

Pair Method for Finding Sources of High-Energy Neutrinos

Ke Fang

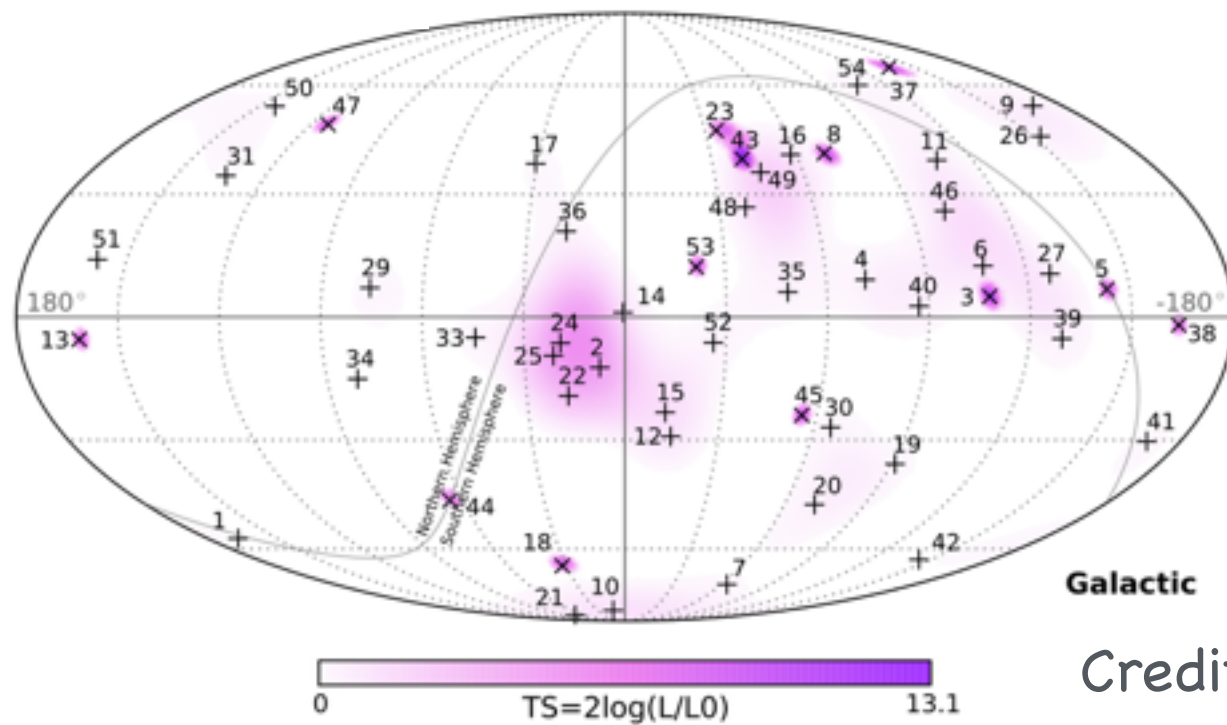
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2nd Anisotropic Universe Workshop, Amsterdam, Apr 13, 2016

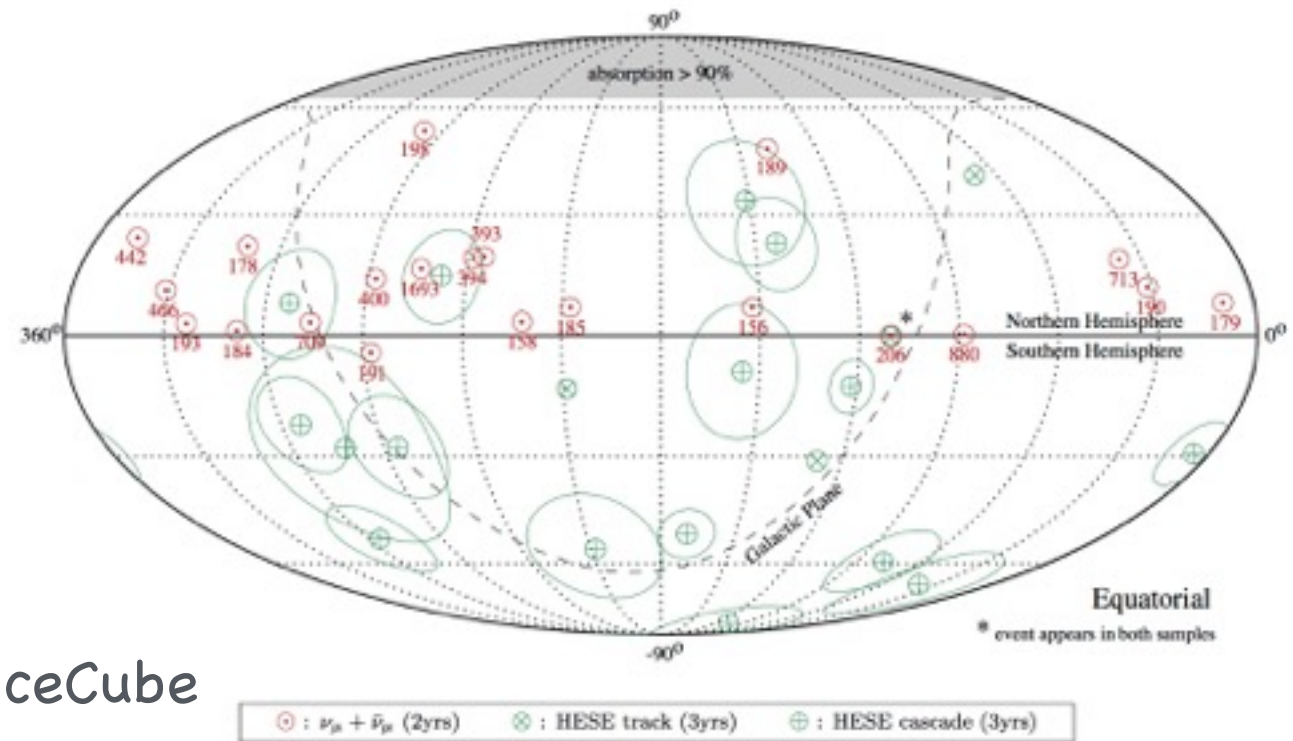
Neutrinos: Story is different

High-energy starting events



Credit: IceCube

Northern-sky muon neutrino events



Events

TeV - PeV:

- low statistics: about 20 per year
- poor angular resolution: 0.5-15 deg

EeV: undetected, predicted to exist

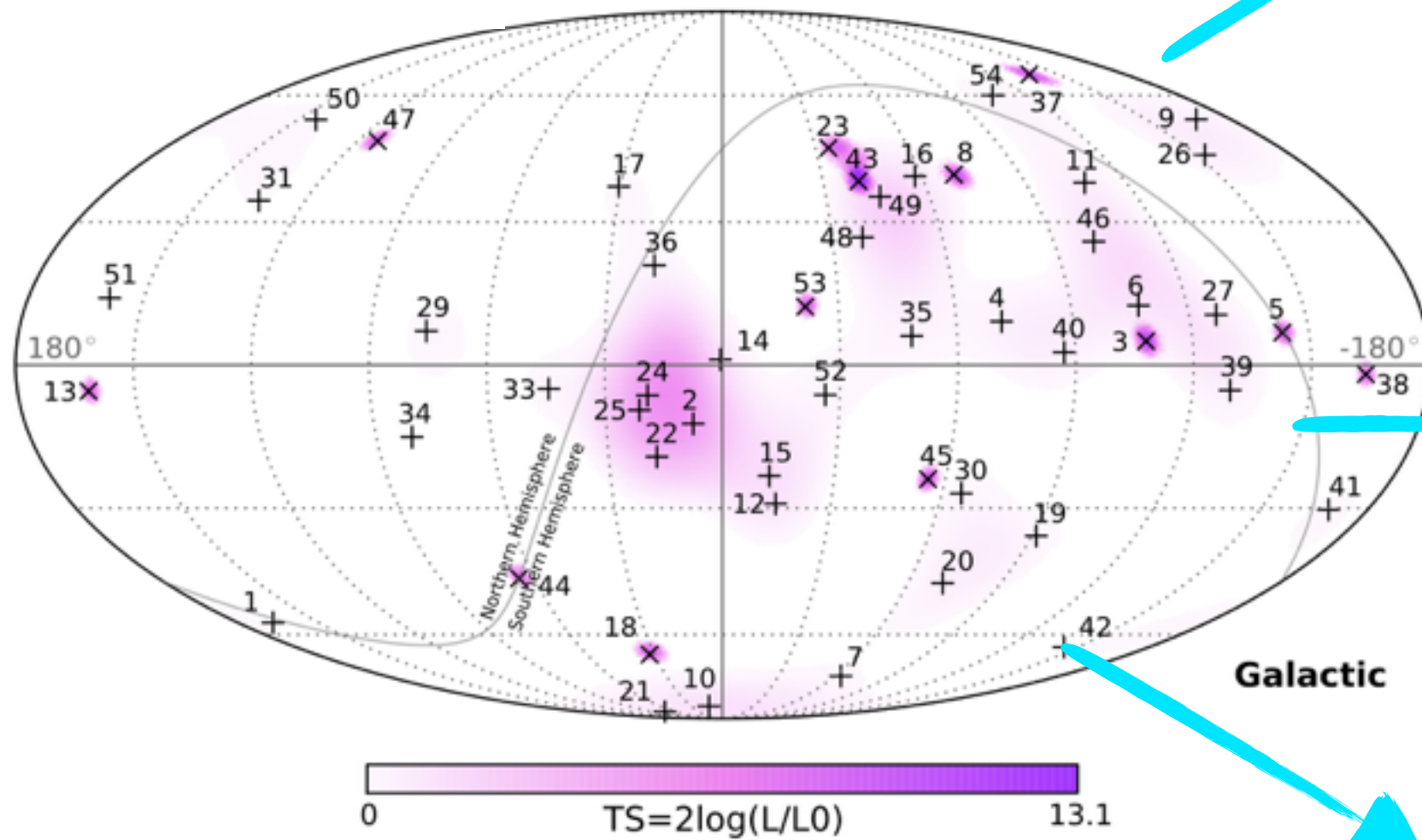
Sources

unclear with possible number density $10^{-8} - 10^{-4} \text{ Mpc}^{-3}$

Aim

find the sources!

