ASKARYAN RADIO ARRAY THE OHIO STATE UNIVERSITY CCAPP

Directional Reconstruction as a Means of Lowering Thresholds for Point-Source Searches in ARA

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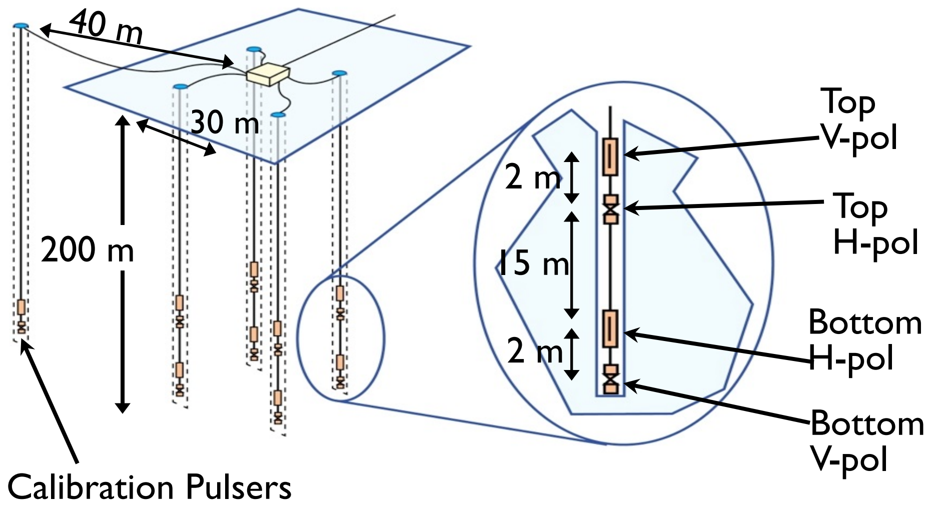
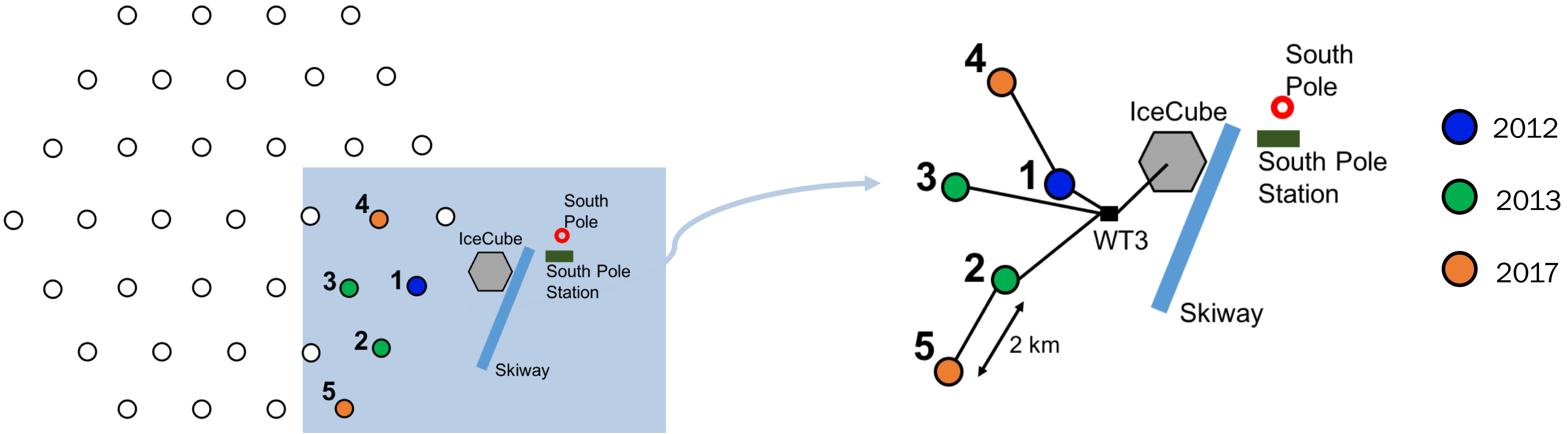
About Askaryan Radio Array

Designed to detect radio impulses from UHE neutrino-ice interactions

- 8 Vpol & 8 Hpol antennas deployed in 200m “boreholes”
- 5 stations so far (2 new this year!)
- Phase 1 goal: 37 stations covering 100 km^2

