Speech

Slide 1: Title Slide

"Good day everyone. I'm Fabio and today I will discuss the significant discovery of neutrino emission from the direction of the blazar TXS 0506+056 (that I'm gonna call TXS) prior to the IceCube-170922A alert.

Before we delve deeper into the argument, let's star with the introduction.

Slide 2: Introduction

The highest-energy cosmic rays are believed to be extragalactic, yet the origin of where those particles are accelerated remains undefined.

The link between high-energy cosmic rays and neutrinos is that the latter are produced when cosmic rays interact with matter and light, creating mesons that decay into neutrinos and other particles.

But why are we so interested in neutrinos? Because we can use them as probes.

Unlike cosmic rays, neutrinos can travel unimpeded through the Universe because of their nature. They are nearly massless, electrically neutral particles and are not deflected by magnetic fields.

Slide 3: Blazars

Let's now talk about blazars.

The image shows Hercules A, an active galactic nucleus (AGN).
Visible light was collected by Hubble Space Telescope and was superposed with a radio image taken by the Very Large Array

AGNs have a supermassive black hole at their center that pulls in matter and produces a lot of energy. As a consequence there is the emission of jets as we can see.

- Blazars, on the other hand, are a type of active galactic nucleus with the jets that aimed towards Earth.
- They are source of emissions across the entire electromagnetic spectrum with high-energy gamma rays photons. -> Those are particularly important as they can be indicative of processes capable of producing high-energy neutrinos.

Due to their powerful jets and the high-energy gamma rays , blazars are considered prime candidates for being the sources of high-energy astrophysical neutrinos.

Slide 4 - 5: IceCube Neutrino Observatory

Let's now discuss how we can detect the astrophysical neutrinos.

The IceCube Neutrino Observatory, located at the Amundsen-Scott South Pole Station in Antarctica, consists of a cubic kilometer of instrumented ice.

- It has 86 vertical strings spaced 125 meters apart.
- These strings extend to a depth of 2450 meters, with 60 optical sensors each.

These optical sensors play a main role in the detection mechanism itself.

The detection mechanism is able to record Cherenkov light from relativistic particles produced by neutrino interactions. They track high-energy muon neutrinos with remarkable directional accuracy, approximately 0.5° accuracy at 30 TeV.

Slide 6: The IceCube-170922A Event

Now that we have enough background, we can understand the detail and importance of the IceCube-170922A Event.

On September 22, 2017, the IceCube detector recorded a high-energy neutrino, designated IceCube-170922A, with an estimated energy of 290 TeV. This event was detected by the Extremely High Energy (EHE) online event filter.

Research Focus

- The event was reported as a public alert.
- The refined directional reconstruction of this event was (RA (77.43^{+0.95}*{-0.65}) and Dec (5.72^{+0.50}*{-0.30})).

This last information is important. Let's see why. The map shows gamma-rays detected by the Fermi Gamma-ray Space Telescope from 2008 to 2017.

It was soon determined that the direction of IceCube-170922A was not only consistent with the location of TXS

But also coincident with a state of enhanced gamma-ray activity observed since April 2017 by the Large Area Telescope (LAT) on the Fermi Gamma-ray Space Telescope.

Slide 10: The Blazar TXS 0506+056

As stated in the paper, "On the basis of this result, we consider the hypothesis that the blazar TXS 0506+056 has been a source of high-energy neutrinos beyond that single event."

Slide 11: Searching for Neutrino Emission

So, as the last sentence stated let's start to search for neutrino emission from the blazar TXS.

Slide 11: IceCube Neutrino Data Samples

Let's first talk about the Data Collection Periods.

There are 6 different datasets because of changing detector configurations, data-taking conditions, improved event selections

- Sample numbers correspond to the number of detector strings that were operational.

For our analysis, we consider six such periods from 2008 to 2017.

Slide 13: Expected Event Types

For the Expected Event Types insted we have to say that

TXS 0506+056 is in the northern sky adn it's observed through Earth by IceCube

There are about 70,000 neutrino-induced muon tracks recorded annually.

We can have the signal: **Astrophysical Neutrinos** that include just the 1% of the detected events. As we said, they originate from distant cosmic sources and the expected flux scales as ($dN/dE \sim E^{-2}$).

The **Background Events** form the vast majority of detected events. They are caused by neutrinos produced in the Earth’s atmosphere and the expected flux scales as ($dN/dE \sim E^{-3.7}$).

The information on the expected flux allows for further discriminating power in point source searches besides directional-only excesses.

Slide 10: Time-Integrated Analysis

Let's now talk about the Analysis Techniques used.

The first method used is the Time-Integrated Analysis.

This analysis uses an unbinned maximum likelihood method to identify neutrino point sources by analyzing spatial clustering and energy distribution over extended periods.

