Analysis Method to Search for Coincidence Events between the LIGO-VIRGO Gravitational-Wave Detector Network and the IceCube Neutrino Detector

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April 12th 2008
American Physical Society April Meeting @ St. Louis

LIGO-G080237-00-Z

Overview

Coincidence detection method for gravitational wave (GW) and neutrino bursts

Targets

Engines of gamma-ray bursts (GRBs), soft gamma-ray repeaters (SGRs) may produce both GW and neutrino bursts

Other unknown sources of simultaneous emission of GW and neutrinos

Detectors

IceCube: Neutrino Detector in Operation and Upgraded Yearly

LIGO, VIRGO: Interferometric Gravitational Wave Detectors in Operation

Both: A few small signals buried in background noise

Completely Independent Detectors

➡ Probability of accidental coincidence by background noise: Very Low

Coincidence analysis ⟶ High confidence detection

Goals

- Detect coincident GW and neutrino events
- If no detection, set an upper limit on the population of such events

Contents

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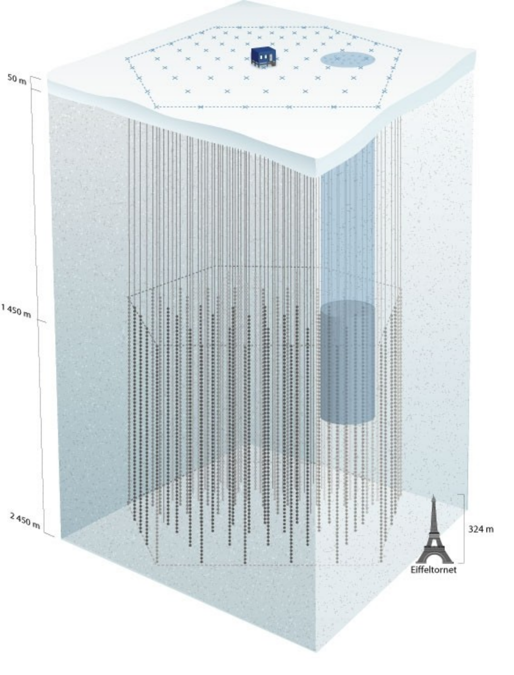
IceCube



- Antarctic neutrino detector
- High energy neutrinos

$$\sim 10^{11} - 10^{21}\,\mathrm{eV}$$

- Good directional resolution
  (~1.5° for 22 strings configuration)
- Upgraded yearly
  - Currently 40 strings
  - Completion expected by 2011

LIGO-VIRGO GW detector network

- Network of km-scale interferometric gravitational wave detectors
- LIGO: 2 sites in the USA (Hanford WA, Livingston LA)
- VIRGO: Near Pisa, Italy

LIGO-VIRGO – IceCube Coincidence Analysis

Motivation

Look for a coincident burst event in GW and neutrino
Possible source: GRBs, SGRs, other unknown sources