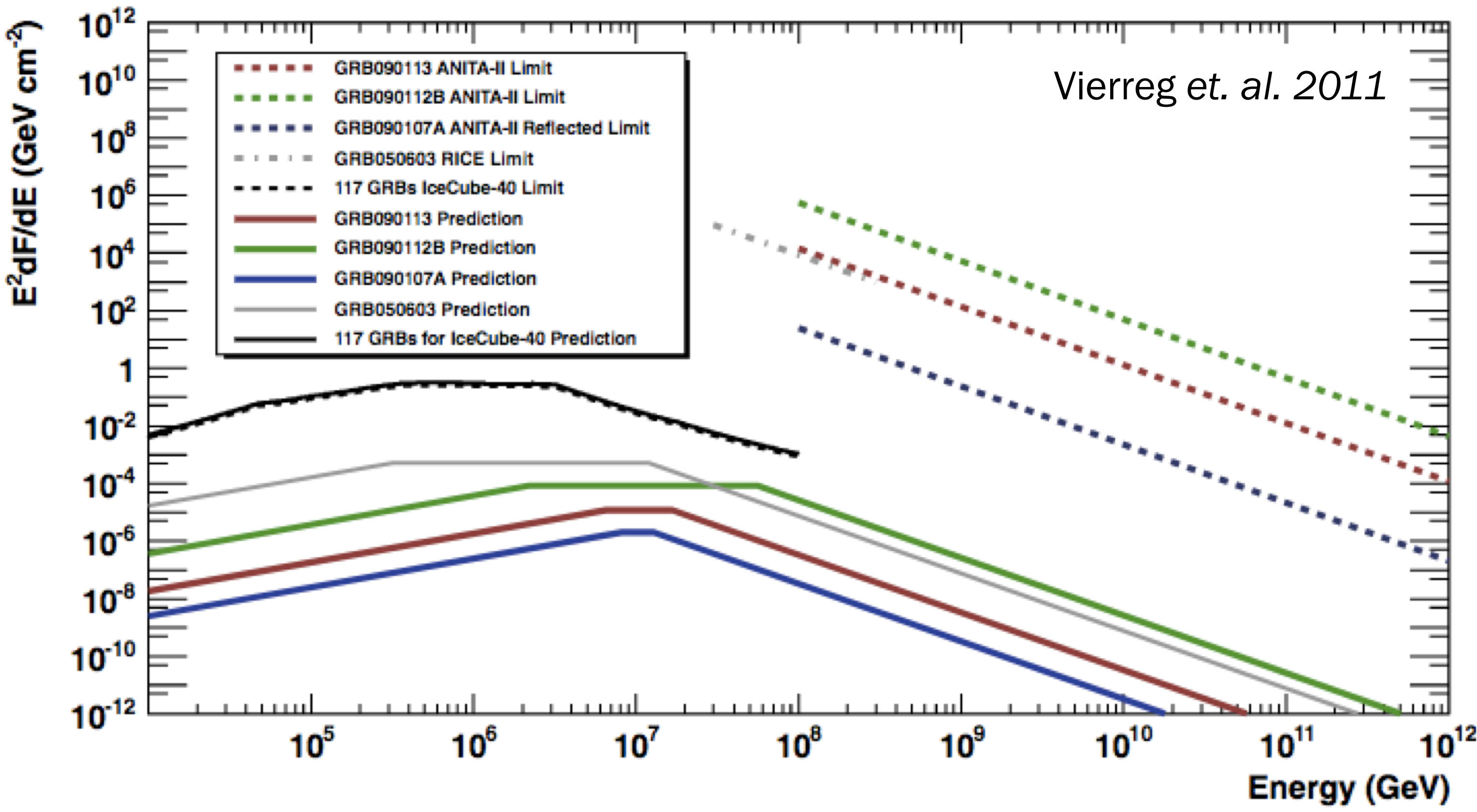




Motivation

Idea: reduce analysis thresholds for neutrino source searches

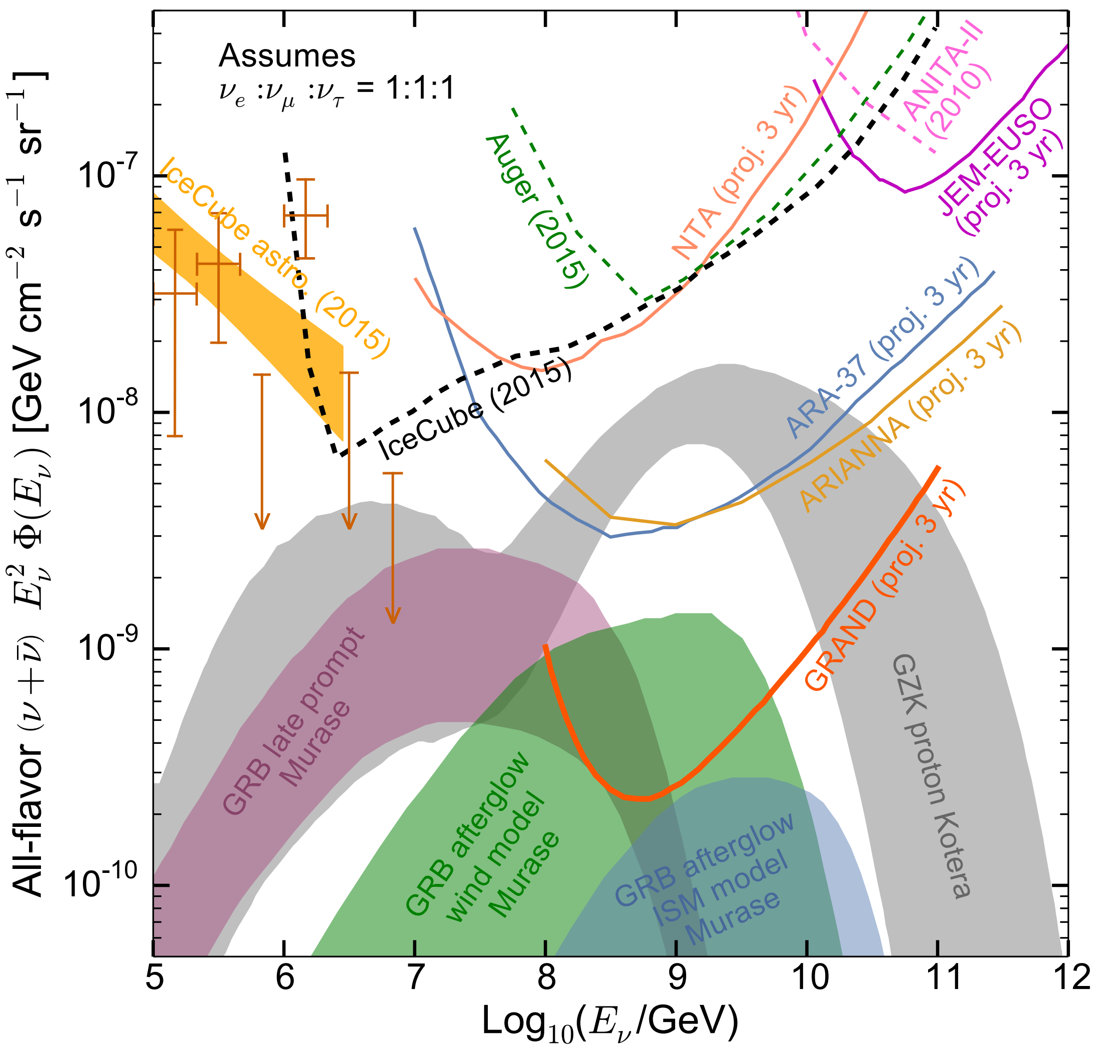
- A standard, *diffuse* searches require the *strictest* cuts
  - Neutrinos can come from "anywhere, anytime"
    → RF background can come from "anywhere, anytime"
- In a transient search, straightforward way to loosen cuts: restricted timing
  - ANITA-II searched for *prompt* neutrinos from GRBs [A. Vieregg *et. al.* ApJ 736 (2011) 50] 10-minute signal window, 12 GRBs in the sample



Motivation (cont.)

