Searching for High Energy Astrophysical ν from the depths of Mediterranean Sea

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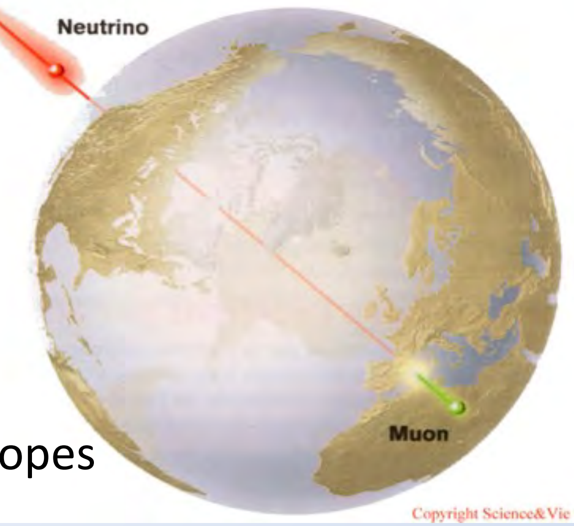
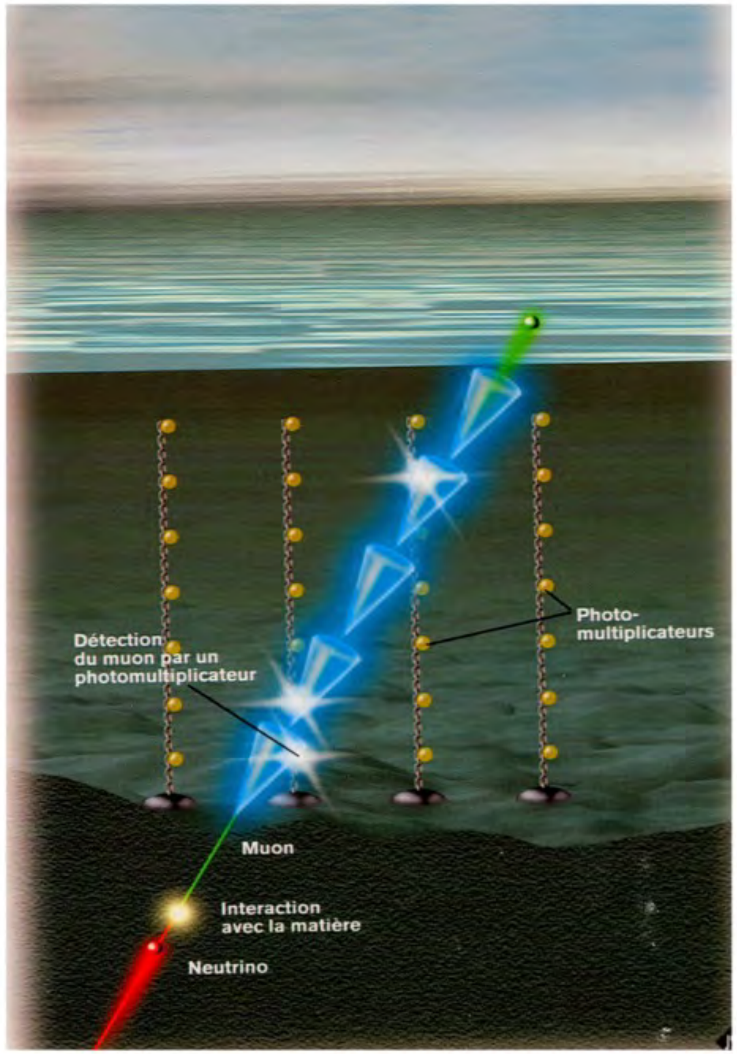




Astrophysical ν detection
- Why ?
- How ?
- Where ?

The ν, γ, HE C.R. connection
- Multimessenger search for H.E. astrophysical sources

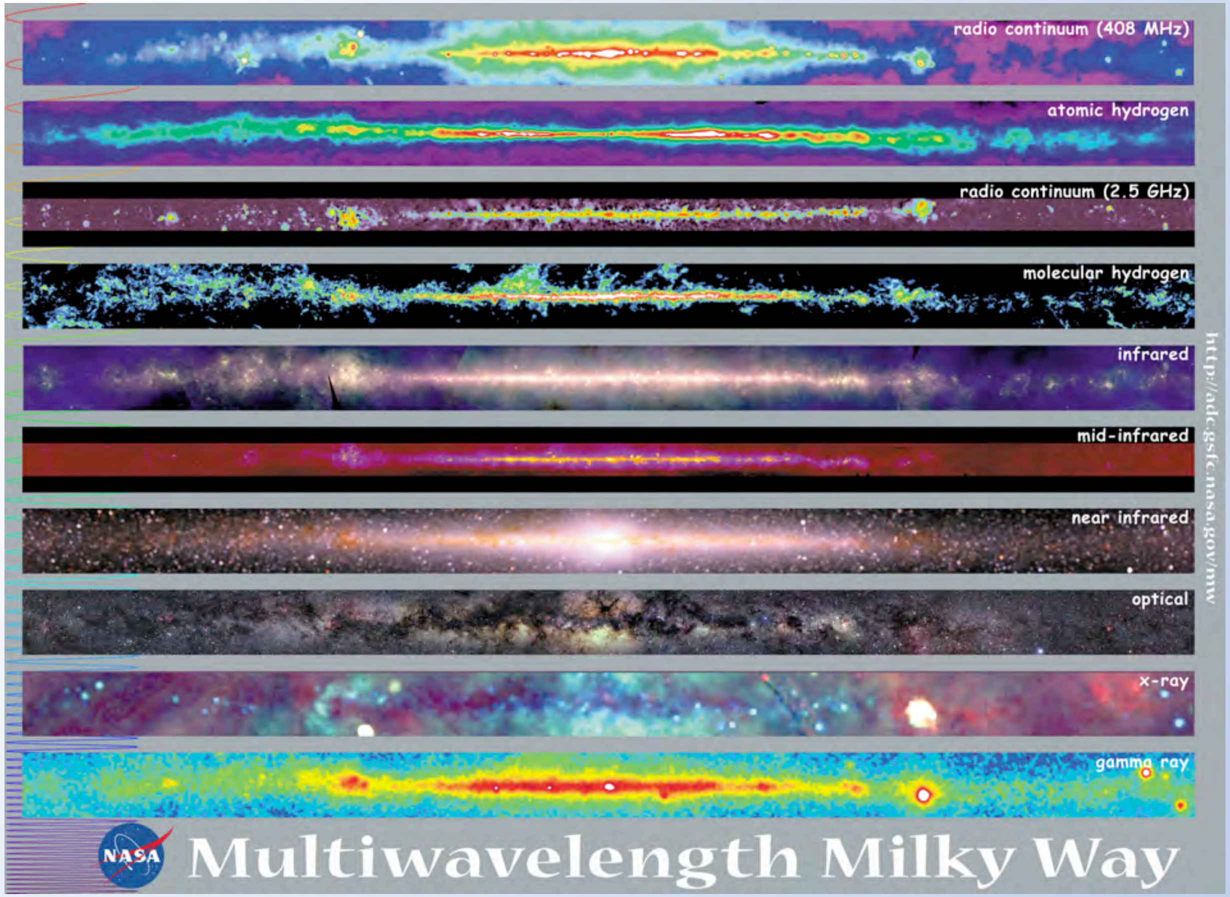
Results from Cherenkov ν Telescopes

The evolution of astronomy …

From Traditional Astronomy (Optics) to Multi-Wavelength Astronomy:

observations of light in the visible band are complemented by radio, X-ray and γ astronomy

Galileo Galilei showing the Doge of Venice how to use the telescope **(1858), fresco by Giuseppe Bertini (1825–1898)**

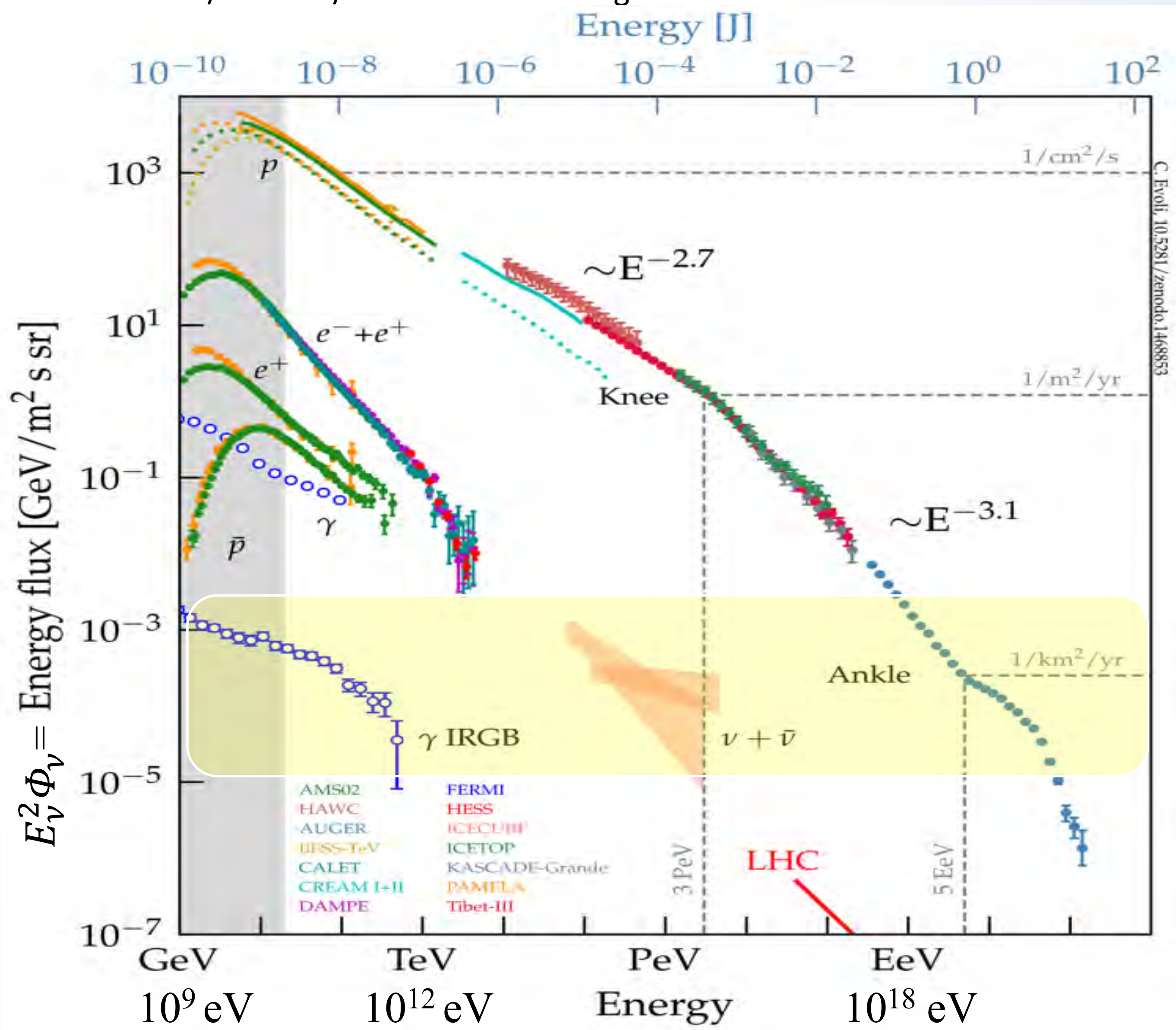


http://mwmw.gsfc.nasa.gov/

… and to Multi-Messengers Astronomy:
HE-CR, photons, neutrinos, GW …

The Cosmic Rays spectrum

Evoli 2018 - DOI/10.5281/zenodo.2360277.svg

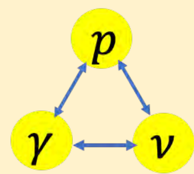


~ 1000 particles/(s·m²)

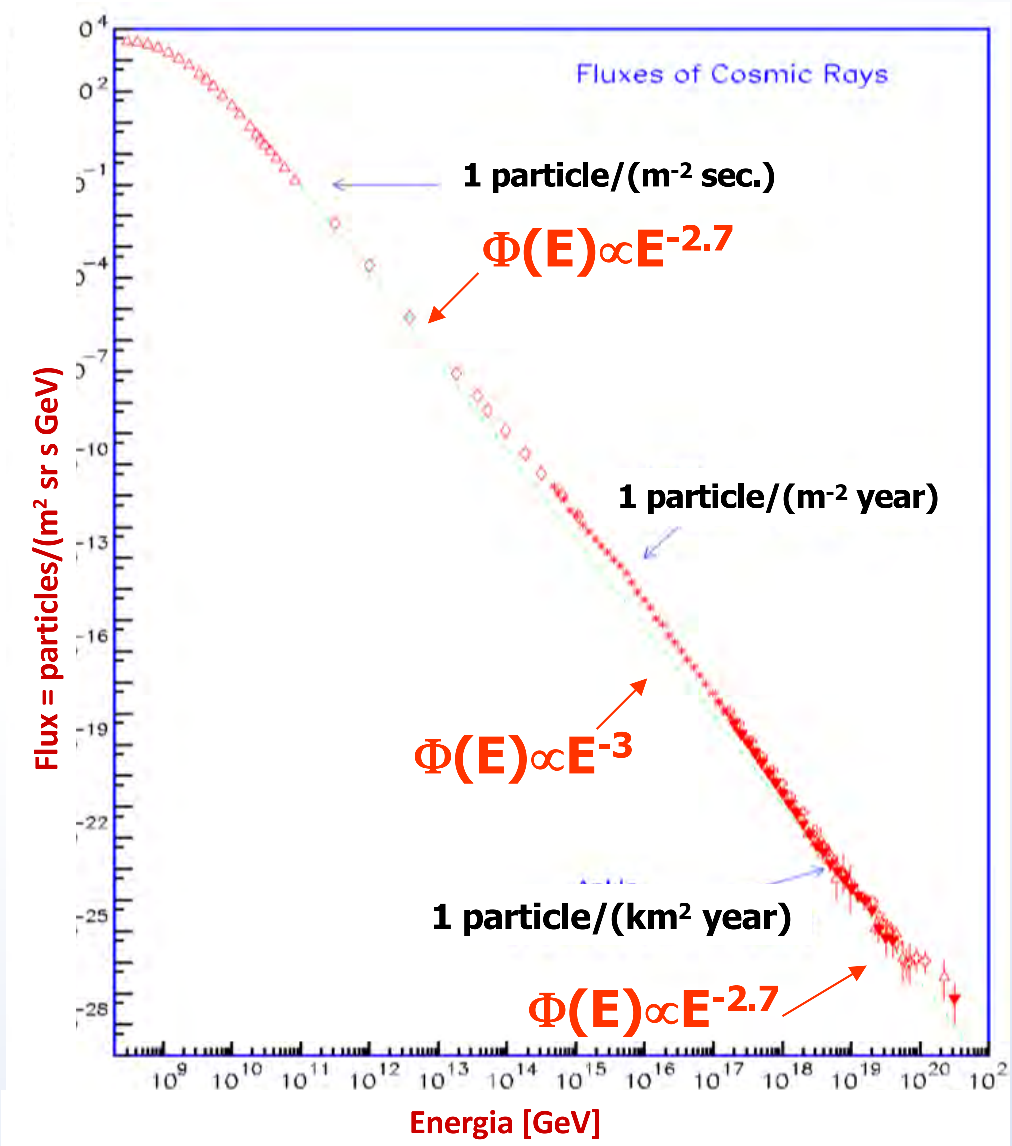
ionized nuclei:

- **90% protons**
- **9% α particles**
- **heavier nuclei**

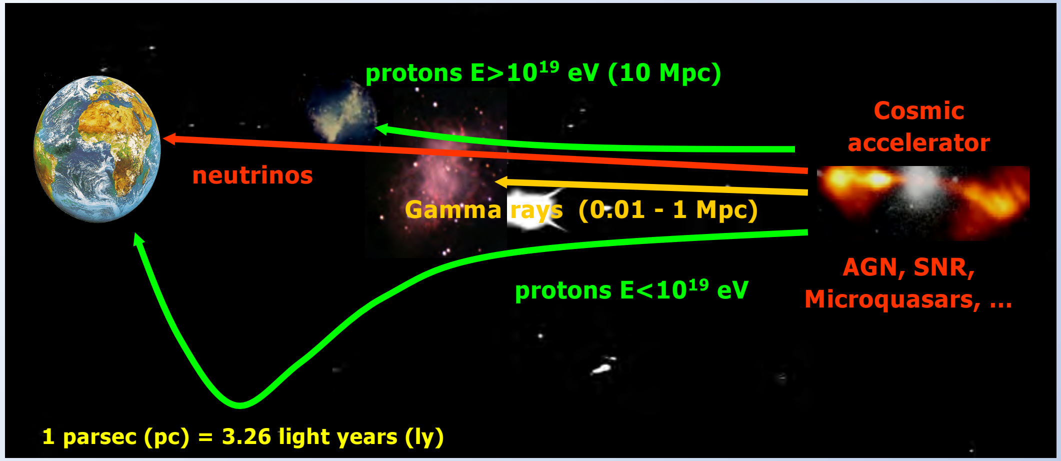
- **what is their origin?**
  - **a small solar**
  - **most with E< $10^{15\text{-}16}$ eV originated in the galaxy**
  - **extragalactic E> $10^{17\text{-}18}$ eV**

