Radio counterparts of high-energy neutrino sources

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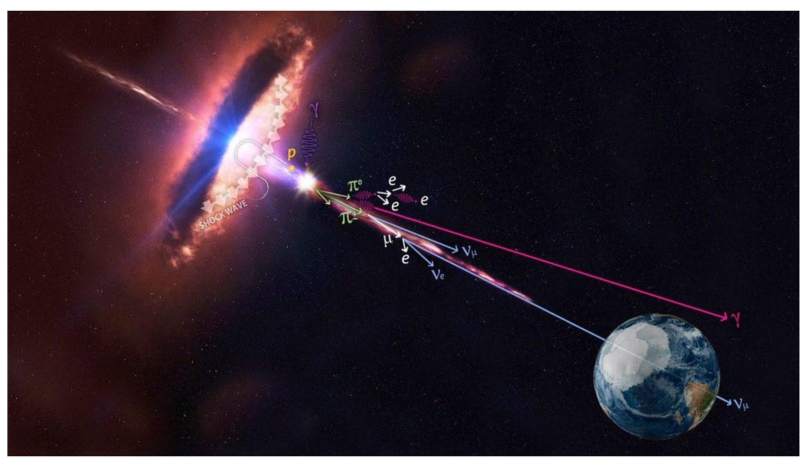
Neutrino sources

Most of the knowledge of the Universe comes from the study of the EM waves emitted by its components.
However, there are other phenomena that are still very little understood that play important roles in the evolution of the Universe.
They are among the most powerful events of the Universe.

Collisions of high energy CRs with matter produces pions.
$p + N \rightarrow p\,(n) + N + \pi^{0,\pm}$
than, in turn, produces electrons, photons, neutrinos:
$\pi^0 \rightarrow 2\gamma$
$\pi^\pm \rightarrow \mu^\pm + \nu_\mu$
$\mu^\pm \rightarrow e^\pm + \nu_\mu + \nu_e$

