ICECUBE SEARCH FOR MEV NEUTRINOS FROM MERGERS USING GRAVITATIONAL WAVE CATALOGS

Nora Valtonen-Mattila* on behalf of the IceCube Collaboration

* nvalto@astro.ruhr-uni-bochum.de

TRANSIENTS

Supernovae

Death of stars

Neutron Star Mergers (NS)

Gamma-ray Burst (GRB)

Arise from death of stars & mergers

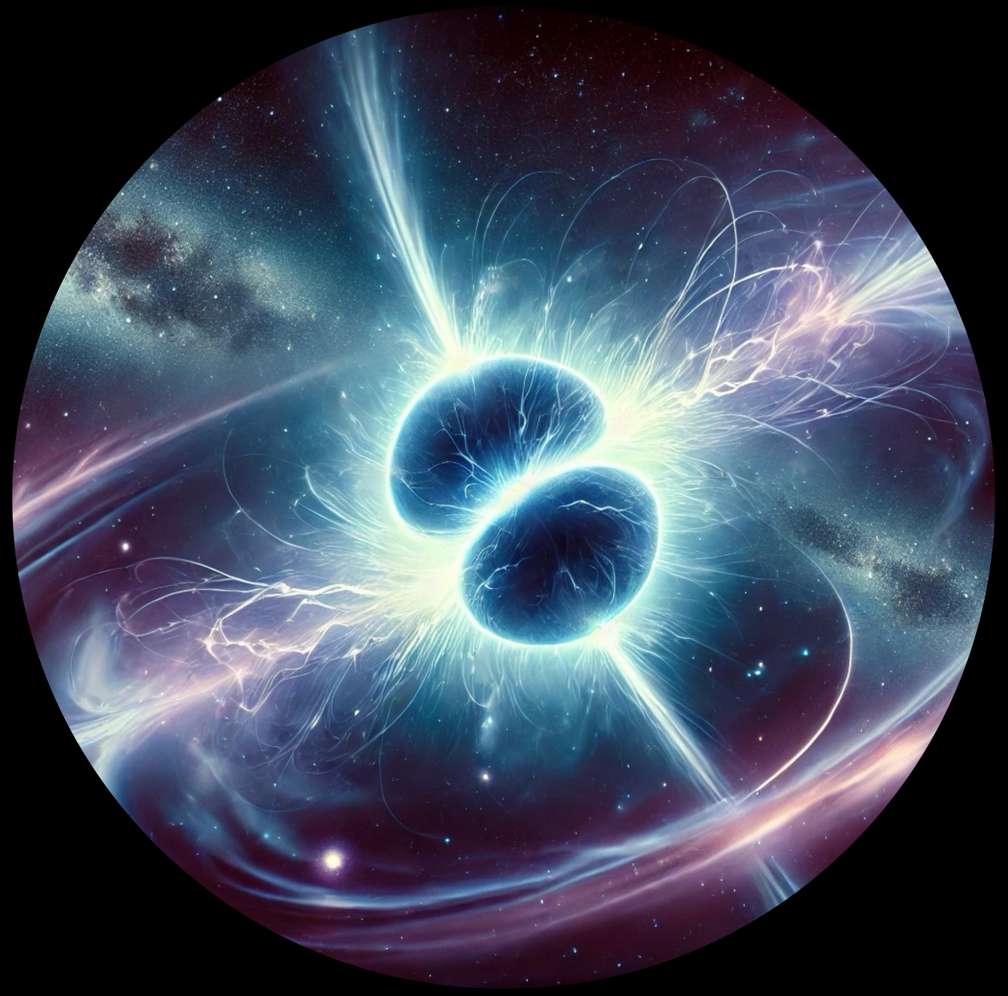
They can produce a plethora of signals, along with gravitational waves (GW) and low and high energy neutrinos.

CR acceleration: pp collisions

Thermal neutrino production: nucleon-nucleon interaction in very dense environment

ICECUBE SEARCHES FOR NEUTRINOS FROM GW SOURCES

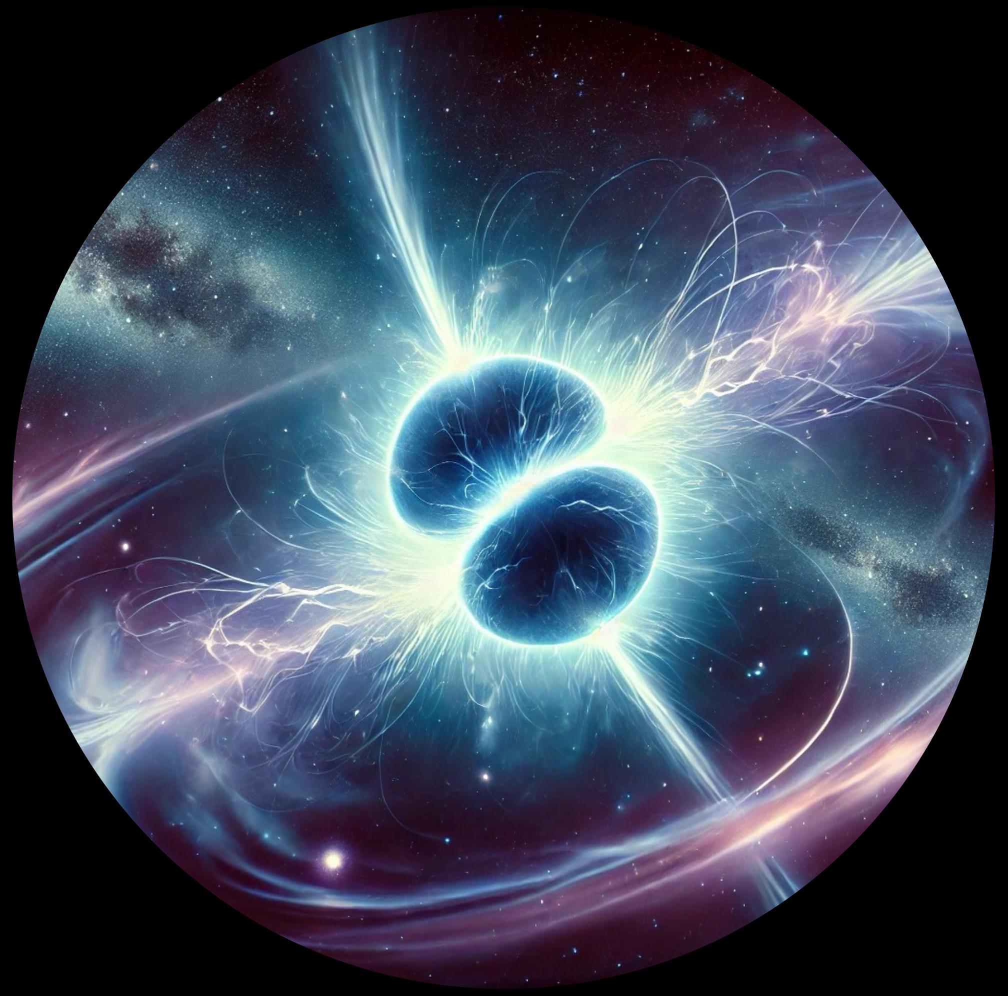
Process: CR acceleration



1 MeV	10 MeV	100 MeV	1 GeV	10 GeV	100 GeV	1 TeV	10 TeV	100 TeV	1 PeV	10 PeV

ICECUBE SEARCHES FOR NEUTRINOS FROM GW SOURCES

Process: CR acceleration



Low energy events

High energy cascades

Low energy tracks and cascades

High energy tracks

1 MeV	10 MeV	100 MeV	1 GeV	10 GeV	100 GeV	1 TeV	10 TeV	100 TeV	1 PeV	10 PeV

ICECUBE SEARCHES FOR NEUTRINOS FROM GW SOURCES

Low energy events

High energy cascades

Low energy tracks and cascades

Consistent with background expectation

High energy tracks

1 MeV	10 MeV	100 MeV	1 GeV	10 GeV	100 GeV	1 TeV	10 TeV	100 TeV	1 PeV	10 PeV

ICECUBE SEARCHES FOR NEUTRINOS FROM GW SOURCES

Low energy events

High energy cascades

Process: In hot, dense matter, frequent nucleon-nucleon collisions produce neutrinos that carry away thermal energy, cooling the system.

Low energy tracks and cascades

This talk

Very low energy events

High energy tracks

1 MeV	10 MeV	100 MeV	1 GeV	10 GeV	100 GeV	1 TeV	10 TeV	100 TeV	1 PeV	10 PeV

MOTIVATION

Mergers with at least one NS could produce a burst ($O(ms-s)$) of MeV neutrinos correlated with GW.

Various production sites: Neutrino dominated accretion flow disk, dynamical ejecta, neutrino-winds etc…

MOTIVATION

Mergers with at least one NS could produce a burst ($O(ms - s)$) of MeV neutrinos correlated with GW.

Various production sites: Neutrino dominated accretion flow disk, dynamical ejecta, neutrino-winds etc⋯

Mostly isotropic emission

Flux is dominated by $\bar{\nu}_e$ due to neutron-rich matter.

Luminosity $\approx 10^{52} - 10^{54}$ergs

MOTIVATION

Mergers with at least one NS could produce a burst ($O(ms - s)$) of MeV neutrinos correlated with GW.

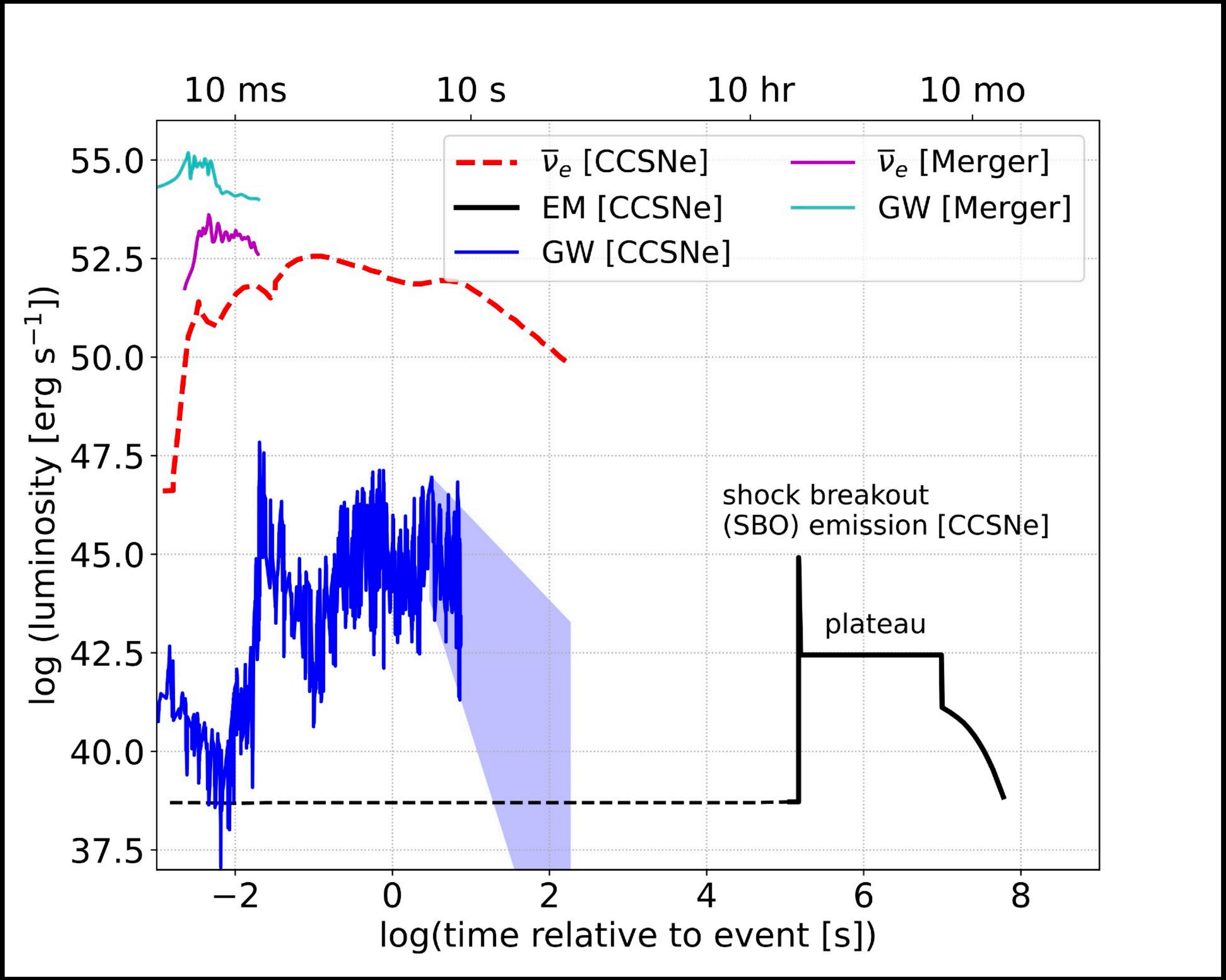
Various production sites: Neutrino dominated accretion flow disk, dynamical ejecta, neutrino-winds etc⋯

Mostly isotropic emission

Flux is dominated by $\bar{\nu}_e$ due to neutron-rich matter.

Luminosity $\approx 10^{52} - 10^{54}$ergs

One example. Not exhaustive!

