Improved directional uncertainties for IceCube realtime alerts

Tianlu Yuan for the IceCube Collaboration

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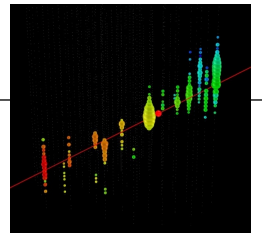
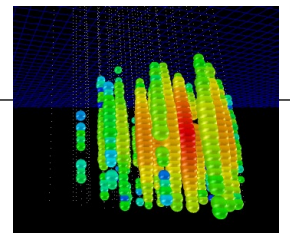
TeVPA24, Chicago, IL

WISCONSIN
UNIVERSITY OF WISCONSIN–MADISON

Realtime alerts in IceCube



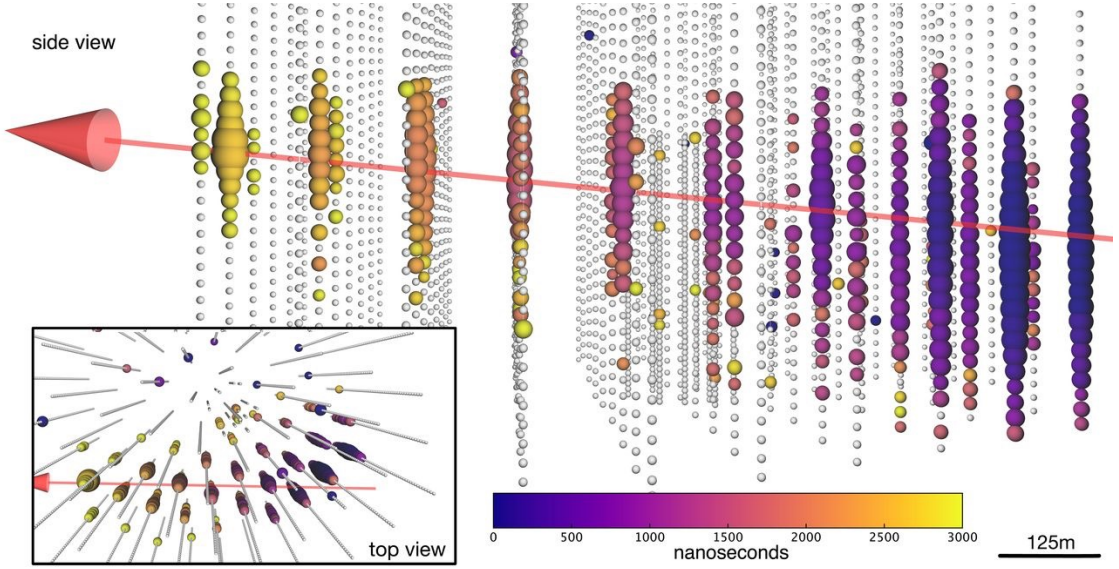


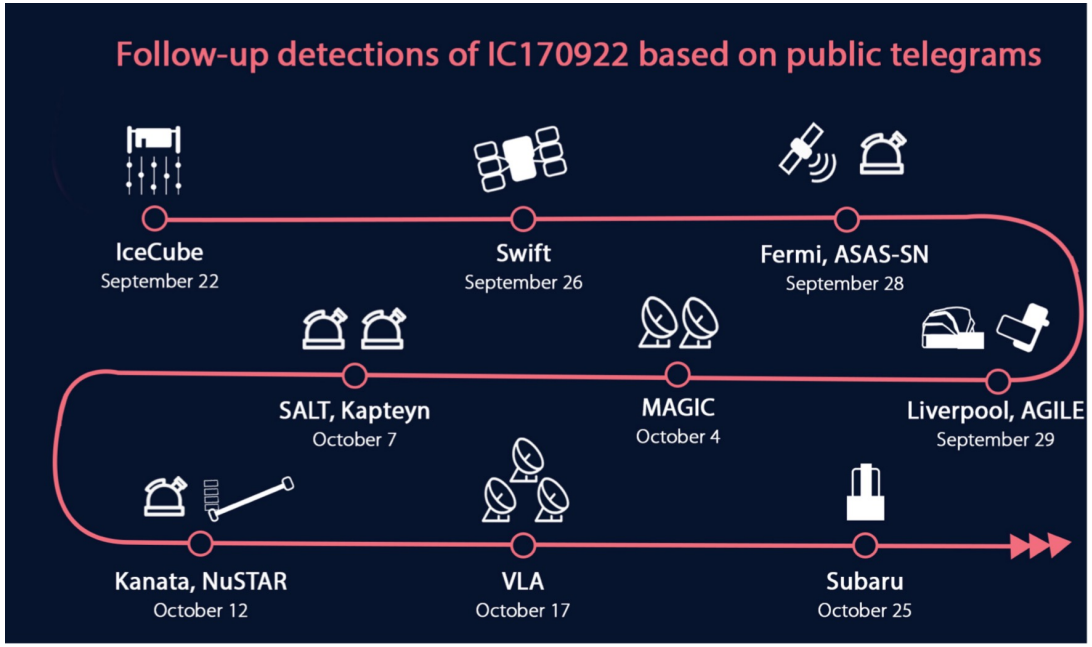
High-quality events at high energies

→ fast circularized error followed up by **likelihood scan** for 50/90 contour

Archival track alerts catalog: 2023 IceCat-1 *ApJS* **269** 25

First astrophysical source TXS 0506+056, 2018 *Science* **361** 6398

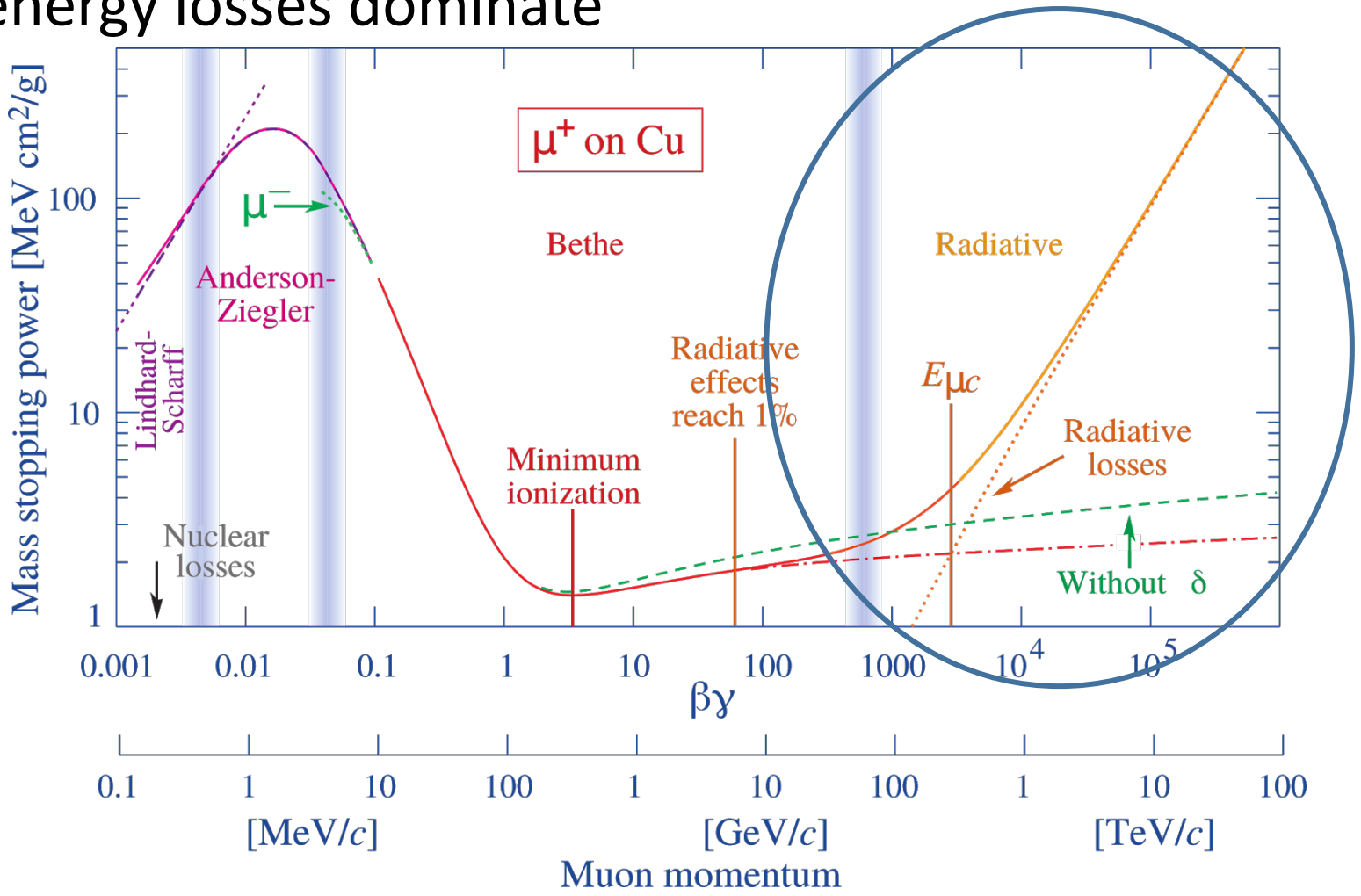




Muon stochastics at high energies

High-energy muons lose energy via **radiative** processes

