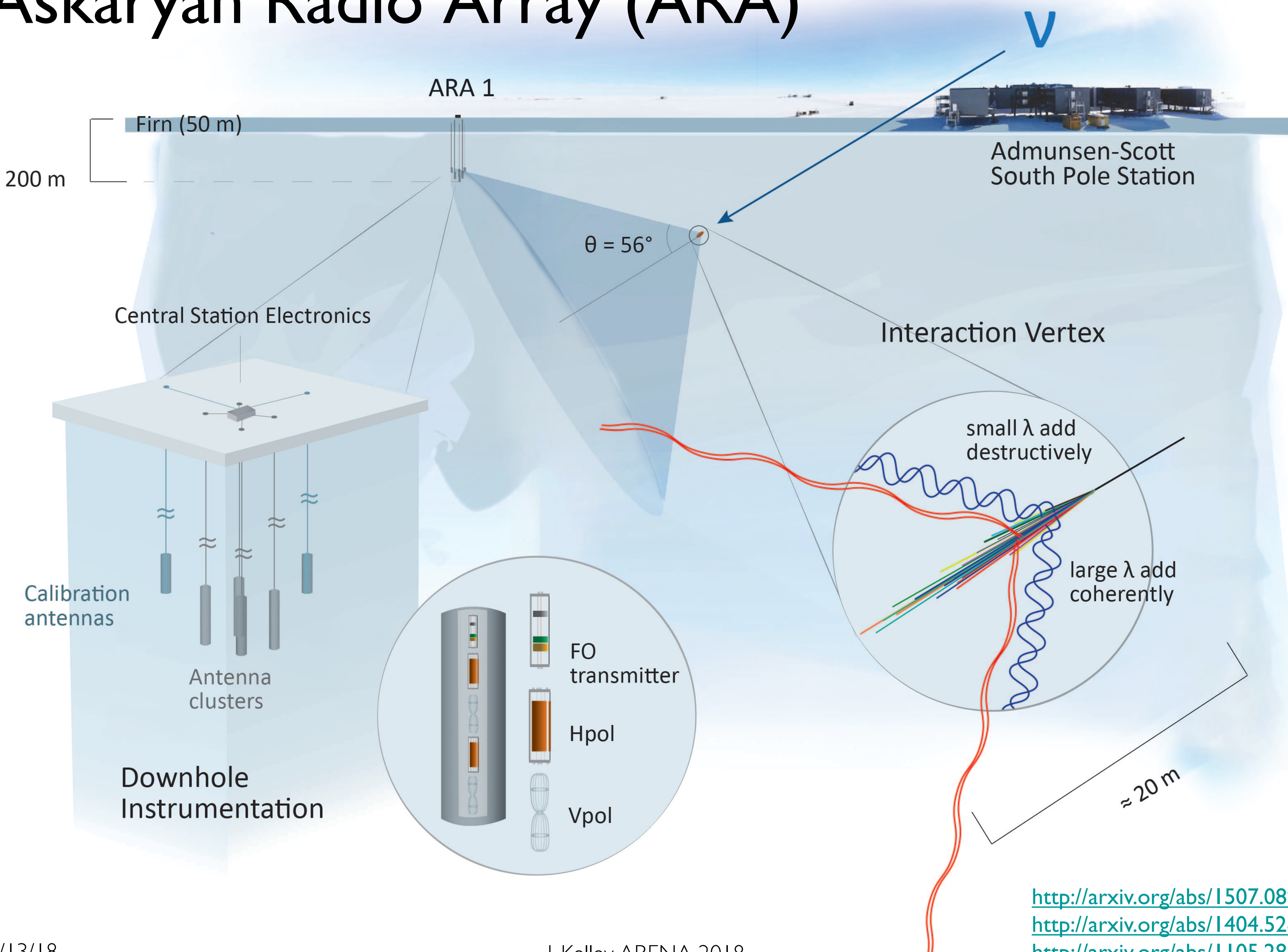
Neutrino Vertex Reconstruction in South Pole Ice

John Kelley for the ARA Collaboration

ARENA 2018

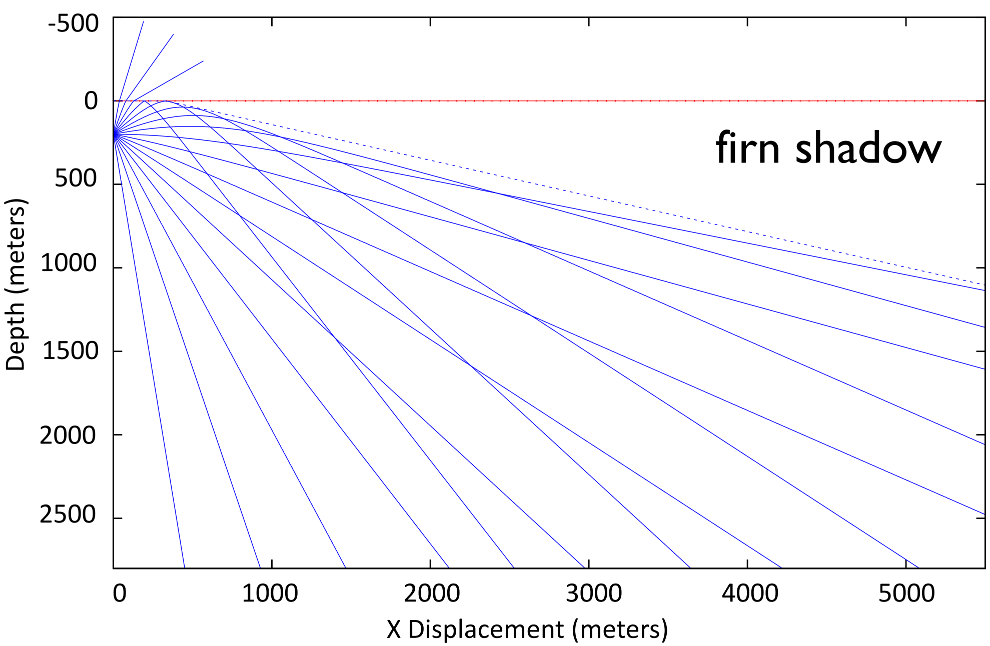
Catania, Sicily

Askaryan Radio Array (ARA)



http://arxiv.org/abs/1507.08991
http://arxiv.org/abs/1404.5285
http://arxiv.org/abs/1105.2854

Optics in South Pole Ice



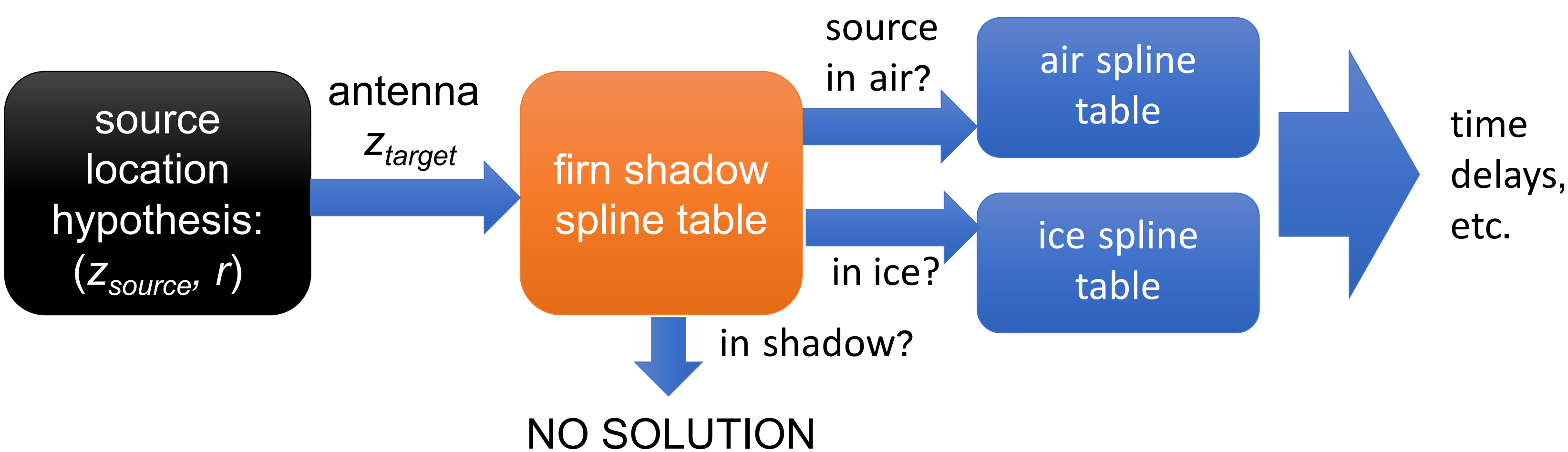
$$n(z) = n_{\text{deep}} + (n_{\text{surface}} - n_{\text{deep}})\, e^{Cz} \text{ for } z < 0.$$

$$n_{\text{deep}} = 1.78,\; n_{\text{surface}} = 1.35,\; C = 0.0132 \text{ m}^{-1}$$

- Index of refraction a function of depth (firn layer)
  - radio waves bend away from surface
- Multiple paths possible
  - direct and reflected signals
  - horizontal / surface propagation not considered in this model
- Neutrino vertex reconstruction needs accurate time delays from raytracing results
  - first step for neutrino energy, direction reconstruction

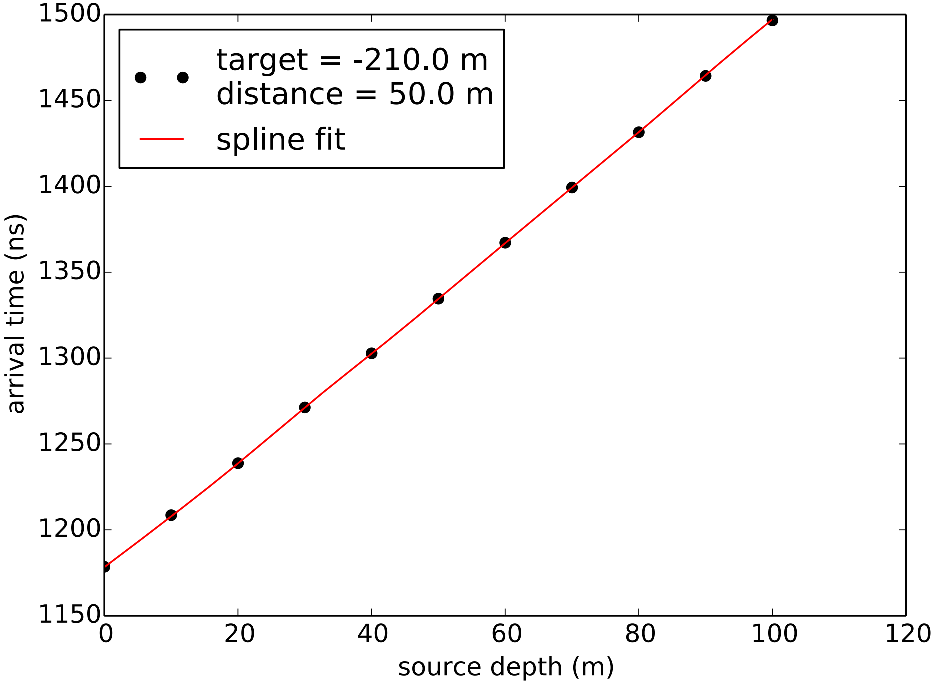
Spline-Fitted Raytrace Tables

- Smoothly interpolate many-dimensional tables with B-splines
- Technical challenges
  - discontinuities due to firn shadow, air/ice boundary cause ringing
  - reflected solutions in addition to direct ray
  - solution: cylindrical coordinates + multi-step table lookup

