IceCube Masterclass

WORKSHOP ACTIVITY #2:
LOOKING FOR NEUTRINO SOURCES

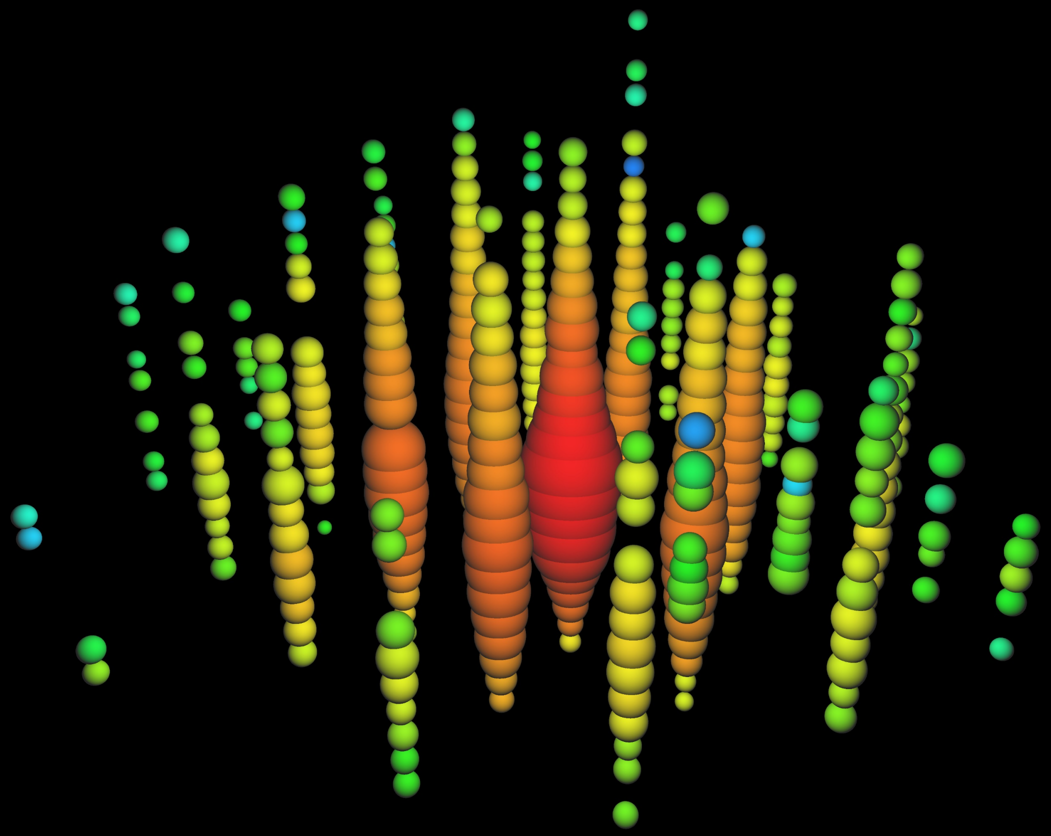
Image credit: Martin Wolf / NSF

BEFORE LUNCH

We figured out how to find neutrinos in our data.

The questions we want to answer are:

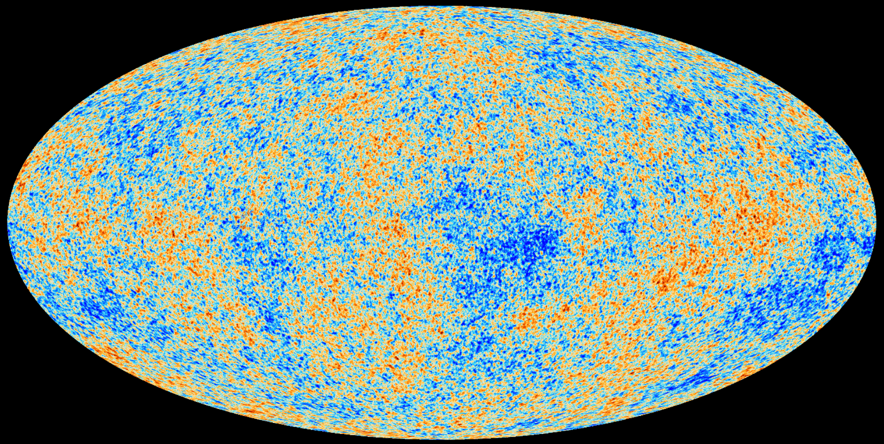
- What can produce these neutrinos?
- Where do these neutrinos come from?



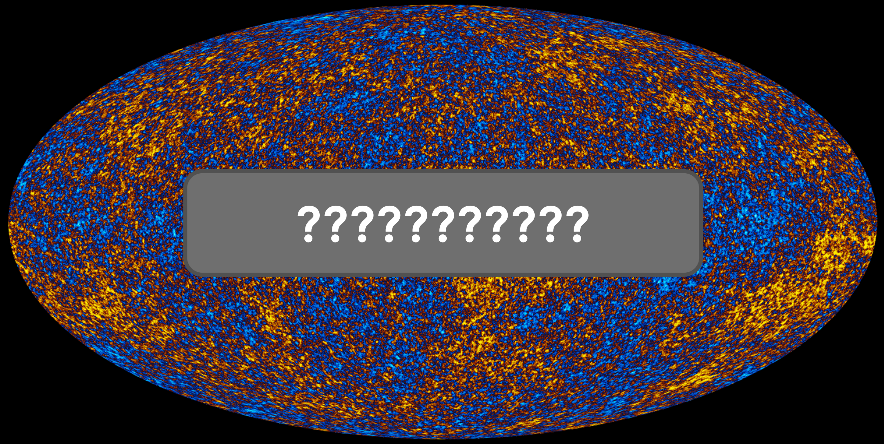
NEUTRINO PRODUCTION IN THE UNIVERSE

The electron-volt (eV) energy scale

The Cosmic Neutrino Background



CMB (photons)



CνB (Neutrinos)

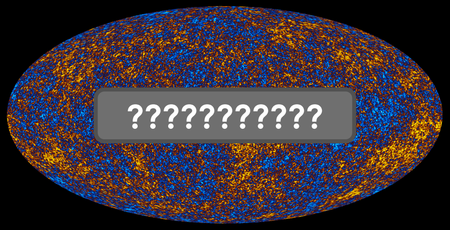
NEUTRINO PRODUCTION IN THE UNIVERSE

The electron-volt (eV) energy scale

Low energy | **High energy**

0.001
(meV)

1.0
(eV)



The Cosmic
Neutrino
Background

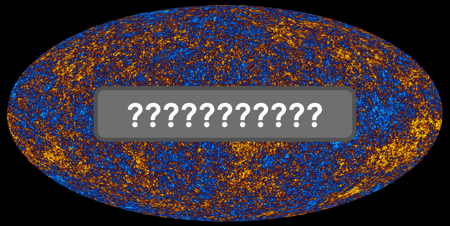
Nothing to see!

NEUTRINO PRODUCTION IN THE UNIVERSE

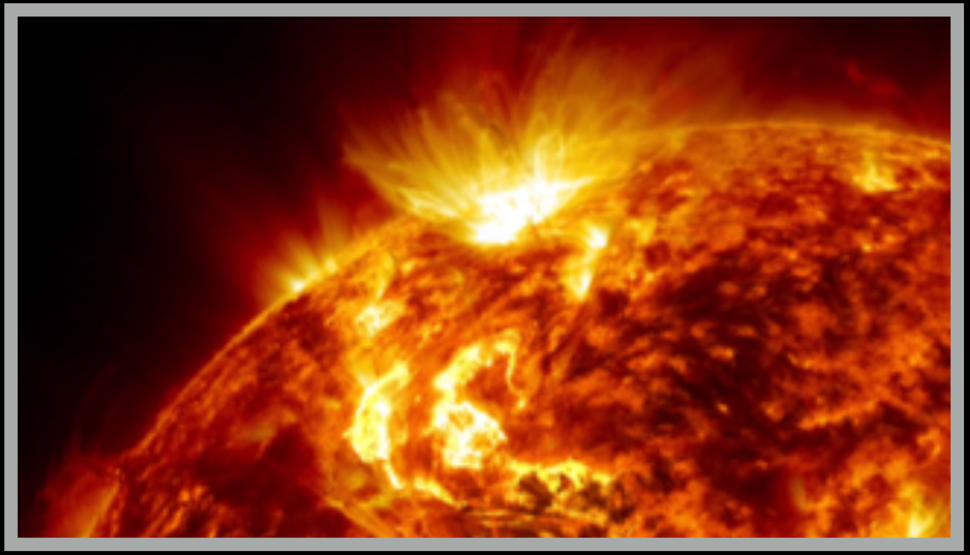
The electron-volt (eV) energy scale

Low energy — **High energy**

0.001 (meV) | 1.0 (eV) | 1000 (keV)



The Cosmic Neutrino Background



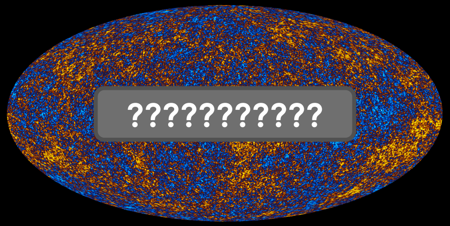
Solar Neutrinos

NEUTRINO PRODUCTION IN THE UNIVERSE

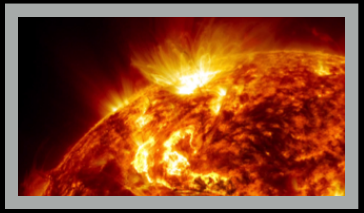
The electron-volt (eV) energy scale

Low energy — **High energy**

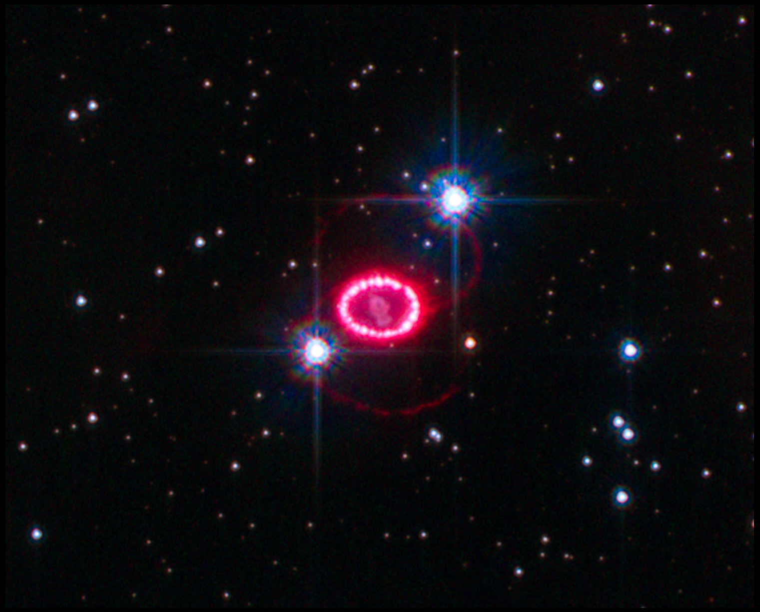
0.001 (meV) | 1.0 (eV) | 1000 (keV) | 10^6 (MeV)



The Cosmic Neutrino Background



Solar Neutrinos



SUPERNOVA!

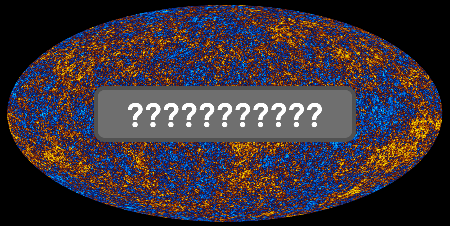
NEUTRINO PRODUCTION IN THE UNIVERSE

The electron-volt (eV) energy scale

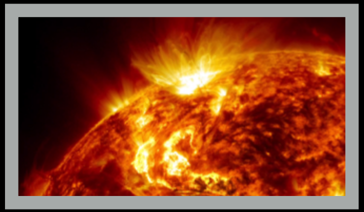
Atmospheric Background

Low energy ← → **High energy**

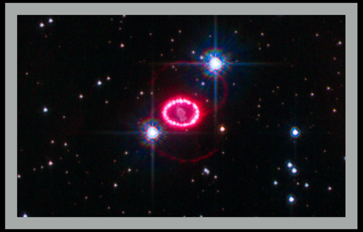
0.001 (meV)	1.0 (eV)	1000 (keV)	10^6 (MeV)	10^9 (GeV)	10^{12} (TeV)