- **The**  **connection**

The "all particle spectrum"

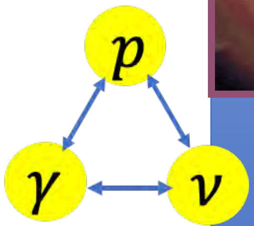


- Observed elementary particles or nuclei carrying a kinetic energy up to 10^{21}eV (like a tennis ball moving at ~150km/h)
- Many open questions:
- Where they come from ?
- Which acceleration mechanisms



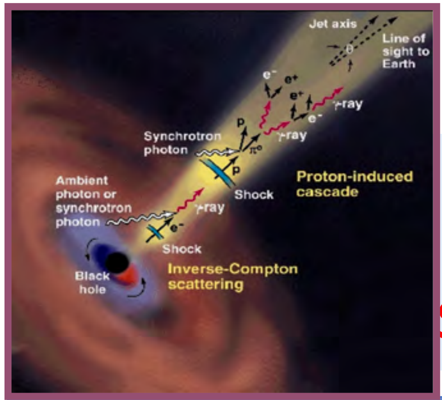
- UHE astrophysical neutrinos will extend the limits of the "visible" Universe.
- Multi-messenger observations

Which processes characterize the High Energy sources



leptonic process

Inverse Compton scattering

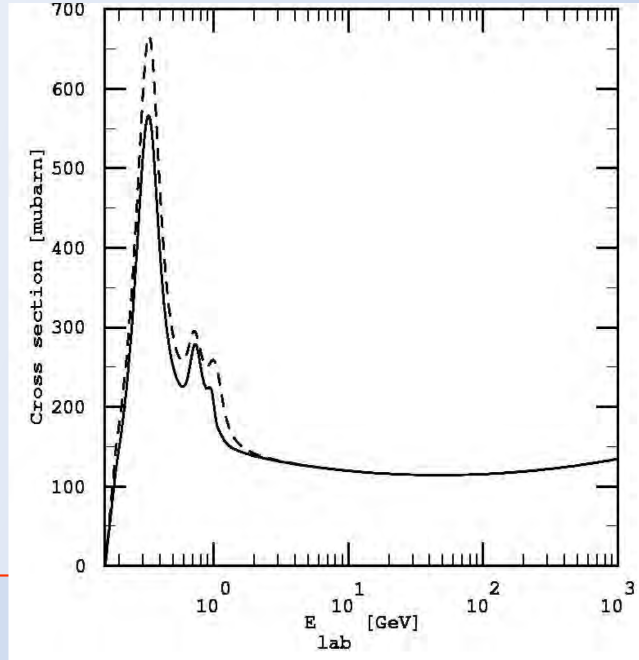


e^- + ambient photons (sync, MWB, IR) → e', γ

We have to consider also hadronic processes like:

p + Ambient matter / ambient photons → $N, \pi^{\pm}, \pi^0$ → γ, ν

Nucleons propagation and interactions in the Universe: the GZK cut-off



$$p + \gamma_{CMBR} \rightarrow \Delta^+ \rightarrow p + \pi^0$$
$$\quad \hookrightarrow \gamma\,\gamma$$
$$\rightarrow n + \pi^+$$
$$\quad \hookrightarrow \mu^+ \nu_\mu$$
$$\quad \hookrightarrow e^+ \nu_e \bar{\nu}_\mu$$

Assuming for the 'target photons' $E_\gamma = 1.4 \cdot 10^{-3}$ eV :

$$s_{out} = (m_p + m_\pi)^2$$

$$s_{in} = (E_p + E_{CMBR})^2 - (\vec{p}_p + \vec{q}_{CMBR})^2 = E_p^2 + E_{CMBR}^2 + 2E_pE_{CMBR} - p_p^2 - q_{CMBR}^2 - 2|\vec{p}_p|\cdot|\vec{q}_{CMBR}|\cos(\theta)$$

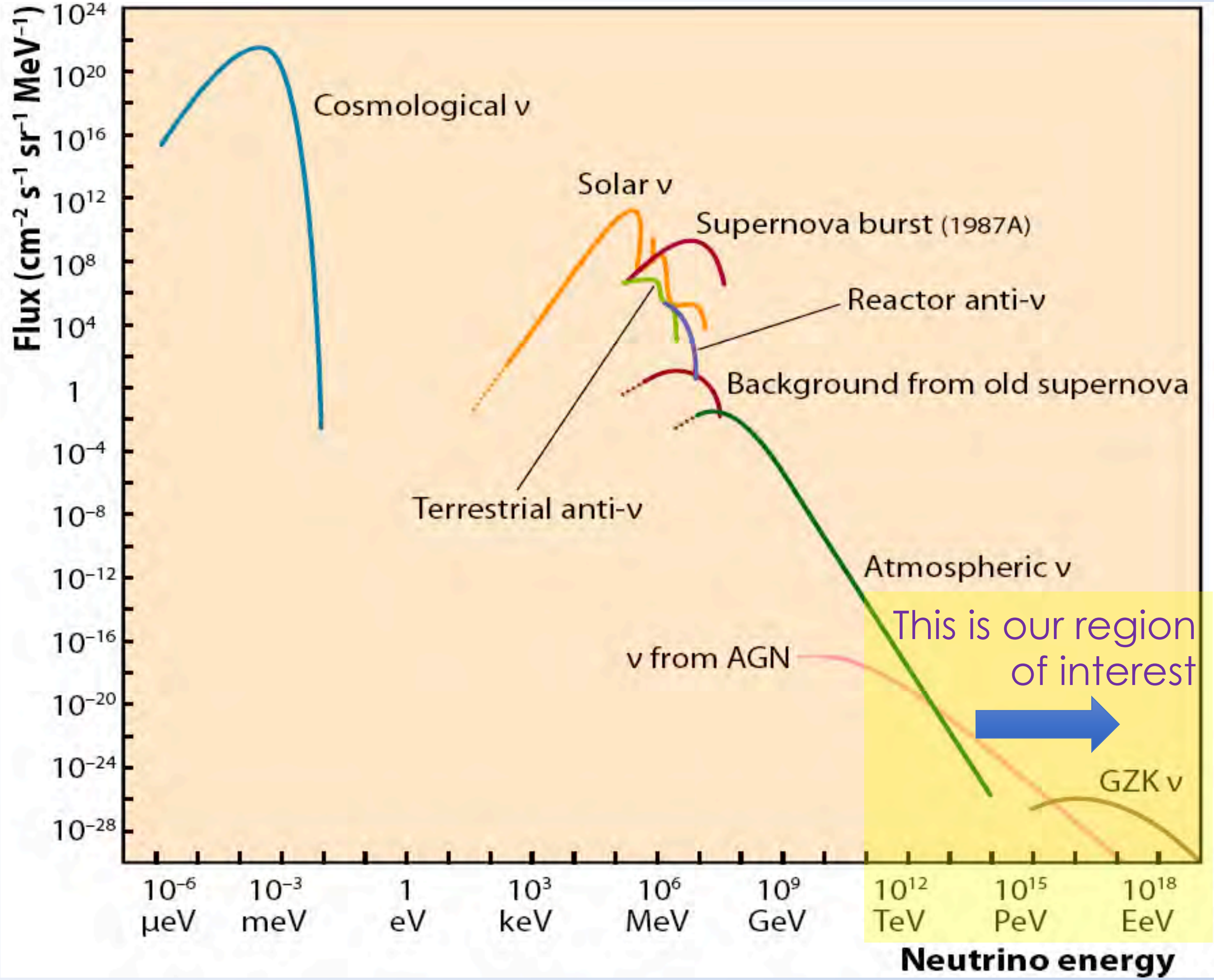
$$s_{in} = E_p^2 - p_p^2 + 2E_pE_{CMBR} - 2|\vec{p}_p|\cdot|\vec{q}_{CMBR}|\cos(\theta) \approx m_p^2 + 2E_pE_{CMBR}(1-\cos(\theta))$$

the condition for the production of the Δ^+ resonance requires $s_{in} \geq (m_p + m_\pi)^2$

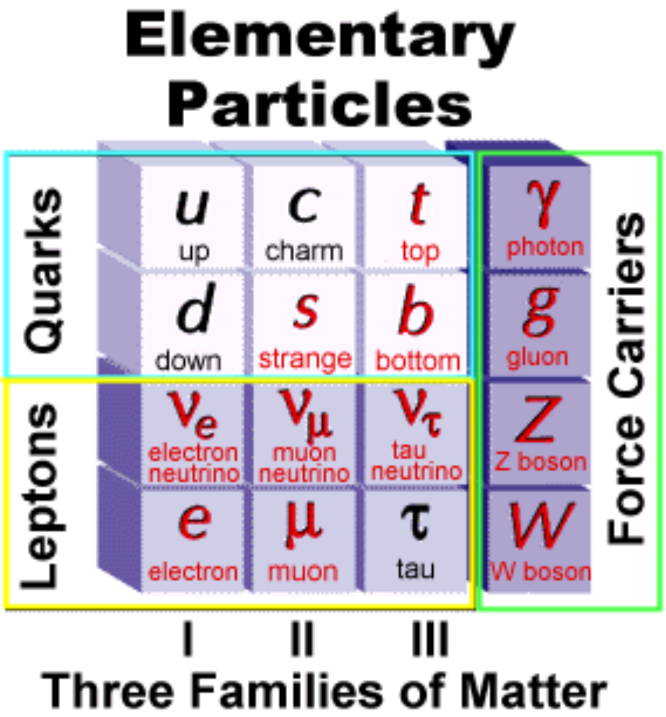
$$m_p^2 + 2E_pE_{CMBR}(1-\cos(\theta)) \geq m_p^2 + m_\pi^2 + 2m_pm_\pi \qquad per \quad \theta = \pi \quad \Rightarrow 1-\cos(\theta) = 2$$

$$E_p \geq \frac{2m_pm_\pi + m_\pi^2}{4E_{CMBR}} = \frac{2\cdot 938\cdot 10^6\cdot 140\cdot 10^6 + (140\cdot 10^6)^2}{4\cdot 1.4\cdot 10^{-3}} \approx 5.0\cdot 10^{19}\,eV = 50\,EeV \sim 8J$$

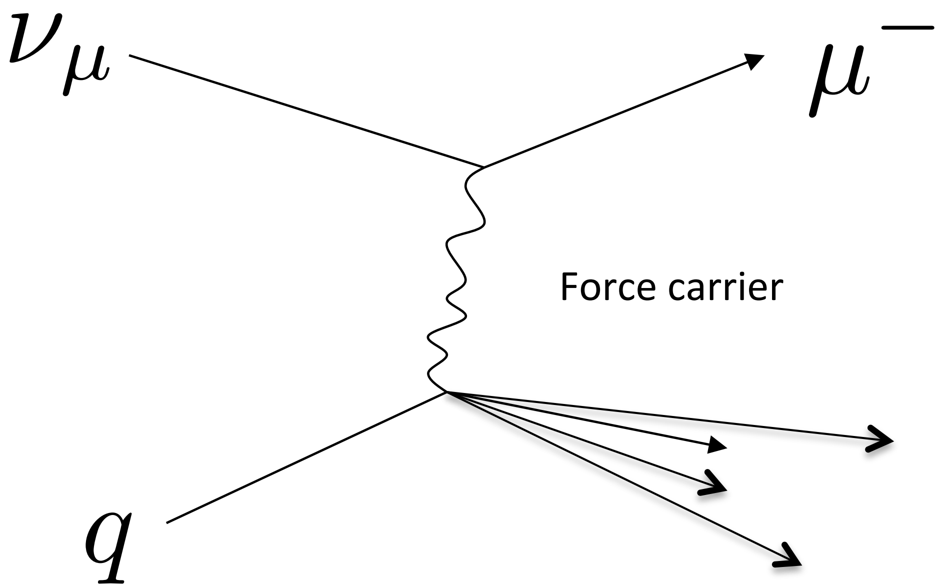
Neutrino fluxes: what do we know/expect ?



Neutrino Interactions – what happens



Charged current ν_μ:



$$\text{Also charged current } \nu_e \to e$$

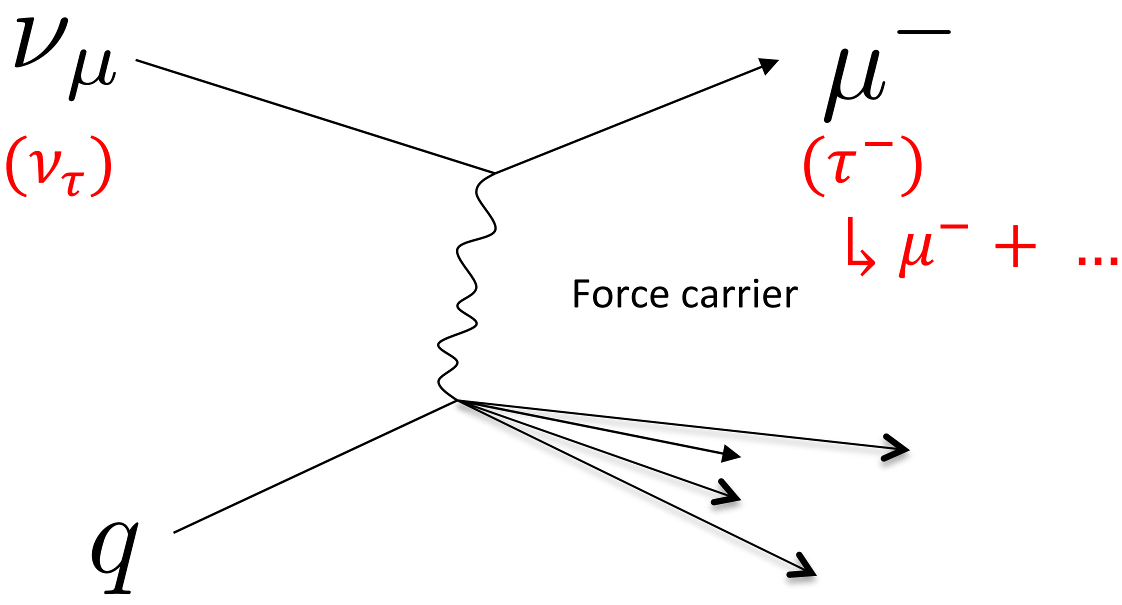
$$\text{and charged current } \nu_\tau \to \tau$$

$$\text{and neutral current } \nu_\alpha \to \nu_\alpha$$

Neutrino Interactions – what can we "see"

