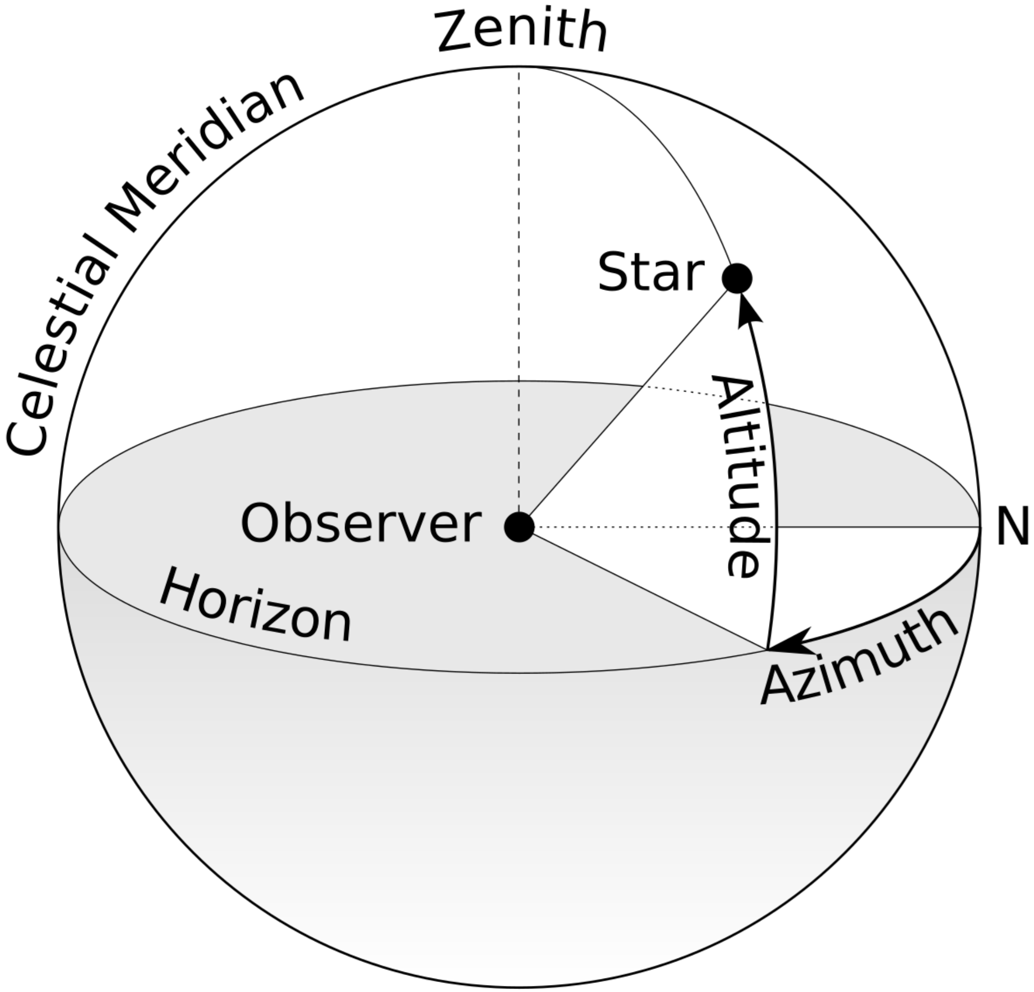
How we locate a point in the sky

The Observer and the Sky

- Imagine the sky as a giant dome surrounding the observer.
- The observer stands at the center.
- The point straight above your head is the zenith.
- In astronomy, the astronomical horizon is defined as the intersection between the celestial sphere and a plane perpendicular to the zenith axis of the observer.
    - This is a geometrical reference plane used to define celestial coordinates.
    - It does not coincide with the place where the sky appears to meet the Earth. That would only be true if the Earth were flat.
    - The line where the sky seems to touch the ground is instead called the visual horizon, which depends on the observer’s position and on the curvature of the Earth.



