Time-Charge HEALPix Direction Fitter for Supernova Neutrinos in Super-Kamiokande

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WNPPC 2026
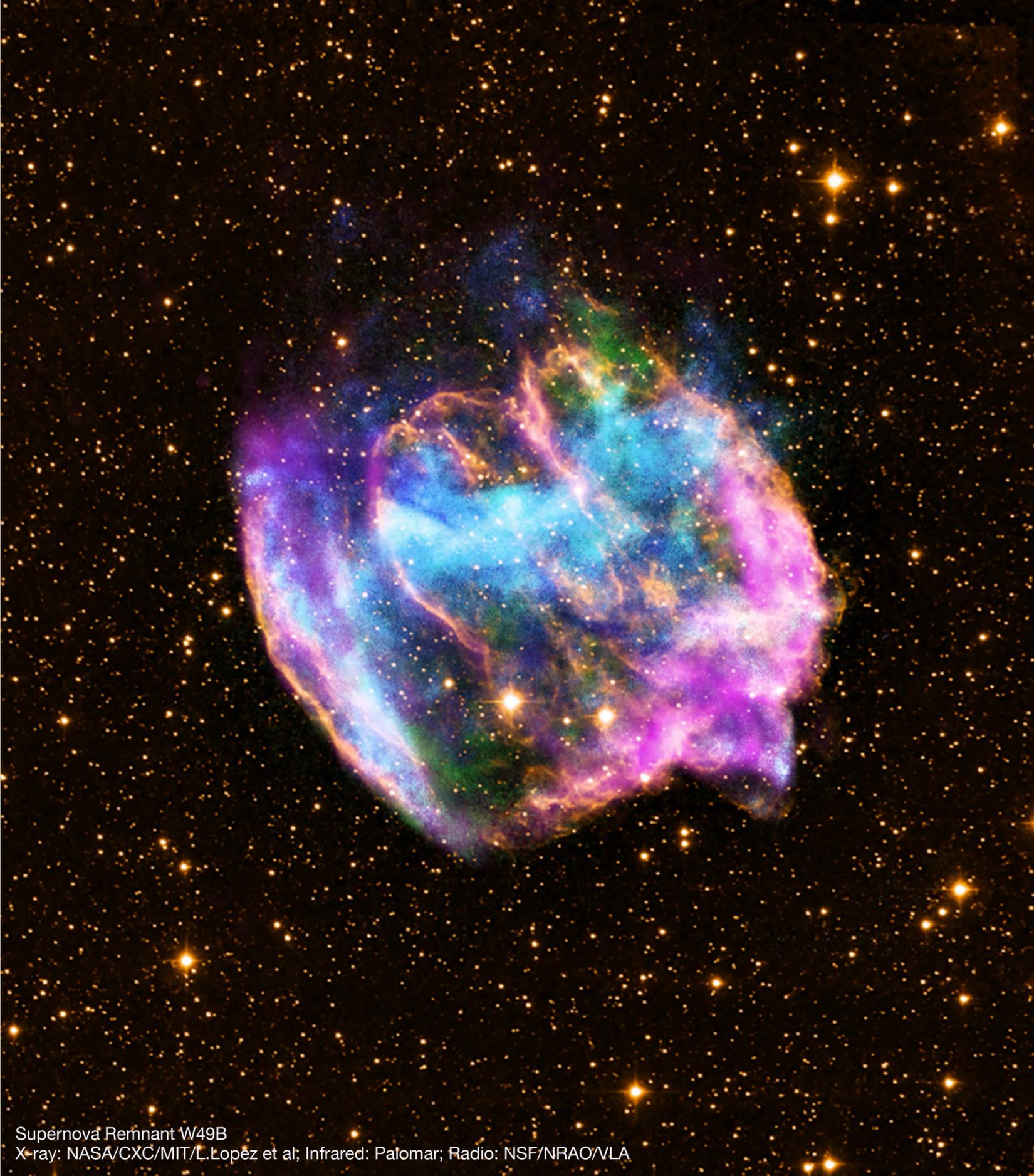
UNIVERSITY of Regina

Go far, together.

Overview

▸ Super-Kamiokande

▸ Supernova ν in WCD

▸ Super-K Direction Fitters

▸ TQ-HEALPix Fitter

▸ Preliminary Findings

▸ Conclusions

Supernova Remnant W49B
X-ray: NASA/CXC/MIT/L.Lopez et al; Infrared: Palomar; Radio: NSF/NRAO/VLA

Super-Kamiokande

- Located near **Hida**, Japan
  - ✦ SK-I constructed **April, 1996**
  - ✦ **SK-VII** currently operating
- Water Cherenkov Detector
  - ✦ **11,146** Inner PMTs
  - ✦ 50 cm diameter
- **41.4 m** tall, **39.6 m** in diameter
  - ✦ **1000 m** under ground

(c) 東京大学宇宙線研究所 神岡宇宙素粒子研究施設
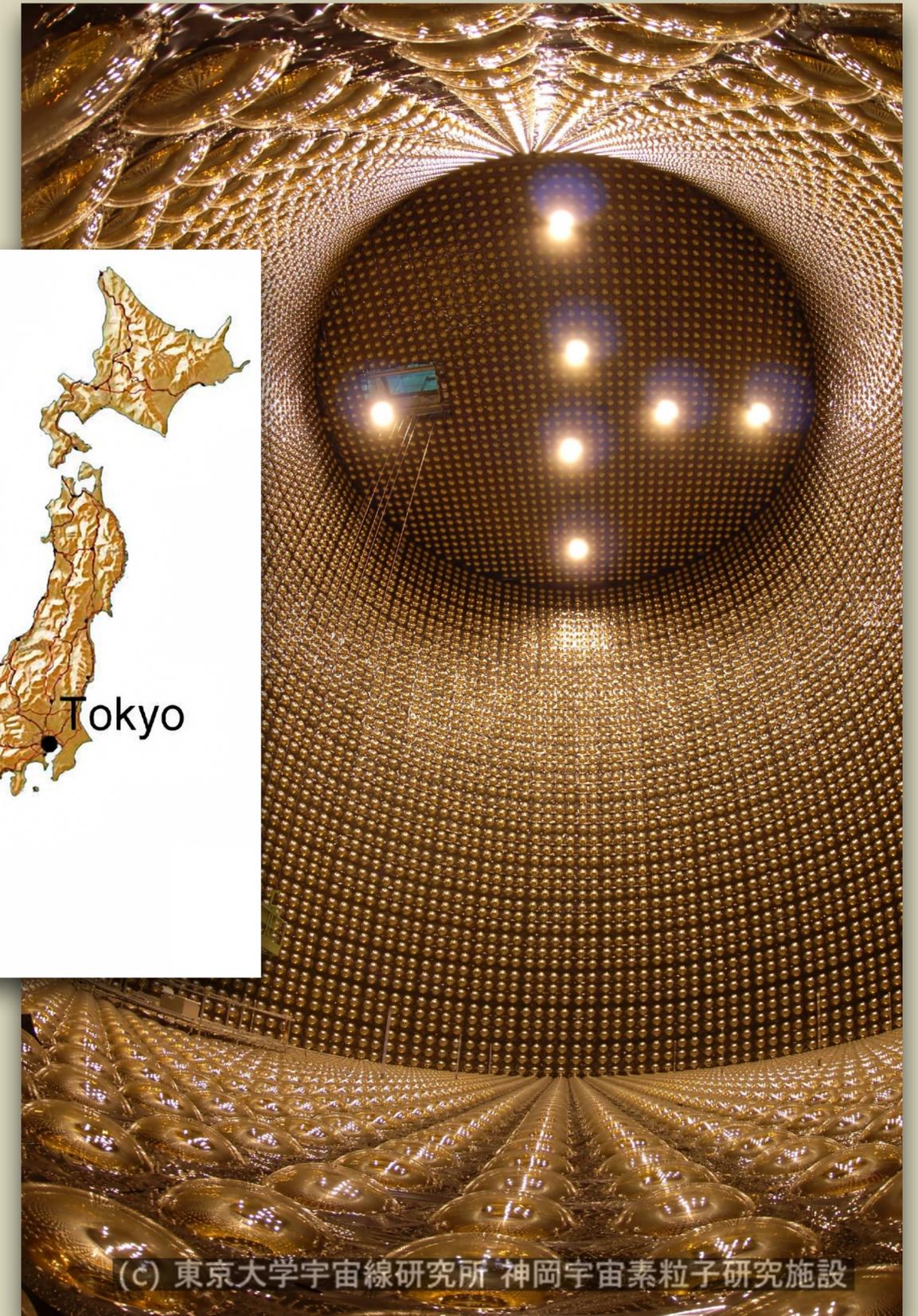
Supernova Neutrinos

MC models for SN ν

▸ Nakazato

▸ Normal mass order neutrino oscillations

▸ <u>Simulated @ 10 kpc</u>

Reaction Channels

▸ Inverse Beta Decay

▸ Elastic Scattering

▸ ^{16}O Reactions

Generated by SKSNSim	Wilson			Nakazato			Mori		
	No Osc.	NMO	IMO	No Osc.	NMO	IMO	No Osc.	NMO	IMO
IBD ($\bar{\nu}_e$)	7431	8207	9970	3542	3893	4693	3275	3422	3745
ES (ν_e)	223	231	229	173	172	171	177	148	156
ES ($\bar{\nu}_e$)	97	97	98	63	66	72	60	61	63
ES (ν_x)	80	79	80	60	60	60	52	57	56
ES ($\bar{\nu}_x$)	69	69	69	52	51	48	45	45	44
^{16}O CC (ν_e)	44	1034	729	48	180	139	8	86	62
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^{16}O NC ($\nu_e,^{15}$N)	4	89	63	4	15	12	1	8	5
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total	8622	10530	12294	4074	4580	5389	3690	3904	4239

