HEALPix-based Analysis of Burst Neutrinos for Supernova Direction Reconstruction at Super-Kamiokande

#575

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## Supernova Early Alerts at Super-Kamiokande (SK)

- The detection of supernova (SN) burst neutrinos provide early alert of a nearby core-collapse supernova.
  - Speed and pointing accuracy vital for early multi-messenger observation of SBO.

- Major upgrades to Super-Kamiokande SN alert, "SNWatch"
  - Gd-loading in detector water volume.
  - SN burst hardware and SNWatch analysis (see Poster **#105**).
  - New automated alert generation on GCN[1].
  - Improved SN direction finding and pointing.

New SN Direction Reconstruction, "HP-fitter"

- Direction reconstruction from SN burst event directions at SK.
  - IBD and O-16 event directions nearly isotropic.
 - Electron elastic scatter (ES) forward peaked around SN neutrino flux direction, $\hat{d}_{\phi,SN}$.
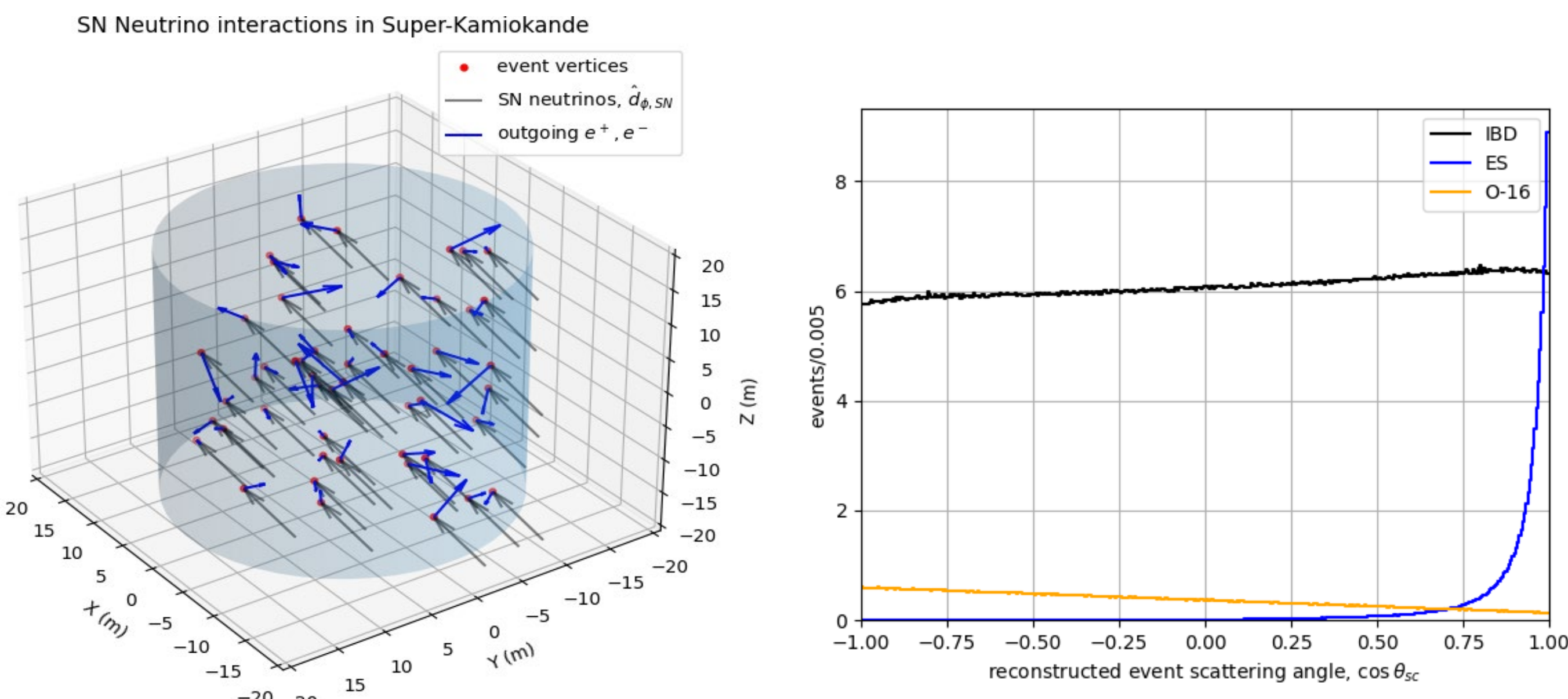
- Reconstructed burst events analyzed in HEALPix[2] data structure.
  - Pixelization scheme for surface of sphere.
  - Pixels have equal area, iso-latitudes, multi-resolution.
  - Used to encode 3-d directional signals (e.g., CMB).

