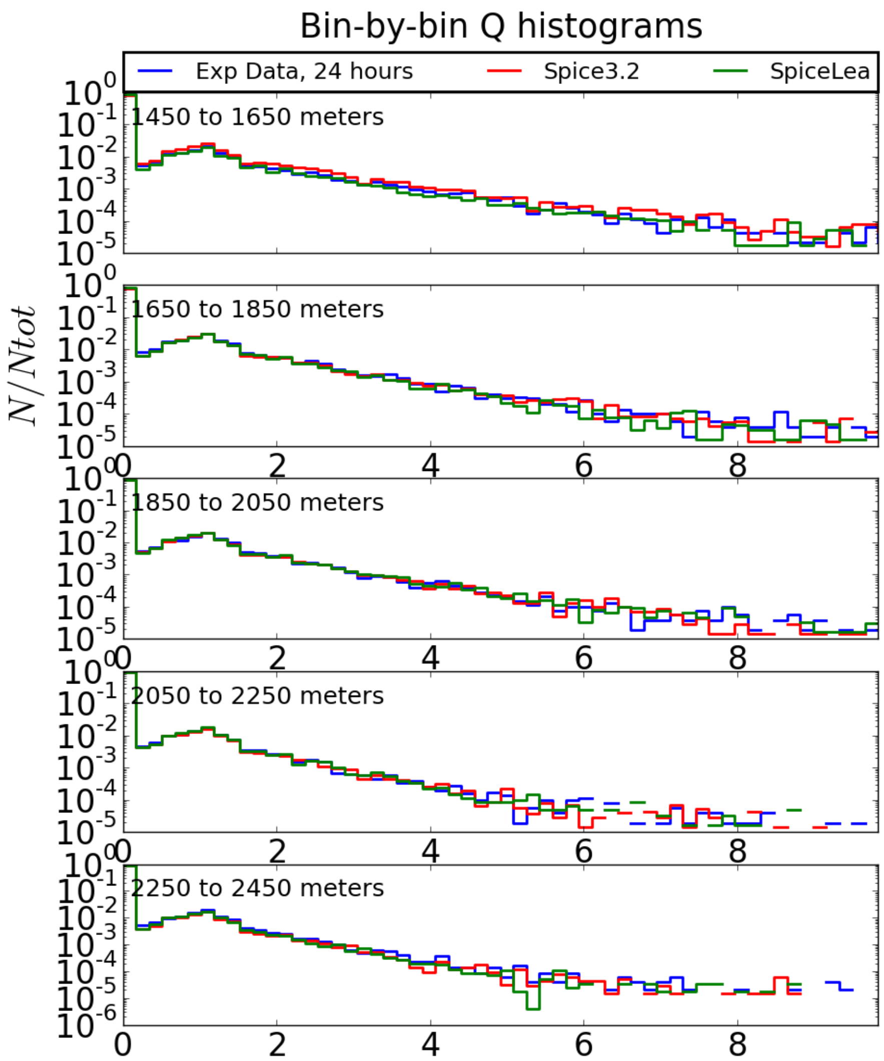
- Can use the fourier decomposition to fit the ω=6 mode as well
  - Gives better fits, but also adds some more parameters



