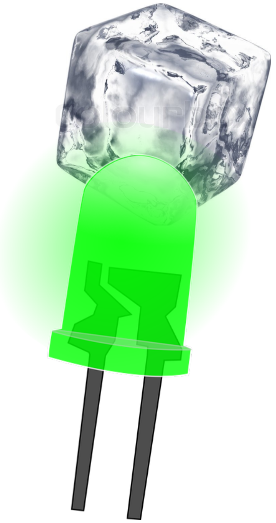
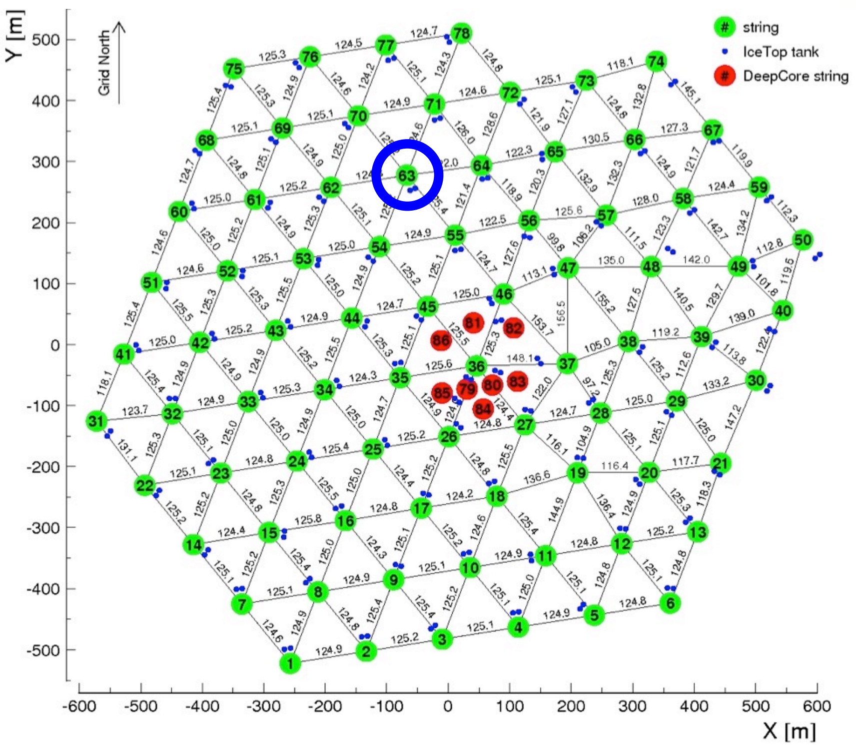
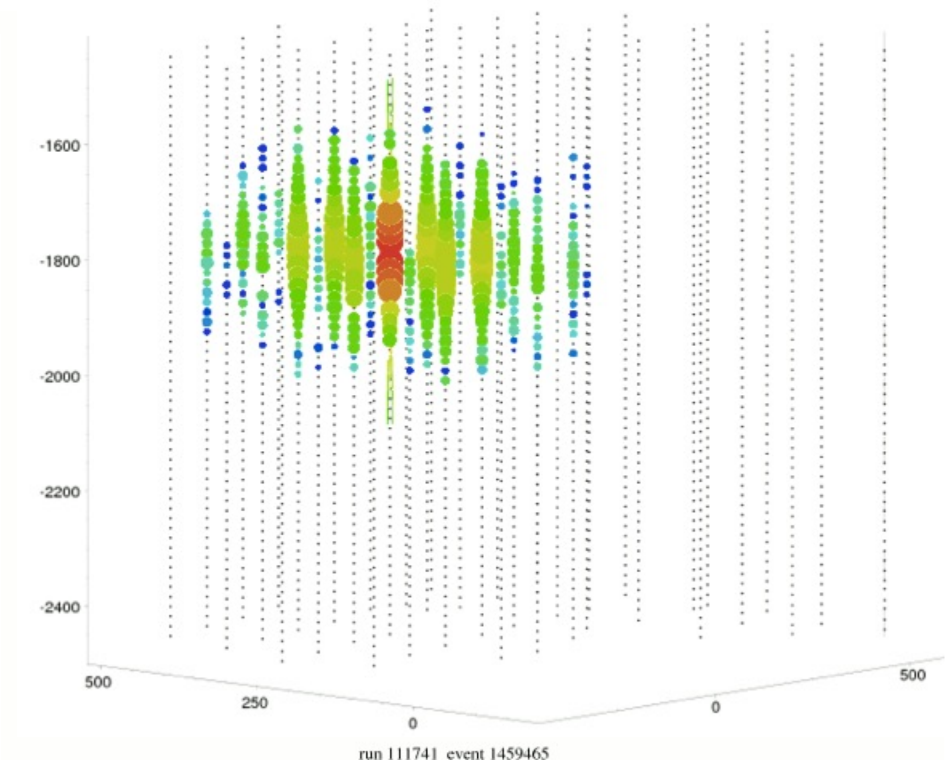
in-ice systematics:
ICE MODEL

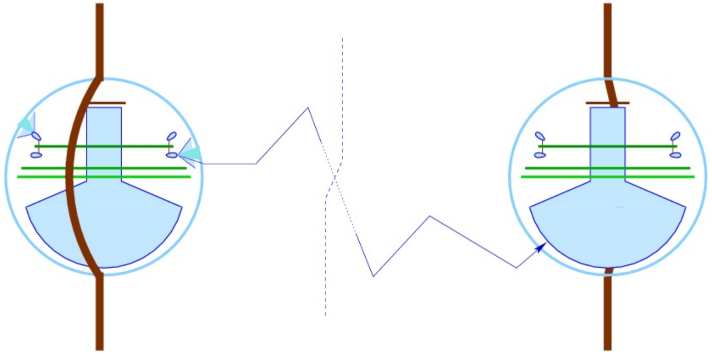


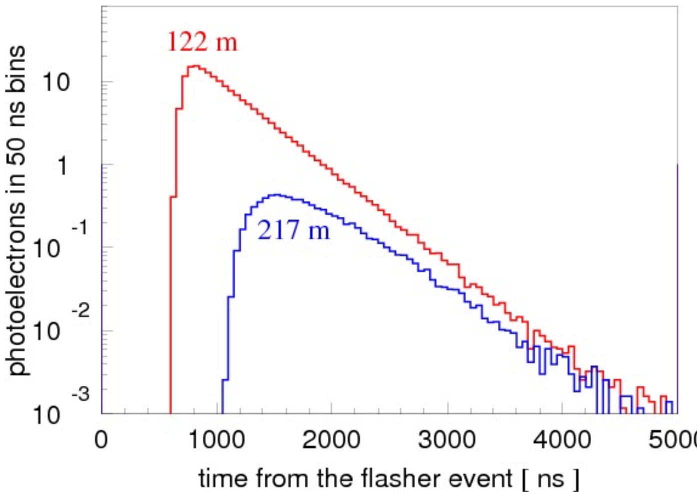
Dima Chirkin, UW-Madison

Fitting ice to in-situ data









Single LED data set, about 60000 configurations, using both horizontal and tilted LEDs

SPICE 3.2 study (2018)

Variations in the fit:

Tilted vs. horizonal LEDs

Nominal vs. fitted RDEs

Angular sensitivity
Flasher/h1-100cm/h2-50cm/h3-50cm

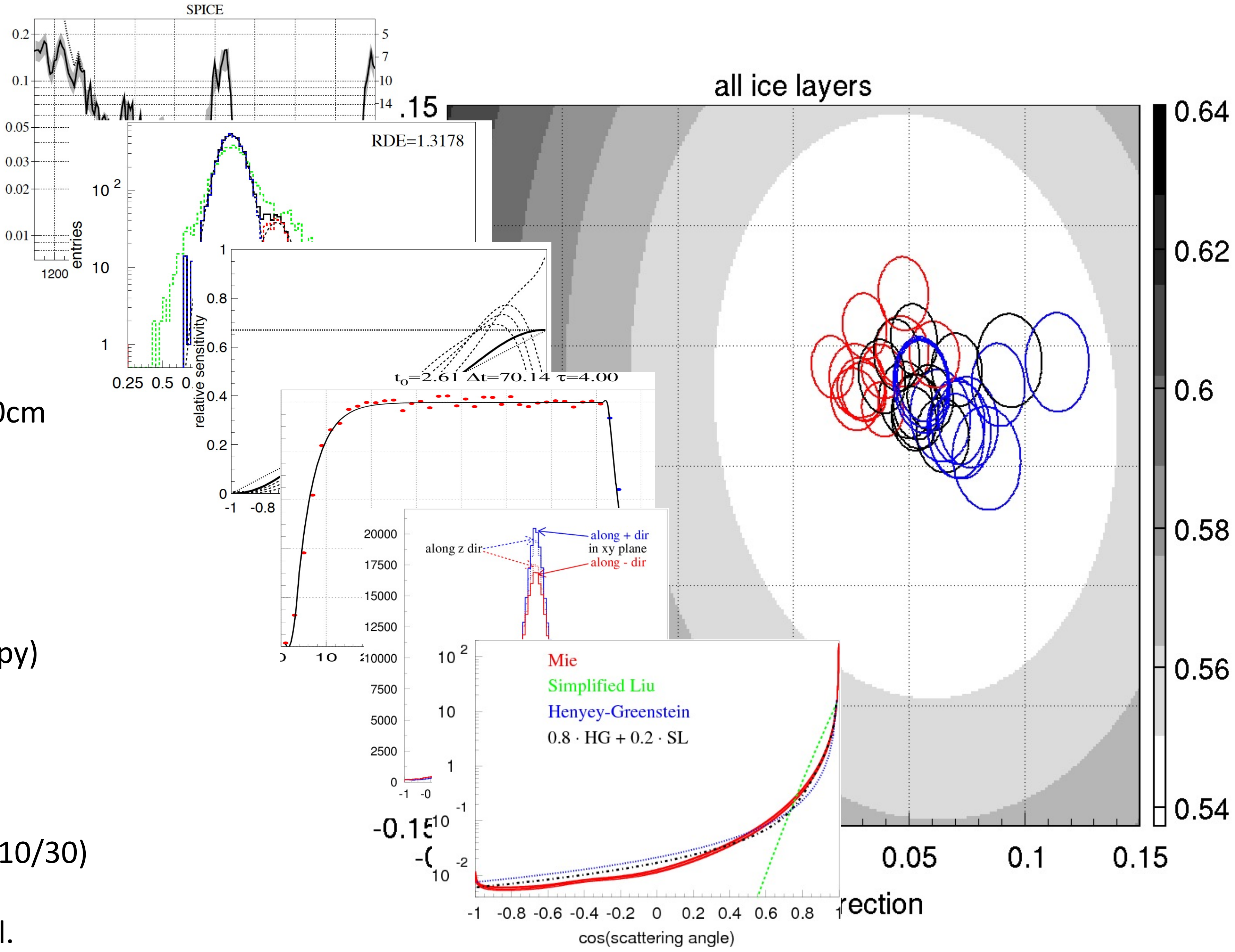
Flasher pulse time profile
50 ns/70 ns with tails vs. square

SPICE 3.2 vs EMRM
(scattering vs. absorption anisotropy)

Scattering function parameter
f_{SL}=0.15 vs. f_{SL}=0.35 vs. f_{SL}=0.55

Number of simulated events (1/3/10/30)

Receivers on same string: incl./excl.



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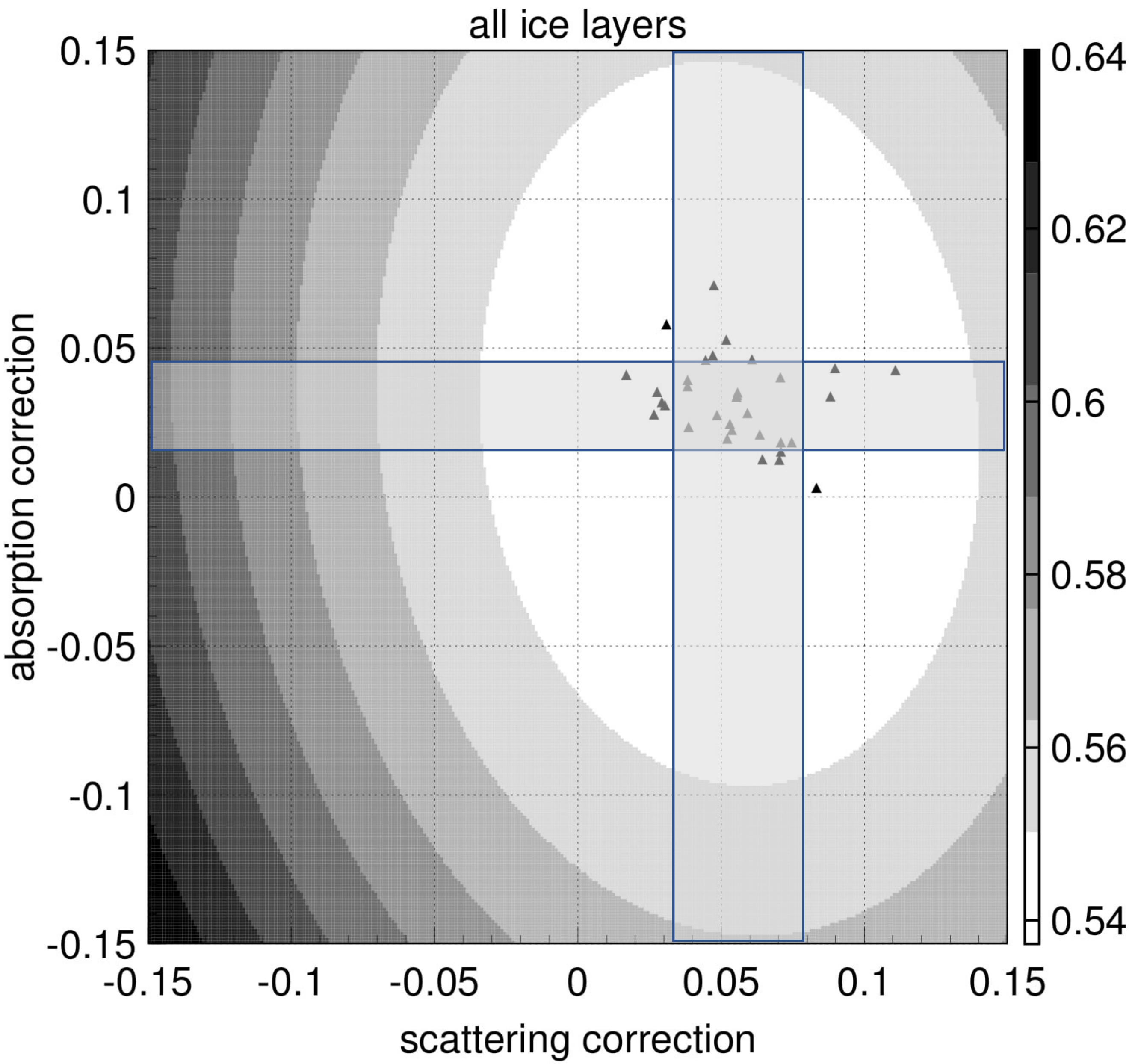


