Observations of HE Neutrino and Multimessenger AstroParticle Physics

Antonio Capone
Univ. La Sapienza
INFN - Roma

Talk outline

- High Energy Astrophysical Neutrino Detection in a multi-messenger scenario
  - **Complementarity**
  - **Unicity**

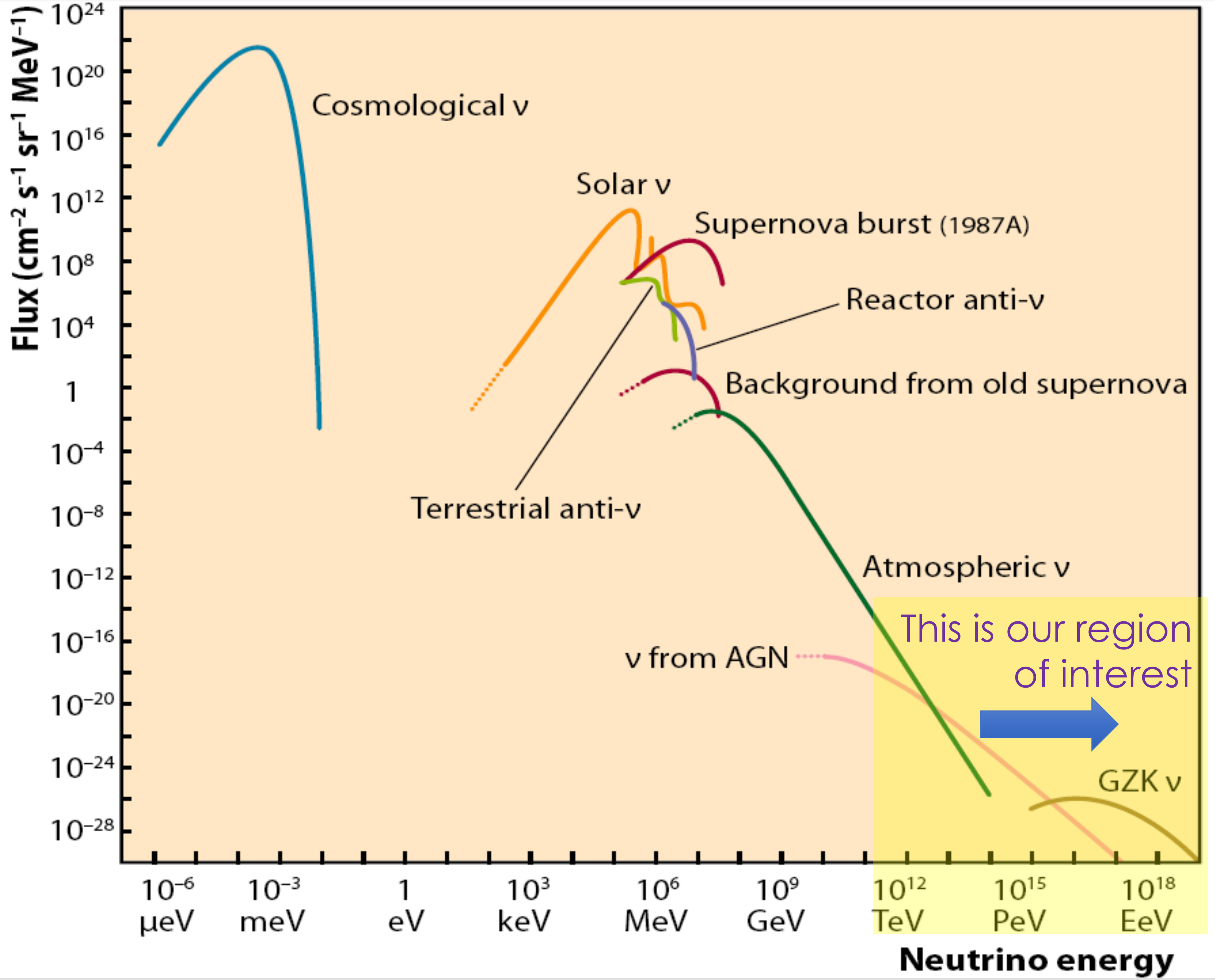
- H.E. astrophysical neutrino detectors: Baikal, IceCube, ANTARES/KM3NeT… and also Pierre Auger Observatory

- Neutrino Telescopes main physics goal: search for astrophysical neutrinos
  - **Search for a diffuse flux** ← **in a multi-messenger scenario**
  - **Search for point-like sources** ← **not discussed in this talk**
  - **indirect D.M. searches, ν oscillations and properties, searches for monopoles/nuclearites** ← **not discussed in this talk**

- Search for transient sources and multi-messenger studies
  - **Search for neutrinos from GRB sources, flaring sources, GW sources**

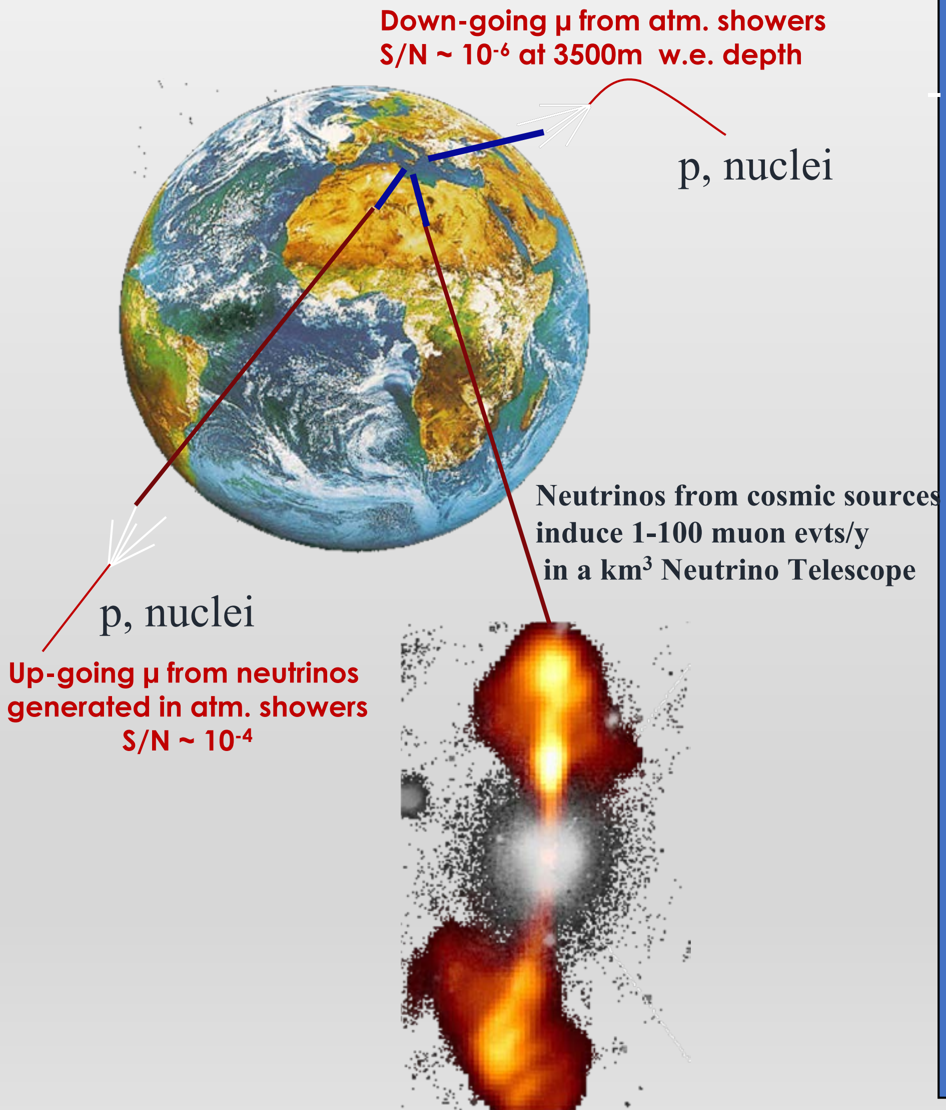
- Conclusions & Summary

Neutrino fluxes: what do we know/expect ?



Cherenkov ν Telescope: Detection principle

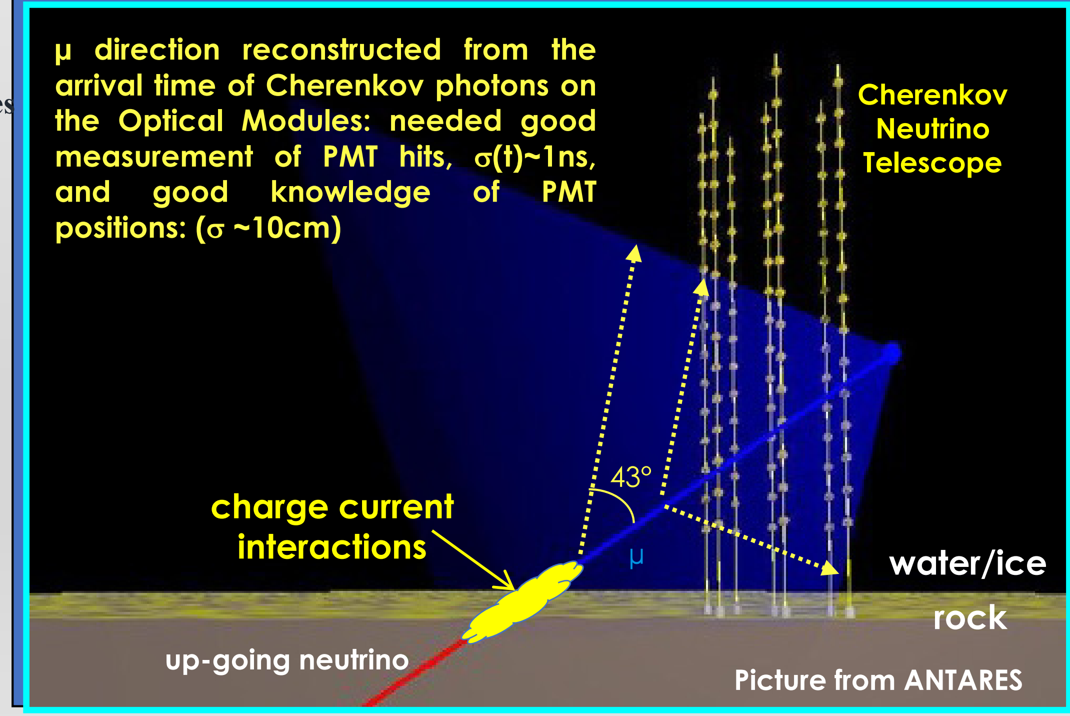
Search for neutrino induced events, mainly $\nu_\mu N \rightarrow \mu X$, deep underwater



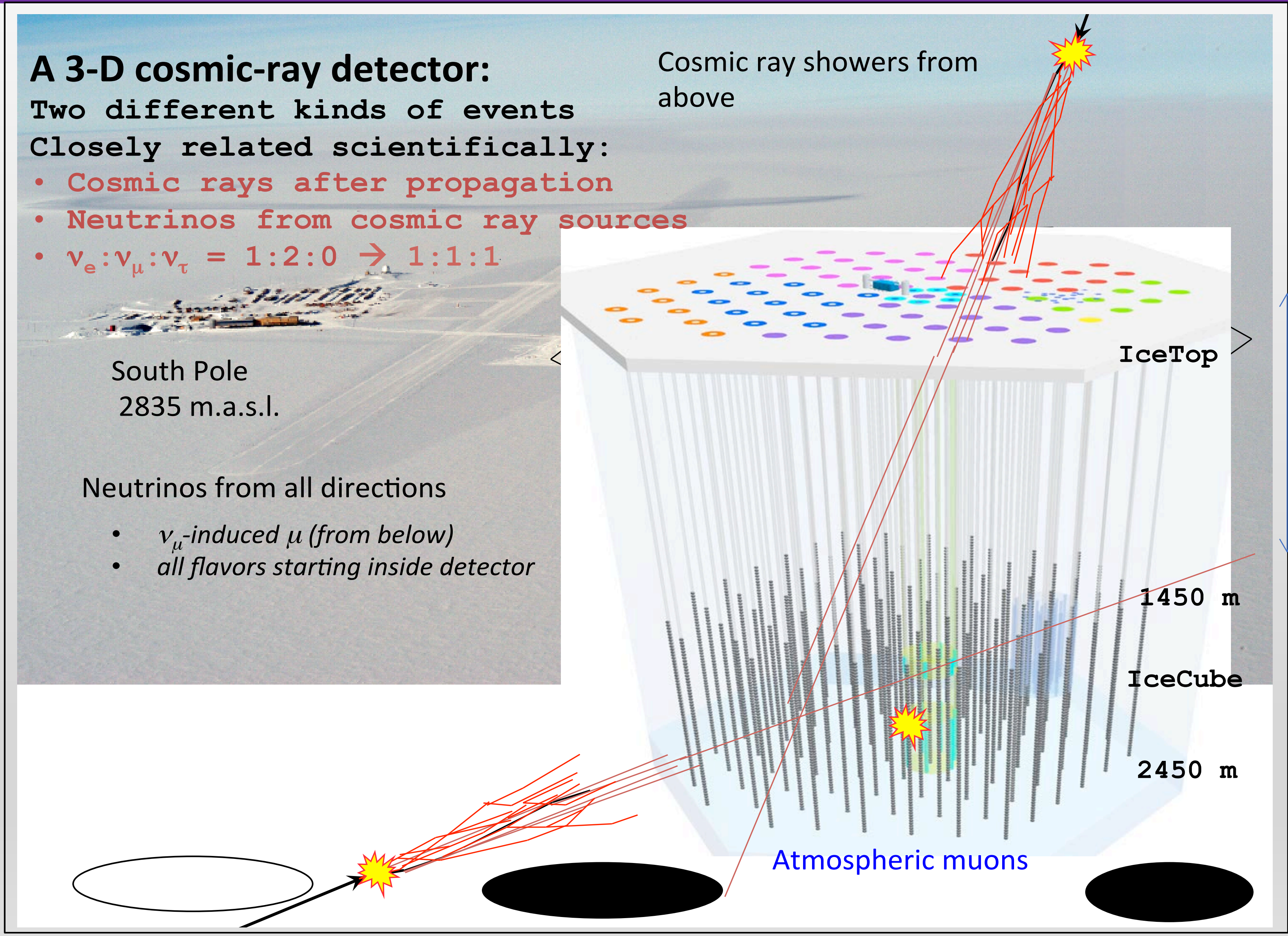
- Atmospheric neutrino flux ~ E_ν^{-3}
- Neutrino flux from cosmic sources ~ E_ν^{-2}
  - Search for neutrinos with E_ν>1÷10 TeV