- SN burst events on HEALPix sphere.
  - Pixel location = 3-d direction.
  - Pixel counts = number of events in pixel direction.
  - e.g., HP-sphere (12,288 pixels) with ~2600 events[A], SN @10 kpc.
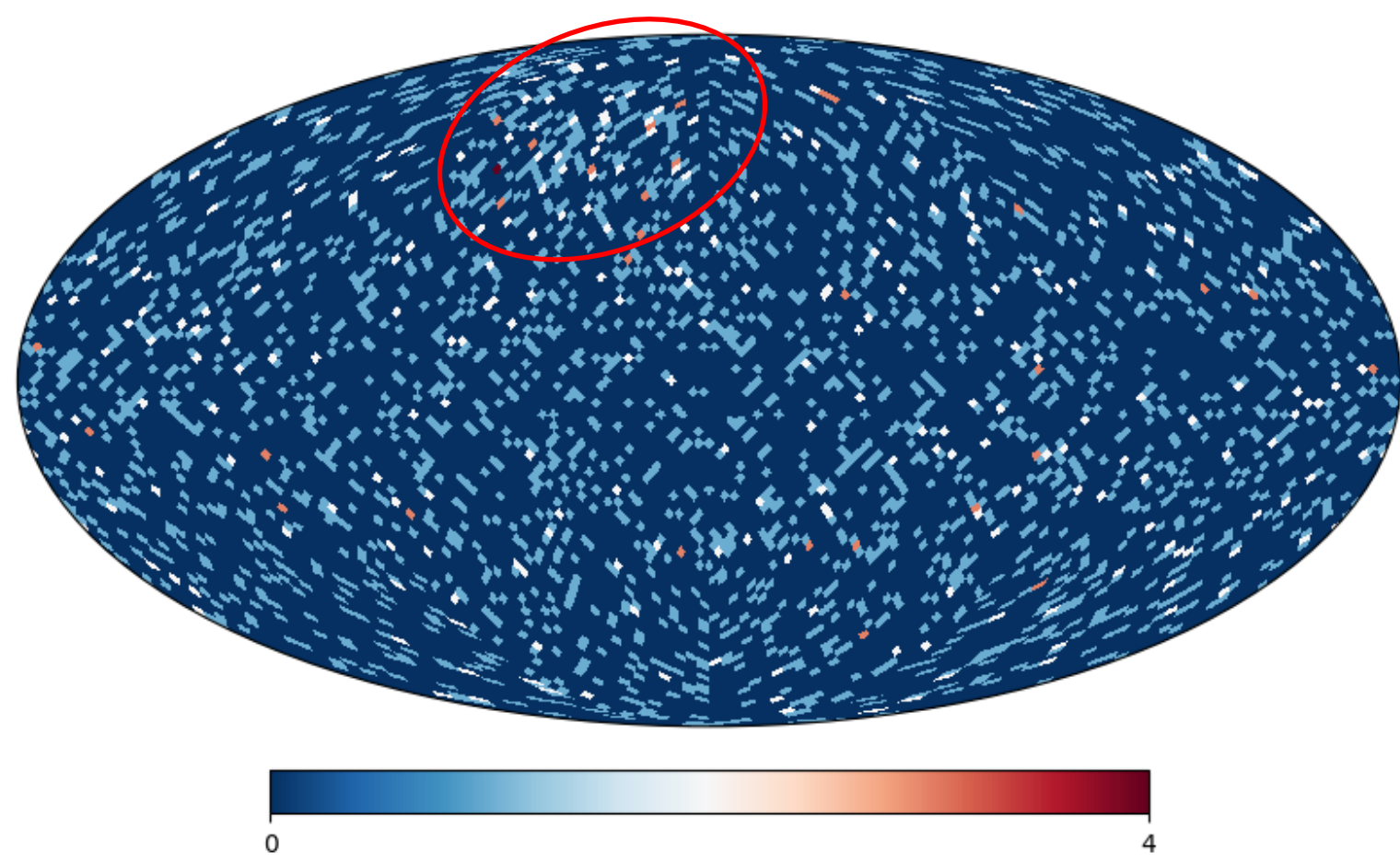
- Distribution nearly uniform.
- Small area of higher density (circled) from ES events.
- Centroid of ES events at $\hat{d}_{\phi,SN}$.
 - Difficult to find b/c sparse event distribution.