Tracks

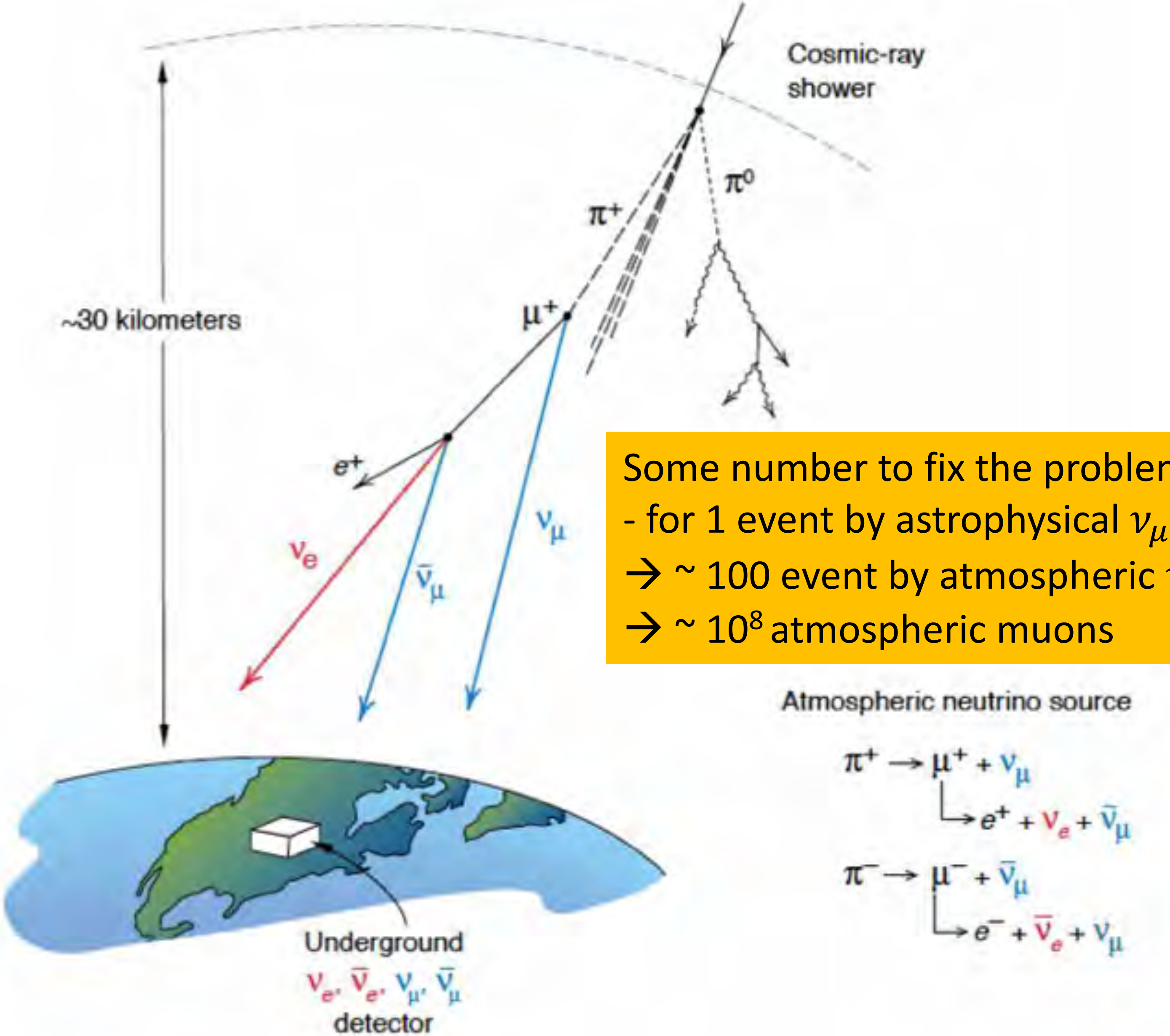
(because of μ)



Cascades

- Also charged current $\nu_e \to e$
- and charged current $\nu_\tau \to \tau$
- and neutral current $\nu_\alpha \to \nu_\alpha$

A very intense muon flux is coming (downgoing) from the atmosphere …

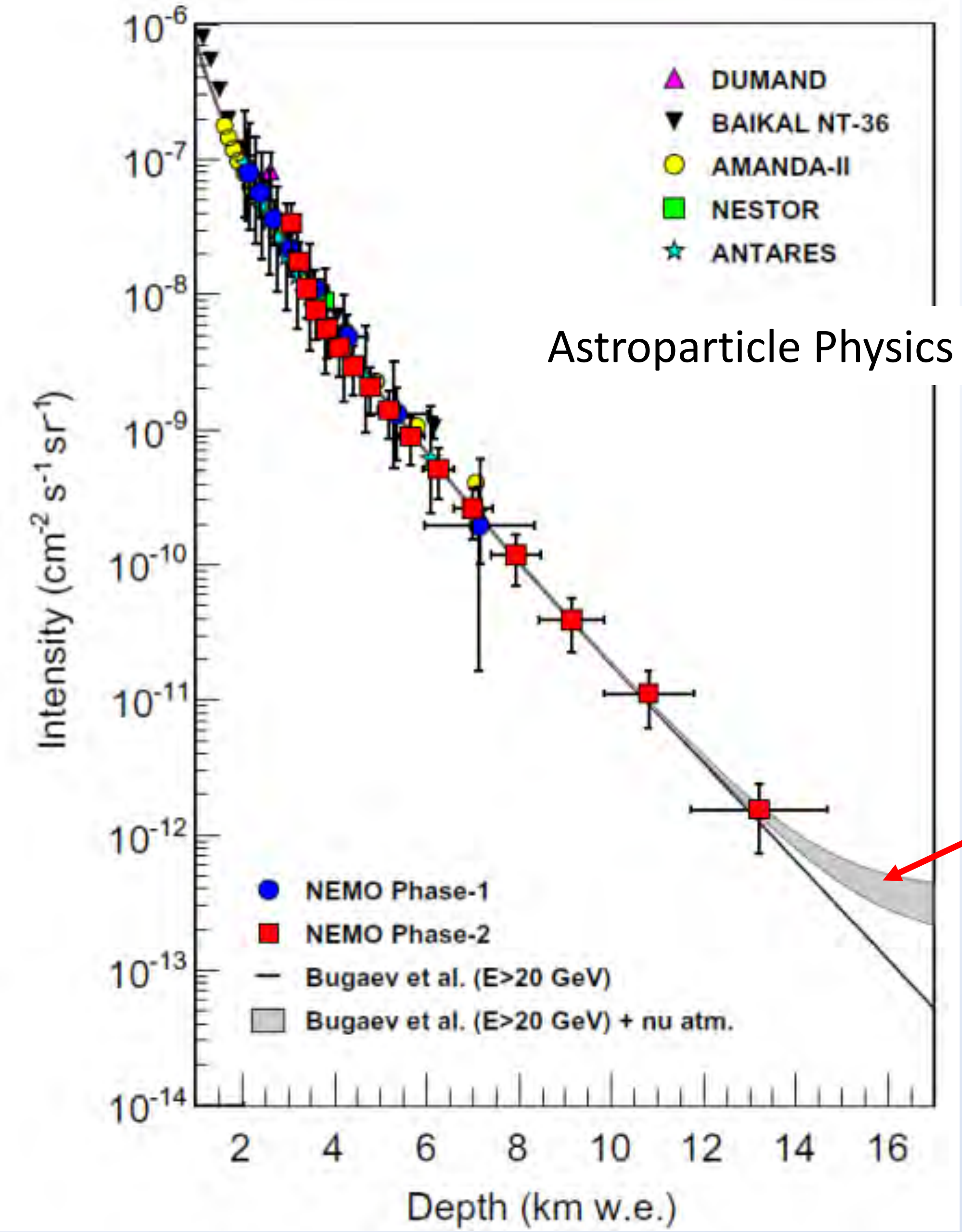


Some number to fix the problem …
- for 1 event by astrophysical ν_μ

→ ~ 100 event by atmospheric ν_μ

→ ~ 10^8 atmospheric muons

Atmospheric muons (down-going): main background



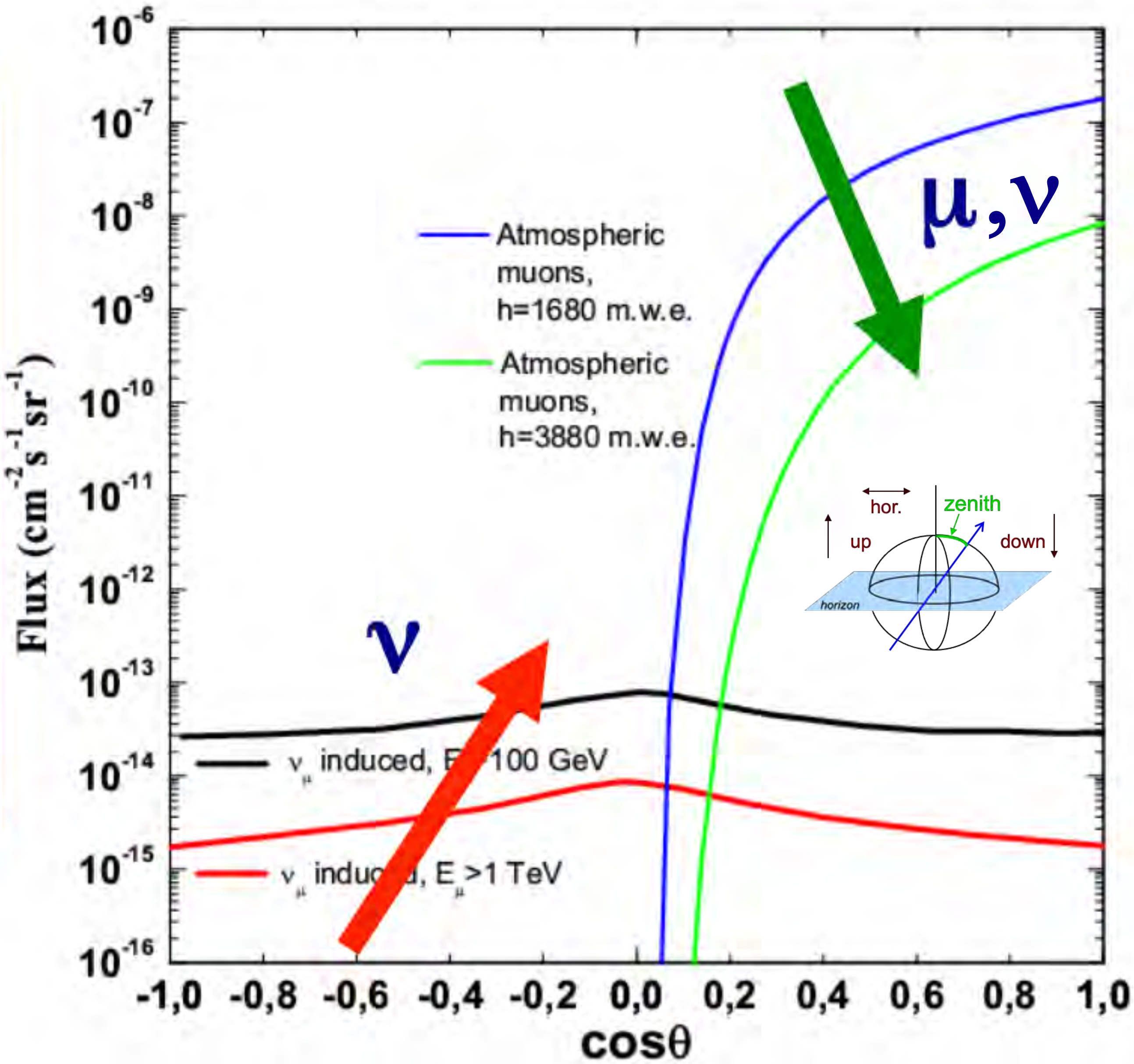
Astroparticle Physics 66 (2015) 1–7

Events with a muon measured in a detector "protected" by > 15km of "water equivalent" are, probably, events where atmospheric neutrinos interact via CC giving a muon

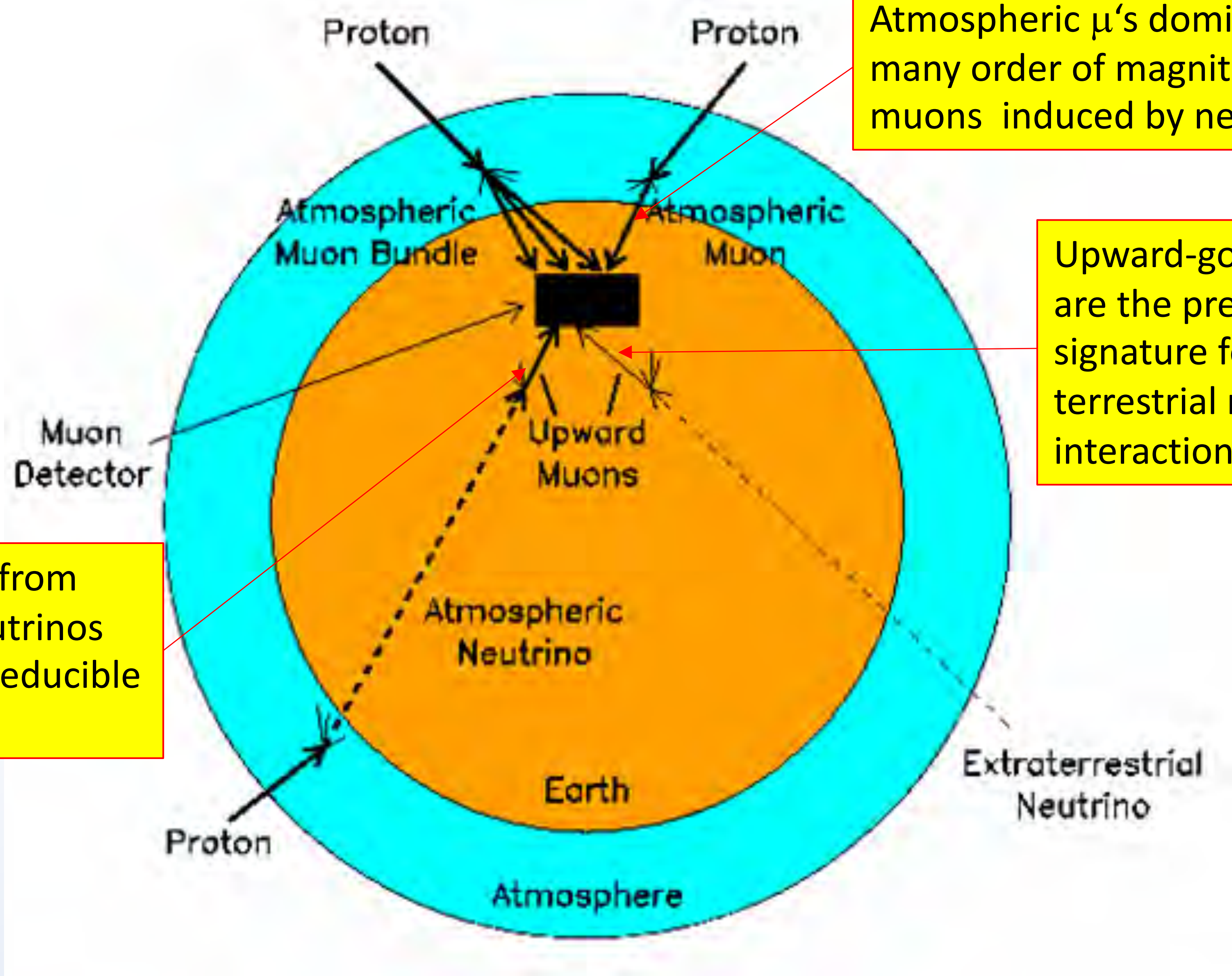
Deep in a transparent medium

Water or Ice:

- large (and inexpensive) target for ν interaction
- transparent radiators for Cherenkov light;
- large deep: protection against the cosmic-ray muon background



Neutrino Telescopes: signal and background



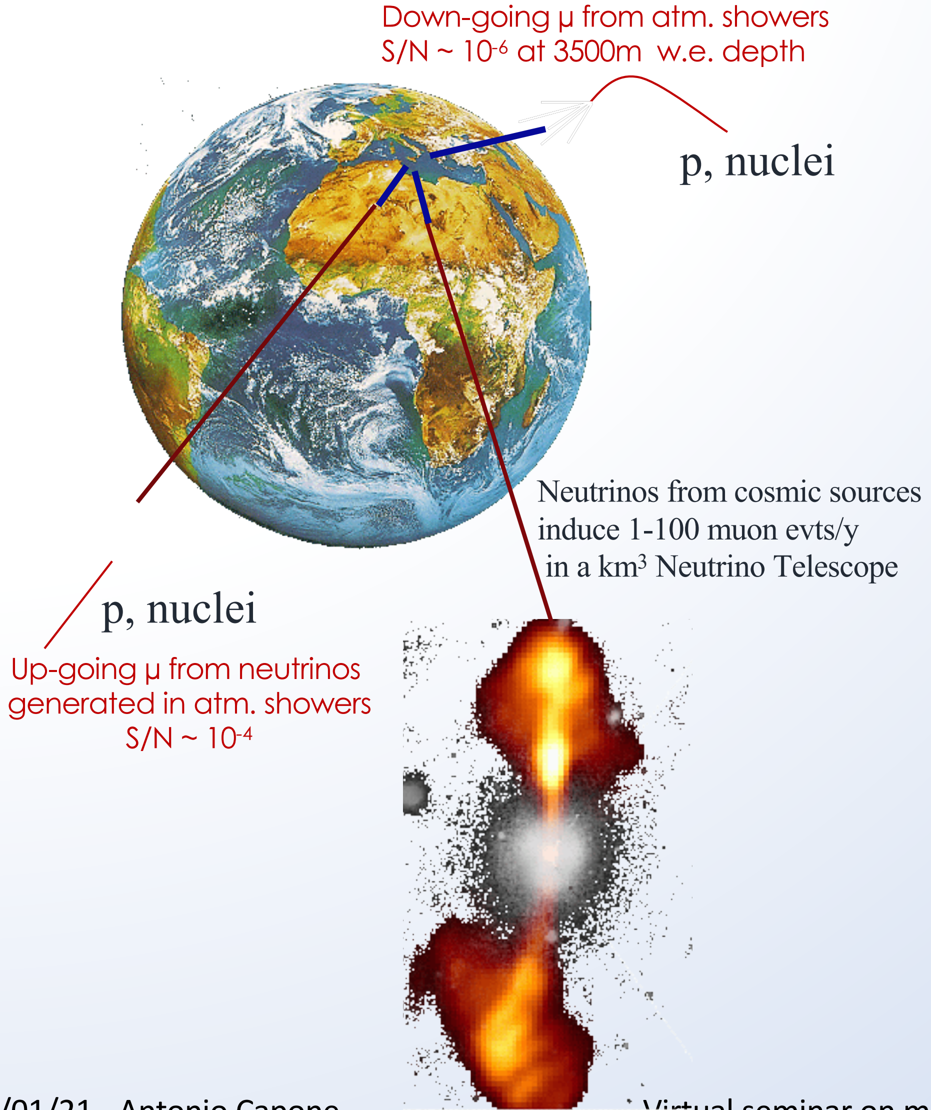
Atmospheric μ's dominate by many order of magnitude the muons induced by neutrinos