Stochastic energy losses dominate

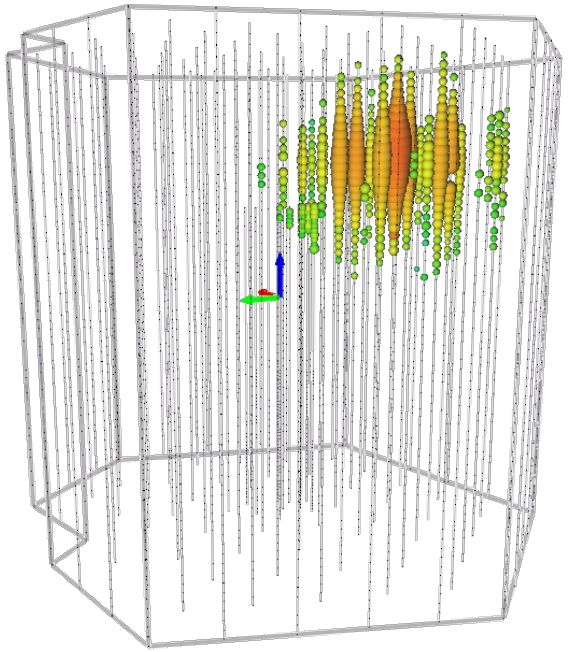


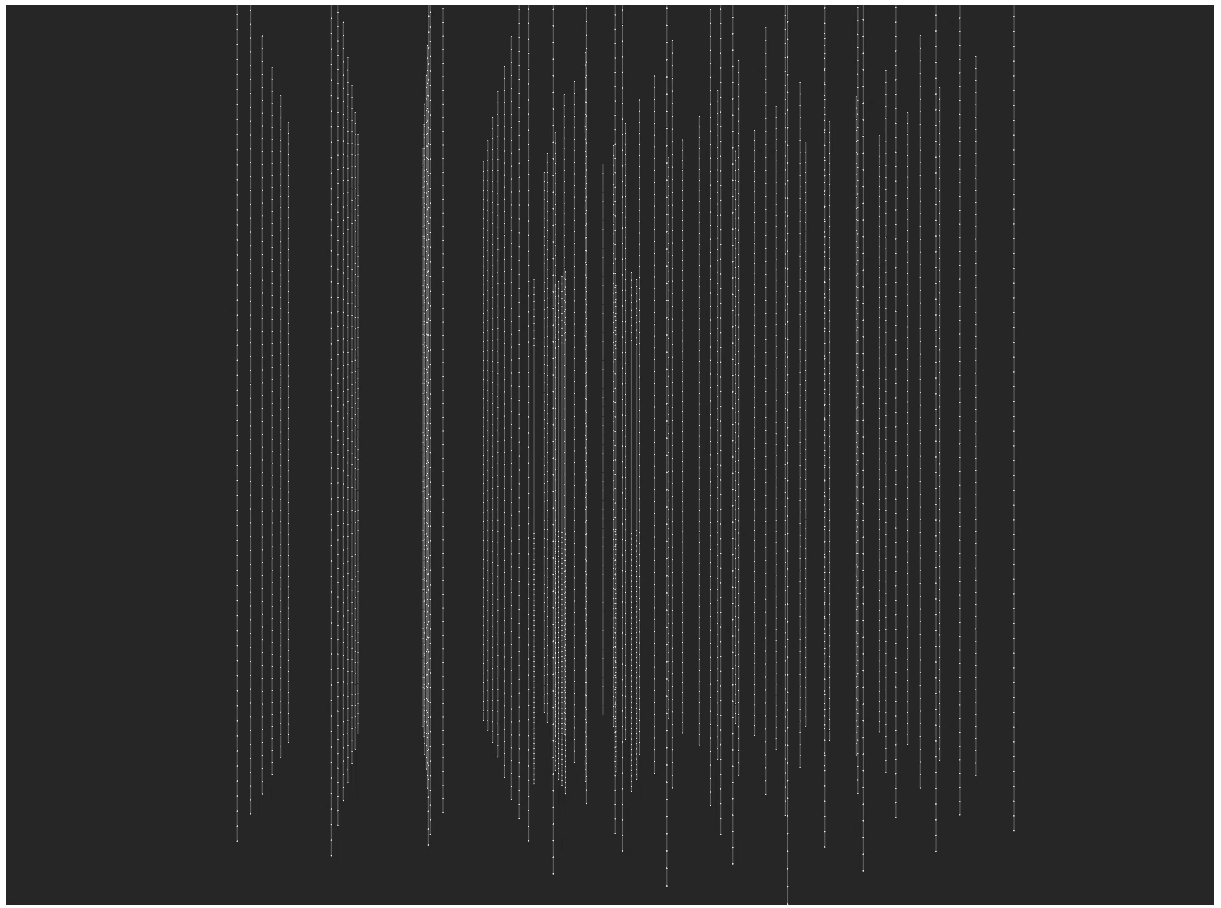
Reconstruction approach

Segment high-energy tracks into multiple colinear cascades

Apply cascade photoelectron-yield models

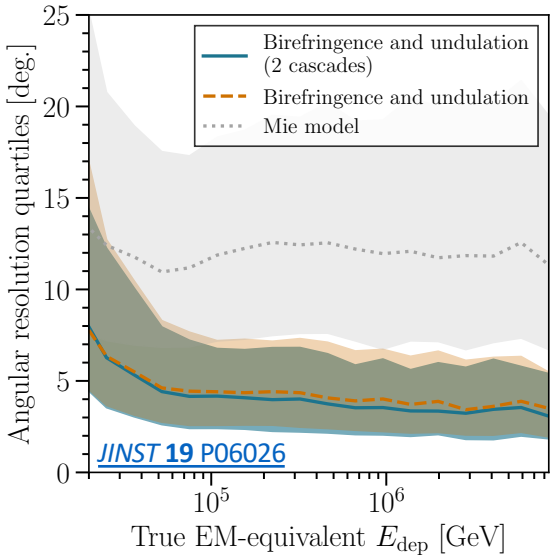
Unfold track into multiple reconstructed cascades to model energy losses (Ref. 2014 *JINST* **9** P03009)



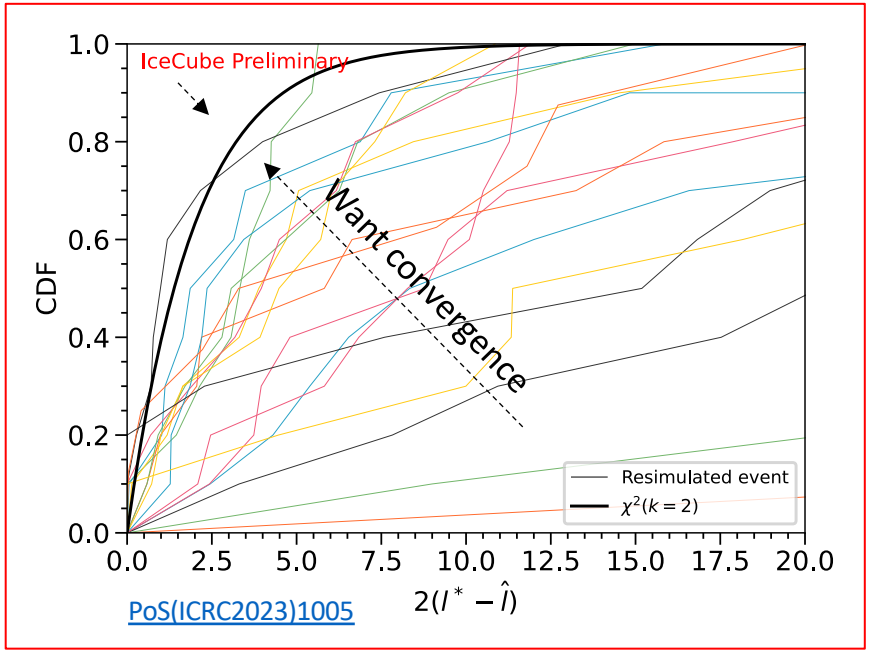


Existing issues

1. Reconstruction of realtime alerts relies on a very outdated ice model (gray, dotted)
   - Many improvements in ice modeling directly applicable for realtime reconstruction



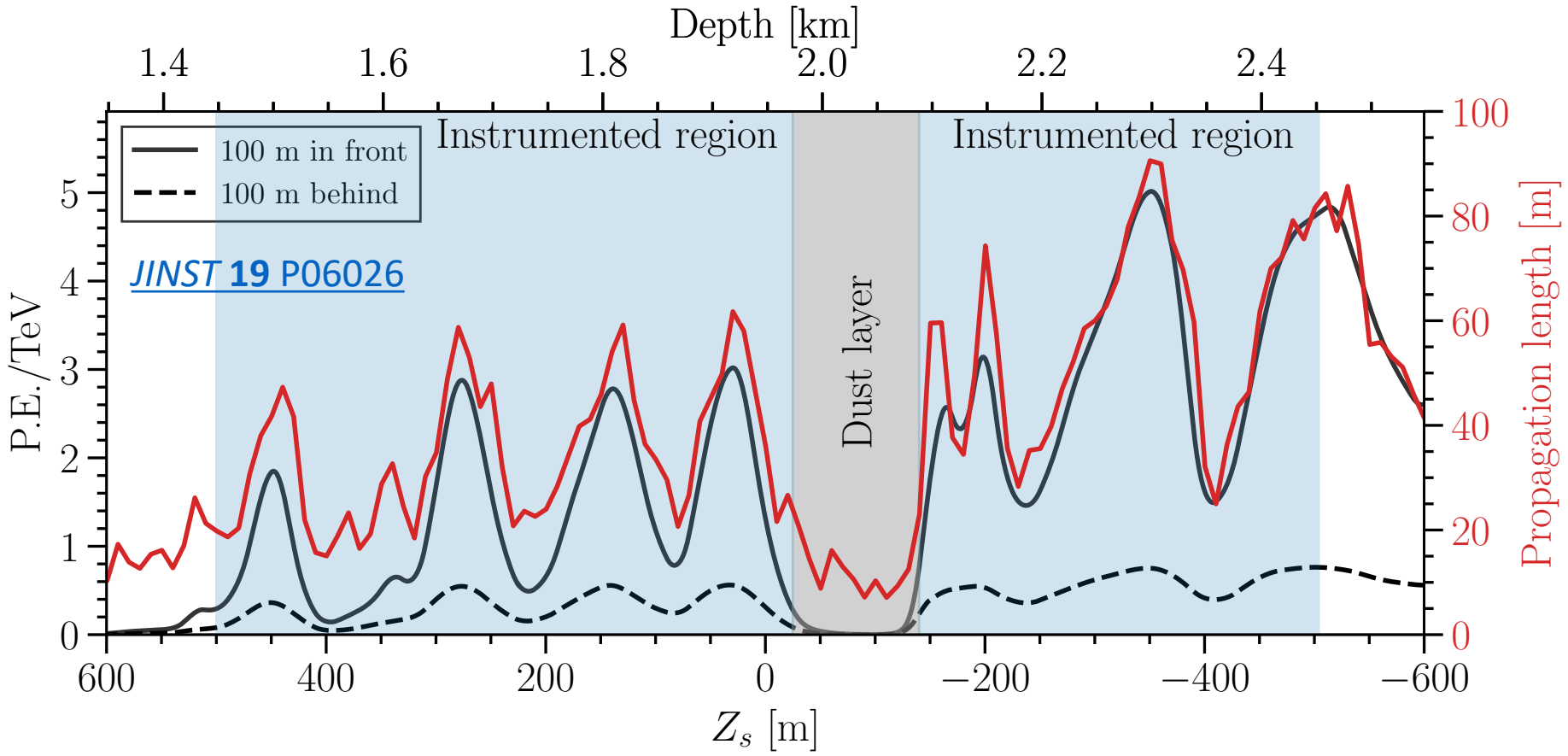
2. Delta-llh space is inconsistent and coverage varies wildly across events
   - Have been assigning 50/90% levels based on resimulations of a single archival alert



