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Time-Charge HEALPix direction reconstruction for supernova neutrinos

A faster direction fitter for Super-K and Hyper-K

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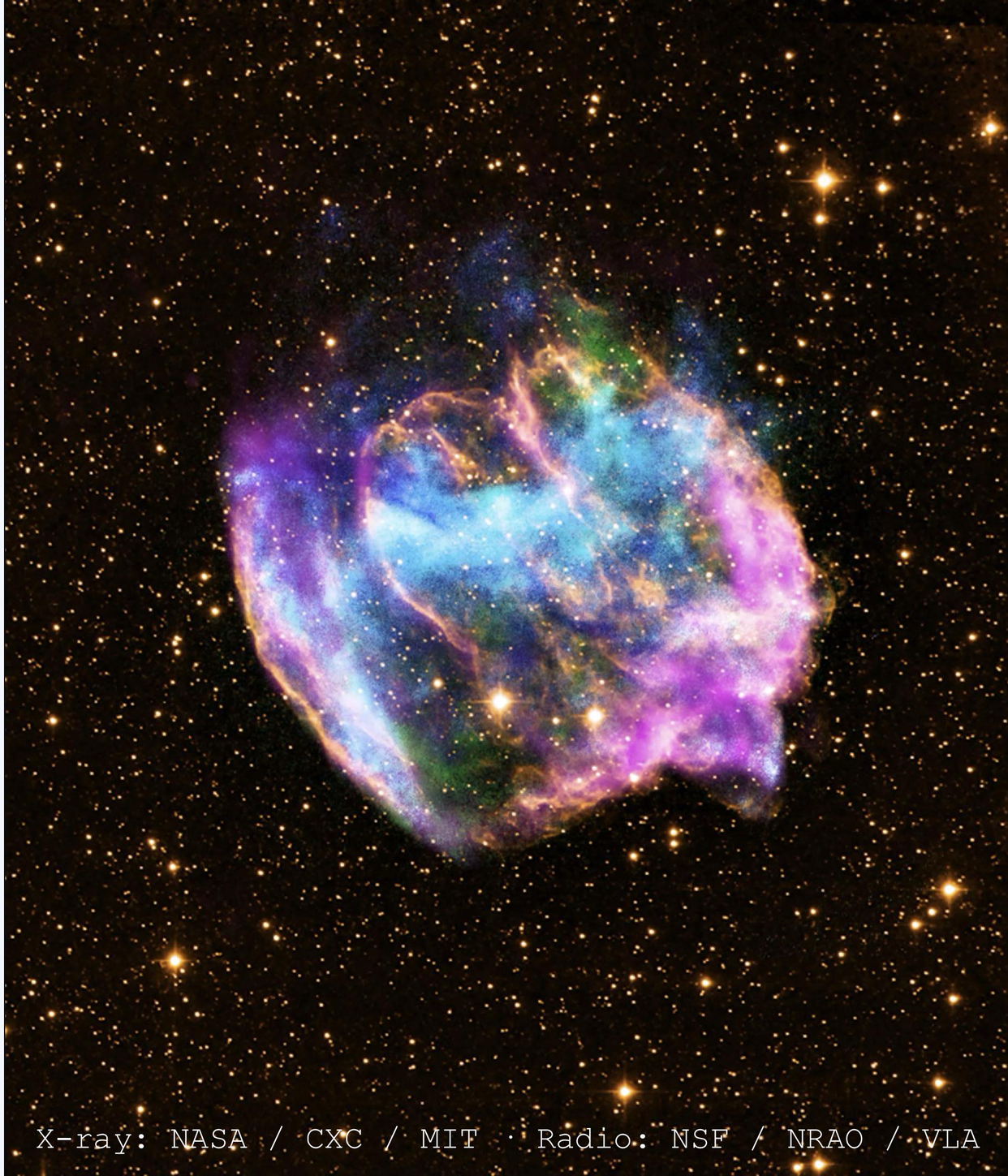


Super-Kamiokande

- Water Cherenkov detector, 1 km underground
- 11,146 inner PMTs, 50 cm diameter

Physics Goals:

Solar neutrino problem, **atmospheric** neutrinos, **proton decay**, neutrino **oscillation** (K2K and T2K), **DSNB**, and **Supernova burst neutrinos**