The Cosmic Neutrino Background

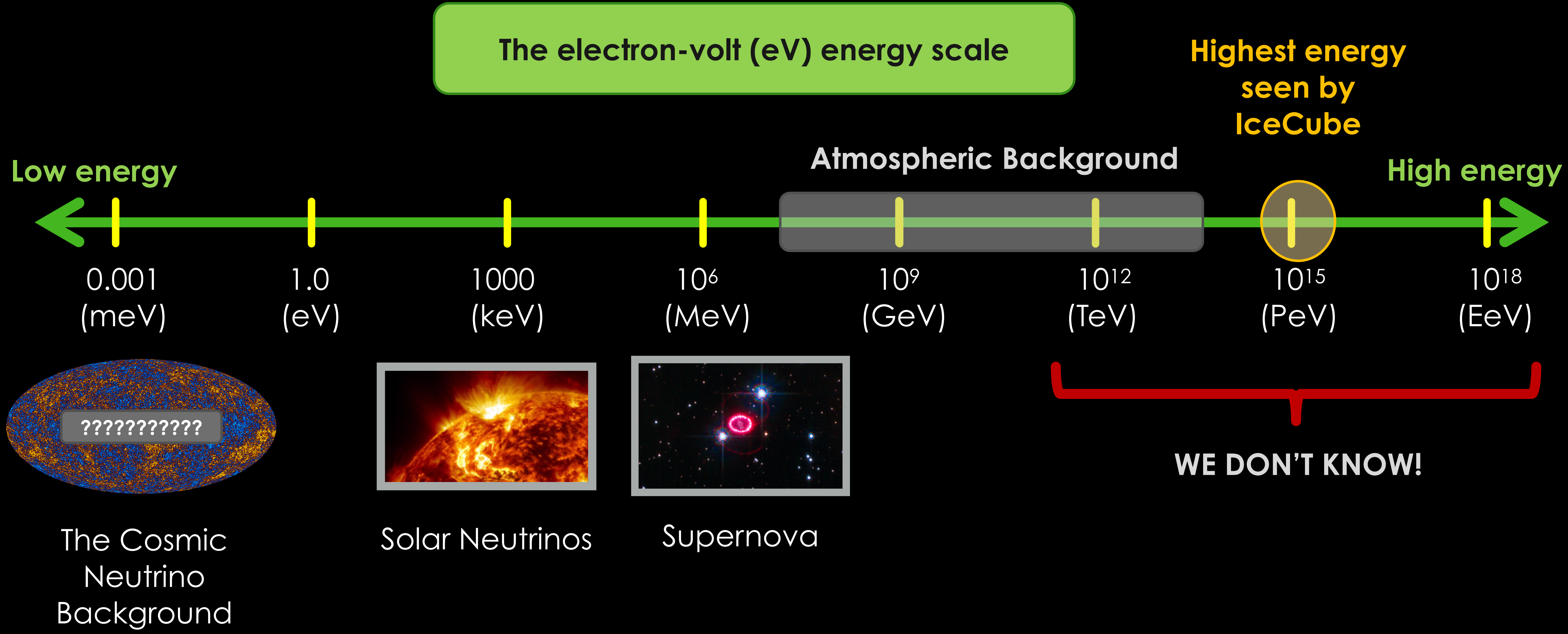


Solar Neutrinos



Supernova

NEUTRINO PRODUCTION IN THE UNIVERSE

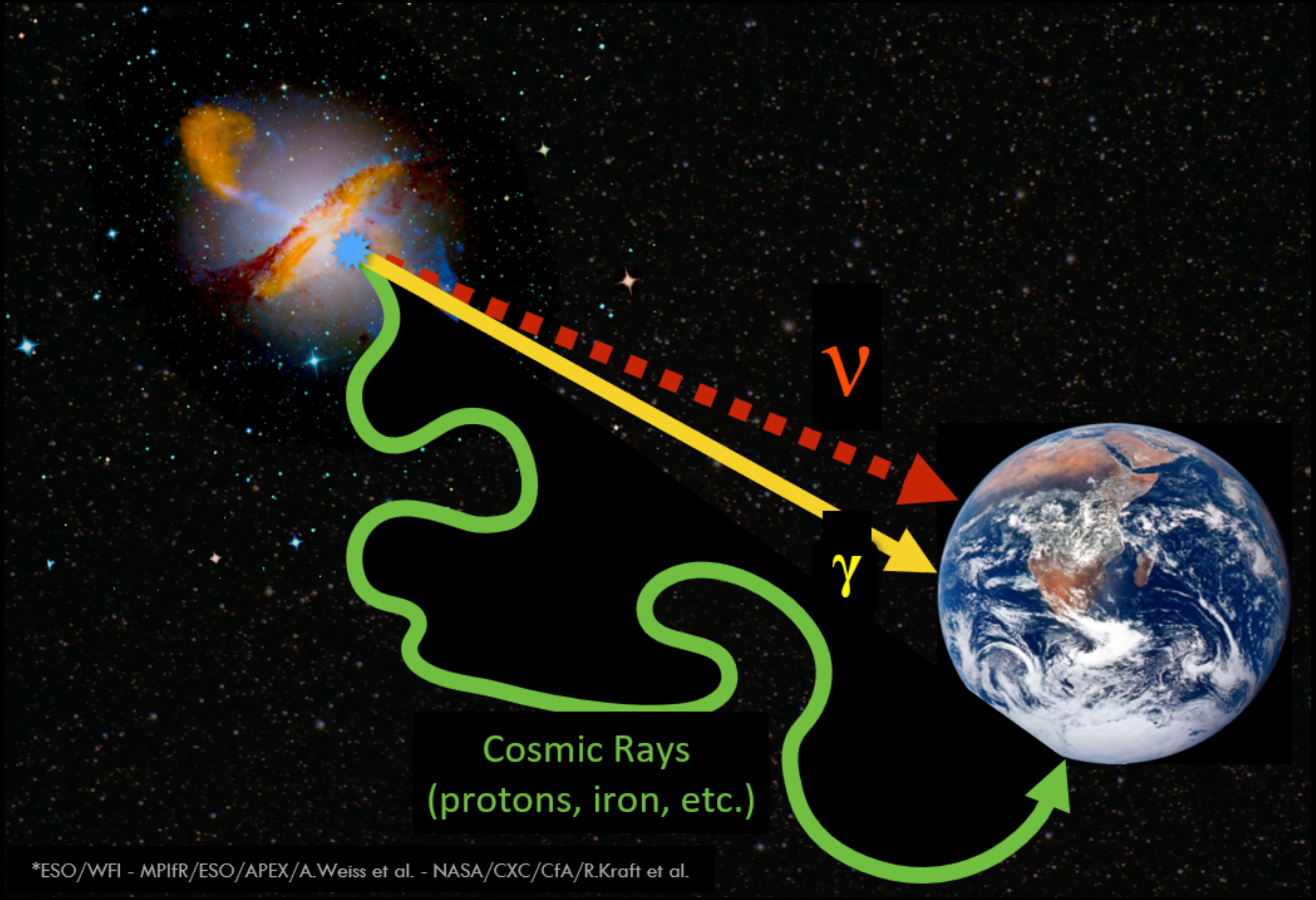


BACK TO NEUTRINO ASTRONOMY

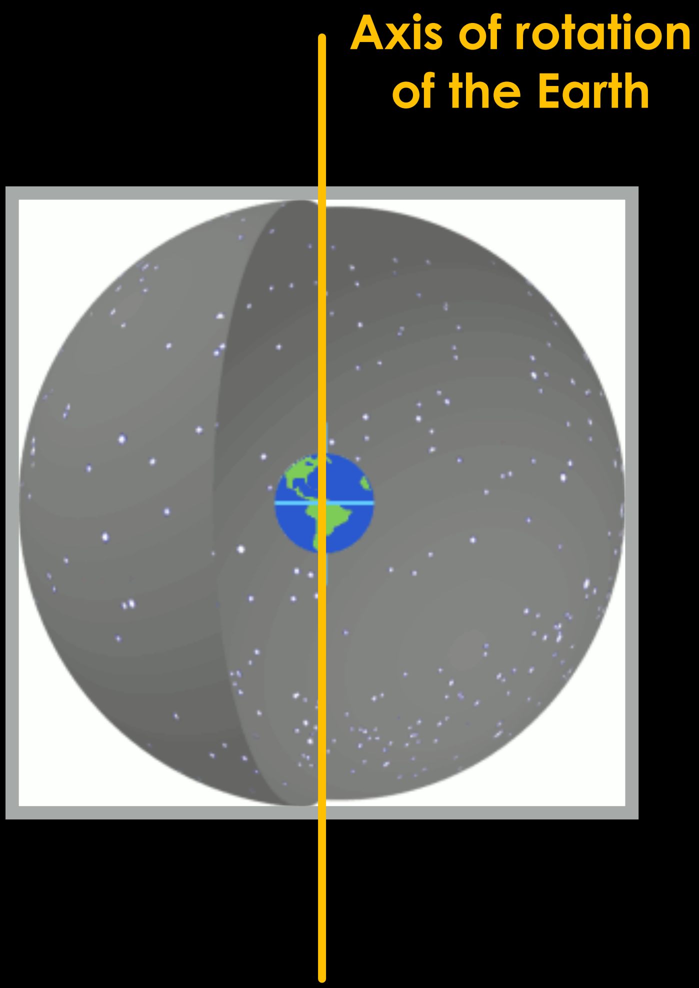
THE PRINCIPLES OF NEUTRINO ASTRONOMY

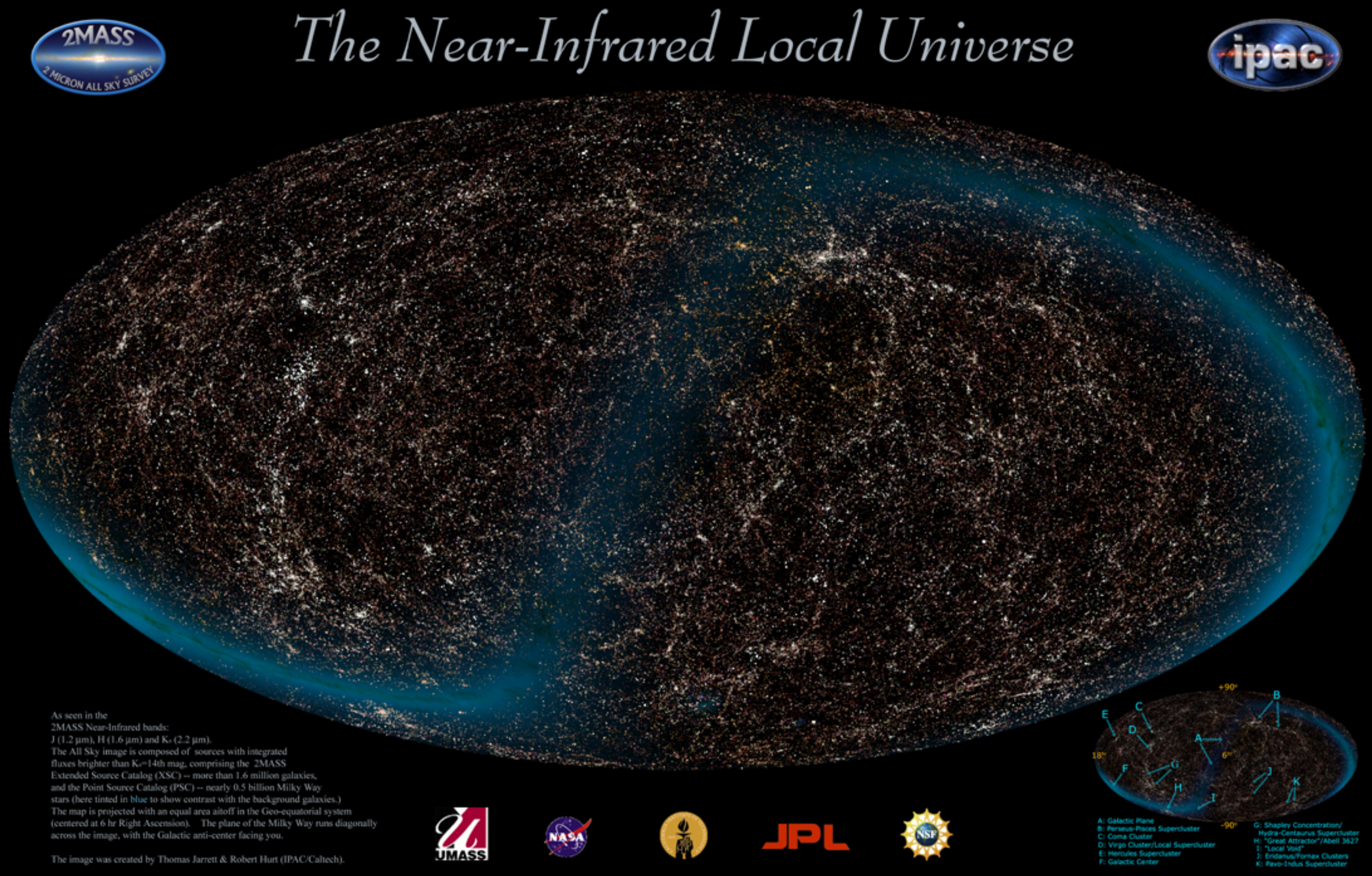
1. Very High-Energy neutrinos come from *cosmic accelerators*

