SnowStorm in IceCube

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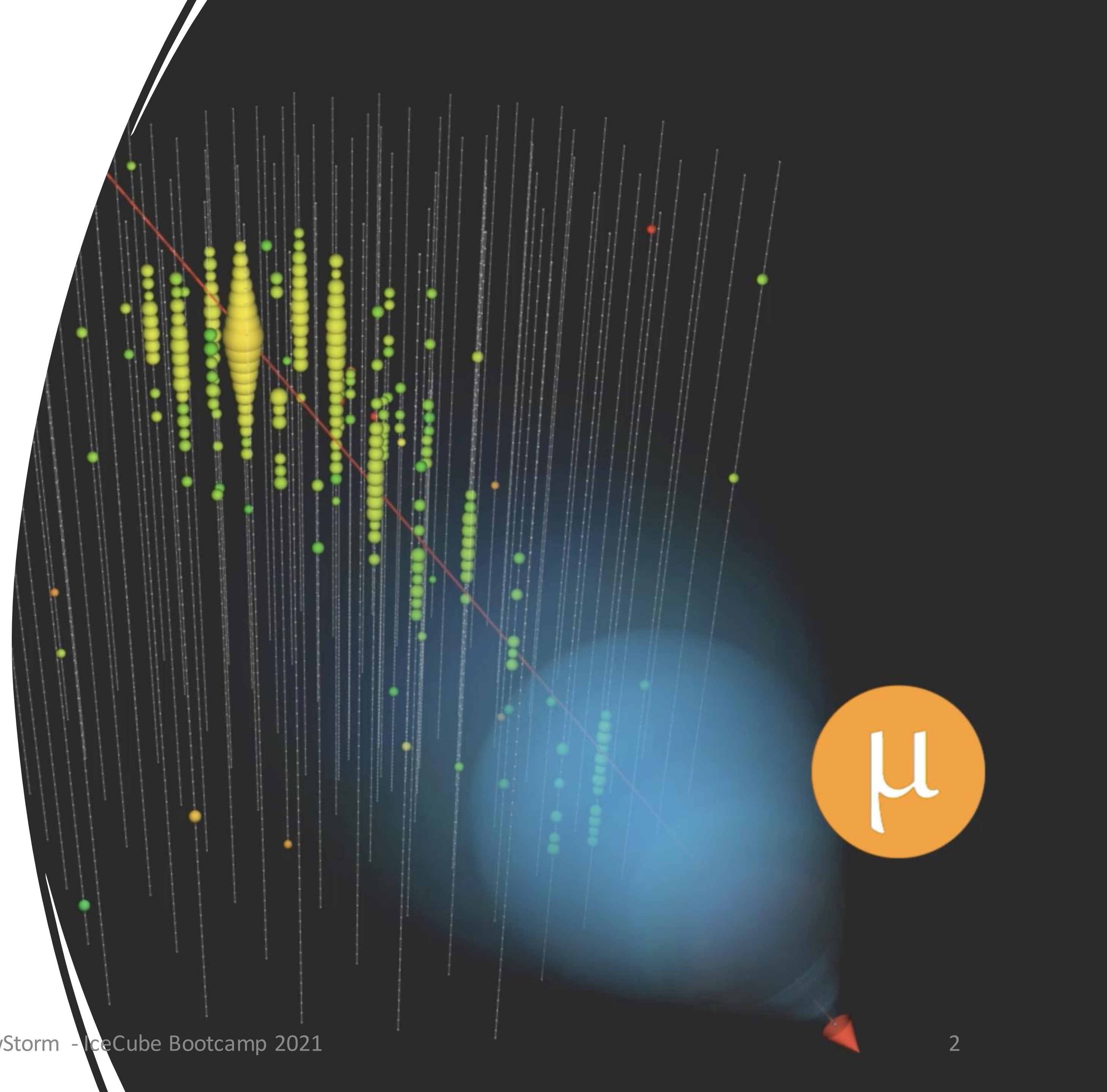
IceCube Bootcamp 2021

NEUTRINOS AND RARE EVENT SEARCHES

IceCube Events

Light ∝ Energy

- ν's Interact – particles make light
- Light Scatters, gets absorbed – How badly?
- Holes are bubbly – How bubbly?
- DOMs see it – How Well?



Uncertainties In Ice and IceCube
=
Uncertainties in Energy and Zenith

"Nuisance Parameters"

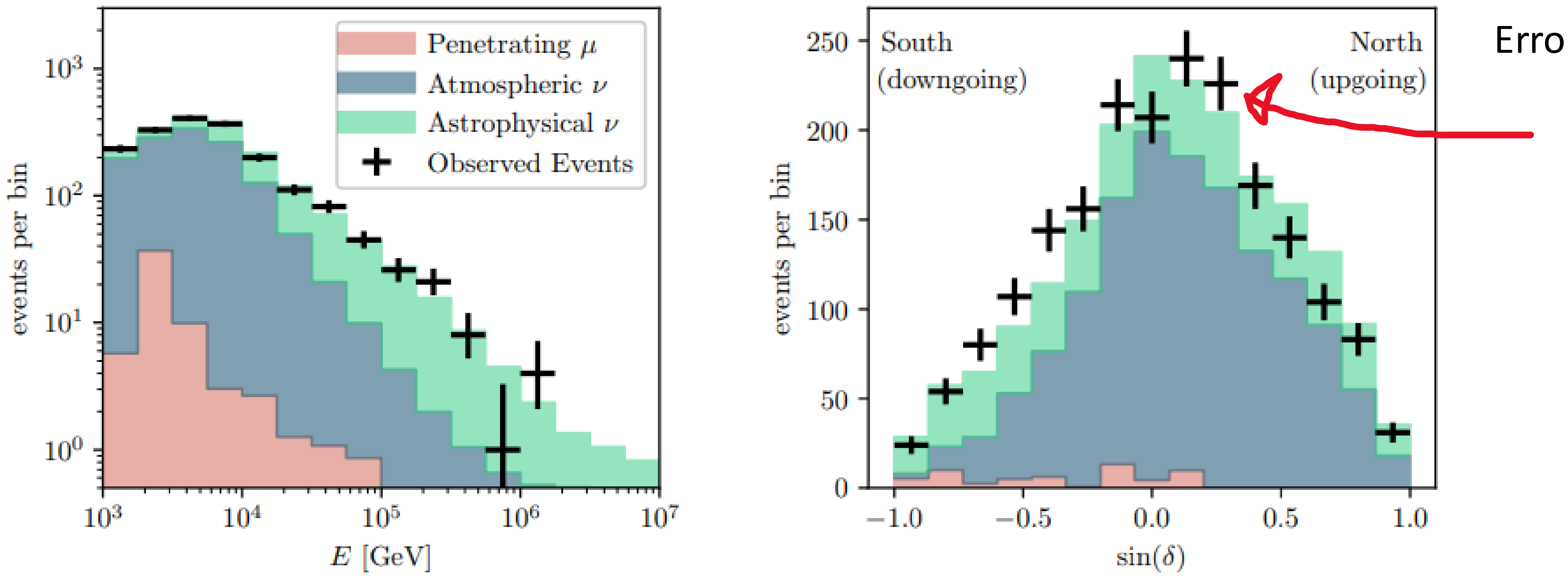
Quantify Your Systematic Uncertainties!

They Quantify...

- Hole Ice Bubbliness
- Ice Absorption
- Ice Scattering
- Neutrino fluxes
- Cross-Sections
- How well do DOMs DOM?

Effect Reconstruction Efficiency!

Why are these *really* necessary?



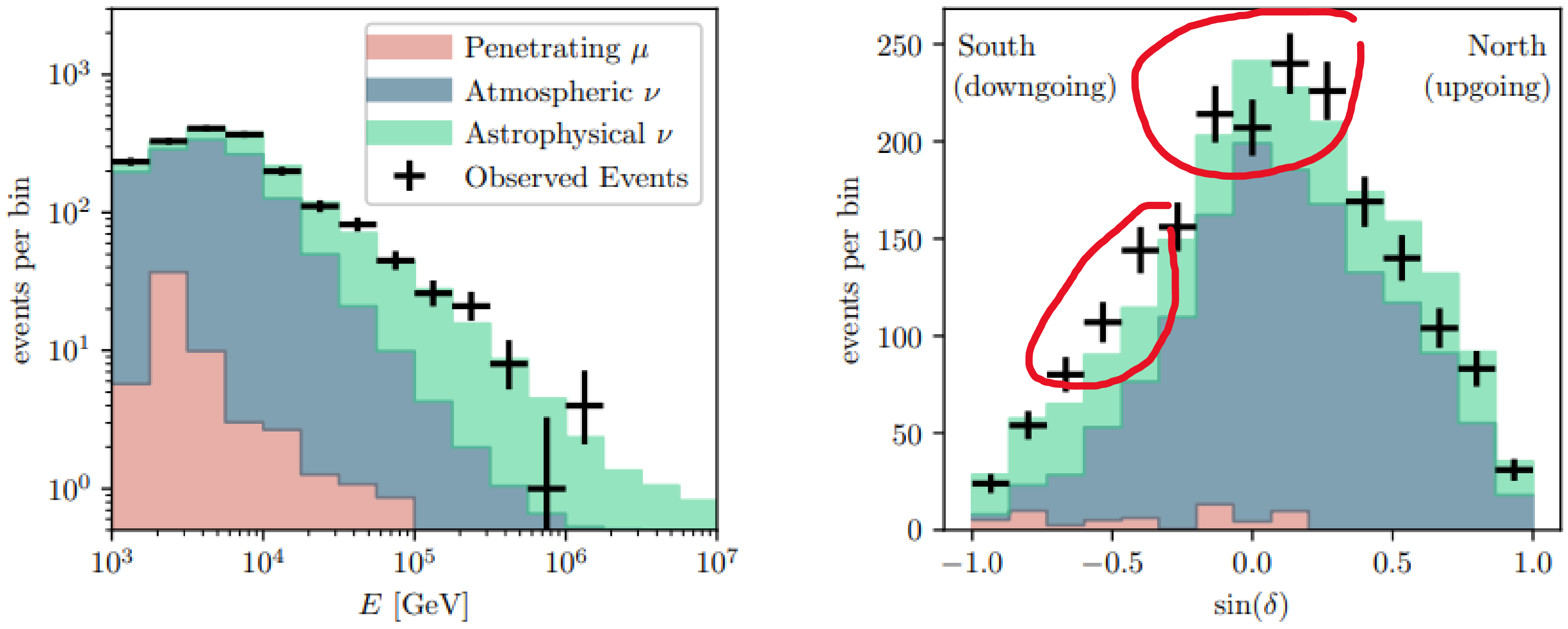
Error bars represent

- Expected **statistical** fluctuations
- Uncertainties in our **detector**

Consider binned events in reconstructed quantities

"Analysis bins" in "analysis space"

Why are these *really* necessary?