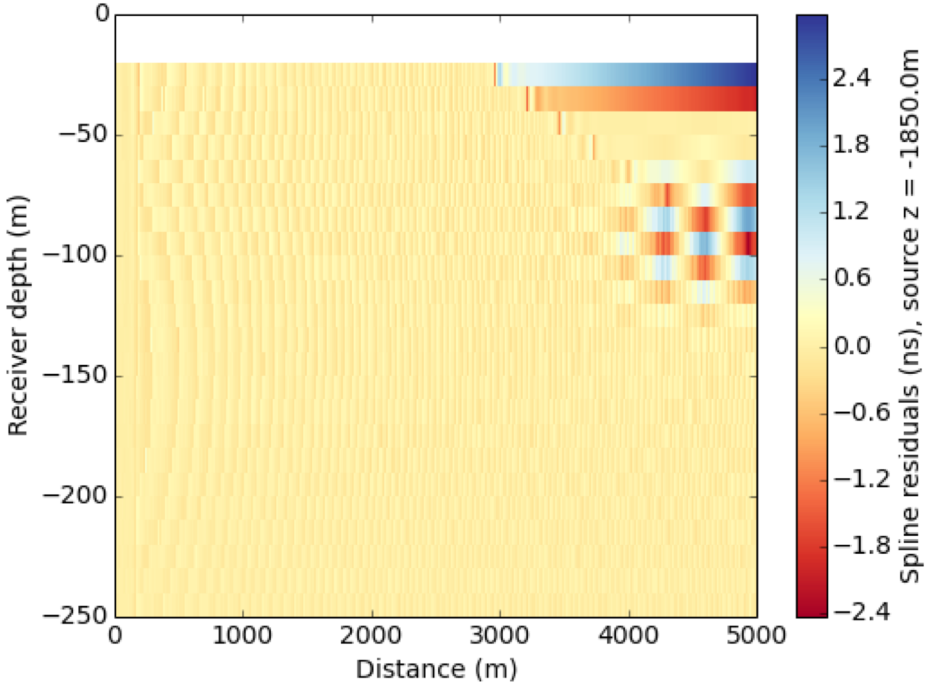


Example raytrace spline fits

source in air: table points with fit



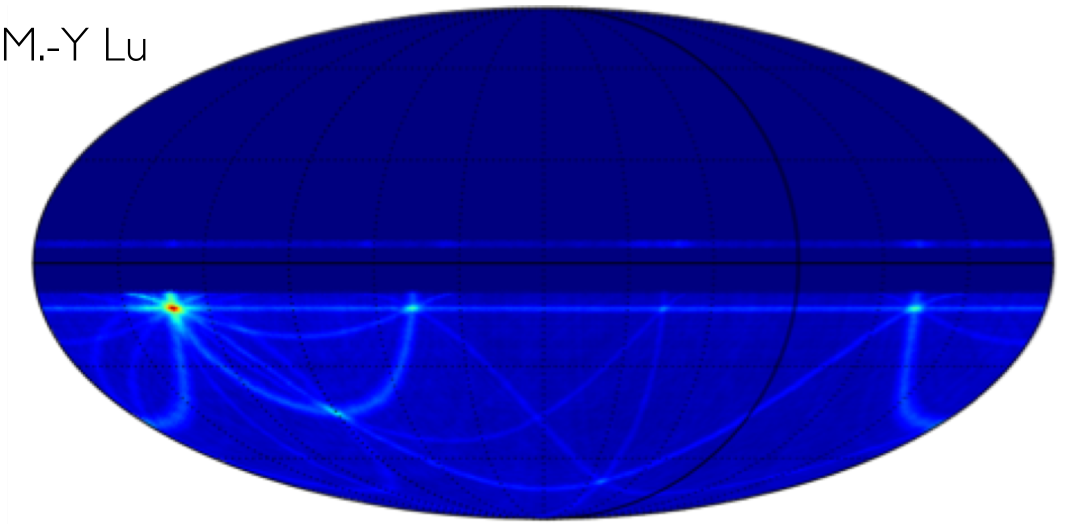
source in-ice: 2D residuals



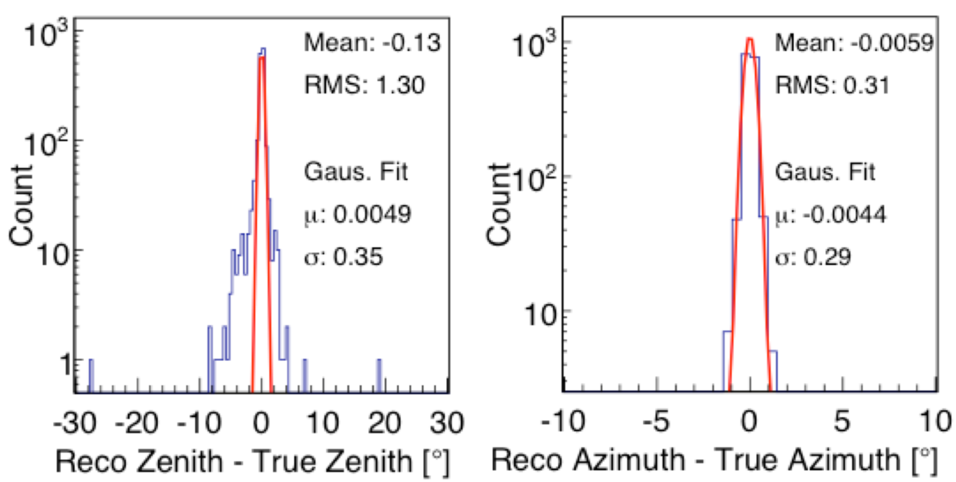
- typical error is ~0.3 ns relative to full raytrace calculation
- spline evaluation is 500 times faster

Reconstruction of Simulated Events

M.-Y Lu



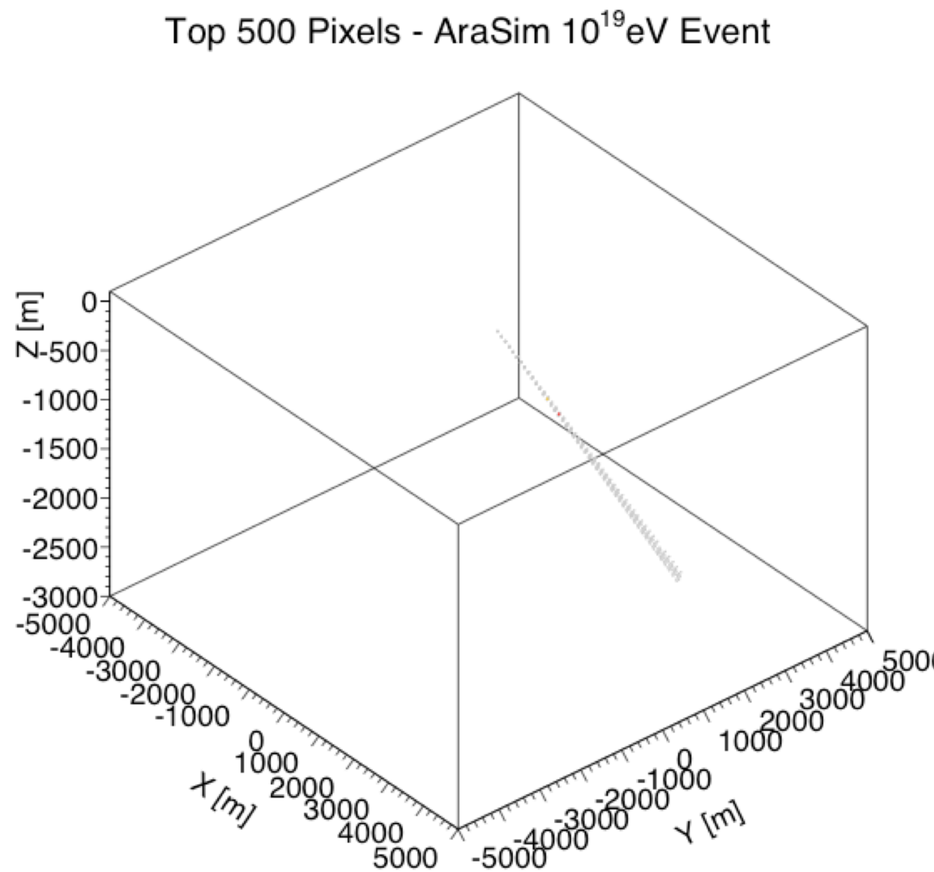
$$P_{\Sigma}(\vec{r}) = \frac{1}{Z_L T}\int_0^T \sum_{i=1}^{N_A}\sum_{j=1}^{N_A} dt\cdot v_i(t+\tau_i(\vec{r}))v_j(t+\tau_j(\vec{r}))$$



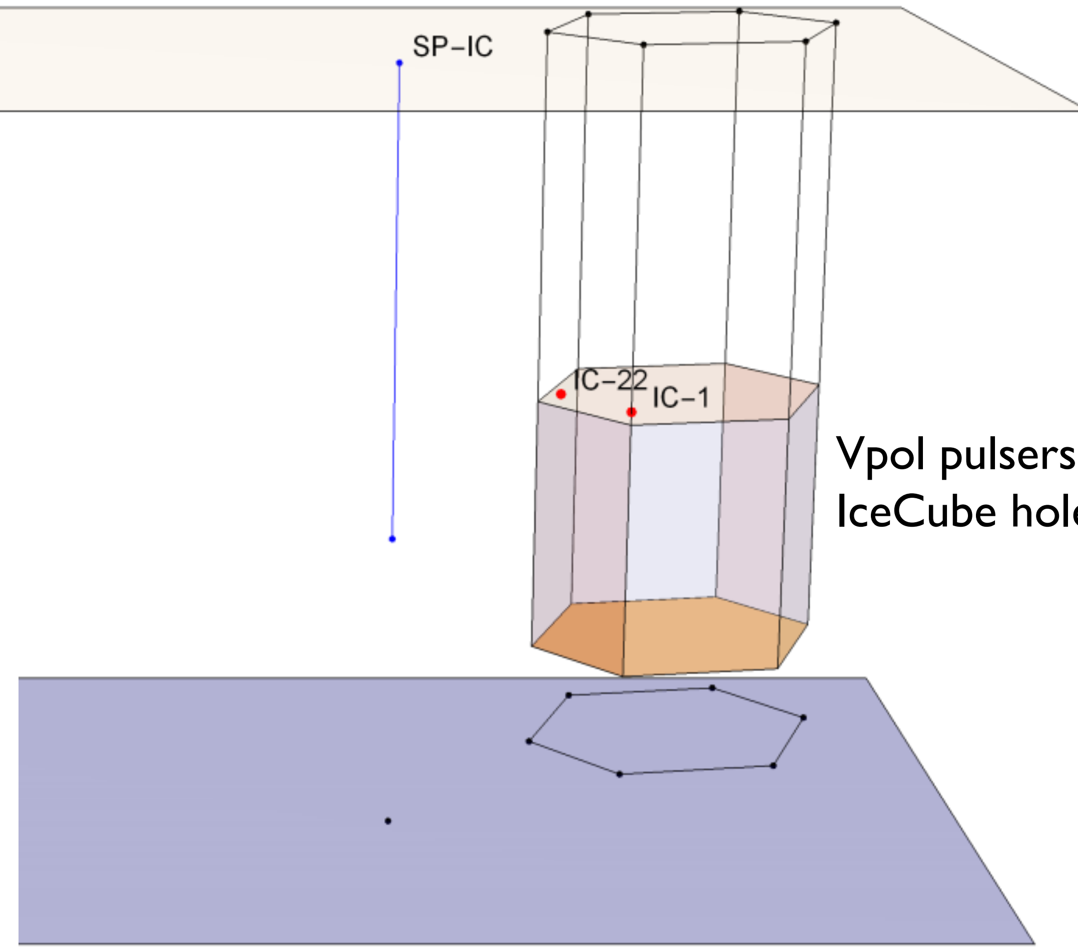
- Cross-correlate over all sky using spline time delays for each direction
  - parallelized for GPUs with OpenCL
- Simulated 10^{18} eV neutrino vertex direction resolution: ~0.3 degree in zenith / azimuth