2. **Neutrinos travel in a straight line from their source**

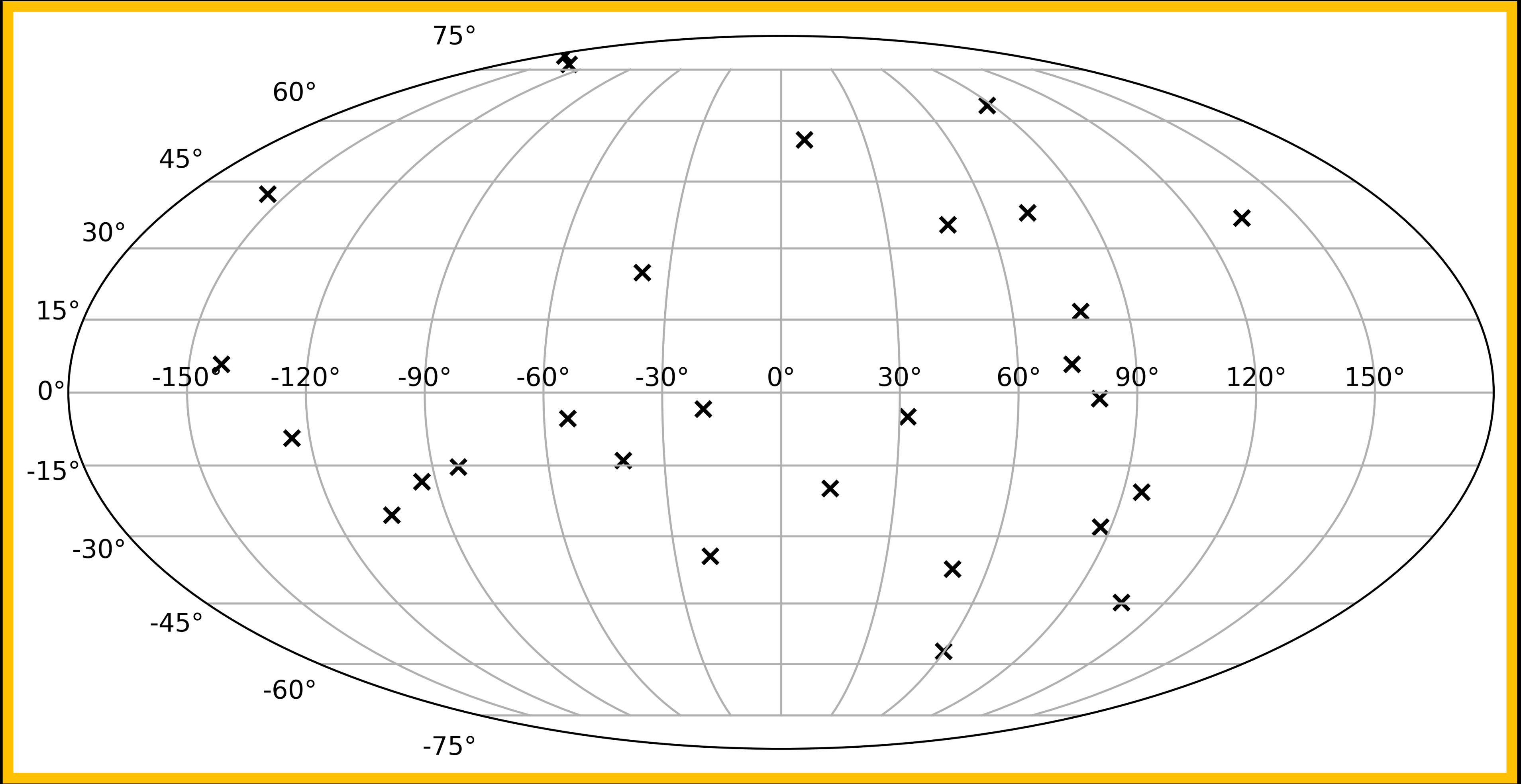


AN INTRODUCTION TO SKYMAPS

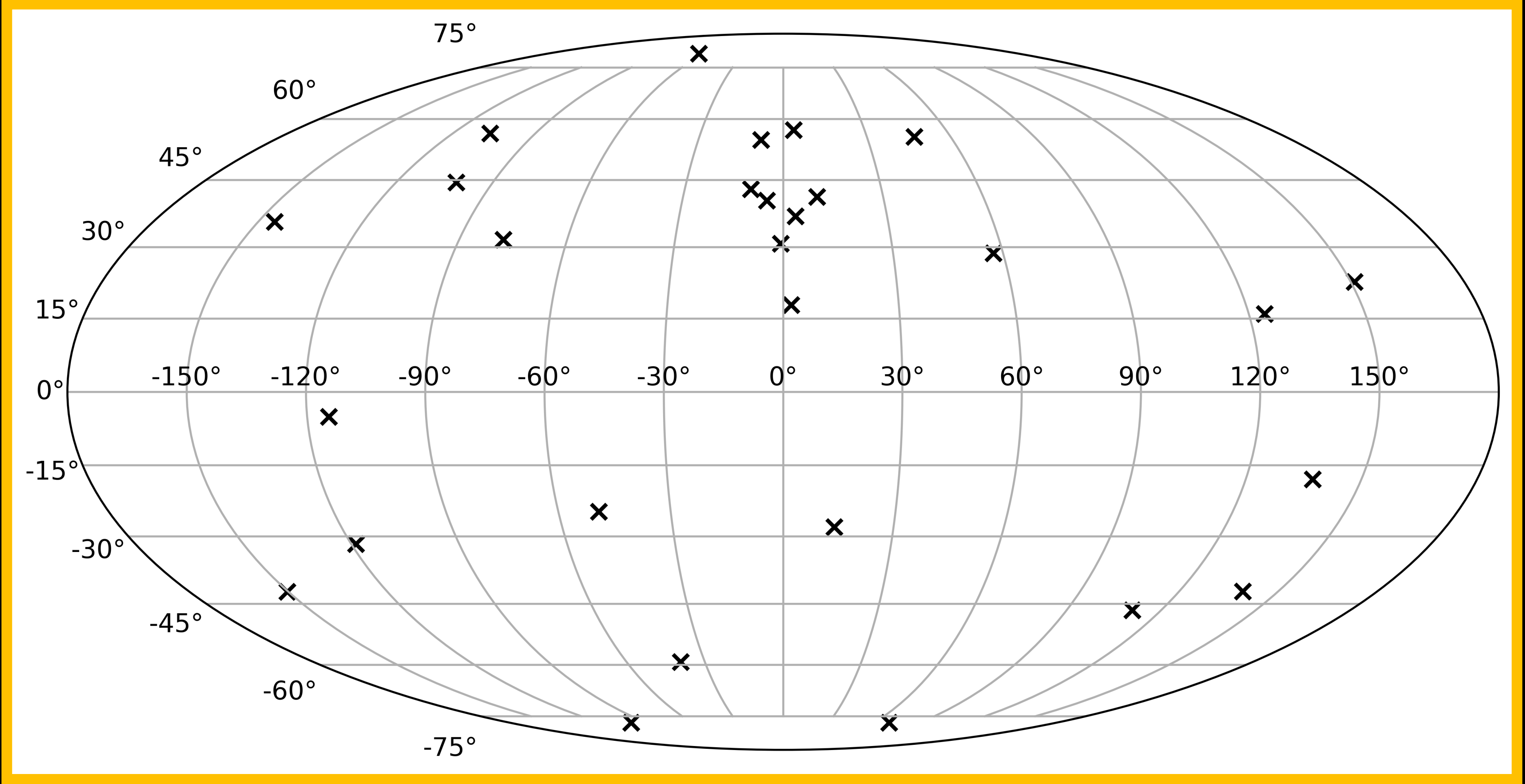




SKYMAP OF 28 EVENTS – RANDOMISED BACKGROUND EVENTS

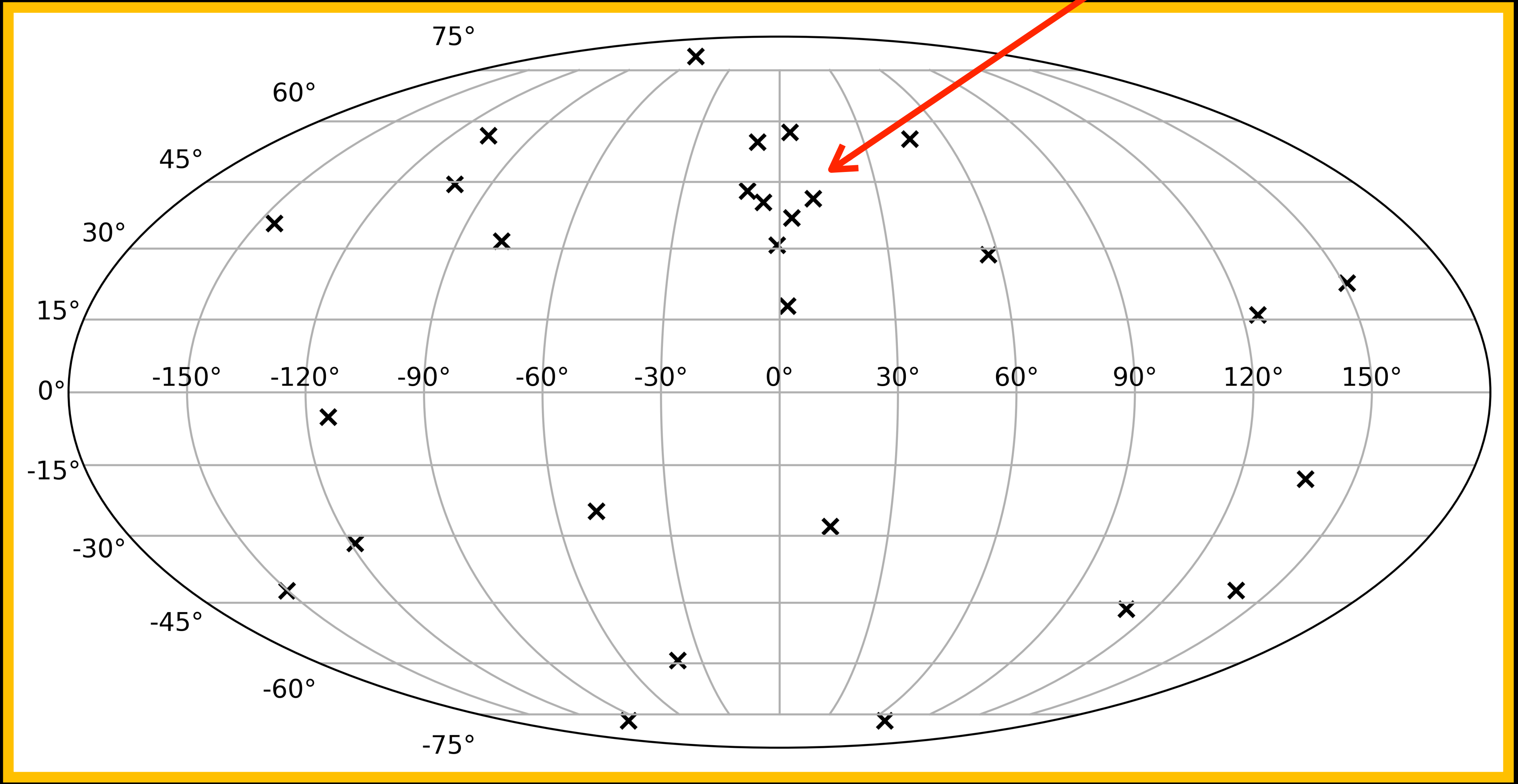


SKYMAP OF 28 EVENTS – WITH A SIMULATED SOURCE

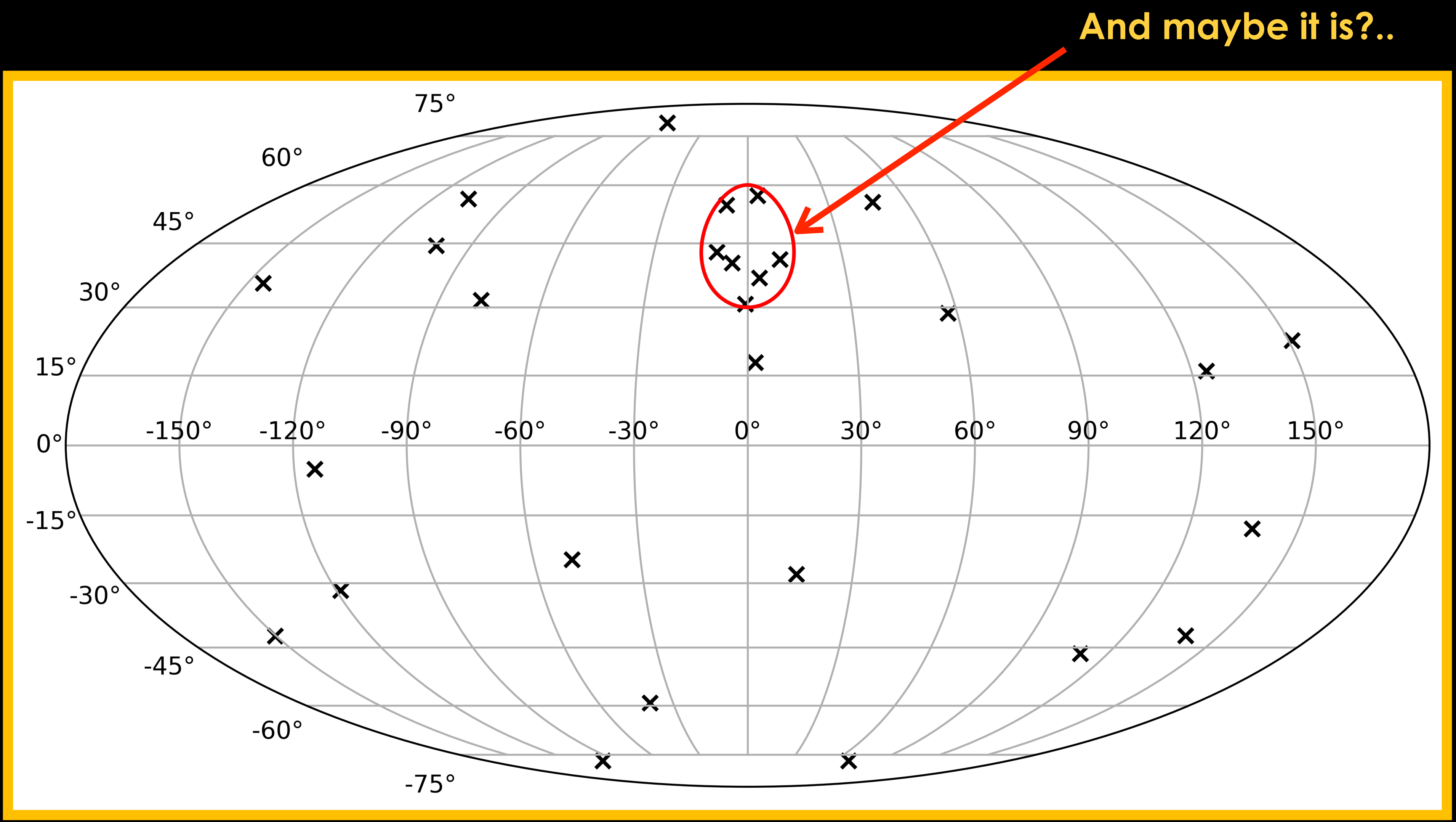


SKYMAP OF 28 EVENTS – WITH A SIMULATED SOURCE

looks like a cluster…

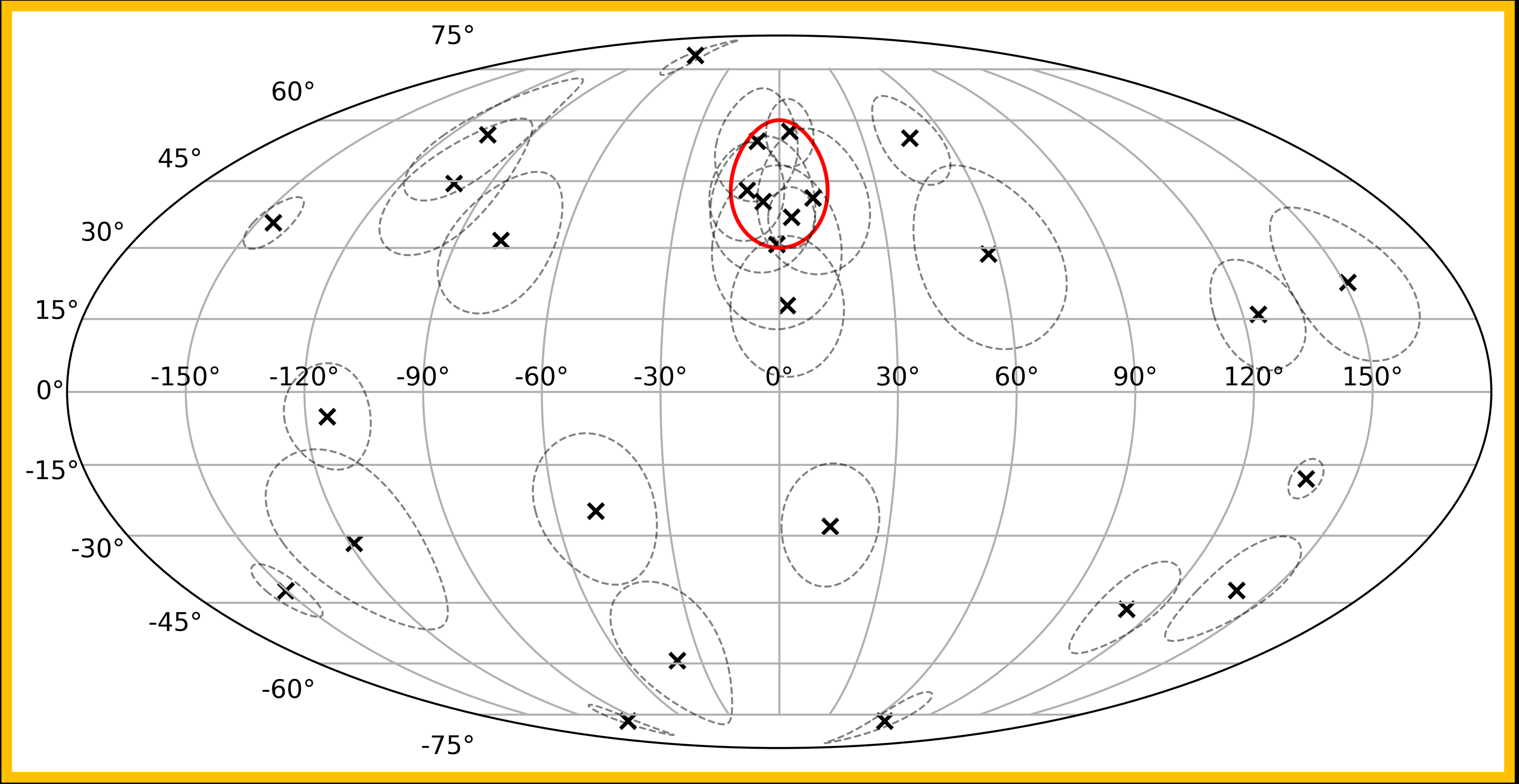


SKYMAP OF 28 EVENTS – WITH A SIMULATED SOURCE



SKYMAP OF 28 EVENTS – WITH A SIMULATED SOURCE

Or were we just lucky to find 7 events inside this particular circle?