- But, not every source search allows for such small time windows
- Example: *afterglow* neutrino fluxes are expected to exceed *prompt* fluxes above ~$10^{17.5}$ eV, where ANITA is more sensitive
- Which is challenging, because afterglows require larger signal windows:
  - Prompt neutrino search: ~10 min signal window
    [A. Vieregg *et. al* ApJ 736 (2011) 50, *P. Allison et. al.* Astropart.Phys. 88 (2017) 7-16]
  - Afterglow neutrino search: >2-3 hrs signal window
    [K. Murase *et. al.* PRD 76 (2007) 123001, J. Thomas *et. al.* arXiv 1710.04025]
- So, need another way to reduce thresholds…

Plot by M. Bustamante



The Goal

Develop techniques to cut on the *direction* of an RF source

- Need another way to reduce thresholds… RF source direction is the natural next thing
- For a transient search: cut on timing and direction
  - Enables *wider* timing windows
- For steady-source search: cut on direction only

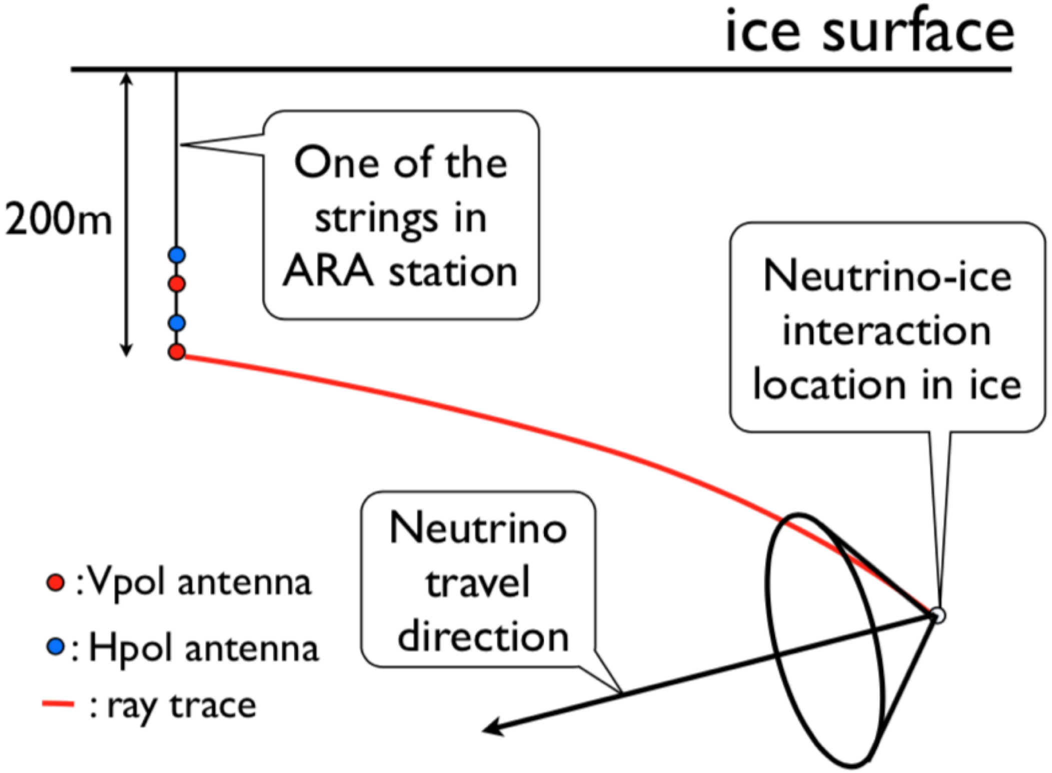
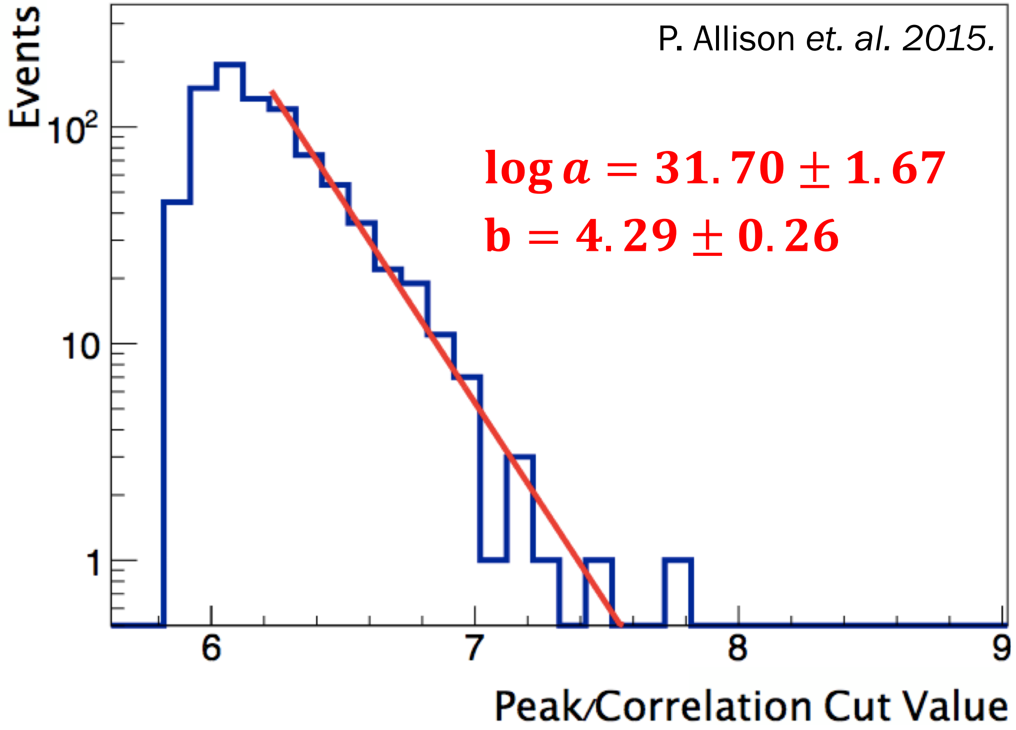


Figure by E. Hong

Oindree Banerjee working on afterglow neutrino search in ANITA-III

Prediction for Improvement

- Case study: exponential background model
  - Used in:
    ARA diffuse search [P Allison *et. al.* Astropart.Phys. 70 (2015) 62-80.]
    ARA GRB search [*P. Allison et. al.* Astropart.Phys. 88 (2017) 7-16.]
    ANITA-III diffuse search [P. Gorham *et. al. arXiv 1803.02719.*]



- Models background with an exponential
  - Plot is distribution of the final cut parameter in the data
  - Line is exponential fit to the data: $\frac{dN}{dx} = ae^{-bx}$

- Background estimate: integrate model from cut value x_i to infinity

$$N_{\text{back},i} = \int_{x_i}^{\infty} ae^{-bx}\,dx = \frac{a}{b}e^{-bx_i}$$

Prediction for Improvement (cont.)

