Ultra High Energy Neutrino Detection
and
TXS 0506+056 observation with IceCube

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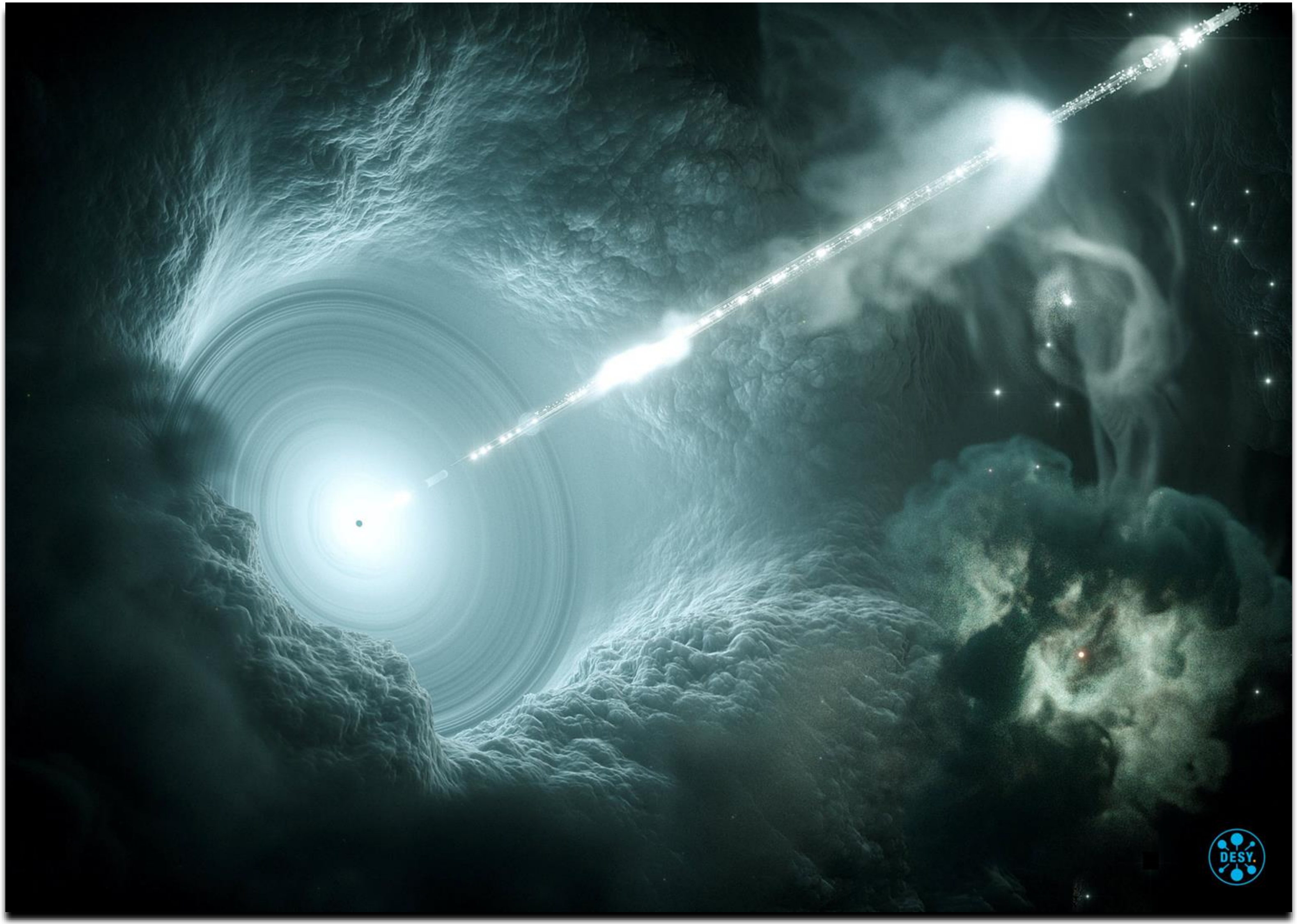
Astrophysics Seminar

Overview



1. Extragalactic Sources
2. Emission models
3. UHE Neutrinos detection
4. IceCube
5. TXS 0506+056 case

Particles from the Universe

Since the beginning of 20th Century, particles from outside the Earth have been discovered in a huge energy range

Several experimental techniques have been developed!

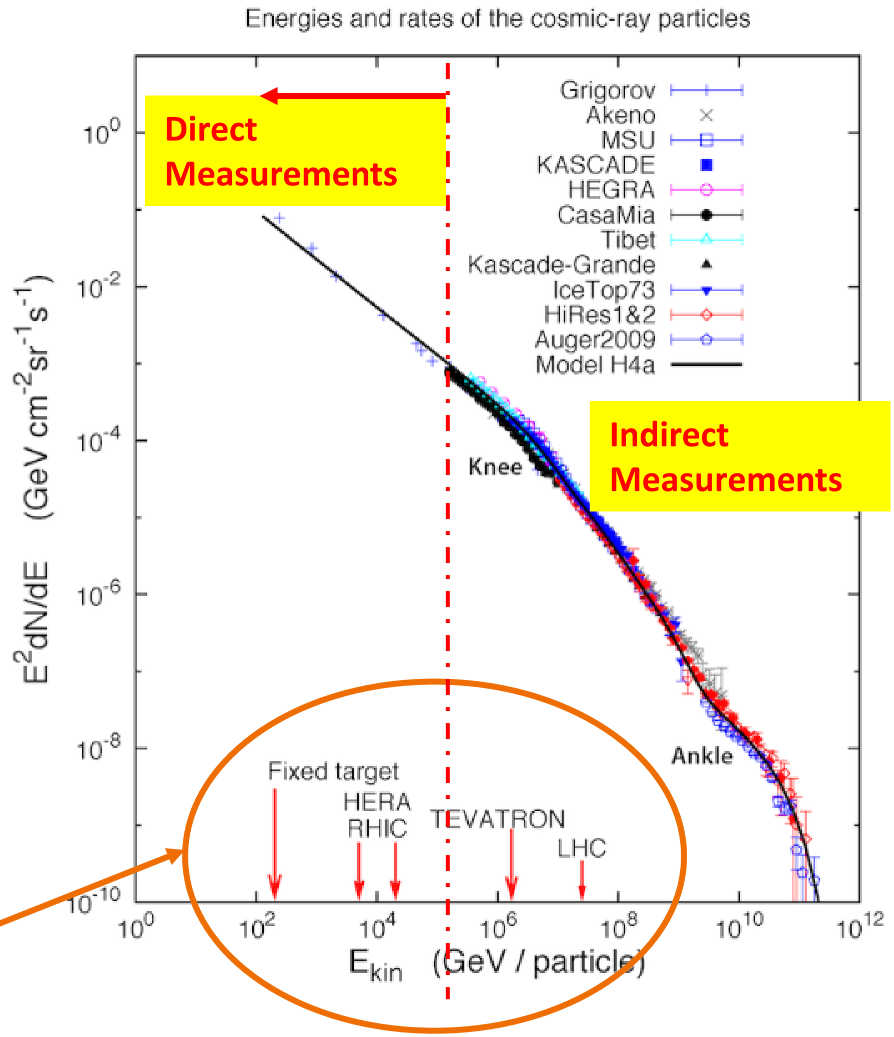
A change in differential flux slope is seen at the level of **knee** and **ankle**

The cosmic rays acceleration is due to different sources:

- **Galactic**
  Supernovae Remnant, Pulsar, Pulsar Wind Nebulae
- **Extragalactic**
  Active Galaxy Nuclei, Gamma Ray Bursts

The maximum energy reachable depends on the source!

The most energetic particles probe a range unreachable by accelerators



Direct Measurements

Indirect Measurements

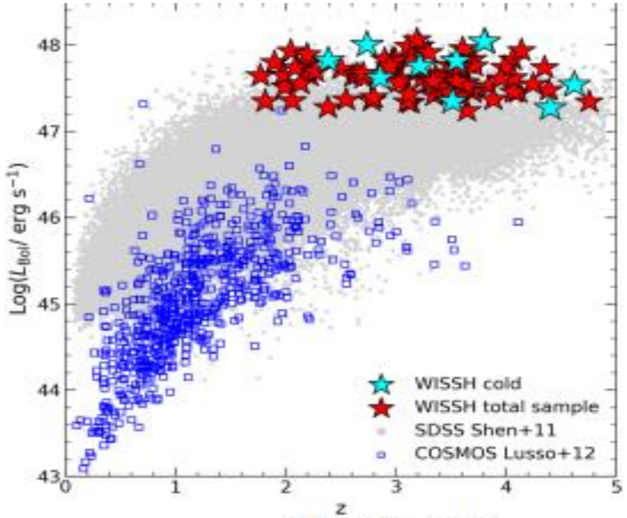
Active Galaxies

“Active galaxies” is a general term that refers to a wide range of phenomena, that can be classified based upon:

1. **Radio-emission**
2. **Optical luminosity**
3. **Orientation towards the observer**

Active galaxies represent **1% of total galaxies**

$$1\ \text{erg} = 10^{-7}\ \text{J}$$



P. Padovani – ν-2022

Main Characteristics

- Most powerful non-explosive sources
- Emitting regions: few milli-parsec
- Strong evolution: higher powers in the past, peak at z=2
- Broad-band emission

What are the **emission mechanisms** involved?

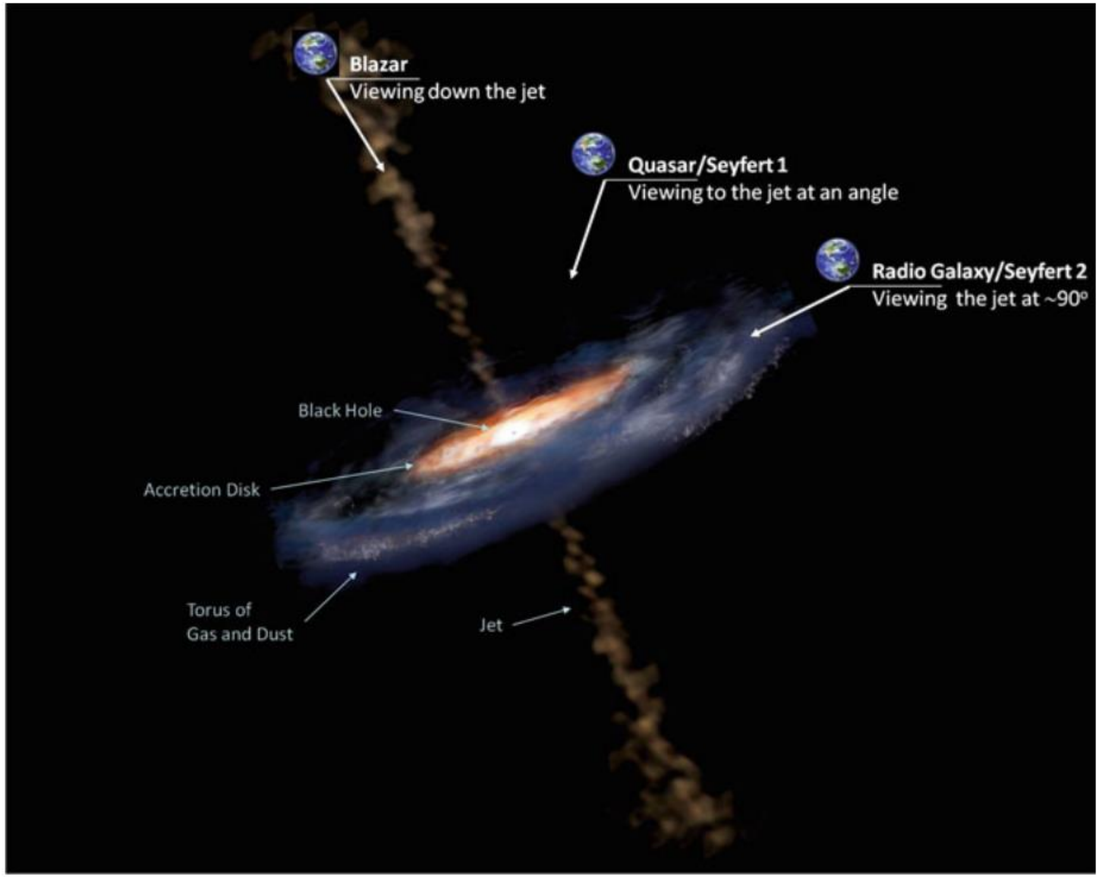
1. **Thermal radiation (90% of AGN):**
   Originating from the heated in-falling matter in the accretion disk near the central black hole
   Thermal dominated or disk dominated AGN

2. **Nonthermal emission:**
   Particles are accelerated in a jet of material ejected from the nucleus
   Jet dominated AGN

Jet dominated AGN

They corresponds mostly to **radio loud AGN**

They can be classified based upon **their jets orientation w.r.t. Earth**:



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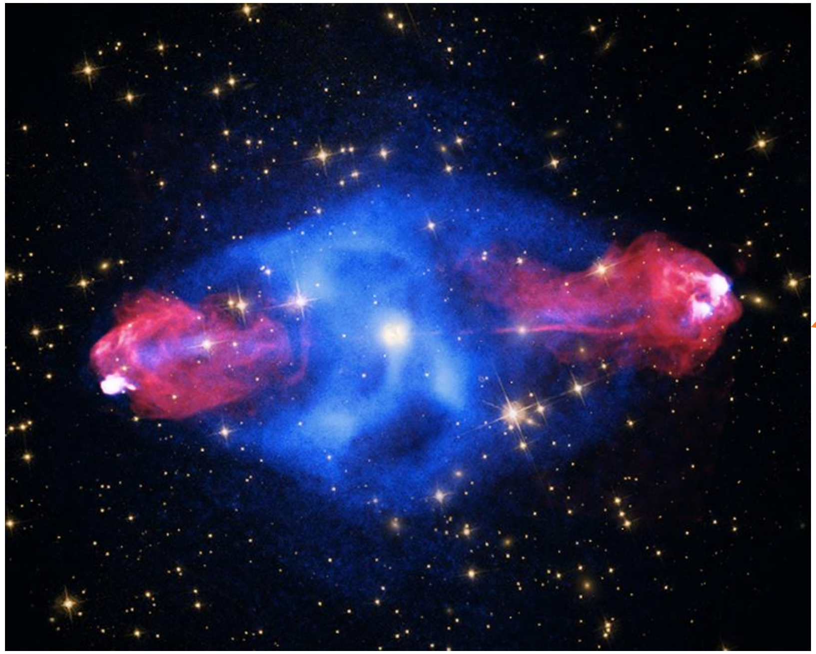
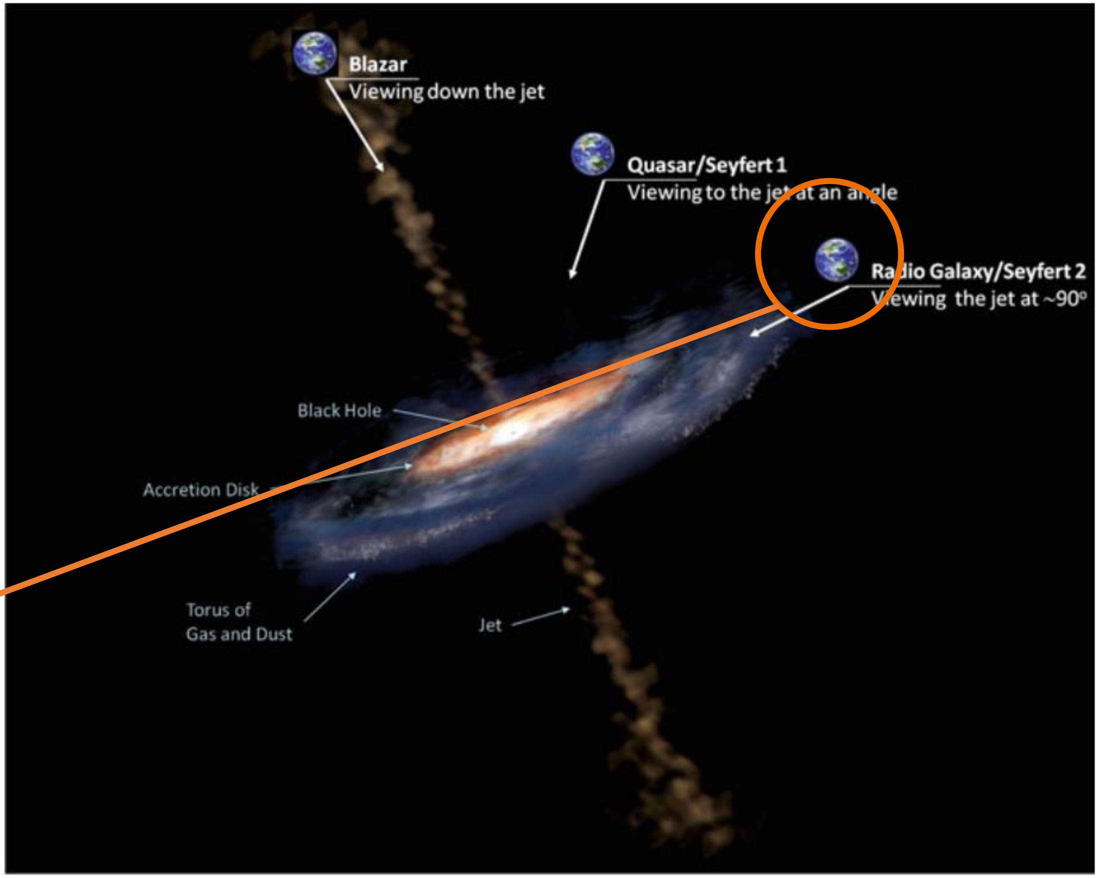
1. **Nonaligned AGN**
- **Radio Galaxies**

