Simulation-based inference for direction reconstruction of ultra-high-energy neutrinos and cosmic rays with radio arrays

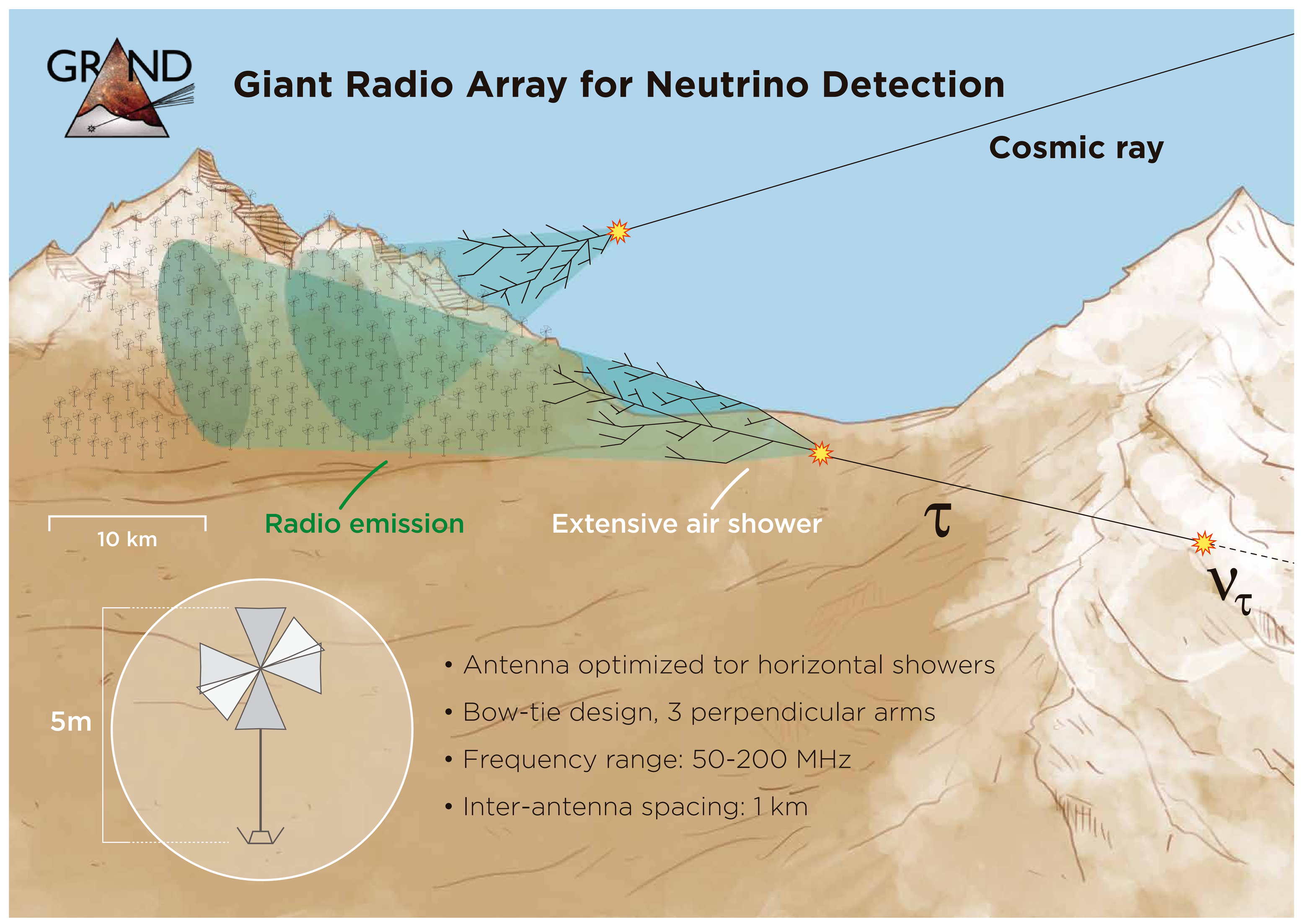
Oscar Macias[1,2], Zachary Mason[1], Matthew Ho[3], Arsène Ferrière[4], Aurélien Benoit-Lévy[4], Matías Tueros[5]
[1]San Francisco State University, [2]GRAPPA, University of Amsterdam, [3]Columbia University, [4]CEA List/LPNHE, [5]IFLP-CONICET/UNLP

Where to find further details?

