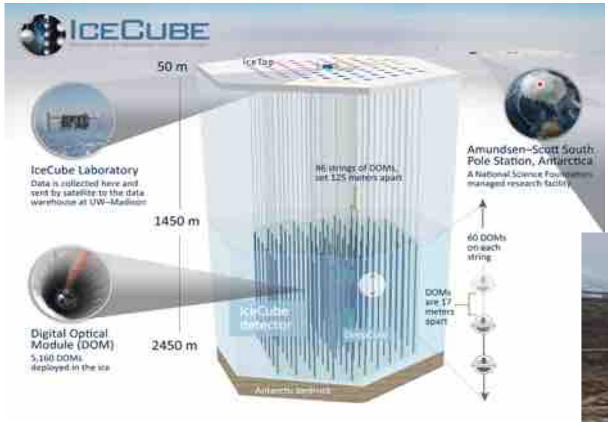
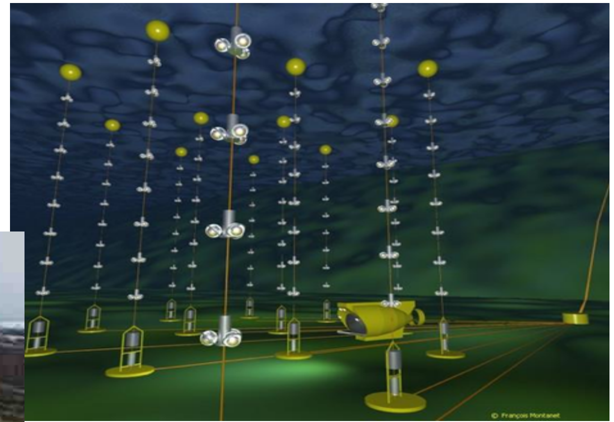
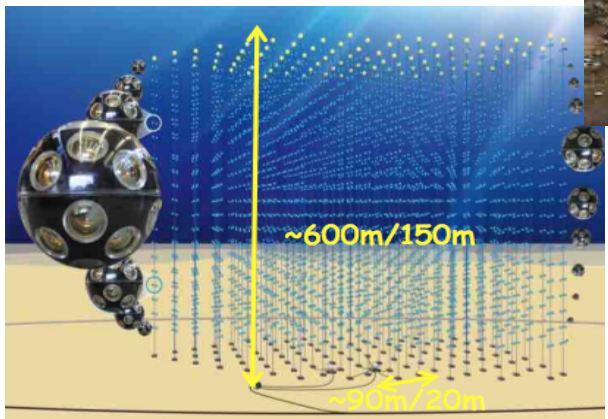
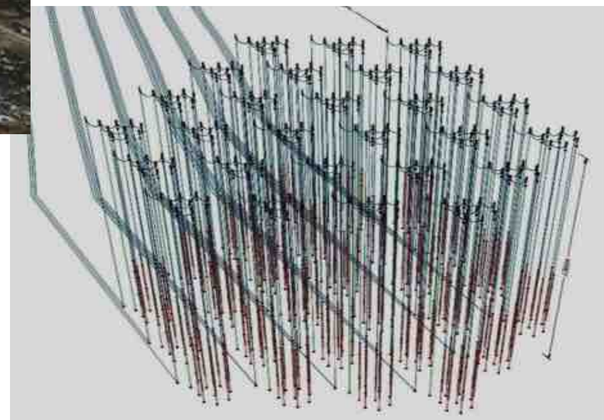
Neutrino Telescopes and LHAASO

Antonio Capone
Physics Department
Univ. La Sapienza & INFN









Neutrino Telescopes and LHAASO

ν and γ complementarity ???

Why ?

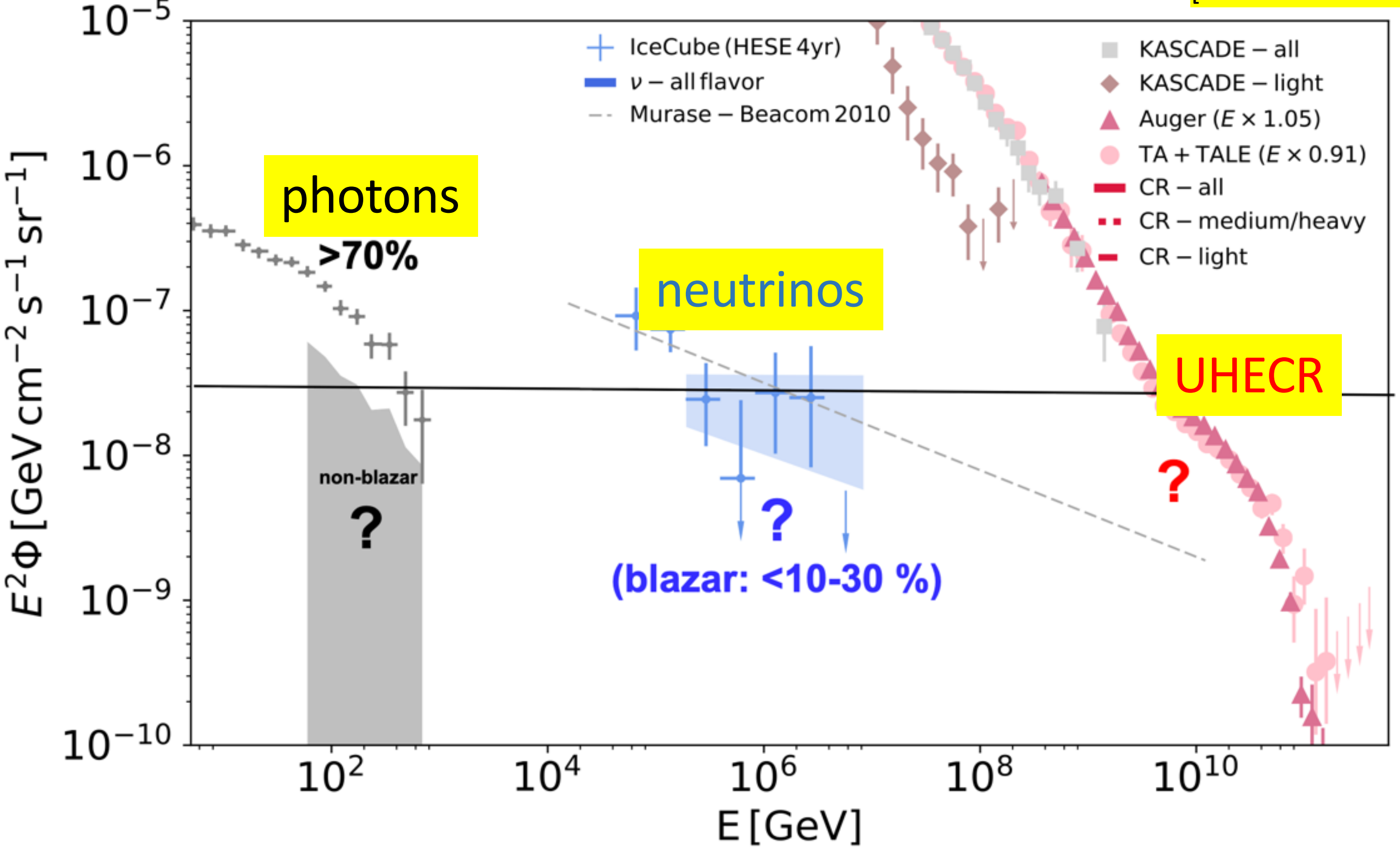
How ?

Where ?

When ?

multi-messengers search for CR sources

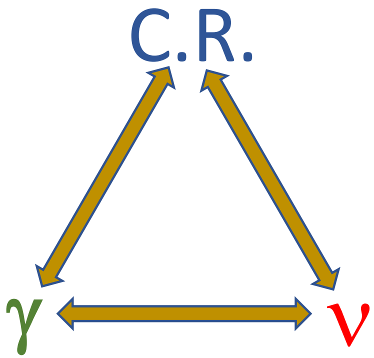
[Kohta Murase – ICRC 2019]



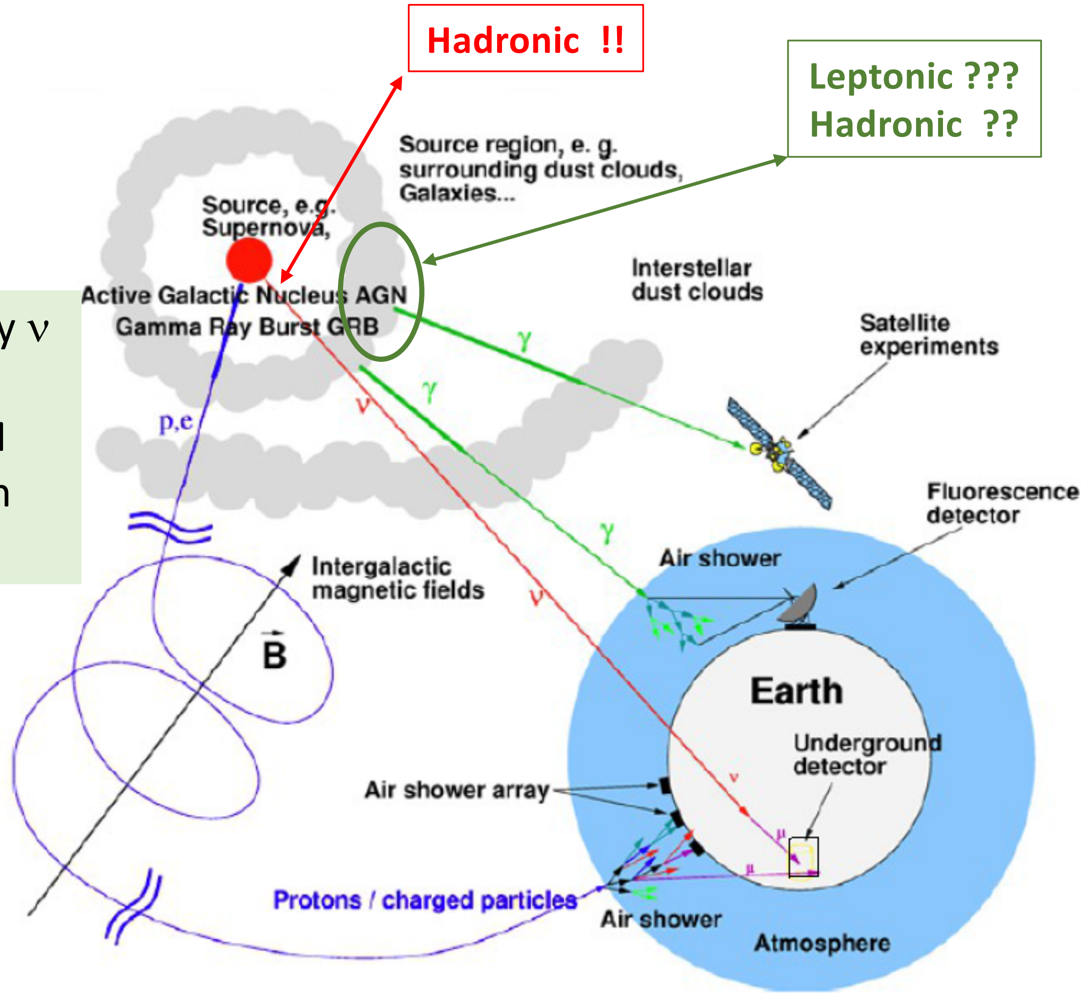
Particle energy budgets are roughly comparable (10^{43} -10^{44} erg Mpc^{-3} yr^{-1})

Energy density of ν in the non-thermal Universe is the same as that in γ

Why neutrinos ??



For extra-galactic sources only ν
- don’t feel magnetic field
- don’t interact with the ISM
- reach from very far horizon
- are suitable for astronomy



Multi-Messengers searches

Diffuse fluxes

- Photons, H.E. Cosmic Rays, Neutrinos, … consistency in Spectral Energy Density
- Anisotropies

Point-like sources

- Low Energy Photons
- High Energy Photons
- H.E. Cosmic Rays
- Neutrinos
- Gravitational Waves

Time integrated searches (AGNs, steady sources, …)

- Low signal rate
- High background

⇒

- Excellent angular resolution
- stacking

Time depended searches (GRBs, flaring sources, …)

- Low signal rate
- Very low backg.