Red:
Hot spot emission
300k l.y. away from
the centre

Blue:
X-rays



Cygnus A
Chandra/Hubble/VLA
7×10^8l. y. away



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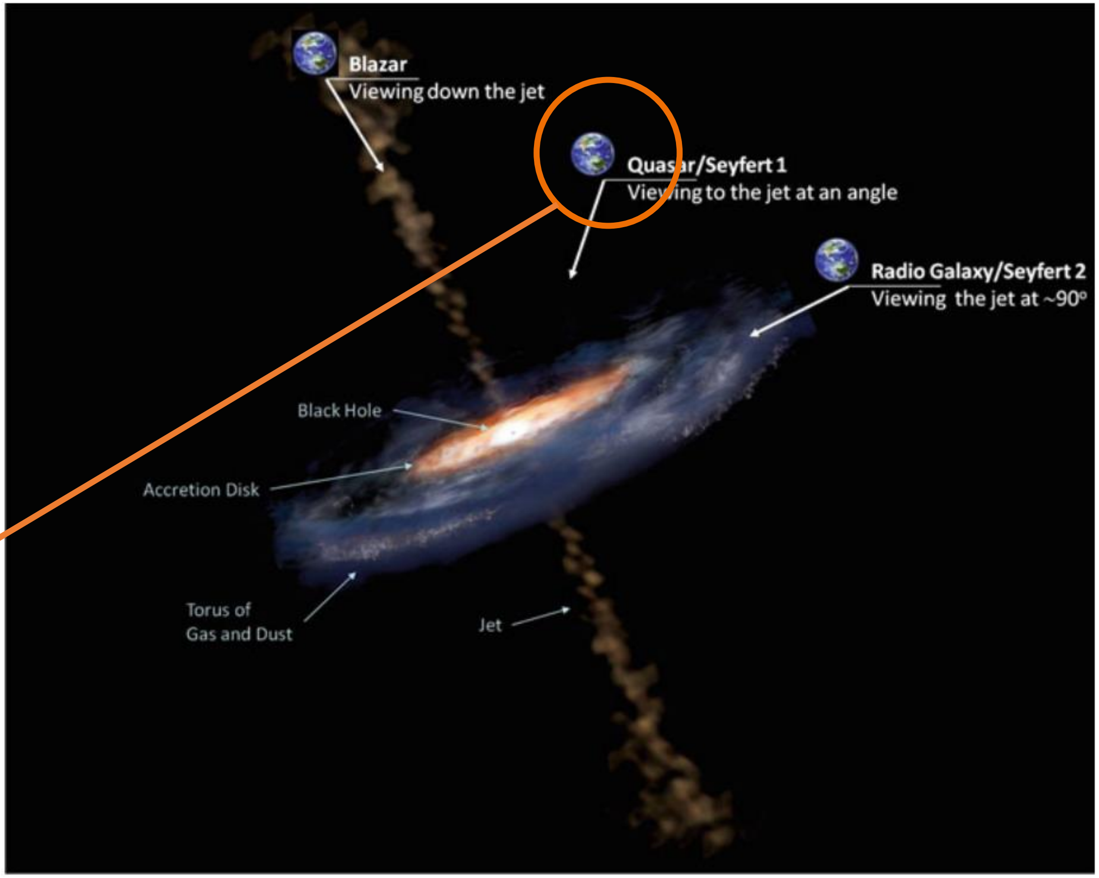
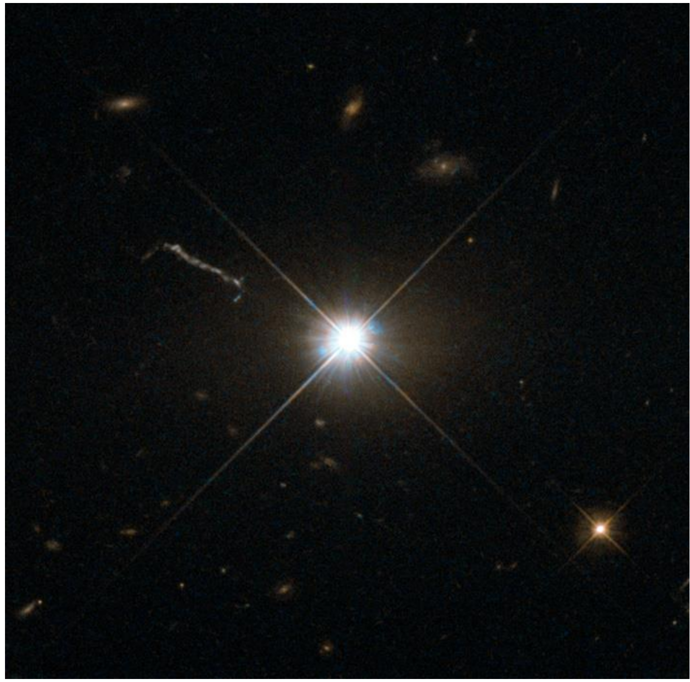
- **Radio Galaxies**
- **Quasars**





Quasar 3C 273

$2.4 \times 10^9 \mathrm{l.y.}$ away

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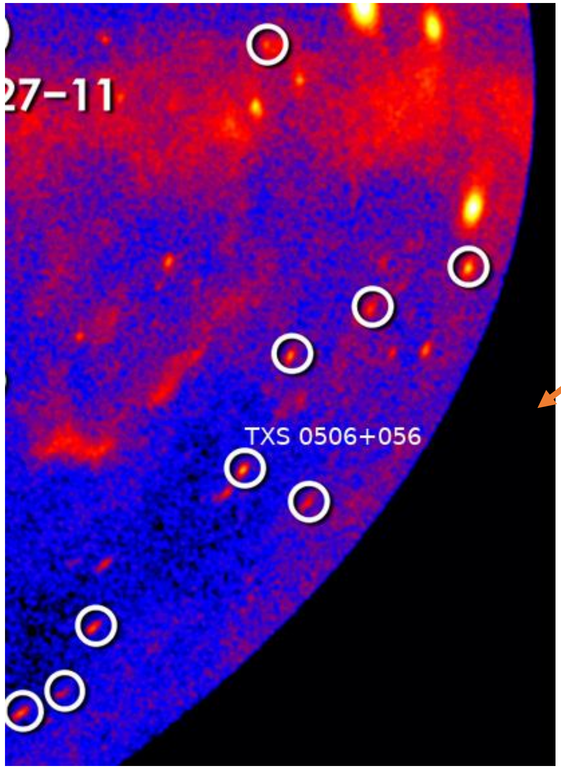
1. **Nonaligned AGN**

- **Radio Galaxies**
- **Quasars**

2. **Blazars**

Strong and rapid variability

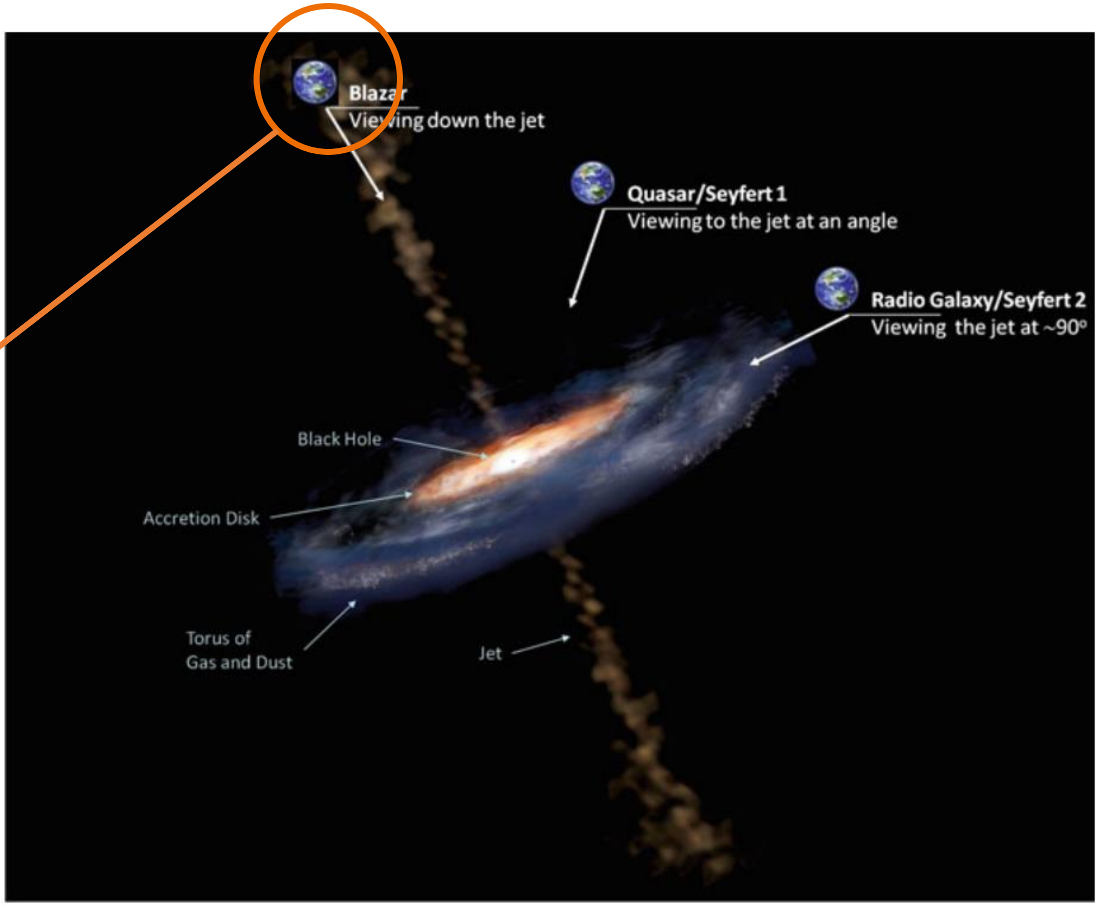
Relativistic effects



TXS0506+056

Fermi Gamma Ray Telescope at Energy > 1 TeV

5.7×10^{9}l. y. away



Blazars make up to 55-90% of Fermi sky (50 MeV-1 TeV)

90% of extragalactic sources with E>1 TeV are blazars

Jets Emission Models

What are jets made of?

1. Electrons
2. Hadrons
3. Both

We should rely on **neutral particles**

Hadronic Models
- p+p collision
- photoproduction

↓

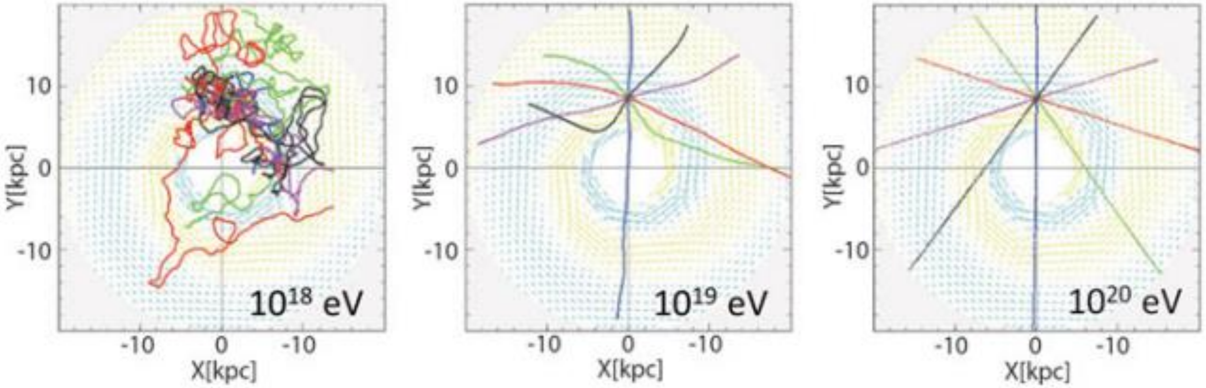
Photons and Neutrinos

Leptonic Models
- Synchrotron emission
- Inverse Compton scattering
- Synchrotron Self-Compton

↓

Photons

Charged particles are influenced by Magnetic Fields



The energy escaping from the source is shared among high-energy protons, photons and neutrinos.
Medium should be **transparent** enough:

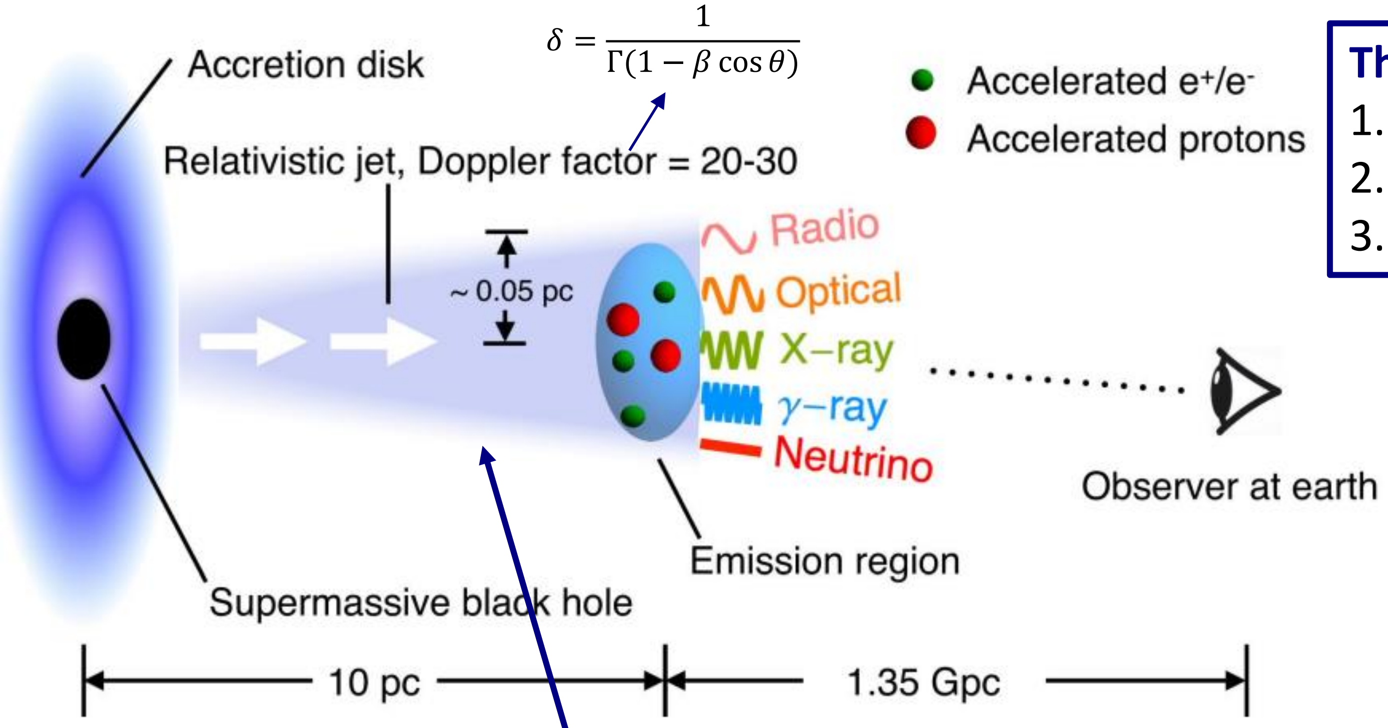
1. Much larger than **proton mean free path**
2. Smaller than **pion interaction length**

$$\phi_{CR}(E) \propto E^{-\alpha_{CR}} \longrightarrow \alpha_{CR} \sim \alpha_{\nu} \sim \alpha_{\gamma}$$

Neutrinos can demonstrate the presence of hadronic mechanisms at work!