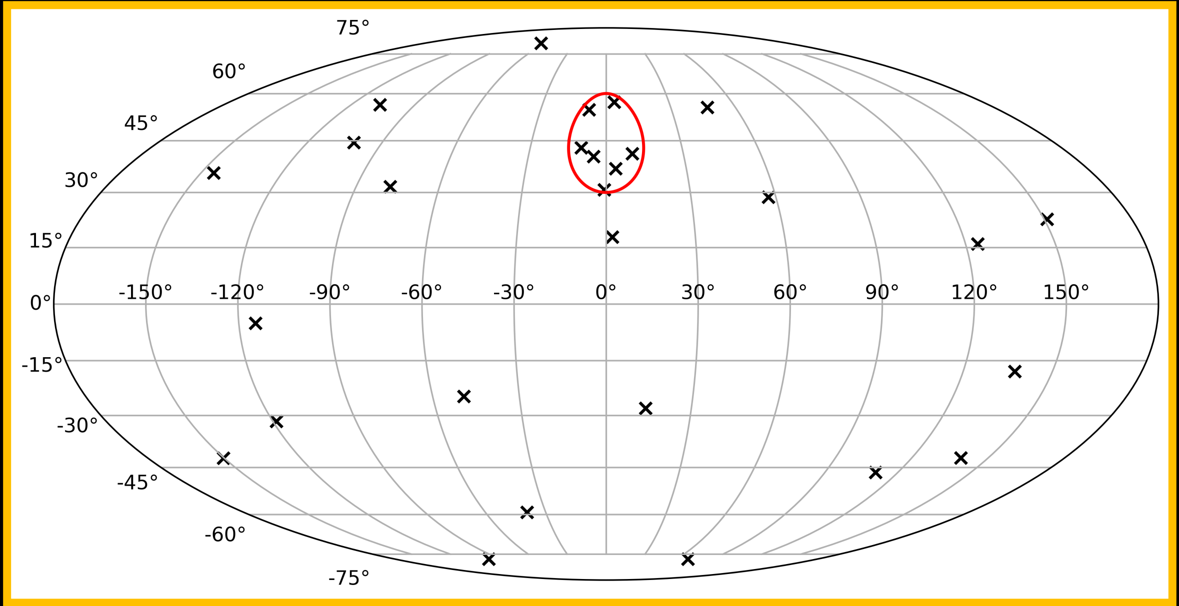


ACTIVITY!

- Is this a significant signal?
- We want to evaluate the likelihood that this clustering comes from a single source in the sky

In your group:

- Can you think of a method we could use to calculate a significance?



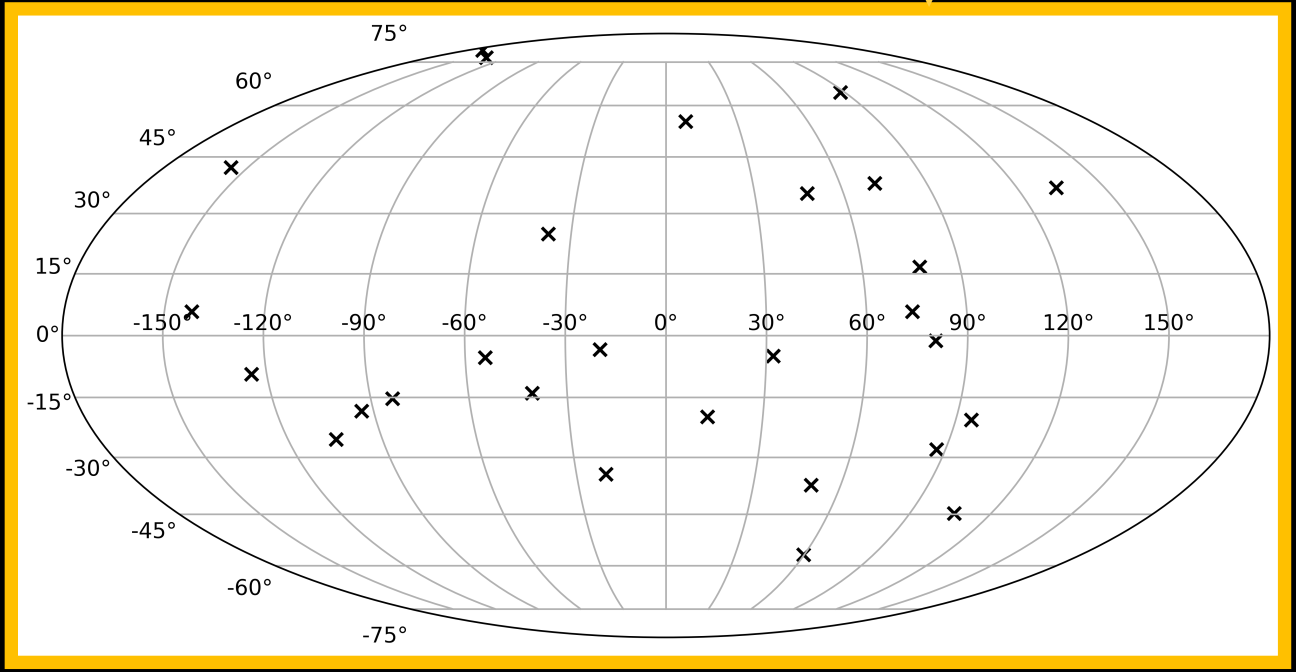
THE P-VALUE SIGNIFICANCE

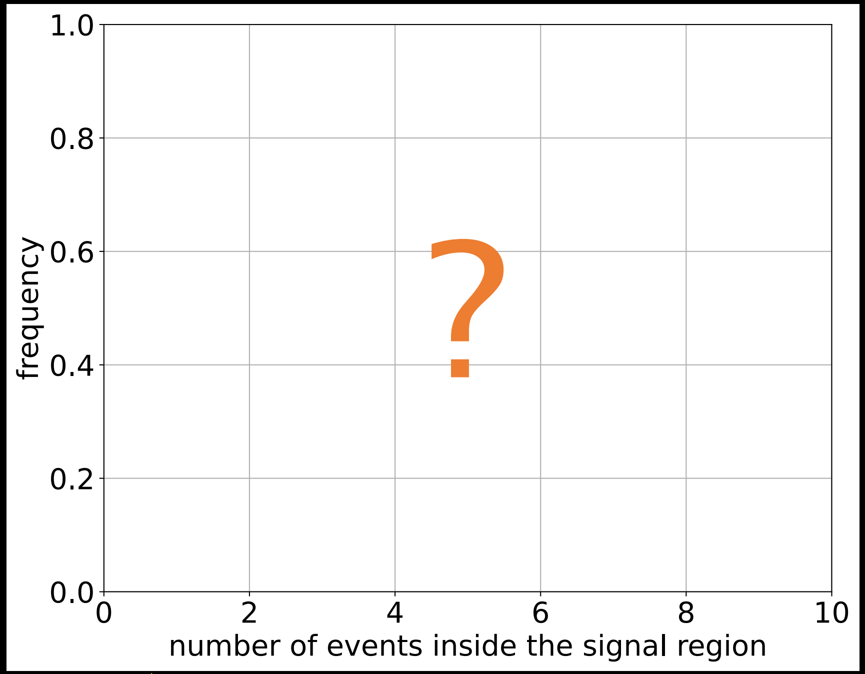
$$\text{P-value} = \frac{\text{\# of randomized « maps » with at least as many events as our data inside a circle}}{\text{total \# of randomized maps}}$$

One needs to compare the distribution of the signal to a large number of randomized maps

ACTIVITY!

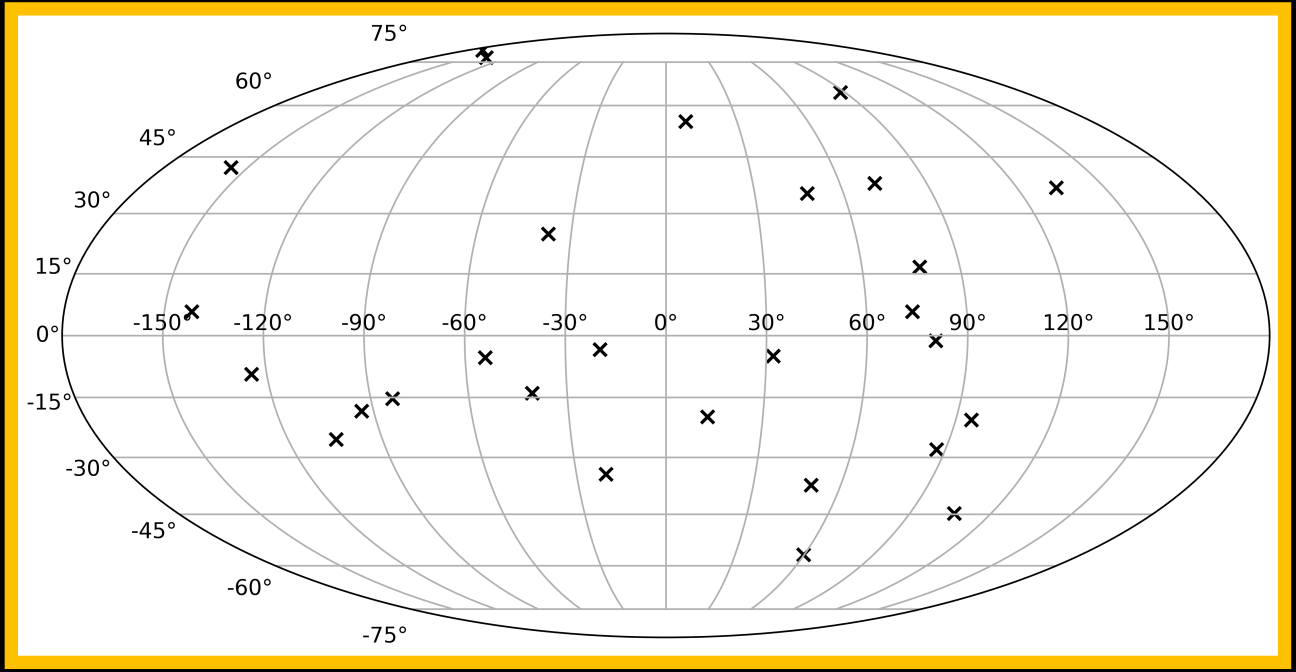
We will make multiple random maps like this…

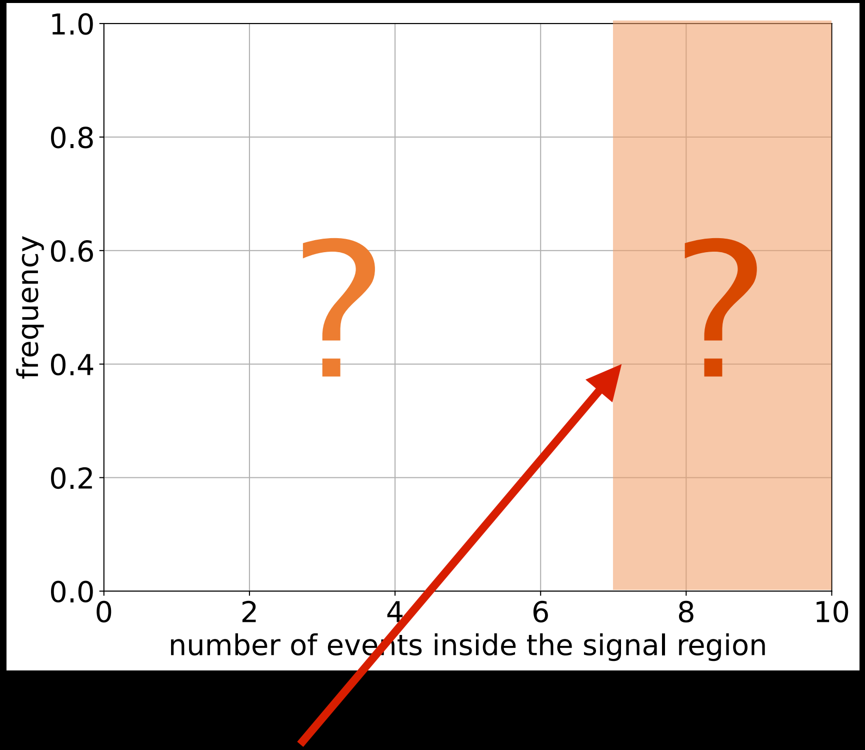




…and count how often we get 1, 2, 3, etc. events inside our circle.

ACTIVITY!





Eventually, we want to find how often we get **7 events or more** to conclude whether our map has a significant association with a neutrino source!

ACTIVITY!

Please follow this link to run the exercise in Python*:

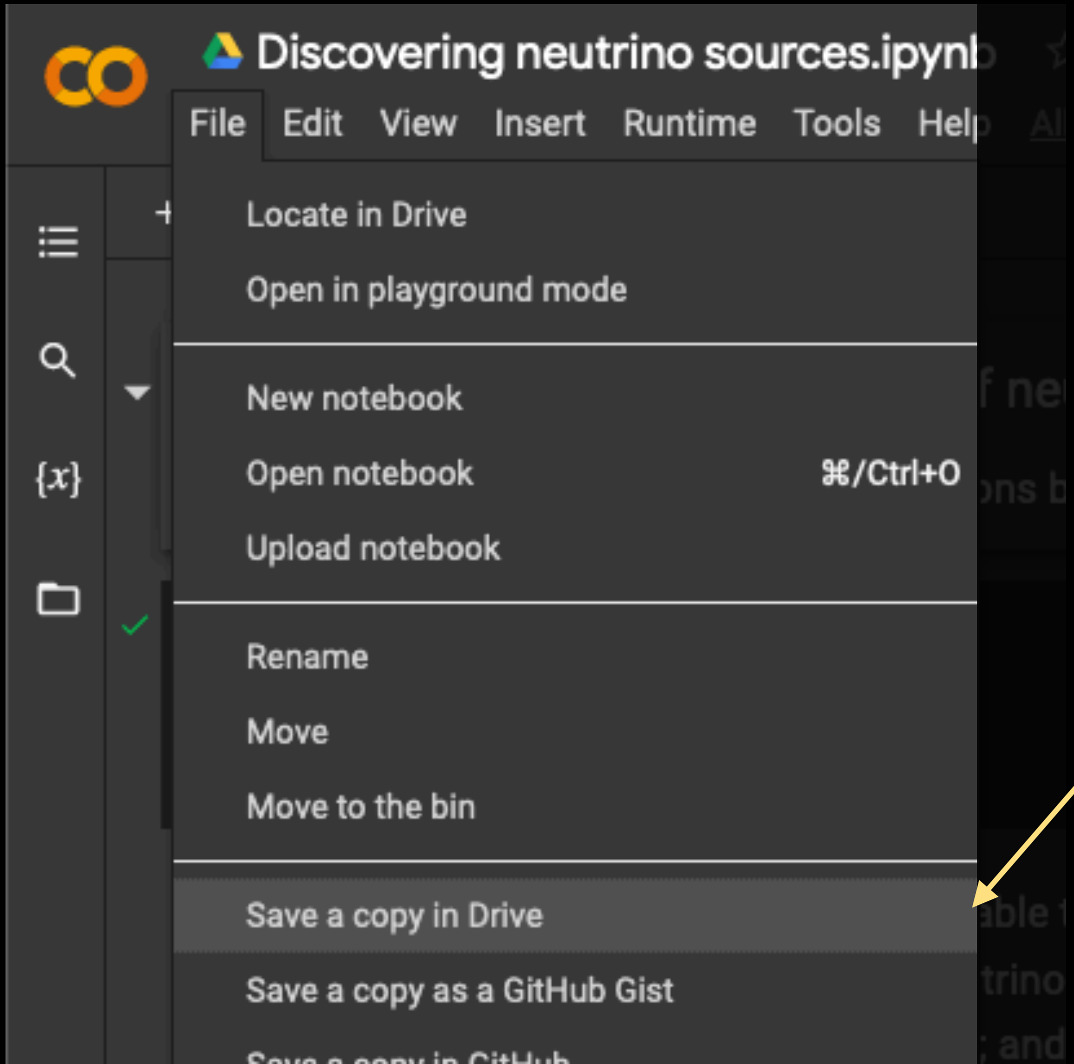
http://bit.ly/IceCubeSources

*PART 1: What does it mean to be random?

