

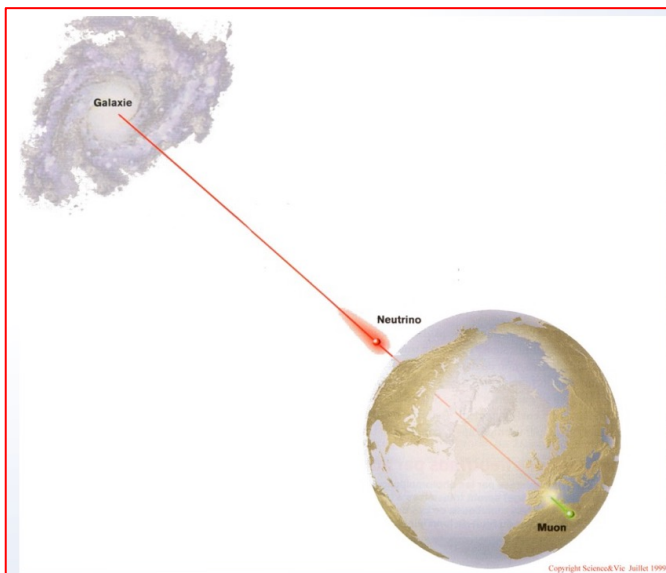


XVIII Vulcano Workshop on Frontier Objects in Astrophysics and Particle Physics

Search for High Energy Astrophysical Neutrinos

Experimental status

Antonio Capone



Astrophysical ν detection

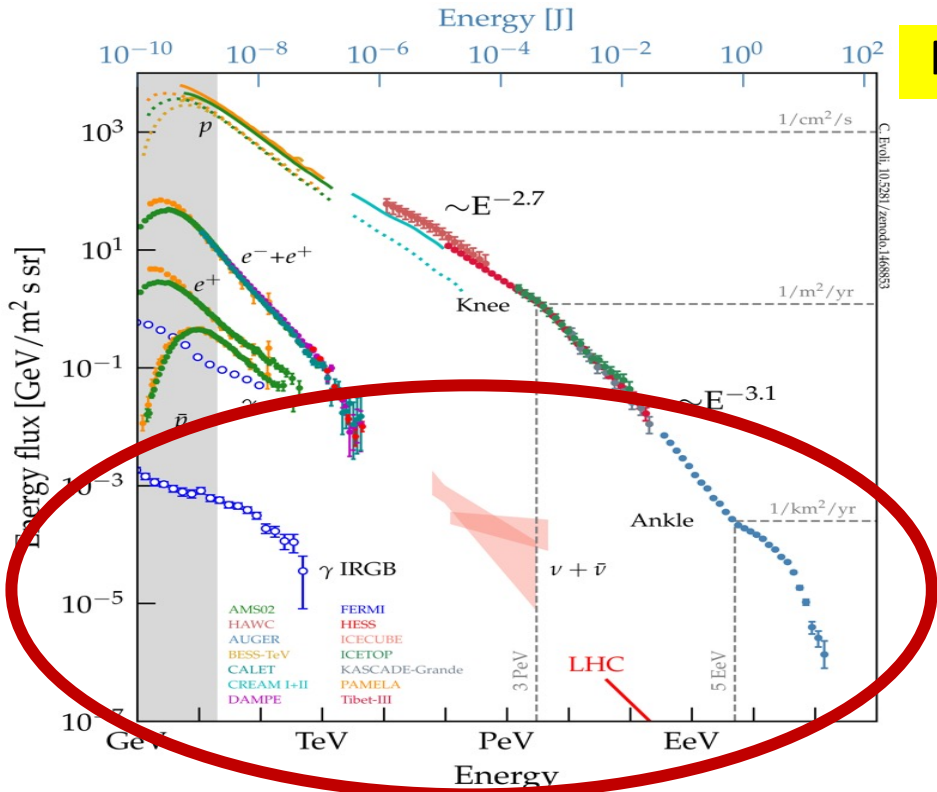
- Why ?
- How ?
- Where ?

The ν , γ , HE C.R. connection

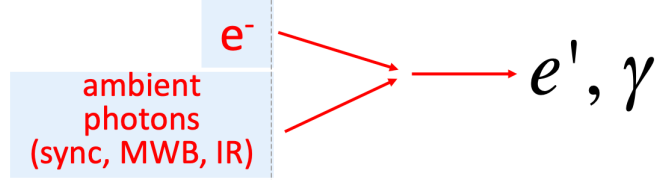
- Multi-messenger search for H.E. astrophysical sources

Results from Cherenkov ν Telescopes

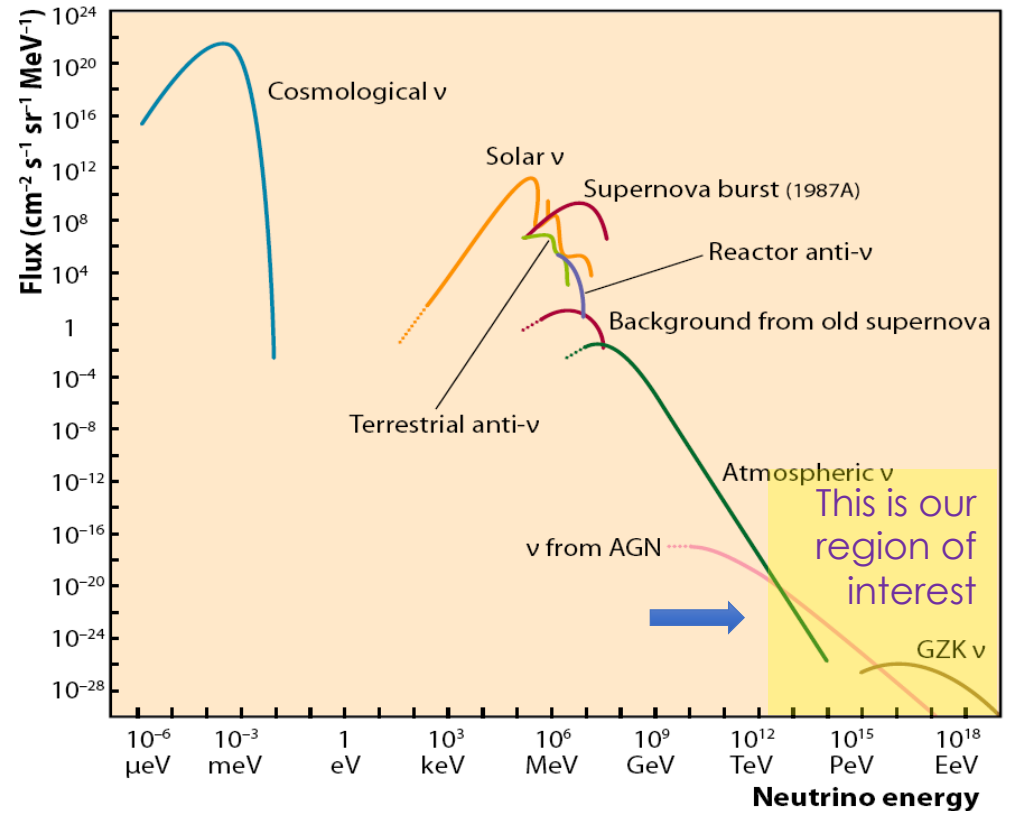
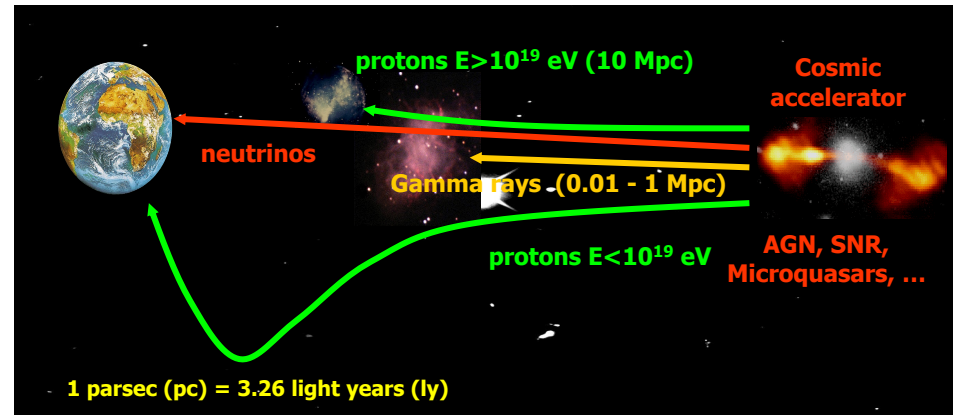
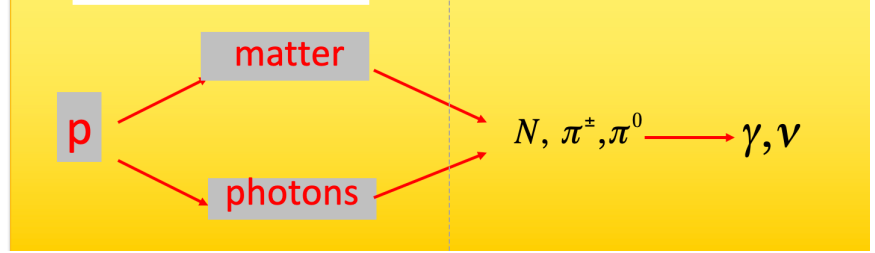
Motivations for High Energy Neutrino Astrophysics



leptonic process Inverse Compton scattering

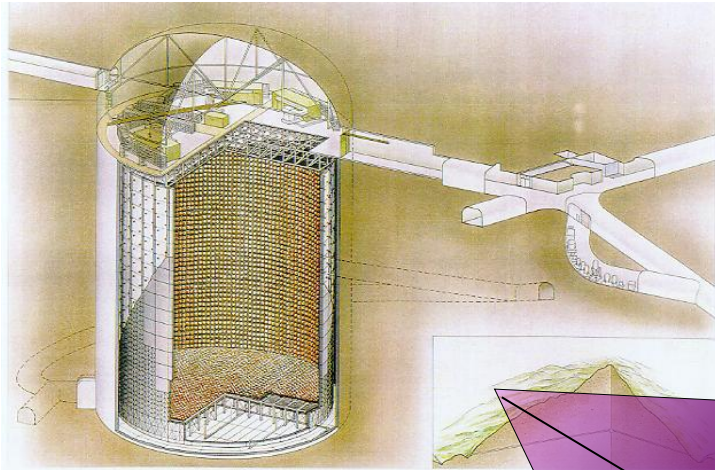


hadronic processes



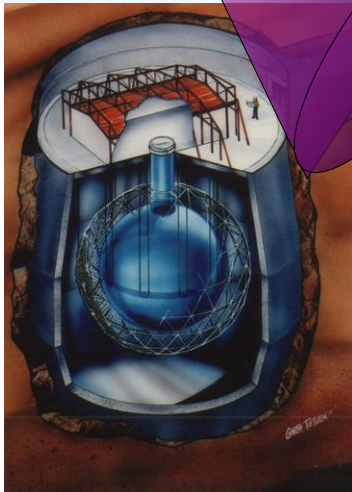
Detecting neutrinos in H₂O

Proposed by Greisen, Reines, Markov in 1960

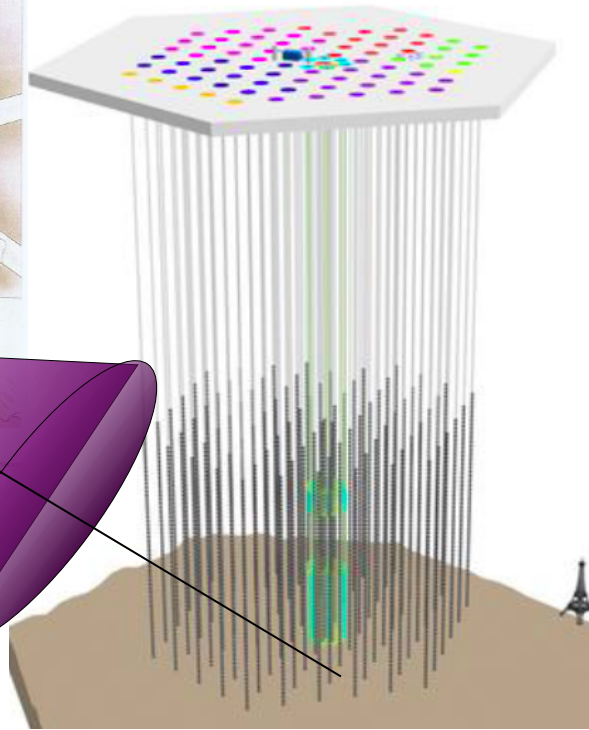


SUPERKAMIOKANDE INSTITUTE FOR COSMIC RAY RESEARCH UNIVERSITY OF TOKYO

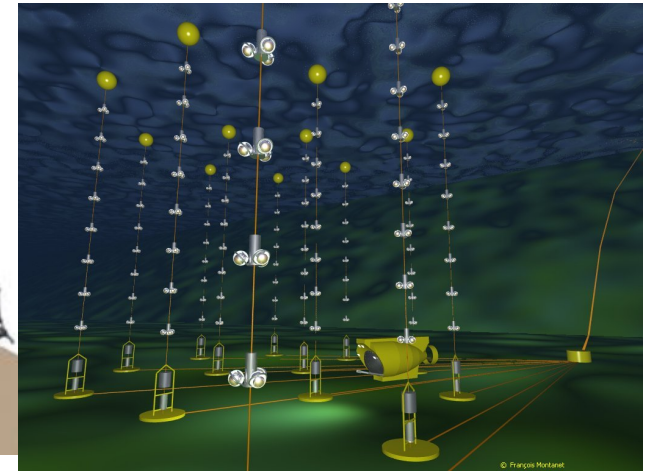
Super-K



SNO



IceCube, Gen2



ANTARES, KM3NeT

- DUMAND
- IMB
- Kamiokande
- Baikal
- AMANDA

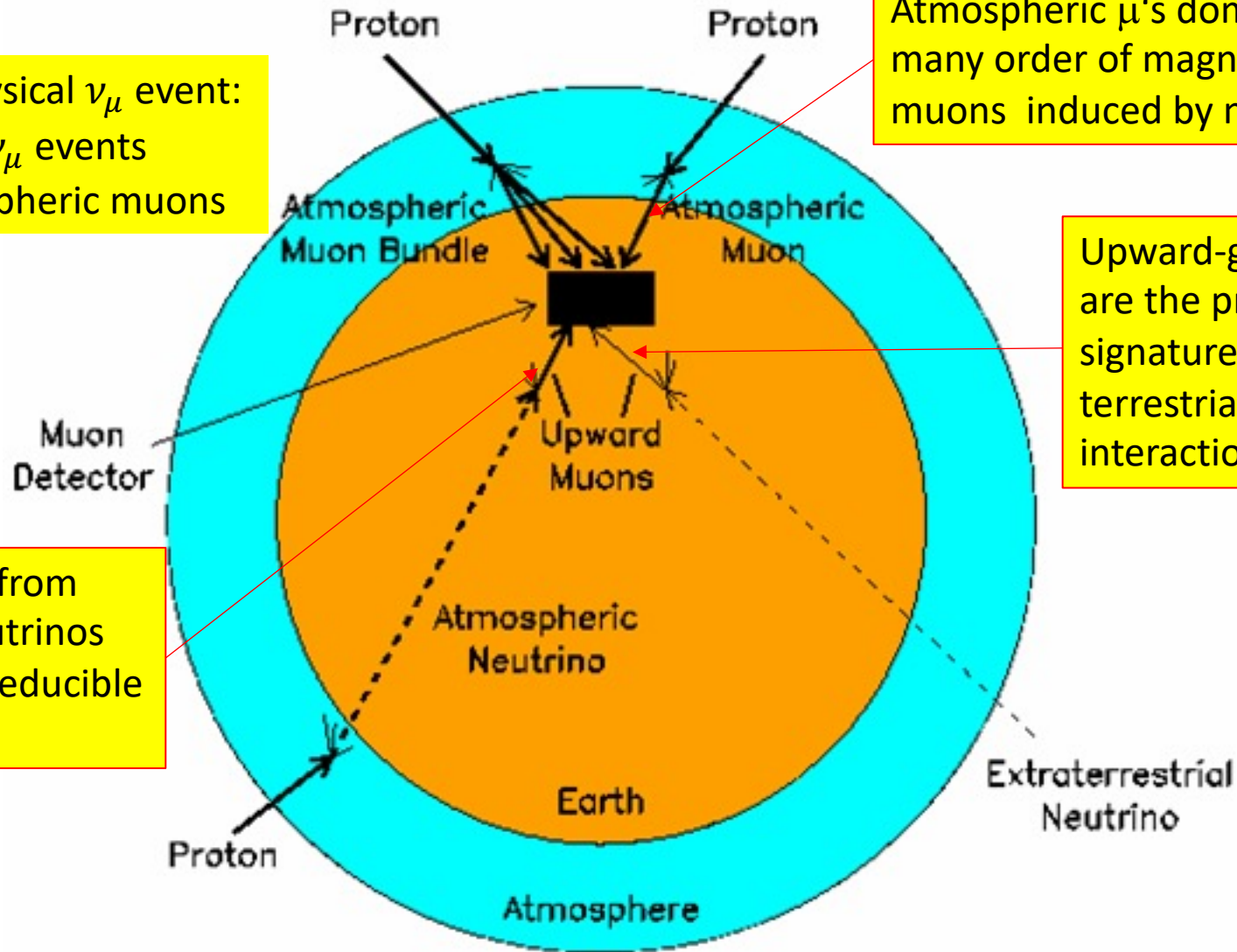
Neutrinos must interact to be detected: use water as target and Cherenkov radiator, use PMT as detectors

Neutrino Telescopes: signal and background

- for 1 astrophysical ν_μ event:
 - ~ 100 atm. ν_μ events
 - $\sim 10^8$ atmospheric muons

Atmospheric μ 's dominate by many order of magnitude the muons induced by neutrinos