The likelihood function is a combination of various factors: the signal part and the background ones.

The model parameters are the Spectral Index (γ) and the Flux normalized at 100 TeV (Φ_{100}).

- N is the total number of neutrino events,
- (nS(\Phi{100}, \gamma)) is the number of signal neutrinos for a signal flux model of the form (\Phi(E) = \Phi{100}(E/100 \text{ TeV})^{-\gamma}), where E is the true neutrino energy, (\gamma) is the spectral index, and (\Phi{100}) is the flux normalization at 100 TeV.

PDF of signal events:

- **Spatial Component:** Two-dimensional Gaussian distribution centered at the source position.
- **Energy Component:** Probability of observing a neutrino with energy (E_i) at a given declination (\delta_i).

PDF of background events:

- **Spatial Component:** Uniform in right ascension.
- **Energy Component:** Derived from experimental data, representing the distribution of energies for background events.

A time-dependent analysis was also used.

This analysis aims to identify clusters of neutrino events in space but also in time, hence time-dependent.

The likelihood function for this analysis is also divided into a term for the background and a term for the signal, and the terms (S) and (B) were defined as before.

This time what is different are the (TS) and (TB): the Signal Temporal Distribution Functions.

For the signal, we use two different PDFs:

1. A **Box-Shaped Time Window:** The box function is given by ..., where (T_0) is the central time and (T_W) is the full width of the box shape.
2. **Gaussian-Shaped Time Window:** It is described by the same parameters but has a Gaussian shape.

The PDF for the time distribution of background events (TB) is given to good approximation by (1/T), where (T) is the total observation time of the data sample.

Statistical Tests

In the analysis, statistical tests were used to determine the significance of the findings.

The Test Statistic helps us evaluate the likelihood of observing the data under the hypothesis that there is a signal present versus the hypothesis that there is no signal (i.e., the null hypothesis).

For the time-integrated analysis, the Test Statistic is given by:

$$TS = 2\log\left(\frac{L(\Phi_{100}, \gamma)}{L(\Phi_{100} = 0)}\right)$$

The denominator, (L(\Phi_{100} = 0)), represents the likelihood under the null hypothesis of no signal.

For the time-dependent analysis, the Test Statistic takes into account the temporal aspect of the data. It is given by:

$$TS = 2\log\left[\frac{T_W}{T} \times \frac{L(\Phi_{100}, \gamma, T_0, T_W)}{L(\Phi_{100} = 0)}\right]$$

The term (\frac{T*W}{T}) accounts for the time-dependency of the analysis, and the denominator (L(\Phi*{100} = 0)) is again the likelihood under the null hypothesis.

P-Value Computation

Once the Test Statistic is calculated, the p-value is computed from the TS.

The p-value represents the probability of observing TS as extreme as, or more extreme than, the value calculated under the null hypothesis.

A lower p-value indicates a higher statistical significance of the observed signal.

Neutrinos from the Direction of TXS 0506+056

It's time to analyze the result of the Time-Dependent Analysis.

The figure summarizes all the findings.

- The orange curve corresponds to the analysis using the Gaussian-shaped Time Distribution Function. The central time (T_0) and width (T_W) are plotted for the most significant findings - with the p-value of that result indicated by the height of the peak.
- The blue curve corresponds to the analysis using the box-shaped Time Distribution Function. **The curve traces the outer edge of the superposition of the best-fitting time windows (durations TW) over all times T0, with the height indicating the significance of that window.** In each period, the most significant time window forms a plateau, shaded in blue.

As we can see, IC86b from 2012 to 2015 contains a significant excess which is identified by both time-window shapes.

The excess consists of 13±5 events above the expectation from the atmospheric background.

Now, the significance of these findings depends heavily on several factors:

1. **Energy of the Events, Proximity to TXS 0506+056 Coordinates, Clustering in Time.**

This is illustrated in the figure.

- Each vertical line represents an event observed at the time indicated by calendar year (top) or MJD (bottom).
- Overlapping lines are shifted by 1 to 2 days for visibility.
- The height of each line indicates the Event Weight: the product of the event’s spatial term and energy term in the unbinned likelihood analysis evaluated at the location of TXS 0506+056 and assuming the best-fitting spectral index $\gamma = 2.1$.
- The color for each event indicates an approximate value in units of TeV of the reconstructed muon energy (Muon Energy Proxy)
- The dashed curve and the solid bracket indicate the best-fitting Gaussian and box-shaped time windows, respectively. The distribution of event weights and times outside of the best-fitting time windows is compatible with background.

Moving forward, our analysis using a Gaussian time window centered at December 13, 2014, with a width ($T_W = 110^{+35}_{-24}$) days, has yielded some critical results.