How big are your error bars, really?

Statistical
AND
Systematic

Are excesses regular fluctuations, or signs of something new?

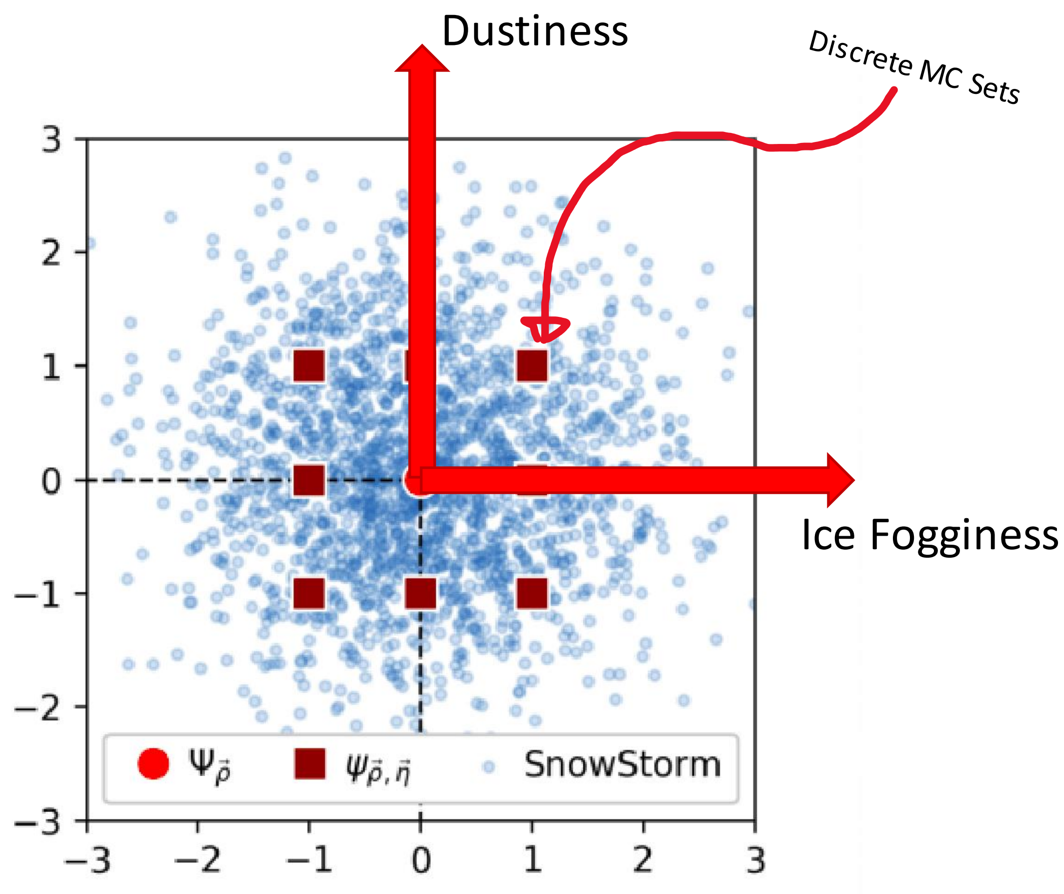
I'm not throwing shade at MESE, don't hate me!

Dealing with nuisances

- High-Level
  - Neutrino fluxes, cross-sections
  - Often easily manageable through reweighting

- Low-Level
  - Ice properties
  - Difficult to propagate effects on reconstructed energy, angles
  - Requires Monte Carlo Simulation

Simulate with Nuisances



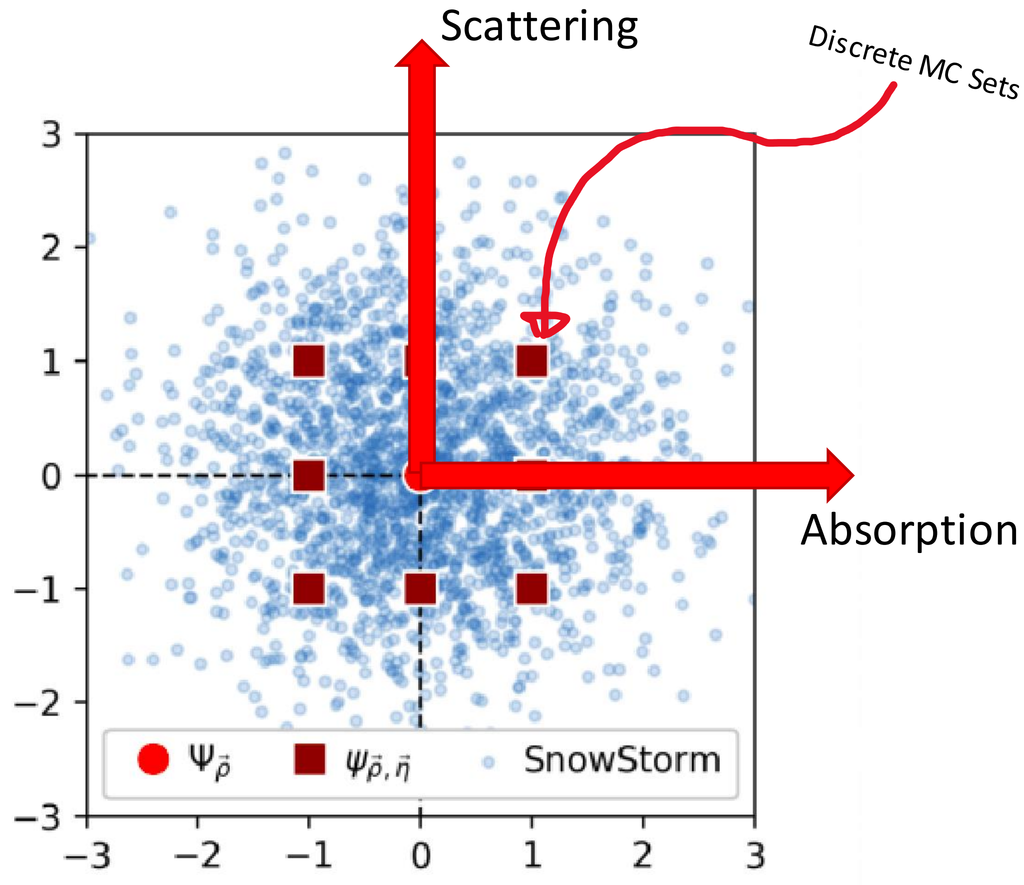
Quantify Your Systematic Uncertainties!

History Times; Full MC sets at

- "Central Model"
- Central Model plus more dust
- CM with more fog
- More fog, less dust...

Computationally Expensive!

Simulate with Nuisances



Quantify Your Systematic Uncertainties!

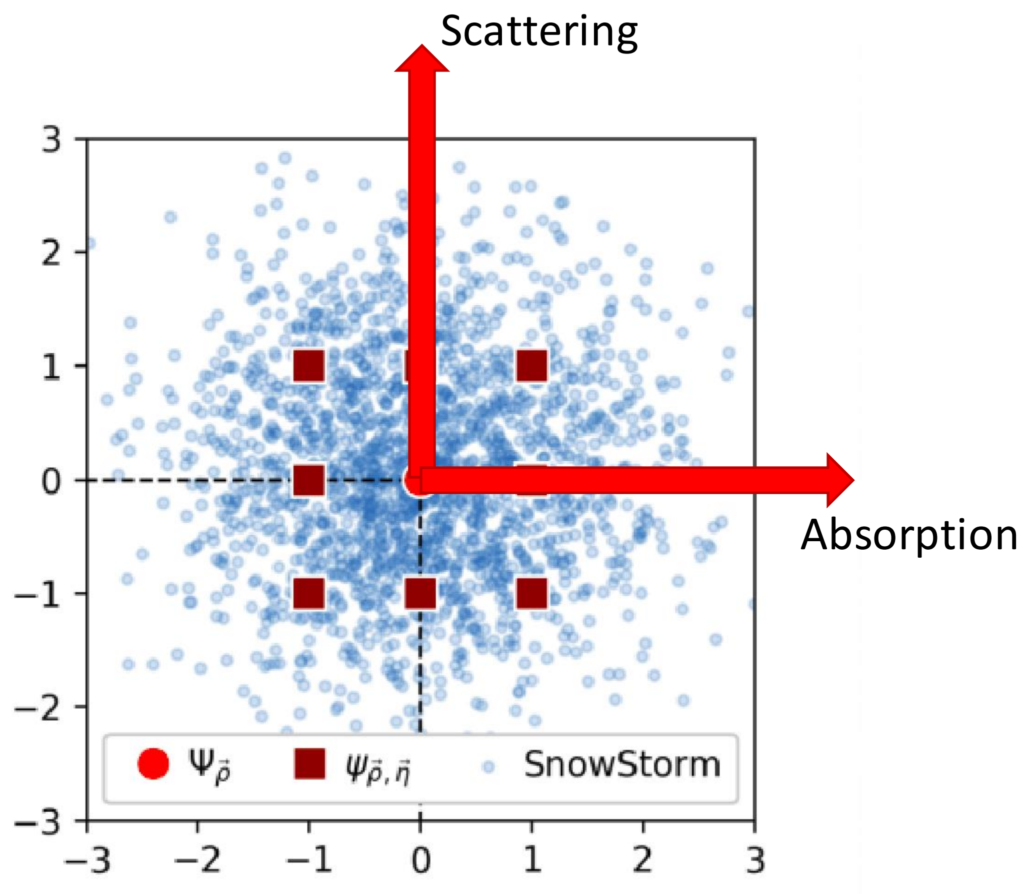
History Times; Full MC sets at

- "Central Model"
- Central Model plus more scatter
- CM with more absorption
- More abs, fewer scattering...

Computationally Expensive!

With the SnowStorm Method!

Quantify Your Systematic Uncertainties!



<u>SnowStorm</u>

Each event samples Nuisance Parameters from continuous prior distributions

Single MC Set!