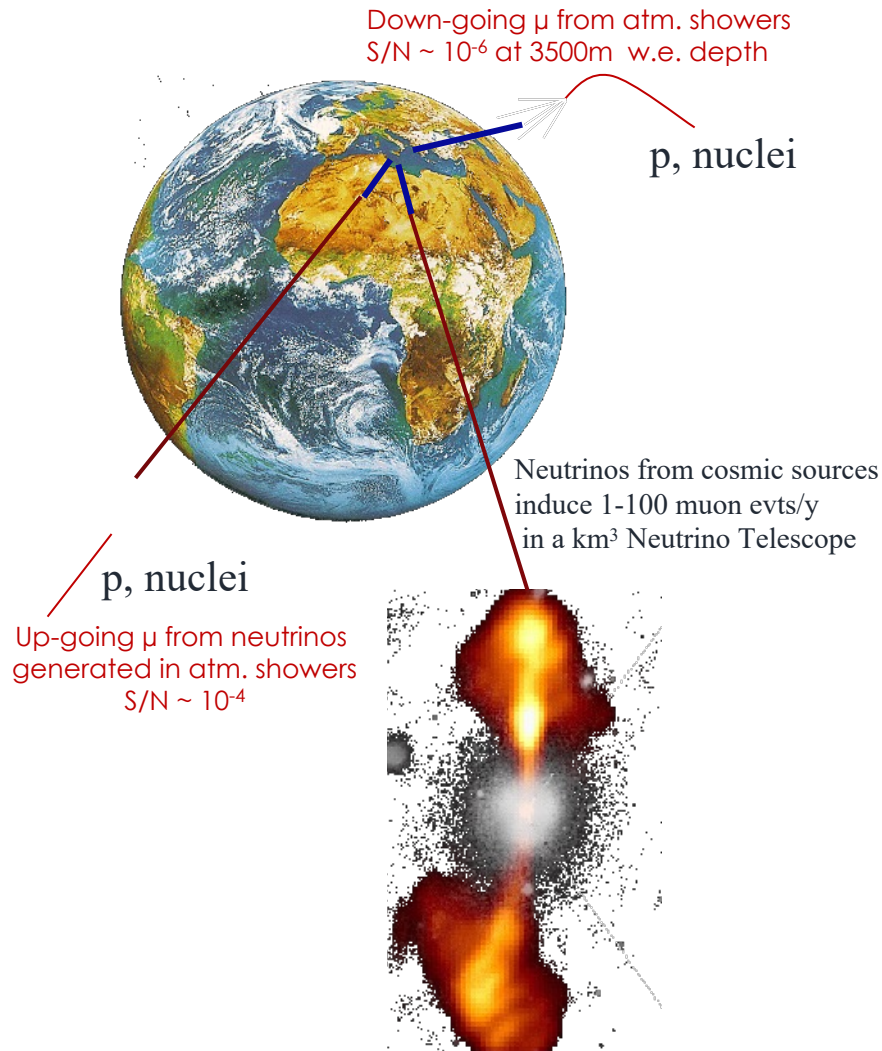
Upward-going particles are the preferred signature for extra-terrestrial neutrino interactions



Upgoing muons from atmospheric neutrinos represent the irreducible background

Cherenkov ν Telescope: Detection principle

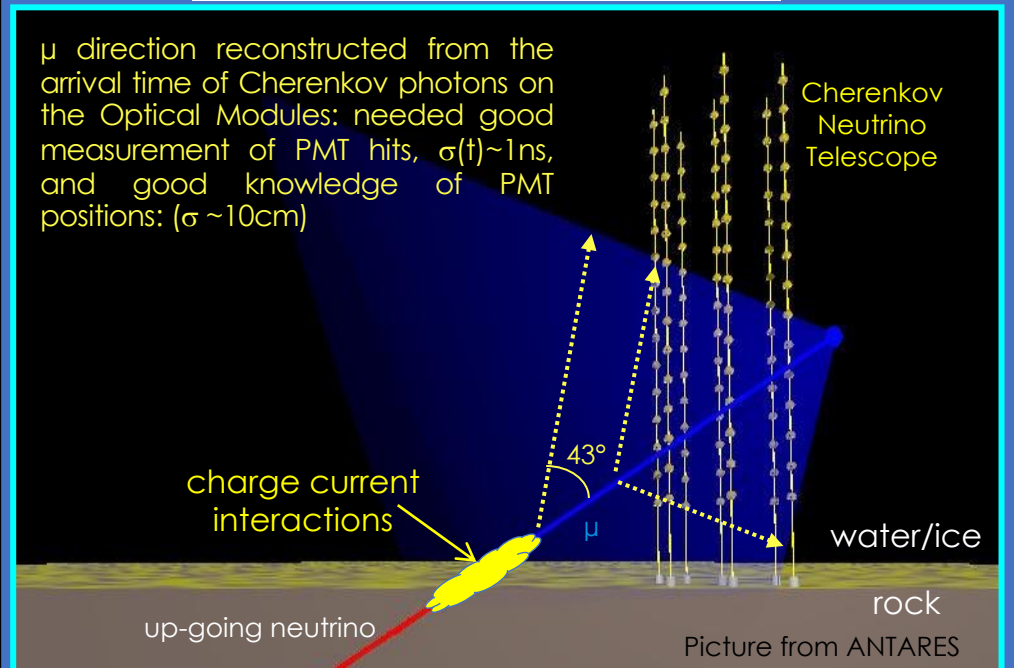
Search for neutrino induced events, mainly $\nu_\mu N \rightarrow \mu X$, deep underwater



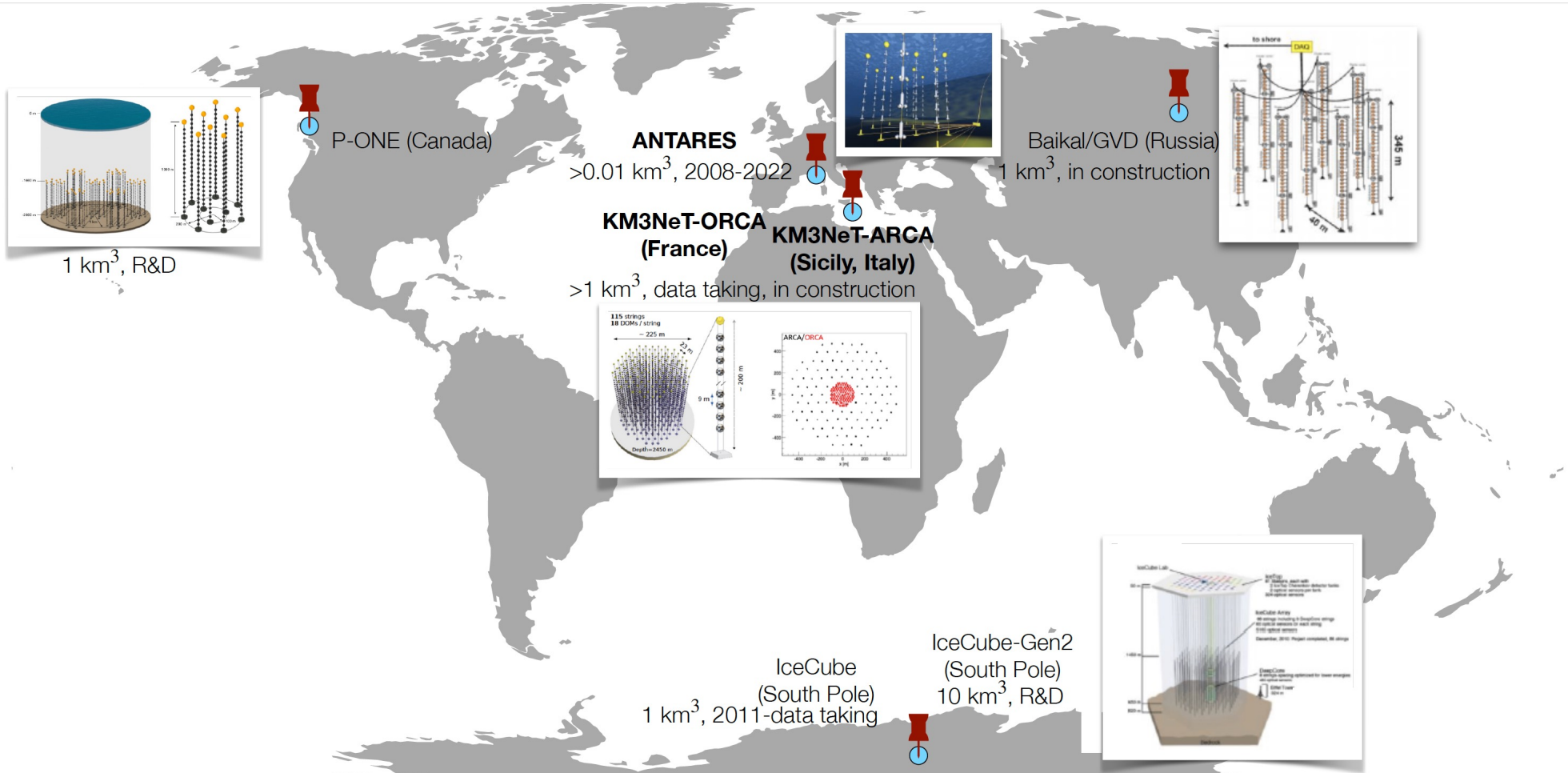
- Atmospheric neutrino flux $\sim E_\nu^{-3}$
- Neutrino flux from cosmic sources $\sim E_\nu^{-2}$
 - Search for neutrinos with $E_\nu > 1\text{--}10 \text{ TeV}$
- $\sim \text{TeV}$ muons propagate in water for several km before being stopped
 - go deep to reduce down-going atmospheric μ backg.
 - long μ tracks allow good angular reconstruction

$$\text{For } E_\nu \geq 1\text{TeV} \quad \theta_{\mu\nu} \sim \frac{0.7^\circ}{\sqrt{E_\nu [\text{TeV}]}}$$

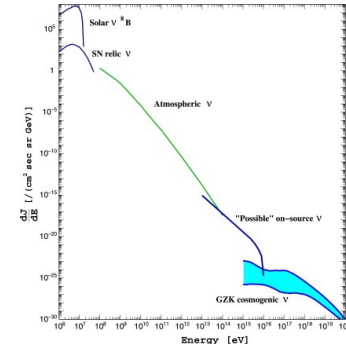
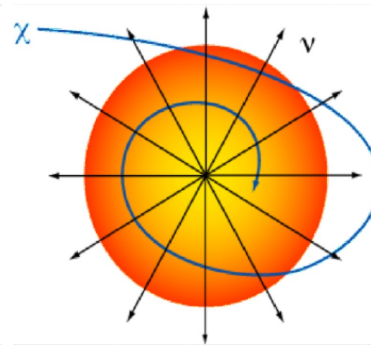
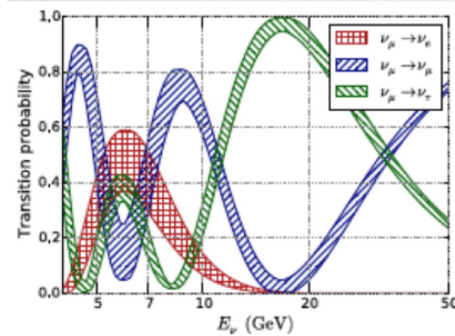
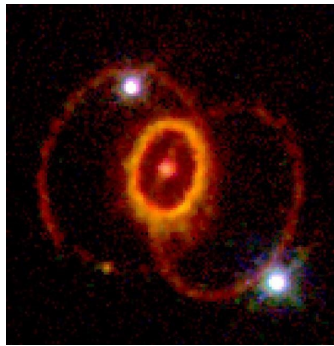
μ direction reconstructed from the arrival time of Cherenkov photons on the Optical Modules: needed good measurement of PMT hits, $\sigma(t) \sim 1\text{ns}$, and good knowledge of PMT positions: ($\sigma \sim 10\text{cm}$)



High Energy ν Telescopes world map



Cherenkov ν Telescope: science goals



CC –SN ν
MeV

ν Oscillations
 $10 < E_\nu < 100$ GeV

Indirect D.M search
 $\text{GeV} < E_\nu < 100$ GeV

Astroph. Sources
 $\text{TeV} < E_\nu < \text{EeV}$

GZK ν , ...
> EeV

- ν from SN

- ν Oscillations
- ν Hierarchy
- Sterile ν

- D. M. search
- Monopoles
- Nuclearites

- ν from extra-terrestrial sources
- Hadronic-leptonic ?
- Origin, acceleration mechanism of HE CR

U.H.E. C.R.
nature and propagation

Cherenkov ν Telescope: science goals

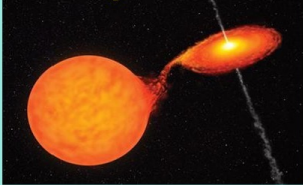
Search for point-like cosmic Neutrino Sources

Galactic

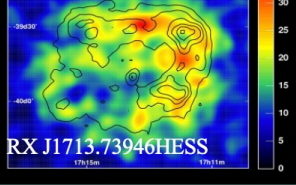
Pulsar Wind Nebulae



Microquasars



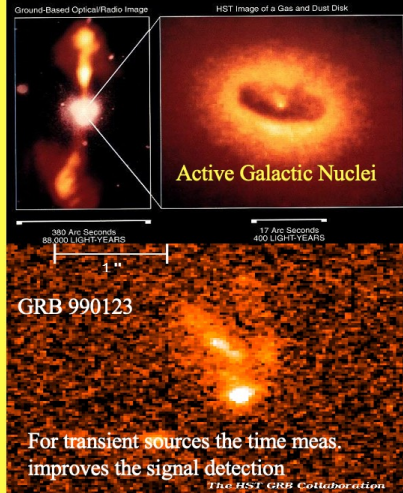
Supernova Remnants



Extragalactic

Core of Galaxy NGC4261

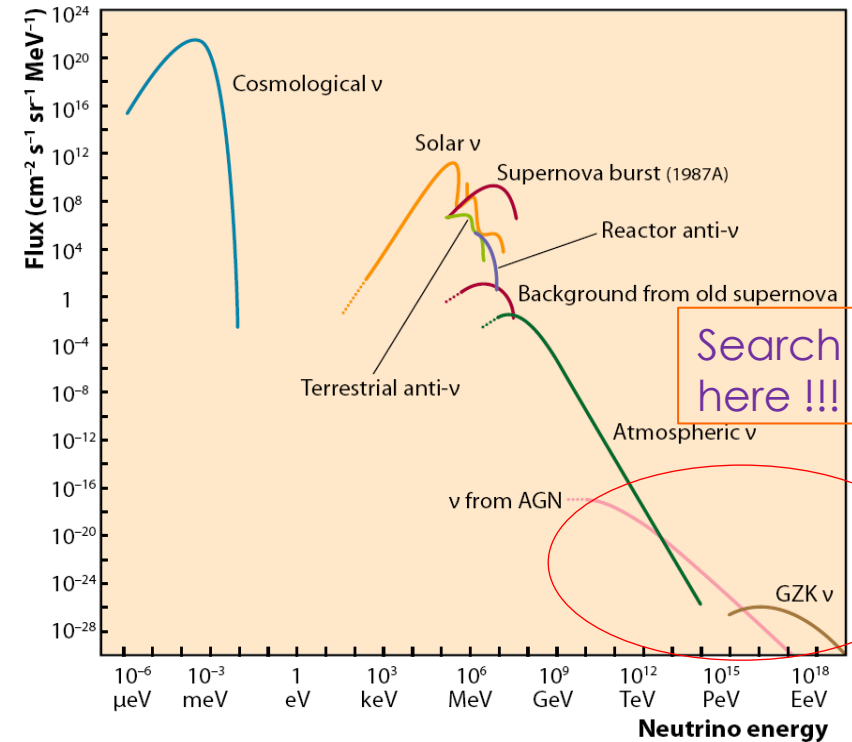
Hubble Space Telescope
Wide Field/Planetary Camera



For transient sources the time meas.
improves the signal detection

The HST GRB Collaboration

Search for Diffuse flux of Cosmic Neutrinos



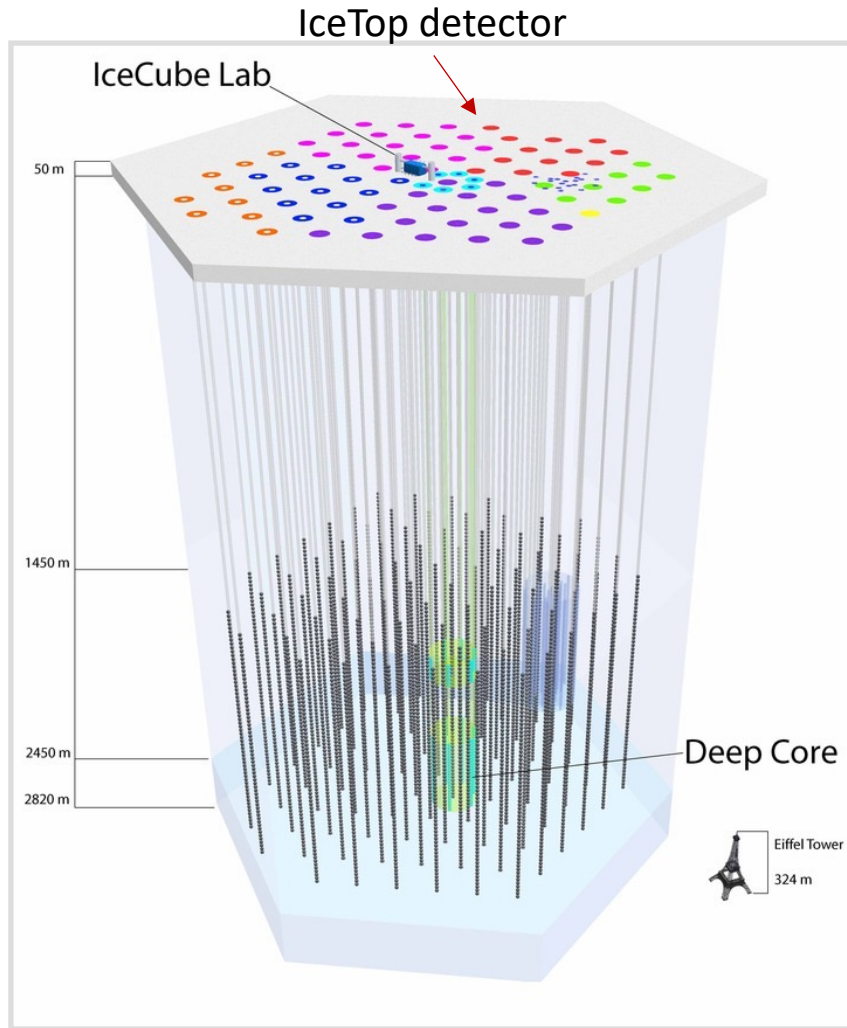
Search
here !!!