Supernova Neutrinos

Scattering Angles

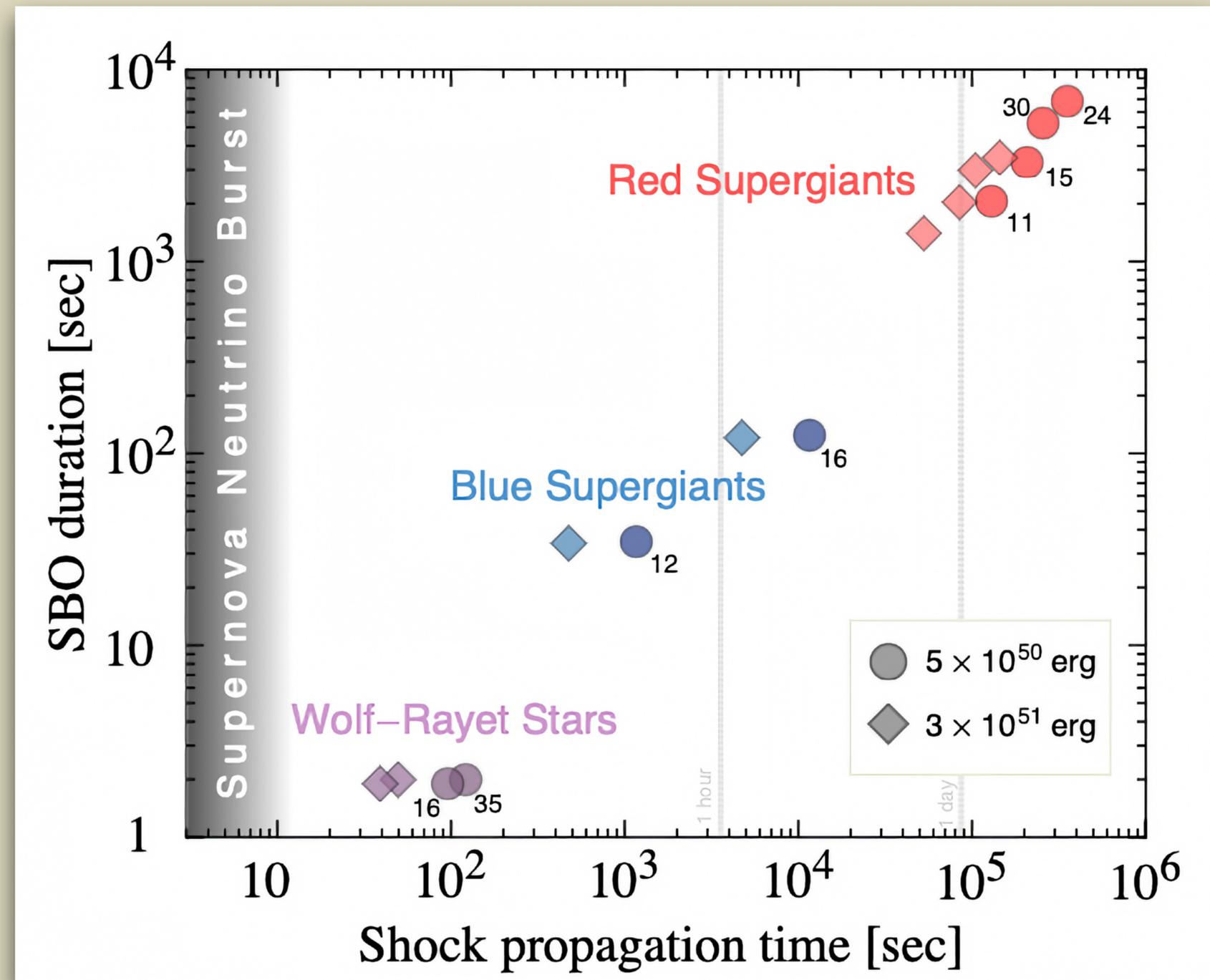▸ θ_{SC} compared to incoming neutrino direction

Elastic Scattering Interactions are highly forward scattered
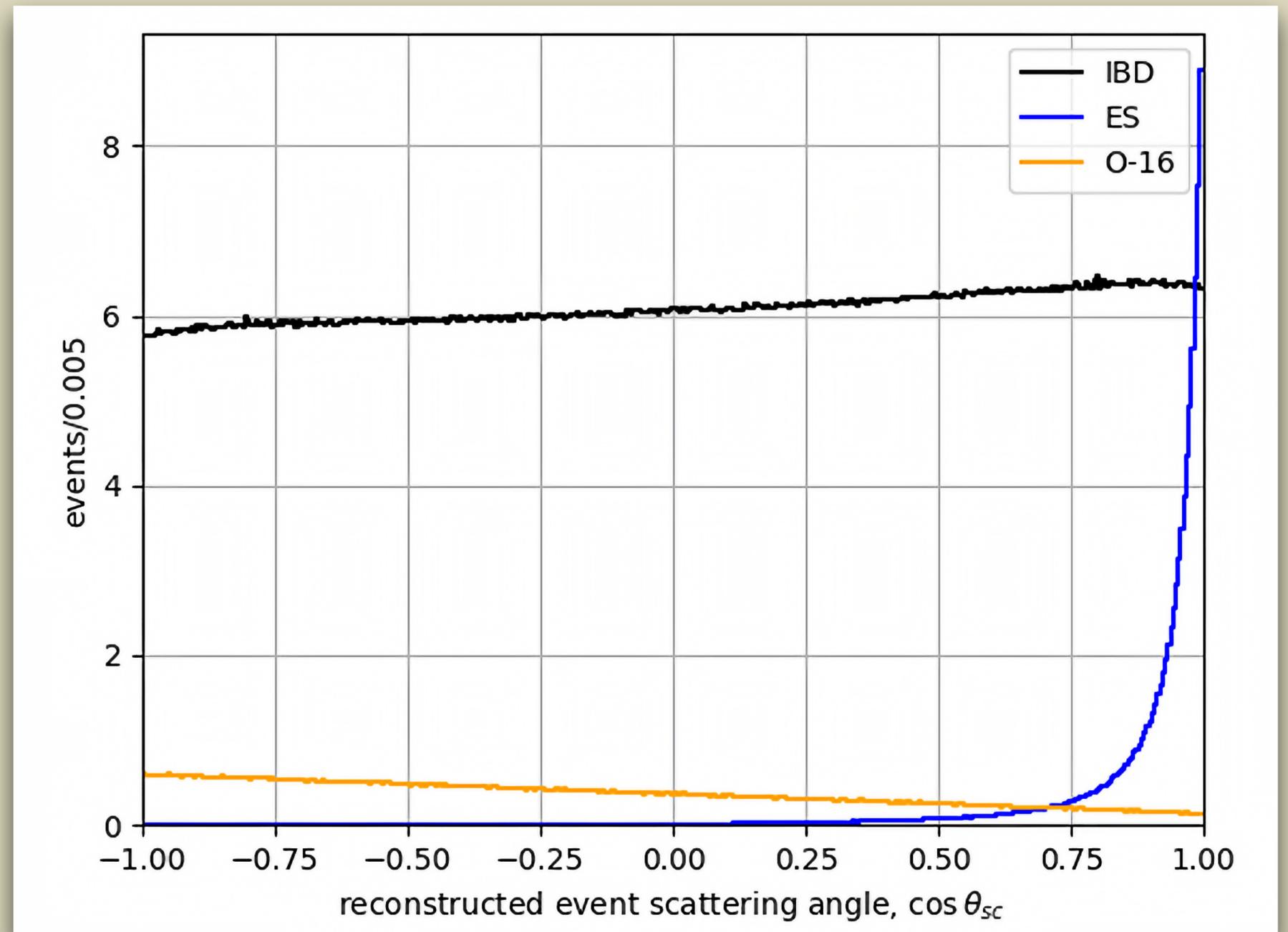
Supernova Neutrinos

Shock Propagation Time

▸ Time delay between ν emission

and **shock breakout** ("first light")

  ✦ Depends on progenitor
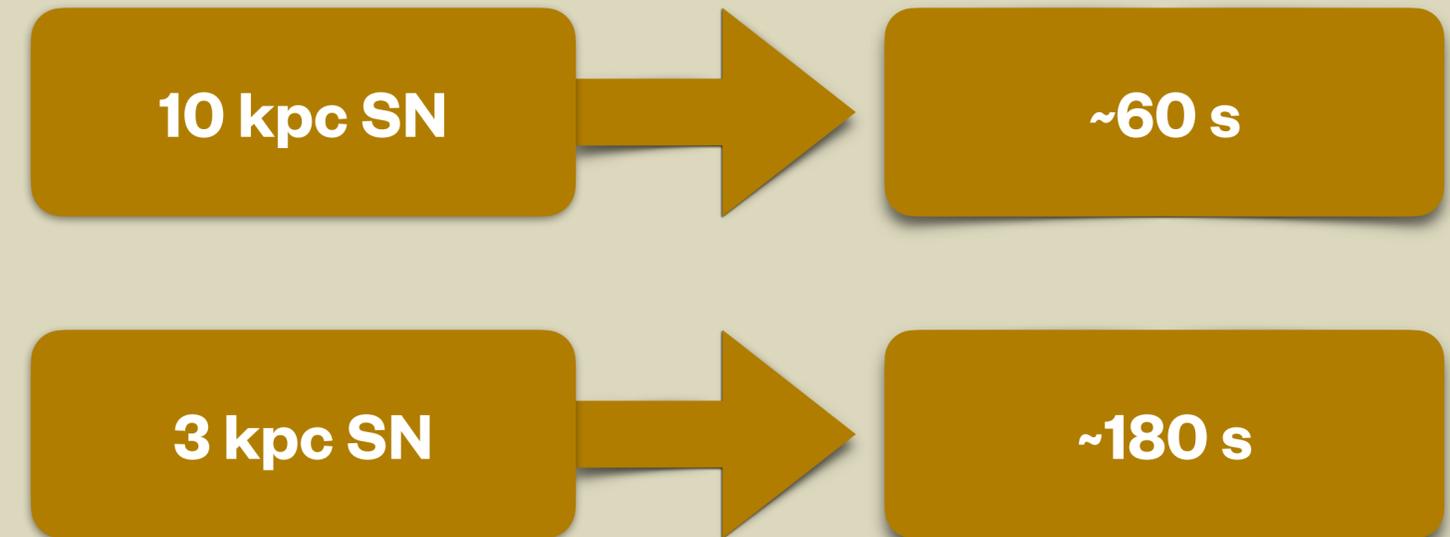
▸ Order of **seconds** to **hours**

Direction Fitters

Current Fitters:

▸ <u>Maximum Likelihood</u> and <u>HEALPix Fitter</u>

Features:

▸ High Angular Resolution ➝ ~1°

▸ Requires *Vertex*, *energy*, and *direction* recon for each **event** in a **burst**

  ✦ Computationally expensive

  ✦ Recon time ∝ SN distance (or, # of events)

| 10 kpc SN	➔	~60 s

3 kpc SN	➔	~180 s

Can we reconstruct SN directions without reconstructing individual events?