SN Direction from HP-Sphere

- Gaussian smoothing produces well defined ES-peak.
- ES-peak centroid at pixel with max amplitude.
- Direction of max pixel = $\hat{d}_{\phi,SN}$.
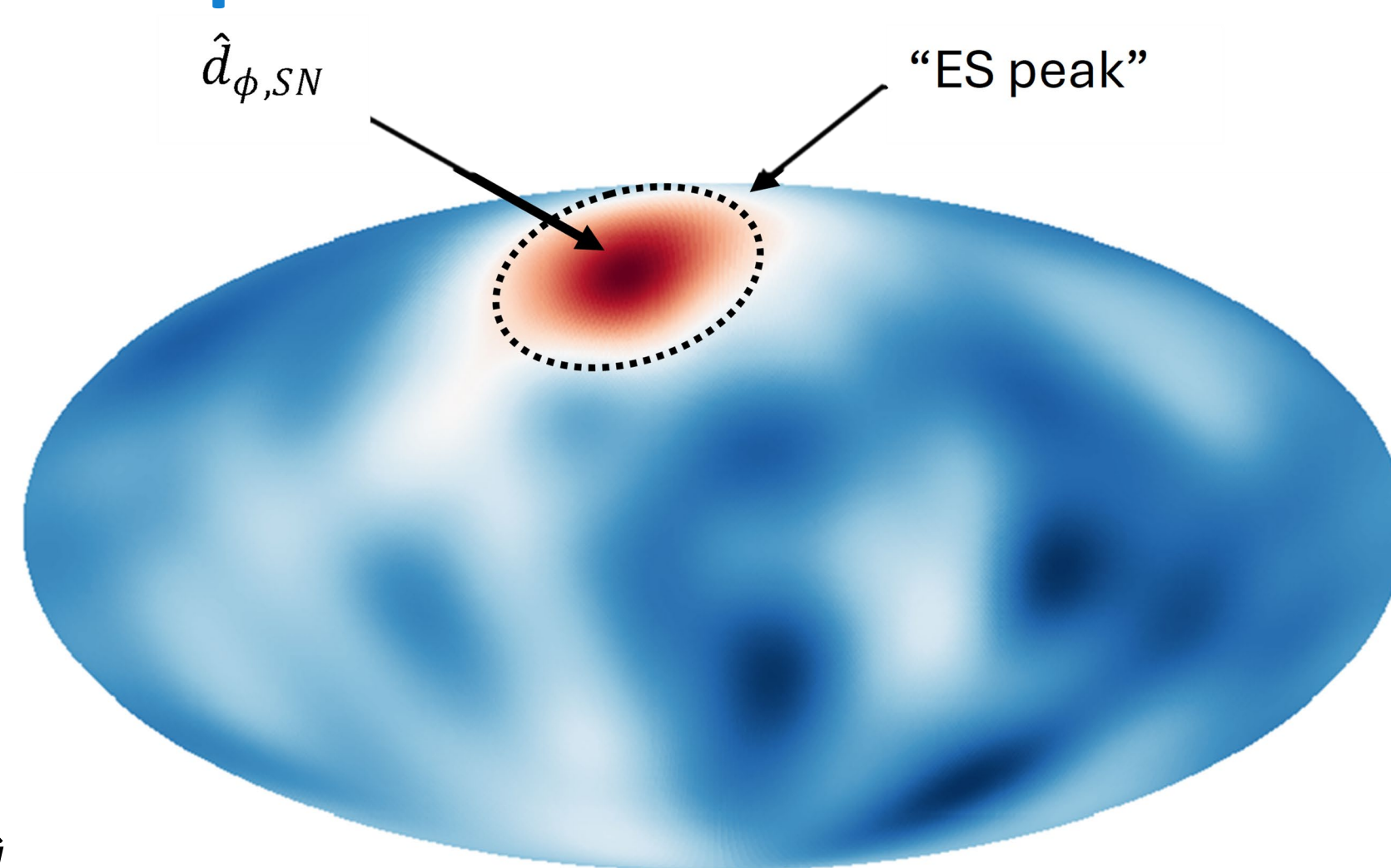
$\hat{d}_{\phi,SN}$ "ES peak"