2015 NOBEL PRIZE

T. Kajita (Super-K) & **A. B. McDonald** (SNO): Confirmation of neutrino oscillations, showing neutrinos have mass.

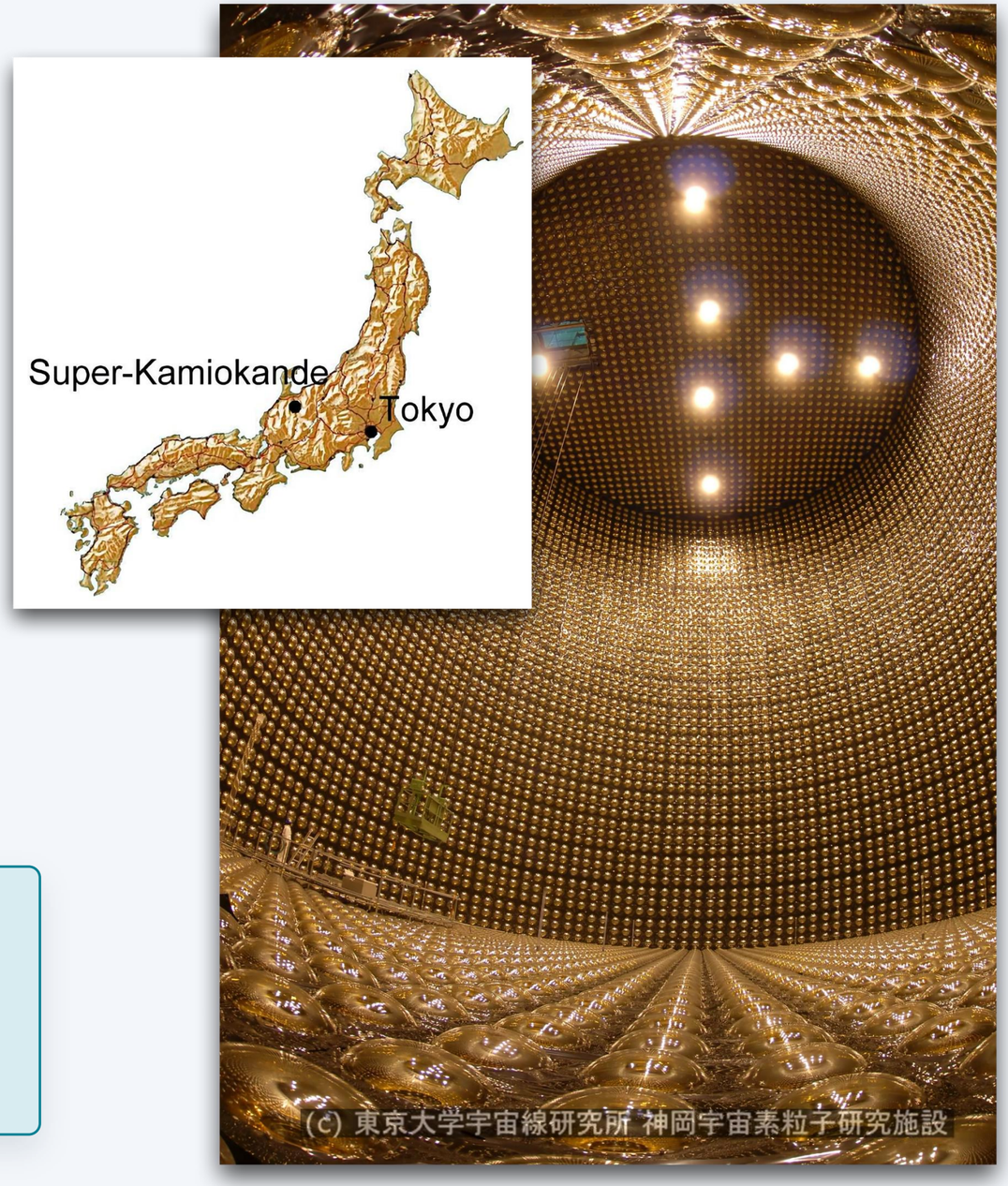


Image: Fukuda et al. (2003) · Kamioka Observatory, ICRR, Univ. of Tokyo

Three interaction channels

85% Inverse beta decay

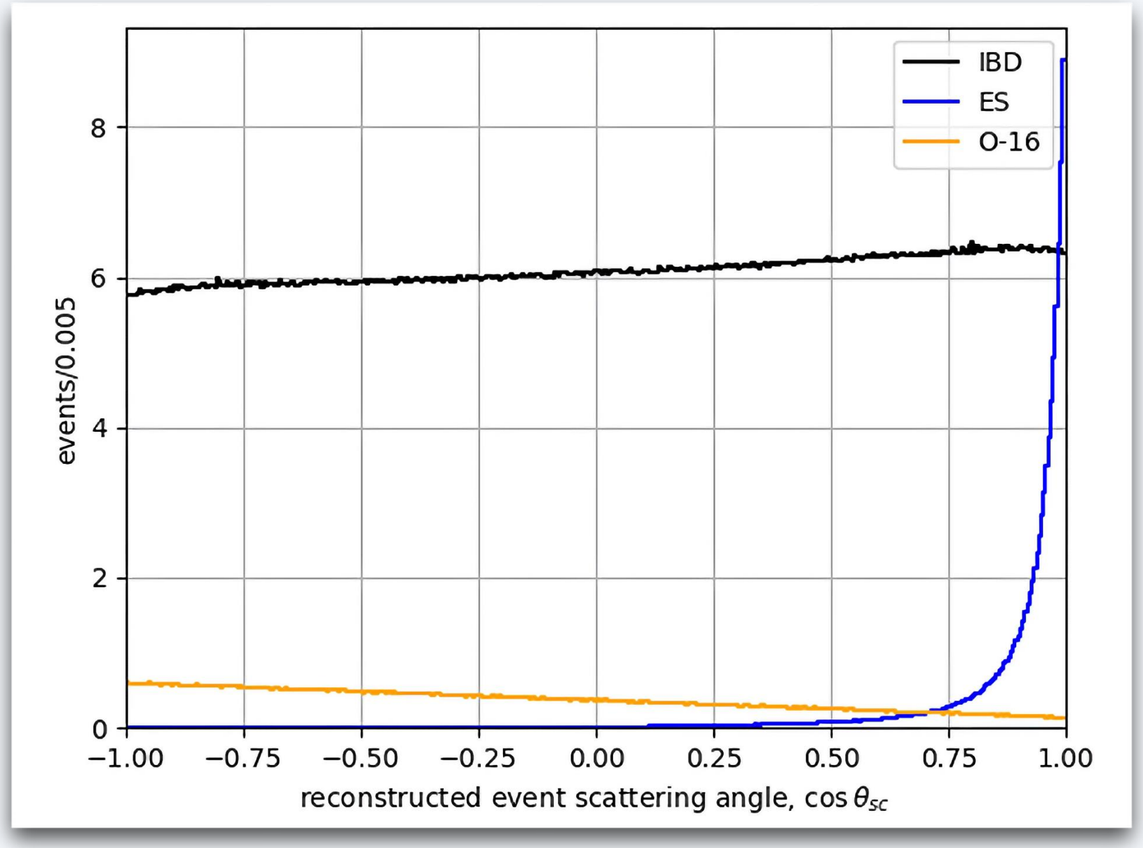
$\bar{\nu}_e + p \rightarrow e^+ + n$ · `nearly isotropic`

4% **Elastic scattering**

$\nu + e^- \rightarrow \nu + e^-$ · `forward-peaked`

11% Oxygen-16 CC / NC

$\nu_e + {}^{16}O \rightarrow e^- + X$ · `back-peaked`



Reaction type distributions using **Nakazato** SN flux neutrino flux model. Assumes **normal mass ordering** oscillations.

The shock-breakout deadline

- The burst escapes in ~10 s, ahead of any light
- Delay to first light: seconds to days
- Real-time pointing enables early multi-messenger follow-up

Reconstruction must be fast

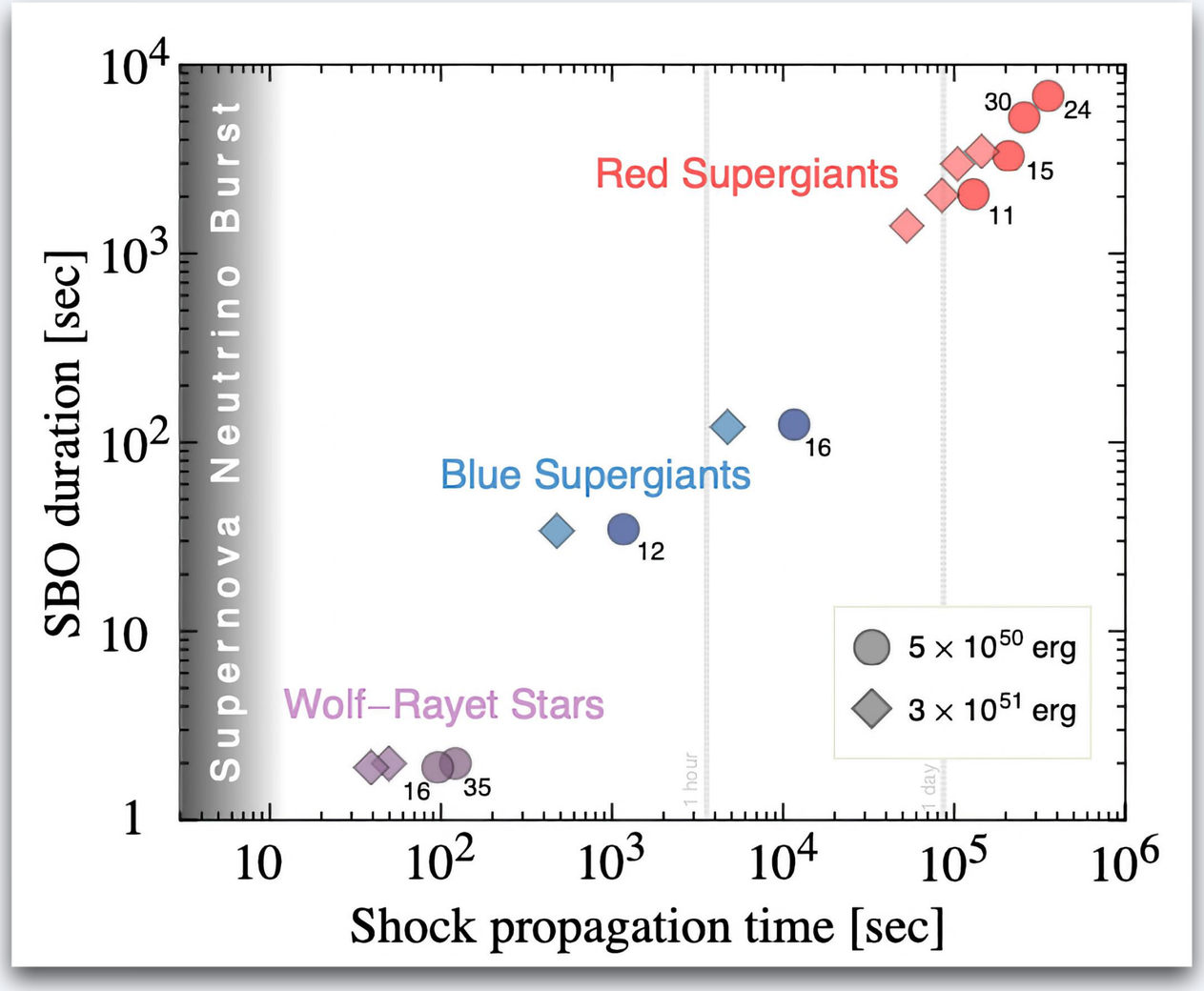


Image: Kistler, Haxton & Yüksel 2018, ApJ 778, 81

Direction recon fitters

Two production dir. recon fitters at Super-K:

- **ML** & **HEALPix** fitters reach **~1°** resolution
- Full event-level **vertex**, **energy** & **direction** recon
- Cost scales with event count. Surges for,
  - **Nearby galactic bursts (<3 kpc)**
  - The higher sensitivity **Hyper-K**

DISTANCE	EVTS/BURST	RECON TIME
10 kpc	~4,000	~60 s
3 kpc	~40,000	**~180 s**
< 1 kpc	~400,000	minutes