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

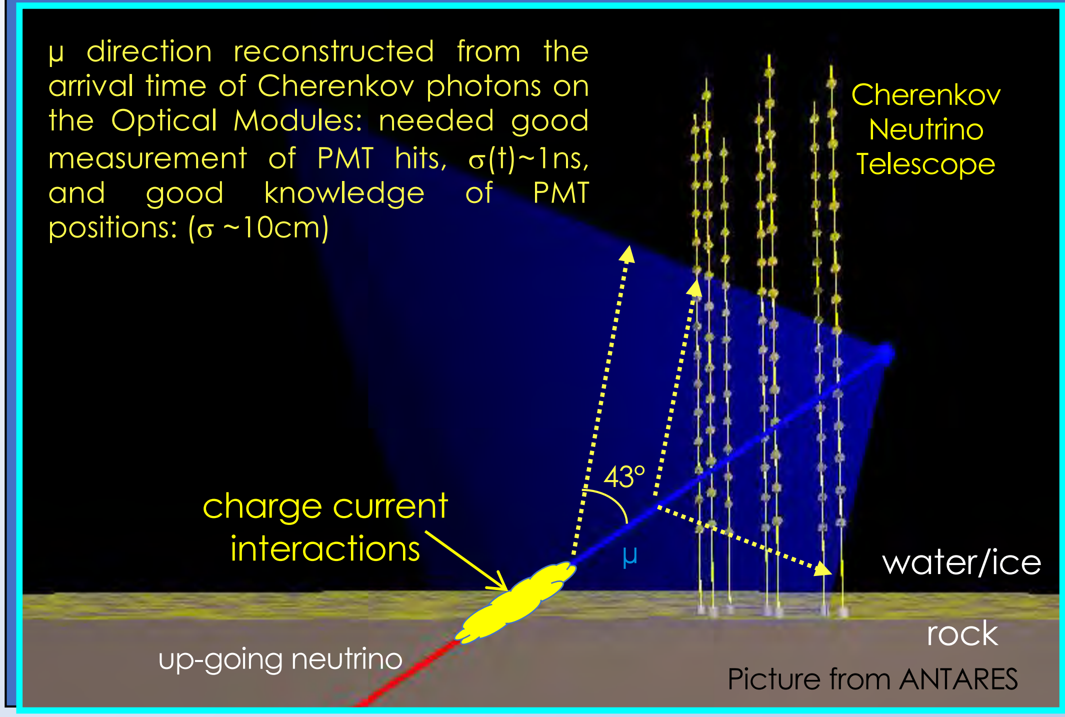
Search for neutrino induced events, mainly $\nu_\mu N \rightarrow \mu X$, deep underwater



- Atmospheric neutrino flux ~ 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

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



Light propagation in water

In a transparent medium the light propagation is limited by absorption (the photon disappears)

$$I(x) = I_o\, e^{-ax}$$

$$L_a = 1/a$$

by diffusion (the photon changes direction),

$$I(x) = I_o\, e^{-bx}$$

$$L_b = 1/b$$

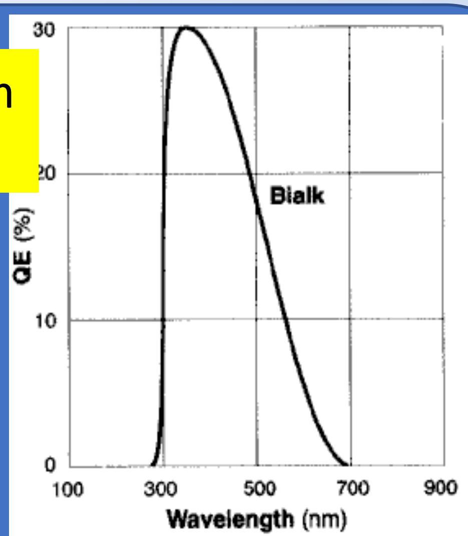
by attenuation

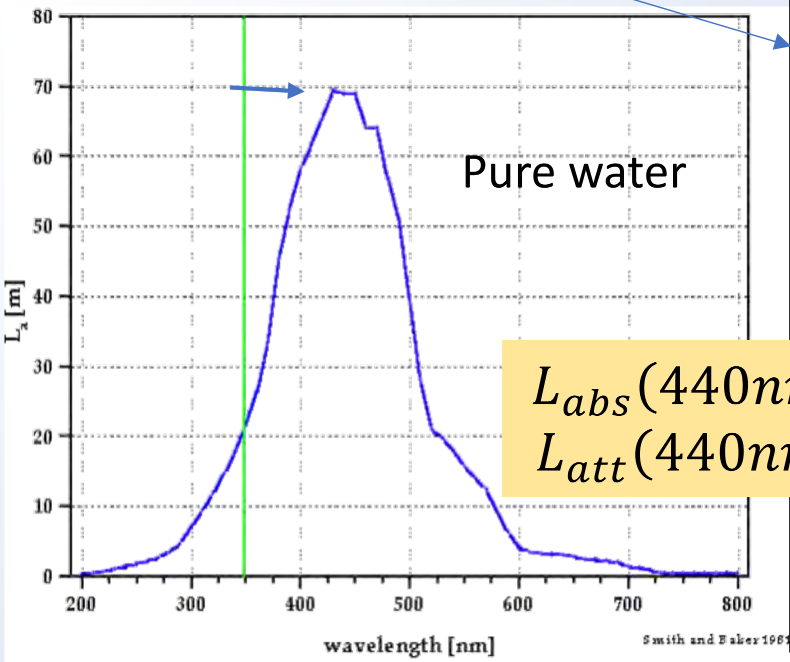
$$c = a + b$$

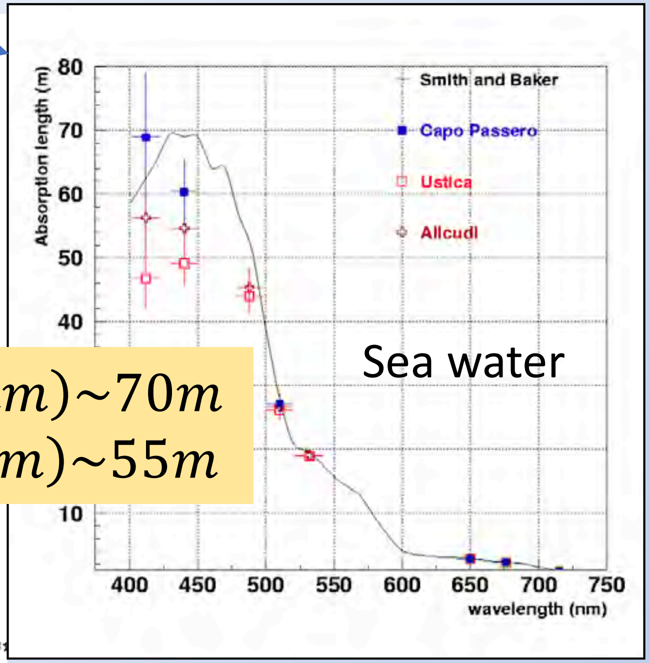
$$I(x) = I_o\, e^{-cx}$$

$$L_c = 1/c$$

PMT quantum efficiency



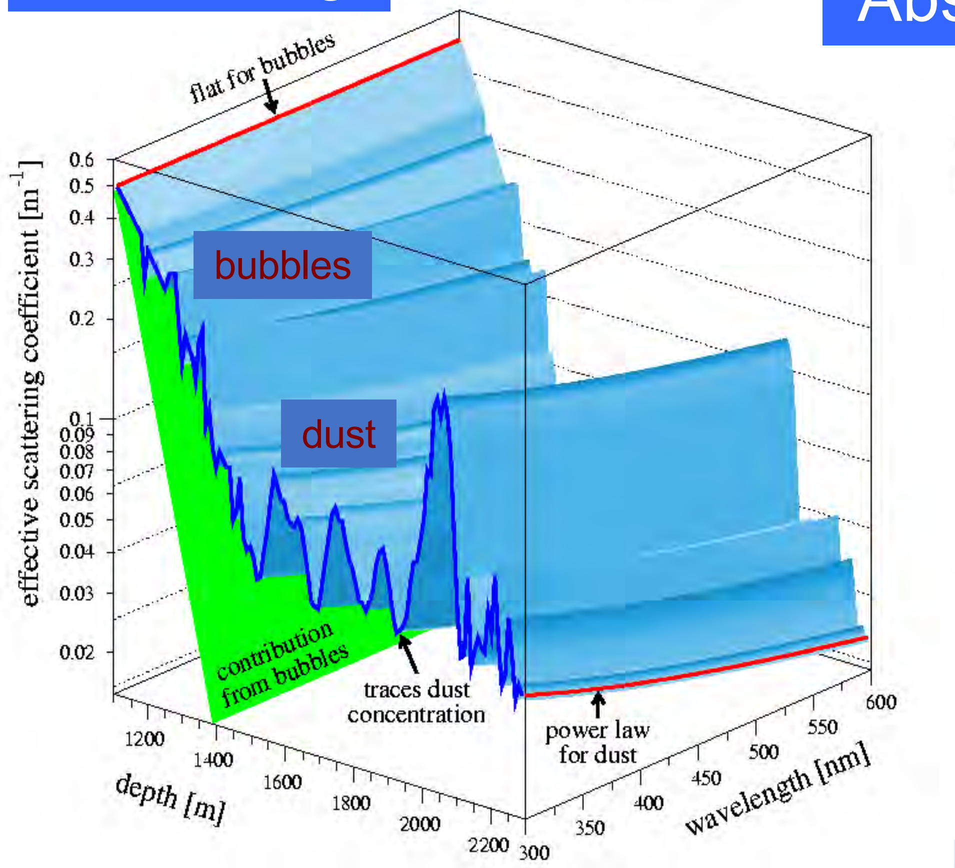




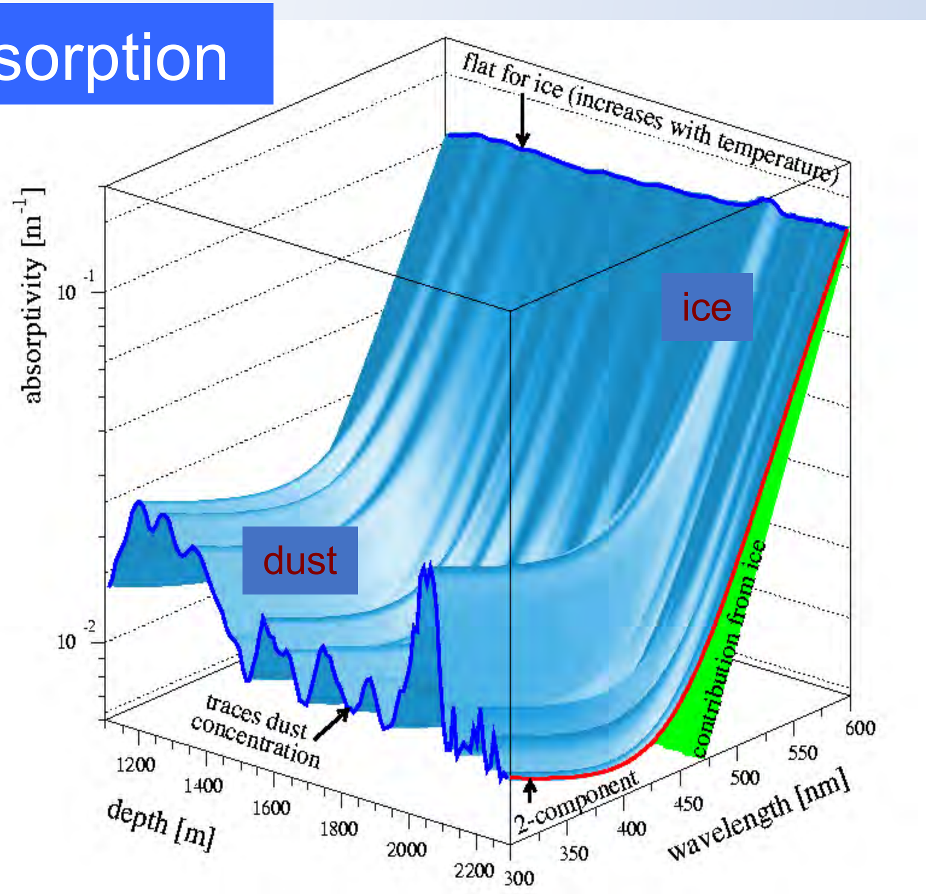
$$L_{abs}(440nm) \sim 70m$$
$$L_{att}(440nm) \sim 55m$$

Light propagation in South Polar ice

Scattering



Absorption



Measurements:

- **in-situ light sources**
- **atmospheric muons**

Average optical ice parameters:

λ_{abs} ~ 110 m @ 400 nm
λ_{sca} ~ 20 m @ 400 nm
λ_{att} ~ 27 m @ 400 nm

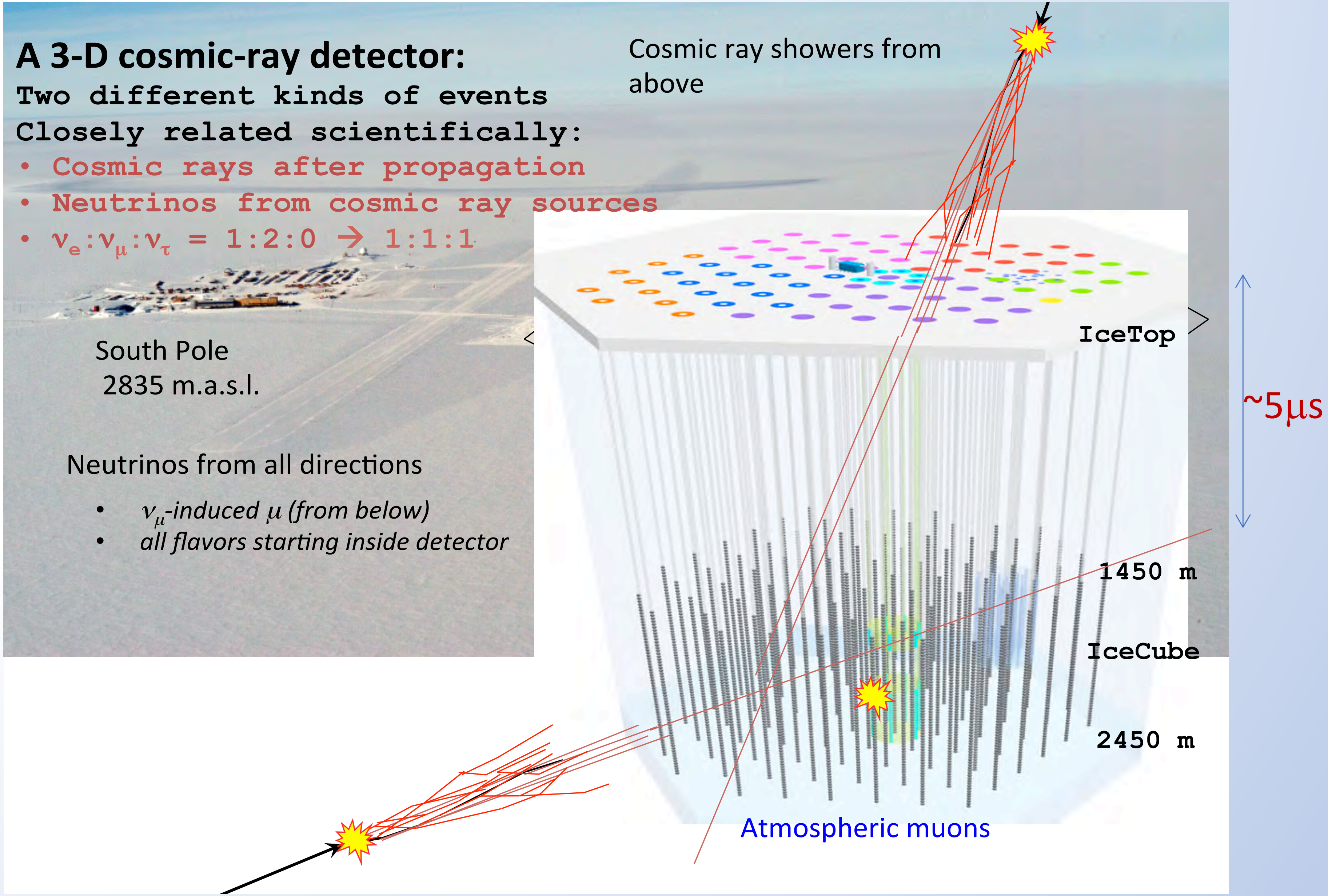
IceCube – The Neutrino Telescope at the South Pole