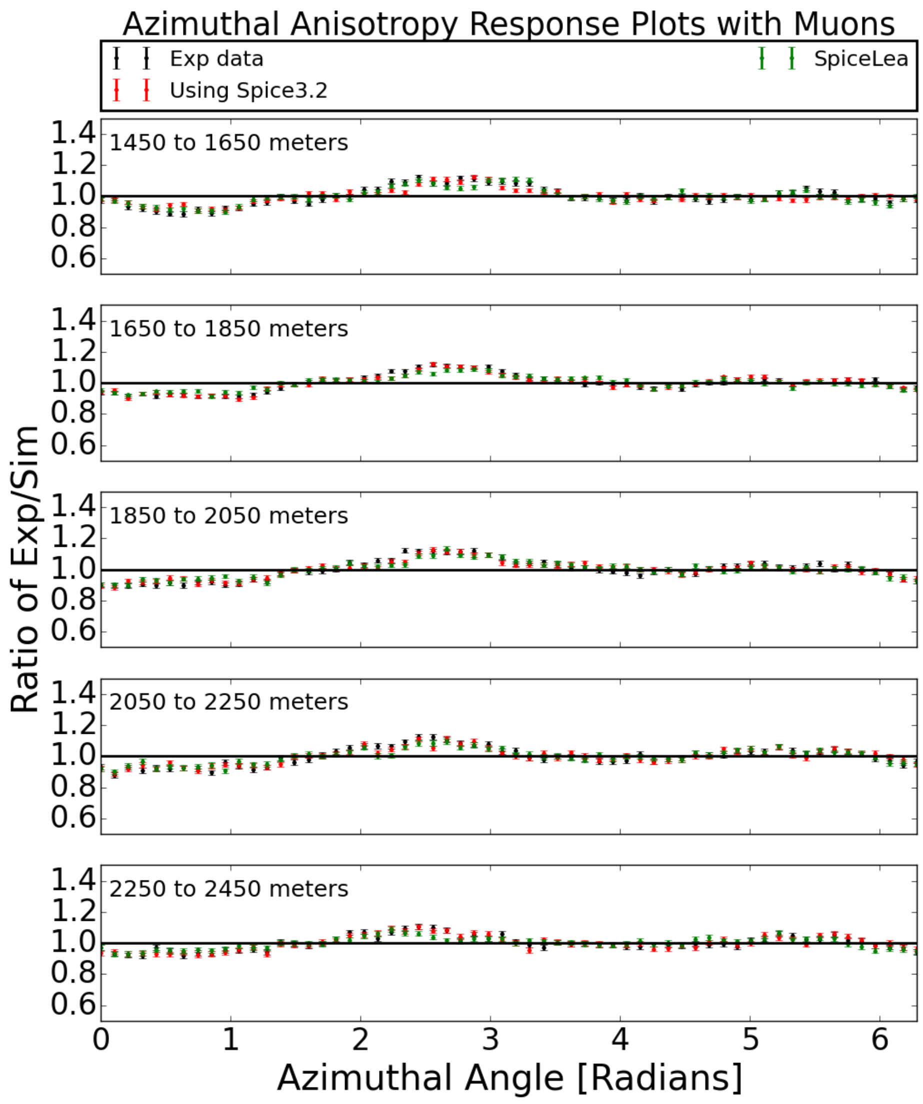


Depth bin problems fixed

- Previous problem getting charge/DOM histograms to match
  - Problem was lower Qtot cut not being applied correctly in depth bins
- Problem now fixed, charge/DOM histograms match for all 3 datasets in all depth bins