Summary of systematics with SPICE 3.2 (2018)

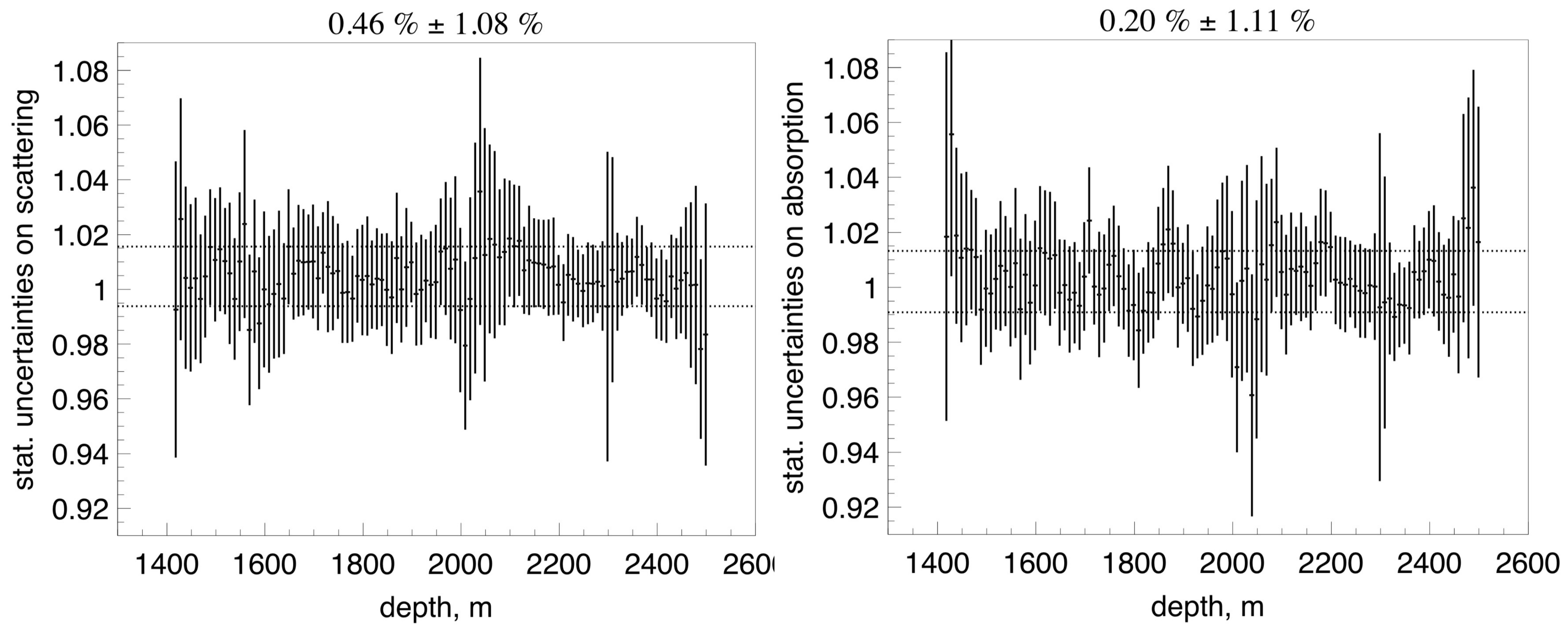
Some difference in fitted ice parameters with single-LED vs. with all-purpose data sets was observed:

- tilted LEDs fit 4-5% more scattering and 0-5% less absorption
  - this difference (not unlike all others) is present at all depths
  - this difference is present in all tested systematic variations
- reduced statistics set fits 2% more scattering and 3% more absorption

Combined range covered by uncertainties:

- +4.3% (scat) +0.7% (abs)
  - changing from all-purpose set to single LED set
  - changing from horizontal-only to fit to all LEDs
- +-2.3% (scat) +-1.5% (abs)
  - covering variations box around the SREP=1 all-LED average
  - (this includes difference between horizonal and tilted LEDs)

Statistical uncertainties (fall 2017)



In SPICE 3.2 the depth-dependent statistical uncertainties average to about 1%. In the interest of being super-conservative we split up the uncertainties and biases and sum them in quadrature. This results in ~3.5%. Individual layers do, however, show an up to 8% statistical uncertainty.

Calibration group recommendations

Ice model	anisotropy	Anisotropy systematics
SPICE 3.2.1	scattering	try depth dependence (ppc)
SPICE BFR v1	**b**ire**fr**ingence	For all: study the effect by splitting data by depth (at 2200 m) and azimuthal direction
SPICE BFR v2	bfr + absorption	

Bulk ice table: uncorrelated 2-D Gaussian prior with 5% standard deviation on absorption and scattering.

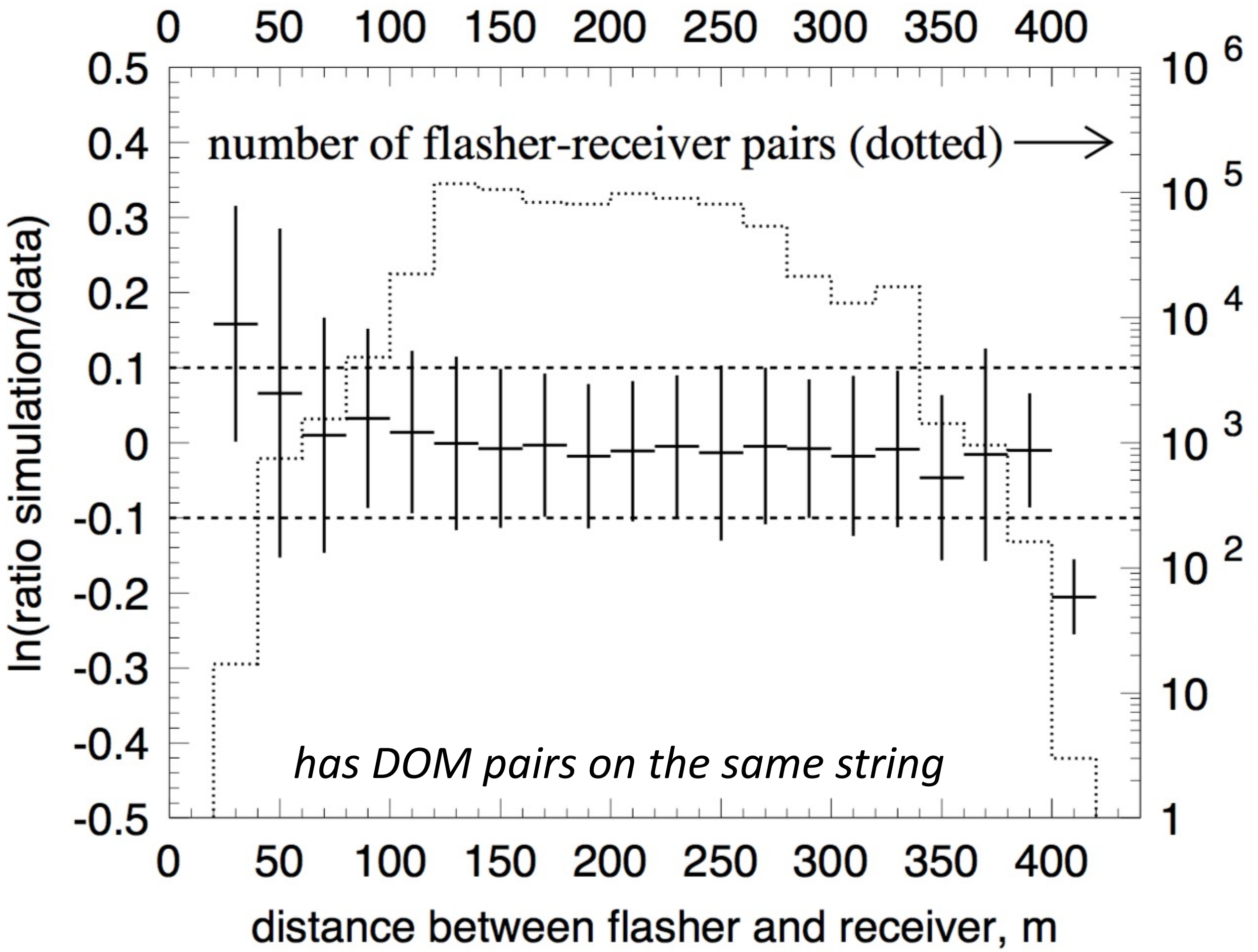
Hole ice: Phillip Eller's Unified Hole Ice Model with hole_ice_p0=[-0.5, 0.3] and hole_ice_p1=[-0.1, 0.05].
try direct hole ice and direct cable shadow simulation (ppc) ← check with oscillation group

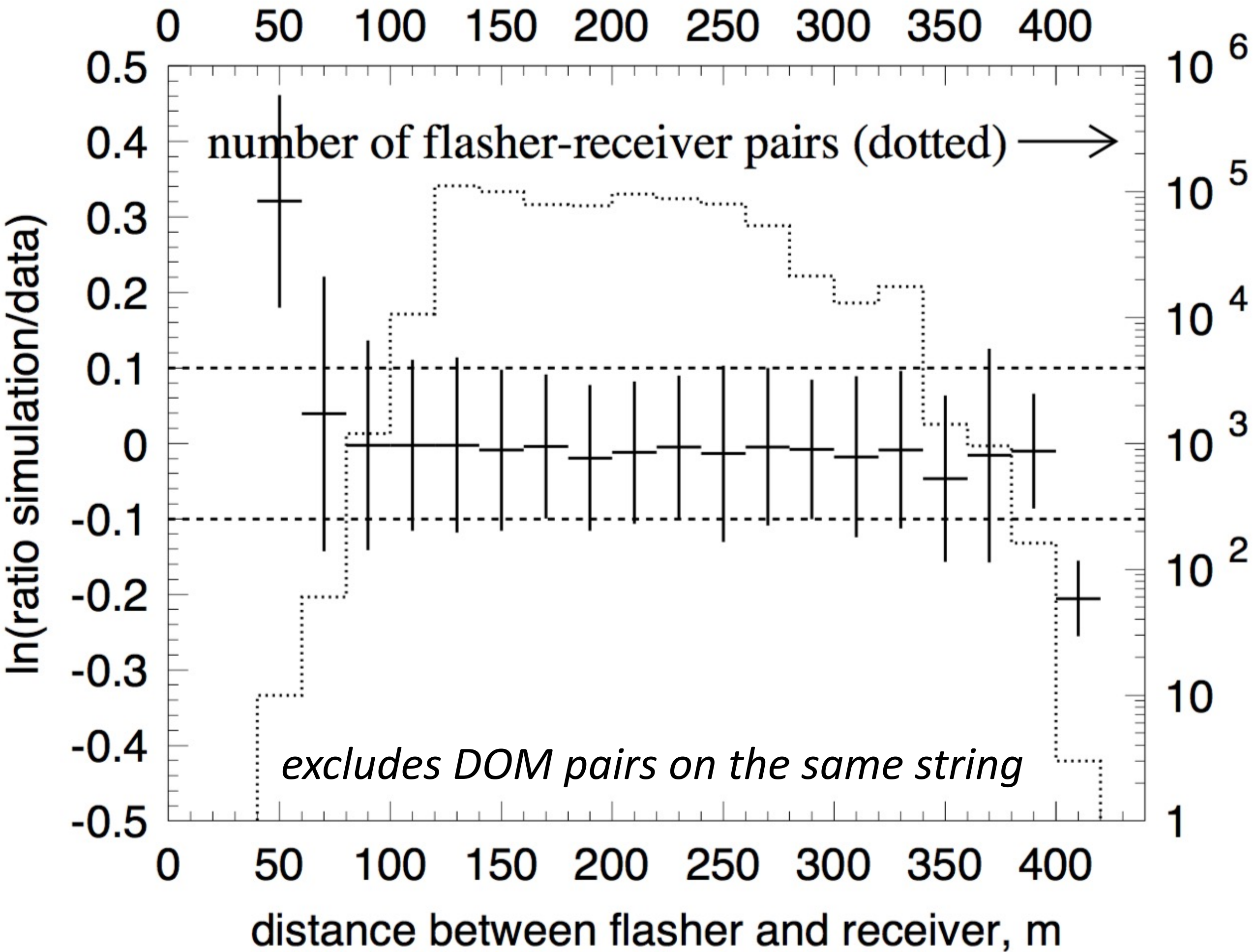
Snowstorm (Ben's presentation)

https://wiki.icecube.wisc.edu/index.php/Ice_models

Ice uncertainty distance dependence

Investigate the model error dependence with distance
by binning the flasher data emitter-receiver pairs into distance bins





Ice uncertainty distance dependence

Investigate the model error dependence with distance
by binning the flasher data emitter-receiver pairs into distance bins