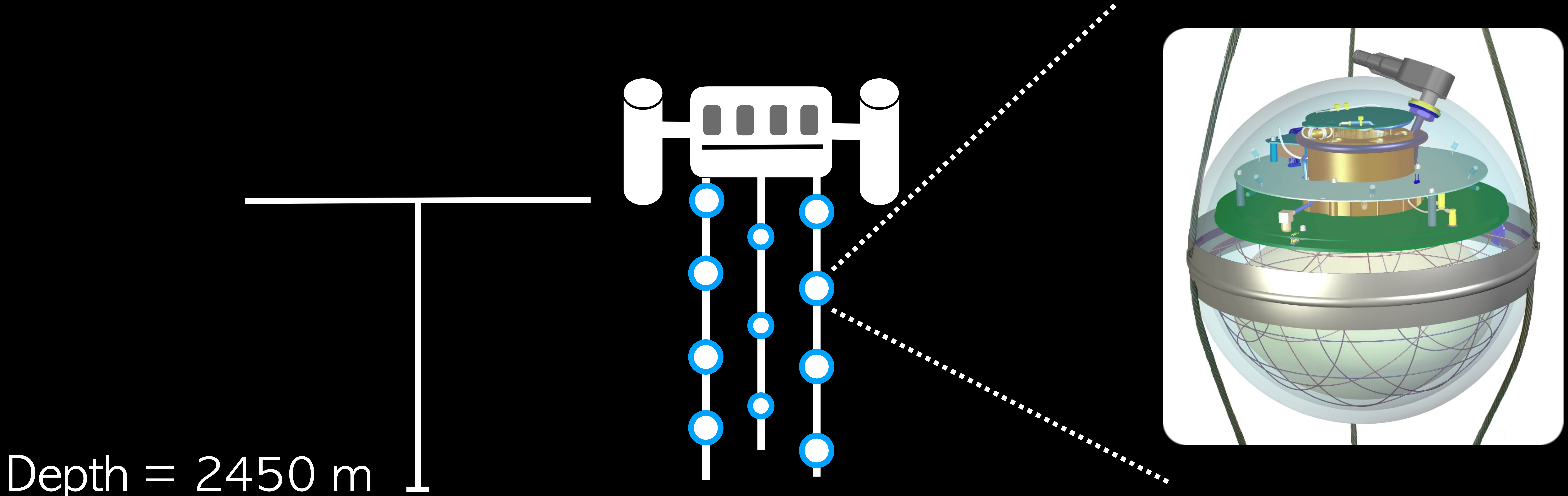


Adapted from Cusinato et al. Eur. Phys. J. A (2022) **58**: 99, and Nakamura et al. MNRAS, Volume 461, Issue 3, 21 September 2016, Pages 3296–3313