- SN pointing direction $\hat{d}_{SN} = -\hat{d}_{\phi,SN}$.

HP-Fitter Results (Preliminary[B])

- HP-sphere and smoothing parameters were optimized.

NSIDE=16, 3072 pixels   NSIDE=32, 12288 pixels

NSIDE=64, 49152 pixels   NSIDE=128, 196608 pixels
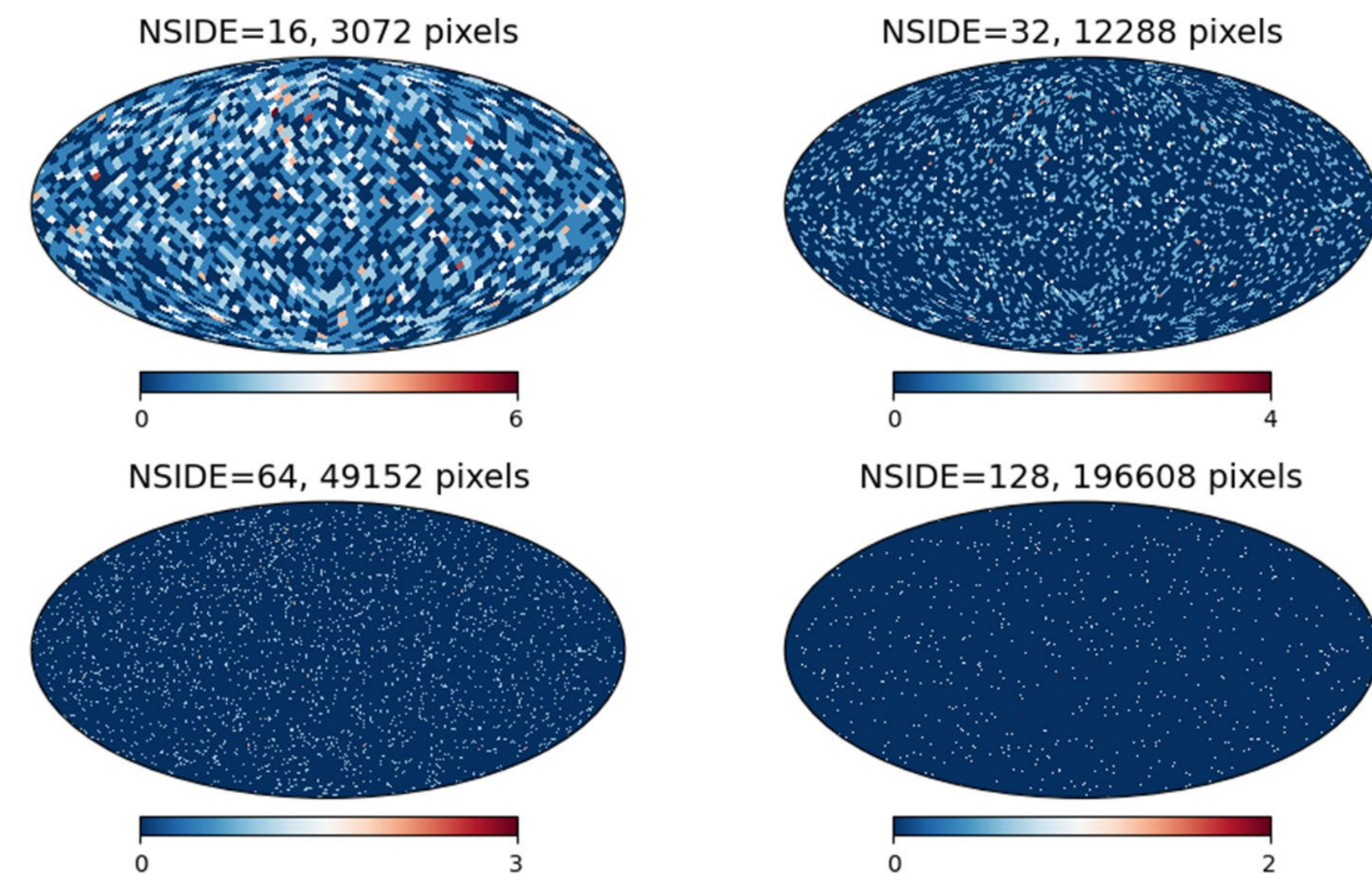
- Number of pixels from "NSIDE" determines pixel angular resolution.