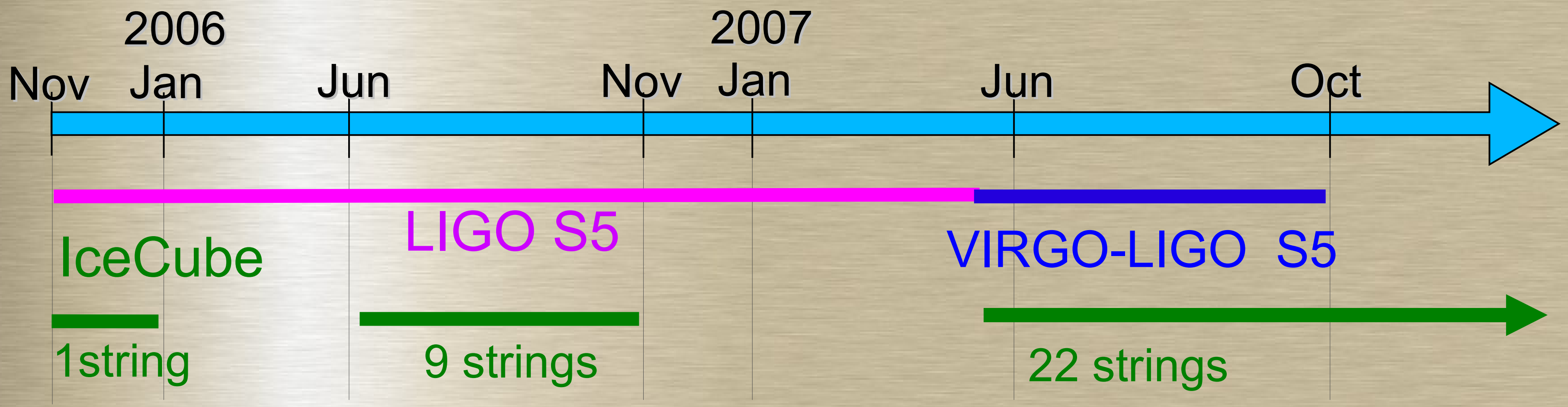
Traditionally

- Signals are buried in noise or background events
- Difficult to declare a detection with high confidence