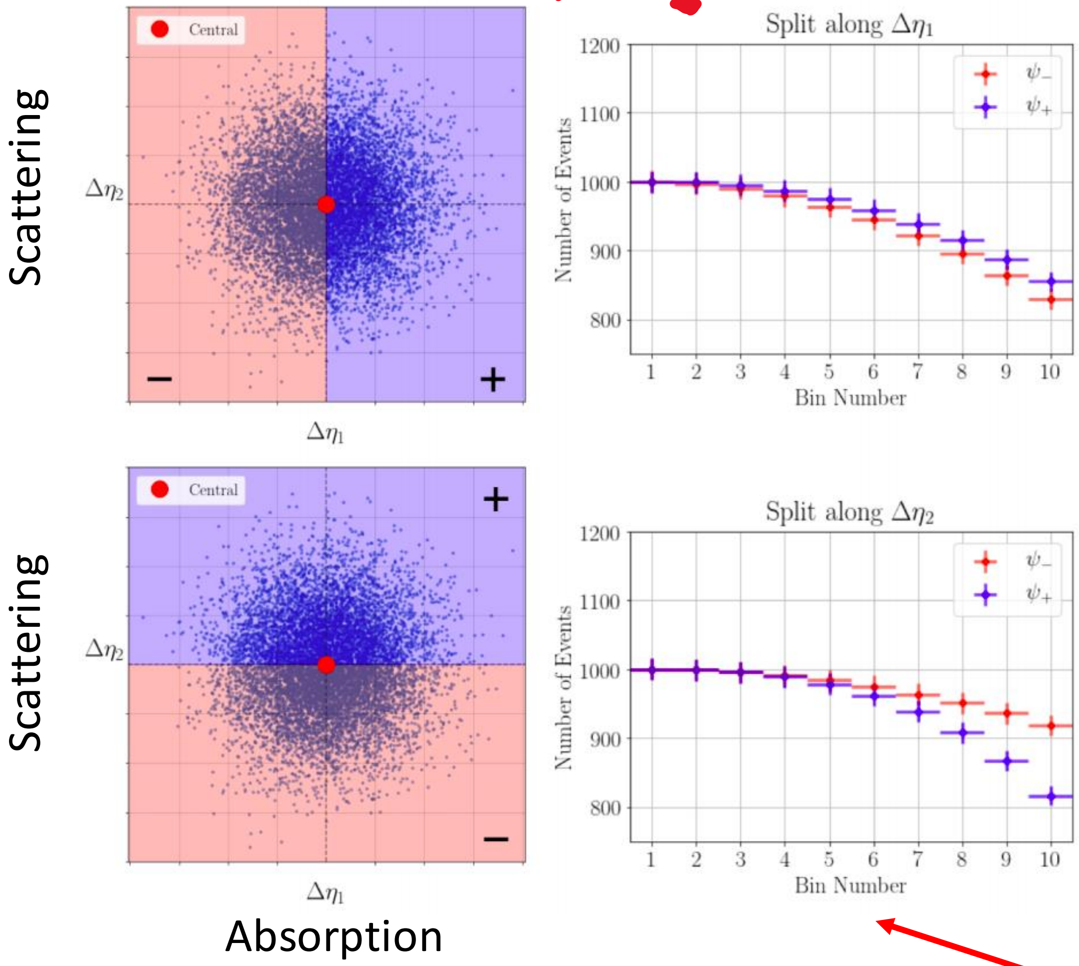
Read the Paper!

Each Event is as unique as a snowflake in a snowstorm

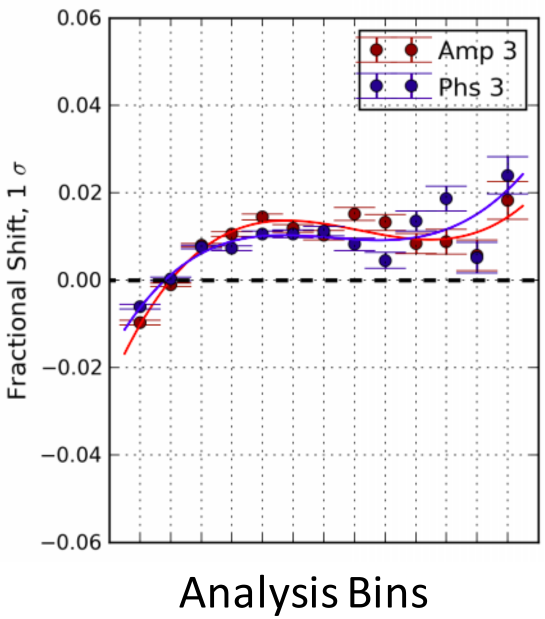
Chop Up the Sample

Divide Sample into subsamples according to nuisances

Reconstruction



Energy, Zenith, ...

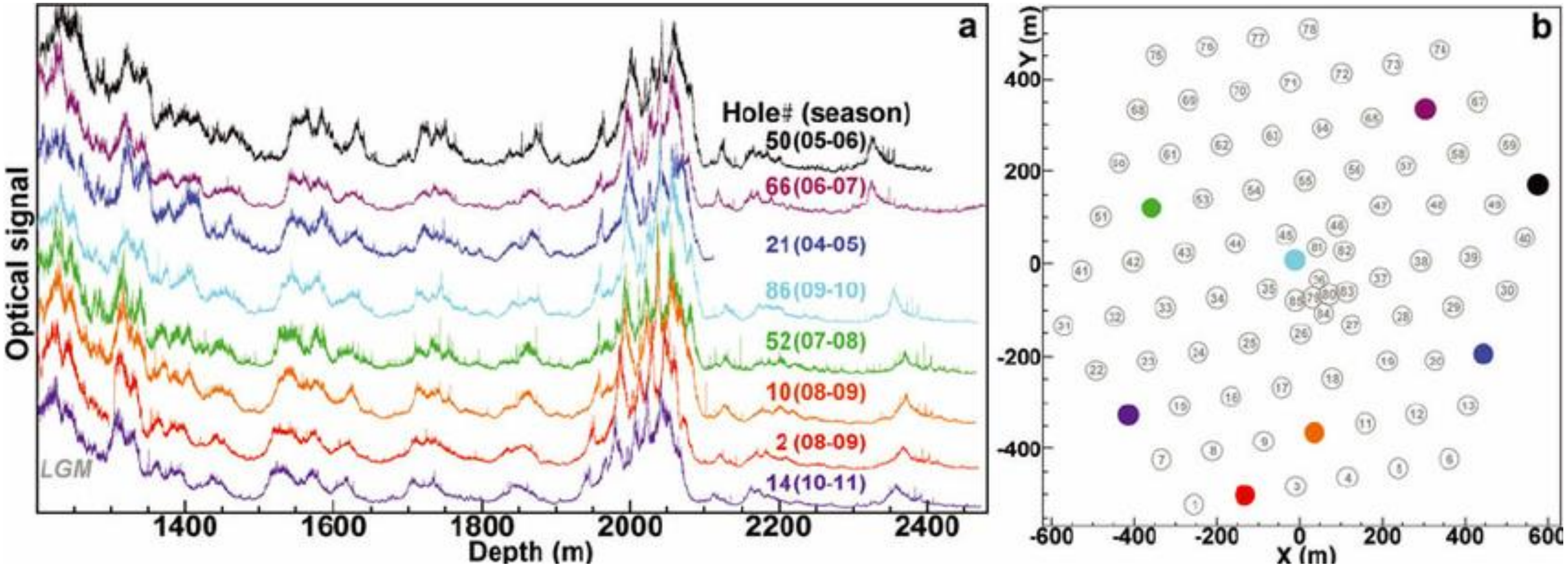


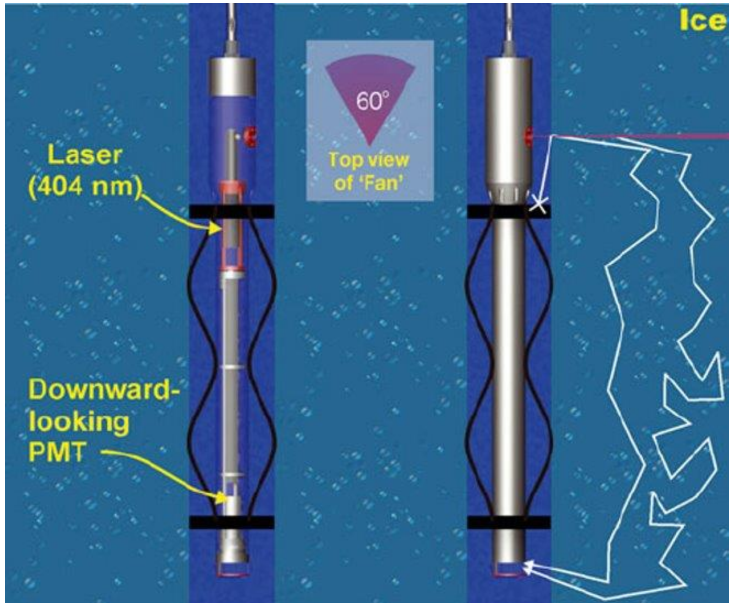
Click here for math details!

How Does This Work in IceCube

Antarctic Ice Isn't Perfect

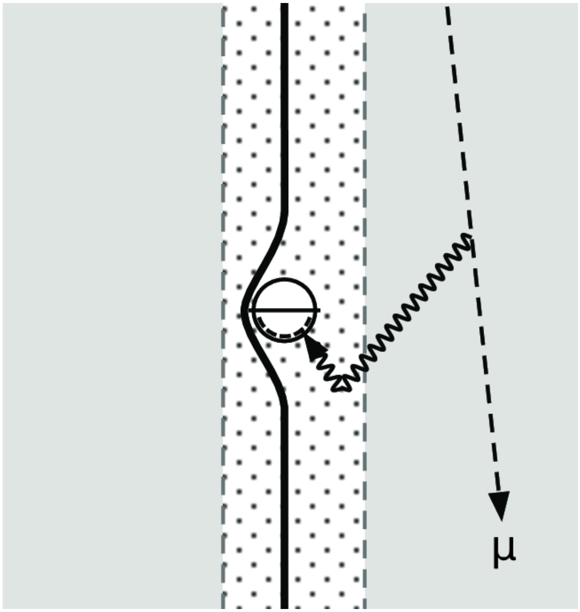
- Dust
- Absorption
- Scattering
- Oh No!