- Their identification requires a detector with accurate angular reconstruction
 $\sigma(\vartheta) \leq 0.5^\circ$ for $E_\nu \geq 1\text{TeV}$
- Their identification requires a detector with **accurate angular reconstruction**
- Search for sources from catalogue
- Auto-correlation search

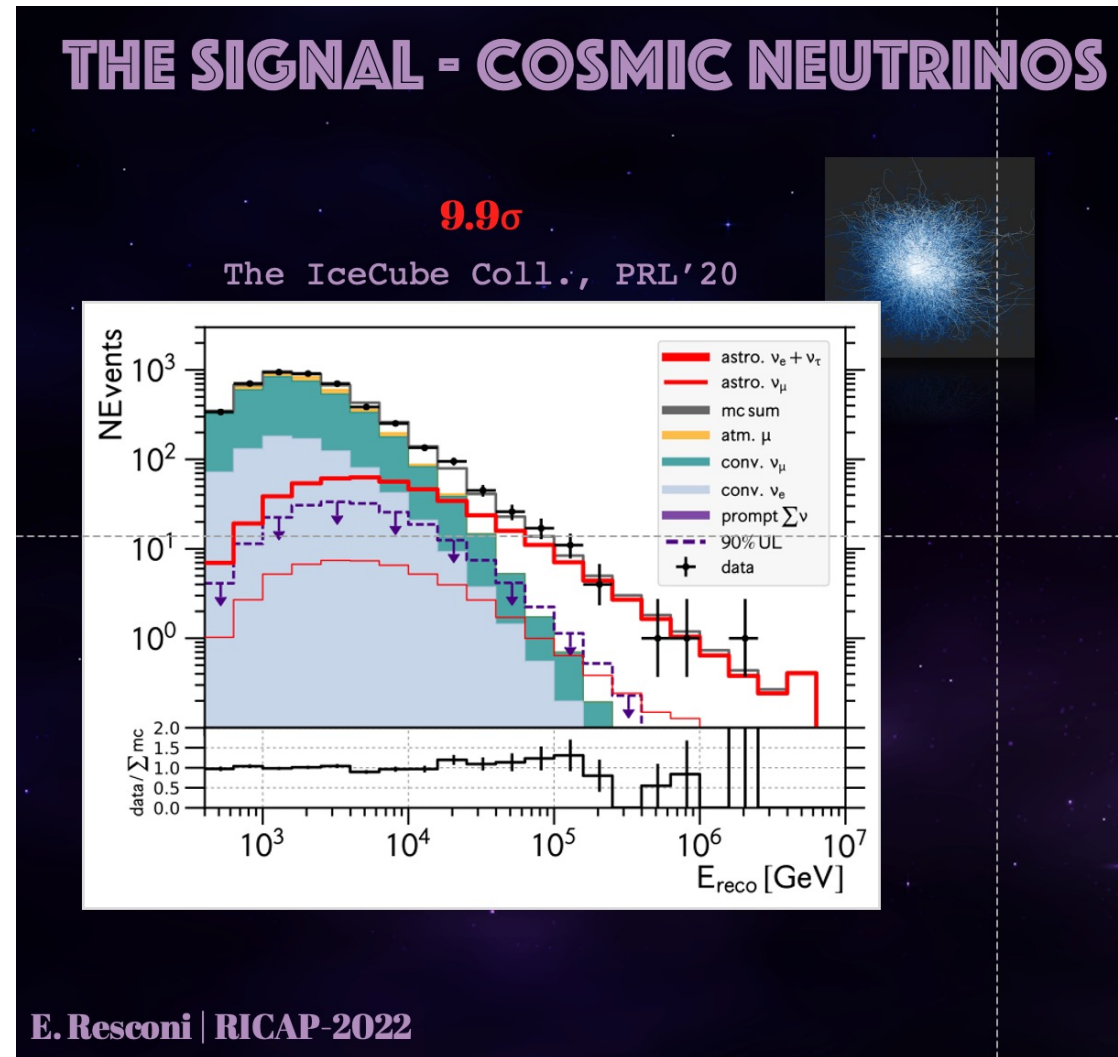
Their identification out of the more intense background of atmospheric neutrinos (and μ) is possible at very high energies ($E_\mu \gg \text{TeV}$) and requires **good energy reconstruction**.

- Neutrinos from:
 - Unresolved AGN
 - "Z-bursts"
 - "GZK like" proton-CMB interactions
- Top-Down models ν
-

IceCube: a flux of "diffuse" ν identified since 2013

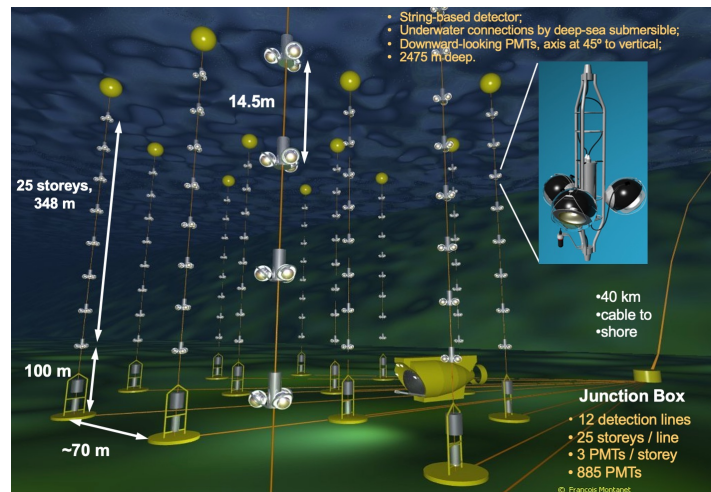


In operation at the South Pole since 2010
Sensitive to TeV – PeV neutrinos

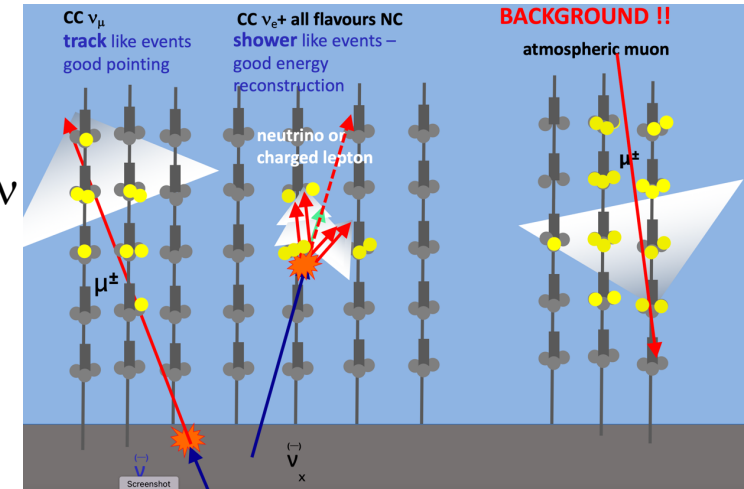


$$\frac{d\phi}{dE} = 6.45 \left(\frac{E_\nu}{100 TeV} \right)^{-2.89} 10^{-18} [GeV^{-1} cm^{-2} s^{-1} sr^{-1}]$$

ANTARES: sensitive to the IC "diffuse" ν flux



In operation 2008 - 2022
Sensitive to TeV – 100 TeV ν



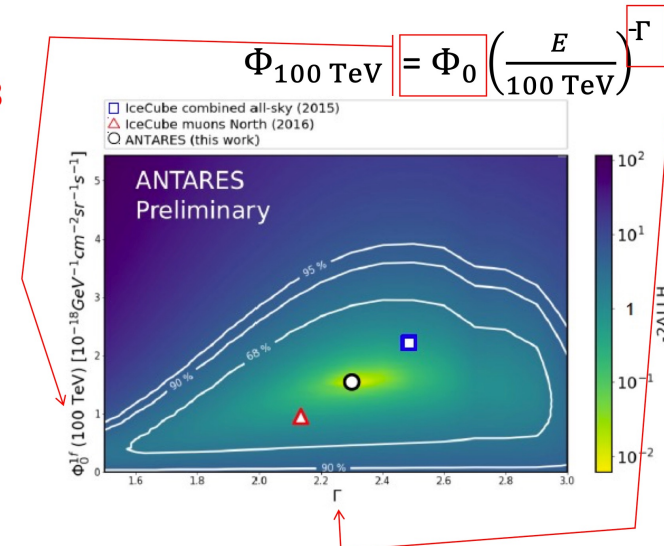
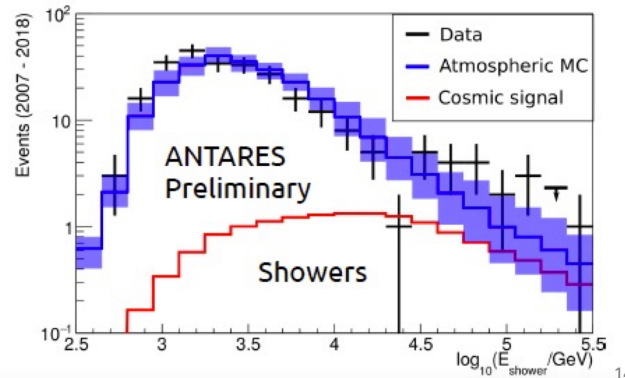
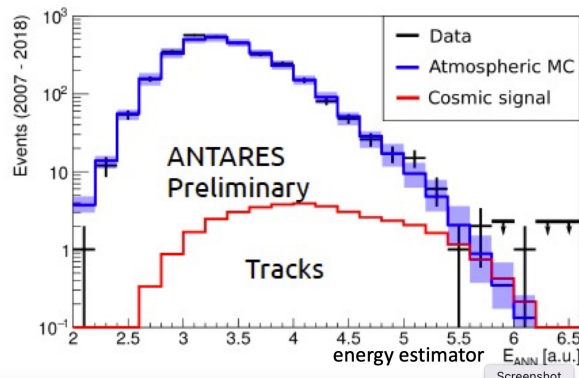
Ap.J.Lett. 853 (2018) 1, L7

[https://pos.sissa.it/358/891/pdf-\(ICRC19\)](https://pos.sissa.it/358/891/pdf-(ICRC19))

Search for an excess of high-energy events w.r.t atmospheric neutrinos

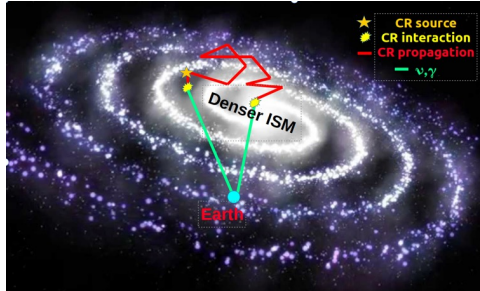
- Selection cuts optimized with MRF procedure (assumed spectral index $\Gamma=2.5$)
- Look for event excess above a given E_{th} both for track & shower samples
- Data with $E > E_{th}$: **50 events (27 tracks + 23 showers)**
- Background with $E > E_{th}$ (atm. Flux=HONDA + Enberg): **36.1 ± 8.7 (19.9 tracks + 16.2 showers)**
- \rightarrow **1.8σ excess** of events with $E > E_{th}$, assumed as cosmic flux (red histogram)

DATA sample 2007-2018



Results fully compatible with IceCube diffuse flux

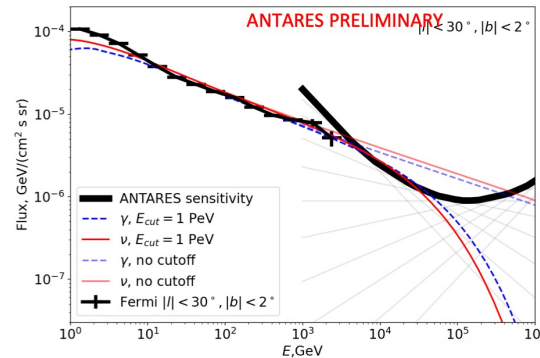
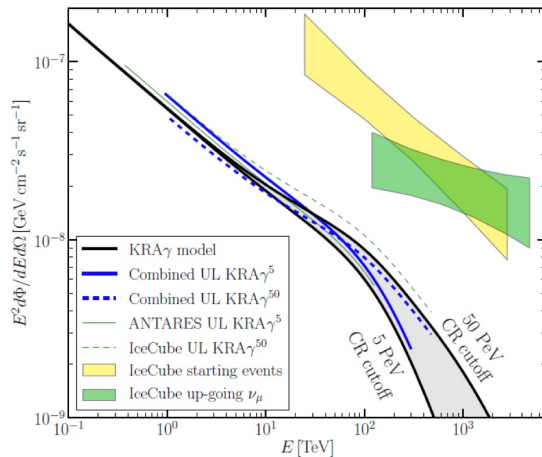
IceCube & ANTARES: search for "diffuse" ν flux from galactic ridge



Neutrinos carry direct information on CR propagation:
 -Non-homogeneous diffusion can enhance γ and ν emission
 -Molecular clouds/dense environments boost γ and ν fluxes

- neutrino signal expected from the Galactic Ridge (gamma-ray data)
- ν flux related to the primary CRs spectrum, if no cut-off below 1 PeV in CR flux
- Analysis in 2016 (7 y data 2007-2013) gives limits close to expectation without cutoff

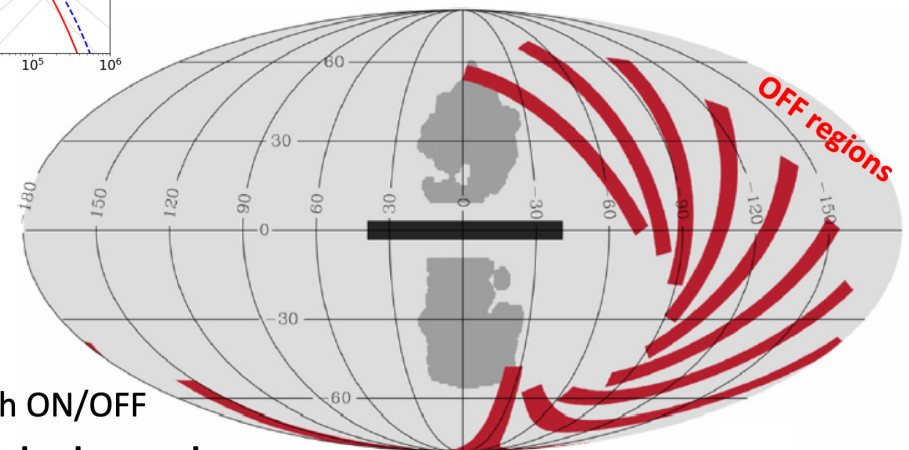
Galactic ridge region :
 $|l| < l_{\text{ridge}} \approx 30\text{-}40^\circ$ and $|b| < b_{\text{ridge}} \approx 2\text{-}3^\circ$



Using the full ANTARES dataset, a sensitivity below the extrapolated gamma-ray is expected

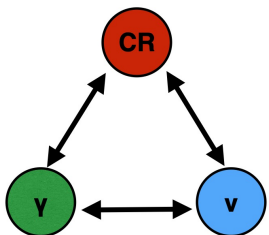
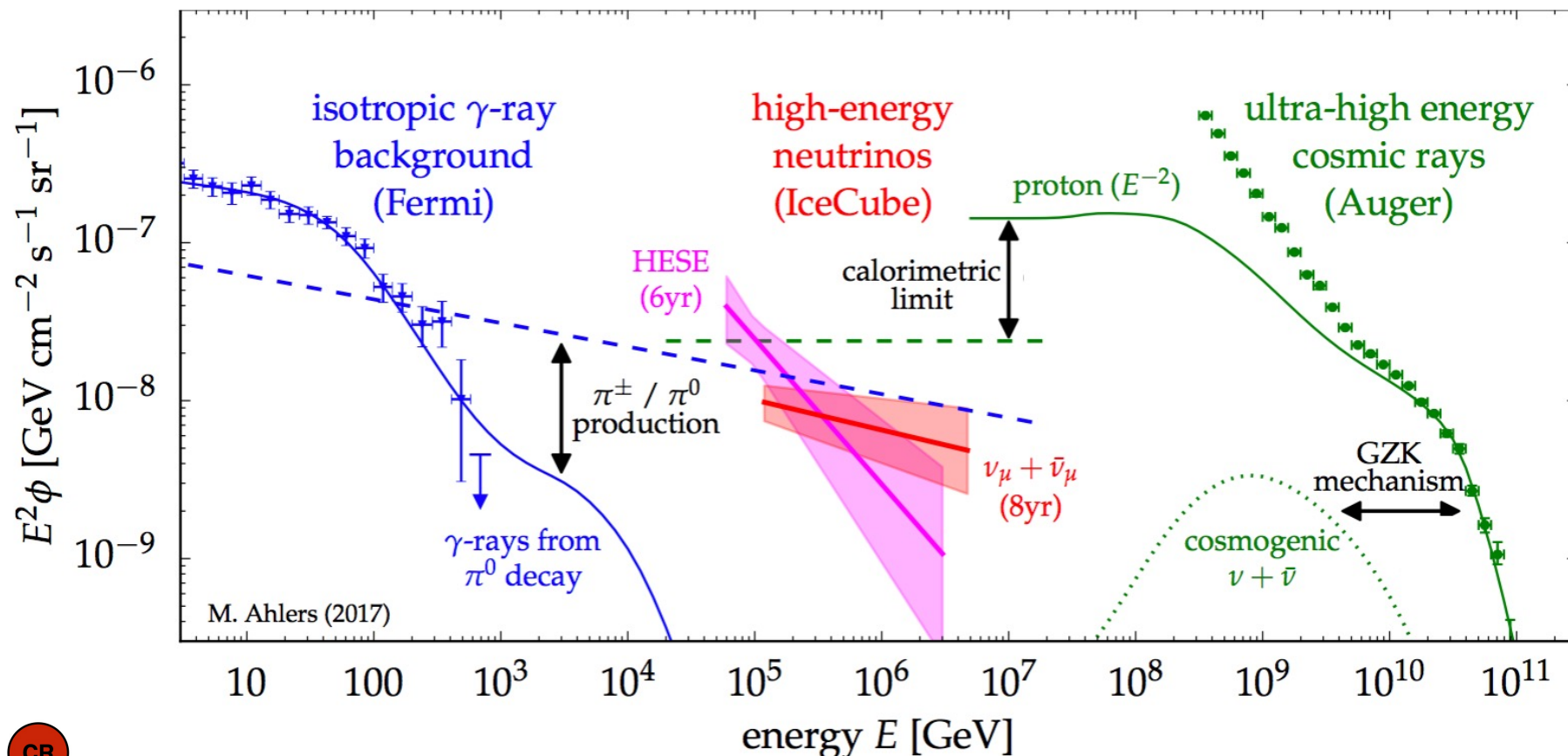
Astrophys.J. 868 (2018) no.2, L20

- Combined analysis ANTARES- IceCube
- at most 10% of the all-sky diffuse flux detected by IceCube can be of Galactic origin



simple approach ON/OFF
NO evidence above background

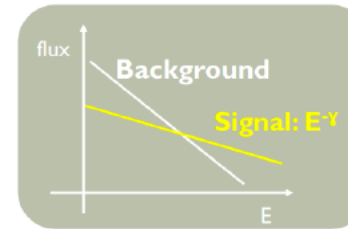
The "diffuse" ν - γ -CR fluxes connection