- ~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

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



IceCube – The Neutrino Telescope at the South Pole

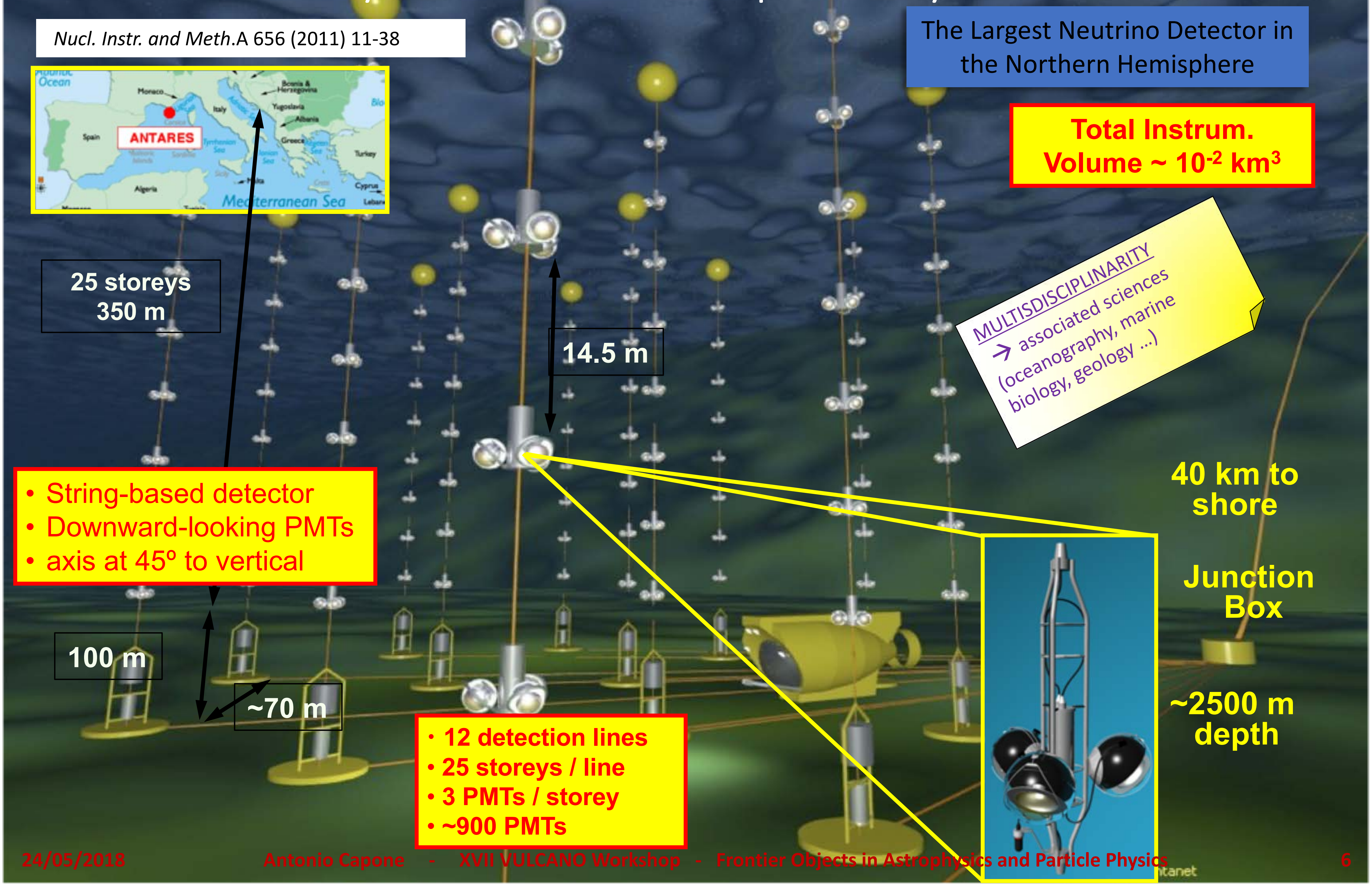


ANTARES: Astronomy with Neutrino Telescope and Abyss environm. RESearch

*Nucl. Instr. and Meth.*A 656 (2011) 11-38

The Largest Neutrino Detector in the Northern Hemisphere

Total Instrum. Volume ~ 10^{-2} km^3

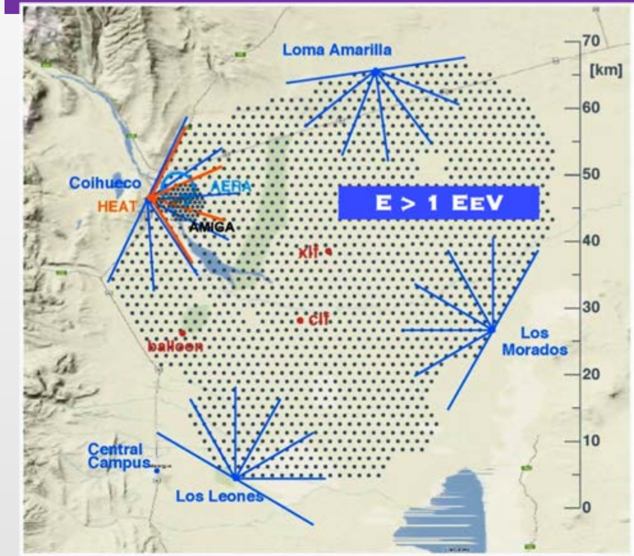


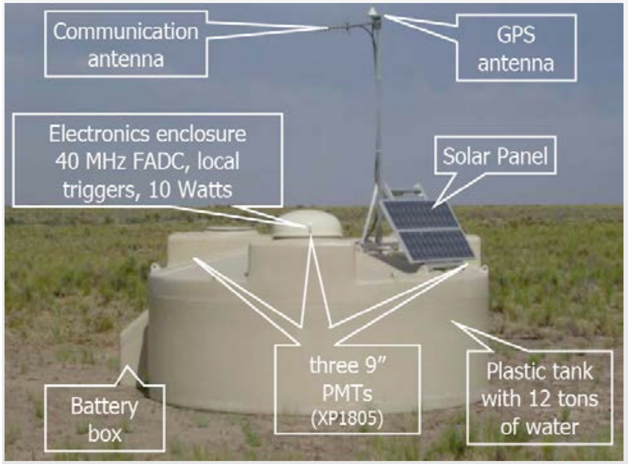
MULTISDISCIPLINARITY
→ associated sciences (oceanography, marine biology, geology …)

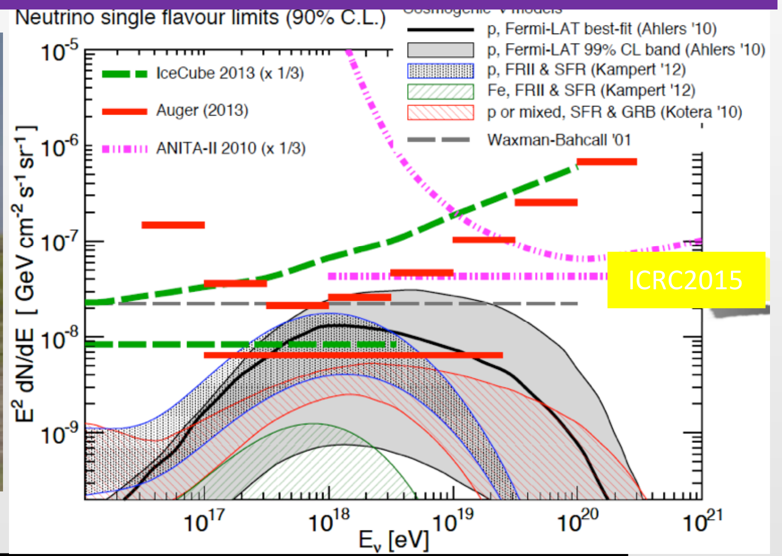
- String-based detector
- Downward-looking PMTs
- axis at 45º to vertical

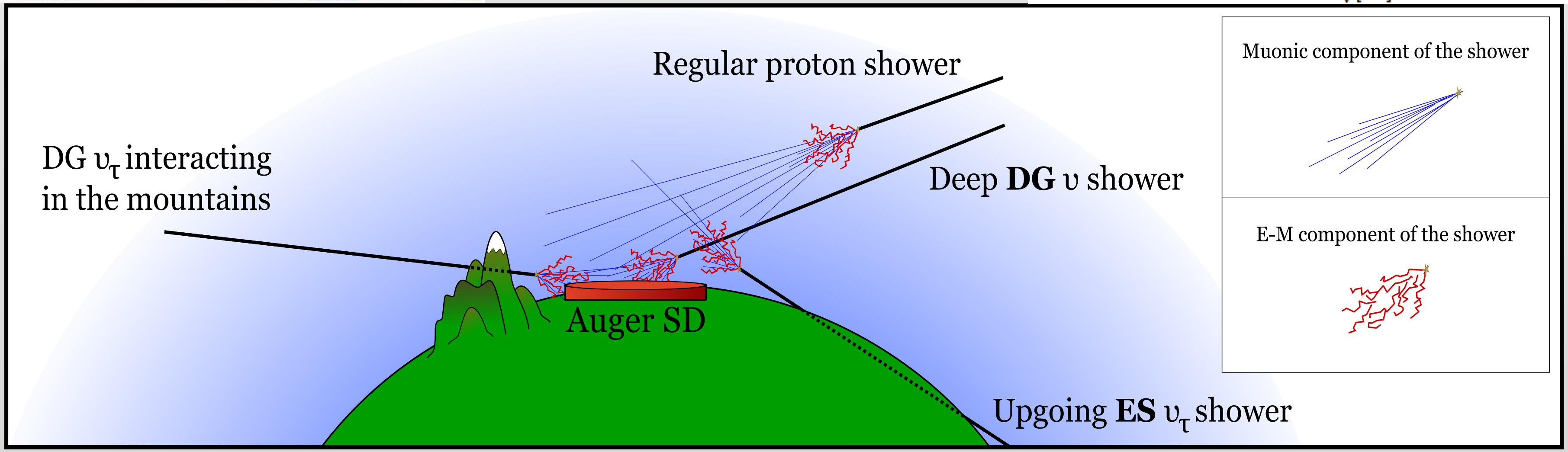
- **12 detection lines**
- **25 storeys / line**
- **3 PMTs / storey**
- **~900 PMTs**

The Pierre Auger Observatory can identify UHE neutrinos





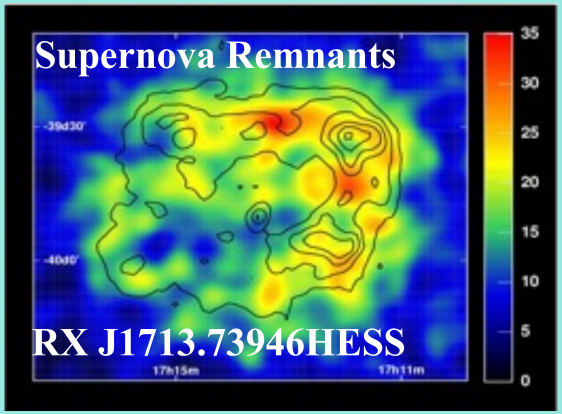


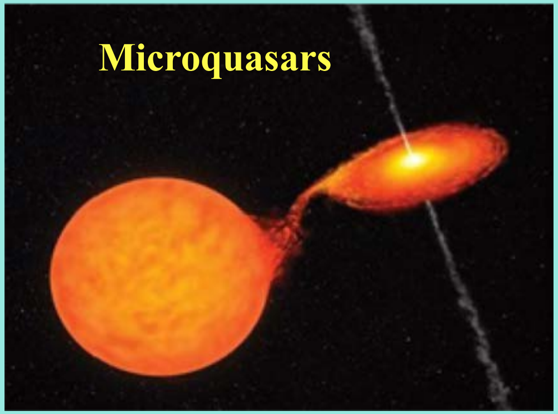


The SD is spread over a surface of ~3000 km² at an altitude of ~1400 m above sea level.
This corresponds to an average vertical atmospheric depth above ground of X_{ground} = 880 g cm⁻².
The slant depth D is the total grammage traversed by a shower measured from ground in the direction of the incoming 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.

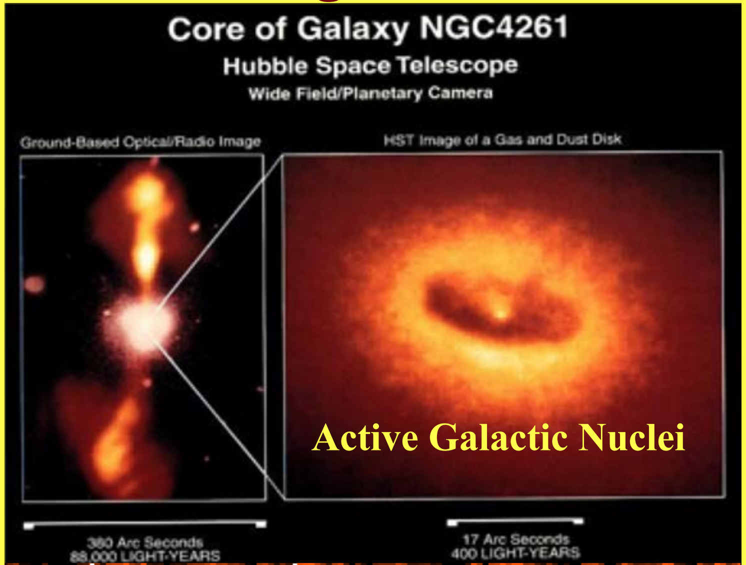
Neutrino Telescope physic's goals: search for point-like cosmic Neutrino Sources

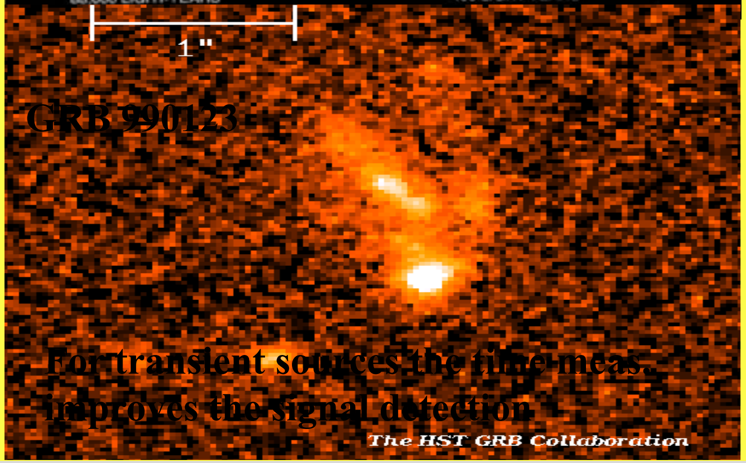
Galactic





Extragalactic





- Their identification requires a detector with accurate angular reconstruction

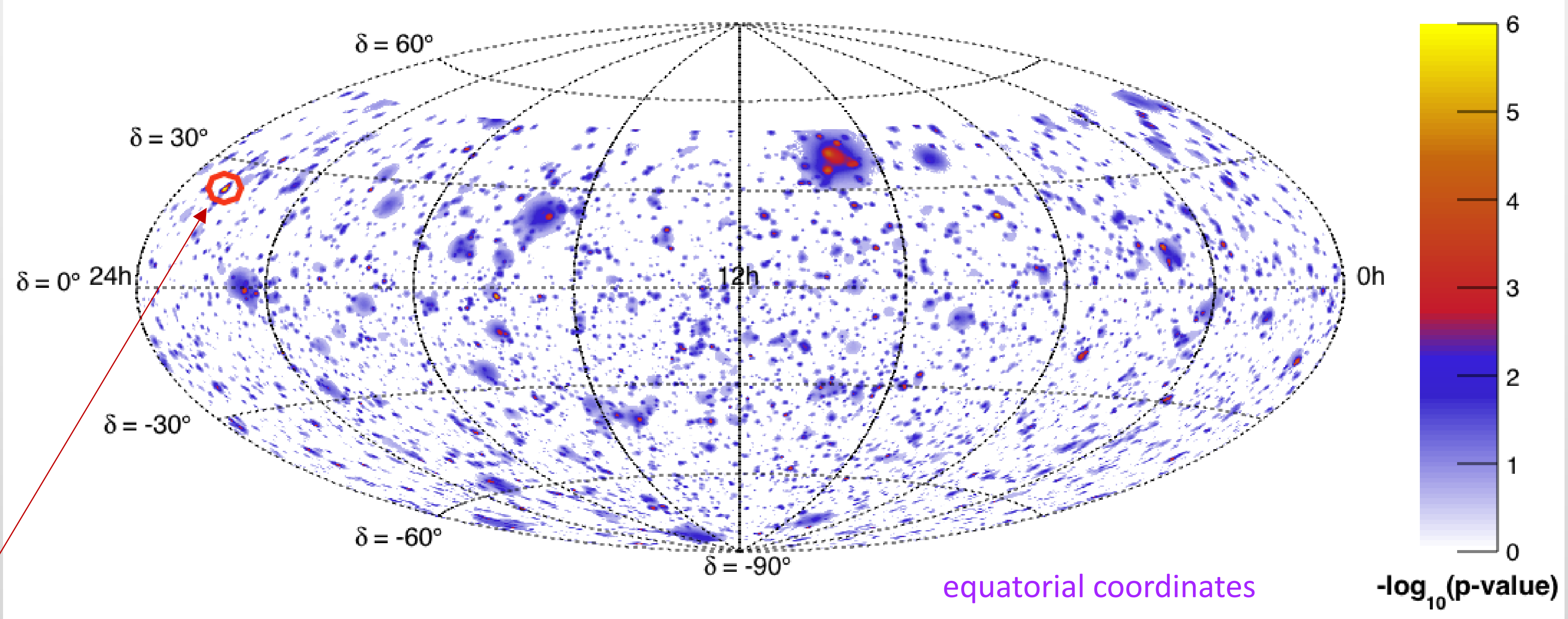
$$\sigma(\vartheta) \le 0.5^{\circ} \text{ for } E_{\nu} \ge 1 TeV$$