Question: What significance do you find?

IMPORTANT REMINDER

Please create your own copy of the notebook to make any edits:



click here!

WHAT CONSTITUTES A DISCOVERY?

How many events must come from the same region of the sky ”discover” a source?

WHAT CONSTITUTES A DISCOVERY?

How many events must come from the same region of the sky ”discover” a source?

Answer: The number of events in the signal region must have **less than 0.000000006% (or 6 x 10^{-7})** chance of coming from randomized background

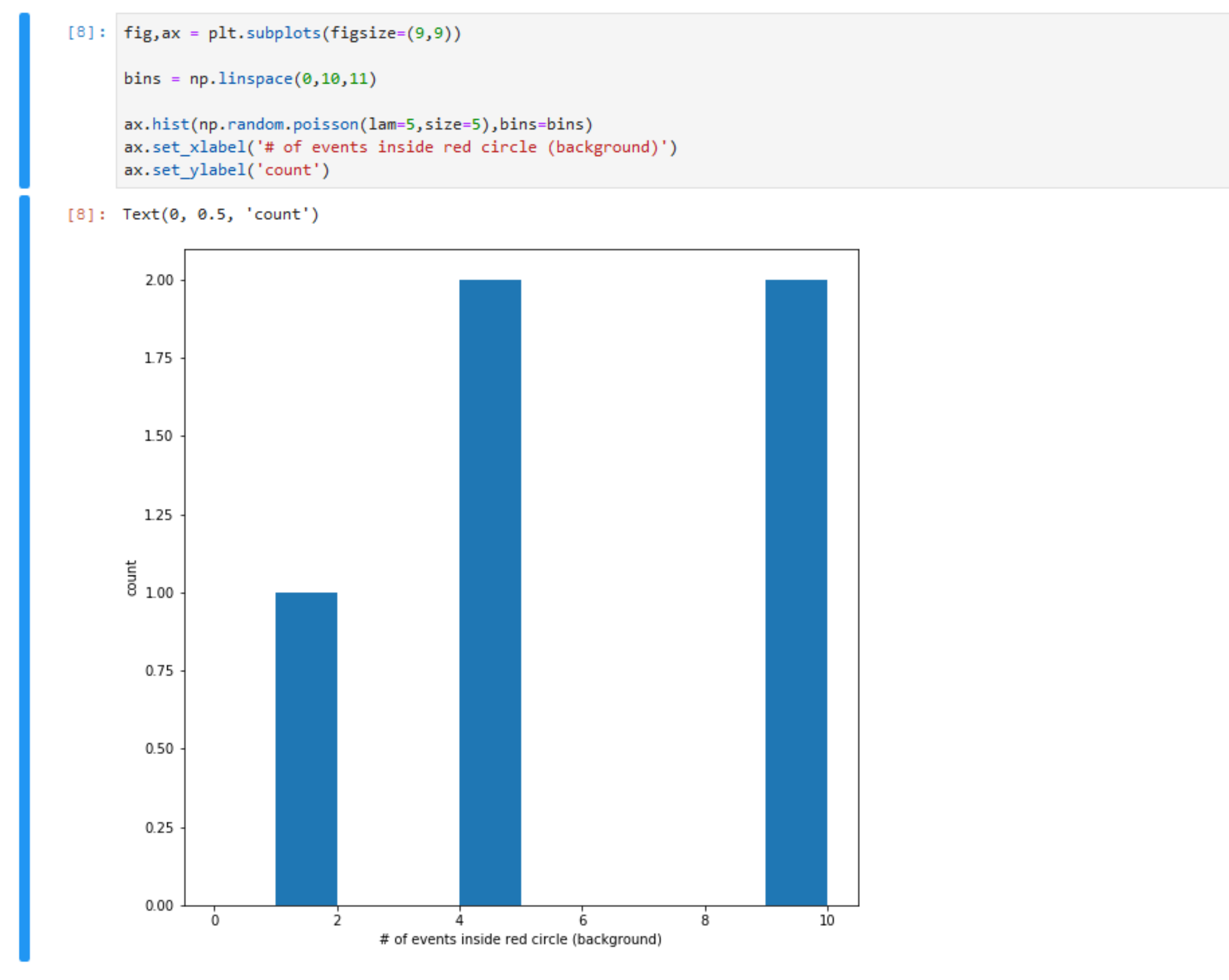
That is, only **one out of 1.7 million** randomized maps has more (or the same number of) events in the red circle than your data

THE POISSONIAN STATISTICS

Say that we expect **on average** 5 background events to occur within our patch of sky.

How many times are we going to see X events?

Here: 5 scrambles



THE POISSONIAN STATISTICS

Say that we expect **on average** 5 background events to occur within our patch of sky.

How many times are we going to see X events?

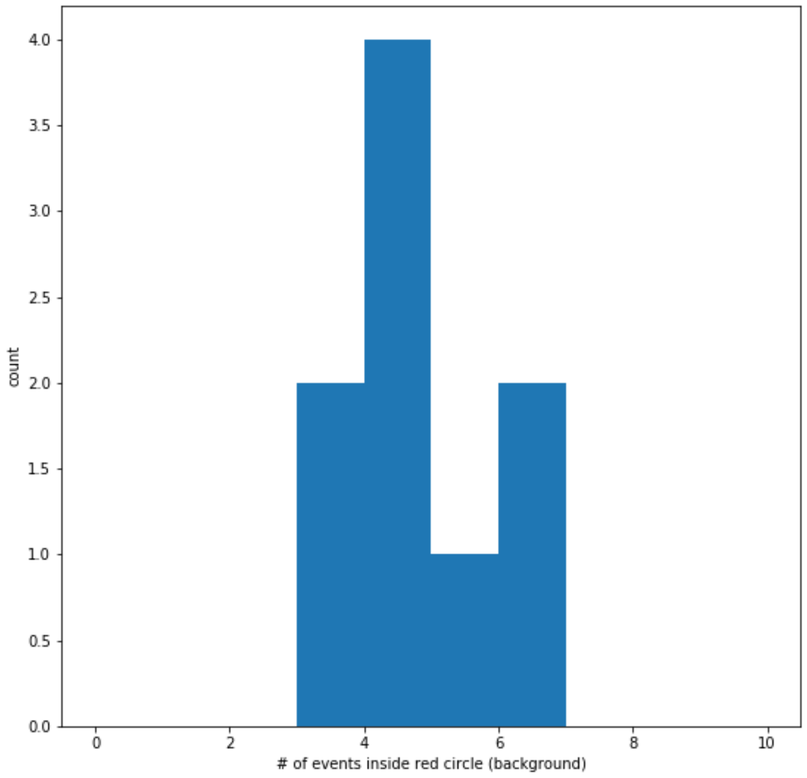
Here: 10 scrambles

```
[9]: fig,ax = plt.subplots(figsize=(9,9))

     bins = np.linspace(0,10,11)

     ax.hist(np.random.poisson(lam=5,size=10),bins=bins)
     ax.set_xlabel('# of events inside red circle (background)')
     ax.set_ylabel('count')
```

```
[9]: Text(0, 0.5, 'count')
```



THE POISSONIAN STATISTICS

Say that we expect **on average** 5 background events to occur within our patch of sky.

How many times are we going to see X events?

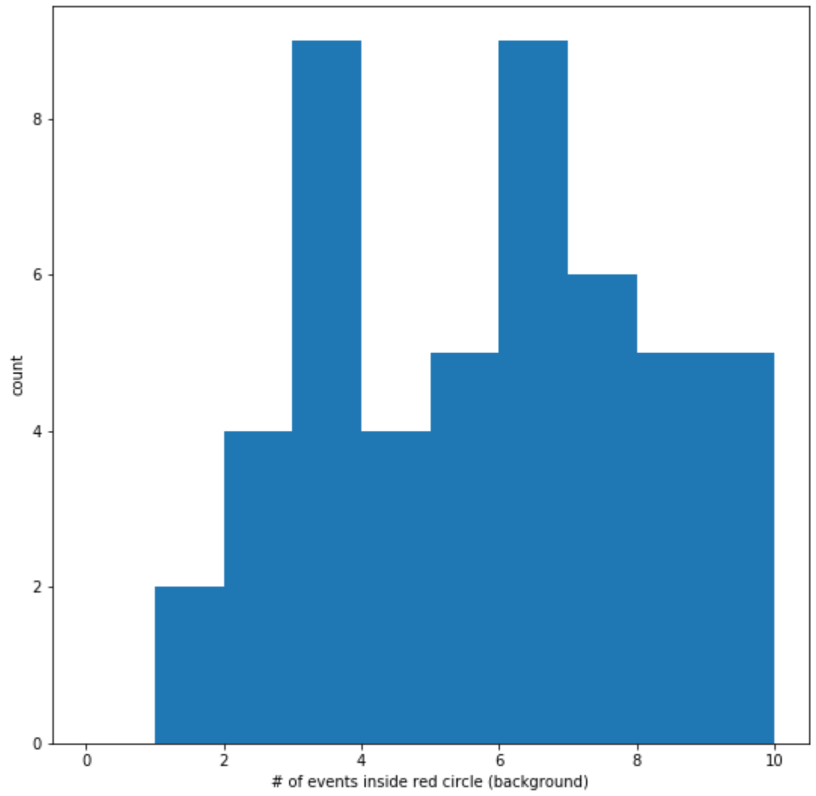
Here: 50 scrambles

```
[10]: fig,ax = plt.subplots(figsize=(9,9))

      bins = np.linspace(0,10,11)

      ax.hist(np.random.poisson(lam=5,size=50),bins=bins)
      ax.set_xlabel('# of events inside red circle (background)')
      ax.set_ylabel('count')

[10]: Text(0, 0.5, 'count')
```



THE POISSONIAN STATISTICS

Say that we expect **on average** 5 background events to occur within our patch of sky.

How many times are we going to see X events?

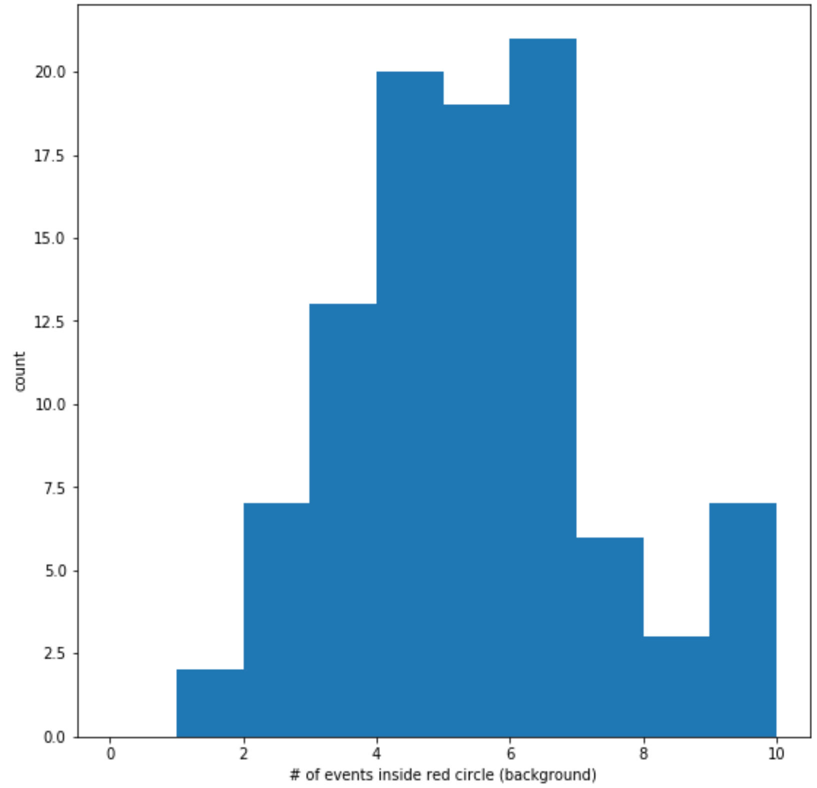
Here: 100 scrambles

```
[13]: fig,ax = plt.subplots(figsize=(9,9))

      bins = np.linspace(0,10,11)

      ax.hist(np.random.poisson(lam=5,size=100),bins=bins)
      ax.set_xlabel('# of events inside red circle (background)')
      ax.set_ylabel('count')
```

```
[13]: Text(0, 0.5, 'count')
```



THE POISSONIAN STATISTICS

Say that we expect **on average** 5 background events to occur within our patch of sky.

How many times are we going to see X events?

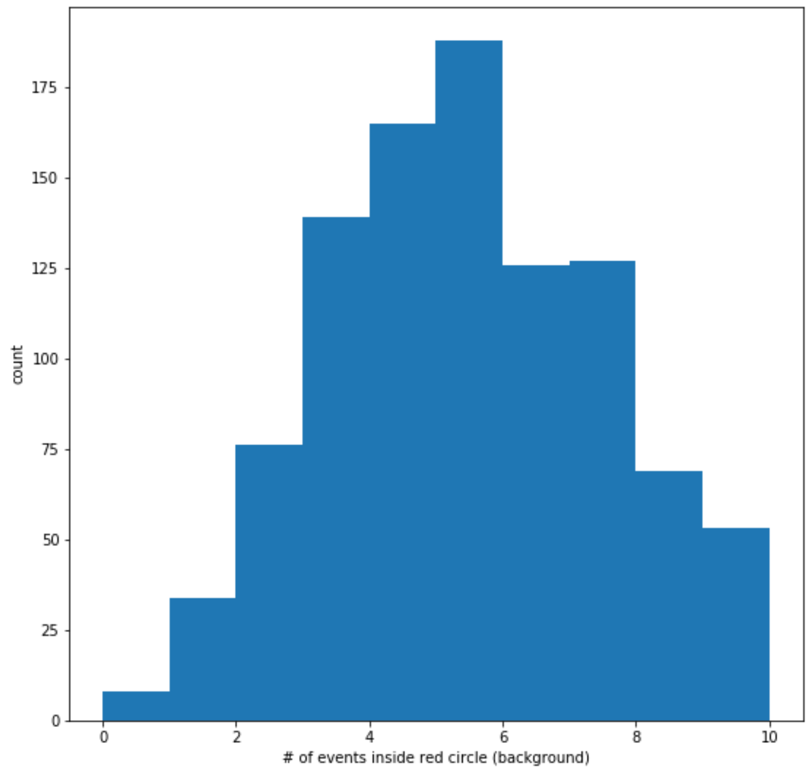
Here: 1000 scrambles

```
[14]: fig,ax = plt.subplots(figsize=(9,9))

      bins = np.linspace(0,10,11)

      ax.hist(np.random.poisson(lam=5,size=1000),bins=bins)
      ax.set_xlabel('# of events inside red circle (background)')
      ax.set_ylabel('count')
```

```
[14]: Text(0, 0.5, 'count')
```