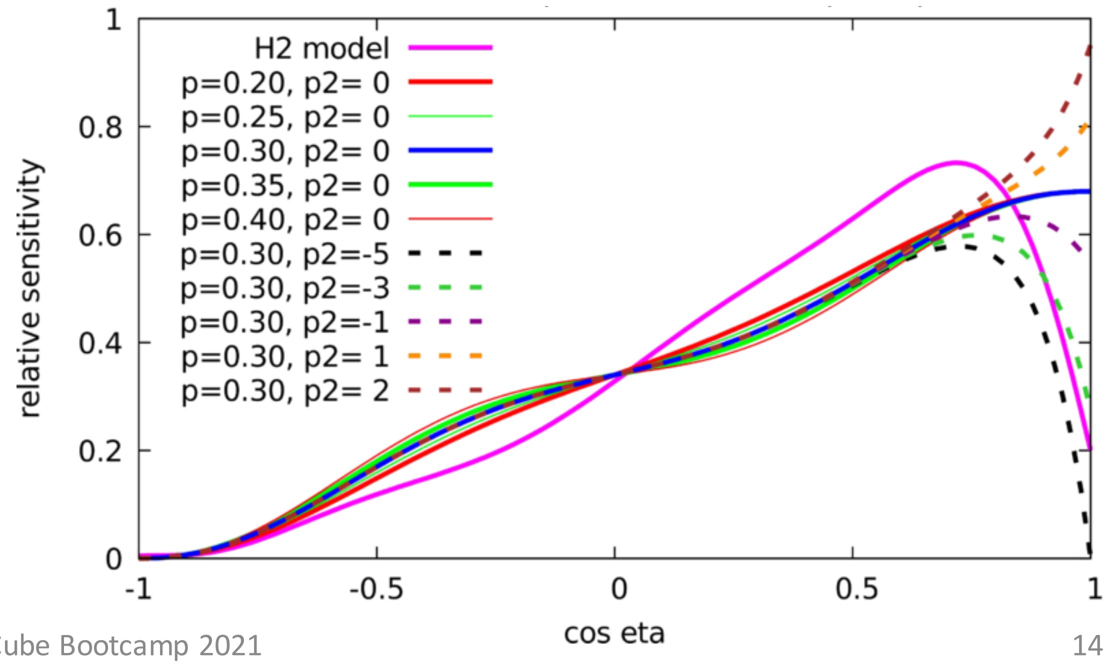




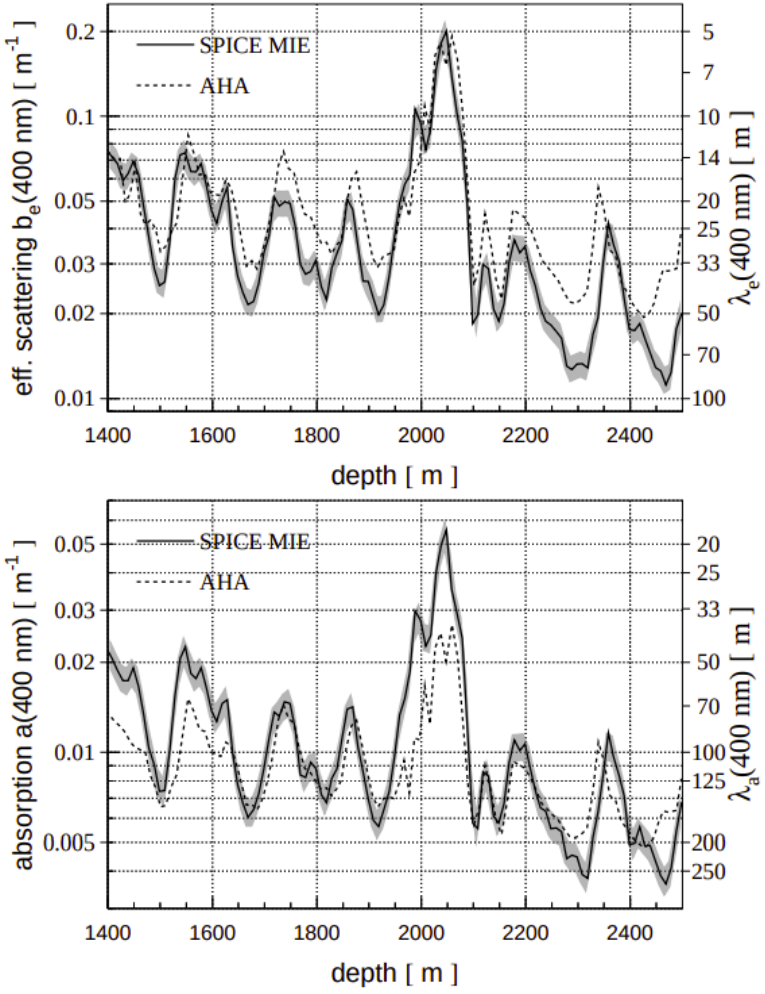
Hole Ice Bubbliness

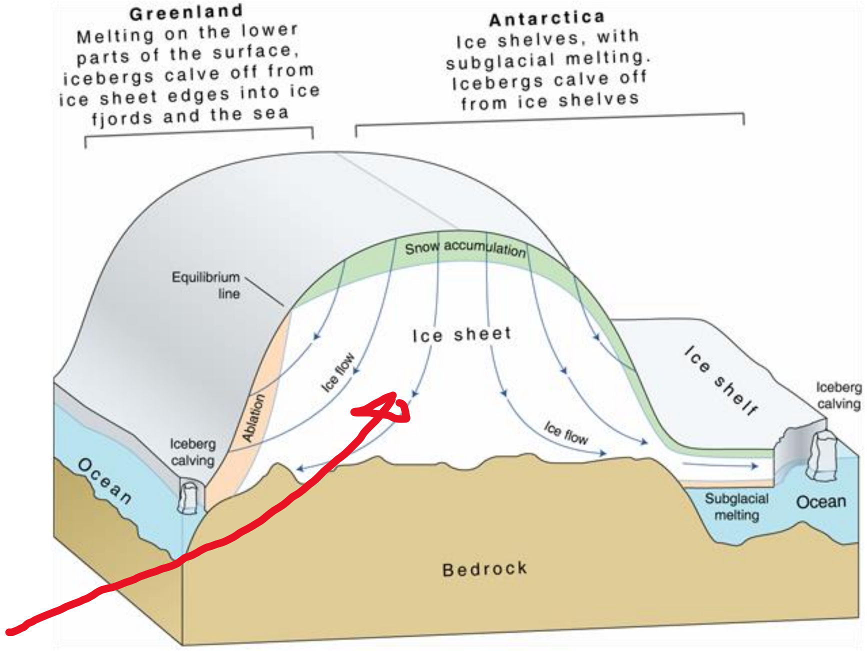
- Light scatters off bubbles in hole ice, affects sensitivity
- Relatively Easy to SnowStorm-ize (MSU Forward Hole Ice)
- For up-going photons $\cos\eta = 1$





Absorption and Scattering





Ice

Old Models:

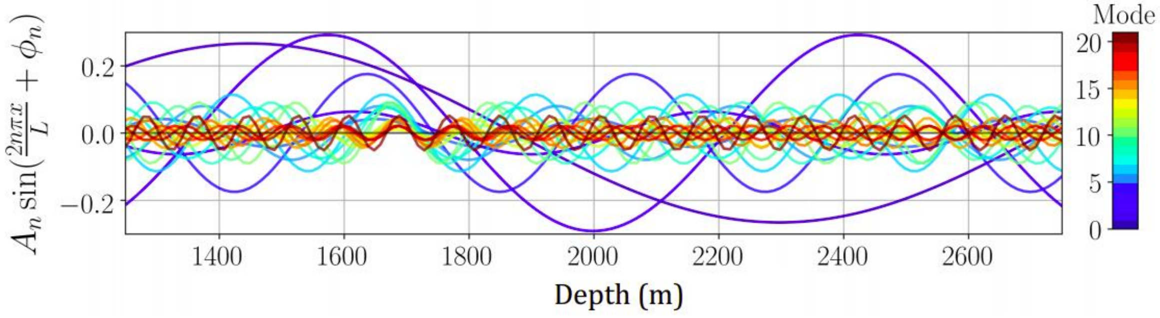
- Divide ice into 10m layers, each with unique absorption and scattering
- Have a *lot* of nuisance parameters
- Unwieldy!

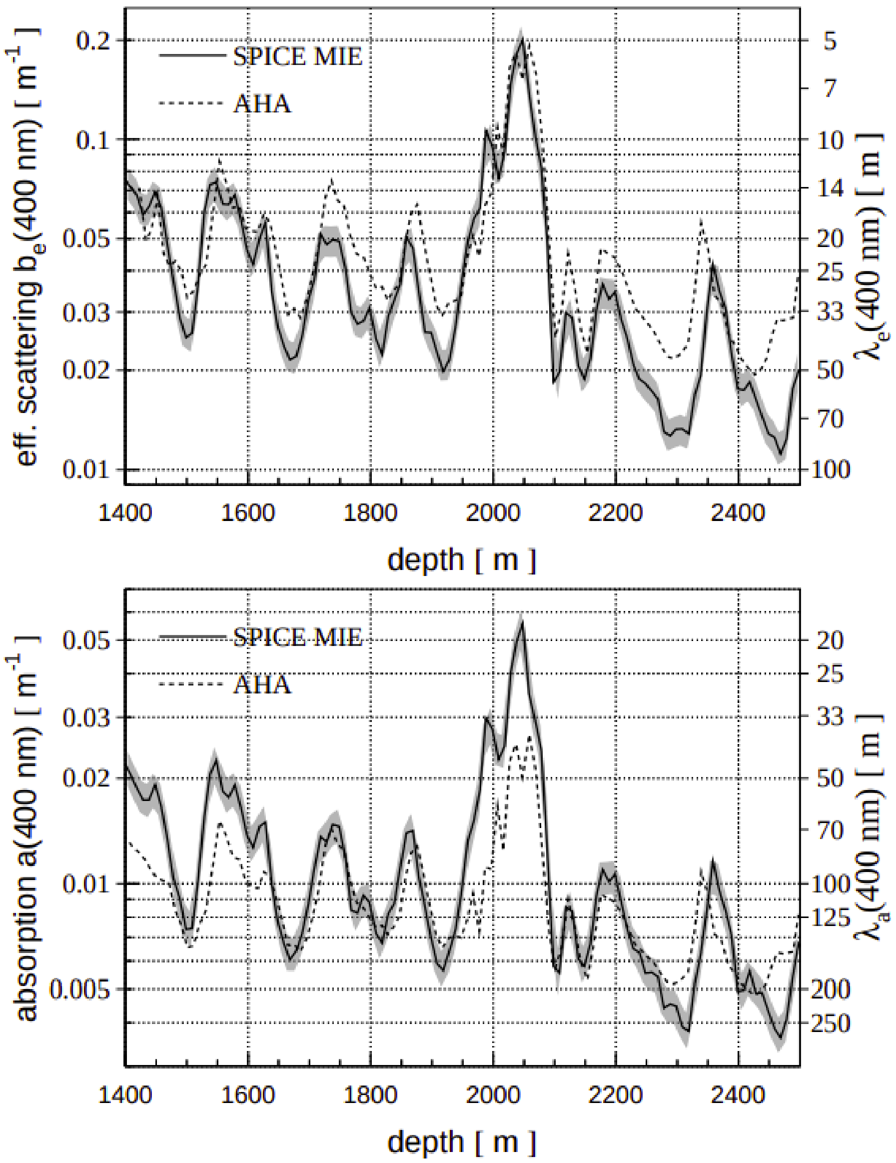
Fourier Series with IceWave!