⇒

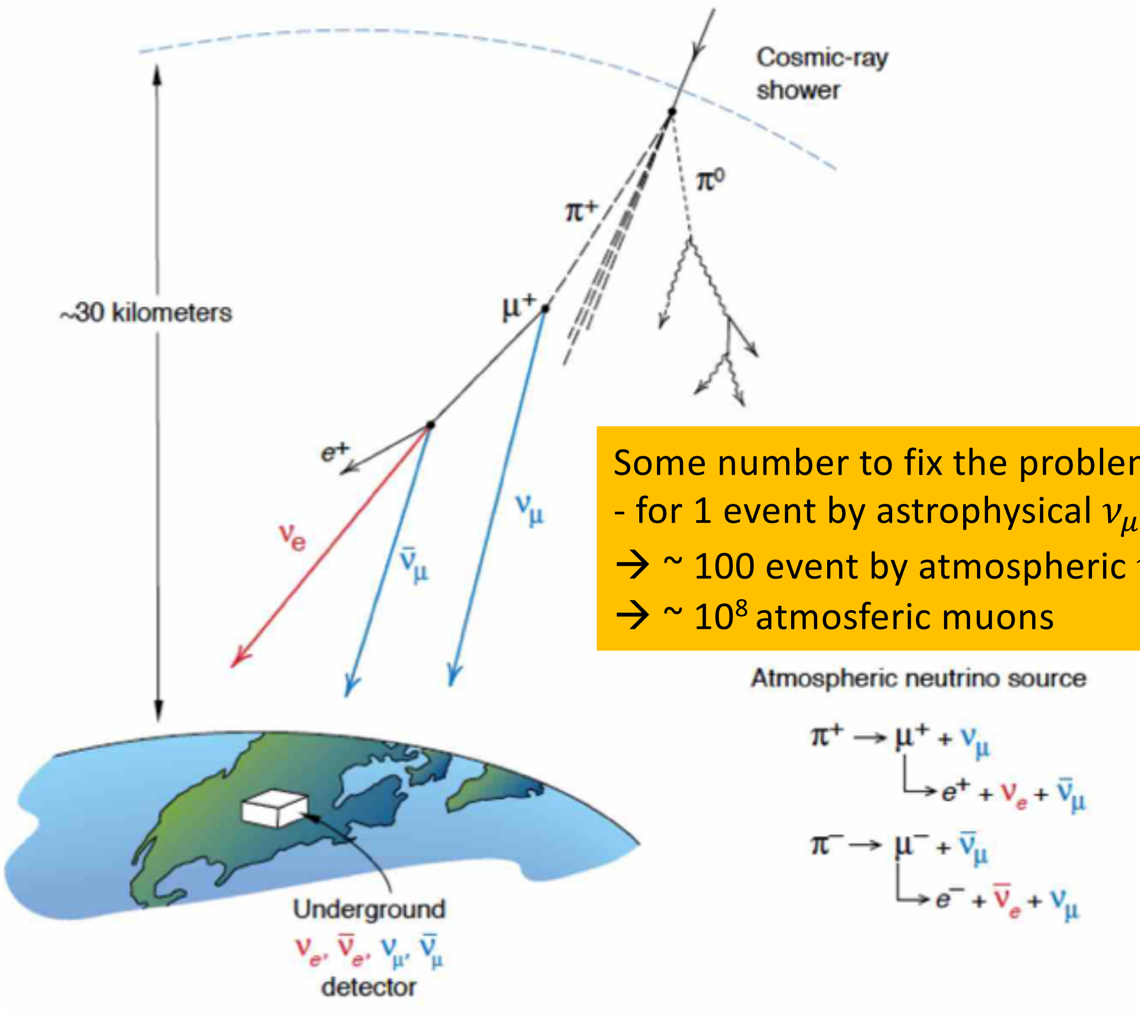
- good angular resolution
- stacking

~~**Core Collapse Supernova 0 – 20 MeV**~~

- ~~Neutrino detectors specialised for low energy events (LVD, BOREXINO, SKK, Juno, …)~~
- ~~Large Volume Neutrino Telescopes, sensitive to the increase of a large number of PMTs single rate (IceCube) or to high number of "local coincidences" (in KM3NeT multiPMT DOMs).~~

Not discussed here

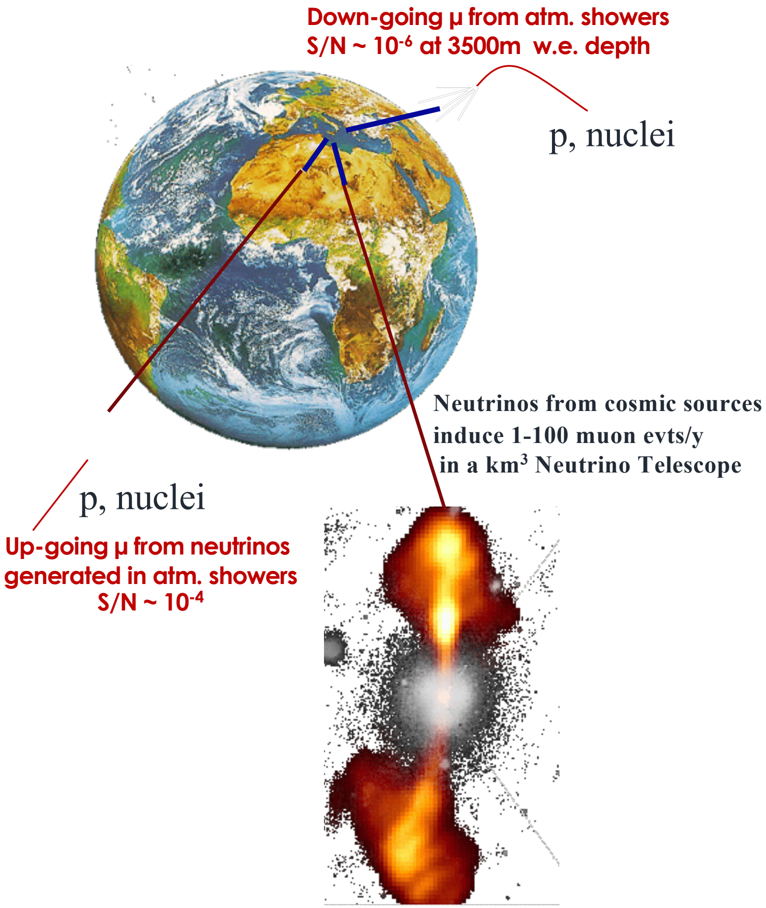
A very intense muon flux is downgoing from the atmosphere …



Some number to fix the problem …
- for 1 event by astrophysical ν_μ
→ ~ 100 event by atmospheric ν_μ
→ ~ 10^8 atmosferic muons

How ? Cherenkov ν Telescope: Detection principle

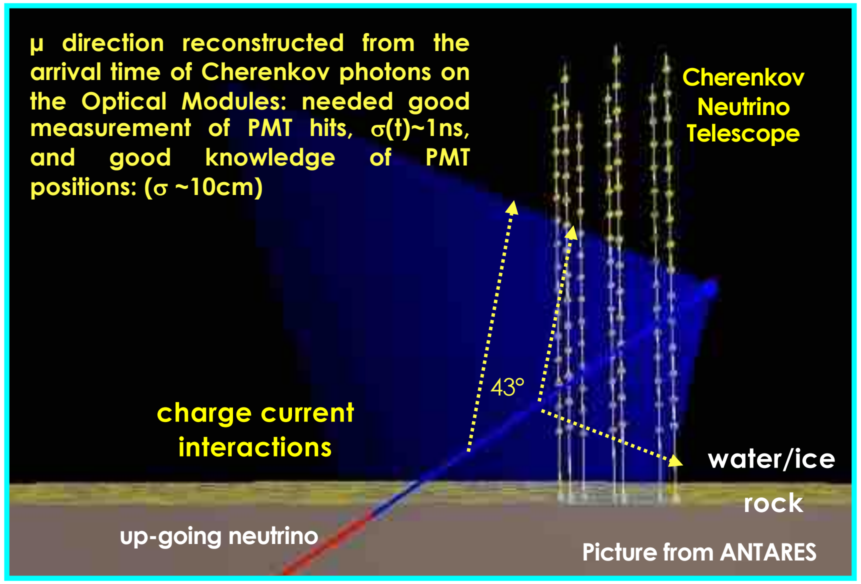
Search for neutrino induced events, mainly $\nu_\mu N \rightarrow \mu X$, deep underwater



- Atmospheric neutrino flux ~ $E_\nu^{-3} \div E_\nu^{-3.7}$
- Neutrino flux from cosmic sources ~ E_ν^{-2}
  - Search for neutrinos with E_ν>1÷10 TeV

- ~TeV muons propagate in water for several km before being stopped
  - go deep to reduce down-going atmospheric μ backg.
  - long μ tracks allow good angular reconstruction

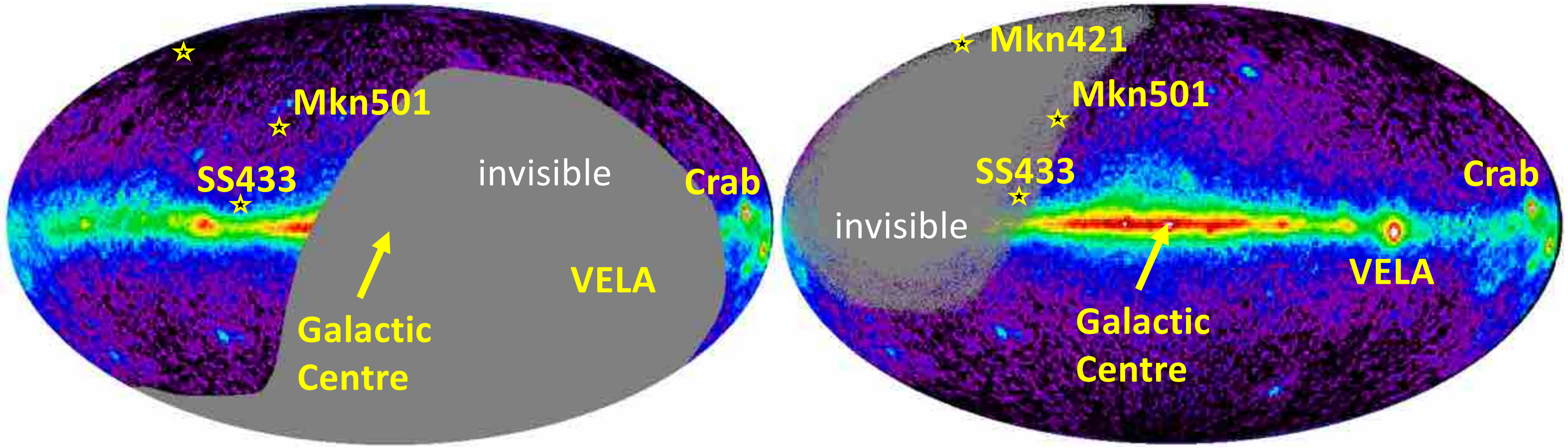
For $E_\nu \geq 1\,TeV \quad \theta_{\nu\mu} \sim \frac{0.7°}{\sqrt{E_\nu\,[TeV]}}$



How many Neutrino Telescopes ??

It will be important to "observe" the Universe in the whole solid angle

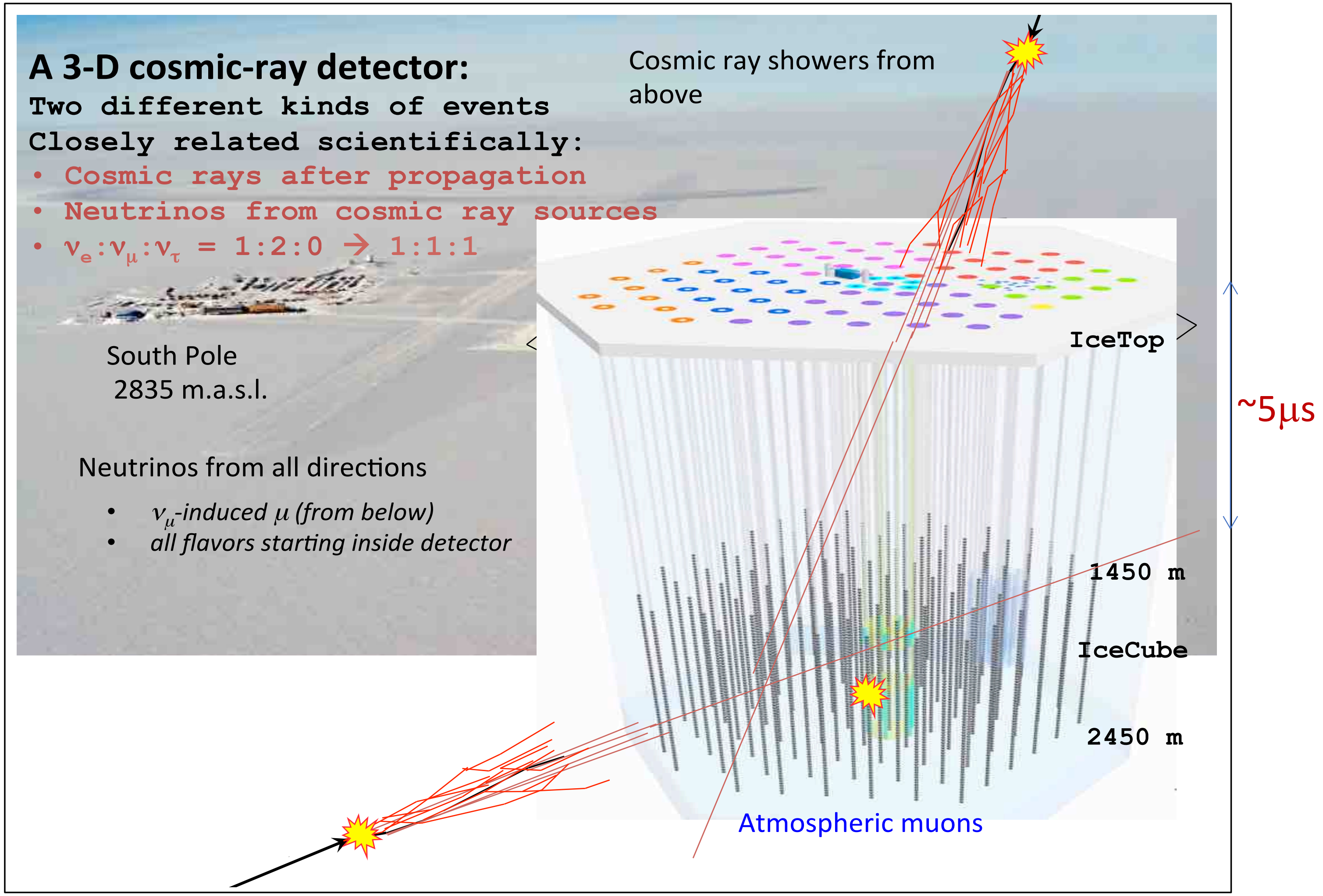
Gamma ray flux >100 MeV observed by EGRET