Sources?

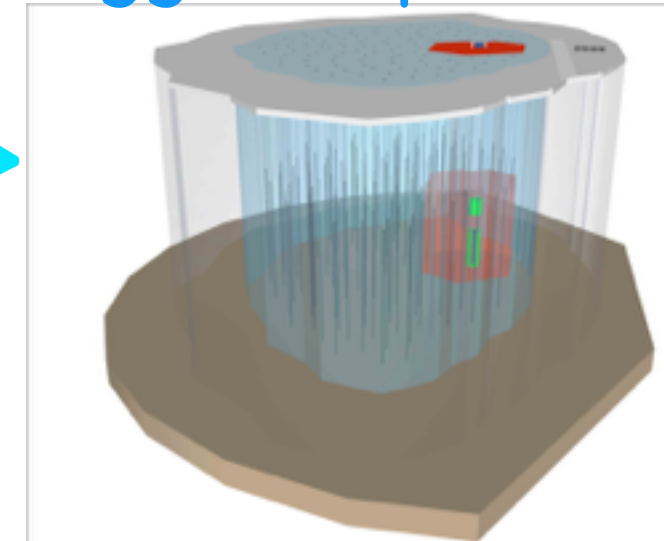


Multi-messenger



See Foteini Oikonomou's talk

Bigger experiment



Sensitive Statistical Tools

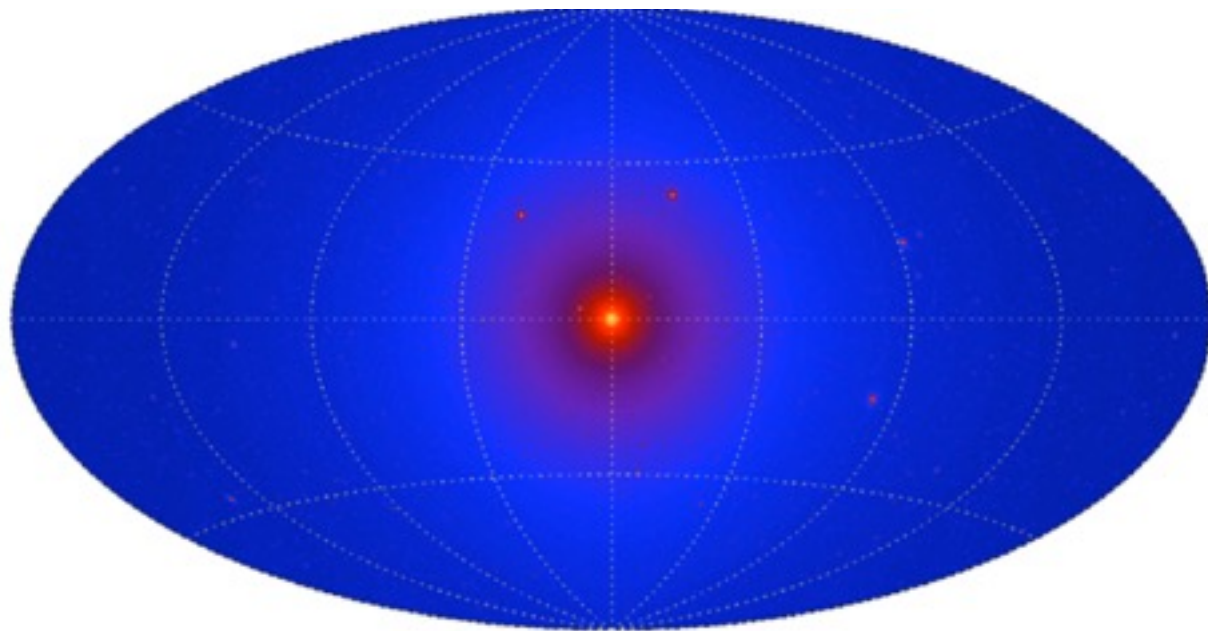


Finding Point Sources

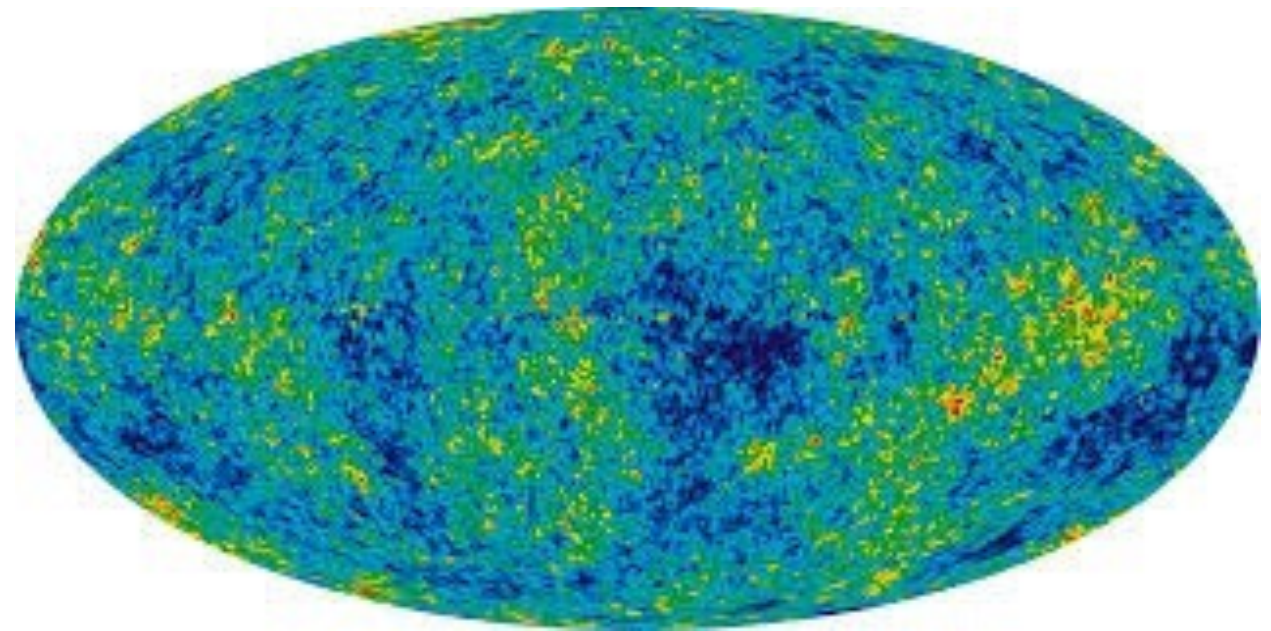
What does it mean?

Compare the following two models:

I. Some fraction of events are from specific point sources

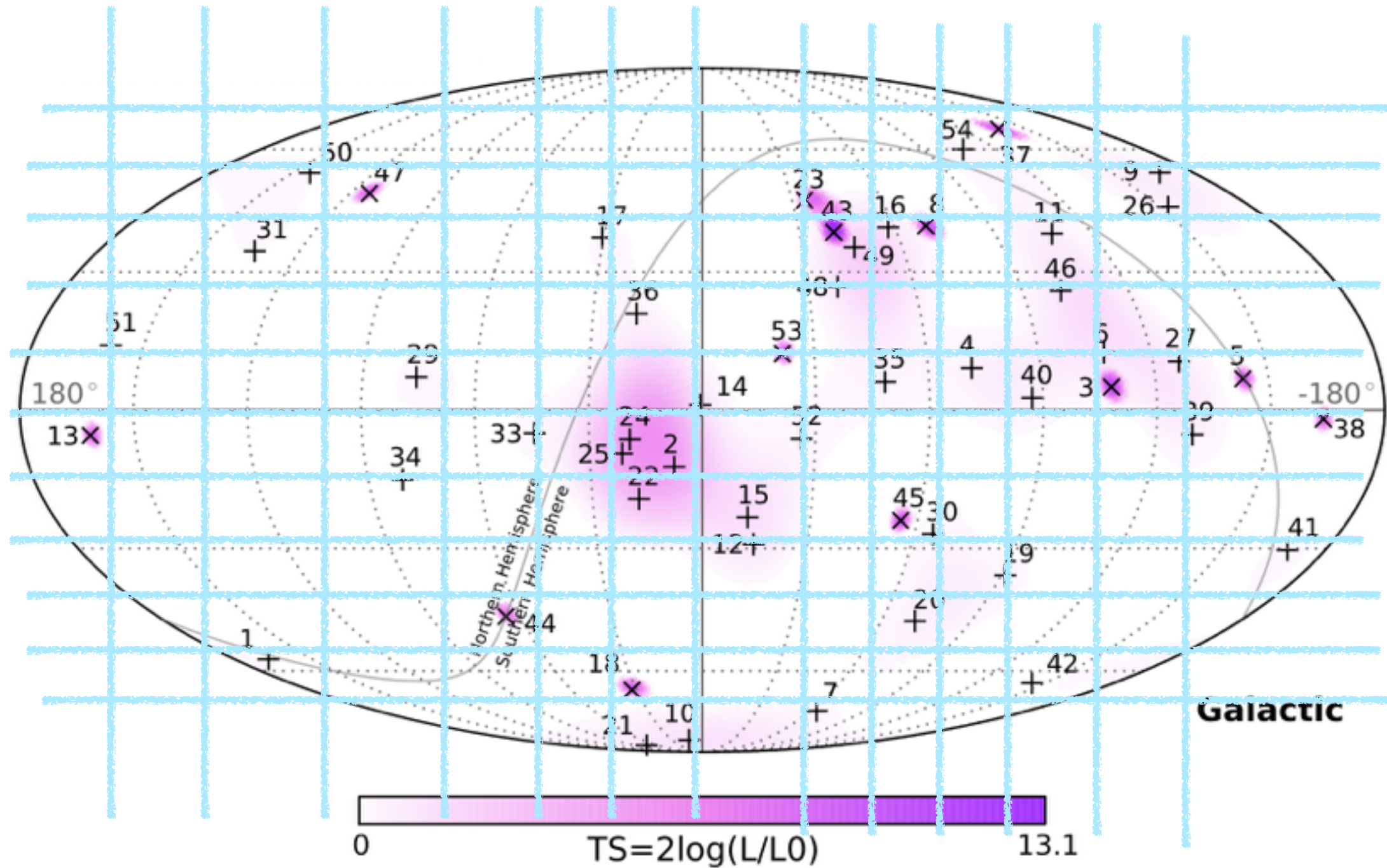


II. All events are from an isotropic background



Standard Point-Source Search Method

Divide the sky!

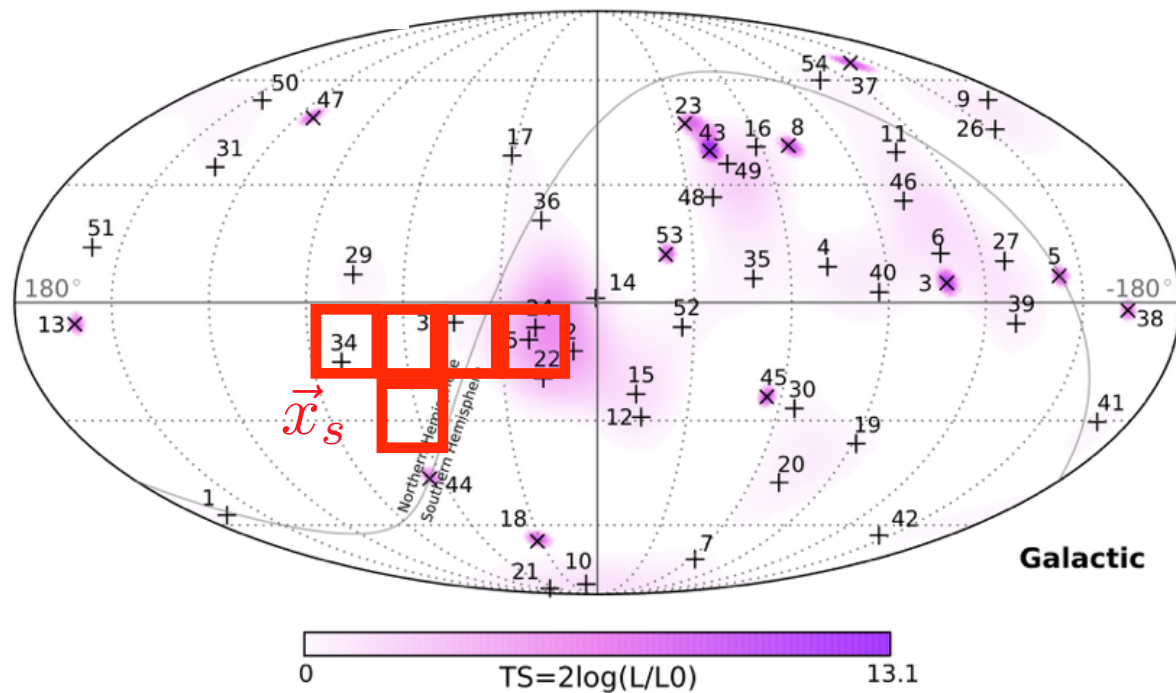


Braun+ 0801.1604
Braun+ 0912.1572

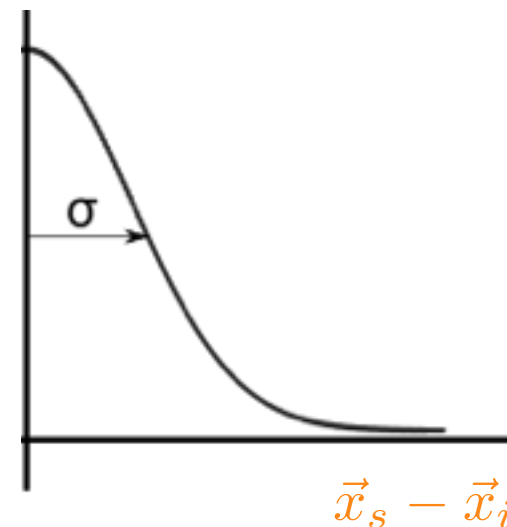
Standard Point-Source Search Method

Assume a source location,

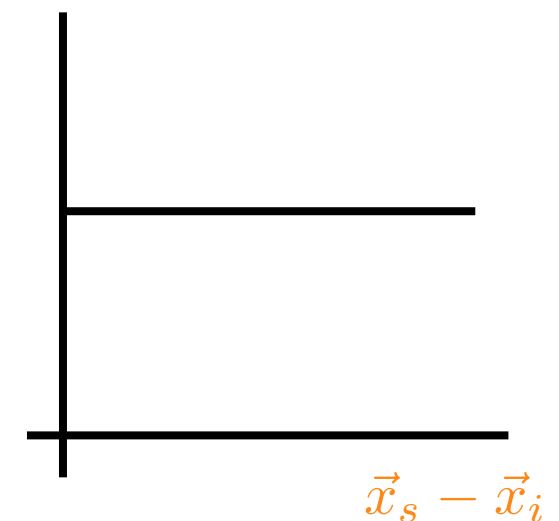
$$\ln \mathcal{L}(f, \vec{x}_s) = \sum_i \ln [f \mathcal{S}_i + (1 - f) \mathcal{B}_i]$$



Source



Background

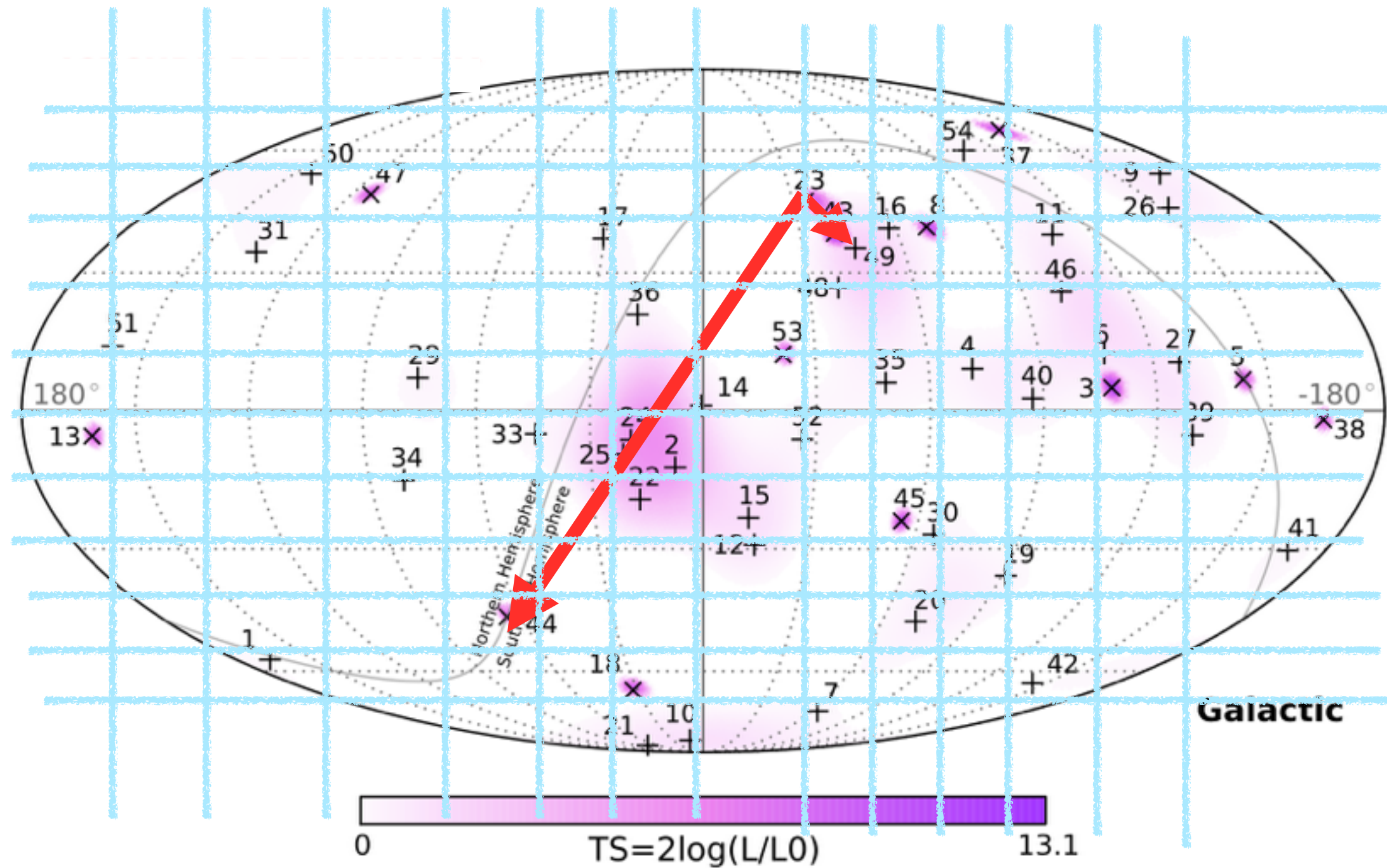


Test Statistics $\text{TS}_{\text{SS}}(\vec{x}_s) = 2 \ln \left[\frac{\mathcal{L}(\hat{f}, \vec{x}_s)}{\mathcal{L}(f = 0)} \right]$

