High Energy Neutrino Astronomy

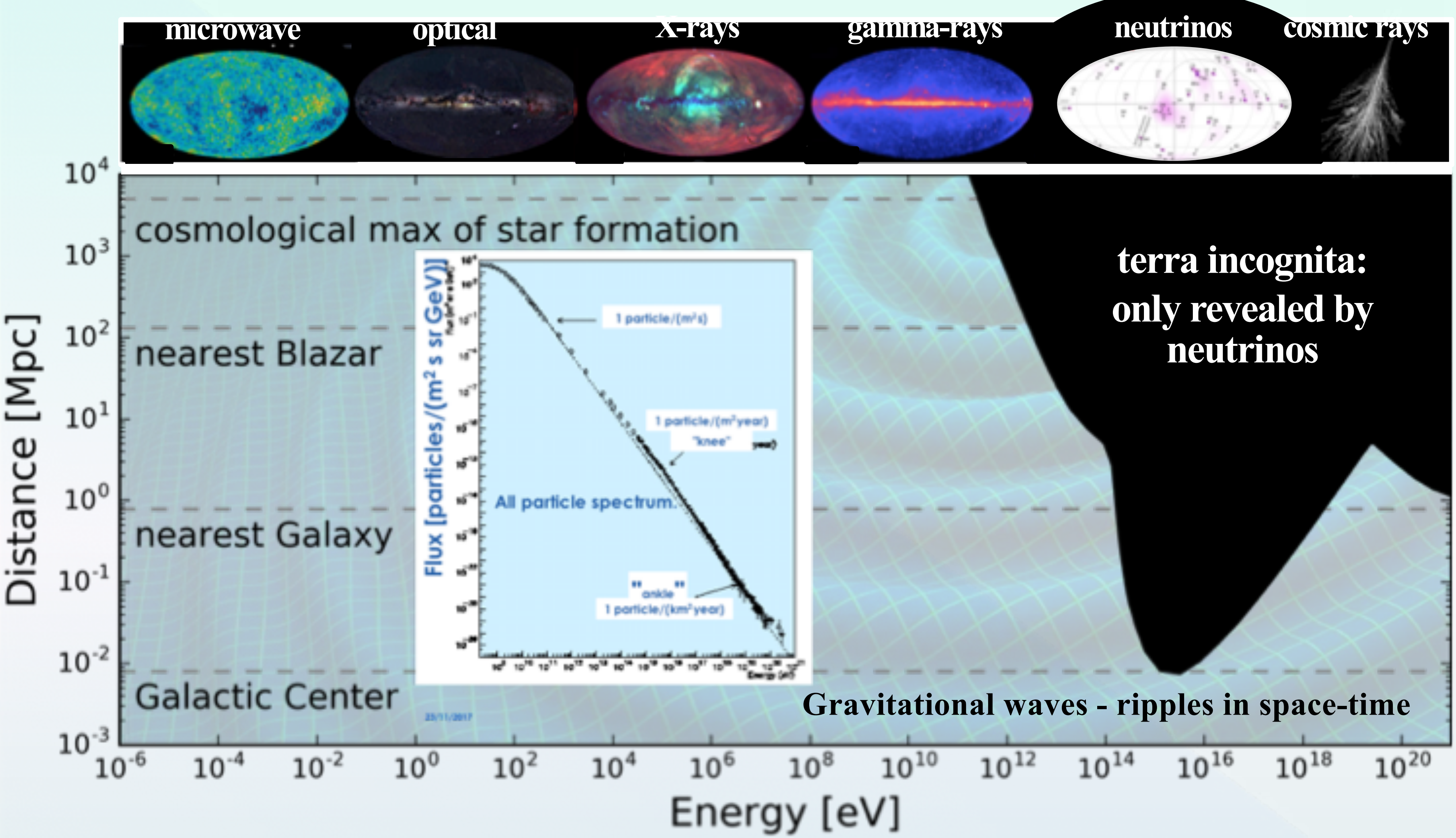
Antonio Capone

Università "La Sapienza", Roma

Talk outline

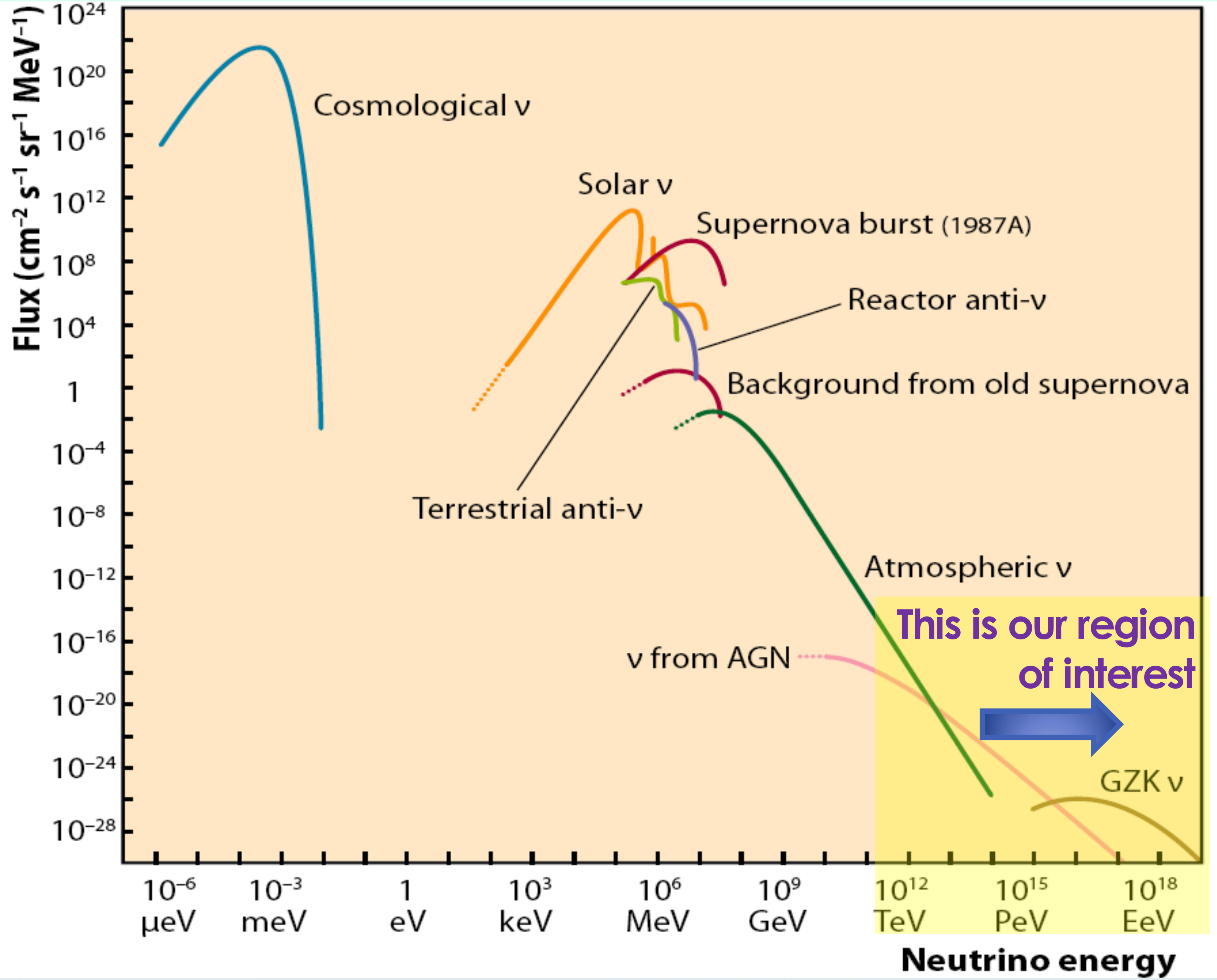
- **Motivation for High Energy Astrophysical neutrino detection**
- **IceCube, ANTARES/KM3NeT… and also Pierre Auger Observatory**
- **Neutrino Telescopes main physics goal: search for astrophysical neutrinos**
  - Search for a diffuse flux
  - Search for point-like sources
- **Transient/multi-messenger studies**
  - Search for neutrinos from GW sources
- **Perspectives for the future**
- **Conclusions & Summary**

Multi-Messenger Astronomy



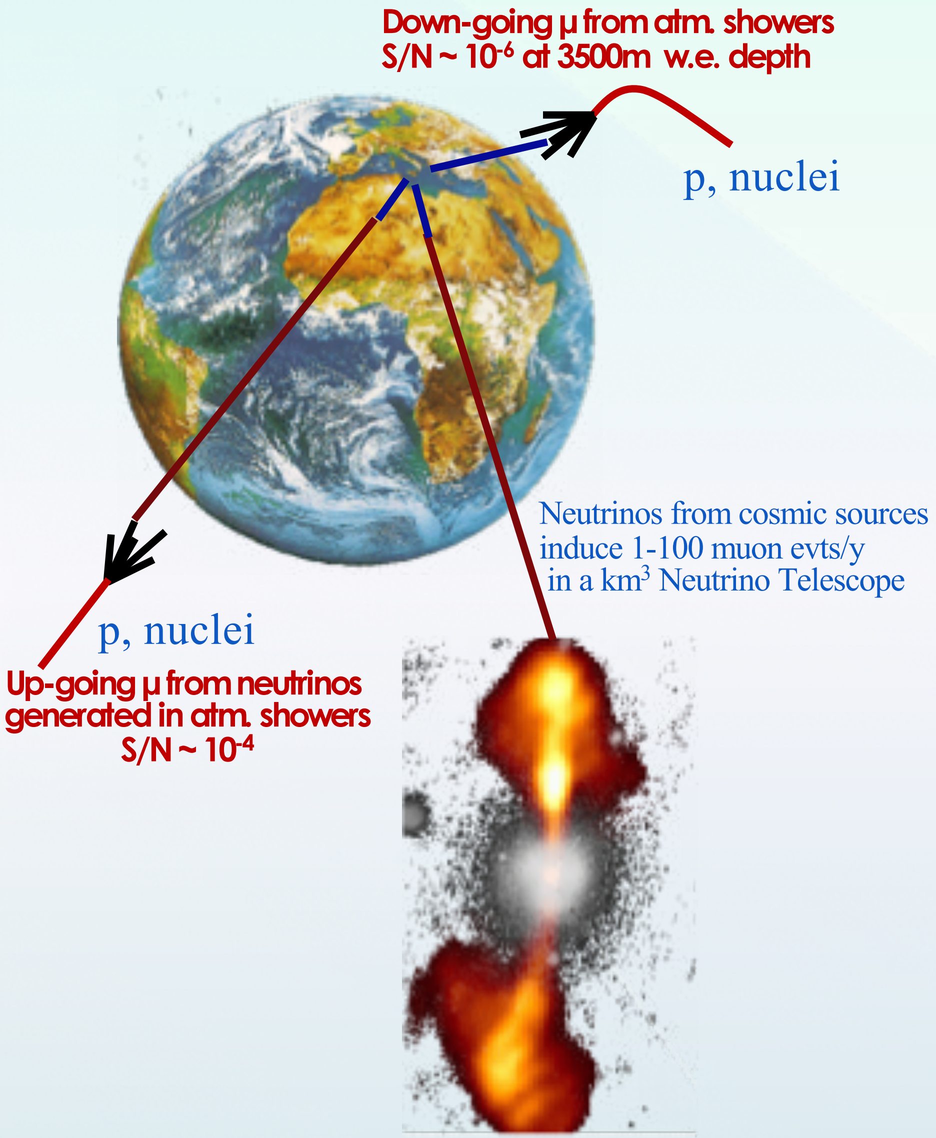
20% of the Universe is opaque to the EM spectrum

Neutrino fluxes: what do we know/expect ?



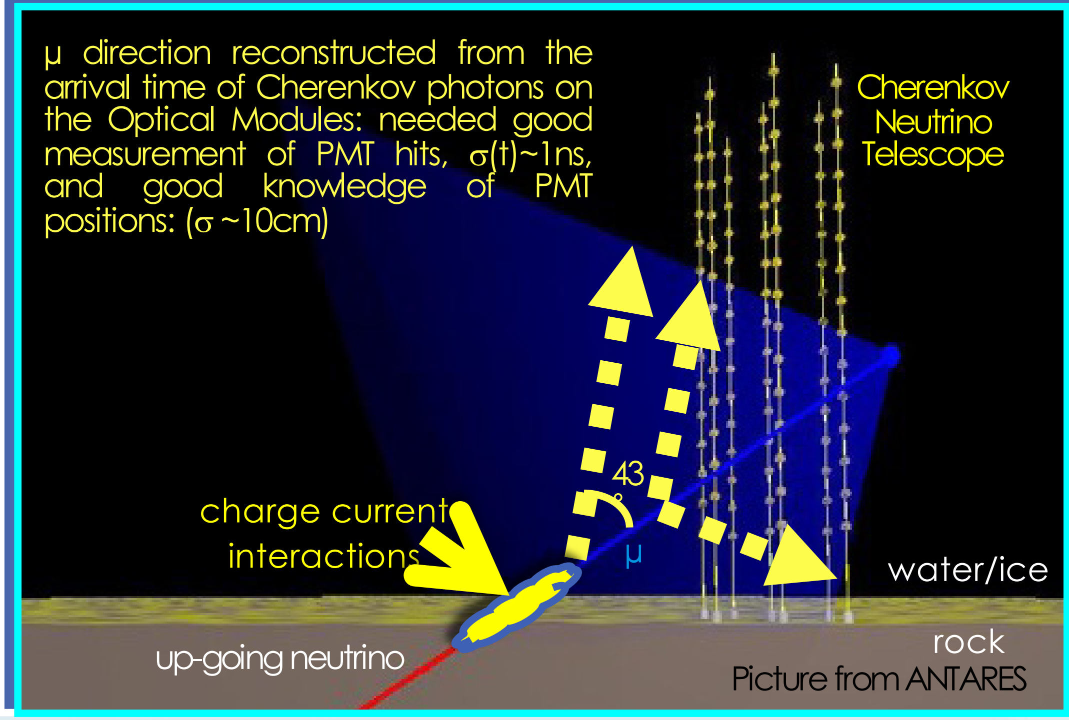
Cherenkov ν Telescope: Detection principle