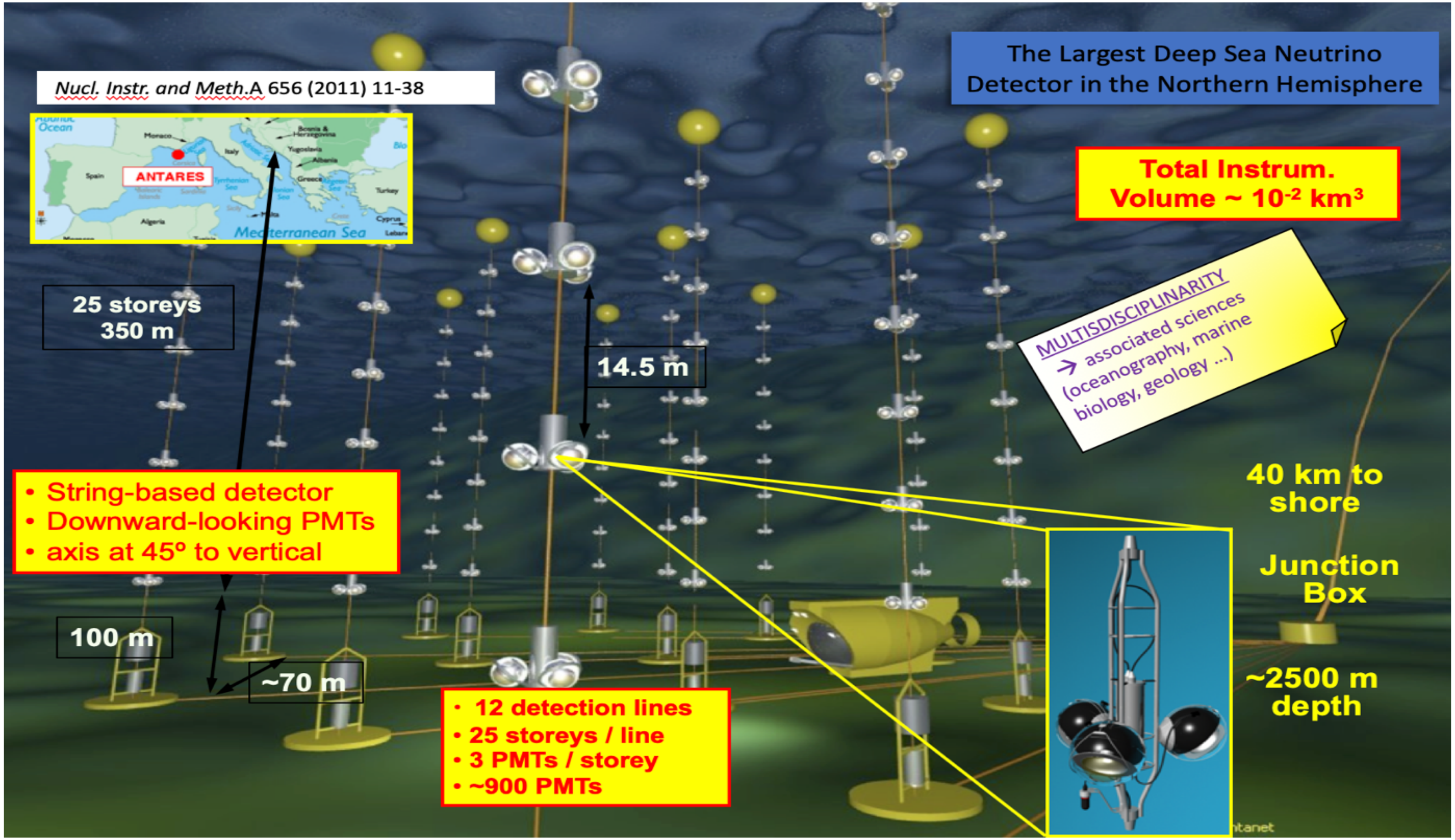
From South Pole: ICECUBE

From North Hemisphere: ANTARES, KM3NeT, ~BAIKAL

IceCube – The Neutrino Telescope at the South Pole

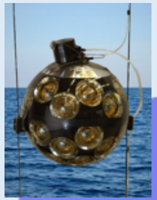


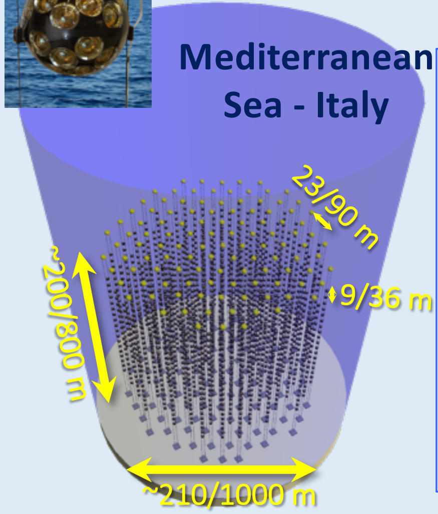
ANTARES: Astronomy with Neutrino Telescope and Abyss environm. RESearch



Future H.E. ν Telescopes: where/when ?

KM3NeT-ARCA: > 2 km^3 detector
search for ν in the PeV to EeV range



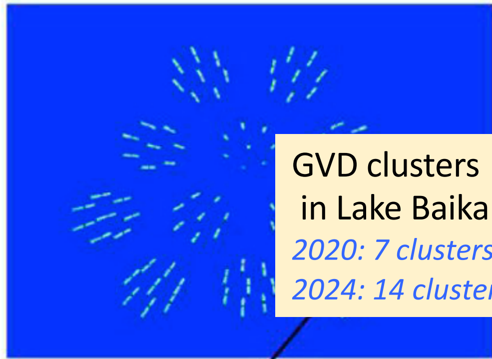


First **ARCA** string deployed Dec 2015
1-2 strings operational
till November 2019
-> Power refurbishment
-> Restart autumn 2020
goal: 2x115 strings 2026

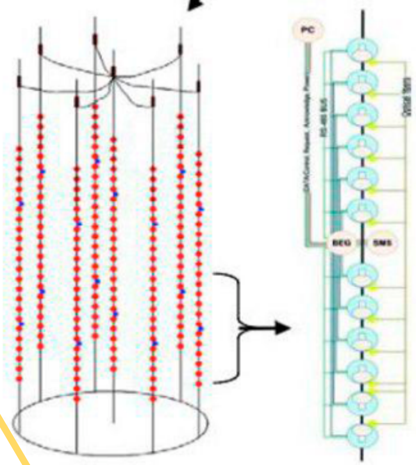
First **ORCA** string deployed Sep 2017
6 strings operational
since January 2020
goal: 115 strings 2024

Baikal – GVD: ~ km^3 detector
search for ν in the ~ PeV range

Cluster: 288 OM in 8 strings.
Clusters distance 300m.
~16.000 total DOM
7 Clusters deployed so far.
Shower reconstruction:
direct. ~4.5° (median value);
energy resolution ~30%

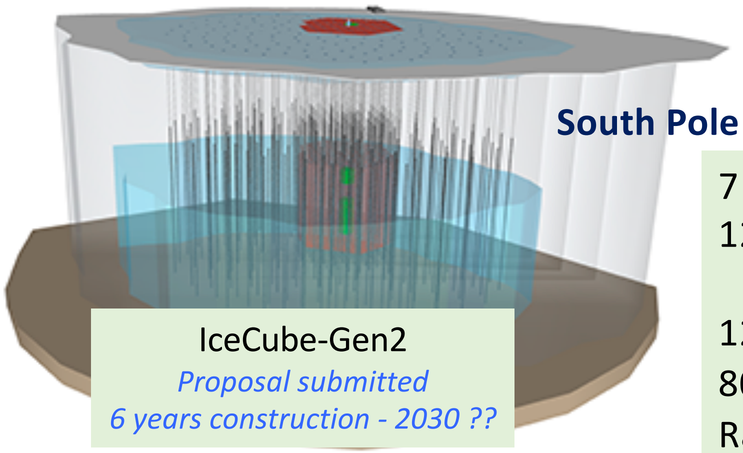


GVD clusters
in Lake Baikal
2020: 7 clusters
2024: 14 clusters



Siberia - Russia

IceCube – Gen2: ~10 km^3 detector
search for ν in the PeV to EeV range



South Pole

IceCube-Gen2
Proposal submitted
6 years construction - 2030 ??

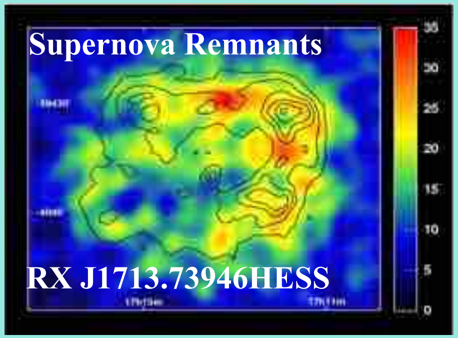
IceCube Upgrade
2022-2023

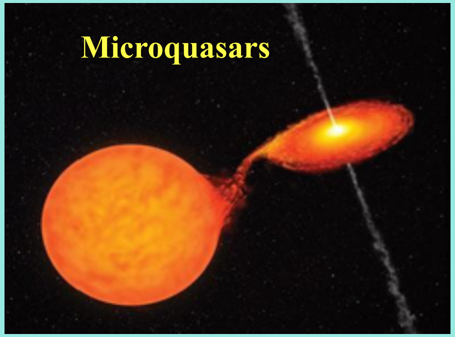
7 strings 20m hor. spacing
125 DOM 2m vert. spacing

120 new strings hor. spaced 240 m
80 DOMs/string length of 1.25 km
Radio detector Array

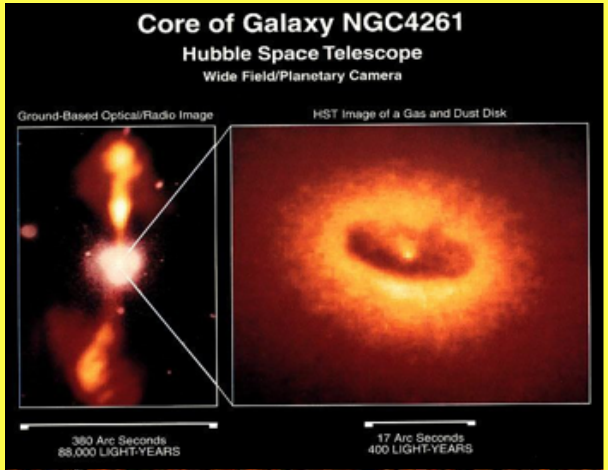
Neutrino Telescope physic's goals: 1 - search for point-like cosmic ν sources

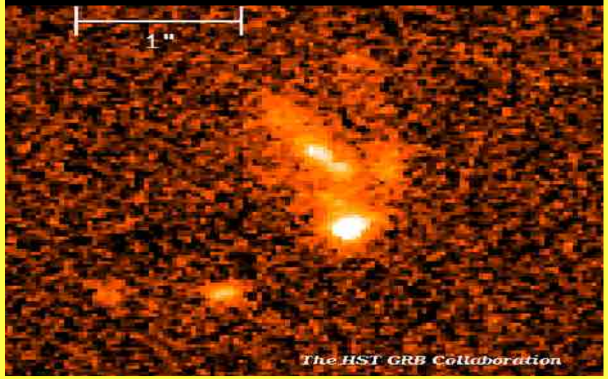
Galactic





Extragalactic

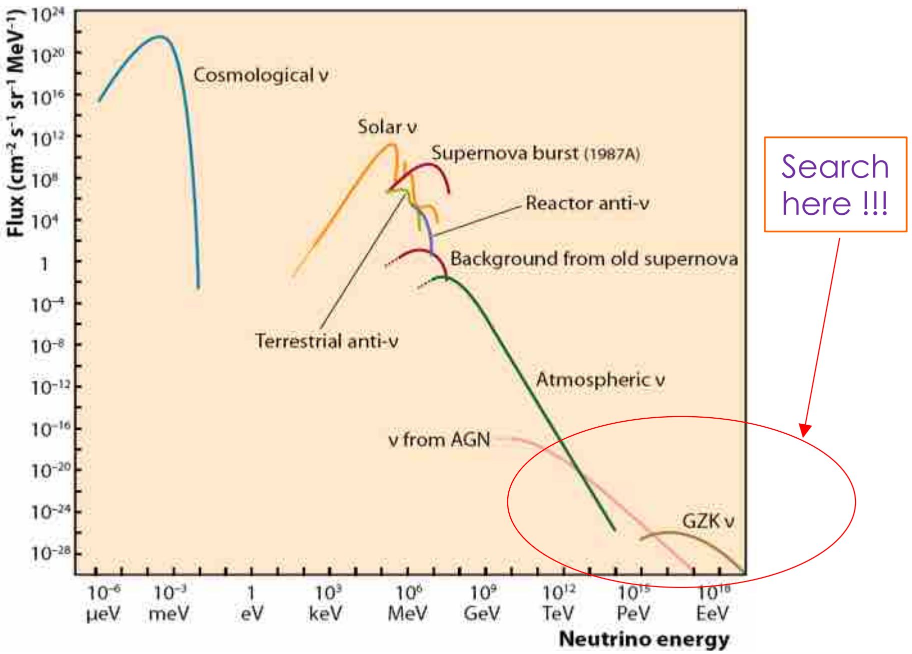




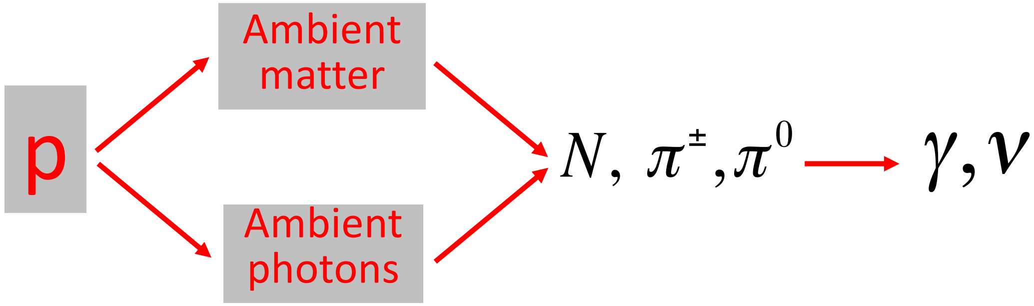
Their identification requires a detector with accurate angular reconstruction: $\sigma(\theta_\nu) < 0.5° \; for \;\; E_\nu > 1TeV$