$$M^+(x) = \frac{1}{2}\log_{10}(\text{Abs}\times\text{Sca}) = \frac{A_0}{2} + \sum A_n \sin\left(\frac{2n\pi x}{L} + \phi_n\right)$$

$$M^-(x) = \frac{1}{2}\log_{10}(\text{Abs}/\text{Sca}) = \frac{B_0}{2} + \sum B_n \sin\left(\frac{2n\pi x}{L} + \gamma_n\right)$$

$$\text{Abs} = 10^{M^+ + M^-} \qquad \text{Sca} = 10^{M^+ - M^-}$$

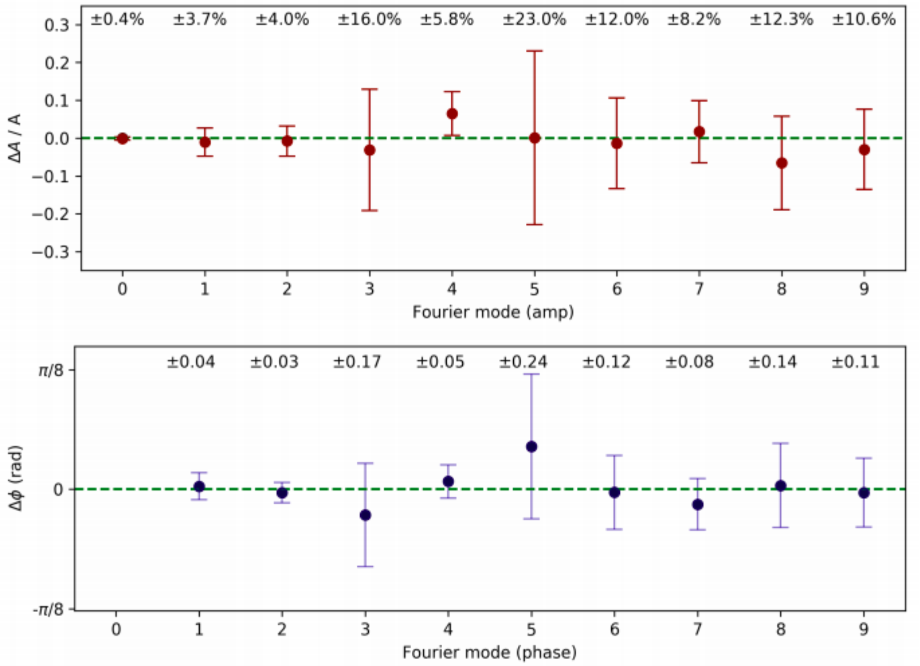




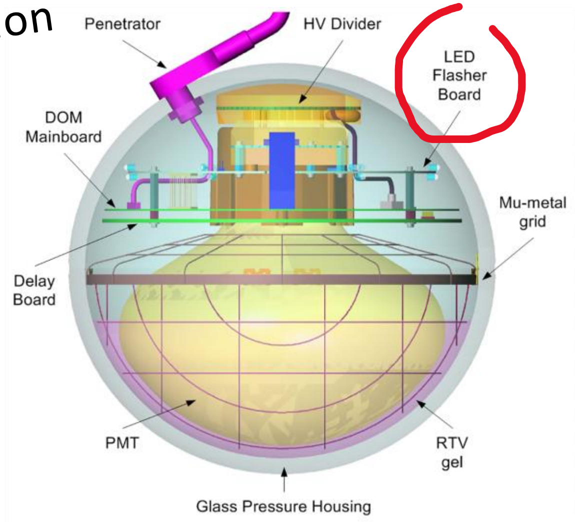
- First terms represent large-scale fluctuations
- Latter terms represent small wobbles

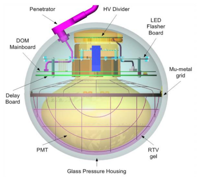
- Build a physically motivated function for absorption/scattering