TQ-HEALPix Fitter

Map TQ data to HEALPix as a data structure

‣ Hierarchal Equal Area Latitude Pixelization

 ✦ 3D Vectors → Pixel Positions on sphere

‣ Burst events mapped to HEALPix sphere

 ✦ Average event direction mapped to pixels

 ✦ Pixels weighted by event information

‣ *Spherical* structure vs. *Cylindrical* Detector

 ✦ **Geometric corrections** are needed
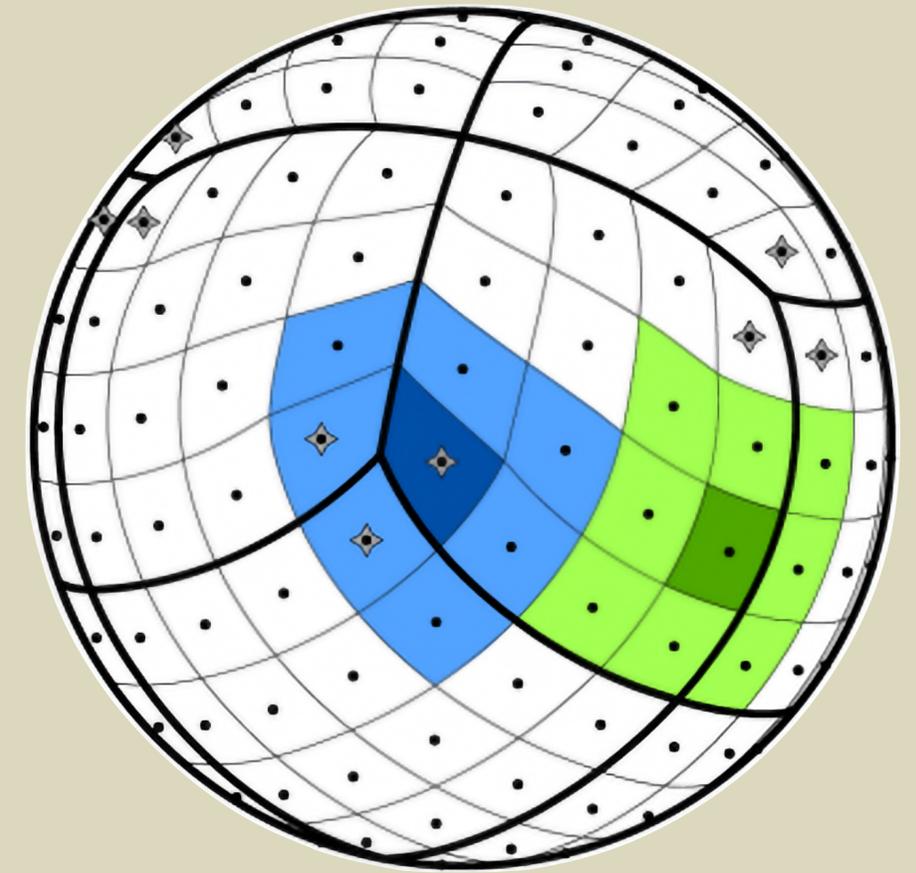
NSIDE	# of Pixels	Ang Res (arcmin)	Pixel area (sq. deg.)
8	768	440	53.7
16	3,072	220	13.4
32	12,288	110	3.4
64	49,152	55	0.84
128	196,608	27	0.21

K.M. Górski et al., HEALPix-a Framework for High Resolution Discretization, and Fast Analysis of Data Distributed on the Sphere. (2005), ApJ, 622, p759 arXiv: 0409513
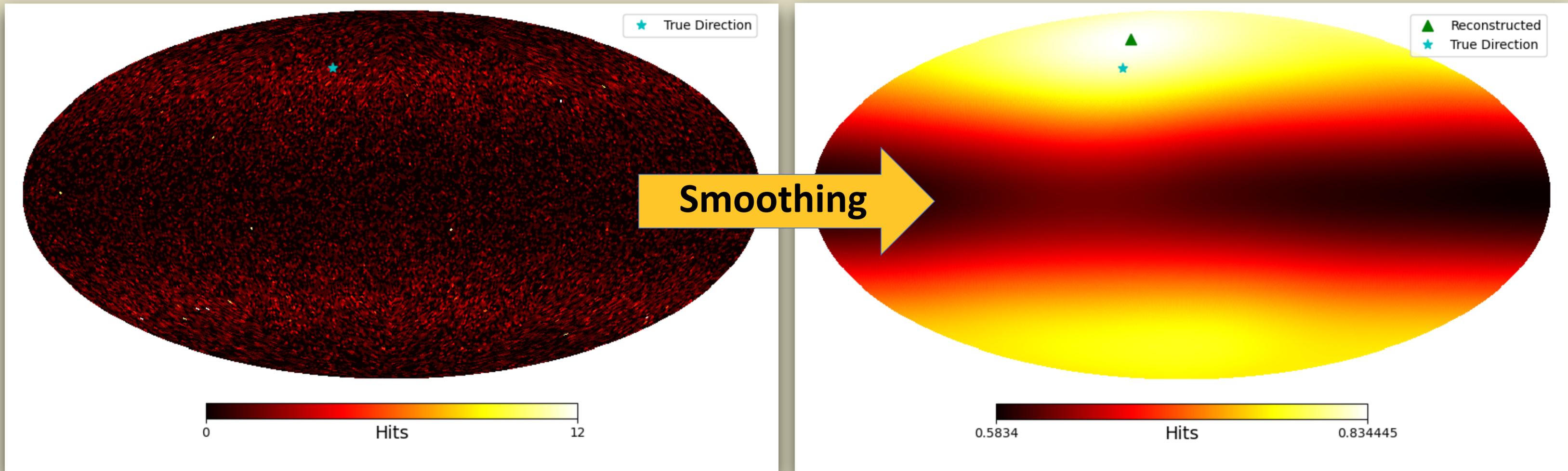
TQ-Fitter Hit Map

Simulated 3 kpc SN Burst

▸ ~60,000 events

  ✦ ~200 hits/event

▸ Hits & events are cut on:

  ✦ Time, Charge, # Hits/Event

▸ Mean event direction

  → Mapped to pixels

  → +1 weighting
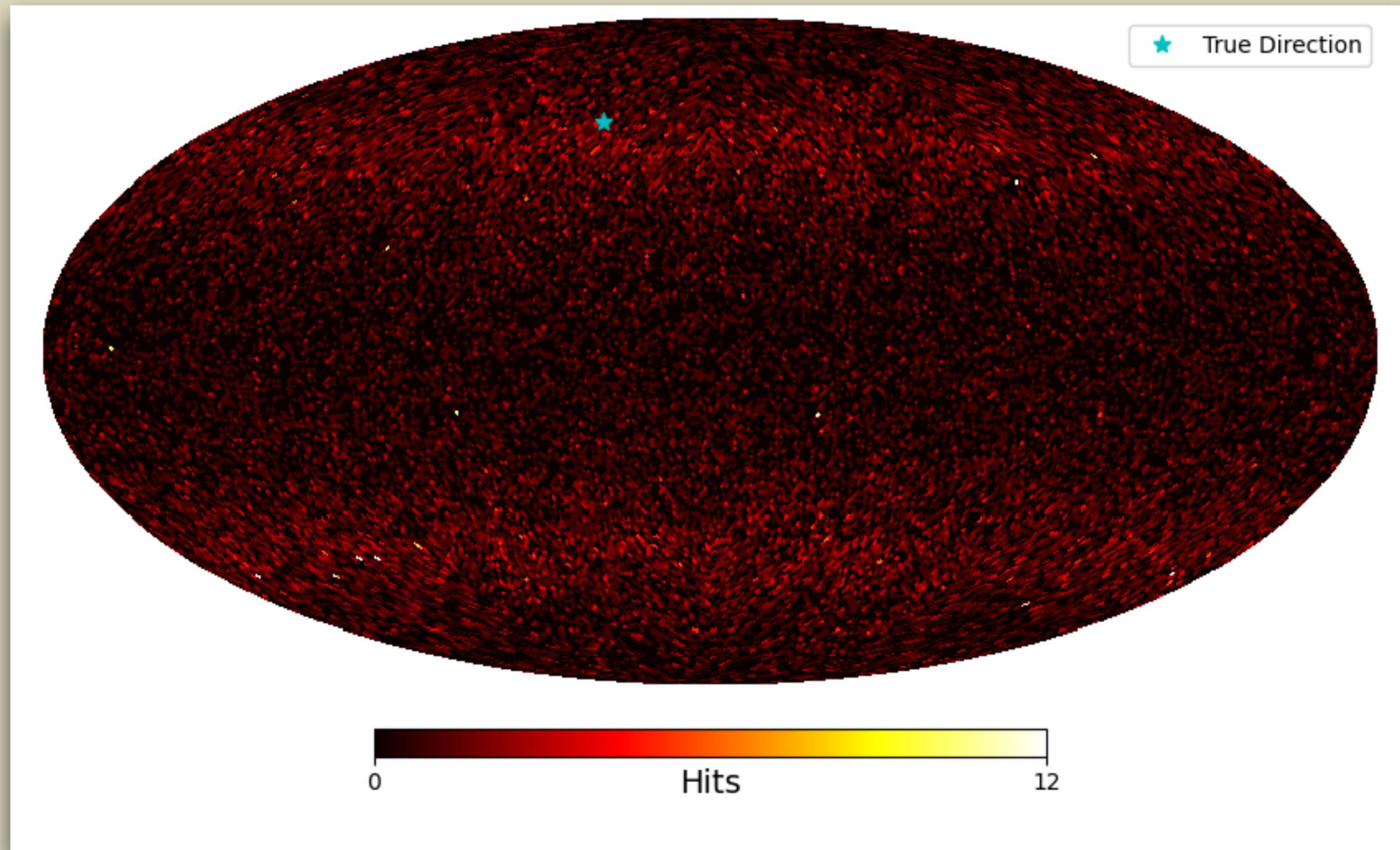
TQ-Fitter Hit Map

- ‣ Gaussian smoothing applied
  - ✦ $\sigma = 0.5$

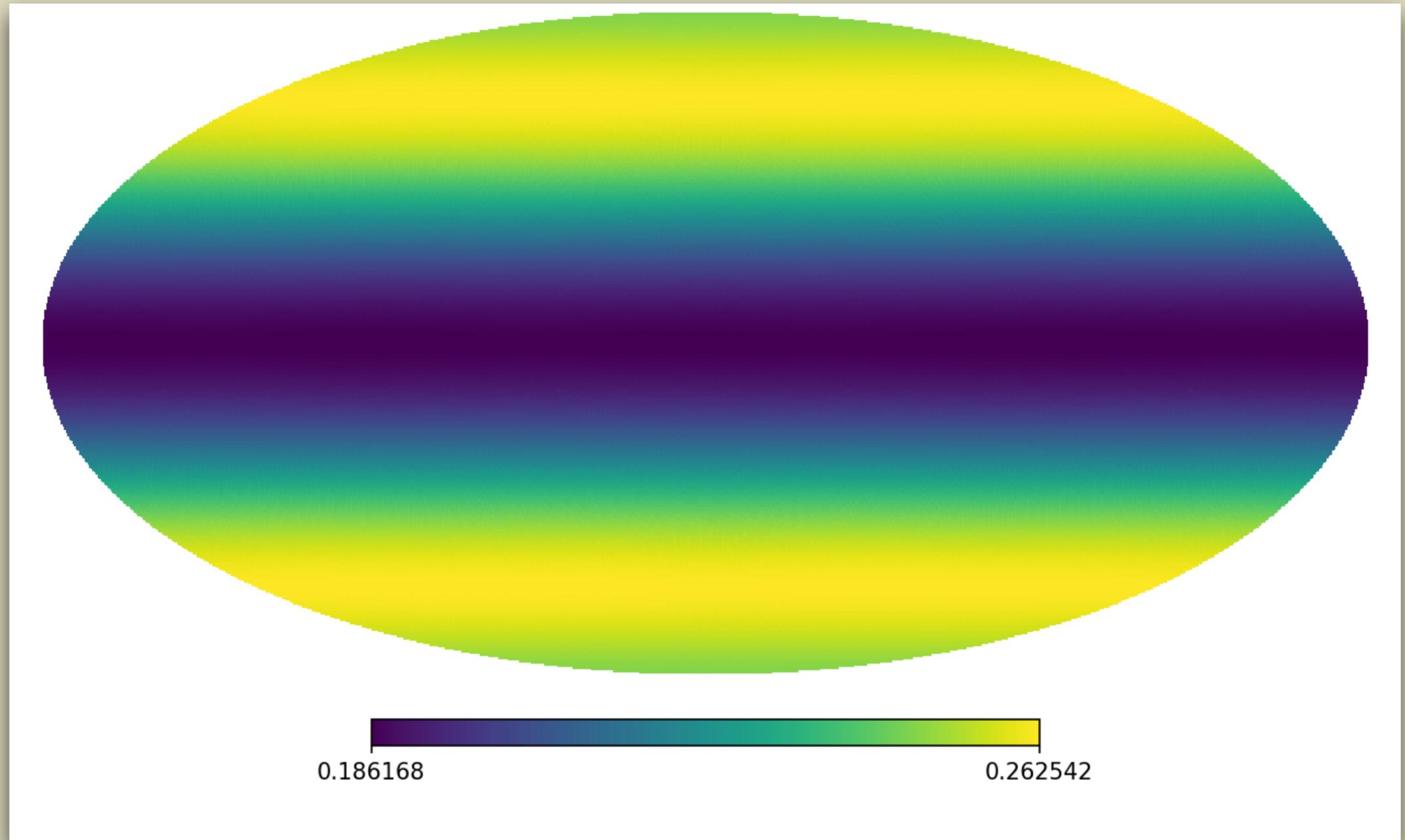- ‣ Geometric distortion revealed
  - ✦ Hot/cold "bands"
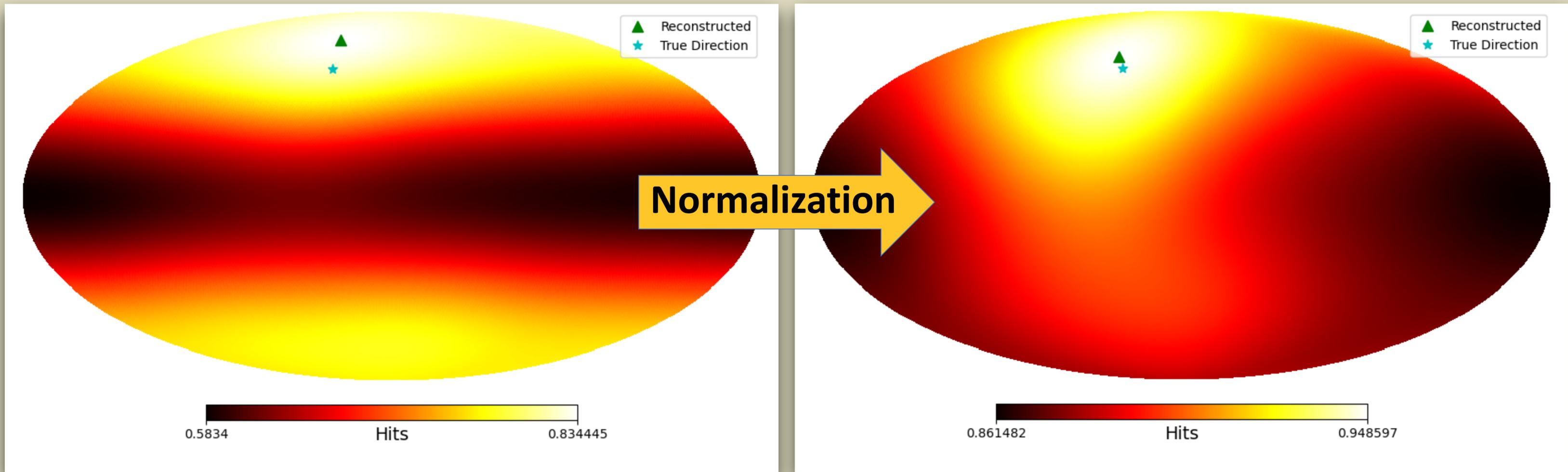
TQ-Fitter Normalization

Sampling Density

‣ PMT vectors to pixels

‣ Low density equator

‣ High density poles

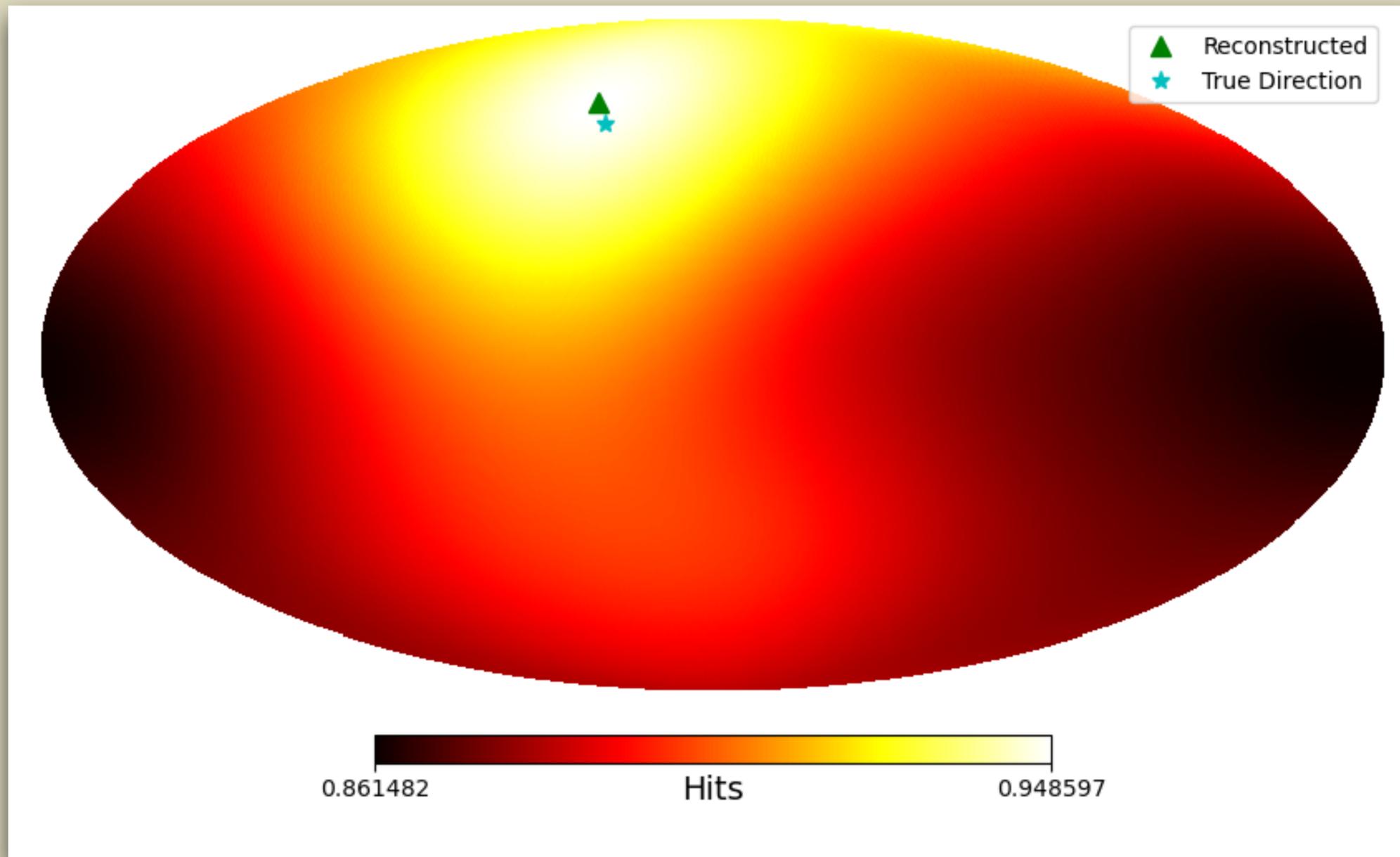HEALPix hit maps must be **normalized** by the sampling density