Experimental signal : statistical evidence of an excess of events coming from the same direction

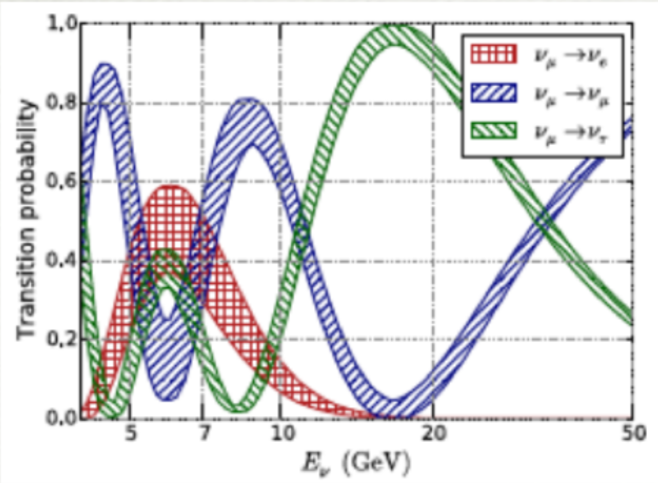
Neutrino Telescope physic's goals: 2 - search for a diffuse flux of Cosmic Neutrinos

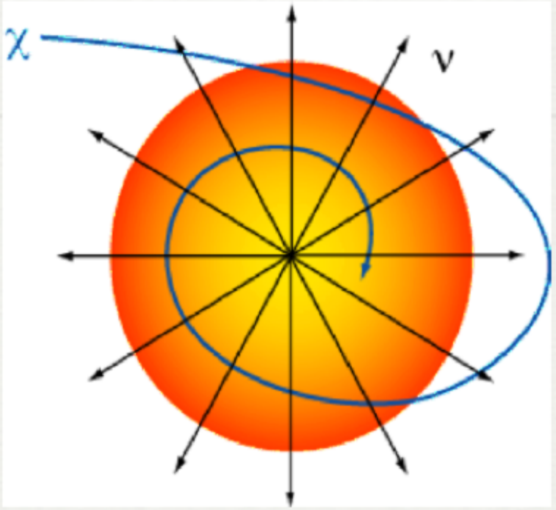


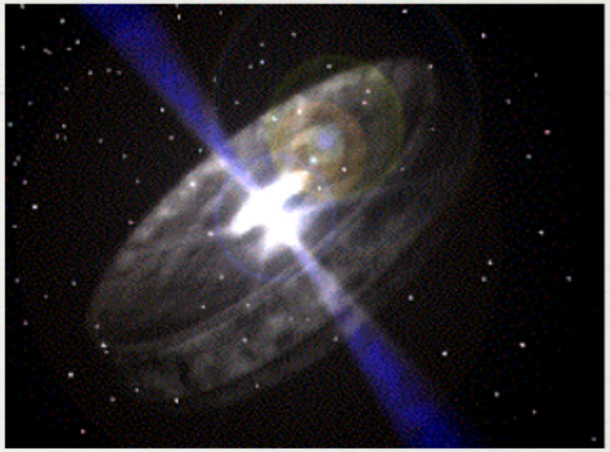
Their identification out of the more intense background of atmospheric neutrinos (and μ) is possible at very high energies (E_{μ} >> TeV) and requires good energy reconstruction.



ν Telescopes: rich program of physics, large Energy Range







IceCube/DeepCore, GVD
ANTARES & KM3NeT/ORCA

Low Energy
$MeV < E_\nu < 100\ GeV$

- ν *oscillations*
- ν *intrinsic properties*
- ν *from Supernovae*

IceCube/DeepCore, GVD
ANTARES & KM3NeT/ARCA&ORCA

Medium Energy
$10\ GeV < E_\nu < 1\ TeV$

- *Indirect search for Dark Matter*
- *Search for Monopoles, nuclearites*

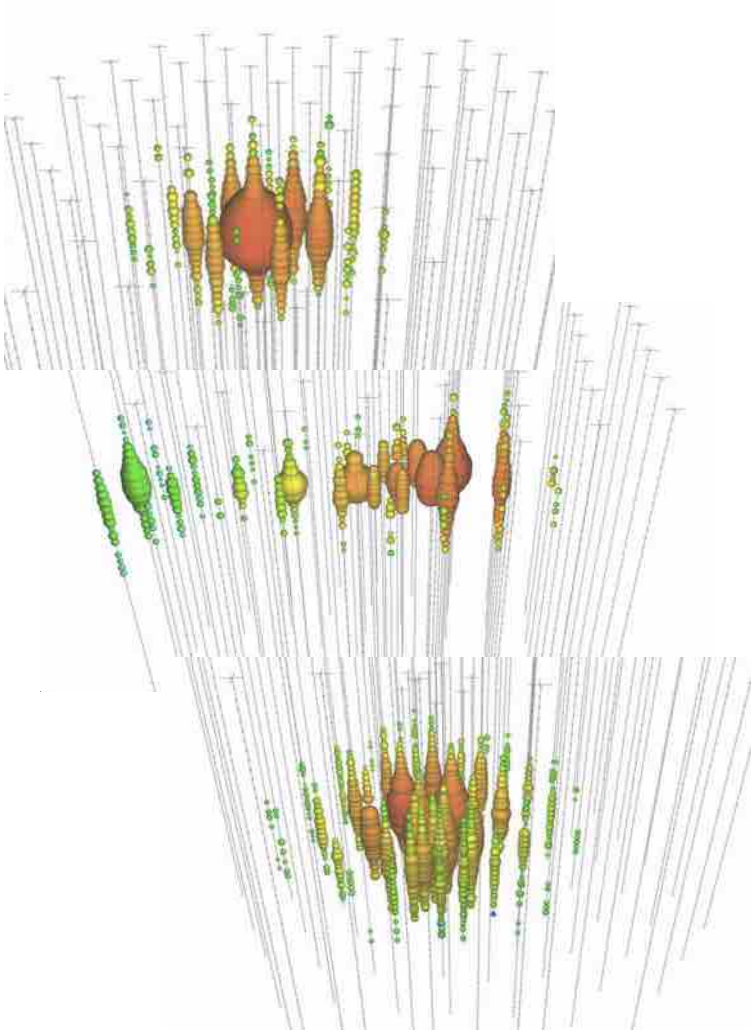
IceCube, Gen2, GVD
ANTARES & KM3NeT/ARCA

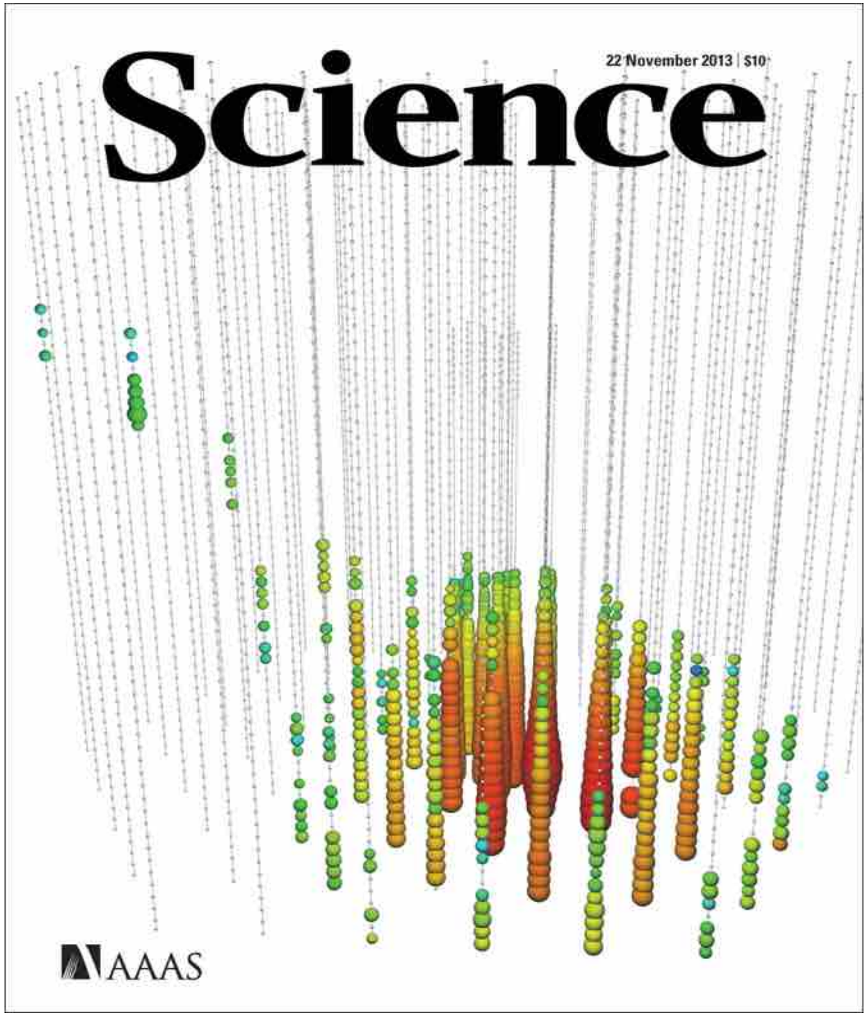
High Energy
$E_\nu > 1\ TeV$

- ν *from extraterrestrial sources*
- *Origin and production mechanism of H.E. Cosmic Rays*

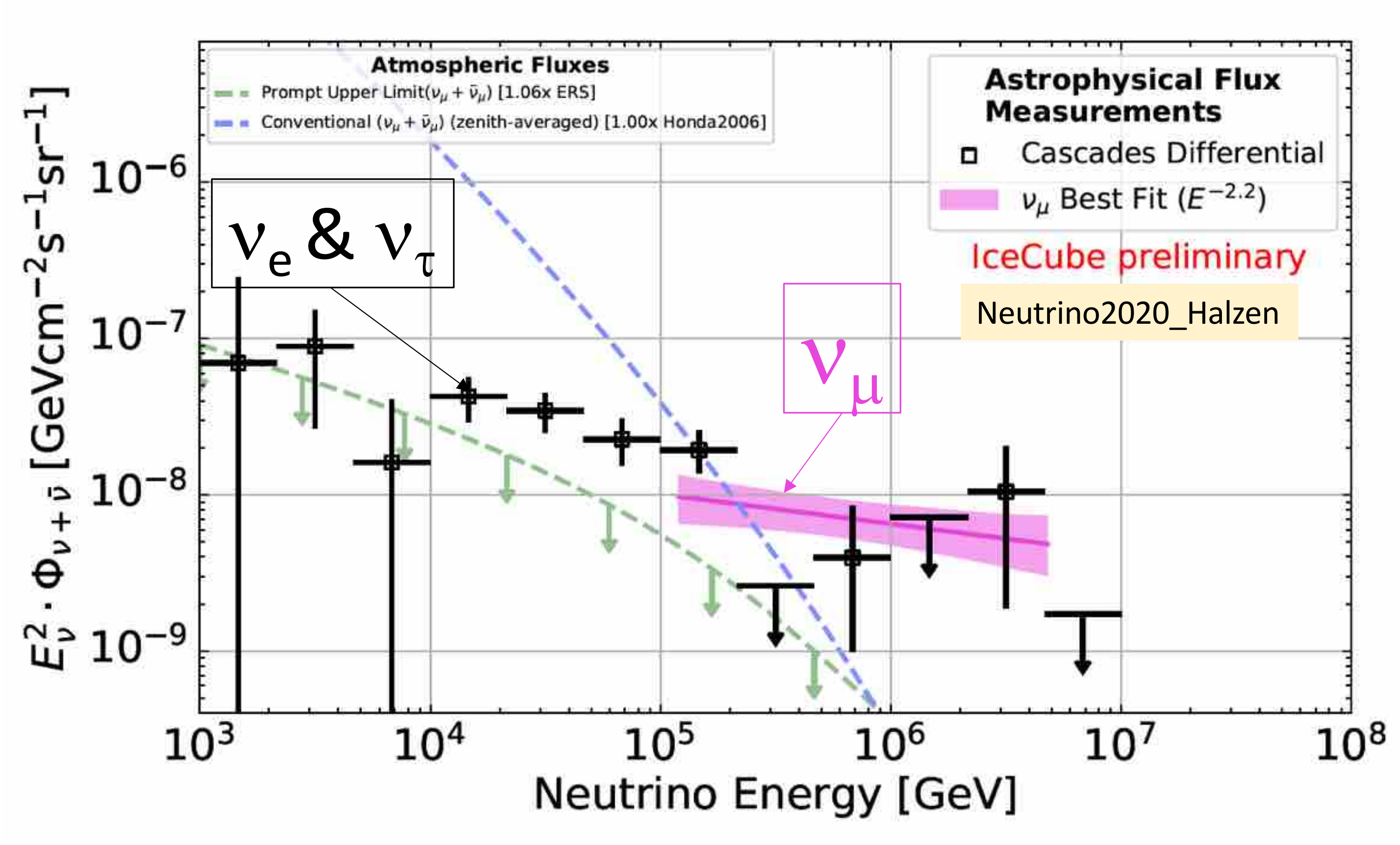
… and (for ANTARES&KM3NeT) also oceanography, biology, seismology, … Earth and Sea sciences