NSIDE=128, SIGMA=0.05   NSIDE=128, SIGMA=0.1
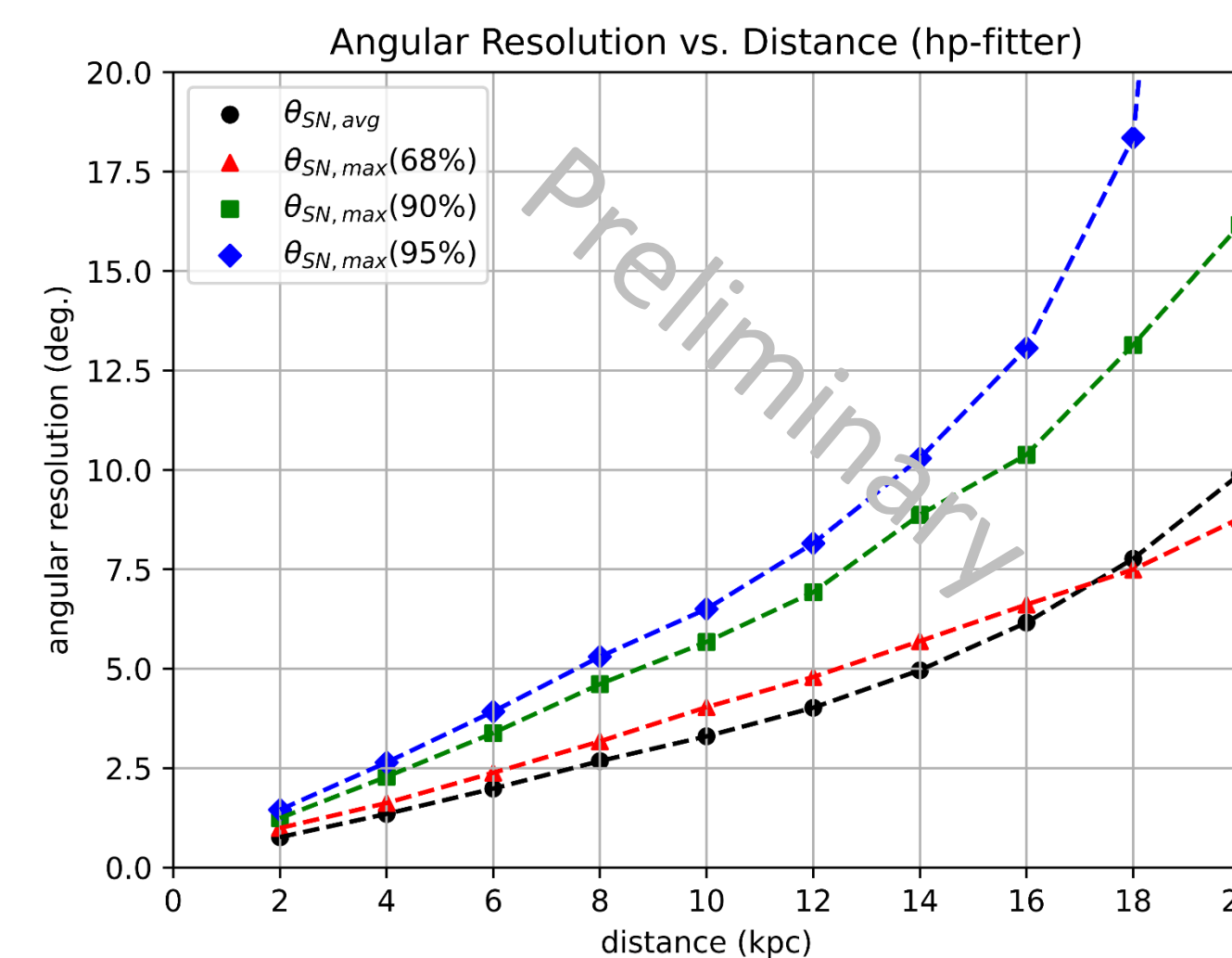
NSIDE=128, SIGMA=0.2   NSIDE=128, SIGMA=0.4