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

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

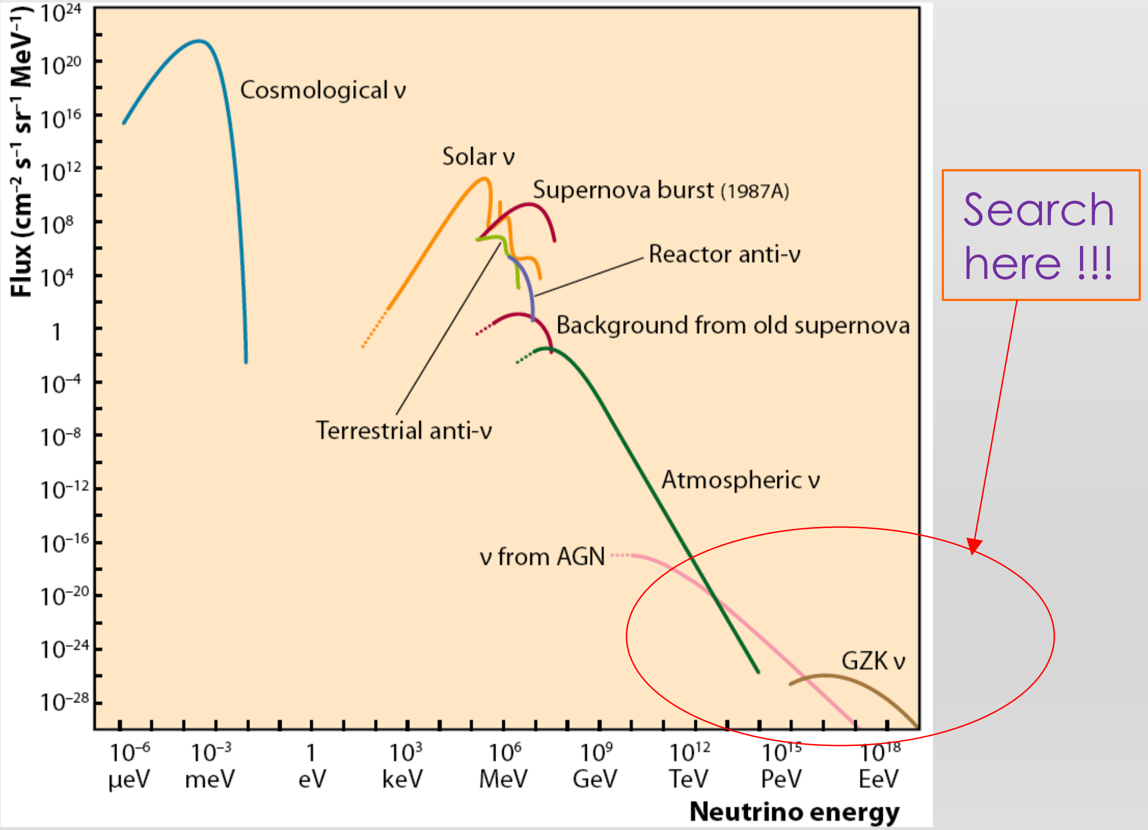


The most significant cluster: decl. δ = 23.5^0, r.a. α = 343.8^0 has a pre-trial p-value of 3.84×10^{-6}

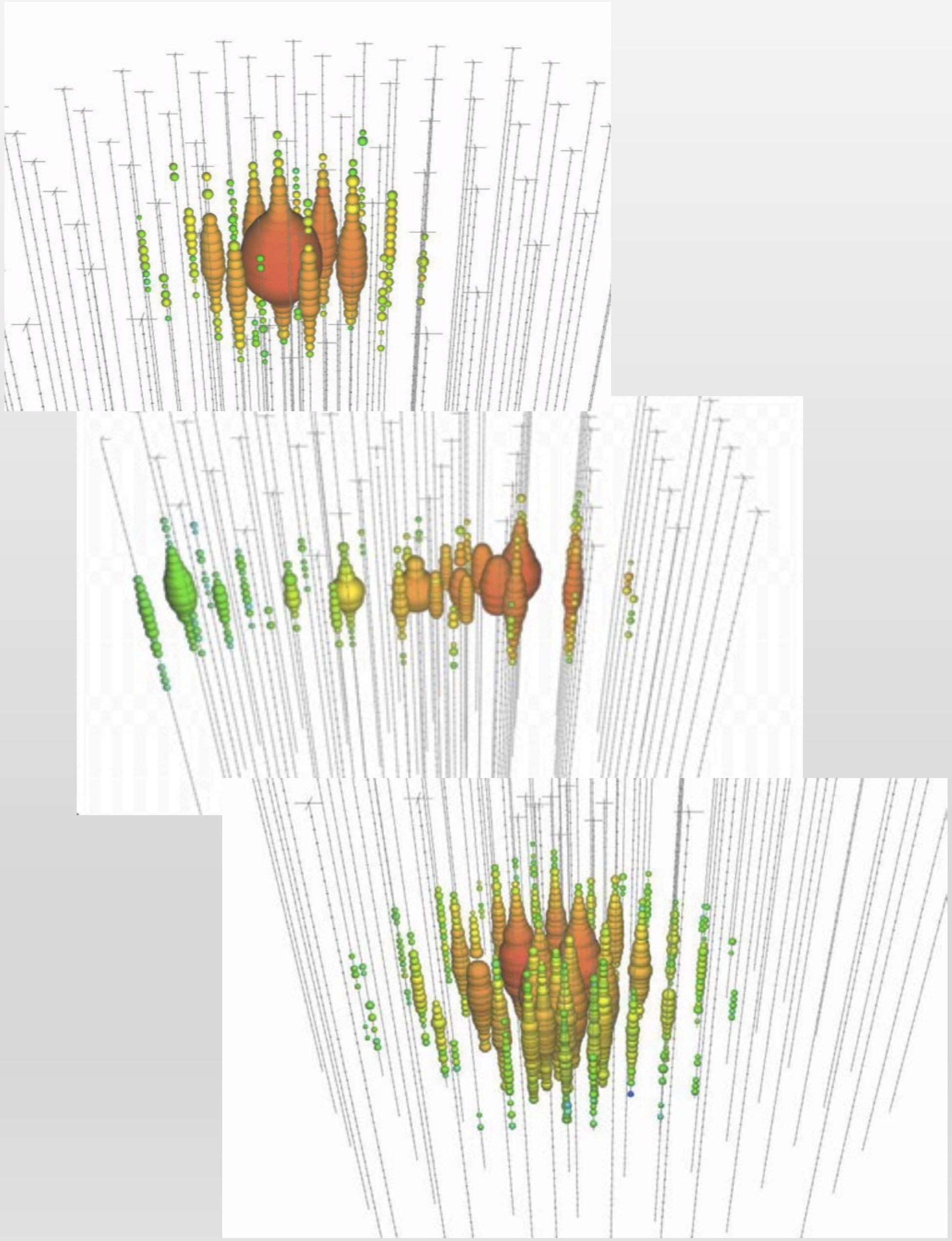
→ U. L. from this sky location $E^2 \frac{d\Phi}{dE} = 3.8\times10^{-8}$ GeV cm^{-2} s^{-1}

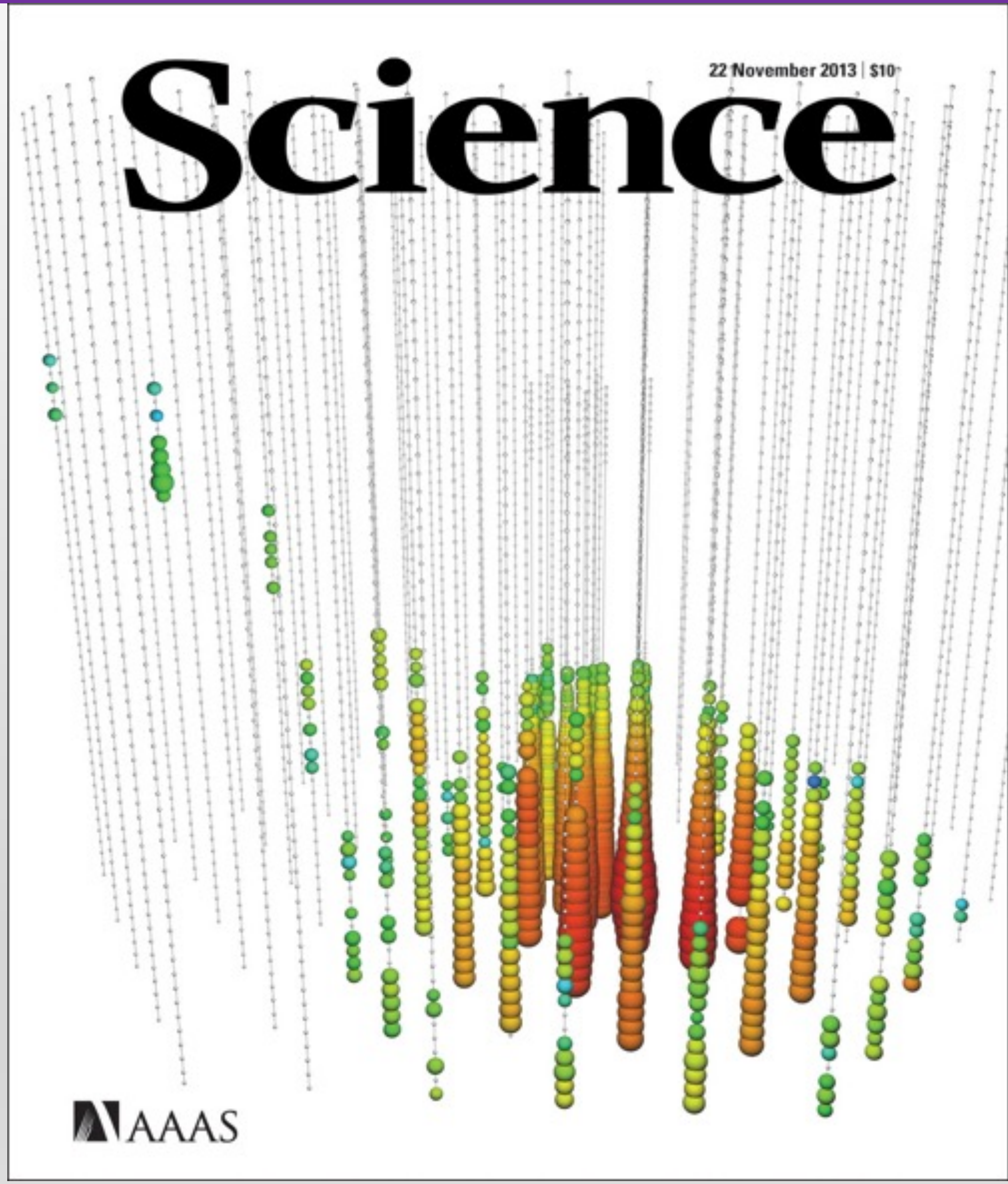
Neutrino Telescope physic's goals: search for Diffuse flux of Cosmic Neutrinos

- 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.



The great discovery (from IceCube 2013)

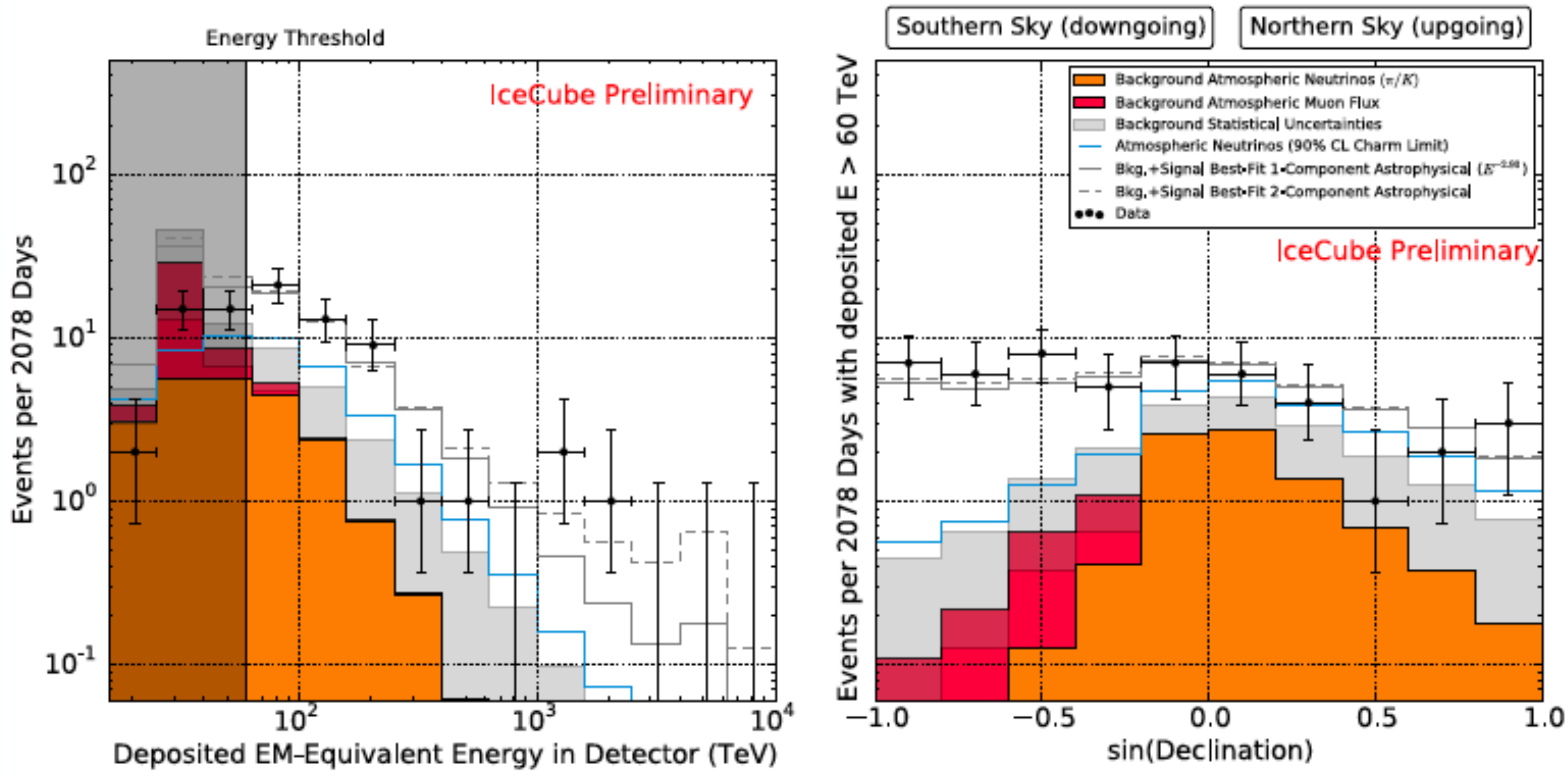




2-year analysis: Science **342**, 1242856 (2013)