Arrival photons and the ice

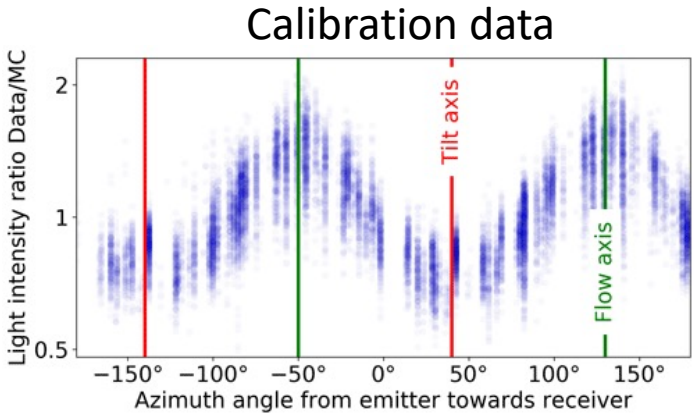
Shown: time-integrated cascade photoelectron yields as a function of depth, 100m in front of (solid) and behind (dashed)

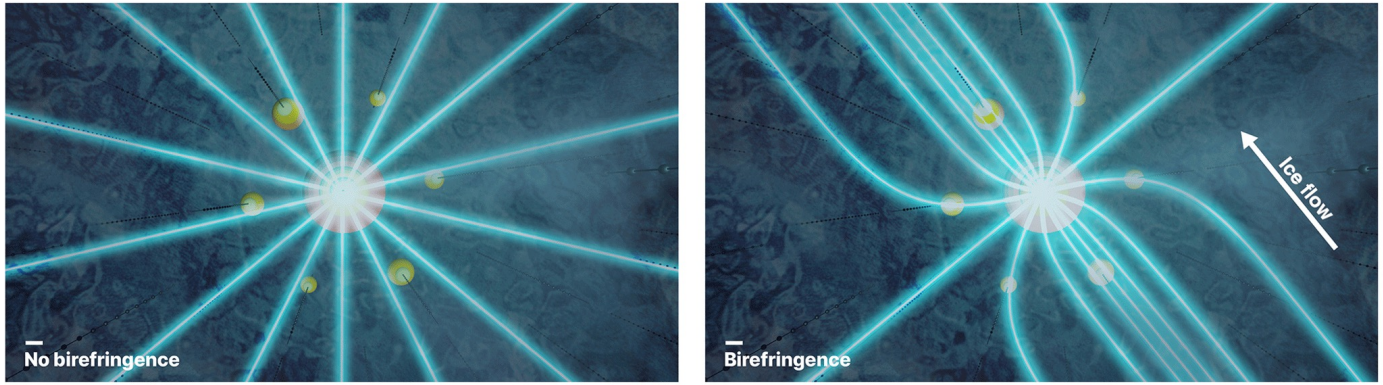
Strong correlation between **ice properties** and arrival photons

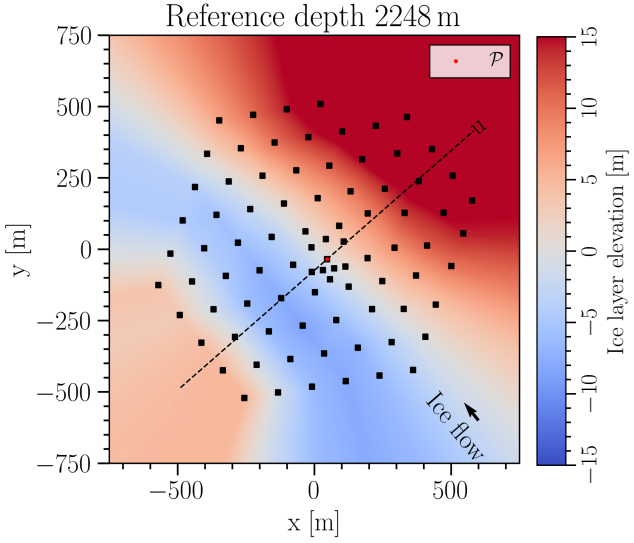


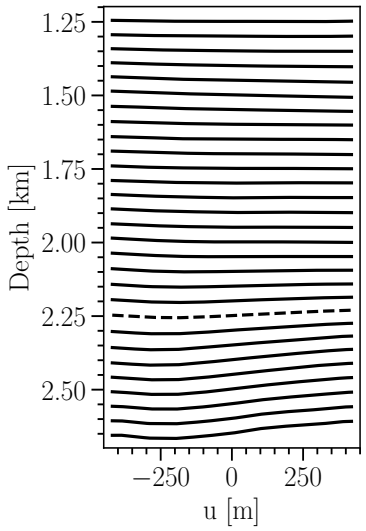
Ice anisotropies: birefringence and undulations

Birefringence due to polycrystalline structure of ice crystals (2024 *The Cryosphere* **18** 75)

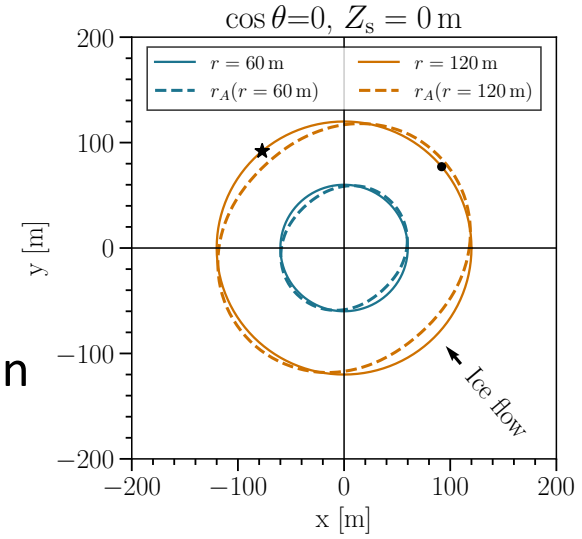


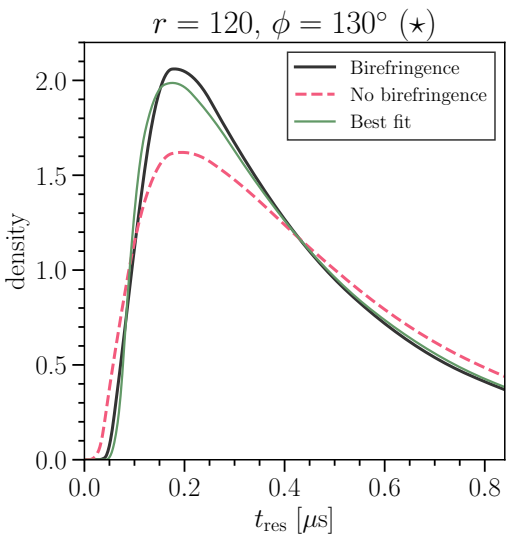






Coordinate transformations for reconstruction





Refs. *PoS* ICRC2023 975, *JINST* **19** P06026

Performance updates for realtime alerts

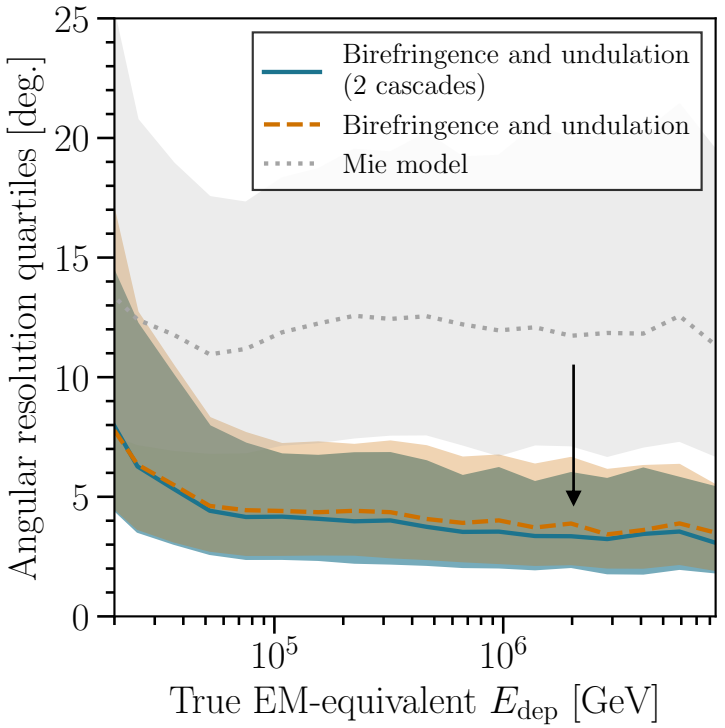
Apply new cascade photon model (*JINST* **19** P06026)

Apply model where it is a good approximation

Help minimizer find true minimum

Introduce a model error to Poisson likelihood (2019 *JHEP* **06** 030)

New skymap scanner framework allows for coverage and robustness checks (*PoS* ICRC2023 1106)



Cascade resolution improvements, usable for track reconstructions based on segmented cascades

Coverage checks

Question of interest: can we obtain accurate confidence regions that cover at the appropriate level

Use (re)simulations of alert-like events

- Each event is resimulated many times with identical MC truth settings

Variations in detected signatures due to randomness in photon propagation and detector response chain