In both cases exclude

the closest pairs (17 m on normal strings or 7 m on DeepCore strings)

and any DOM that receives more than 500 p.e. charge

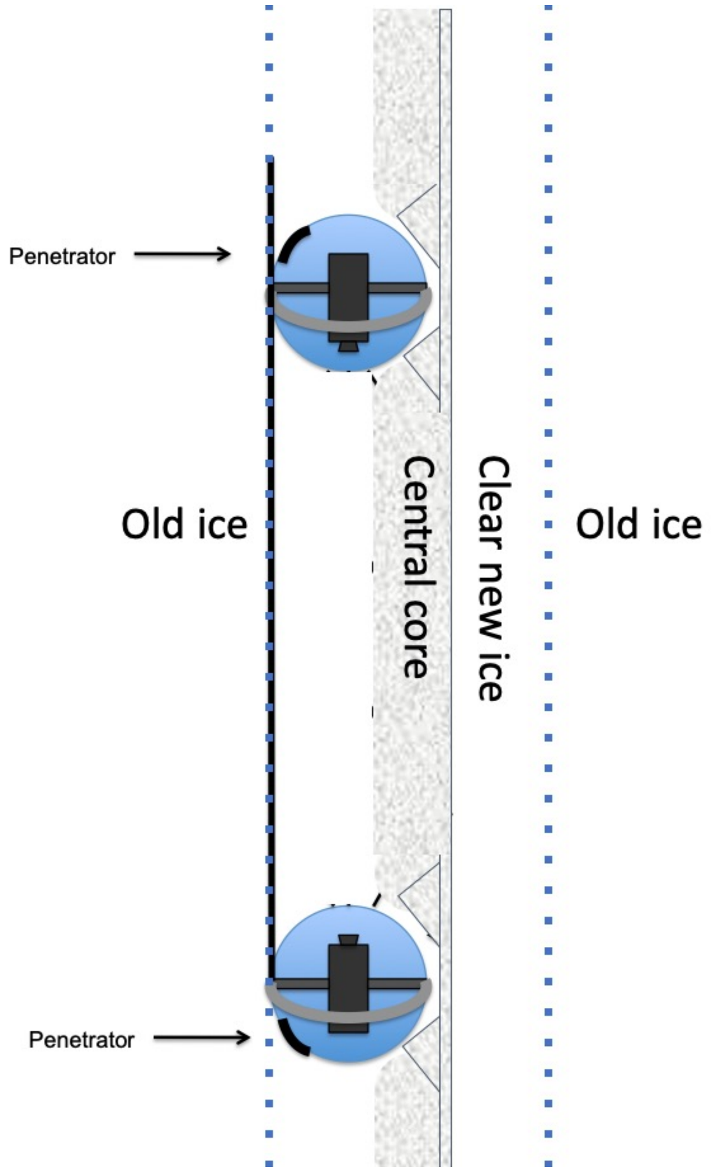
so mainly DOMs up and down the string of the emitting flasher

(but also some on the next string in many cases)

The central points indicate bias, and error extensions indicate the model error (nominally ~10% for the entire set).
The scale to the right of the plot is number of pairs in the corresponding bin, and shown in dotted histogram.

The average total for this set (summed over all distances) is -0.7% bias, 10.3% rms (i.e. model error). There appears to be some widening and increasing bias in the low 3 bins, i.e. distances below 80 m.

hole ice model from Swedish Camera pictures



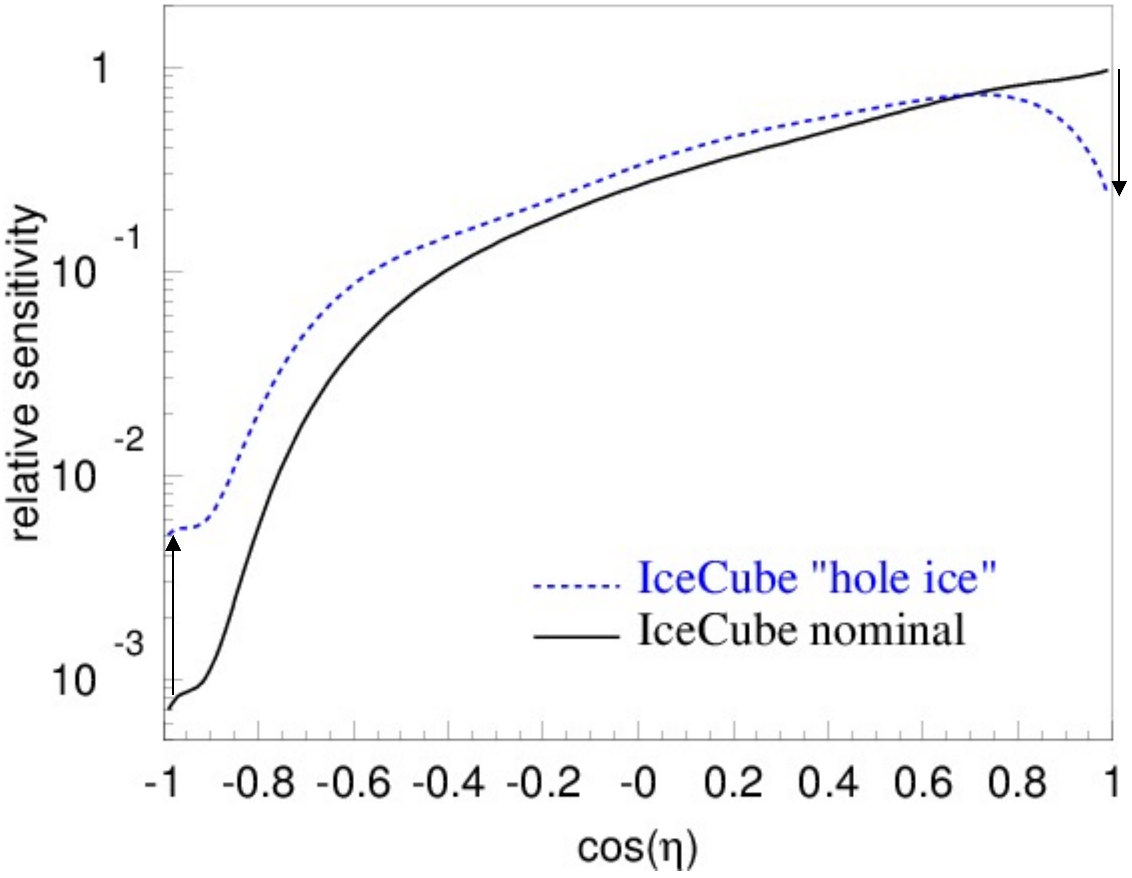
We find:

DOM touches the hole wall, is 2/3 of the hole diameter

Most of the HI is transparent, except for the milky central column centered in the hole and 1/3 of hole diameter (referred to as HI in the following, starting with the next line)

HI diameter is ½ of DOM diameter

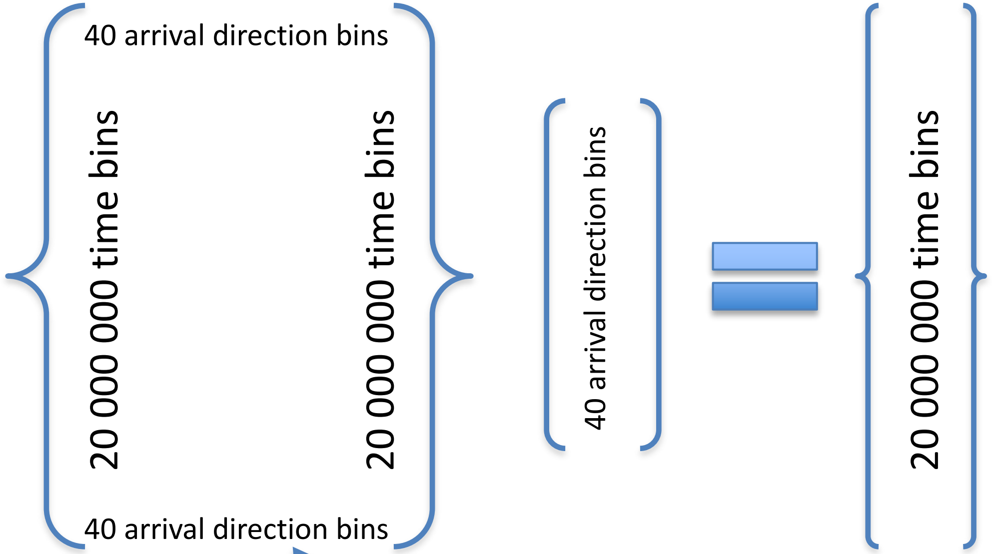
Traditional “hole ice” angular sensitivity

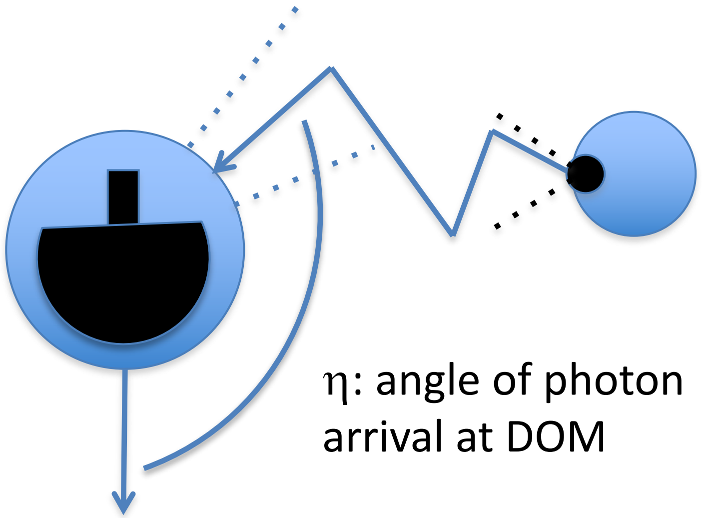


Unfolding the angular sensitivity to flasher data

Same likelihood construction as in SPICE^3 fit to flasher data

<u>Nuisance parameters:</u>
5046 receiver DOM efficiencies
(72+2)*4746 flasher parameters