Perturbing Models

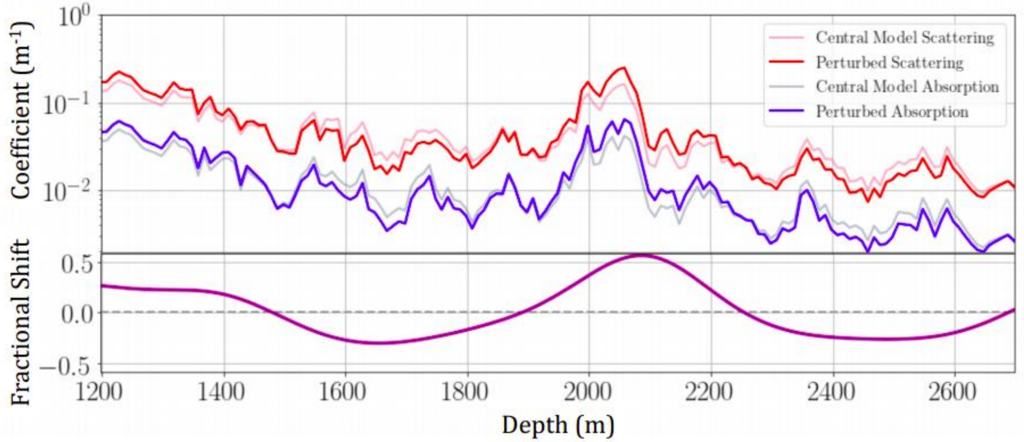


Flasher Fits to get Fourier Expansion



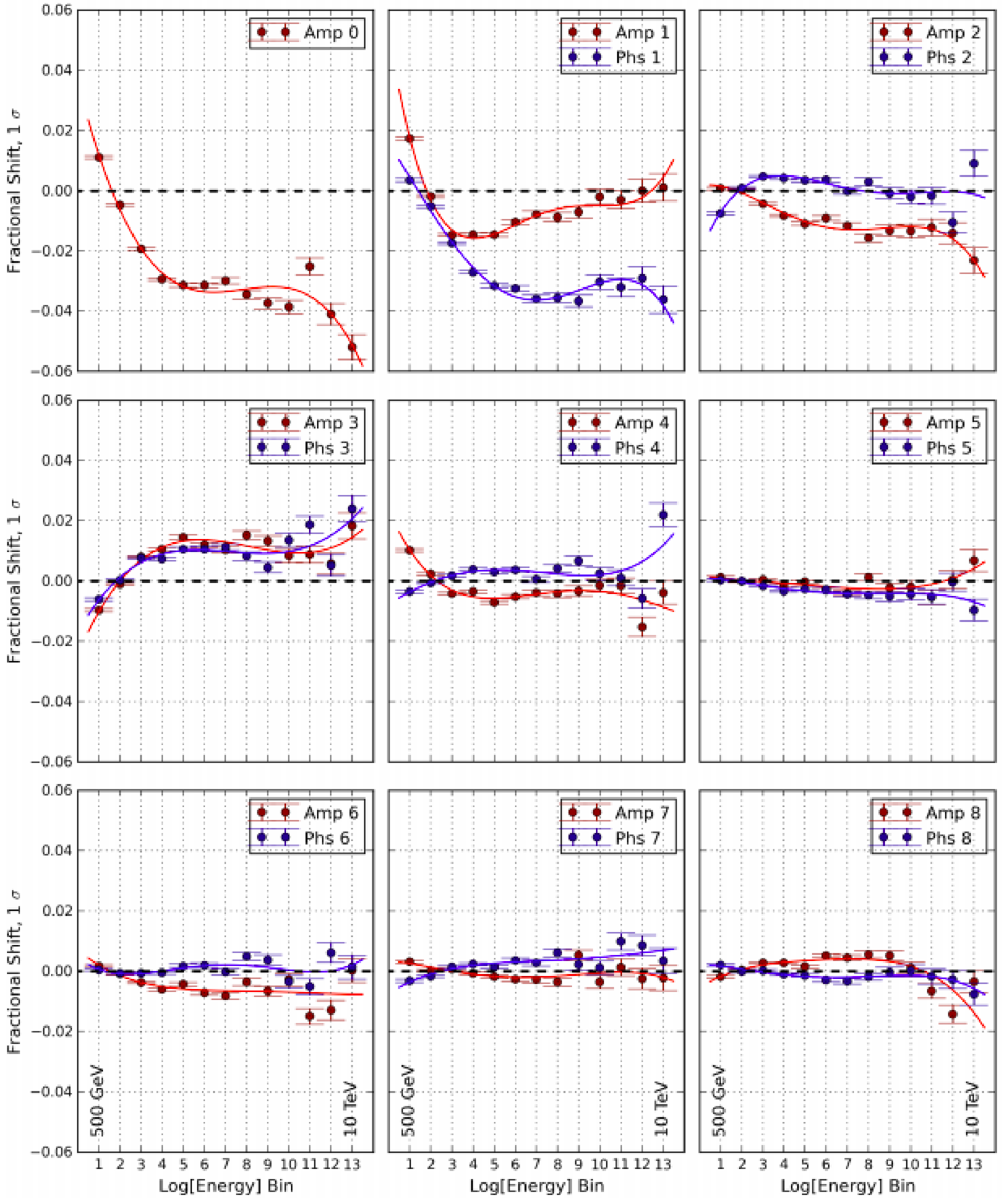


Perturb amplitudes, phases, within calibration uncertainty



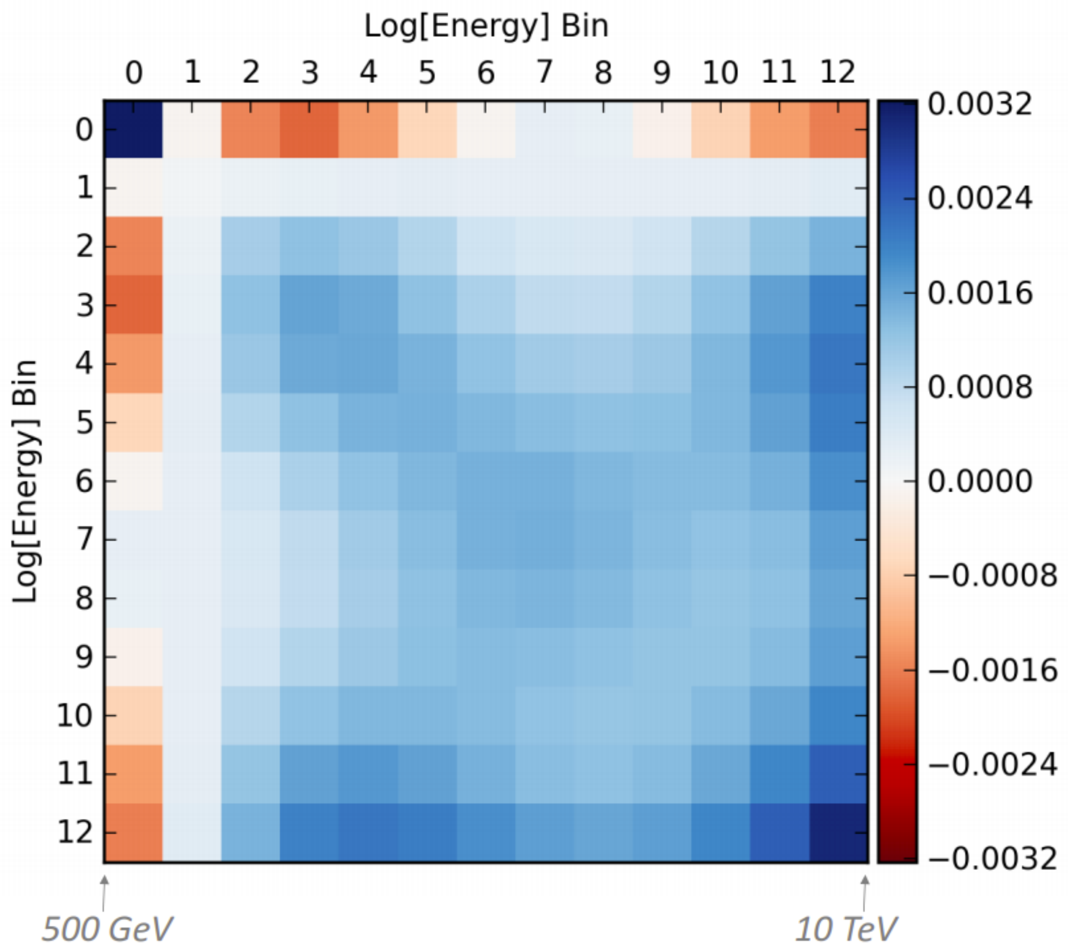
Extract Effects

- Fractional effects on analysis bins
- Decreasing impact with higher mode
- Fourth-order fits to smooth out MC discretization effects
- Zenith effects are pretty small, *for this example*



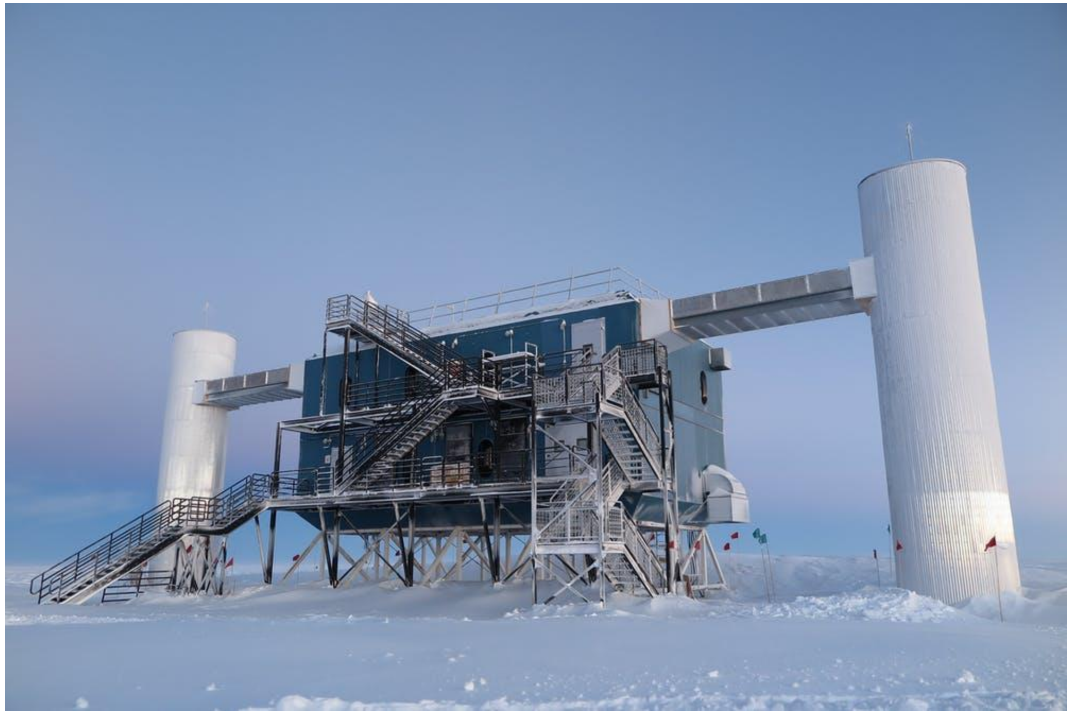
Analysis Space Covariance

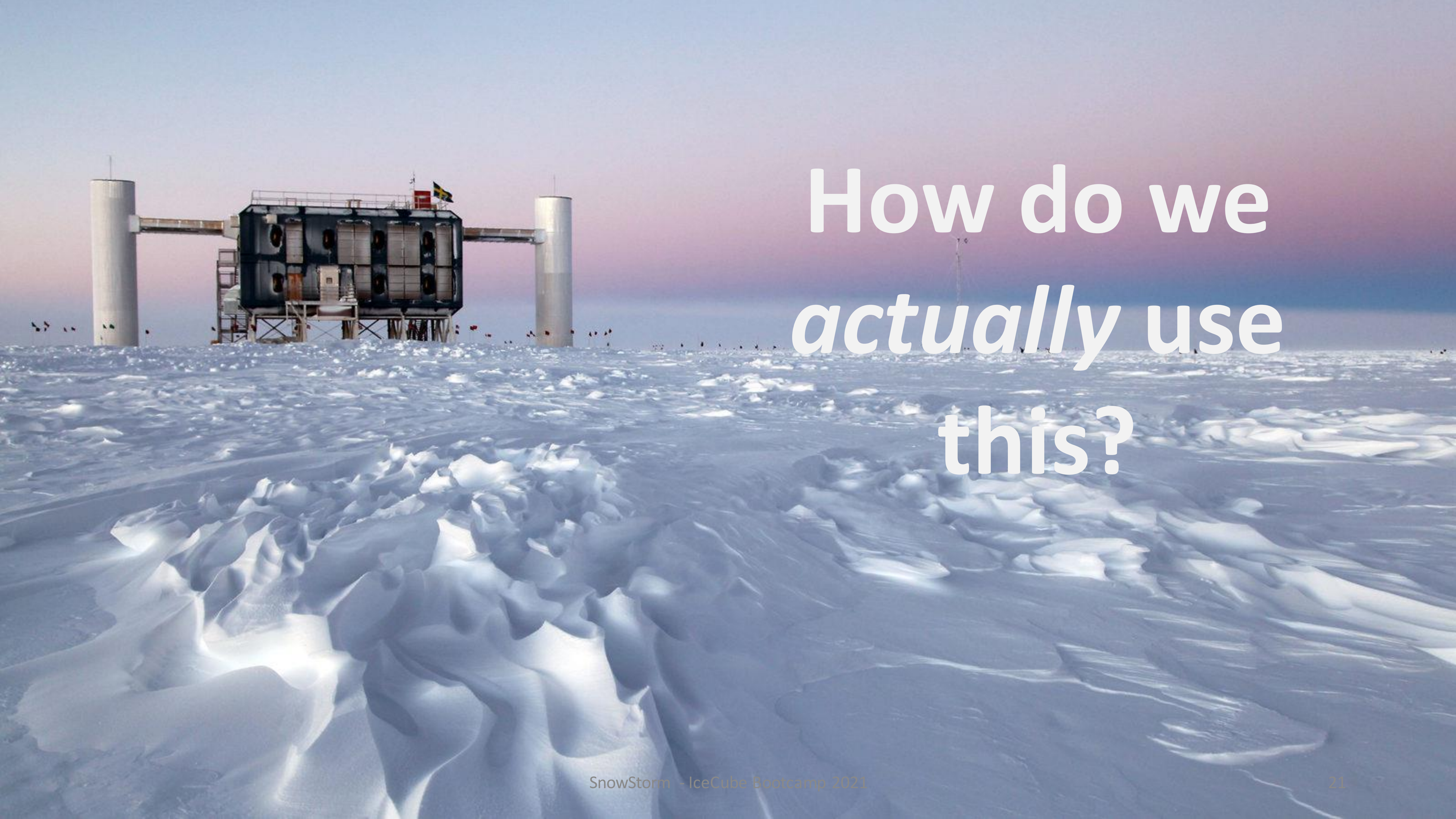
- Uncertainties in one bin closely tied to others
- Analysis-dependent
- Zenith effects were minimal – only need covariance in energy space



Wow!

- One MC Sample
- Handles all the uncertainties
- Account for all nuisance parameters in analysis space
- How is it used?





How do we *actually* use this?

SnowStorm Is In IceTray!

Implemented in *SnowSuite* – a set of python scripts in Icetray

Polyplopia

LeptonInjector

1. Event Generation
2. Background Injection
3. **Photon, Particle Propagation**

icetray/simprod-scripts/resources/scripts/SnowSuite

SnowStorm Processor

- Particle, CLSim Photon propagation

- Multiple Miniature I3Trays
    - 100-frame bundles with unique ice properties
    - Properties stored in M frames

- Shuffles
    - IceWavePlusModes (scattering/abs)
    - Anisotropy Scale
    - DOMEfficiency
    - MSU Hole Ice Model