Low accidental coincidence rate between the detectors

If we see something → High confidence detection

Overlap of observation time



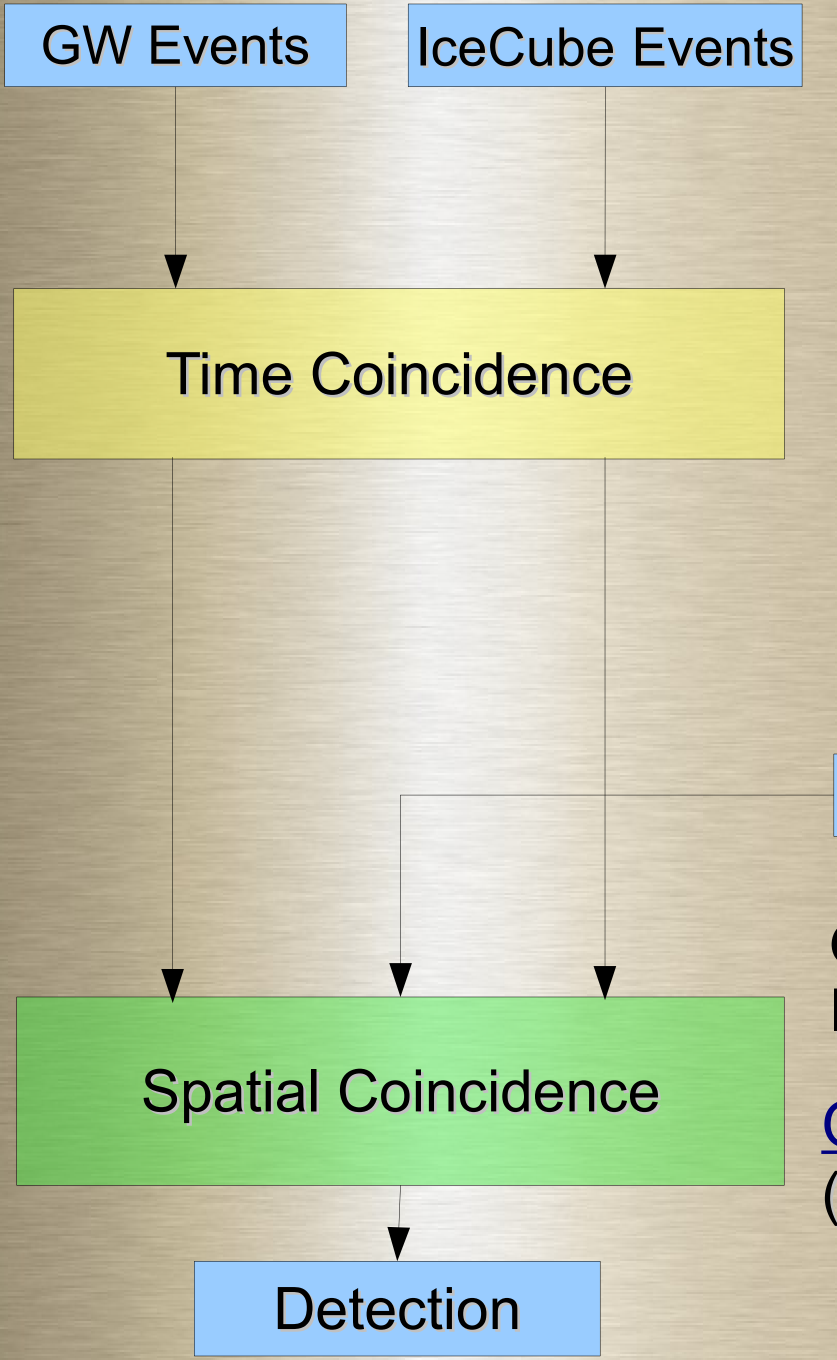
2006
2007
Nov Jan Jun Nov Jan Jun Oct

LIGO S5
VIRGO-LIGO S5

IceCube
1string
9 strings
22 strings

note: there is no official data exchange agreement yet

Flow of the Analysis


GW Events

IceCube Events

Time Coincidence

Spatial Coincidence

Detection

GW trigger generation algorithm:
We used Q-pipeline

S. Chatterji, et al., *Class. Quantum Grav.*, **21** (20):S1809, 2004.

GW triggers and IceCube events within a time window: Pass

Size of the time window:

- Larger than the time delay between GW and neutrino bursts
- Source/model dependent
- Use several time windows
  1 sec, 1 min, 1 hour etc...

Background GW & IceCube Events

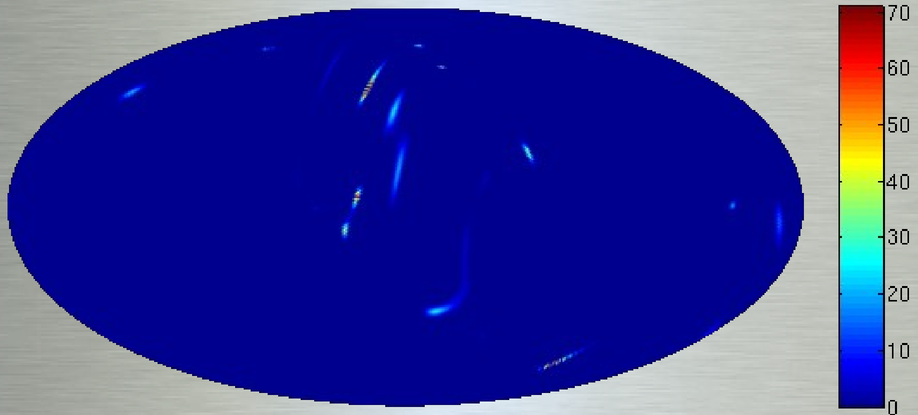
Background generation method
GW: Time shift data between interferometers
IceCube: Monte Carlo

Overlap of likelihood skymaps
(explained in the following slides)

Source Likelihood

GW likelihood skymap

Reconstructed from GW data streams using coherent network analysis method: We used X-pipeline*



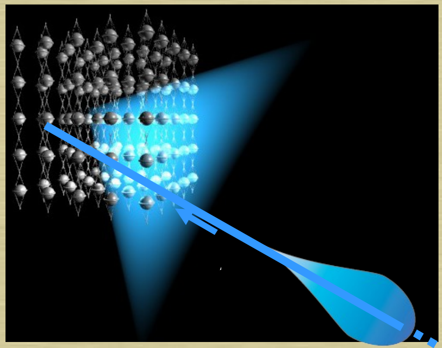
$$L_{\mathrm{GW}}(\theta,\phi)\propto\exp(-E_{\mathrm{null}})$$

(normalized over the sky)

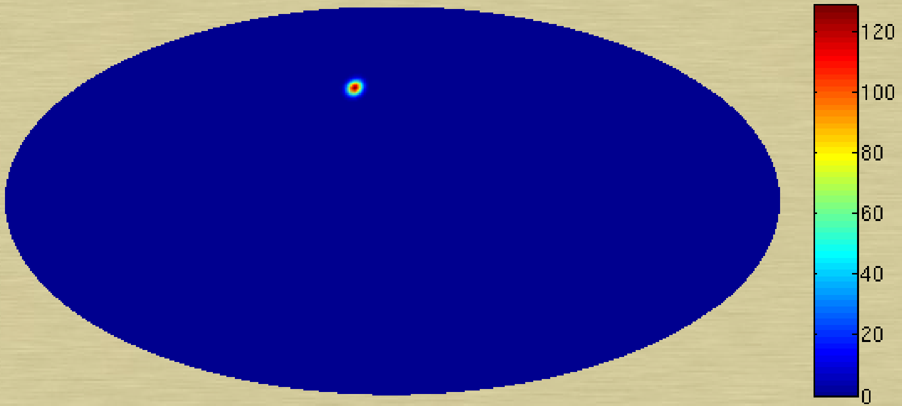
E_{null} = Null energy:
Energy of the combined GW data streams constructed to cancel the GW signal contribution.