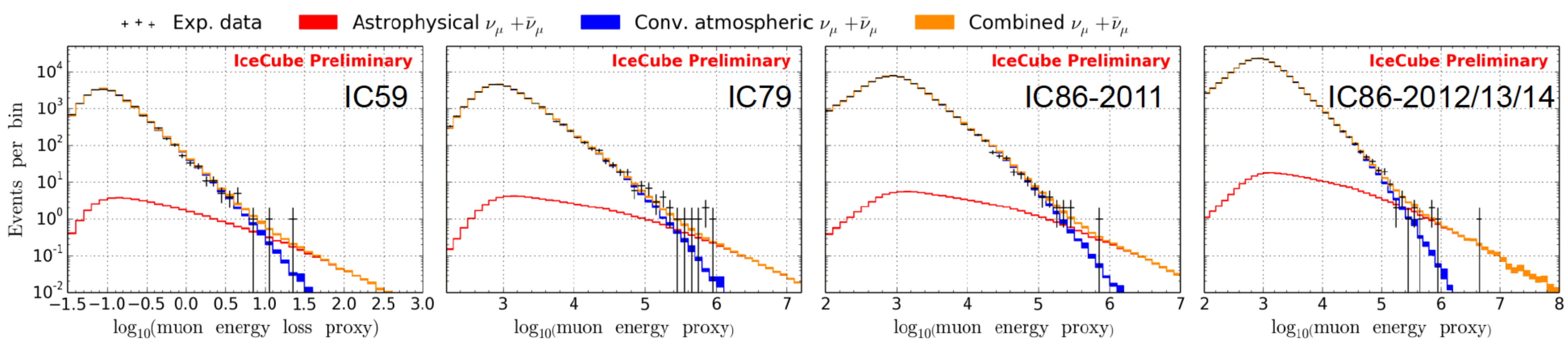
IceCube 2017 - High Energy Starting Event Analysis

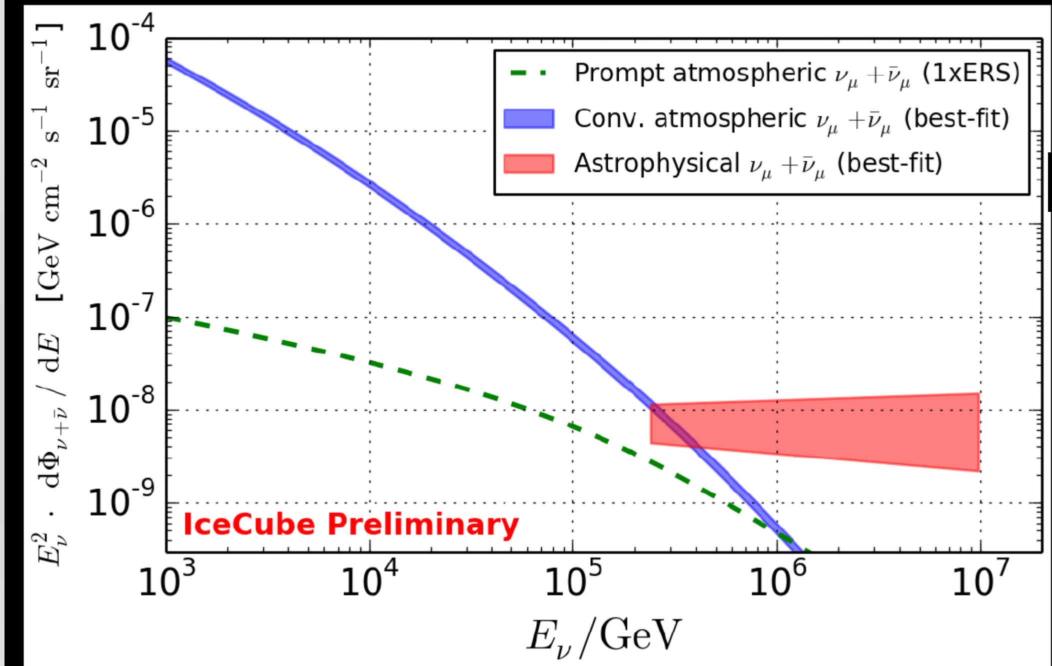
starting events: now 6 years → 8σ



IceCube today: diffuse ν_μ flux with up-going muons

after 7 years → 6.4 sigma





- Best-fit astrophysical normalization:

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

- Best-fit spectral index:

  γ_{astro} = 2.16 ± 0.11

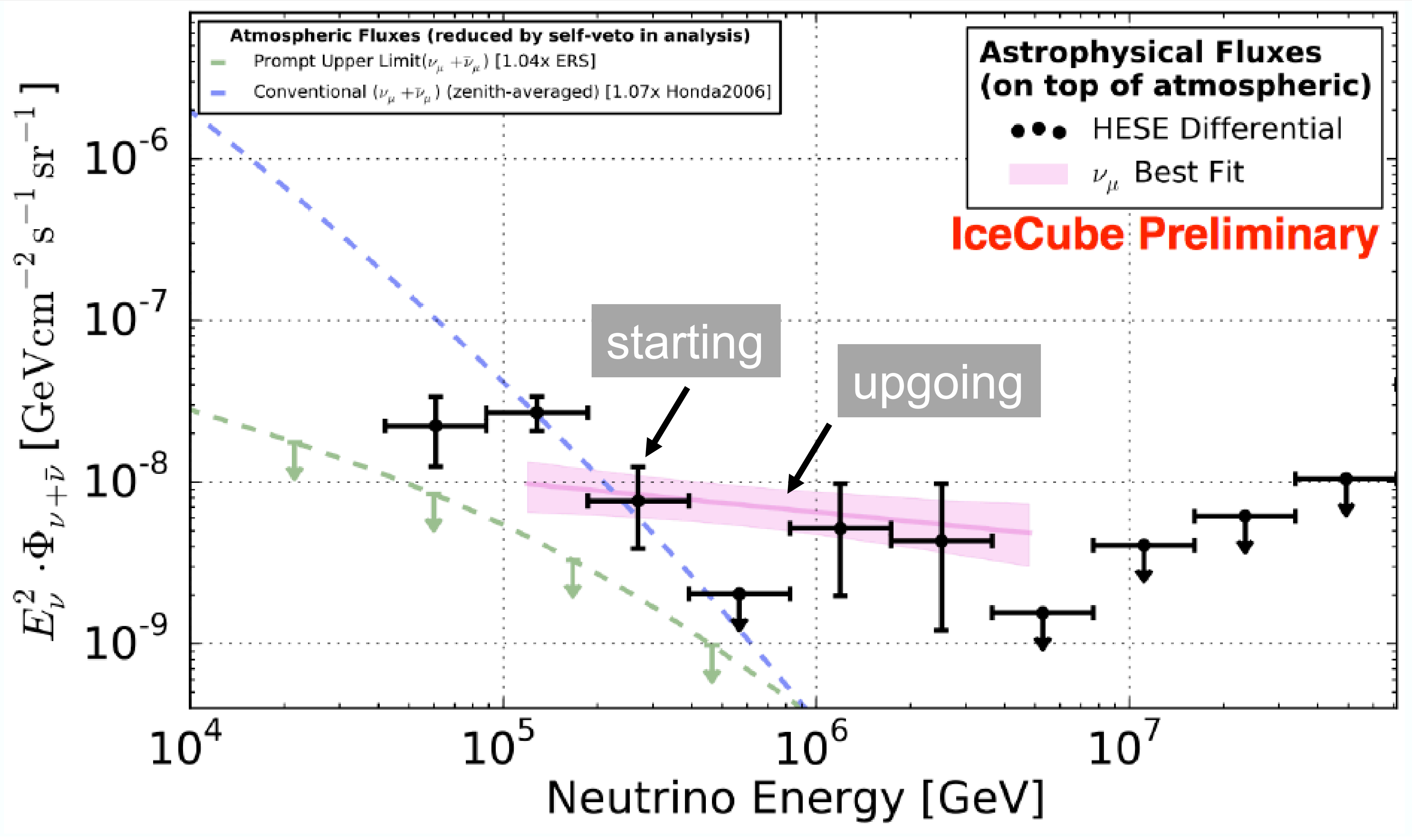
- Energy ranges:

  240 TeV – 10 PeV

- Atmospheric-only hypothesis excluded by 6.0σ

IceCube 2017

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



Latest ANTARES results on the search for diffuse ν flux

Tracks

Data: 2007-2015 **(2451 live-days)**

Above E_{cut}: Bkg: 13.5 ± 3 evts, IC-like signal: 3 evts

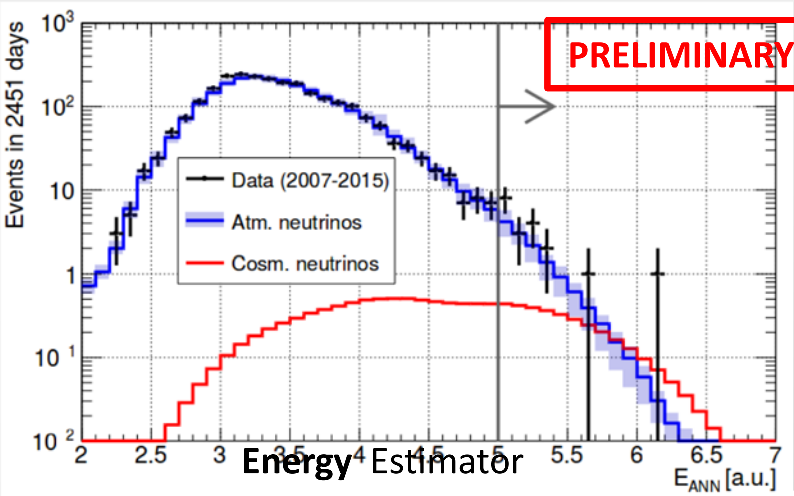
Observed: **19 evts**

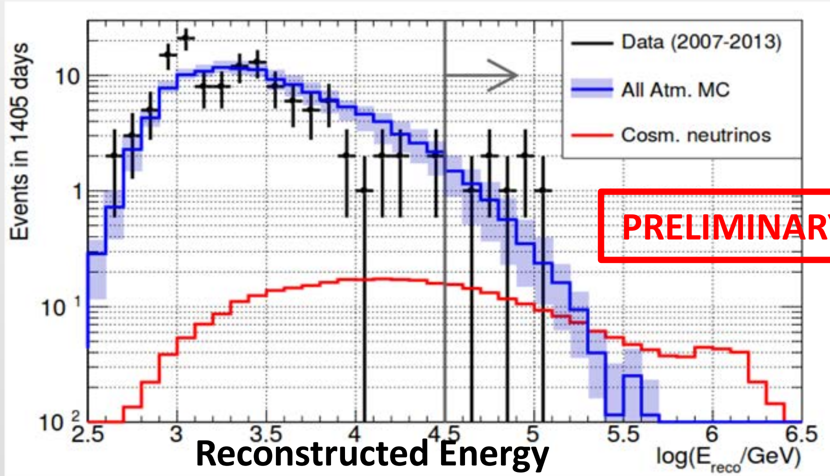
Cascades

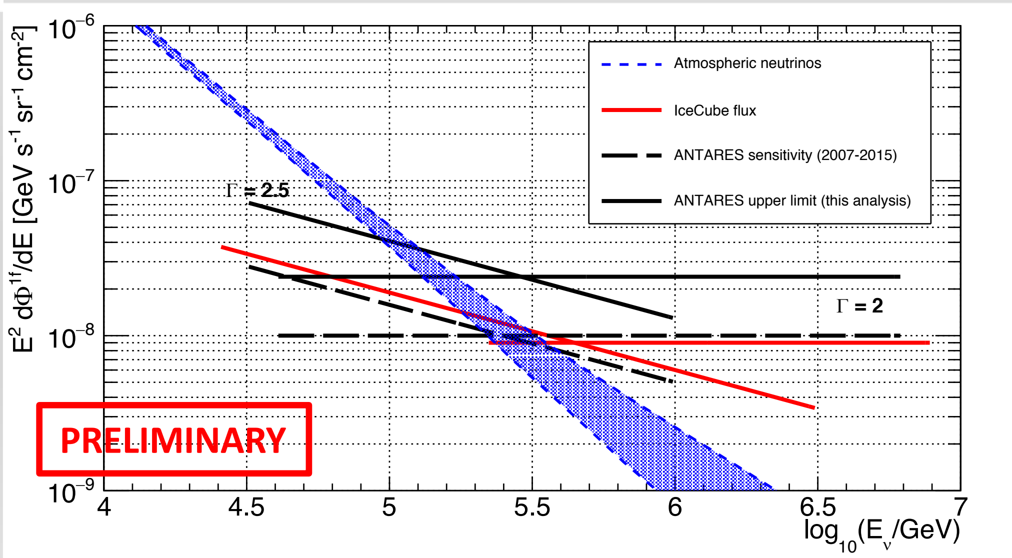
Data: 2007-2013 **(1405 live-days)**

Above E_{cut}: Bkg: 5 ± 2 evts, IC-like signal: 1.5 evts

Observed: **7 evts**



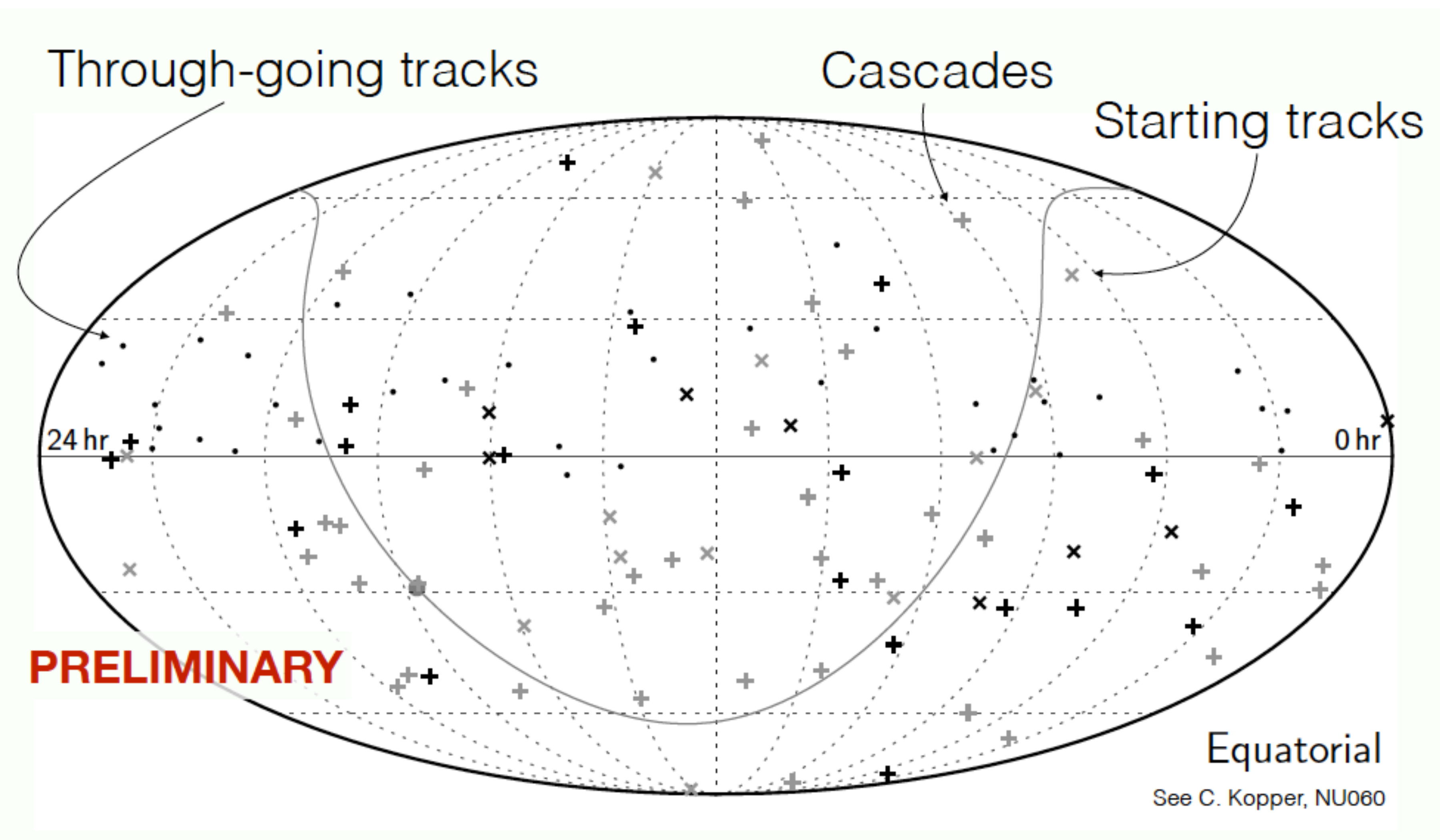




ANTARES

combined upper limits and sensitivities for 9 years data sample (2007-2015) tracks + cascades

Where these neutrinos are coming from ??