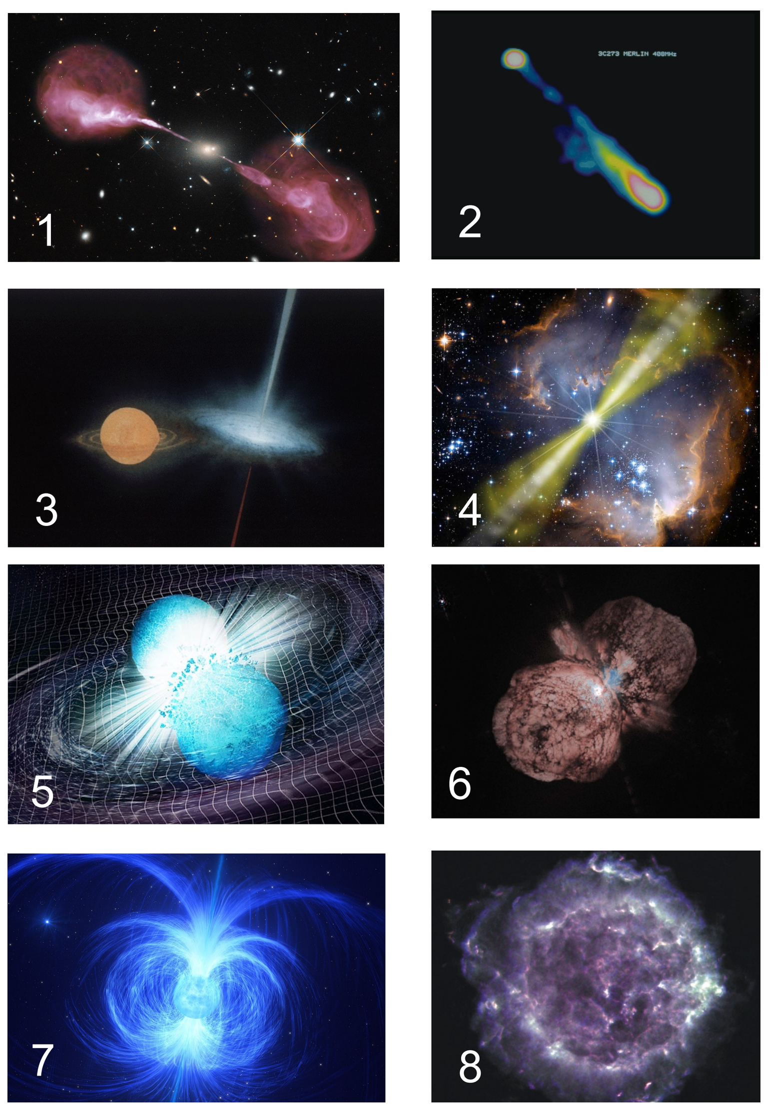


Flux of neutrinos is expected proportional to that of γ rays.
However, γ rays suffer of absorption by environment.

Transient HE events → HE gamma-rays and particle.
Gamma-rays can be absorbed by CMB.
GW and neutrinos are unperturbed messengers of these events.

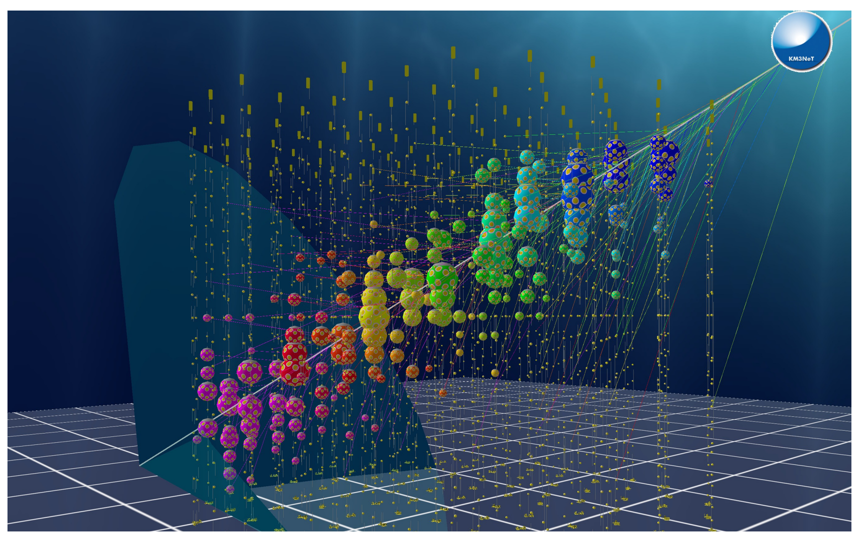
Excluding sources where neutrinos come from nuclear reactions (Sun, Supernovae), the High Energy neutrinos are generated in the interaction of **VHE CRs with matter:**

1. **Active Galactic Nuclei (AGN)**
2. **Blazars**
3. **Micro Quasars**
4. **Gamma-Ray Busts (GRB)**
5. **Kilonovae**
6. **Luminous Blue Variable (LBV)**
7. **Magnetars (FRB?)**
8. Supernovae Remnant (SNR)
9. Pulsar Wind Nebulae
10. Pulsar