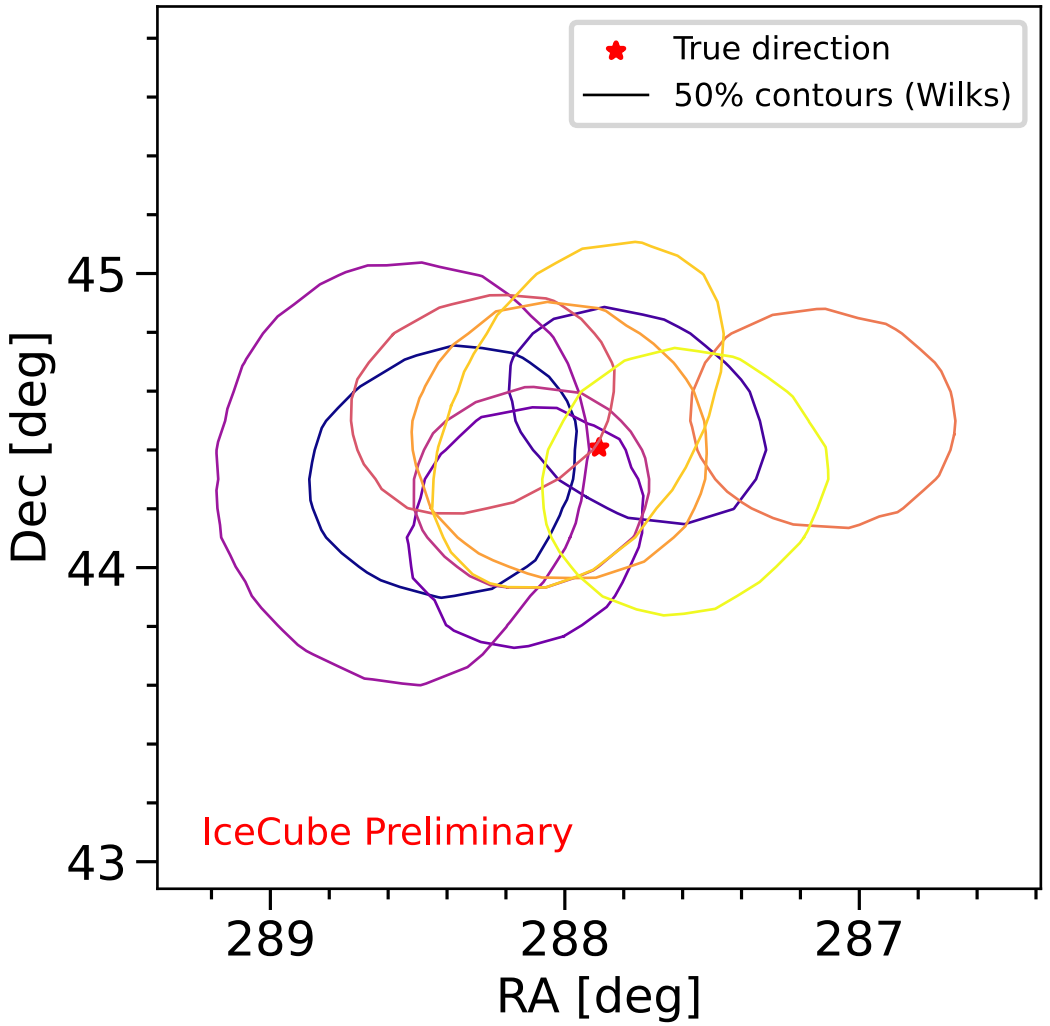
Goal: consistent, per-event directional llh maps

Details of coverage calculations

Figure shows 50% contours from ten resimulations of a single MC event

Metrics of interest

- Distribution of delta-llh between true direction and each scan's minimum should converge to chi2(k=2)
- Count of how often true direction lies within 50% (and 90%) contours

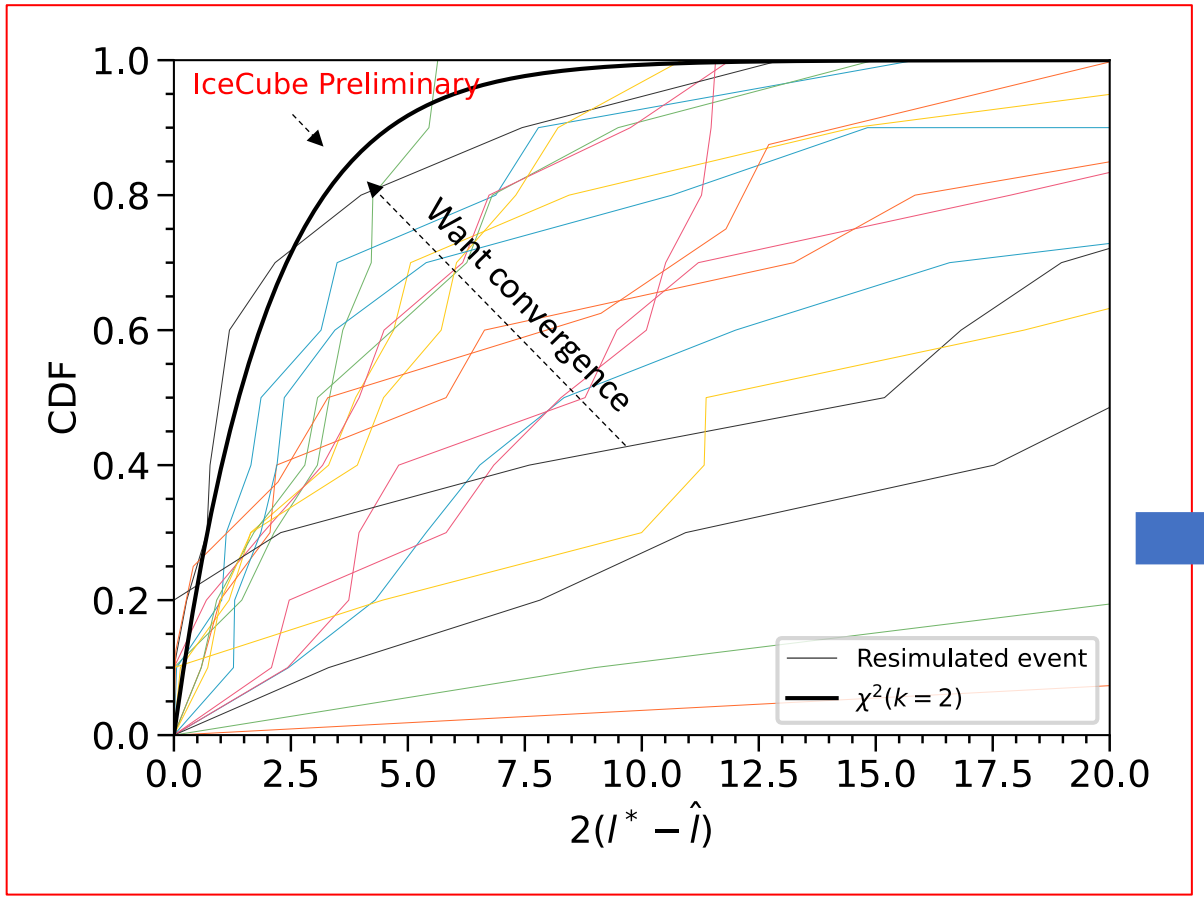


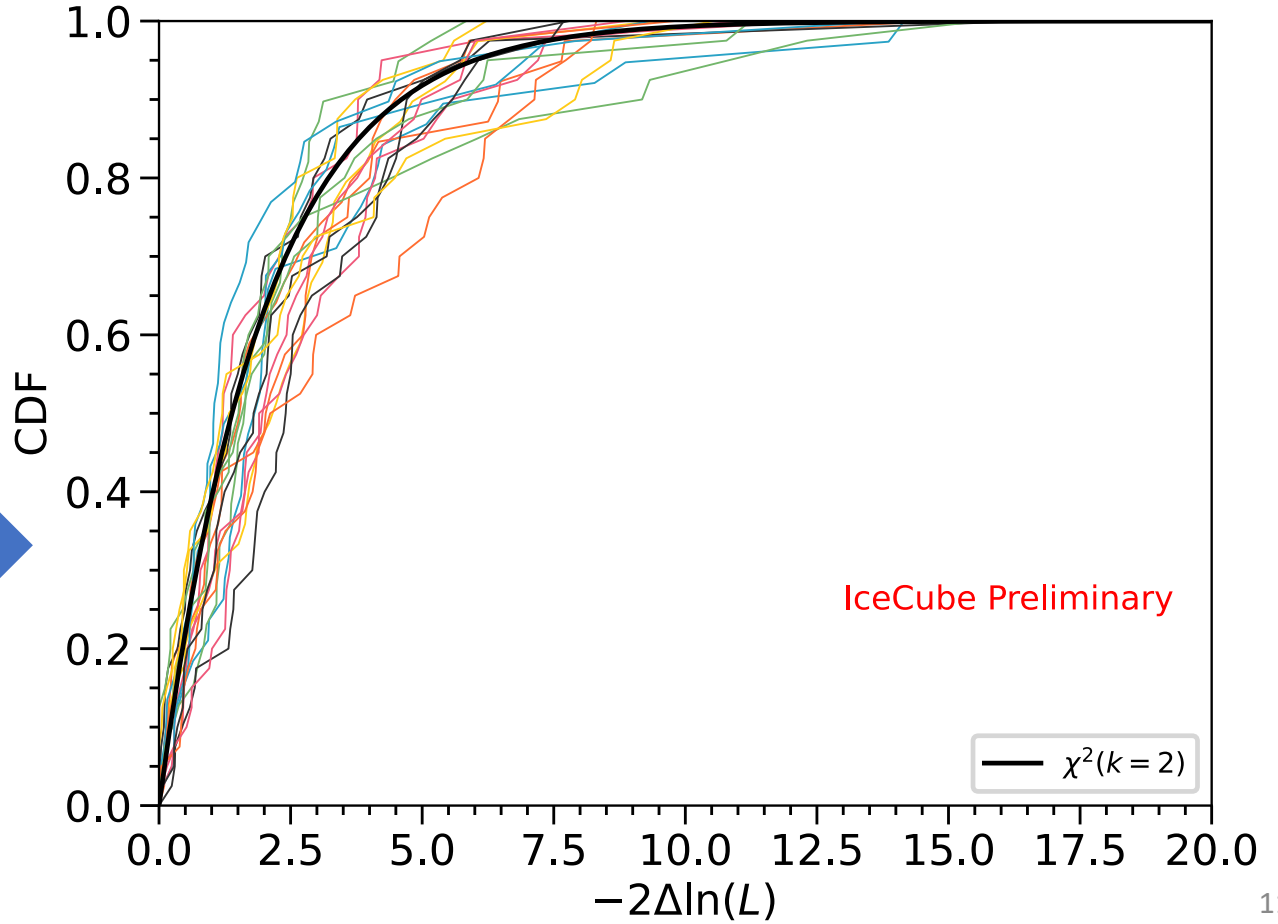
Contours assuming Wilks' theorem, **chi2(k=2)**