- For a search, have:
  - Background prediction: N_{back}
  - Neutrino efficiency: $N_{\mathrm{pass}}/N_{\mathrm{predicted}}$

- **Question: with a cut on timing/direction, and a fixed N_{back}, how much can we loosen our final cut parameter?**

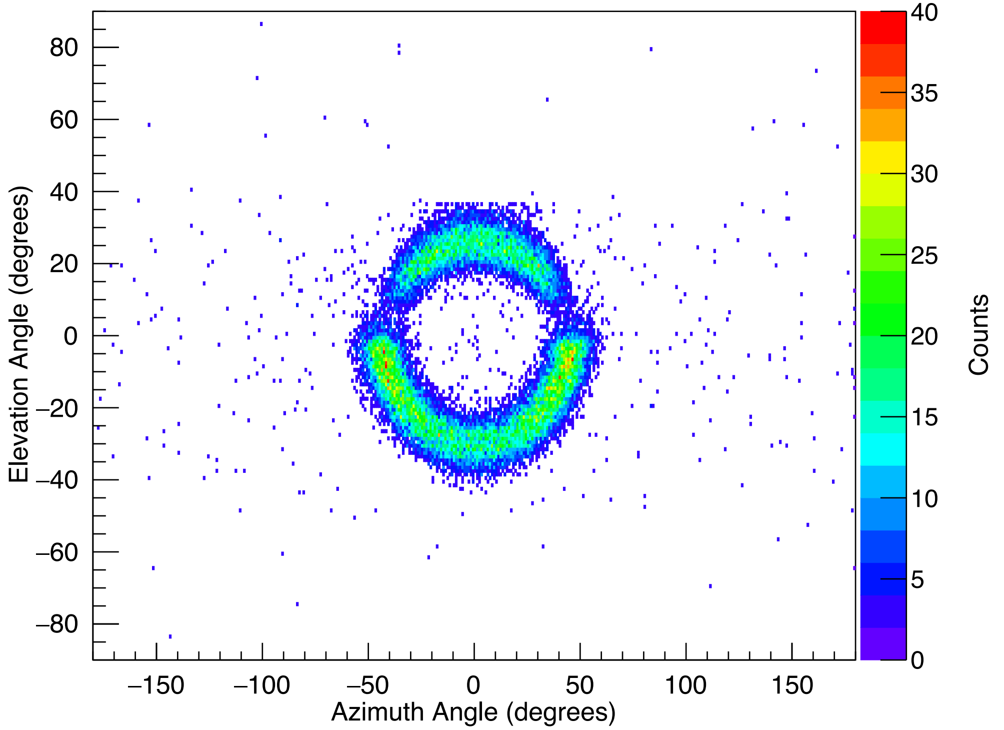
- Suppose we reduce the number of events after directional restriction by a factor $\alpha > 0$: $a_{\mathrm{new}} = a_{\mathrm{old}}/\alpha$

- We can predict the reduction in threshold: $x_{\mathrm{old}} - x_{\mathrm{new}} = \dfrac{\ln \alpha}{b}$

Prediction for Improvement (cont.)

What α might be possible?

- Example:
  - Simulate flux of 10^{18} eV neutrinos from source in the sky
  - Do interferometry on every event w/ 300 m source distance hypothesis
  - Examine distribution of reconstructed RF directions
- Given this:
  - Might expect $\alpha \sim \frac{20{,}000 \text{ deg}^2}{1{,}600 \text{ deg}^2} \sim 12$
  - Which is is a reduction: $x_{\text{old}} - x_{\text{new}} \sim 0.5$
- Don't forget: signal events are usually *steeply* falling distributions of x_i. Small reductions in x_i significantly affect neutrino acceptance.



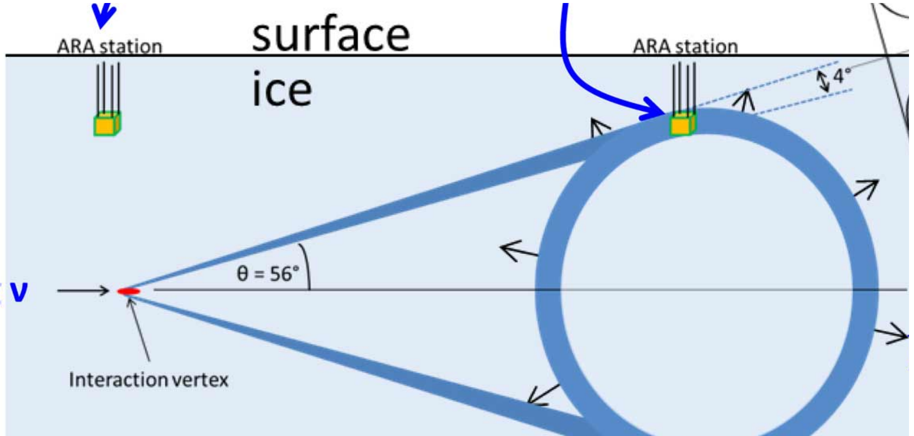
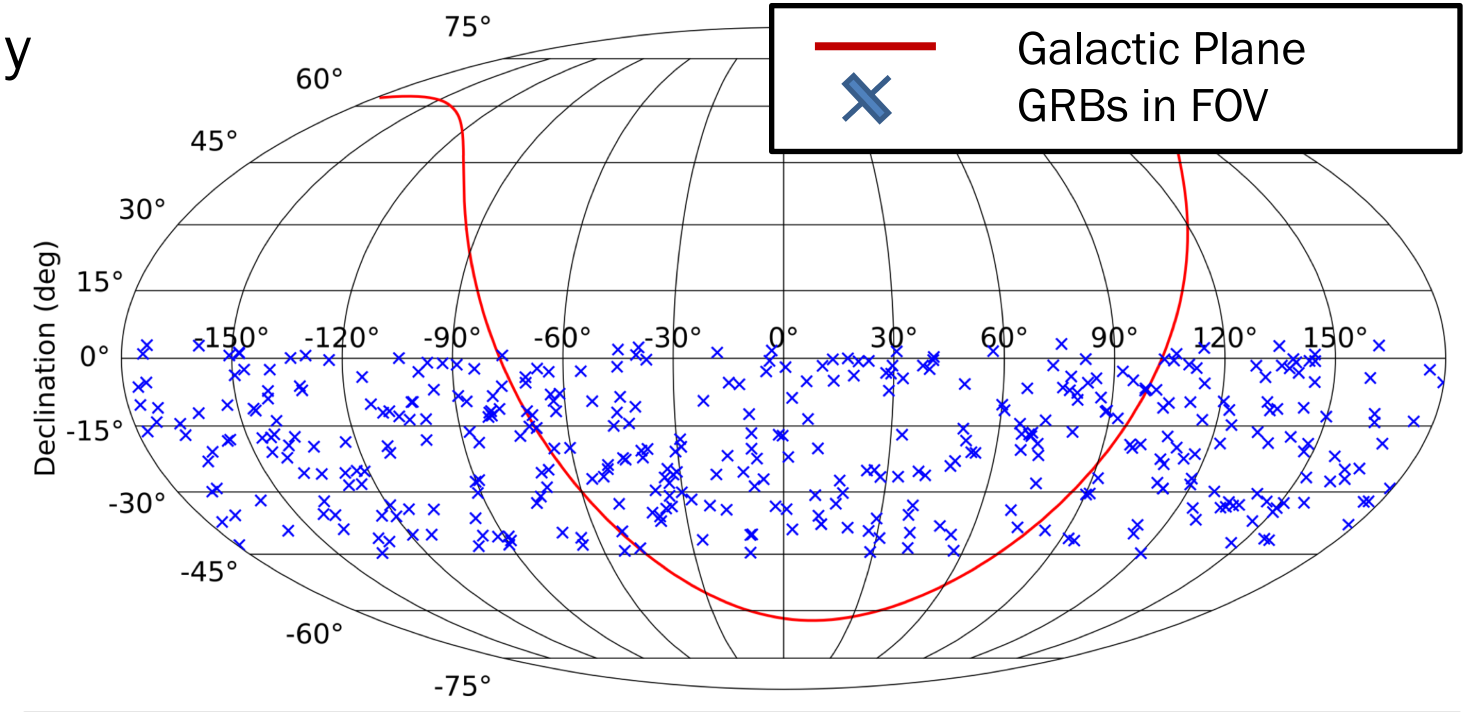