Please find our paper and code at the following links:

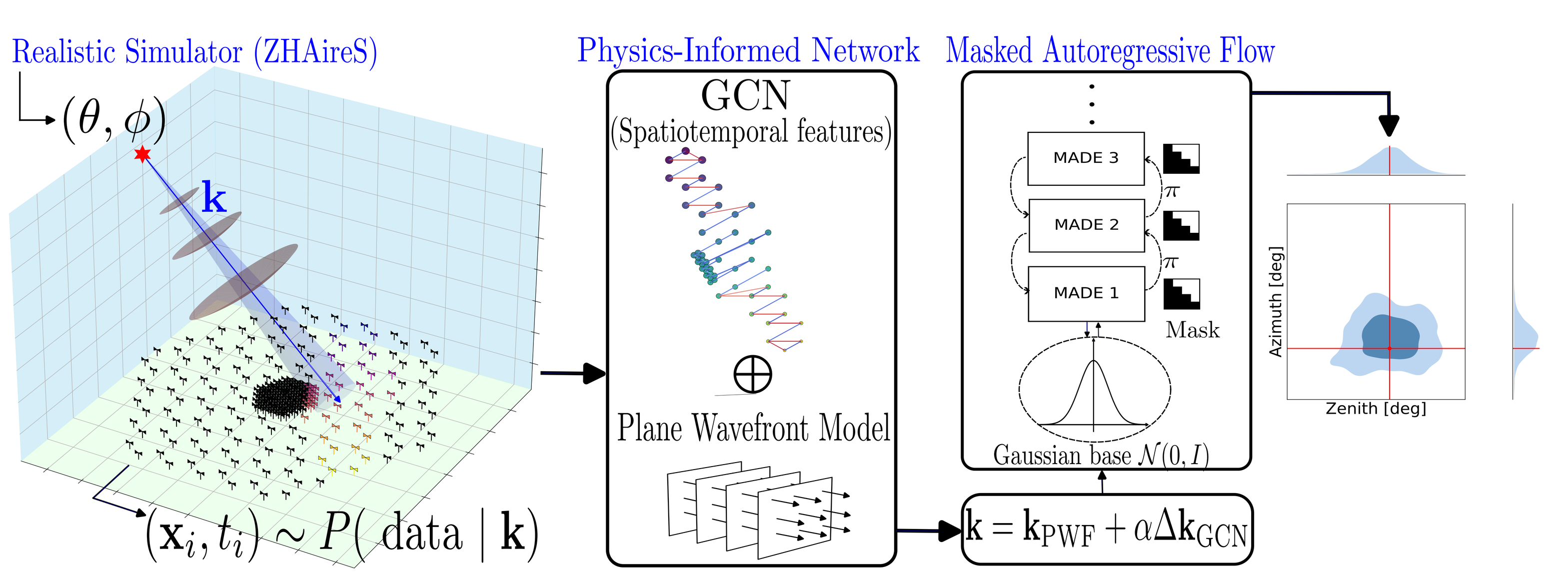
arXiv/PRD | Github | Zenodo

GRAND Detection Principle



GRAND is a planned radio array designed to detect ultra-high-energy neutrinos, cosmic rays, and gamma rays [Image credit: arXiv:1810.09994].