- Gaussian width from "SIGMA" determines ES peak SNR and width.
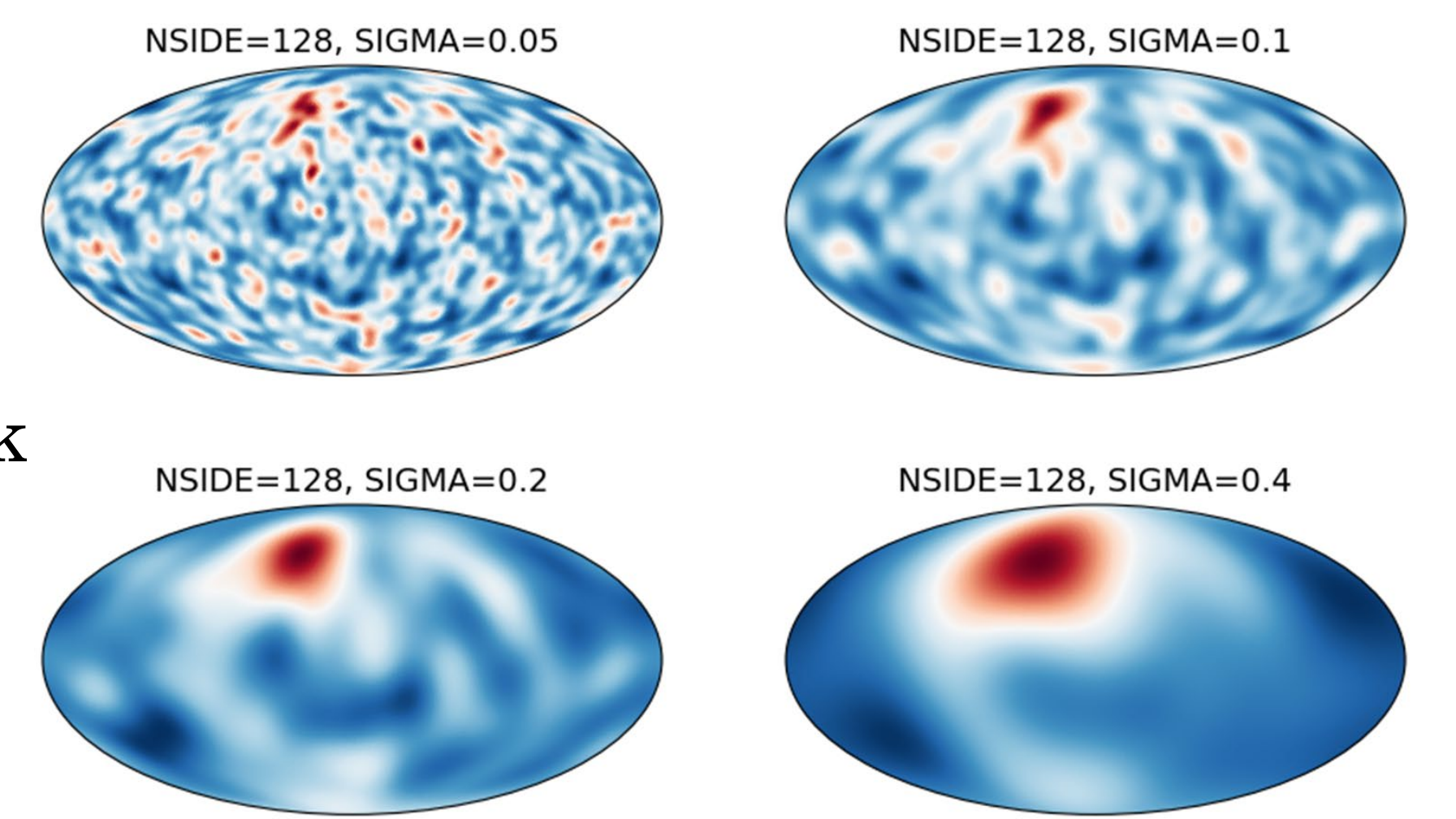
Speed