Jets in AGN

Jets are a source of **non thermal emission**
Not enough evidence to support one of the theoretical models as explanation



The leading proposed model is the following:

1. Matter in the accretion disk falls into black hole
2. Gravitational energy is converted into **kinematic energy**
3. Velocity can arrive up to give $\Gamma \sim 50$

The jet region is very difficult to probe, we can study:

1. Time variability
2. Interferometry with radio telescopes

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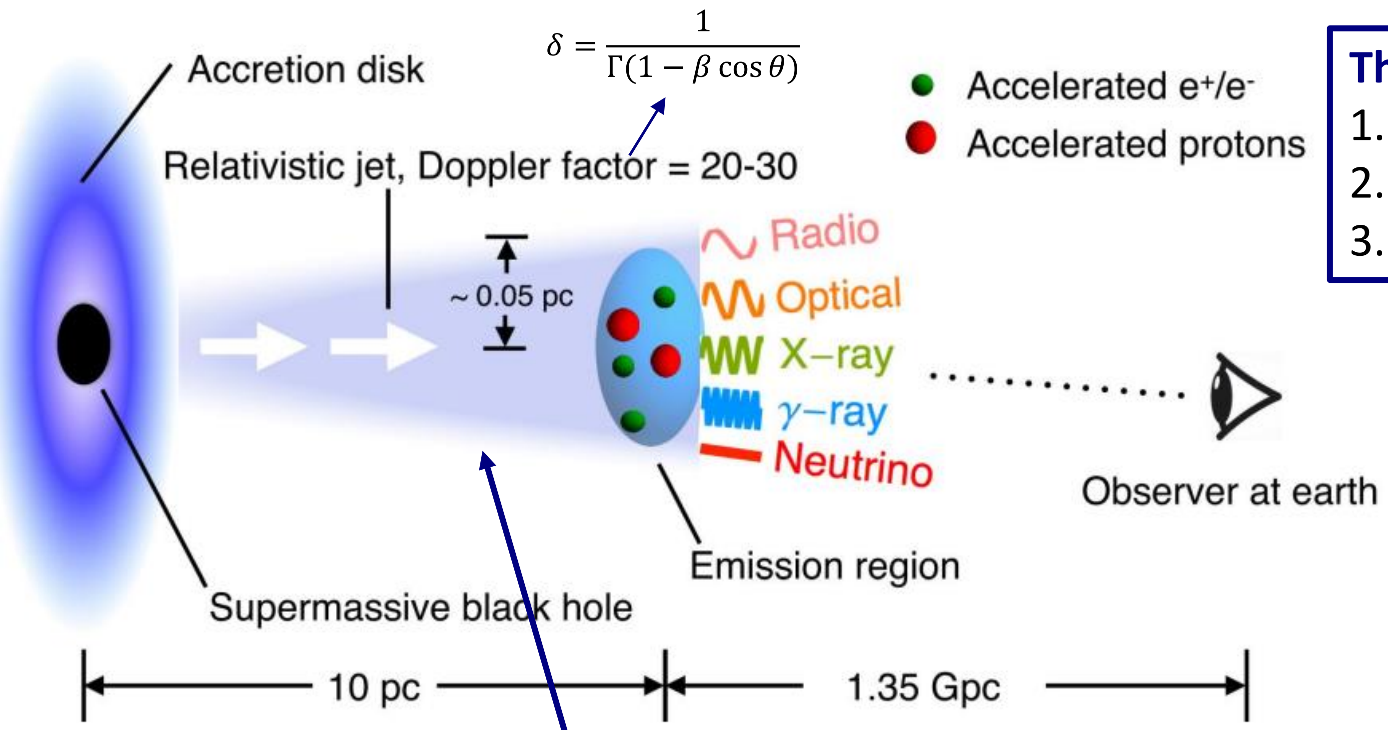

$$\delta = \frac{1}{\Gamma(1-\beta\cos\theta)}$$

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Open questions:

- Leptonic or hadronic origin of emitted γ −rays
- Point of emission along jets

The region of emission has a relation with **time variability in the photon flux**

$$R \sim 10^{15} \cdot \left(\frac{\Gamma}{10}\right) \cdot \left(\frac{\Delta t_{\mathrm{TeV}}}{1\ \mathrm{h}}\right) \mathrm{cm}$$

$\Delta t \sim 1\ h$ is linked with $R_{sch} \sim \frac{2GM}{c^2} \rightarrow M_{bh} \sim 10^9 M_{sun}$

The jet region is very difficult to probe, we can study:

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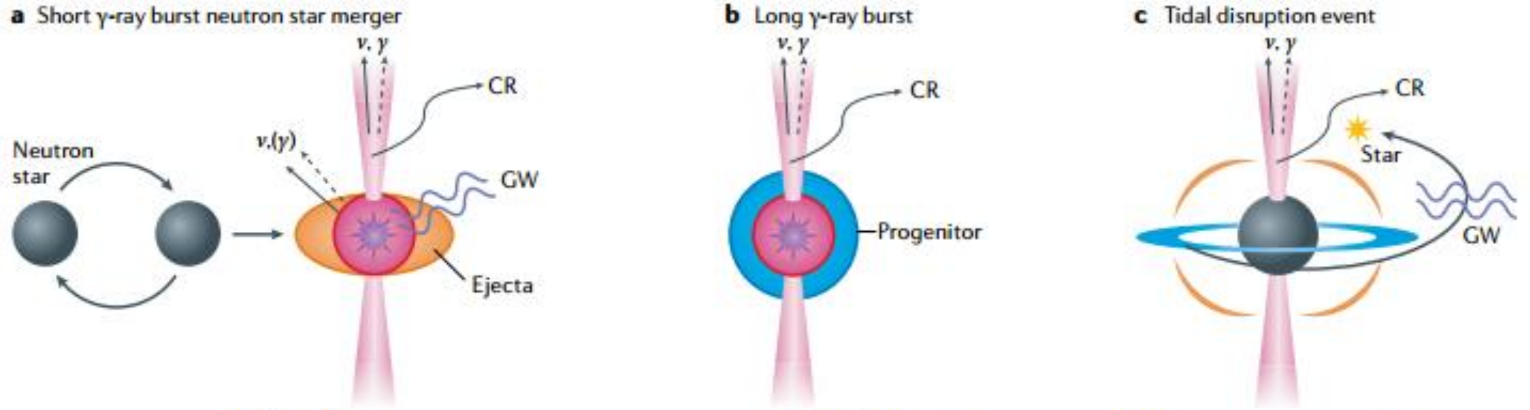
Multi-messenger Astrophysics

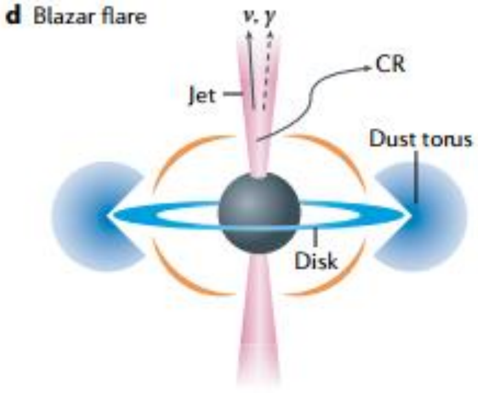
It gives a unique insight on astrophysical phenomena by combining information of:

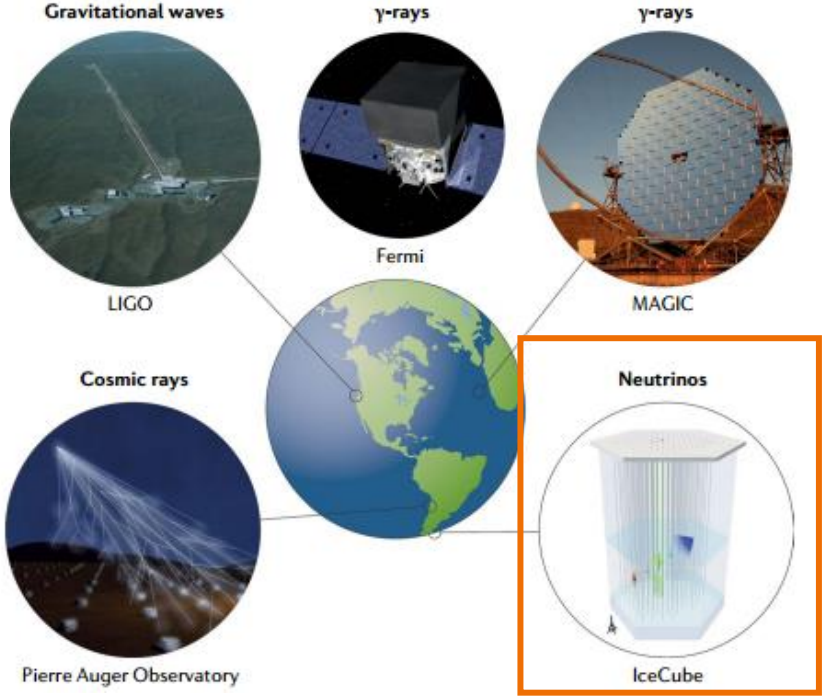
- Photons
- Cosmic Rays
- Neutrinos
- Gravitational waves

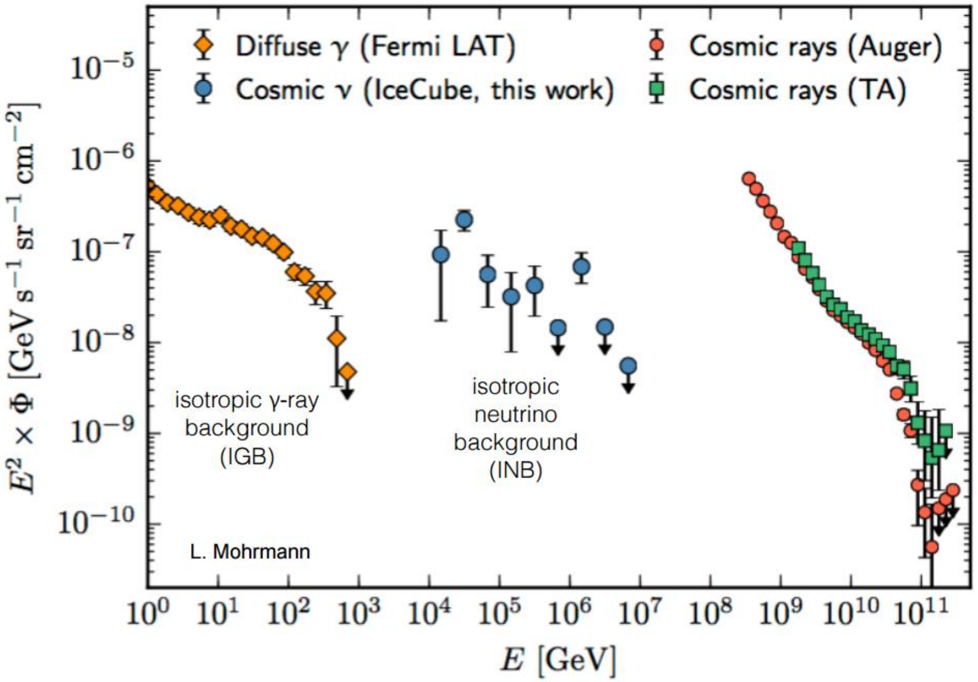
Earliest multi-messenger neutrino detection:

- Solar neutrinos from Sun in Homestake mine
- Neutrinos from SN1987A





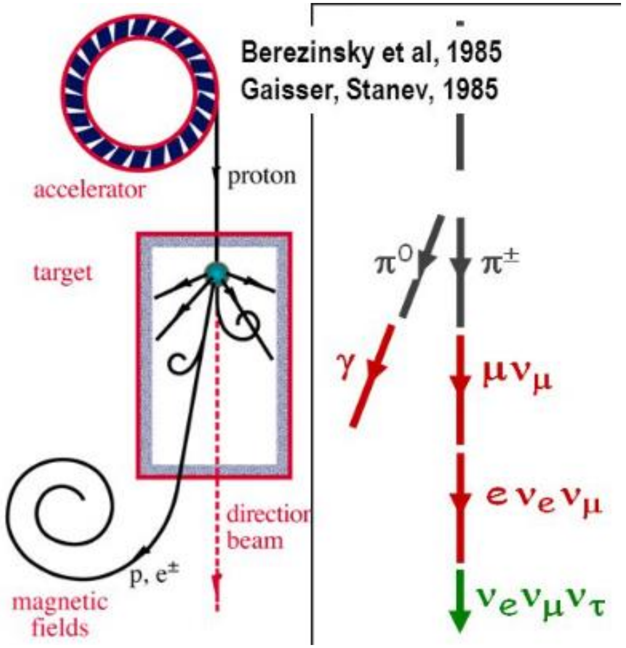




The detection of neutrinos from blazar TXS 0506+056 was the first association of UHE neutrinos with a known source

High-Energy Neutrino Astrophysics

Neutrinos are produced in **hadronic processes** caused by highly energetic protons interacting with particles near the acceleration site, like in a **beam dump.**



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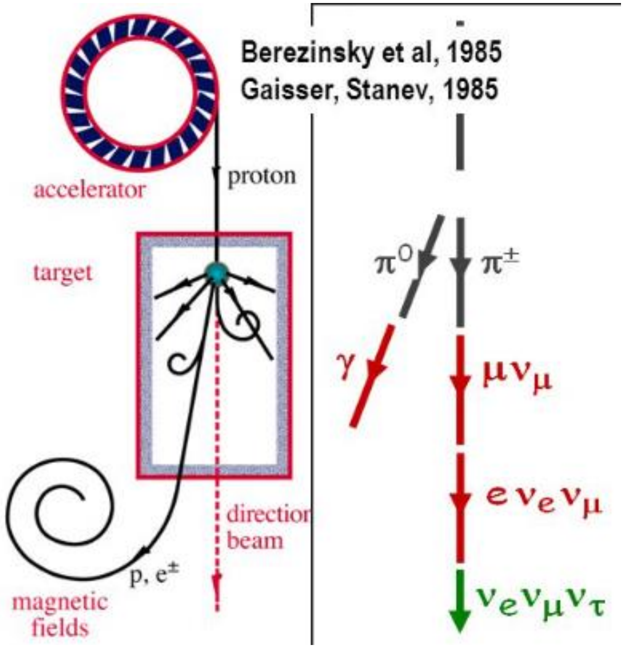

$$p + p \to \pi^+ + \pi^- + \pi^0 + X$$

$$\pi^0 \to \gamma + \gamma$$

$$p + \gamma \to \Delta^+ \to \begin{cases} p + \pi^0 \\ n + \pi^+ \end{cases}$$

$$\pi^+ \to e^+ + \boxed{\nu_\mu + \overline{\nu_\mu} + \nu_e}$$

In photoproduction processes: $E_\nu \sim \frac{1}{20} E_p$

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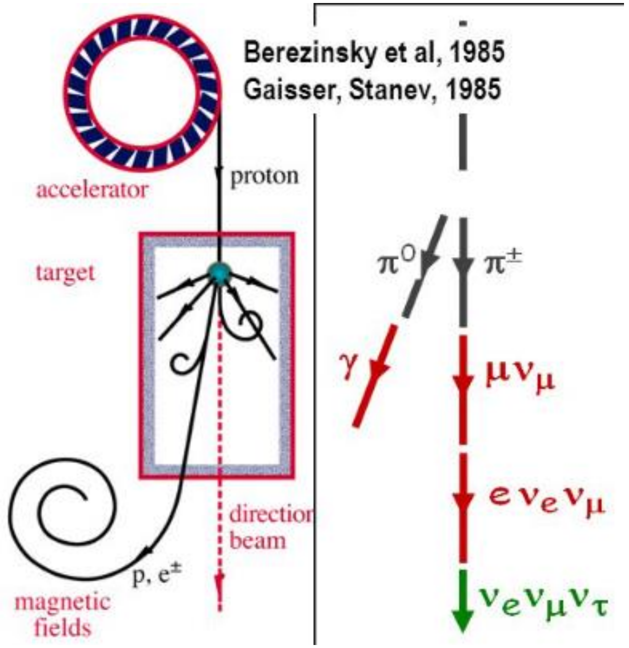