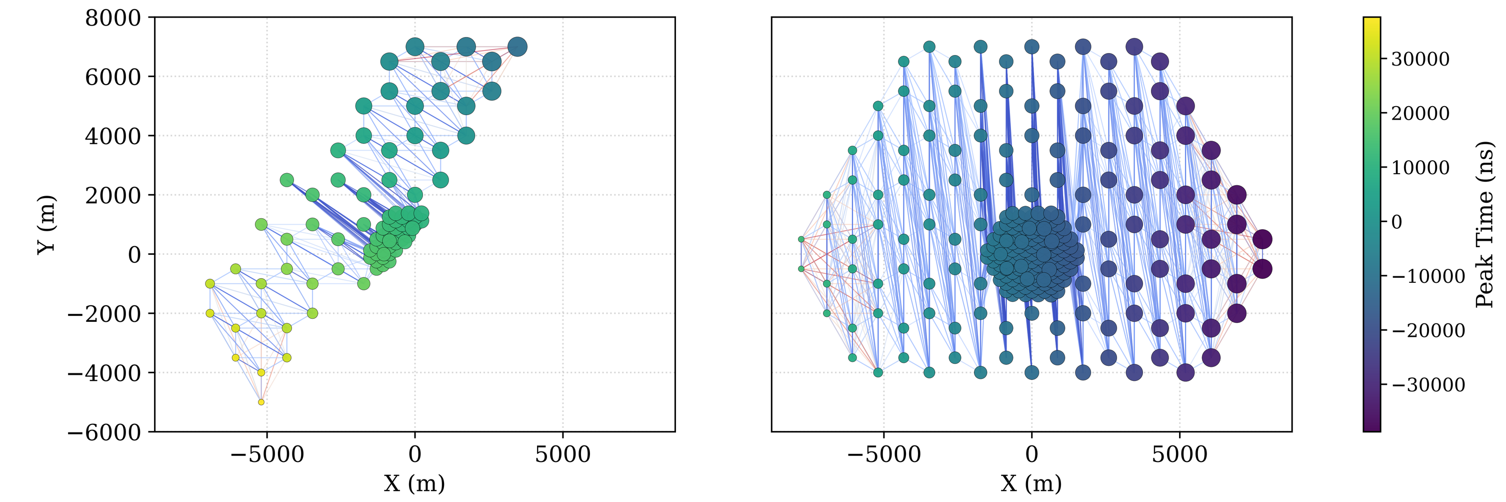
Simulation-based inference pipeline



A physics-informed Graph Convolution Network compresses the timing graph and an analytic wavefront model prior. An eight-block masked autoregressive flow returns the posterior $p(\boldsymbol{k} \mid x)$.

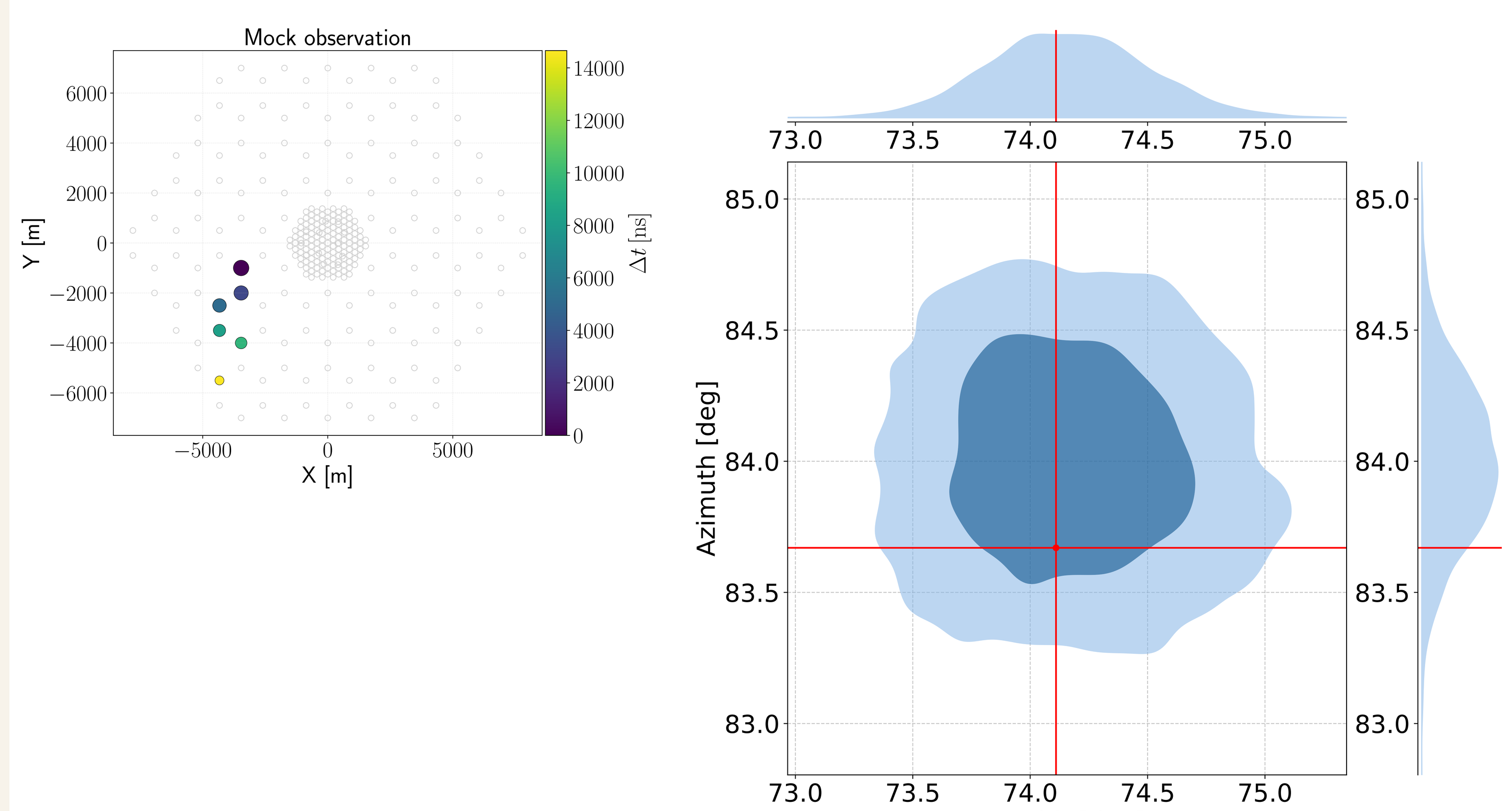
Data ingested with Graph Convolutional Networks