A 3-D cosmic-ray detector:

Two different kinds of events

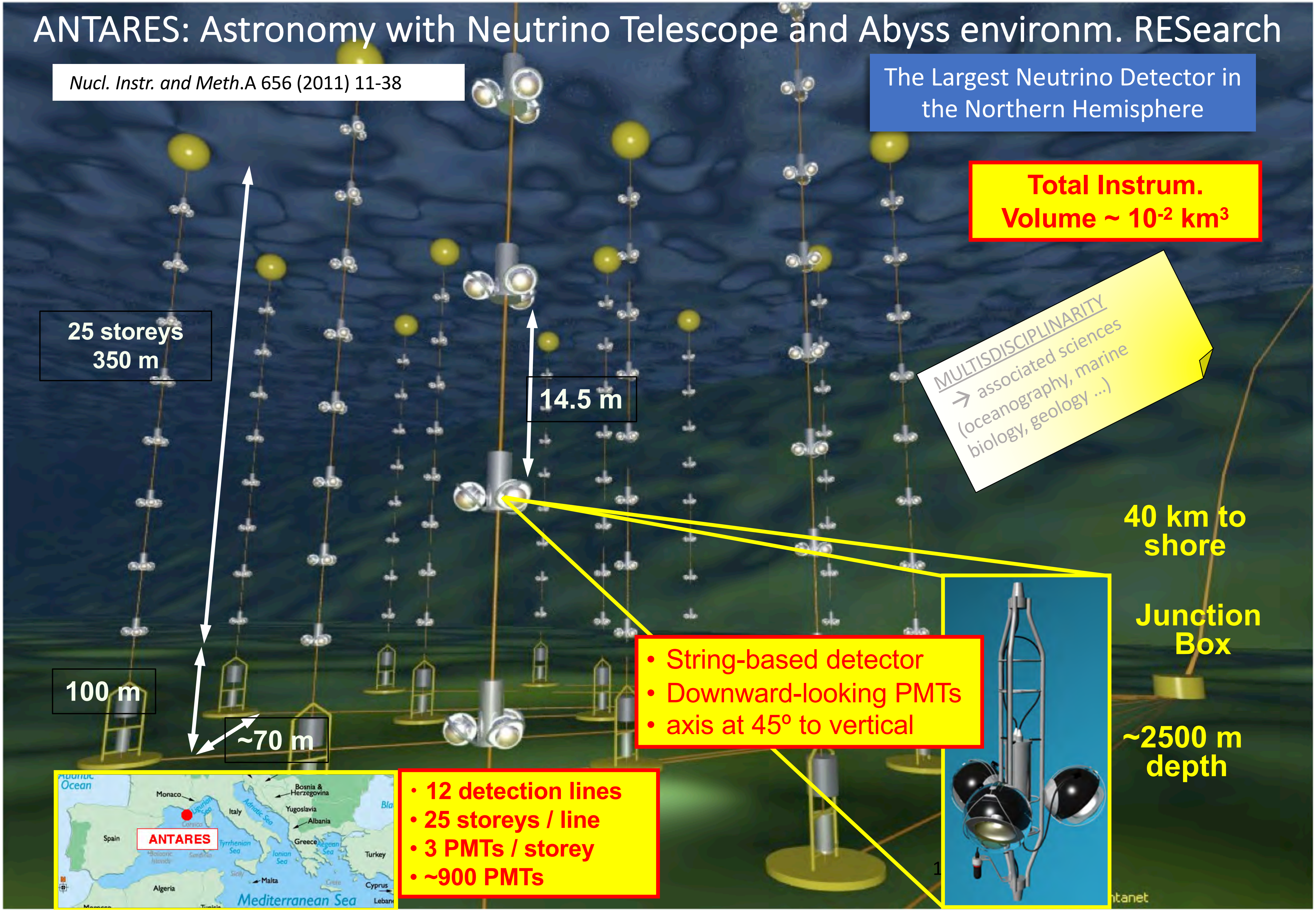
Closely related scientifically:

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

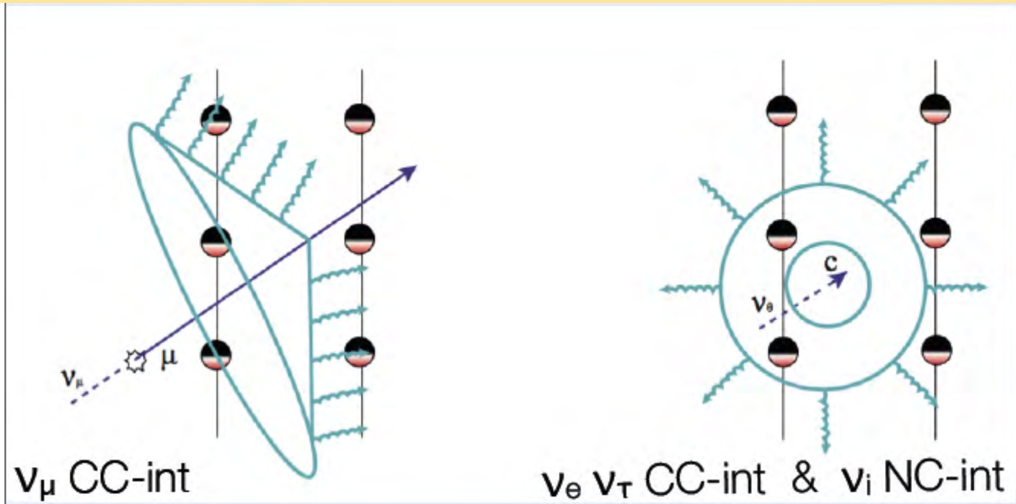


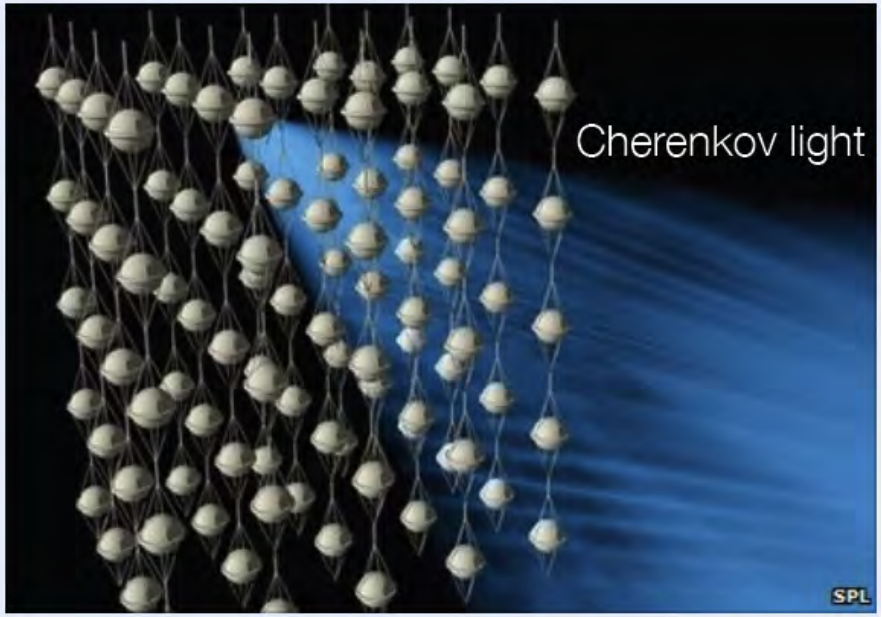
Neutrinos from all directions

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

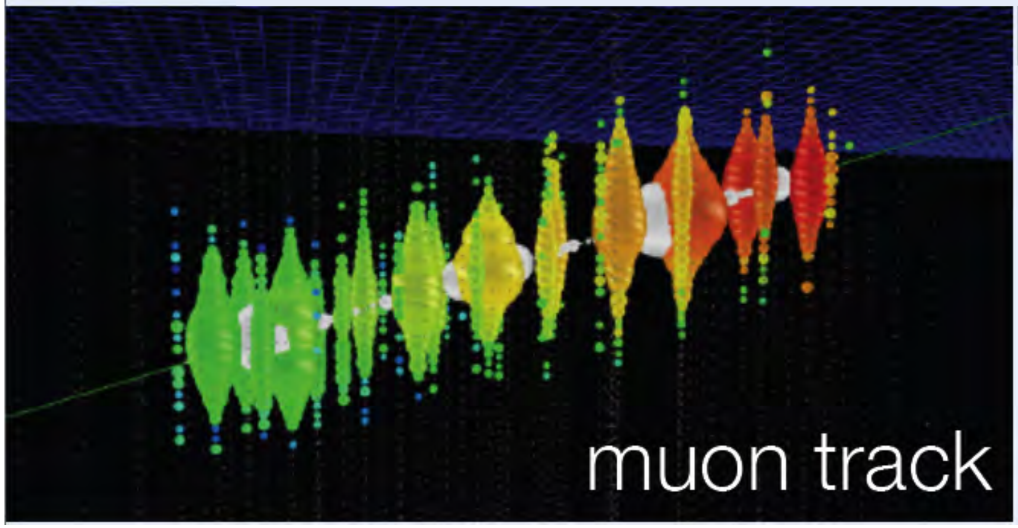

ANTARES: Astronomy with Neutrino Telescope and Abyss environm. RESearch
Nucl. Instr. and Meth.A 656 (2011) 11-38
The Largest Neutrino Detector in the Northern Hemisphere
Total Instrum. Volume ~ 10^{-2} km^3
MULTISDISCIPLINARITY
→ associated sciences (oceanography, marine biology, geology ...)
25 storeys
350 m
14.5 m
100 m
~70 m
40 km to shore
Junction Box
~2500 m depth
• String-based detector
• Downward-looking PMTs
• axis at 45º to vertical
• 12 detection lines
• 25 storeys / line
• 3 PMTs / storey
• ~900 PMTs
ANTARES
Monaco
Italy
Spain
Algeria
Bosnia & Herzegovina
Yugoslavia
Albania
Greece
Turkey
Malta
Cyprus
Tyrrhenian Sea
Ionian Sea
Aegean Sea
Mediterranean Sea