*S. Chatterji, et al., *Phys. Rev. D* **74**, 082005 (2006)

IceCube likelihood skymap



Muon track reconstructed from Cherenkov photons



A spot on the sky
(The northern sky only)

Likelihood Distribution

$$L_{\nu}(\theta,\phi)$$

(normalized over the sky)

Background likelihood

Divide the likelihood skymaps with
the background likelihood = likelihood of the event being background noise

Background likelihood for GW events

$L^{\mathrm{BG}}_{\mathrm{GW}} = P_{\mathrm{BG}}(\min(E_{\mathrm{null}}/E_{\mathrm{inc}}))$: minimum over the sky

E_{inc} : Incoherent energy. Autocorrelation part of the null energy

Noise events: $E_{\mathrm{null}} \approx E_{\mathrm{inc}}$ GW signal: $E_{\mathrm{null}} < E_{\mathrm{inc}}$

Process a large number of background events

$\longrightarrow$ P_{BG} = Probability distribution of $\min(E_{\mathrm{null}}/E_{\mathrm{inc}})$ for background

S. Chatterji, et al., *Phys. Rev. D* **74**, 082005 (2006)

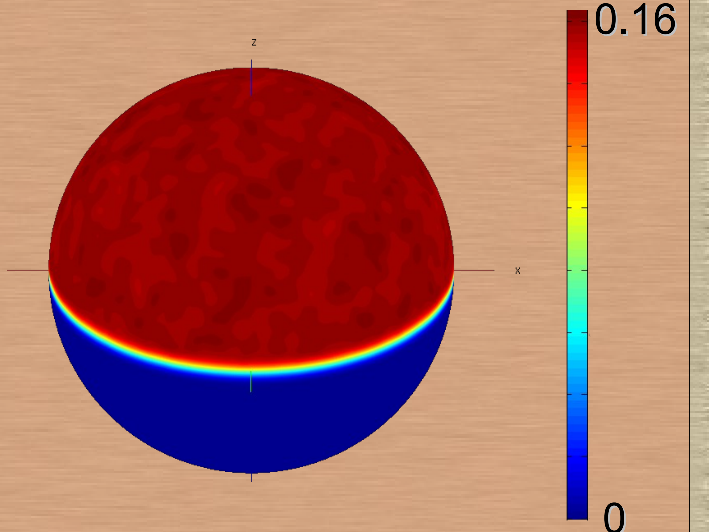
Background likelihood for IceCube events

Likelihood of an event being background given the reconstructed event direction (θ_{ev}, ϕ_{ev})

$$L^{BG}_{\nu} = \underbrace{\sum_{i=1}^{N} L_{\nu}(\theta_{ev}, \phi_{ev}, i)/N}$$