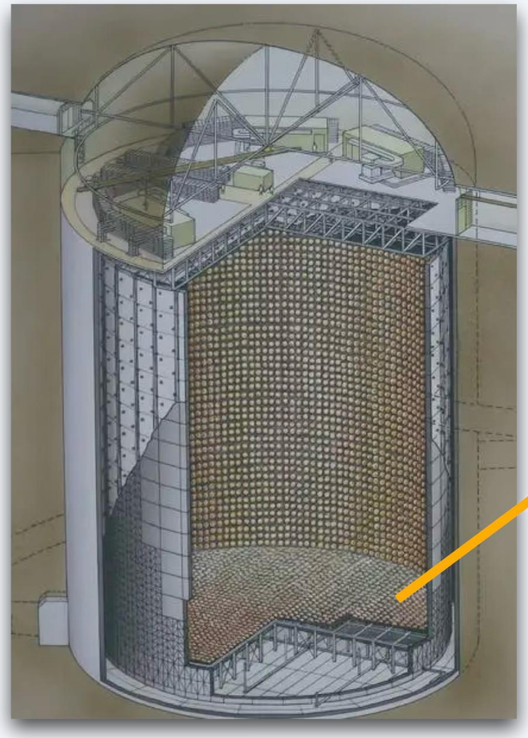
✦ **Minutes-scale latency misses the shock-breakout window**

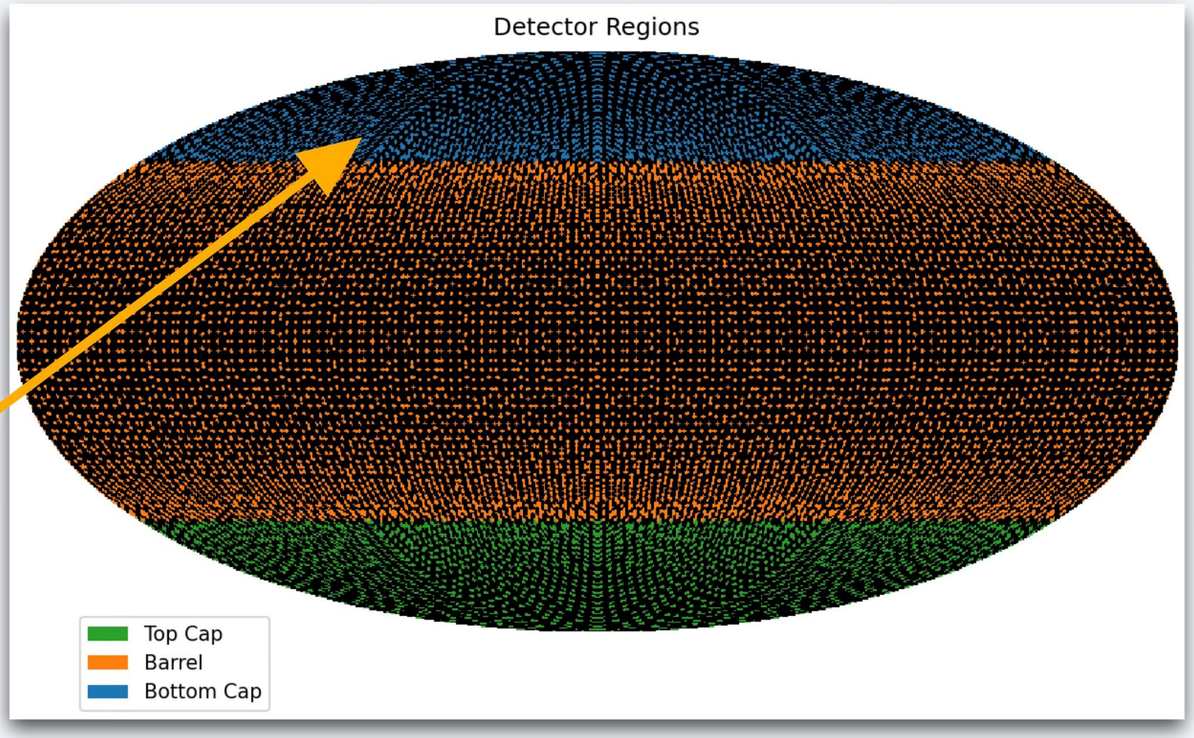
From cylinder to sphere

- Map raw TQ data directly onto a HEALPix sphere
- Each PMT's 3D direction → one pixel

✦ **No per-event reconstruction → low latency**

- Cylinder vs sphere → geometric distortions





`PMT positions → HEALPix pixels, colored by detector region: barrel, top cap, bottom cap`

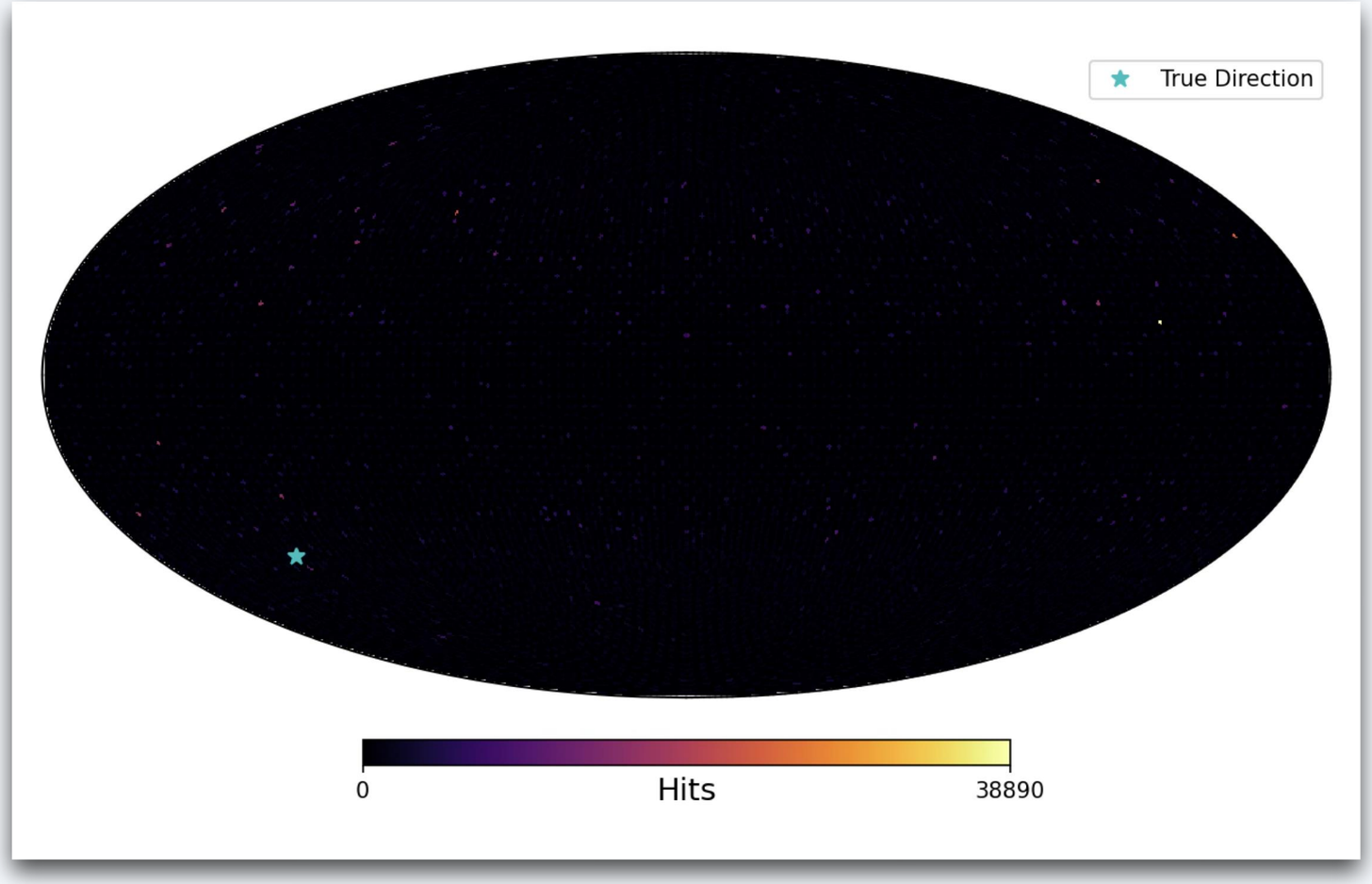
Mapping a burst at 3 kpc

- Each PMT hit adds +1 to its pixel

~44k
events / burst

~360
hits / event

```
Simulated SN burst @ 3 kpc
Nakazato SN flux model
Normal mass ordering
```