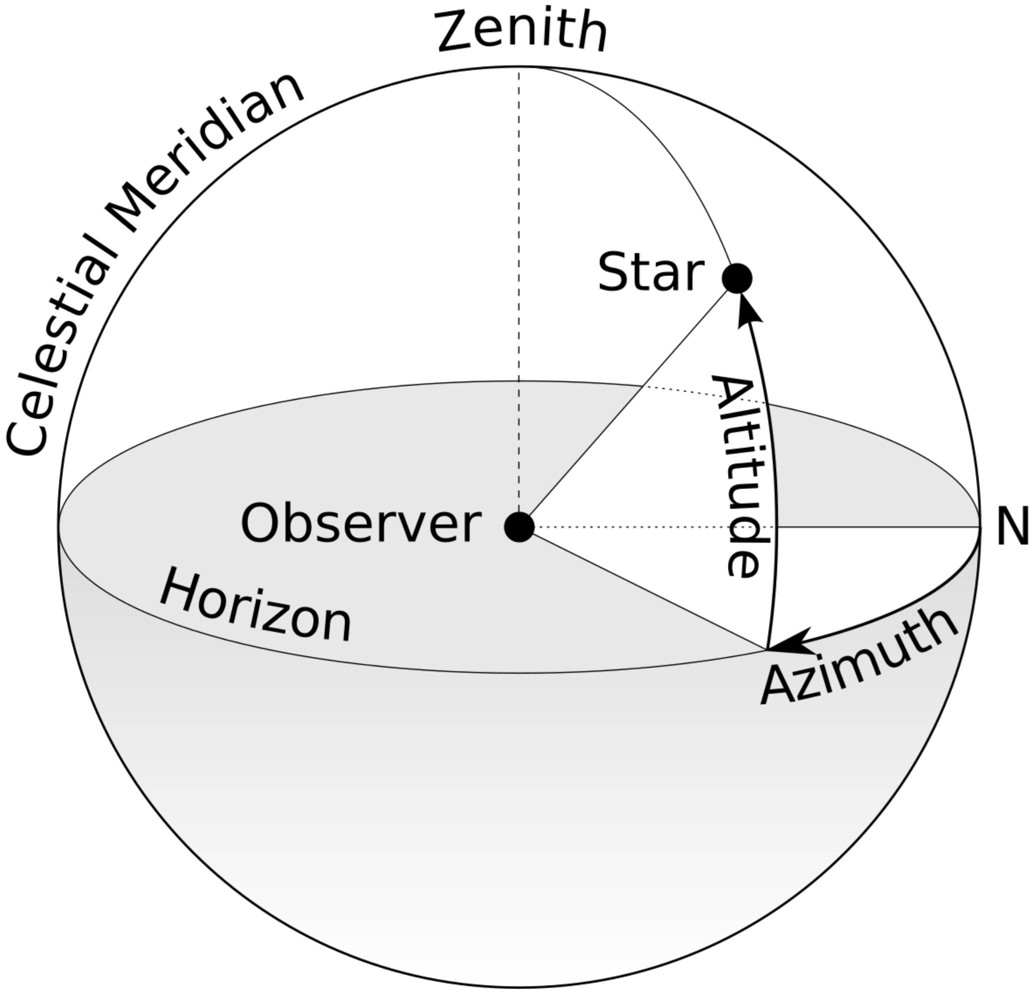
How we locate a point in the sky

Altitude = “Sky Latitude”

- Altitude tells us how high an object is in the sky.
- It is measured upward from the horizon.
  - 0° → object is on the horizon
  - 90° → object is at the zenith (straight overhead)

Analogy:

Like latitude on Earth, which tells how far North or South a location is.



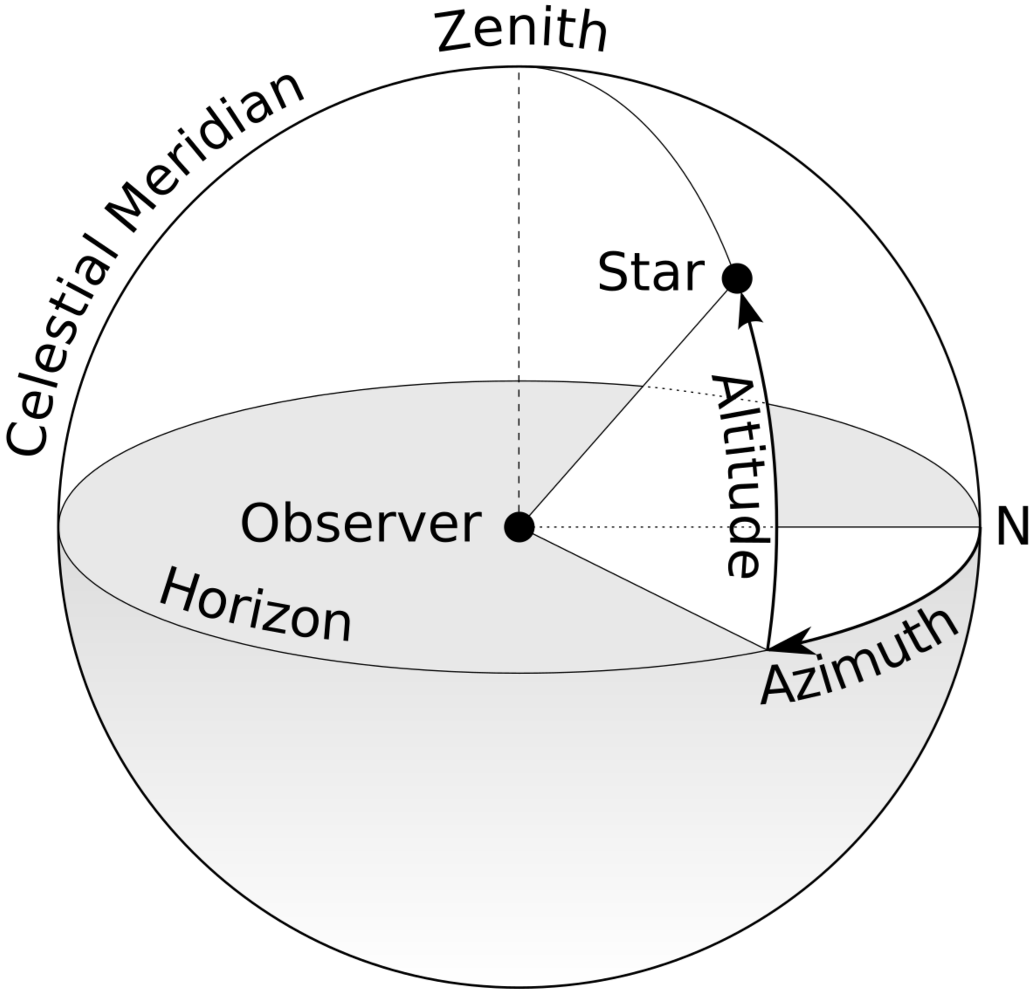
How we locate a point in the sky

Azimuth = “Sky Longitude”

- Azimuth tells us which direction to look along the horizon.
- It is measured around the horizon, starting from North.
    - North = 0°
    - East = 90°
    - South = 180°
    - West = 270°

Analogy:

Like longitude on Earth, which tells how far East or West a location is.