All-sky All-Distance Reconstruction

- Form cross-correlation skymap for all distances
  - "onion" reconstruction
- Distance reconstruction is very limited
  - curvature is negligible at O(km) distances

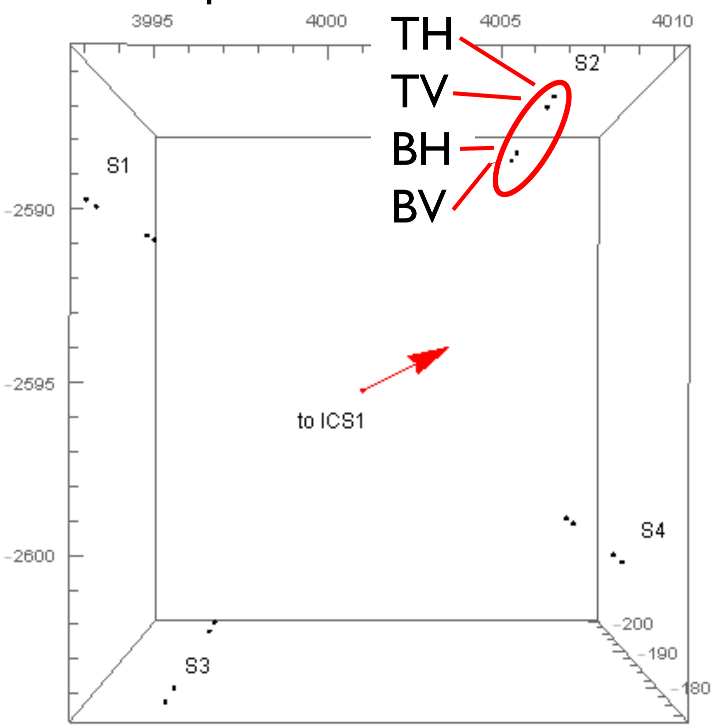


Deep Calibration Pulsers



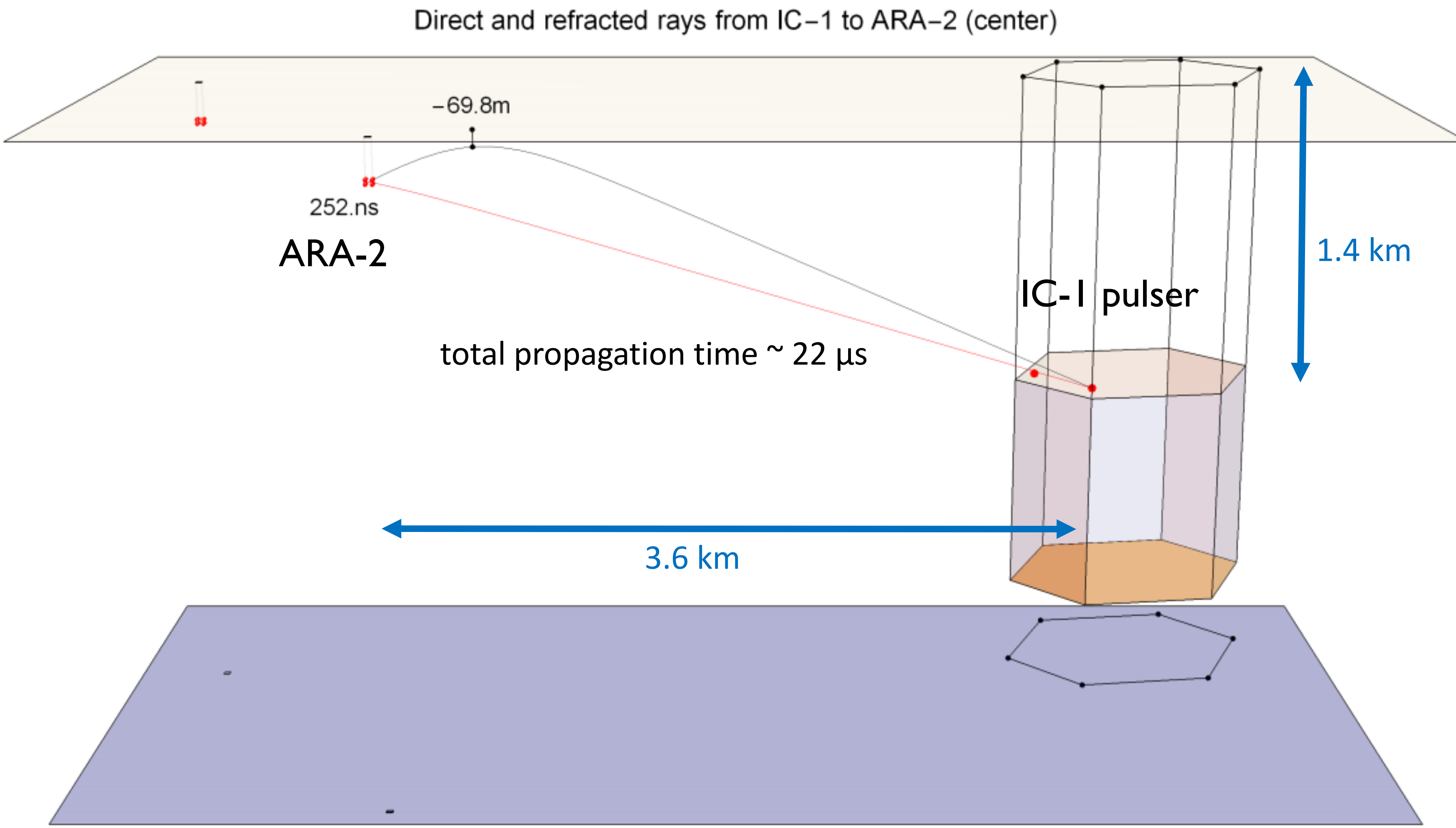
Vpol pulsers in IceCube holes

ARA-2 top view



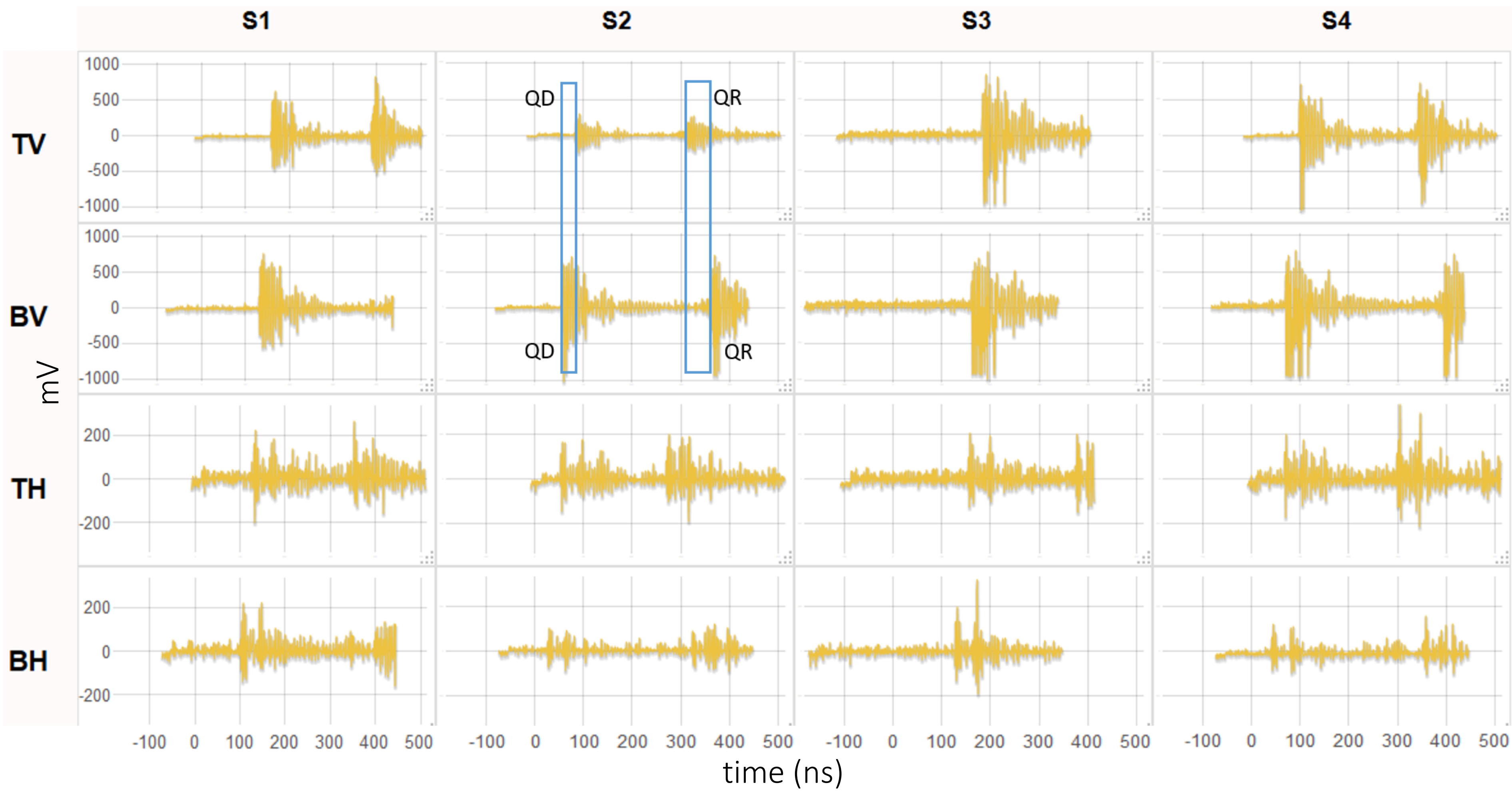
D. Seckel

Raytraced Radio Paths



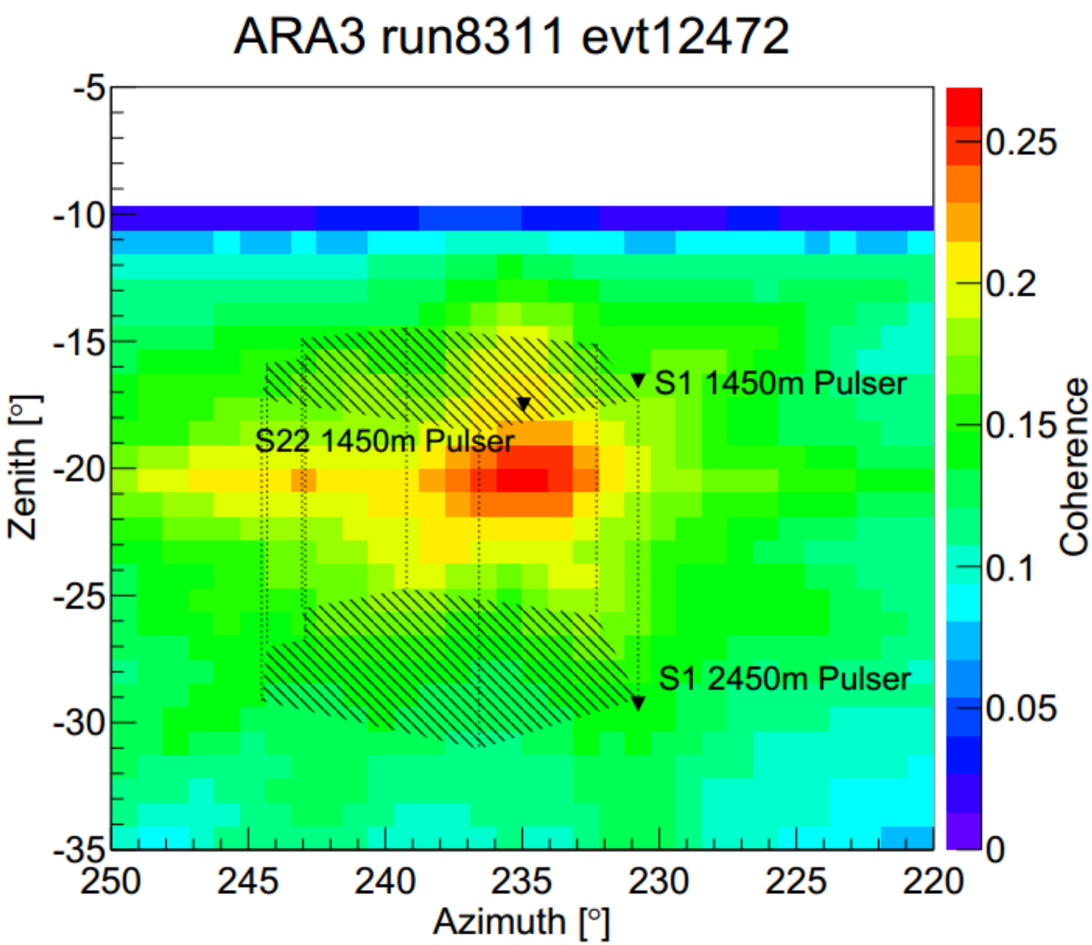
D. Seckel

Deep Pulser Event (IC-1 to ARA-2)



both pulses observed: direct (upgoing) and refracted (downgoing)

Directional Reconstruction of Pulser



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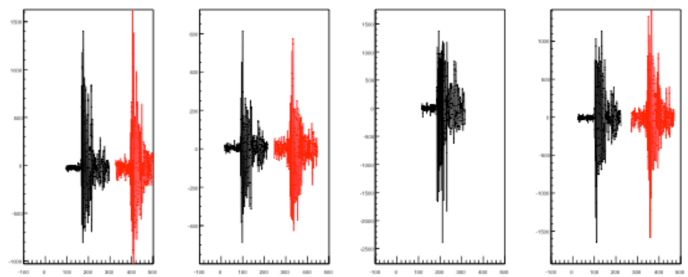