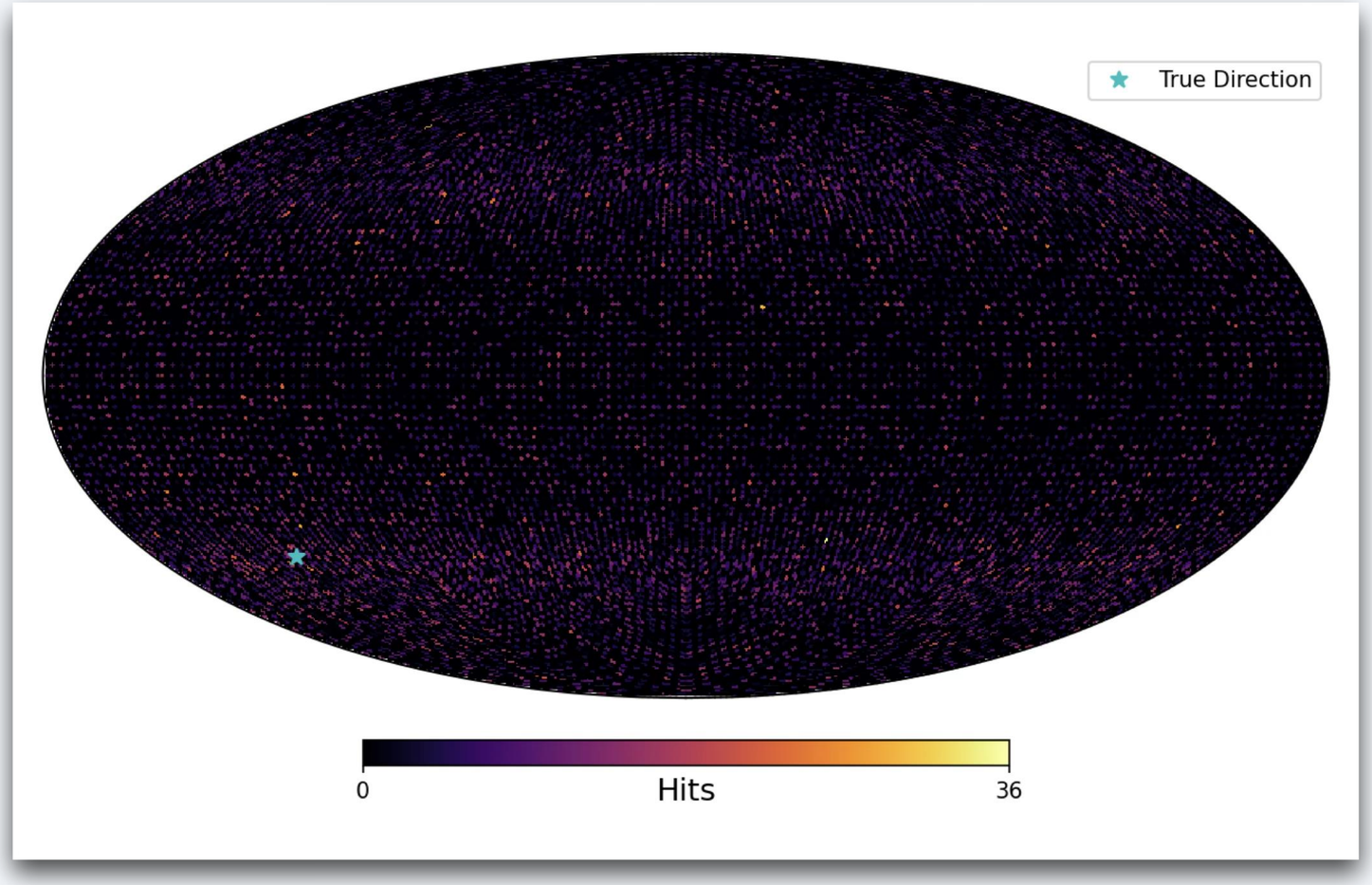


TQ cuts and PMT dark noise

- Data cuts on,
  - hit **time**
  - # **hits/event**
  - **Q/event**
- Dark hits estimated per PMT & subtracted