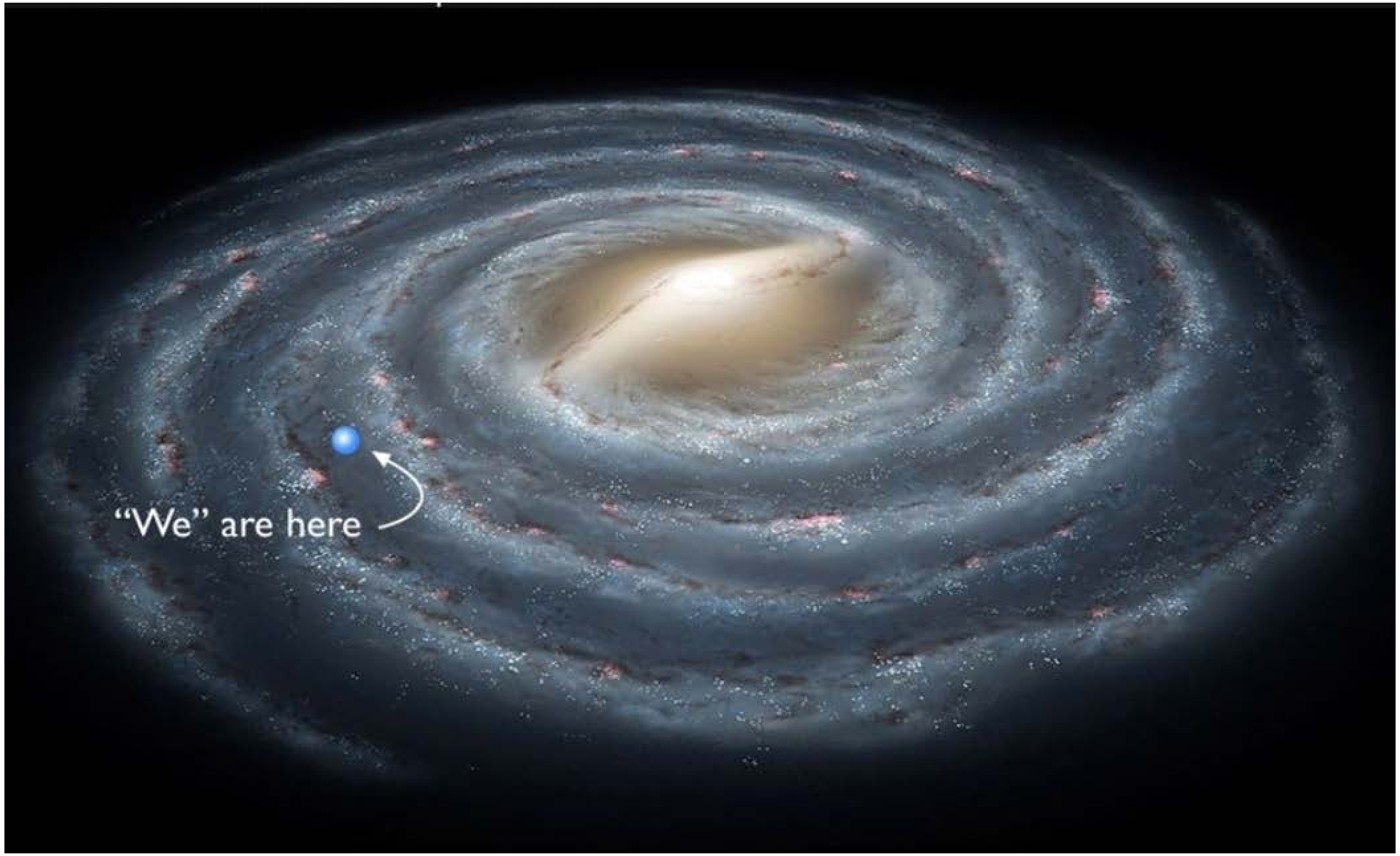
What we can try to measure with KM3NeT in a local coordinate sky map

- Above the horizon (altitude > 0°):
  - mainly the huge contribution of atmospheric muons (background)
  - atmospheric and cosmic neutrinos are completely overwhelmed by muons
- Slightly below the horizon (-10° < altitude < 0°)
  - many poorly reconstructed downgoing muons that decrease more and more as we move to more negative altitude (background)
  - atmospheric and cosmic neutrinos are still significantly overwhelmed by muons
- Below the horizon (altitude < -10°)
  - No atmospheric muons (muons cannot cross the Earth to reach the detector from below)
  - some atmospheric neutrinos (background)
  - a few cosmic neutrinos (signal!)

Galactic coordinates

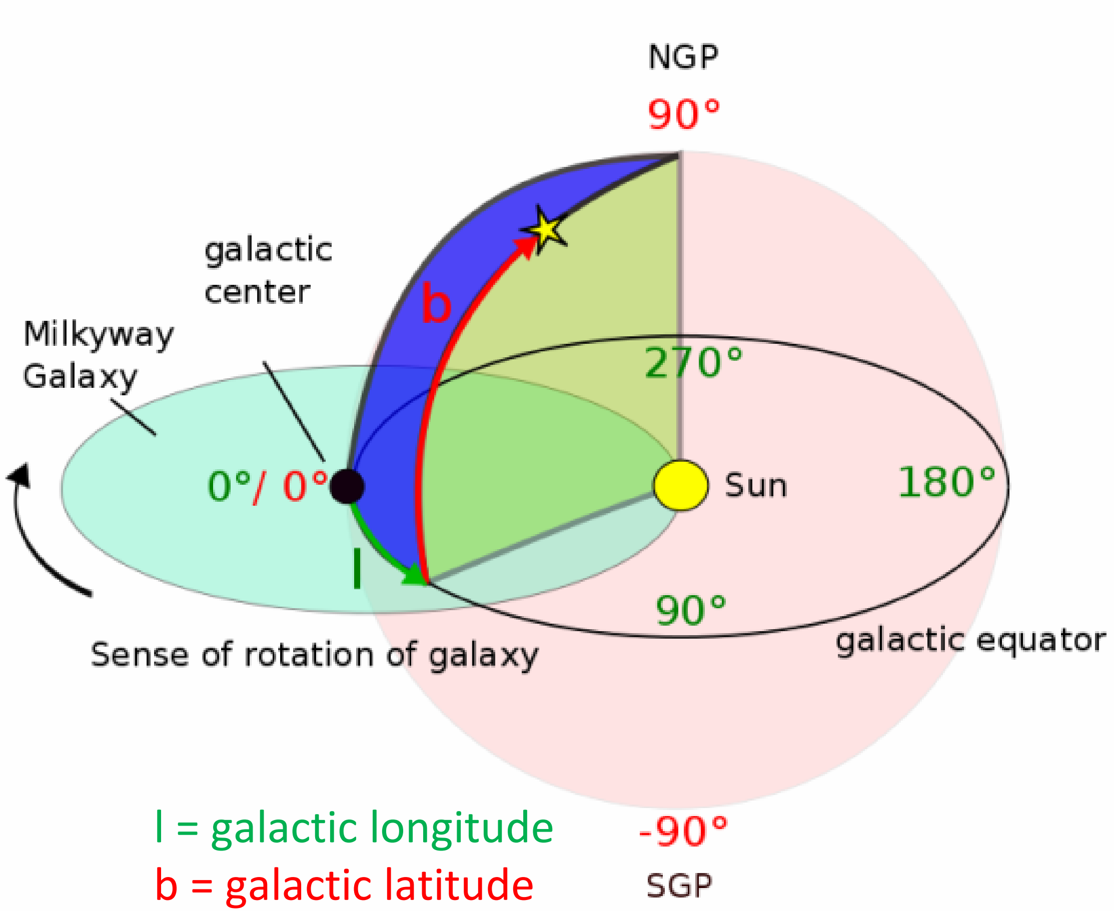
- The Milky Way is shaped like a flat disk (like a giant pancake).