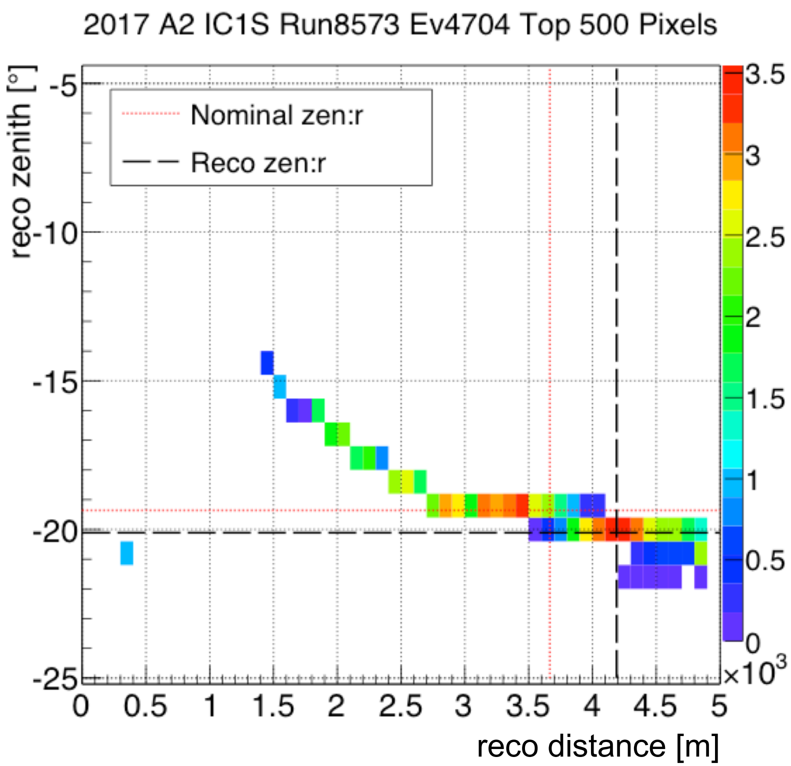
- cross-correlation reconstruction of direct pulses
  - sum of CC pairs for all directions in sky
- O(degree) directional resolution
- Distance reconstruction very difficult due to near-plane-wave timing
  - solution: use reflected ray

Double-pulse Distance Reconstruction

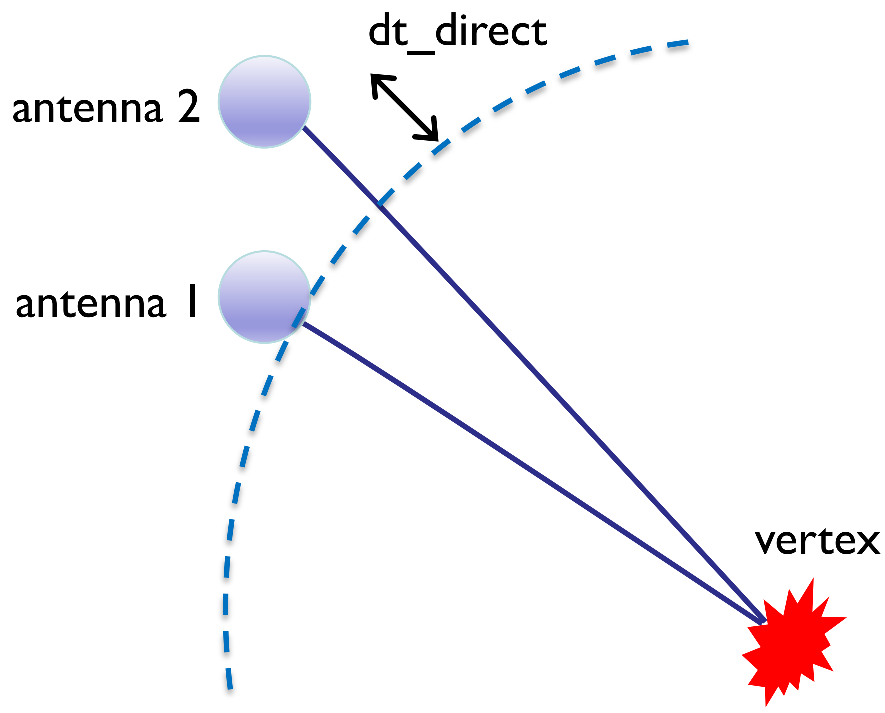




- Separate direct and reflected pulses into "snippets"
- Include reflected pulses into cross-correlation
  - spline tables also support reflected rays
- Deep pulser distance reconstructed to 13%
  - systematic offset; statistical spread is much less

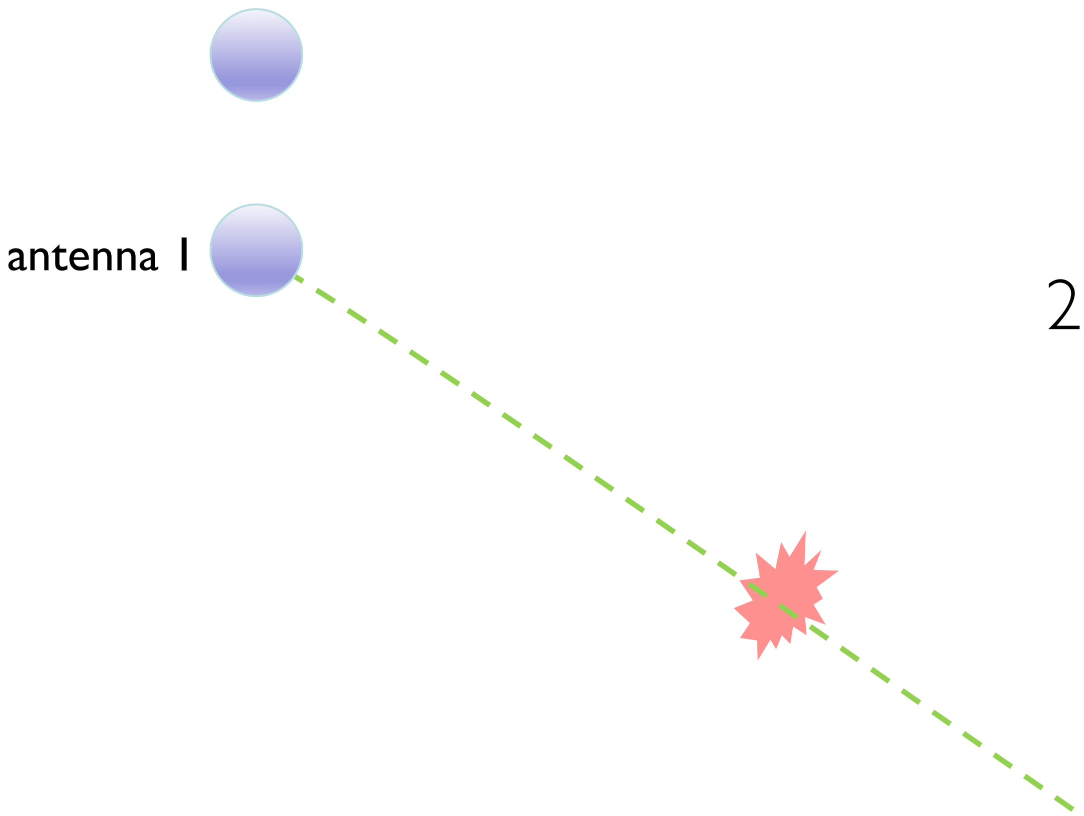
Double-Pulse Raytracing and Geometric Limitations