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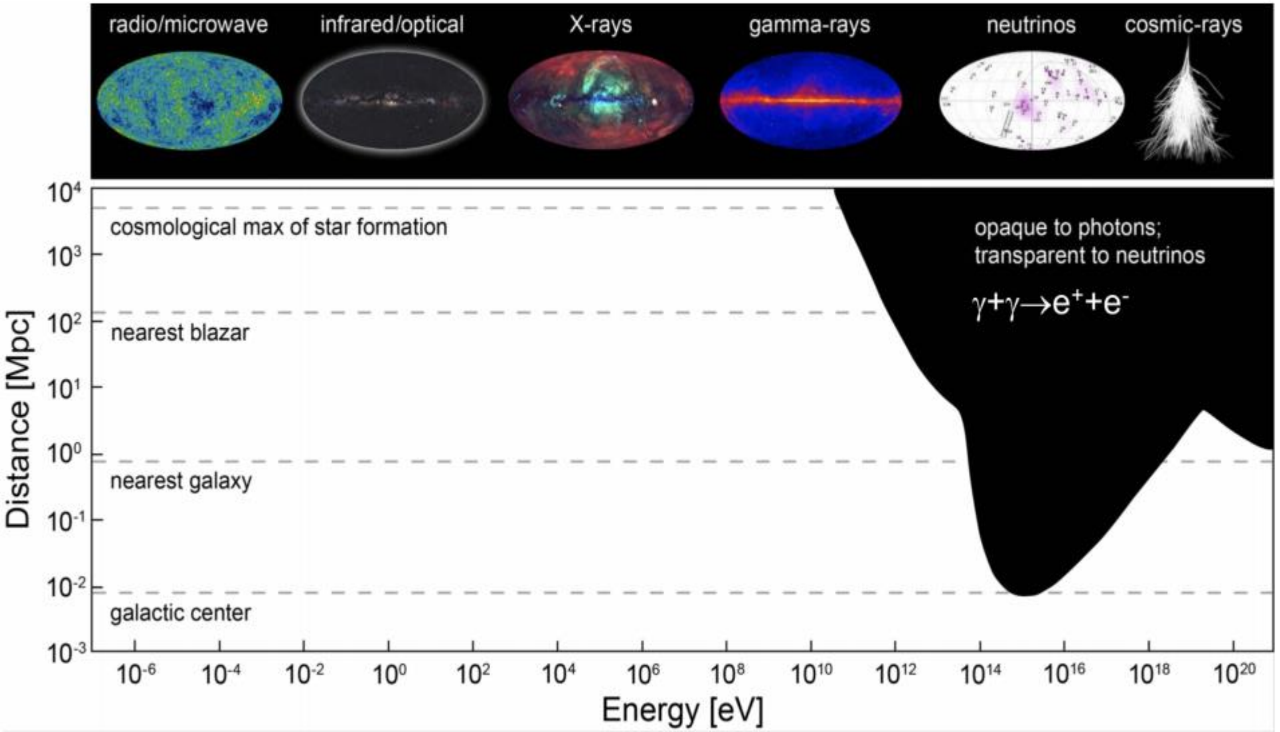

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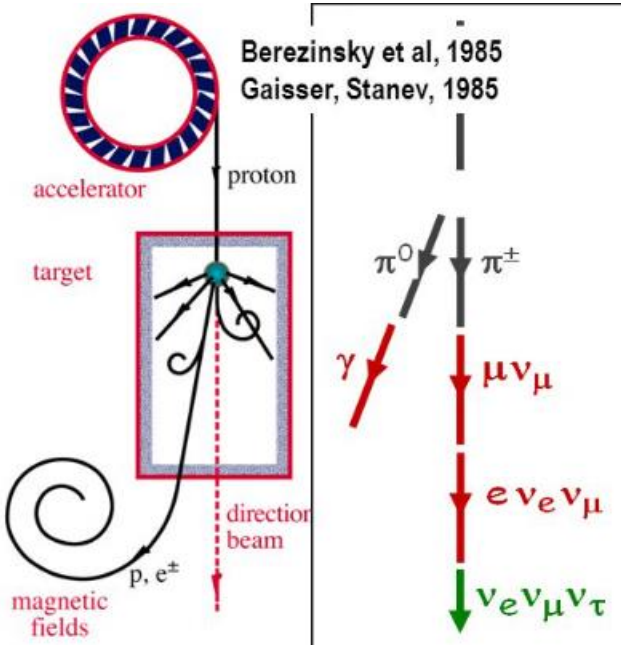

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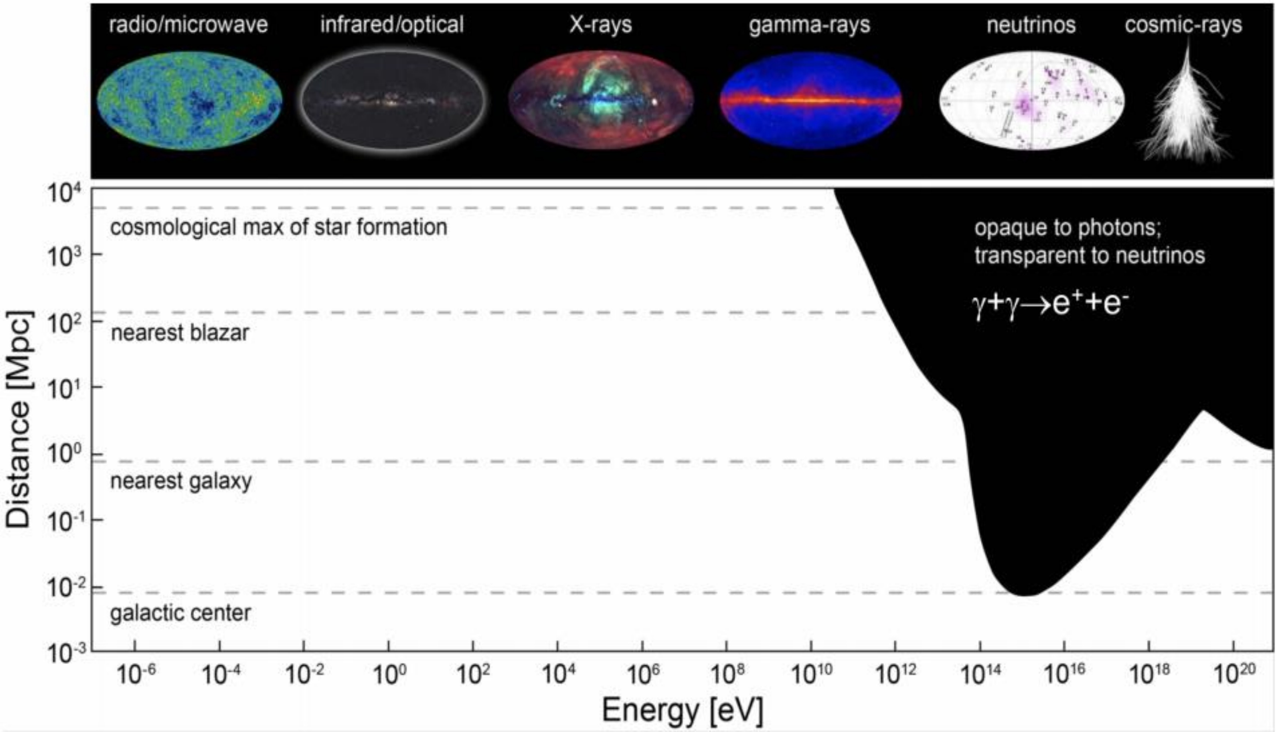
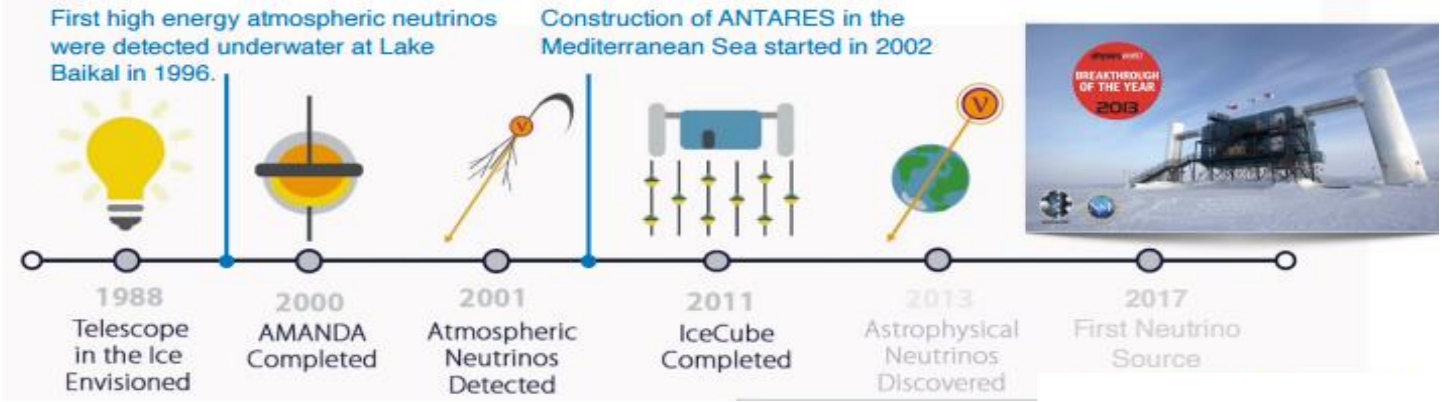




Neutrino detection has to face many challenges due to:

- Small cross section
- Large background

Neutrino Interaction with matter

High energy neutrinos interact with a **nucleon N** via:

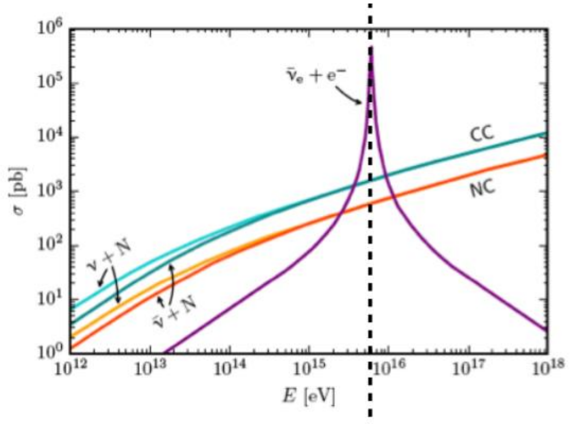
- **Charged Current (CC)** interaction $\nu_l + N \rightarrow l + X$
- **Neutral Current (NC)** interaction $\nu_l + N \rightarrow \nu_l + X$

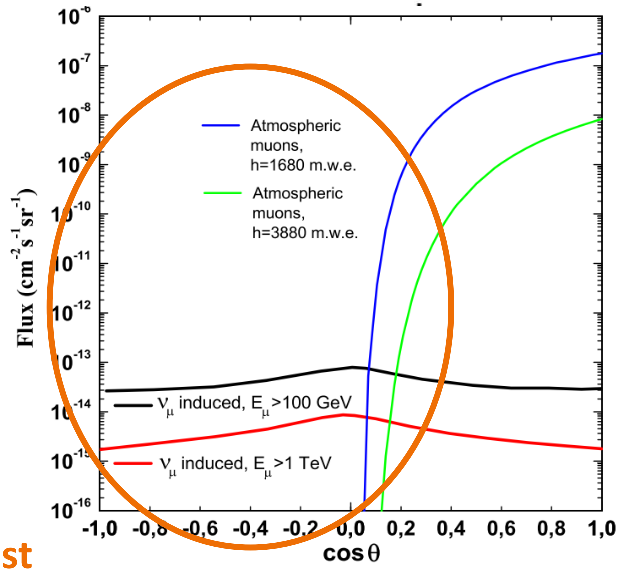
For CC interactions:

$$\frac{d^2\sigma_{\nu N}}{dxdy} = \frac{2G_F^2 m_N E_\nu}{\pi} \cdot \frac{M_W^4}{(Q^2+M_W^2)^2} \times [xq(x,Q^2) + x(1-y)^2\bar{q}(x,Q^2)]$$

- Angular resolution is achieved only thanks to CC interactions

Up to 10^{13} eV, the increase is **linear**





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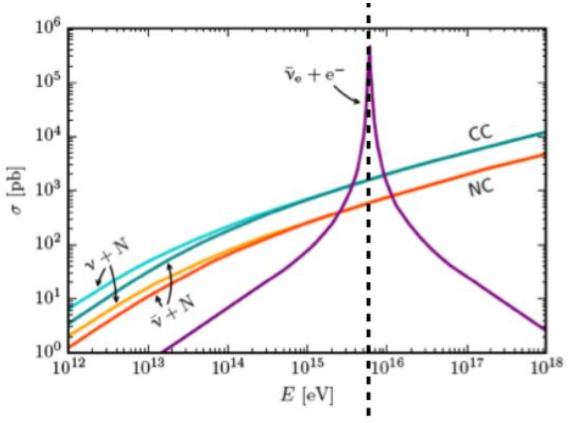


Neutrino detection example

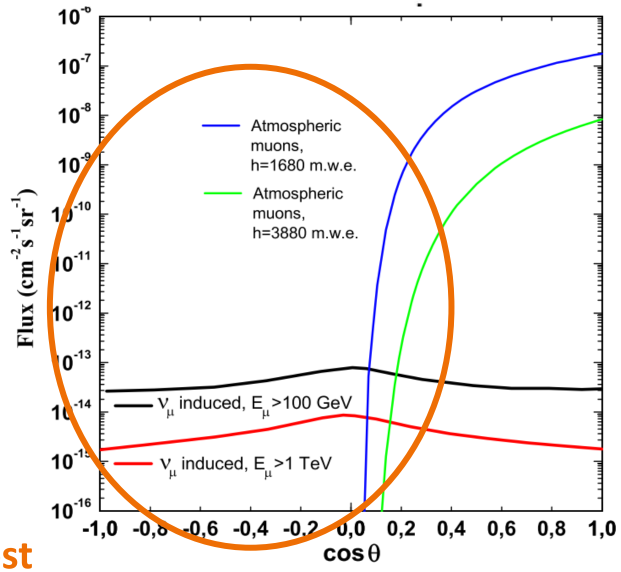
The flux of incoming photons is related to the one from Crab Nebula:

$$\mathrm{E}_\gamma^2 \frac{\mathrm{d}\phi_\gamma}{\mathrm{dE}_\gamma} = 10^{-11}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{TeV} = 1\ \mathrm{C.U.}$$ →

From recent observations at 1 TeV:

$$I_0 = (3.76 \pm 0.07_{stat}) \times 10^{-11} cm^{-2} s^{-1} TeV^{-1}$$

Assumption: $\mathrm{E}_\gamma^2 \frac{\mathrm{d}\phi_\gamma}{\mathrm{dE}_\gamma} \sim \mathrm{E}_\nu^2 \frac{\mathrm{d}\phi_\nu}{\mathrm{dE}_\nu}$



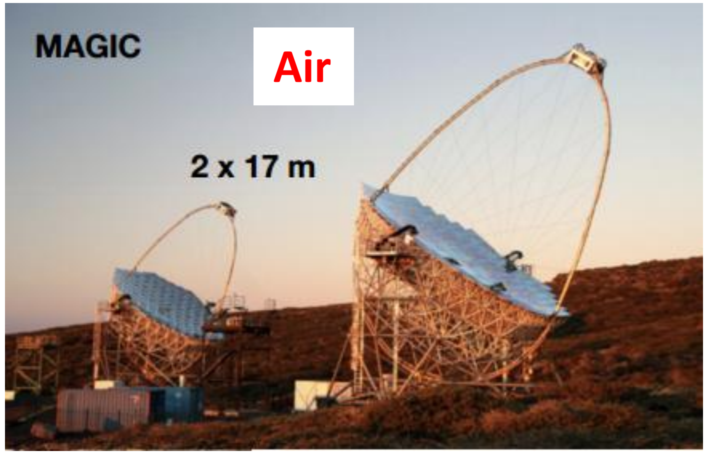
Neutrinos up-going are almost background free!