- We live inside this disk, not outside it.



Galactic coordinates

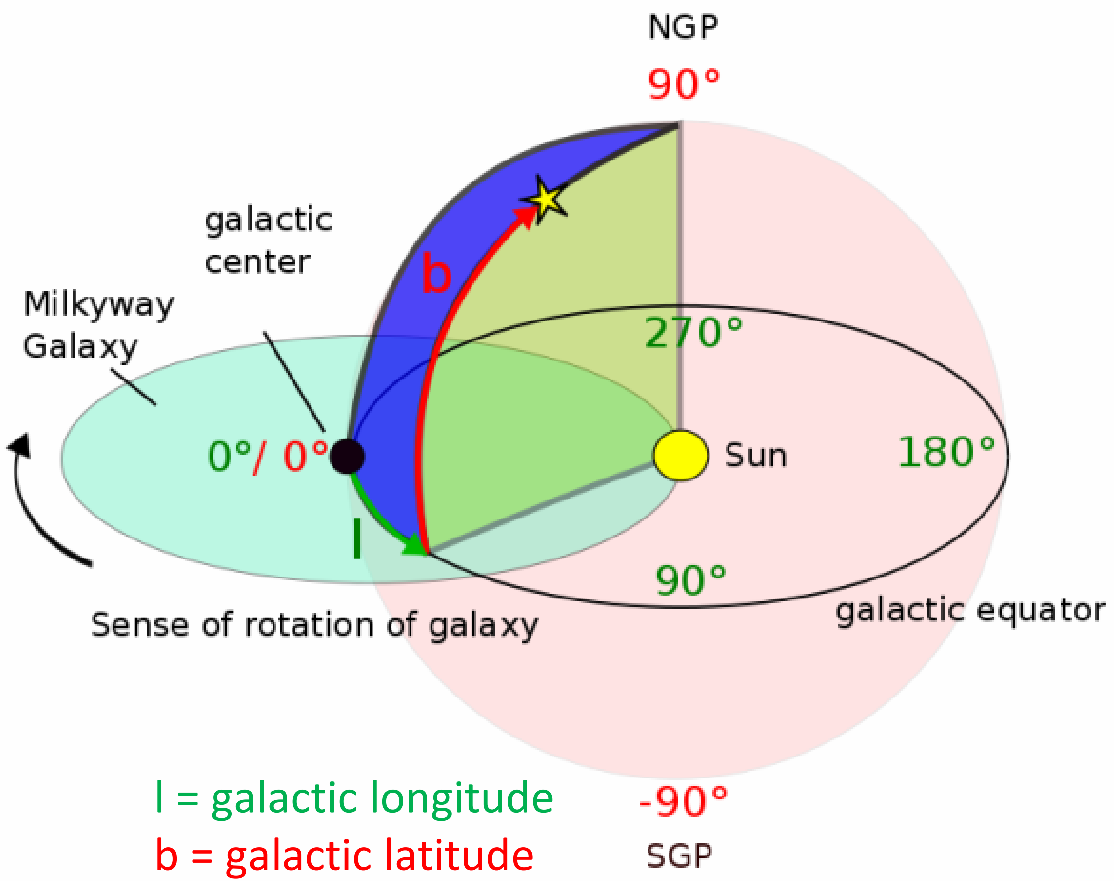
- The Sun is our reference point (yellow dot).
- The galactic centre is the middle of the galaxy (black dot).



Galactic coordinates

Galactic Longitude (Gal Lon)

- Galactic longitude tells us which direction we look within the galaxy.
- It is measured around the galactic disk:
  - 0°→ toward the galactic center
  - 90°, 180°, 270° → other directions around the galaxy



Analogy:

Like longitude on Earth, measuring East–West position.