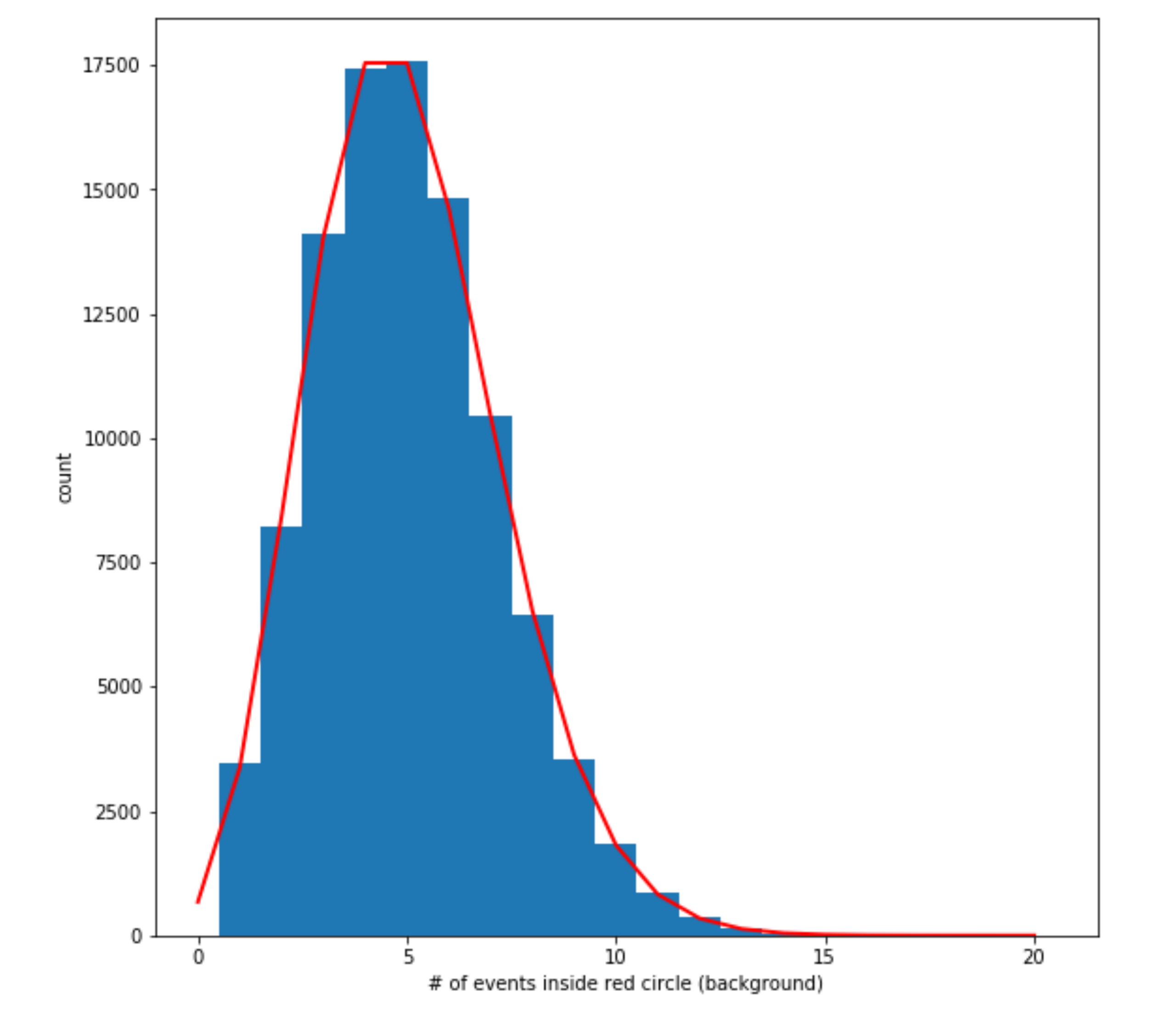
THE POISSONIAN STATISTICS

After a loooot of trials, a clear shape appears… and that shape follows the equation:

$$P(n) = \frac{\lambda^n}{n!} e^{-\lambda}$$

Probability of getting n background events in your red circle

Expected number of events



QUANTIFYING SIGNIFICANCE

- You can save yourself a lot of computation time by guessing how your background behaves. This behaviour is characterized by a **probability distribution function (PDF)**
- For a purely random background, the number of events in a region is determined by a **Poisson distribution:**

$$\mathrm{P(n)} = \frac{\lambda^n}{n!} e^{-\lambda}$$

Expected number of events

Probability of getting n background events in your red circle

ACTIVITY!

- What is the expected number of background events for a signal region of ~0.0685π rad^2 (the area of your circle)?

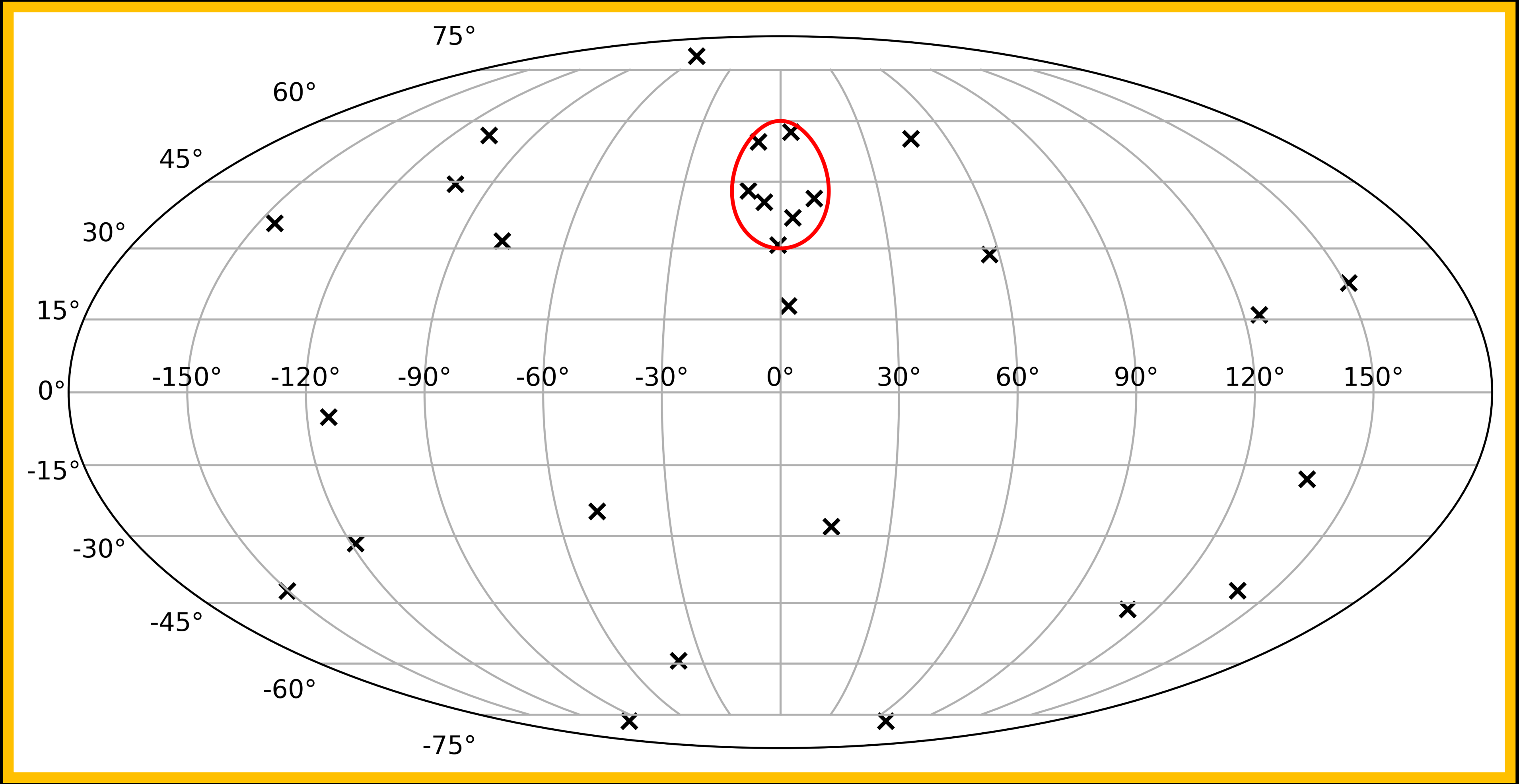
ACTIVITY!

- What is the expected number of background events for a signal region of ~0.0685π rad² (the area of your circle)?

Answer = 28 events $\cdot\, 0.0685\pi / 4\pi \approx 0.48$

(It's OK to *expect* non-integer values!)

WOULD THIS BE A SIGNIFICANT EVENT?



WOULD THIS BE A SIGNIFICANT EVENT?

Going back to our Python exercise*:

http://bit.ly/IceCubeSources

*PART 2: Poisson statistics: Quantifying how lucky we need to be

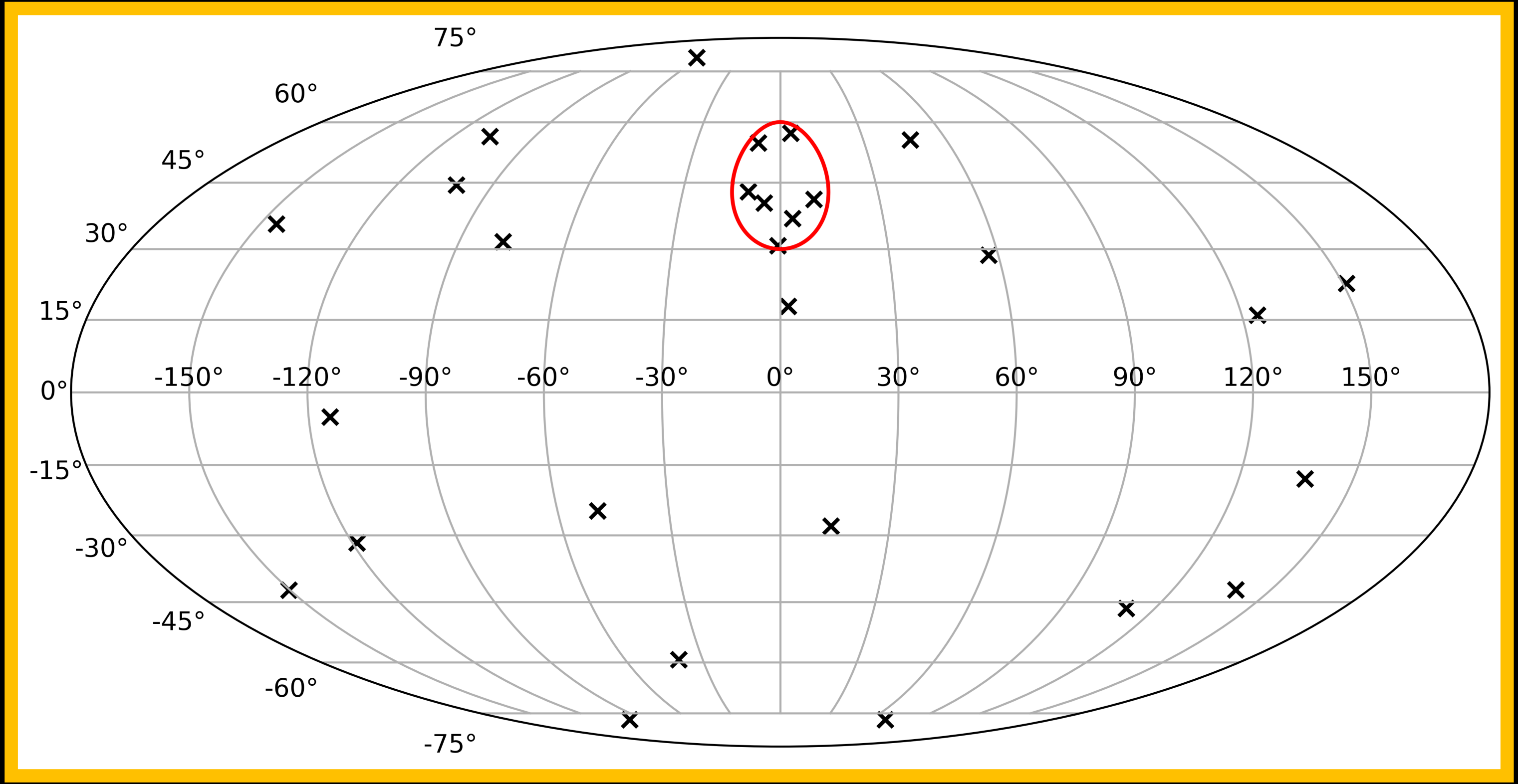
WOULD THIS BE A SIGNIFICANT EVENT?

Not quite!

Probability of getting 7 events or more by pure luck:

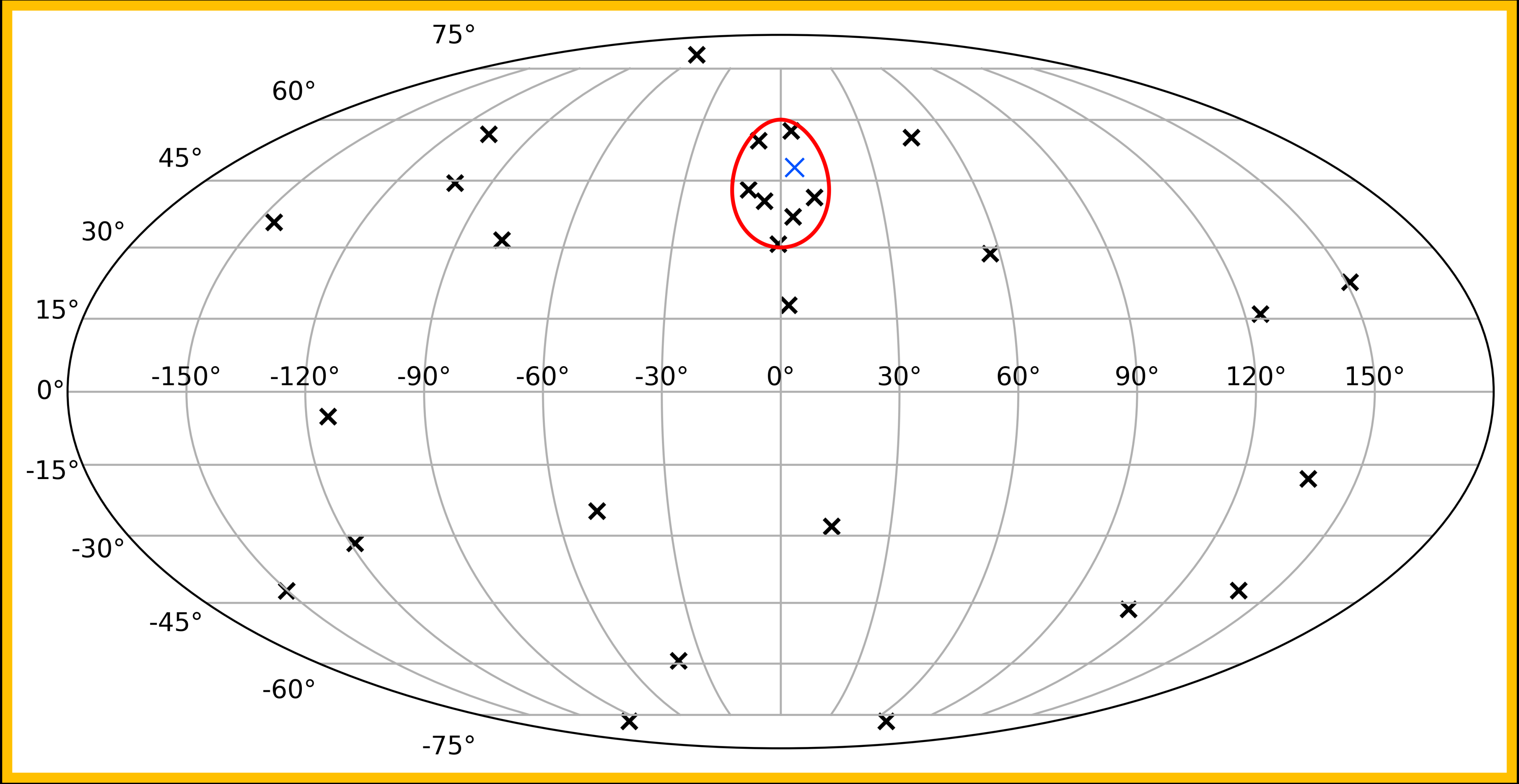
P ~ 7.64×10^{-7}

Small, but still greater than 6×10^{-7}



…We still cannot rule out a background at our desired confidence :(

WHAT IF ANOTHER EVENT ENDS UP IN THE CIRCLE?