In an experiment like IceCube $N(E_\mu > 1\ \mathrm{TeV}) \sim 2.8\ \mathrm{yr}^{-1}$

Cherenkov Radiation

Cherenkov radiation arises any time a **charged** particle travels in a **medium** with a speed larger than the one of the light in that medium

$$\boxed{\beta > \frac{1}{n}}$$



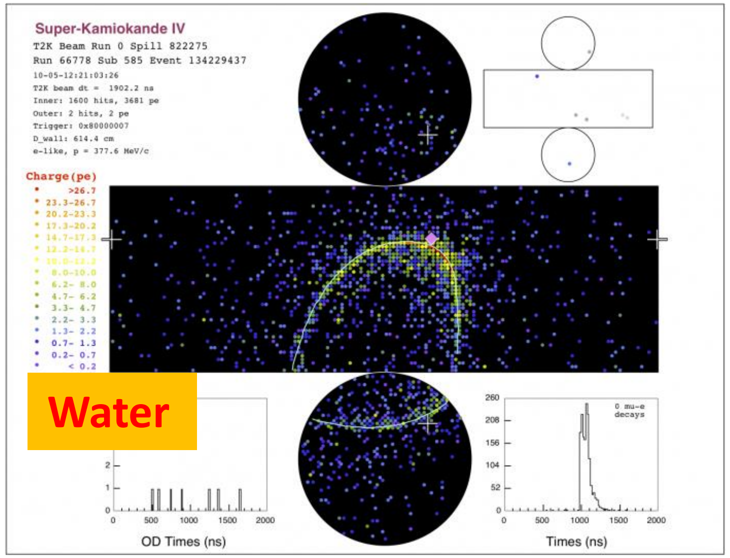
This means that there is an **energy threshold** depending on the **refraction index** $n(\lambda)$

A wave front arises with a given angle:

$$\boxed{\cos\theta_C = \frac{1}{\beta n}}$$

The light yield for Cherenkov photons is:

$$\frac{d^2N}{dx\,d\lambda} = \frac{2\pi\alpha Z^2}{\lambda^2}\sin^2\theta_C = \frac{2\pi\alpha Z^2}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2}\right) \propto \frac{1}{\lambda^2}$$



The total light that a PMT receives is: (we need to take into account the PMT efficiency)

$$\frac{dN}{dx} = \int_{\lambda_1}^{\lambda_2} \frac{2\pi\alpha Z^2}{\lambda^2}\sin^2\theta_C\, d\lambda \sim 400 - 500\sin^2\theta_C$$

Typical media:

Water

Air

Ice

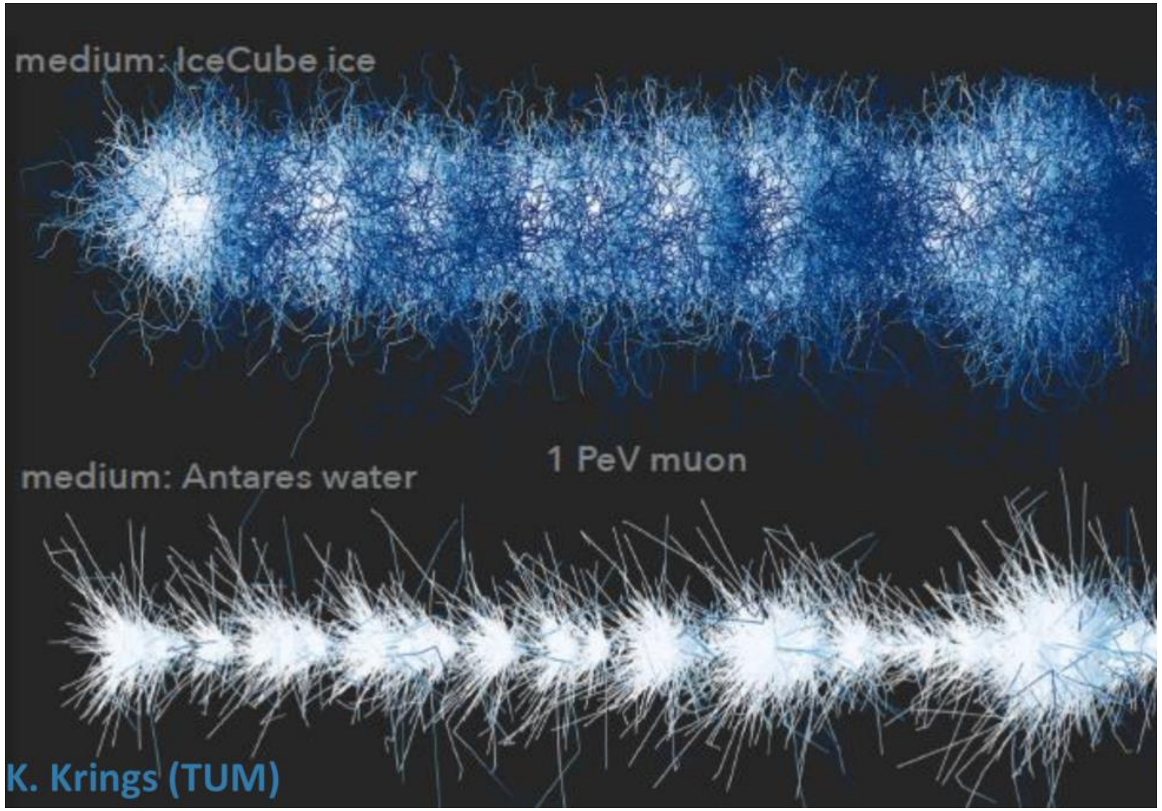
Particle detection in transparent media

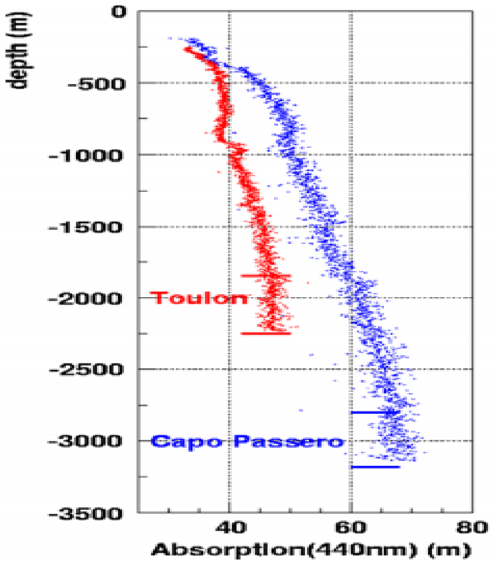
Water

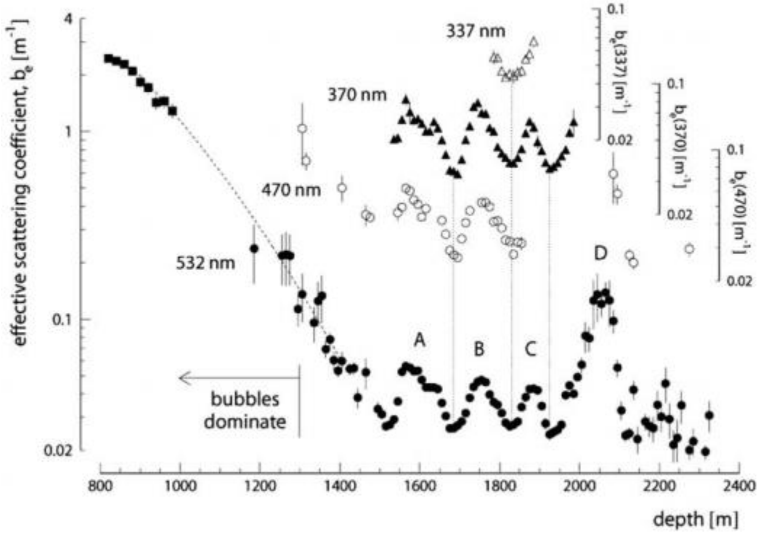
1. Transparent in a narrow range $350\ \mathrm{nm} \leq \lambda \leq 550\ \mathrm{nm}$
2. Absorption length $\lambda_{abs} \sim 70\ \mathrm{m}$
3. Larger scattering length
4. Background from bio-luminescence

Ice at South Pole

1. Absorption length $\lambda_{abs} \sim 100\ \mathrm{m}$ maximum in blue region
2. Smaller scattering length
3. Impurities trapped such as **bubble** and **dust**
4. Large formation time







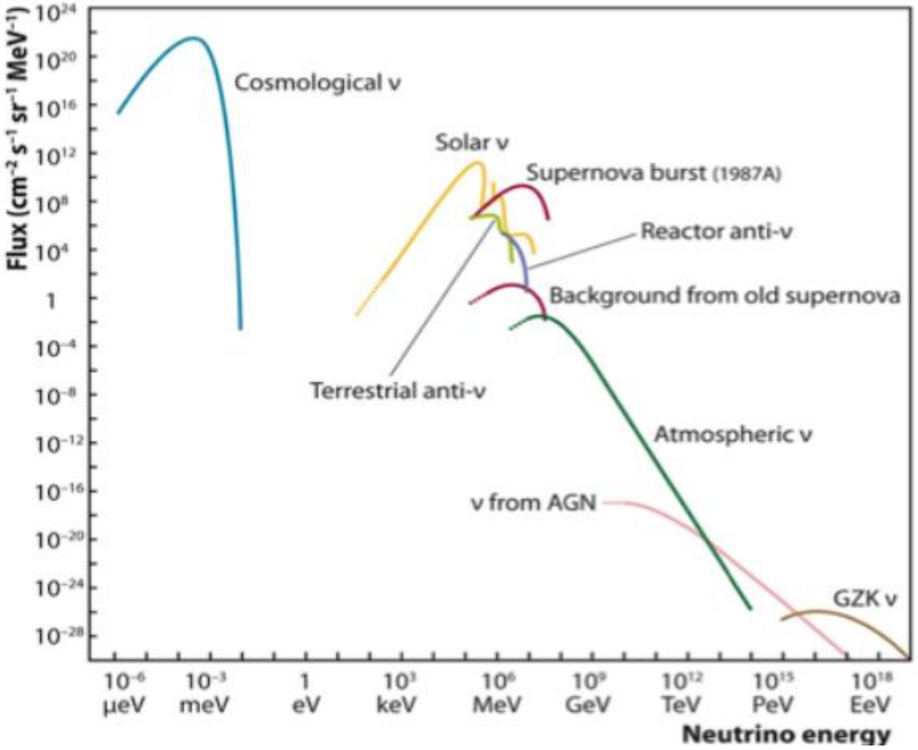
The Waxman-Bachall Bound

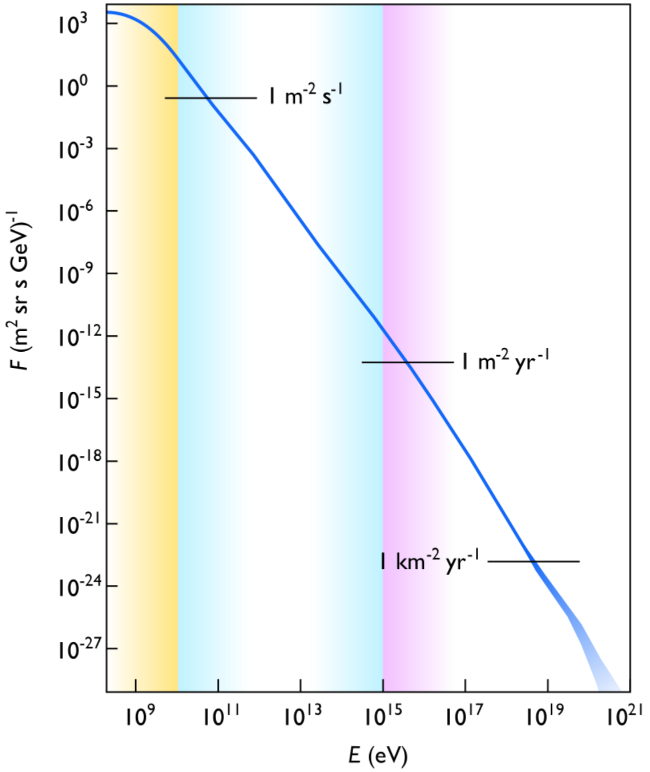
What is the limit that we can expect from UHE neutrinos?
Cosmic rays are well characterized at energies $\geq 10^{19}\mathrm{eV}$
The idea is to derive a **model independent** bound on the flux of associated neutrinos

Assumptions:

1. Protons are accelerated with a power-law spectrum of $\Gamma = 2$
2. All protons undergo p-γ or p-p interactions, producing:
   Neutrons, neutrinos, photons
3. Sources are **thin** to neutrons:
   Neutrons can escape the interaction regions and decay
   $$n \rightarrow p + e^- + \overline{\nu_e}$$
4. Luminosity evolution of far away source is not stronger than all known sources

$$\boxed{\mathrm{E}_\nu^2 \phi_\nu < 2 \times 10^{-8} \frac{\mathrm{GeV}}{\mathrm{cm}^2 \mathrm{s\ sr}}}$$





Expected event rate in a neutrino telescope

$$\frac{N_\mu\left(E^\mu_{thr}\right)}{\boxed{T}} = \int dE_\nu \frac{d\phi_\nu}{dE_\nu}(E_\nu)\cdot \underbrace{\boxed{A}\cdot\boxed{P_{\nu\mu}\left(E_\nu, E^\mu_{thr}\right)}\cdot\boxed{e^{-\sigma(E_\nu)\rho N_A Z(\theta)}}}_{A^{eff}_\nu = \frac{N_x}{N_{gen}} \times V_{gen}(\rho N_A) \times \sigma(E_\nu) \times e^{-\sigma(E_\nu)\rho N_A Z(\theta)}}$$

Neutrino absorption in Earth

Probability of a neutrino to produce a muon

Detector area

Observation time

From Crab Nebula:

$$\frac{\mathrm{N_\mu\left(E^\mu_{thr}\right)}}{\mathrm{T}} \sim \mathbf{2.8\ yr^{-1}}$$

As a result we obtain: $\frac{\mathrm{N_\mu\left(E^\mu_{thr}\right)}}{\mathrm{T}} = 5 \times 10^{-19} \cdot \mathrm{A} \cdot\ \mathrm{cm^{-2}s^{-1}}$

For a 1 TeV muon:

- $\mathrm{R} \sim 2.42\ \mathrm{km} \rightarrow \mathrm{A} \sim 5\ \mathrm{km^2}$

$$\longrightarrow \frac{\mathbf{N_\mu\left(E^\mu_{thr}\right)}}{\mathbf{T}} \sim \mathbf{1\ yr^{-1}}$$

Expected event rate in a neutrino telescope

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Expected photo-electrons in a **1 km^3 experiment:** $N_{p.e.} = \boxed{N_\gamma} \times \boxed{R} \times \boxed{\epsilon_{om}} = 1.8\times10^{-2}\cdot N_{PMT}$

Cherenkov photons emitted by a muon with 1 km range in the PMT working bands $N_\gamma \sim 3.5\times10^7$

Ratio between instrumented and effective volume $R \sim N_{PMT}\cdot\frac{V_{PMT}}{10^9\ m} \sim 2.5\times10^{-9}N_{PMT}$

A photon falling inside a PMT produces a p.e. with a probability of $\epsilon_{om} \sim 0.2$

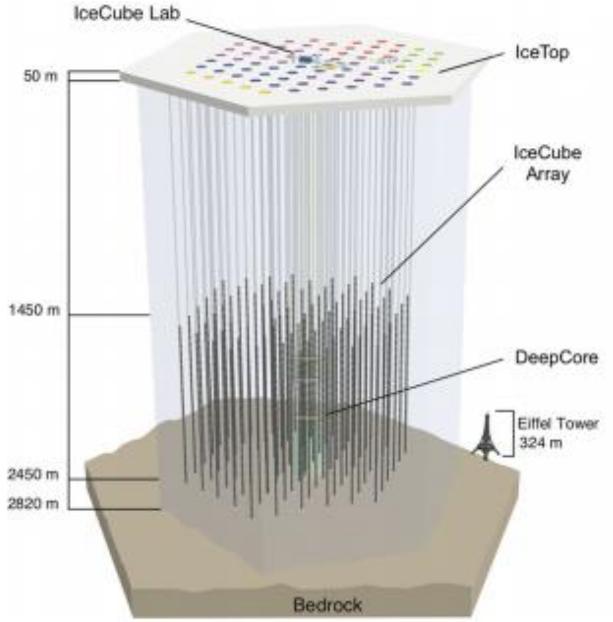
$N_{p.e.} \sim 100\ p.e.$ are needed to affect few tens of OM

$$N_{PMT} \sim \frac{100}{1.8\cdot10^{-2}} \sim \mathbf{5000}$$

- IceCube 4800 O.M.
- Km3Net 6000 O.M.