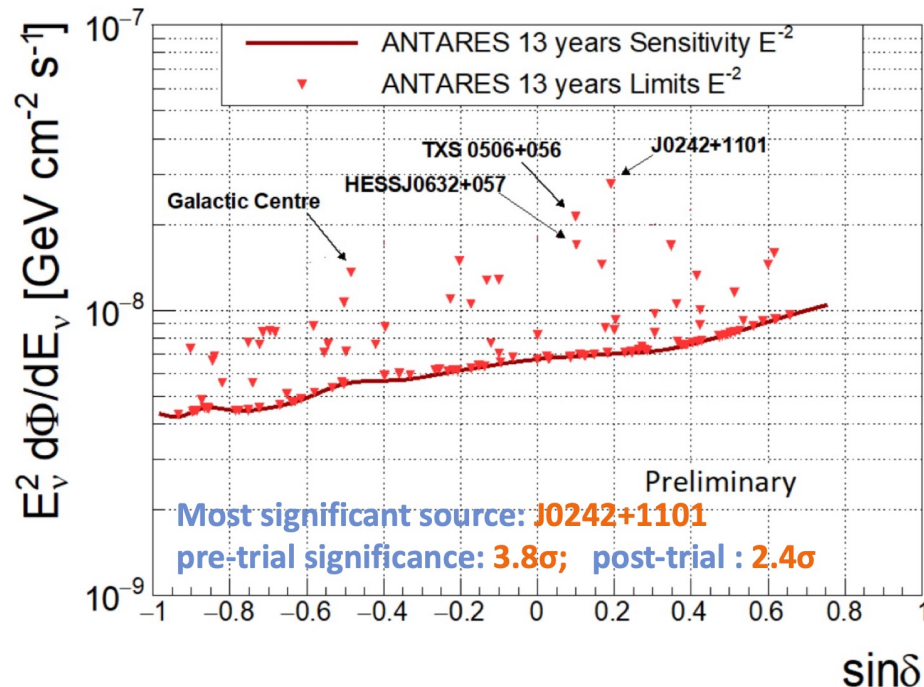
ANTARES: search for point like ν sources

- 13 years (2007-2020) data sample: 3845 days, 10162 traks, 225 showers
- Searching for a statistical excess from given sky point (sources catalogue)

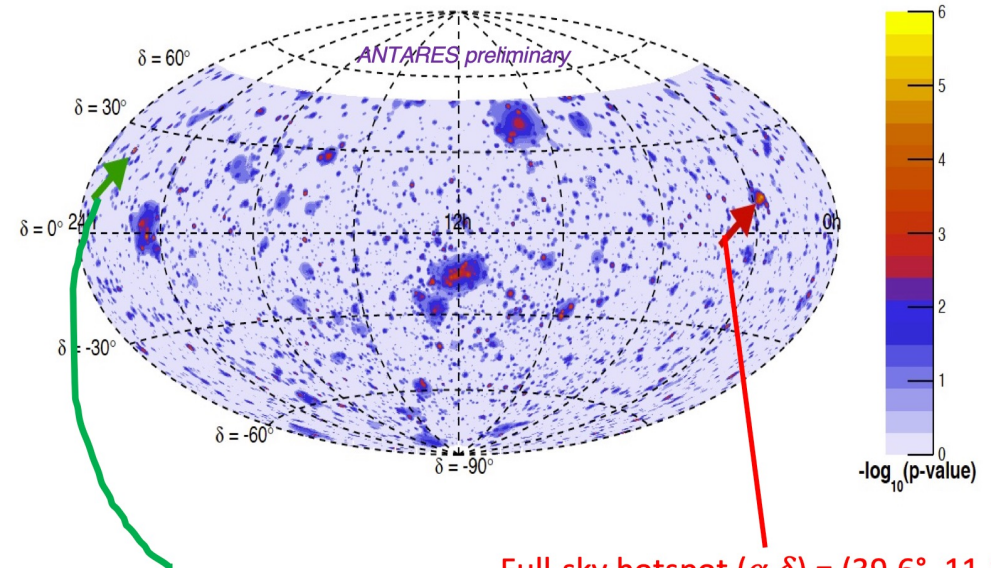
PRD 96, 082001 (2017)
PoS(ICRC2021)1161



Using a pre-definite candidate-list search:
121 investigated sources



With a unbinned full-sky search



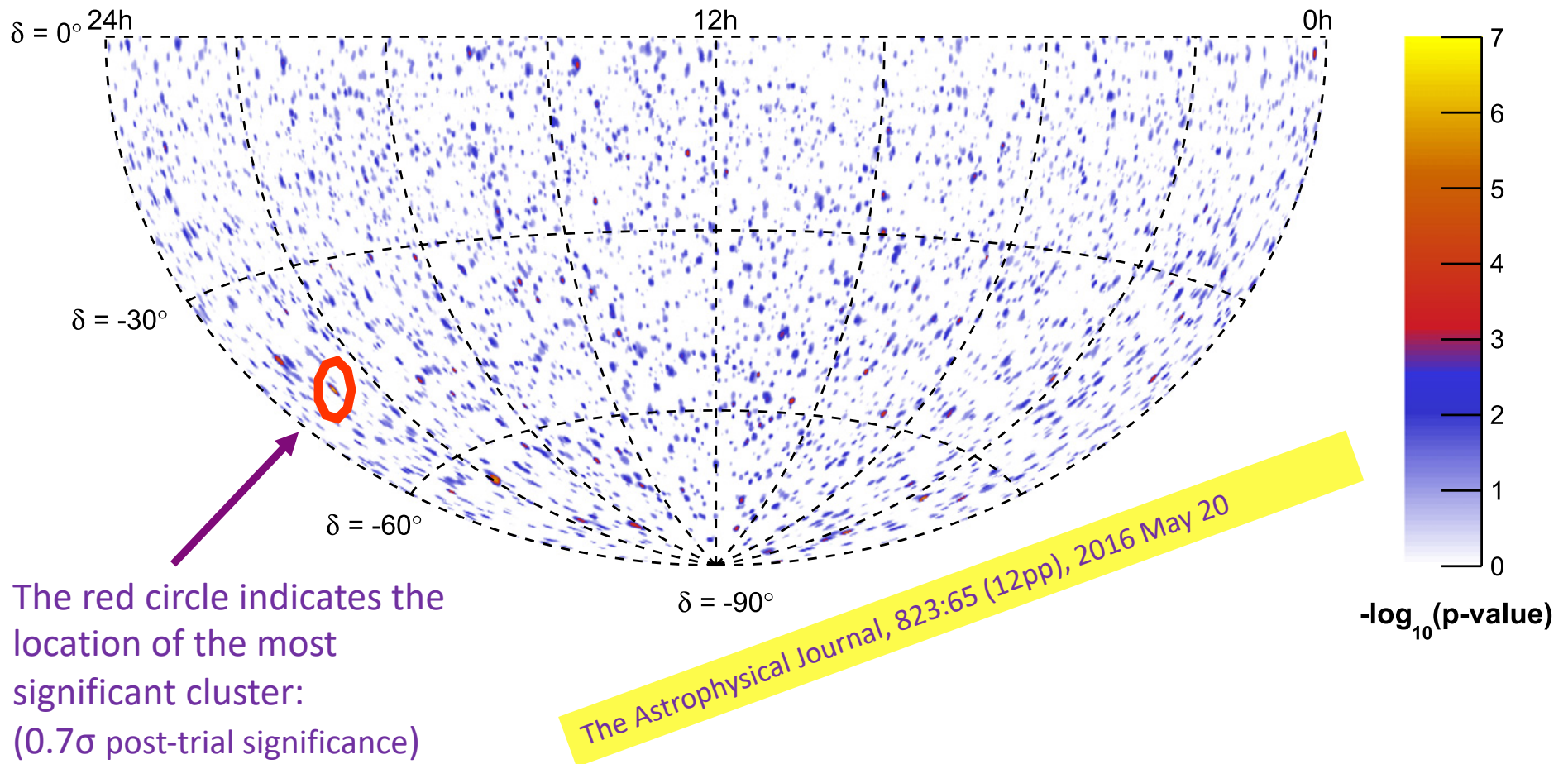
2nd most significant cluster:
RA=343.8° δ=+23.5°
Pre-trial: 4.2 σ

Close to blazar MG J225517+2409

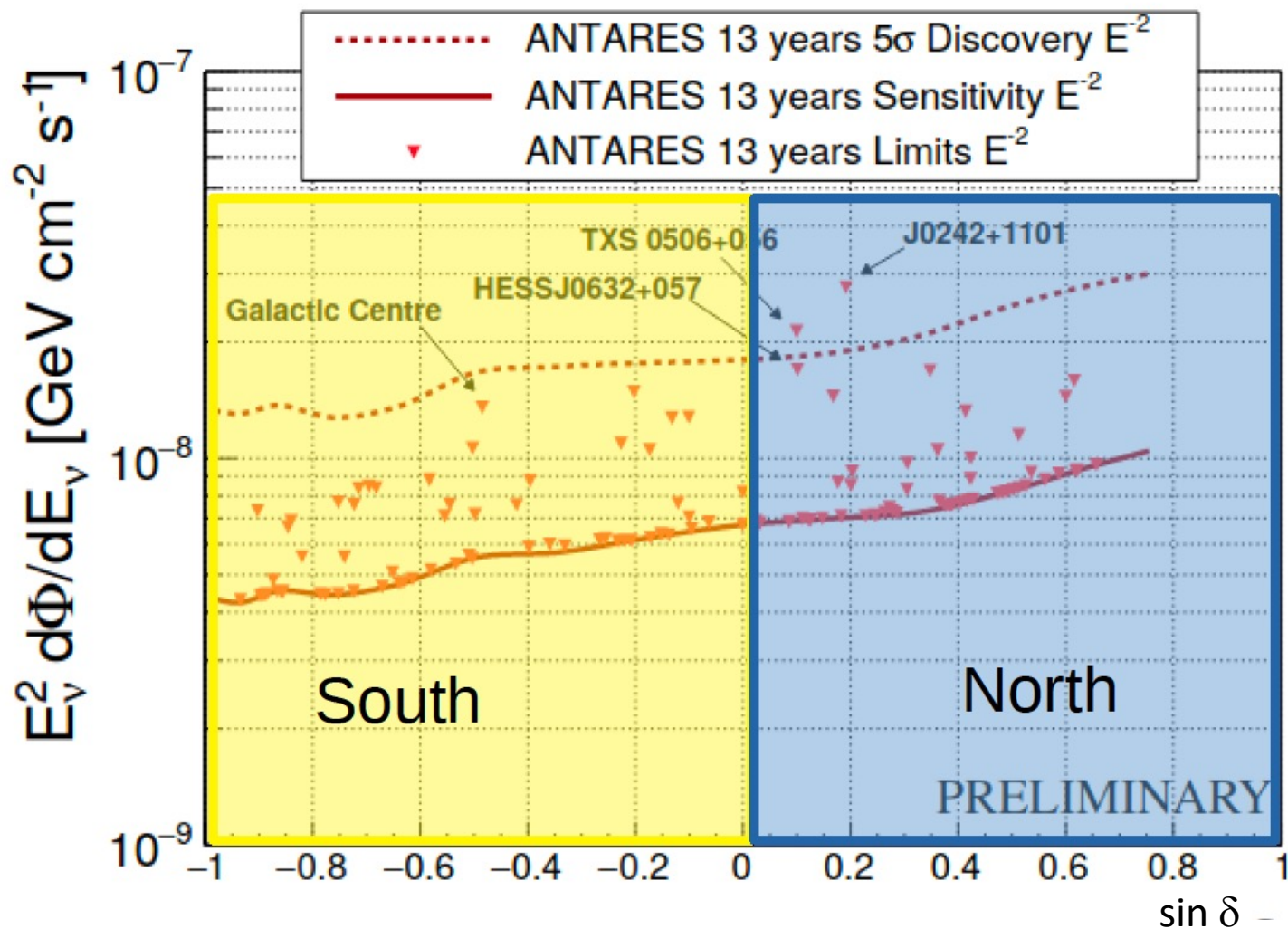
Full-sky hotspot $(\alpha, \delta) = (39.6^\circ, 11.1^\circ)$
pre-trial p-value: (4.3σ) (48% post)
Within 1 degree from J0242+1101

IceCube & ANTARES: search for point like ν sources

Skymap of pre-trial p-values for the combined
ANTARES 2007/12 and IceCube 40, 59, 79
point-source analyses.



ANTARES: search for point like ν sources

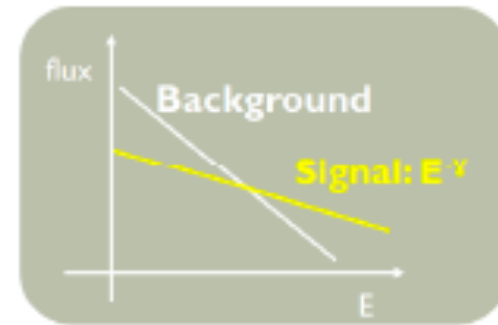


POS(ICRC2021)1161

Point like ν sources with a multi-messengers approach

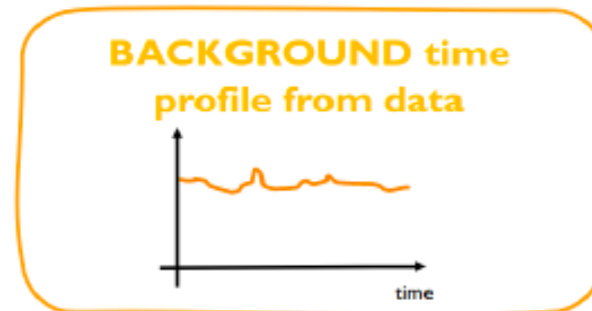
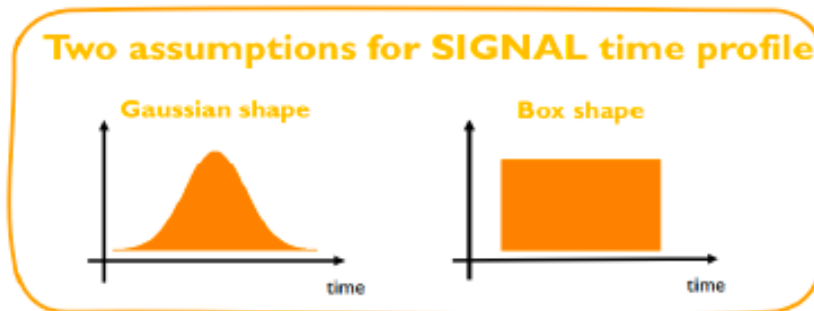
For steady sources (AGN, ...): signal and background integrated over long time

- search for a statistical evidence in the distribution of tracks around the source
- S/B favoured at high energy

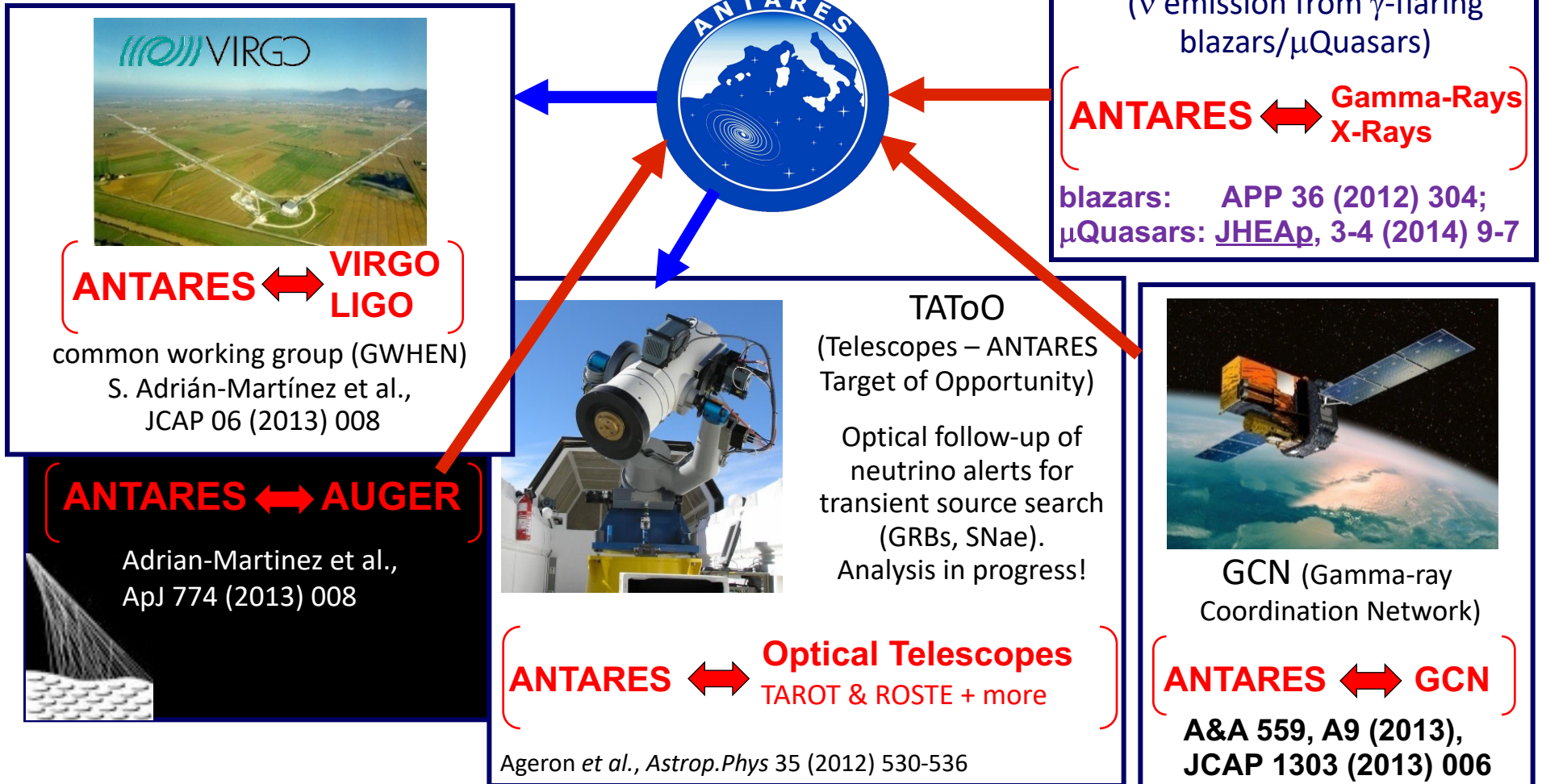
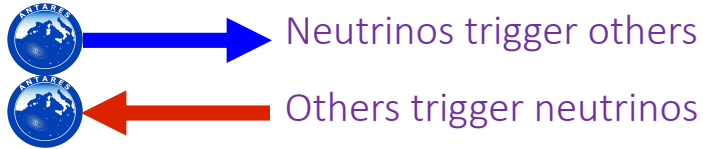


For transient sources (GW, flaring blazars, GRBs, ...) : signal and background integrated over emission time:

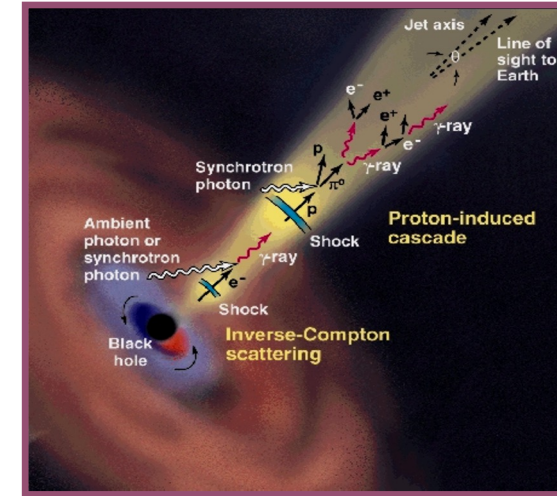
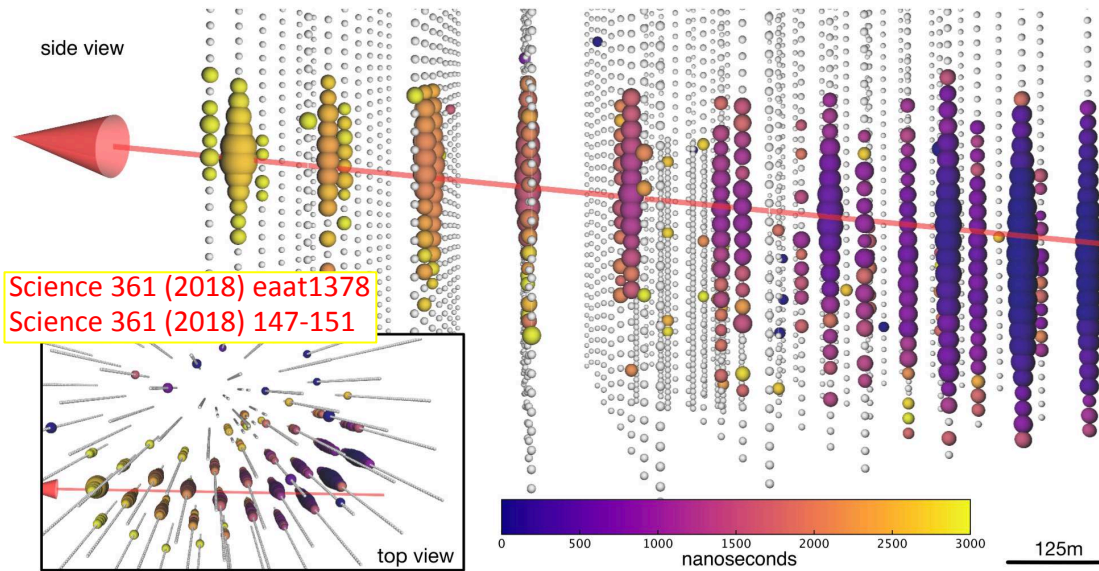
- e.g.: negligible background for GRB neutrinos
- relaxed selection criteria, increased efficiency for neutrinos
- need for an external trigger



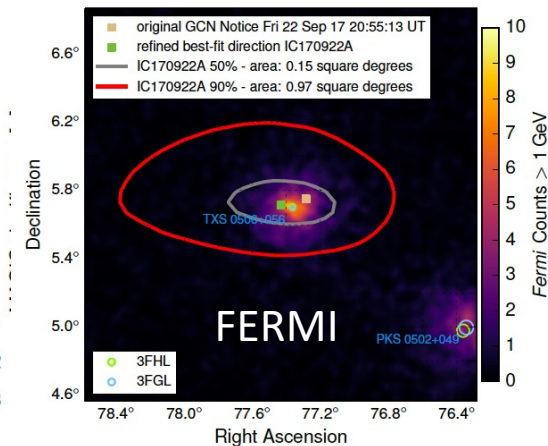
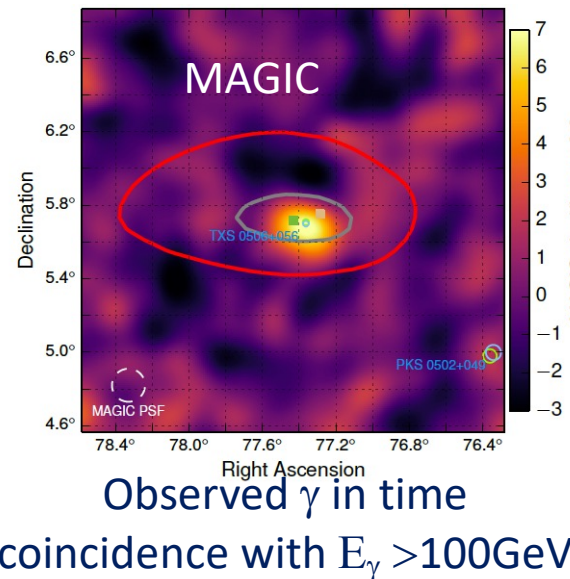
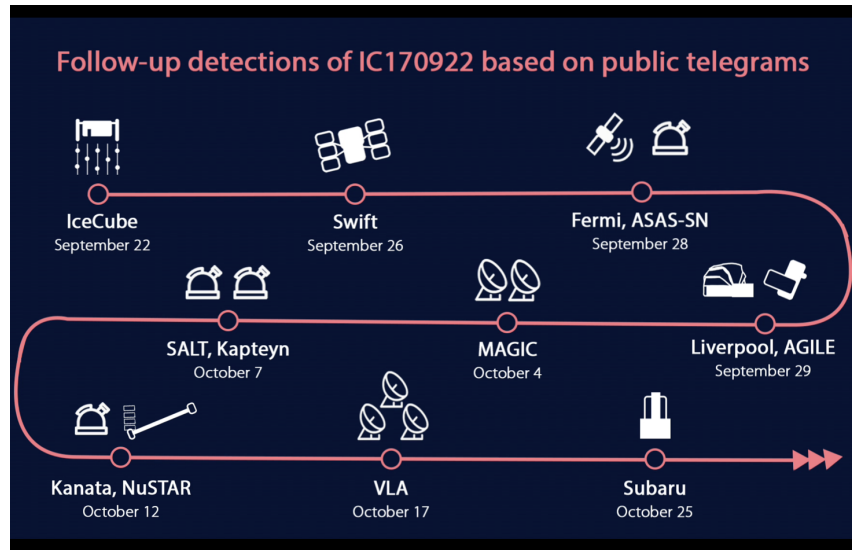
The multi-messengers search program with ANTARES



IceCube & FERMI a ν triggered observation of TXS 0506+056 blazar emission

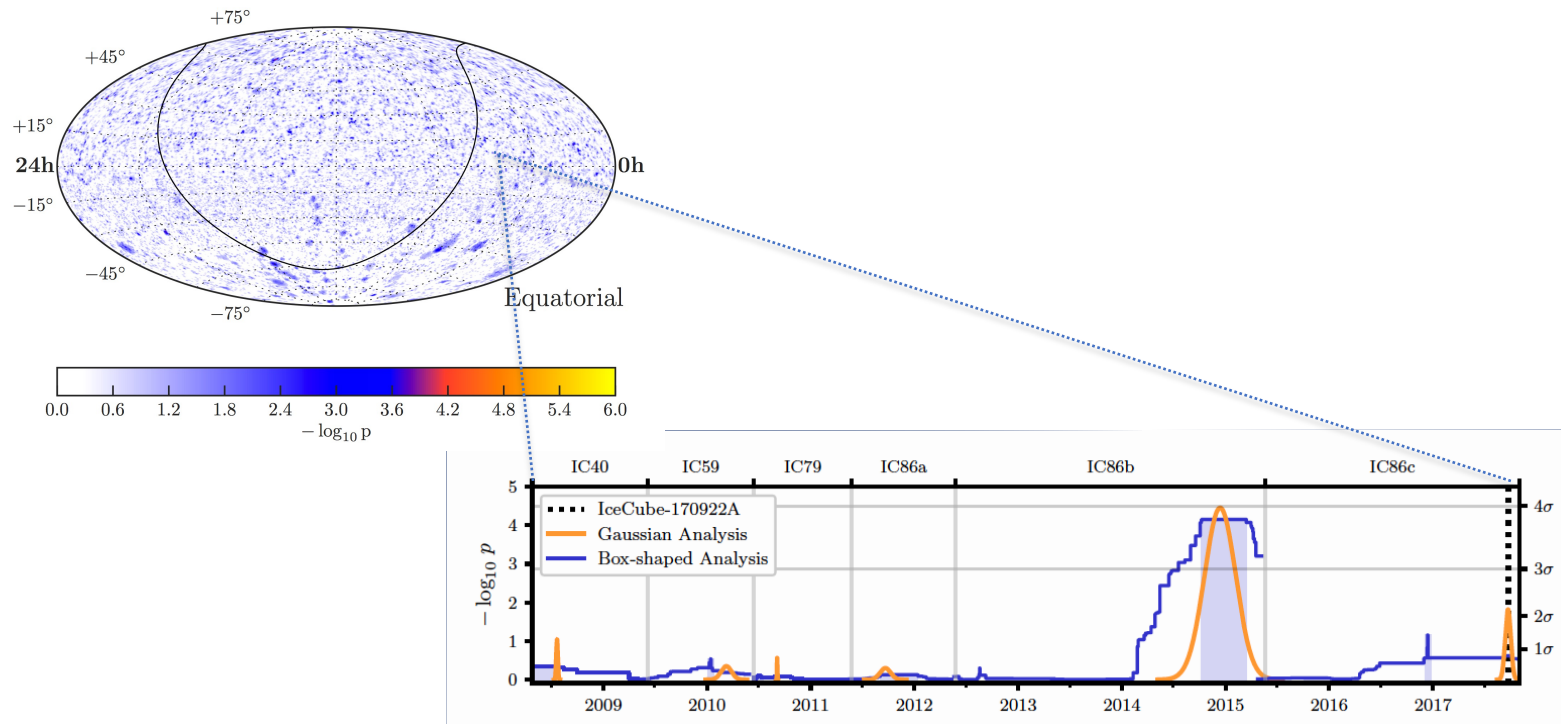


Very H.E. (~ 290 TeV) event
announced by IceCube with a
GCN notice 43s after the trigger



IceCube: searching for other ν from TXS 0506+056 blazar

More neutrinos (~ 10) emission from the direction of the blazar TXS 0506+056 IceCube-170922A alert”,
IceCube Collaboration: M.G. Aartsen et al. Science 361, 147-151 (2018). pointing to TXS0506+056



3.5 σ evidence (a-priori following predefined tests procedures)

E. Resconi | RICAP-2022

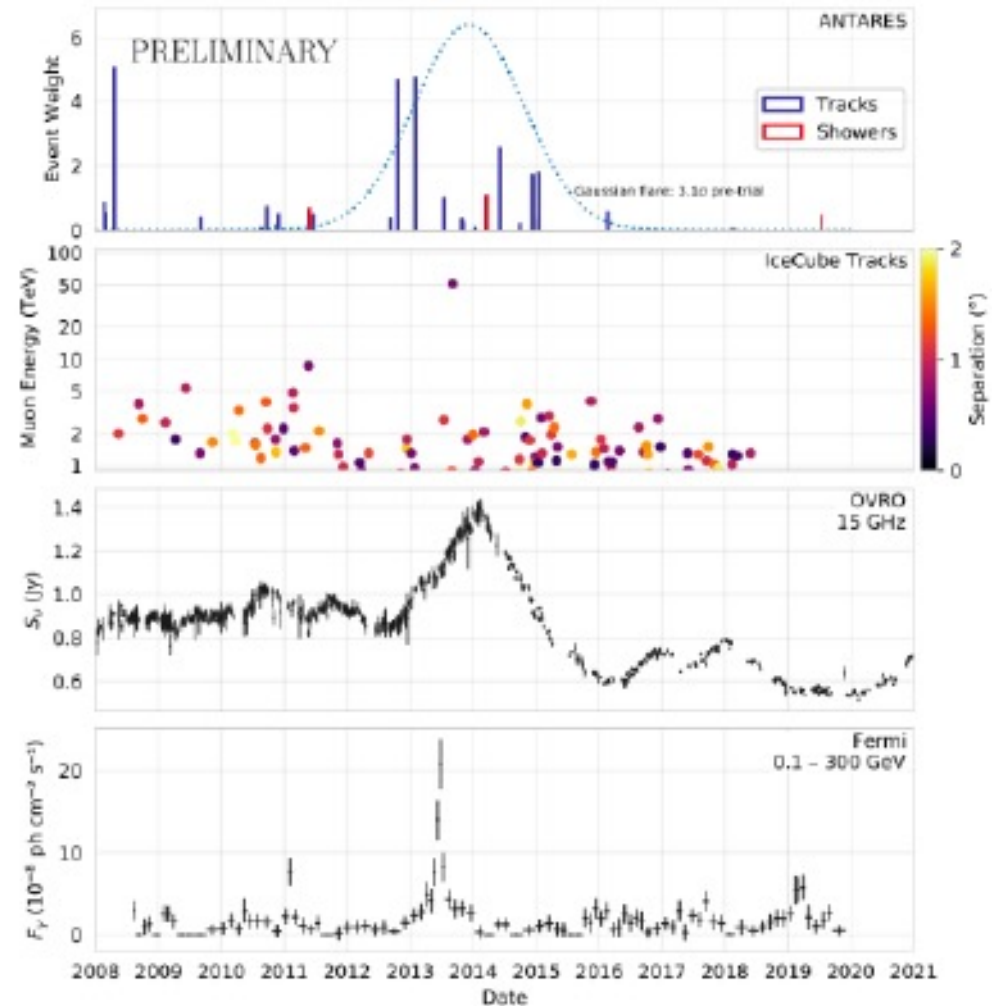
IceCube & ANTARES: search for ν – Radio bright blazars

Search for spatial and temporal coincidence of neutrinos with radio blazars

2774 radio-bright blazars investigated.

No significant evidence of neutrino flare found.

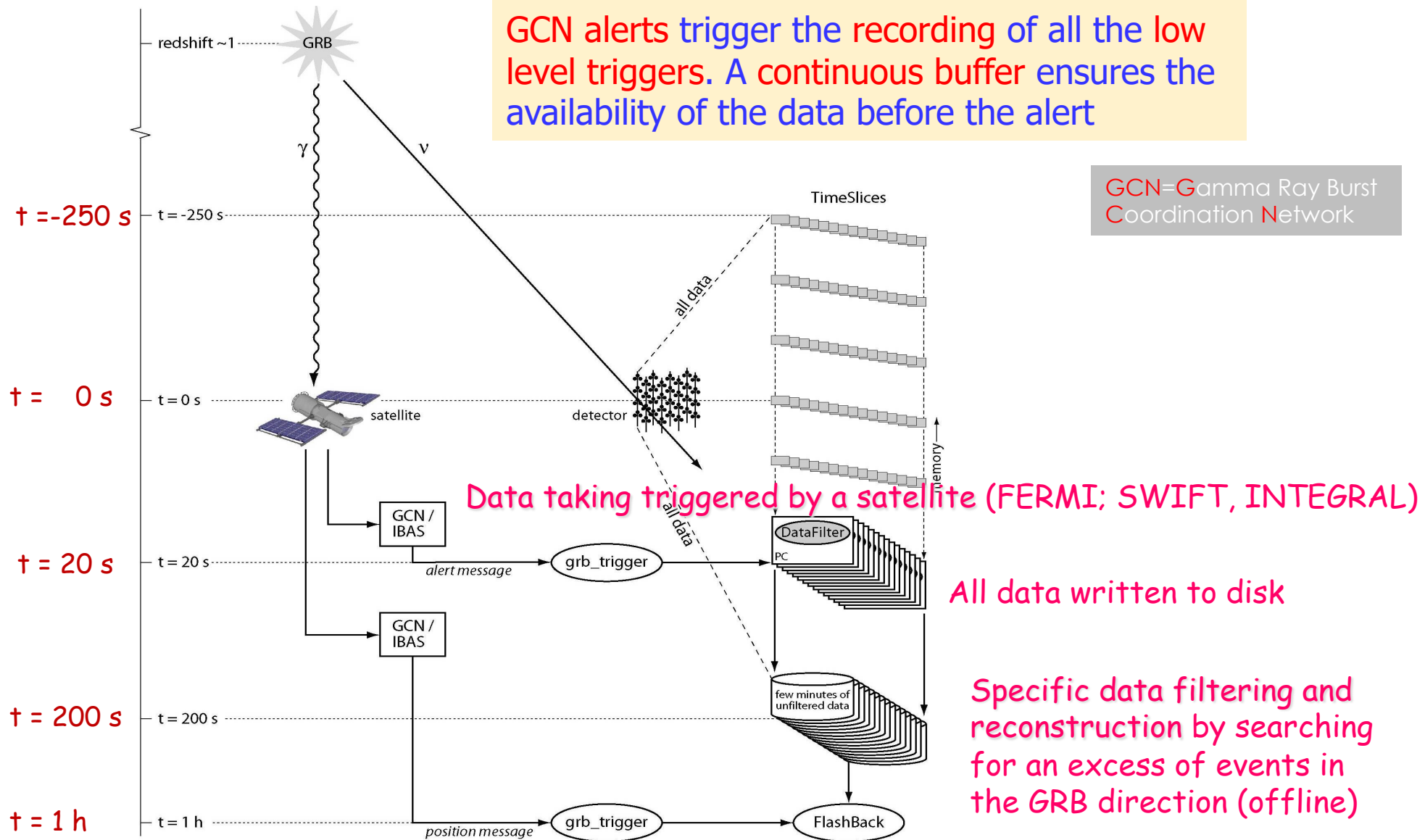
G. Illuminati @Neutrino2022



Notable case of **J0242+1101 (PKS 0239+108)**

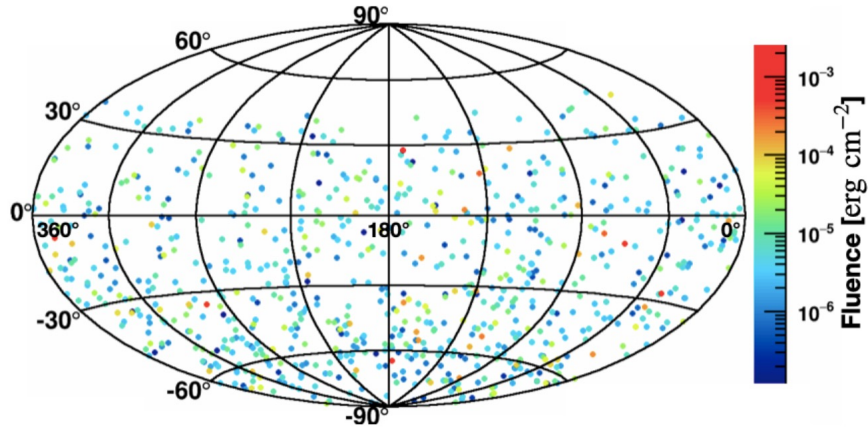
Post-trial p-value of 56% (40%) for the Gaussian (Box) shape.