0.186168   0.262542

TQ-Hit Map

Normalization

- Normalization applied
  - Dividing by sampling density

- Supernova source revealed
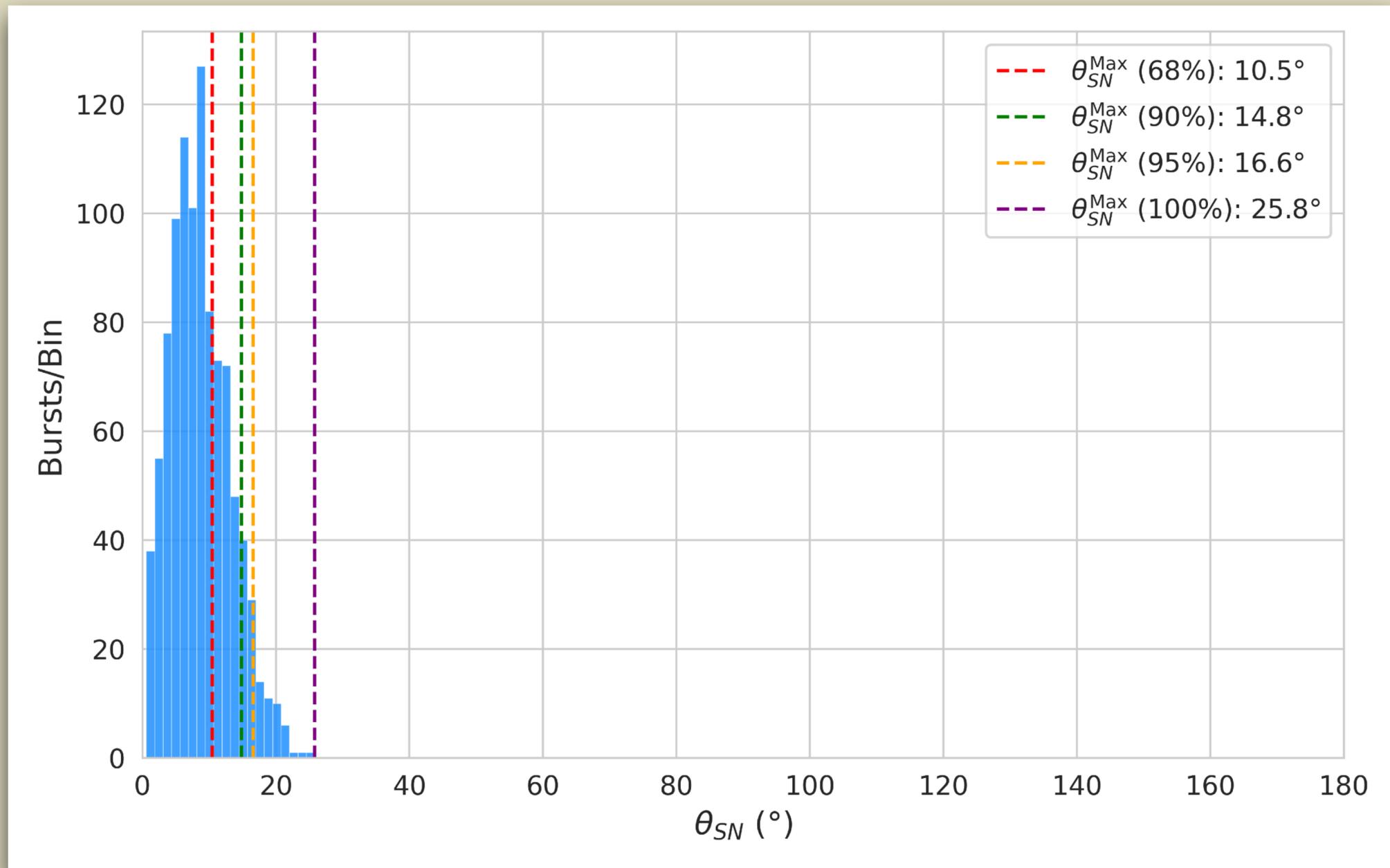 - Defined hot spot at true SN dir

TQ-HEALPix Hit Map

Processing Details

‣ Hits/event: $[30, 170]$

‣ Hit time: $[0, 90 \text{ ns}]$

‣ Smoothing: $\sigma = 0.4$

‣ Sample Density Norm

Reconstruction Statistics:

‣ 62,321 total events

‣ 34,051 "good" events

‣ **7° angular discrepancy**

‣ **0.75 second recon time**

Distribution of Recon Angular Discrepancies

Batch Details:

▸ <u>1,000 SN Bursts @ **3 kpc**</u>

   ✦ ~60,000 events/burst

Reconstruction:

▸ **0.75 s/burst**

   ✦ Data cuts: 0.55 s/burst

   ✦ Dir recon: 0.3 s/burst

▸ $\theta_{SN}^{Max}(100\%) \approx 26°$

Summary of TQ-Fitter

- **NO event** reconstruction
  - ✦ Skips event-level *vertex*, *energy*, and *direction* recon
- **Low latency** reconstruction time
  - ✦ ~1 sec @ 3 kpc
- Angular discrepancy less resolved
  - ✦ $\theta_{SN}^{Max}(68\%) \approx 11°$
- Further characterization needed
- **Project extension to Hyper-K**

Reconstruction Statistics for SN Burst @ 3 kpc

	ML	HEALPix	TQ
Ang Res (68%)	~1 deg	~1 deg	~11 deg
Event Recon Time	~180 s	~180 s	ZERO
Dir. Recon Time	11 s	0.4 s	0.8 s
Total (s)	**~190 s**	**~180 s**	**0.8 s**

Extra Slides

TQ-HEALPix Direction Reconstruction Fitter

Direction Reconstruction Fitters

Can we reconstruct SN directions without reconstructing individual event vertices, energies, and directions?

What we have:

▸ SN bursts with **thousands** or **tens of thousands** of events

   ✦ 10 kpc ⟶ ~6,000 events

   ✦ 3 kpc ⟶ ~60,000 events

▸ Each **event** has **hundreds** of **PMT hits**

   ✦ Time and charge information for each hit

   ✦ Hits **encode direction information** of the SN neutrino flux

Supernova Neutrinos

Inverse Beta Decay

▸ ~90% of interactions

▸ ID with Gd tagging

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

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Supernova Neutrinos

Elastic Scattering

▸ ~5% of interactions

$$\nu + e^- \rightarrow \nu + e^-$$

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Supernova Neutrinos

^{16}O Reactions

▸ ~5% of interactions

▸ Charged Current (CC)

▸ Neutral Current (NC)

$$\bar{\nu}_e + {}^{16}O \rightarrow e^+ + X$$

$$\nu_e + {}^{16}O \rightarrow e^- + X$$

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Distribution of Recon Angular Discrepancies
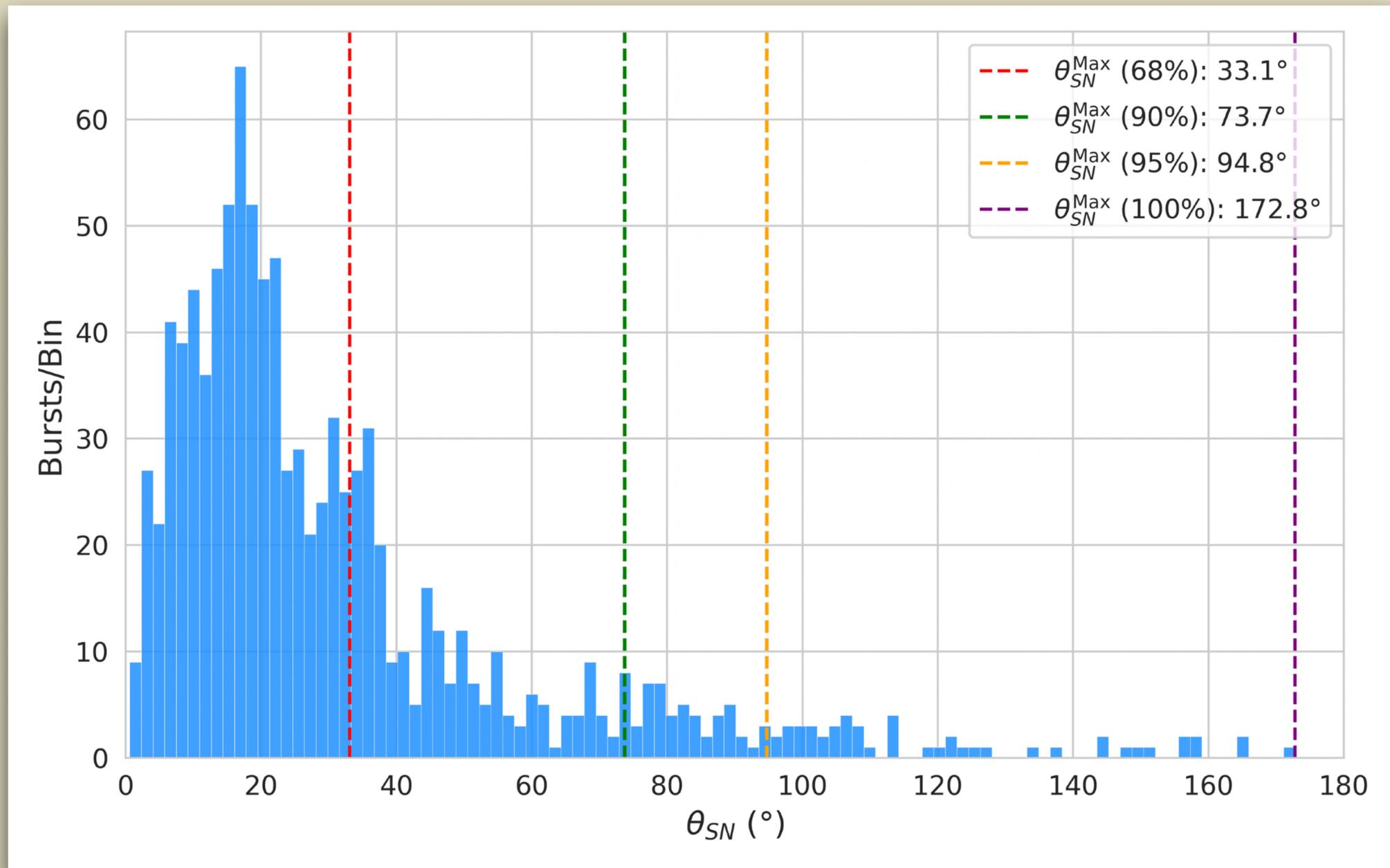
Batch Details:

▸ 1,000 SN Bursts @ **10 kpc**

✦ ~6,000 events/burst

Reconstruction:

▸ **0.07 s/burst**

✦ Data cuts: 0.04 s/burst

✦ Dir recon: 0.03 s/burst

▸ $\theta_{SN}^{Max}(100\%) \approx 170°$

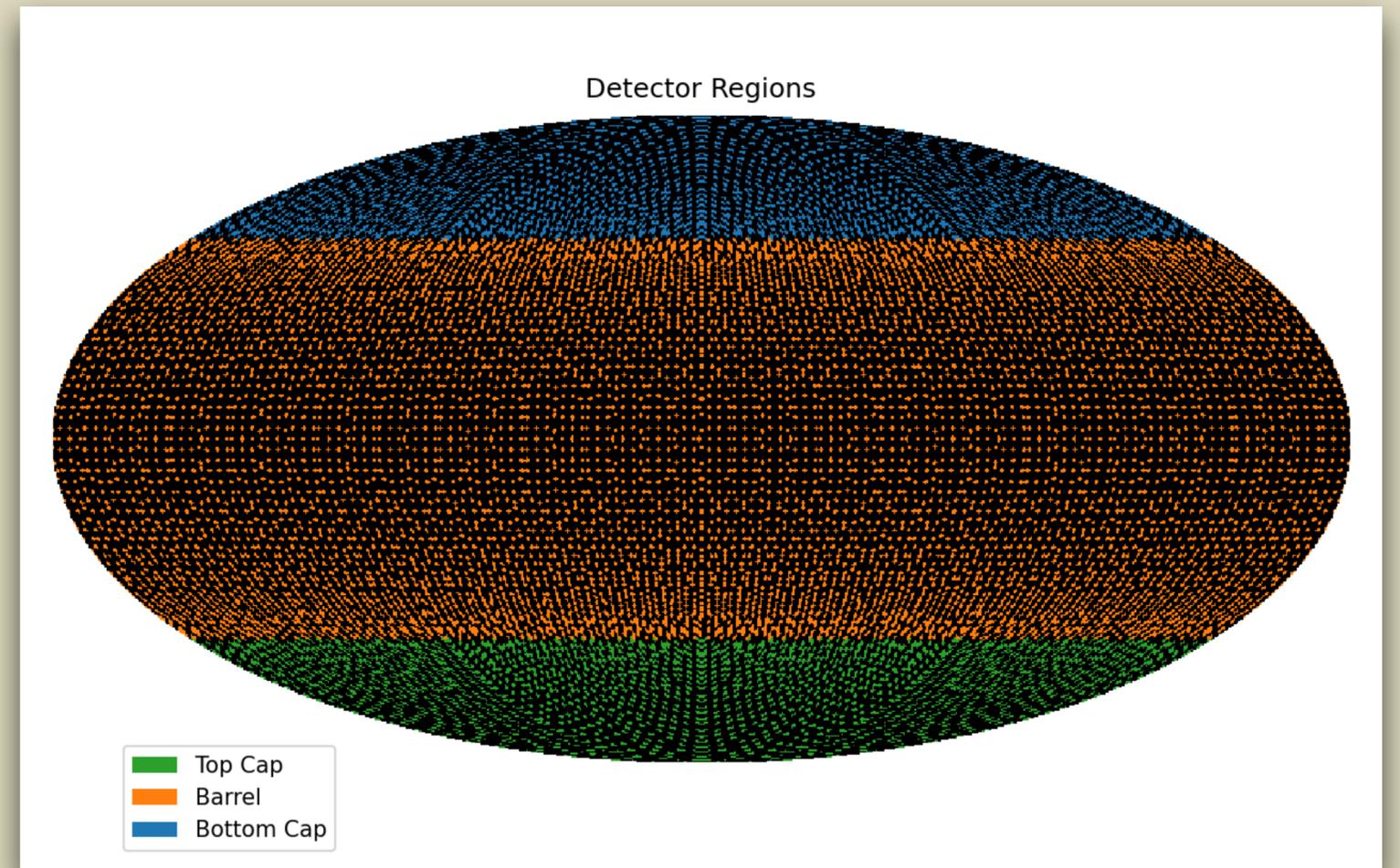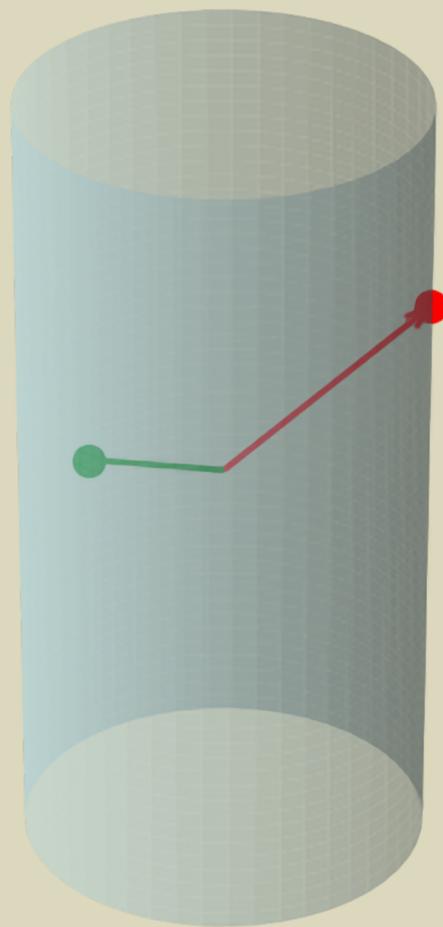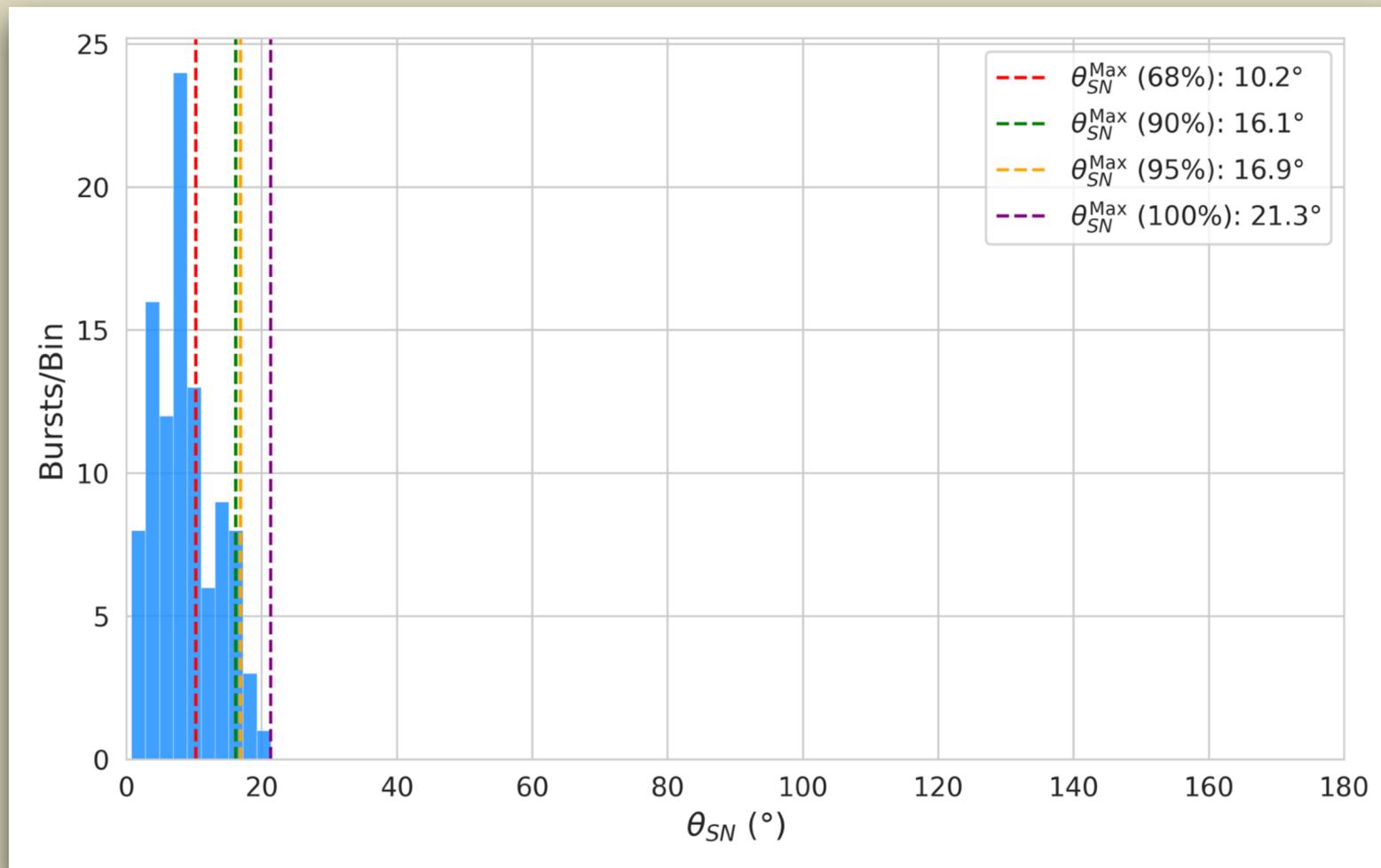✦ Low statistics

Distribution of Recon Angular Discrepancies
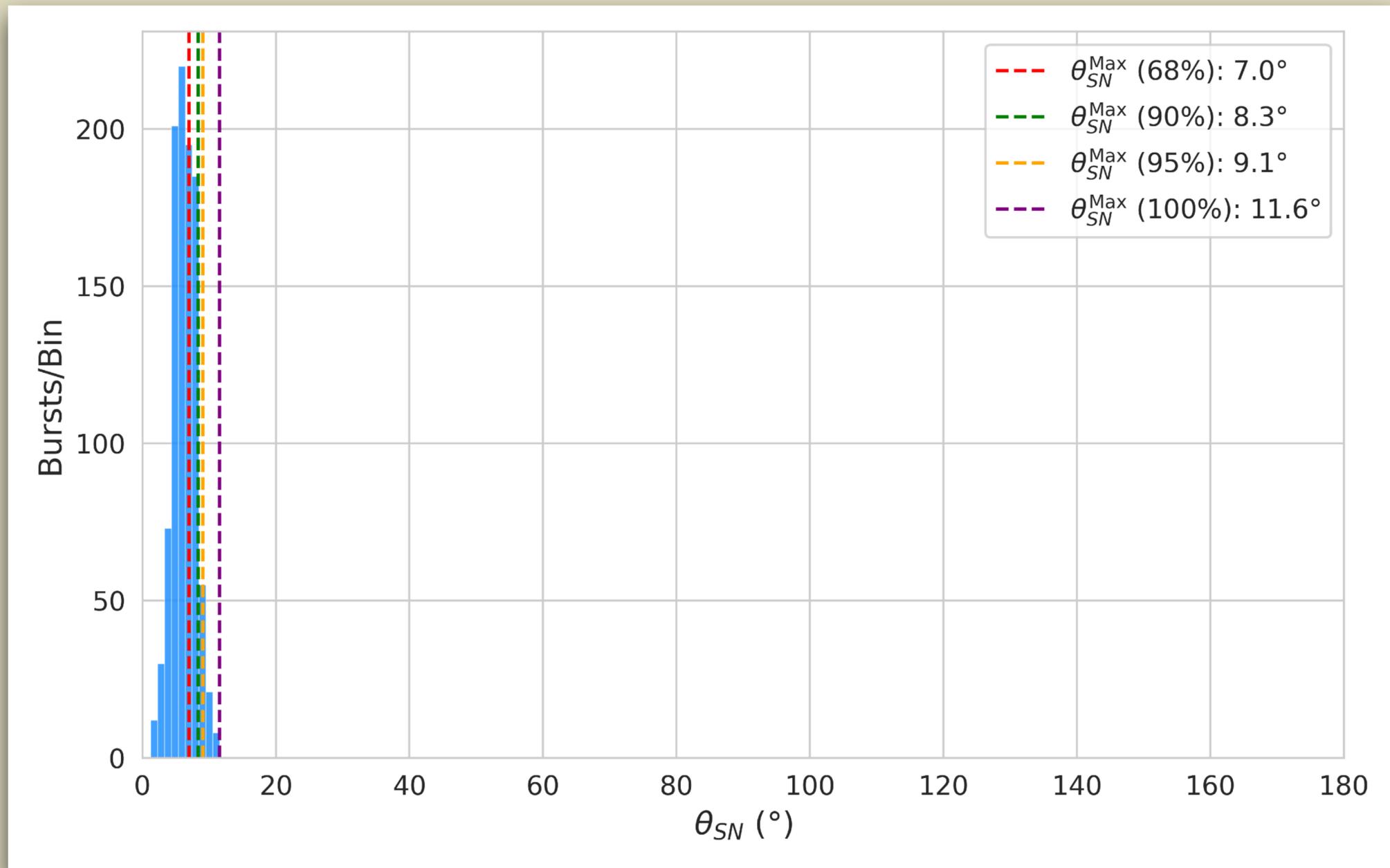
Batch Details:

▸ 1,000 SN Bursts @ **1kpc**

　✦　~600,000 events/burst

Reconstruction:

▸ **7.7 s/burst**

　✦　Data cuts: 5.7 s/burst

　✦　Dir recon: 2.0 s/burst

▸ $\theta_{SN}^{Max}(100\%) \approx 12°$

TQ-HEALPix Fitter

Mapping
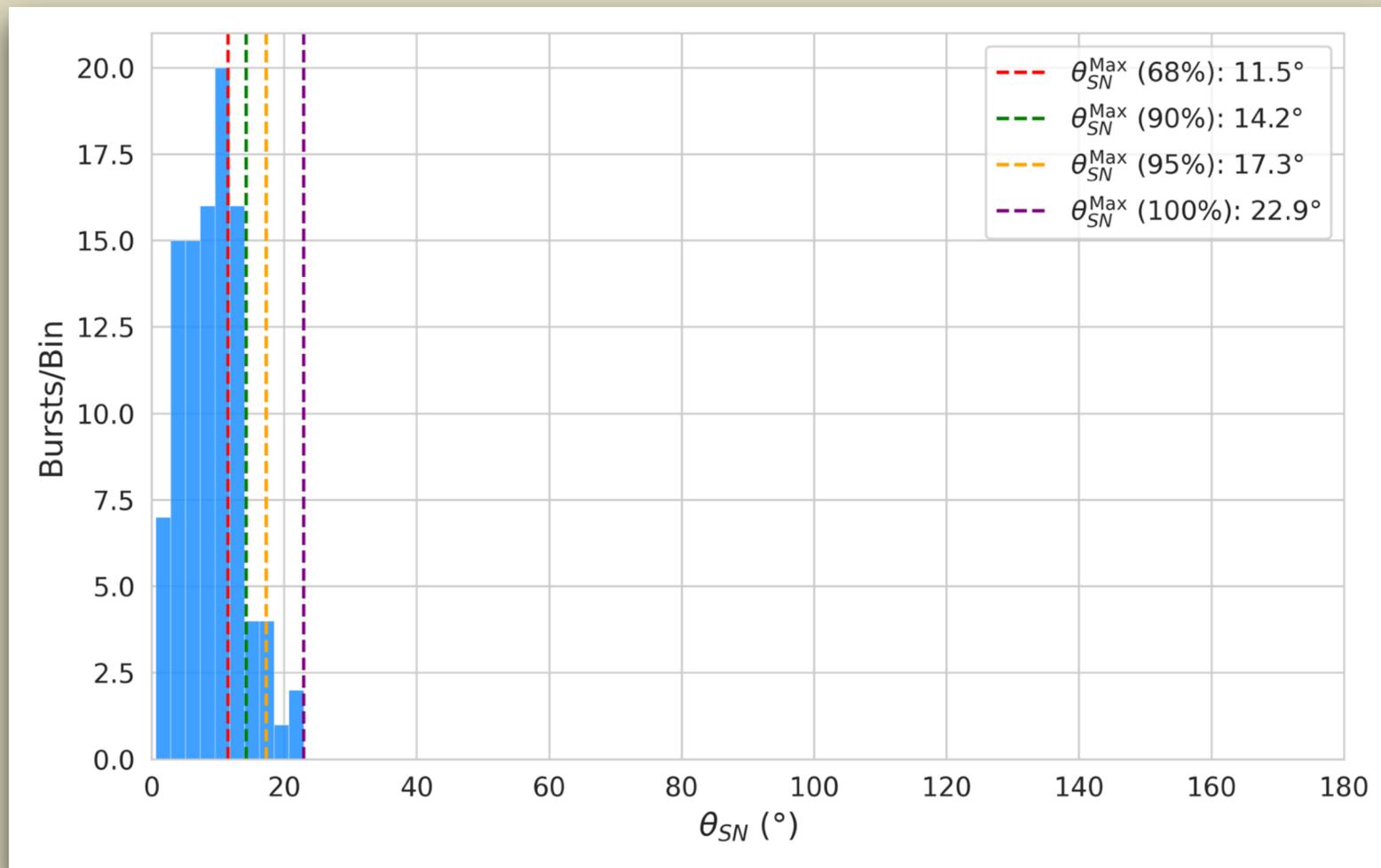
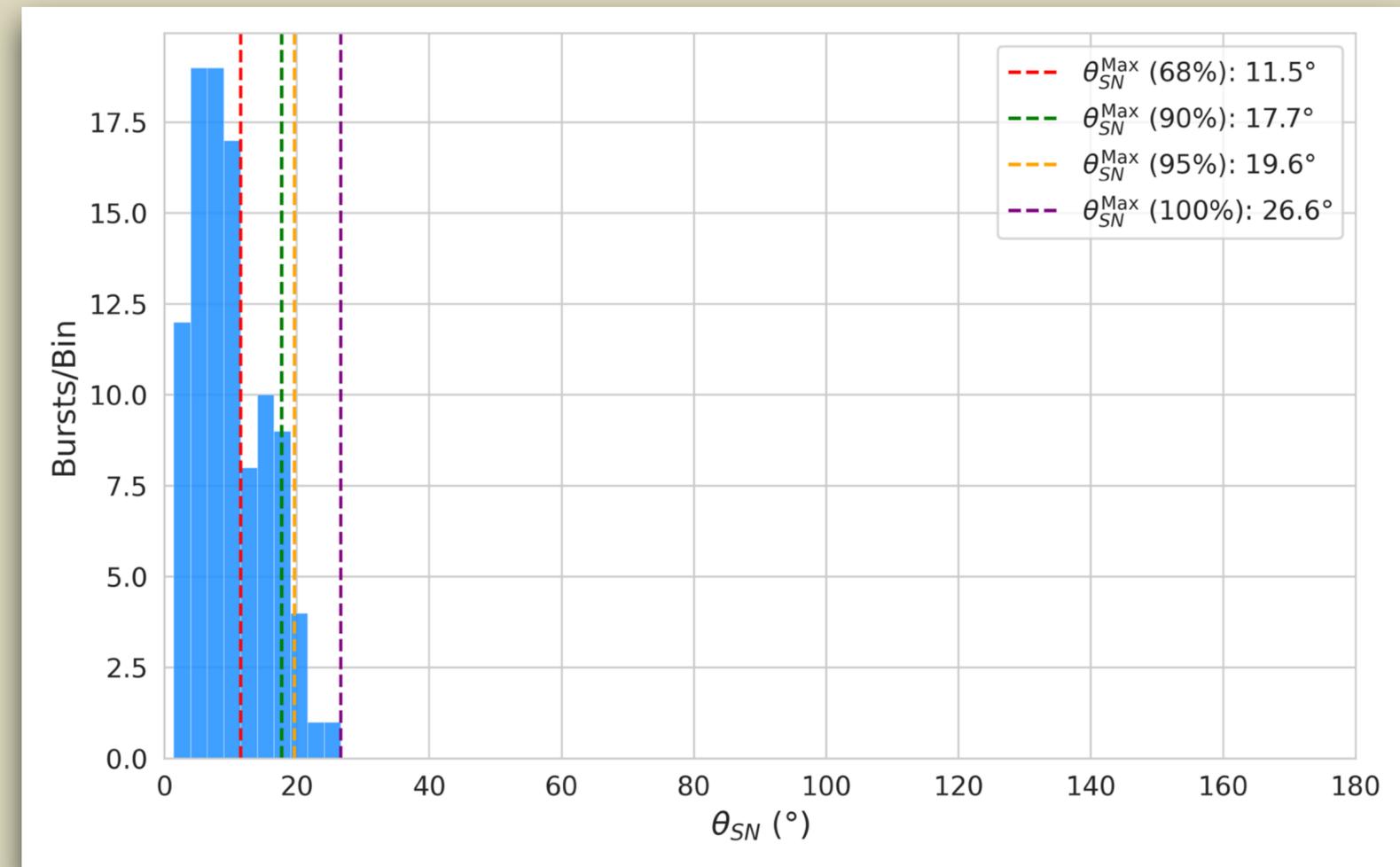# Cardinal Direction Results

Direction A: [0,0,1]