The IceCube Neutrino Observatory

It consists of a in-ice array (**IceCube**) and a surface air shower array (**IceTop**)



IceCube utilises one cubic kilometer of the deep ultra-clear glacial ice at South Pole as medium
It is instrumented with **5160 Digital Optical Modules (DOMs):**

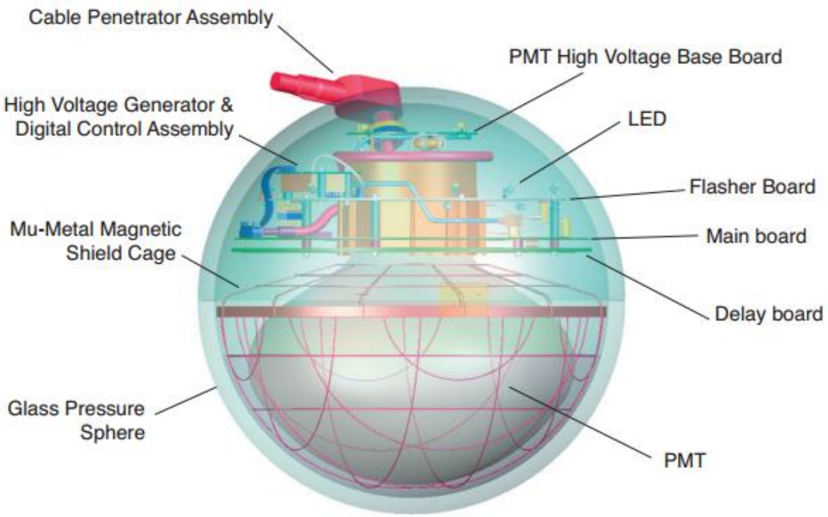
- 86 read-out and support cables
- Depth between 1.5-2.5 km
- 8 central strings are instrumented with a larger number of DOMs

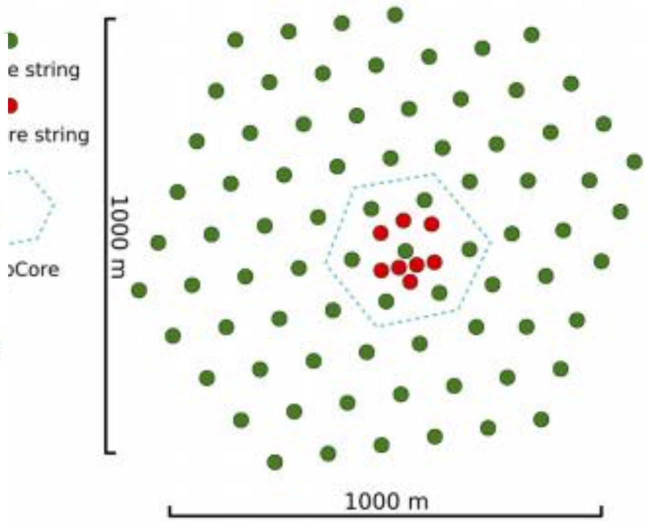
Digital Optical Modules

DOMs are set to operate on single p.e. threshold
Dark noise is of the order of 500 Hz (limit on radioactivity)
Working temperature down to -55°C
90% survival after 15 yr

Search for Neutrinos

Continuous observation since 5 April 2008





Identification of Neutrino sources

- **EM showers**
- **Hadronic showers**
- **Neutral Current Interactions**

Cosmic accelerator
$\nu_e : \nu_\mu : \nu_\tau = 1:2:0$

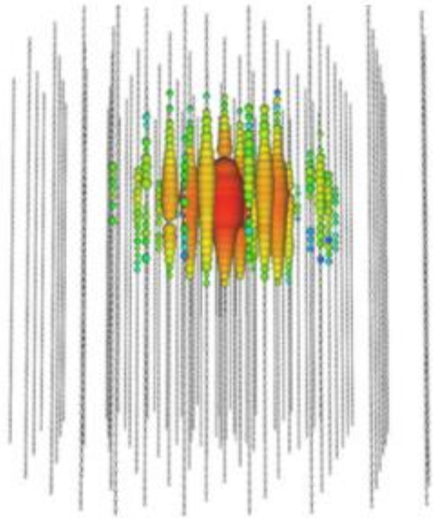
→

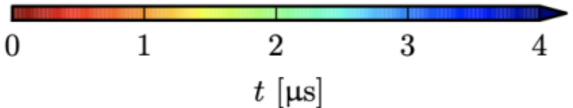
After propagation
$\nu_e : \nu_\mu : \nu_\tau = 1:1:1$

They represent a **point source of Cherenkov photons** radiated by shower particles
Detection of all flavors has become important:

Electron neutrinos

- Deposit of 0.5-0.8% of their energy into an EM shower
- Cherenkov light spreads over a radius of 130 m at 10 TeV
- A direct hit of $10^{15}\mathrm{eV}$ neutrinos will saturate a $1\ \mathrm{km}^3$detector
- shower is elongated





Identification of Neutrino sources

Neutrino telescopes detect the Cherenkov light radiated by secondary particles showers produced by neutrinos of all flavors. It includes:

- **EM showers**
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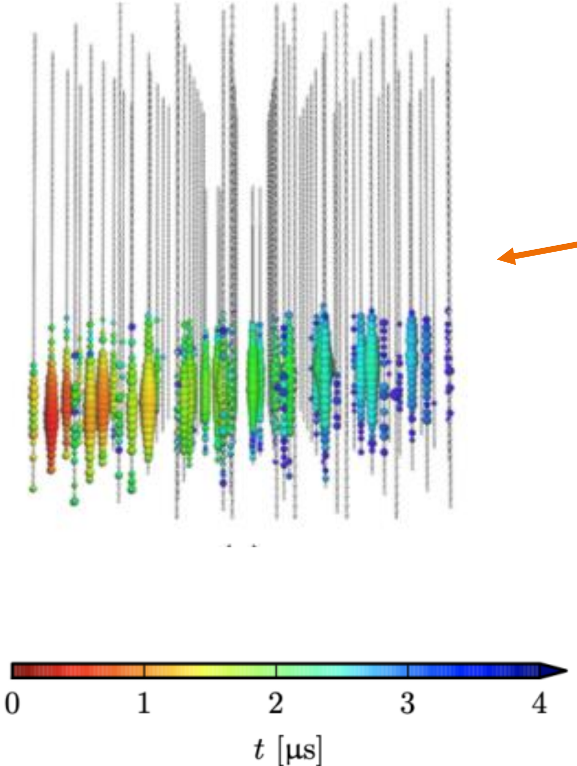
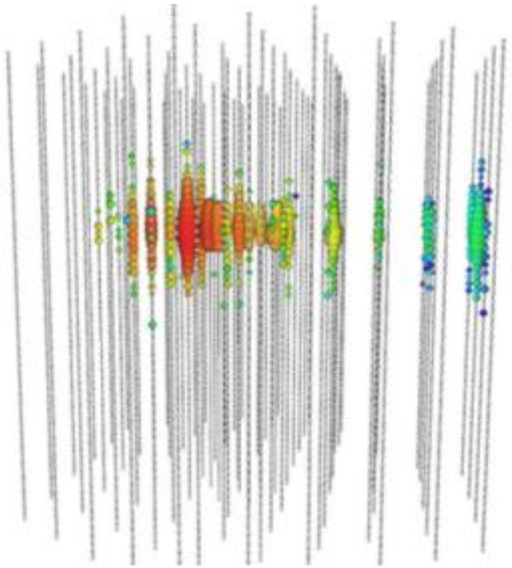


Muon neutrinos

- Muon range is tens of kilometers at 10^{18} eV.
- Km-long cones with gradually decreasing radius:

$$\frac{dE}{dx} = -\alpha - \beta E$$

$$\alpha = 2.0 \times 10^{-6} \text{TeV cm}^2\text{g}^{-1}$$
$$\beta = 4.2 \times 10^{-6} \text{cm}^2\text{g}^{-1}$$



Mean lifetimes
$\tau_\mu = 2.2 \times 10^{-6}\text{s}$
$\tau_\tau = 2.9 \times 10^{-13}\text{s}$

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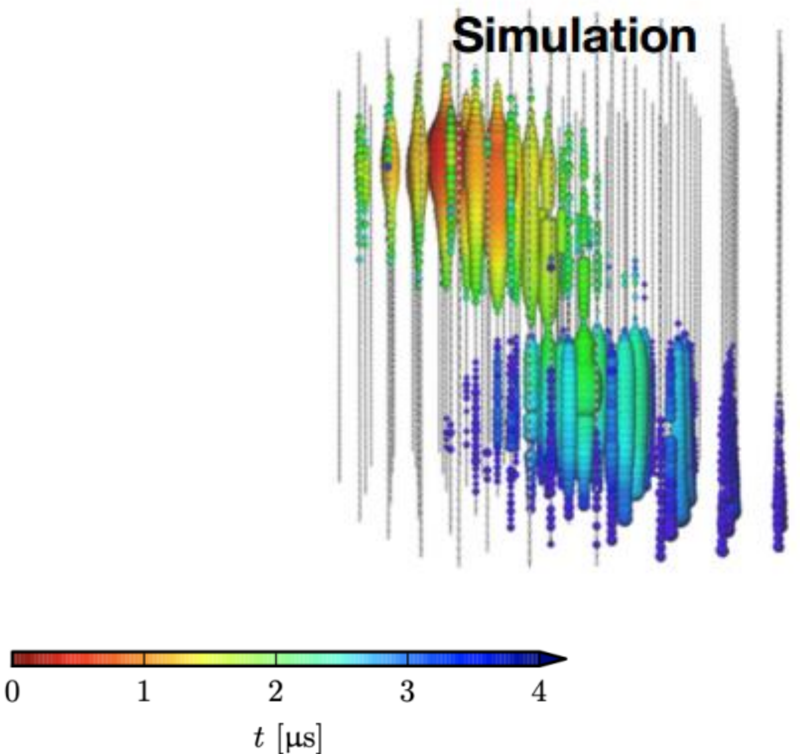

Tau neutrinos

Flux is not attenuated traversing Earth

- Double bang event
- Lollipop

Energy loss is less catastrophic respect to muons

At 10 PeV, probability to detect a double bang is 10% w.r.t. same energy ν_μ.

Mean lifetimes

$\tau_\mu = 2.2 \times 10^{-6}$s

$\tau_\tau = 2.9 \times 10^{-13}$s

Detection of neutrinos from TXS 0506+056

Sky region in which TXS 0506+056 is located is observed **through Earth**

Approximately **70000 neutrino-induced muon** tracks are recorded each year from that emisphere:

- 1% from astrophysical sources
- Background neutrinos with median energy 1 TeV

A **high-significance point-source** detection can require from **2 to 30** signals over background, depending on:

- Energy spectrum
- Clustering in time

$$\frac{\mathrm{dN_{astro}}}{\mathrm{dE}} \sim \mathrm{E}^{-2}$$

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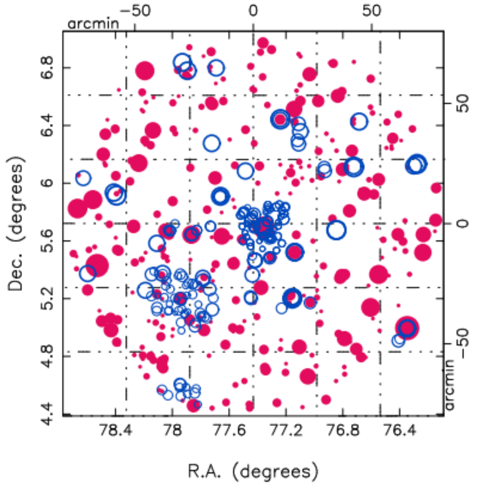
1. IceCube-170922A

An up-going muon track was sent out as an alert

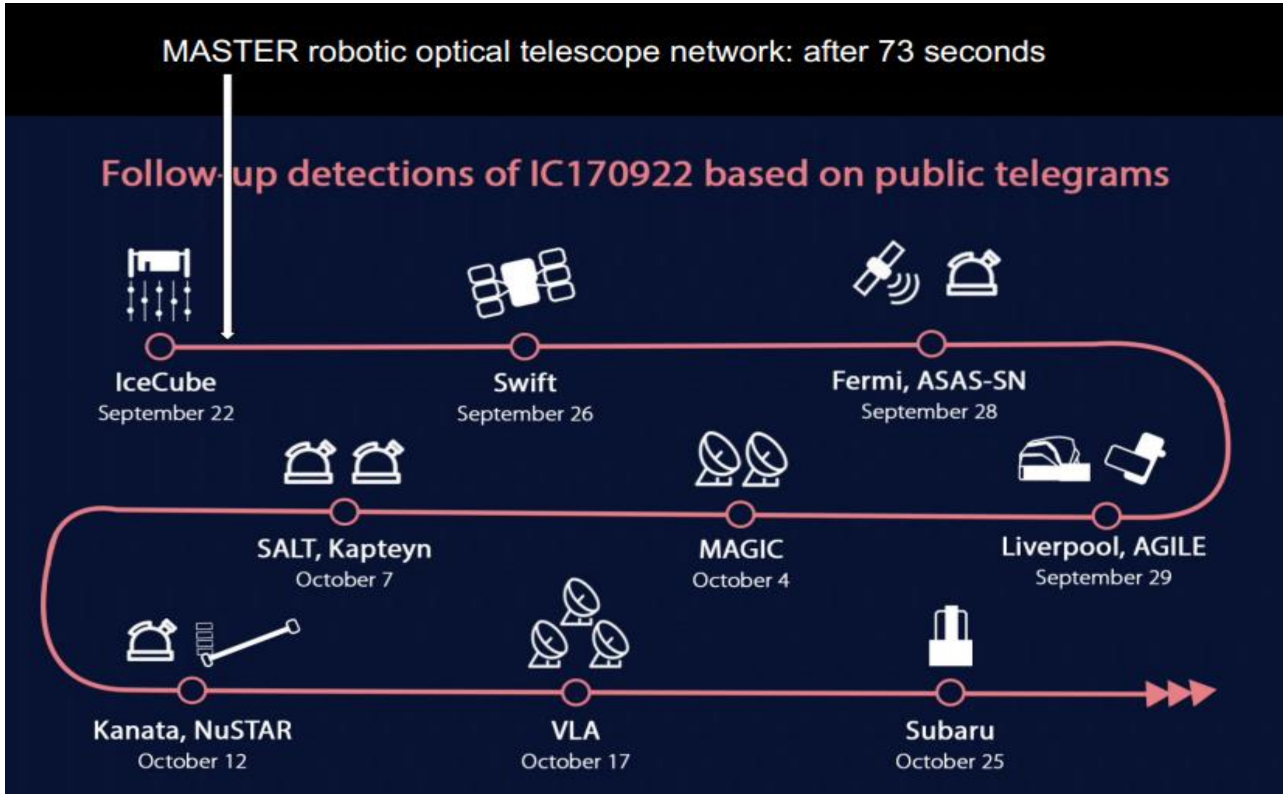
Probable neutrino energy $E_\nu \sim 290\ \mathrm{TeV}$

TXS 0506+056 was found at 0.1° distance

Post-trial chance of coincidence: $3 - 3.5\ \sigma$



Known radio (red) and X-ray (blue) emitters near IceCube-170922A



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2. Archival data Search (2014-15)

Analysis

Power law energy spectrum $E^{-\gamma}$ is assumed

Parameters:

1. Spectral index $\boldsymbol{\gamma}$
2. Flux normalization at 100 TeV $\boldsymbol{\phi_{100}}$
3. Time window $\boldsymbol{T_w}$
4. Starting point $\boldsymbol{T_0}$

↓

Time integrated analysis (9.5 yr sample)

- $\phi_{100} = \left(0.8^{+0.5}_{-0.4}\right) \times 10^{-16}\ \text{TeV}^{-1}\text{cm}^{-2}\text{s}^{-1}$
- $\gamma = 2.0 \pm 0.3$