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



- Atmospheric neutrino flux ~ E_ν^{-3}
- 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

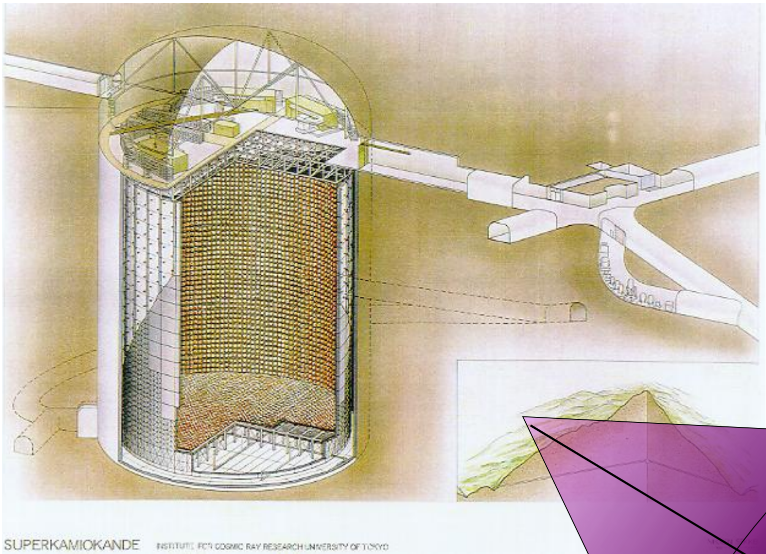
$$For\ E_\nu \geq 1 TeV \quad \theta_{\mu\nu} \sim \frac{0.7°}{\sqrt{E_\nu[TeV]}}$$



Detecting neutrinos in H_2O

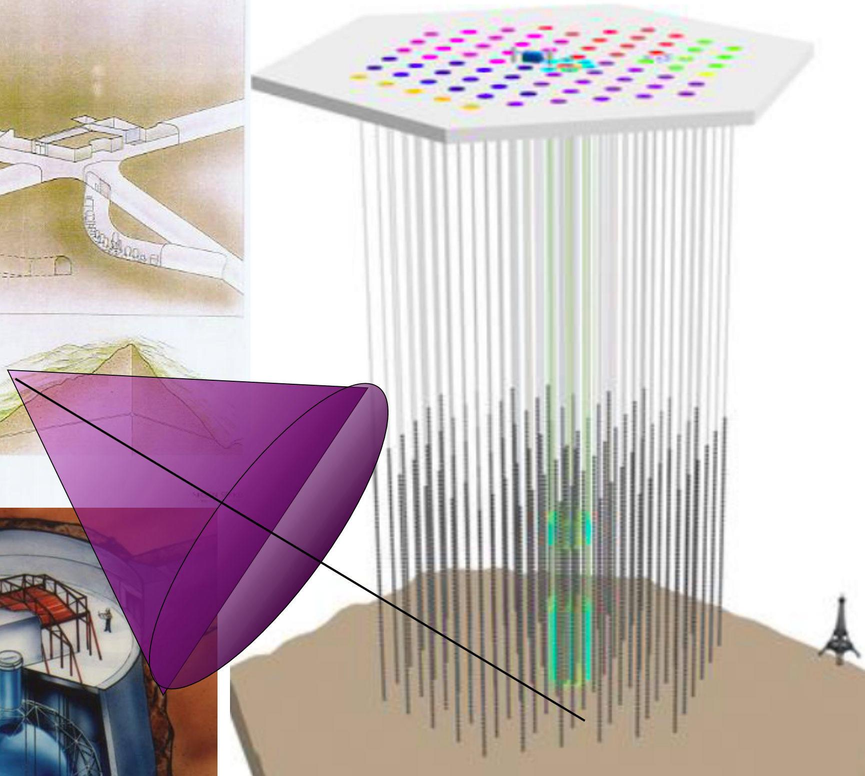
Proposed by Greisen, Reines, Markov in 1960

- DUMAND
- IMB
- Kamiokande
- Baikal
- AMANDA

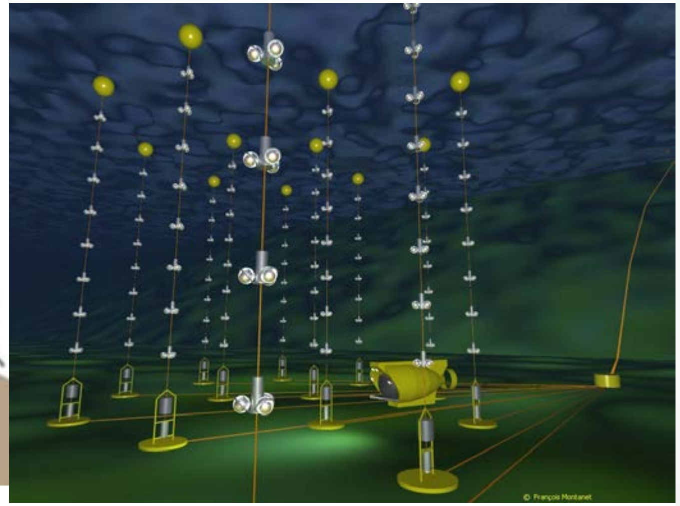


Super-K

SNO



IceCube



ANTARES

Neutrino must interact to be detected

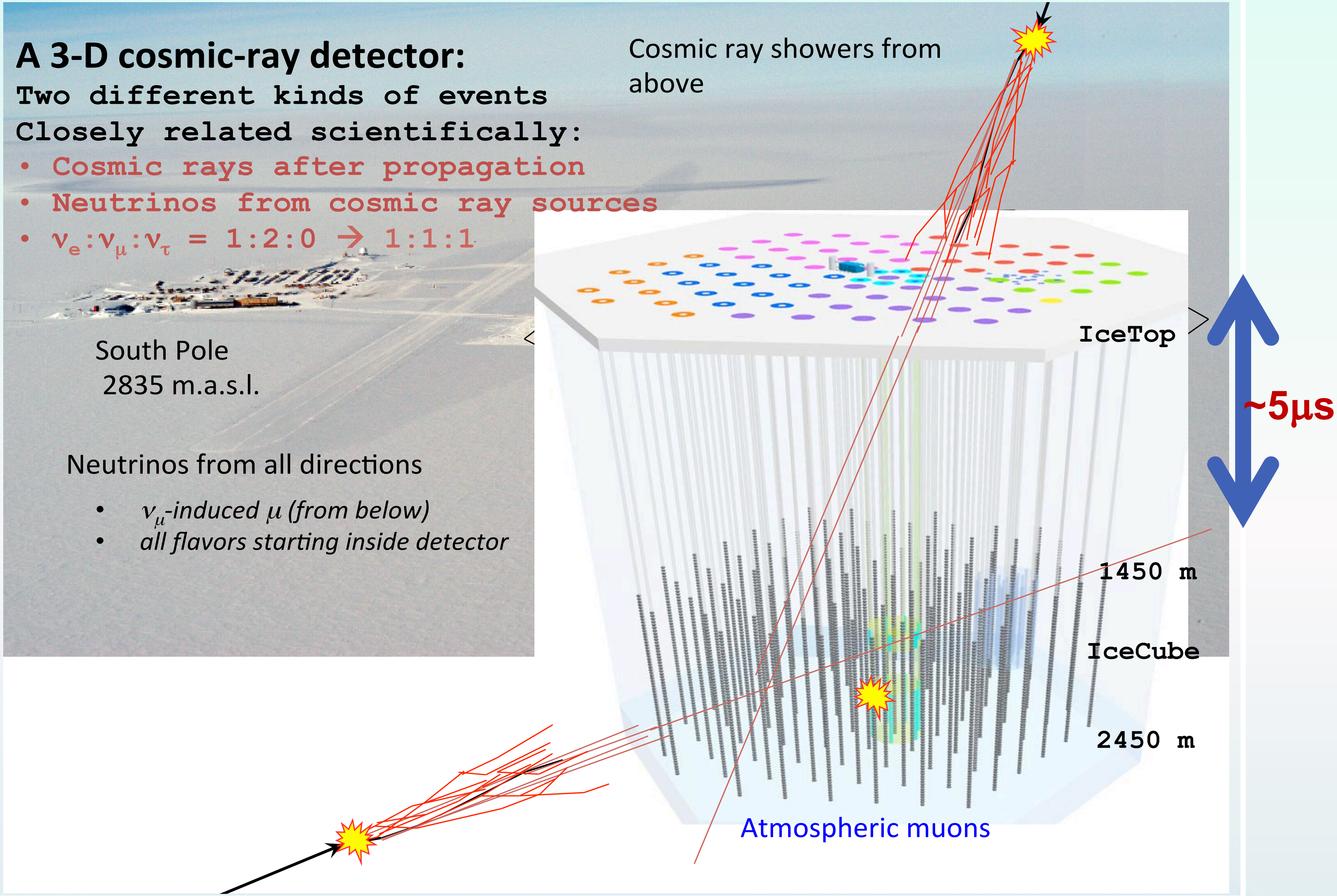
IceCube – The Neutrino Telescope at the South Pole

A 3-D cosmic-ray detector:

Two different kinds of events

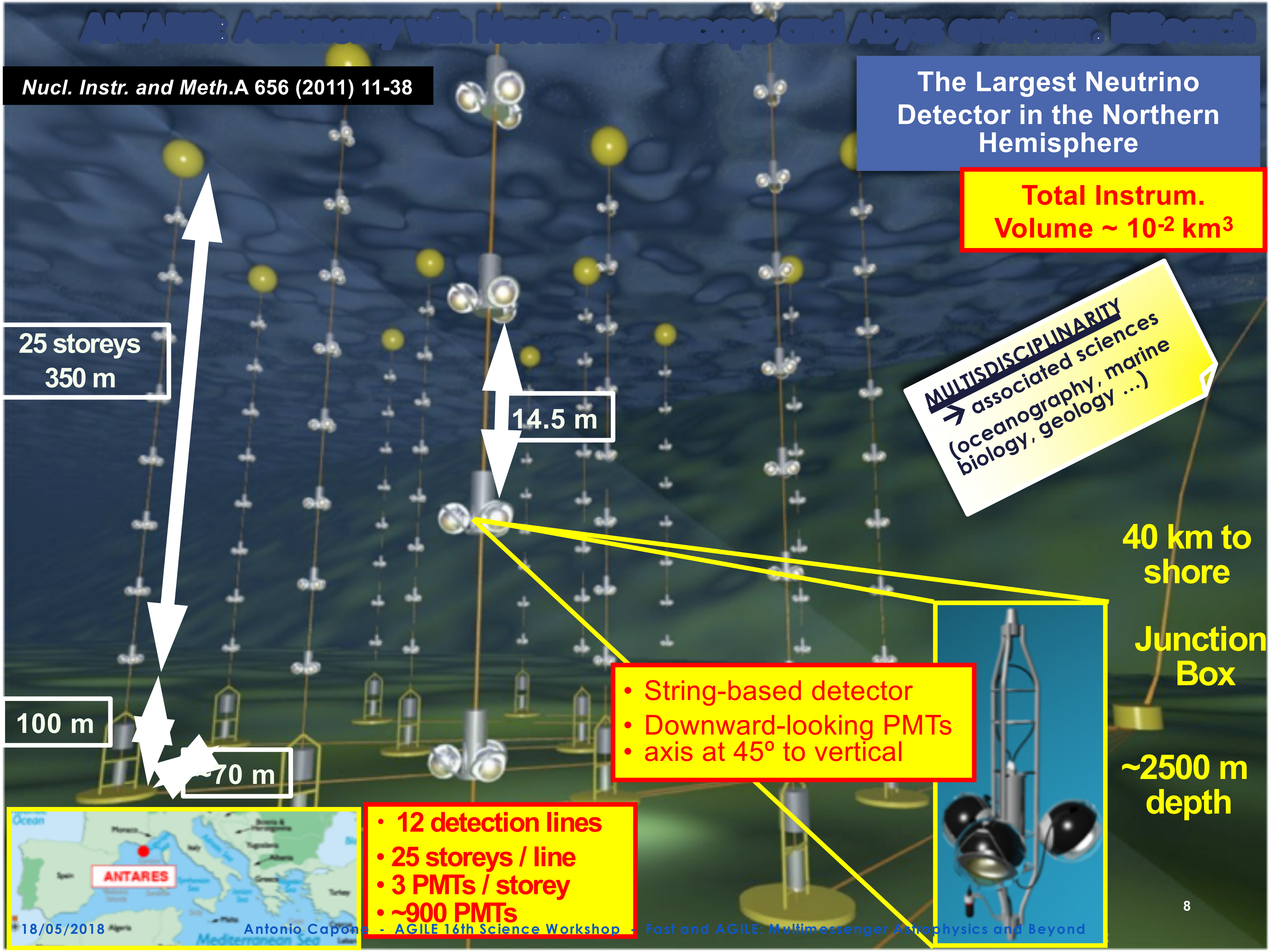
Closely related scientifically:

- Cosmic rays after propagation
- Neutrinos from cosmic ray sources
- $\nu_e:\nu_\mu:\nu_\tau$ = 1:2:0 → 1:1:1