Figure by T. Mueres

Potential ARA GRB Sample

- Utilize IceCube catalog for all GRBs occurring in the four year (2013-16) two-station (A2, A3) livetime currently undergoing a diffuse analysis—see talk by Carl Pfendner.
- Require events be within the ARA field-of-view: -5° ⟶ 45° in elevation
- Sample has 391 GRBs (without accounting for system livetime)



[IceCube Catalog: http://grbweb.icecube.wisc.edu/]

Summary

Restricting on the direction of an RF source is a way to reduce thresholds in point-source searches.

- What's Next:
  - Assessment of systematic uncertainties on ARA's RF reconstruction
  - Finding methods to recover where an RF event might sit on the Cherenkov cone (e.g., slope of power spectrum)

United States – Israel
Binational Science Foundation

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- The OSU Department of Physics
- The OSU Center for Cosmology and Astroparticle Physics
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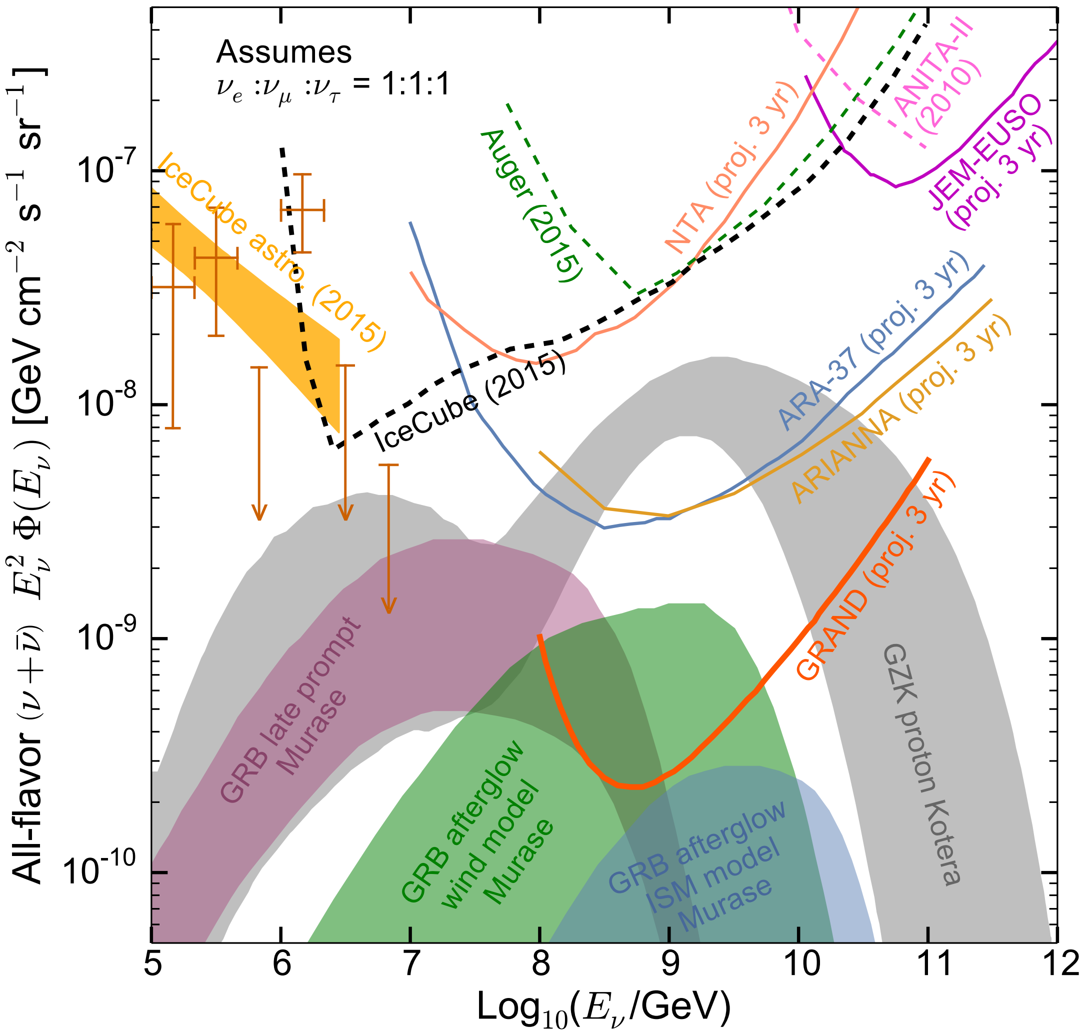
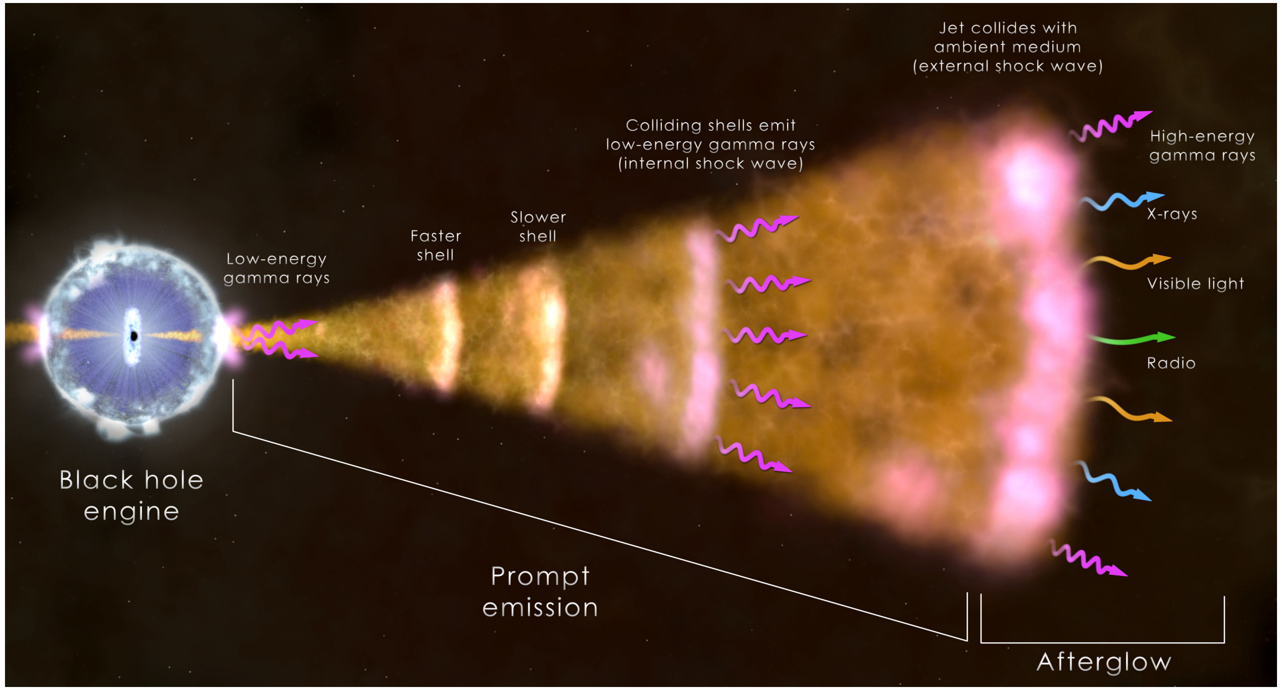
Back-up Slides