Don't know the actual source locations → Scan the sky for maximum

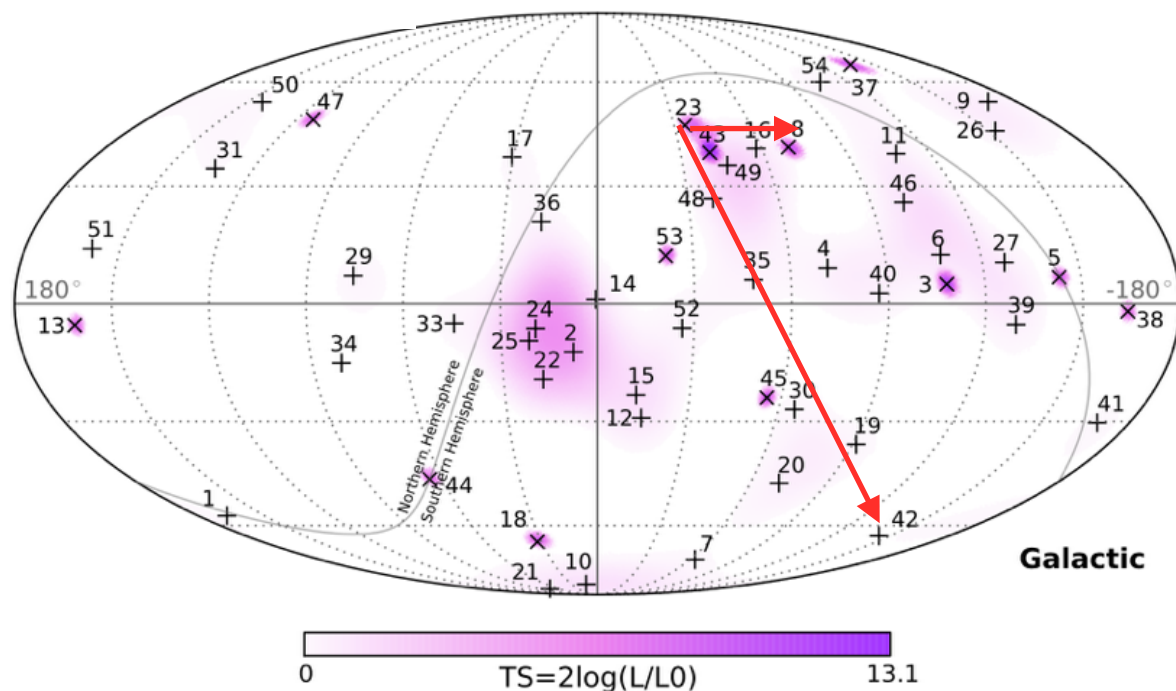
$$\text{TS} = \max(\text{TS}(\vec{x}_s))$$

But... Boxes = Trials + Boundaries
Go without boxes?

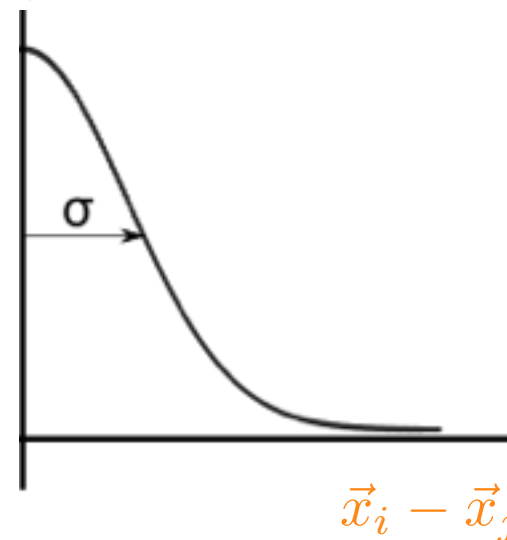


An Unbinned Likelihood Method with Event Pairs

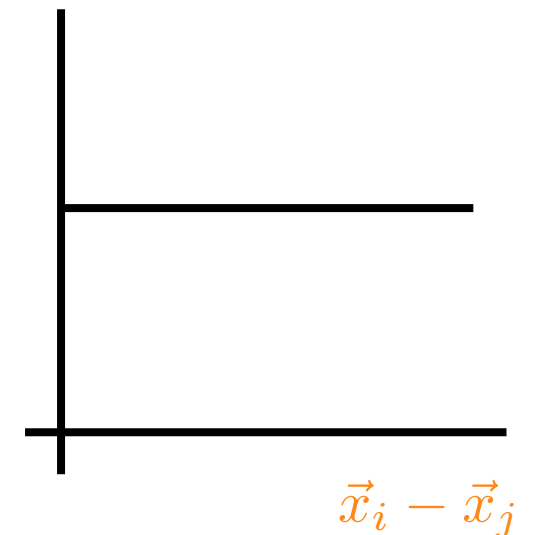
$$\ln \mathcal{L}(f) = \sum_{i,j>i} \ln [f A_{\text{point}}(\bar{a}_{ij}) + (1 - f) A_{\text{diff}}(\bar{a}_{ij})]$$



A_{point}



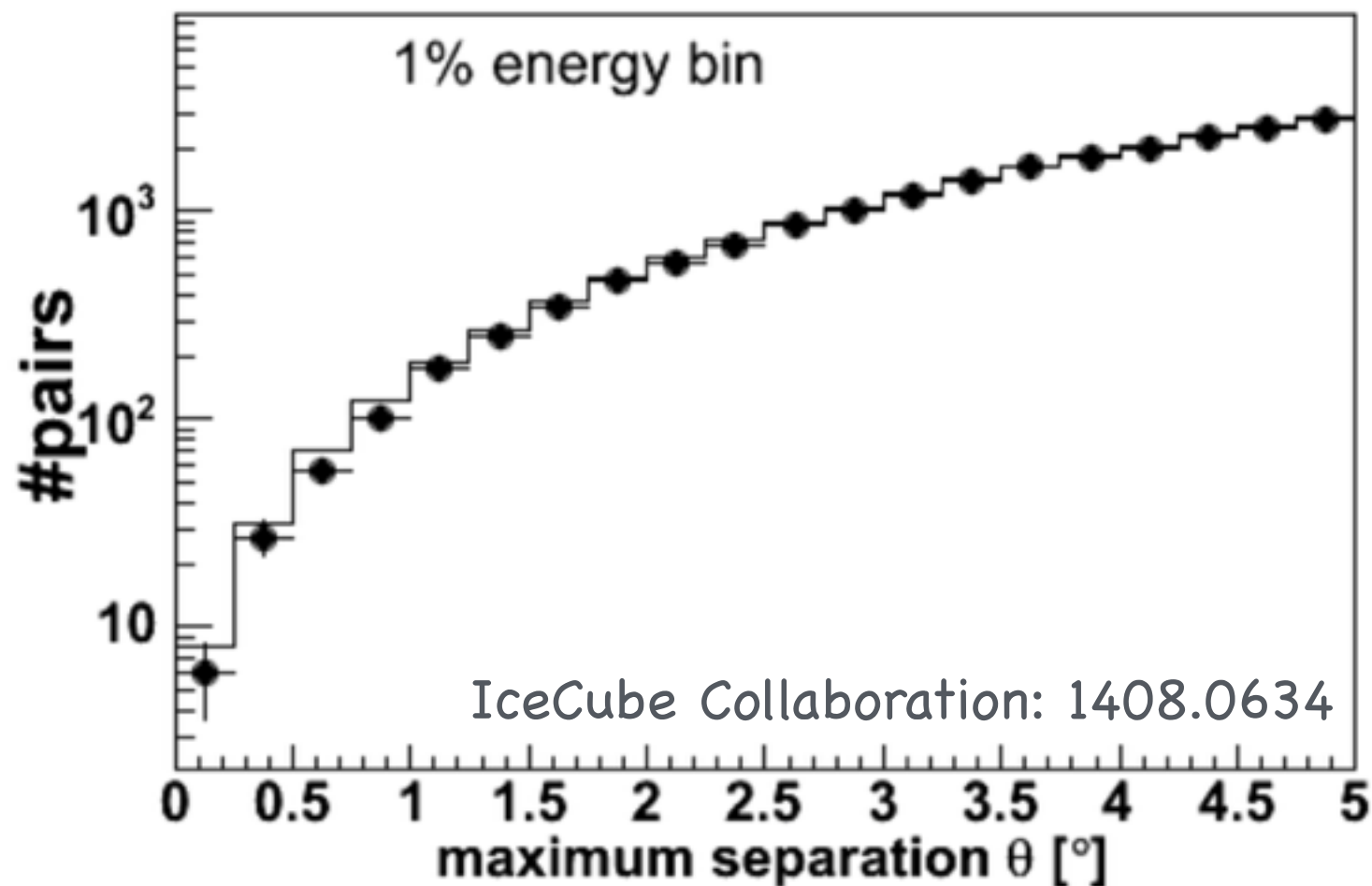
A_{diff}



Test Statistics

$$TS = 2 \ln \left[\frac{\mathcal{L}(\hat{f})}{\mathcal{L}(f = 0)} \right]$$

Different from a 2-point autocorrelation test
Pair method has no trials; incorporate PSF information