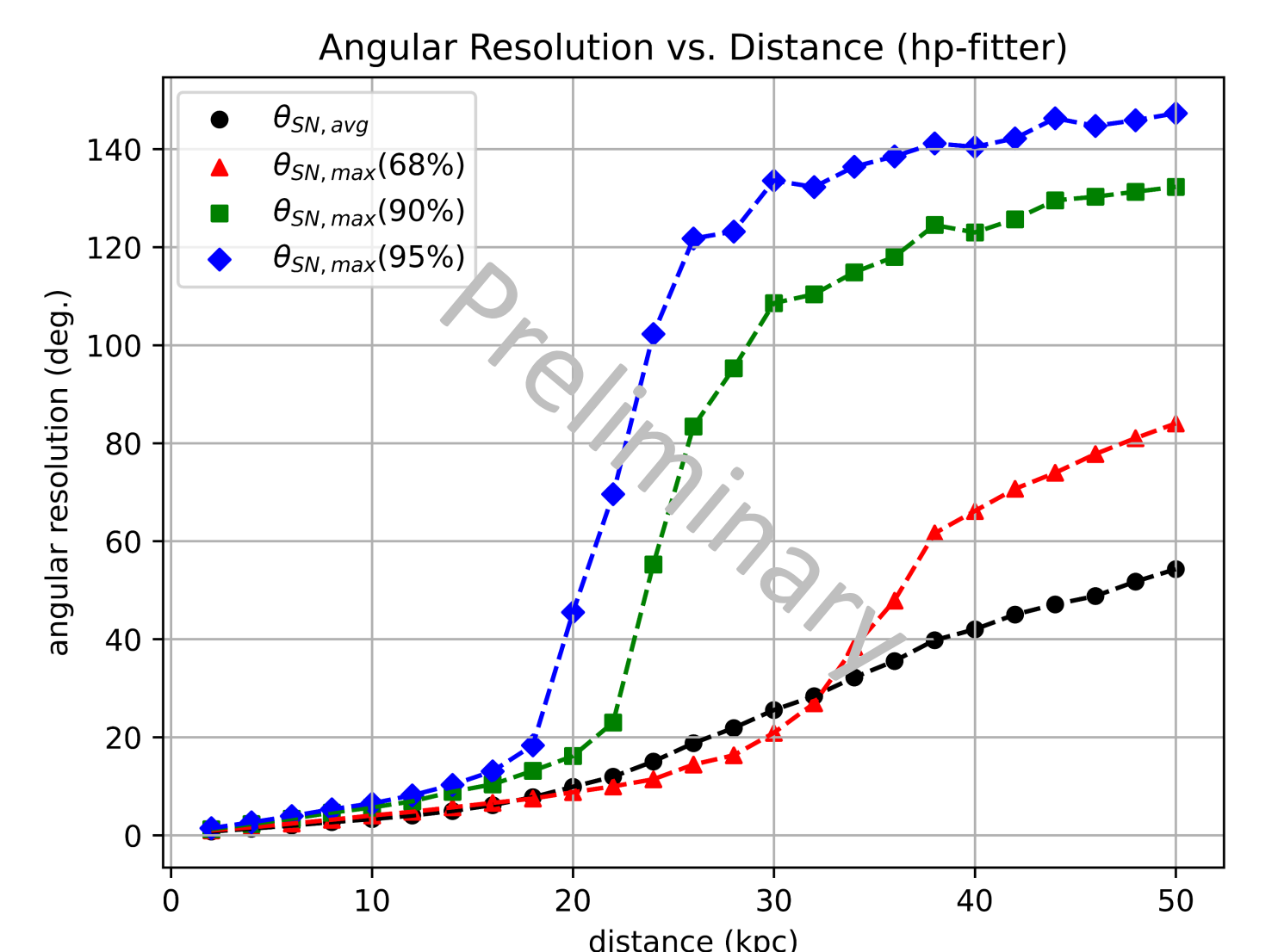- HP-fitter, $\mathcal{O}(1\ sec)$ vs older ML-fitter, $\mathcal{O}(mins)$