- ZHAireS electric-field simulations for GRANDProto300 geometry.
- Inputs per antenna: (x, y, z, t) plus a 5 ns Gaussian error in measured trigger time.
- Edges connect antennas close in arrival time.



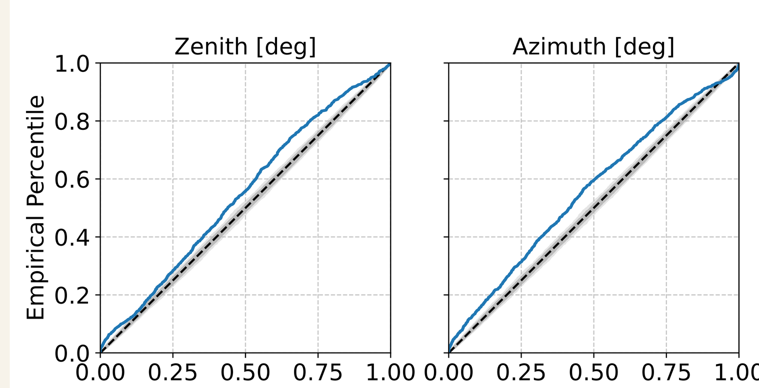
Temporal k-nearest-neighbor graphs for two simulated events. Color and marker size encode relative trigger time.