2D Idealized Example



1. Time difference of direct pulse to two antennas gives receipt angle of ray

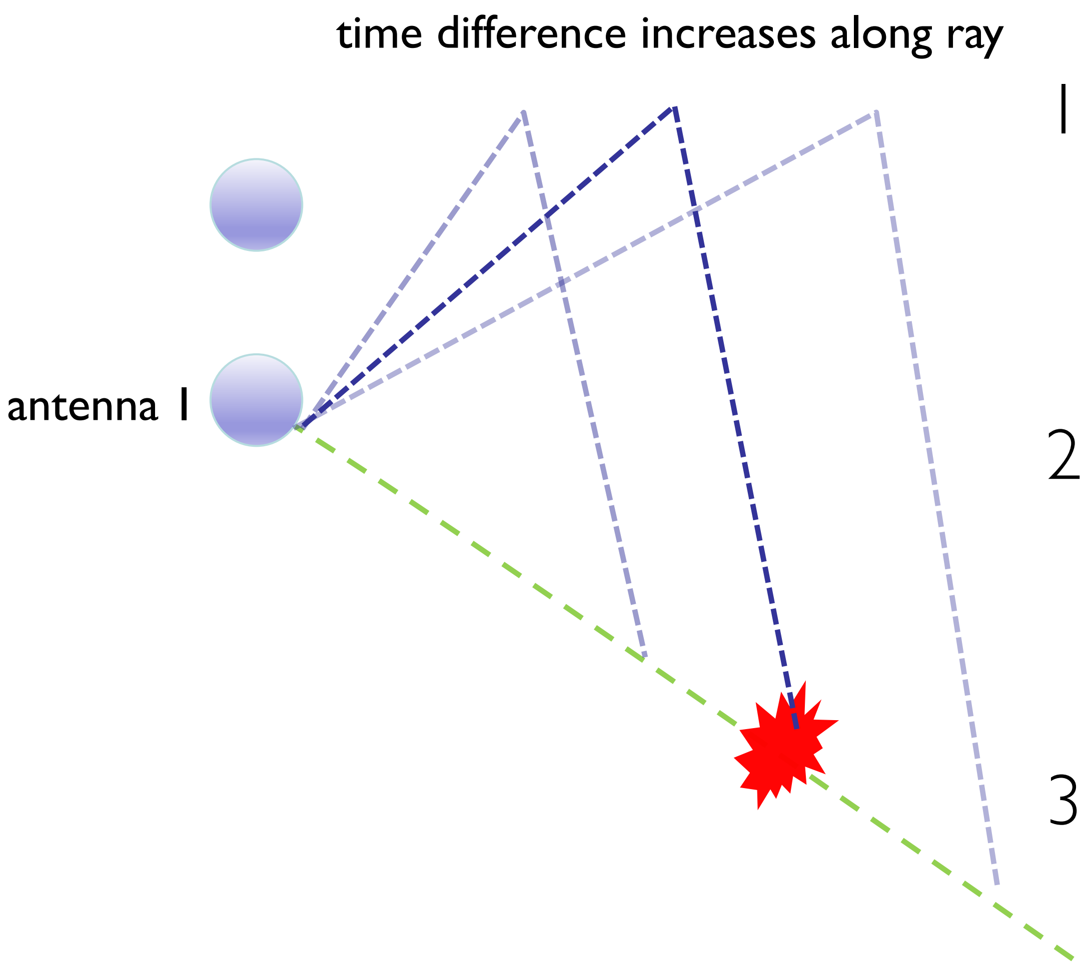
2D Idealized Example



1. Time difference of direct pulse to two antennas gives receipt angle of ray

2. Raytracing gives a path along which the vertex lies

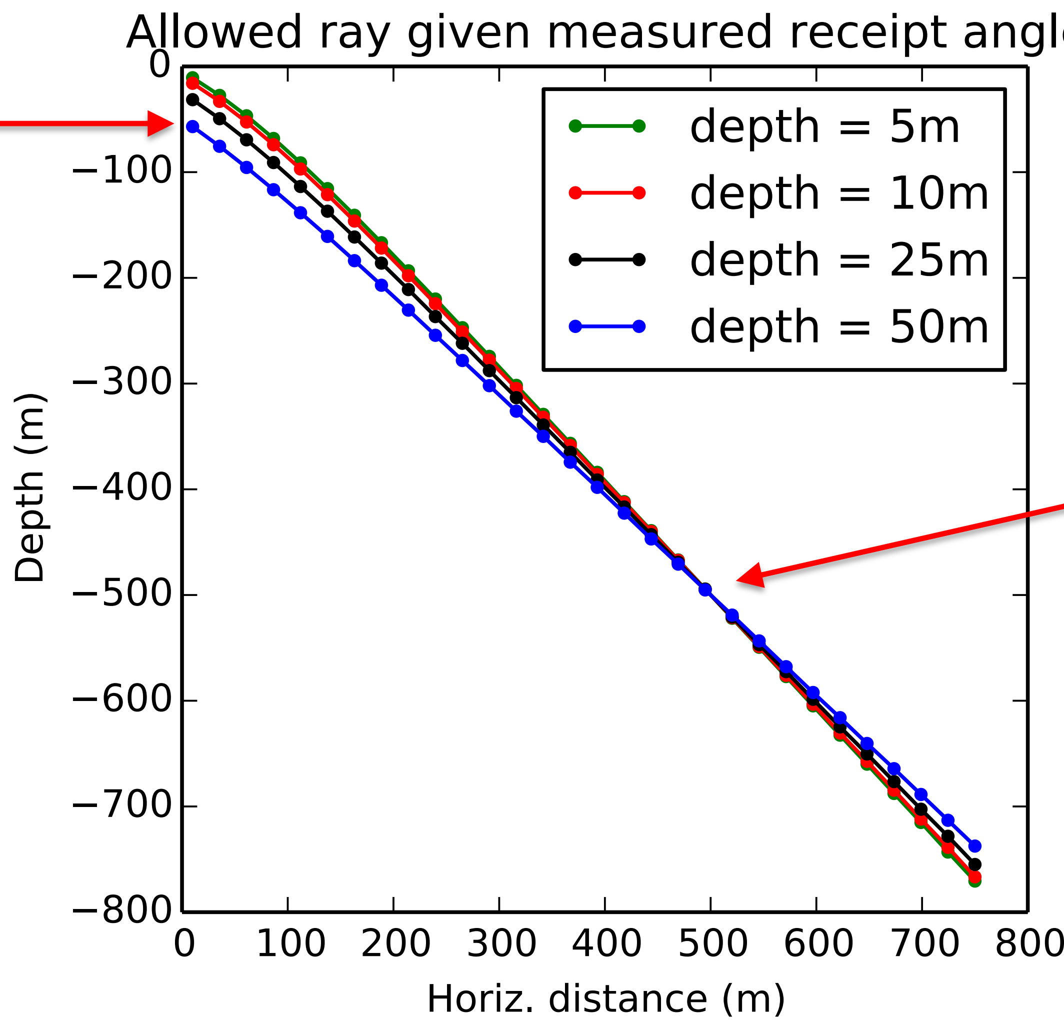
2D Idealized Example



1. Time difference of direct pulse to two antennas gives receipt angle of ray
2. Raytracing gives a path along which the vertex lies
3. Time from direct to reflected pulse in a single antenna identifies vertex

Different Antenna Depths: Reverse Raytrace

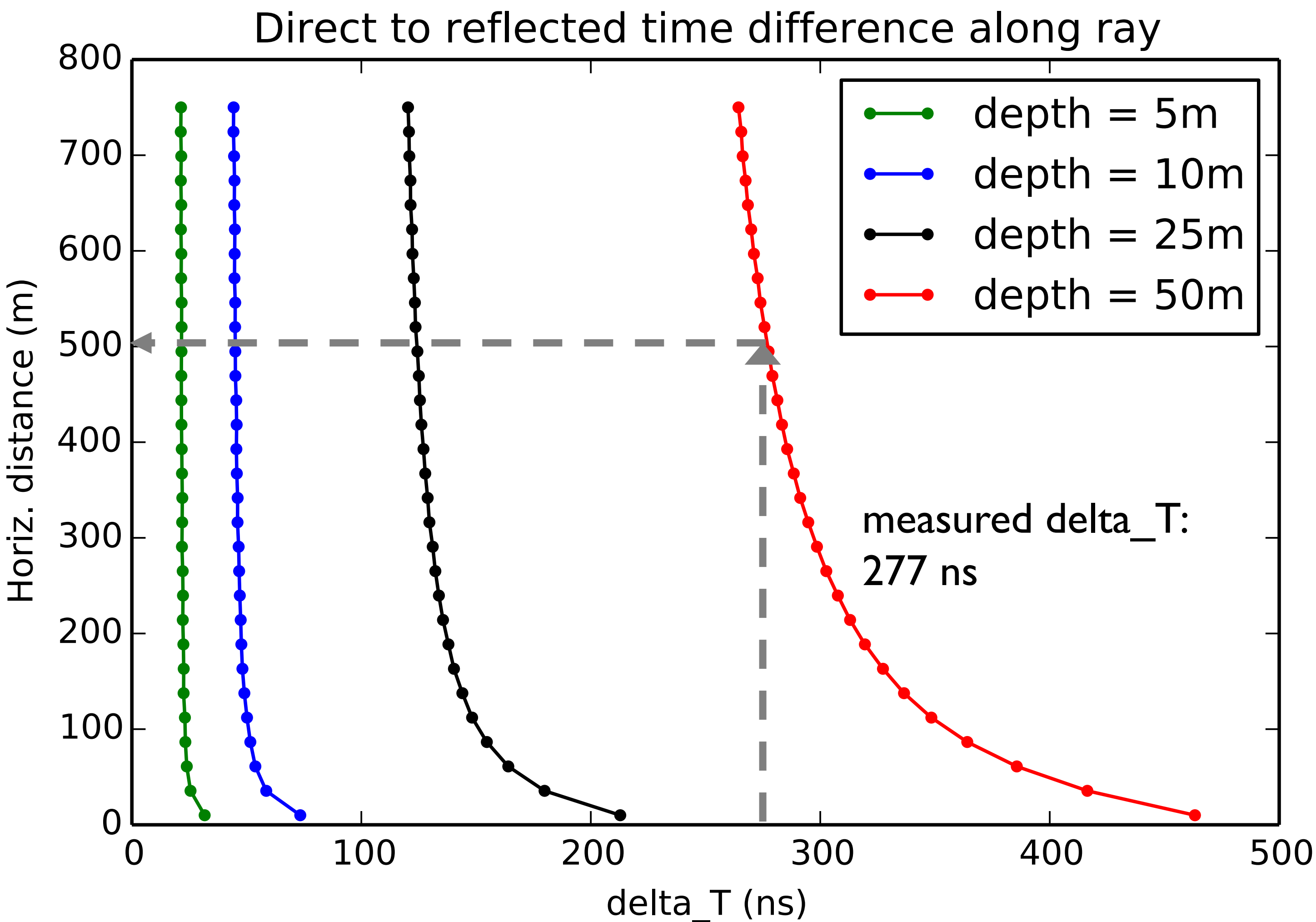
antenna pair



vertex at
(r, z) = (500, -500) m

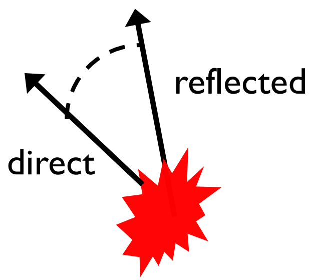
NB: assumes perfect measurement of receipt angle