ICECUBE

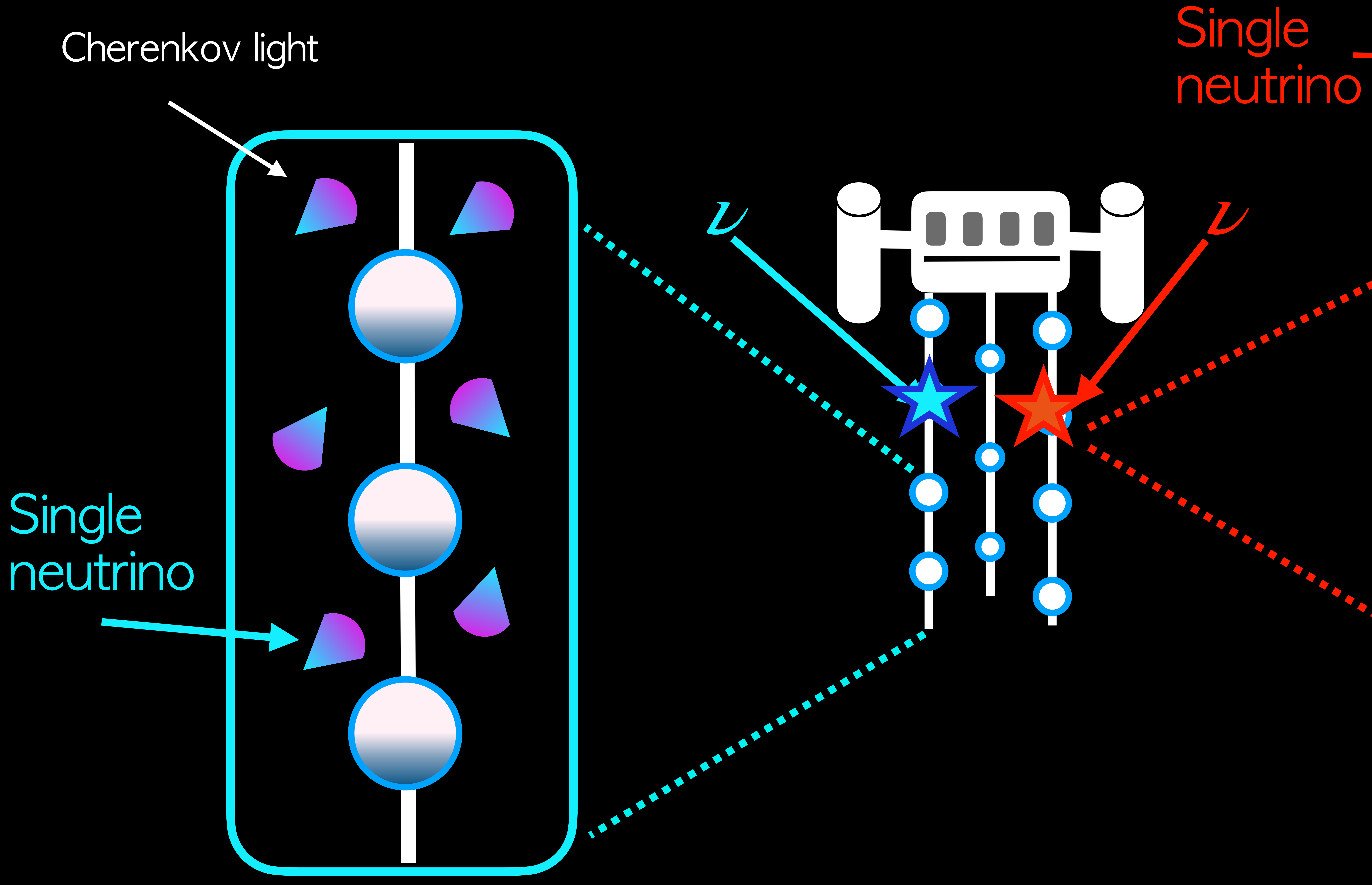
Located at the South Pole

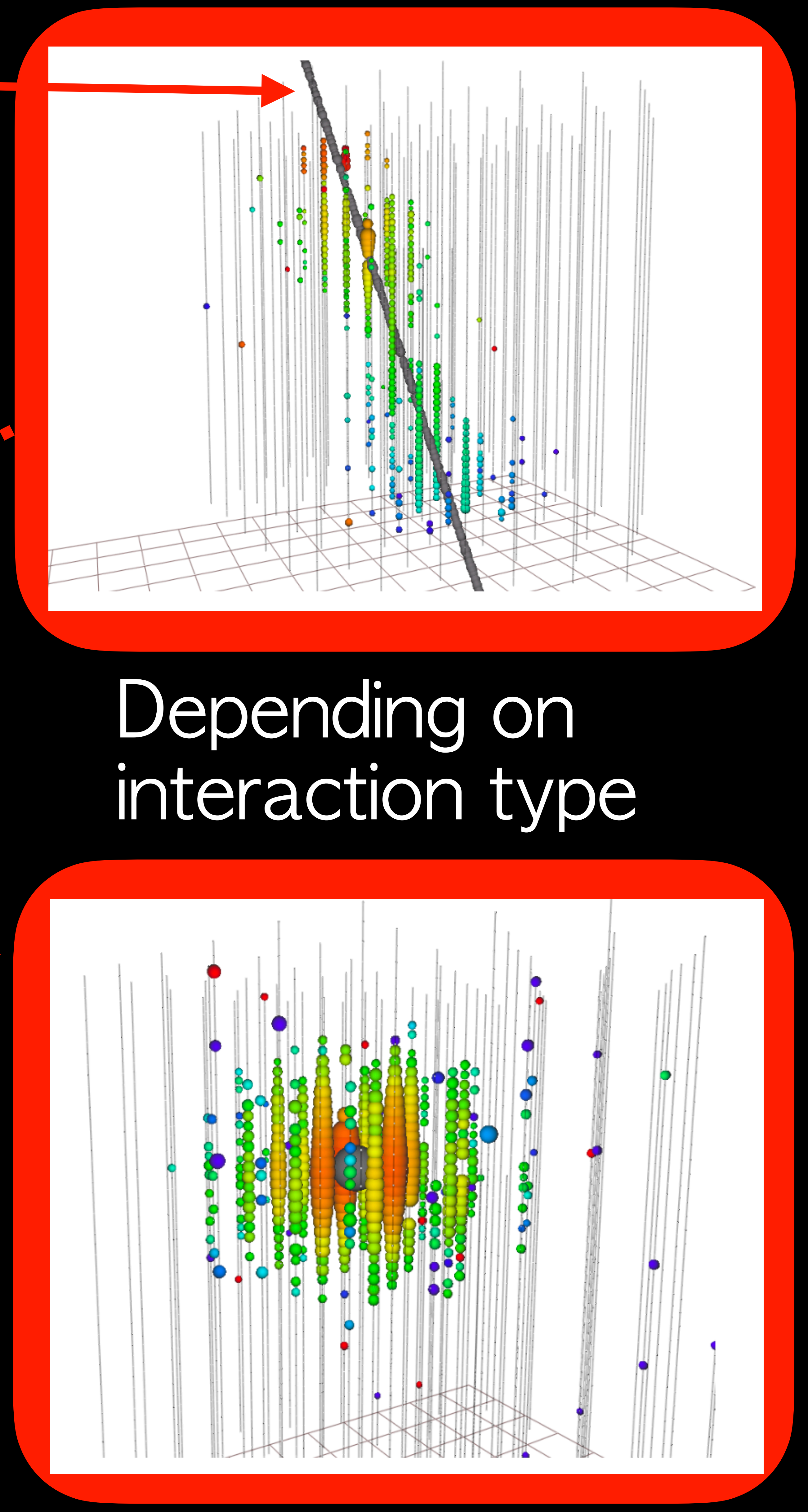
5160 sensors buried in 1km^3 of ice



We detect Cherenkov light produced when charged particles pass through ice

MeV ν 〉GeV - PeV ν



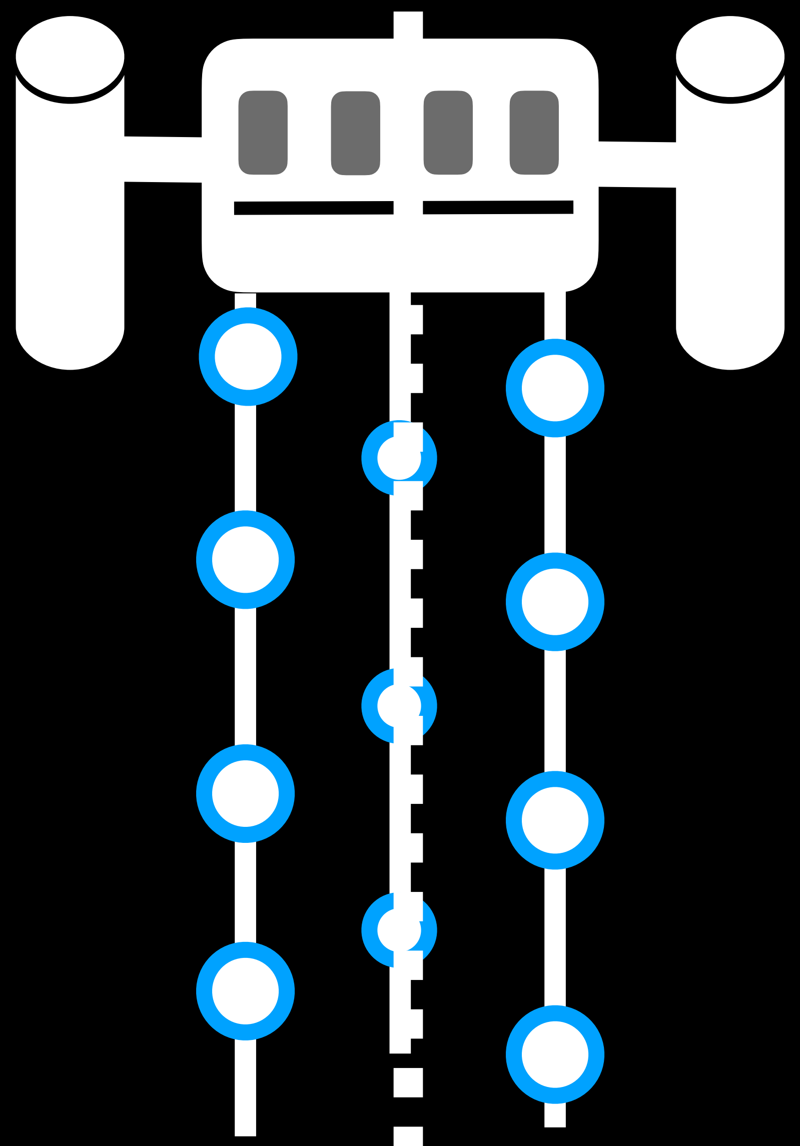


Main process: Inverse beta decay

MeV ν

〉GeV - PeV ν

Different approach depending on energy

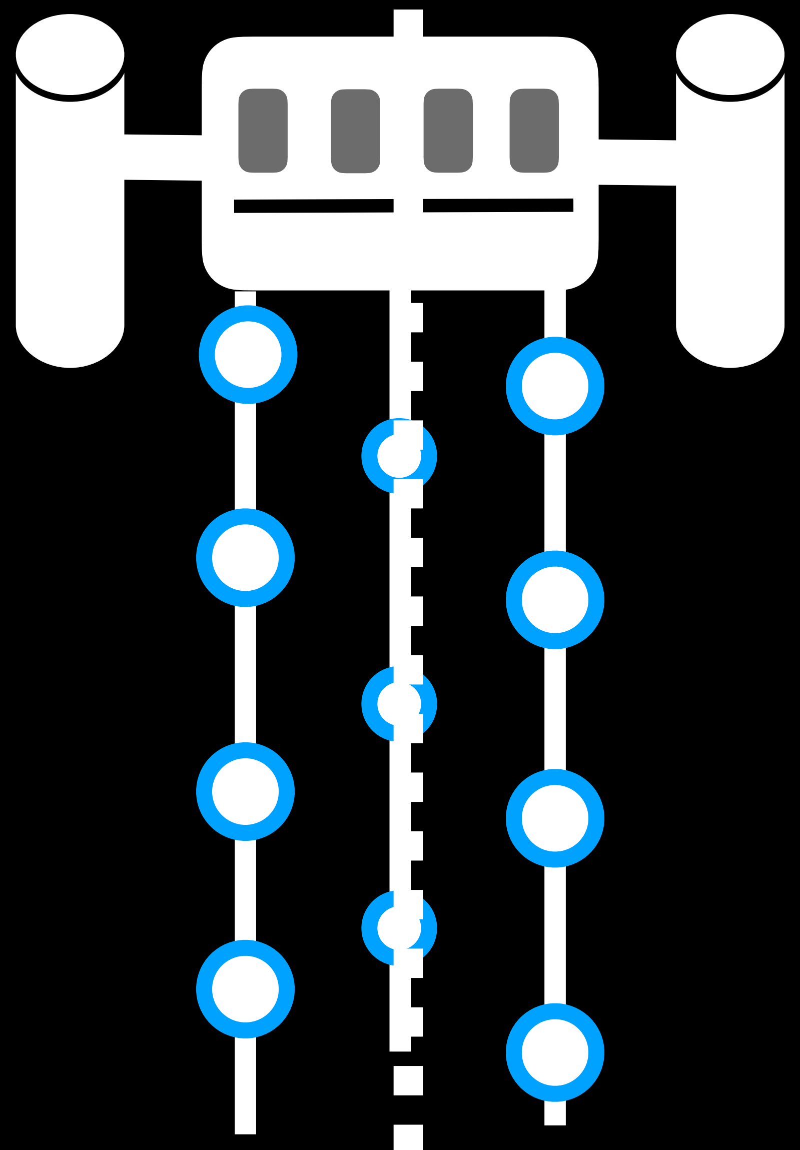


- We can reconstruct direction and energy of neutrinos
- We search for astrophysical neutrinos using direction and energy information to separate from noise: we can use single neutrinos.

MeV ν | $>$GeV - PeV ν

Different approach depending on energy

- No direction or direct energy information
- Search for an increase in total detector count above noise: High flux of neutrinos in a burst

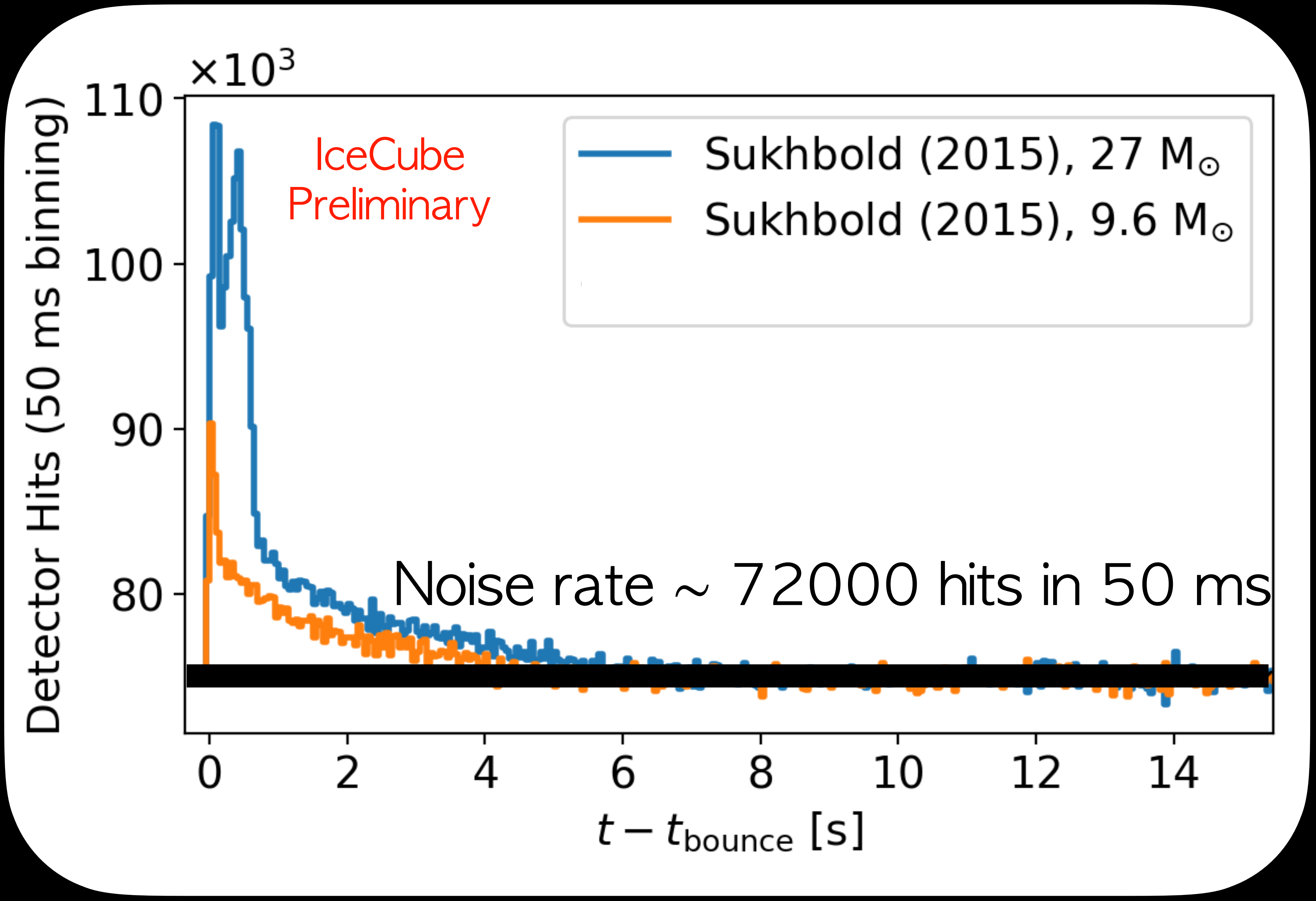


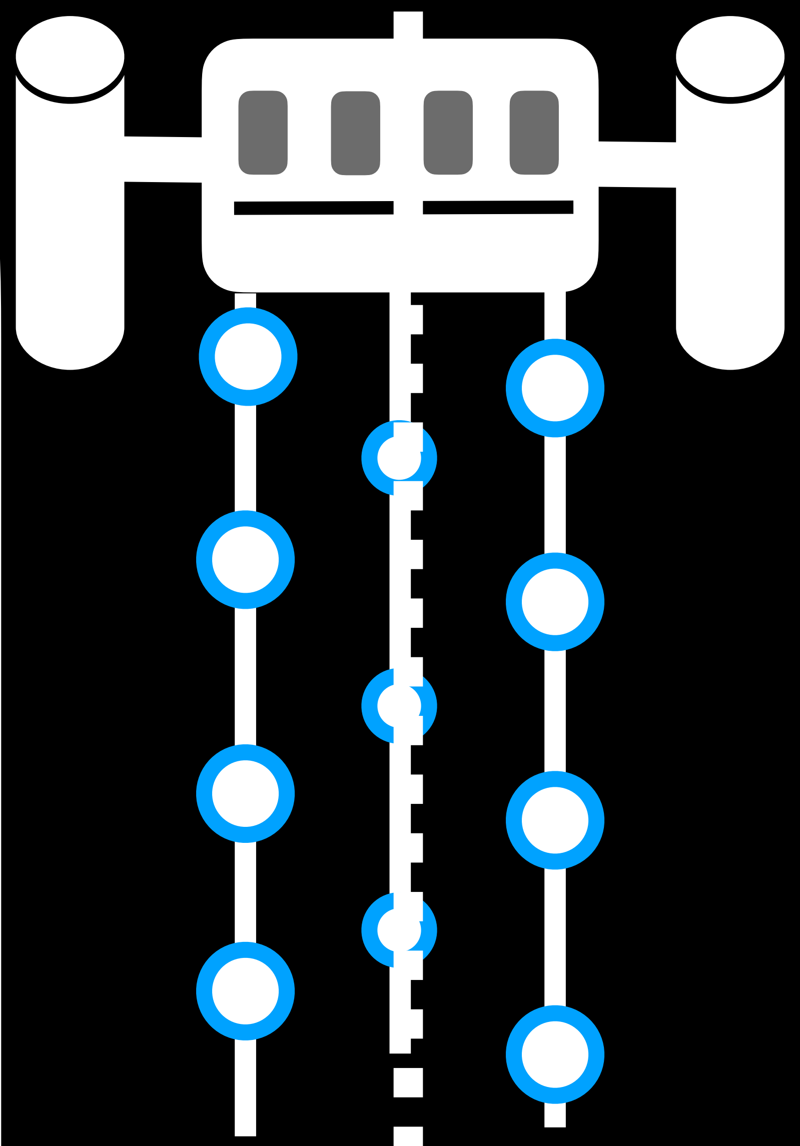
- We can reconstruct direction and energy of neutrinos
- We search for astrophysical neutrinos using direction and energy information to separate from noise: we can use single neutrinos.

MeV ν | 〉GeV - PeV ν

We need a burst

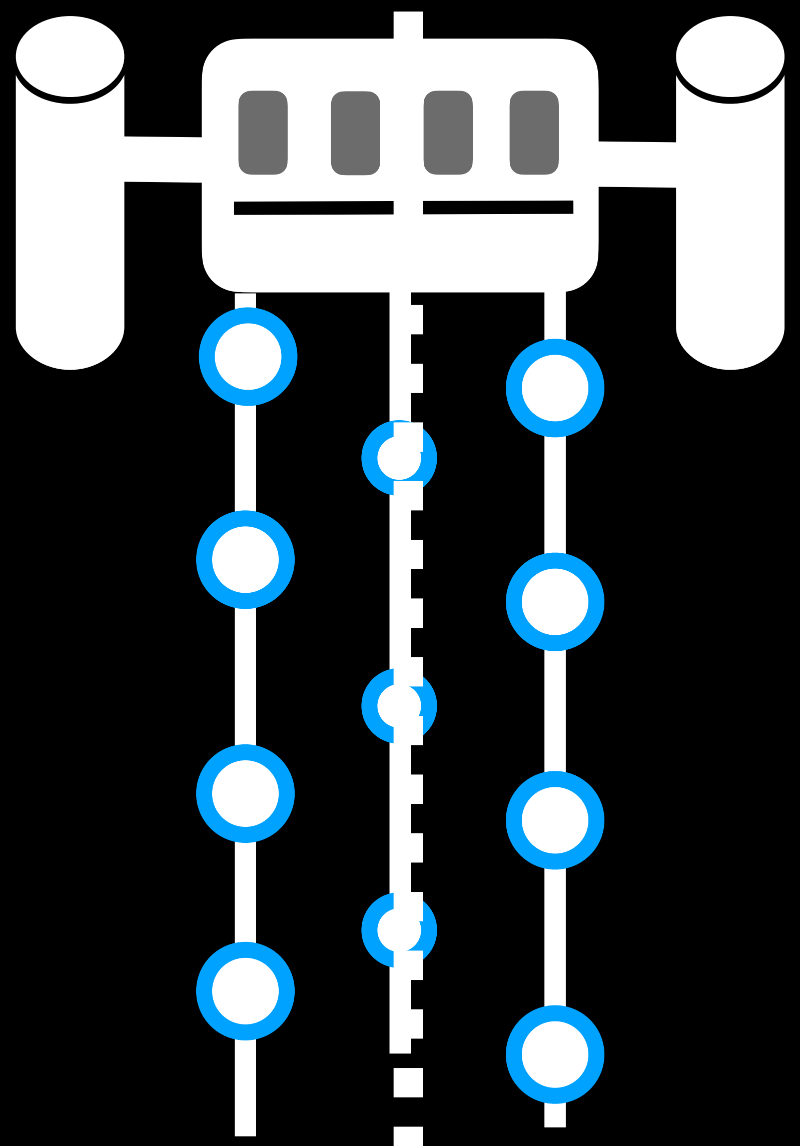
Signal ~ 50% increase in hits





- We can reconstruct direction and energy of neutrinos
- We search for astrophysical neutrinos using direction and energy information to separate from noise: we can use single neutrinos.