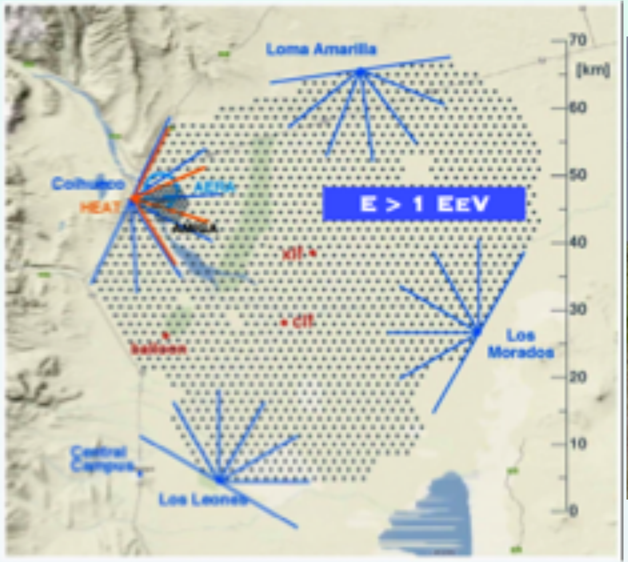


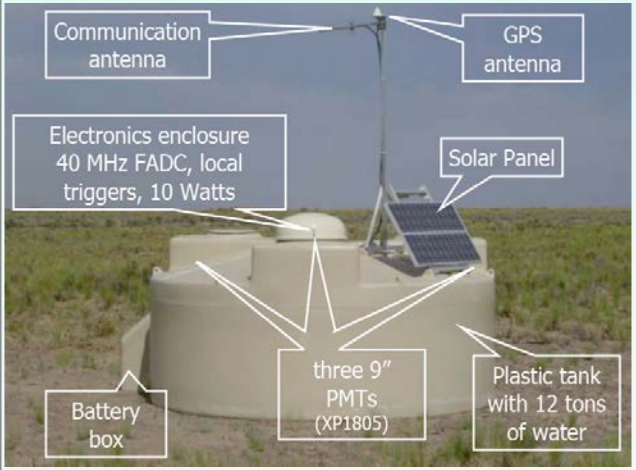
Neutrinos from all directions

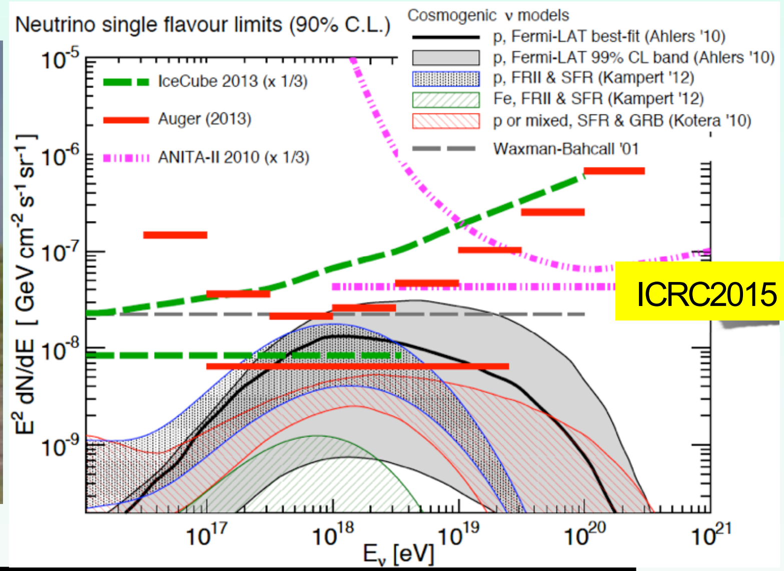
- *ν_μ-induced μ (from below)*
- *all flavors starting inside detector*

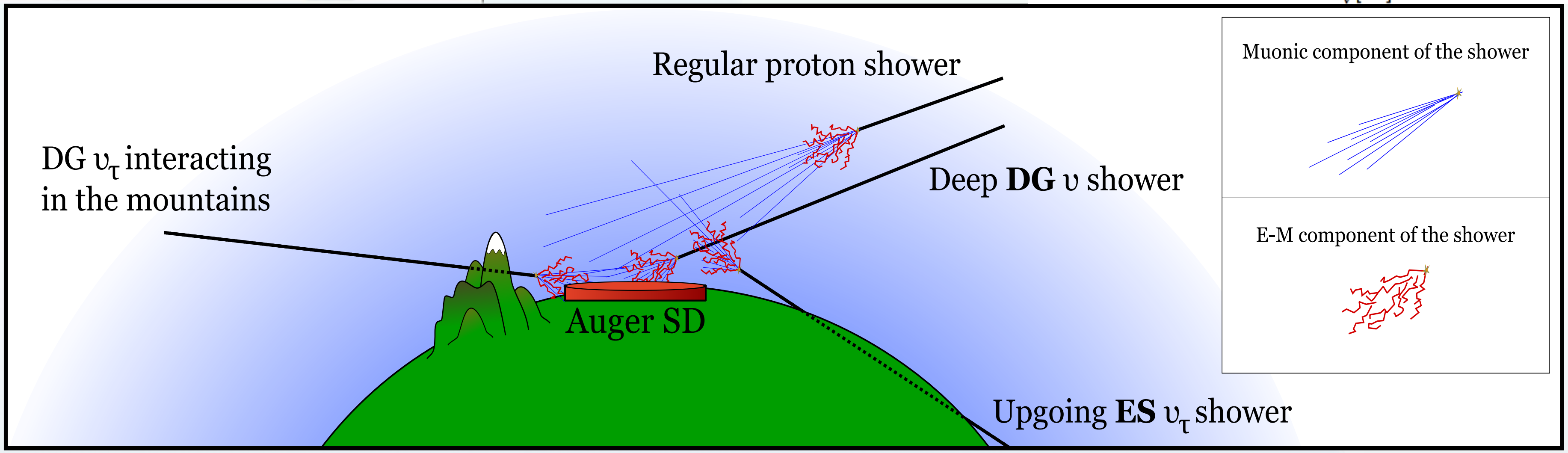

ANTARES: Astronomy with Neutrino Telescope and Abyss environm. RESearch
Nucl. Instr. and Meth.A 656 (2011) 11-38
The Largest Neutrino Detector in the Northern Hemisphere
Total Instrum. Volume ~ 10-2 km3
MULTISDISCIPLINARITY
→ associated sciences
(oceanography, marine biology, geology …)
25 storeys
350 m
14.5 m
40 km to shore
Junction Box
~2500 m depth
100 m
~70 m
• String-based detector
• Downward-looking PMTs
• axis at 45° to vertical
• 12 detection lines
• 25 storeys / line
• 3 PMTs / storey
• ~900 PMTs
ANTARES
Ocean
Mediterranean Sea

The Pierre Auger Observatory can identify UHE neutrinos









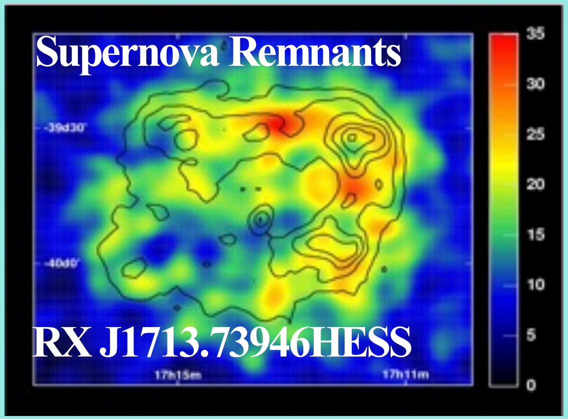
The SD is spread over a surface of ~3000 km² at an altitude of ~1400 m above sea level.

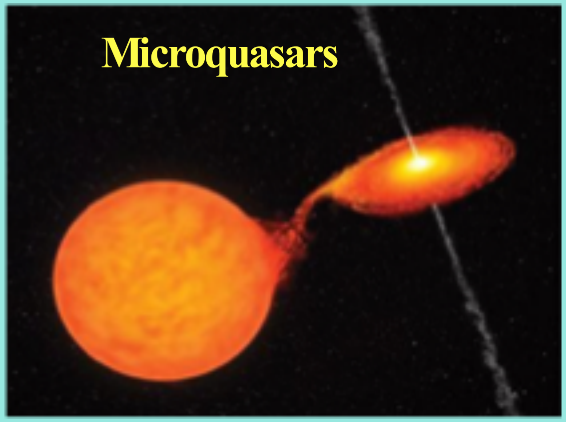
This corresponds to an average vertical atmospheric depth above ground of X_{ground} = 880 g cm^{-2}. The slant depth D is the total grammage traversed by a shower measured from ground in the direction of the incoming primary particle. In the flat-Earth approximation $D = (X_{ground} - X_{int})/\cos\theta$, where X_{int} is the interaction depth and θ the zenith angle.

Neutrino Telescope physic's goals

Search for point-like cosmic Neutrino Sources

Galactic

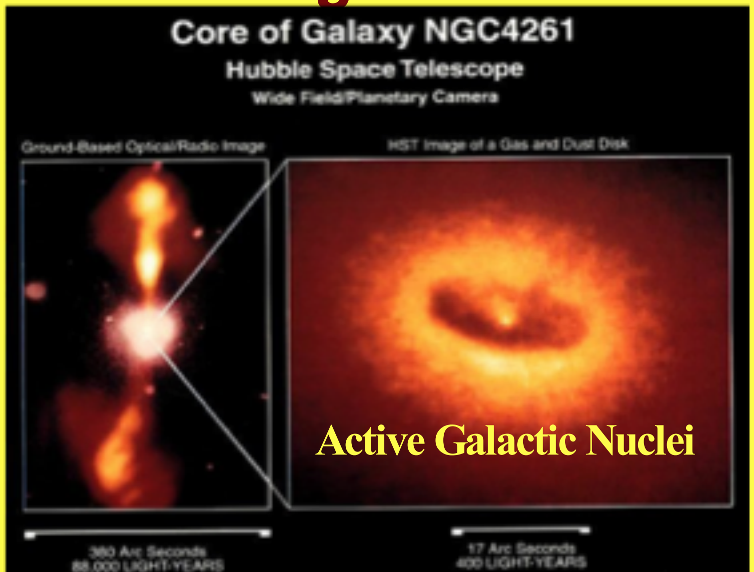


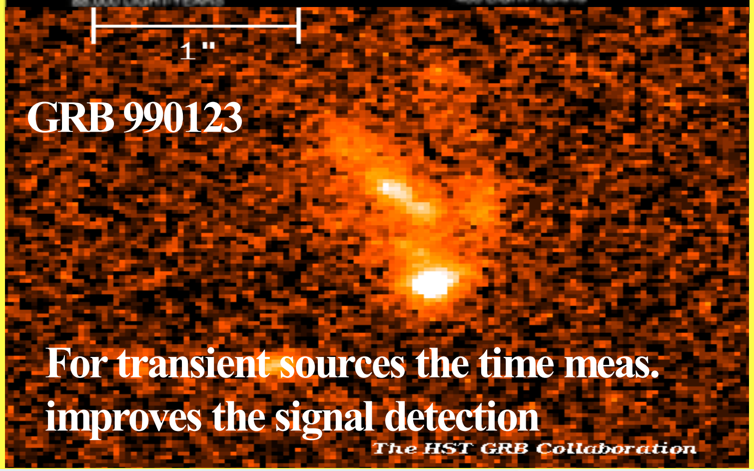


- Their identification requires a detector with accurate angular reconstruction

$$\sigma(\vartheta) \leq 0.5° \text{ for } E_\nu \geq 1 TeV$$

Extragalactic



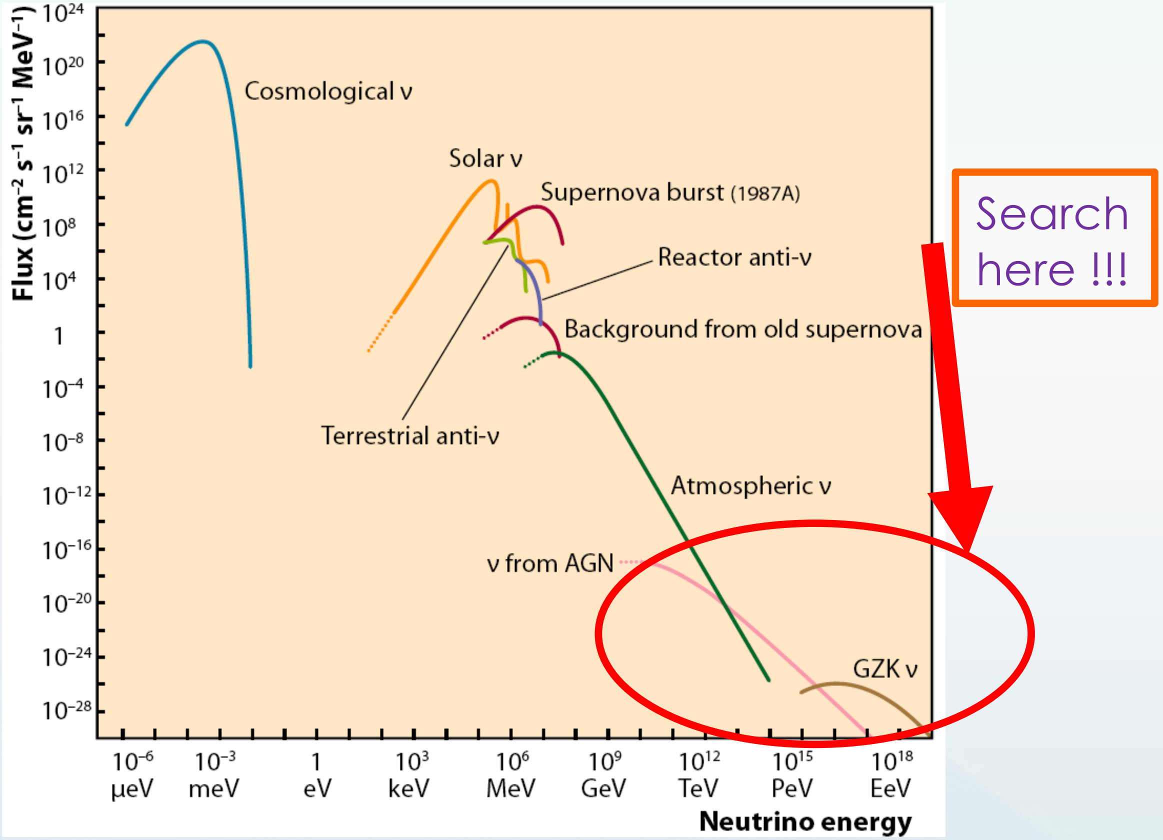


Experimental signal : statistical evidence of an excess of events coming from the same direction