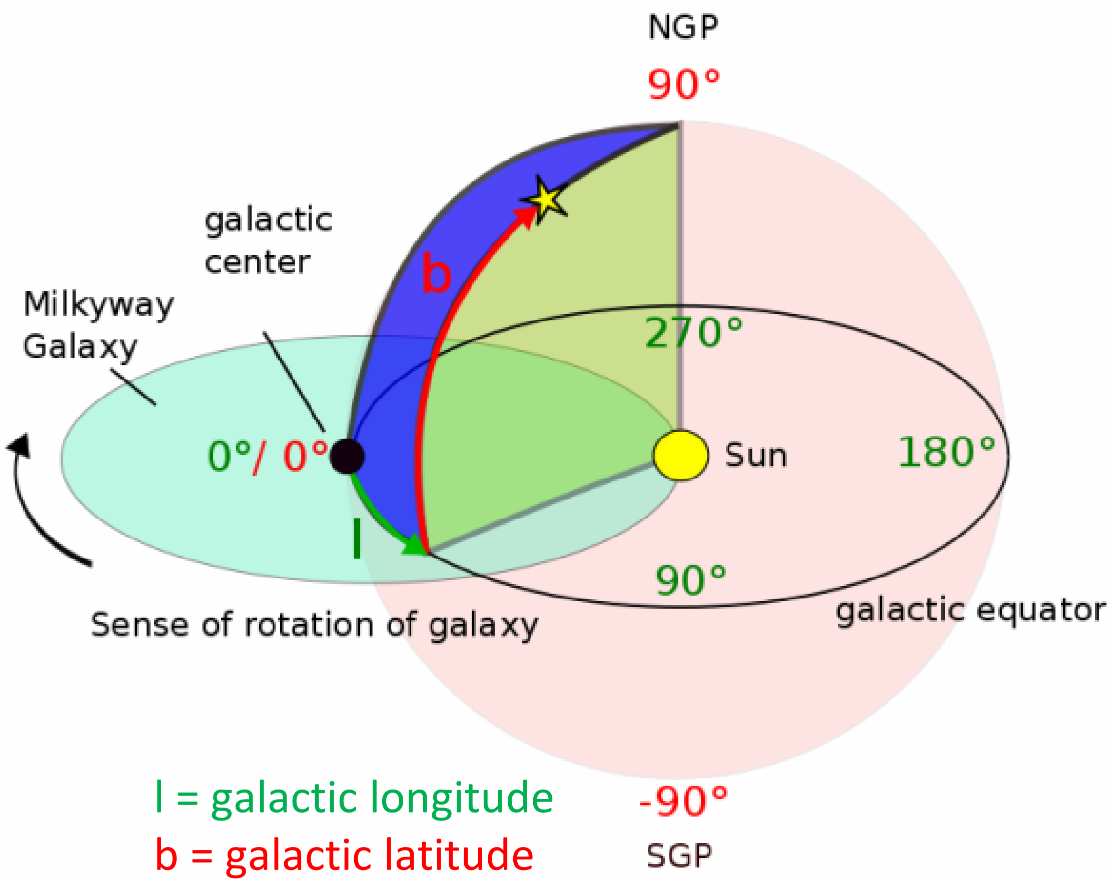
Galactic coordinates

Galactic Latitude (Gal Lat)

- Galactic latitude tells us how far above or below the galactic disk an object is.
- It is measured up or down from the galactic equator:
  - 0°→ inside the galactic disk
  - +90° → North Galactic Pole (NGP)
  - −90° → South Galactic Pole (SGP)

Analogy:

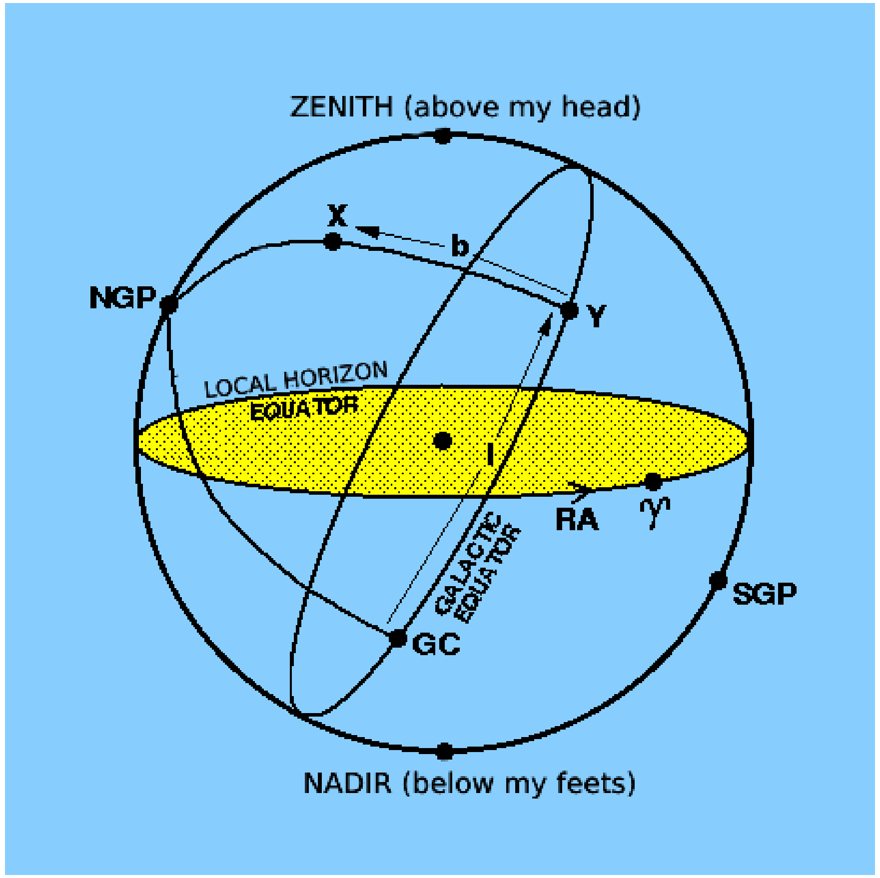
Like latitude on Earth, measuring North–South position.



Local coordinates vs Galactic coordinates

The celestial sphere does not change!

- All stars are projected onto the same celestial sphere
- What changes is how we draw the reference plane on that sphere
- The picture shows different planes crossing the same sphere

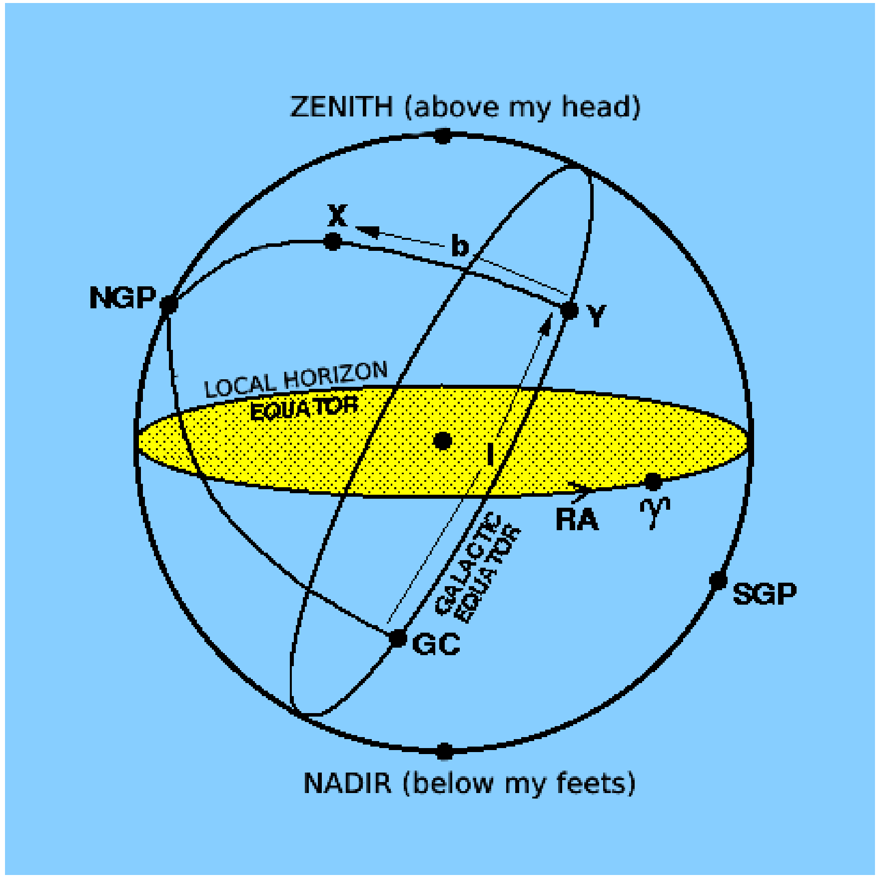


Local coordinates vs Galactic coordinates

A star stays in the same position in space

But its coordinates change because:

- We rotate the reference plane (Earth rotates!)
- Mathematically, this is like rotating the coordinate system, not moving the star



Local coordinates vs Galactic coordinates

Local Coordinates (Altitude & Azimuth)

- Based on where you are standing on Earth
- Dependant on:
  - Your location
  - The time of day
- Great for:
  - Pointing a telescope
  - Saying “Look there, above the horizon!”
- Problem:
  - The same star has different coordinates for different observers
- They answer the question:
  - “Where is the object in my view right now?”

Galactic Coordinates (Galactic Lat/Lon)

- Based on the structure of the Milky Way
- Independent of:
  - The observer
  - The time
- Ideal for:
  - Making sky maps
  - Sharing scientific data
- Advantage:
  - Everyone measures the same coordinates
- They answer the question:
  - “Where is the object in the universe?”

Candidate sources

In this exercise, we will investigate four sources belonging to two different categories:

Blazars

- Blazars are extremely energetic galaxies with a supermassive black hole at their center.
- The black hole launches powerful jets of particles moving close to the speed of light.
- When one of these jets points toward Earth, we observe very strong radiation across many wavelengths (from radio waves to gamma rays).
- They are among the brightest and most variable objects in the universe.

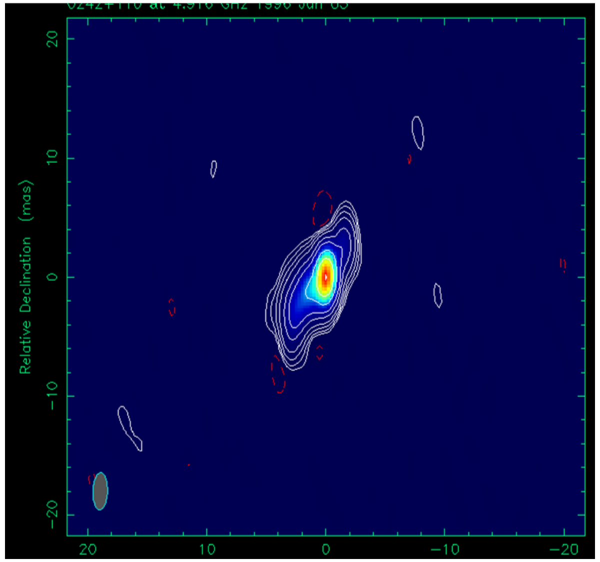
Pulsar Wind Nebulae (PWN)

- A pulsar wind nebula forms around a pulsar, which is a rapidly spinning neutron star left after a supernova explosion
- The pulsar emits a wind of very energetic particles.
- These particles interact with the surrounding material and magnetic fields, creating a glowing nebula.
- PWNe are important sources of high-energy radiation such as X-rays and gamma rays.