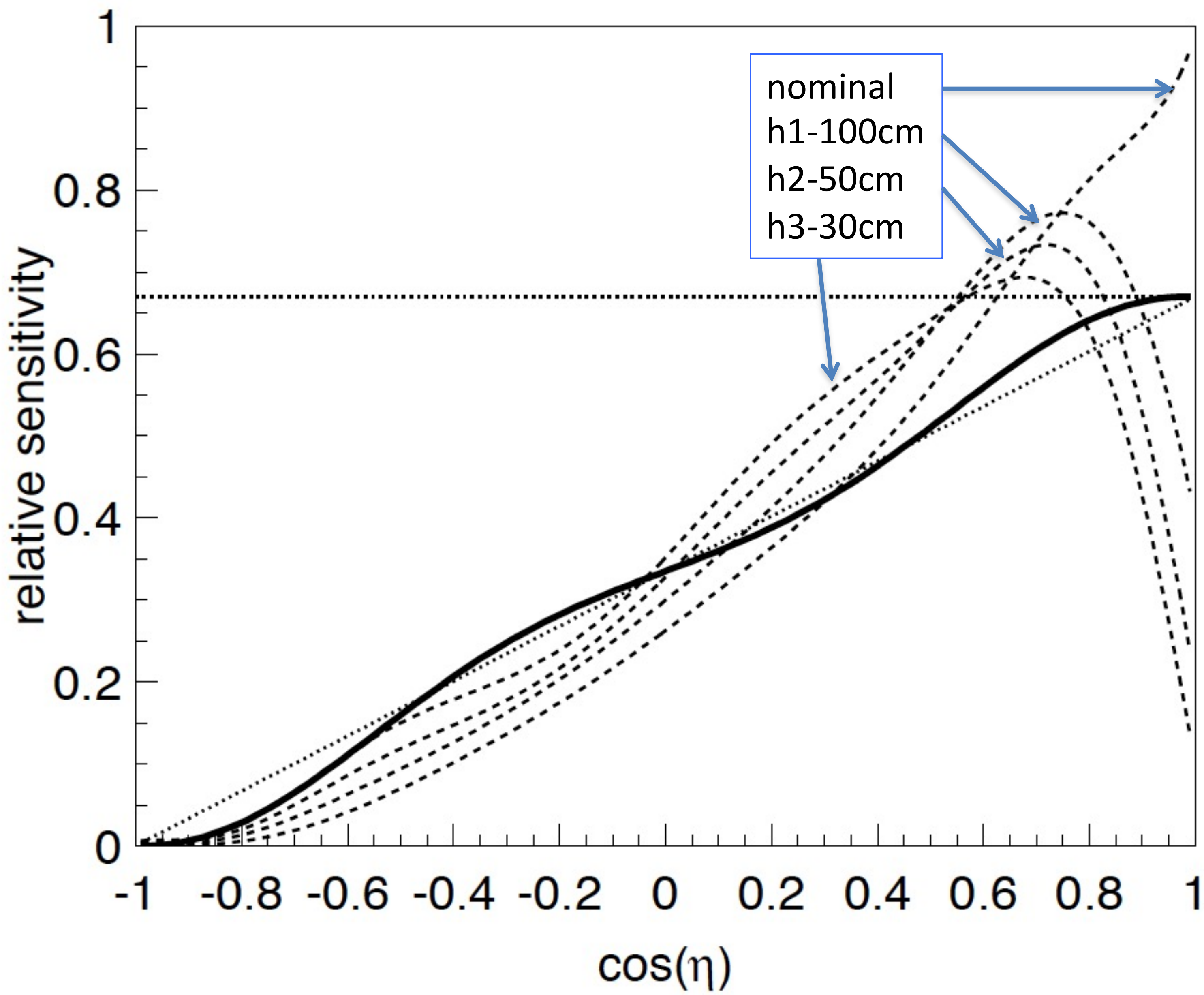


<u>Unfolding matrix (from simulation):</u>

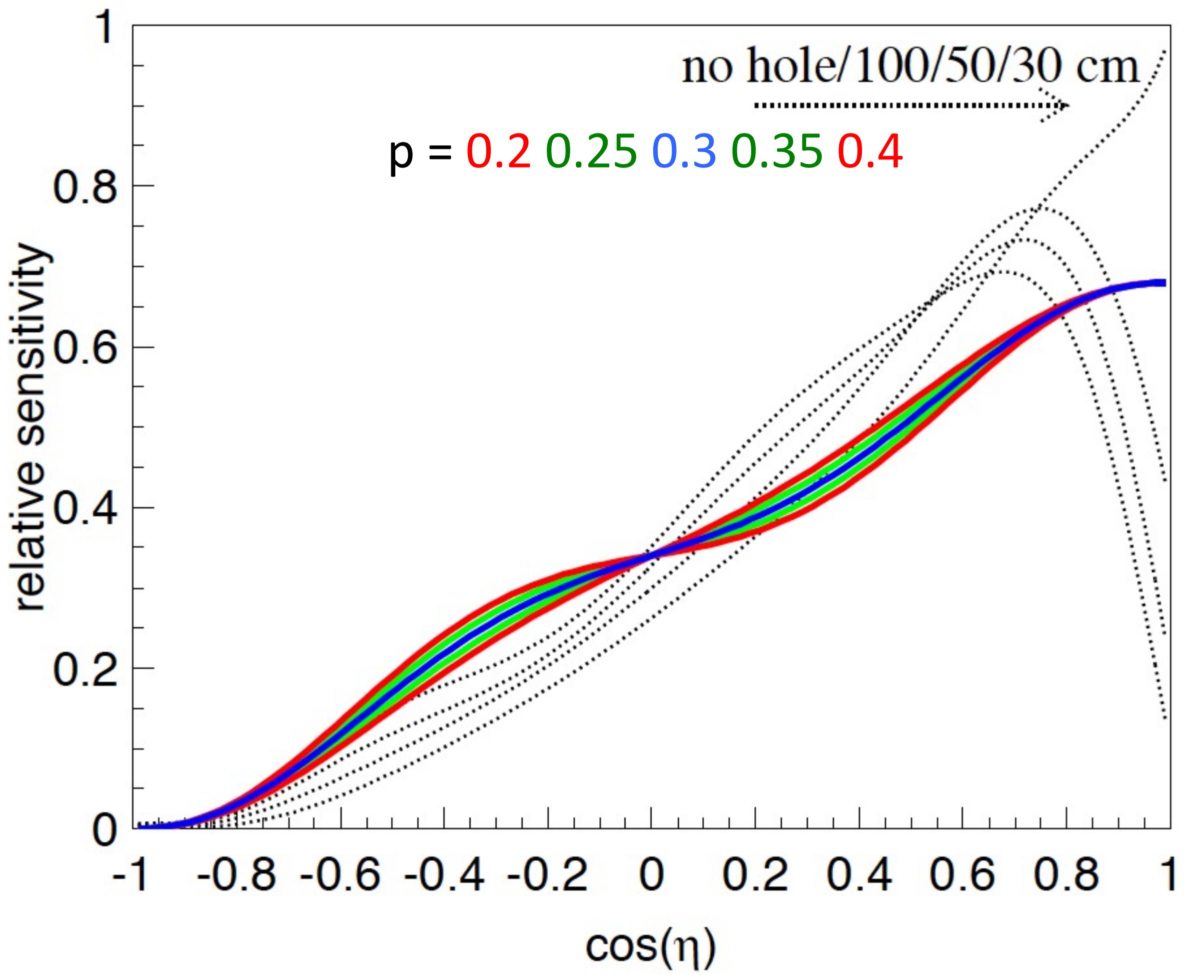
40 cos(η) unfolding bins

20 000 000 charge values of emitter-receiver time bin pairs (4746 flashers)

Best fit to all-string flasher set

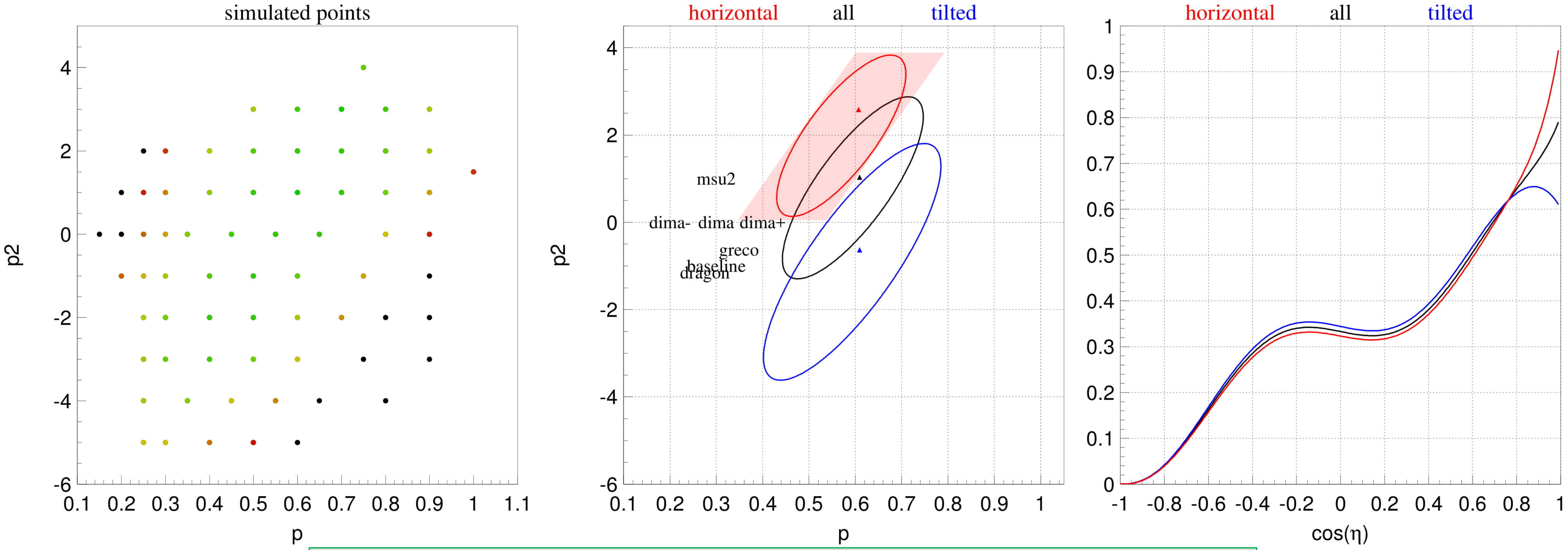


Fitted shape parameter: p=0.3+-0.1



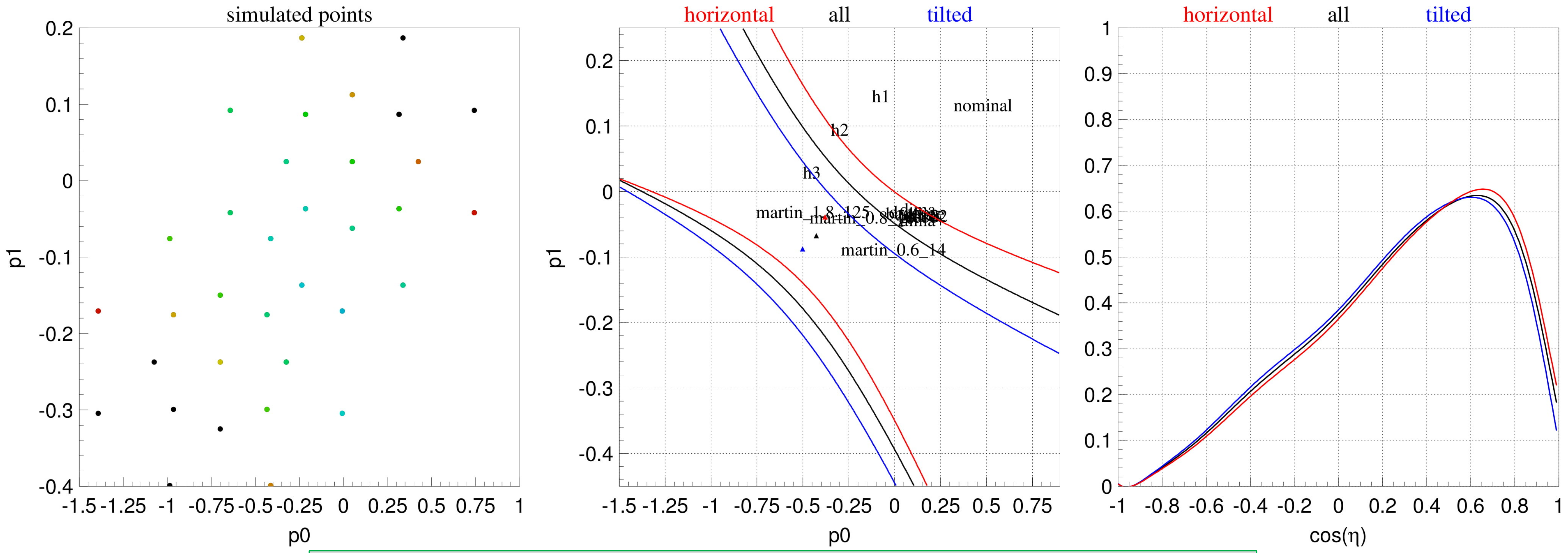
An unfolded solution as fitted to the all-purpose flasher data

p/p2 MSU parametrization



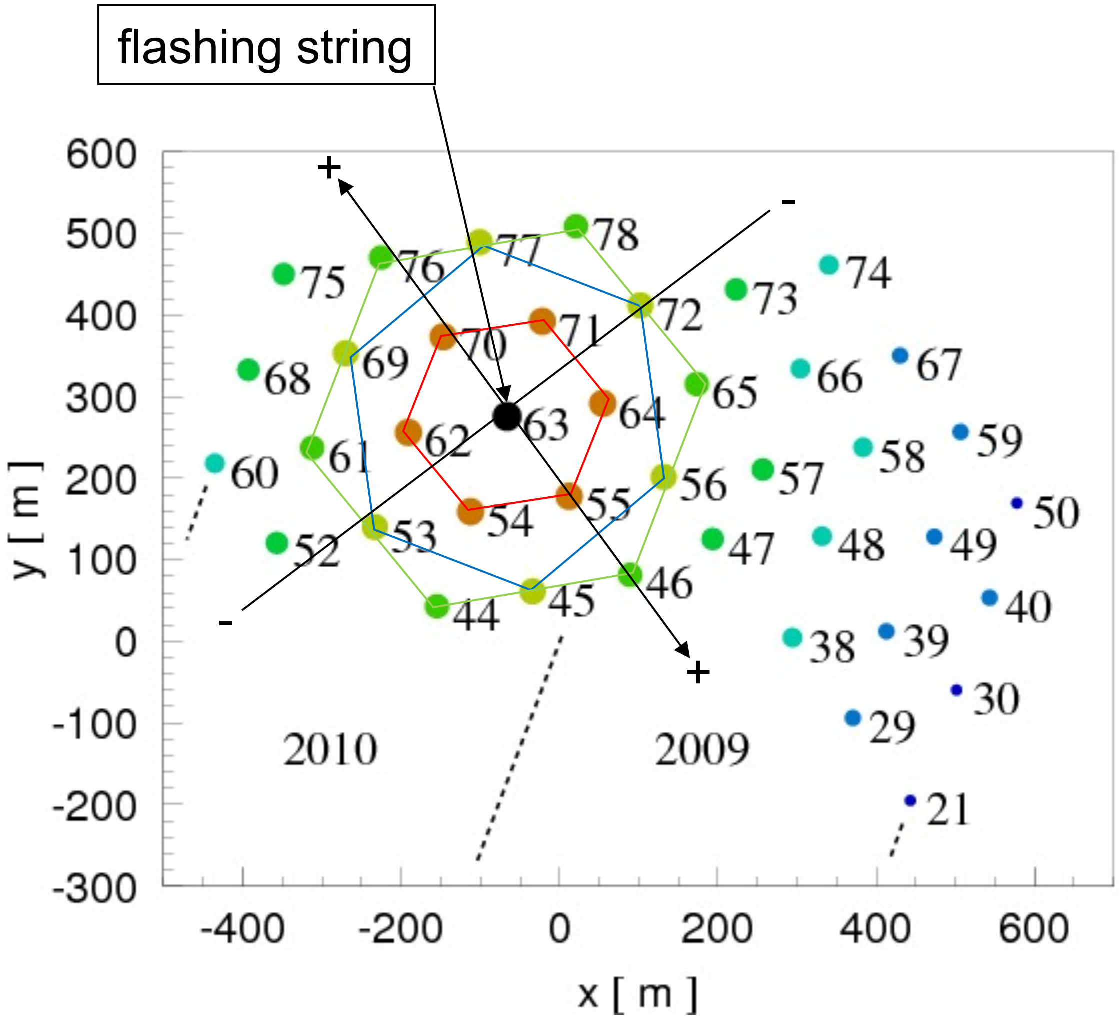
LEDs	LLH	p	p2
All	0.540102	0.609257	1.03204
Tilted	0.579212	0.608929	-0.629148
Horizontal	0.500006	0.606597	2.58268

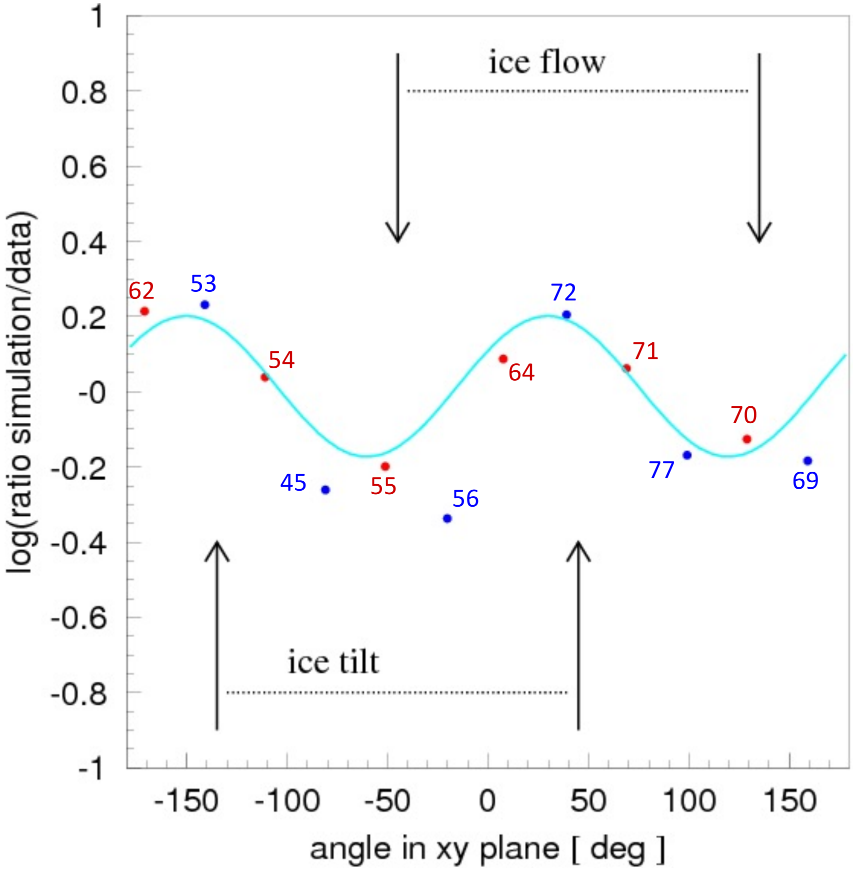
Philipp parametrization 2 (with Martin), settling for a more reasonable description