$$N_{dark}(i) = R_i \times \Delta t \times N_{good}$$

~360 hits/evt before → **~30** “good” hits/evt

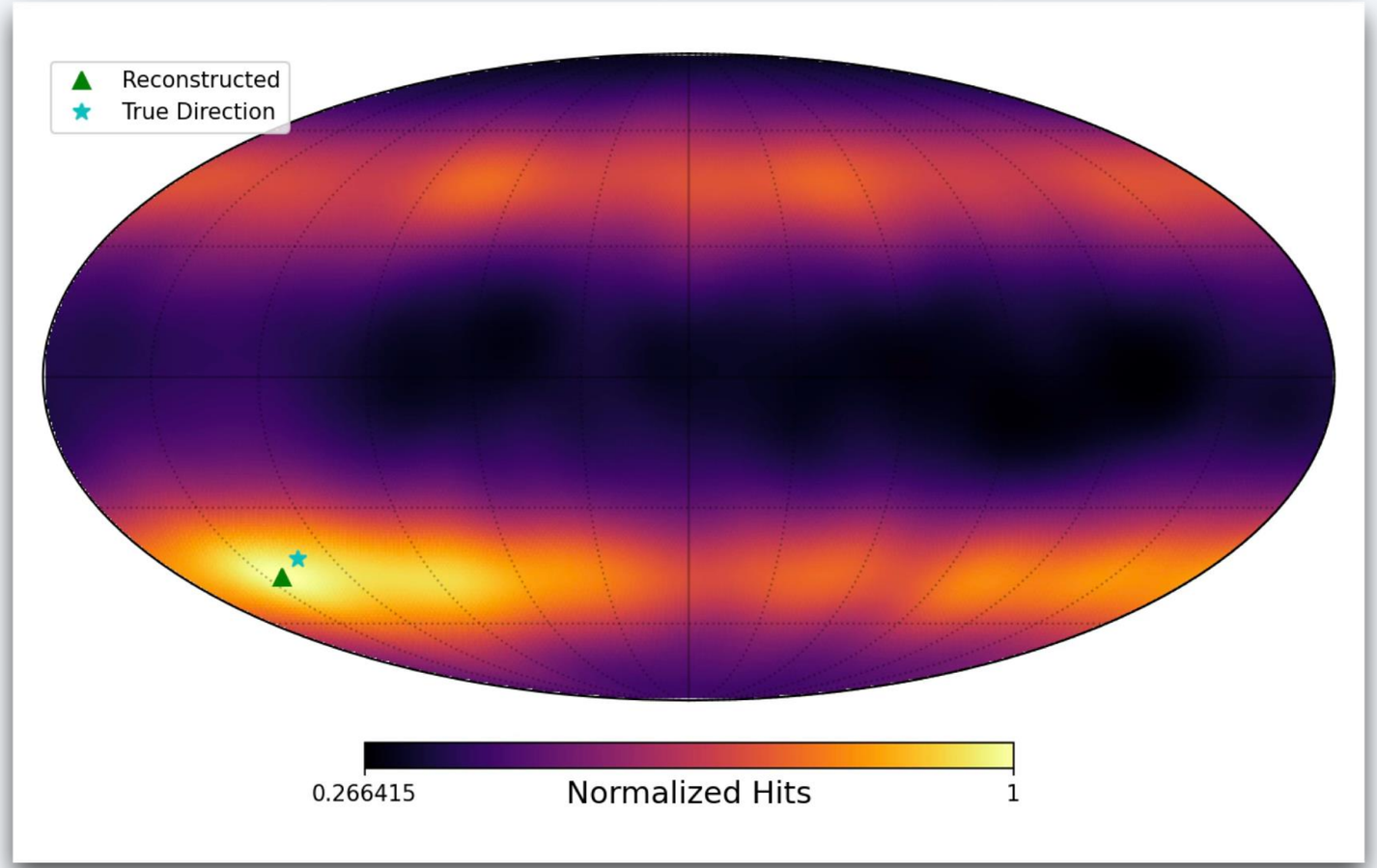


Smoothing a sparse map

- Gaussian smoothing, $\sigma = 0.15$

✦ **Hot / cold bands appear**

- PMT vectors sampled unevenly, sparse equator, dense poles

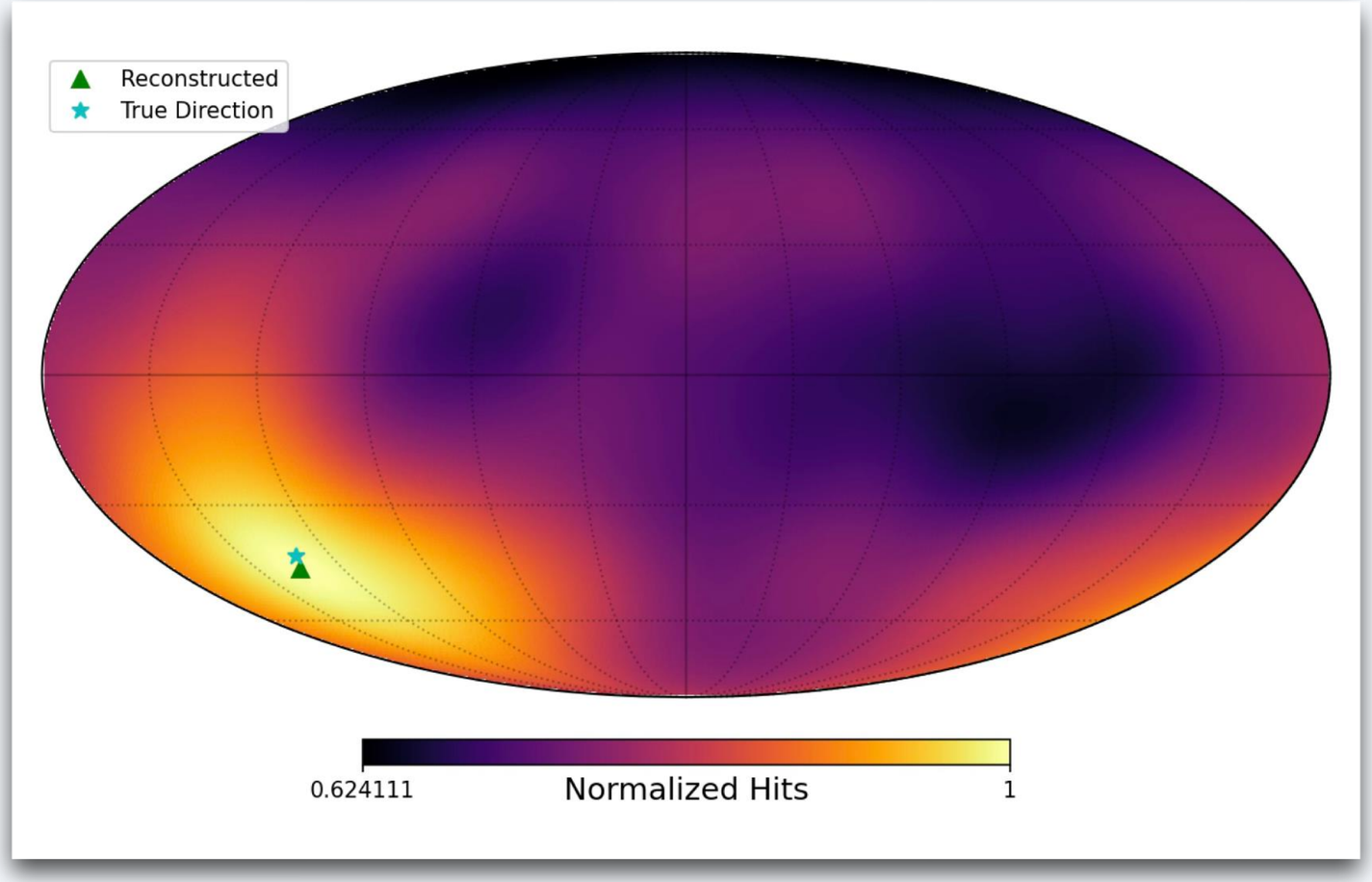


Normalizing for sample density

- Normalize by sampling density

Bands flatten to a smooth gradient

→ **the source emerges**



The full processing chain

PROCESSING PARAMETERS

Hits / event	[10, 40] hits
Q / event	[11, 60] p.e.
Hit time	[0, 215] ns
Smoothing σ	0.6
Density σ	0.4

SINGLE-FIT RESULT @ 3 KPC

43,788
total events

7,505
“good” events

3.9°
angular discrepancy

~1 s
recon time

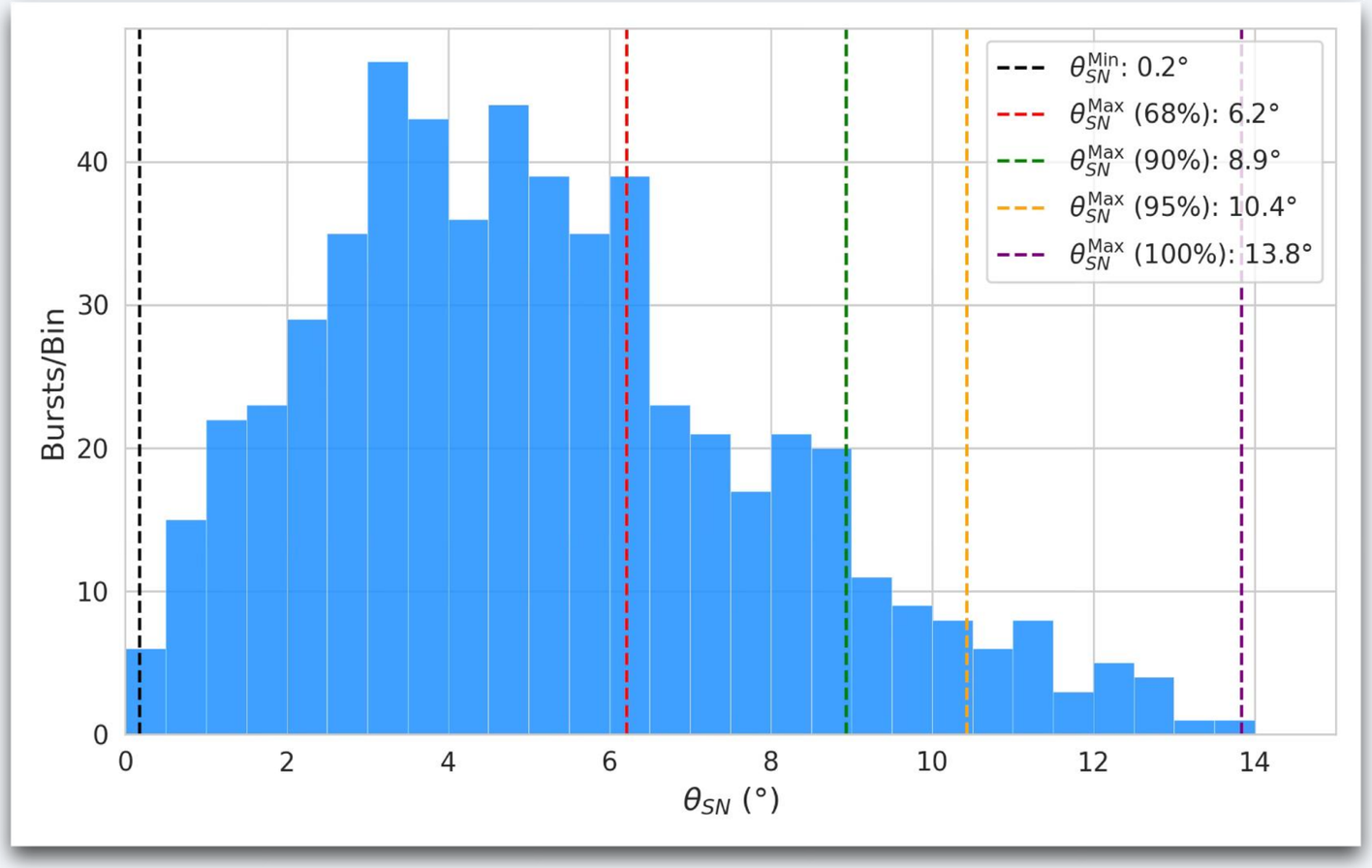
Preliminary angular discrepancy at 3 kpc

570 SN bursts @ 3 kpc · 57 sky positions

~6°
$\theta_{68\%}$ containment

< 1 s
per burst

90% containment	8.9°
95% containment	10.4°
Maximum	13.8°



TQ-Fitter: Summary of preliminary results

	ML	HEALPIX	TQ*
Ang. disc (68%)	~1°	~1°	**~6°**
Event recon	~180 s	~180 s	**none**
Dir. recon	11 s	0.4 s	**~1 s**
Total	~190 s	~180 s	**~1 s**