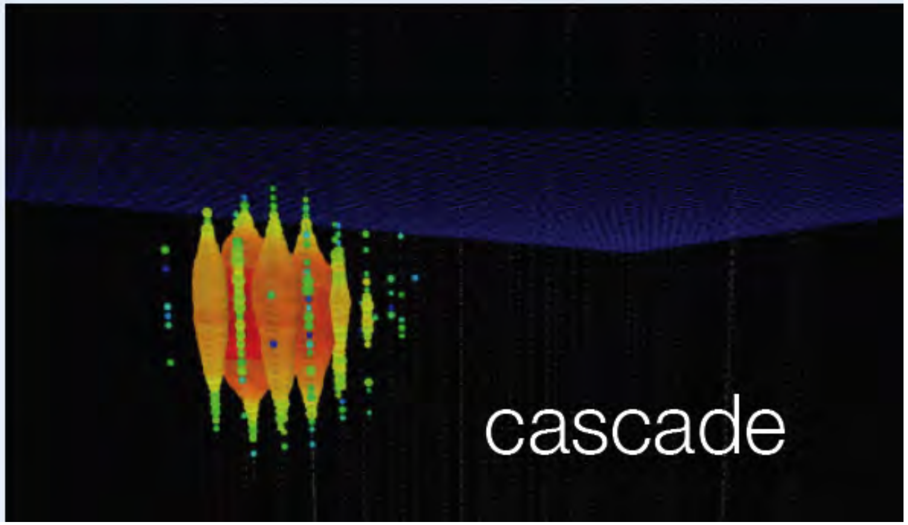
Events in IceCube Detector



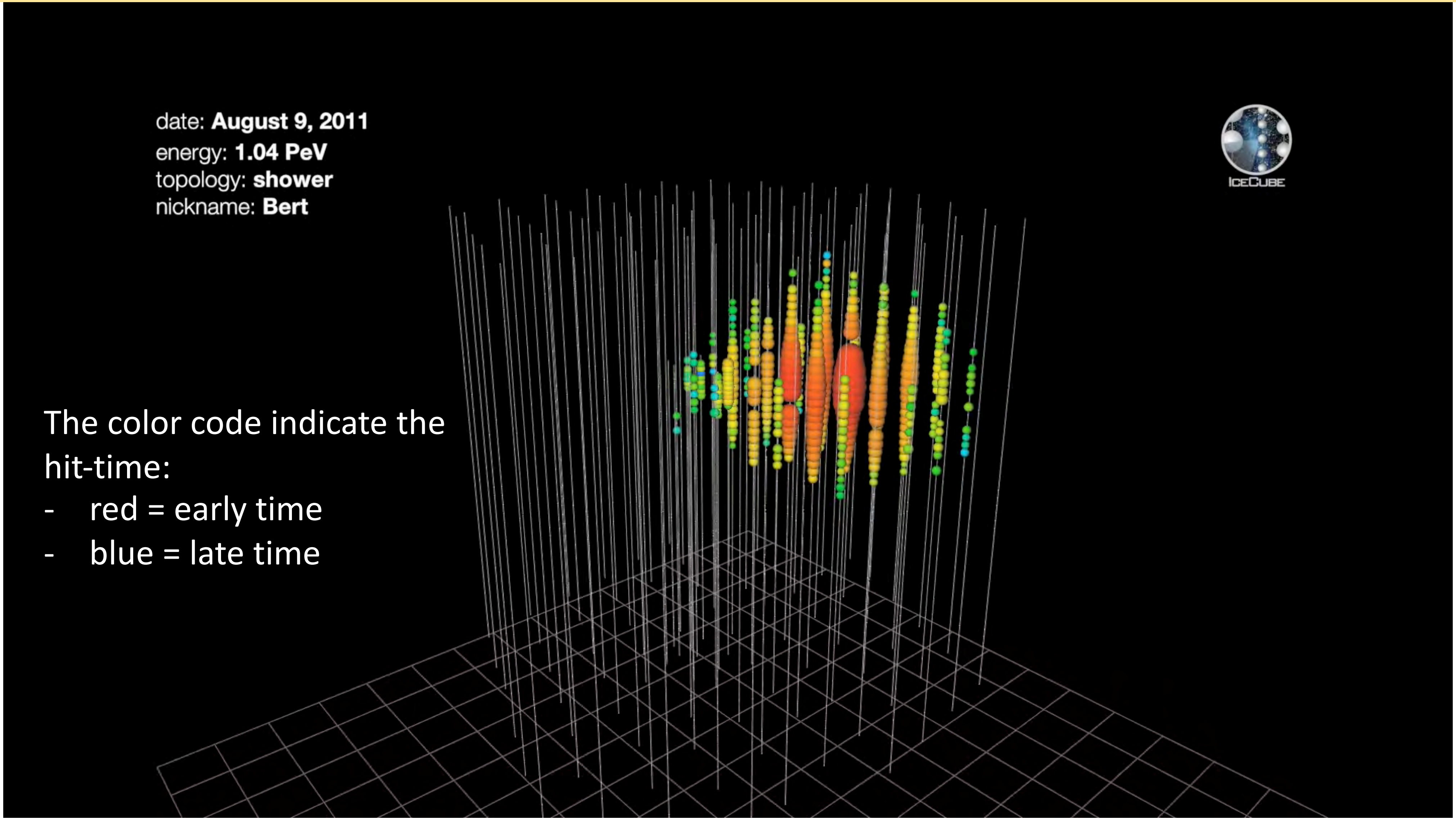


In the event display:
radius ~ number of photons
time ~ red → purple





A cosmic neutrino interacts in IceCube detector



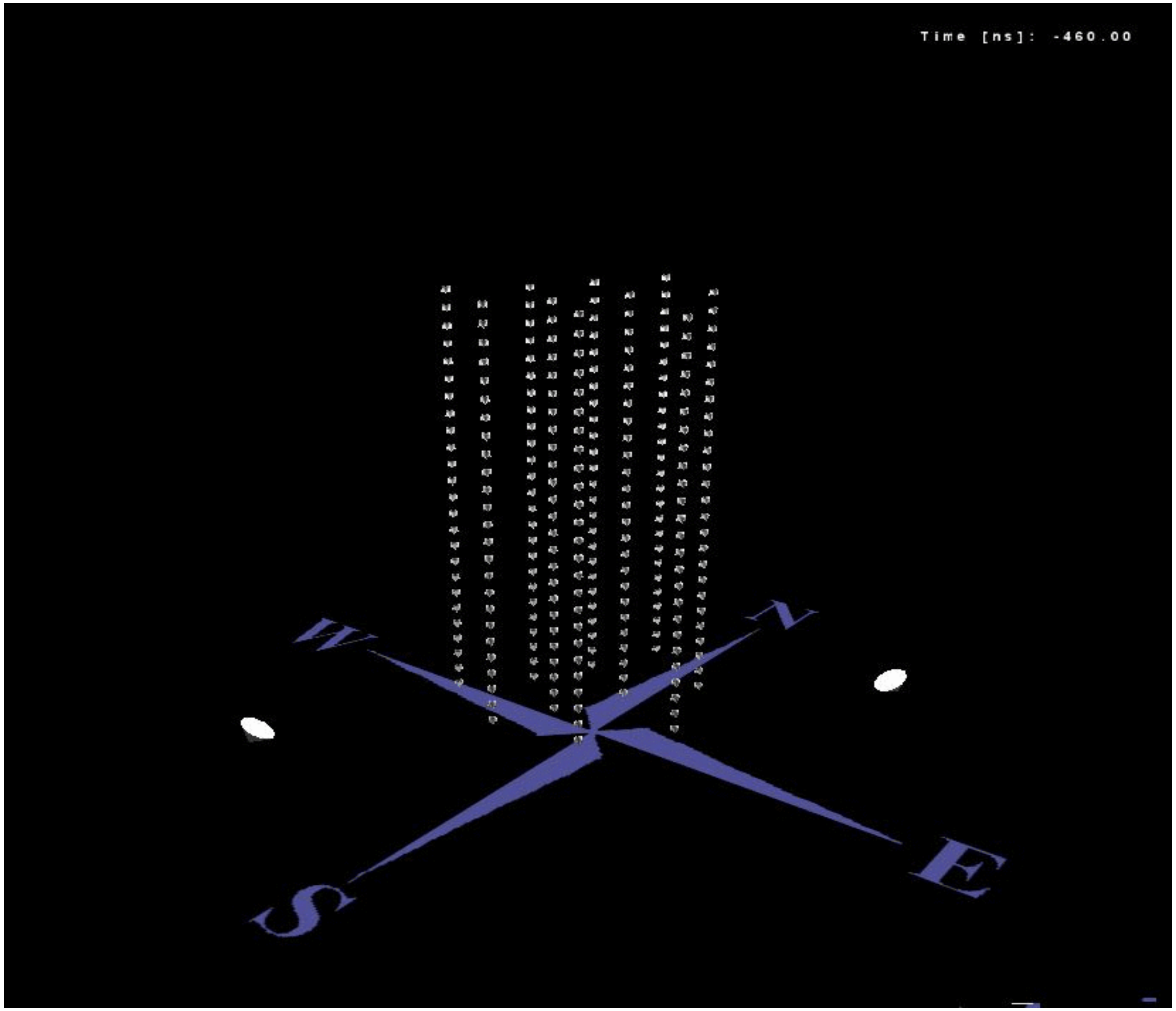
The color code indicate the hit-time:

- red = early time
- blue = late time

> 300 optical sensors; > 100,000 photons; 2 nsec time resolution

Up-going track in ANTARES: a neutrino candidate

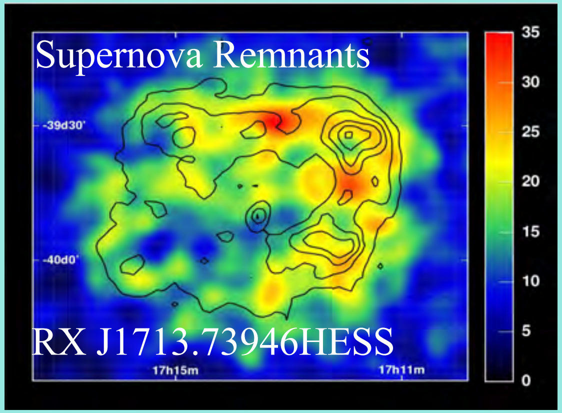
Example of a reconstructed up-going muon (i.e. a neutrino candidate)

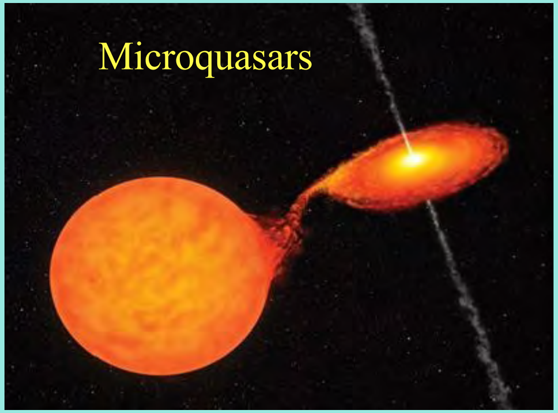


Neutrino Telescope physic's goal - 1

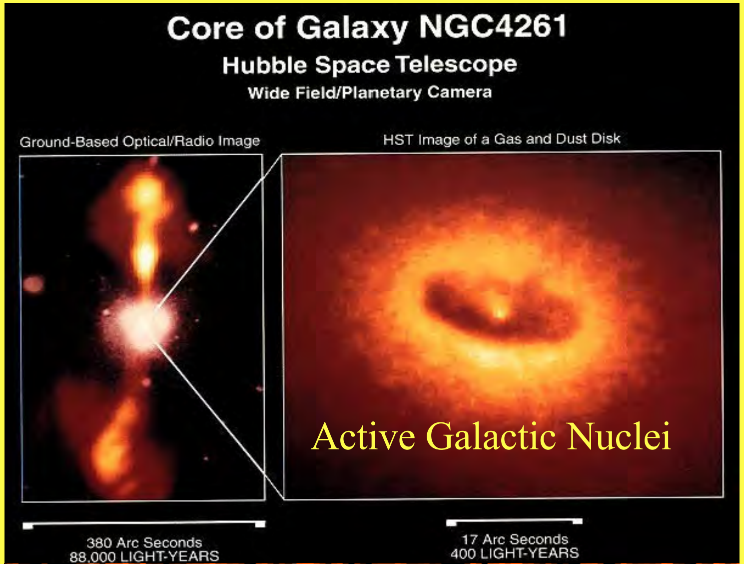
Search for point-like cosmic Neutrino Sources

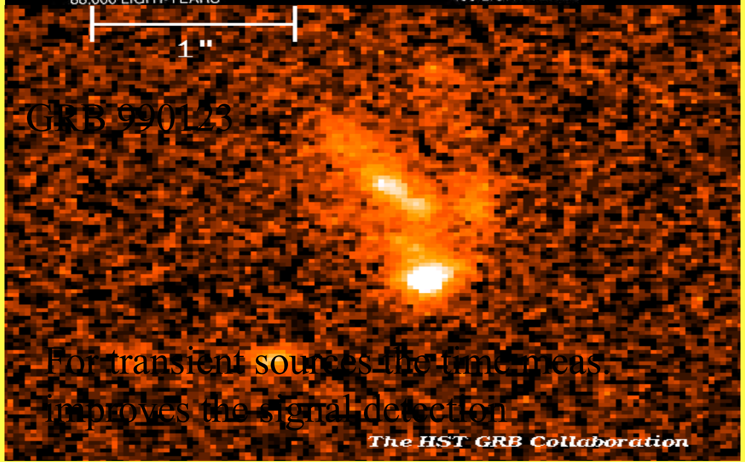
Galactic





Extragalactic





- Their identification requires a detector with accurate angular reconstruction

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

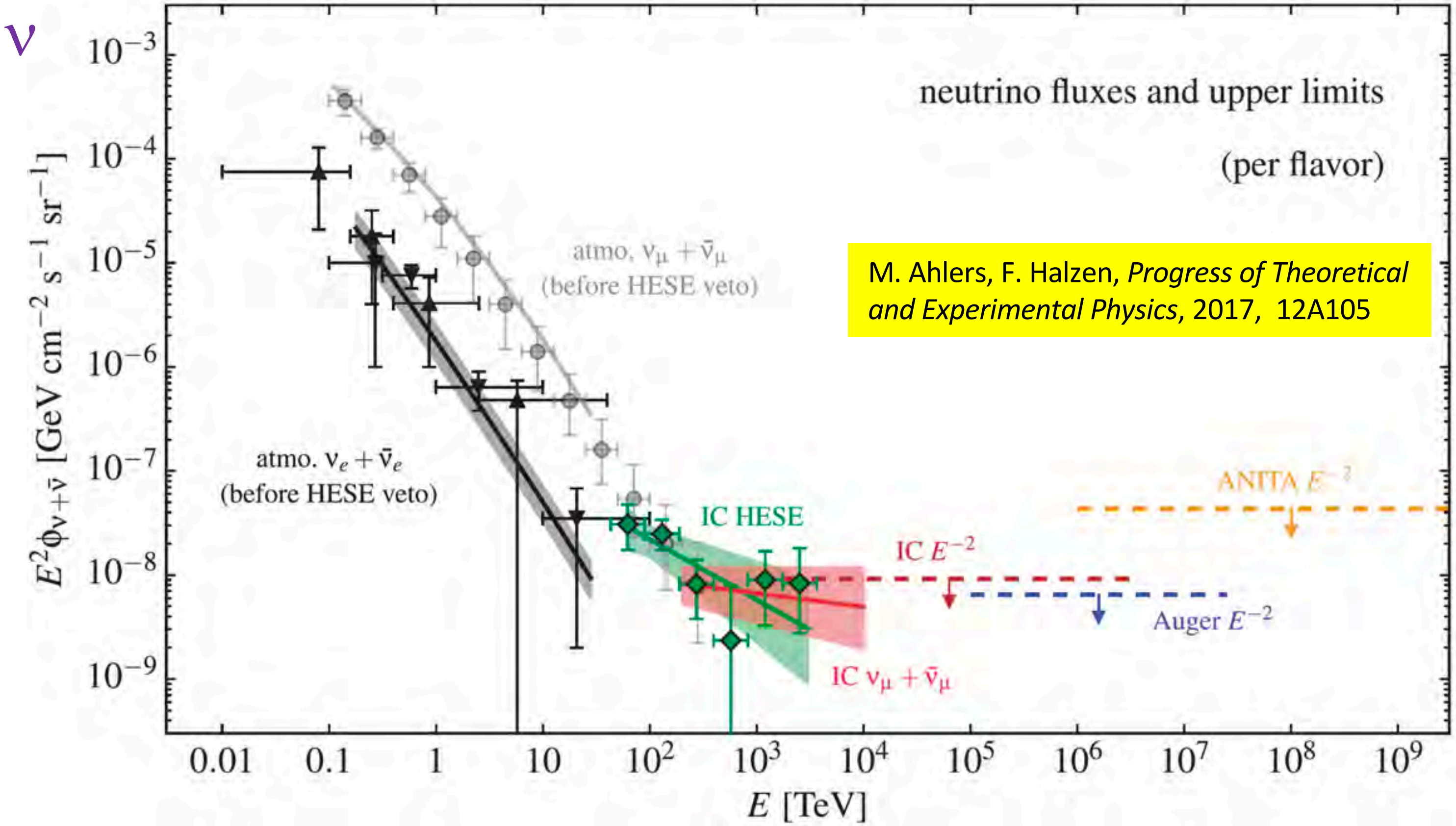
Experimental signal : statistical evidence of an excess of events coming from the same direction

Neutrino Telescope physic's goal - 2

Search for Diffuse flux of Cosmic Neutrinos

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

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.



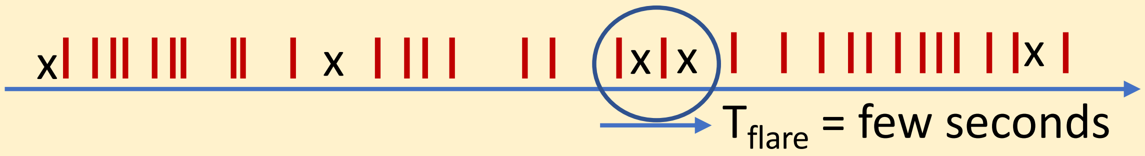
Neutrino Telescope physic's goal - 3

Neutrino Telescopes in a multi-messenger framework

- **Search for Coincident events, in a restricted time and direction windows, with EM/γ/GW counterparts (flaring sources, transient events, …)**
  - **Relaxed energy/direction measurement**
  - **Transient/ multi-messenger information**
  - **Observing γ, ν, CR, GW, … from the same source (or cosmic region):**
    - **propagation models**
    - **acceleration mechanisms**
    - **protons or electrons accelerated ?**

Steady source: data sample collected along large time interval, events integrated over observation period

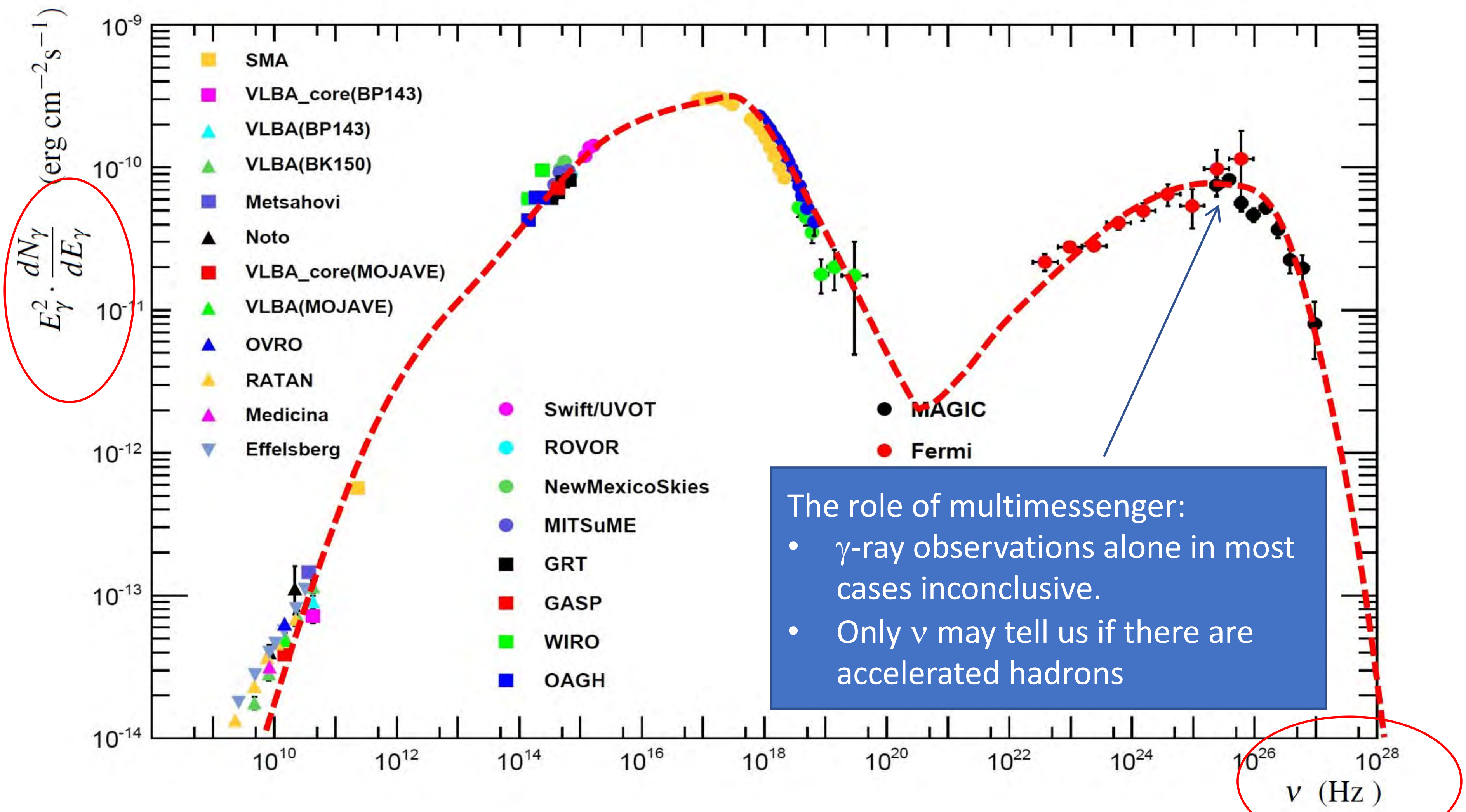
B_{tot} =30 events
S_{tot} = 5 events
T_{tot} =1year