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

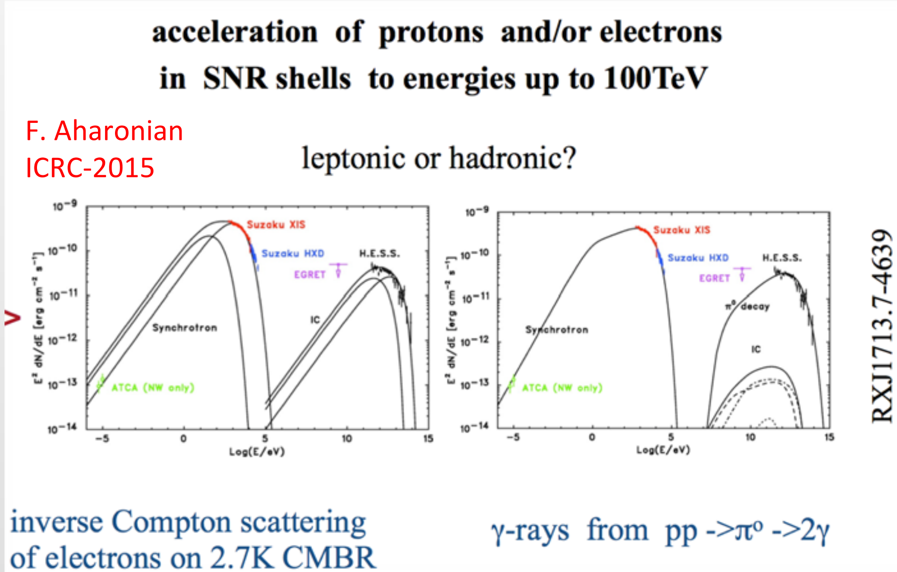
Neutrino Telescope physic's goal

- search for ν from point like–sources:

- **hadronic**

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

- **or leptonic ? (no ν expected)**



- search for "diffuse neutrino fluxes". is their origin related to:

- **H.E. C.R. propagation ? What is the effect of the Galactic Ridge on their production?**
- **diffuse galactic γ background ?**

- search for a connection

- **H.E. ν (IceCube, ANTARES) - diffuse γ fluxes (FERMI)**
- **H.E. ν (IceCube, ANTARES) - U.H.E. C.R. (AUGER and T.A.)**

Search for neutrinos from the Galactic ridge - 1

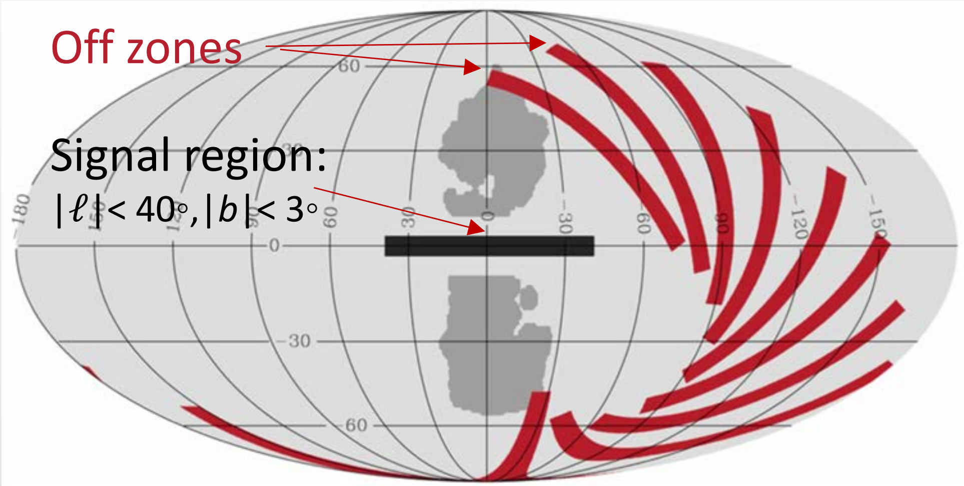
- **ν's and γ-rays produced by CR propagation**

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

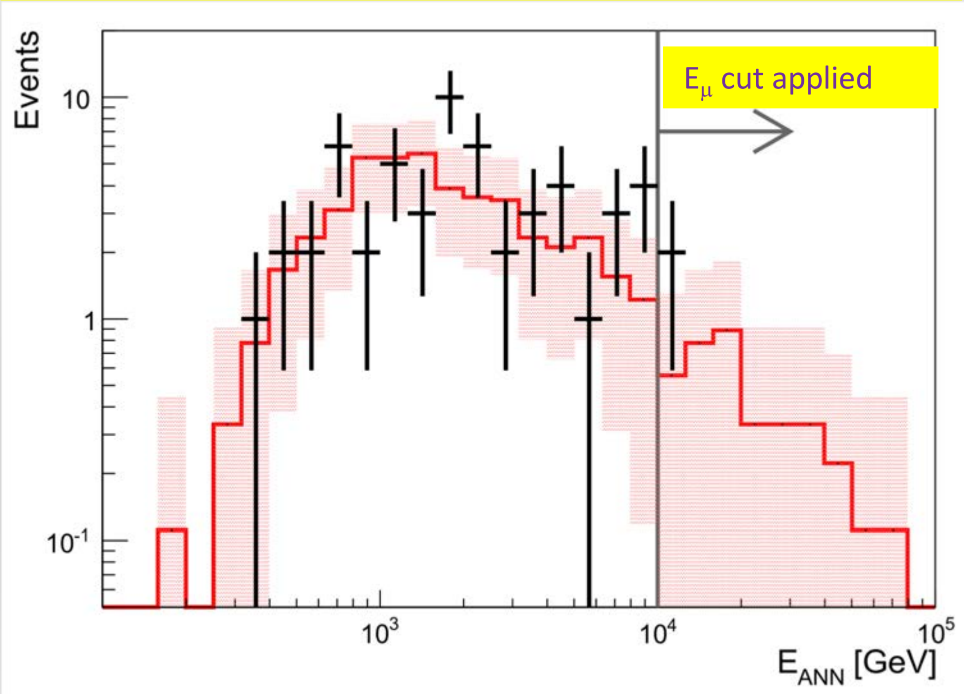
ANTARES has good visibility of the Galactic Center, can put limits on the flux of ν from the Galactic Ridge

- ANTARES search for ν_μ, data 2007-2013
- Search region $|\ell|<30^\circ$, $|b|<4^\circ$
- 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

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).



Physics Letters B 760 (2016) 143–148



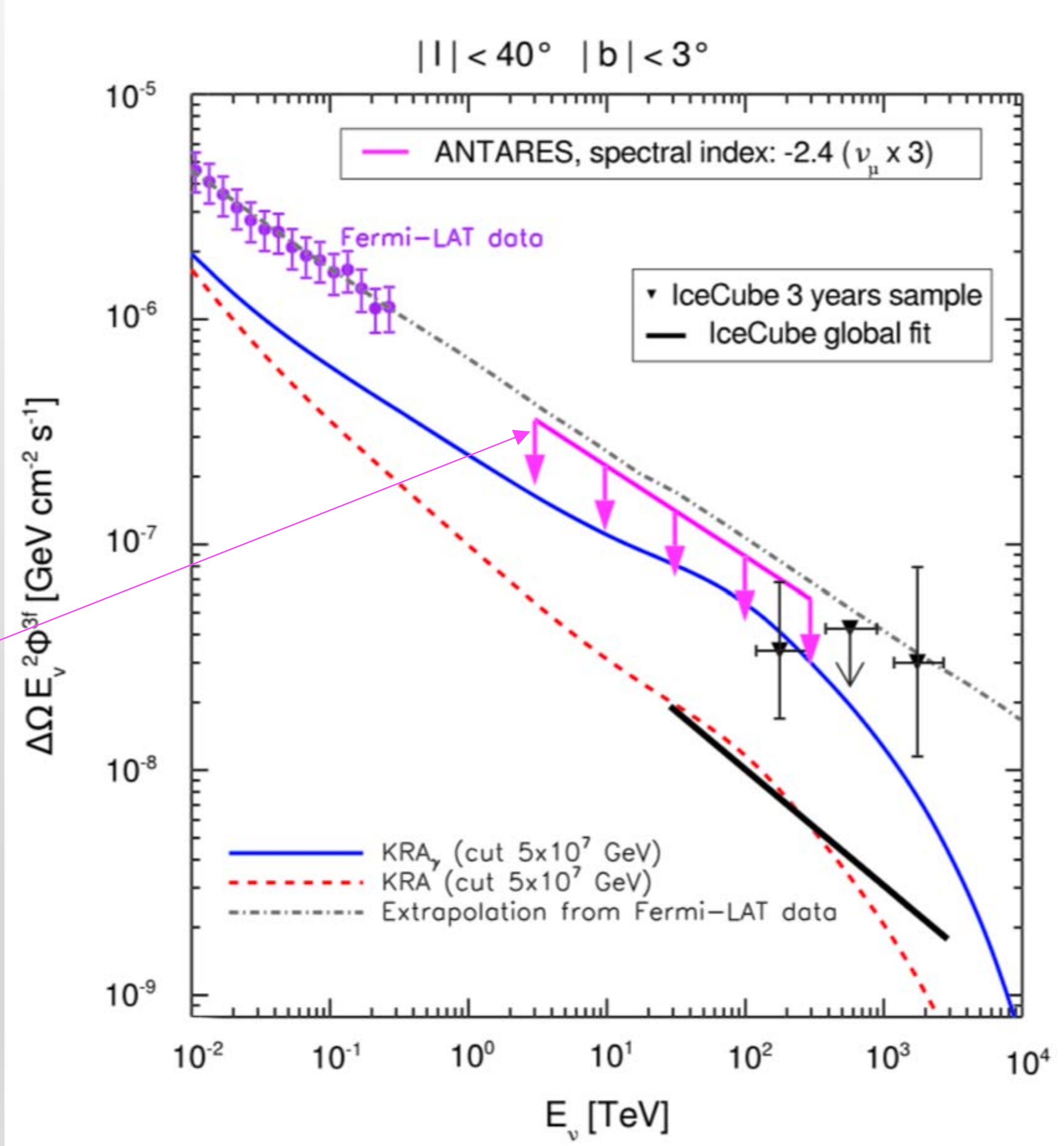
Search for neutrinos from the Galactic ridge - 2

Assuming a direct connection between the emission of γ-rays and ν from pion decay in hadronic mechanisms, the diffuse γ- flux measured by *Fermi*-LAT is used to estimate the flux of Galactic neutrinos.

Expected backg. from off-zone= 3.7 events
Observed ν in the on-zone: = 2 events

ANTARES upper limit on the neutrino flux integrated over the solid angle ΔΩ = 0.145 sr corresponding to the Galactic Plane region |ℓ| < 40◦ , |*b*|<3◦.

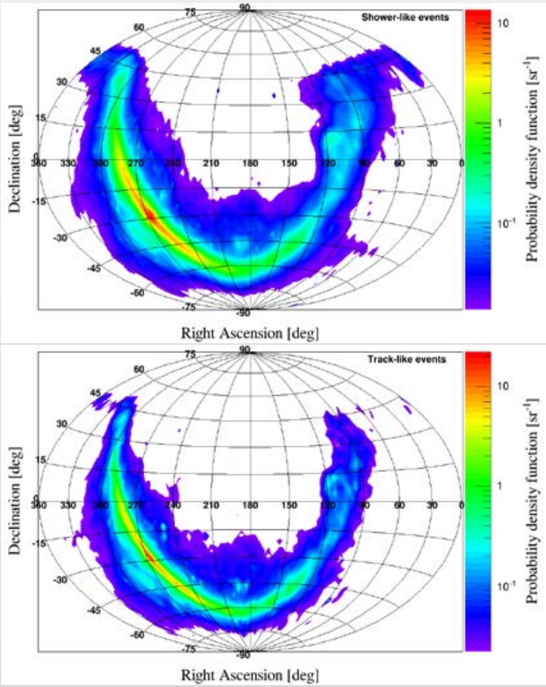
This results excludes that in the IC 3 years HESE sample (37 events) more than 3 events are originates from the Cosmic Ray interactions in the Galactic Ridge



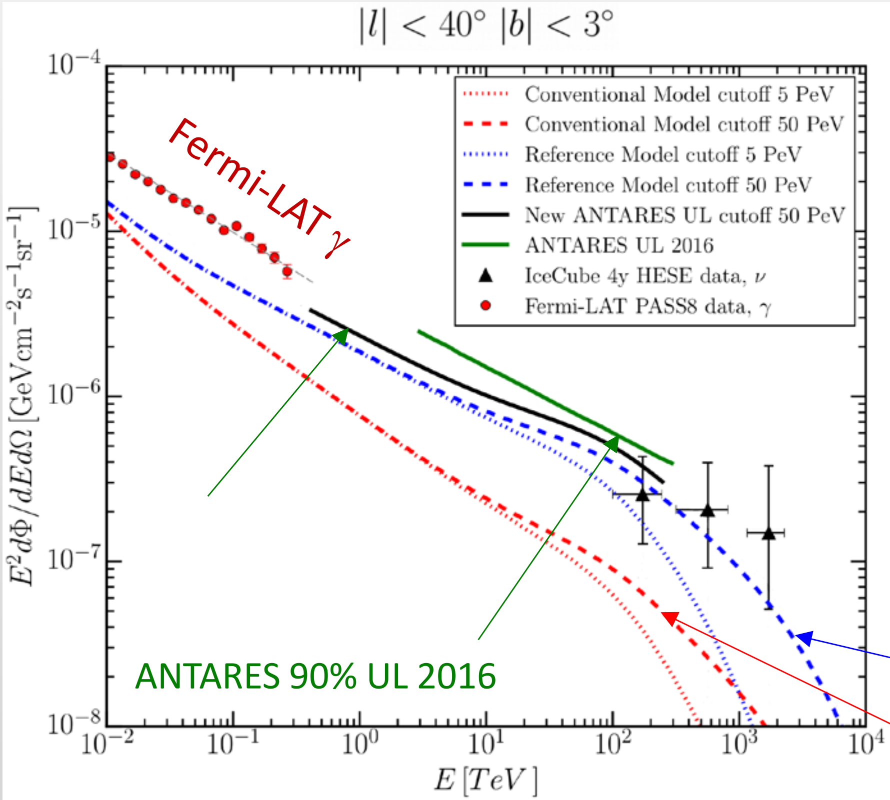
Search for neutrinos from the Galactic plane - 3

ANTARES 9 years data analysis on tracks and showers, based on Max. Lik. signal-backg. separation