MeV ν | >GeV - PeV ν



- Supernova Data Acquisition System (SNDAQ) monitors the detector in realtime for an excess in detector hits.

- It also produces a dataset of the detector hits —> SN Data.

OUTLINE OF ANALYSIS

CATALOGS AND DATA

INPUT

Gravitational wave alerts from LIGO-Virgo-KAGRA catalogs

- We used LVK O1, O2 and O3 catalogs and MeV neutrino data (SN data).
- We followed-up 83 sources: 77 BBH and 6 BNS/NSBH

We follow a frequentist on-off approach:

Off time: Time where we do not expect our signal

MeV Analysis

On-time: Time where we expect our signal to be (aligned with GW onset time)

Analysis with SN data

Four search windows: 0.5, 1.5, 4 and 10 s

MEV ANALYSIS

We follow a frequentist on-off approach:

We apply our analysis on the on and off datasets

INPUT

Off time: Time where we do not expect our signal

Gravitational wave alerts from LIGO-Virgo-KAGRA catalogs

MeV Analysis

OUTPUT

On-time: Time where we expect our signal to be (aligned with GW onset time)

- Is any particular population producing an excess in rate?

Analysis with SN data

Four search windows: 0.5, 1.5, 4 and 10 s

OUR TEST STATISTIC

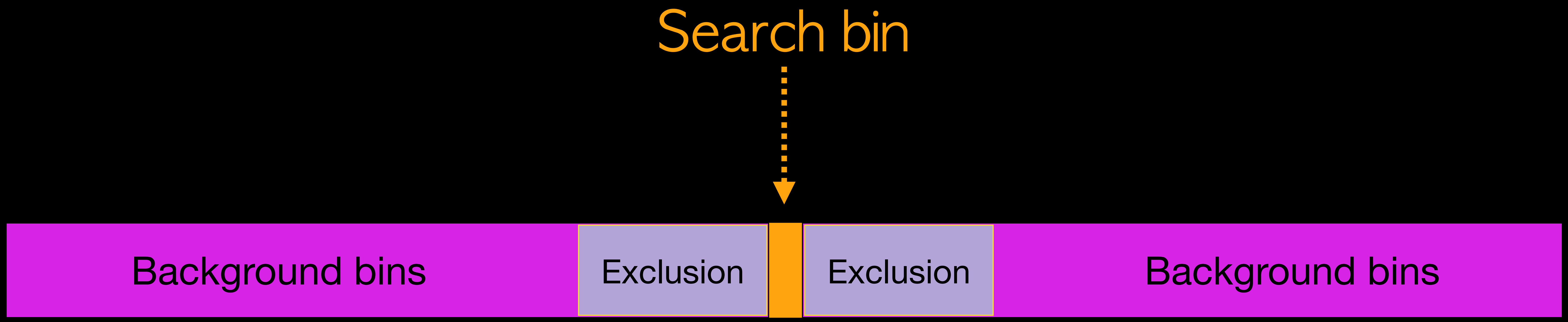
We look for an increase in detector rate

How significant is the deviation in the bin of interest compared to an average?

OUR TEST STATISTIC

We look for an increase in detector rate

How significant is the deviation in the bin of interest compared to an average?

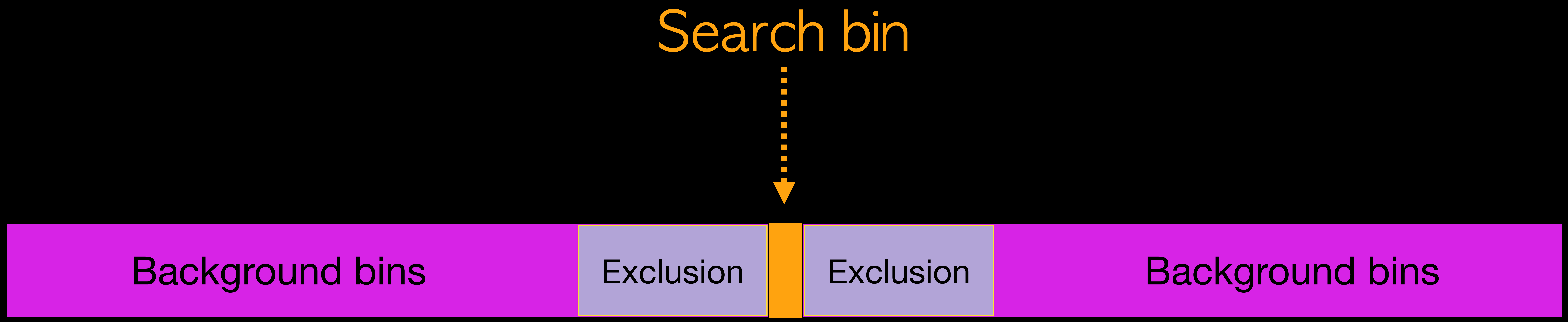


We compare the rate in the search bin to the average in the background bins.

OUR TEST STATISTIC

We look for an increase in detector rate

How significant is the deviation in the bin of interest compared to an average?



We compare the rate in the search bin to the average in the background bins.

This results in a test statistic $\xi = \frac{\Delta\mu}{\sigma_{\Delta\mu}} = \frac{\text{deviation from sliding average}}{\text{uncertainity of deviation}}$

OUTPUT

Binomial test on 2 populations:

Binary black hole mergers (BBH) —> Not thought to produce neutrinos

Neutron star-black hole (NSBH) or binary neutron star (BNS) mergers —> Thought to produce neutrinos

OUTPUT

- Did we see an excess in detector rate for any of the alerts?
- Is any particular population producing an excess in rate?

BINOMIAL TEST

1 GW → 4 search windows → Best p-value

1 GW → 4 search windows → Best p-value

.

.

Nth GW

BINOMIAL TEST

BINOMIAL TEST

We repeat the binomial test on off-time data to characterize the expectation.

We then apply it on on-time data and compare with expectation.

RESULTS

Individual sources

Population test

INDIVIDUAL SOURCES

We searched 83 sources: 77 BBH and 6 BNS/NSBH.

INDIVIDUAL SOURCES

We searched 83 sources: 77 BBH and 6 BNS/NSBH.

After correcting the p-value for picking the best time window:

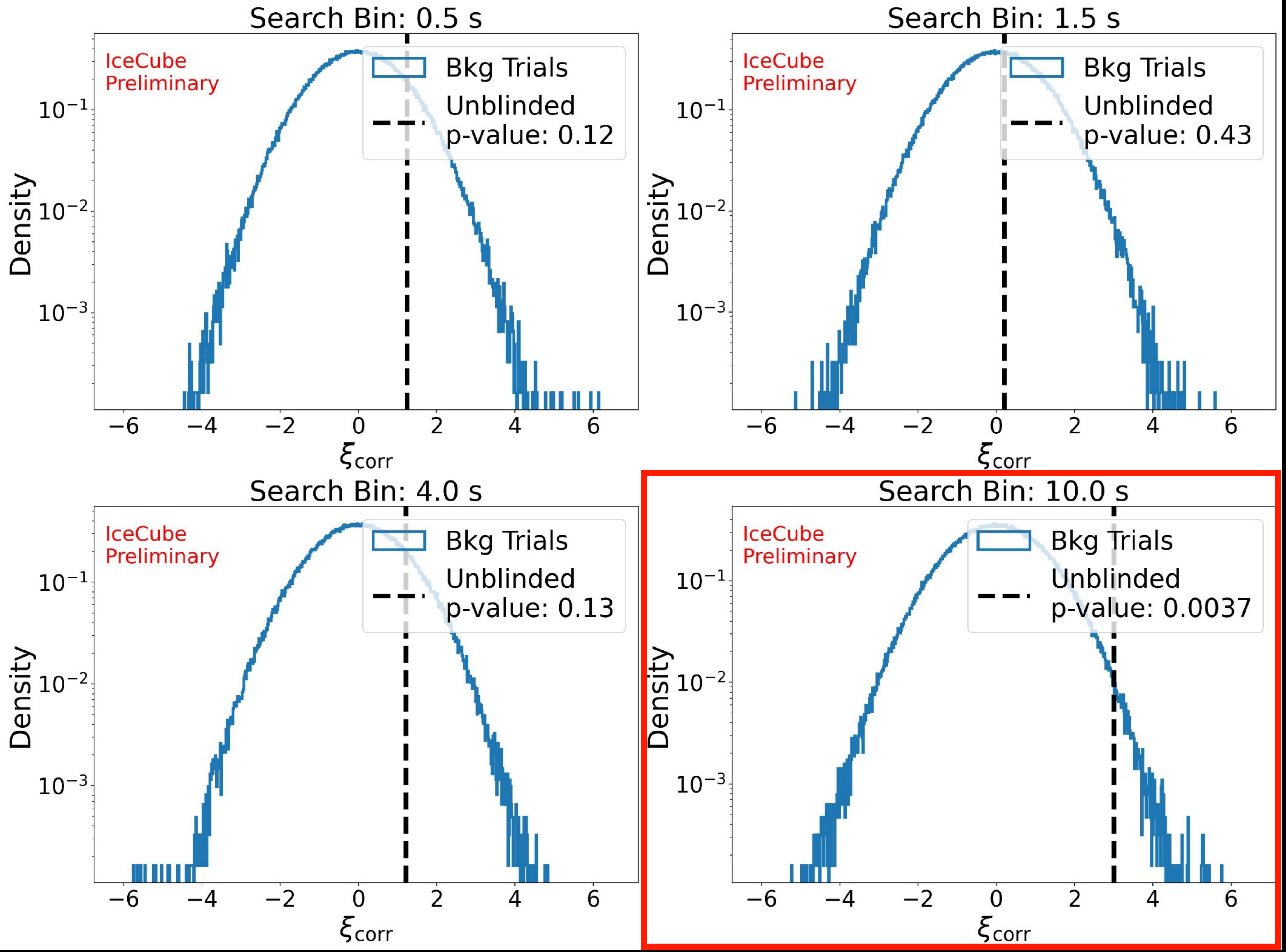
INDIVIDUAL SOURCES

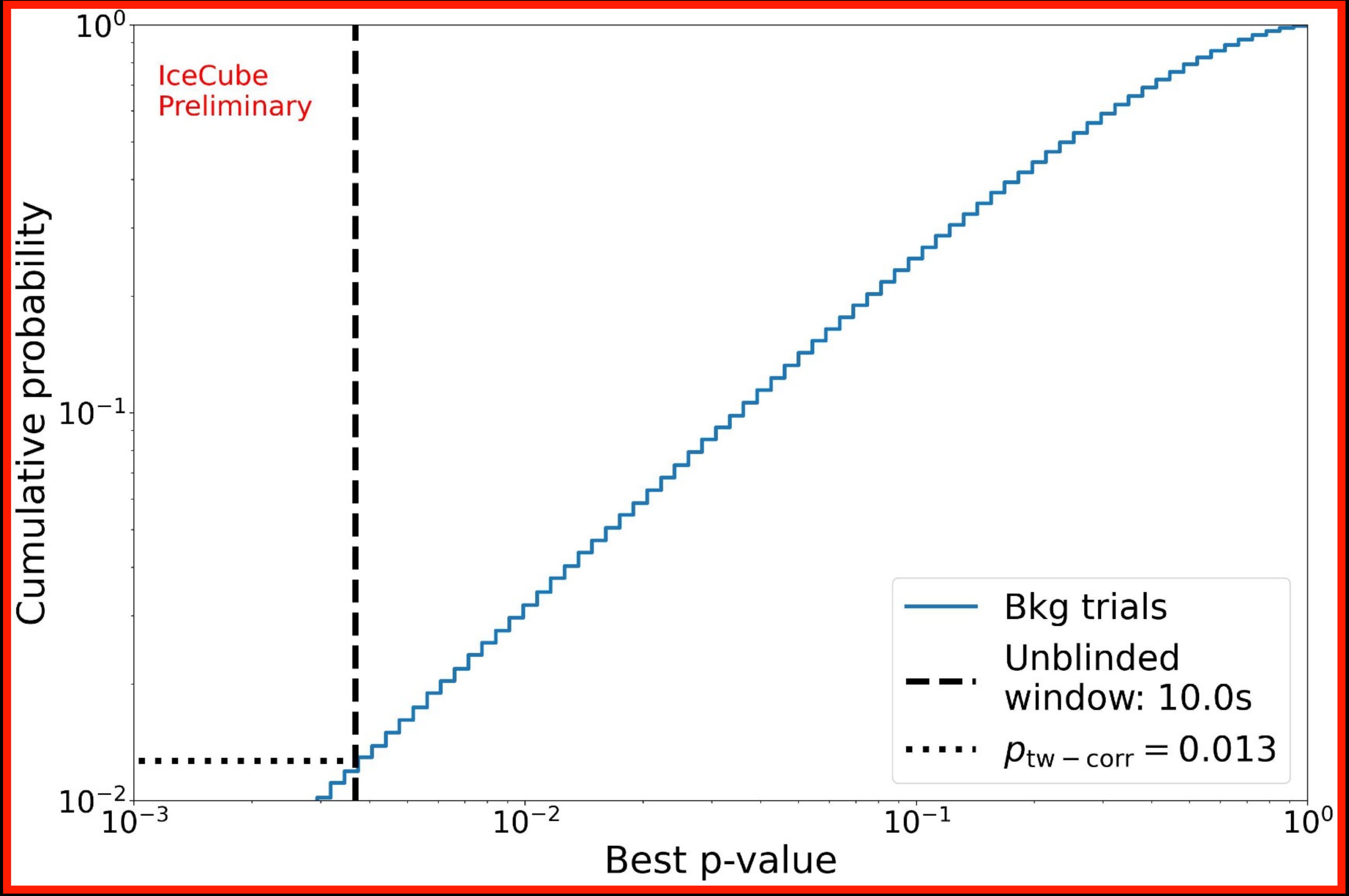
We searched 83 sources: 77 BBH and 6 BNS/NSBH.