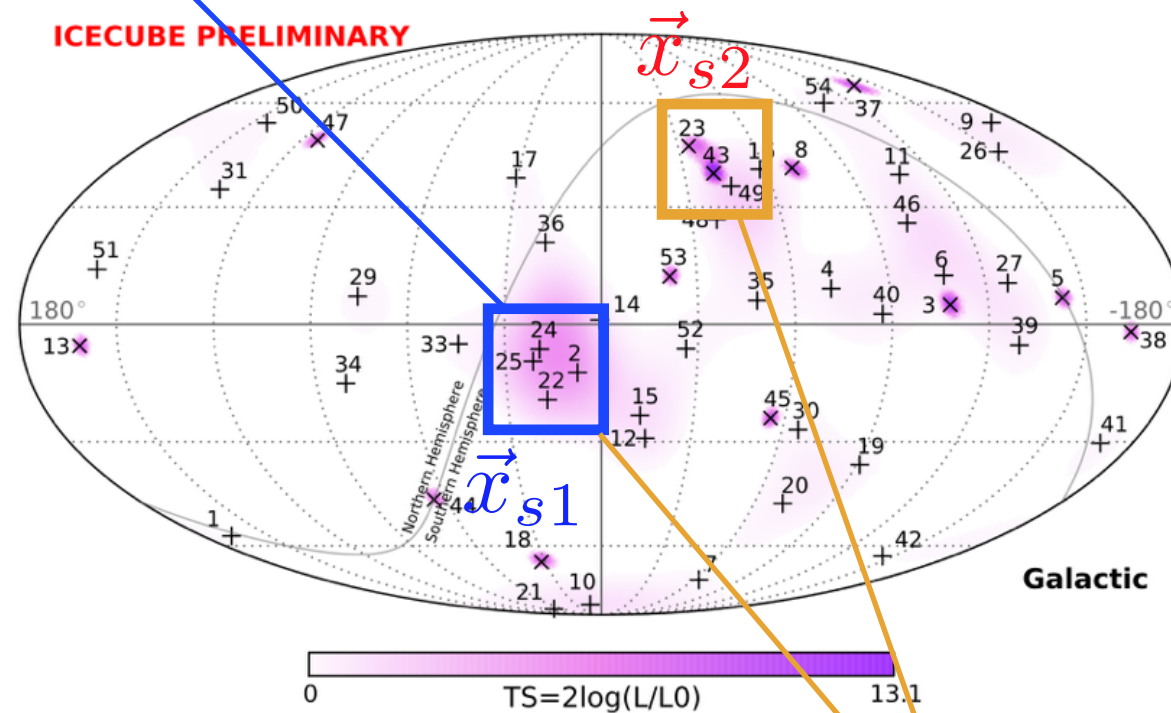
2-pt autocorrelation: search for small-scale anisotropy in the arrival direction of neutrinos

Difference with the standard method

More than one source can contribute to evidence

Single-Source method

$$\ln \mathcal{L}(f, \vec{x}_s) = \sum_i \ln [f \mathcal{S}_i + (1 - f) \mathcal{B}_i]$$

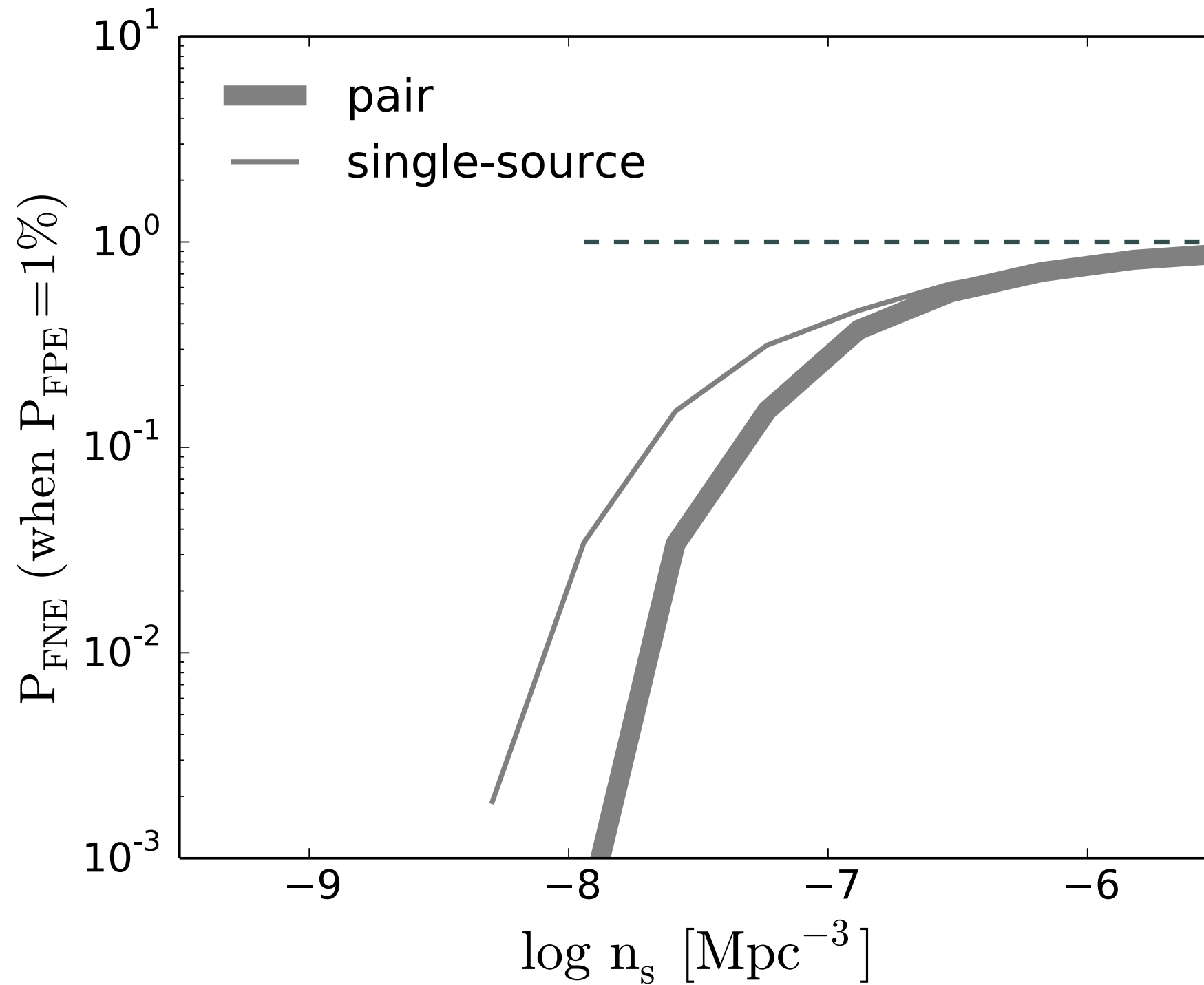


Pair method

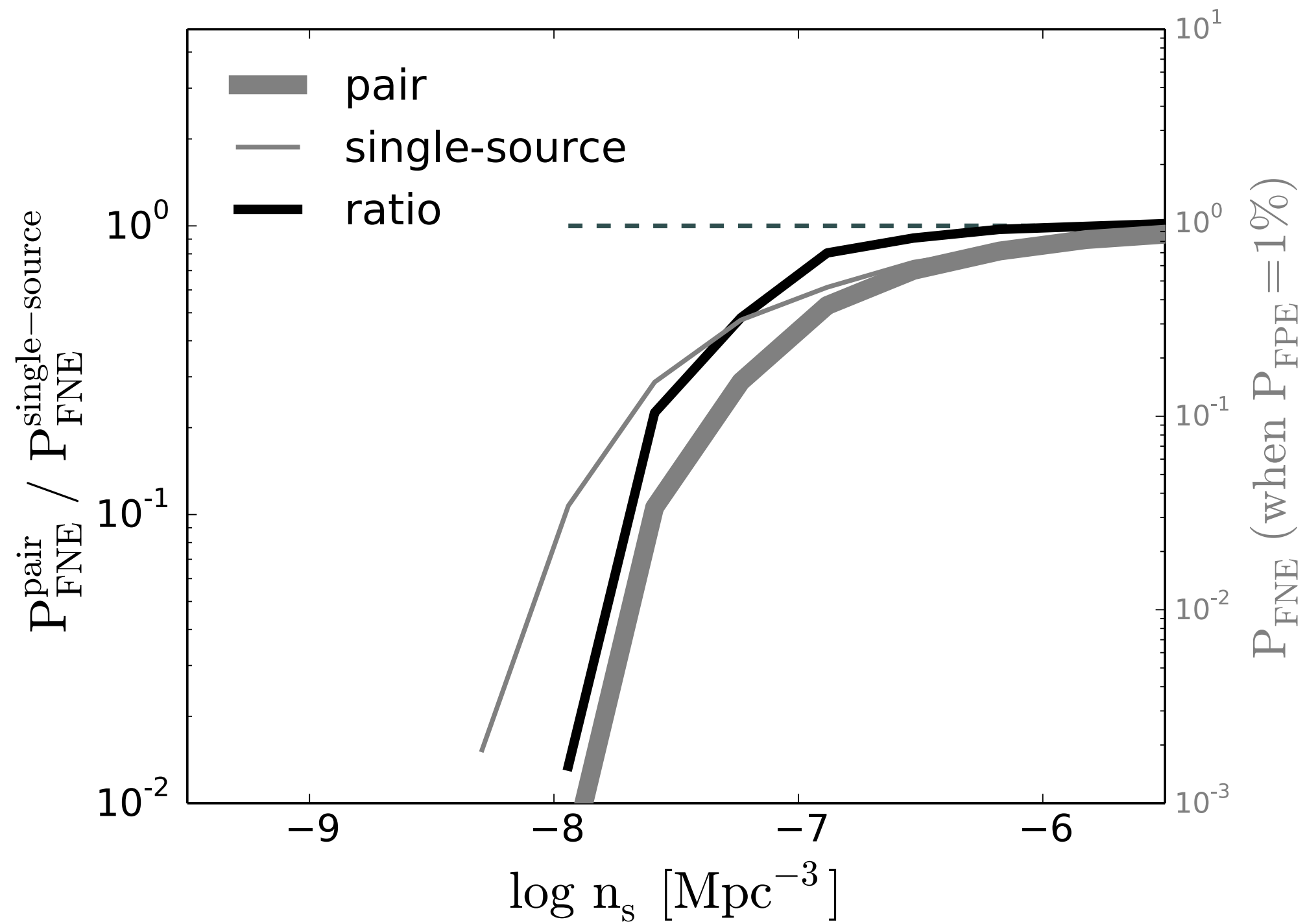
$$\ln \mathcal{L}(f) = \sum_{i,j>i} \ln [f A_{\text{point}}(\bar{\alpha}_{ij}) + (1 - f) A_{\text{diff}}(\bar{\alpha}_{ij})]$$