Neutrino Telescope physic's goal: Search for Diffuse flux of Cosmic Neutrinos

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



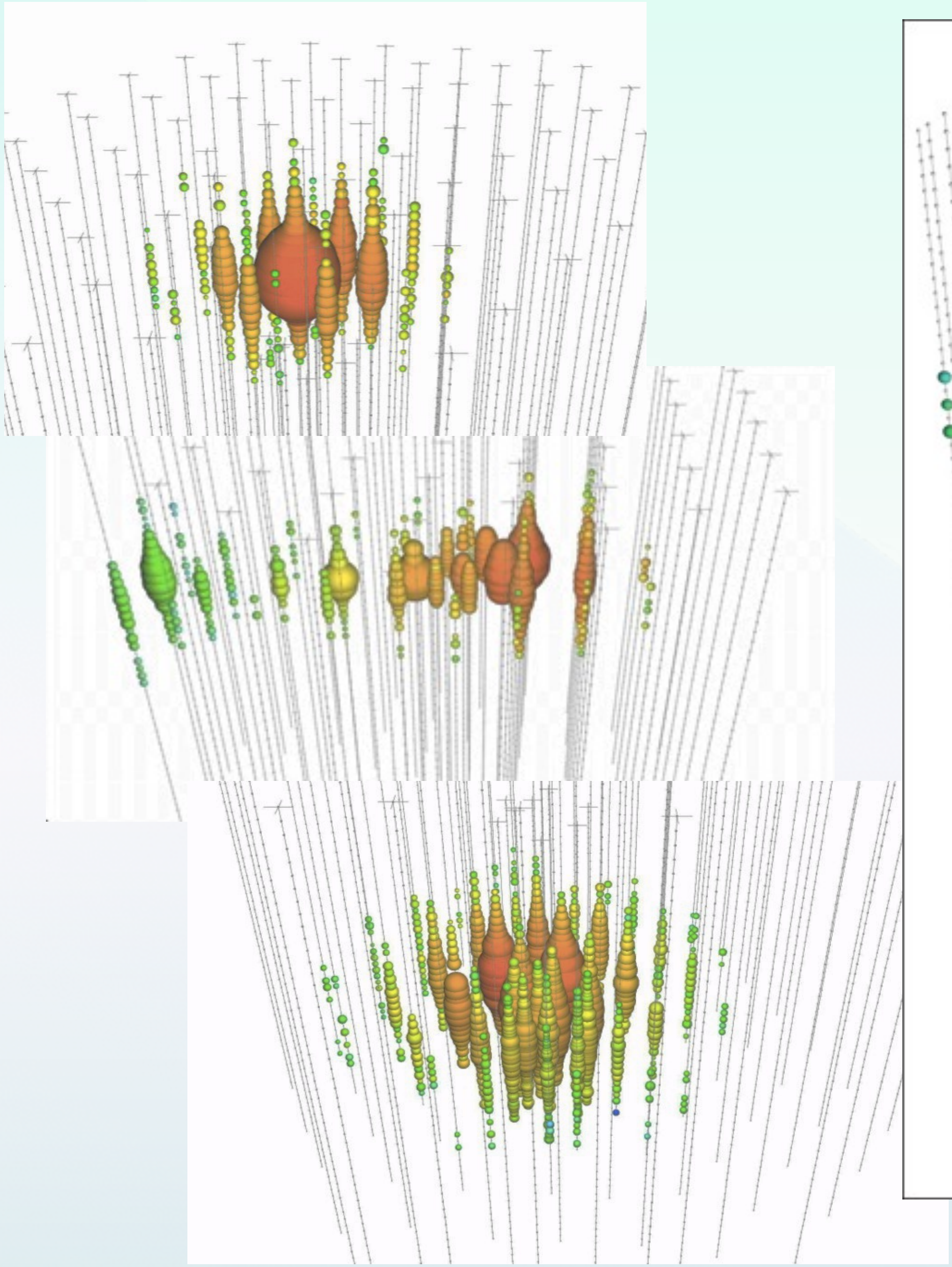
Neutrino Telescope physic's goal

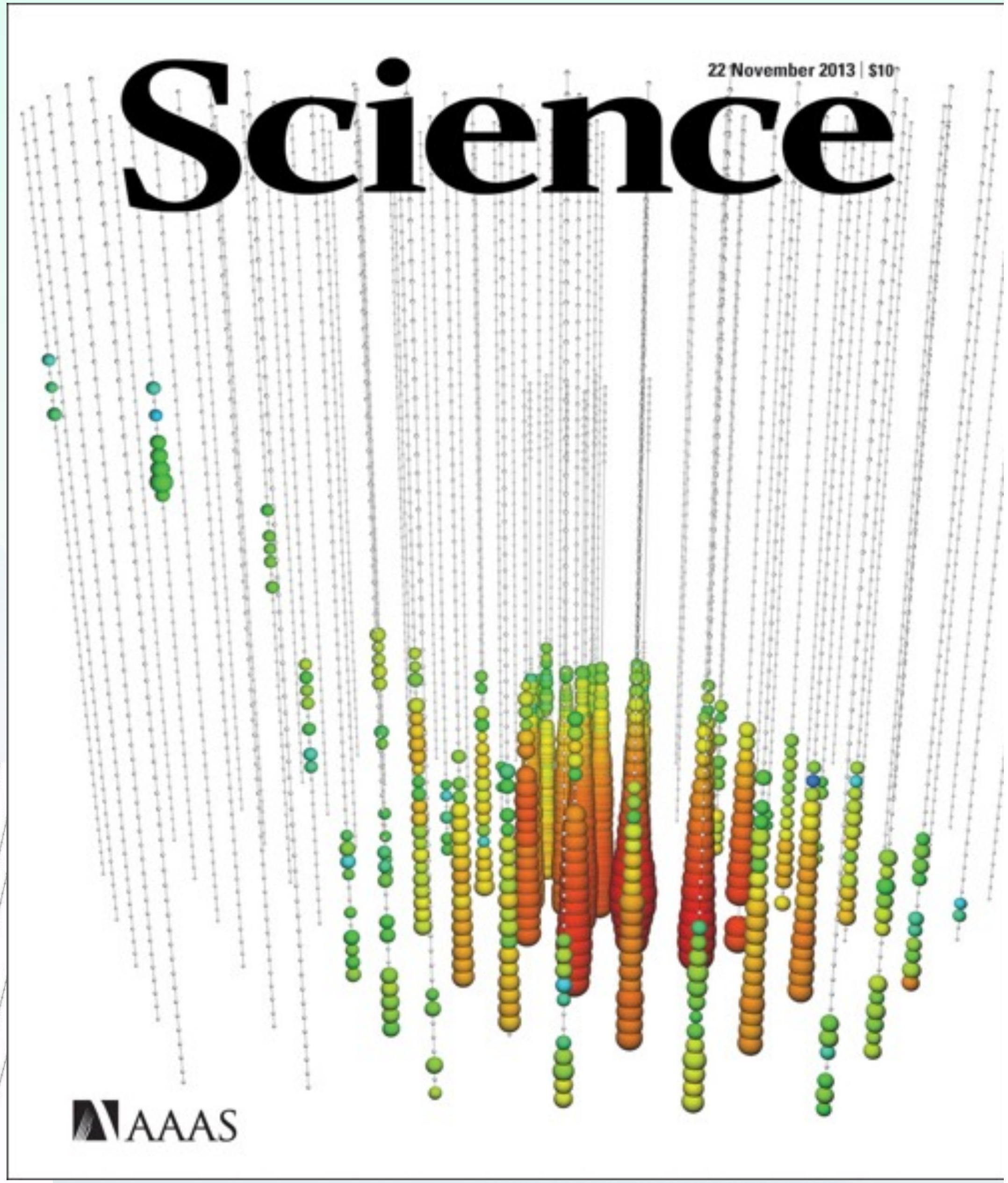
astronomy/astrophysics in a multi-messenger framework

Search for Coincident event in a restricted time/direction windows with EM/γ/GW counterparts (flaring sources, transient events, ...)

Relaxed energy/direction measurement + transient/ multi-messenger information

The great discovery (from IceCube 2013)

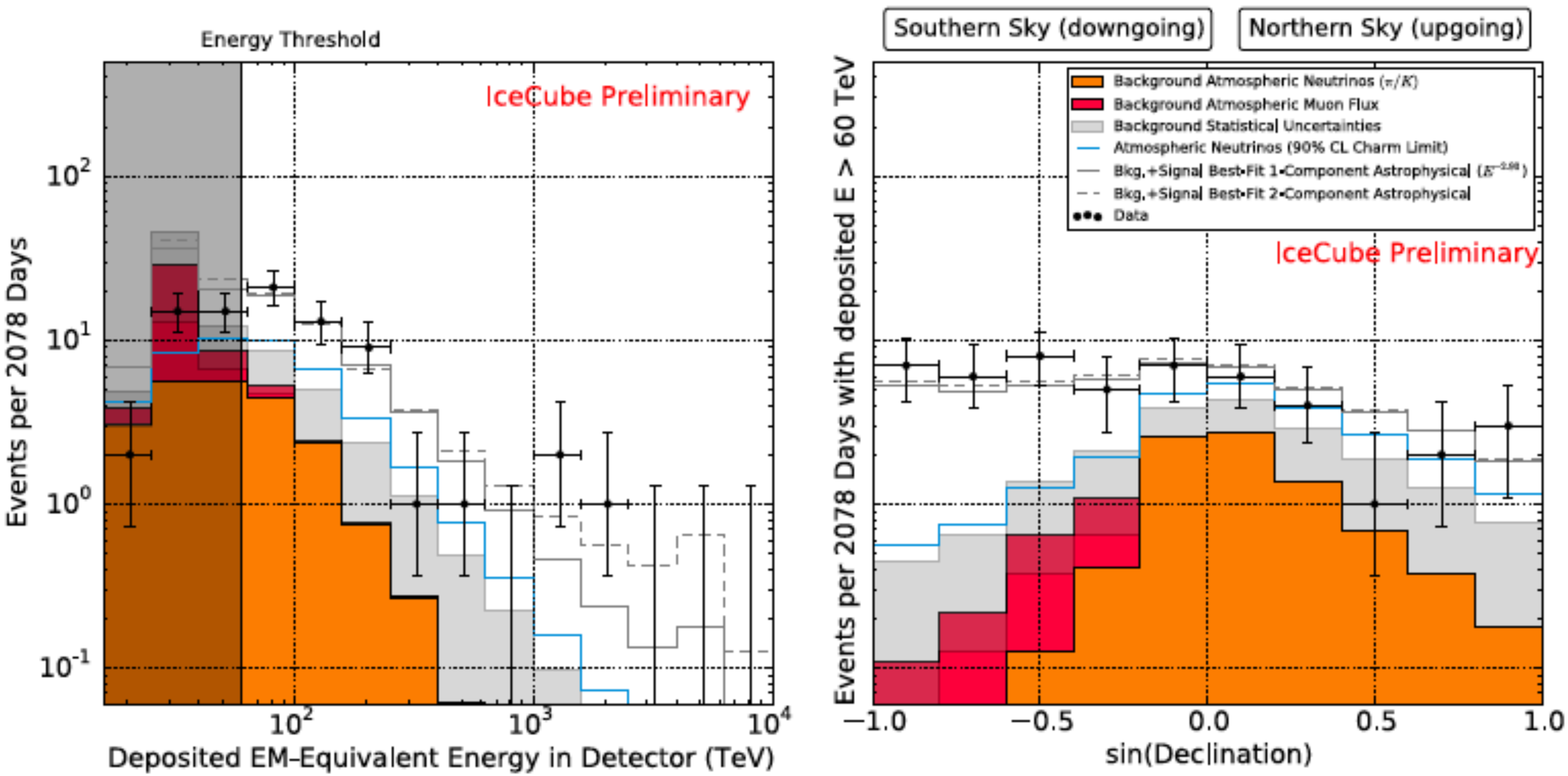




2-year analysis: Science 342, 1242856 (2013)

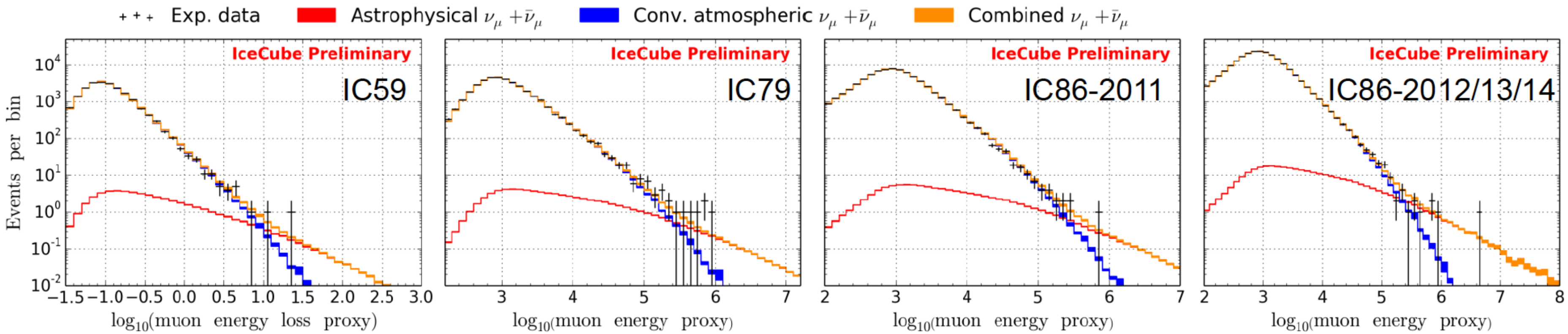
IceCube 2017 - High Energy Starting Event Analysis