(picture not in scale …)

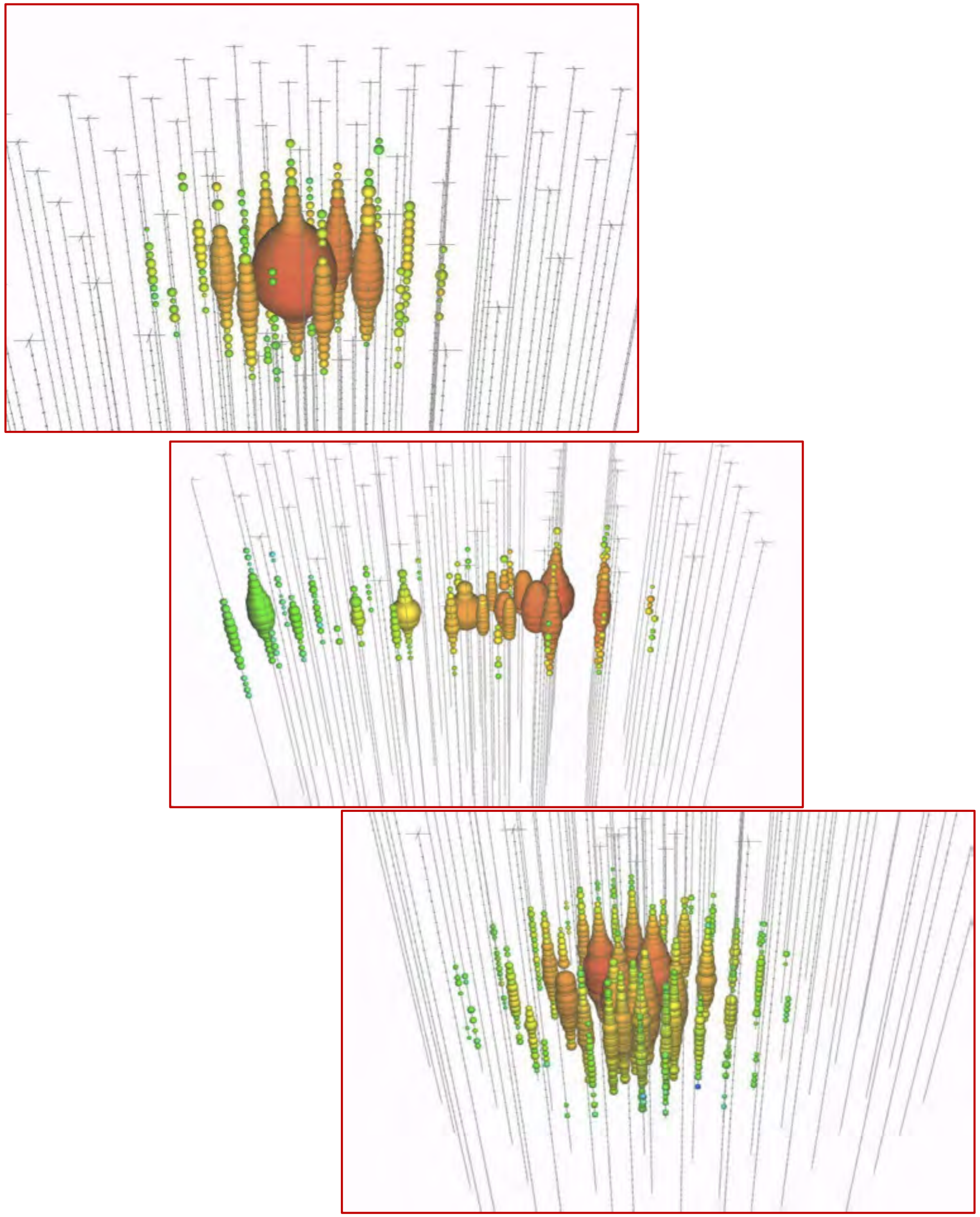
Flaring source: all Signal events collected, background integrated only during flaring time. **B_{flare} = 2 events** **S_{flare} = 2 events**

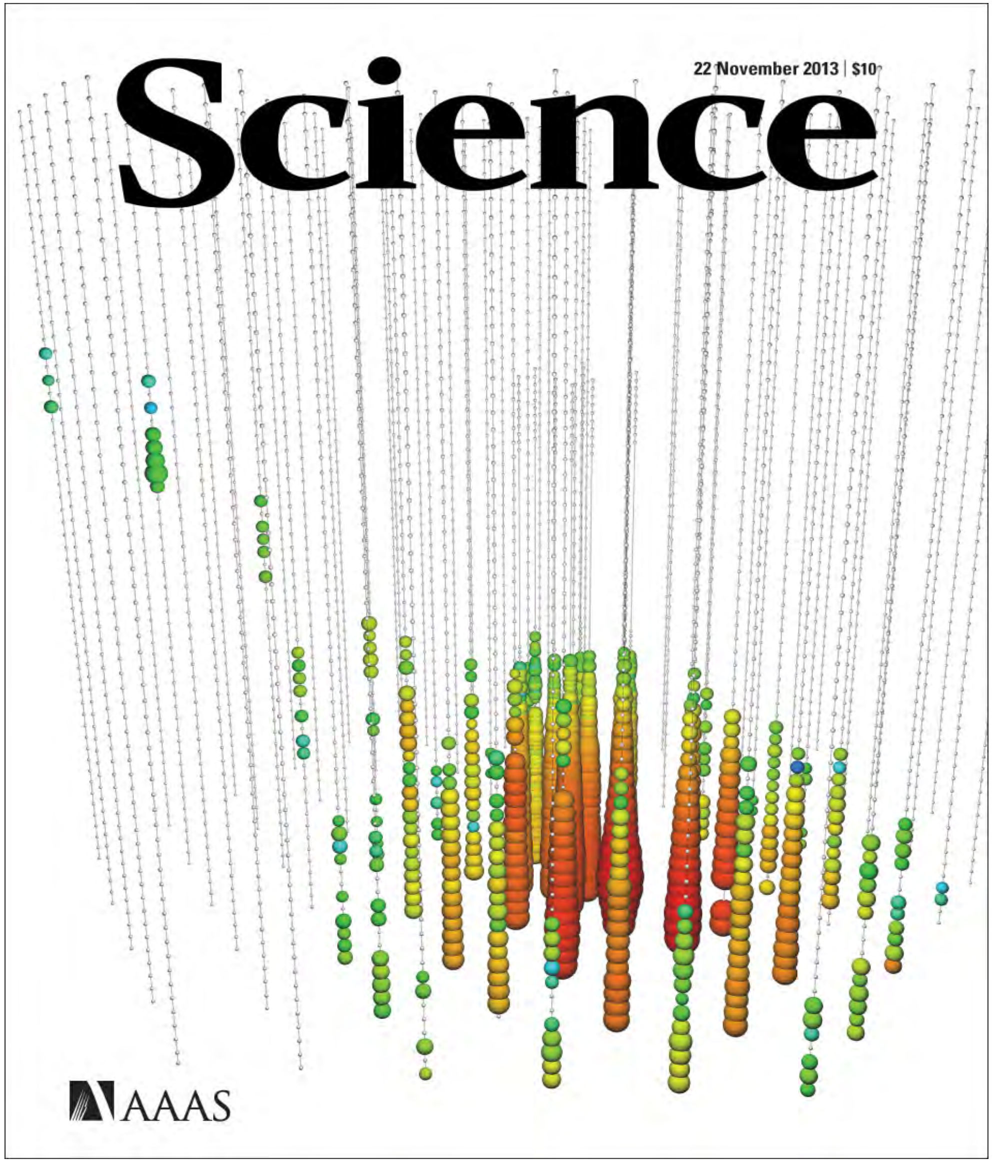
Multi-wavelength observation: Mrk421
an example



Extensive multi-wavelength measurements showing the spectral energy distribution (SED) of Markarian 421 from observations made in 2009. The dashed line is a fit of the data with a leptonic model. Abdo et al. ApJ 736(2011) 131 for the references to the data

2013 - The great IceCube discovery





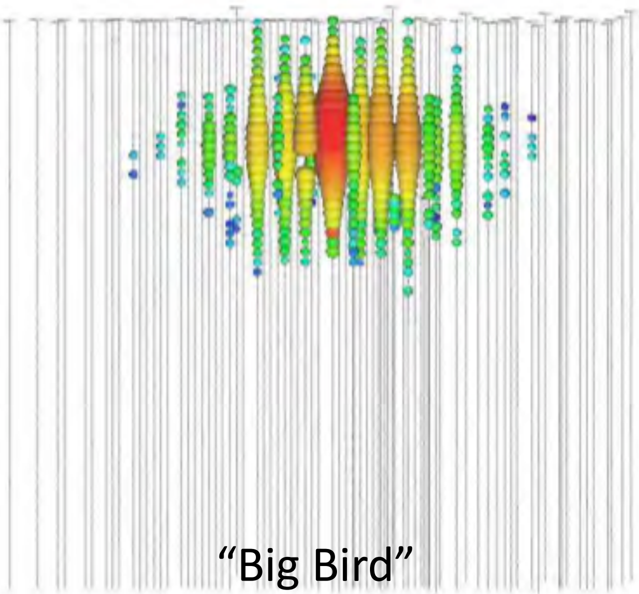
2-year analysis: Science 342, 1242856 (2013)

IceCube 2013 - High Energy Starting Event Analysis

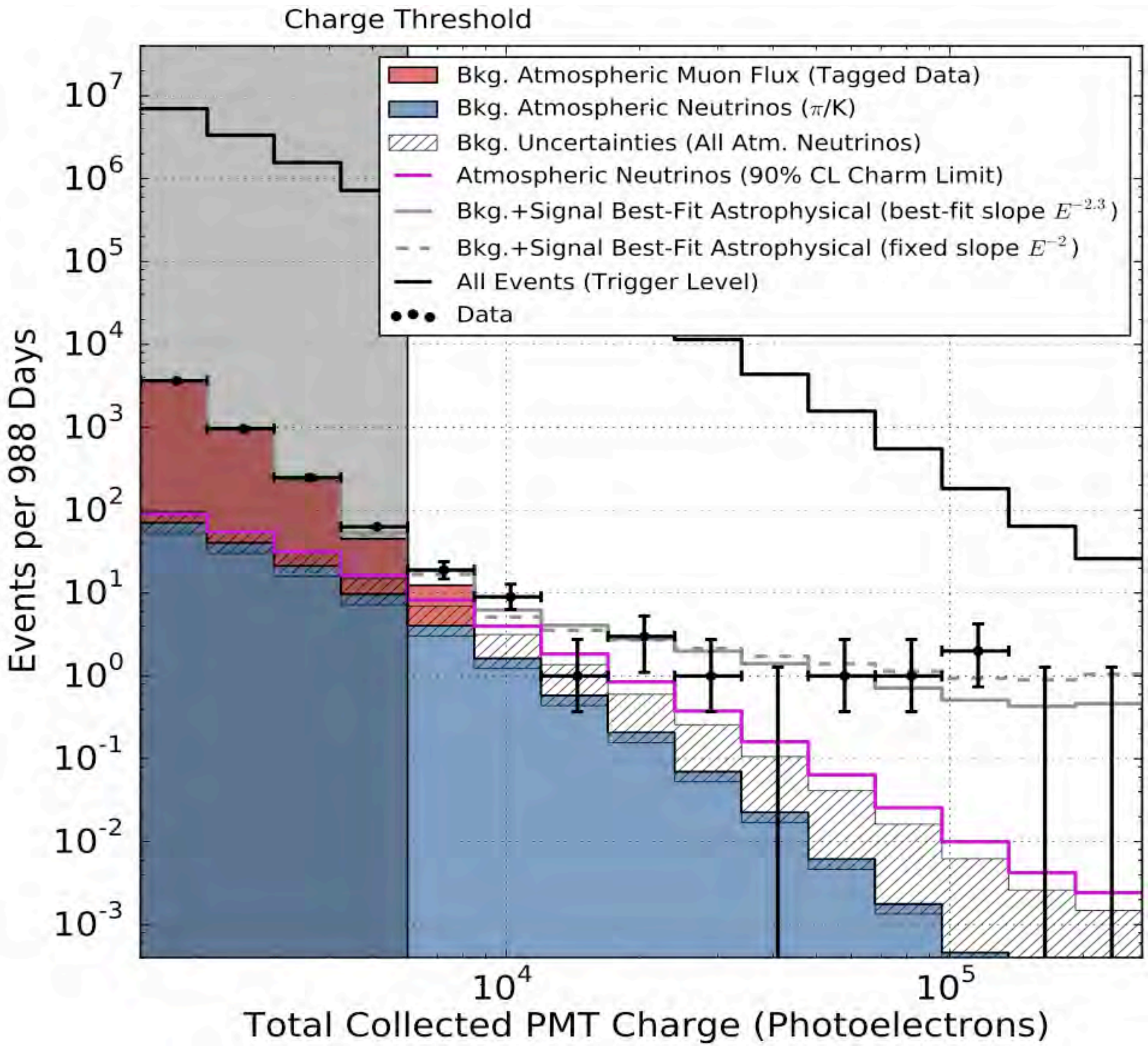
3-Year Analysis
PRL 113, 101101 (2014)

36 events in 3 years

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

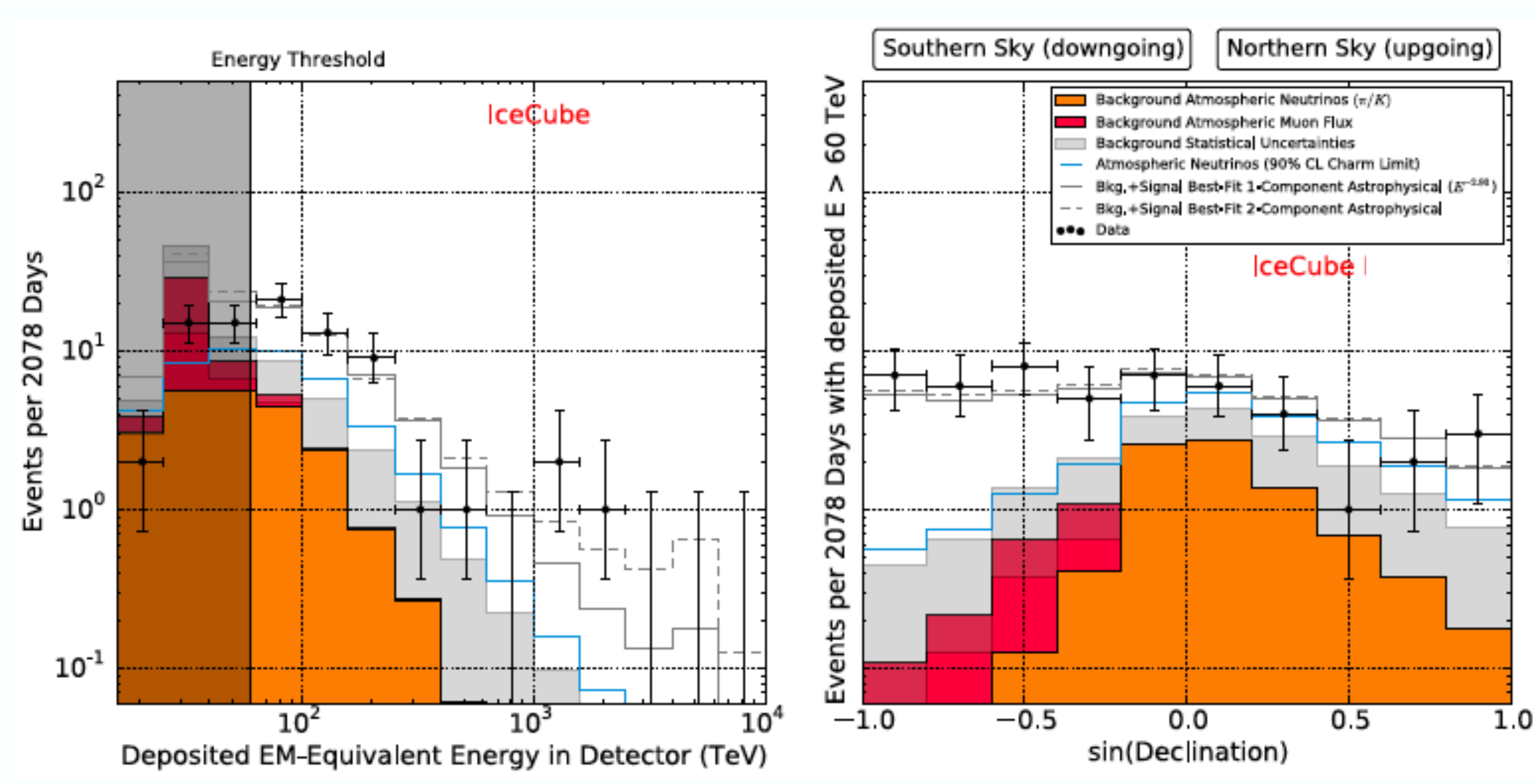


"Big Bird"