LEDs	LLH	p0	p1
All	0.544099	-0.427318	-0.0675806
Tilted	0.582394	-0.501349	-0.0876635
Horizontal	0.505175	-0.378935	-0.0385643

Ice anisotropy (ICRC 2013)

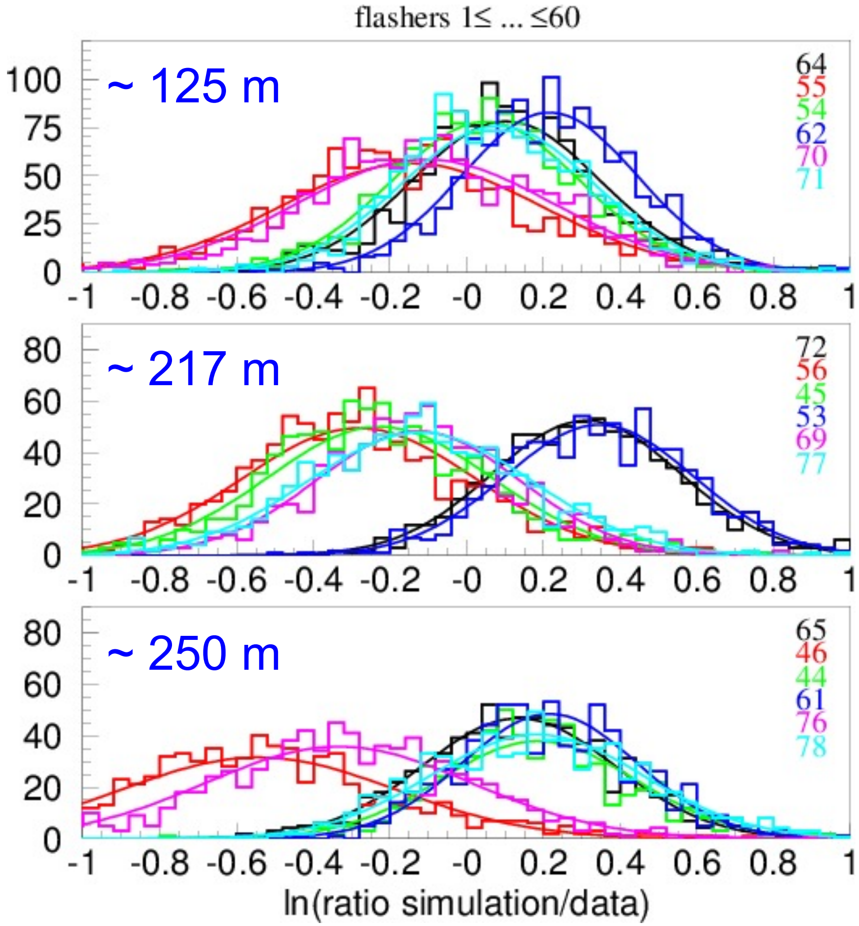


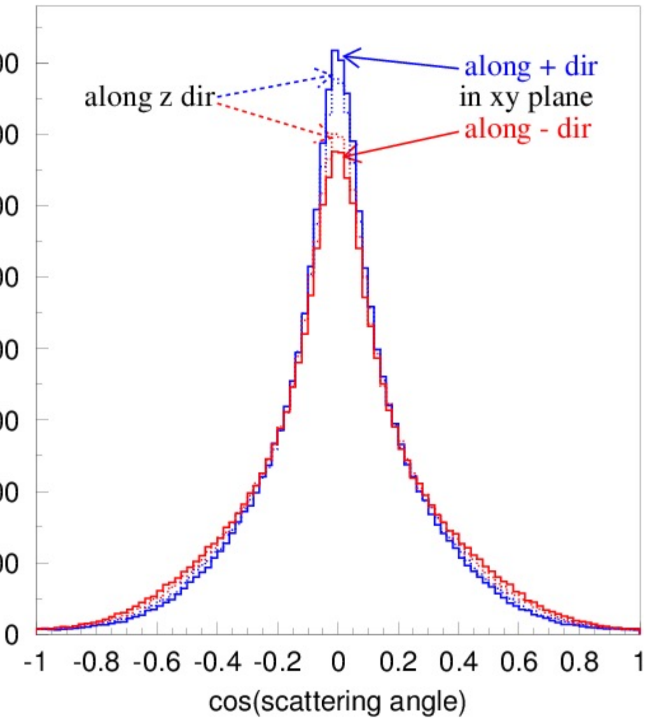


10-20% per 100 m azimuth modulation in charge observed!

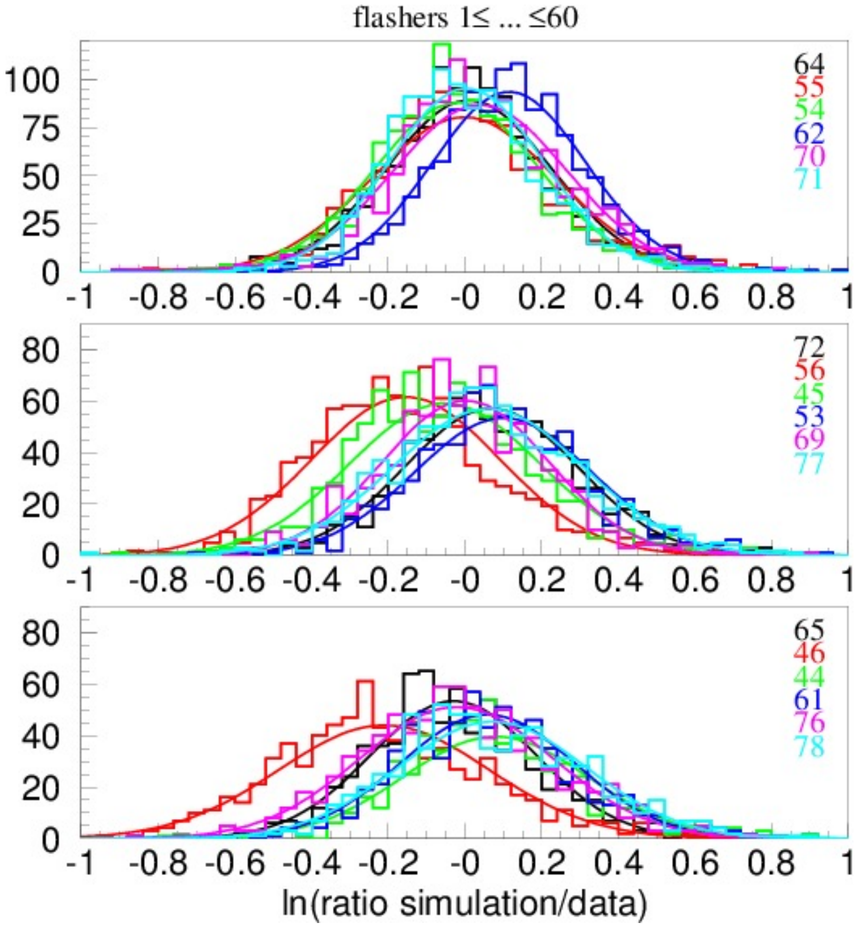
Charge variation vs. distance

SPICE Mie [SPICE Paper]





SPICE Lea



Scattering function:

$$f(\vec{n_i} \cdot \vec{n_o}) \rightarrow f(\vec{k_i} \cdot \vec{k_o}), \quad \vec{k}_{i,o} = \frac{A\vec{n}_{i,o}}{|A\vec{n}_{i,o}|}$$

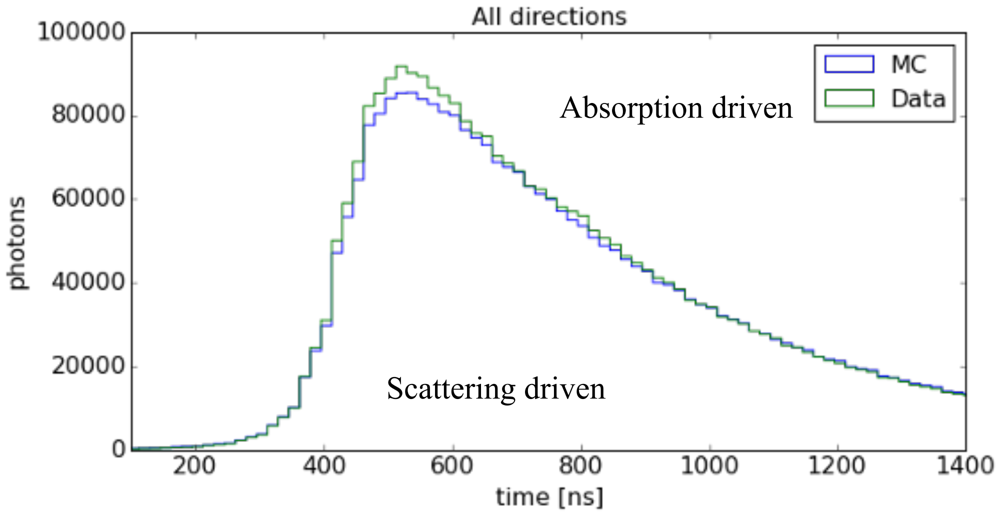
Models of optical ice anisotropy in IceCube

1. Scattering (mainly): direction dependent scattering function (ICRC 2013)
2. Absorption (mainly): direction dependent absorption (studied in 2018)

Introduced depth-dependence (2017)

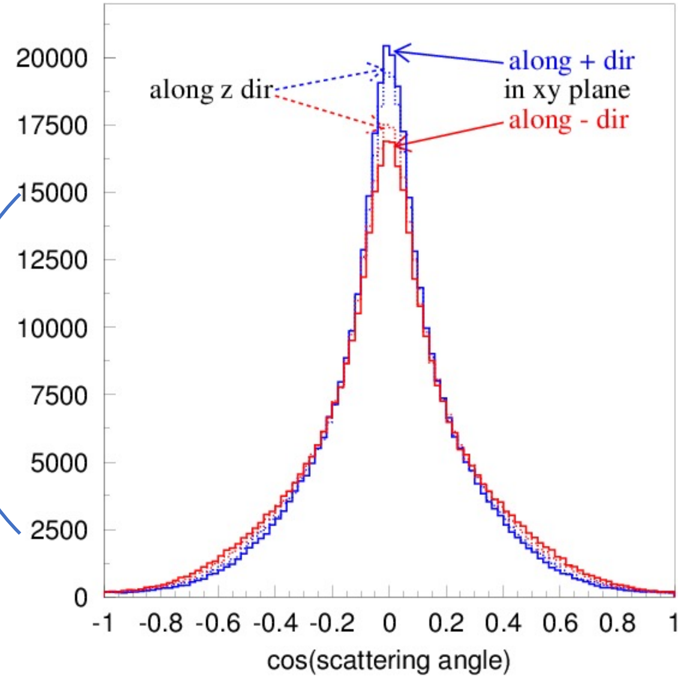
Discrepancies between data and simulation remain

Cannot simultaneously fit total charge and arrival time distribution to statistical precision



scattering-based

SPICE Lea, 3.2.x

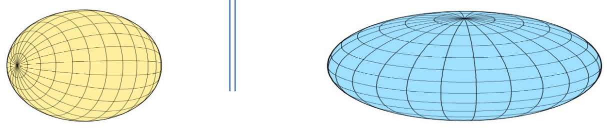


absorption-based

SPICE EMRM

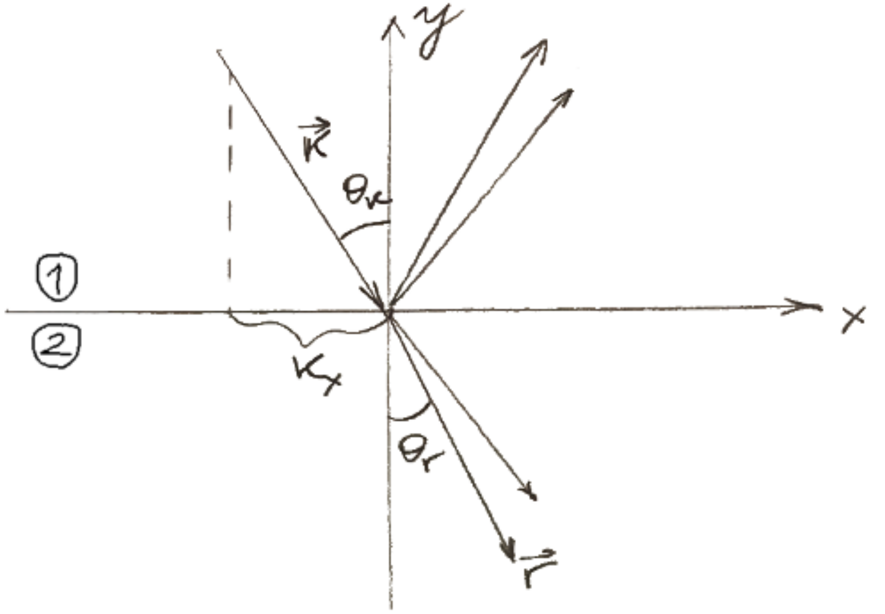
prolate

oblate



Birefringence

- Ice is a birefringent material with n_e-n_o=0.0015. This tiny difference builds to a macroscopic effect due to 1000s of ice crystal boundaries crossed per meter of traveled distance
- At each grain boundary every ray is split into two reflected and two refracted rays, one ordinary and one extraordinary ray each
- Wave vector component parallel to surface is conserved, norm is proportional to the refractive index
- Poynting vectors are derived from wave vectors and boundary conditions
- Outgoing ray is randomly sampled from Poynting vectors according to Poynting theorem (Poynting vector component through the plane is conserved)



$$\begin{aligned} \hat{n}\cdot \boldsymbol{D}_2 &= \hat{n}\cdot \boldsymbol{D}_1 \\ \hat{n}\cdot \boldsymbol{B}_2 &= \hat{n}\cdot \boldsymbol{B}_1 \\ \hat{n}\times \boldsymbol{E}_2 &= \hat{n}\times \boldsymbol{E}_1 \\ \hat{n}\times \boldsymbol{H}_2 &= \hat{n}\times \boldsymbol{H}_1. \end{aligned}$$

Hence we can make the following observations:

1. Normal components of $\boldsymbol{D}$ and $\boldsymbol{B}$ are continuous across a dielectric interface
2. Tangential components of $\boldsymbol{E}$, $\boldsymbol{H}$ are continuous across a dielectric surface

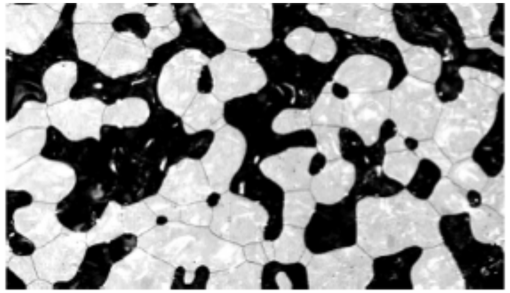
Scattering patterns in birefringent ice

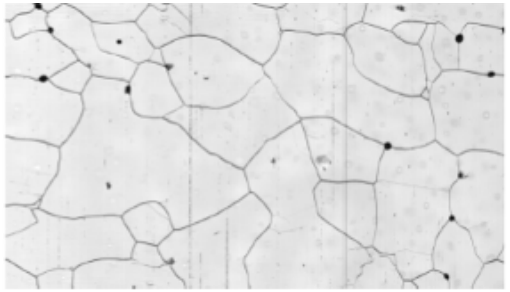
Running MC simulation with realistic crystal size, elongation, and orientation distributions (correlated to flow direction):

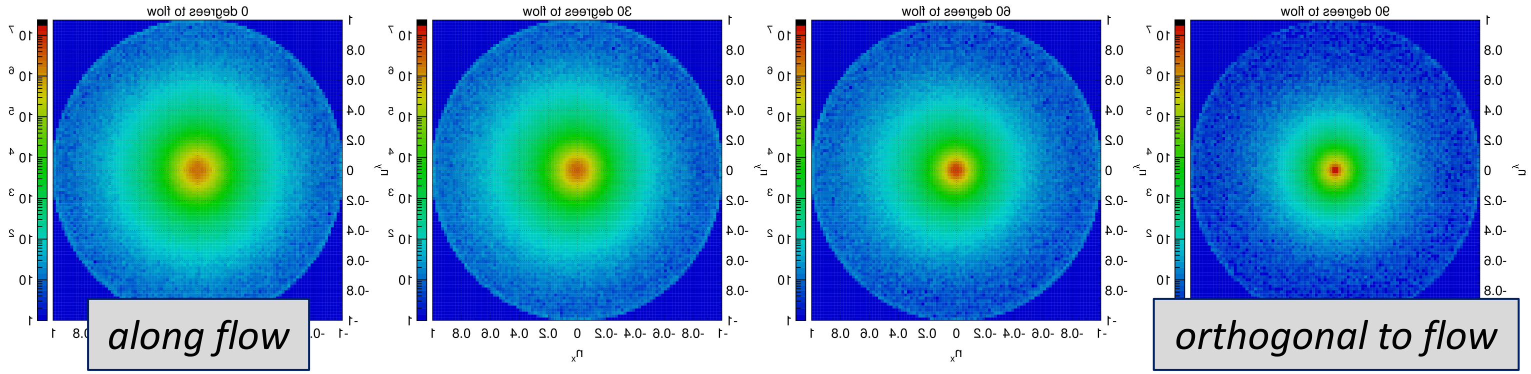
Diffusion is largest on flow axis and smallest orthogonal to it

Photons on average get deflected towards the flow axis

→ photons effectively fly a curve towards the flow axis



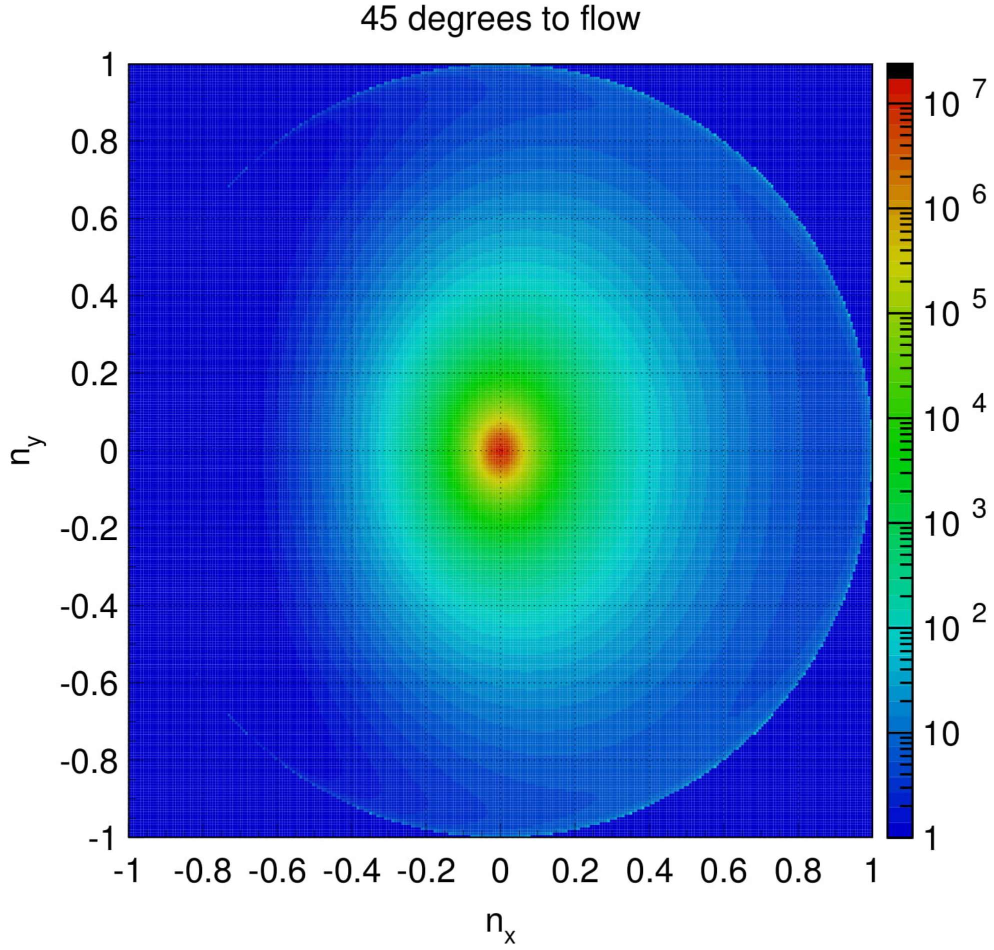




along flow

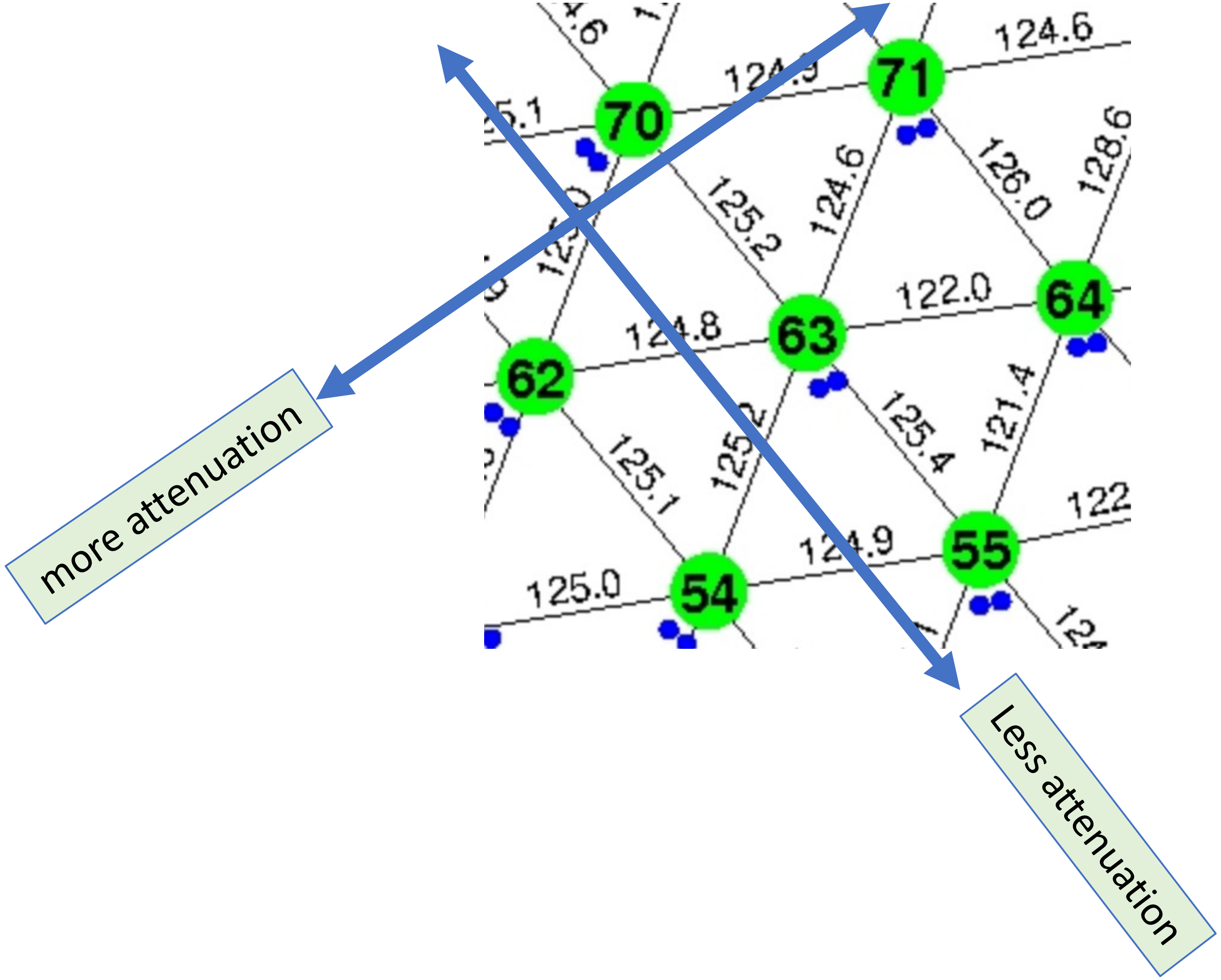
orthogonal to flow

after ~ 1 m of propagation:



towards flow

Our best tool to gauge the quality of our description of anisotropy



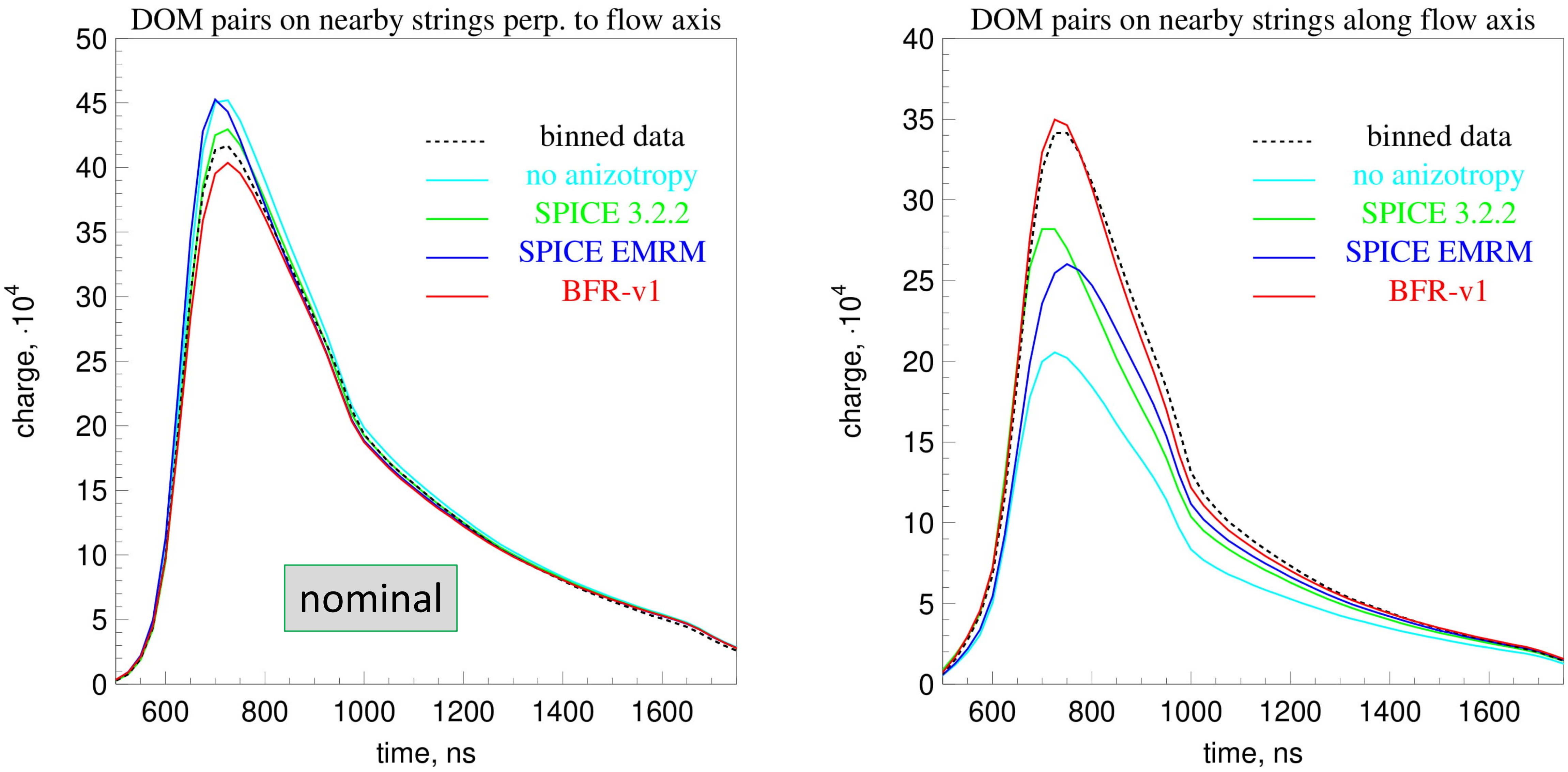
Next slide shows average waveform for nearby emitter-receiver DOM pairs aligned with the two directions (along and perpendicular to ice flow).