YOU KNOW WHAT TO DO!

http://bit.ly/IceCubeSources

WHAT IF ANOTHER EVENT ENDS UP IN THE CIRCLE?

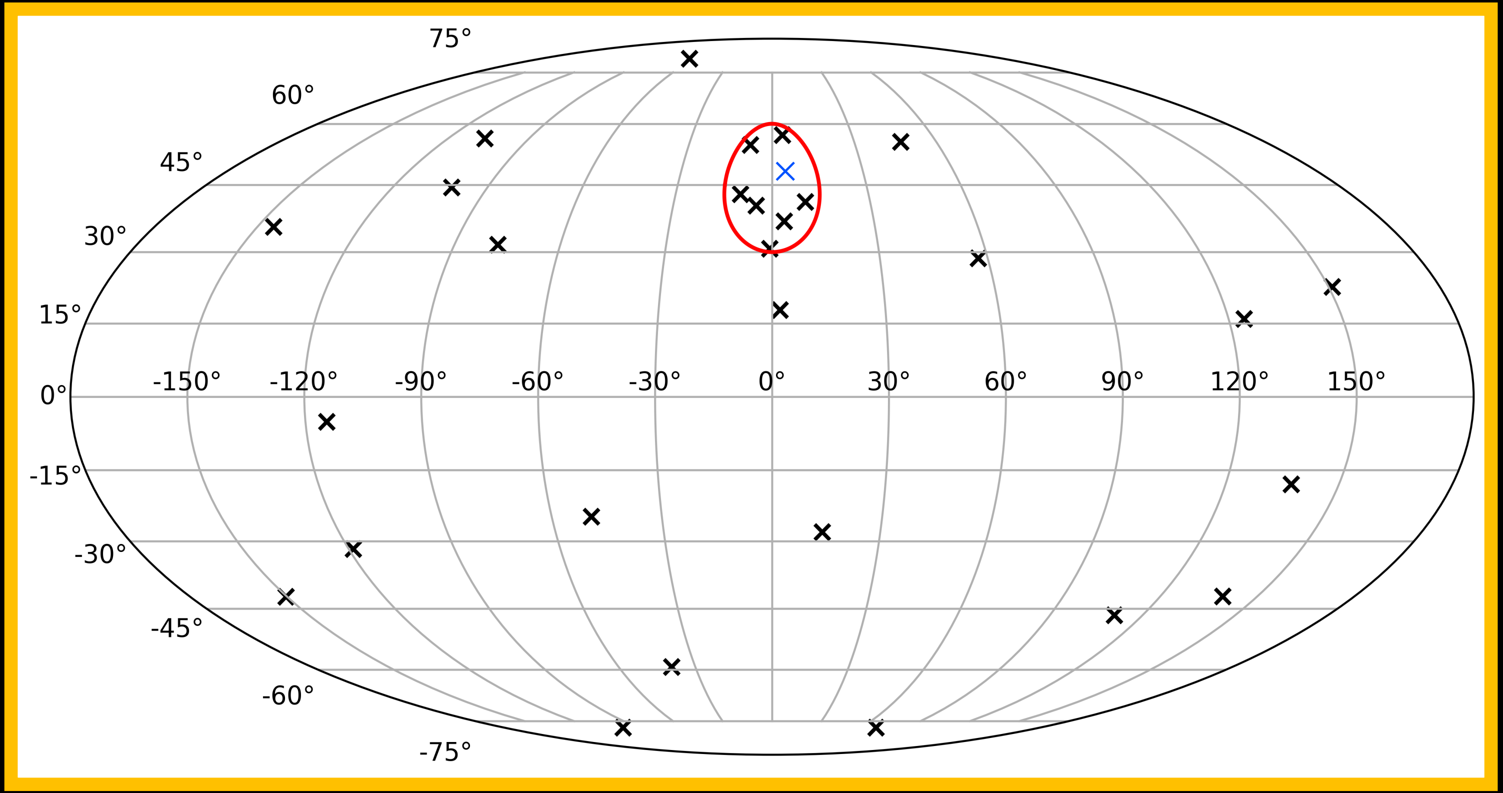
First, we need to update our background expectation:

We now expect 29 x 0.0685 / 4 ≈ 0.496 events per circle

Plug in numbers…

P ~ 5.9x10^{-8}

Now we have a discovery!



Every single neutrino matters.

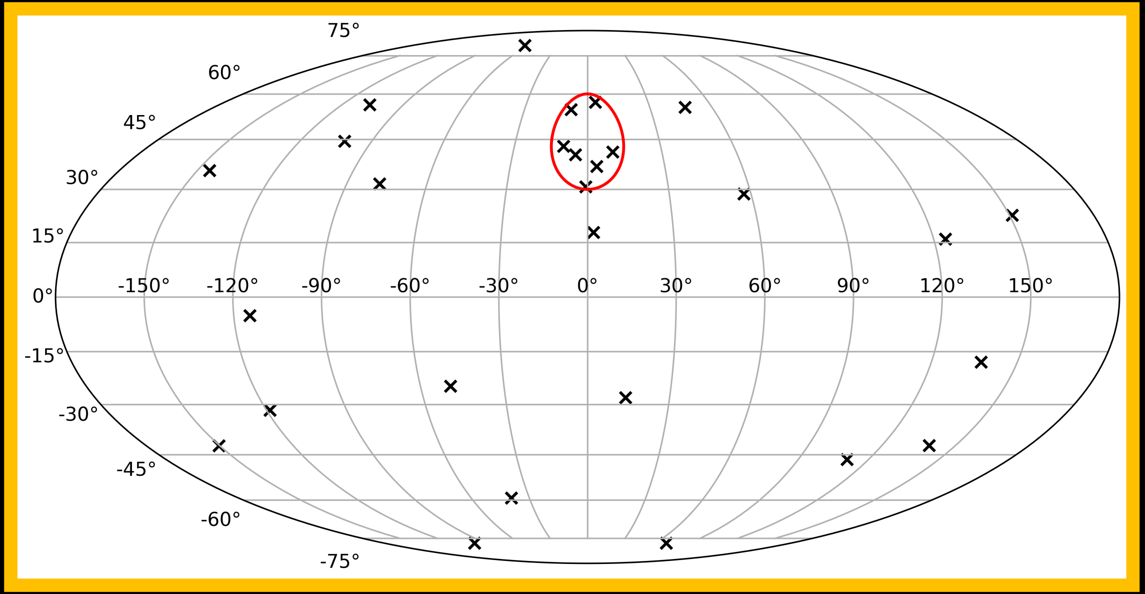
MAKING THINGS A LITTLE MORE REALISTIC…

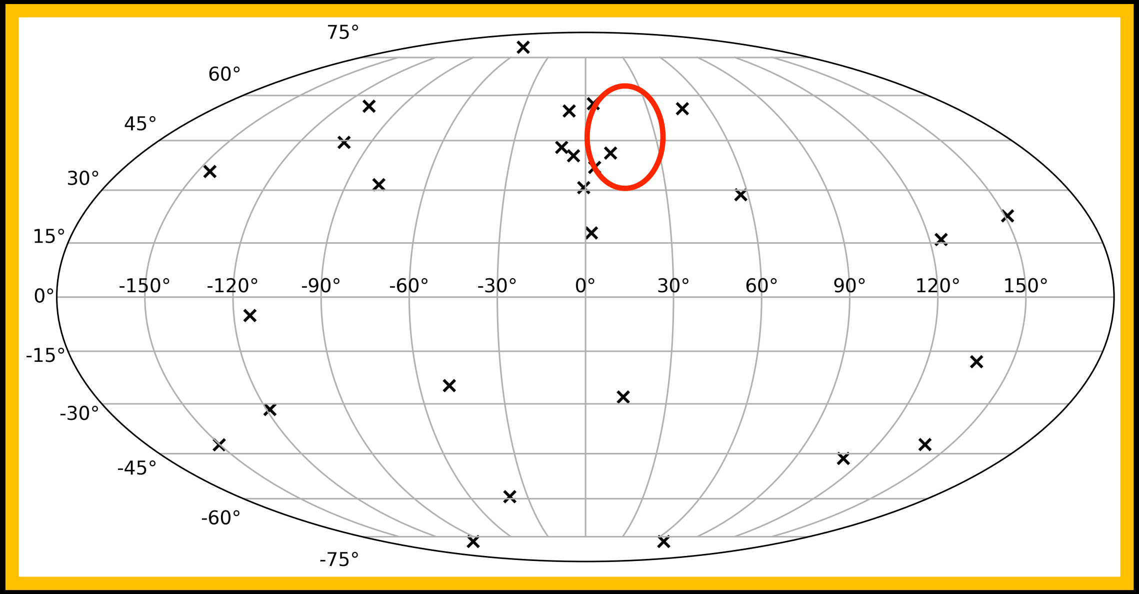
- **What are the limitations of this approach?**

- **Do you think we could use more information to get our probability?**

- **Can you think of cases where binning may cause a problem?**

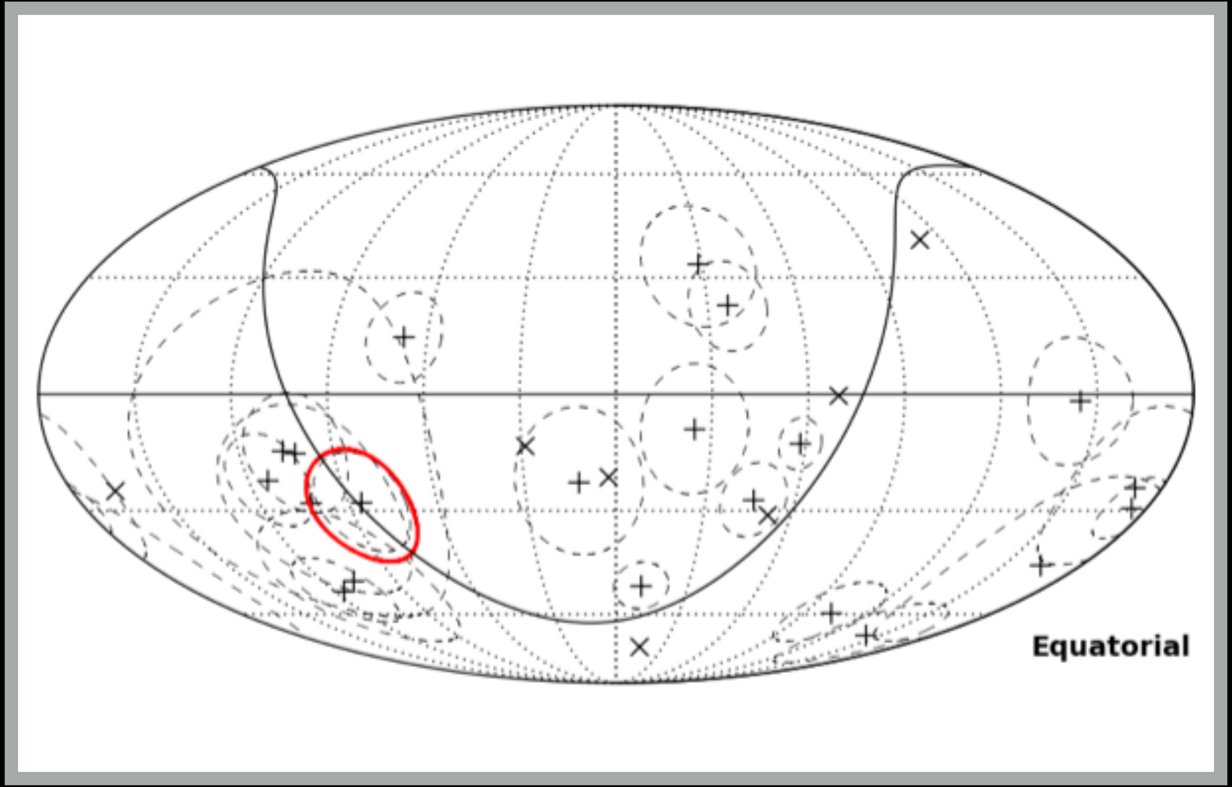
MAKING THINGS A LITTLE MORE REALISTIC…





Would I still be able to detect a source using the bin on the right?