The great discovery (from IceCube 2013)



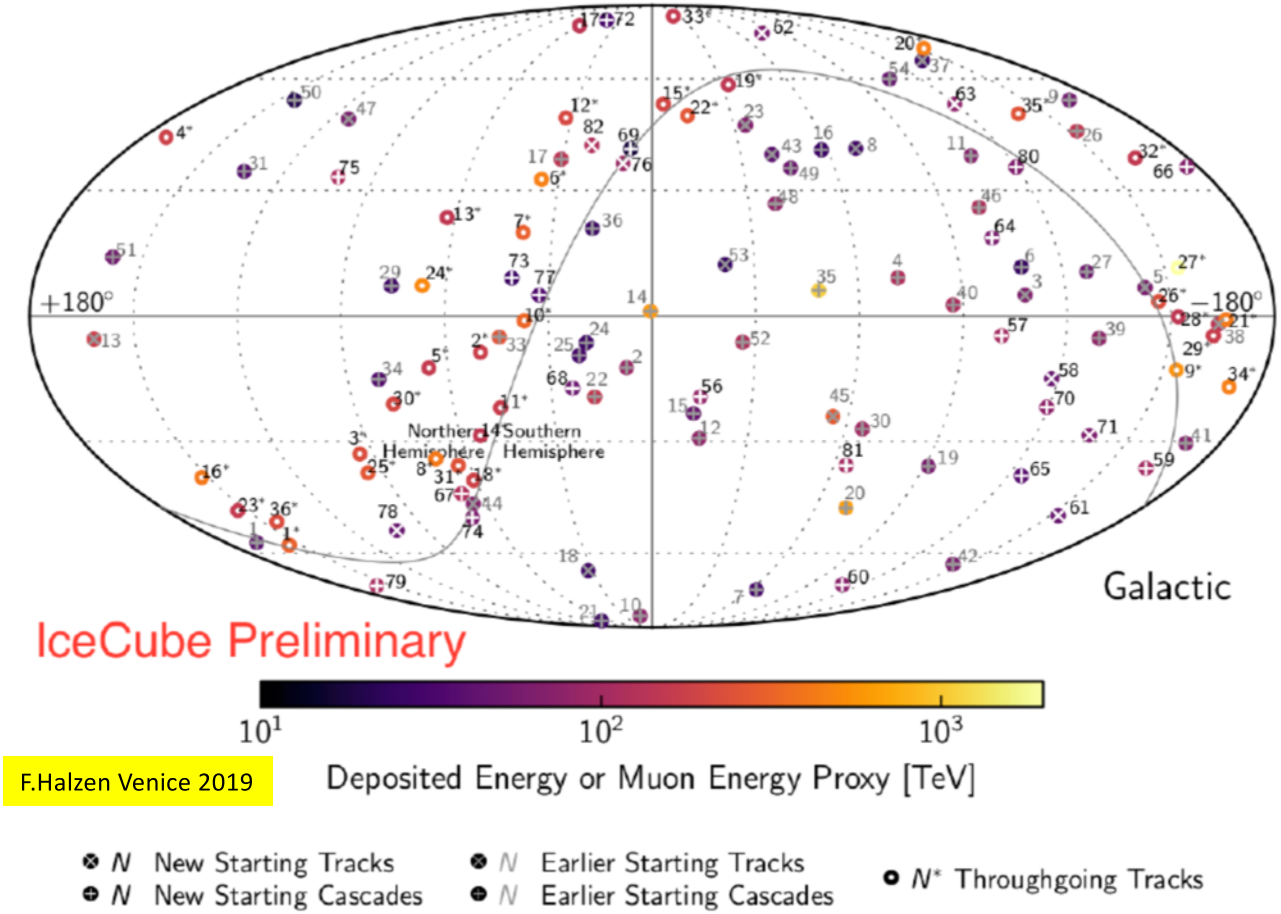


IceCube measured the diffuse cosmic ν flux



Where these H.E. neutrinos are coming from ??

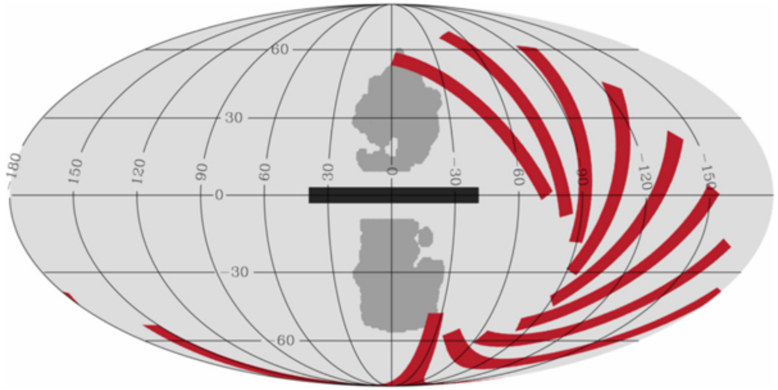
Point like sources still have not been identified as a statistical evidence based on neutrino data only.
Isotropic distribution of ν origin: mainly extragalactic origin. No evidence for ν associated to galactic sources.



ANTARES search for neutrinos from the Galactic ridge - 1

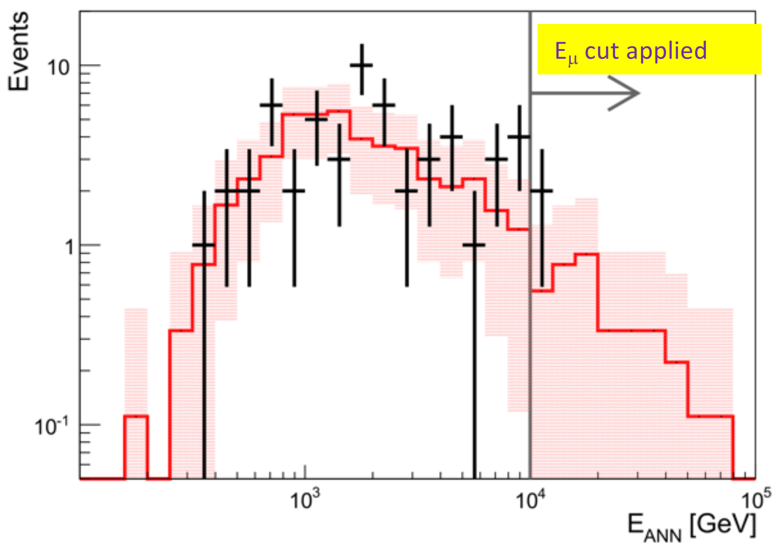
- ν's and γ-rays produced by CR propagation

$$p_{CR} + p_{ISM} \rightarrow \pi^0 \pi^\pm \dots$$
$$\pi^0 \rightarrow \boldsymbol{\gamma\gamma(EM\ cascade)}$$
$$\pi^\pm \rightarrow \boldsymbol{\nu_\mu, \nu_e} \dots$$



- Search for ν_μ , data 2007-2013
- Search region |l|<30°, |b|<4°
- Cuts optimized for neutrino energy spectrum ~$E^{-\gamma}$ (γ=2.4-2.5)
- Counts in the signal/off zones
- No excess in the HE neutrinos
- 90% C.L. upper limits: 3<E_ν<300 TeV

Physics Letters B 760 (2016) 143–148



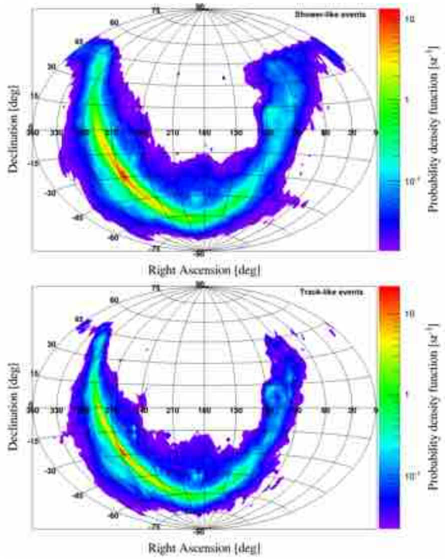
Distribution of the reconstructed E_μ of up-going muons in the Galactic Plane (black crosses) and average of the off-zone regions (red histogram).

ANTARES search for neutrinos from the Galactic ridge - 2

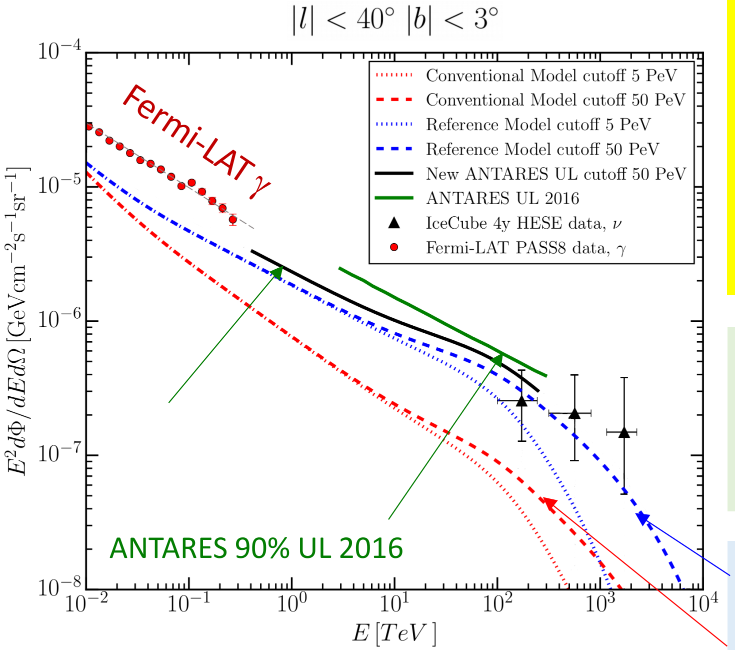
New analysis on tracks and showers, based on Max. Lik.

$$\mathcal{L}_{sig+bkg} = \prod_{\tau\in\{tr,sh\}} \prod_{i\in\tau} [\mu^{\tau}_{sig} \cdot pdf^{\tau}_{sig}(E_i,\alpha_i,\delta_i) + \mu^{\tau}_{bkg} \cdot pdf^{\tau}_{bkg}(E_i,\alpha_i,\delta_i)]$$

KRA$_\gamma$ new model to describe the C.R. transport in our galaxy. It agrees with C.R. measurements (KASCADE, Pamela, AMS, Fermi-LAT, HESS). FERMI-LAT diffuse γ flux from along the galactic plane ($\pi^0 \rightarrow \gamma\gamma$) well explained above few GeV.



ANTARES arXiv:1705.00497v1
1 May 2017



KRA$_\gamma$ allows to predict the ν flux by $\pi^{\pm}$ decays induced by galactic CR interactions

KRA$_\gamma$ 50PeV cut-off for CR

KRA$_\gamma$ 5PeV cut-off for CR

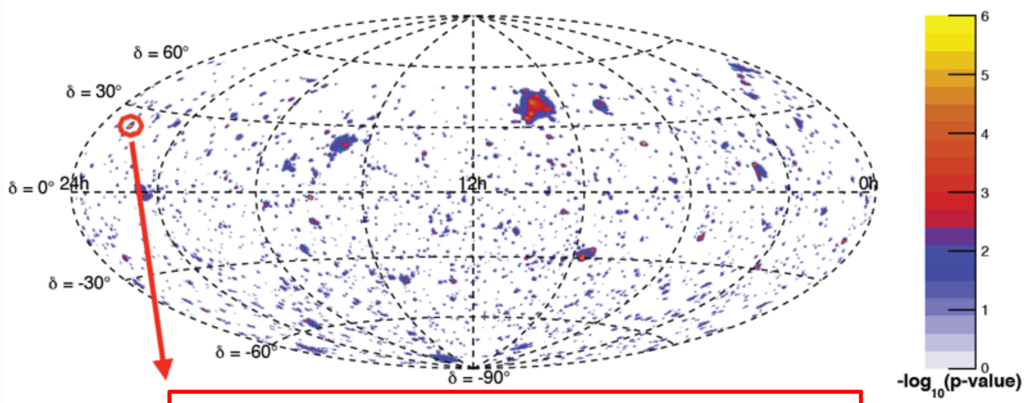
KRA$_\gamma$ assuming a neutrino flux $\propto E^{-2.5}$ and a CR spectrum with 50 PeV cut-off can explain ~20% of the IceCube observed HESE.

ANTARES, with an good visibility of the Galactic Plane well suited to observe these fluxes or to put competitive limits: no signal found → set 90%C.L. upper limits.