After correcting the p-value for picking the best time window:

- Most (80) have $p_{tw-corr} \geq 0.05$.

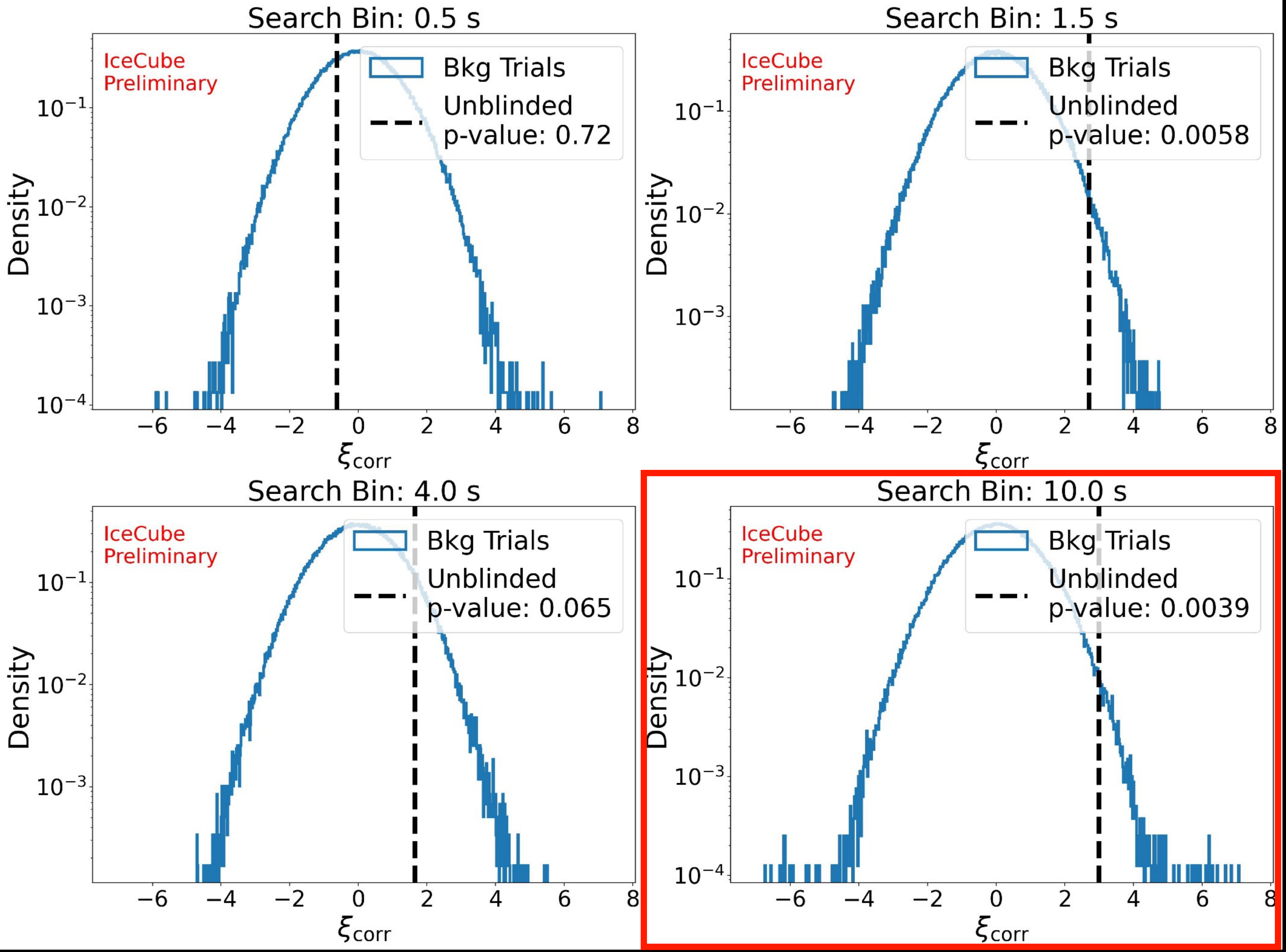
GW190421

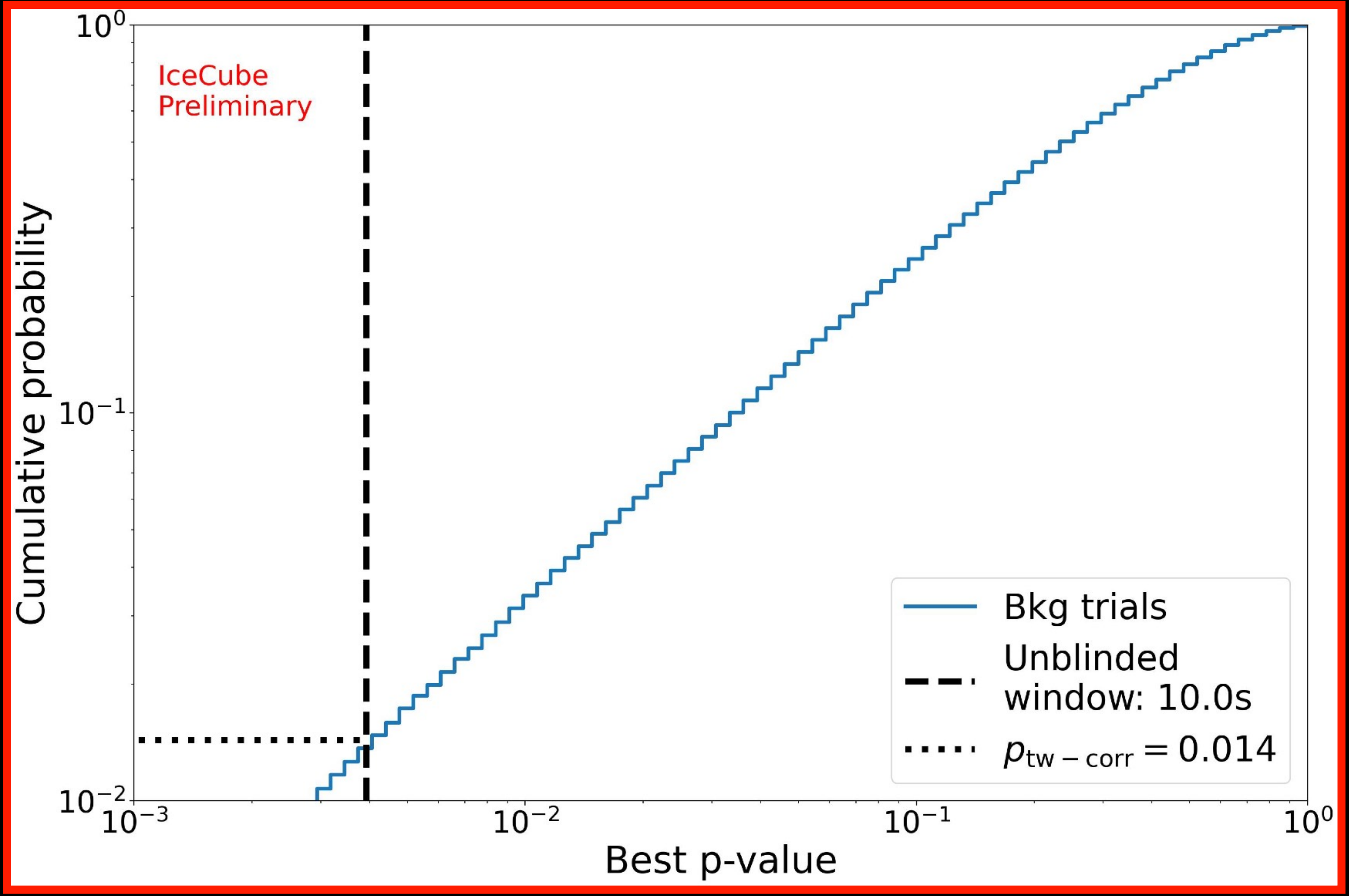




- Best p-value: 0.004
- Time window corrected p-value $p_{tw-corr} = 0.013$
- $p_{post} = 0.65$

GW190412





- Best p-value: 0.004
- Time window corrected p-value $p_{tw-corr} = 0.014$
- $p_{post} = 0.70$

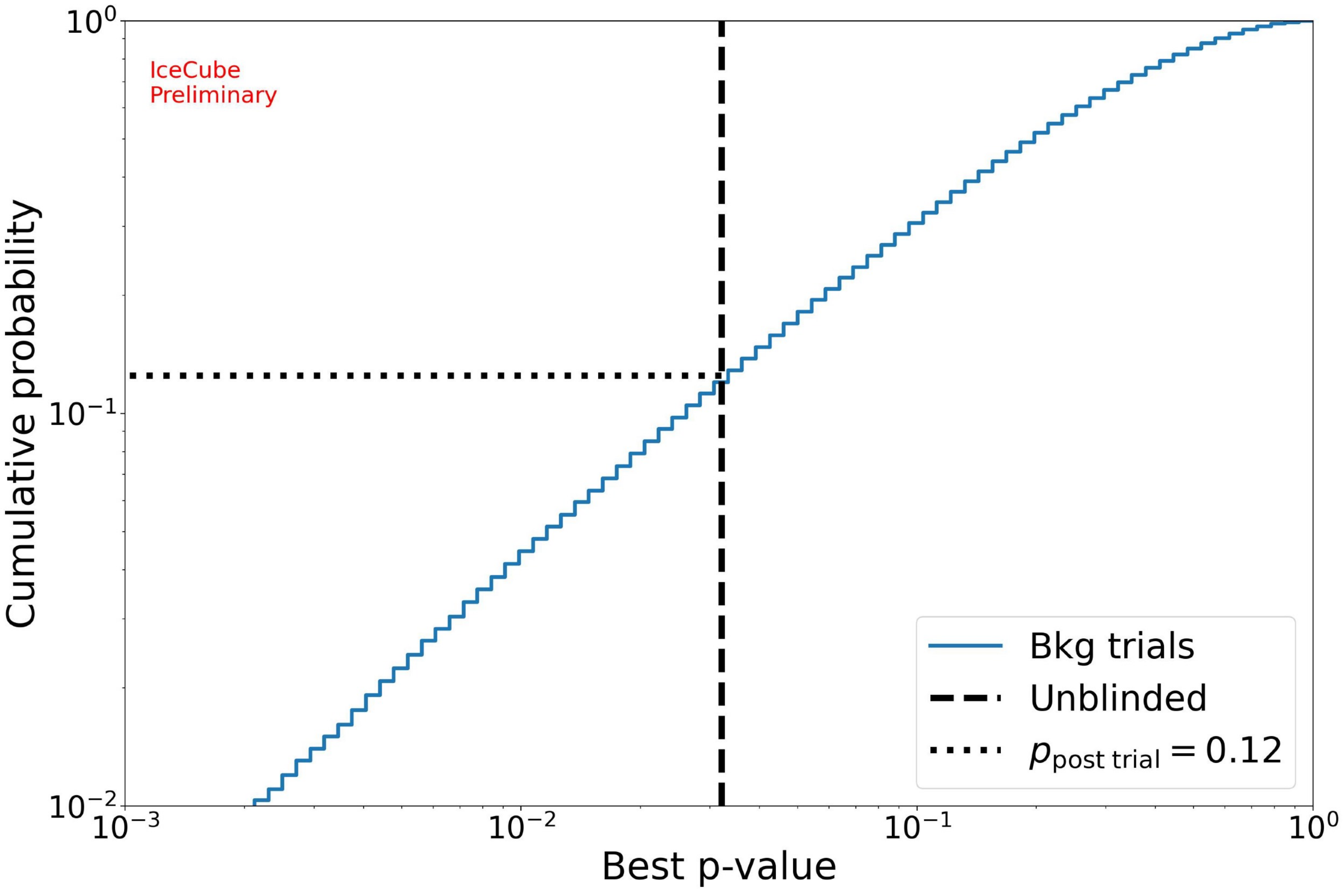
INDIVIDUAL SOURCES

We searched 83 sources: 77 BBH and 6 BNS/NSBH.

After correcting the p-value for picking the best time window:

- Most (81) have $p_{tw-corr} \geq 0.05$.
- 2 have $p_{tw-corr} \leq 0.01$
- After trials correction, all have $p_{post} \geq 0.65$.
- GW170817 has $p_{post} \geq 0.99$.