Resulting coverage

Much improved when viewed over same events as shown earlier

Convergence towards chi-2 with NDOF=2

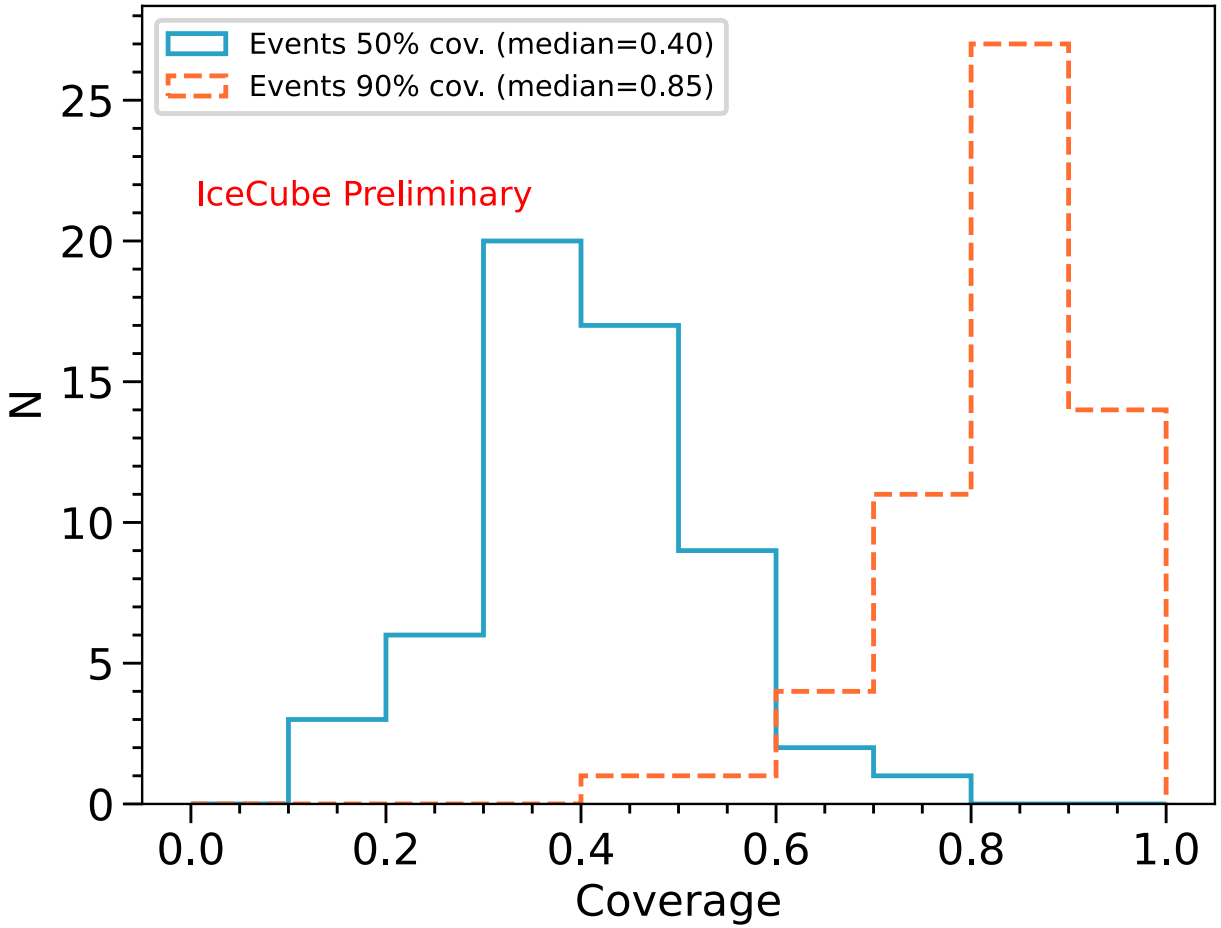


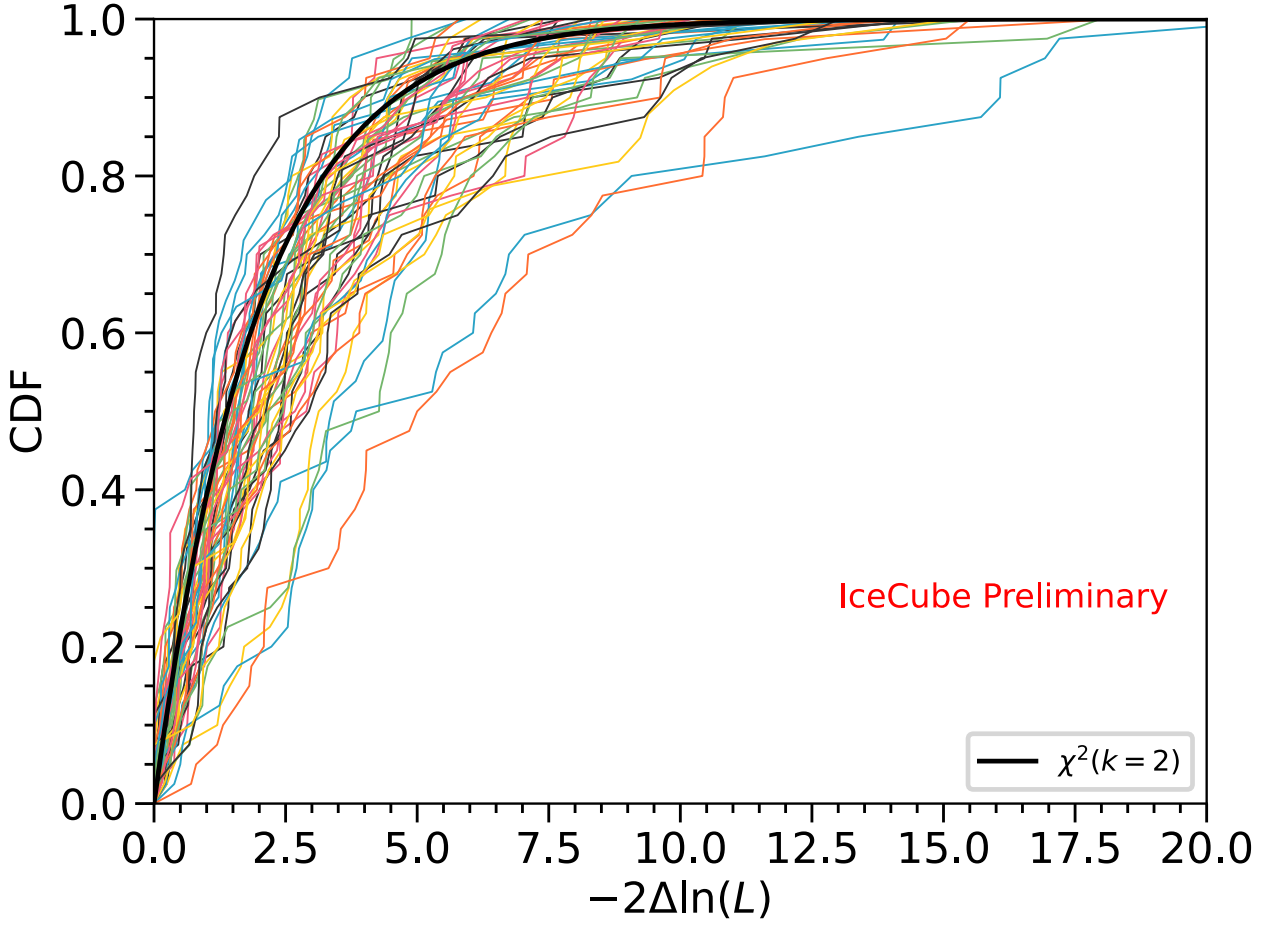


With added statistics

Adding in additional resimulated events

Some outlier events indicates room to improve



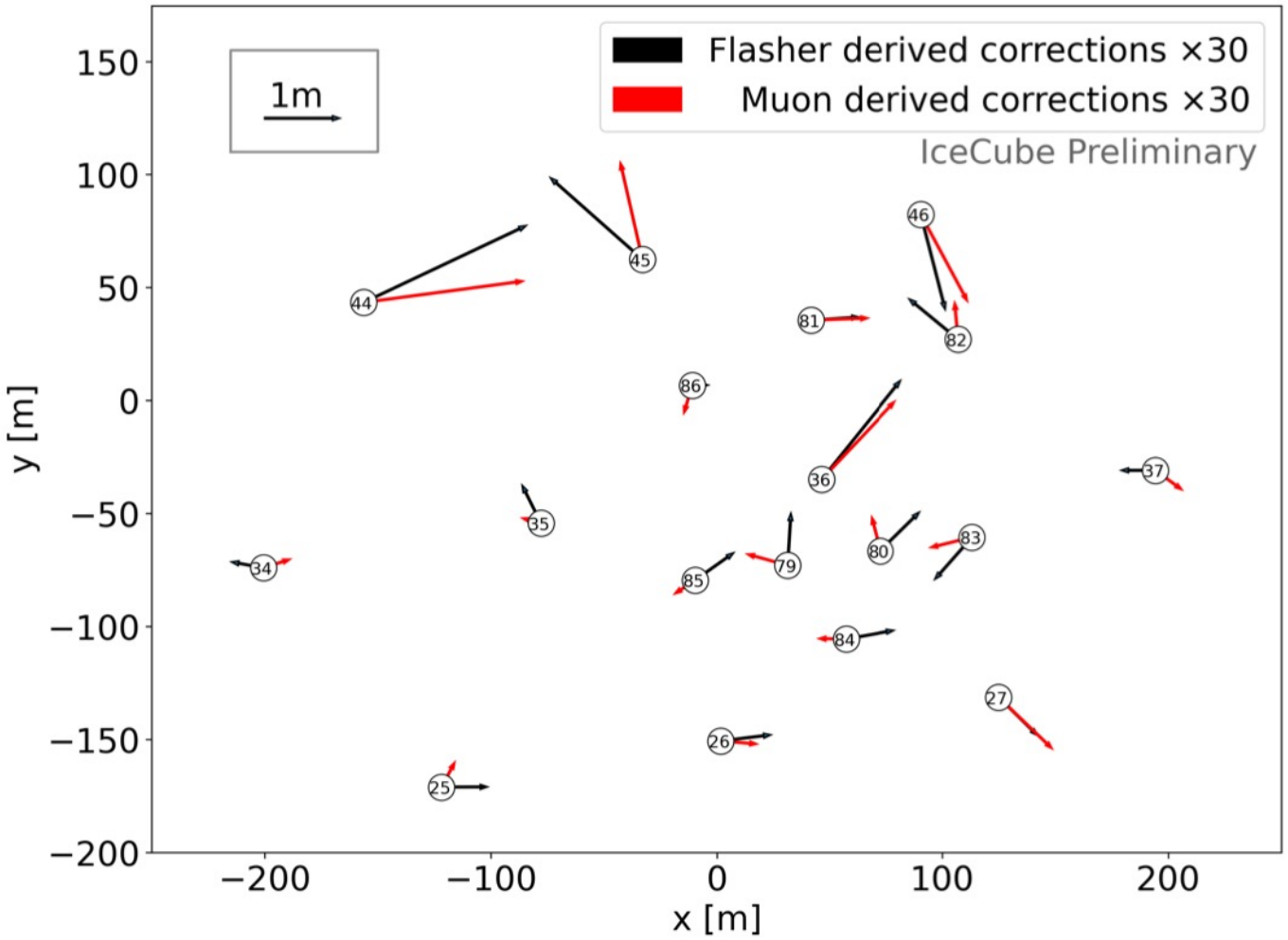


Geometry calibration

Ref: PoS(ICRC23) 988

Ongoing calibration work to refine string and DOM positions