ANTARES: multimessenger search for ν GRBs



ANTARES: searching for ν from 784 GRBs (10 years)

Neutrino fluence simulation for each GRB
within the framework of the IS model

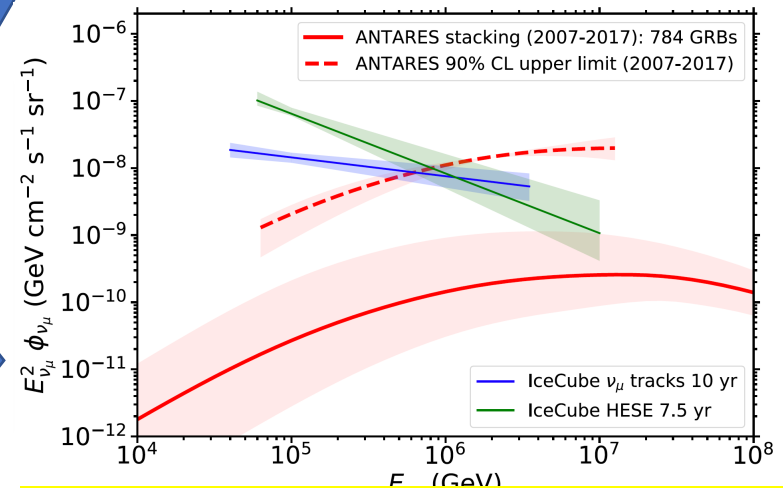
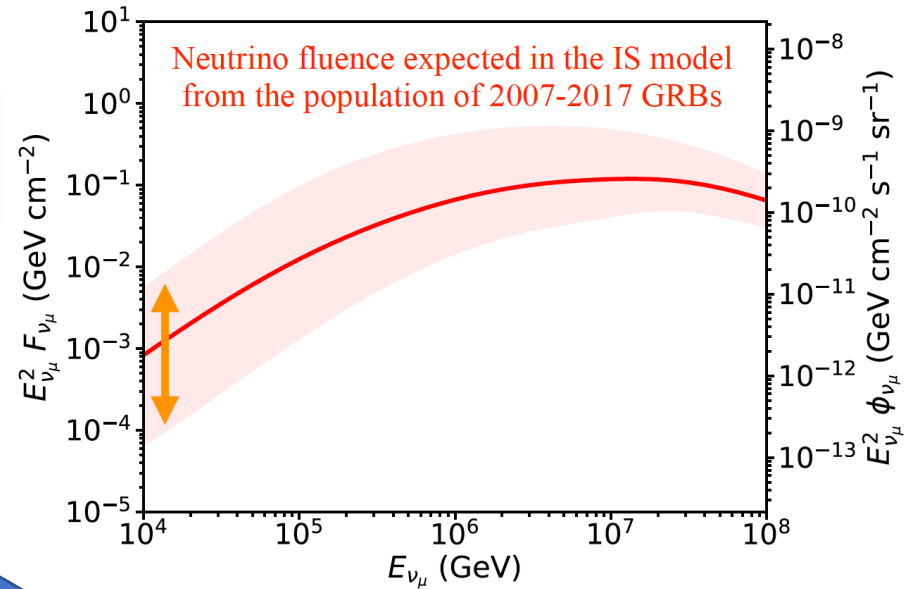


784 GRBs (2007-2017)

ANTARES, MNRAS 500, 5614–5628 (2021)

Search for spatial & temporal coincidence
with gamma-ray emission:

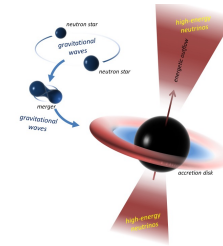
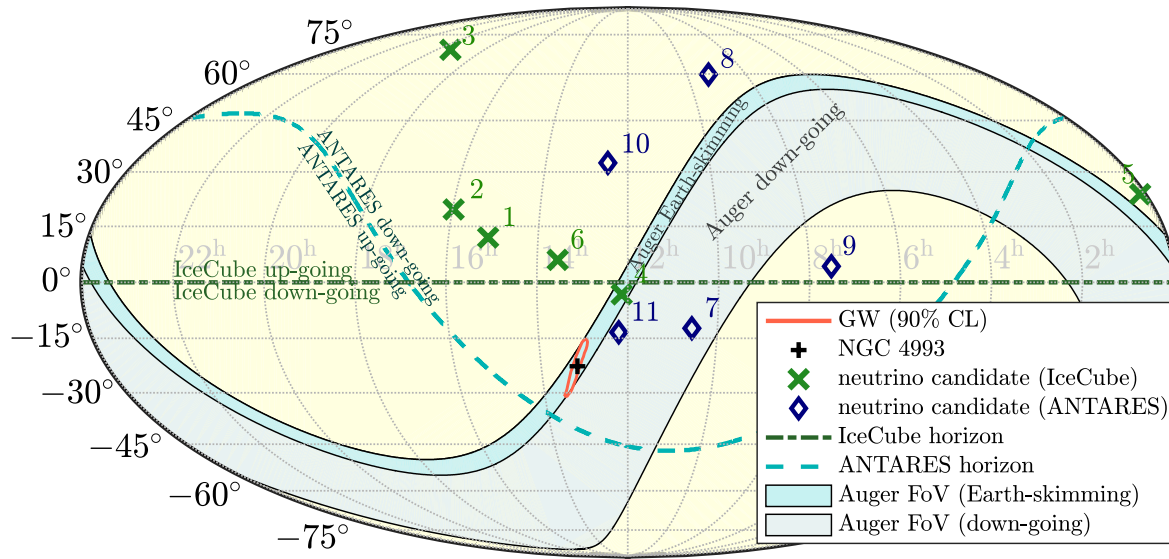
**NO neutrino event found in coincidence
with the prompt phase of the long GRB
sample**



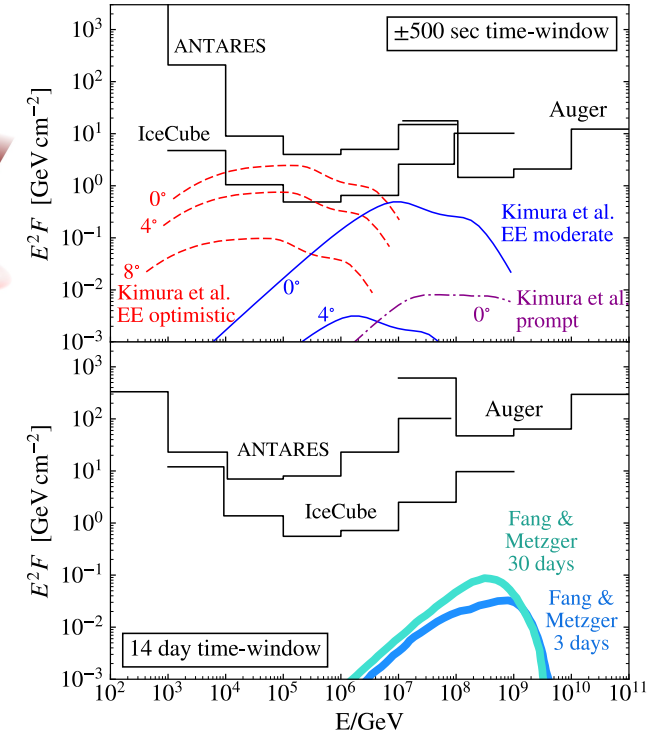
For $E_\nu \sim 100$ TeV GRBs do contribute by
 $\leq 10\%$ to the IceCube flux of diffuse ν

Search for ν from the source of GW170817

ANTARES/IceCube/LigoSC/Virgo/Auger "follow-up" analysis



GW170817 Neutrino limits (fluence per flavor: $\nu_x + \bar{\nu}_x$)



The Astrophysical Journal Letters, 848:L12 (59pp), 2017 October 20

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.

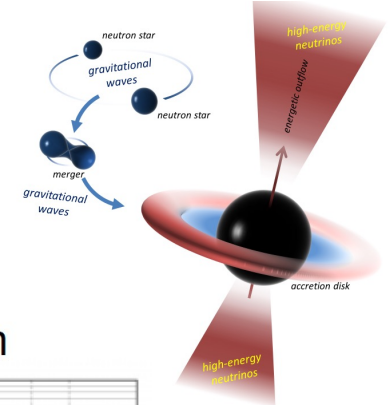
ANTARES, IceCube, and Pierre Auger Observatories searched for high-energy neutrinos from the merger in the GeV–EeV energy range.

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.

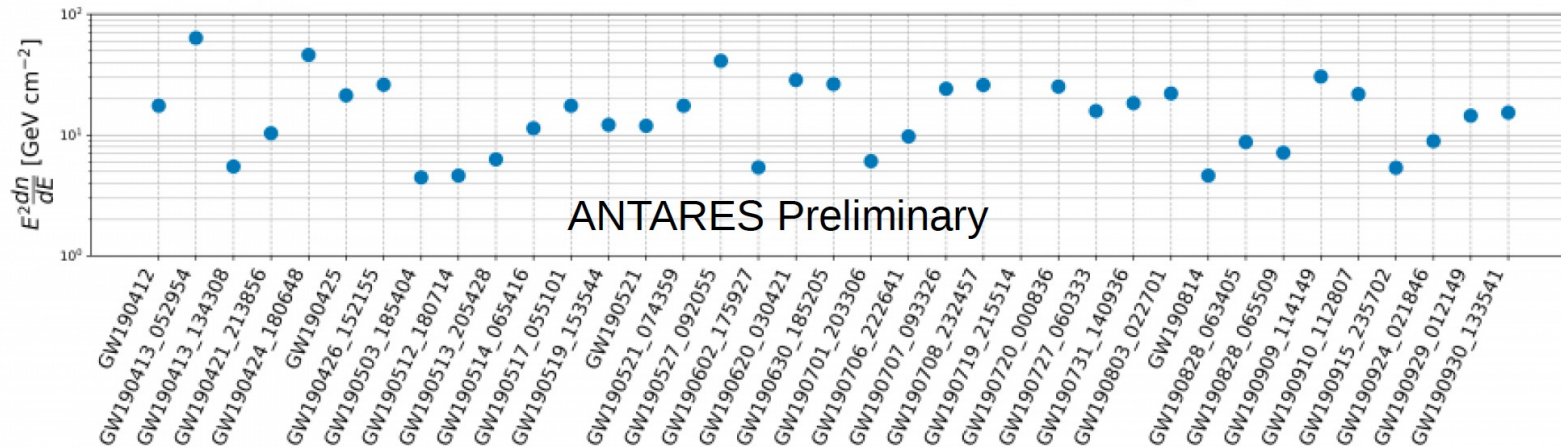
ANTARES: search for ν – GW common sources

39 gravitational wave sources in GWTC-2 catalog

- 37 sources followed with ANTARES data (2 during downtime)
- Total expected background: ~ 0.38 events over the 37 GWs
- Observed number of events: 0 for all sources



Upper limits on the all-flavour neutrino flux, assuming E^{-2} spectrum



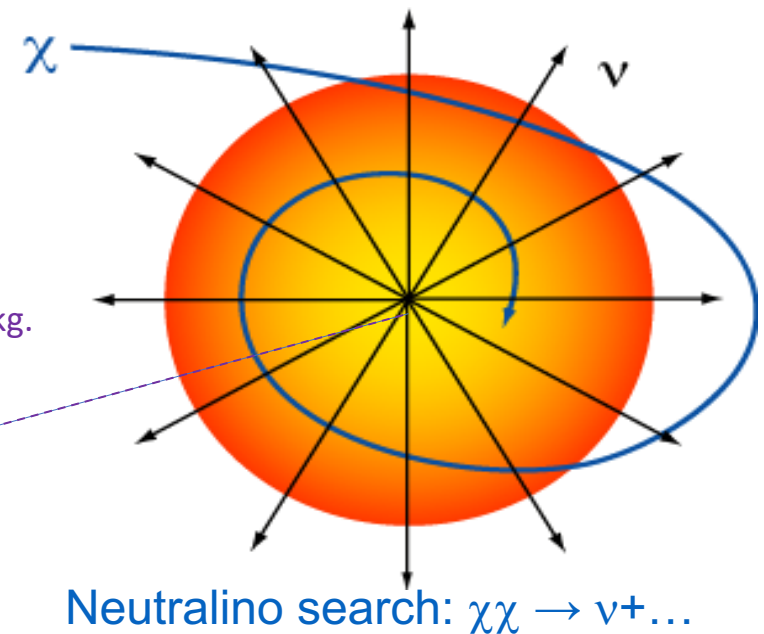
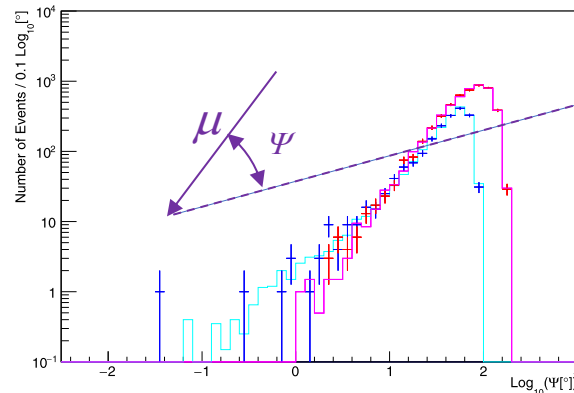
M. Lamoureux @Neutrino2022

... not only neutrino astrophysics...

... also open problems in particle physics ...

- Dark Matter searches:
 - Neutralino annihilation in Sun, Earth, Galactic Center
- Magnetic Monopoles
- Particle acceleration mechanisms
- Multi-messenger searches
- Neutrino Oscillations
- Search for Sterile Neutrinos
- ...

search for excess observed over the expected backg.

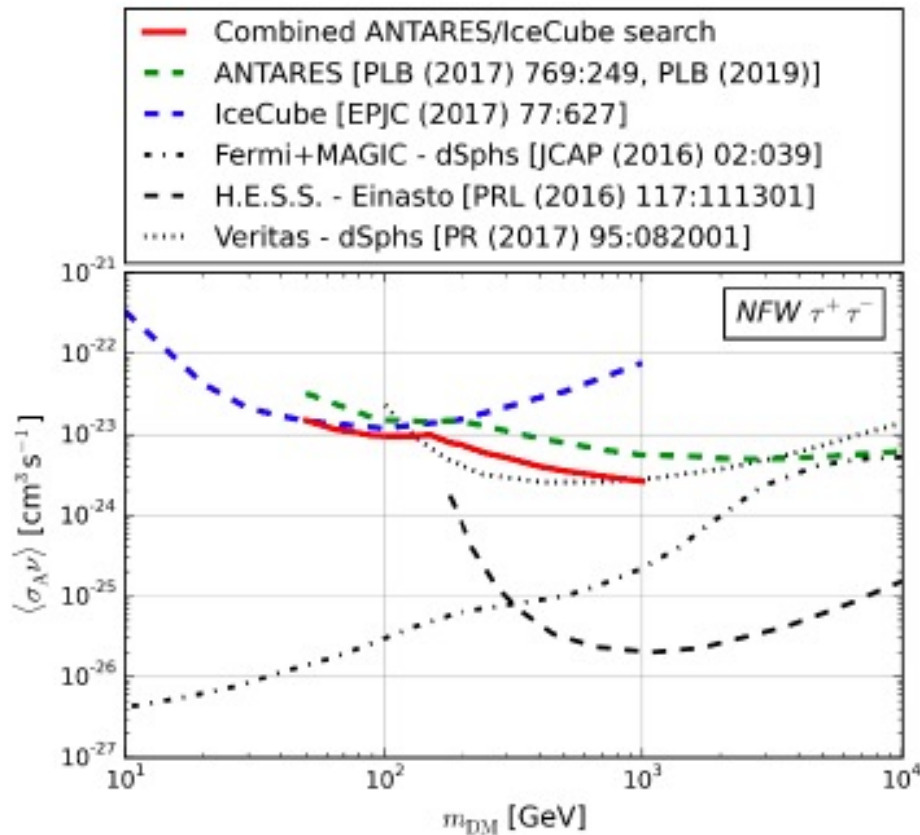


Indirect searches from Dark Matter: ν from massive bodies (Sun, Galactic center, ...)