✦ **~1 s latency at 3 kpc, ~200× faster**

- **ZERO** event-level reconstruction
- Latency improvements for **nearby galactic SN**
- Technique applicable to **Hyper-Kamiokande**
  - **~10-20x** SN burst neutrinos detected
  - Latency of TQ-Fitter allows speedy GCN

Extra slides

Backup detail: models · pipeline · cuts · dark noise · batch results

Hyper-K Sensitivity Curves

- Hyper-K will have increased sensitivity
  - ✦ Most sensitive to **IBD** events
- TQ-Fitter relies on high statistics achievable with Hyper-K, even at closer distances:

~54k – 90k
Evts/burst @ 10 kpc

~10-20x
Super-K Sensitivity

~4,000 ES
Evts/burst @ 10 kpc

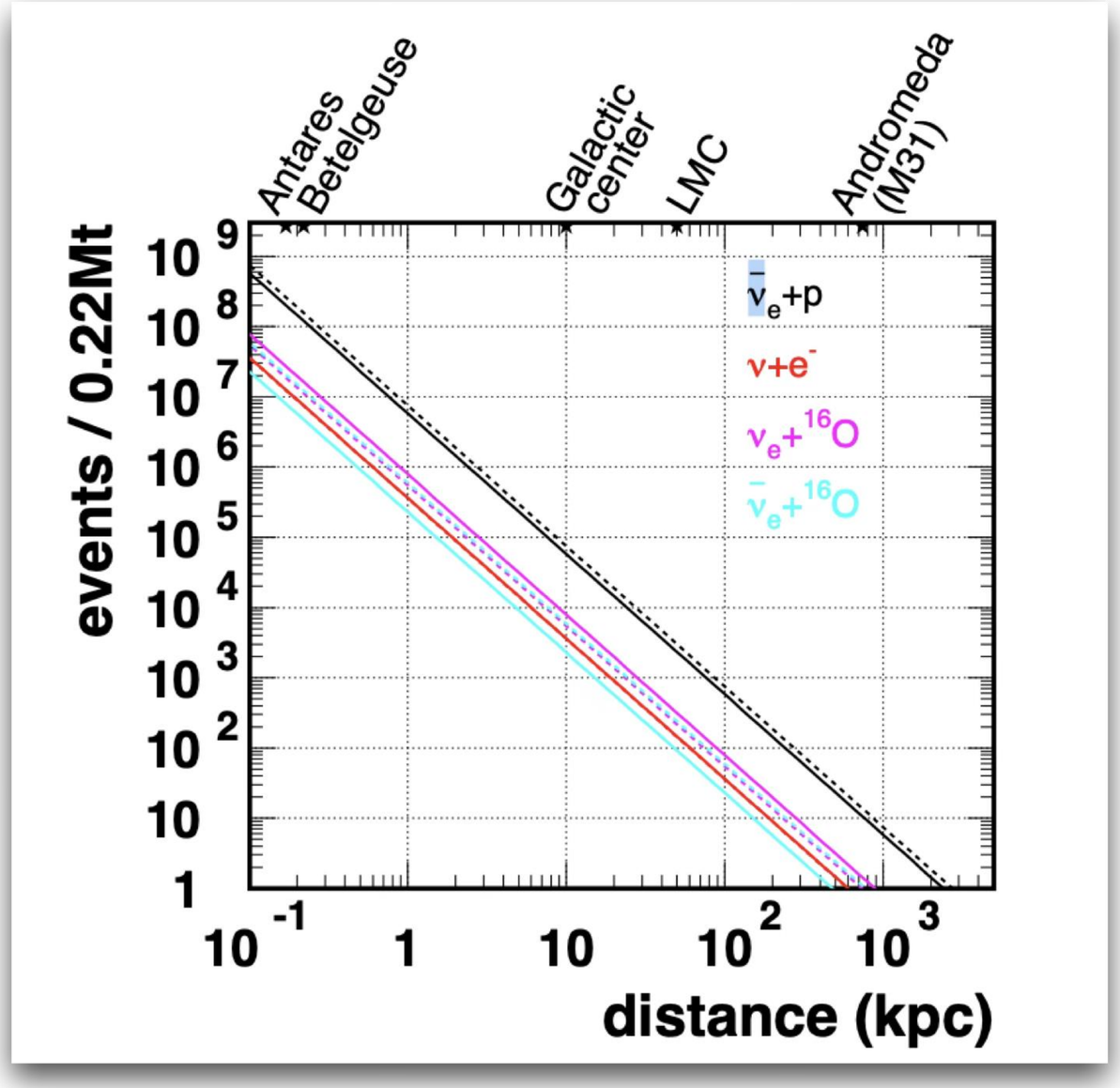


Figure: K. Abe et al. 2021 ApJ 916 15

Preliminary recon angular-discrepancy distribution

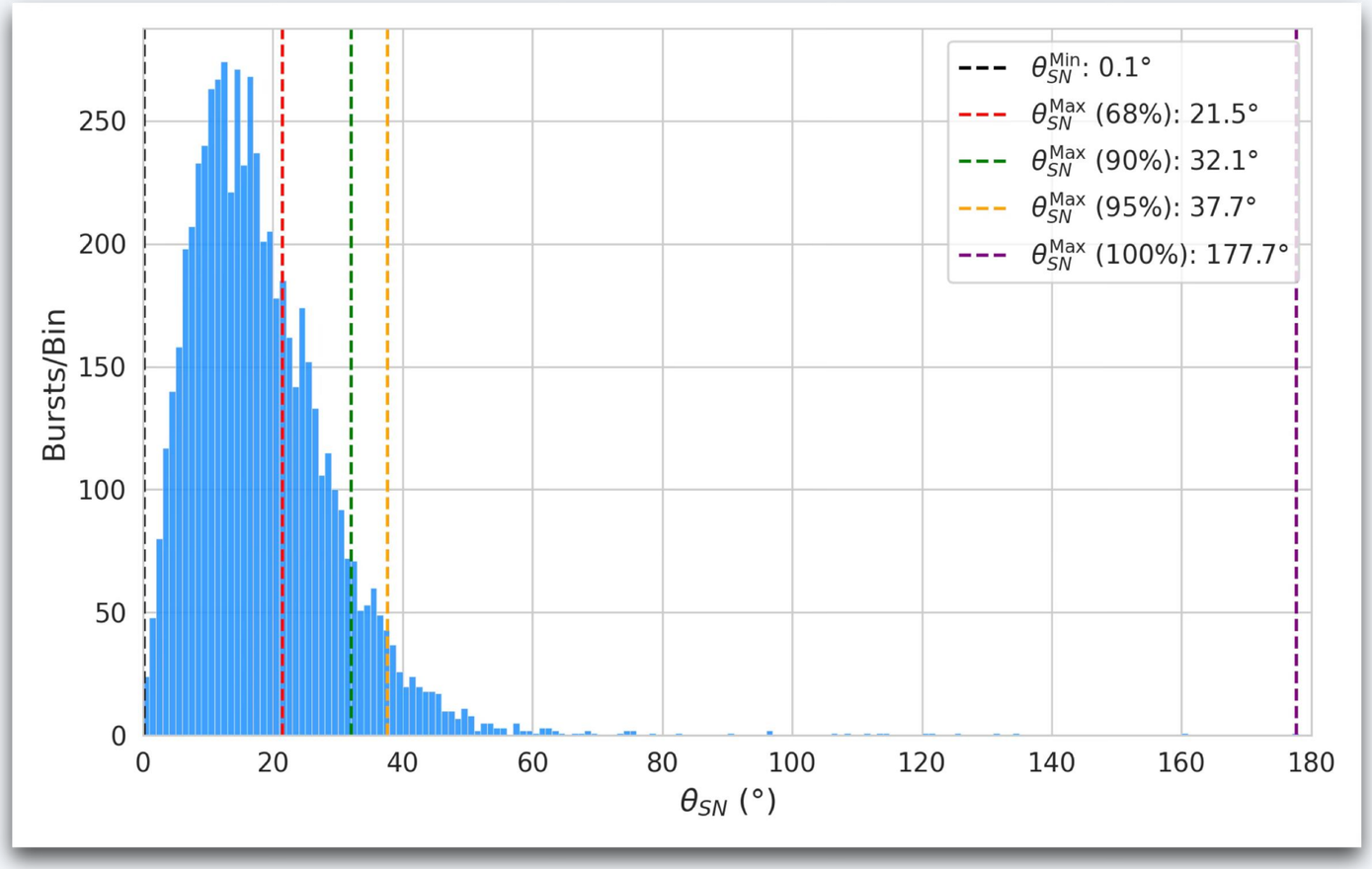
BATCH DETAILS

- 5710 SN bursts @ 10 kpc
  - ✦ ~4,000 events / burst

0.2 s
per burst

~22°
$\theta_{68\%}$

data cuts 0.15 s dir. recon 0.05 s

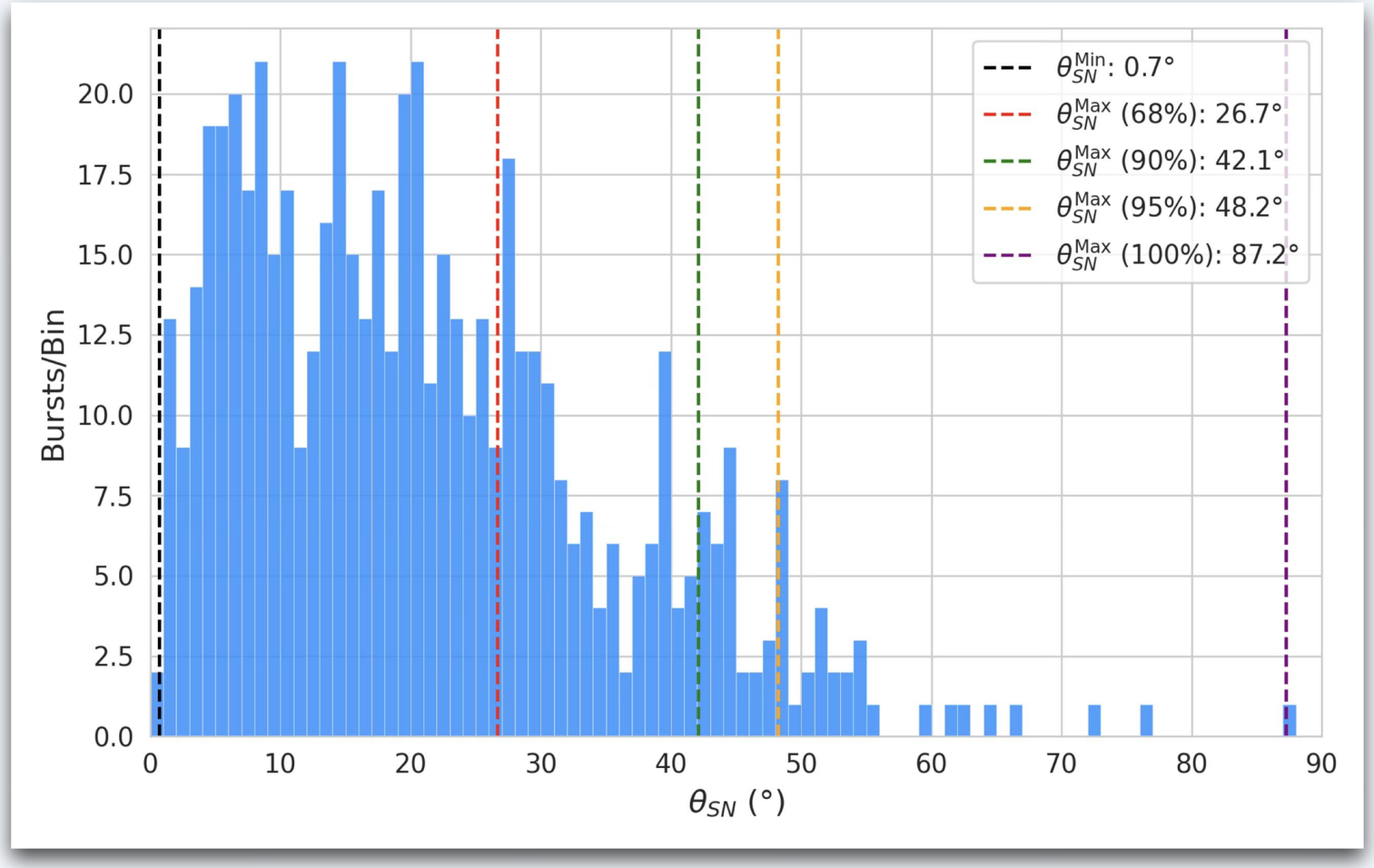


Preliminary recon angular-discrepancy distribution

BATCH DETAILS

- 570 SN bursts @ 3 kpc
  - ✦~44,000 events / burst
  - ✦1° bin width

NO dark-rate subtraction



Models & reaction channels

MODELS FOR SN

- Nakazato flux model
- Simulated @ 10 kpc

REACTION CHANNELS

Inverse beta decay

Elastic scattering

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

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
^{16}O CC ($\bar{\nu}_e$)	195	329	633	46	68	116	30	42	71
^{16}O NC (ν_e,^{15}N)	4	89	63	4	15	12	1	8	5
^{16}O NC ($\bar{\nu}_e$,^{15}N)	22	43	89	5	8	16	3	4	8
^{16}O NC (ν_x,^{15}N)	177	93	119	31	20	23	15	8	10
^{16}O NC ($\bar{\nu}_x$,^{15}N)	177	156	112	31	28	21	15	14	10
^{16}O NC (ν_e,^{15}O)	1	24	17	1	4	3	0	2	1
^{16}O NC ($\bar{\nu}_e$,^{15}O)	6	12	24	1	2	4	1	1	2
^{16}O NC (ν_x,^{15}O)	48	25	32	9	5	6	4	2	3