Not a conclusive picture yet



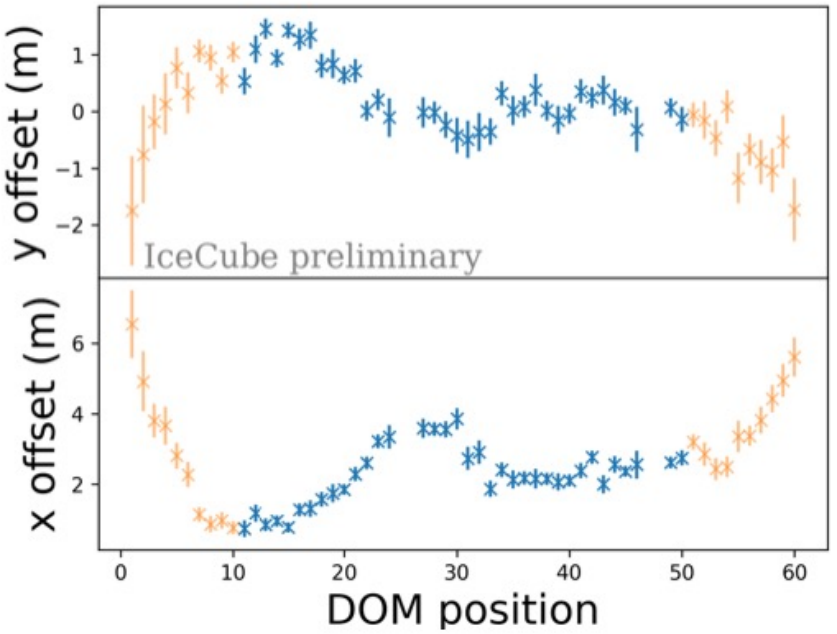
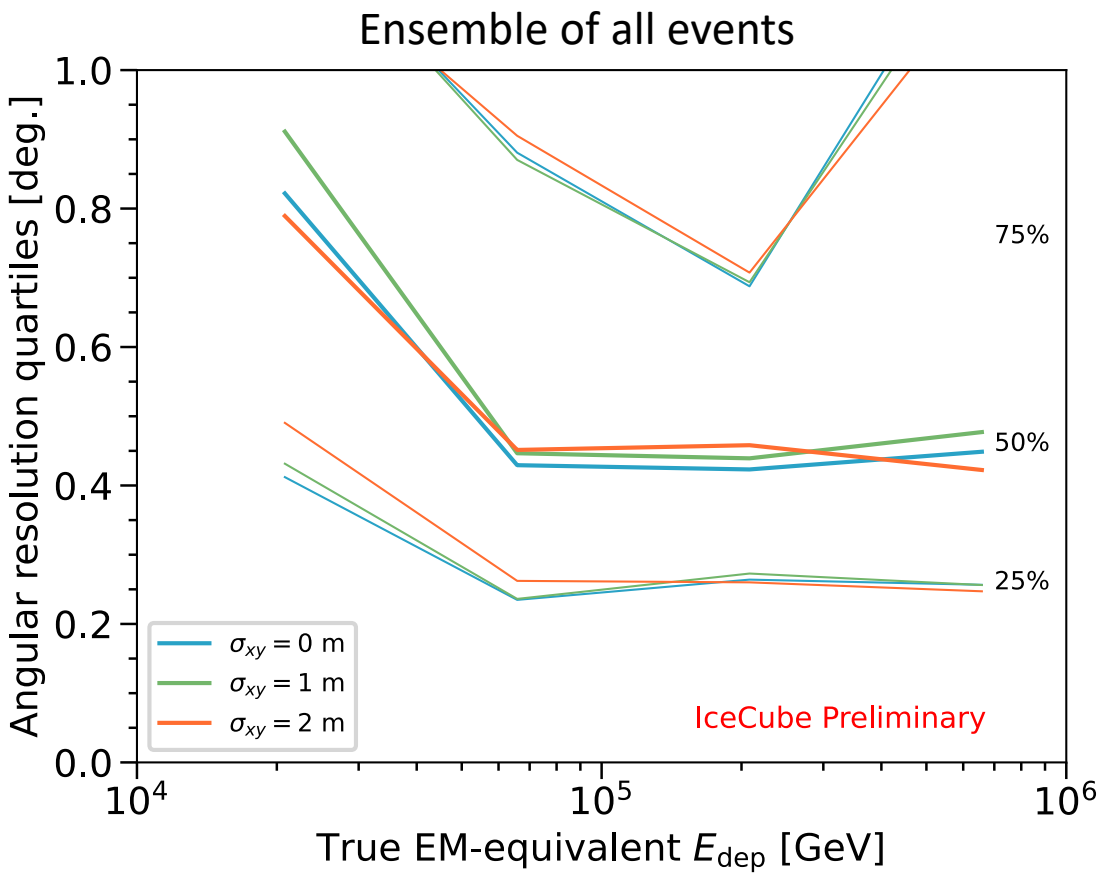


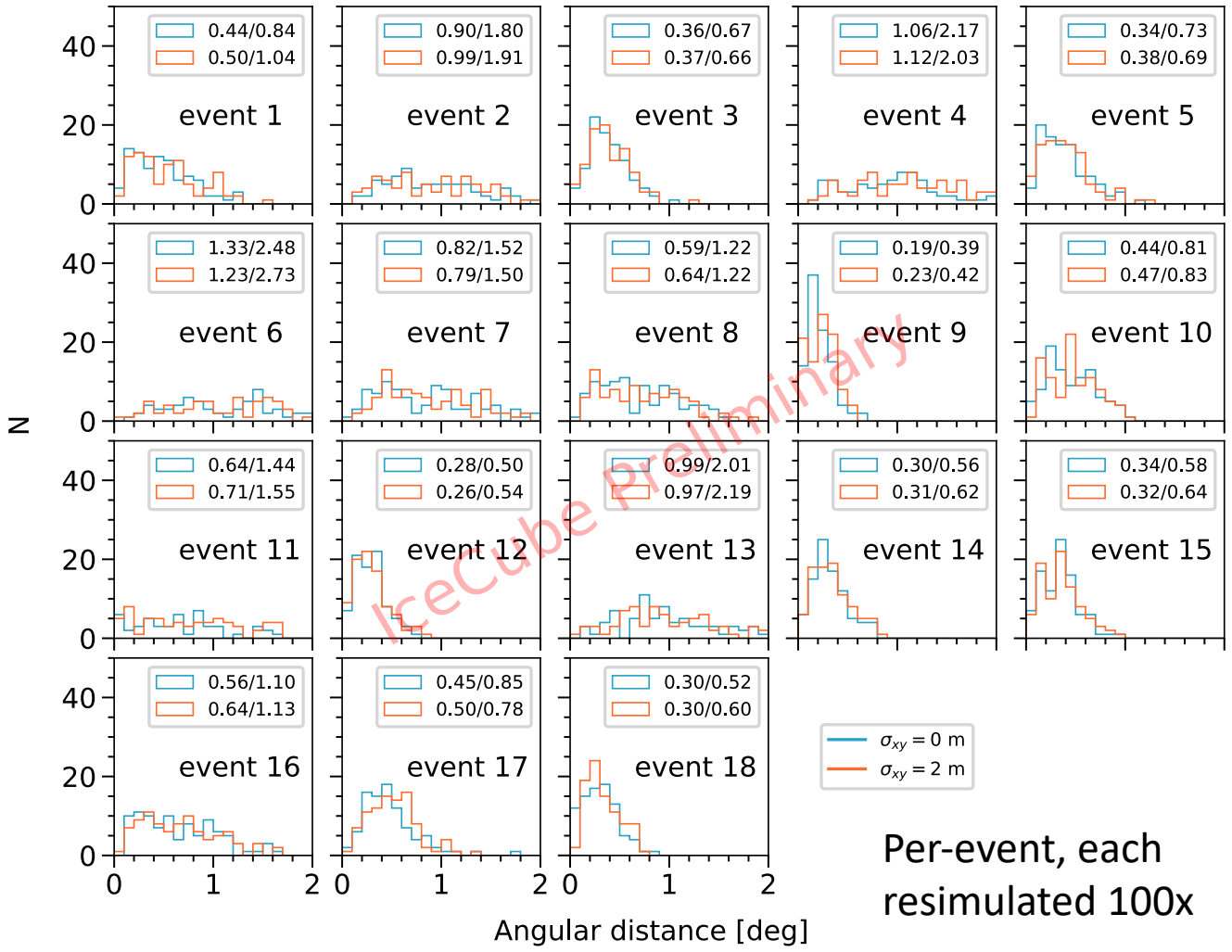
Figure 2: Per-DOM lateral positions as fitted for string 44. Note the continuous development with depth. For the top and bottom DOMs large biases are systematically observed. Thus the 10 DOMs at the top and at the bottom are excluded when calculating the string-average position.