This might be the best tool to rank ice models on how well they describe the anisotropy

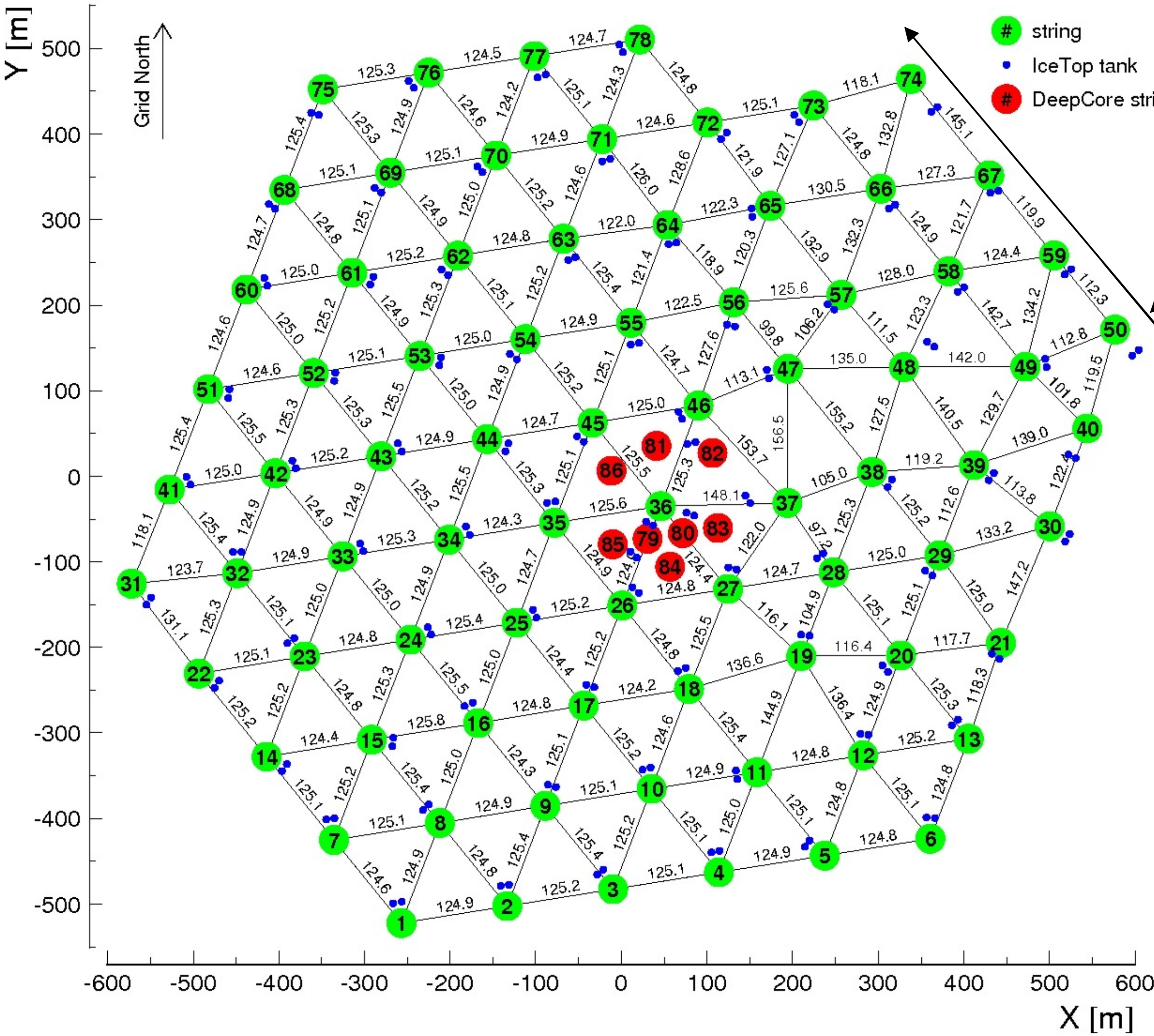
Here used string pairs one ~125 m spacing away (excludes DeepCore and far distances)

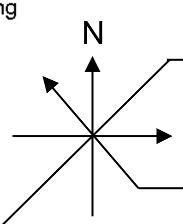
134 string pairs along flow
272 string pairs perpendicular to flow

Using DOM pairs at the same position (depth)


DOM pairs on nearby strings perp. to flow axis
charge, ·10^4
time, ns
binned data
no anizotropy
SPICE 3.2.2
SPICE EMRM
BFR-v1
nominal
DOM pairs on nearby strings along flow axis
charge, ·10^4
time, ns
binned data
no anizotropy
SPICE 3.2.2
SPICE EMRM
BFR-v1