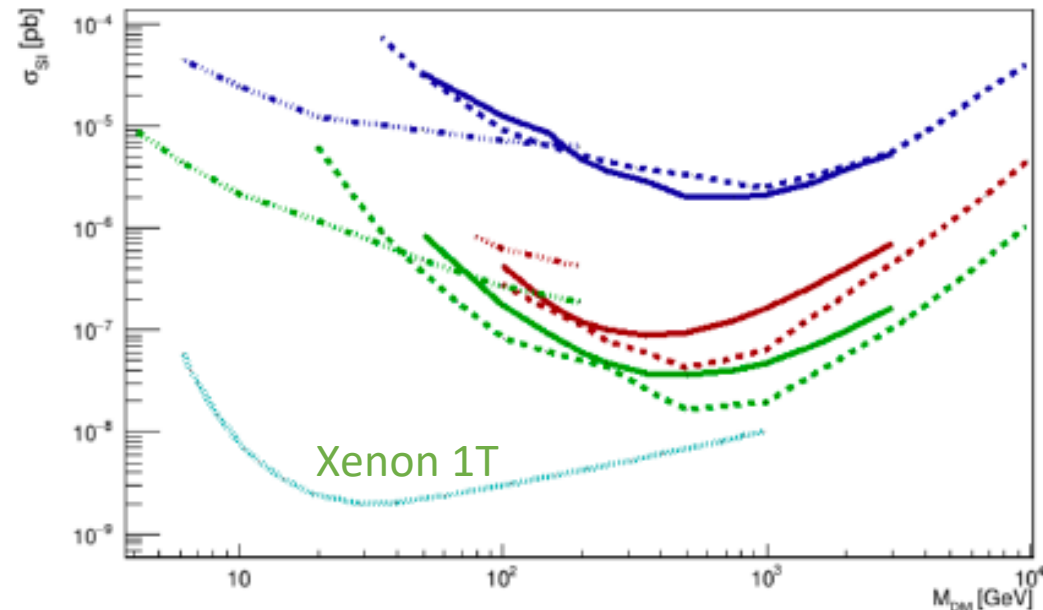
Galactic Centre \rightarrow annihilation cross-section

Sun \rightarrow scattering cross-section

$$\frac{d\Phi_{\nu_\mu+\bar{\nu}_\mu}}{dE_{\nu_\mu+\bar{\nu}_\mu}} = \frac{\langle\sigma v\rangle}{8\pi M_{WIMP}^2} \cdot \frac{dN_{\nu_\mu+\bar{\nu}_\mu}}{dE_{\nu_\mu+\bar{\nu}_\mu}} \cdot J_{int}(\Delta\Omega)$$



Phys. Rev. D 102, 082002 (2020)



$\tau\tau$ WW bb

Solid lines: ANTARES

Dashed: IceCube

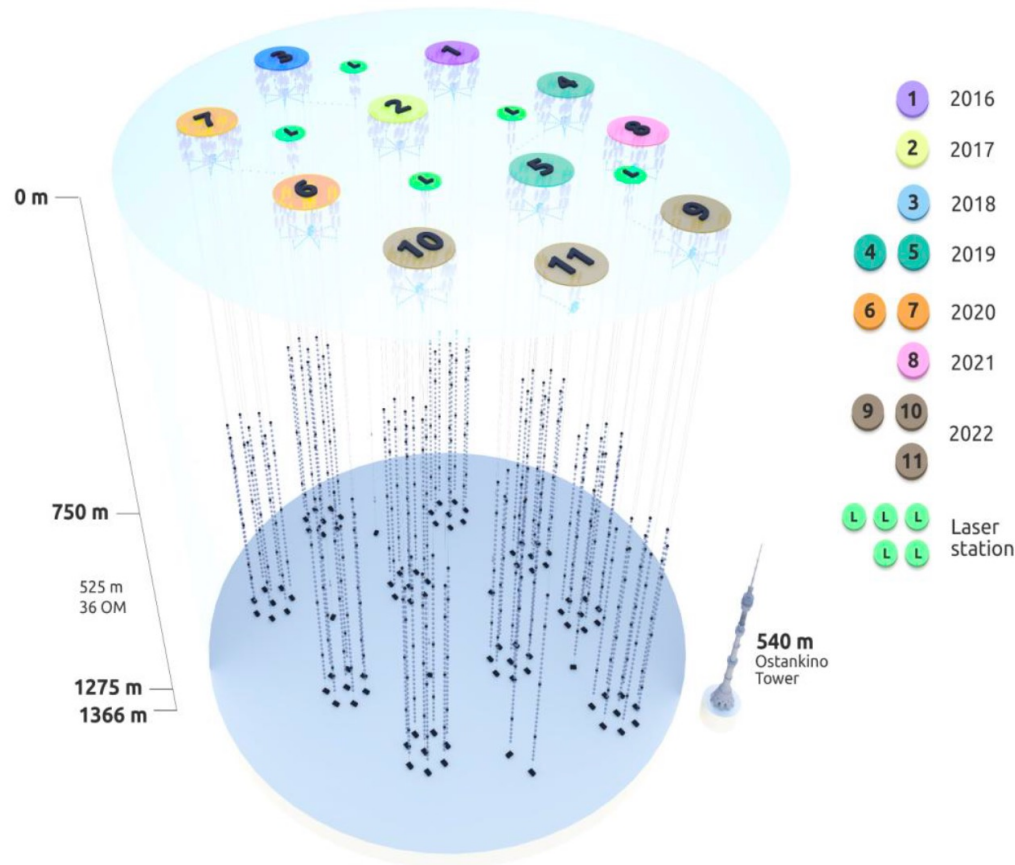
Dot-Dashed: SuperK

C. Poiré@Neutrino2022



Baikal-GVD construction status and schedule

Status 2022: 10 clusters, 5 laser stations, experimental strings



Deployment schedule

| Year | Number of clusters | Number of OM's |
|------|--------------------|----------------|
| 2016 | 1 | 288 |
| 2017 | 2 | 576 |
| 2018 | 3 | 864 |
| 2019 | 5 | 1440 |
| 2020 | 7 | 2016 |
| 2021 | 8 | 2304 |
| 2022 | 10 | 2880 |
| 2023 | 12 | 3456 |
| 2024 | 14 | 4032 |
| 2025 | 16 | 4608 |
| 2026 | 18 | 5184 |

by courtesy of Koljia Budnev

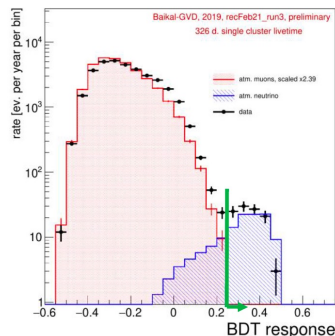


Single-cluster muon neutrino candidates

Sensitivity of analysis was improved with new reconstruction and neutrino selection methods

Event reconstruction:

- Hit finder: efficient hit-finding algorithm [\[PoS-ICRC2021-1063\]](#)
- Track fit: $\chi^2(t)$ - based fitter
- Energy estimation based on dE/dX proxy
- Neutrino selection based on BDT

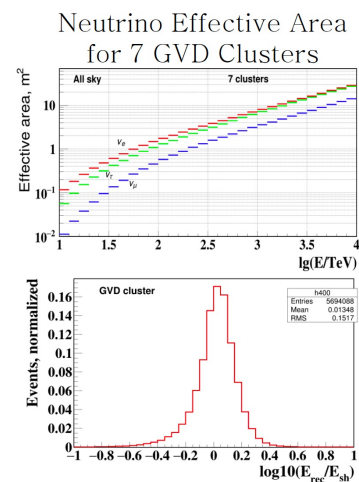


- A sample of 106 neutrino candidate events was obtained for 326 days of single-cluster livetime
- Factor ~2 improvement with respect to previous analysis
 - An MC expectation: 81.2 events \Rightarrow possible ~30% contamination with background in data

An effort to extend single-cluster analysis to the full dataset is ongoing

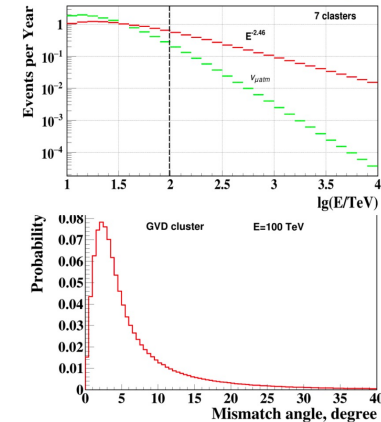


Cascades detection with GVD Cluster



Energy resolution : $\delta E/E \sim 10\%-30\%$

Expected number of events in 7 GVD Clusters from astrophysical



Directional resolution for cascades:
2°– 4° – median value of

18



Conclusion

- Baikal-GVD is now the largest neutrino telescope in the Northern Hemisphere and growing
- Modular structure of GVD design allows a search for HE neutrinos and multimessenger studies at the early phases of array construction.
- Observations of atmospheric neutrinos by Baikal-GVD agree with expectations
- First 25 astrophysics neutrino candidate events have been selected -
Baikal-GVD confirms IceCube observation of astrophysical diffuse neutrino flux at 3σ level

OUTLOOK

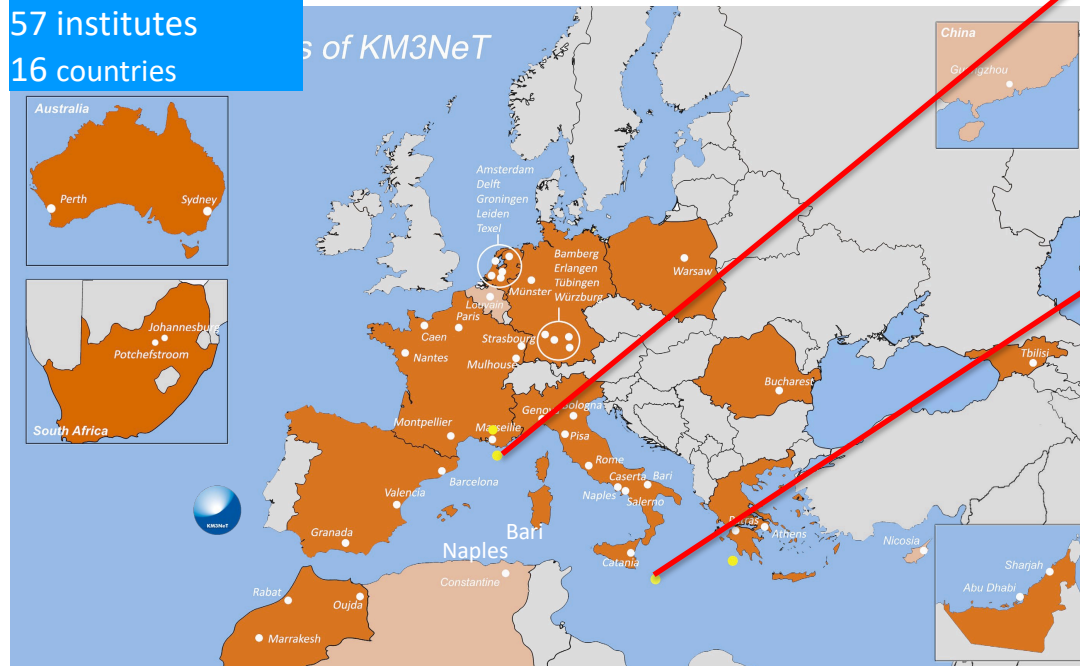
- 2025/2026 – ~ 1km³ GVD with total of 16-18 clusters
- 2022-2024 – “Conceptual Design Report” for next generation neutrino telescope in Lake Baikal

by courtesy of Koljia Budnev

KM3NeT the future of ν astronomy in the Mediterranean

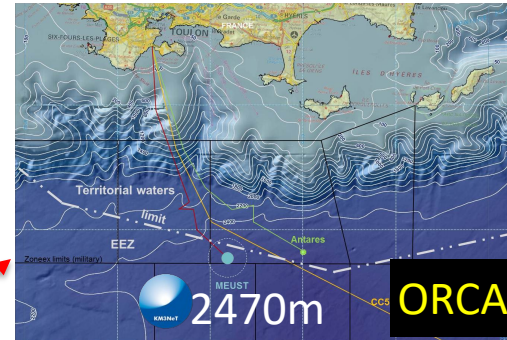
- Multi-site, deep-sea neutrino telescope
- Selected by ESFRI roadmap
- Single collaboration, Single technology

250 scientists
57 institutes
16 countries



KM3NeT 2.0: Letter of Intent

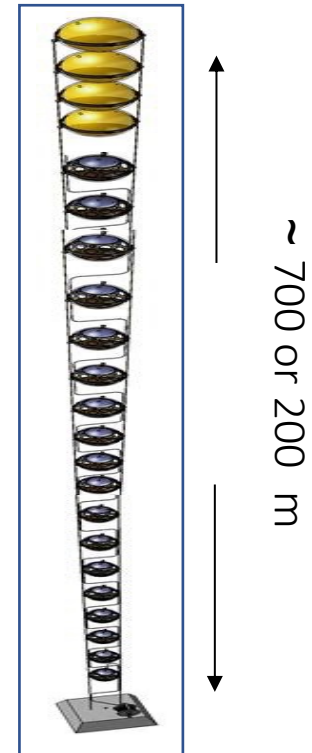
J. Phys. G: Nucl. Part. Phys. 43 (2016) 084001



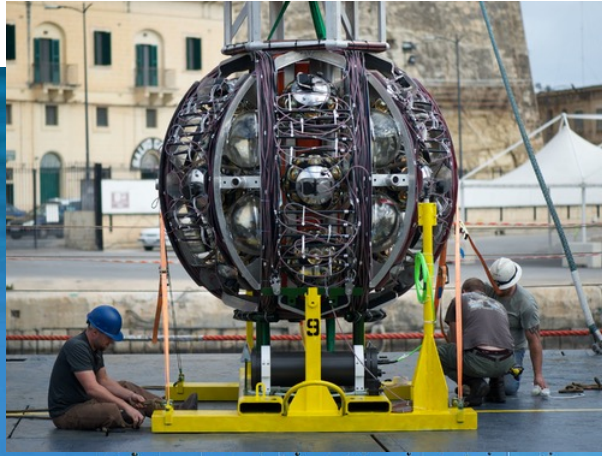
Oscillation **R**esearch
with **C**osmics In the **A**byss



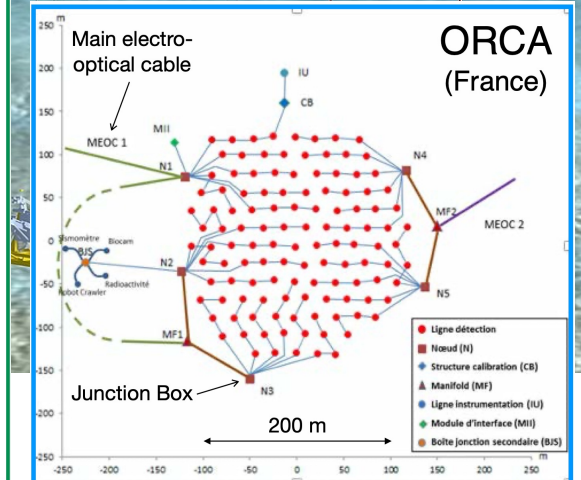
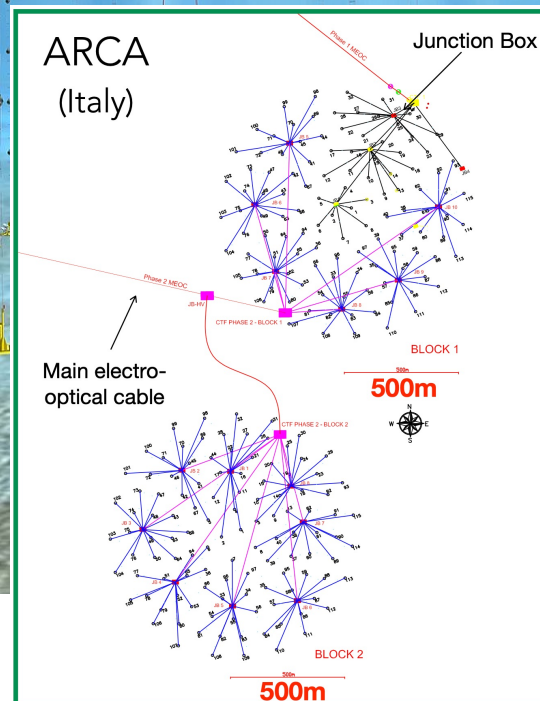
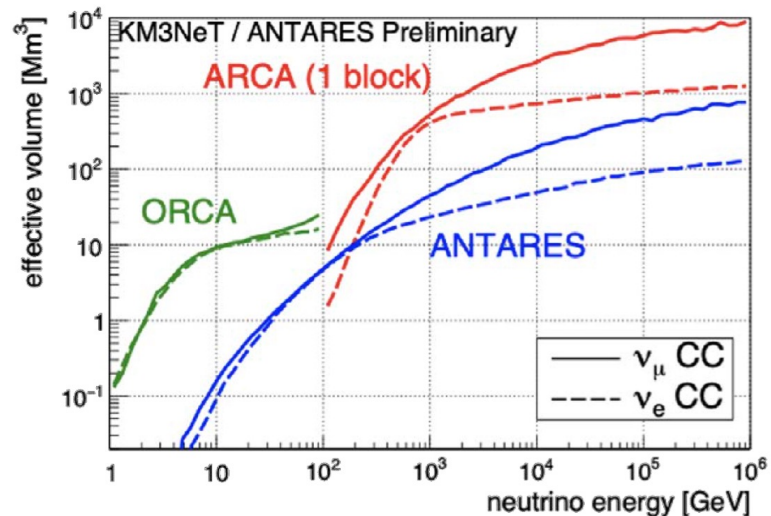
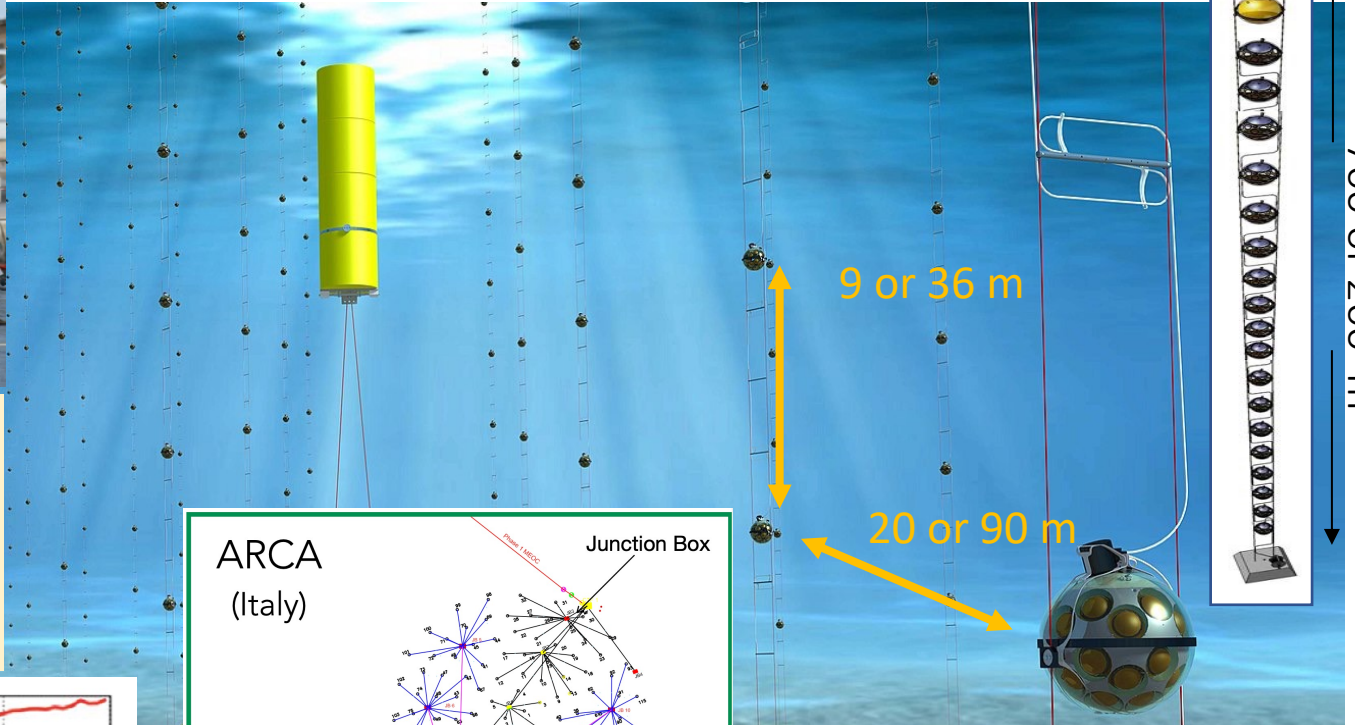
Astroparticle **R**esearch
with **C**osmics In the **A**byss