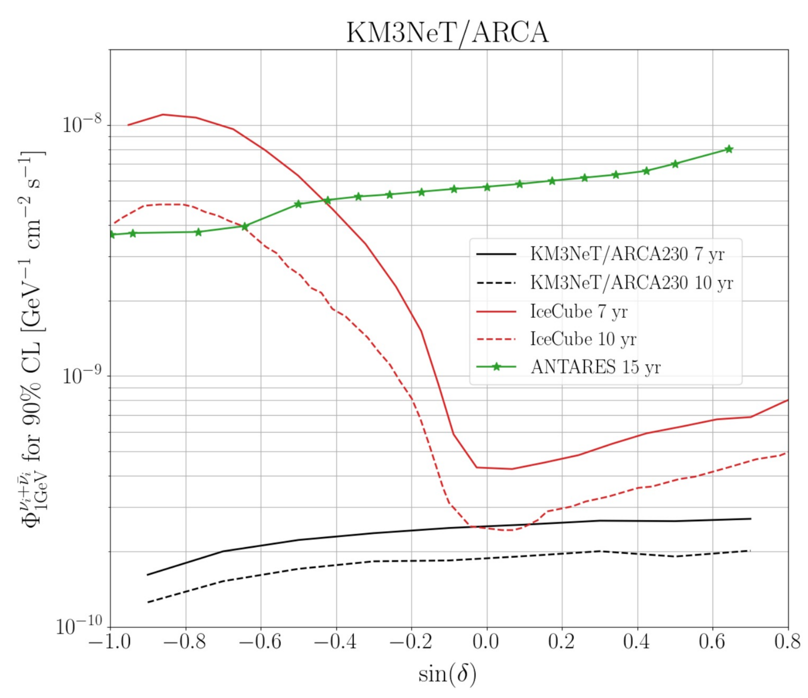


Neutrino Telescopes

New generation of neutrino telescopes, such as IceCube and KM3NeT, are devoted to detect high energy neutrinos (TeV to PeV).
KM3NeT is in the Mediterranean sea, at a depth of 3.500 m, offshore Capo Passero (Sicily, Italy).



HE neutrinos, after crossing the Earth, can interact with sea water inducing secondary particles that, in turn, produce Cherenkov light. This is detect by photo-multiplier tubes; the relative delays in detection permit a reconstruction of energy and direction of the incoming neutrinos.



Sensitivity as a function of source declination. KM3NeT is the most sensitive telescope to galactic neutrino sources close to the galactic centre, in particular at lower energies.

Correlation with EM emission

The angular resolution of the current Neutrino telescopes (~1° 0.1°) does not permit a good identification of source. Many EM counterpart are possible.

There are sources:
1. that can continuously produce HE neutrinos (SNRs, AGNs, PWNs, Pulsars);
2. with transient behaviour (AGN, Blazars, microquasars, GRB, LBV…).

How to identify the EM counterpart?

First type: correlate with surveys at all bands of EM spectrum.
Second type: correlate with EM emission. Temporal behaviour, monitoring of EM emission.

Gamma-ray vs Radio emission

Gamma-ray photons and neutrinos are generated by the same event.
However, **HE gamma-ray photons can be absorbed by matter**.
Conversely, **Radio emission travels free of absorption**.

Neutrinos vs Radio emission

Radio-Neutrinos Correlation in sources with strong synchrotron emission

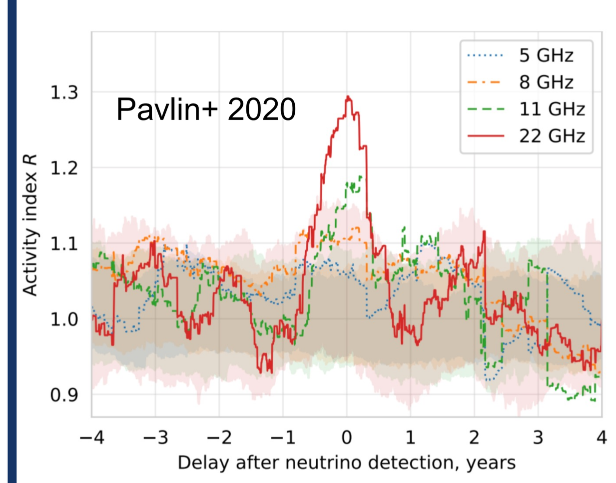
Theoretical works: (Sikora+1987; Stecker+1991; Murase & Stecker 2023)
HE electrons+B → synchrotron at radio → Synchrotron self Compton → X-rays
photohadronic interactions X-rays + Protons → $\pi \rightarrow \gamma + \nu$