Searching for single point like sources, recent results

Data sample: 11 years (3136 days of livetime) track and cascade analysis

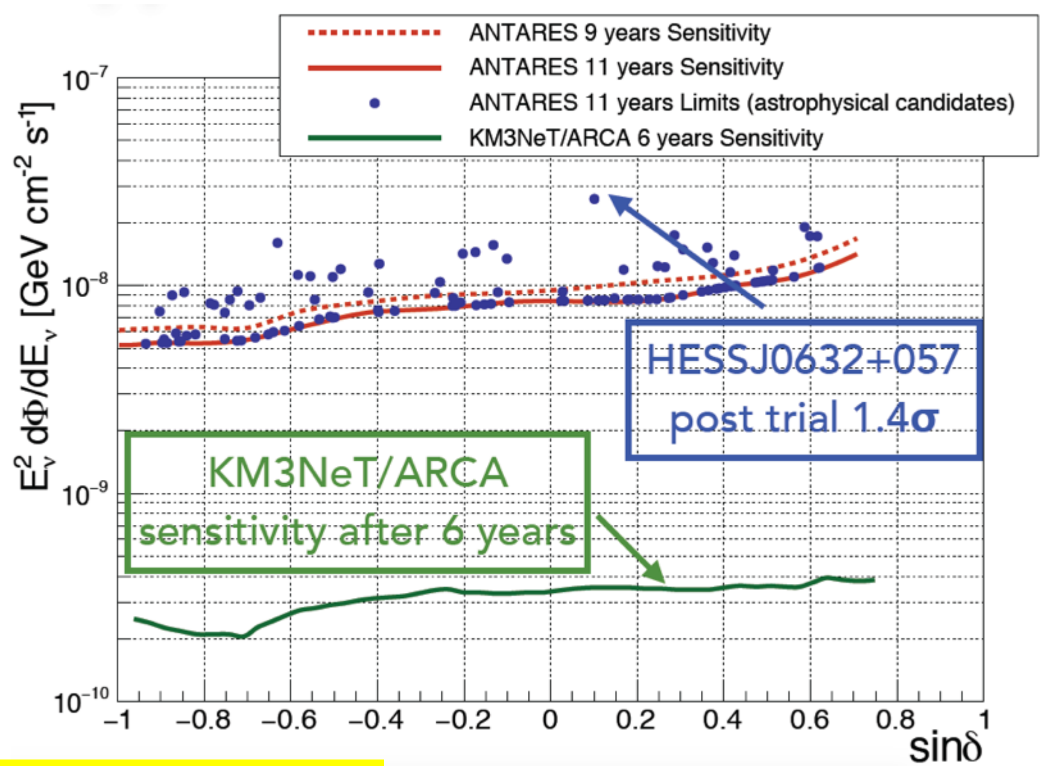
Full sky search



The most significant cluster

- α=343.7° δ=+23.6°
- p-value: pre-trial 1.5 10^{-6} (4.8 σ)
  post trial 0.23 (1.2 σ)
- 3 track events within 1°
  15 tracks + 1 shower within 5°

upper limits and sensitivities



G. Illuminati, S. Navas – PoS(ICRC2019)920

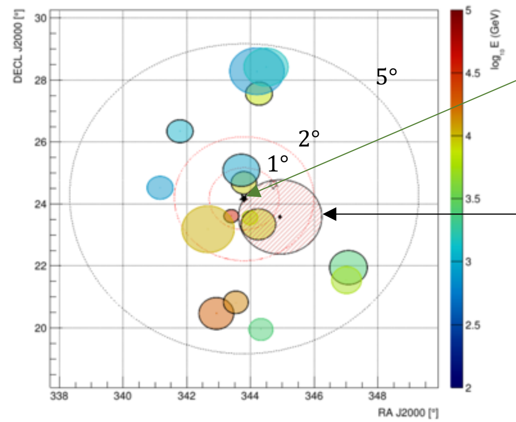
Stacking sources could bring to discoveries: the ANTARES analysis

Data sample: 11 years (3136 days of livetime) track events analysis

CATALOG	PRE-TRIAL	POST-TRIAL	DOMINANT SOURCE
Fermi 3LAC All Blazars	0.19	0.83	
Fermi 3LAC FSRQ	0.57	0.97	
Fermi 3LAC BL Lacs	**0.088**	**0.64**	**MG3J225517+2409**
Radio-galaxies	**4.8 10^{-3}**	**0.10**	**3C403**
Star Forming Galaxies	0.37	0.93	
Obscured AGN	0.73	0.98	
IC HE tracks	0.05	0.49	

J. Aublin – PoS(ICRC2019)840

1.6 σ

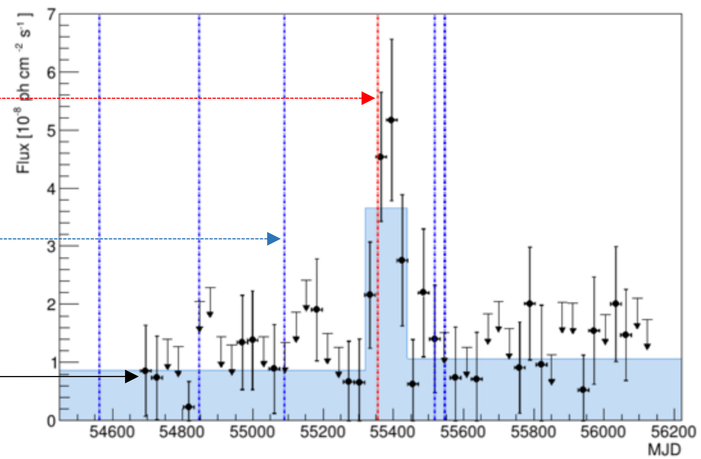


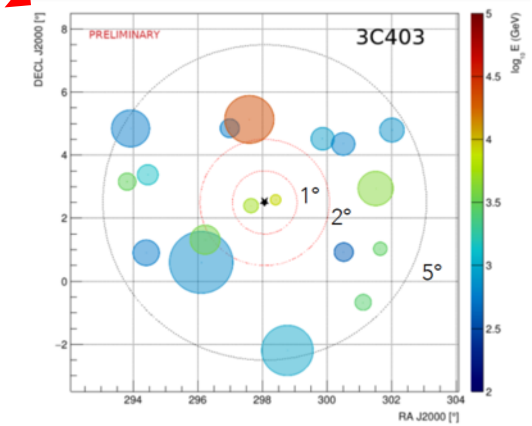
The most significant population is the Radio-galaxies

Red dashed lines: arrival time of IceCube EHE IC#3 event (track #3)

Blue dashed lines: arrival time of ANTARES events with $\Delta\theta_{\nu-source} < 2°$

Fermi gamma-ray flux for the BL Lac 3FGL J22551.1+2411





Radio-Galaxy 3C403: α=298.06° δ=+2.5°

An example of multi-messenger program: ANTARES

ANTARES generate alerts:

- **a single high energy neutrino (HE)**
- **a very high energy (VHE) neutrino**
- **a neutrino associated with specific directions in the sky**
- **at least two neutrinos coming from close directions**

After On-line reconstruction (<delay>: ~6 s, $\sigma(\theta)$ ~0.4°-0.5°)
send alerts as Gamma-ray Coordinates Network circular

ANTARES receives a GCN alert:

- **GRB (FERMI, Swift, IPN, …)**
- **GW (LIGO/VIRGO)**
- **H.E. neutrinos (IceCube)**
- **H.E. CR (AUGER, TA, …)**
- **Supernovae (Optical Telescopes)**
- **Fast radio burst (Radio Telescopes)**
- **H. E. Gamma (HESS, HAWC)**

In 10 years
311 alerts set to robotic telescopes

- 18/25 followed by Swift
- 4 followed by Integral
- 4 followed by MWA
- 2 followed by HESS

NO TRANSIENT SOURCE ASSOCIATED SO FAR TO ANTARES ALERTS

Follow-up of

- GW - runs O2 and O3
- 11 high energy IC alerts
- GRB triggers (226 Swift and 536 Fermi GRBs.)

NO NEUTRINO ASSOCIATED TO EXTERNAL ALERTS SO FAR

Searches for ν from Gamma Ray Bursts

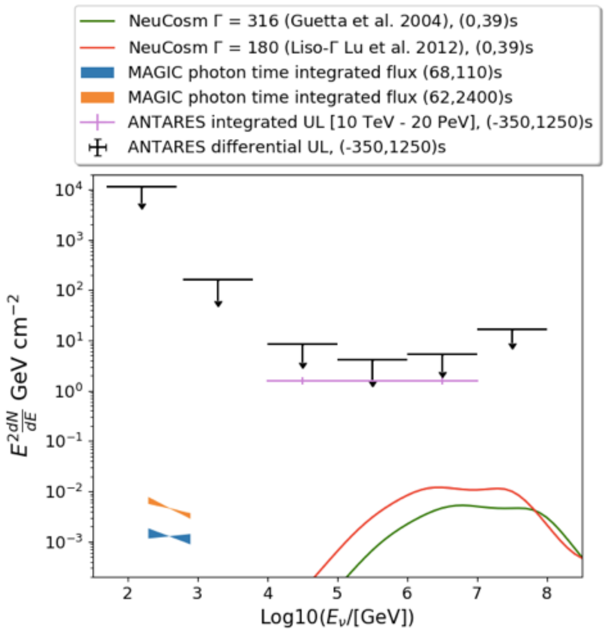
Stacking analysis of 784 GRBs
ANTARES tracks 2007-2017

- No coincidences found
- GRBs contribute <10% of astrophysical flux <100TeV

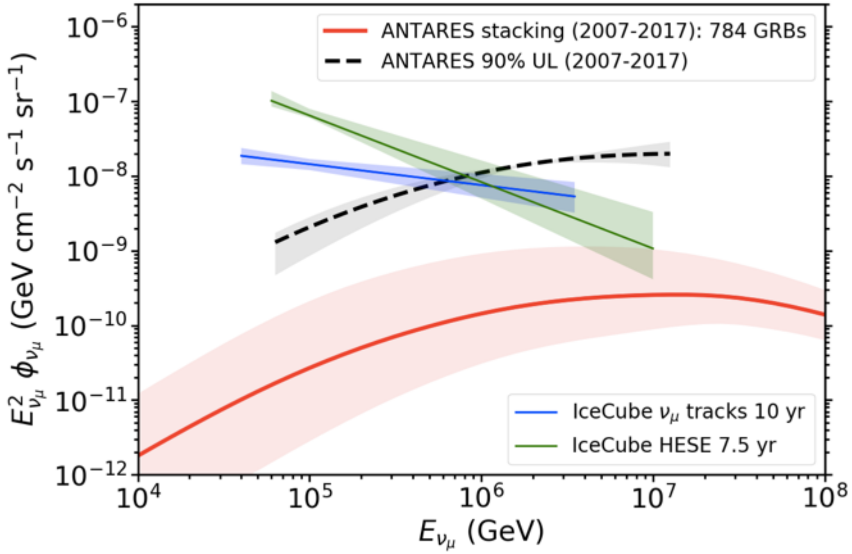
High energy gamma ray emission observed for 3 GRBs by H.E.S.S./MAGIC:
GRB180720A, GRB190829B (H.E.S.S.)
GRB190114C (MAGIC)

-> Follow-up search using ANTARES tracks & cascades during time of γ-ray emission

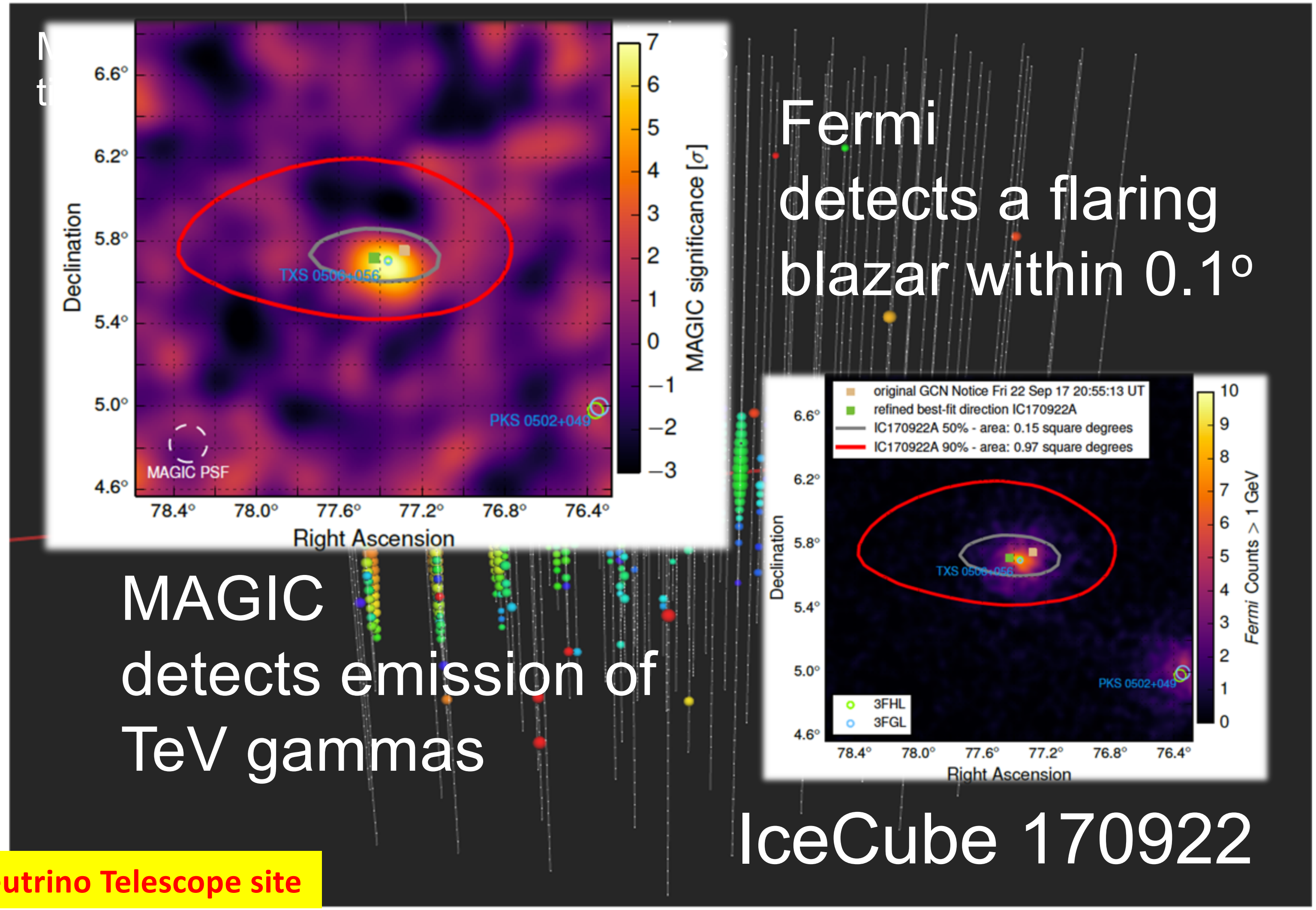
-> No events found in time & space coincidence



No neutrino detected so far from these extremely energetic sources: which 'hadronic component ?'