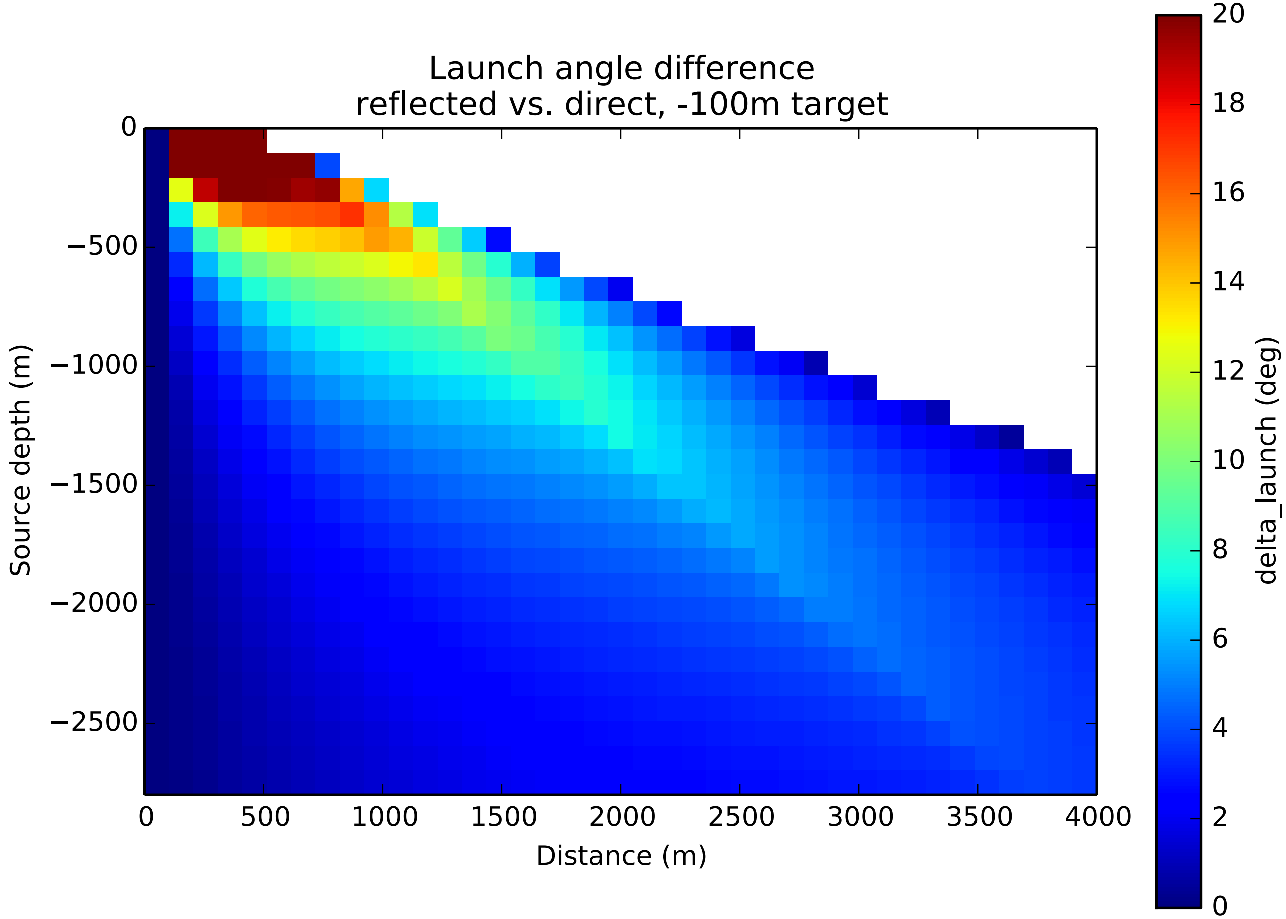
Reflected Time Difference Lookup



Slope of curve maps time resolution to distance resolution — shallower is more challenging

Raytracing Launch Angle Difference

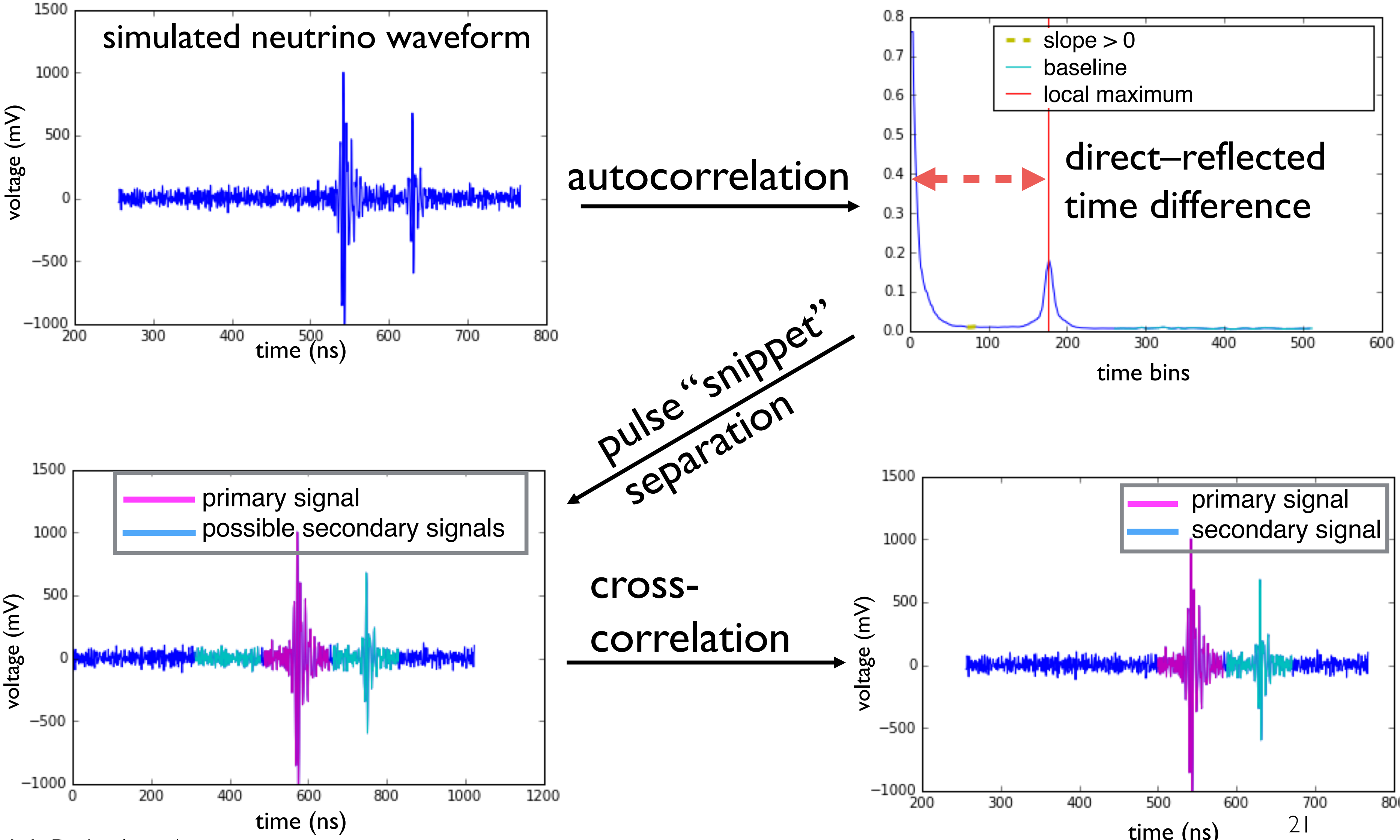


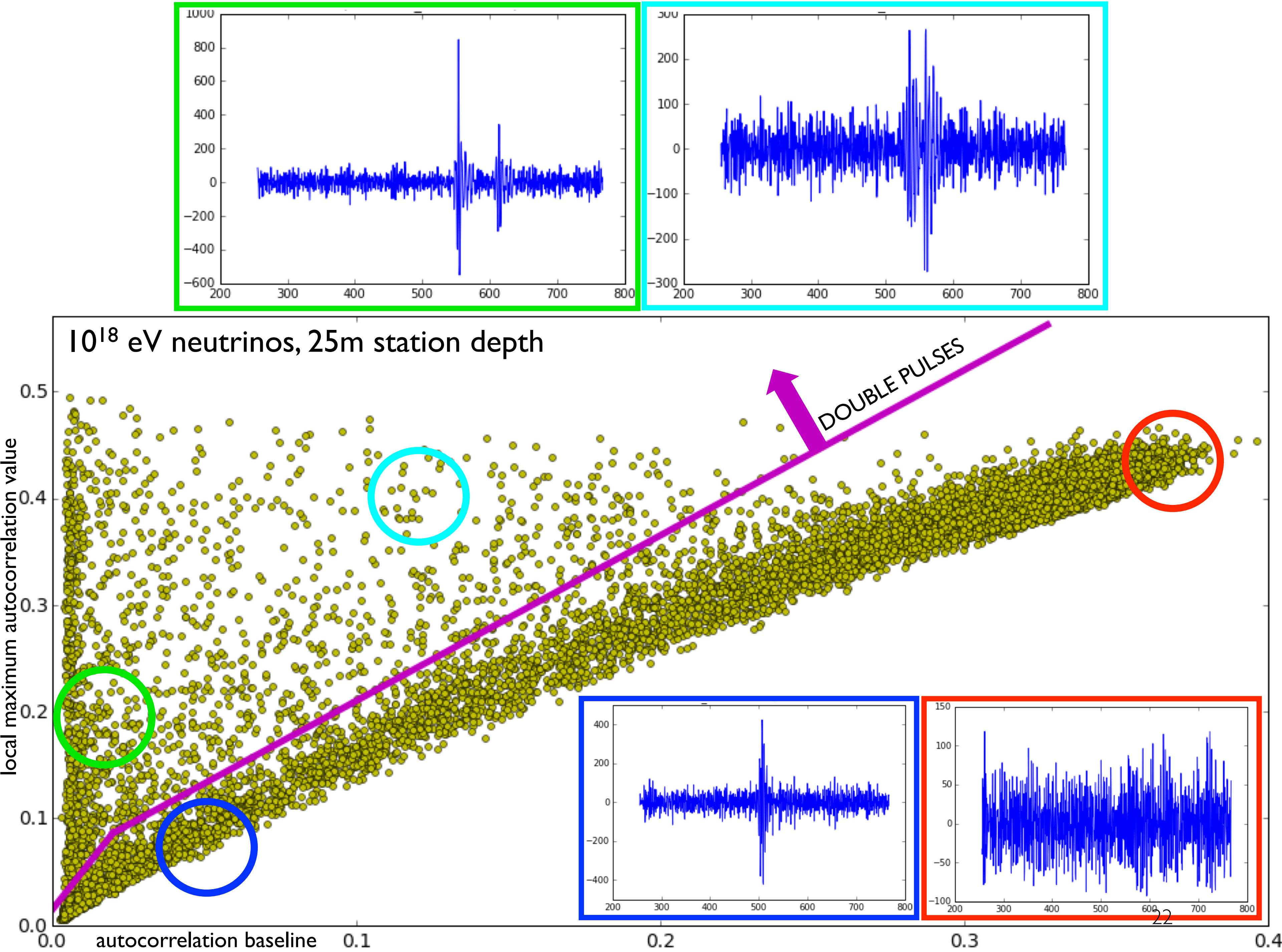


Smaller is better (more likely that both rays are near Cherenkov cone)
But the real story is more complicated (and 3D!)