Neutrino Flux Models

Plot by M. Bustamante



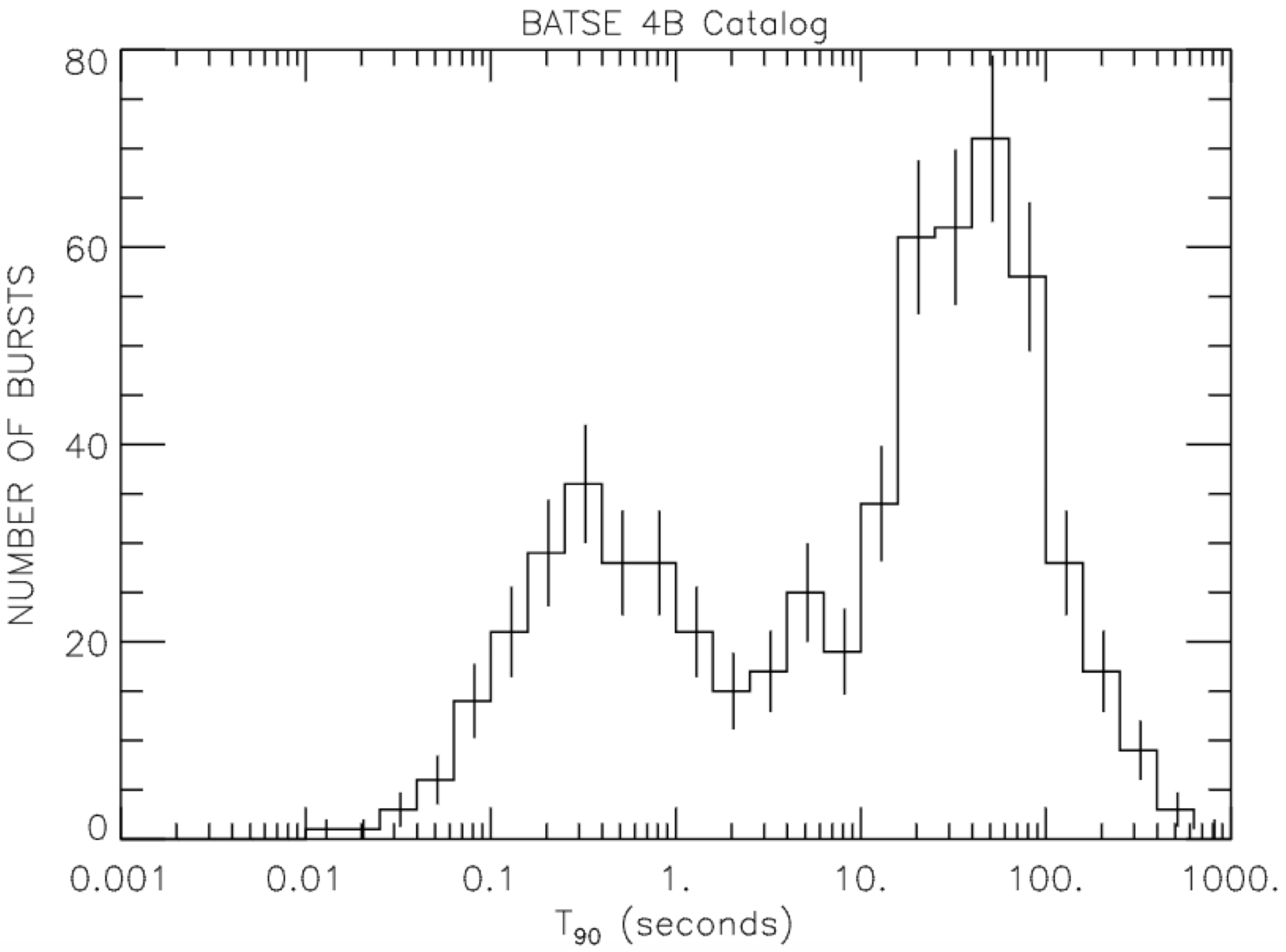


Artist rendering from NASA

GRB Theory

"This image shows the durations of the 4B Catalog Gamma-Ray Bursts recorded with the Burst and Transient Source Experiment on board NASA's Compton Gamma-Ray Observatory. The duration parameter used is T90, which is the time over which a burst emits from 5% of its total measured counts to 95%."