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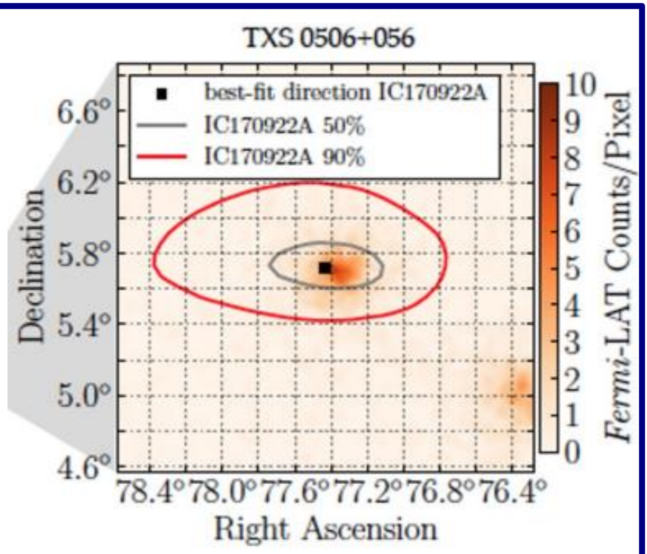
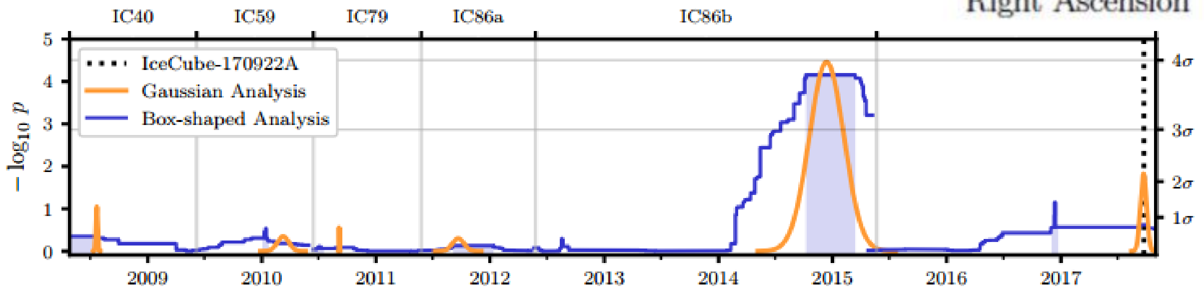
Time dependent analysis

- Gaussian time window
  - $T_w = 110^{+35}_{-24}$ days
  - $E^2 J_{100} = (2.1^{+0.9}_{-0.7}) \times 10^{-4}\ \mathrm{TeV\ cm^{-2}}$
  - $\gamma = 2.1 \pm 0.2$
- Box shaped
  - $E^2 J_{100} = (2.2^{+1.0}_{-0.8}) \times 10^{-4}\ \mathrm{TeVcm^{-2}}$
  - $\gamma = 2.2 \pm 0.2$
  - $\phi_{100} = (1.6^{+0.7}_{-0.6}) \times 10^{-15}\ \mathrm{TeV^{-1} cm^{-2} s^{-1}}$

$J_{100} = \int \phi_{100}(t)dt$





TXS 0506+056 properties (I)

The signal identified during the 5 month period in 2014/15 consists of **13 ± 5 muon induced signals** over background

Redshift measurements: z=0.34

$$\boxed{\mathrm{E^2 J_{100}} = (2.1^{+0.9}_{-0.7}) \times 10^{-4}\ \mathrm{TeV\ cm^{-2}}}$$

Total neutrinos fluence $\sim 3 \times \mathrm{E^2 J_{100}} \rightarrow (4.2^{+2.0}_{-1.4} \times 10^{-3})\ \mathrm{erg\ cm^{-2}}$

Given the distance, the isotropic neutrino luminosity $\mathrm{L}_\nu = (1.2^{+0.6}_{-0.4}) \times 10^{47} \mathrm{erg\ s^{-1}}$ over 158 days

From Fermi-LAT observations, the isotropic gamma ray luminosity is $L_\gamma = 0.28 \times 10^{47} erg\ s^{-1}$ in the range 0.1-100 GeV

What happens to photons related to neutrino production mechanisms?

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- **Photons have energy outside Fermi-LAT energy band**

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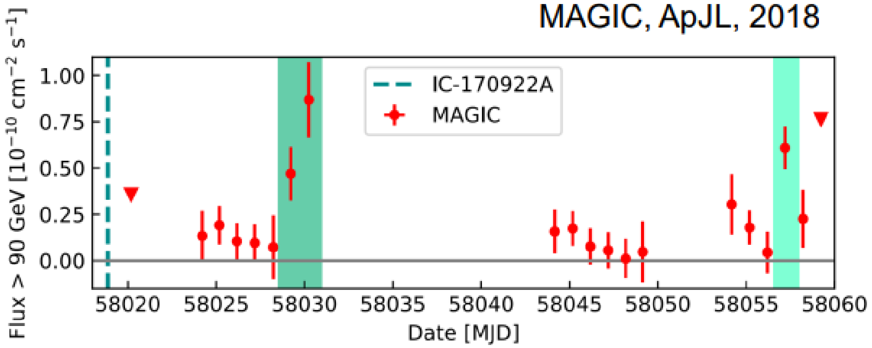
MAGIC, ApJL, 2018



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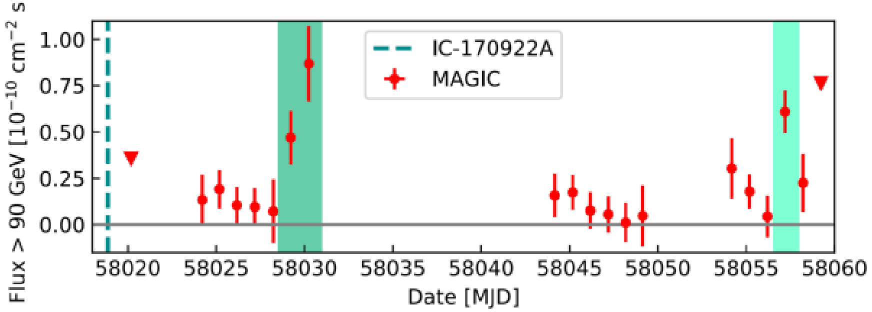

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3. Radio interferometry revealed a jet that loses its tight collimation beyond 5 milliarcseconds **running into matter**
   Merging with another galaxy?
   Interaction of jet with dense molecular clouds of a star-forming region?
   Interaction with supermassive stars in the central region?

Eddington bias

Since the cross section for neutrinos is very small, what can we conclude if we see one of them related to a known source?

Idea:

if a newspaper write an article about a win at the lottery the perception is that the probability is high. We have to consider the large quantity of trials.

↓

The neutrino sources are systematically overestimated!

Quantification of the bias

Sources detection probability depends on:

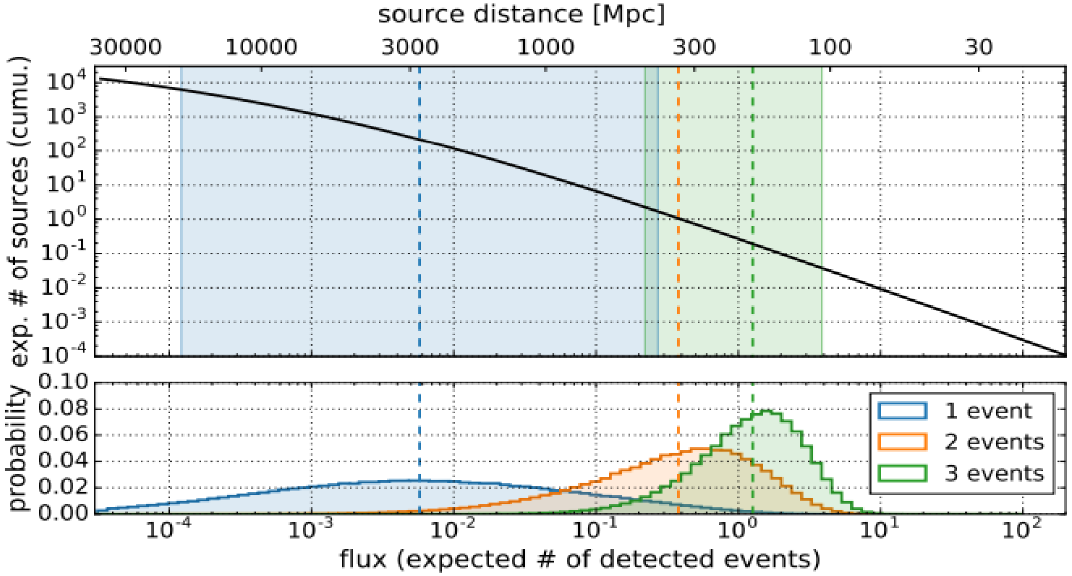
- Density, evolution and luminosity function, acceptance of the detector

Simulation

Sources are considered equally luminous

Constant density: $8 \times 10^{-9}\ \mathrm{Mpc}^{-3}$

Total # of sources: 1.2×10^{4}



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- The median flux of a source detected with a single event is much smaller than one expected event
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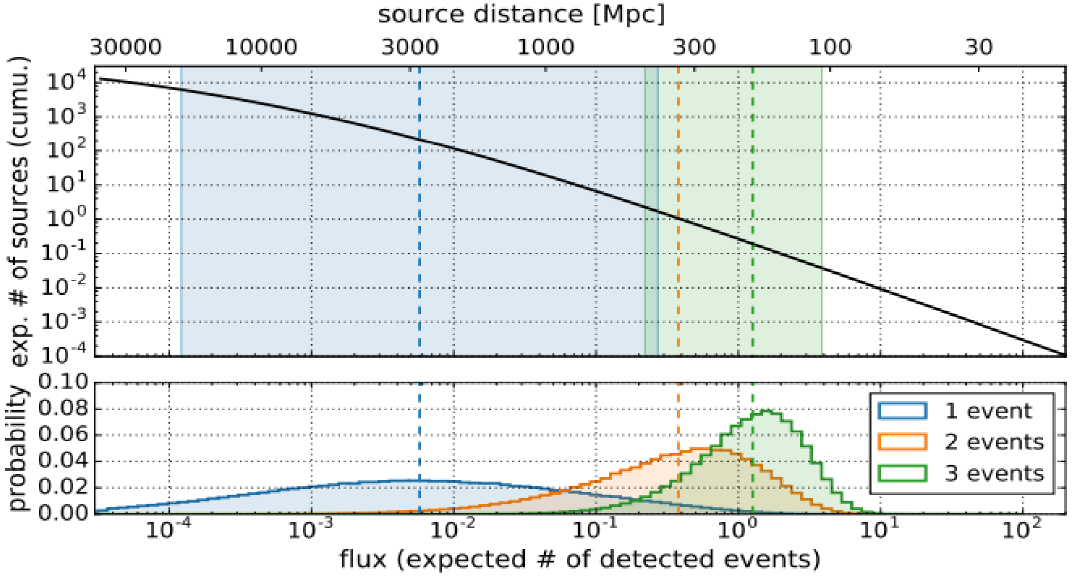

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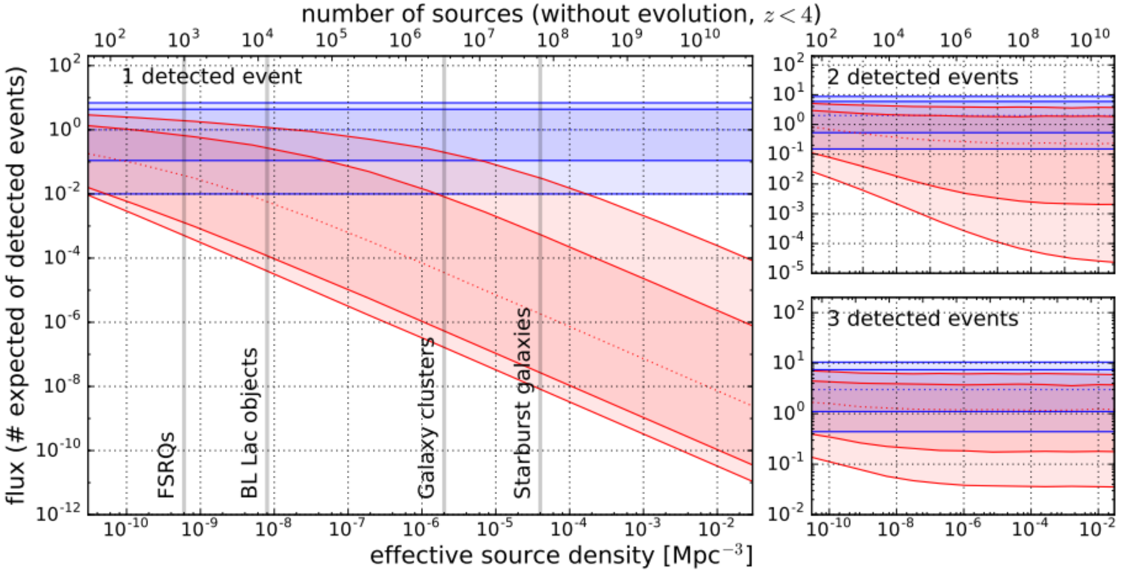


- Expected flux is normalized to 10 events
- The median flux of a source detected with a single event is much smaller than one expected event
- Many fainter sources have a higher probability of producing such a signal

- For sources detected with just a single event there is a strong discrepancy between the real flux (red bands) and the Poisson estimate (blue bands)
- Flux might be orders of magnitude smaller!
- Bias decreases with more neutrinos detected

Results for Neutrino Astrophysics

An hard spectrum for neutrino flux is expected from models of CR production at sources

$\phi_\nu(E) \propto E^{-\Gamma_\nu}$ with $\Gamma_\nu = 2$

1. The spectrum obtained from events originating in the Northern sky gives $\Gamma_\nu \sim 2.2$

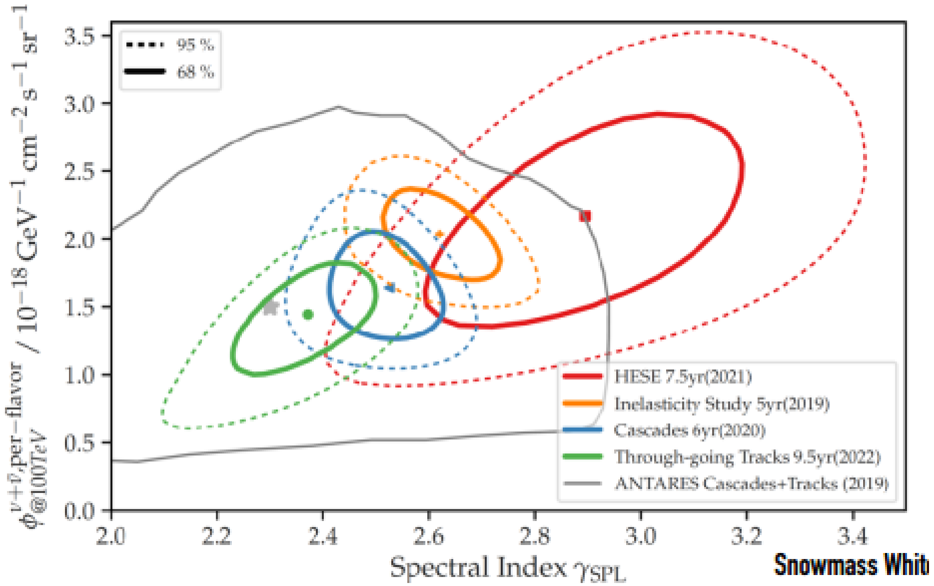
2. HESE presents a softer spectrum, with $\Gamma_\nu \sim 2.9$

The source of discrepancy is still an open question!

- Two different extragalactic components?
- Galactic+Extragalactic component?
- Statistical fluctuations?