Double-Pulse Efficiency in Full Neutrino Simulation

Double-Pulse Selection Algorithm

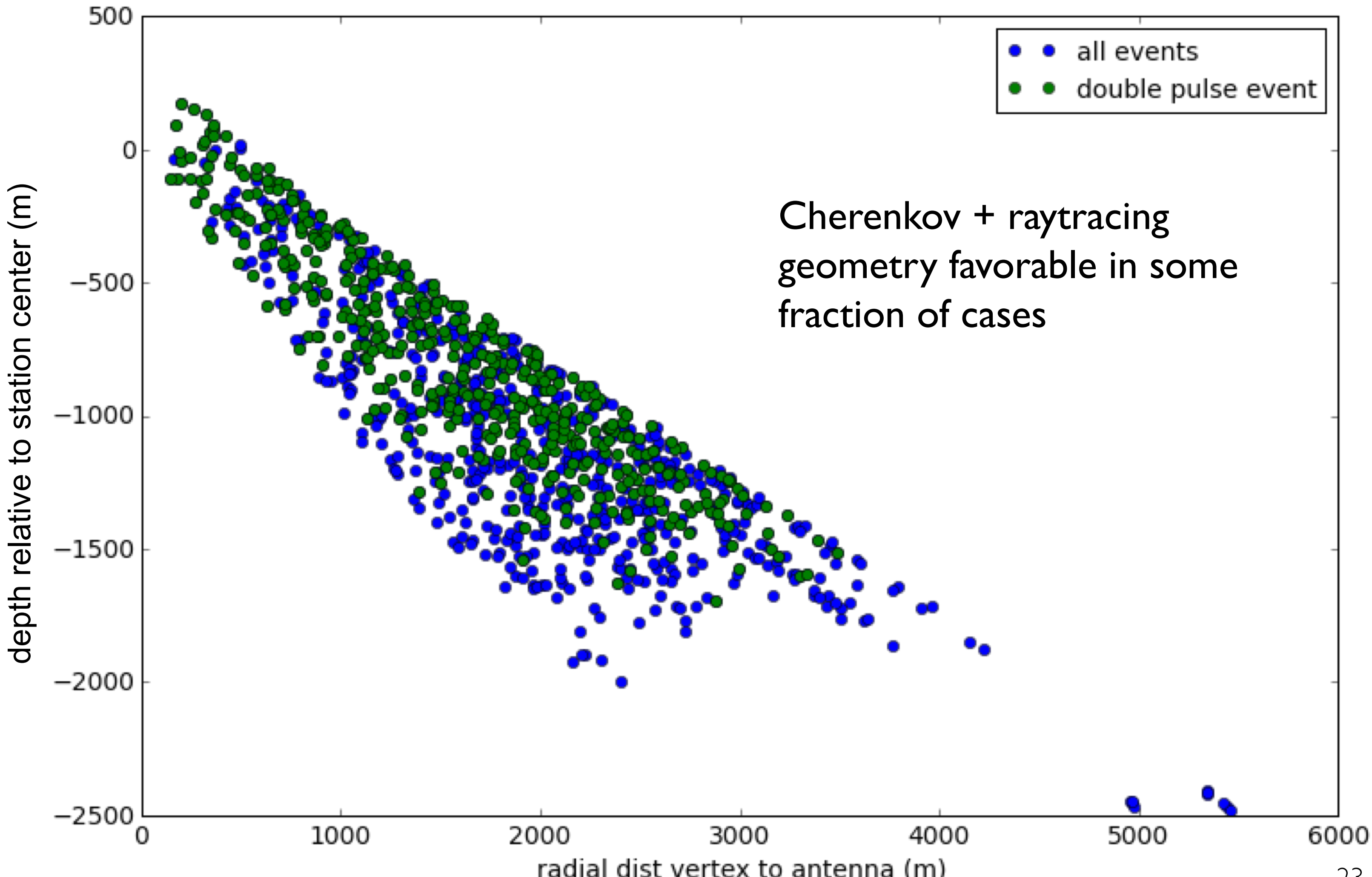




10^18 eV neutrinos, 25m station depth
DOUBLE PULSES
local maximum autocorrelation value
autocorrelation baseline

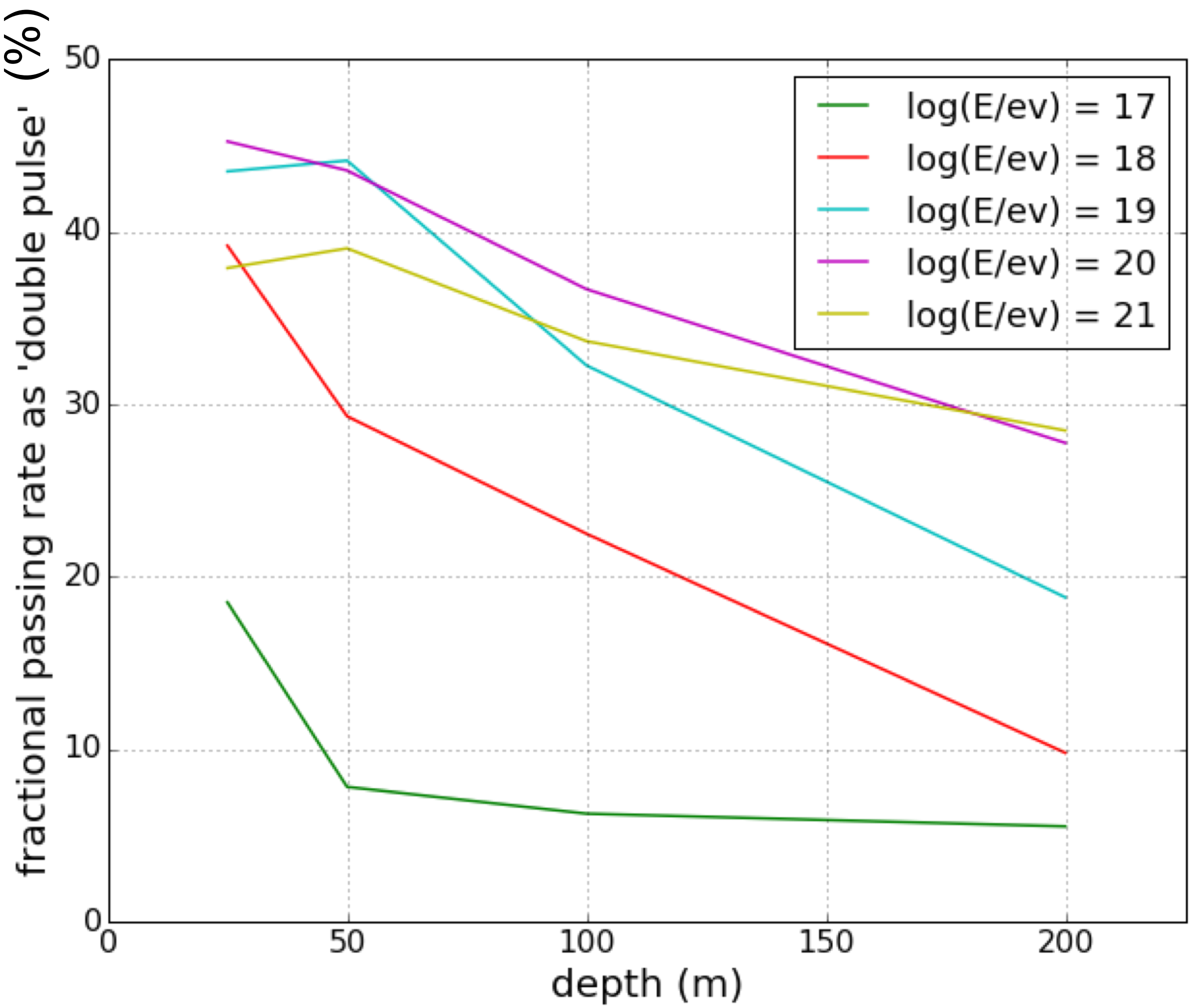
Vertex Distribution

simulated neutrino energy = 10^{18} eV, antenna z = -50 m, 1000 events



Cherenkov + raytracing geometry favorable in some fraction of cases

Double-Pulse Efficiency vs. Station Depth



Shallower is better for detecting more double pulses

Summary and Next Steps

- Spline framework provides fast raytracing approximation
  - enables all-sky, all-distance interferometric reconstruction

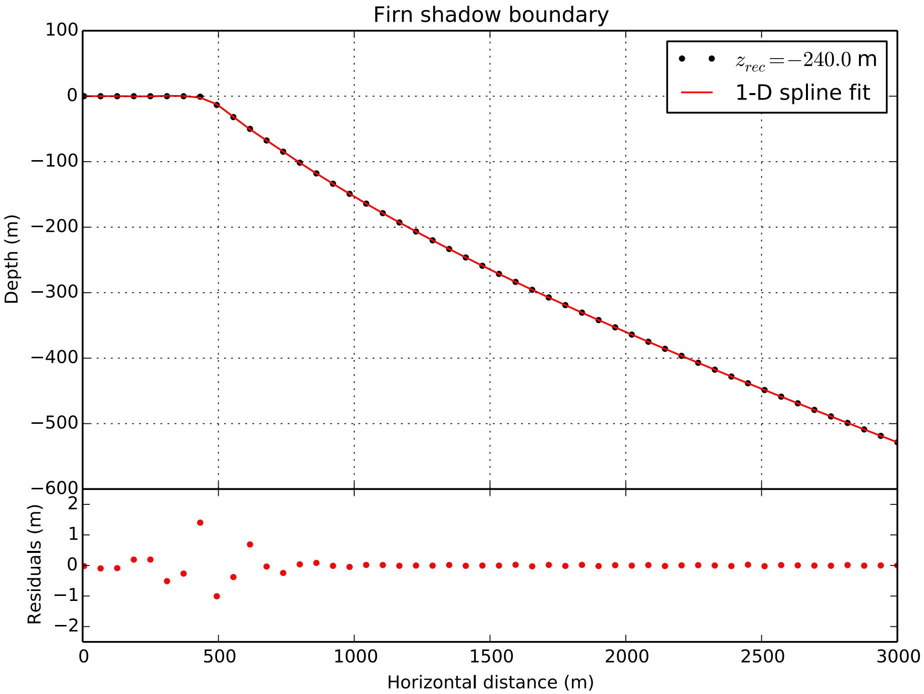
- Cross-correlation vertex directional resolution of O(1) degree