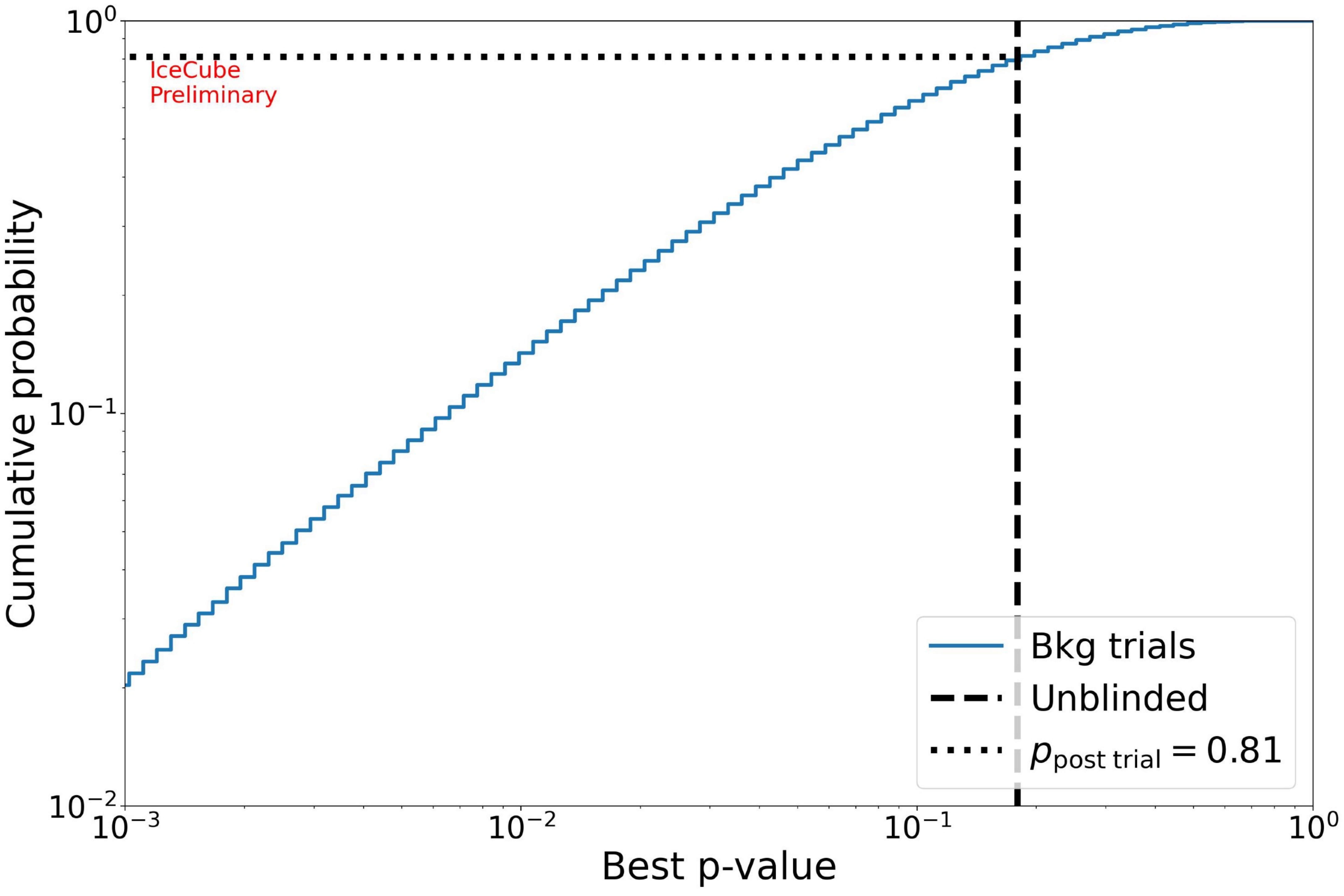
BINOMIAL TEST FOR BNS/NSBH



Best binomial p-value: 0.03

Corrected best binomial p-value: 0.12

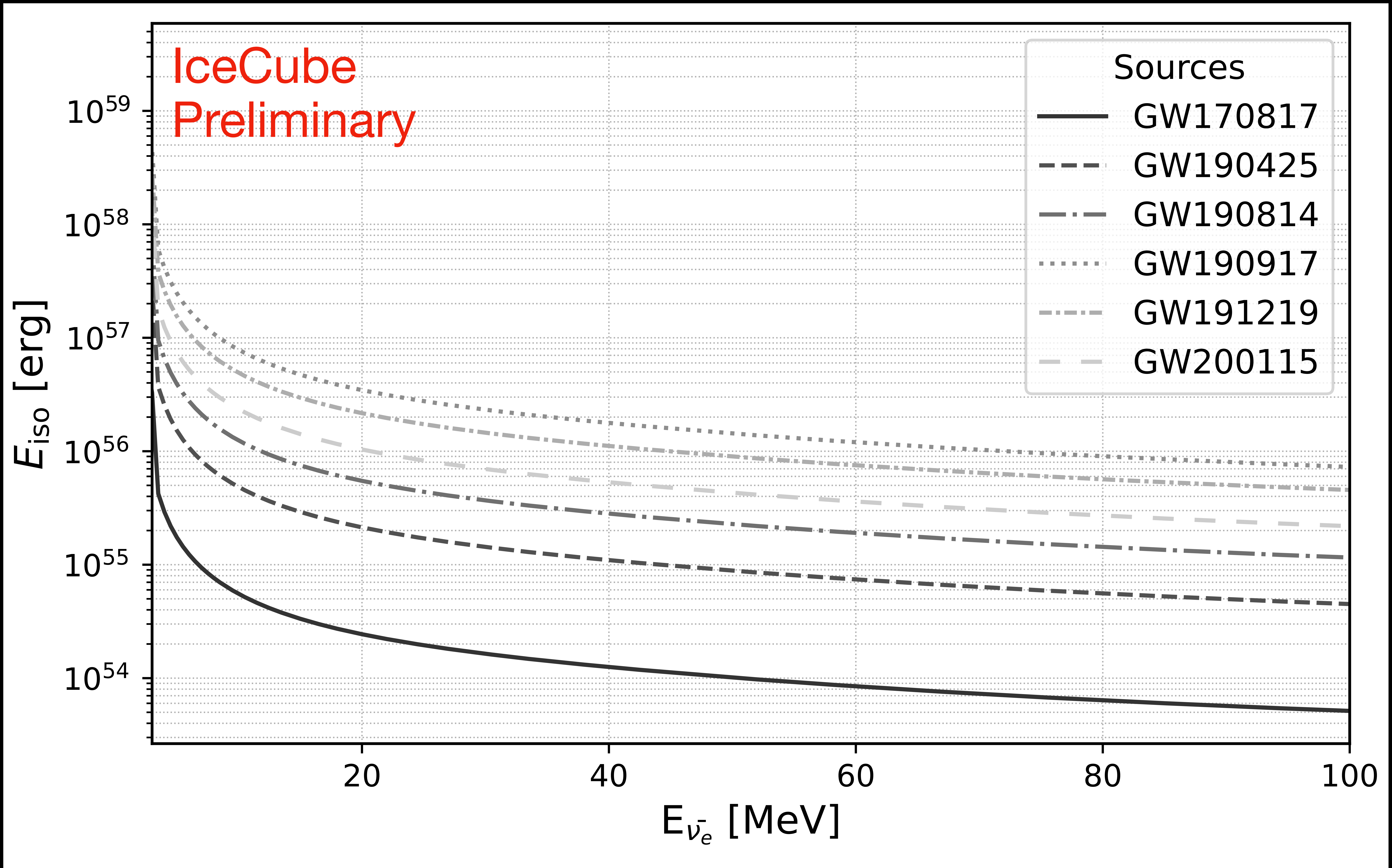
BINOMIAL TEST FOR BBH



Best binomial p-value: 0.18

Corrected best binomial p-value: 0.81

MONO-CHROMATIC UPPER LIMITS FOR BNS/NSBH



SUMMARY

- First IceCube constraints on MeV neutrino emission from GW sources.
  - Searched for thermal neutrino emission from GW sources using LVK catalogs O1-O3.
  - No significant excess for either individual sources or the population study.
  - We set U.L. on the thermal neutrino emission from BNS/NSBH, which are potential thermal neutrino emitters.
- This work demonstrates a method to search for transient neutrino signal using the IceCube Supernova system, paving the way toward the first MeV-GW detection.

BACK UP

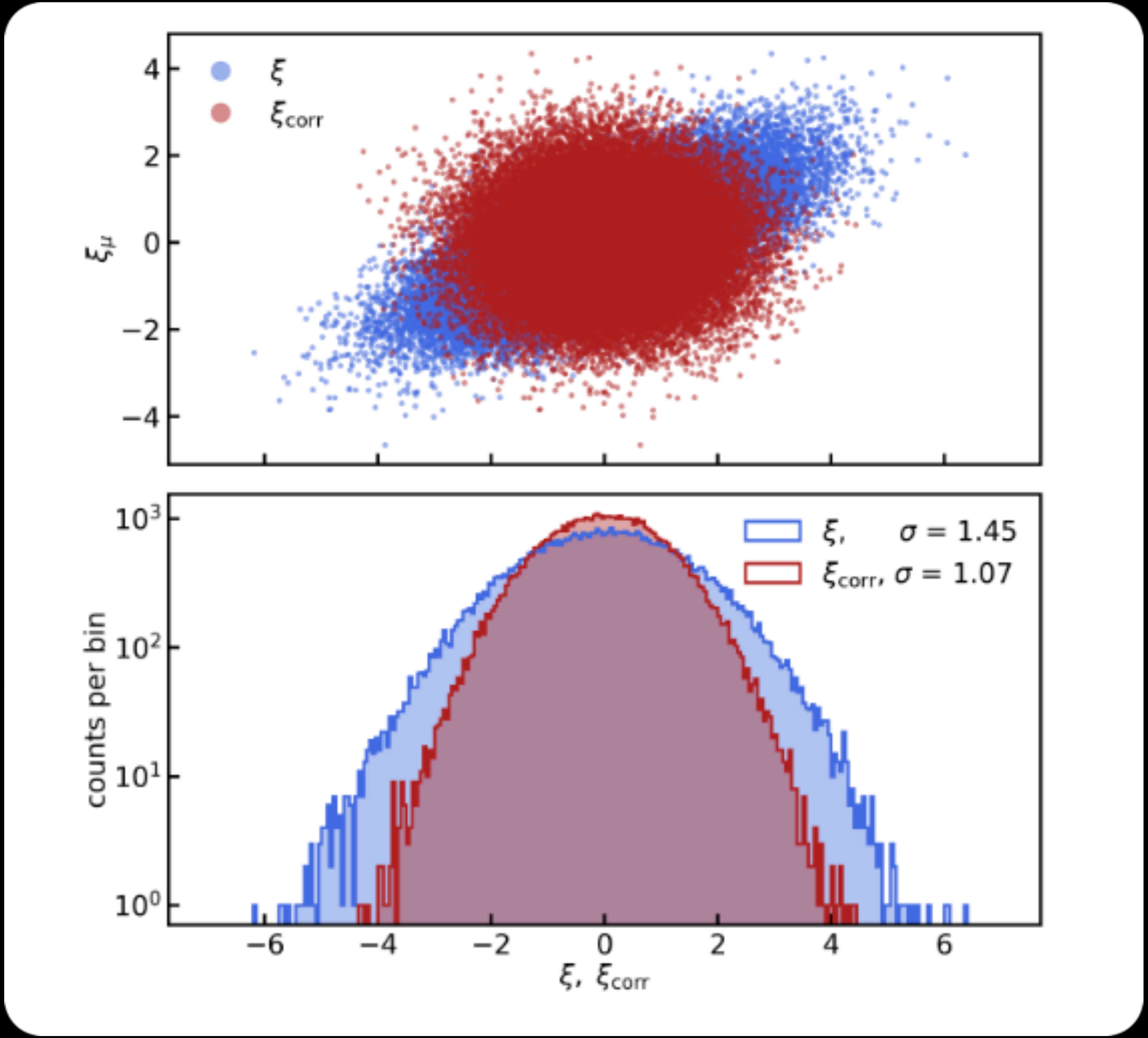
BACKGROUND

Background sources: Thermal noise, radioactive decay, atmospheric muons

- Single DOM correlations: Noise ≈ Poissonian distribution. We apply a deadtime at the DAQ stage. Reduces rate from 540 Hz to 286 Hz.