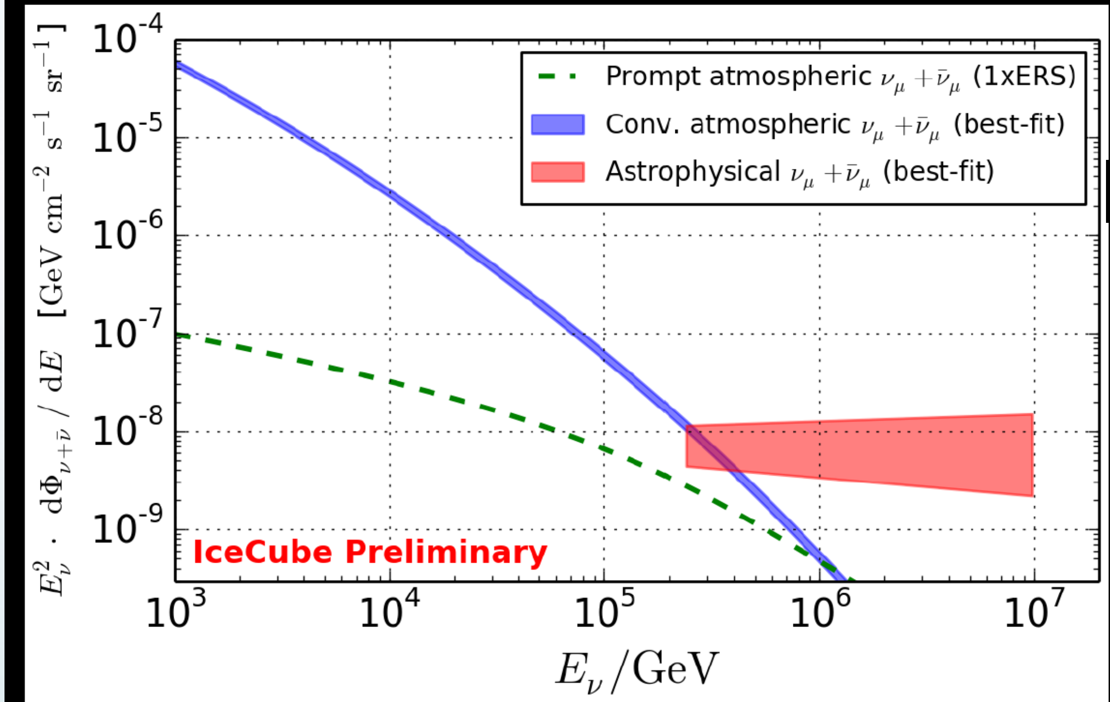
starting events: now 6 years → 8σ



IceCube today: diffuse ν_μ flux with up-going muons

after 7 years → 6.4 sigma





- Best-fit astrophysical normalization:

0.97+.27-.25 $\times 10^{-18}$ GeV^{-1}cm^{-2}s^{-1}sr^{-1}

- Best-fit spectral index:

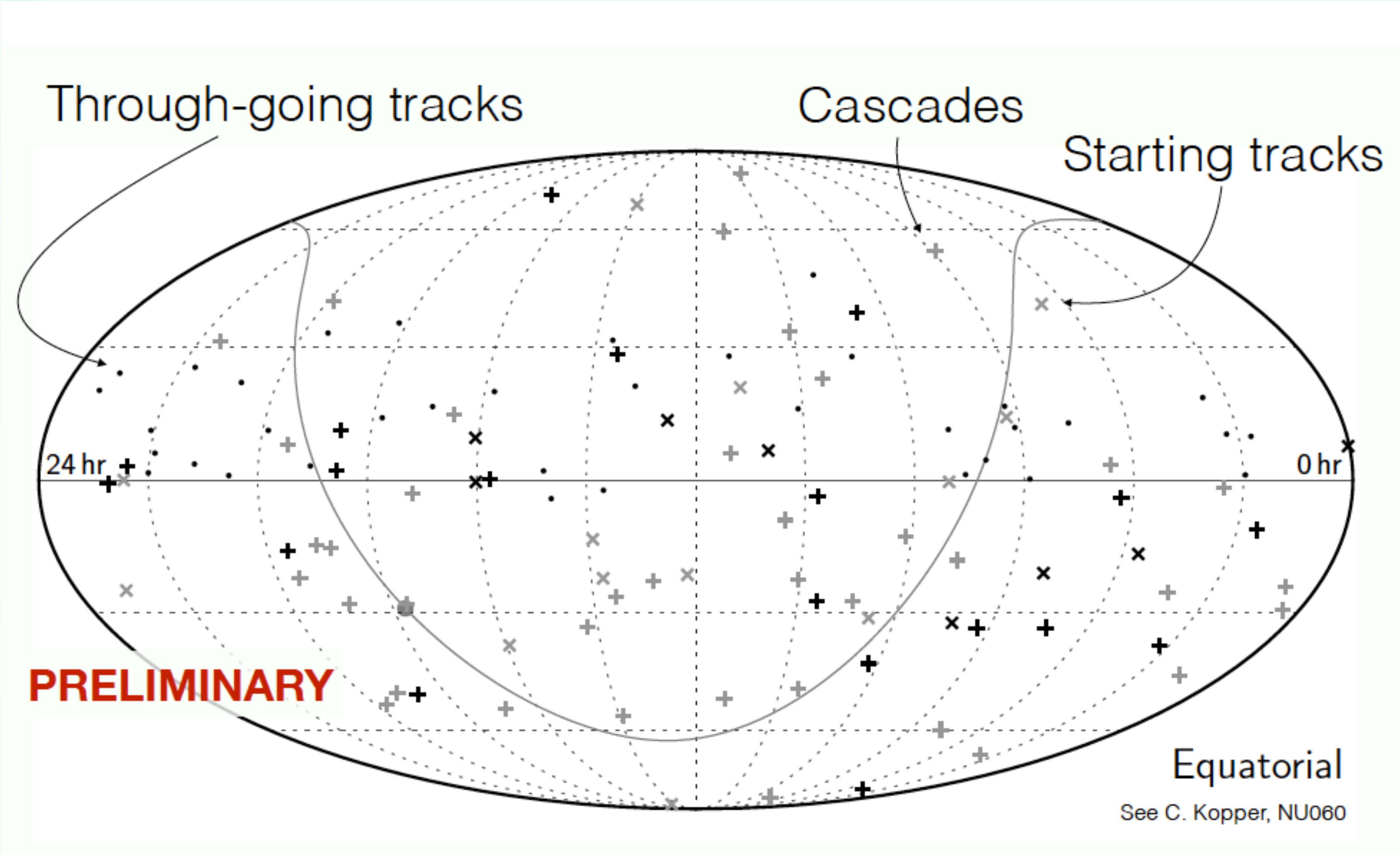
γ_{astro} = 2.16 ± 0.11

- Energy ranges:

240 TeV – 10 PeV

- Atmospheric-only hypothesis excluded by 6.0σ

Where these neutrinos are coming from ??



A diffuse flux from extragalactic sources
A subdominant Galactic component cannot be excluded

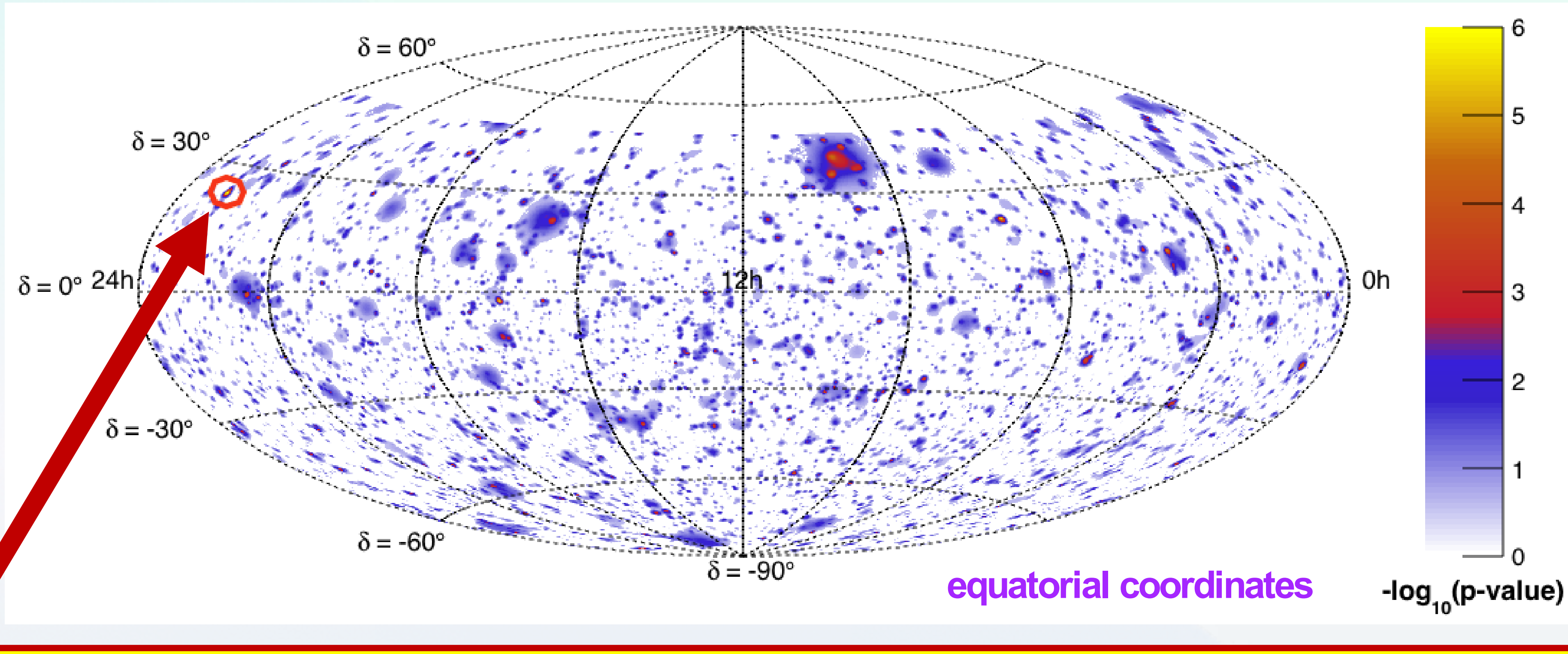
It's mandatory now !!!!

- **Let search for neutrino point like sources:**
  - Large size detector required (very small fluxes expected)
  - Very good accuracy in angular reconstruction (high background, the irreducible atmospheric background has to be subtracted statistically)

ANTARES results: "full sky search" of ν sources

The visible sky of ANTARES divided on a $1^0 \times 1^0$ (r.a x decl.) boxes.
Maximum Likelihood analysis searching for clusters

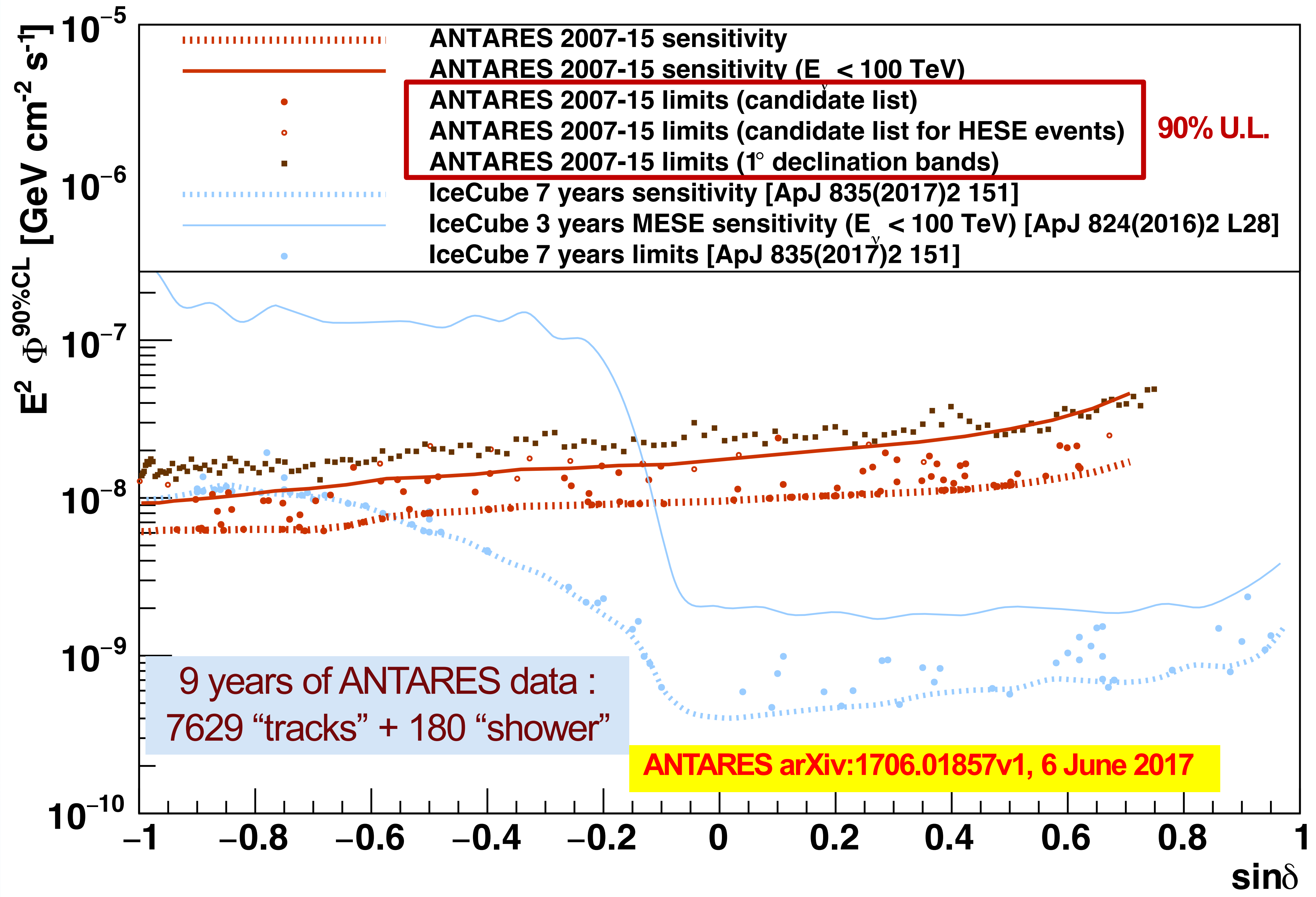
ANTARES arXiv:1706.01857v1, 6 June 2017



The most significant cluster: decl. δ = 23.5^0, r.a. α = 343.8^0 has a pre-trial p-value of 3.84×10^{-6}

→ U. L. from this sky location $E^2 \frac{d\Phi}{dE} = 3.8 \times 10^{-8}$ GeV cm^{-2} s^{-1}

ANTARES results: "full sky search" of ν sources



The Multi-Messenger Search Programme with ANTARES

Neutrinos trigger others

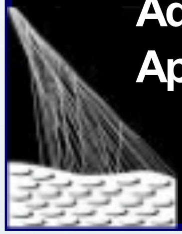
Others trigger neutrinos

ANTARES ⇔ VIRGO
LIGO

common working group (GWHEN)
S. Adrián-Martínez et al.,
JCAP 06 (2013) 008

ANTARES ⇔ AUGER

Adrian-Martinez et al.,
ApJ 774 (2013) 008



TAToO
(Telescopes – ANTARES Target of Opportunity)

Optical follow-up of neutrino alerts for transient source search (GRBs, SNae). Analysis in progress!