Example reconstruction with one held-out mock observation

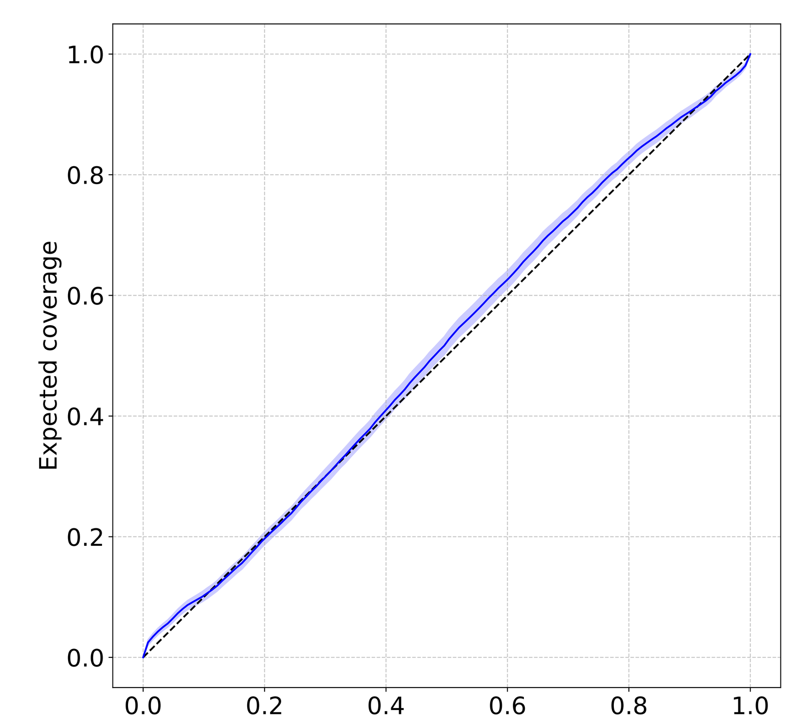


The output is a high-density posterior contour for the direction of the UHE particle.

Calibration is measured on withheld mock observations



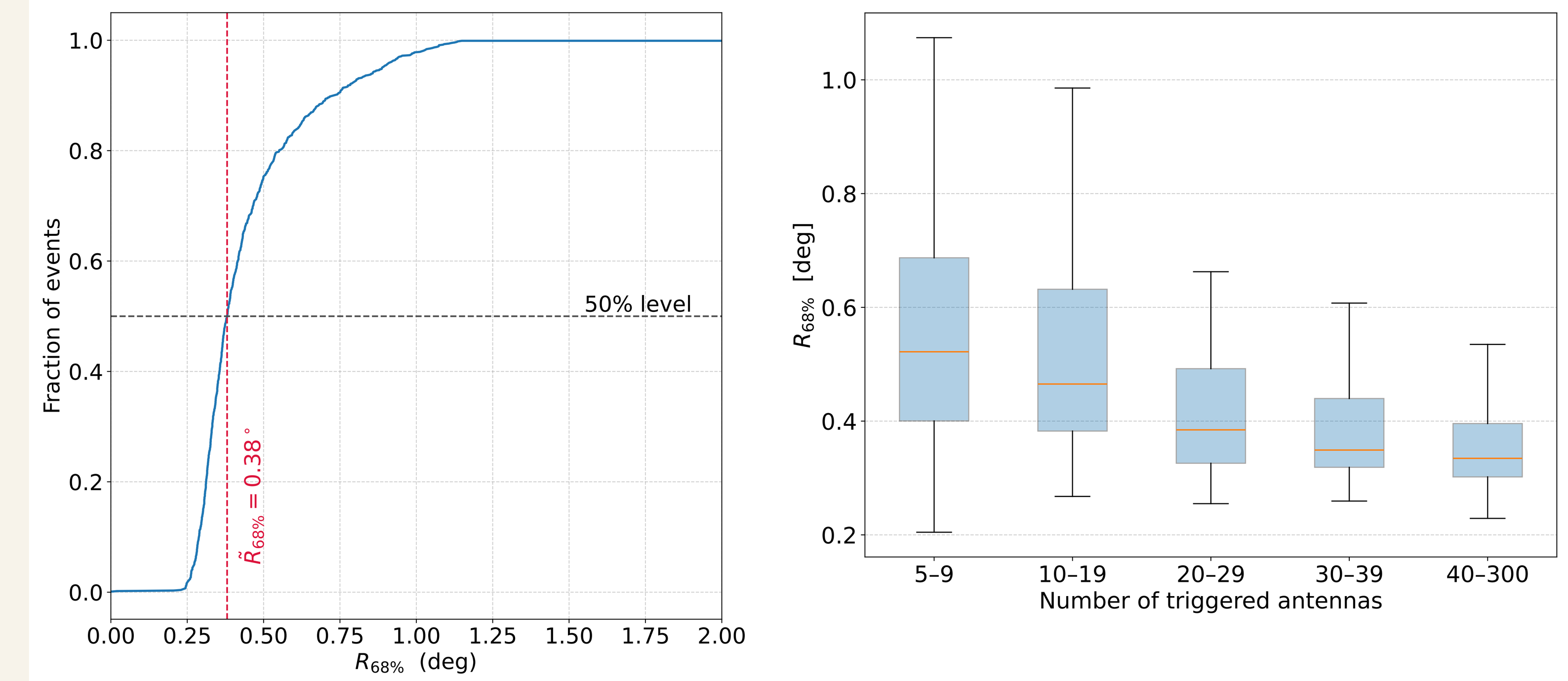
P-P curves in zenith and azimuth.