Robustness check 1 (geometry)

Study impact of geometry uncertainty

Vary DOM positions by gaus(σ={1m, 2m}), check impact on resolutions





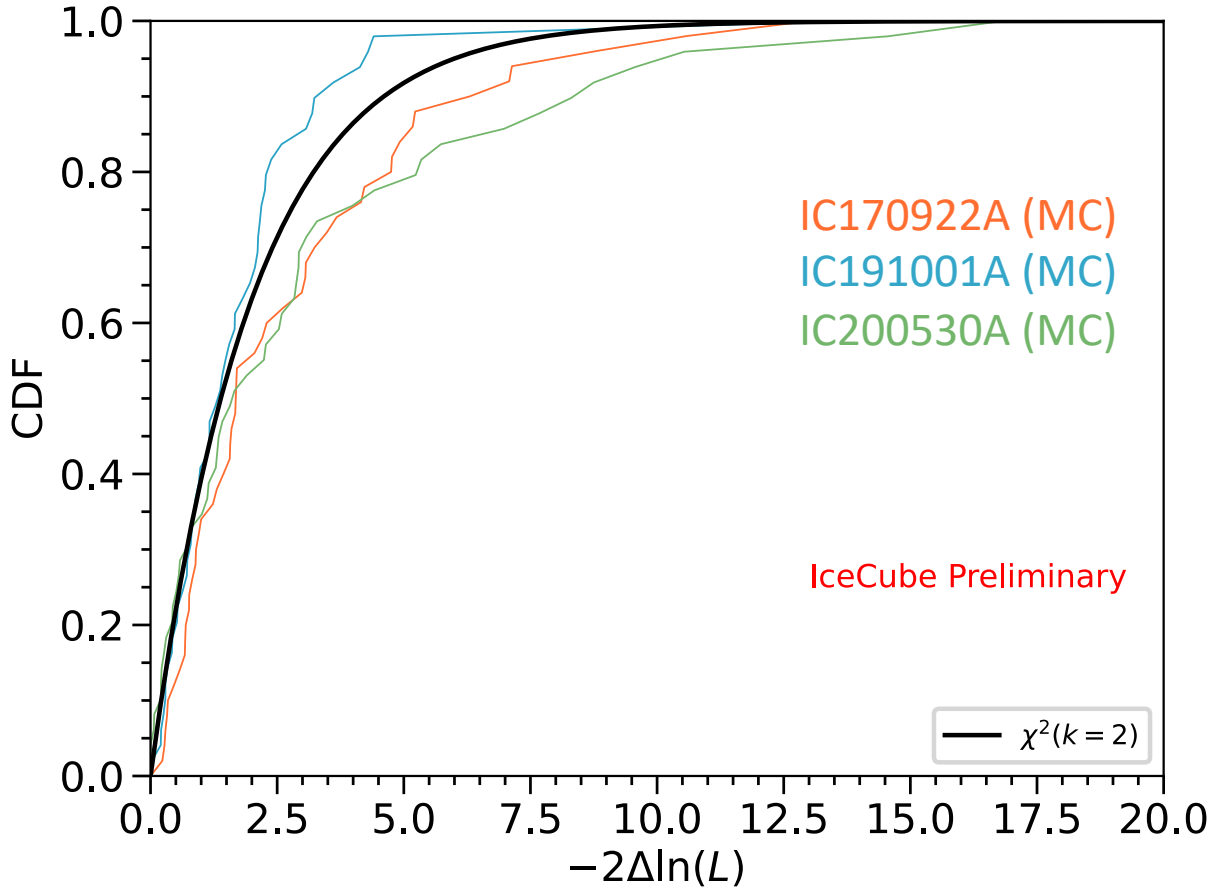
Per-event, each resimulated 100x

Robustness check 2 (event properties)

Check impact of slight **variations** in event properties including position, direction and stochastic energy losses

Based on resimulations of three real data alerts

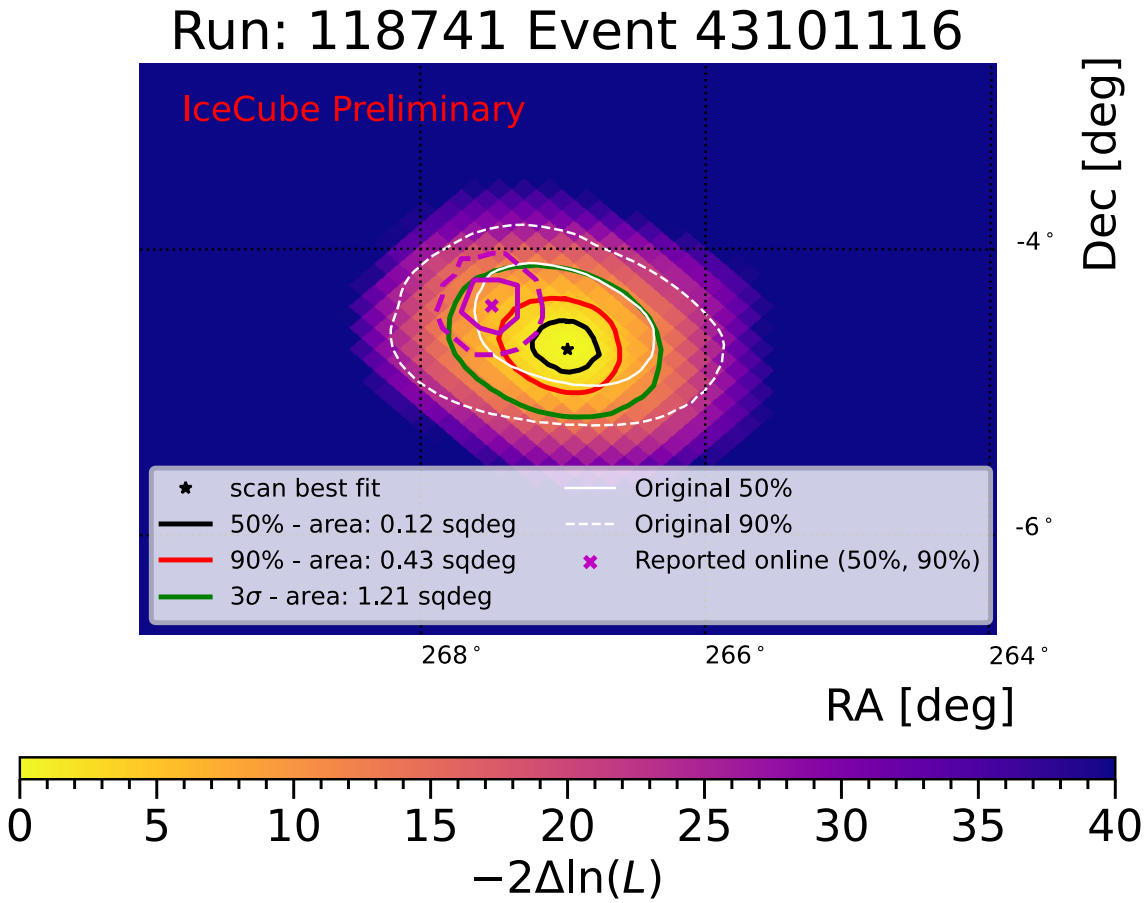
- Used for contour calibration
- *Previously* resulted in significant differences in contour size
- With *updated* algorithm, Wilks' contour would be more robust

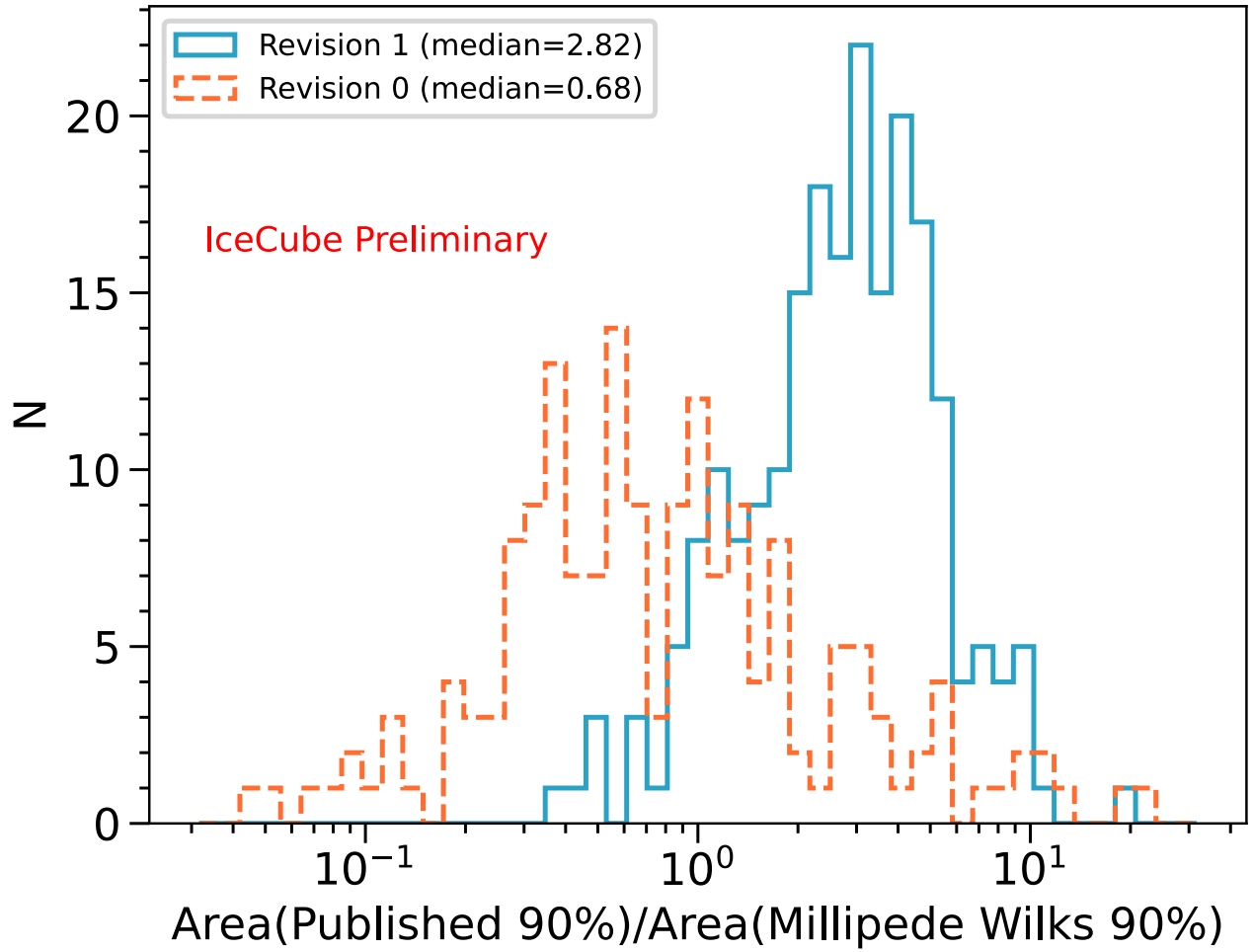


Real data comparison

Reperformed scans over IceCat-1 events

Compared to published Rev. 1, updated 90% areas tend to be smaller by factor of ~2.8x