ANTARES ⇔ Optical Telescopes
TAROT & ROSTE + more

Ageron *et al.*, *Astrop.Phys* 35 (2012) 530-536

Flaring Sources
(ν emission from γ-flaring blazars/μQuasars)

ANTARES ⟷ Gamma-Rays
X-Rays

blazars: APP 36 (2012) 304;
μQuasars: JHEAp, 3-4 (2014) 9-7

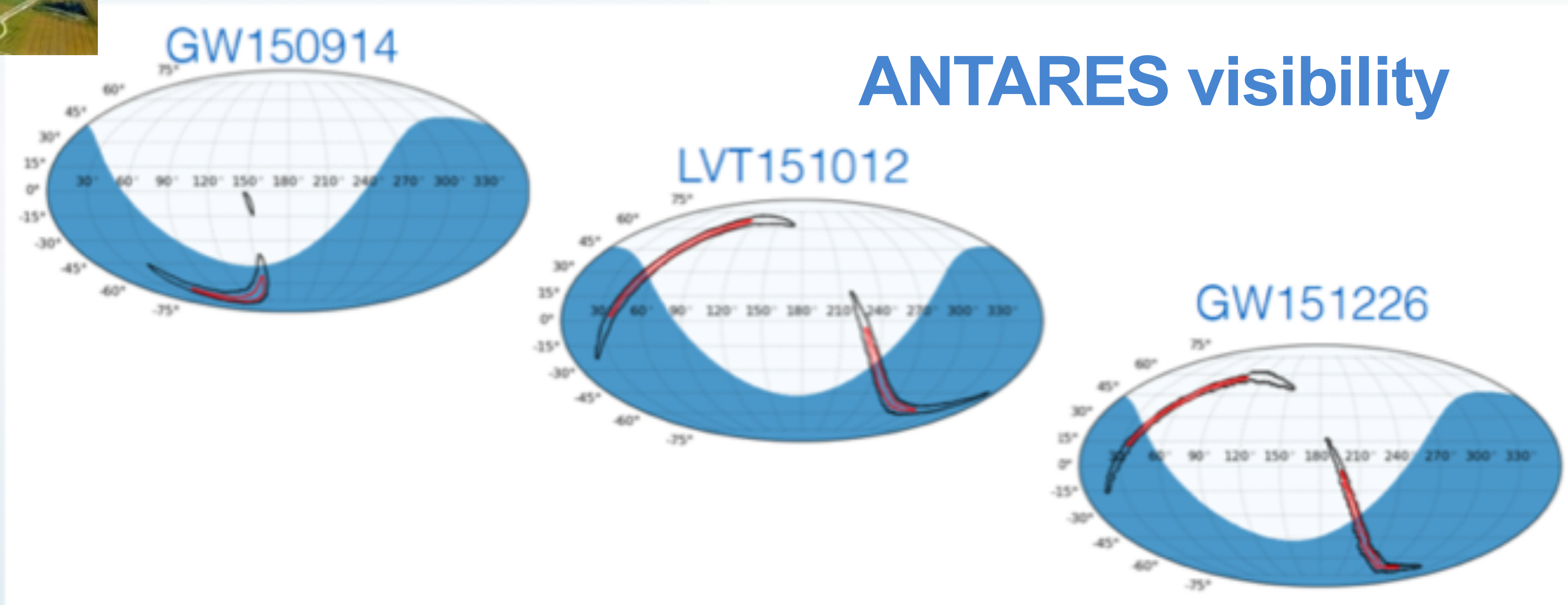
GCN (Gamma-ray Coordination Network)

ANTARES ⇔ GCN
A&A 559, A9 (2013),
JCAP 1303 (2013) 006

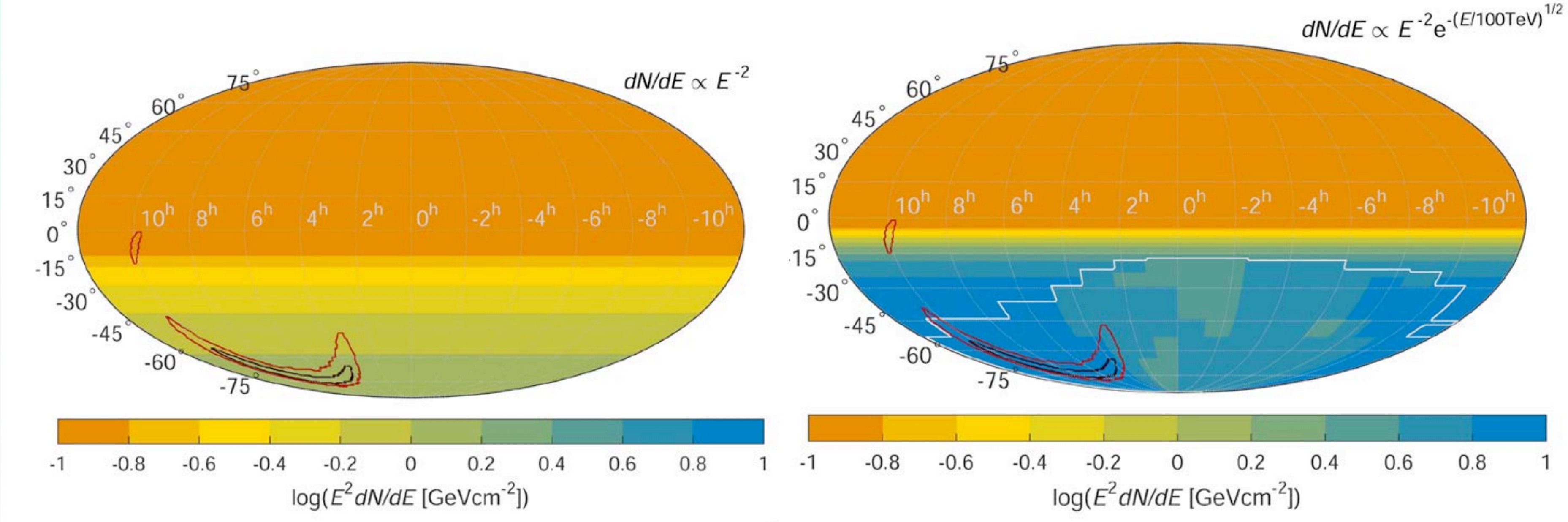
ANTARES Multi-messenger program
ν follow-up of GW sources - 1

3 alerts sent by LIGO during the run 01 (2015/09 → 2016/01):

- GW150914: merging of 2 BHs (M= 36/29 M_{Sun} - 410 Mpc - 5.1σ)
- LVT151012: merging of 2 BHs (M= 23/13 M_{Sun} -1000 Mpc - 1.7σ)
- GW151226: merging of 2 BHs (M= 14/7 M_{Sun} - 440 Mpc -> 5σ)



A joint ANTARES/IceCube/LigoSC/Virgo analysis performed as “Neutrino follow-up” of GW150914



Phys.Rev. D93 (2016), 122010

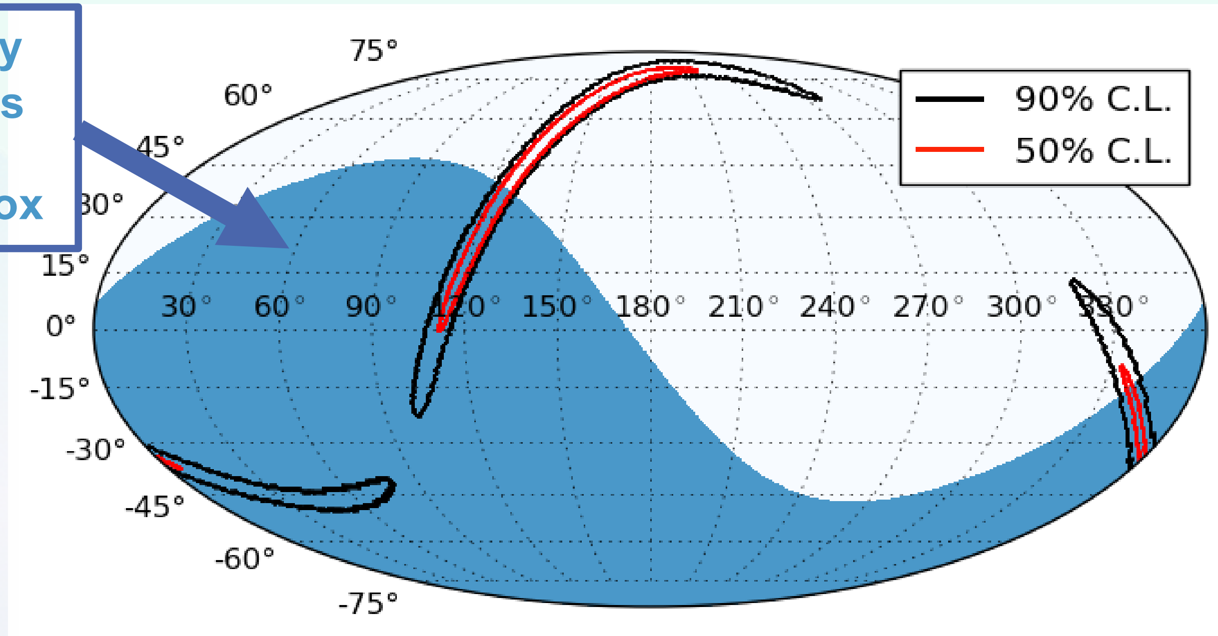
- No ANTARES events in ±500 s from the GW time (0.015 expected)
- Limits from ANTARES dominates for E_ν < 100 TeV
- U.L. from IC dominated above 100 TeV
- Size of GW150914 : 590 deg^2 ANTARES resolution: <0.5 deg^2
- Limits on total energy radiated in neutrinos: <10% GW
- Future: Receive / send alerts in real time

ANTARES Multi-messenger program
ν follow-up of GW sources - 2

The LIGO event GW170104 during run 02 (Nov. '16 – Aug. '17):

- GW170104: merging of 2 BHs (M= 31/19 M_{Sun} - 880 Mpc)

ANTARES visibility for up-going tracks includes 51% of LIGO/Virgo error box

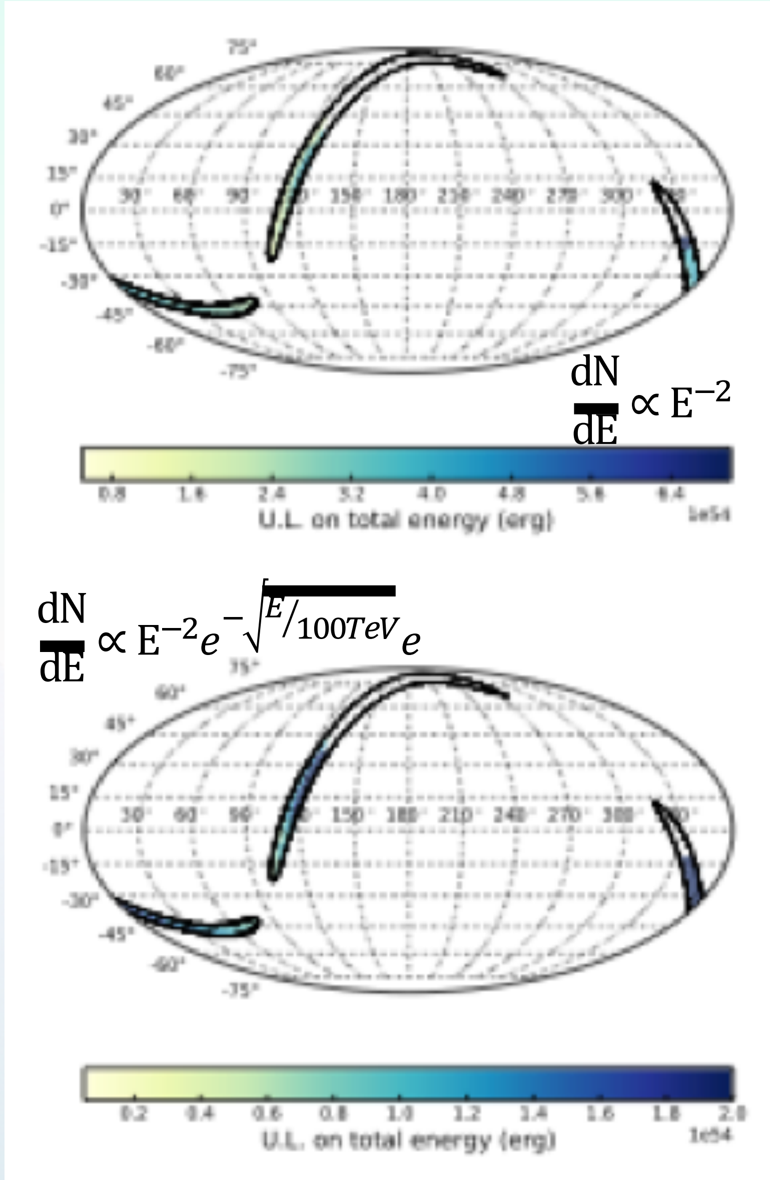


No neutrino candidates were found within ±500 s around the GW event time (result in <24h after the alert) nor any time clustering of events over an extended time window of ±3months.