^{16}O NC ($\bar{\nu}_x$,^{15}O)	48	42	30	8	8	5	4	4	3
total	8622	10530	12294	4074	4580	5389	3690	3904	4239

Table credit: Kashiwagi et al. (2024), arXiv:2403.06760

APPENDIX · SIMULATION PIPELINE

Supernova neutrino modeling

INPUT PARAMETERS

SN flux model

Distance [kpc]

SN sky position

Mass oscillation ordering

→

SKSNSim

Event generation

→

SKG4

Detector simulation

→

THIS WORK

Direction recon

→ SN point direction

Pipeline after Kashiwagi et al. (2024), arXiv:2403.06760

APPENDIX · SIMULATION PIPELINE

Supernova neutrino modeling

INPUT PARAMS

SN flux model · Distance [kpc] · SN position · ν oscillation

↓

SKSNSim: event generation

SKG4: detector simulation

Direction recon

MC PARAMETERS

- Nakazato flux model
- 10 kpc distance
- Variable SN position
- NMO oscillation

Table credit: Kashiwagi et al. (2024), arXiv:2403.06760

Supernova neutrino modeling

Input params: flux, distance, position, oscillation

↓

SKSNSim
Event generation

↓

SKG4: detector simulation

Direction recon

SKSNSIM

- Event generation
  - ✦ Energy selection
  - ✦ Vertex selection
  - ✦ Reaction type (ES, IBD, O-16)
- Vector file describes burst

Table credit: Kashiwagi et al. (2024), arXiv:2403.06760

Supernova neutrino modeling

Input params

↓

SKSNSim: event generation

↓

SKG4
Detector simulation

↓

Direction recon

SKG4

- Simulate SK event response
  - ✦ rType interactions in WCD
  - ✦ PMT dark noise injected
- SK TQReal ROOT
  - ✦ Raw PMT information
  - ✦ Hit time + charge

Table credit: Kashiwagi et al. (2024), arXiv:2403.06760

Supernova neutrino modeling

Input params

↓

SKSNSim: event generation

↓

SKG4: detector simulation

↓

Direction recon
This work

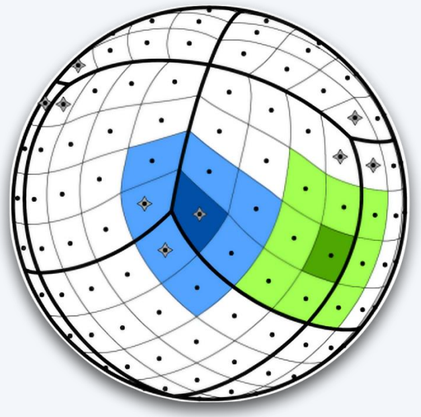
→ point direction

DIRECTION FITTER

- SK PMT response analyzed
- SN direction fitted
  - ✦Angular discrepancy
- Current work