Summary

Current IceCube realtime alert reconstructions suffer from a couple issues

1. Outdated ice model
2. Inconsistent llh space

Includes improvements to account for

- updated knowledge of ice properties
- cascade modeling
- minimization and more

→ Improved coverage properties, interpretable llh map

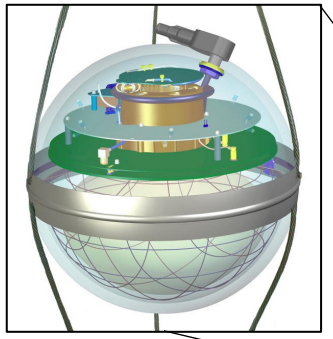
Robust against geometry systematic and variations in event properties

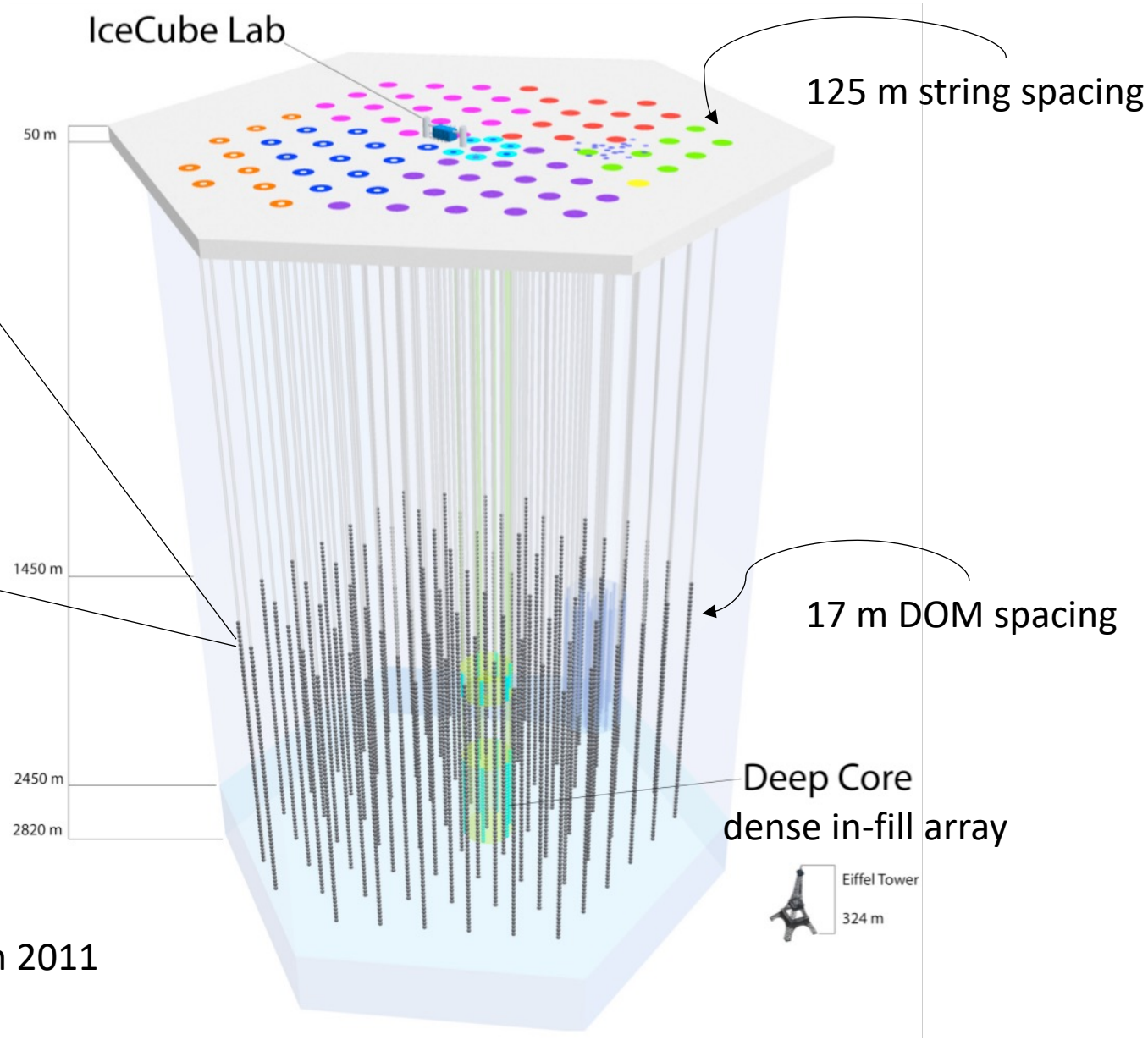
- in part due to exclusion of nearest, difficult-to-model DOMs

Backups

The IceCube neutrino observatory

Digital Optical Module (DOM)





5160 DOMs

Fully operational in 2011

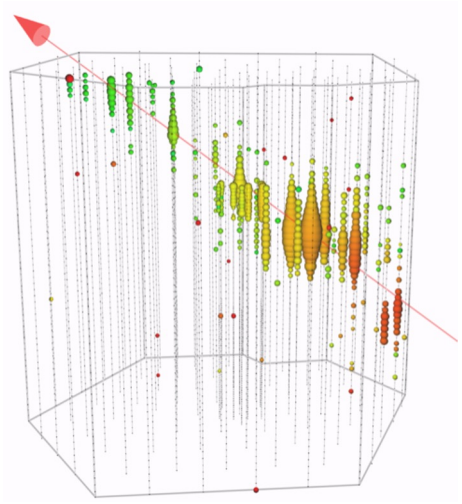
Distributed processing

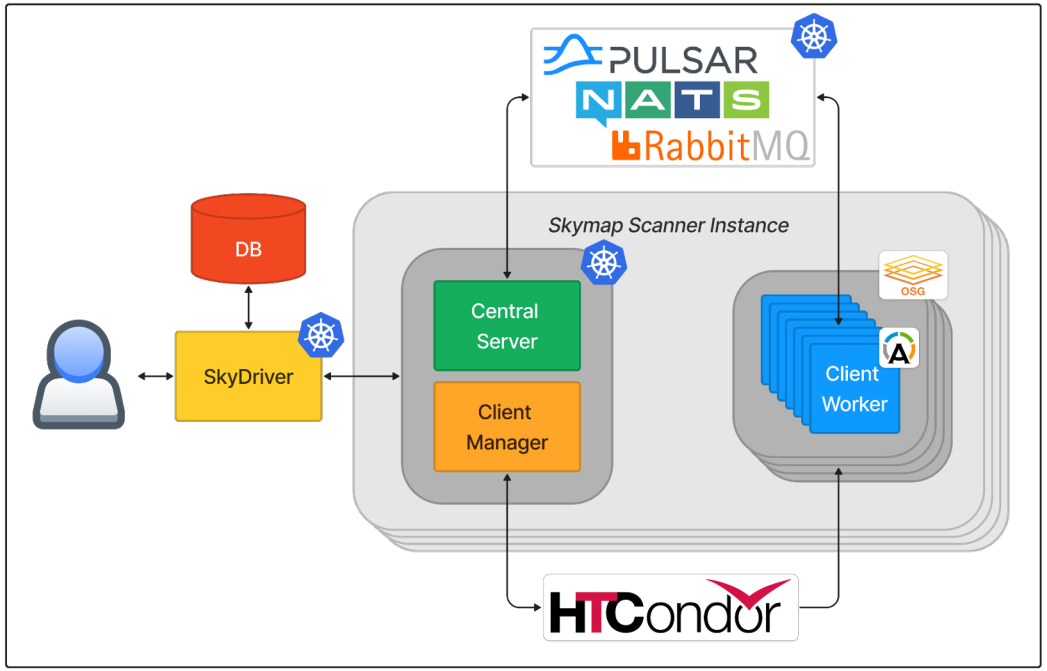
Full scans over the sky can be performed in massively parallel fashion

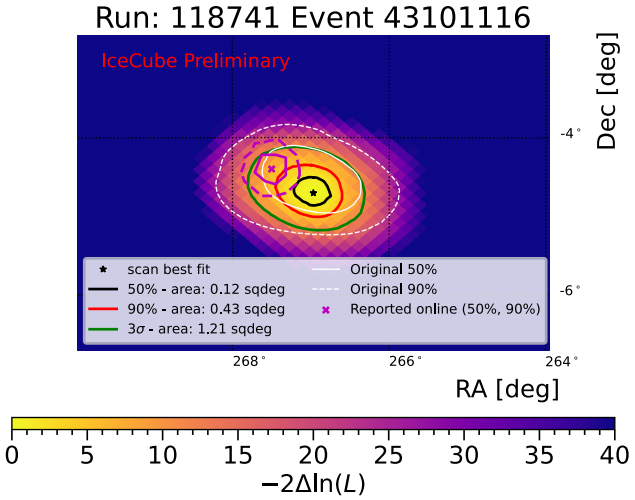
Still, requires coordination and CPUs

skymap-scanner github, 2023 CHEP proceedings SkyDriver

- Utilize OSG resources via HTCondor; O(10) min for ~finished state







Overall TS distribution

Chi2(k=2) for comparison