ANTARES Multi-messenger program
ν follow-up of GW sources - 3

The search for neutrinos over ±3 months around the GW170104 alert was performed by looking for time clustering of up-going neutrino events. No events observed.

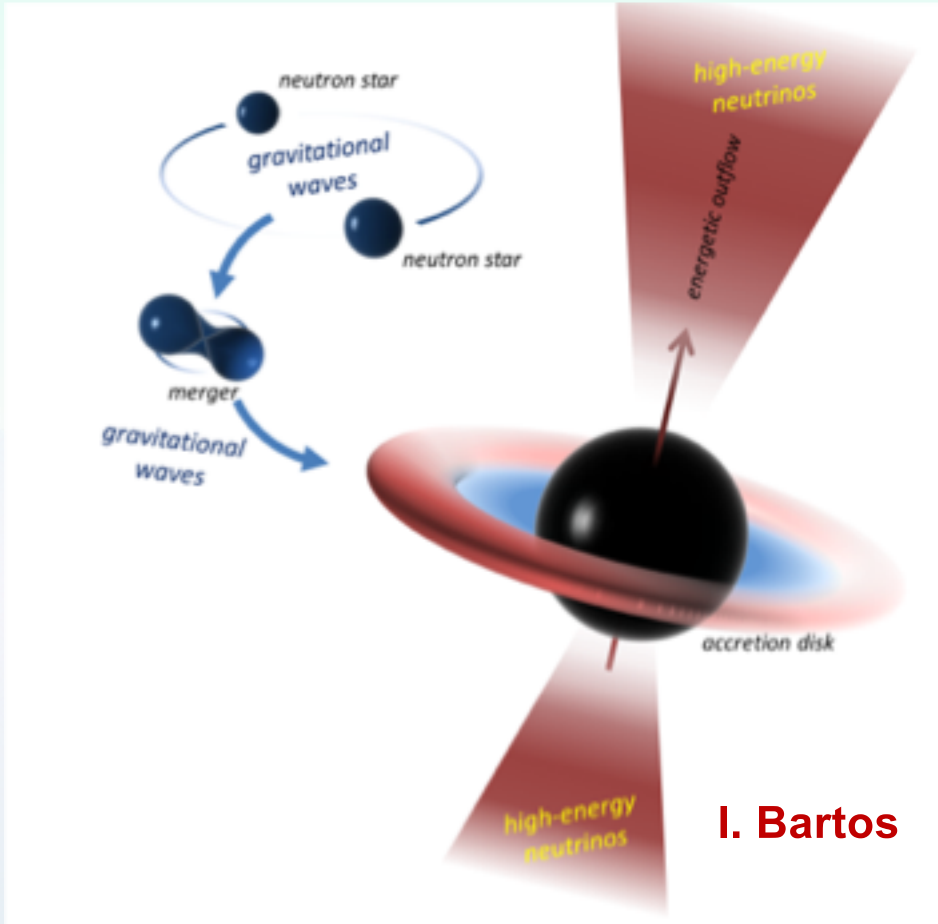
The non-detection is used to constrain isotropic-equivalent high-energy neutrino emission from GW170104 to less than $4 \cdot 10^{54}$ erg for a E^{-2} spectrum.



The most wanted object: NS-NS (NS-BH)

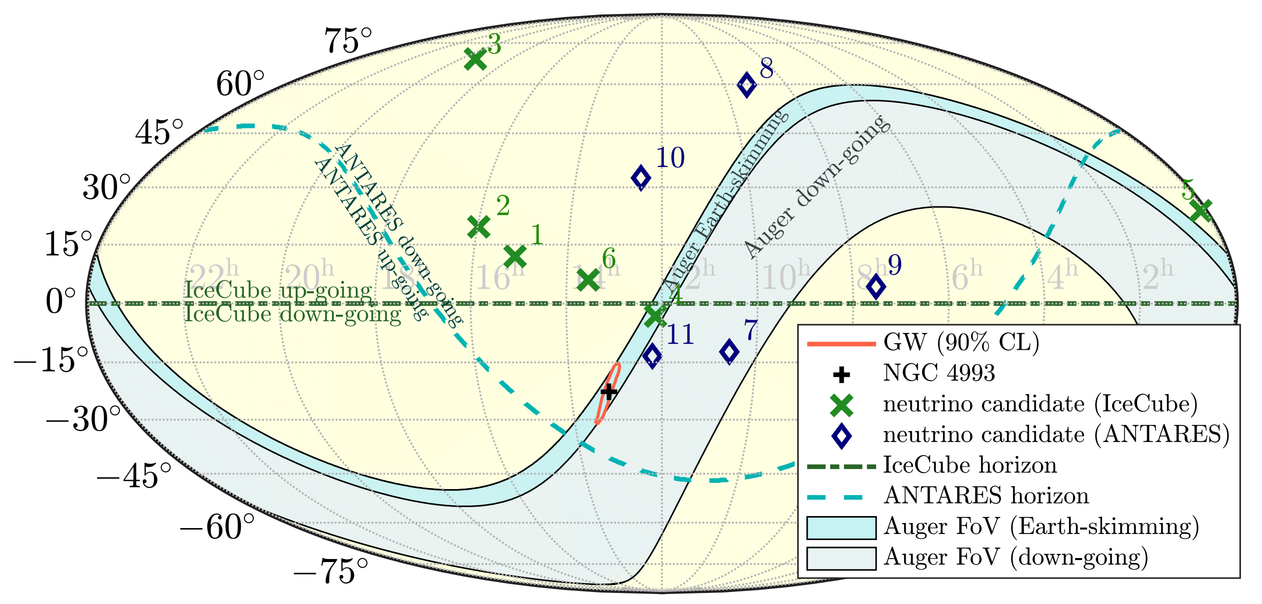
GW

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



(*) 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

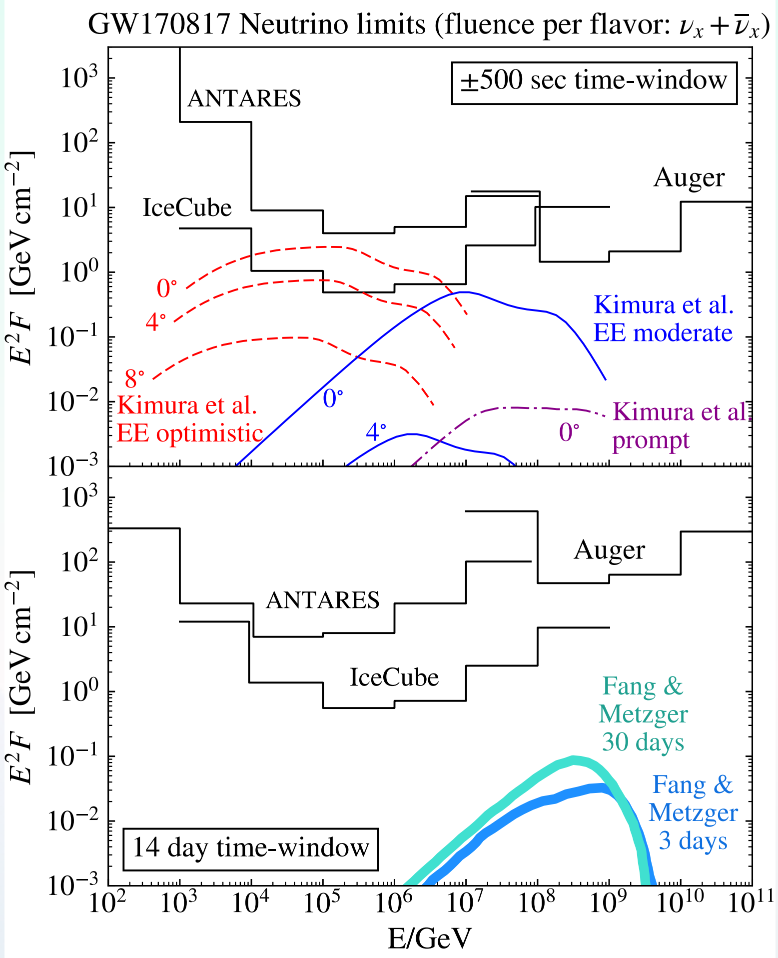


The location of this source was nearly ideal for Auger. It was well above the horizon for IceCube and ANTARES for prompt observations. IceCube and ANTARES sensitivity is then limited for neutrinos with E_ν < 100 TeV.

- A **short gamma-ray burst** (GRB) that followed the merger of this binary system was **recorded by the Fermi-GBM** (E_{iso} ~$4 \cdot 10^{46}$ erg) and **INTEGRAL.**
- Advanced LIGO and Advanced Virgo observatories reported **GW170817**
- Optical observations allowed the precise localization of binary neutron star inspiral in **NGC4993** at ~ **40Mpc**.
- **ANTARES**, **IceCube**, and **Pierre Auger Observatories** searched for high-energy neutrinos from the merger in the **10^{11} eV–10^{20} eV** energy range .
- **IceCube** detector is also sensitive to outbursts of **MeV neutrinos** via a simultaneous increase in all photomultiplier signal rates.

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

- **No neutrinos** directionally coincident with the source were **detected within ±500 s** around the merger time**.**
- Additionally, **no MeV neutrino burst signal was detected (in IceCube) *coincident with the merger.***
- In **Pierre Auger Observatory no** inclined showers passing the Earth-skimming selection (**neutrino candidates**) **were found in the time window ±500 s** around the trigger time of GW170817**.**
- **No neutrino found in an extended search in the direction within the 14-day period following the merger.**
- **GRB170817A's** observed **prompt gamma-ray emission**, as well as Fermi-GBM's luminosity constraints for extended gamma-ray emission, are **significantly below typical values for observed short GRBs**. One possible explanation for this is the **off-axis observation of the GRB**.



- **The non observation of neutrinos allow to put limits both extended emission (EE) and prompt emission (scaled to a distance of 40 Mpc): limits are shown for the case of on-axis viewing angle (0) and selected off-axis angles to indicate the dependence on this parameter.**

Summary

- ANTARES studied the **Southern sky** with ν_μ competitive sensitivities and excellent angular resolution for both ***tracks*** and ***cascades***;
  - Upper limits on known GeV-TeV γ-ray sources $<10^{-8}$ GeV/(cm^2 s)
  - Sensitivity for a diffuse flux close to the level of the IC signal

- A large **multi-messenger** effort
  - EM radiation: radio (MWA), optical, X-ray, γ-rays (LAT,IACTs)
  - P.A.O. and IceCube possible sources
  - Gravitational Wave and neutrino common sources ?

- **KM3NeT-Arca** Neutrino Telescope under construction will soon be able to observe the neutrino sky with unprecedented sensitivities.

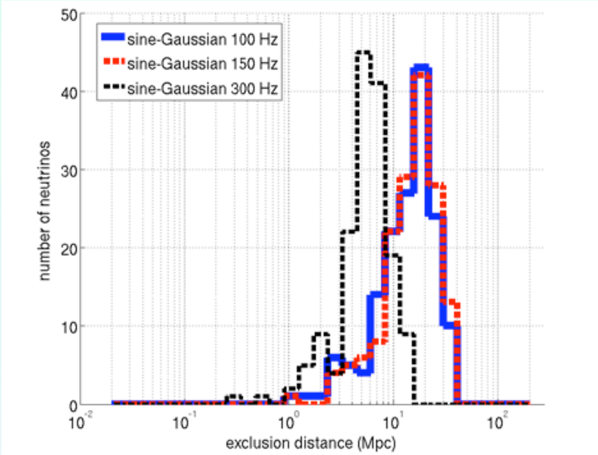
ANTARES sensitivity

For binary neutron star systems of (1.35-1.35) M_{Sun} and black hole-neutron star systems of (5-1.35) M_{Sun} typical distance limits are 5Mpc and 10Mpc respectively.

For the sine-Gaussian waveforms with $E_{GW} = 10^{-2}\ M_{sun}\ c^2$ we find typical distance limits between 5Mpc and 17Mpc in the low-frequency band and of order 1Mpc in the high-frequency band.

For other E_{GW} the limits scale as $D_{90\%} \propto (E_{GW}/\ 10^{-2}\ M_{Sun}\ c^2)^{1/2}$. For example, for $E_{GW} = 10^{-8}\ M_{Sun}\ c^2$ (typical of core-collapse supernovae) a signal would only be observable from a Galactic source.

ANTARES sensitivity



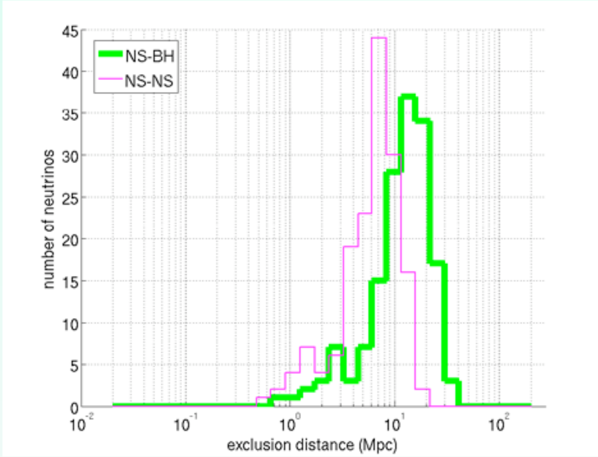


Figure 7. Low-frequency analysis: the top plot is the histogram for the sample of analysed neutrinos of the distance exclusions at the 90% confidence level for the 3 types of sine-Gaussian models considered: 100 Hz, 150 Hz and 300 Hz. A standard siren gravitational wave emission of $E_{GW} = 10^{-2} M_\odot c^2$ is assumed. The bottom plot shows the distance exclusions for the 2 families of binary inspiral models considered: NS-NS and BH-NS.