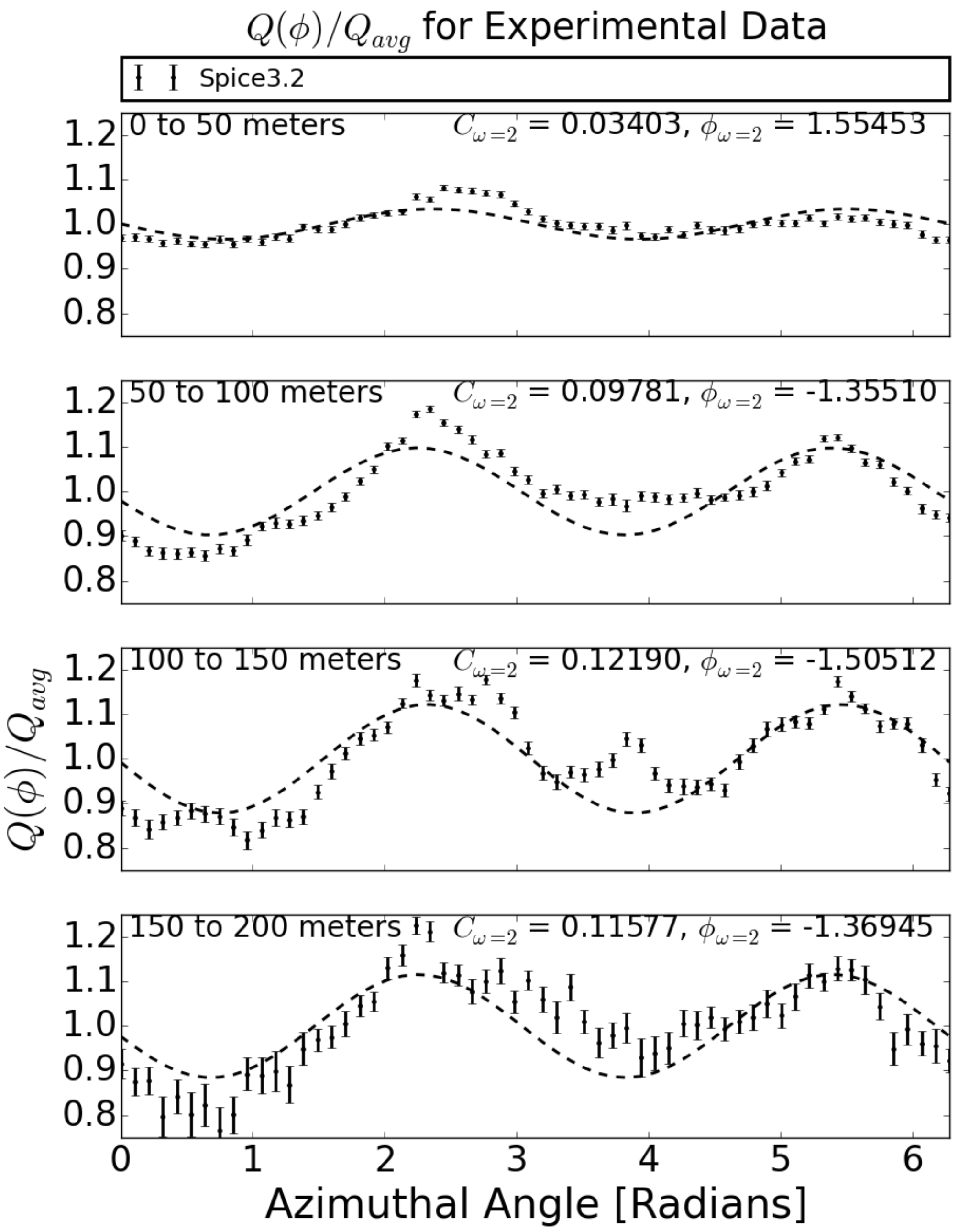


Depth Bin Non-Ratio Plots

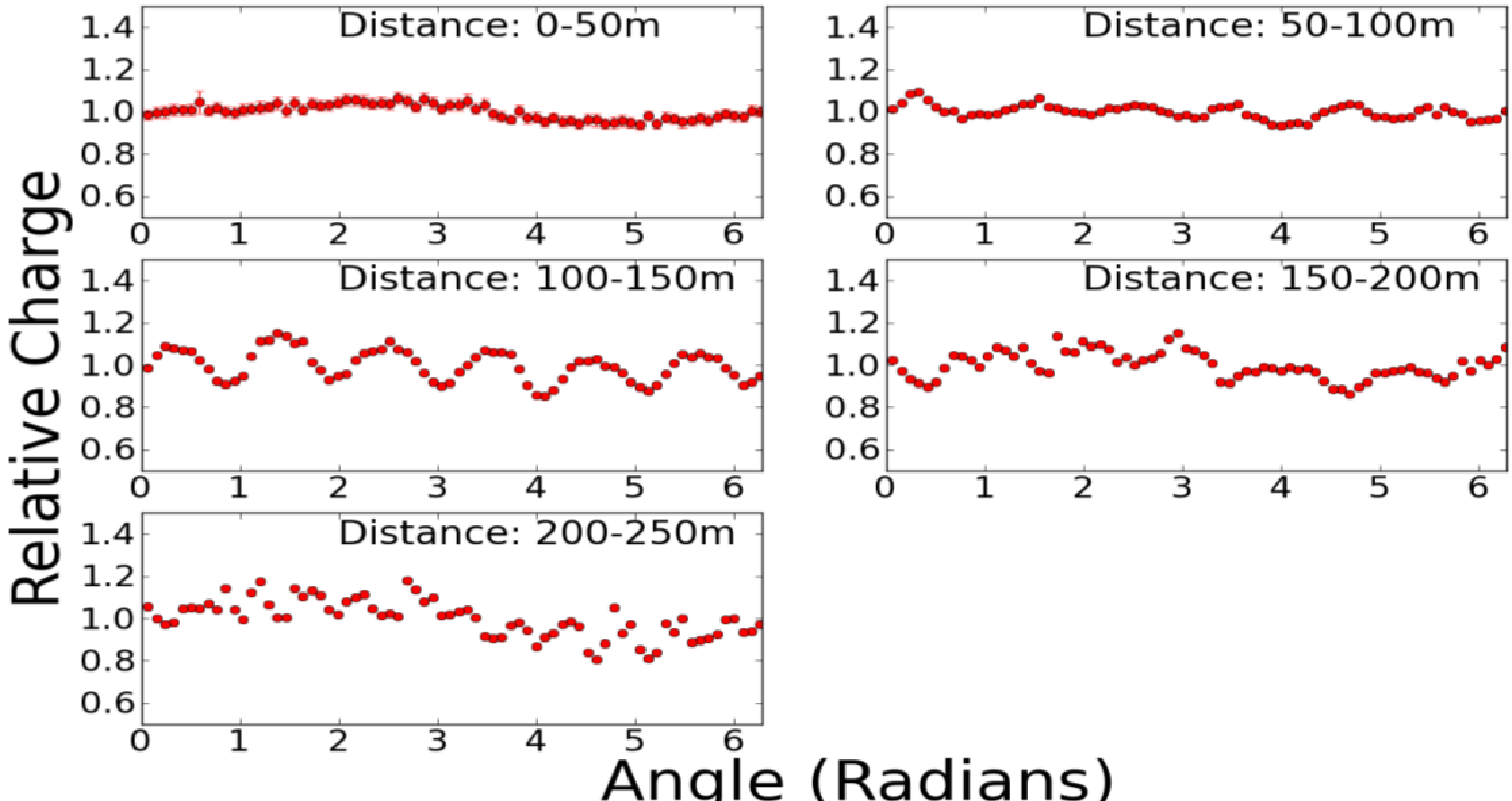


Transform of Q/Qavg for Exp Data

- Clear ω=2 mode, even in nonratio plots
  - Is this variation still present for SpiceMie?
    - If not, can maybe claim these variations are due to anisotropy alone
- Is there a way to convert C_2's back into anisotropy values?



Results for simulation (SPICE MIE - no propagation anisotropy)



Observations:

- No large scale oscillation structure with period π
- Smaller scale structure for different distances
    - Likely due to geometry effects