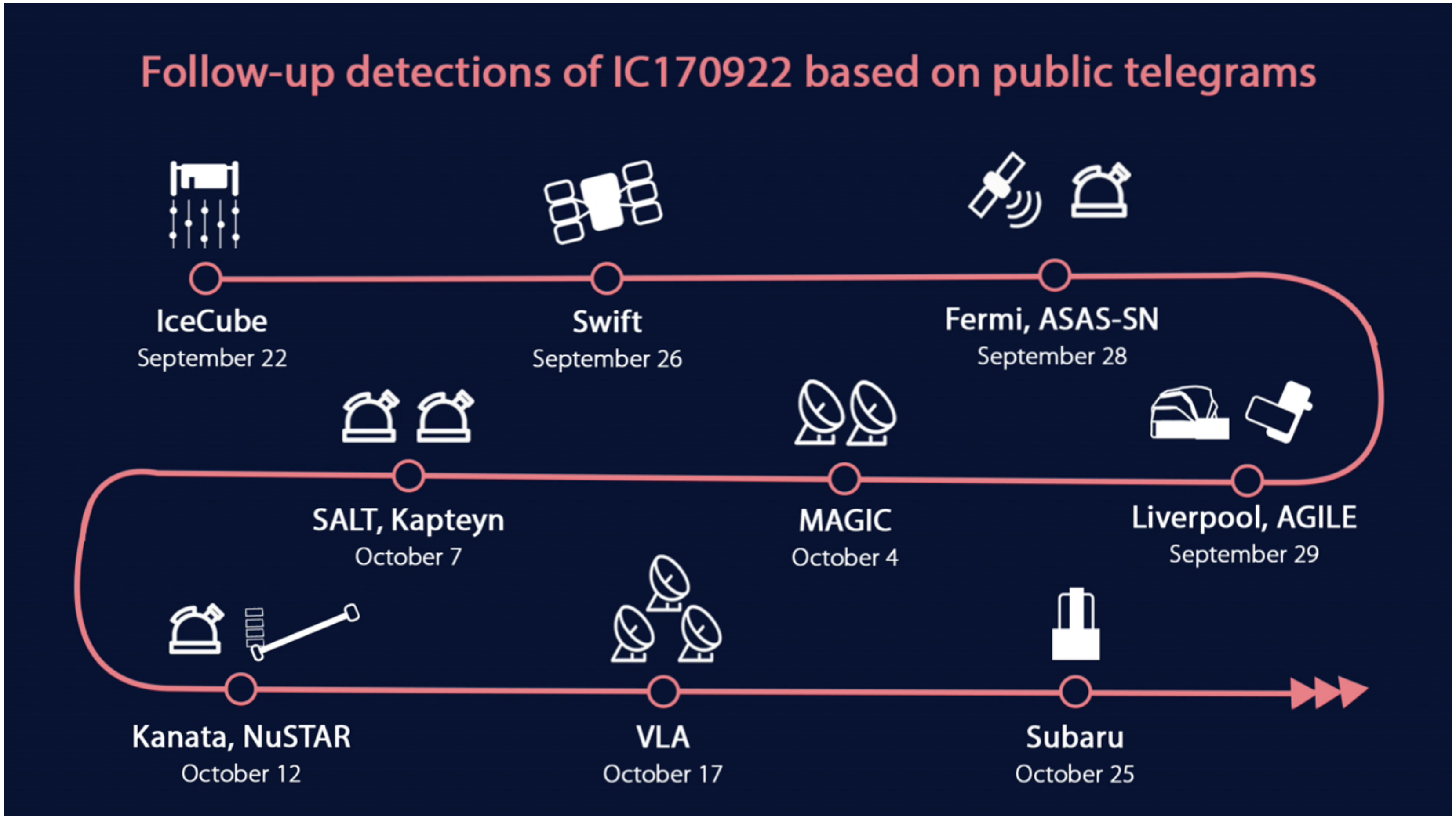


A very interesting event: a real example of multimessenger astrophysics



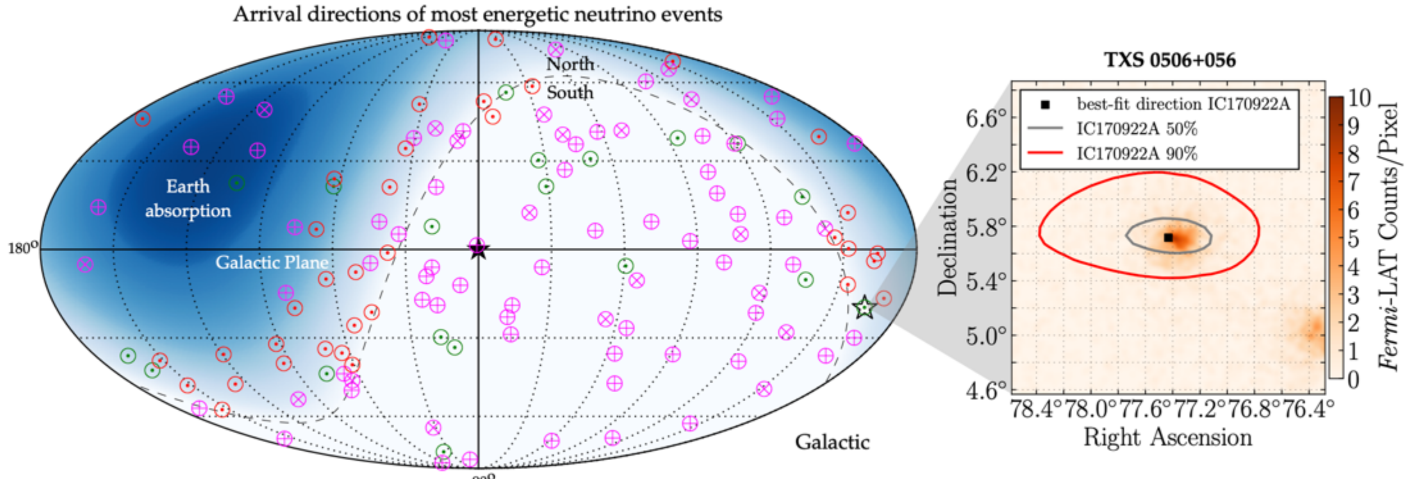
Triggering on Neutrino Telescope site

A very interesting event: a real example of multimessenger astrophysics

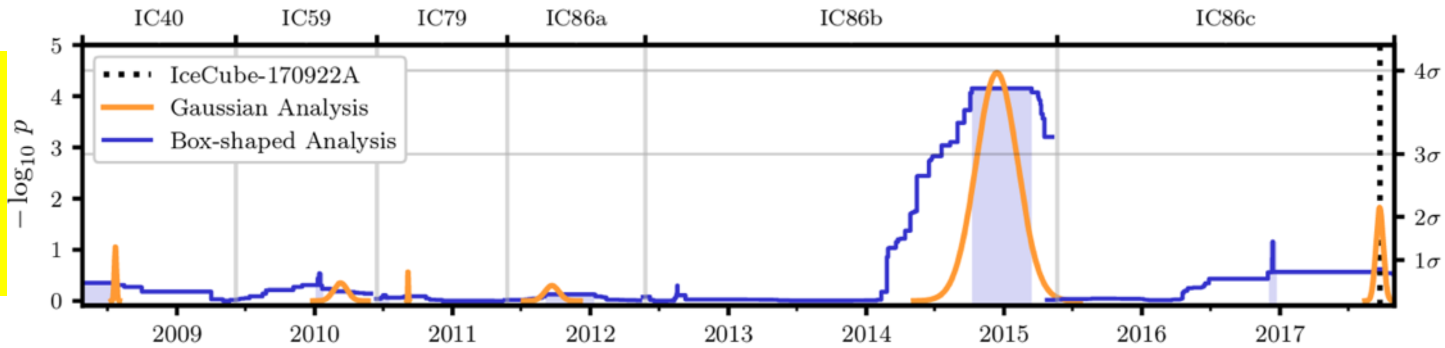


Sky Map of H.E. neutrino events detected by IceCube

IC170922A origin close to the position of the blazar TXS 0506+056
IceCube found in his previous years data other events compatible with the source TXS 0506+056.

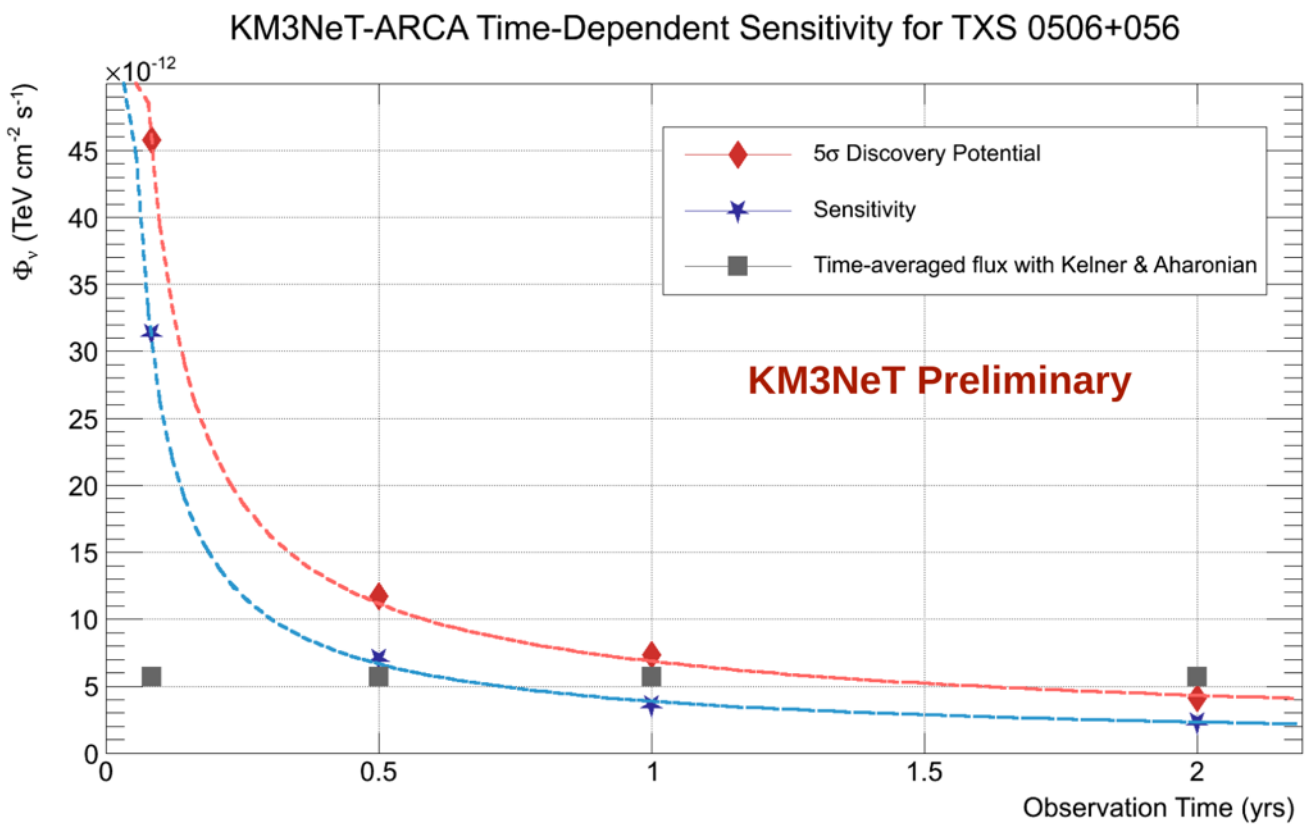


- 150 day flare in December 2014 with 19 events (bkg <6)
- 10^{-5} bkg. probability
- spectrum $E^{-2.1}$



Is TXS 0506+056 the first known extragalactic source of high energy cosmic rays ???