Candidate sources

A - Markarian 421

Blazar

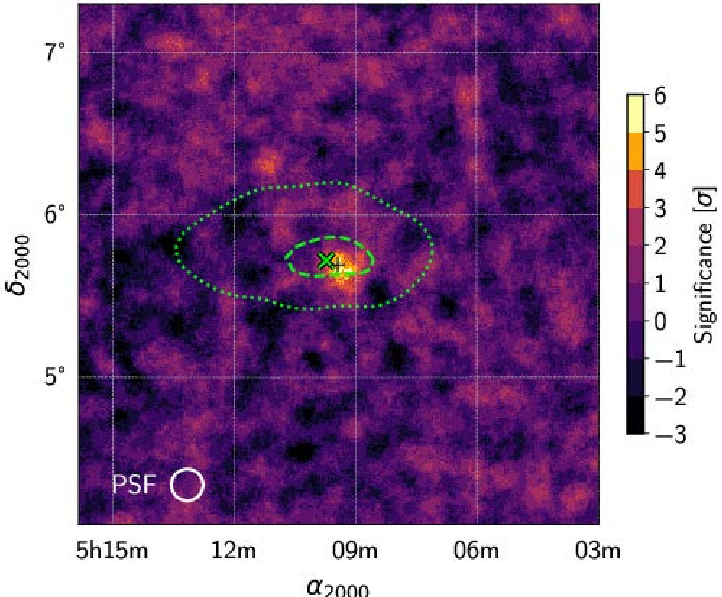


B - PKS 0239+108

Blazar

C - Vela X

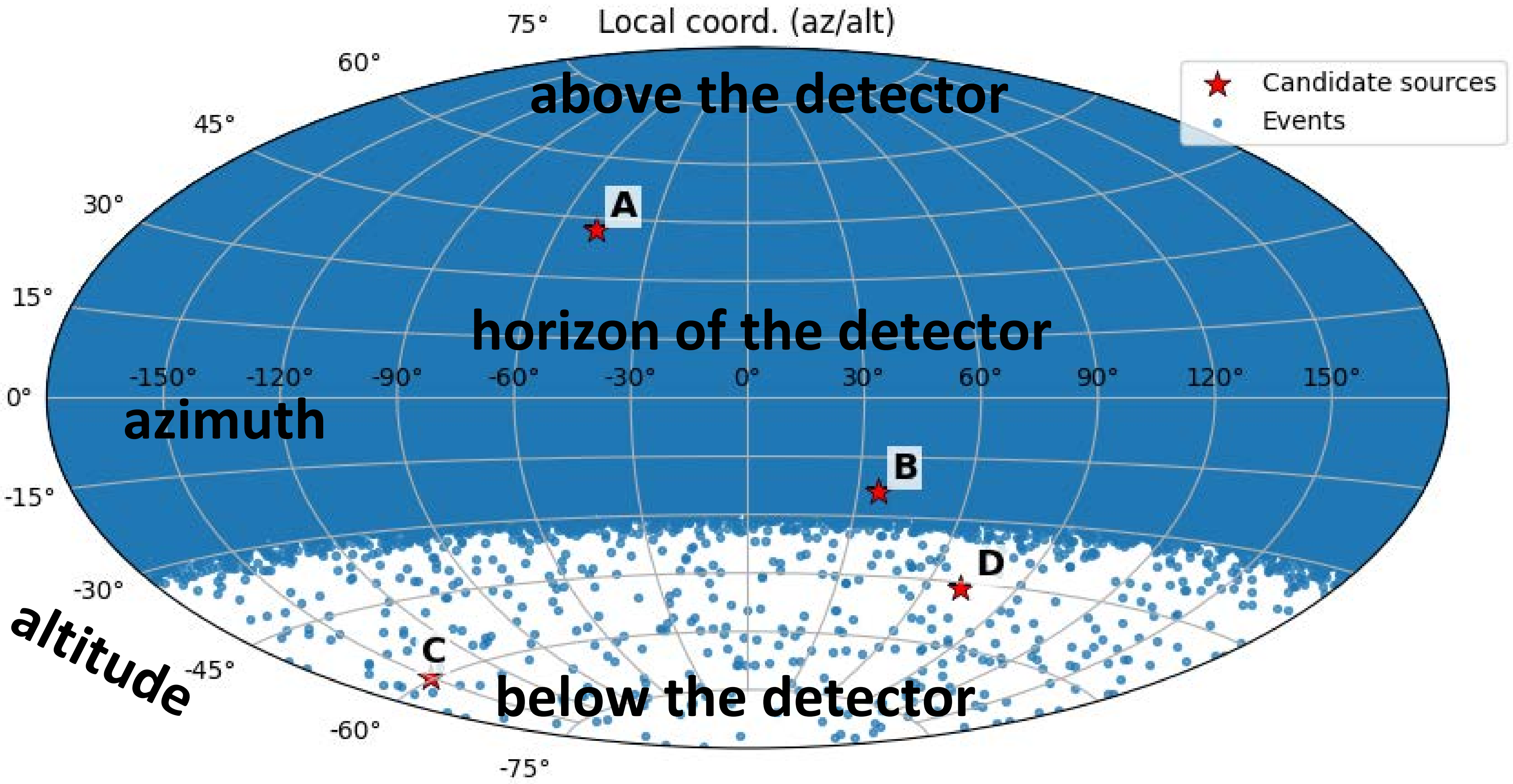
Pulsar wind nebula



D - TXS 0506+056

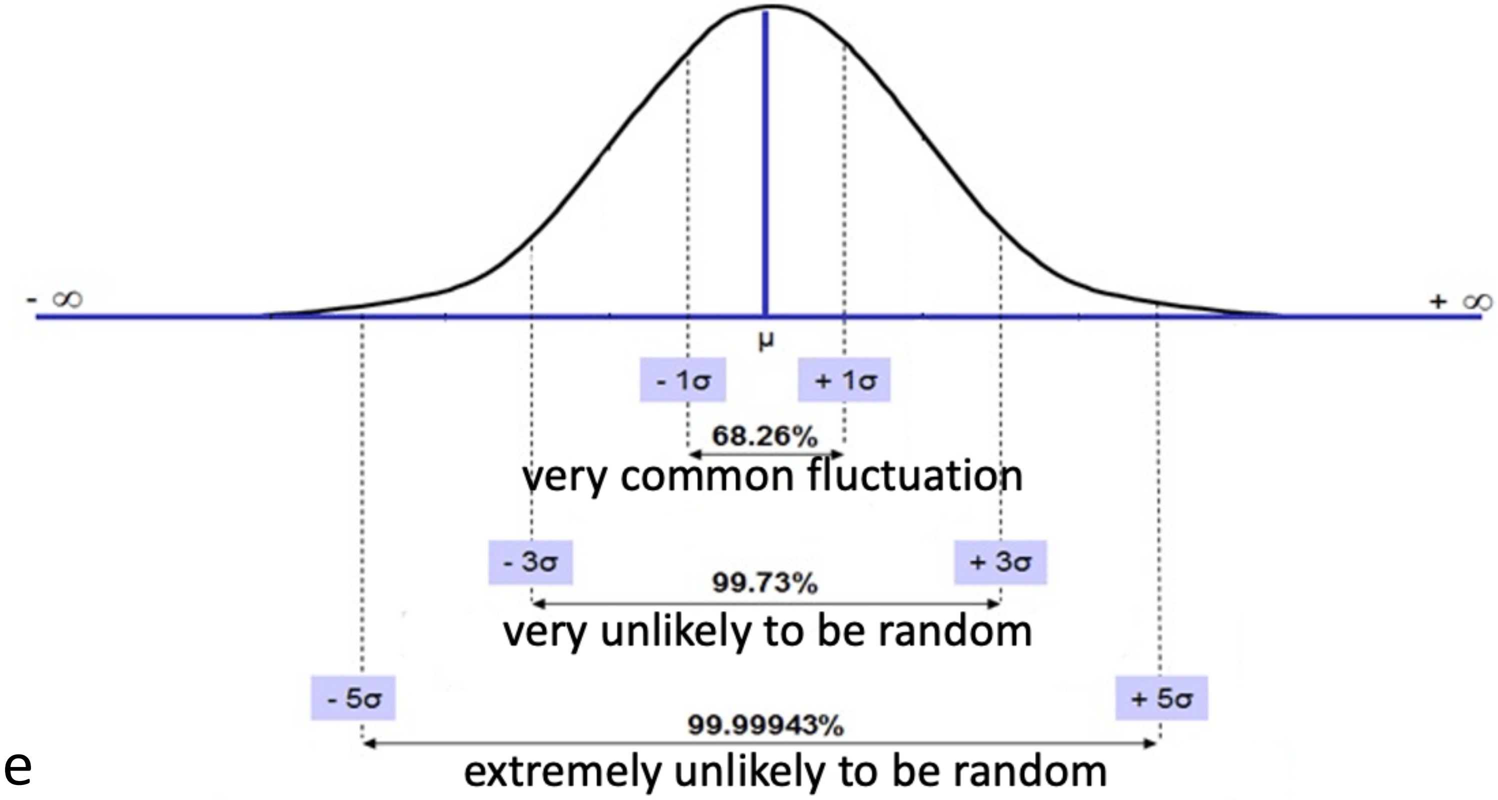
Blazar

Location of the candidate sources



What is “statistical significance”?