M Frames

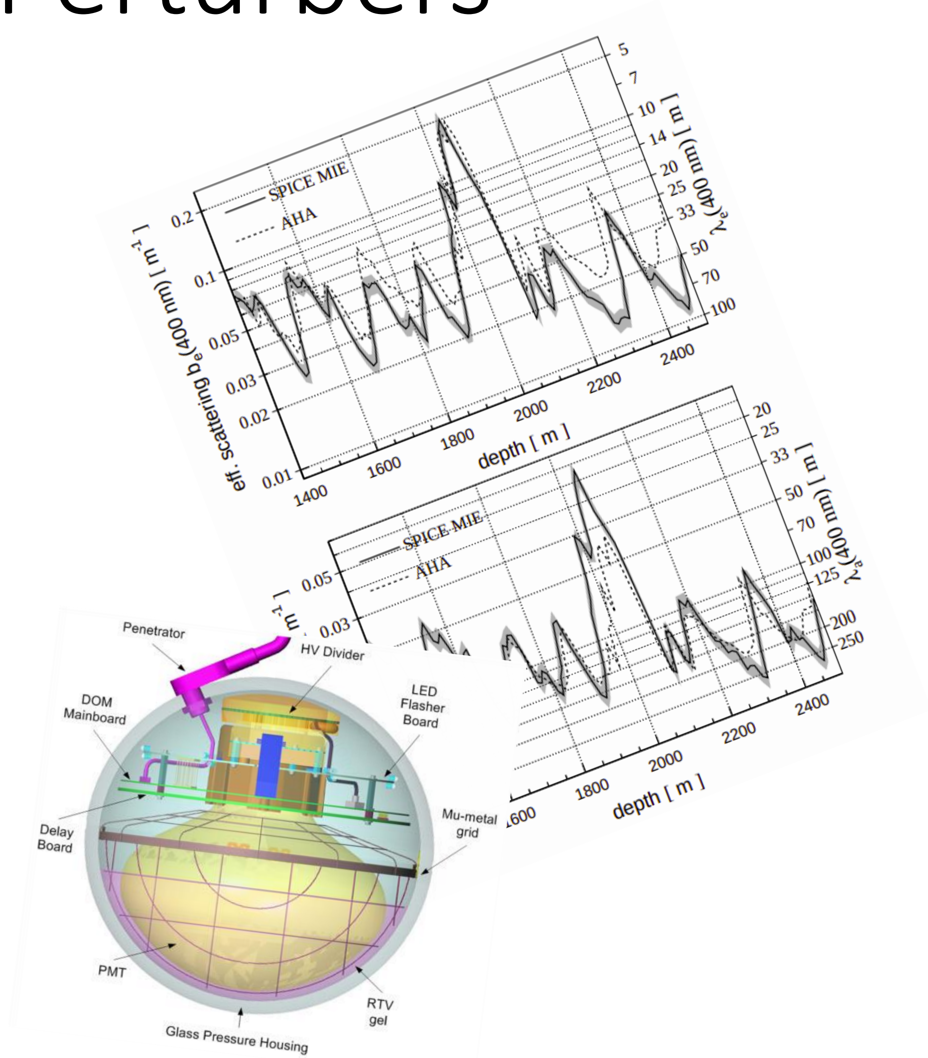
- Contain relevant SnowStorm Parameters

- Perturbed nuisances
  - *SnowstormParameters* ← Vector of numbers

- Order Indicated by
  - *SnowstormParametrizations* ← Perturber names
  - *SnowstormParameterRanges* ← [start, end) indices of perturbers

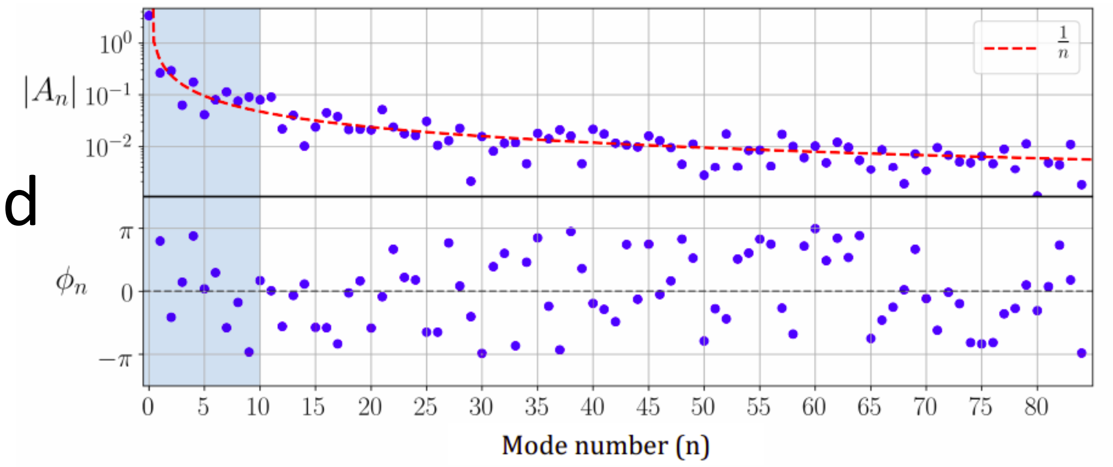
Existing SnowStorm "Perturbers"

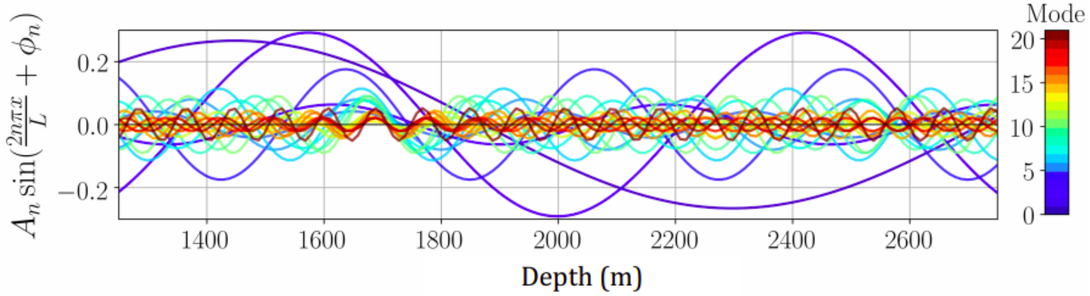
- (24) IceWavePlusModes
  - Fourier Depth Dependence
- (2) Global Abs/Scattering
  - Uniform scaling
- (1) AnisotropyScale
  - Scales magnitude
- (1) DOMEfficiency
  - Scales wavelength acceptance
- (2) Forward HoleIce
  - Perturbs p, p2



IceWavePlusModes

- Only Plus Mode Amplitudes perturbed
  - Twelve amplitudes
  - Then twelve phases
- Deviations *from mean* are stored
- Chop around zero





$$M^{+}(x) = \frac{1}{2}\log_{10}\left(\mathrm{Abs} \times \mathrm{Sca}\right) = \frac{A_0}{2} + \sum A_n \sin\left(\frac{2n\pi x}{L} + \phi_n\right)$$

SnowStorm YAML

- YAML (text) files for nuisance parameters
  - Easy to edit!
- Configure nuisance parameter widths, distributions
  - Uniform, Gaussian
- Toggle systematic uncertainties

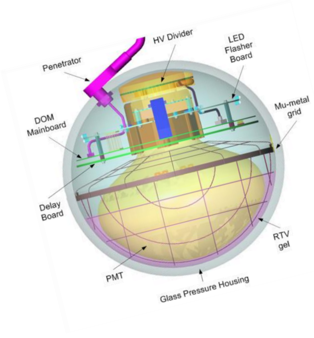
```
Perturbations:
    # IceWavePlusModes for depth dependent absorption/scattering scaling
    IceWavePlusModes:
        apply: true
        type: default

    # Global ice scattering scaling
    Scattering:
        type: uniform
        uniform:
            limits: [[0.9, 1.1]]

    # Global ice absorption scaling
    Absorption:
        type: uniform
        uniform:
            limits: [[0.9, 1.1]]

    # Ice anisotropy scaling
    AnisotropyScale:
        type: uniform
        uniform:
            limits: [[0., 2.0]]

    # DOM efficiency scaling
    DOMEfficiency:
        type: uniform
        uniform:
            limits: [[0.9, 1.1]]
```

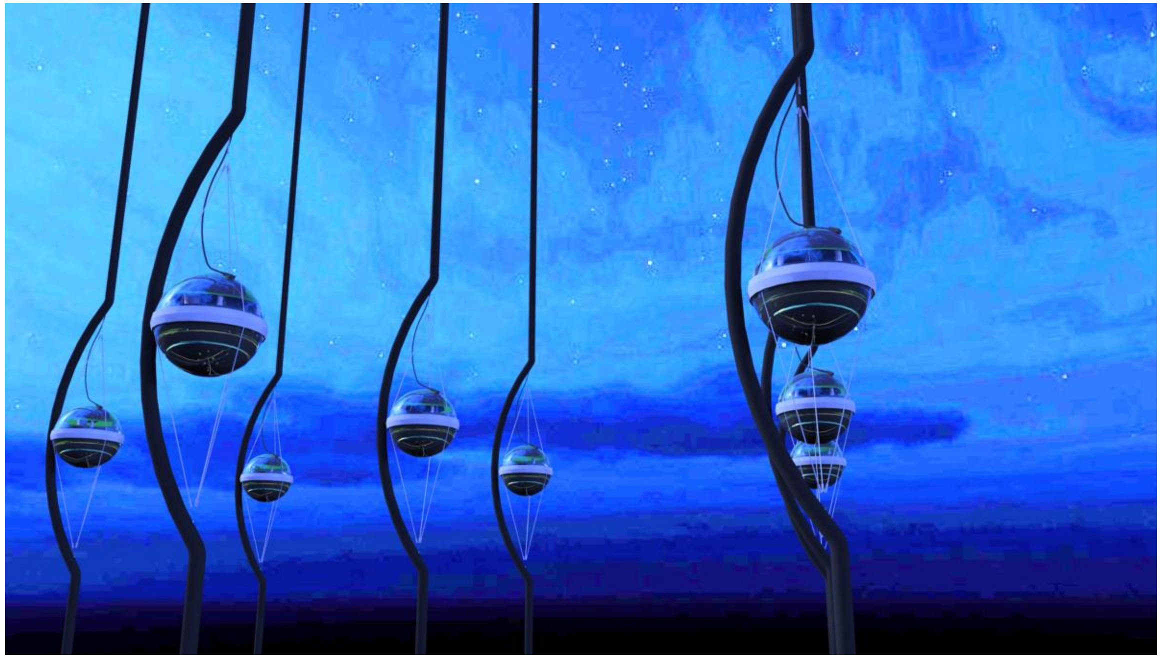


Creating New Perturbers

- Implement SnowStorm "Parametrization" class
- Define 'transform' function taking relevant nuisance vector, I3Frame
- See snowstorm for examples

Beyond SnowStorm

- Use your favorite Detector and Filter Sims
- IceModel details kept in "M" frames – keep them!
- Can extract uncertainties for your sample



Summary

- Quantify detector and systematic Uncertainties
- Snowstorm uses one MC Set, incorporates all low-level systematic uncertainties
- Use Snowstorm Parameters to extract uncertainties, covariances

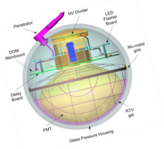
Thank you for your time!
Any Questions?

Backup

Extraction Effects in Analysis

Extract Covariances of nuisance, covariance in analysis too!

Perturbation in Analysis from perturbing nuisance!