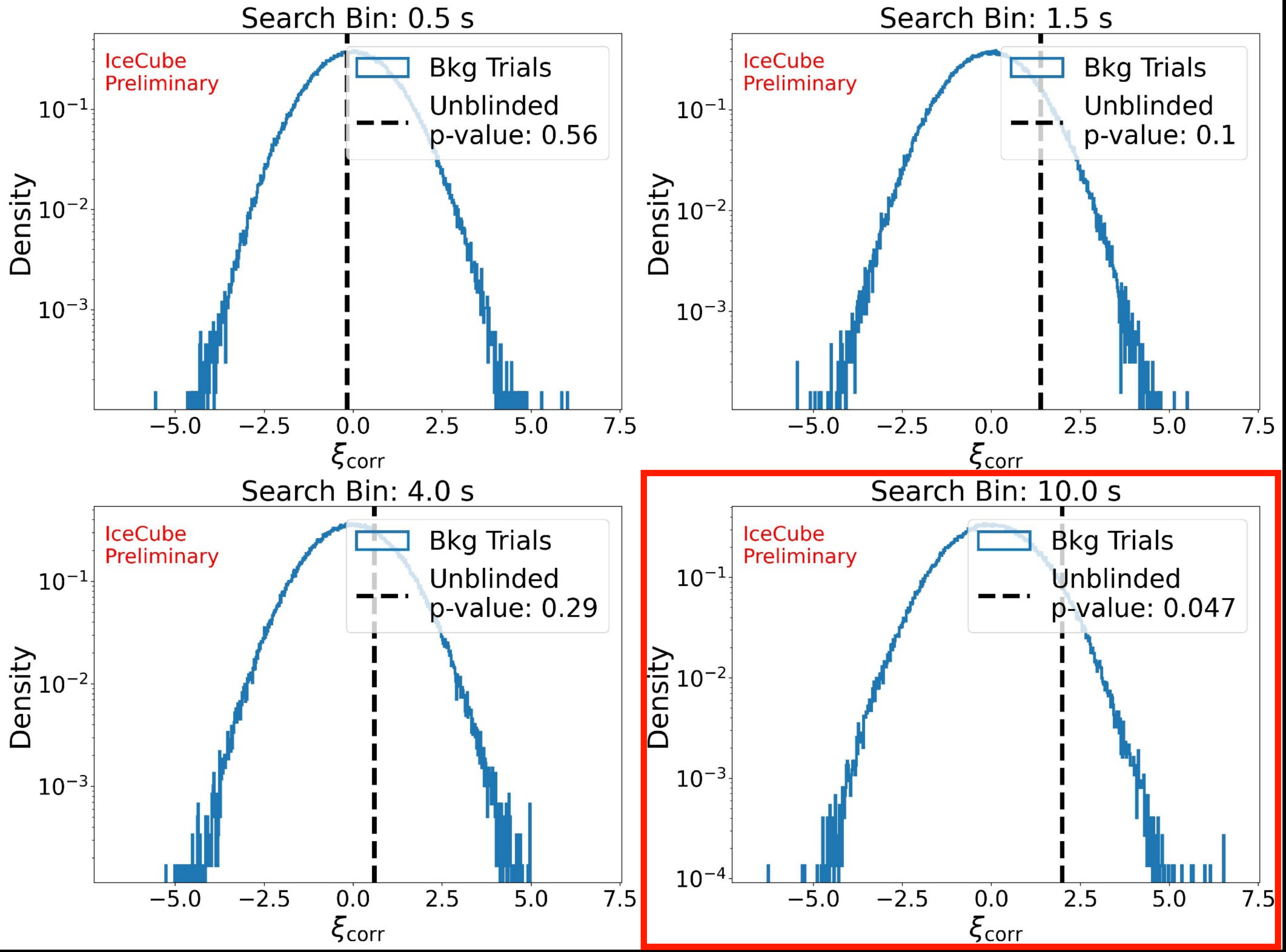
- DOM-to-DOM correlations: Atmospheric μ produce correlated hits when passing through the detector. To remove them, we apply a linear correction to ξ using muon rates at the time of trigger.

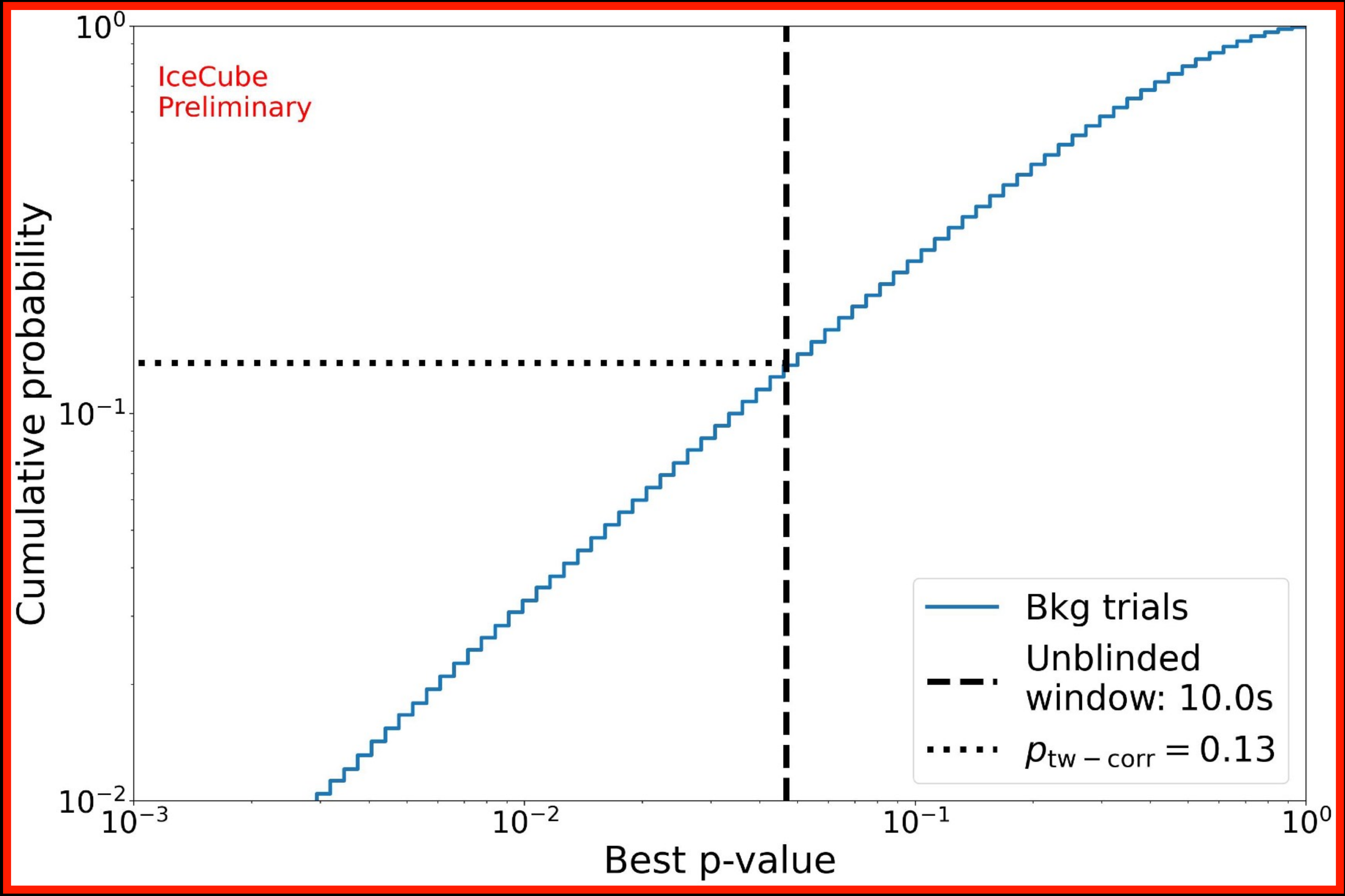
ξ': Test statistic with the atmospheric μ contribution removed



Credit: R. Abbasi at al., IceCube Collaboration, 2024, ApJ 961, 84

GW170817



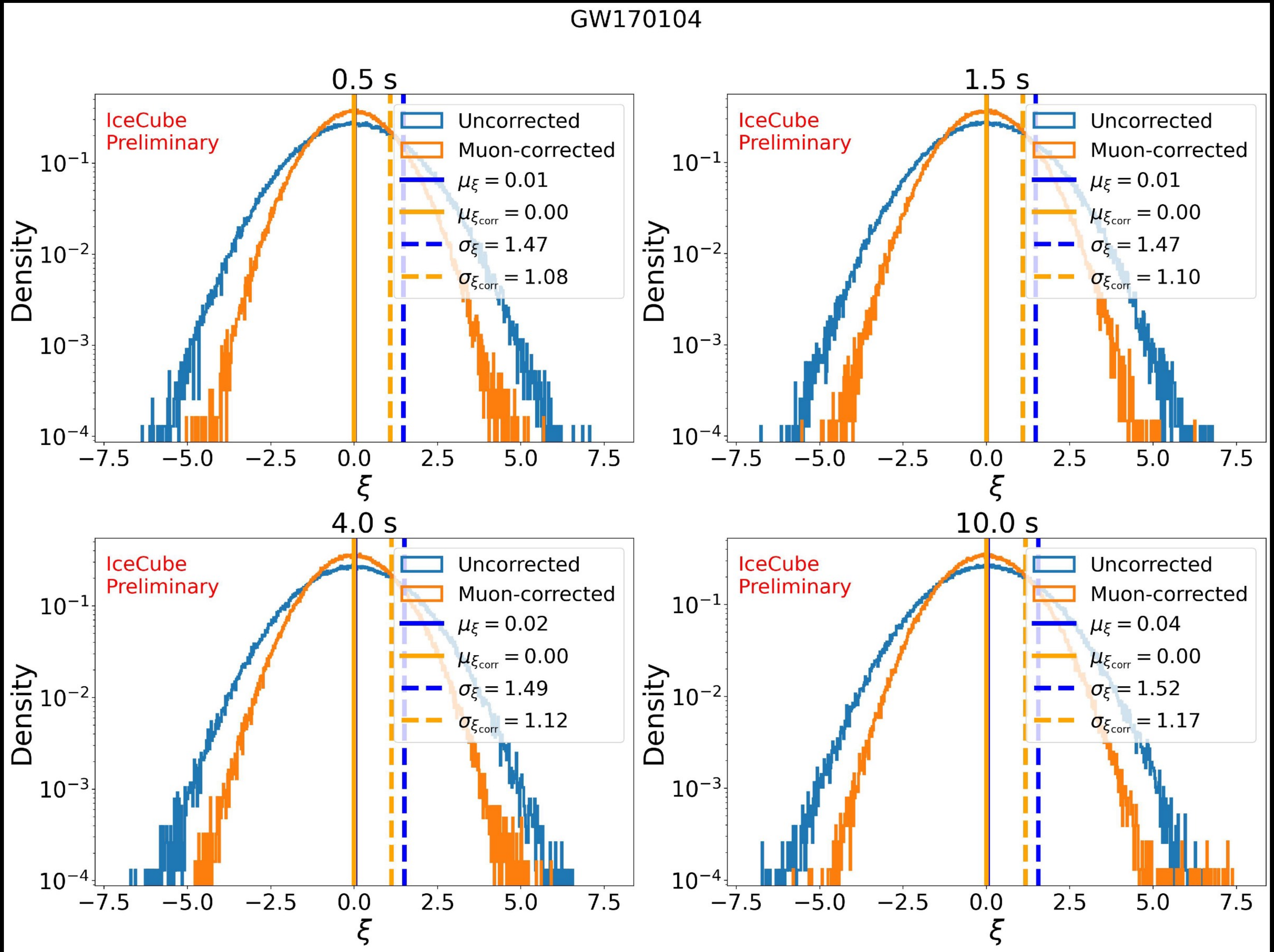


- Best p-value: 0.05
- Time window corrected p-value $p_{tw-corr} = 0.13$
- $p_{post} = 0.99$