- When we do repeated measurements of something, the results are never exactly the same
- Small differences come from:
  - Random fluctuations
  - Measurement errors
- Statistics helps us decide:
  - Is this result real, or just due to a random chance?



3σ → evidence

5σ → discovery

Significance estimation with ON/OFF zones

- Neutrino detectors see many events
- Most of them are background (not signal from a source)
- We need a way to tell if a source is really producing neutrinos

- ON zone:
  - a 0.3° circle around the astrophysical source
  - If the source emits neutrinos, extra events should appear here

- OFF zone:
  - the rest of the sky outside the ON zone (at the same altitude)
  - It is assumed to contain:
    - Only background neutrinos
    - No contribution from the source
- It tells us how many background events we expect

Significance estimation with ON/OFF zones

- Compare ON and OFF
  - Count events in the ON zone
  - Use the OFF zone to estimate the background
  - Ask: “Are there more events in the ON zone than those expected *by chance* based on the background estimate?”

- Statistical significance
  - If ON zone events ≈ expected background → no detection
  - If ON zone events > background by 3σ → evidence of a signal
  - If ON zone events > background by 5σ → discovery of a source

Significance estimation with likelihood

Why go beyond ON/OFF?

- ON/OFF counts how many events we see
- But it ignores where exactly the events are inside the region
- Likelihood uses all the information we have

- Signal hypothesis
  - Cosmic neutrinos come from the source direction
  - Signal centered on the source
  - Signal width → KM3NeT angular resolution
  - Events closer to the source are more likely signal

- Background hypothesis
  - Background events come from everywhere
  - Their directions are uniformly spread
  - Same probability everywhere in the region

Significance estimation with likelihood

- For each detected event, we ask:

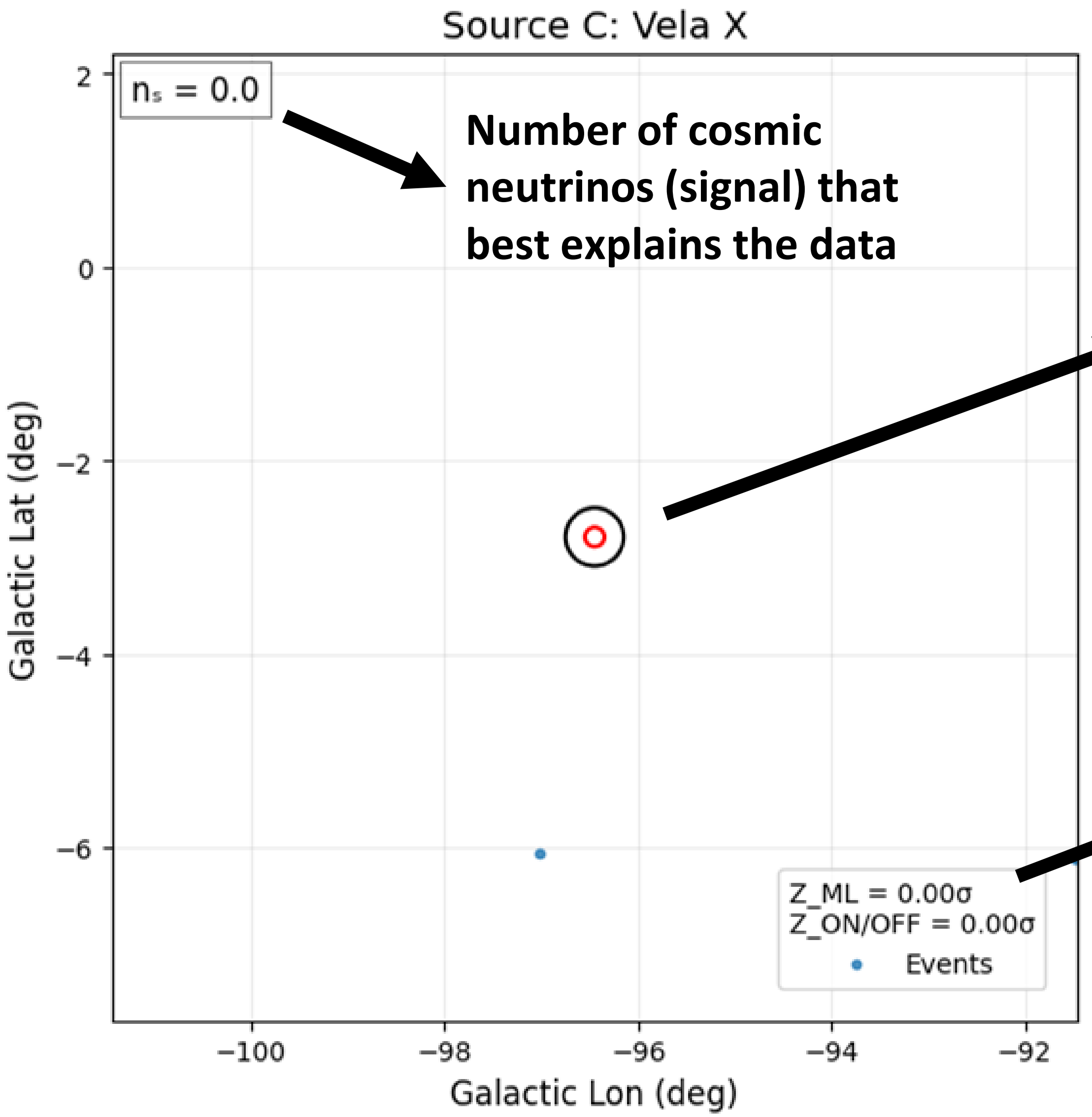
  "Is this event more likely signal or background?"

- We combine all events together

- We estimate the amount of signal that best explains the data

- We compute the significance of our observation

How to interpret the plots



Number of cosmic neutrinos (signal) that best explains the data

Red circle: 0.1° distance from the source
Black circle: 0.3° distance from the source

Significance computed with the likelihood method
Significance computed with the ON/OFF method

3σ → evidence
5σ → discovery!