3. ANTARES complements IceCube field of view.

A recent study shows a small excess of events w.r.t. background only predictions. Best fit is $\Gamma_\nu \sim 2.9^{+0.5}_{-0.4}$



Snowmass Whit

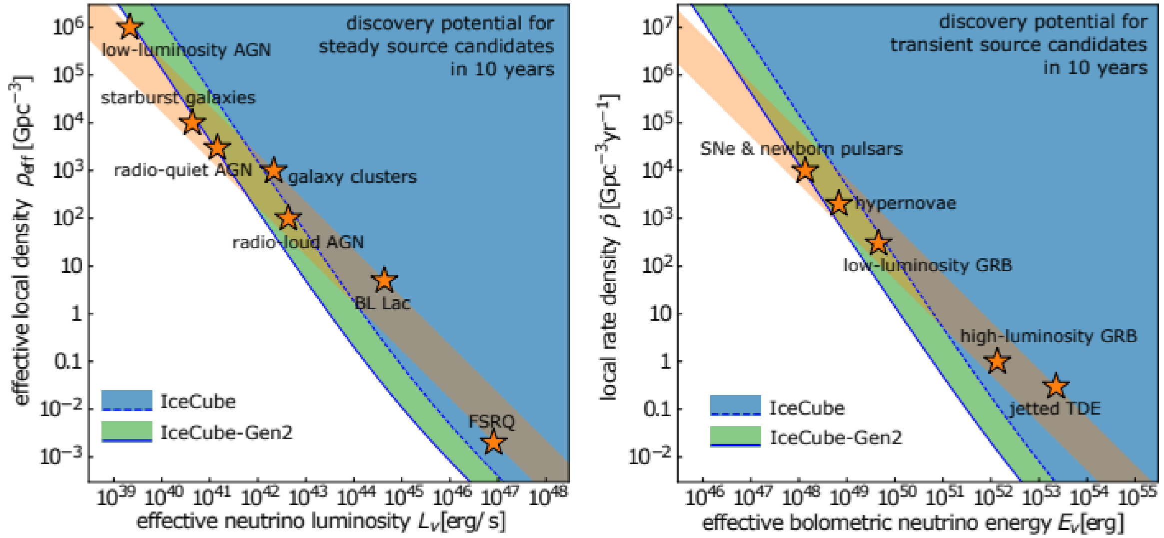
Next Steps (I)

The search for UHE neutrinos will be continued with a new generation of detectors, as:

1. IceCube Gen-2

Designed to achieve five times better sensitivity than IceCube array

- **Optical Array:**
  8x larger active volume w.r.t. IceCube filled with improved OM from IceCube upgrade
- **Surface air shower array:**
  Matching with the optical array throughput
  40x higher coincidence events
- **Radio array:**
  $500\ \mathrm{km}^2$ of the antenna array for detection of 10^{18} eV neutrinos



New Optical module design

- Multi-PMTs per module

Larger photocatode area

Increased angular acceptance

Next Steps (II)

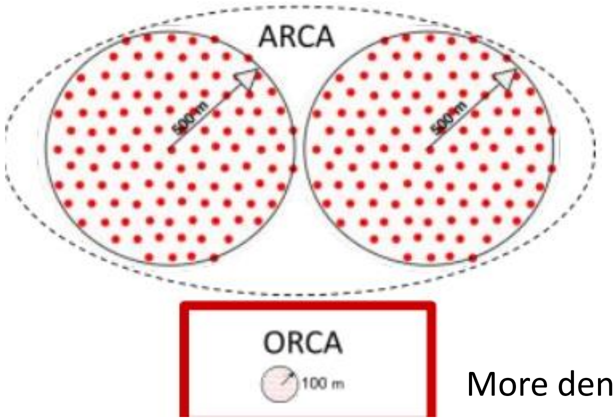
The search for UHE neutrinos will be continued with a new generation of detectors, as:

ANTARES: Precursor of KM3Net
14 years of operation
Competitive results for Northern emisphere

2. KM3Net

Multi-site deep-sea neutrino telescope: **ARCA** and **ORCA**

- Same technology: Digital Optical modules (31 PMTs each)
- **ARCA:**
  - Capo Passero (Sicily) at 3.5 km of depth
  - Studies of Astrophysical neutrino sources
- **ORCA:**
  - Toulon (France) at 2.5 km of depth
  - Studies on neutrino oscillations and mass ordering



More dense to reach GeV range

- Distance of strings:

ARCA: 90 m
ORCA: 20 m

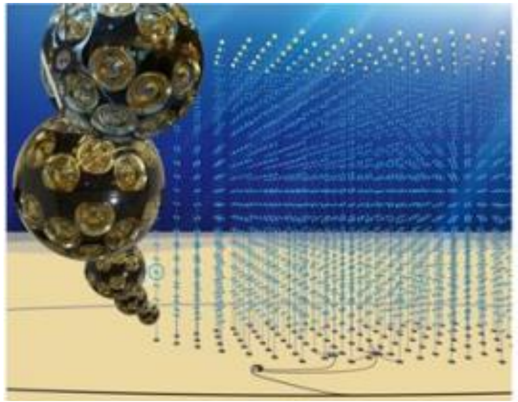
- Distance of DOMs:

ARCA: 35 m
ORCA: 9 m

New Optical module design

- Multi-PMTs per module

Larger photocatode area
Increased angular acceptance



Thanks for your attention!

Backup

Neutrinos from Blazars

For a population of sources with **source density** ρ and neutrino luminosity L_ν, the diffuse neutrino flux is:

$$E^2\frac{dN}{dE} = \frac{1}{4\pi}\int d^3r\,\frac{L_\nu}{4\pi r^2}\rho = \frac{c}{4\pi}t_H\boxed{\xi}L_\nu\rho$$

From Halzen, Francis, and Ali Kheirandish. "IceCube and High-Energy Cosmic Neutrinos." arXiv preprint arXiv:2202.00694 (2022).

Integration over redshift history of the source

Considering:

- Duration of flares Δt
- Total time of observation T_{obs}
- Fraction of sources F

$$E^2\frac{dN}{dE} = \frac{c}{4\pi}t_H\xi L_\nu\rho\frac{\Delta t}{T}F$$

$$3\times10^{-11}\mathrm{TeV cm^{-2} s^{-1} sr^{-1}} = \frac{F}{4\pi}\left(\frac{R_H}{4.3\mathrm{Gpc}}\right)\left(\frac{\xi}{0.7}\right)\left(\frac{L_\nu}{1.2\times10^{47}\mathrm{erg\,s^{-1}}}\right)\left(\frac{\rho}{10^{-8}\mathrm{Mpc^{-3}}}\right)\left(\frac{\Delta t}{110\mathrm{d}}\times\frac{10\mathrm{yr}}{T_{obs}}\right)$$

From which we can conclude that $\mathbf{F\sim 0.05}$

The energetics in neutrino production from these sources match the energy flux of the highest energy cosmic rays:

$$E^2\frac{dN}{dE}\sim\frac{c}{4\pi}\frac{1}{2}\left(1-e^{-f_\pi}\right)\xi t_H\frac{dE}{dt}$$

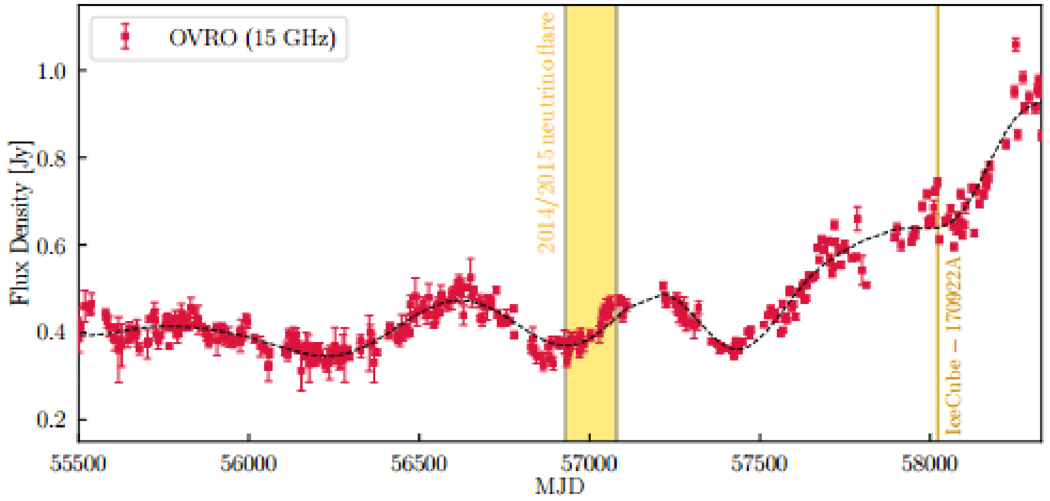
Observed cosmic rays injection rate:
$(1-2)\times10^{44}\mathrm{erg\,Mpc^{-3}yr^{-1}}$

$$\left(\frac{F}{0.05}\right)\left(\frac{\xi}{0.7}\right)\left(\frac{L_\nu}{1.2\times10^{47}\mathrm{erg\,s^{-1}}}\right)\left(\frac{\rho}{10^{-8}\mathrm{Mpc^{-3}}}\right)\left(\frac{\Delta t}{110\mathrm{d}}\times\frac{10\mathrm{yr}}{T_{obs}}\right)\sim\frac{1}{2}\left(1-e^{-f_\pi}\right)\frac{dE}{dt}\frac{1}{(1-2)\times10^{44}\mathrm{erg\,Mpc^{-3}yr^{-1}}}$$

Pion production efficiency at source is $f_\pi\sim0.8$

TXS 0506+056 properties (II)

4. Robotic optical telescope MASTER monitored the blazar since 2005. It found that the strongest variation in a period of two hours happened after IC170922 and 2014-15 burst



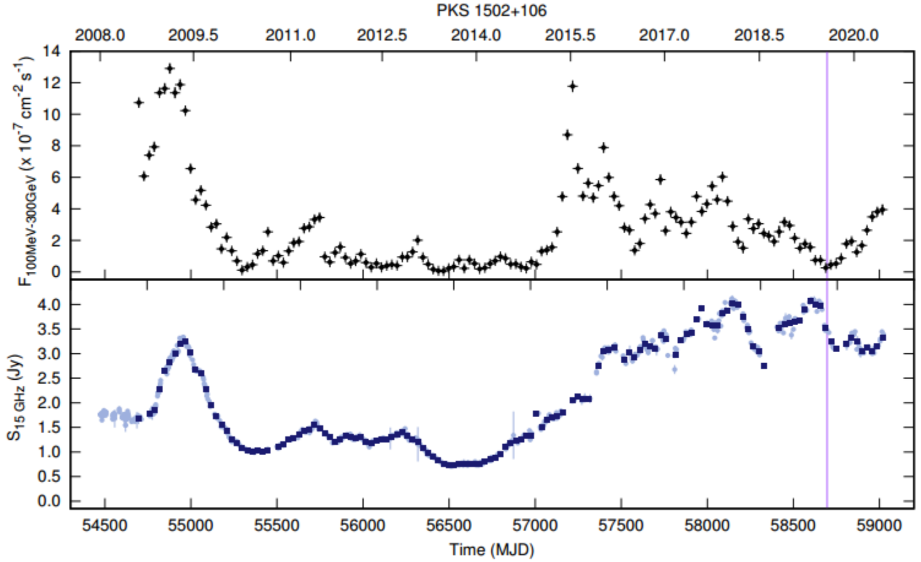
Neutrino emissions detected during a period of enhanced gamma activity

If we consider 1-10% of blazars bursting once in 10 years like TXS0506+056, the diffuse cosmic neutrino flux observed by IceCube would be explained

IC190730 and IC170922

Alert recorded on 30th July 2019 provides support for the idea that cosmic neutrinos are produced by temporarily gamma-suppressed blazars:

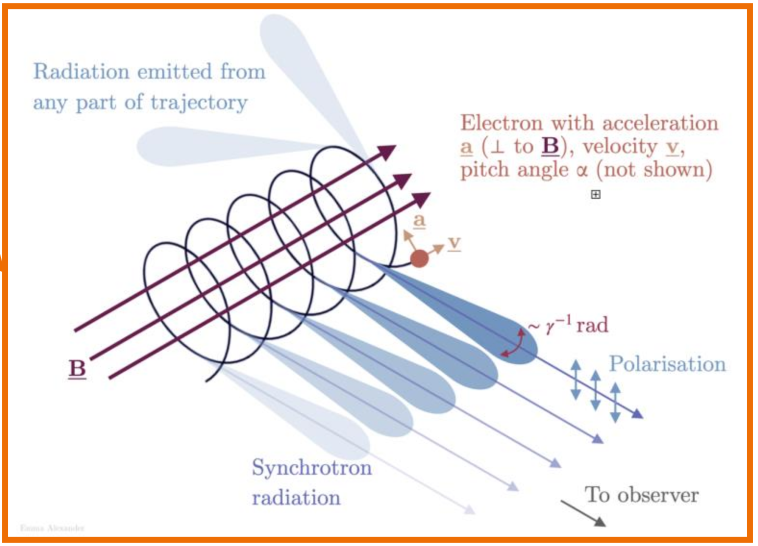
- 300 TeV muon neutrino in spatial coincidence with blazar PKS 1502+106
- From OVRO, neutrino is in coincidence with the highest flux density of a flare started 5 years ago
- Clear minimum in gamma ray flux seen by Fermi

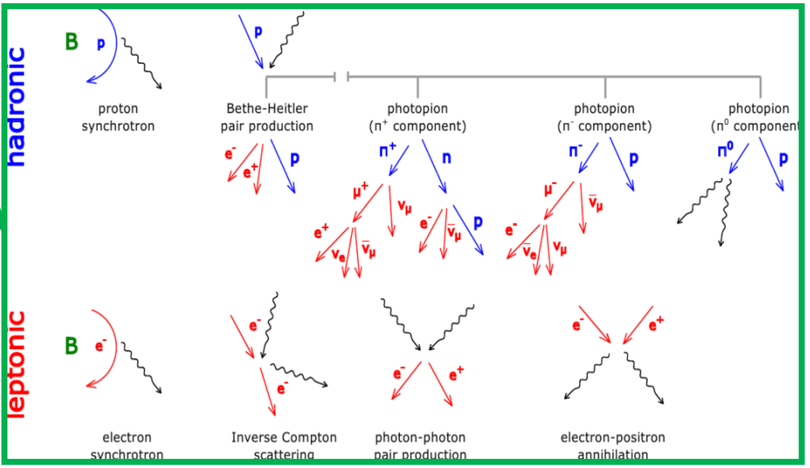


Blazar Classification

BL Lac and FSQR present two humps:

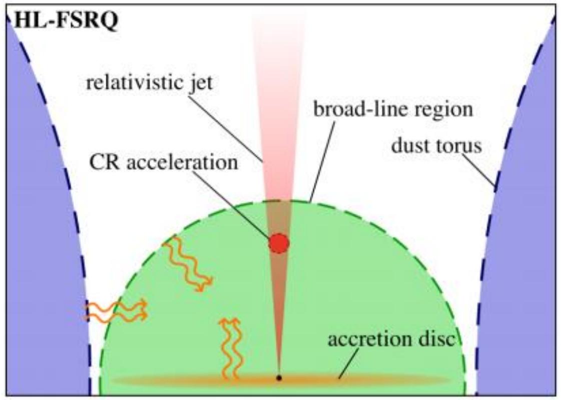
1. Low energy (left)
2. High energy (right)



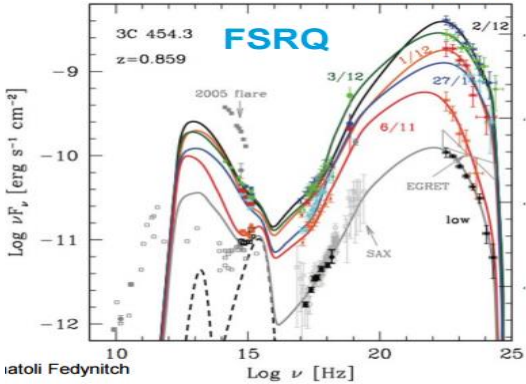


FSRQ

1. Line, disk and thermal emissions
2. High luminousity (high 2nd peak)
3. Low maximal photon energy



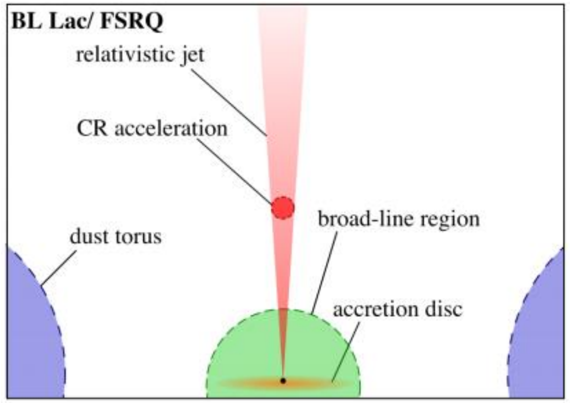
Bonnoli+ 11



$1\ \text{eV} \rightarrow 2.4 \times 10^{14}\ \text{Hz}$

BL Lac

1. No lines and dust
2. Less luminous



Abdo+ 11