Angular Resolution

- Accuracy comparable to ML-fitter results.
- Angular resolution from analysis of angular discrepancy, θ_{SN}, where:
  $$\cos \theta_{SN} = \hat{d}_{SN,true} \cdot \hat{d}_{SN}$$

- Accurate to large SN distances.
- At distances $\gtrsim$ 20 kpc sharp changes in ang. res. indicate increasing rate of failed direction finding.

Summary

- Novel HP-fitter gives <u>fast</u> and accurate pointing info for Super-Kamiokande SN alert.
  - Now integrated into SNWatch.
- Shorter lag between burst detection and alert with pointing info improves chance of multi-messenger observation of SBO.
- Astronomers should review SN alert response plans based on new SNWatch capabilities.

A. The simulated burst events and results in this presentation were all based on the Nakazato1 SN model (Z=0.02, 20 M$_\odot$, t_revival=200ms) with MSW oscillations assuming normal mass ordering (NMO) generated using a Geant4-based SK simulation.
B. Paper in preparation.
1. "SK_SN Notice at https://gcn.nasa.gov/missions/sksn
2. Gorski, K.M., et al., HEALPix: A Framework for High-Resolution Discretization and Fast Analysis of Data Distributed on the Sphere, et al. 2005, ApJ, 869 622, 759. The HEALPix Python wrapper is 'healpy', Andrea Zonca, et. al. healpy: equal area pixelization and spherical harmonics transforms for data on the sphere in Python, 2019, Journal of Open-Source Software, 4, 1298.