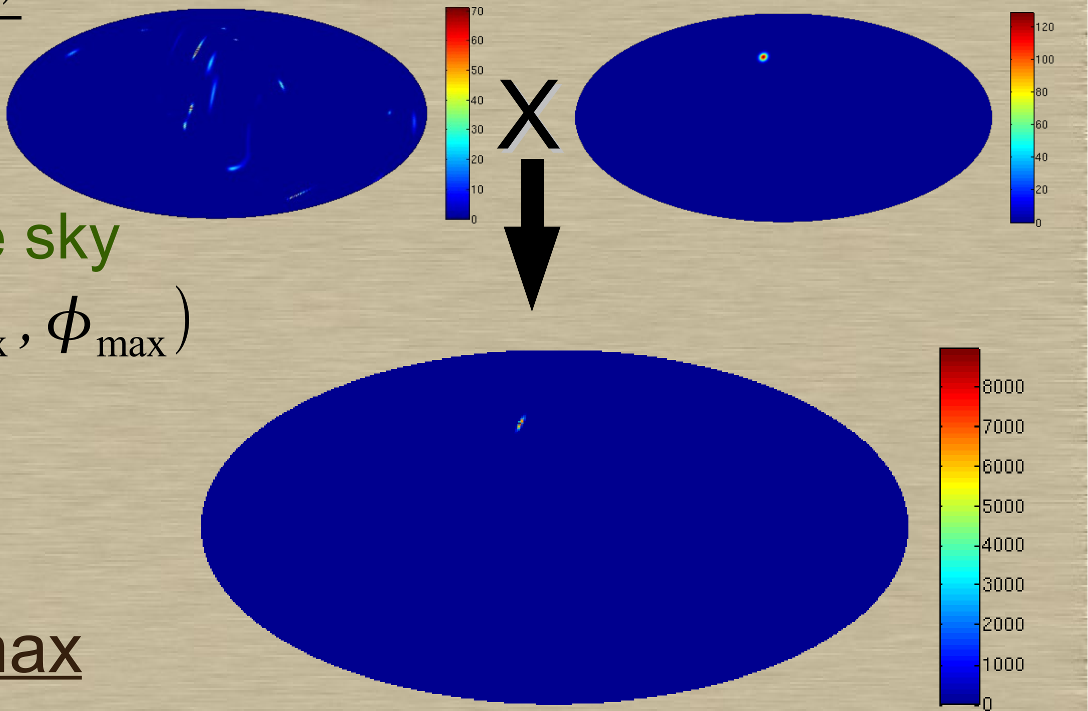
Average over many background events

Almost uniform over the northern sky



Combined Likelihood Skymap

$$L_{\mathrm{comb}}(\theta,\phi)=\frac{L_{\mathrm{GW}}(\theta,\phi)}{L_{\mathrm{GW}}^{\mathrm{BG}}}\times\frac{L_{\nu}(\theta,\phi)}{L_{\nu}^{\mathrm{BG}}}$$



Find the maximum value over the sky

$$L_{\mathrm{max}}=\max(L_{\mathrm{comb}}(\theta,\phi))=L_{\mathrm{comb}}(\theta_{\mathrm{max}},\phi_{\mathrm{max}})$$

Lmax is the final test statistic

Statistical significance of Lmax

From Background Events

→ Distribution of Lmax for background: $P_{\mathrm{BG}}(L_{\mathrm{max}})$

Each event: $L_{\mathrm{max}}^{\mathrm{event}}$ How significant is this from the background ?

p-value: $p=\int_{L_{\mathrm{max}}^{\mathrm{event}}}^{\infty}P_{\mathrm{BG}}(L_{\mathrm{max}})\,dL_{\mathrm{max}}$

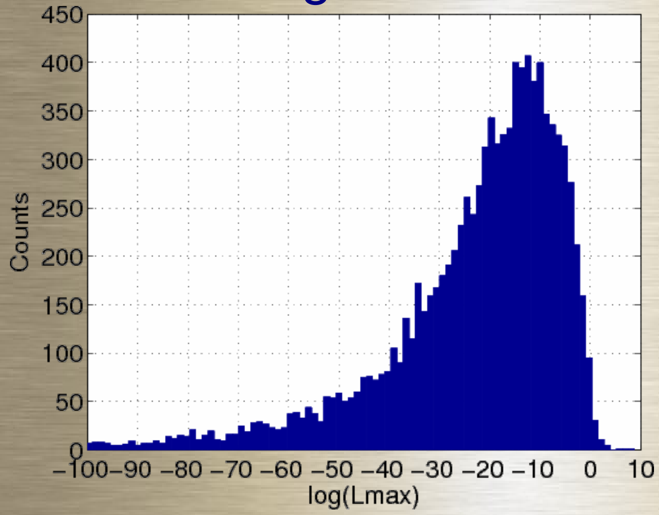
(Chance of a background event having $L_{\mathrm{max}}\geq L_{\mathrm{max}}^{\mathrm{event}}$)