Comparison of the two methods

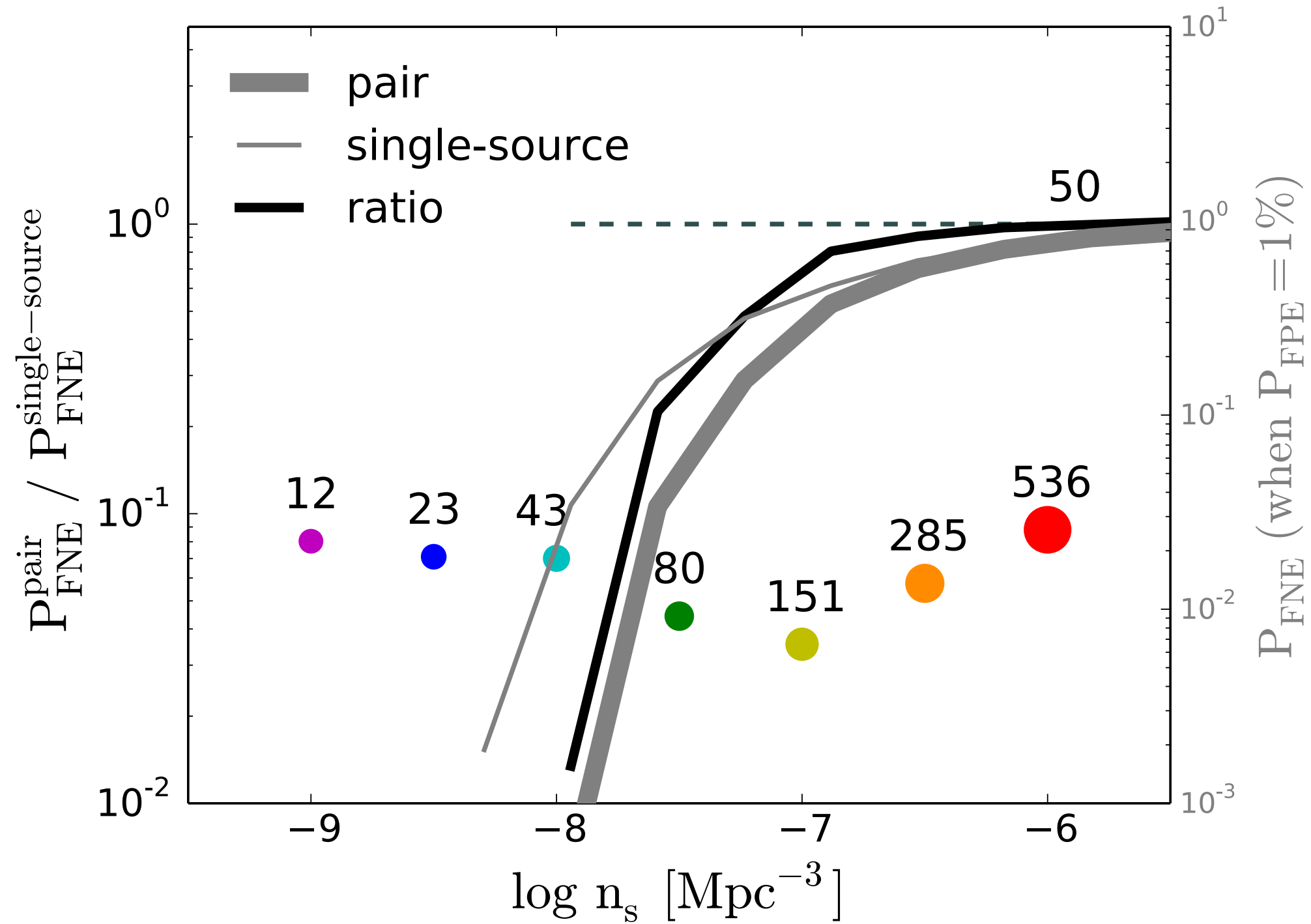
Rate of False Negative Error (FNE)