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



ANTARES arXiv:1705.00497v1
1 May 2017



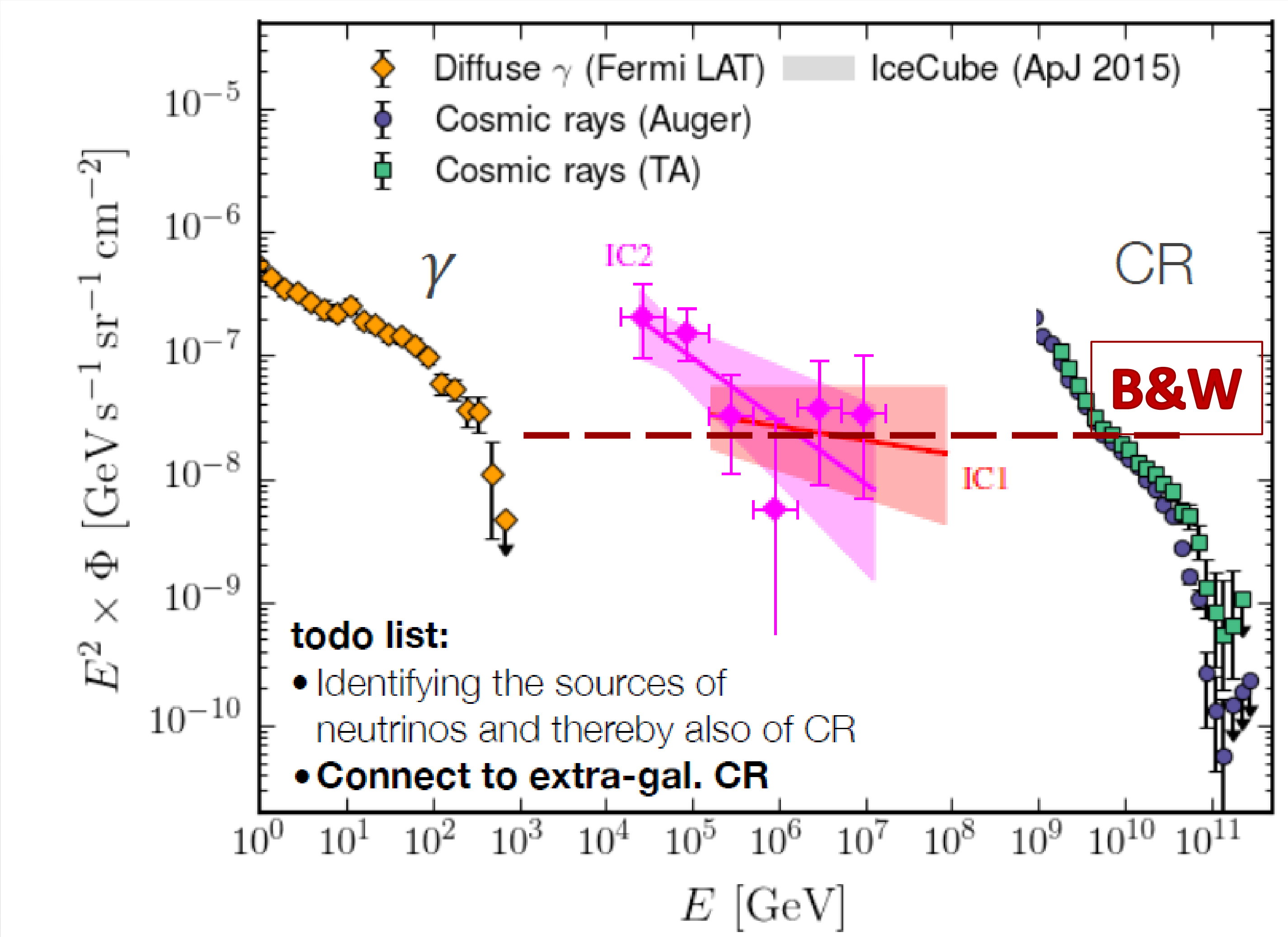
KRA_γ new model to describe the C.R. transport in our galaxy.
It agrees with C.R. measurements (KASCADE, Pamela, AMS, Fermi-LAT, HESS).
FERMI-LAT diffuse γ flux from along the galactic plane ($\pi^0 \rightarrow \gamma\gamma$) well explained above few GeV.

KRA_γ allows to predict the ν flux by $\pi^\pm$ decays induced by galactic CR interactions

KRA_γ 50PeV cut-off for CR
KRA_γ 5PeV cut-off for CR

KRA_γ assuming a neutrino flux ∝ $E^{-2.5}$ and a CR spectrum with 50 PeV cut-off, allows that no more than ~19% of the IceCube observed HESE can be originated in the Galactic Plane. 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.

Diffuse galactic fluxes: γ,ν (at least part galactic), CR



Neutrino Telescope physic's goal: search for point-like sources in a multi-messenger framework

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

- **searches for cluster of events in known positions of the sky**
- **if transient sources: background integrated only over a short time period, improving the S/B ratio and the detector sensibility**

Relaxed energy/direction selection: improved efficiency

a multi-messenger program

A long list of activities:

Real-time (follow-up of the selected neutrino events):

Follow-up of neutrino candidates

- optical telescopes [TAROT, ROTSE, ZADKO, MASTER]
- X-ray telescope [Swift/XRT]
- GeV-TeV γ-ray telescopes [HESS, HAWC]
- radio telescope [MWA]
- Online search of fast transient sources [GCN, Parkes]

Multi-messenger correlation with:

correlations with other observations

- Gravitational wave [Virgo/Ligo]
- UHE events [Auger]

Time-dependent searches:

searching for ν from transient sources

- GRB [Swift, Fermi, IPN]
- Micro-quasar and X-ray binaries [Fermi/LAT, Swift, RXTE]
- Gamma-ray binaries [Fermi/LAT, IACT]
- Blazars [Fermi/LAT, IACT, TANAMI…]
- Crab [Fermi/LAT]
- Supernovae Ib,c [Optical telescopes]
- Fast radio burst [radio telescopes]

Search for ν from flaring AGN – 2008-2012

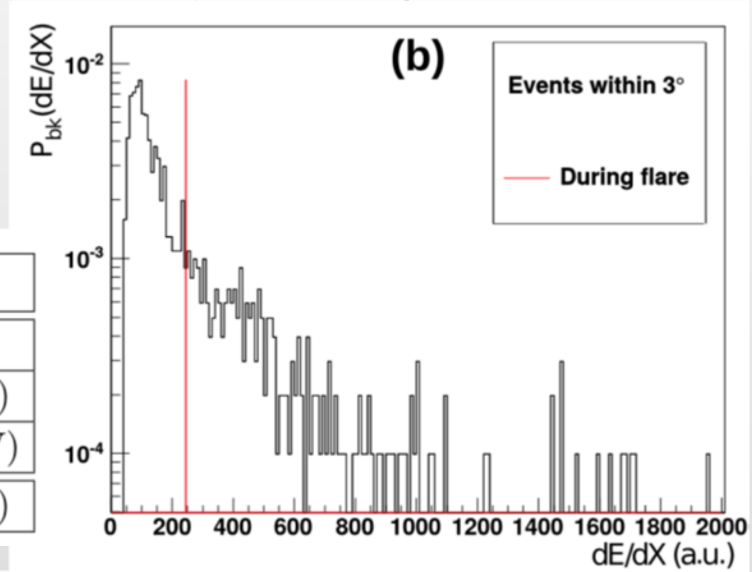
[40 sources, 86 flaring periods] **ANTARES ⟺ FERMI/LAT**

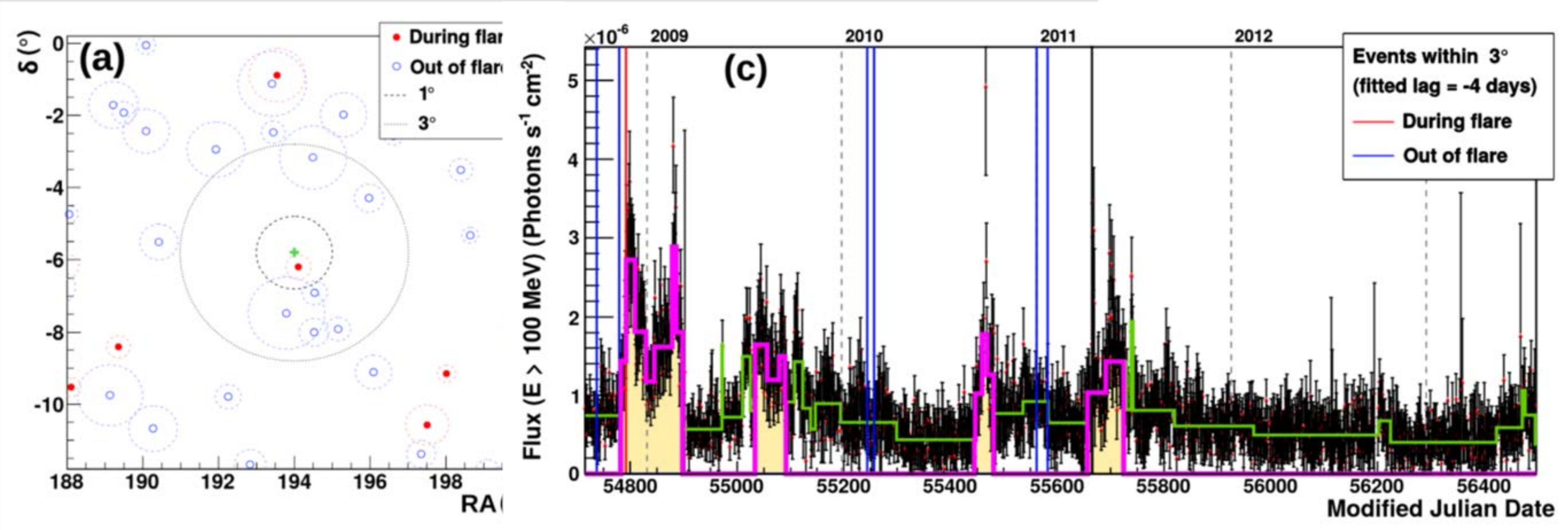
…to be extended to IACT blazars (HESS, MAGIC, VERITAS)

4 specially significant flares

JCAP12(2015)014

Source	ΔT	Λ_{opt}	$N_{3\sigma}$	N_{fit}	Lag	P-value	Post-trial	Spectrum
3C279	279 d	-5.3	2.5	0.8	-4 d	0.033	0.67	E^{-2}
PKS1124-186	73 d	-5.4	3.1	0.7	+4 d	0.059	0.94	$E^{-2}\exp(-E/1TeV)$
PKS0235-618	25 d	-5.7	1.5	0.6	-4 d	0.045	0.91	$E^{-2}\exp(-E/10TeV)$
PKS0447-439	10 d	-5.4	0.75	0.1	+5 d	0.10	0.55	$E^{-2}\exp(-E/1TeV)$

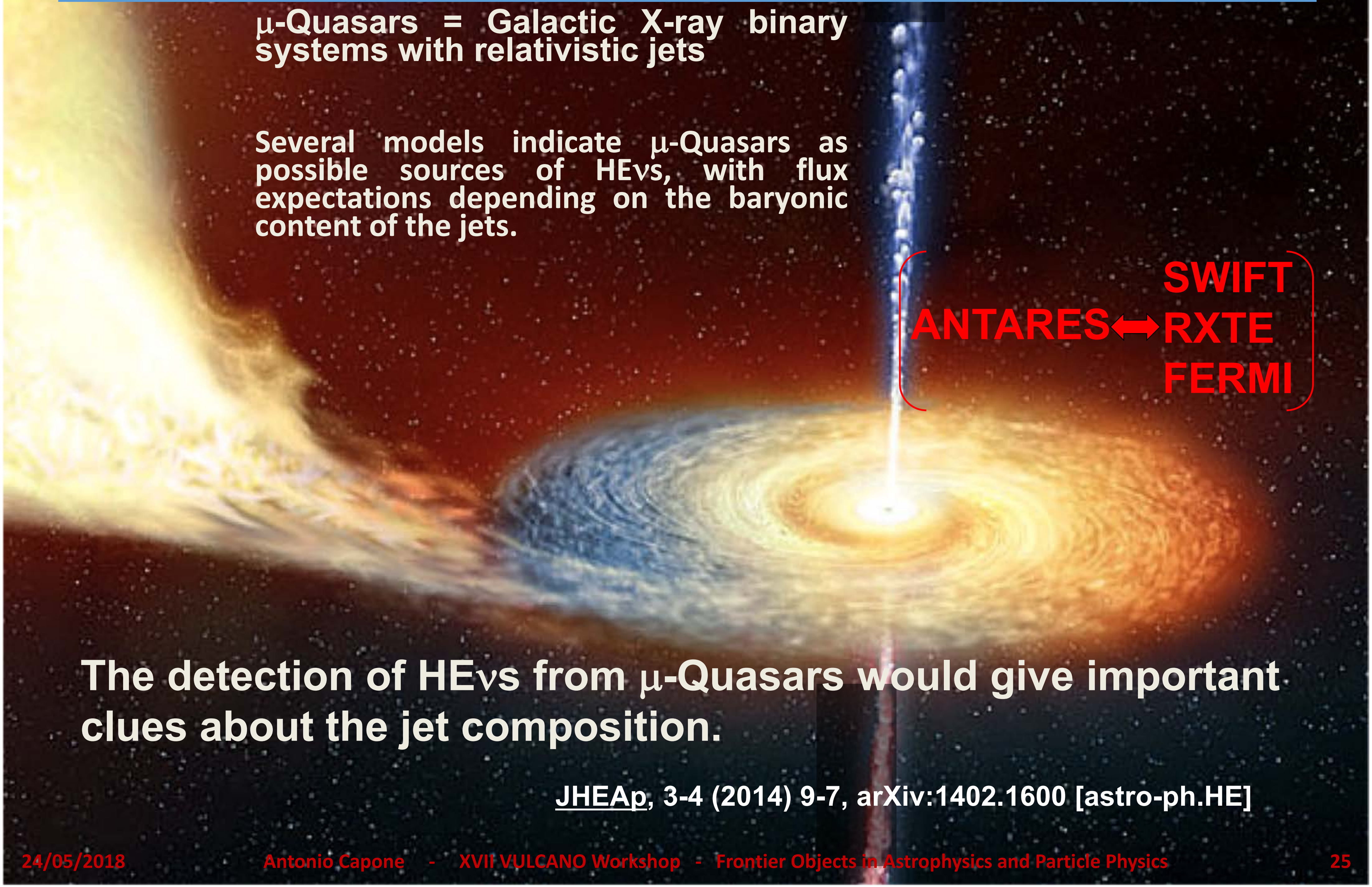




ANTARES and ν from μ-Quasars

μ-Quasars = Galactic X-ray binary systems with relativistic jets

Several models indicate μ-Quasars as possible sources of HEνs, with flux expectations depending on the baryonic content of the jets.



The detection of HEνs from μ-Quasars would give important clues about the jet composition.