https://gammaray.nsstc.nasa.gov/batse/grb/duration/



Some Math

$$N_{back} = \frac{a_{old}}{b} e^{-bx_{old}} = \frac{a_{new}}{b} e^{-bx_{new}}$$

$$= \frac{a_{old}}{\alpha b} e^{-bx_{new}}$$

↓

$$-bx_{new} = \ln\left(\frac{\alpha b N_{back}}{a_{old}}\right)$$

$$and \quad \frac{bN_{back}}{a_{old}} = e^{-bx_{old}}$$

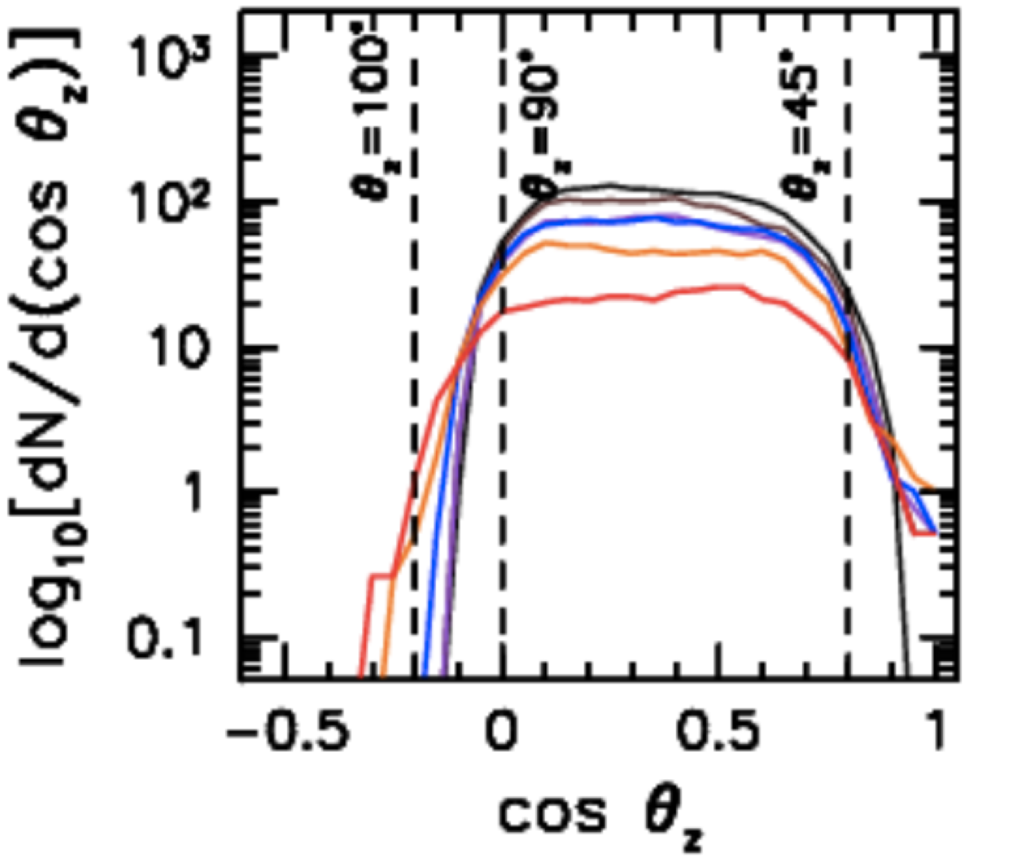
↓

$$x_{new} = x_{old} - \frac{\ln \alpha}{b}$$

The ARA Field-of-View

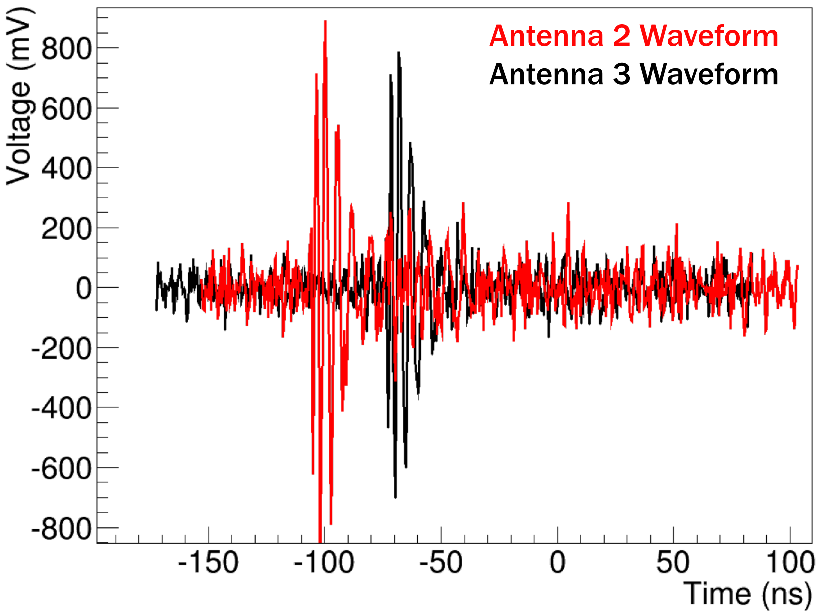
"Zenith angle distribution of detected neutrino arrival directions for a range of neutrino energies. Events are detected over a range from ~ 45◦ above the horizon to ~5◦ below it."

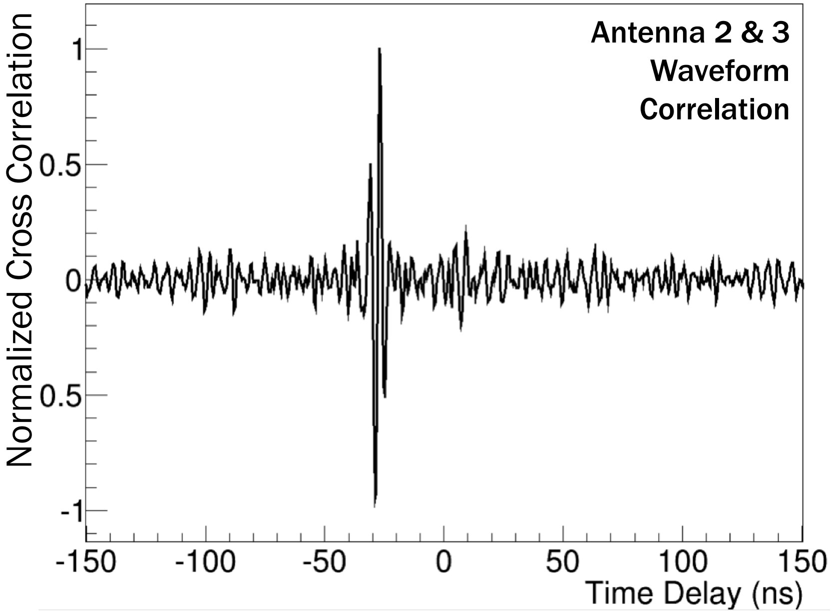
P. Allison *et. al.* "*Design and Initial Performance of the Askaryan Radio Array Prototype EeV Neutrino Detector at the South Pole.*" Astroparticle Physics (2011). https://www.sciencedirect.com/science/article/pii/S092765051100209X