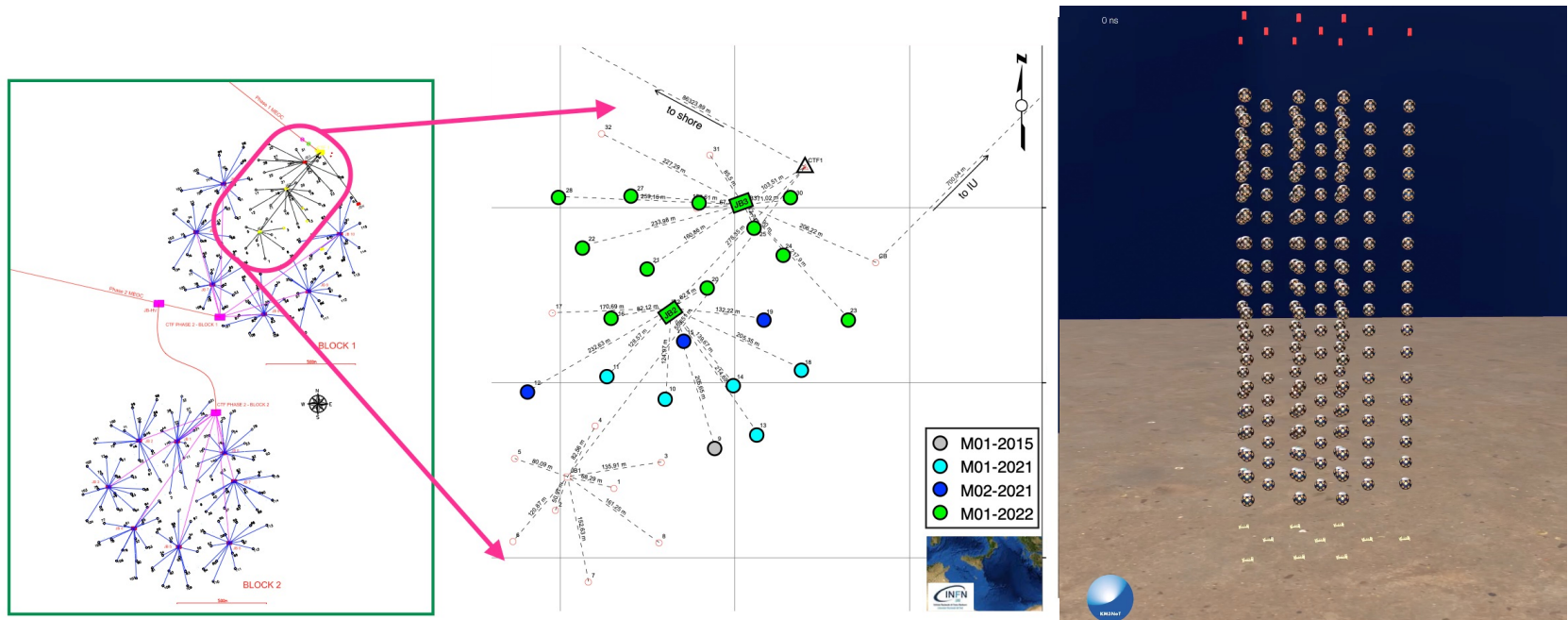
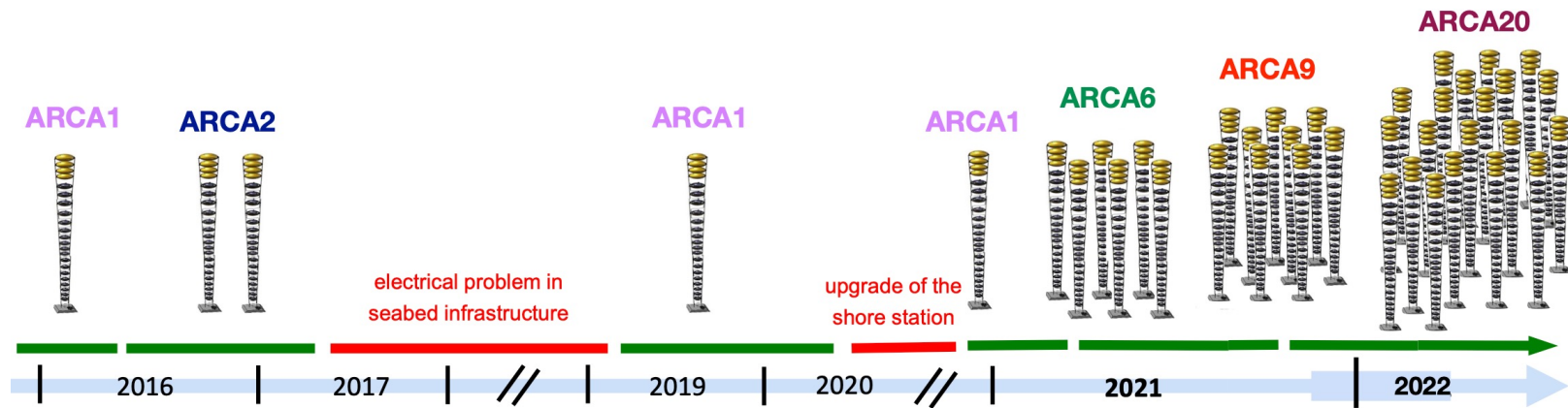
ORCA and ARCA schematic view



- Rapid deployment
- Multiple strings/sea campaign
- Autonomous/ROV unfurling
- Reusable



ARCA construction phase

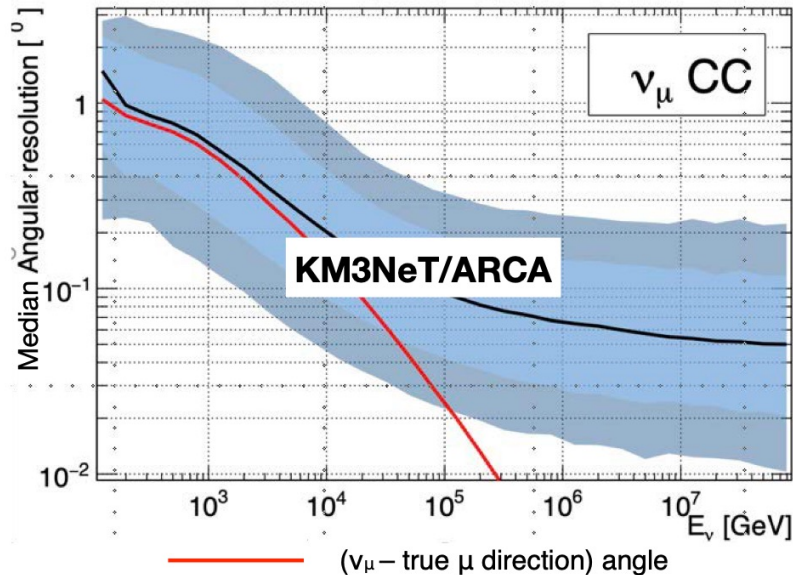


ARCA Reconstruction Performances

Track-like and shower-like events

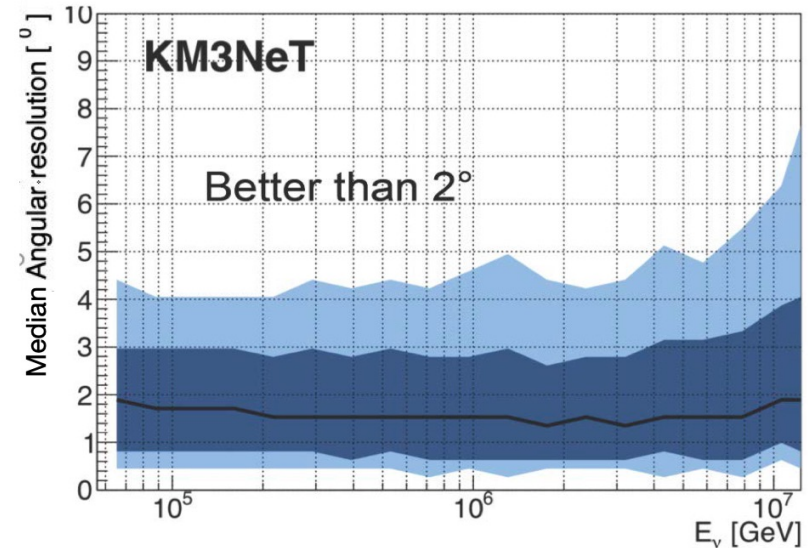
Tracks (ν_μ CC) ideal tool for astronomy

- **Ang. Resol.** $< 0.2^\circ$ above 10 TeV
- **Energy Resol.** ~ 0.27 in $\log_{10}(E_{\text{reco}}/E_\mu)$
(10 TeV $< E_\mu < 10$ PeV)



Shower (ν_x NC + ν_e CC) contained events

- **Ang. Resol.** $< 2^\circ$ above 50 TeV
- **Energy Resol.** $< 5\%$



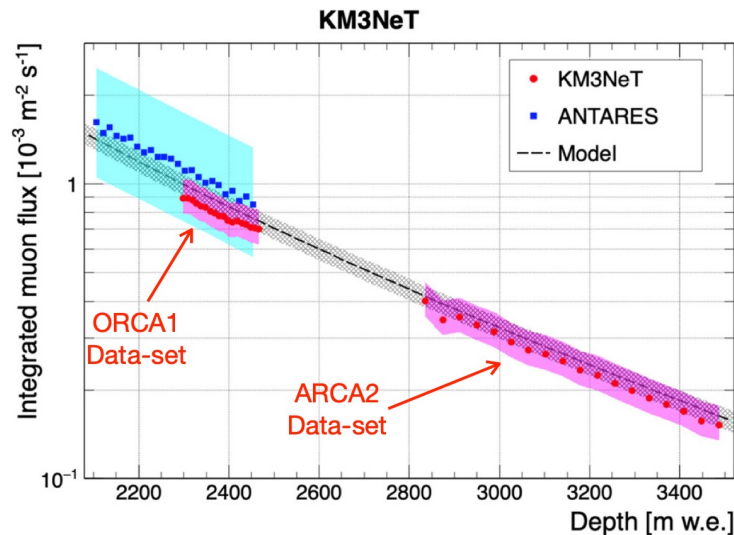
KM3NeT vs IceCube:

Con: ^{40}K background, bioluminescence, need for real-time positioning, deep-sea operations

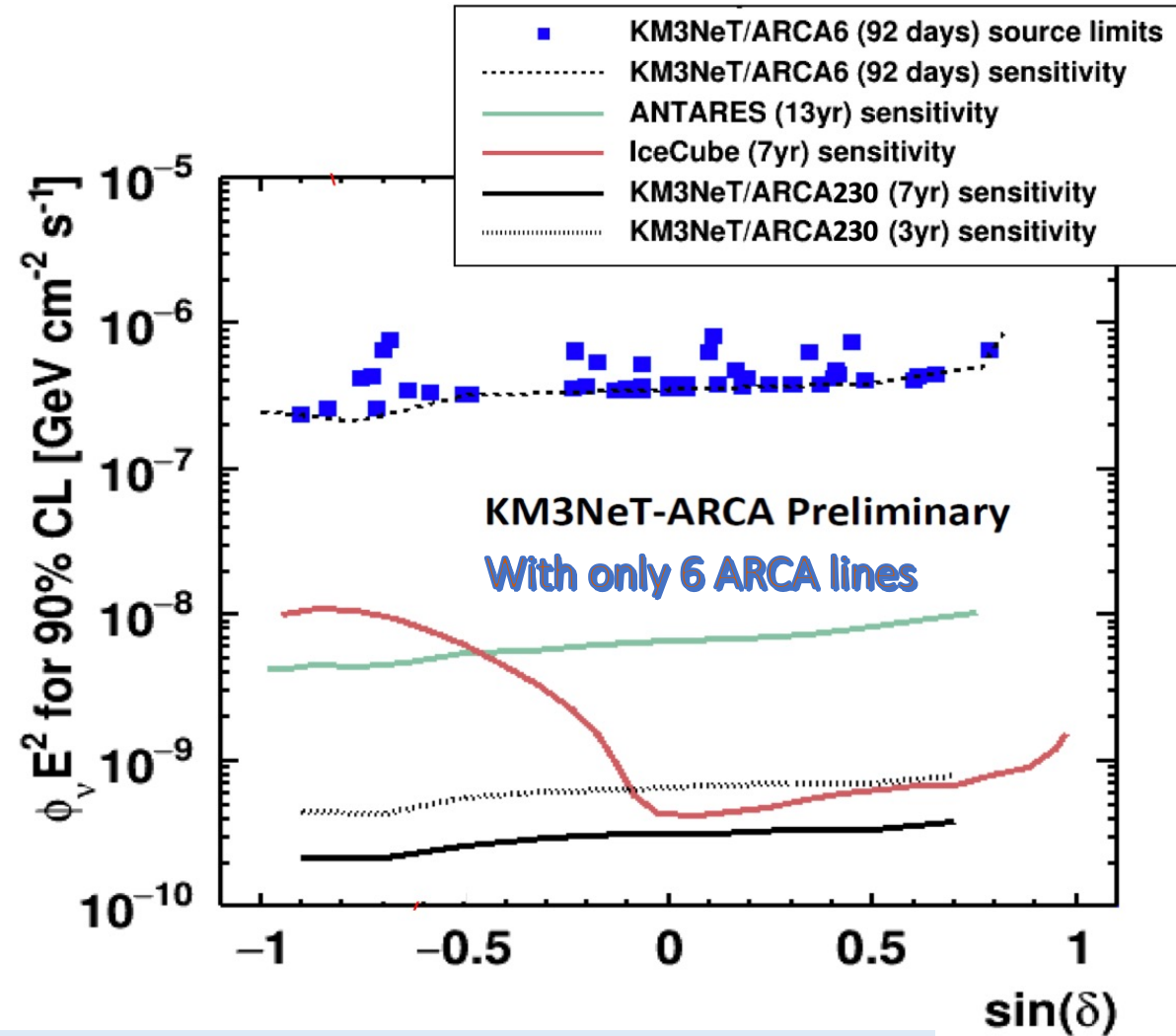
Pro: ^{40}K calibration, better view of the galactic center, no bubbles/dust \rightarrow better angular resolution

ARCA very preliminary results

- Single-DOM measurement
- Useful to validate the calibration process
- Results compared with ANTARES and Bugaev model



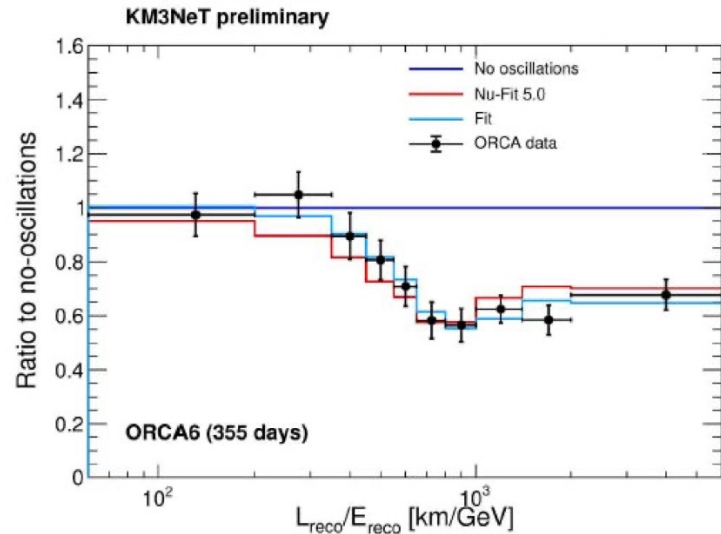
Eur. Phys. J. C 80 (2020) 99



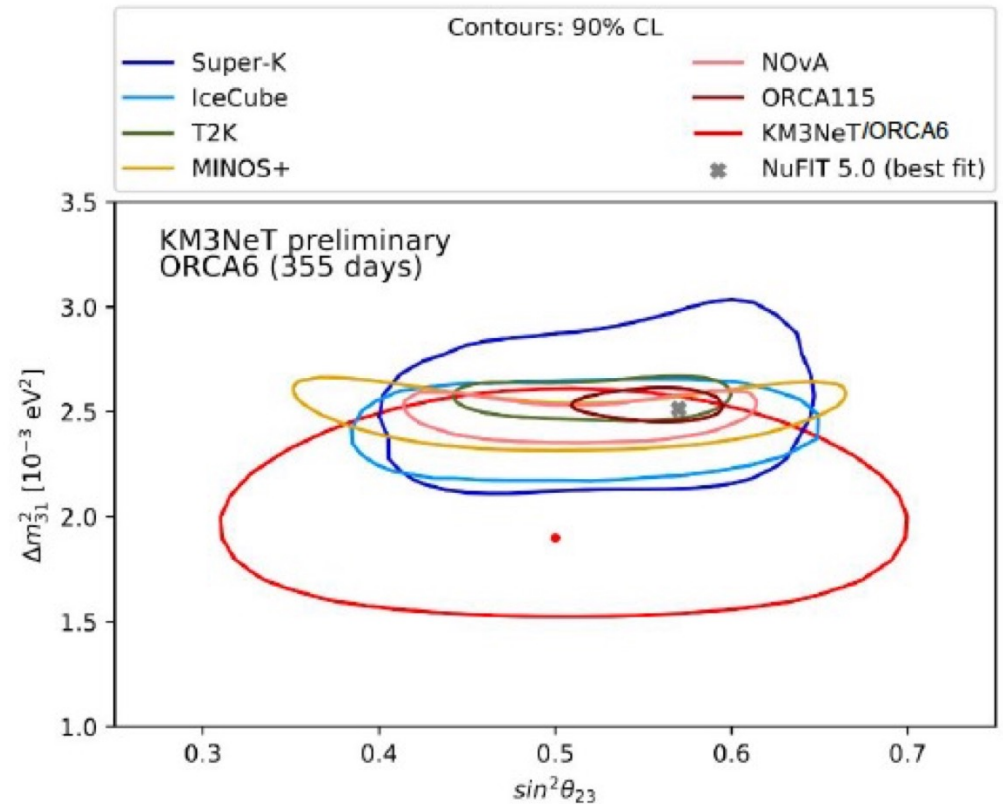
At present taking data with 21 lines.

Funding assured, procurement and construction in progress, for ~130 strings

ORCA very preliminary results



| Parameter | Treatment | Fit value |
|--|-----------|------------------------|
| $\Delta m_{31}^2 [10^{-3} \text{ eV}^2]$ | Free | $1.95^{+0.24}_{-0.21}$ |
| $\theta_{23} [\text{deg}]$ | Free | $45.4^{+5.6}_{-5.7}$ |



With only 6 ORCA lines

21

- Oscillation fit, binned in E_{reco} , θ_{zenith}
- Normalization left free, various systematics on flux, energy scale, tau- and NC normalization

Summary

High Energy Neutrino astrophysics has an important role in the Multi-messenger contest

- Absolute and precise pointing to the source
- Wider horizon
- Provides information:
 - On the nature of the source (Hadronic ??, Leptonic ??)
 - On the acceleration of parent particle

High Energy neutrino astrophysics started:

- Diffuse ν flux measured
- H.E. ν events (IceCube) associated with known gamma sources

New large and high resolution detectors (KM3NeT, IceCube Gen2, BAIKAL/GVD) in construction (or under project: P-One ?) ready to work in a Multi-messenger framework