Table credit: Kashiwagi et al. (2024), arXiv:2403.06760

Mapping TQ data to HEALPix

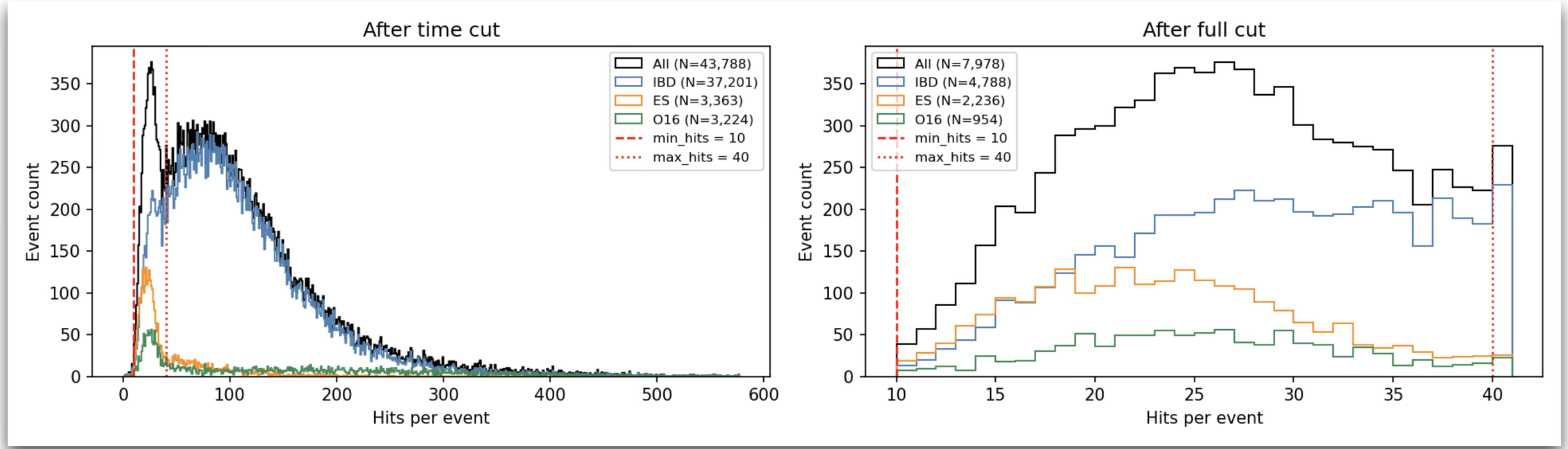


- Hierarchical Equal Area isoLatitude Pixelization
  - ✦ 3D vectors → pixel positions on sphere
- Burst events mapped to HEALPix sphere
  - ✦ Pixels weighted by event information
- Spherical vs cylindrical → geometric corrections

NSIDE	# PIX	RES ′	□°
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

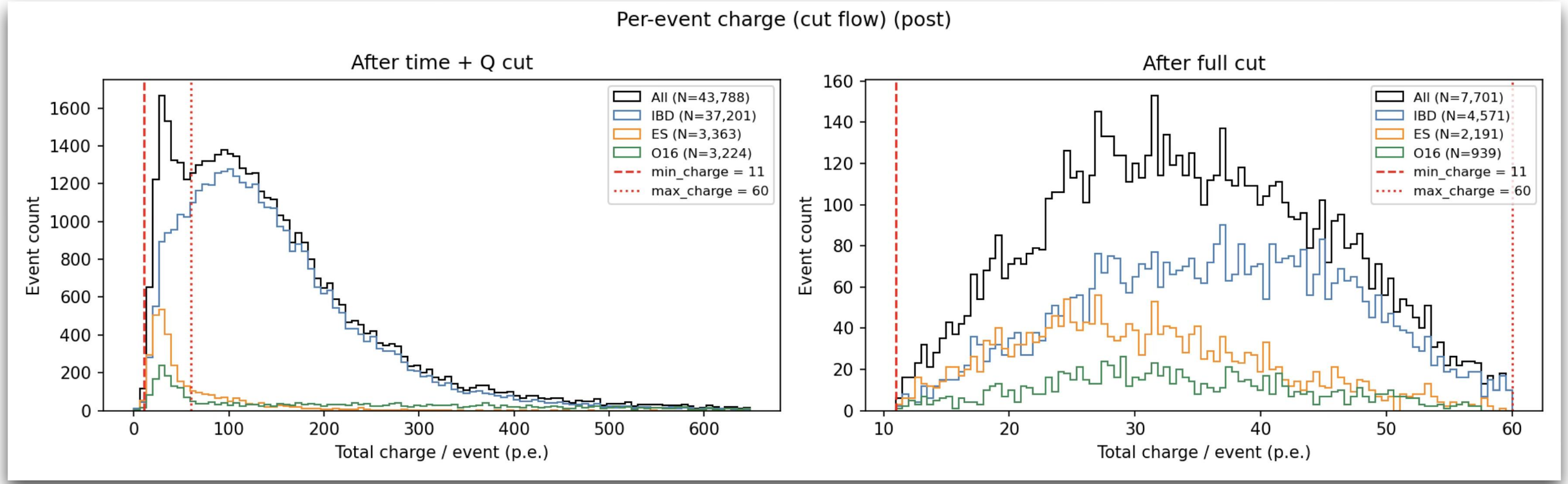
Górski et al. (2005), ApJ 622, 759 · arXiv:astro-ph/0409513

Time–charge–hit cuts



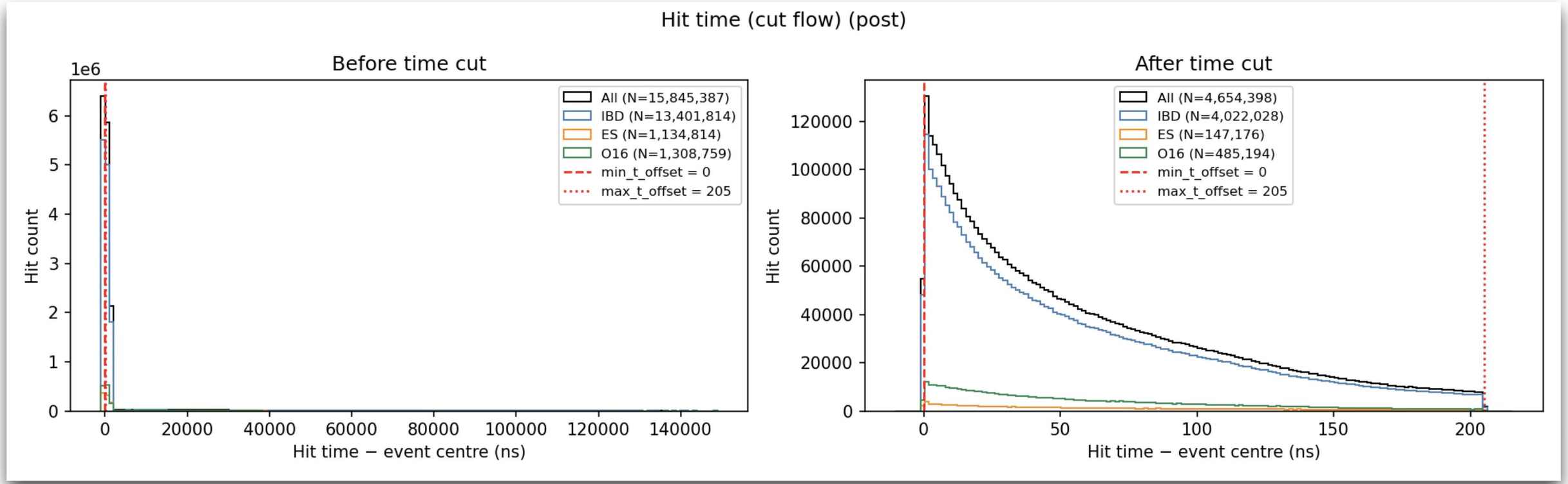
HITS/EVENT CUT DISTRIBUTION

Time–charge–hit cuts



CHARGE/EVENT CUT DISTRIBUTION

Time cuts



HIT-TIME CUT DISTRIBUTION

Pre-prompt dark-noise estimation

- Window prior to prompt signals
  - ✦ T in `[0, 750] ns`
  - ✦ This is all dark noise
- Find distribution of hits
- Scale to prompt window & surviving events
- Apply background subtraction