Glacial ice flow, ice layer tilt at the South Pole

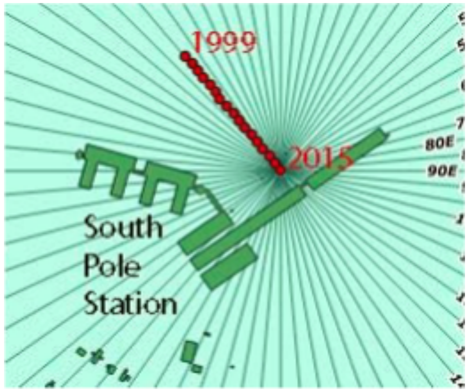


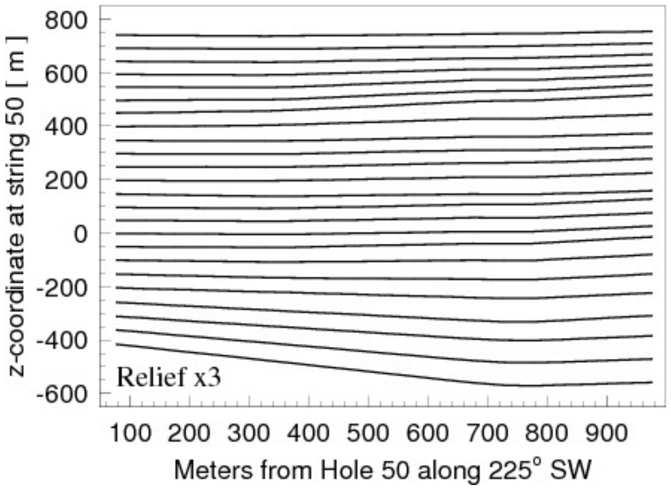


Ice Layer tilt direction
225° SW

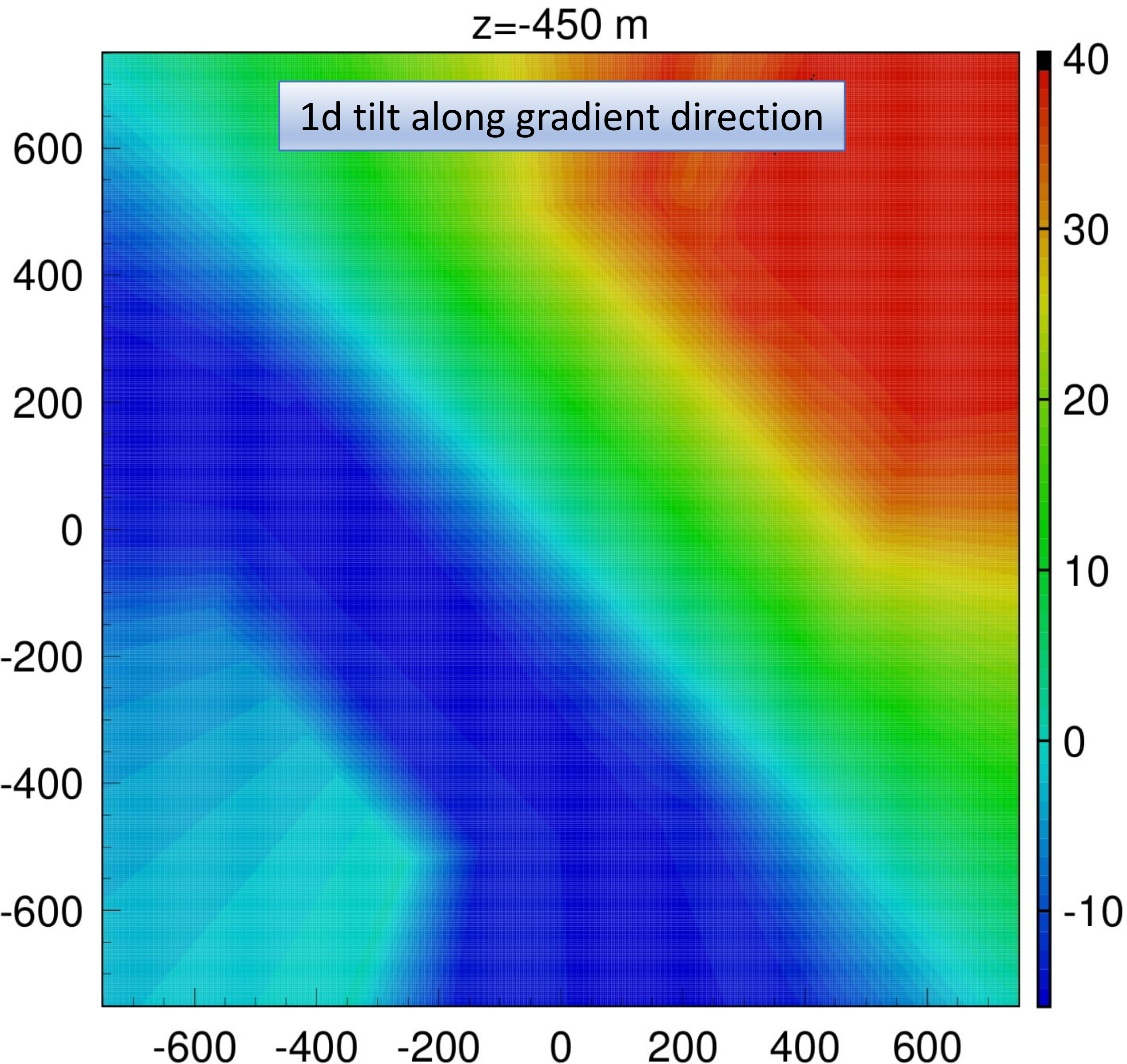
Ice flow direction
41° NW

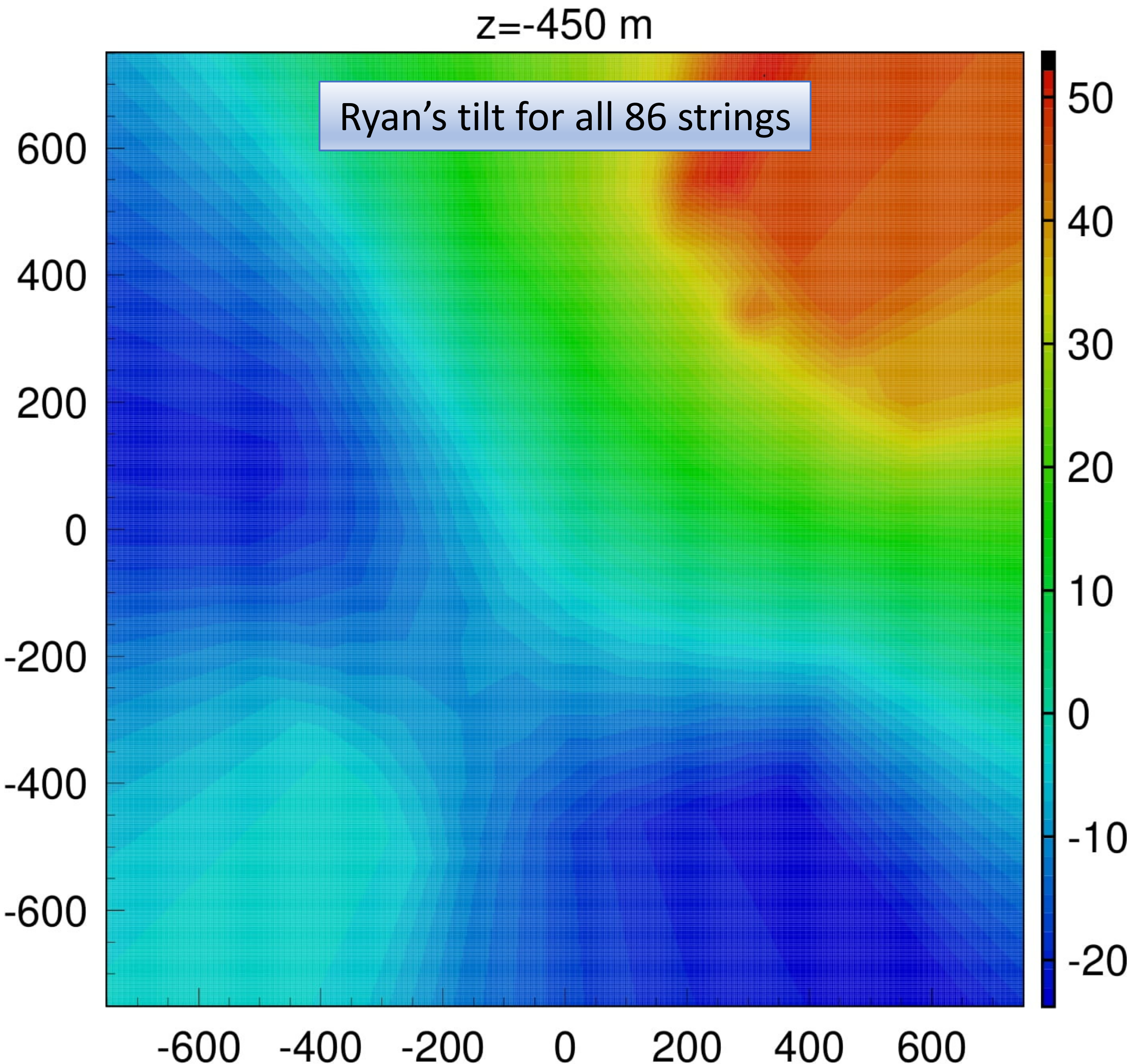
Less attenuation
41° NW



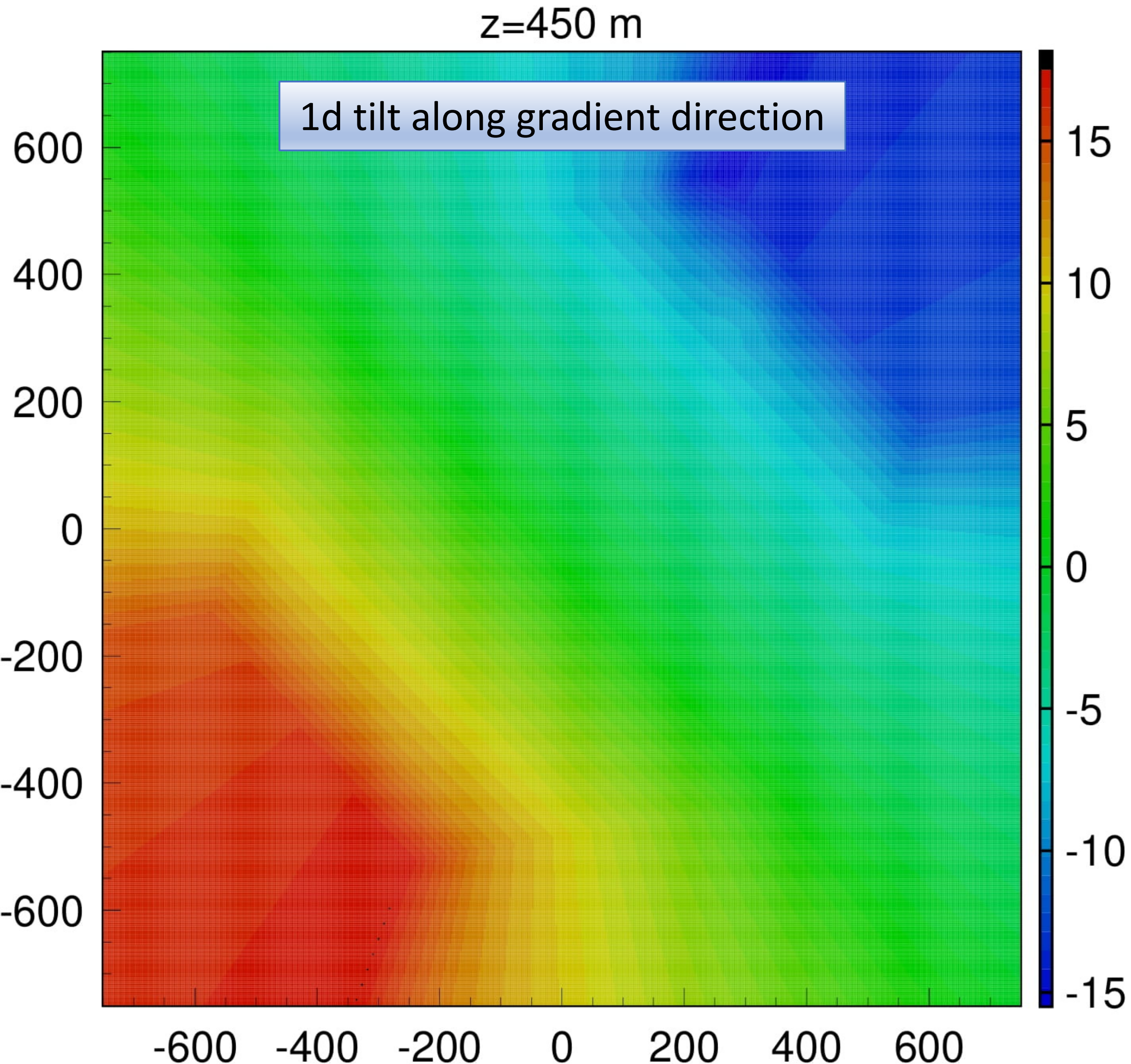


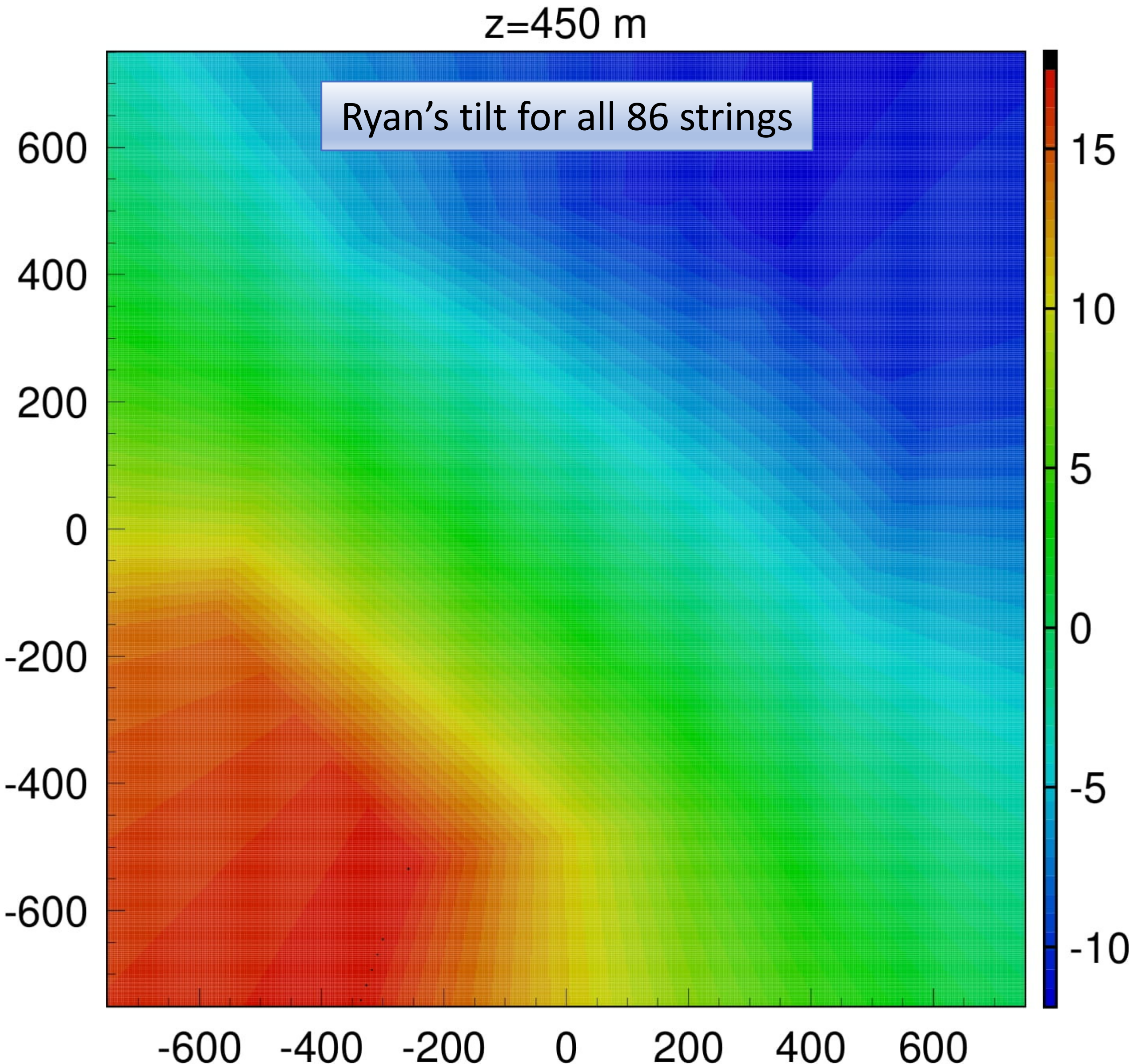
Parameterized tilt maps



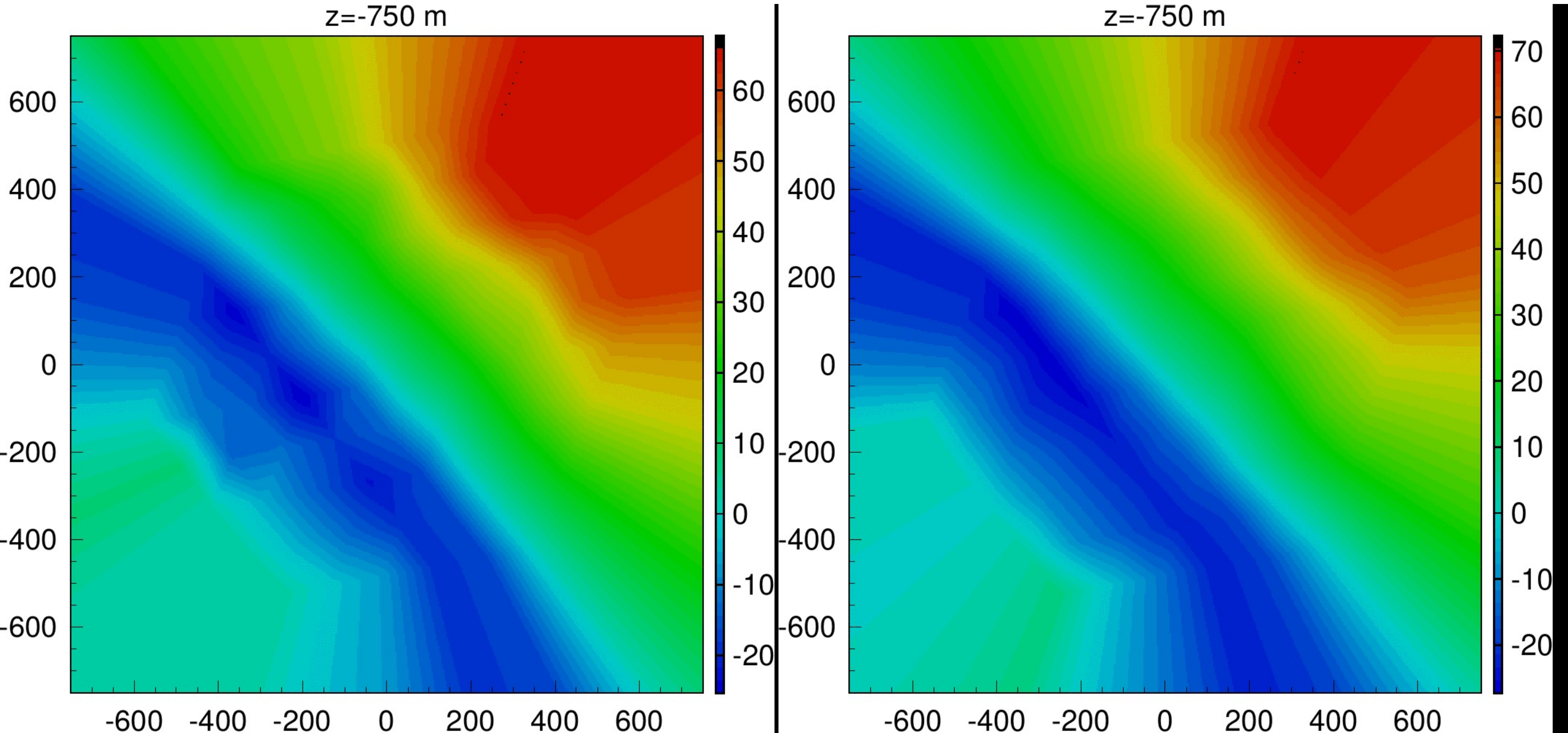


Parameterized tilt maps

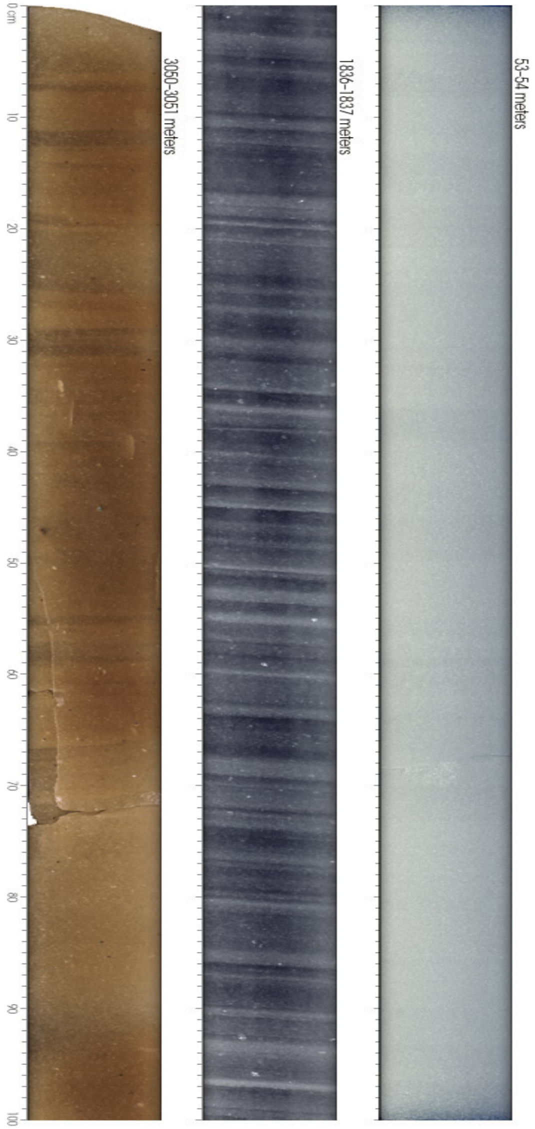




Fit to flasher data



Timeline



Ice models	Year	Description	model error
AMANDA ice models:			
bulk, f125, mam, mamint, stdkurt, sudkurt, kgm, …			
millennium (published 2006) → AHA (2007)			55%
IceCube ice models:			
WHAM	(2011)		42%
SPICE 1	(2009)		29%
SPICE 2, 2+, 2x, 2y	(2010)	added ice layer tilt	
SPICE Mie	(2011)	fit to scattering function	29%
SPICE Lea	(2012)	fit to scattering anisotropy	20%
SPICE (Munich)	(2013)	7-string, LED unfolding	17%
$SPICE^3$ (CUBE)	(2014)	llh fixes, DOM sensitivity fits	11%
SPICE 3.0	(2015)	improved RDE, ang. sens. fits	10%
SPICE 3.1, 3.2	(2016)	85-string, correlated model fit	<10%
SPICE HD, 3.2.2	(2017)	direct HI and DOM sens., cable, DOM tilt	
SPICE EMRM	(2018)	absorption-based anisotropy	*single*
SPICE BFR	(2020)	birefringence-based anisotropy	*LEDs*
SPICE BFRv2	(2021)	bfr+abs+sca anisotropy, 2d tilt	

Model error (precision in charge prediction): <10%
Extrapolation uncertainty: 13% (sca) / 15% (abs)
Linearity: < 2% in range 0.1 … 500 p.e.