Direction B: [0,0,-1]
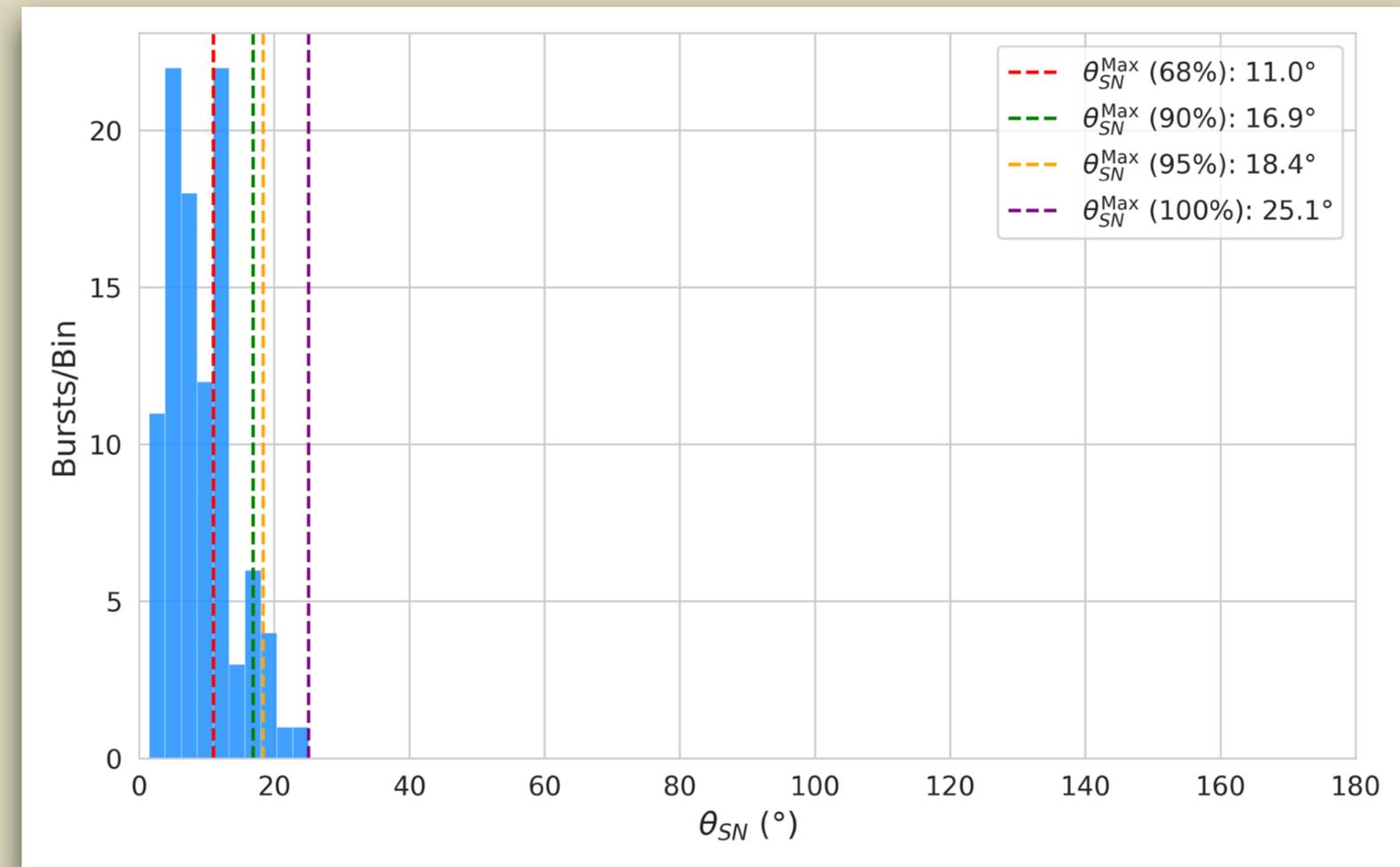
100 SN @ 3 kpc

Cardinal Direction Results
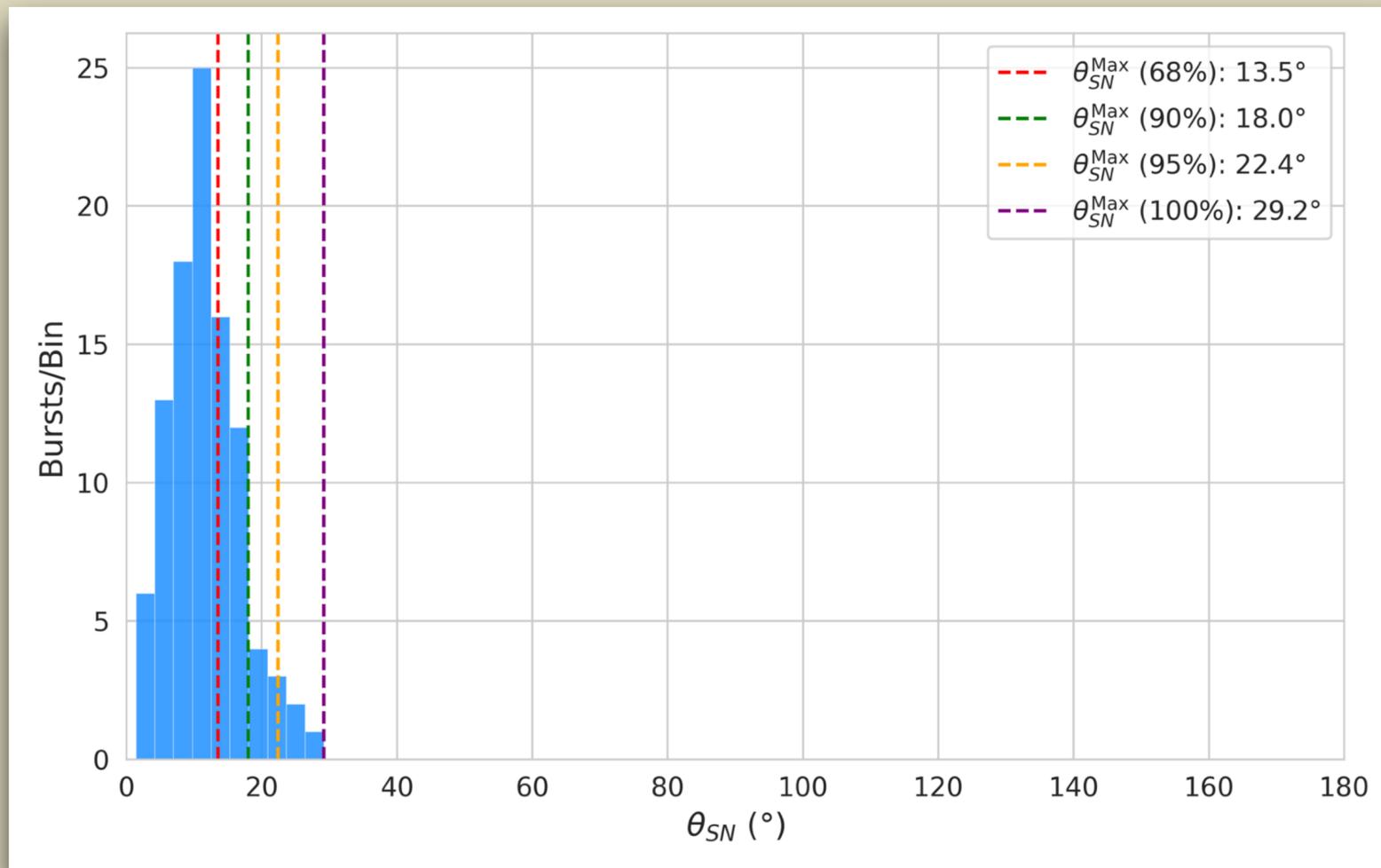
Direction C: [0,1,0]
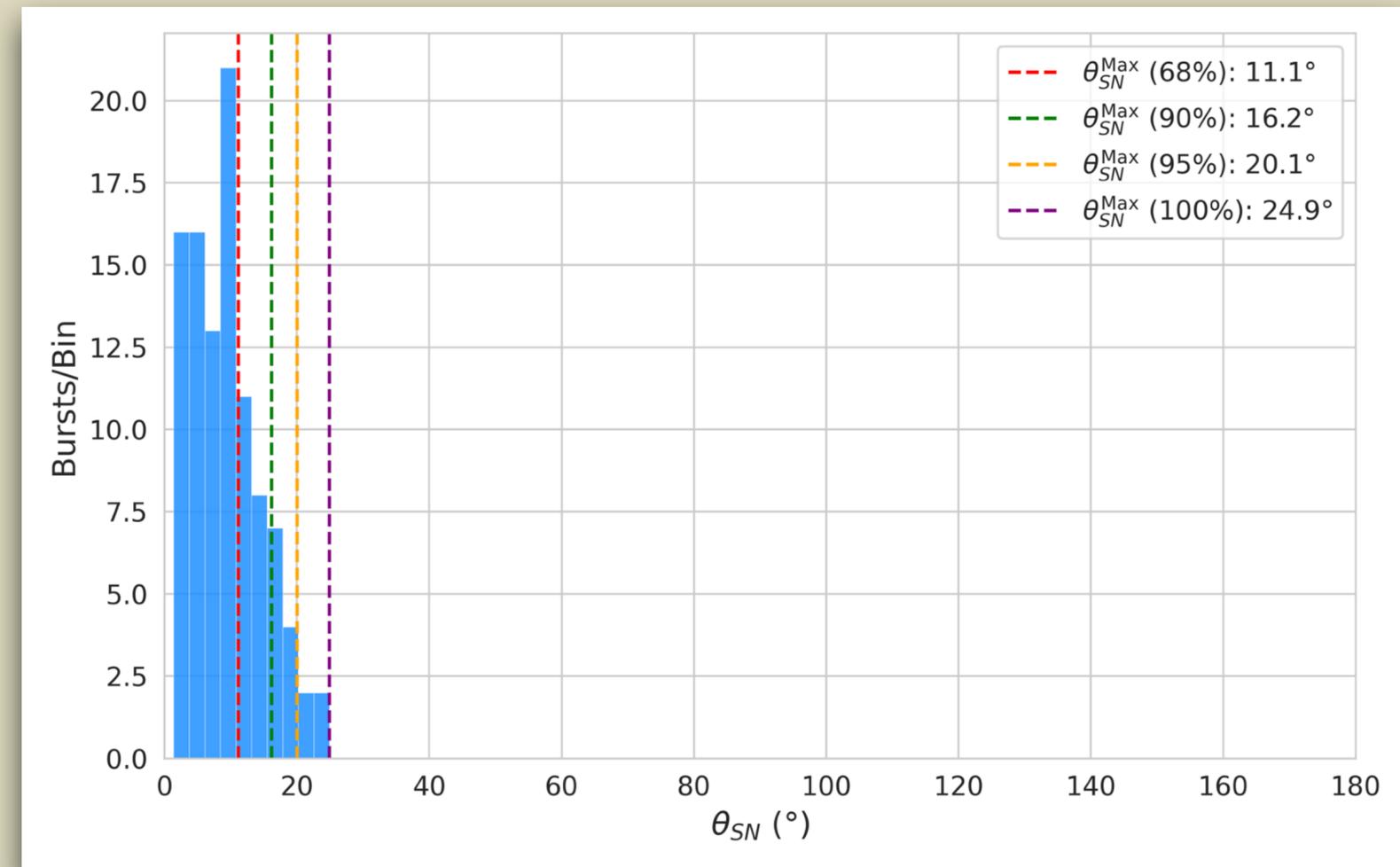
Direction D: [0,-1,0]

100 SN @ 3 kpc

Cardinal Direction Results

Direction E: [1,0,0]

Direction F: [-1,0,0]

100 SN @ 3 kpc