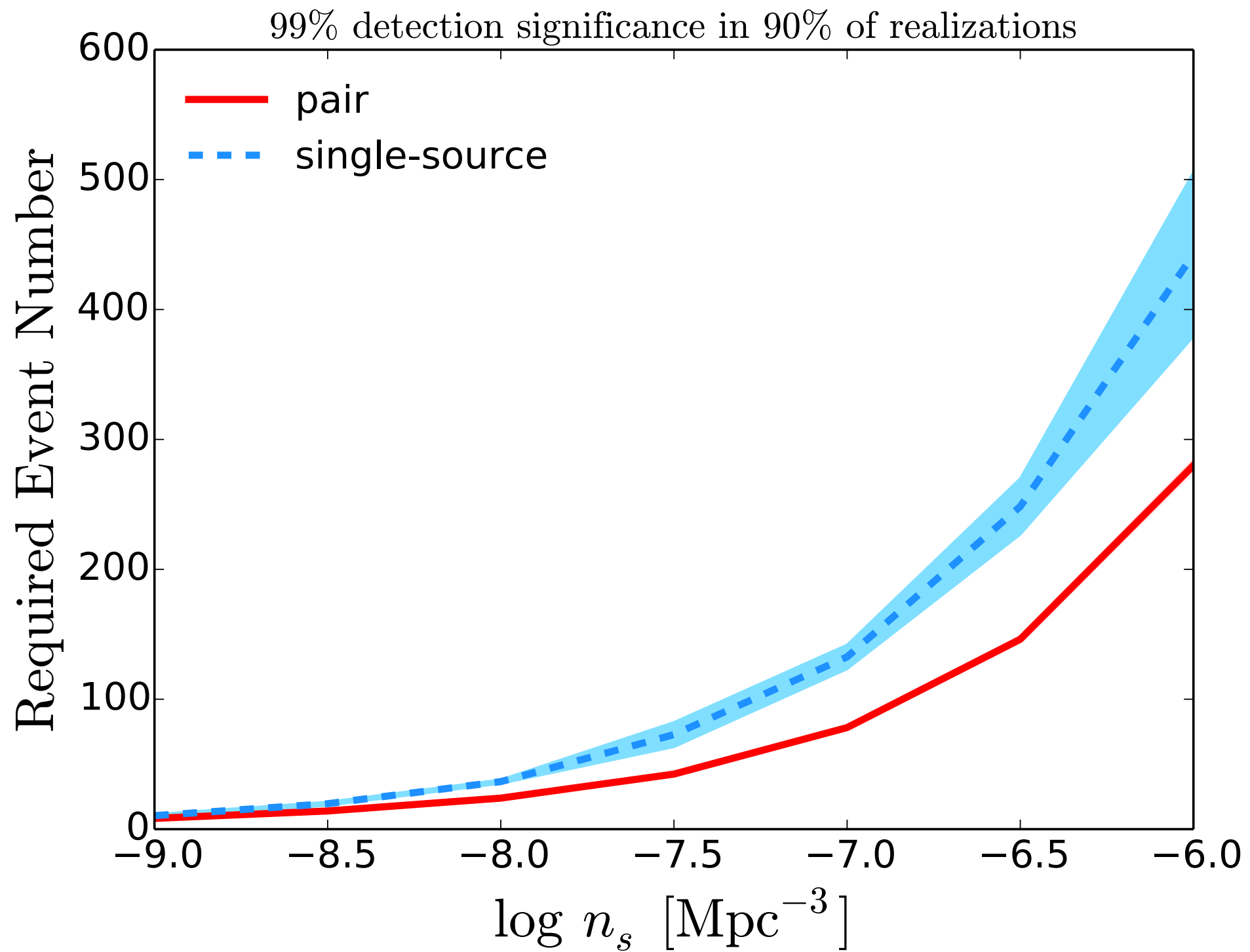
Ratio of the Chances of FNE



Same Ratio with More Events for Larger Source Density

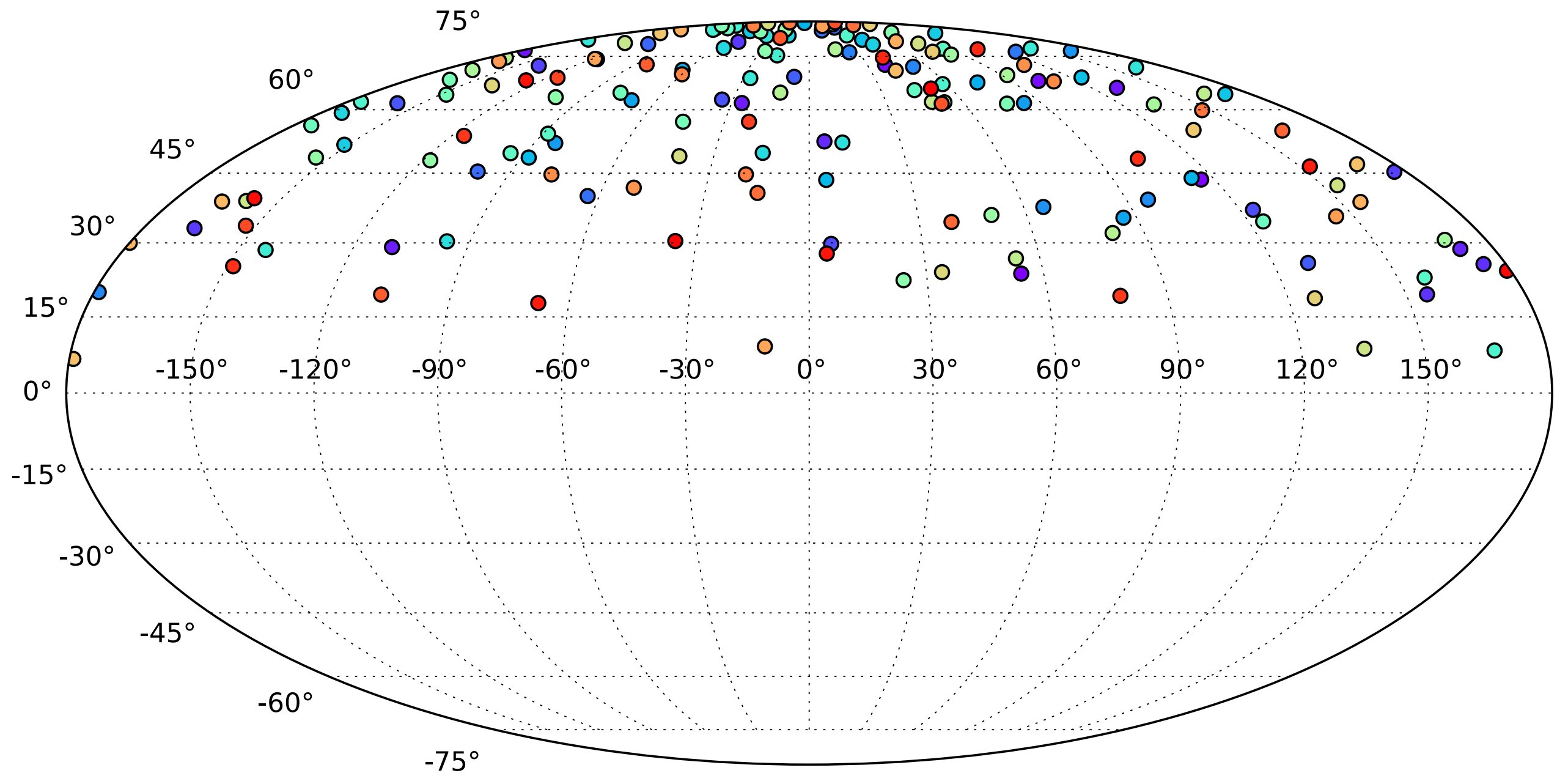


Number of Events Needed for Detection

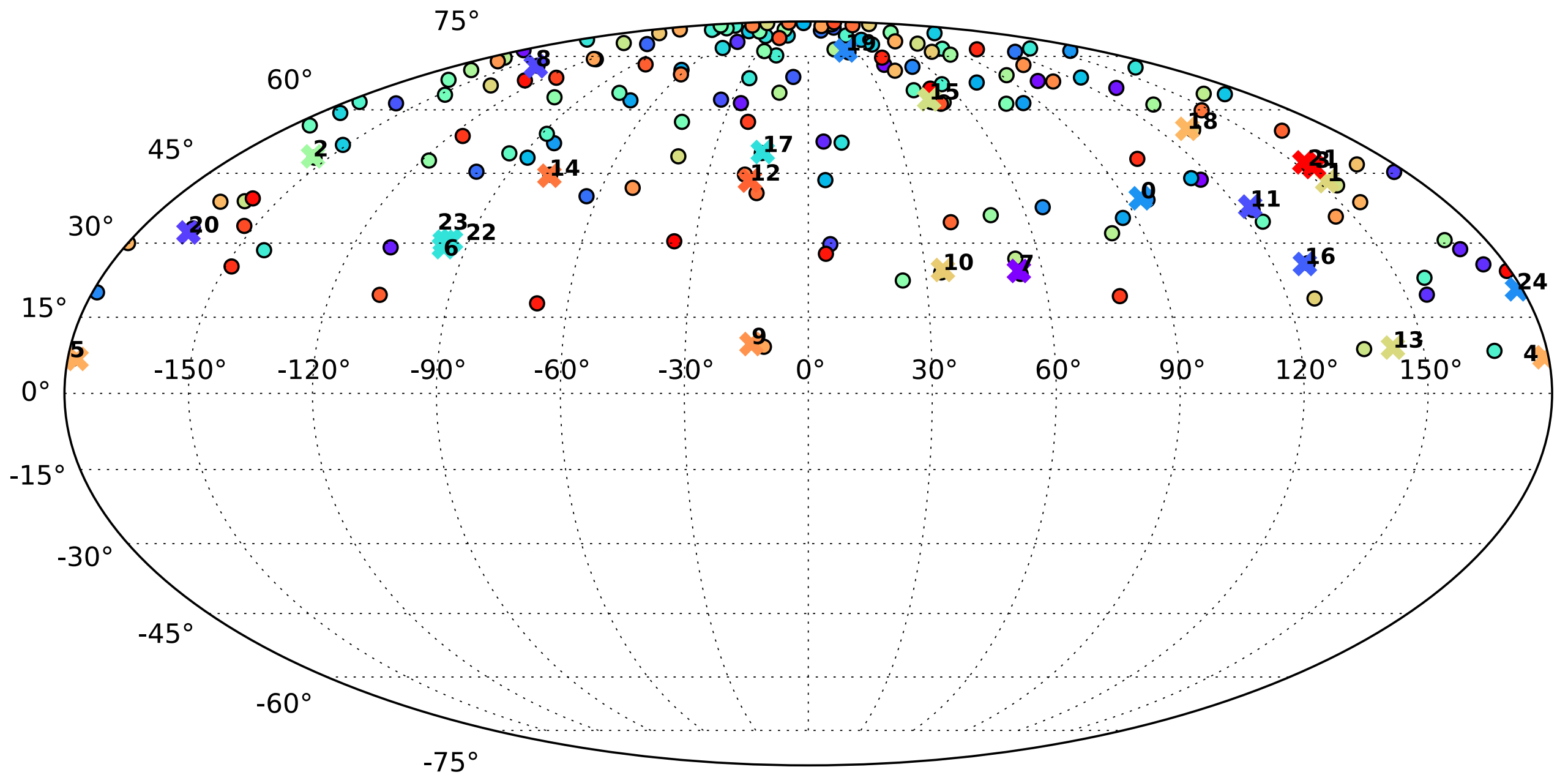


Localization of the Sources

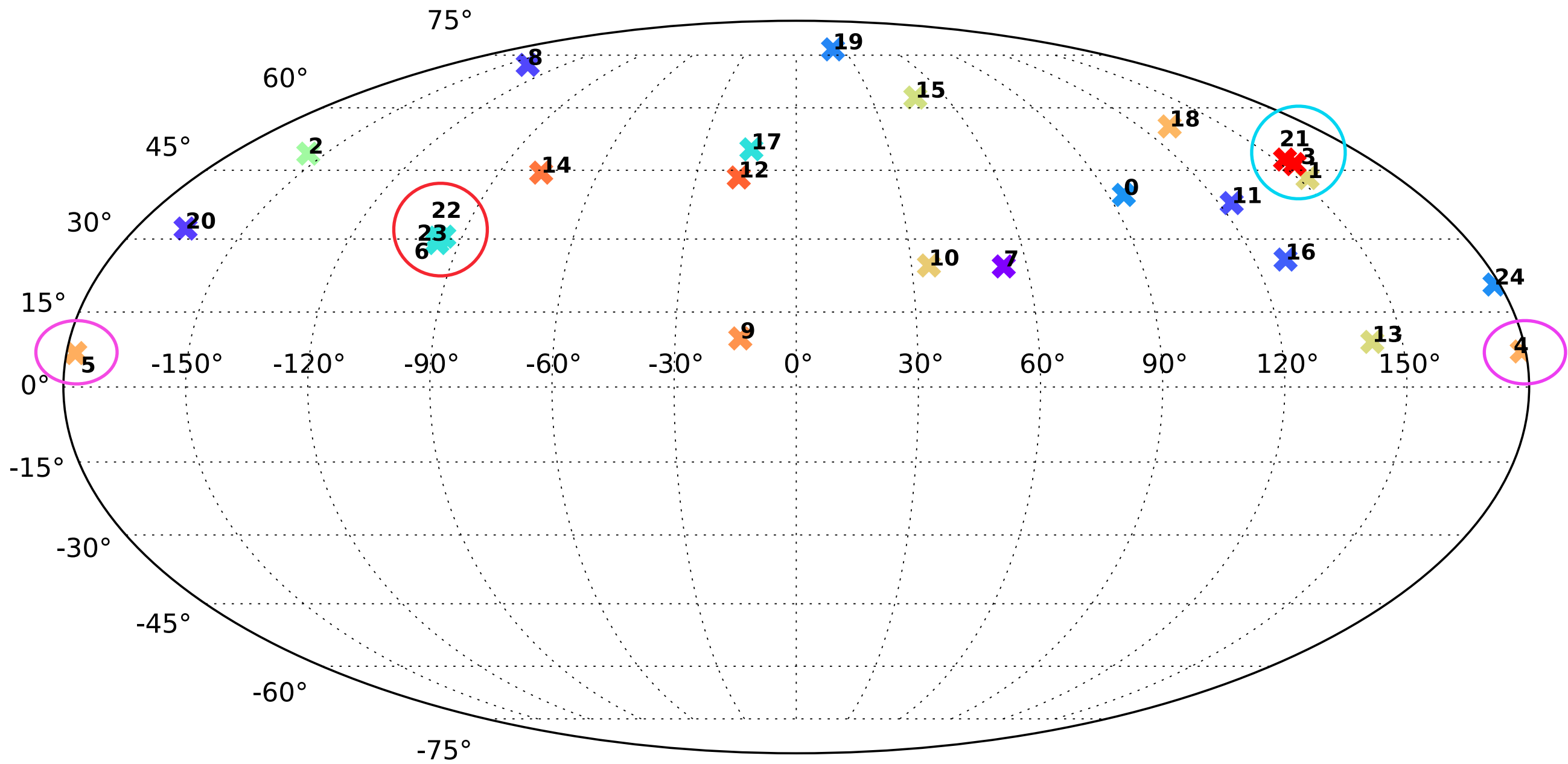
Source Map (N~130)