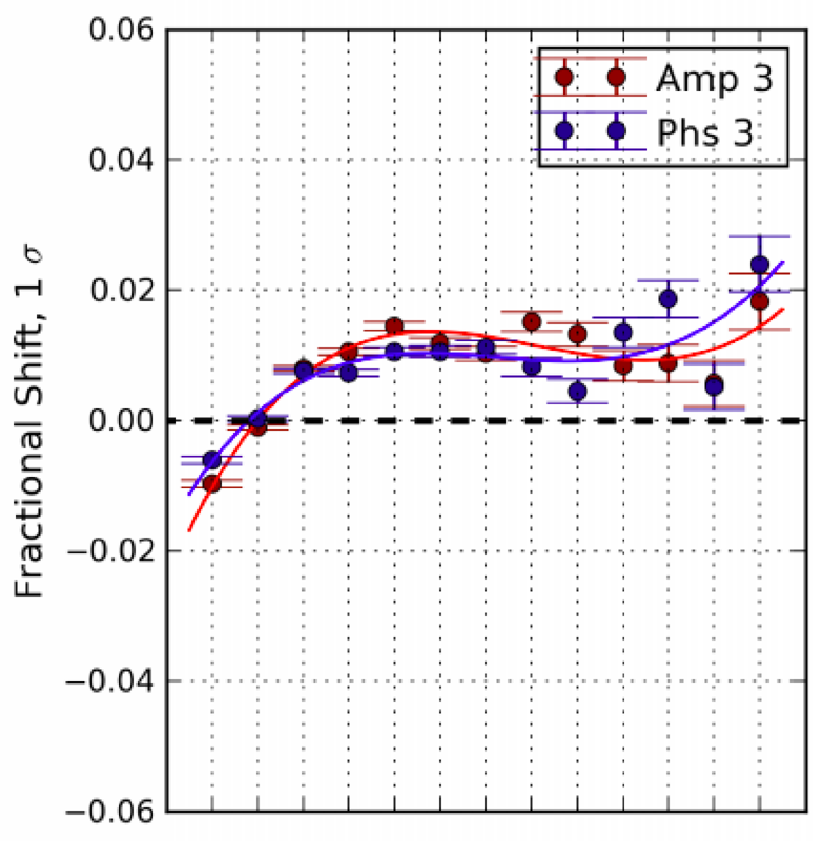


$$G_{b,i} = \frac{1}{\sigma}\sqrt{\frac{\pi}{2}}\left(\Phi^{+}_{i,b} - \Phi^{-}_{i,b}\right)$$

$$\Phi_{(b,\vec{\eta})} = \Phi_{(b,0)} + G_{(b,i)}\eta_i$$

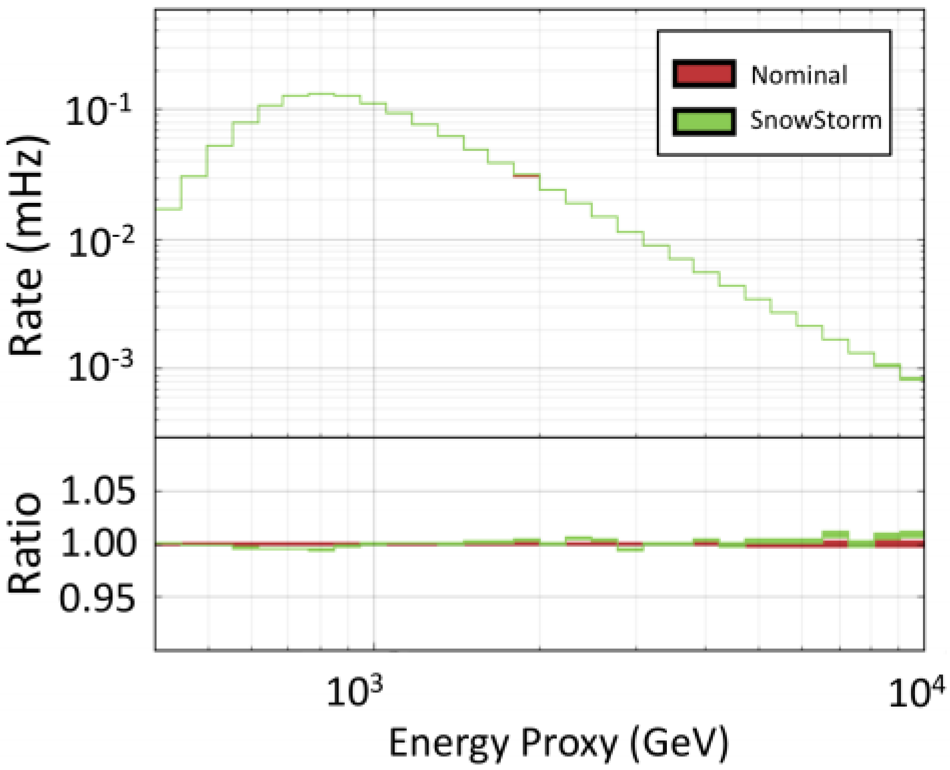
Central Expectation

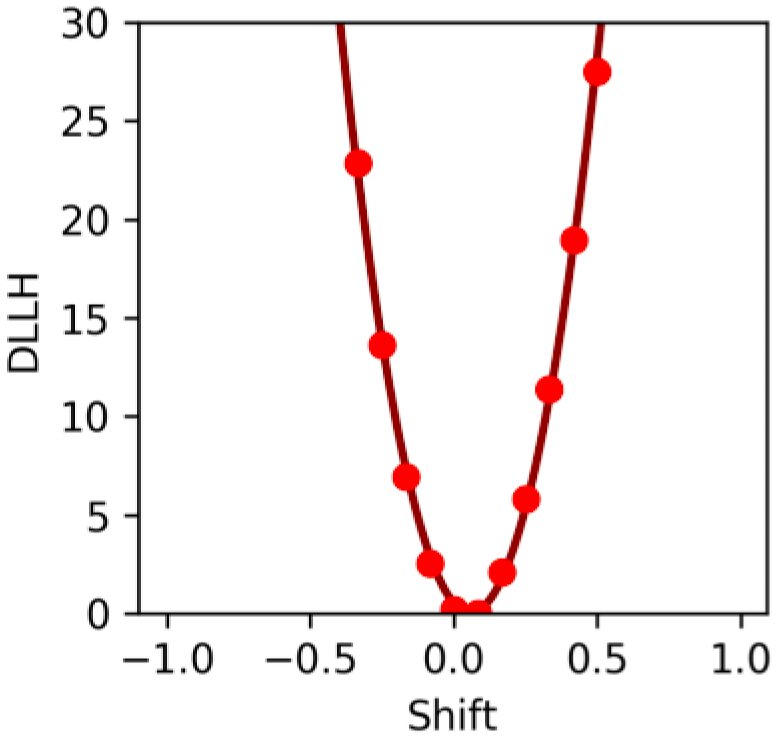
Some Choice of Nuisances



Click here for math details!

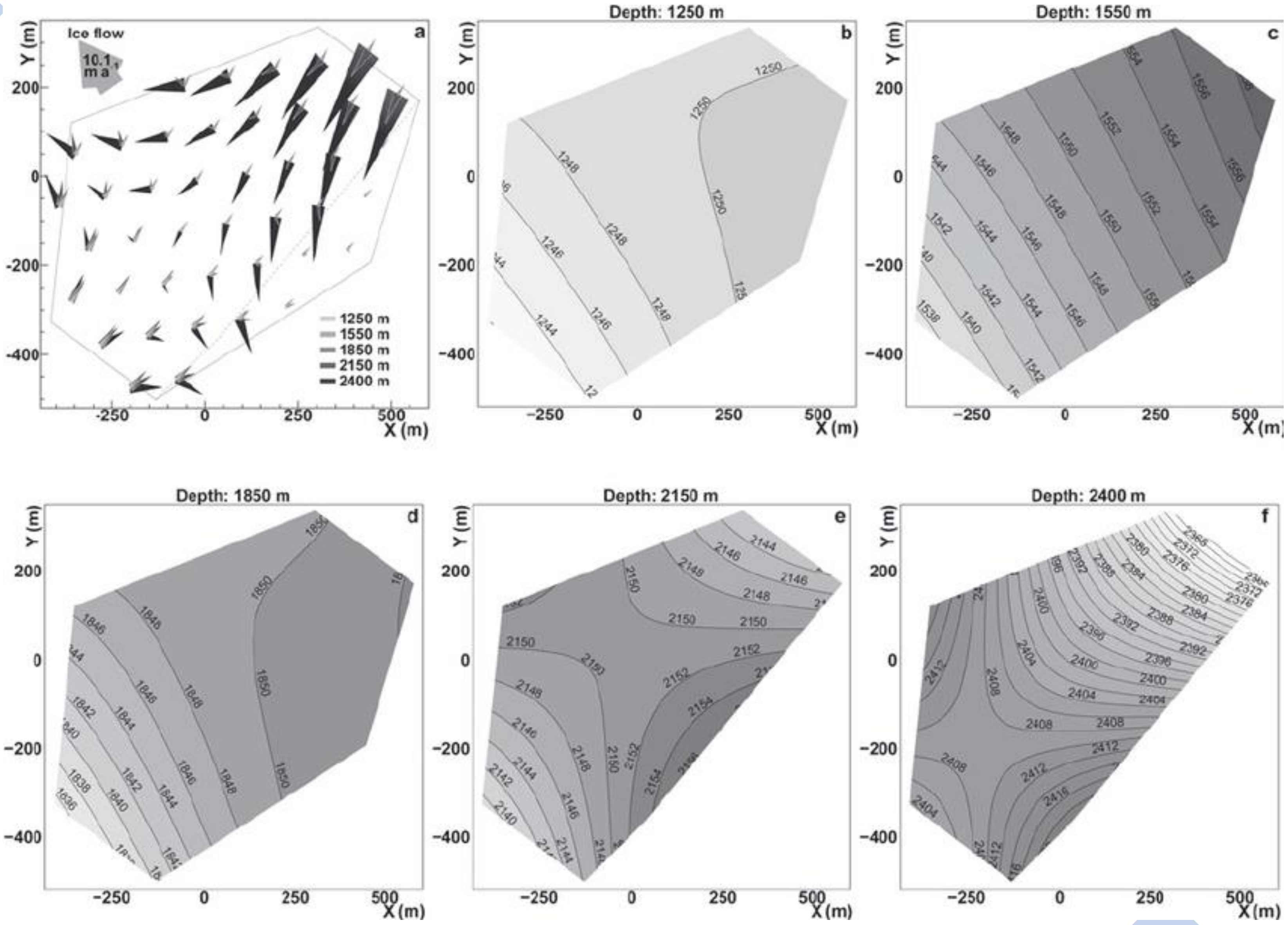
Tests of Validity





DOM Deployment

Ice Tilt


Ice flow
10.1 m a⁻¹
1250 m
1550 m
1850 m
2150 m
2400 m
Depth: 1250 m
Depth: 1550 m
Depth: 1850 m
Depth: 2150 m
Depth: 2400 m
a
b
c
d
e
f
Y (m)
X (m)

Energy Loss Rates

Muon Energy Loss is Stochastic at high energies!