BACKGROUND TRIALS

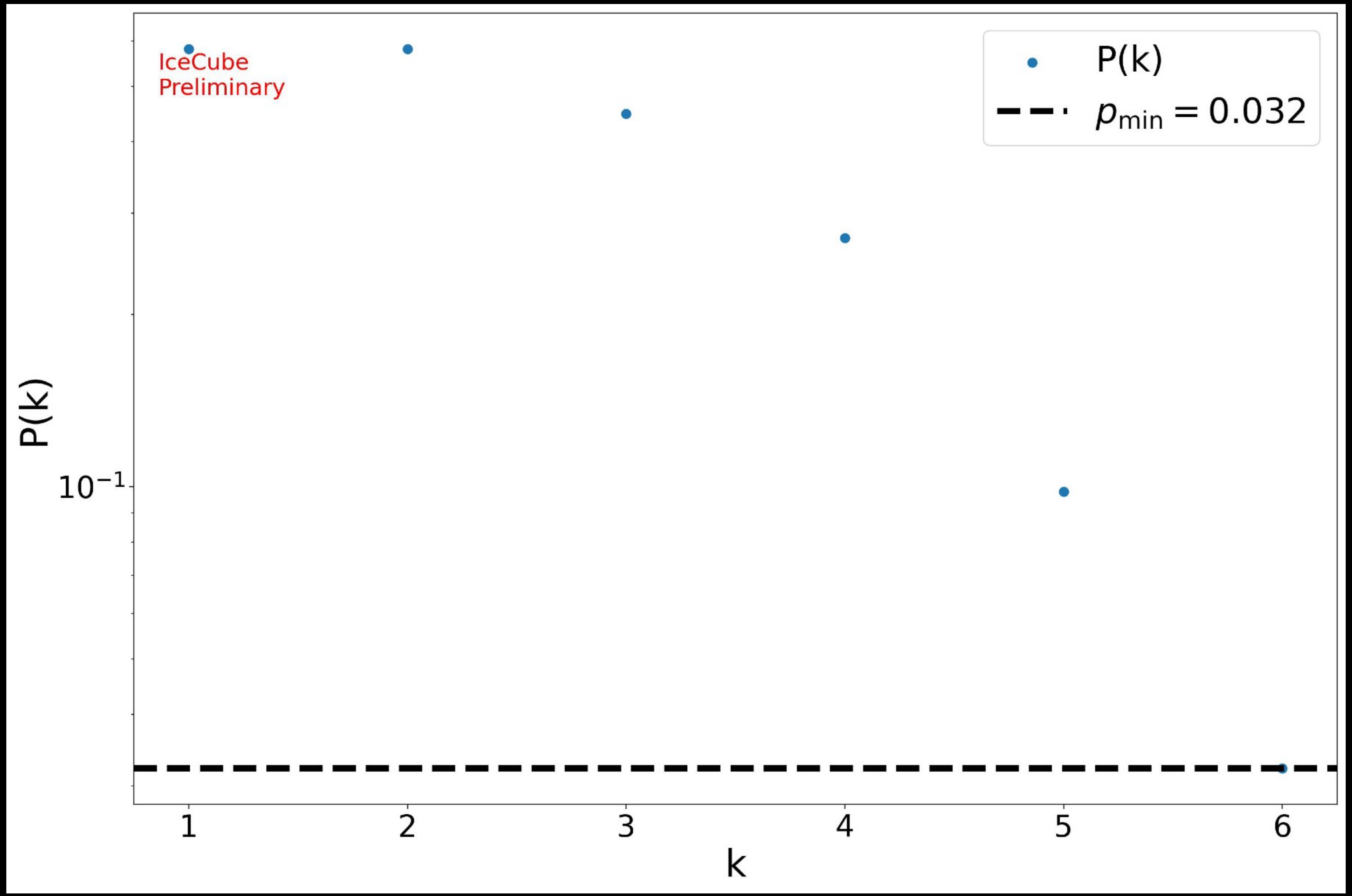
Blue: uncorrected TS

Orange: corrected TS

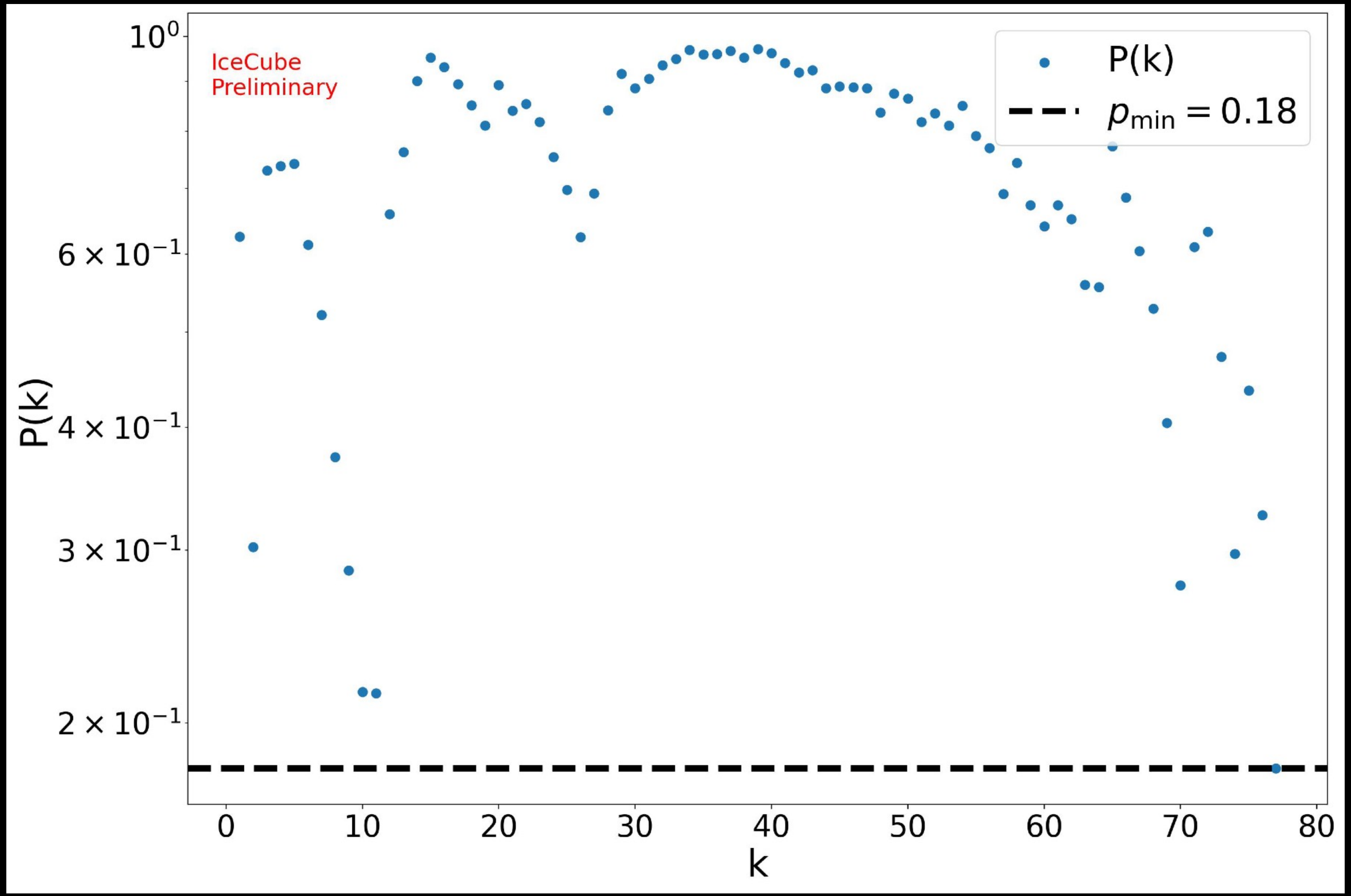


BINOMIAL TRIALS: BEST-K

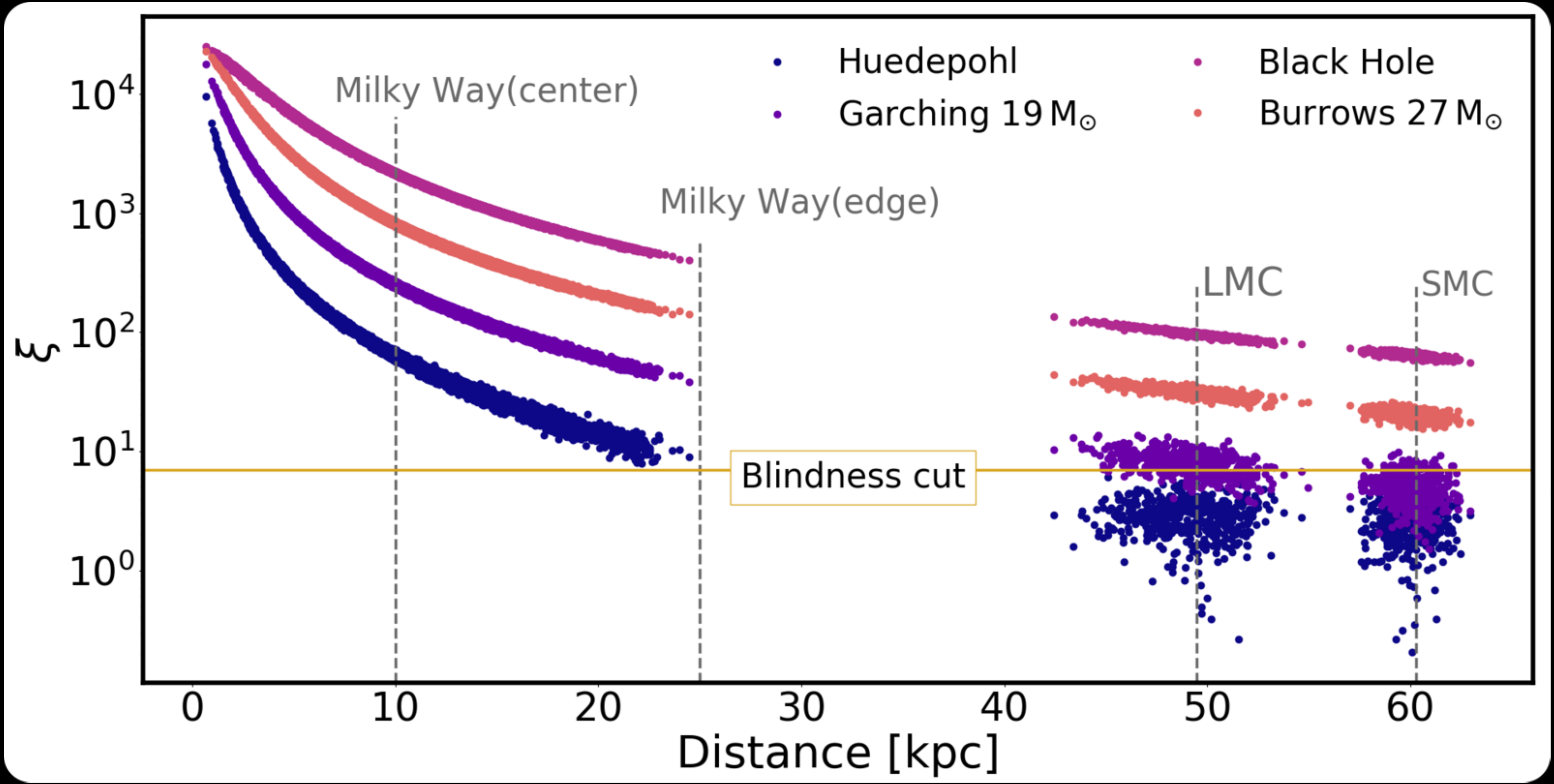
BNS/NSBH



BBH

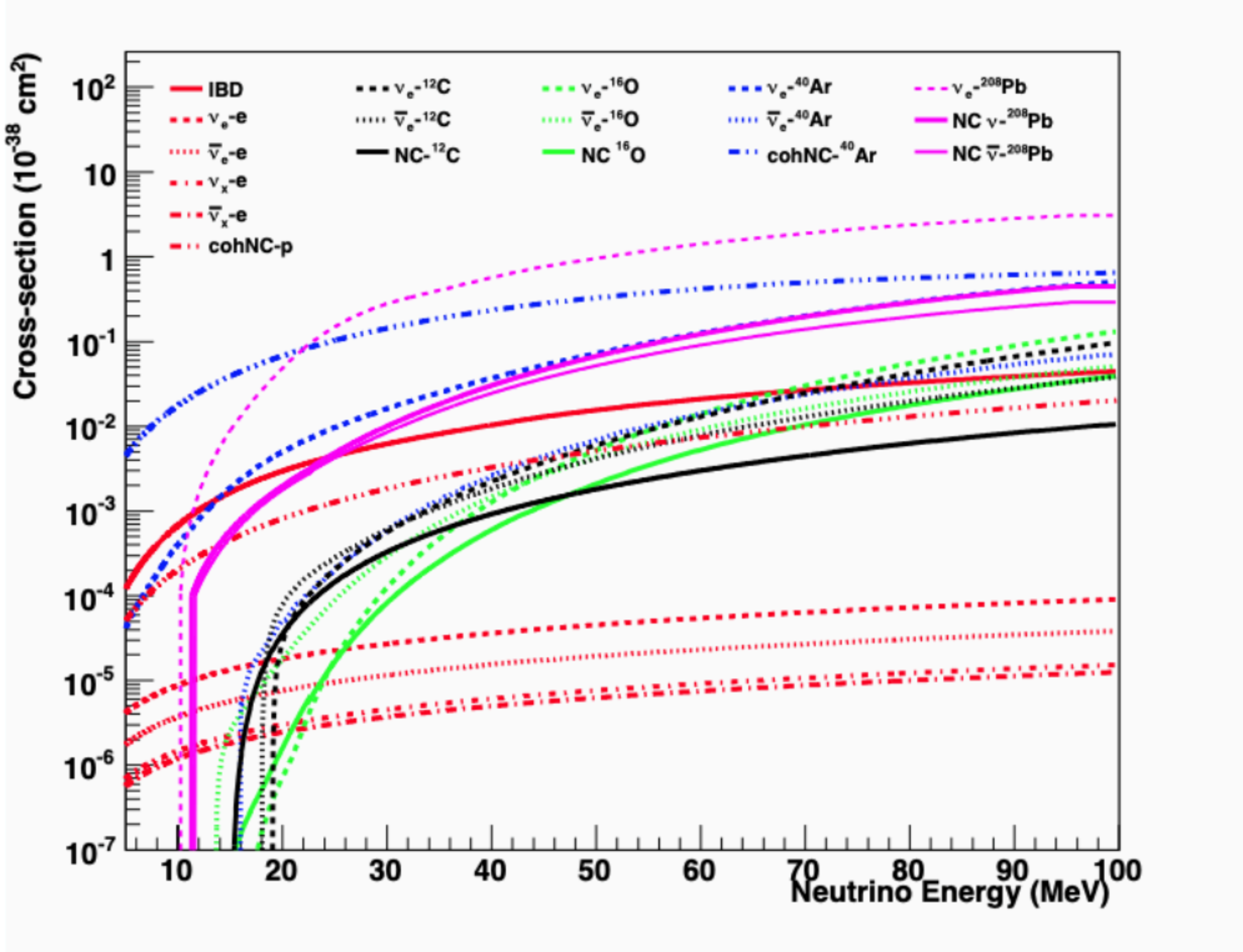


GALACTIC SENSITIVITY



Credit: R. Abbasi at al., IceCube Collaboration, 2024, ApJ 961, 84

MEV NEUTRINO CROSS SECTION



Credit: Scholberg In: Annu. Rev. Nucl. Part. (2012), 62, 81-103