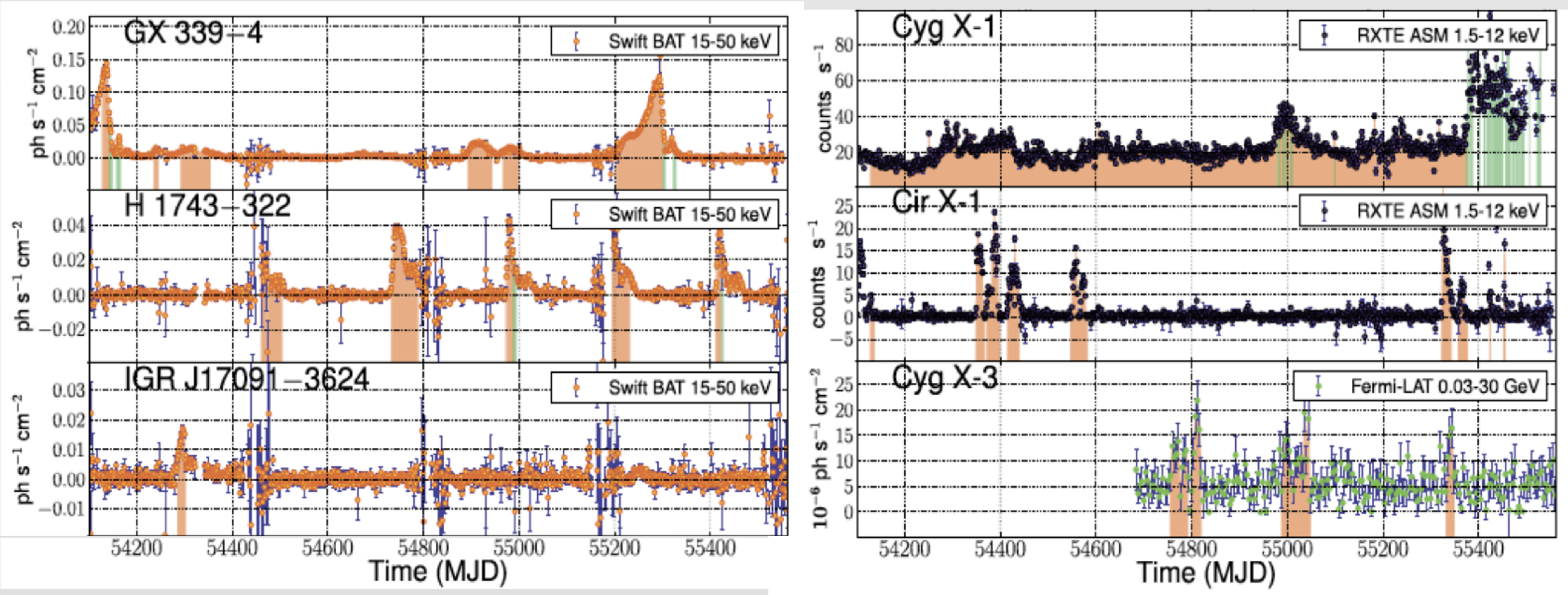
JHEAp, 3-4 (2014) 9-7, arXiv:1402.1600 [astro-ph.HE]

ANTARES and ν from μ-Quasars

ANTARES data set: 2007-2010 → 6 sources selected, **with requisites:**

- **in the ANTARES visible sky;**
- **showing an outburst in the period 2007-2010.**

Time-Dependent Analysis: for each source, the data analysis has been restricted to the flaring time periods, selected in a multi-wavelength approach (X-rays/γ-rays) and with a dedicated outburst selection algorithm (+ additional criteria, customized for the features of each μQ).



ANTARES and ν from μ-Quasars

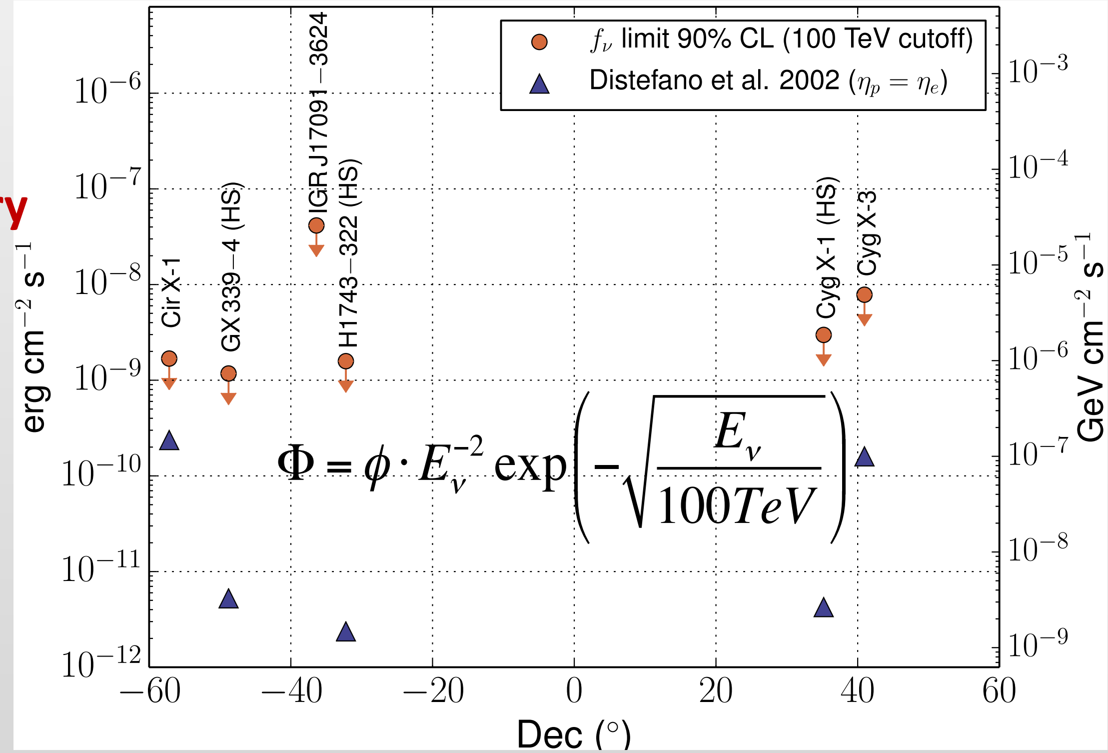
Data Analysis & Results

METHOD
- **unbinned search**
- **likelihood ratio test statistic**
- **quality cuts optimized for 5σ discovery**

RESULTS
- **no statistically significant excess above the expected atmospheric bkg**

90% C.L. upper limits on the flux normalization ϕ

JHEAp, 3-4 (2014) 9-7, arXiv:1402.1600 [astro-ph.HE]



[systematic uncertainties included]

...assuming a neutrino spectrum following:
- **a power-law**
- **a power-law with expo. cut-off**

→ INFER INFORMATION on JET COMPOSITION: constraints on η_p/η_e = ratio of proton to electron luminosity in the jet

A Multi-Messenger Search of n from GRB

GCN alerts trigger the recording of all the low level triggers. A continuous buffer ensures the availability of the data before the alert

GCN=Gamma Ray Burst Coordination Network

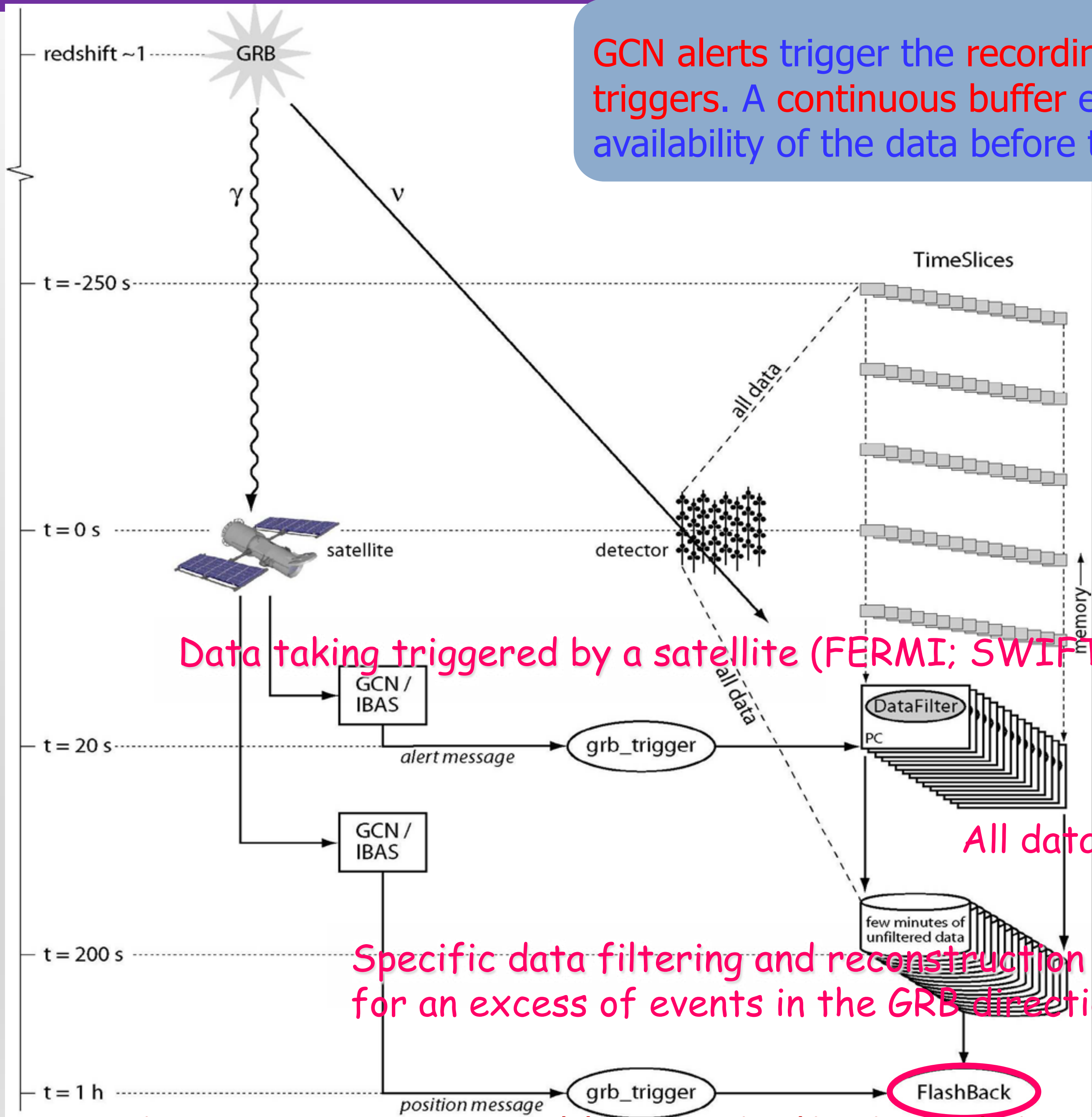
t =-250 s

t = 0 s

t = 20 s

t = 200 s

t = 1 h



Data taking triggered by a satellite (FERMI; SWIFT, INTEGRAL)

All data written to disk

Specific data filtering and reconstruction by searching for an excess of events in the GRB direction (offline)

ANTARES Multi-messenger program: search for ν_μ from very bright GRB sources

The search was performed for 4 bright GRBs:

GRB080916C, GRB 110918A, GRB 130427A and GRB 130505A)

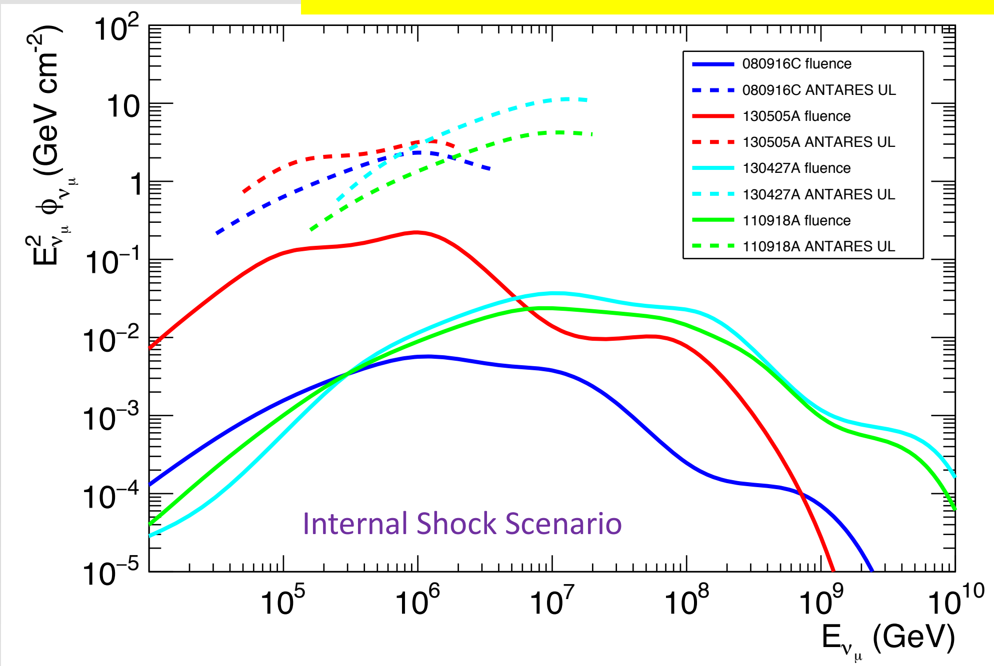
observed between 2008 and 2013.

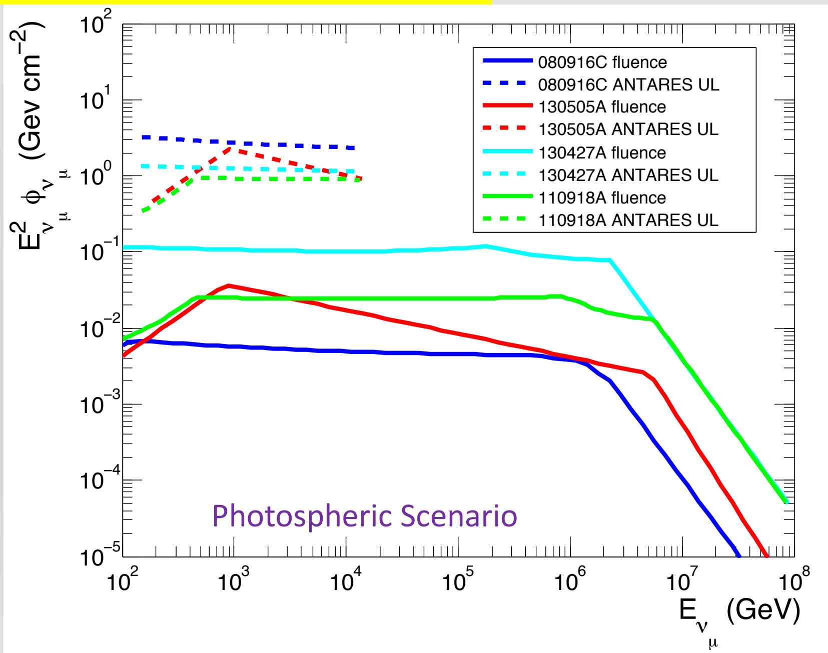
The expected neutrino fluxes evaluated in the framework of:

- the fireball model have with the internal shock scenario ($E_\nu \geq 100 TeV$)
- the photospheric scenario ($E_\nu < 10 TeV$)

No events have been found: 90% C.L. upper limits to the neutrino fluence.

Monthly Notices Royal Astronomical Society (2017) 469 (1): 906-915.