Sources + 25 events

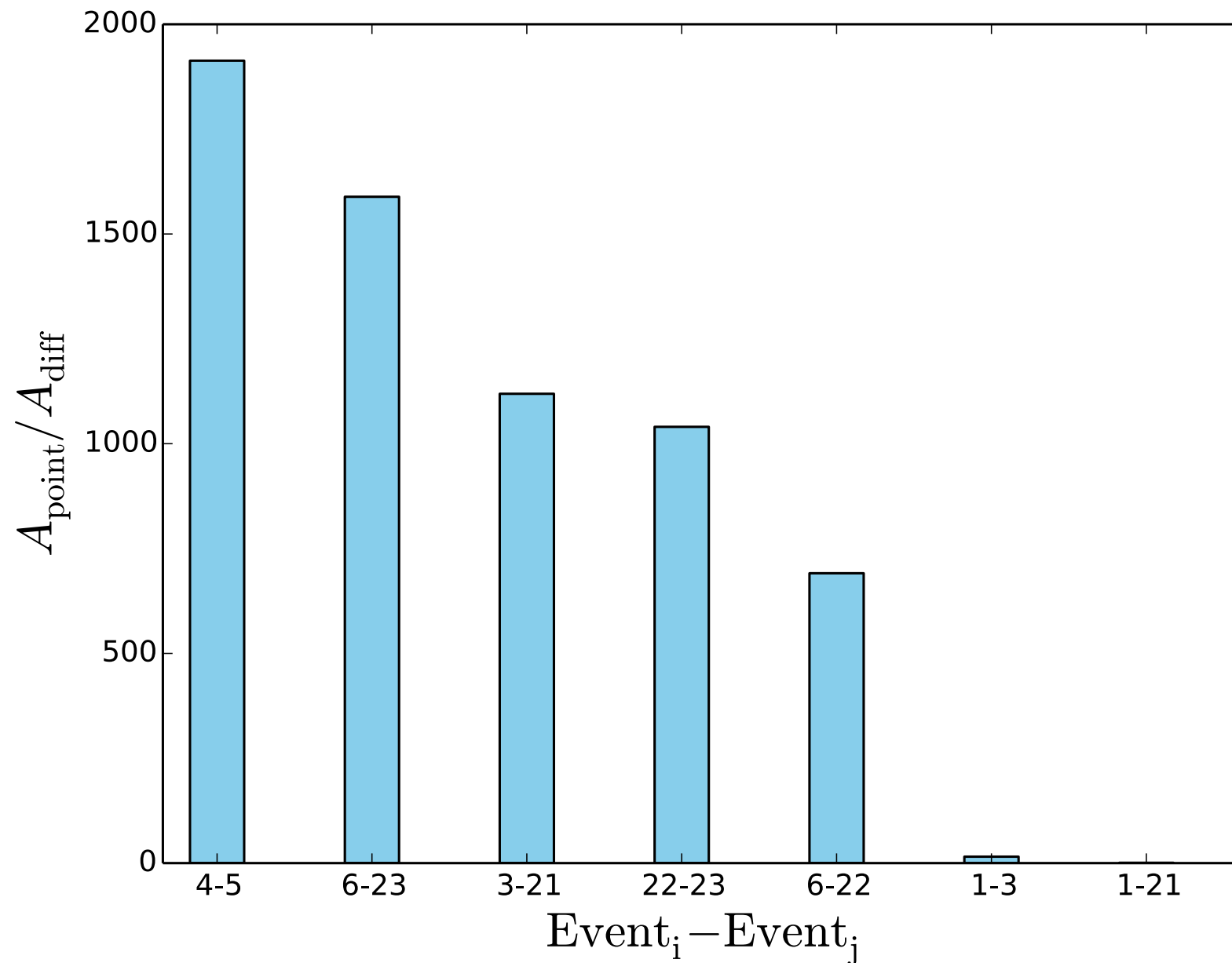


3 Sources with Multiplets

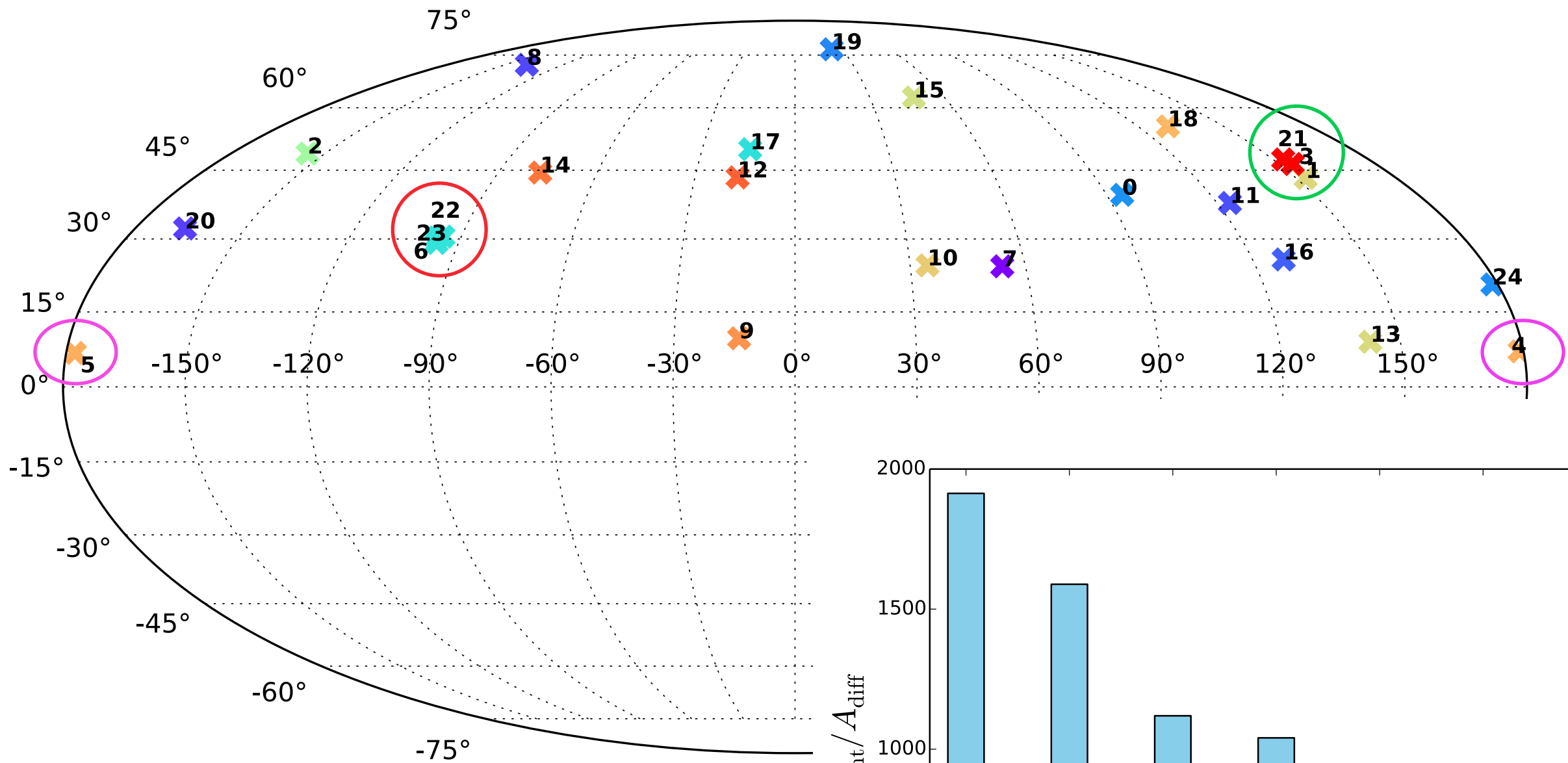


Apoint / Adiff Chart

$$\ln \mathcal{L}(f) = \sum_{i,j>i} \ln [f A_{\text{point}}(\bar{\alpha}_{ij}) + (1 - f) A_{\text{diff}}(\bar{\alpha}_{ij})]$$



Source Localization



An efficient way of searching for point sources – using event pairs!