Test on Simulated Data

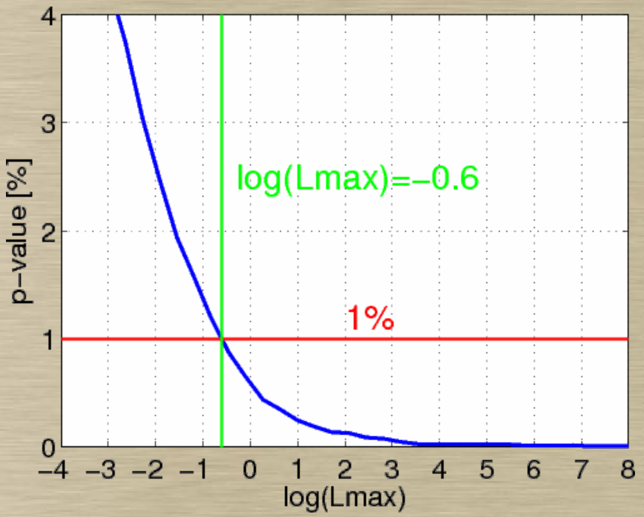
GW: Simulated data with the LIGO design like spectrum
(three hypothetical detectors at the locations of H1, L1, VIRGO)

IceCube: Random events over the northern sky

Histogram of Lmax
for background events



p-value vs log(Lmax)



Detection threshold

$$\log(L_{\max}) \geqslant -0.6$$

for 1% p-value

Injection Test

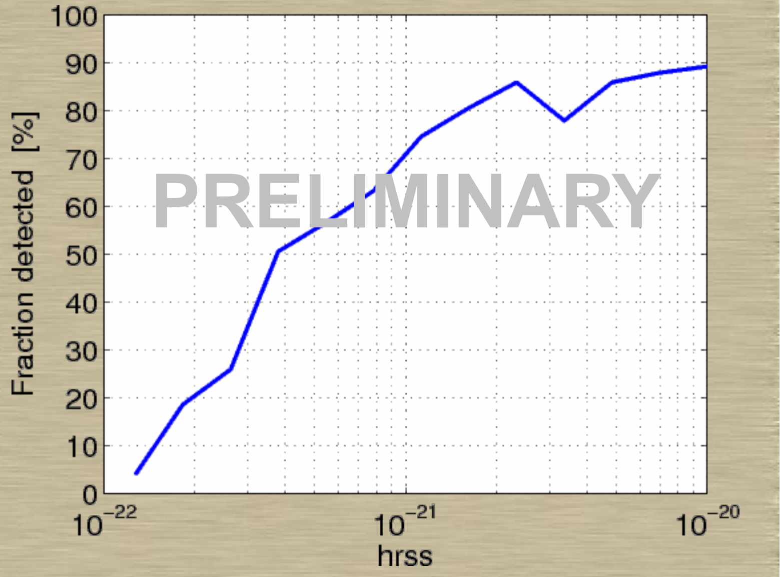
GW signal: Sine-Gaussian(153Hz, Q=8.9)
Linear polarization (random angle)
Random source location (northern sky)
Various hrss

IceCube: One neutrino event from the same direction as the GW signal

Corresponding fluence (assuming E^{-2} source spectrum) is

$$F_0 = 9\times10^{-5}\,\mathrm{TeV}^{-1}\mathrm{cm}^{-2}, \quad dF/dE = F_0(E/\mathrm{TeV})^{-2}$$

Detected fraction vs hrss



Conclusion

- Coincidence analysis method: LIGO-VIRGO-IceCube
- Time coincidence with various window sizes
- Spatial coincidence by finding the max value of the combined likelihood skymap
- Tests on simulated data are on going.

$$\mathrm{FAR} = \frac{1}{1184}\left(\frac{p}{1\%}\right)\left(\frac{T_{\mathrm{w}}}{1\,\mathrm{sec}}\right)\left(\frac{R_{\mathrm{GW}}}{1/\mathrm{day}}\right)\left(\frac{R_{\nu}}{10/\mathrm{day}}\right)[\mathrm{events/year}]$$

p-value threshold time window GW BG event rate IceCube BG event rate

Small FAR → Relaxed trigger threshold → Dig deeper into the noise

Future Plans

- More injection tests
- Better GW likelihood
- Multiple neutrino events
- Apply the method to real Data
- Other Neutrino Detectors ?