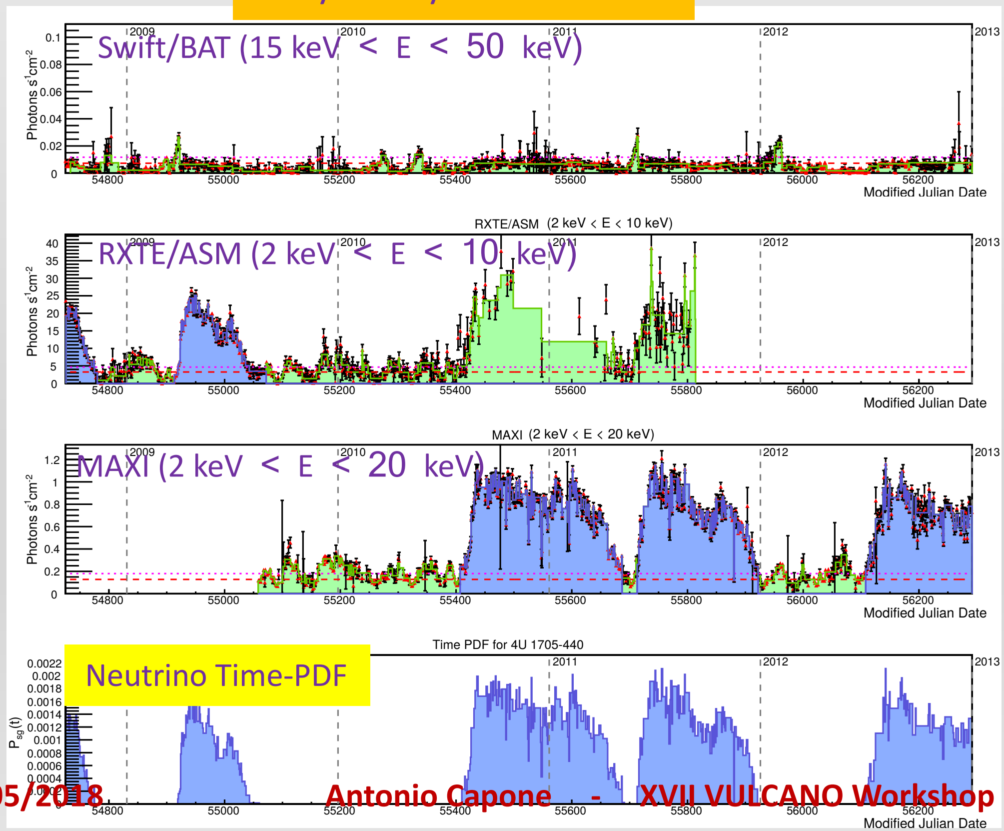
ANTARES Multi-messenger program

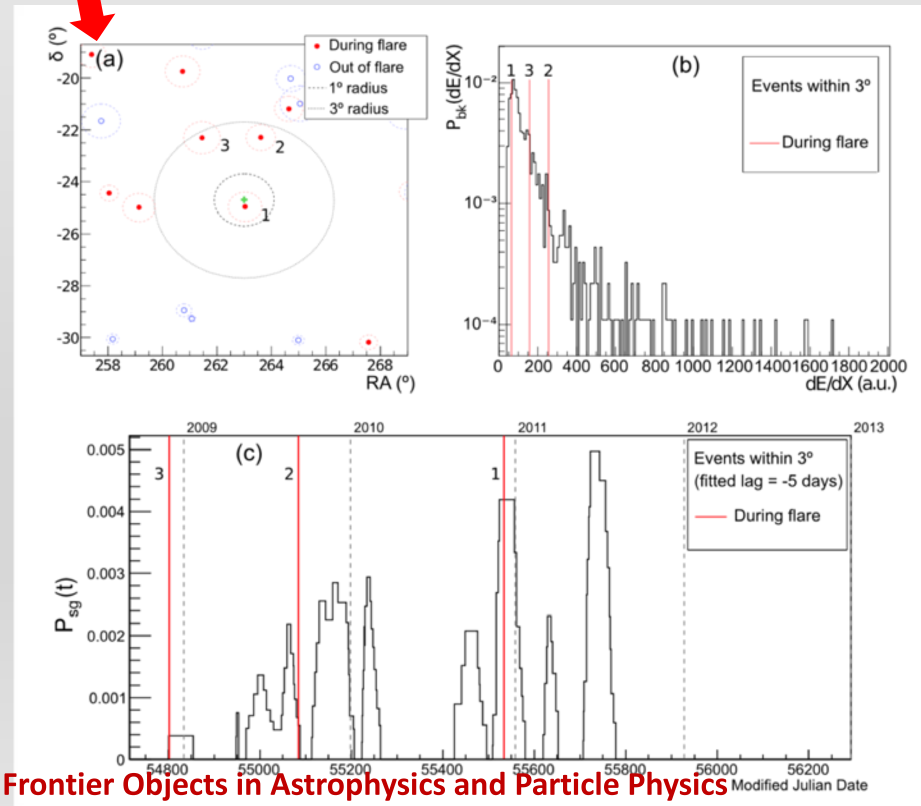
ν associated with GeV-TeV γ-ray flaring blazars and X-ray binaries

- Search for ν's (2008-2012) correlated with **high activity state**
- Blazars monitored by **FERMI-LAT and IACTs** (JCAP 1512 (2015), 014)
- **33 X-ray binaries during flares** observed by **Swift-BAT, RXTE-ASM** and **MAXI**. Transition states from telegram alerts
- No significant excess (best post-trial 72% for **GX 1+4**), then → Upper limits on ν fluence and model parameters constrain

JCAP04(2017)019

X-ray binary 4U 1705-440





ANTARES Multi-messenger program

ν associated to a source of Fast Radio Burst (FRB 150215)

MNRAS **469,** 4465–4482 (2017)

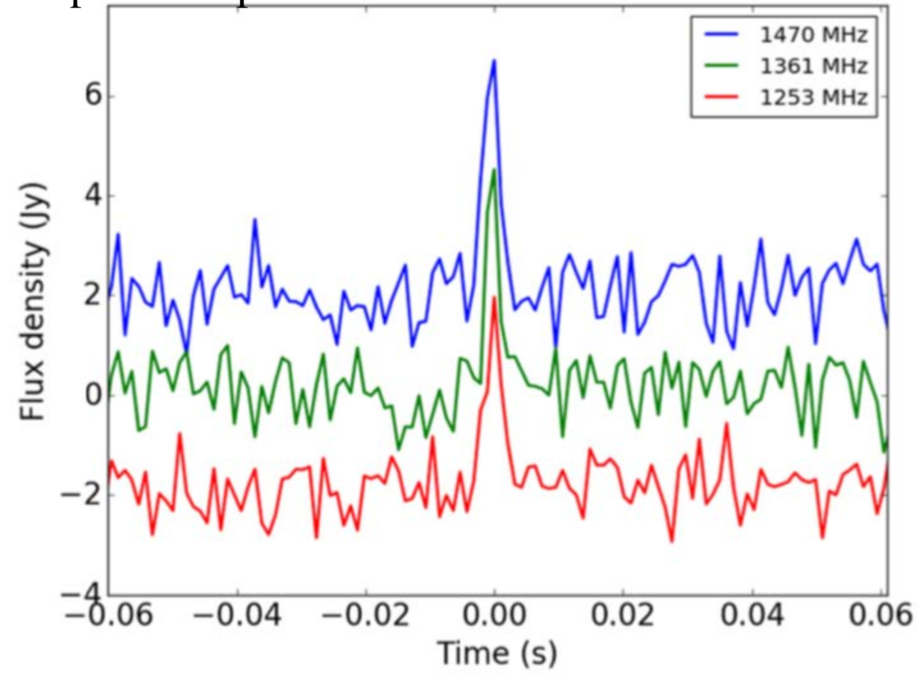
- FRB 150215 observed by Parkes radio telescope (15/02/2015)
- FRB was followed by 11 telescopes to search for radio, optical, X-ray, γ-ray and neutrinos emissions
- No other emissions have been observed
- A neutrino signal was searched in 3 time windows
  - ± 500s, ± 1h, ± 1 day
  - no events was found from the FRB event location
- From this null result ANTARES put a limit

$$F_\nu^{90\%C.L.} < 1.4{\times}10^{-2}\ erg\ cm^{-2}\ for\ \ E^{-2}\ spectrum$$

or

$$F_\nu^{90\%C.L.} < 0.47\ erg\ cm^{-2}\ for\ \ E^{-1}\ spectrum$$

The pulse shape of FRB 150215 in three sub-bands



No transients were detected at any wavelength temporally associated with FRB 150215.

H.E. astrophysical ν candidates (like IC-160731) trigger multi-messenger observations (AGILE, …)

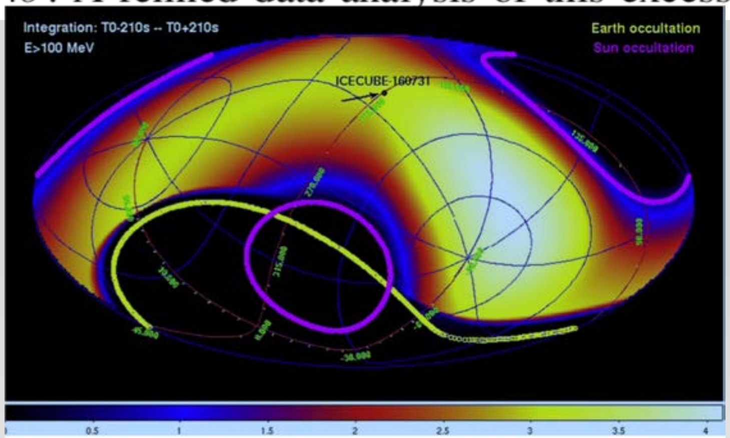
The Astrophysical Journal, 846:121 (12pp), 2017 September 10 https://doi.org/10.3847/1538-4357/aa81c8

CrossMark

AGILE Detection of a Candidate Gamma-Ray Precursor to the ICECUBE-160731 Neutrino Event

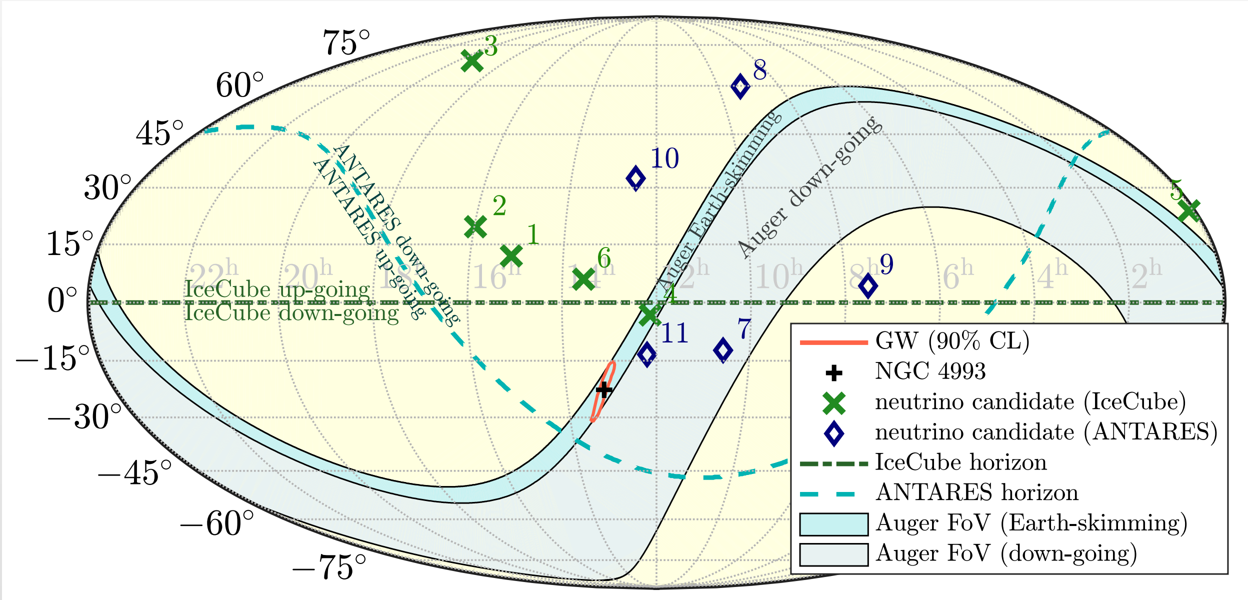
F. Lucarelli[1,2], C. Pittori[1,2], F. Verrecchia[1,2], I. Donnarumma[3], M. Tavani[4,5,6], A. Bulgarelli[7], A. Giuliani[8], L. A. Antonelli[1,2], P. Caraveo[8], P. W. Cattaneo[9], S. Colafrancesco[2,10], F. Longo[11], S. Mereghetti[8], A. Morselli[12], L. Pacciani[4], G. Piano[4], A. Pellizzoni[13], M. Pilia[13], A. Rappoldi[9], A. Trois[13], and S. Vercellone[14]

On 2016 July 31 the ICECUBE collaboration reported the detection of a high-energy starting event induced by an astrophysical neutrino. Here, we report on a search for a gamma-ray counterpart to the ICECUBE-160731 event, made with the *AGILE* satellite. No detection was found spanning the time interval of ±1 ks around the neutrino event time T_0 using the *AGILE* "burst search" system. Looking for a possible gamma-ray precursor in the results of the *AGILE*-GRID automatic Quick Look procedure over predefined 48-hr time bins, we found an excess above 100 MeV between 1 and 2 days before T_0, which is positionally consistent with the ICECUBE error circle, that has a post-trial significance of about 4σ. A refined data analysis of this excess confirms, a posteriori, the automatic



A joint ANTARES/IceCube/LigoSC/Virgo/Auger analysis

performed as “Neutrino follow-up” of GW170817



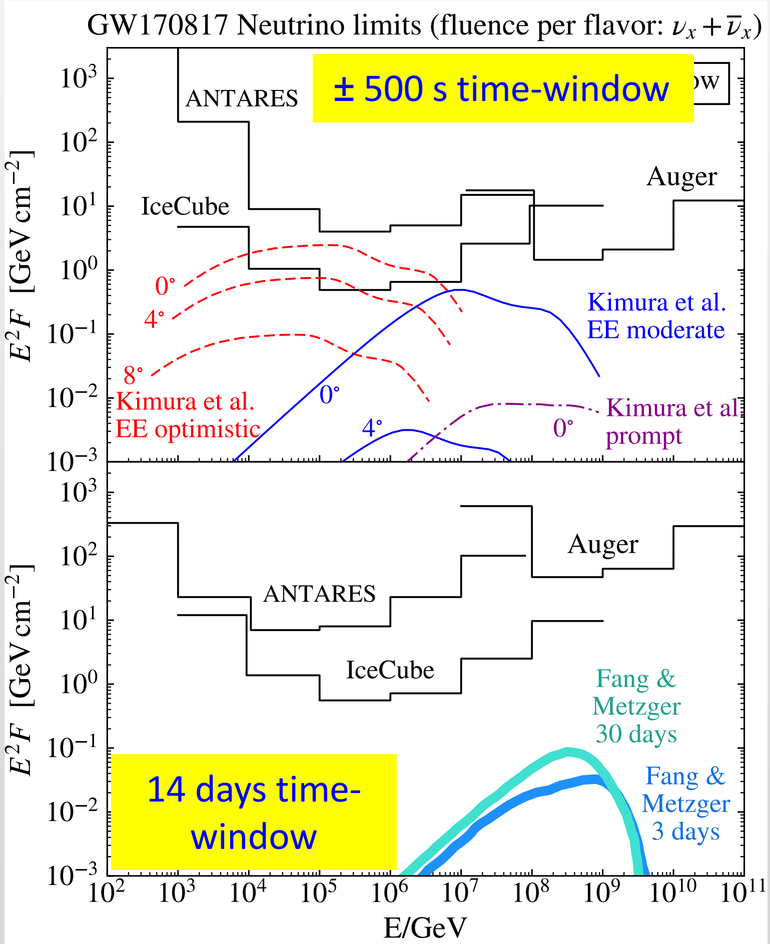
The location of this source was nearly ideal for Auger.
It was well above the horizon for IceCube and ANTARES for prompt observations.
IceCube and ANTARES sensitivity is then limited for neutrinos with E_ν < 100 TeV.

- A **short gamma-ray burst** (GRB) that followed the merger of this binary system was **recorded by the Fermi-GBM** (E_{iso} ~$4\cdot10^{46}$ 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.

The Astrophysical Journal Letters, 848:L12 (2017)

Summary

- IceCube, BAIKAL, ANTARES neutrino telescopes monitor continuously the sky searching for astrophysical neutrinos. AUGER detector sensitive to U.H.E. neutrinos.
- A large **multi-messenger** effort to characterize the C.R.s composition, spectrum, sources location and dynamics, joining different observations
  - **EM radiation: radio, optical, X-ray, γ-rays**
  - **U.H.E. C.R.s**
  - **Gravitational Waves**
  - **neutrino**
- **KM3NeT** Neutrino Telescope under construction in the Mediterranean Sea will soon be able to observe the neutrino sky with unprecedented sensitivities.