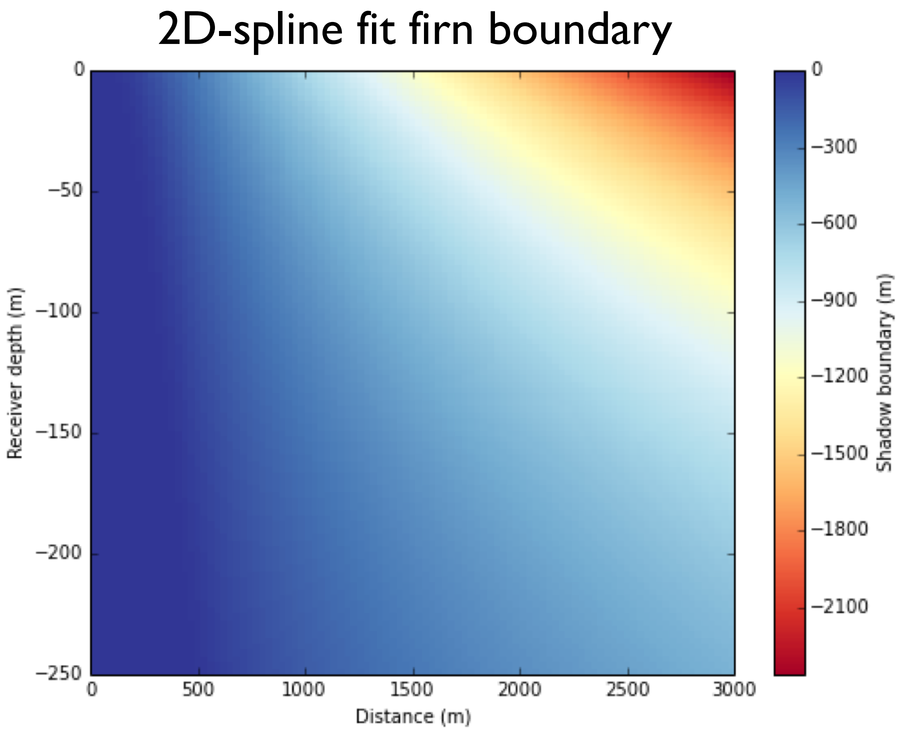
- Additional information from reflected ray enables distance reconstruction
  - O(10%) distance resolution at several km distance
  - 10%-40% of simulated events have at least one double pulse

- To do: continue to evaluate antenna depth dependence
  - double-pulse efficiency decreases with depth
  - distance resolution increases with depth

- To do: full double-pulse vertex distance reconstruction using automated pulse snippet selection algorithm

Firn Boundary Spline Table

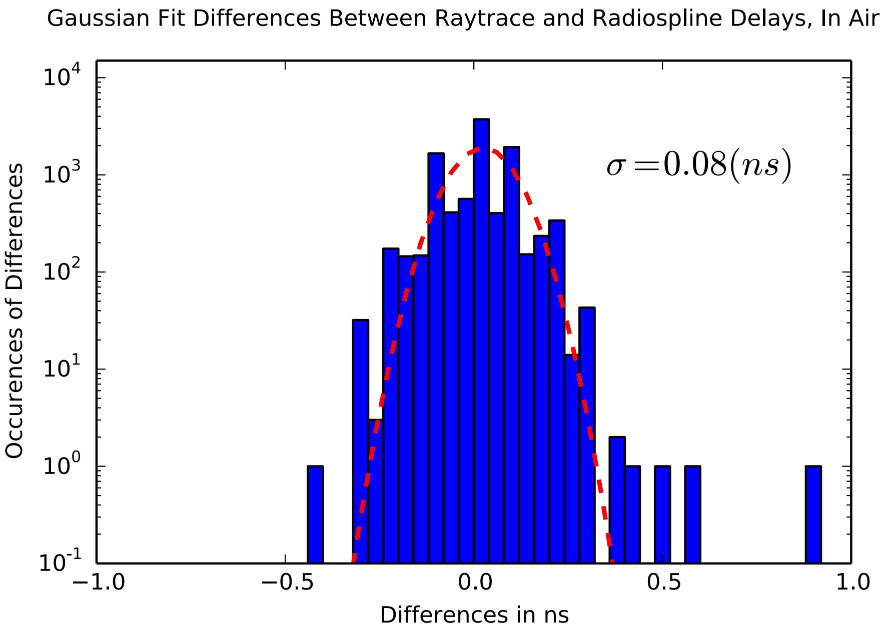




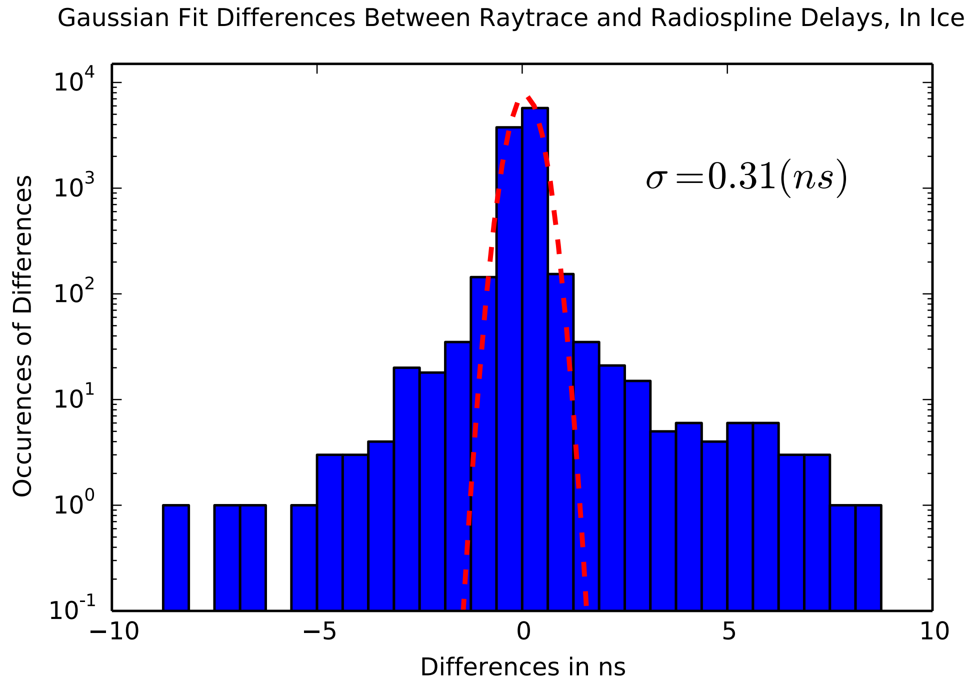
Firn boundary table: fast determination if source / receiver solution possible

Errors relative to raytracer

random sources in air



random sources in ice



M. Beydler

Agreement of in-air tables excellent;
some outliers in ice (known issue with spline fits)

radiospline Performance

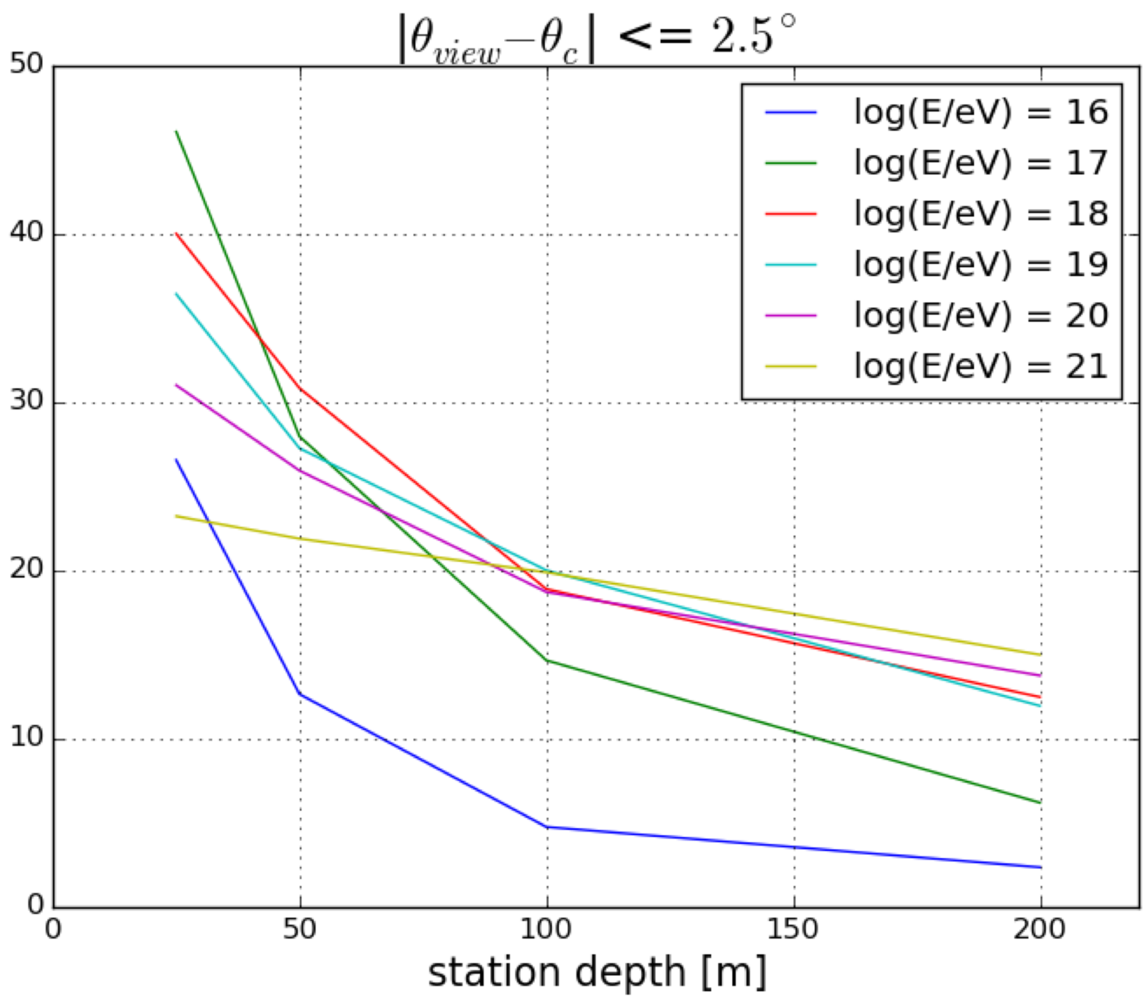
Random source/target locations (2.3 GHz Core i7)

Method	Average computation time / ray (ms)
AraSim raytracer	0.21
radiospline	0.00037

Spline lookup+evaluation is > 500 times faster than full point-to-point raytrace calculation

Cherenkov Cone Angle Difference

double pulse efficiency estimate from simulation, no noise, cone angle selection



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