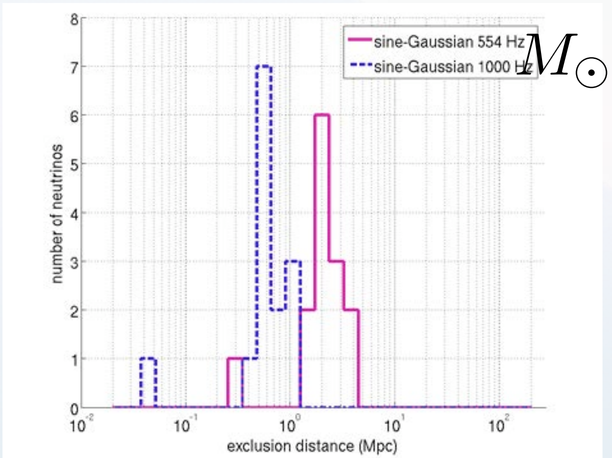


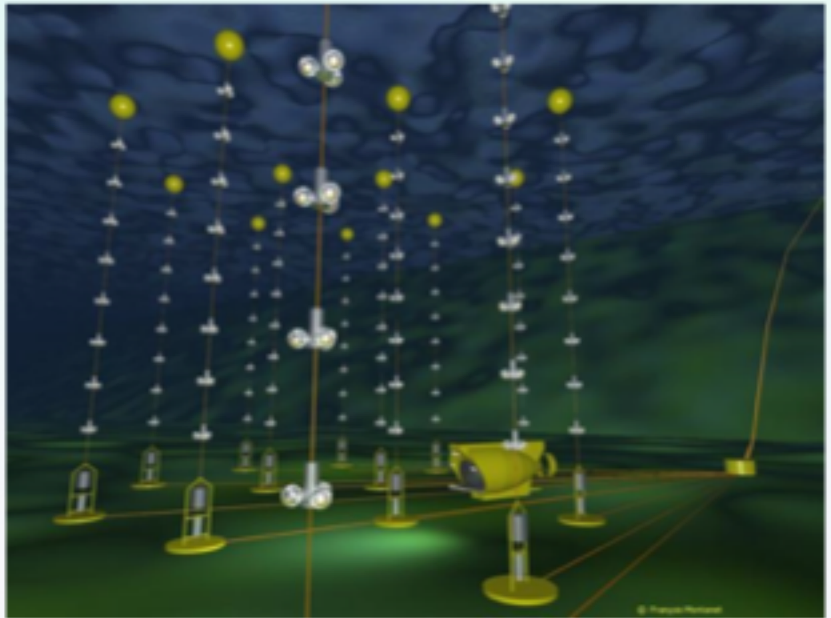
Figure 8. High-frequency analysis: the histogram for the sample of analysed neutrinos of the distance exclusions at the 90% confidence level for the 2 frequencies of circular sine-Gaussian models considered: 554 Hz and 1000 Hz.

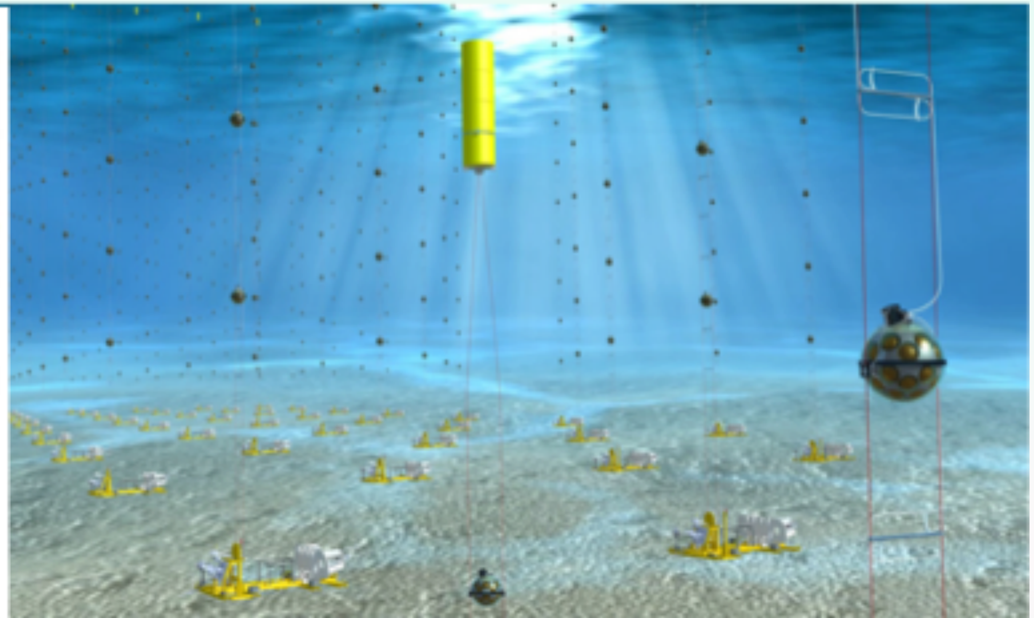
The future of Neutrino Astronomy in the Mediterranean Sea

ANTARES → KM3NeT

12 Lines, 885 OM

3 Building Blocks on 2 Sites
3*115 lines, ~6210 OMs, ~ 192510 PMTs

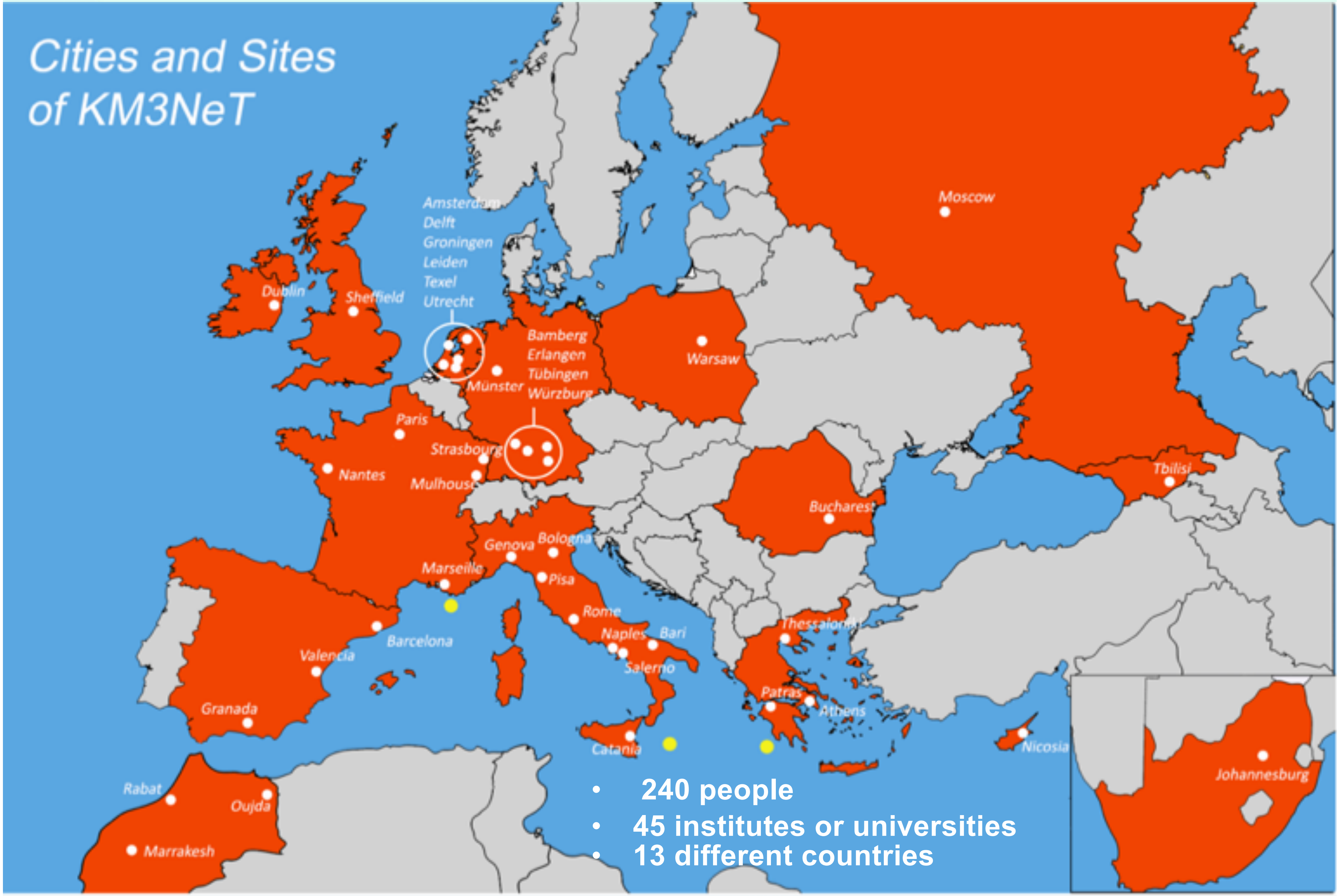




Basic active element:
Digital Optical Module
31 x 3” PMTs

18 OMs/line

KM3NeT - Collaboration



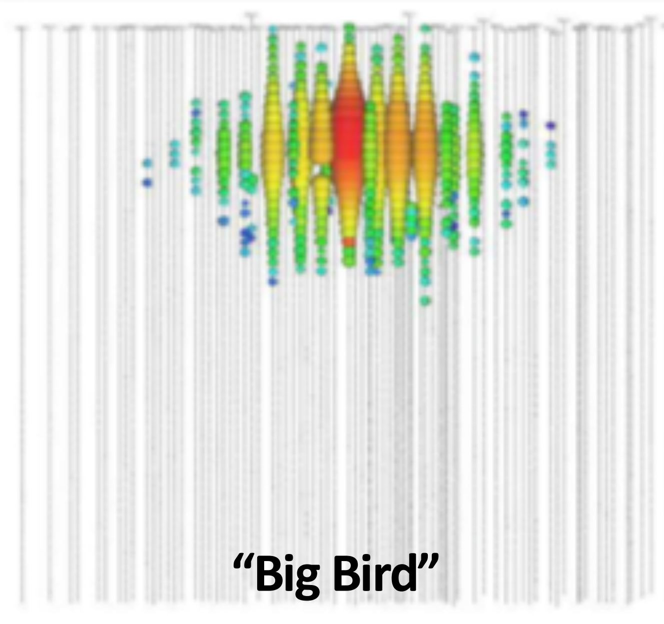
- 240 people
- 45 institutes or universities
- 13 different countries

IceCube 2013 - High Energy Starting Event Analysis

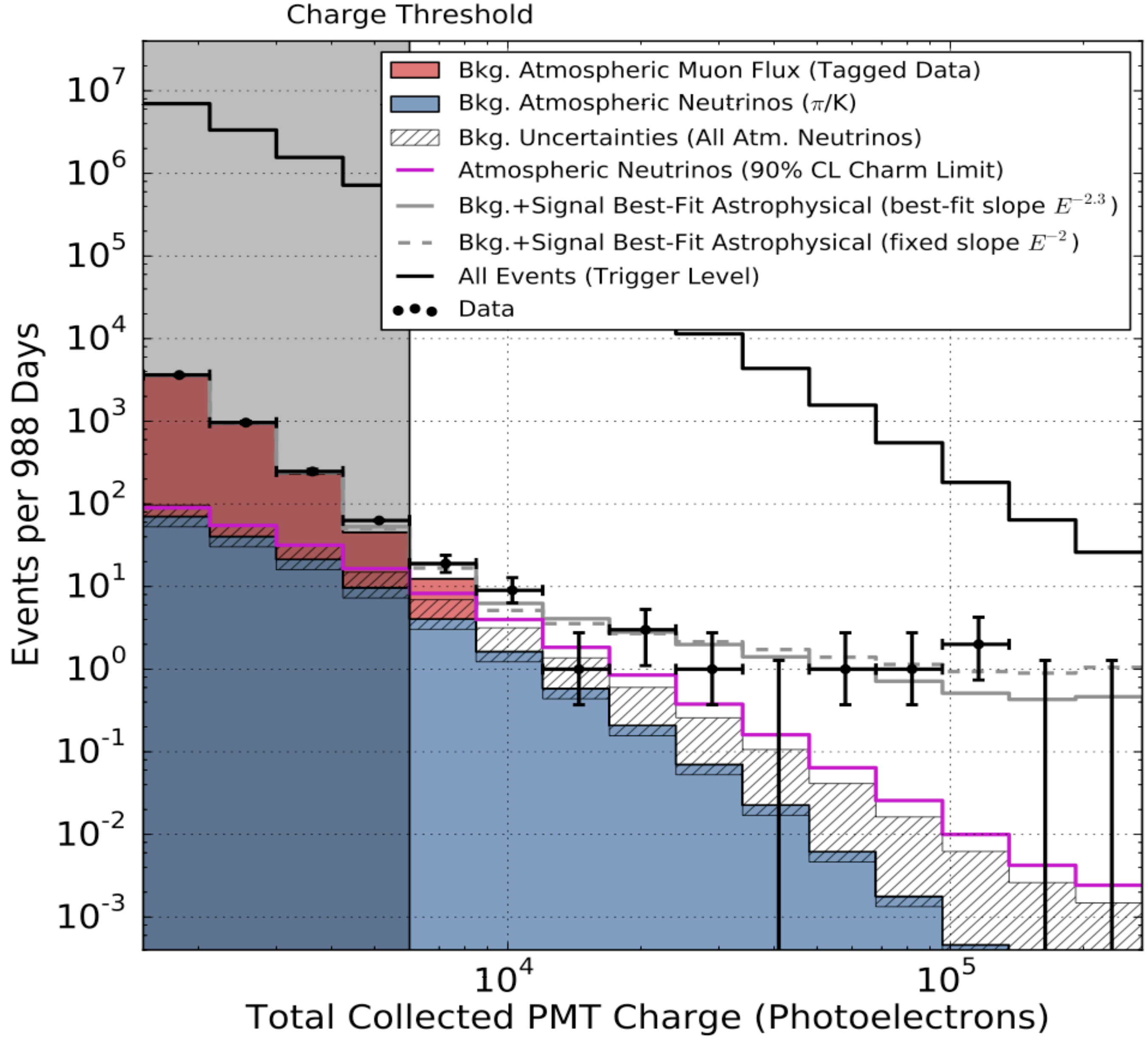
3-Year Analysis
PRL 113, 101101 (2014)

36 events in 3 years

Three > PeV events seen in three years, including a 2-PeV neutrino



"Big Bird"



IceCube 2017

High Energy Staring events (showers) and up-going muons analyses give consistent results