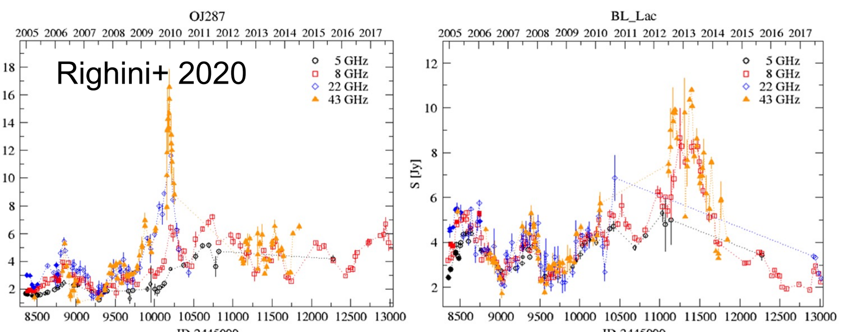
This can apply to:
- AGN and Blazars (extragalactic)
- Micro Quasar (galactic)
- GRB, LBV…

Search in AGN - IceCube - Mojave XV (Abbasi+ 2024)
No significant correlation in time averaged analysis.
Better correlation in time-dependent analysis.

Importance of a tight monitoring of radio flux

Activity index
blazars radio variability vs neutrino events
Temporal correlation between radio flux and neutrino detection





Example of radio monitoring with Medicina and Noto radiotelescopes (Noto at 43Gz).
During flares, when neutrinos are expected, the flux density is higher at high frequency.

Tighter correlation at high radio frequency

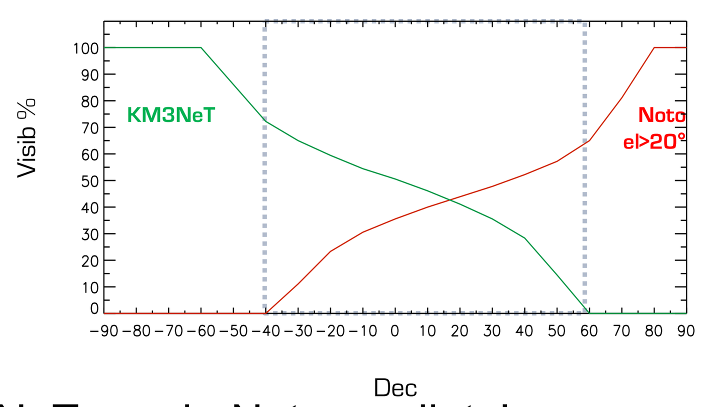
Observational campaigns at high radio frequency are important to correlate any neutrino event with
- EM counterpart
- acceleration of particles and physics of the event
- trigger any follow-up observation

The Project

It is funded by Next Generation EU, inside the project KM3NeT4RR, by INFN. It is aimed at observing radio sources that are potential sources of high-energy neutrinos.

There are two main streams:
- Technological: Upgrade of the 32m radio telescope at Noto (INAF) to extend its observing capabilities up to 100 GHz and to have an efficient acquisition system.
- Scientific: Build an observational program to perform close cadence monitoring at high radio frequency to build a database of long-term source behaviour.

By this monitoring, detections of any flare/transient will be used to investigate possible correlations with neutrino events detected by KM3NeT, and thus to consider follow-up observations by both telescopes.



KM3NeT and Noto radiotelescope are few hundred kilometres apart. KM3NeT sees the southern sky (Dec<55°) while Noto the norther sky (Dec>-34°). **The overlap is 55% of the sky.**
A sample of Blazars and micro Quasar have been selected for the monitoring (about 300 sources).

New secondary mirror
surface accuracy 20 μm rms
Upgrade main mirror
Frequency agility
New receiver: Triband: **18-26, 34-50, 80-116 GHz**
New synthesizer
New control system
New backend (SKARAB)→ simultaneous 4 band acquisition, 2 polarizations
Automatic data acquisition (not supervised)
Automatic data reduction
Data archive

The new Triband receiver will allow the simultaneous measurements at K, Q, W bands. With the two SKARAB boards and acquisition system, the determination of the spectrum of the source.