MAKING THINGS A LITTLE MORE REALISTIC…

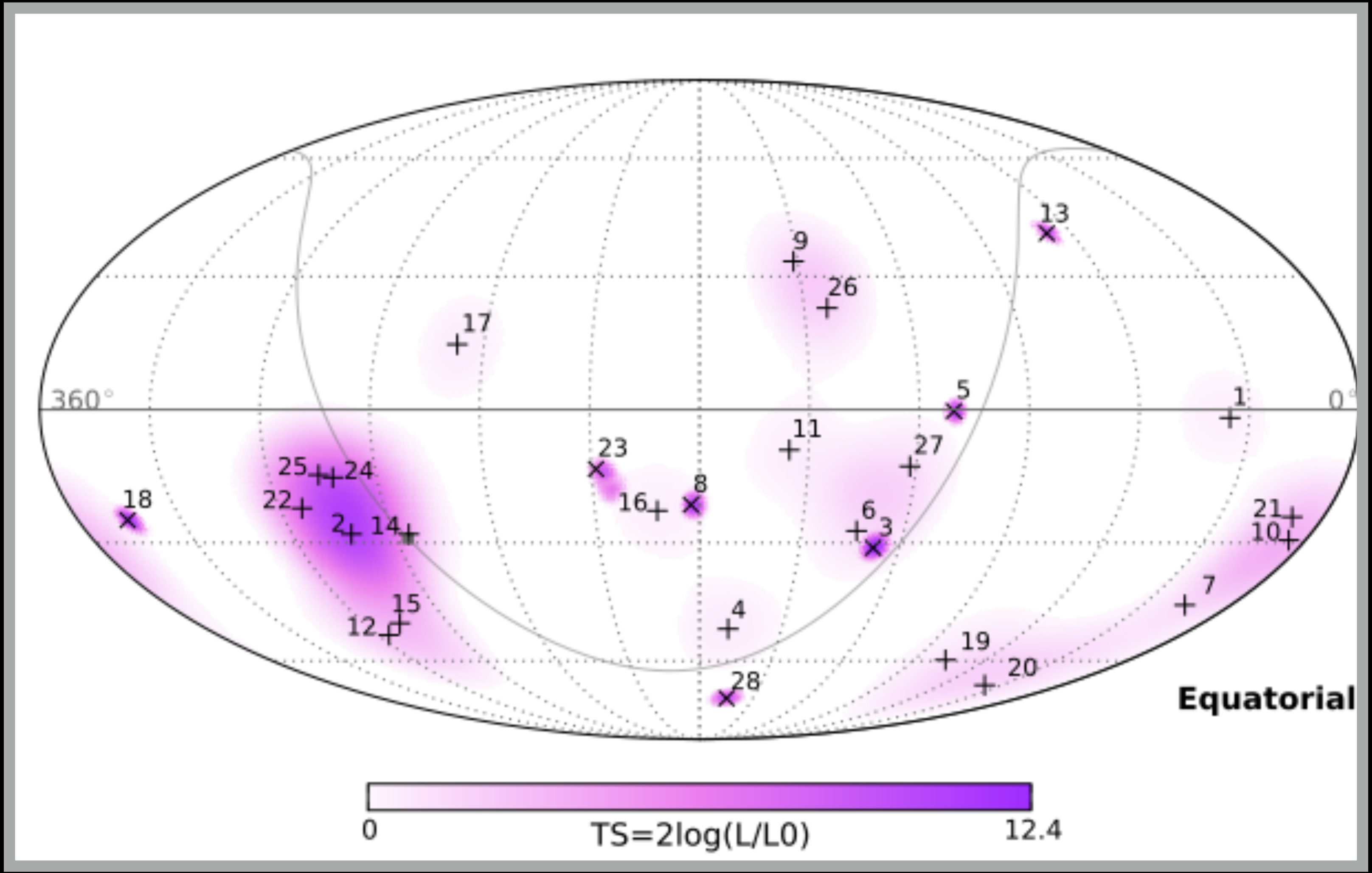


Should all events have the same contribution?

THE REAL DEAL: THE LIKELIHOOD METHOD

p-value of the cluster: 0.08

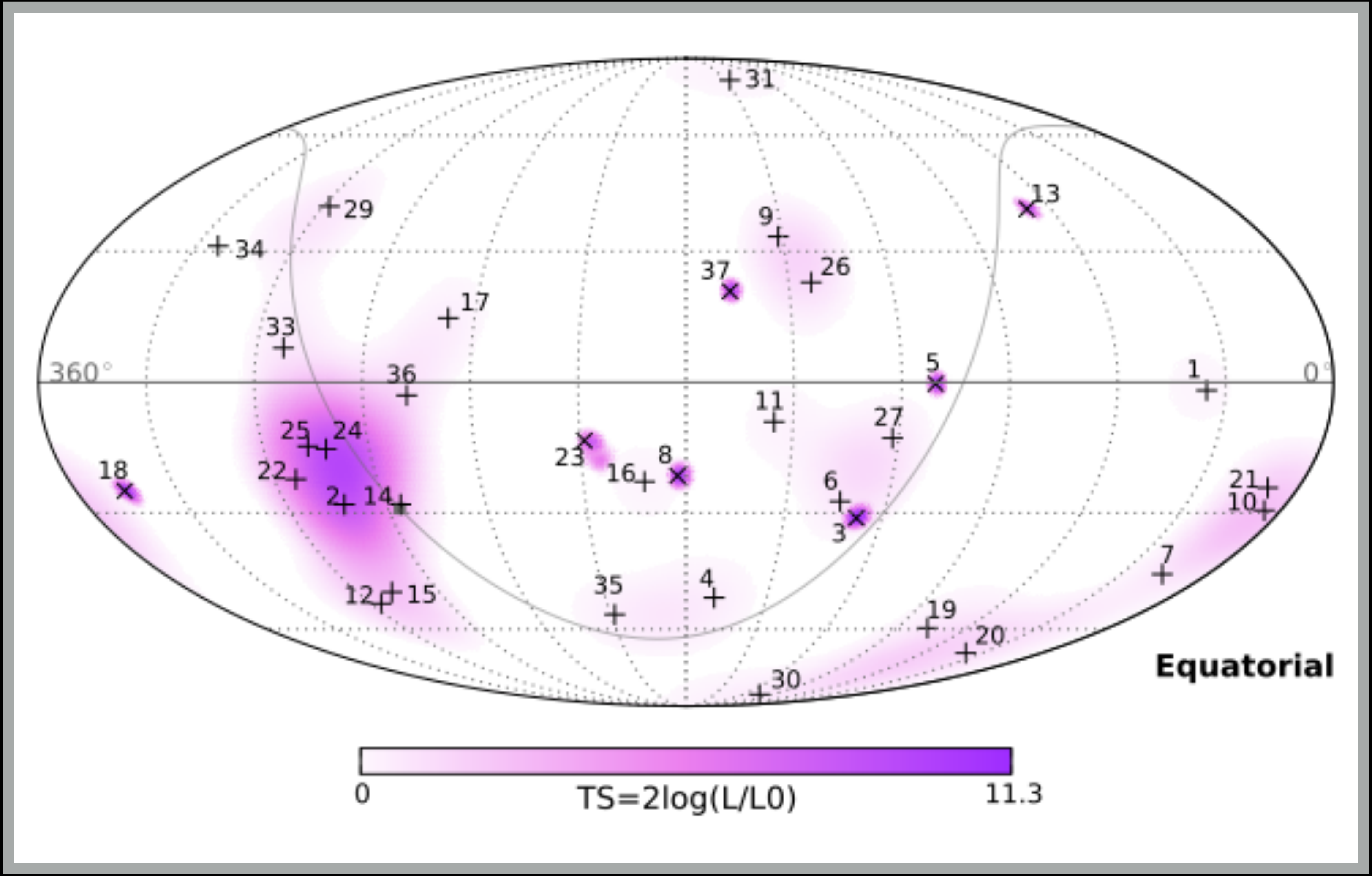
[So, only expect the same cluster or weirder 8% of the time!]



FULL ANALYSIS WITH 3 YEARS OF DATA

p-value of the cluster: 0.84

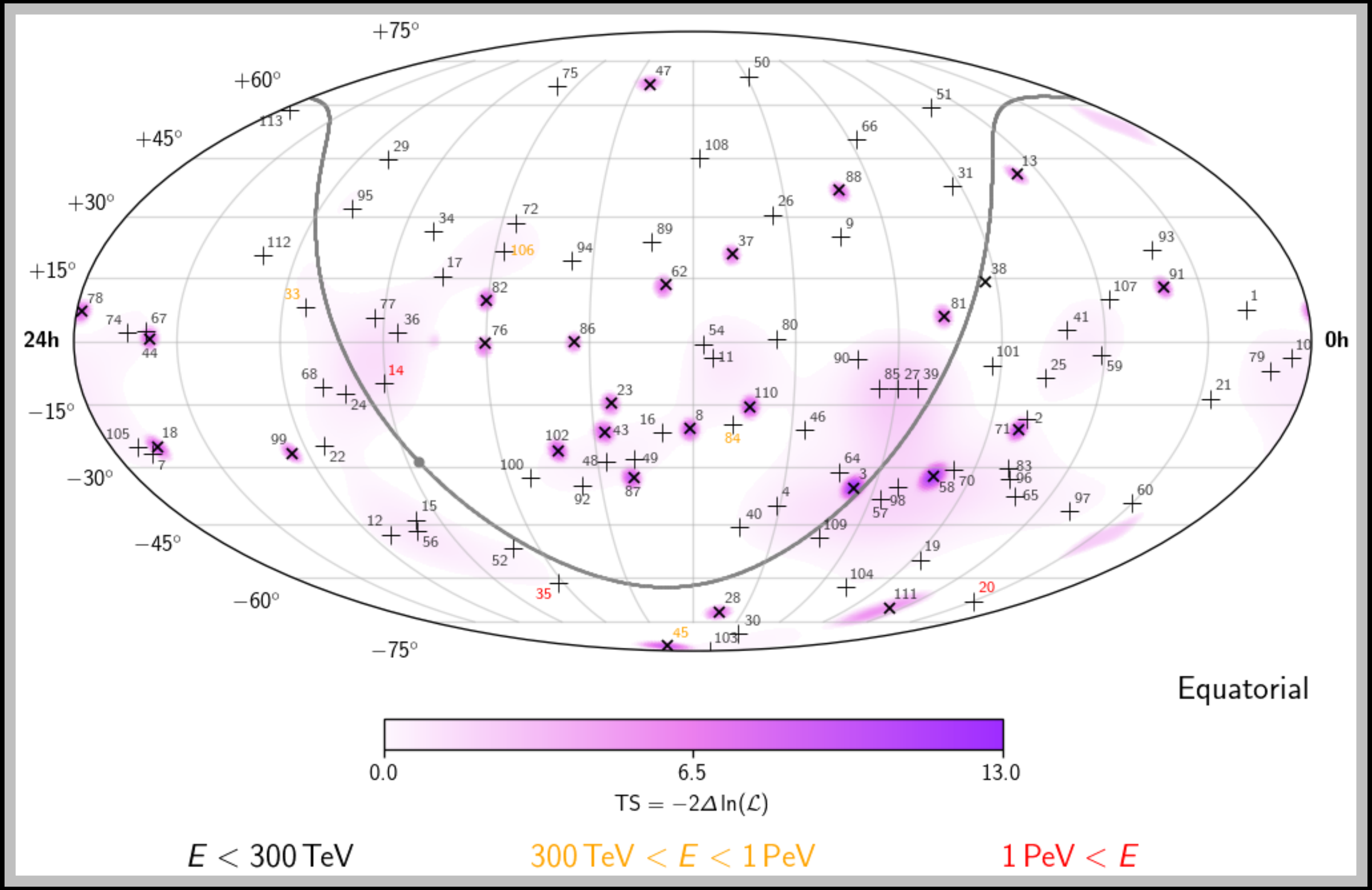
[after 3 years, we see that it's possible to get the same cluster of weirder 84% of the time…]

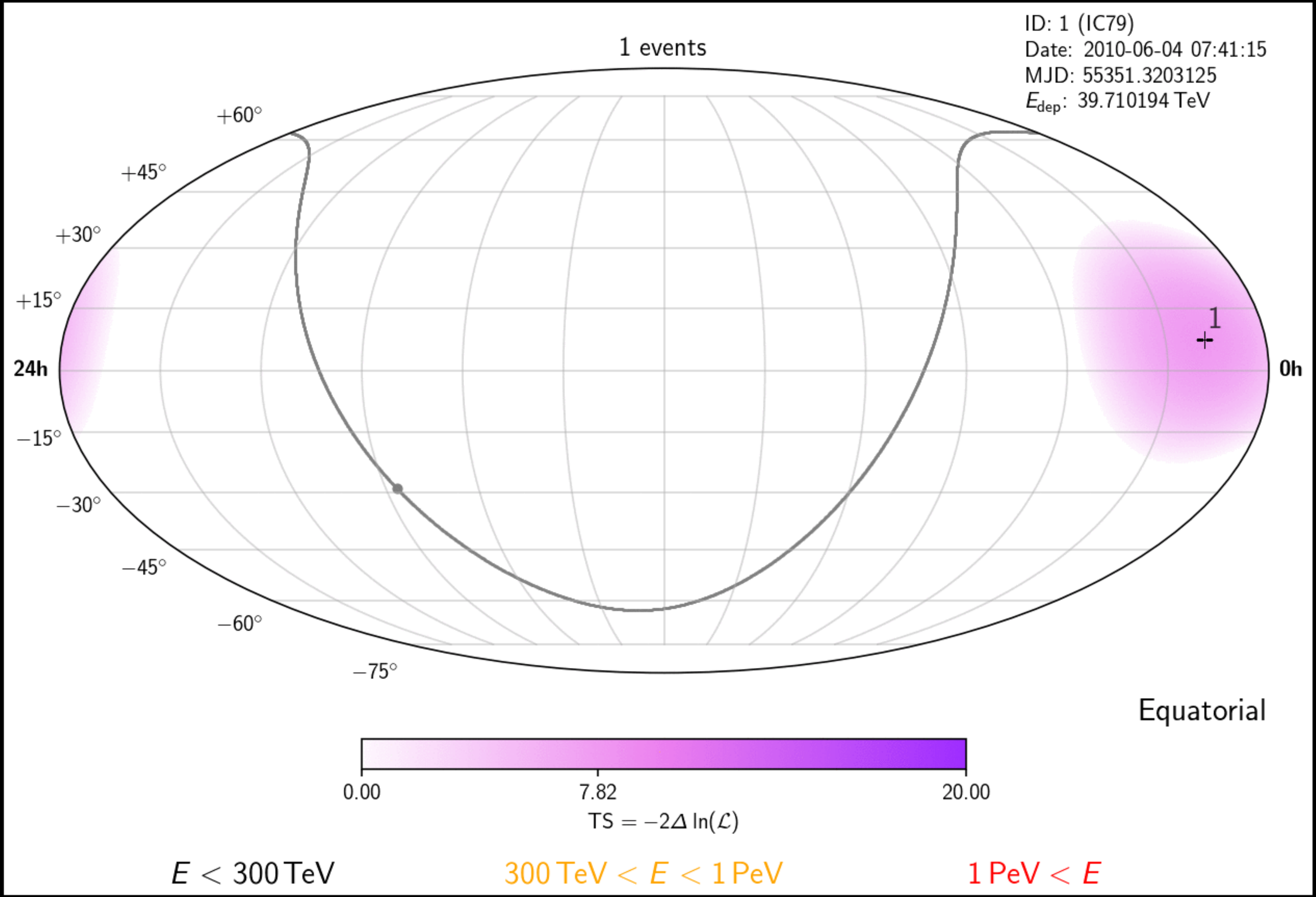


FULL ANALYSIS WITH 7 YEARS OF DATA

p-value of the cluster: 0.81

[after 7 years, we see that it's possible to get the same cluster of weirder 81% of the time…]





ID: 1 (IC79)
Date: 2010-06-04 07:41:15
MJD: 55351.3203125
E_{dep}: 39.710194 TeV
1 events
+60°
+45°
+30°
+15°
24h
−15°
−30°
−45°
−60°
−75°
0h
1
Equatorial
0.00
7.82
20.00
TS = −2Δ ln(ℒ)
E < 300 TeV
300 TeV < E < 1 PeV
1 PeV < E

LESSONS LEARNED?

> We can't just find a cluster of neutrinos and claim that it is a significant source!
It can also be "isotropic background", and we need to know how likely.

> We can either generate random maps many times or use analytical background expectation (such as Poissonian probability) to quantify significance.

> Often, if we know the analytical form of the background expectation, it can save us a lot of computational time!

> Finally, it is better to know where we're looking instead of searching across the entire sky. Multimessenger observations can help guide our searches!

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> Finally, it is better to know where we're looking instead of searching across the entire sky. **Multimessenger observations can help guide our neutrino searches!**