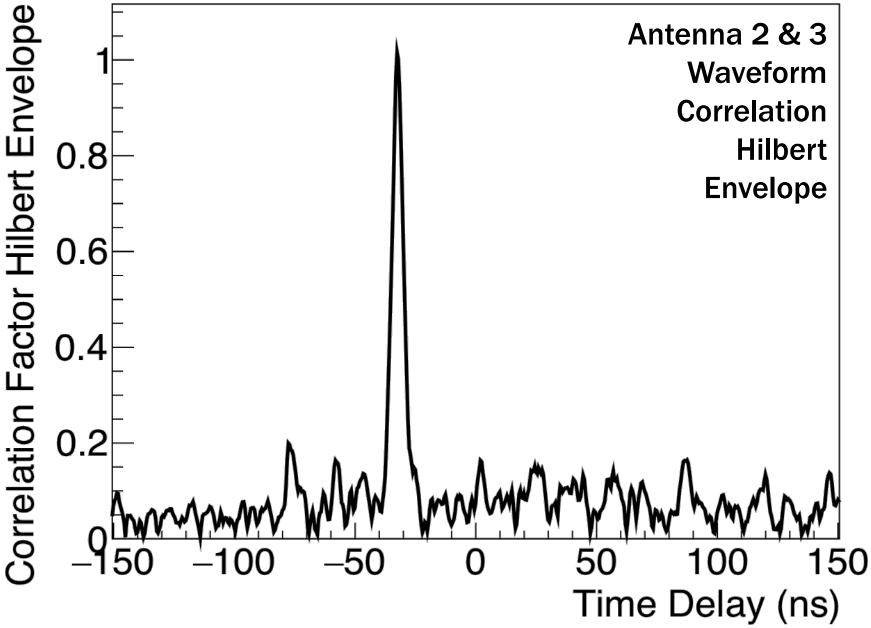


Reconstruction Details

- Interferometry based reconstruction:
  - Putative source angle → Time Delay between antennas → Correlation Value
  - Take Hilbert envelope to interpret as power





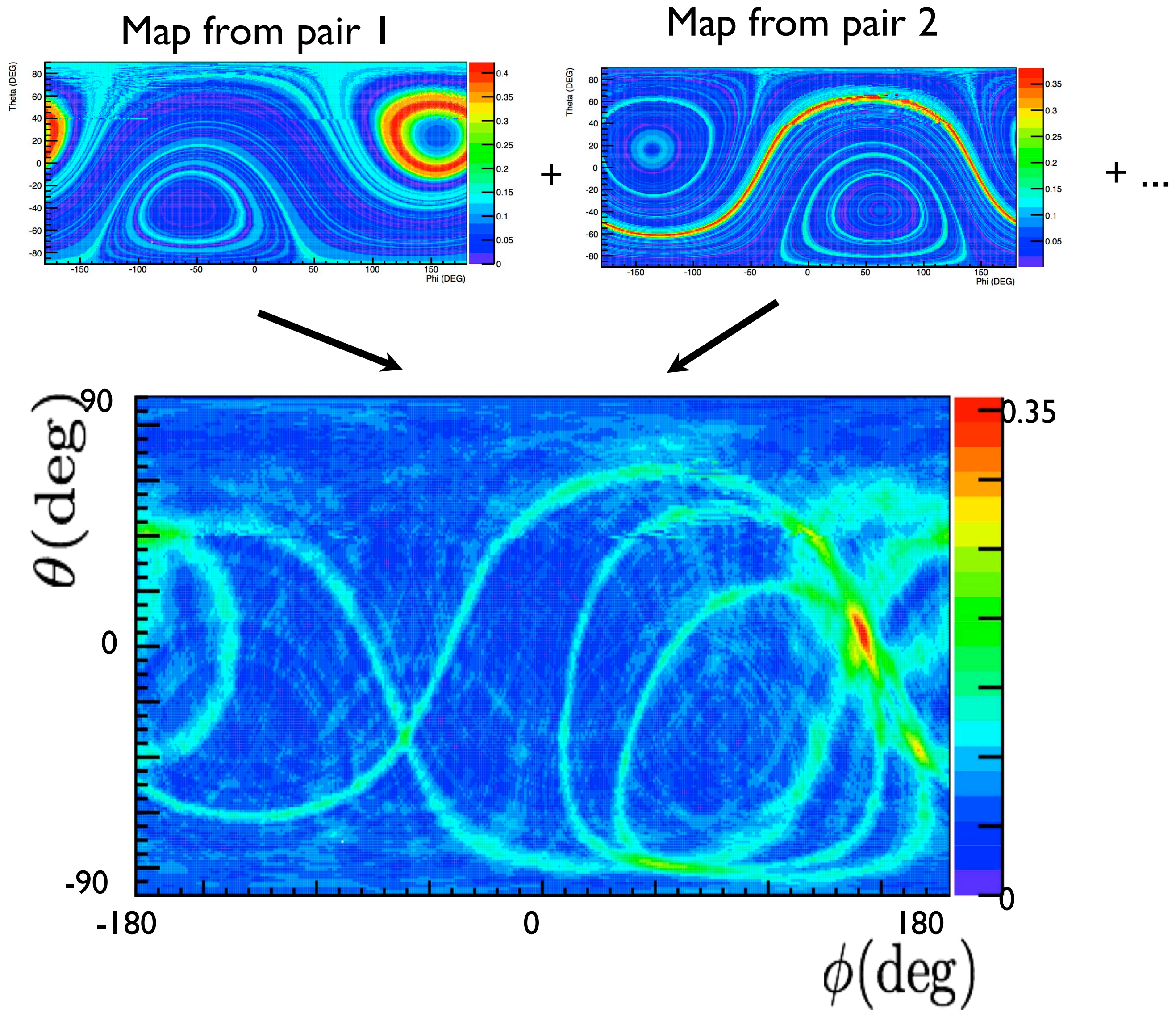


2. P. Allison *et. al.* j.astropartphys.2015.04.006
3. P. Allison *et. al.* j.astropartphys.2016.12.003

Interferometry (cont.)

Interferograms by E. Hong

- For pair of antennas, compute time delays and correlation values for all points on the sky
  - Propose a source distance, θ, and ϕ
  - Trace ray from source to array center
- Sum up correlation value for many pairs of antennas
- **Interpret peak in map as source direction**



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ARA GRB Study

- ARA searched for prompt neutrinos from GRBs
  - 10-minute signal window
  - Significantly looser cuts → factor 2.4 higher neutrino efficiency