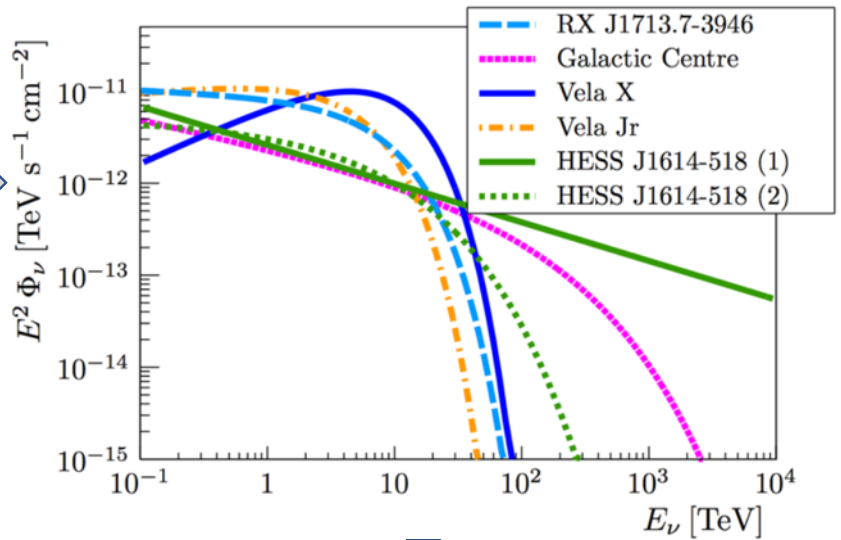
KM3NeT-ARCA expectations for TXS 0506+056



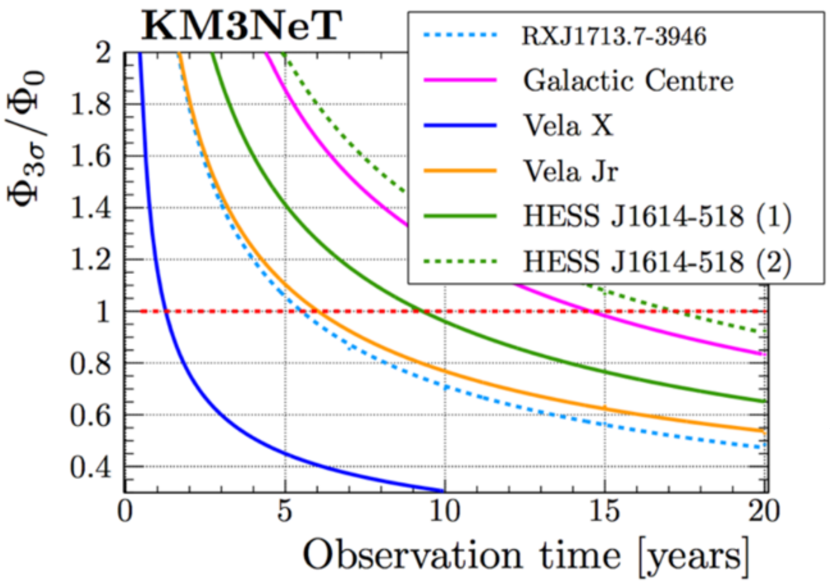
The expected neutrino flux from the blazar TXS 0506+056 and the KM3NeT-ARCA (2 blocks) 90% C.L. sensitivity and the 5σ discovery potential (with 50% probability) as function of observation time.

KM3NeT-ARCA : sensitivity for ν from galactic sources

- Select sources with observed intense γ fluxes
- Assume: γ originated in hadronic processes
  $p + \gamma \rightarrow \pi^0 + X$ (and also $p + \gamma \rightarrow \pi^{\pm} + X$)
  $\hookrightarrow \pi^0 \rightarrow \gamma\,\gamma$ (and also $\hookrightarrow \pi^{\pm} \rightarrow \nu_\mu\,\mu$)
- Assume the source transparent (to γ)
- From the observed γ spectra/flux evaluate the expected ν flux



R. Coniglione – PoS(ICRC2019)006



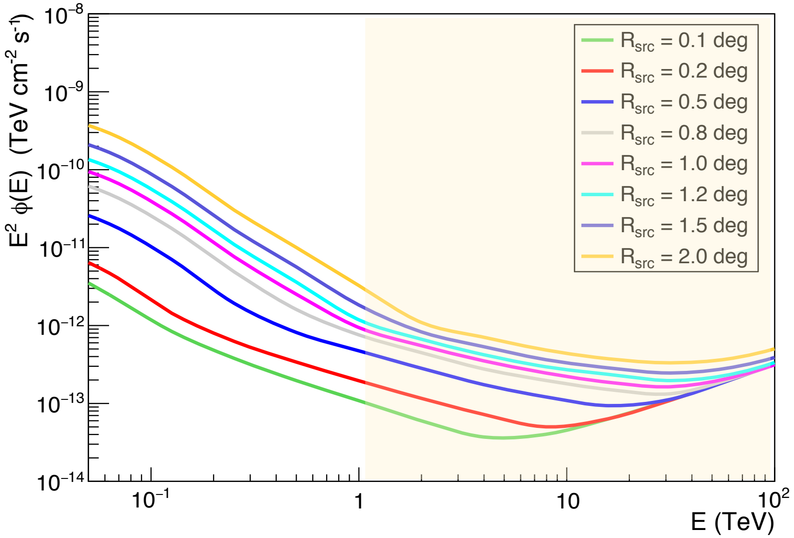
Then is possible to evaluate the time needed for KM3NeT/ARCA to DISCOVER, with **3σ** statistical accuracy, the selected sources:

- ~5 years for the SNR RXJ1713
- ~3 years stacking RXJ1713 & Vela Jr

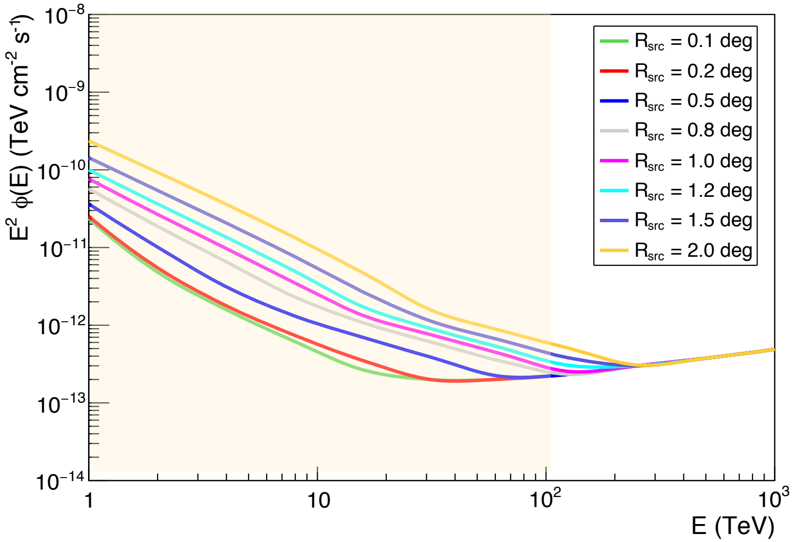
γ and ν telescopes complementarity

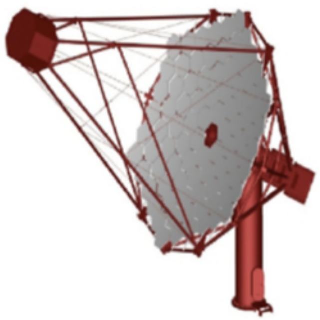
Ambrogi, Celli & Aharonian, Astropart. Phys. 100 (2018)

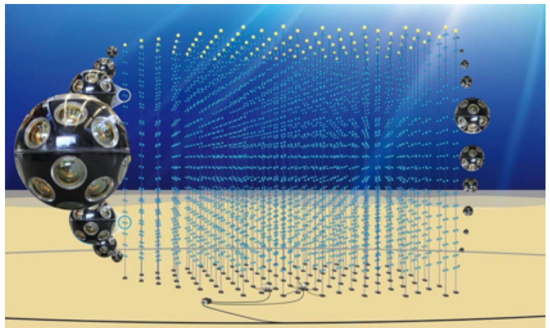
CTA 50 hrs



KM3NeT 10 yrs (upgoing tracks)



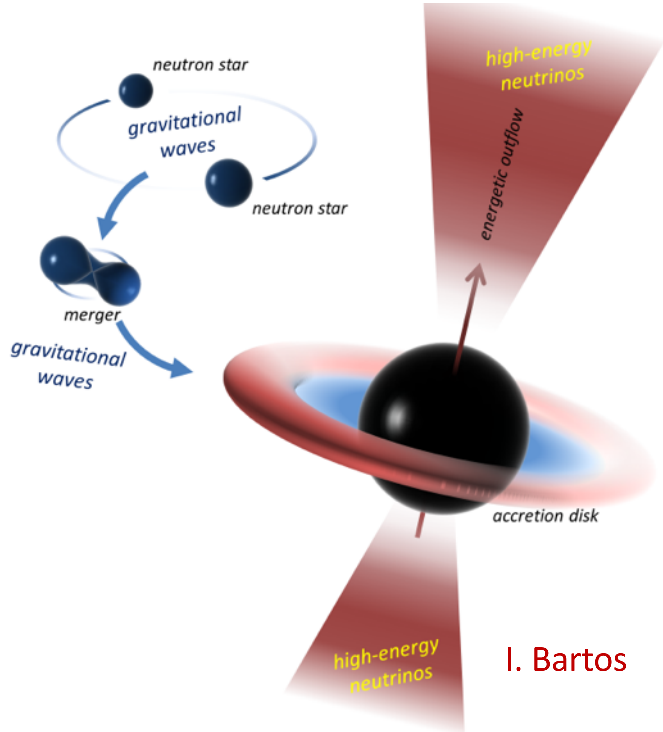




Searches for neutrinos with GW alarms

... a very interesting case

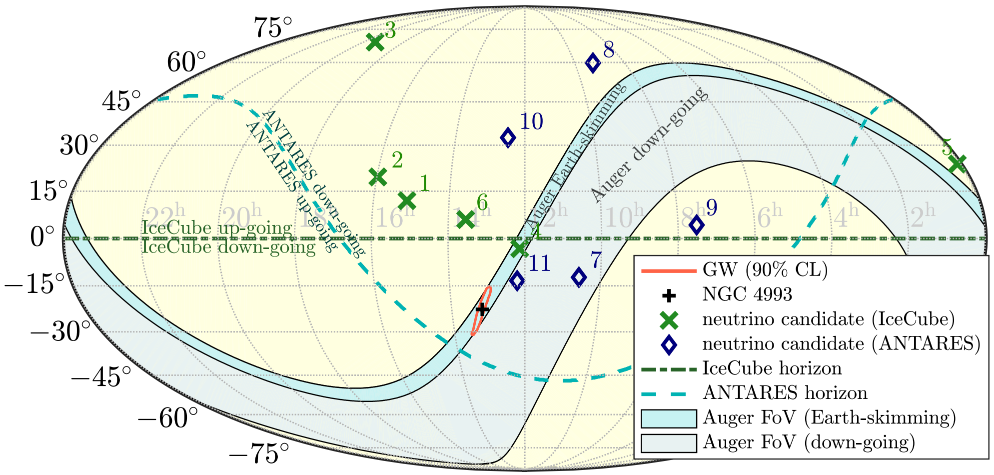
- A rich variety of phenomena in the case of NS-NS merging
- *GW* standard "sirene"
- Neutrinos ν
- EM counterpart
  - Fast emission (GRB)
    - Beamed emission
    - Afterglow (X-ray,...)
  - Kilonova (*)
    - Isotropic emission
    - Neutron-rich ejecta
  - Radio emission
- UHECR's acceleration?

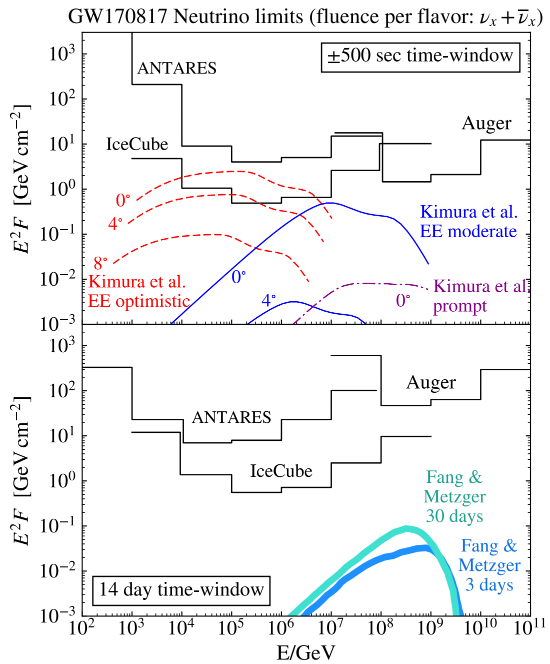


I. Bartos

(*) By radioactive decay of heavy elements produce via r-process nucleosynthesis in the neutron-rich merger ejecta

A joint ANTARES/IceCube/LigoSC/Virgo/Auger analysis performed as “Neutrino follow-up” of GW170817





- Advanced LIGO and Advanced Virgo observatories reported GW170817 (binary neutron star inspiral).
- A short gamma-ray burst (GRB) that followed the merger of this binary was also recorded by the Fermi-GBM and INTEGRAL.
- ANTARES, IceCube, and Pierre Auger Observatories searched for high-energy neutrinos from the merger in the GeV–EeV energy range .
- No neutrinos directionally coincident with the source were detected within ±500 s around the merger time. Additionally, no MeV neutrino burst signal was detected coincident with the merger. No neutrino found in an extended search in the direction within the 14-day period following the merger.

Conclusions

- Neutrino Astronomy will complement in a multimessenger scheme the study of most energetic accelerators in the Universe
- IceCube results demonstrated the existence of astrophysical neutrinos and paved the way for future searches
- ANTARES: hints of Astrophysical Diffuse Neutrino flux in agreement with IceCube results
- Analysis of collected data going on (also joint to IceCube data) and promising
- CTA – LHAASO – IceCube Gen2 – KM3NeT – GVD – LIGO/VIRGO …. will be able, in a multimessenger scheme, to identify the sources of H.E. Cosmic Rays and will pave the way to understand the acceleration and propagation processes.