TARP on the full direction vector $\boldsymbol{k}$.

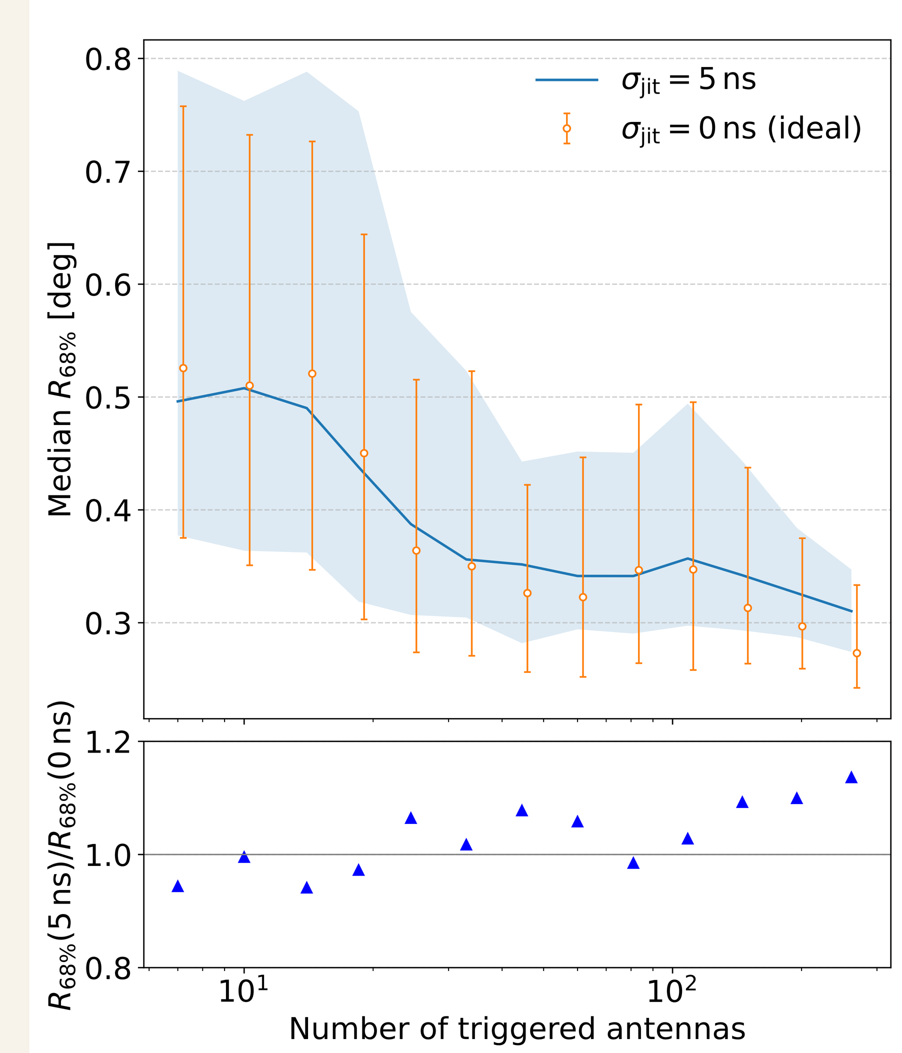
P-P and TARP tests show the learned posteriors are mildly conservative.

Resolution increases with the number of triggered antennas



The reconstruction is sharpest for inclined showers observed by several antennas, reaching a median 68% posterior containment angle of 0.38°.

Impact of instrumental noise on the angular resolution



Once $\gtrsim 30$ antennas trigger, more stations keep narrowing the posterior but do not move the centroid below the stochastic timing offset. In these simulations the floor sits near 0.3° for 5 ns antenna clock jitter.

UHE neutrino/CR direction reconstruction resolution

A plane-wavefront physical model gives a strong direction prior. A normalizing flow learns the direction reconstruction error. On realistic radio air-shower simulations, our pipeline reconstructs events with a median resolution of

0.38°	$71 \pm 2\%$	3%
median R_{68}	**coverage of 68% cones**	**events above 1°**