The best-fitting parameters are as follows:

- **Fluence**: ($E^2J_{100} = (2.1^{+0.9}_{-0.7}) \times 10^{-4} \text{ TeV cm}^{-2}$) at 100 TeV.
- **Spectral Index**: ($\gamma = 2.1 \pm 0.2$).
- **P-value**: (0.0002), corresponding to a significance of (3.5σ).

For the box-shaped time window, the results are similar to those of the Gaussian window, but the uncertainties are discontinuous and not well-defined, making the Gaussian window a more reliable indicator.

In Figure 3, we see the joint uncertainty on the Gaussian shape fitted parameters while holding the time parameters fixed (T0 = December 13, 2014, TW = 110 days). This plot shows the change in test statistic (Δ TS) as a function of the spectral index parameter (γ) and the fluence at 100 TeV.

Figure 3b shows a skymap of the P-value from the time-dependent analysis performed at the coordinates of TXS 0506+056 and surrounding locations. The analysis reveals an excess of events consistent with the position of TXS 0506+056, reinforcing the significance of our findings.

Outside the 2012-2015 period, the next most significant excess is found in 2017, centered around the IceCube-170922A event. This excess is characterized by:

- **Duration:** $T_W = 19$ days.
- **Spectral Index:** $\gamma = 1.7 \pm 0.6$.
- **Fluence:** $E^2J = 0.2^{+0.4}_{-0.2} \times 10^{-4} \text{ TeV cm}^{-2}$ at 100 TeV.

Notably, no other event besides IceCube-170922A significantly contributes to the best-fit for this period.

Next, let's consider the results from the **time-integrated analysis**, which utilizes the full data sample.

The best-fitting parameters for the full 9.5-year sample are:

- **Flux Normalization (Φ_{100}):** $(0.8^{+0.5}_{-0.4}) \times 10^{-16} \text{ TeV}^{-1} \text{ cm}^{-2} \text{s}^{-1}$.
- **Spectral Index (γ):** 2.0 ± 0.3.
- **P-value:** 0.002%, corresponding to a significance of 4.1σ.

But this is an a posteriori significance estimate because it includes the IceCube-170922A event which motivated performing the analysis at the coordinates of TXS 0506+056.

For the 7-year sample, the results are:

- **Flux Normalization (Φ_{100}):** $(0.9^{+0.6}_{-0.5}) \times 10^{-16} \text{ TeV}^{-1} \text{ cm}^{-2} \text{s}^{-1}$.
- **Spectral Index (γ):** 2.1 ± 0.3.
- **P-value:** 1.6%, corresponding to a significance of 2.1σ.

This excess is not significant in the time-integrated analysis because of the additional background during the rest of the 7-year period.

Blazars as Neutrino Sources

Redshift and Luminosity

Let’s now discuss why TXS 0506+056 stands out as a significant source of high-energy neutrinos by examining its redshift and luminosity.

1. **Redshift:**
   - TXS 0506+056 has a redshift $z = 0.3365 \pm 0.0010$.
   - Determining the redshift is essential for determining the isotropic luminosity of the blazar in both neutrinos and gamma rays.
2. **Luminosity:**
   - The isotropic neutrino luminosity was calculated to be $(1.2^{+0.6}_{-0.4}) \times 10^{47}\ \mathrm{erg\ s^{-1}}$ averaged over 158 days.
   - Remarkably, this neutrino luminosity is higher than the gamma-ray luminosity observed during the same period.

- The difference suggests that some gamma rays produced in association with neutrinos are either absorbed or have energies outside the detection range of the Fermi-LAT telescope.

Position and Inclination of TXS 0506+056

Now let's explore the position and inclination of TXS 0506+056, which play a significant role in the detection likelihood and the observed neutrino excess.

- **Detection Likelihood:**
  - Favorable declination increases IceCube detection chances.
  - IceCube is highly sensitive to high-energy neutrinos near the equatorial plane, viewed from the South Pole.

2. **Neutrino Excess:**
   - Blazars with jets aimed directly at Earth, such as TXS 0506+056, are prime candidates for significant neutrino emission.
   - This alignment increases the likelihood of detecting a higher number of neutrino events, as observed in the case of TXS 0506+056.

Conclusions

Summarizing the key points:

- TXS 0506+056 is confirmed as a high-energy neutrino source with evidence at a 3.5σ significance level from the 2014-2015 period.
- This evidence is independent of the IceCube-170922A event, suggesting a consistent source of neutrino emission.
- The isotropic neutrino luminosity observed is higher than the gamma-ray luminosity during the active period, indicating efficient neutrino production mechanisms.
- A significant excess of muon-neutrino events supports the hypothesis that TXS 0506+056 is a major source of high-energy cosmic rays.
- These findings collectively support the role of blazars as key sources of high-energy astrophysical neutrinos, enhancing our understanding of cosmic ray origins and particle acceleration processes in the universe

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Thank you for your attention. I'm open to any questions you may have.