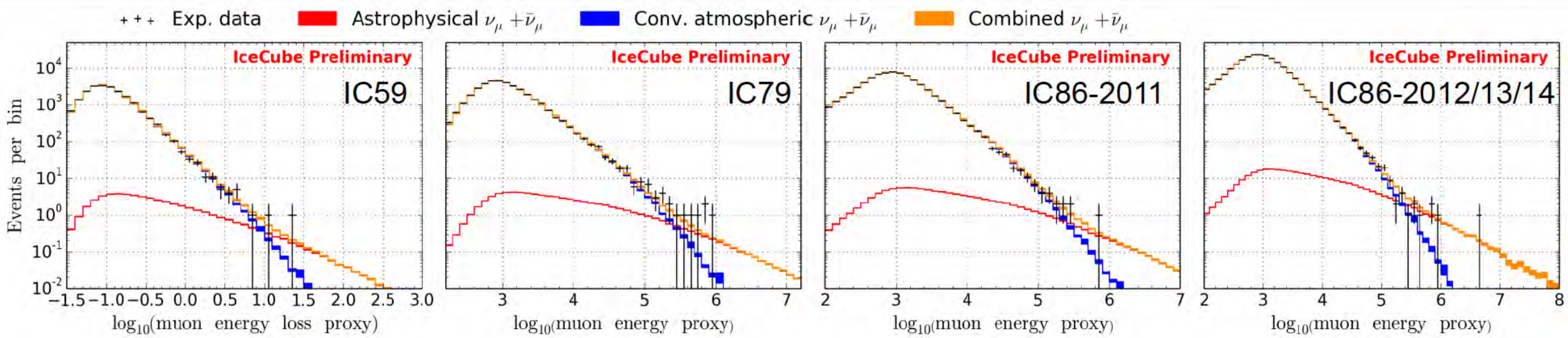
IceCube 2017 - High Energy Starting Event Analysis

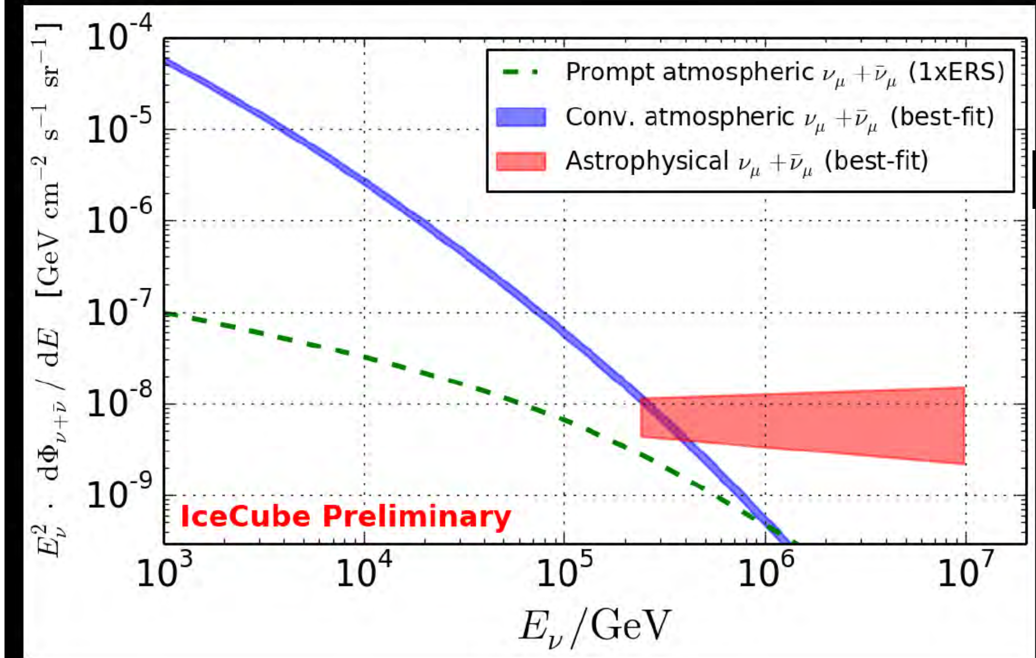
starting events: 6 years → 8σ



IceCube: 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:

$\gamma_{astro} = 2.16 \pm 0.11$

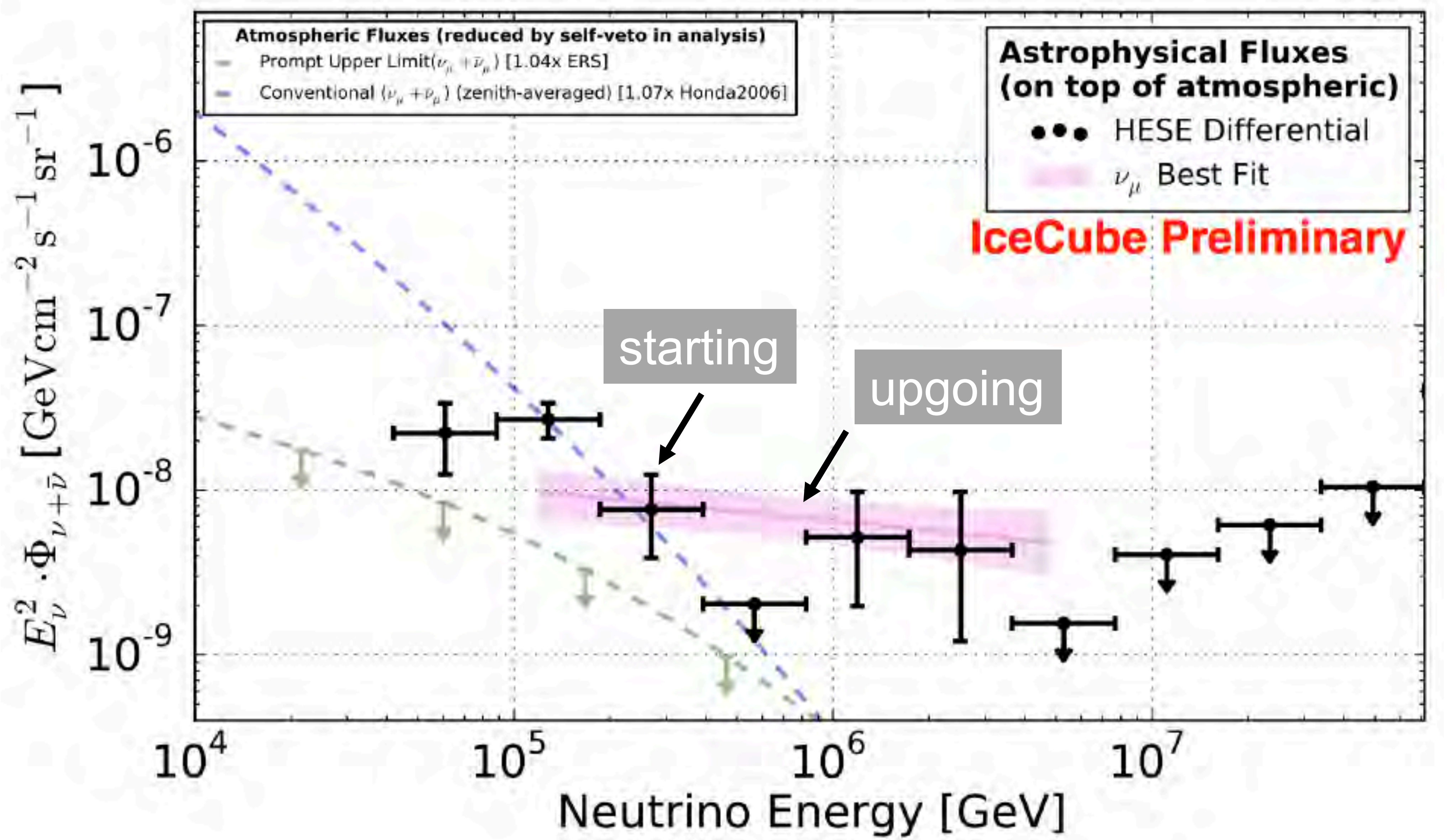
- Energy ranges:

240 TeV – 10 PeV

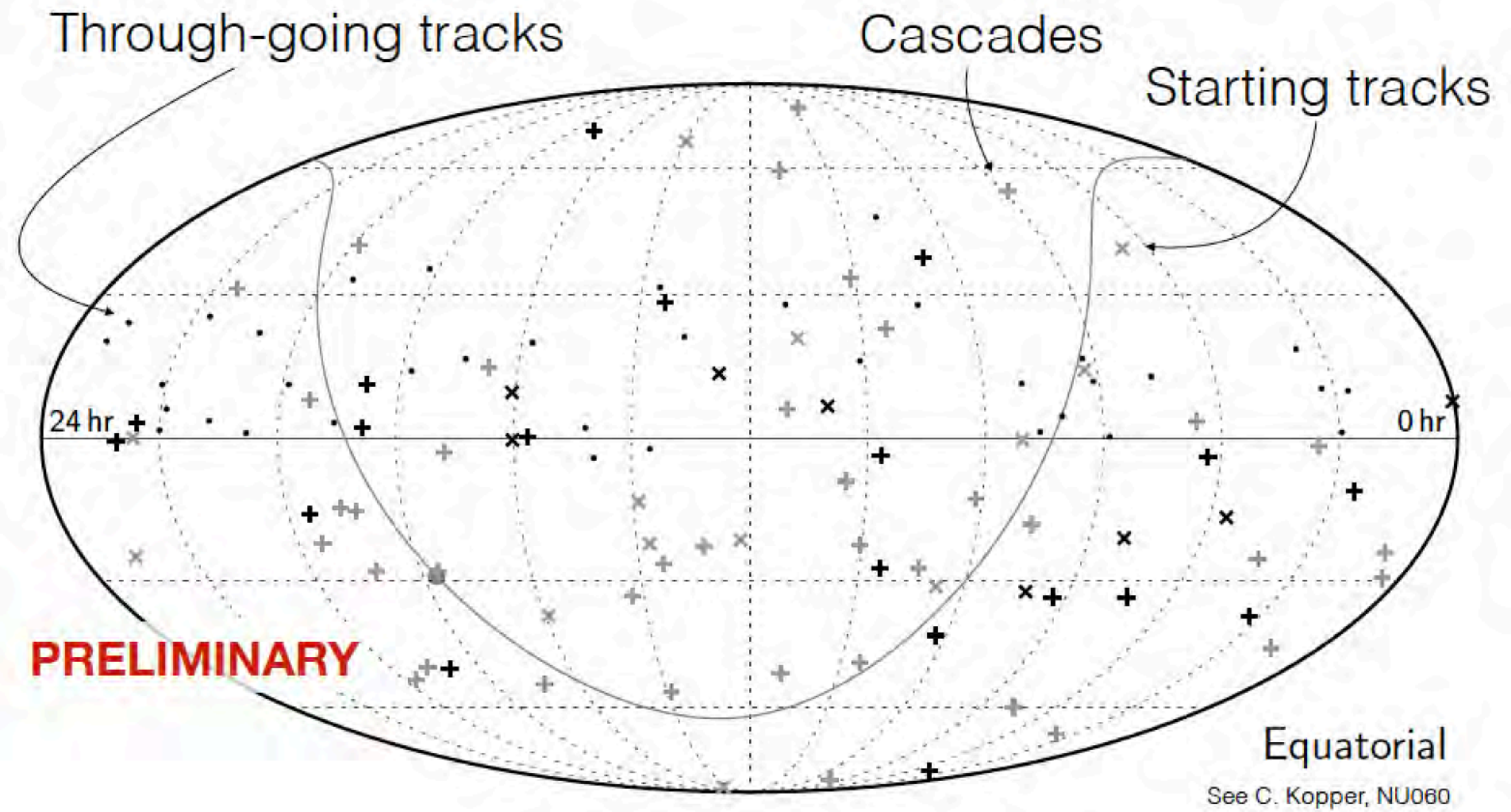
- Atmospheric-only hypothesis excluded by 6.0σ

IceCube 2017

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



Where these neutrinos are coming from ??



No indications of a strong anisotropy from extended emission regions which could indicate a contribution from Galactic sources along the Galactic plane. A subdominant Galactic component cannot be excluded. Hypothesis: H.E. ν diffuse flux from extragalactic sources.

ANTARES can help to understand the origin of this HE diffuse ν flux ???

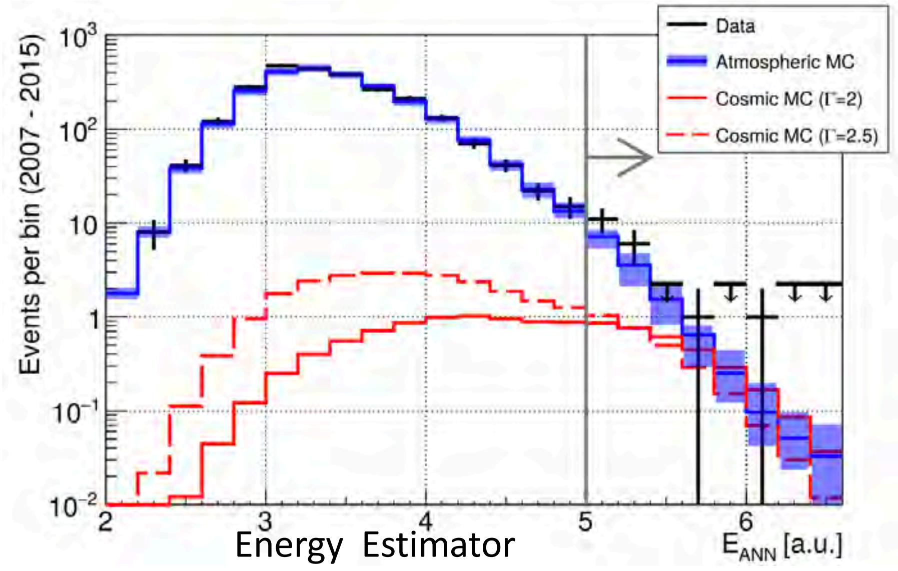
Latest ANTARES results on the search for diffuse ν flux

Tracks

Data: 2007-2015 (2451 live-days)

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

Observed: 19 evts

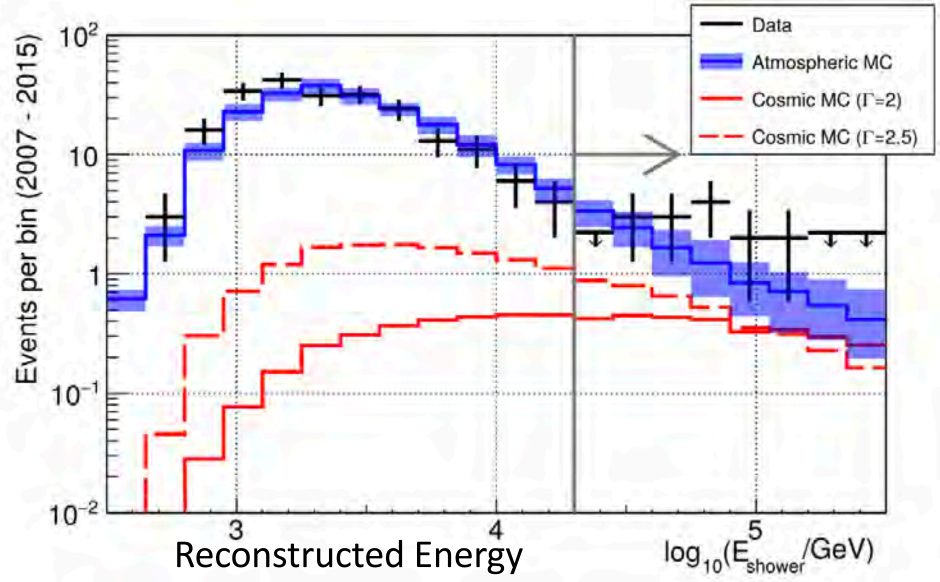


Cascades

Data: 2007-2013 (1405 live-days)

Above E_{cut}: Bkg: 10.5 ± 4 evts, IC-like signal: 1.5 evts

Observed: 14 evts



The Astrophysical Journal Letters, 853:L7, 2018

ANTARES

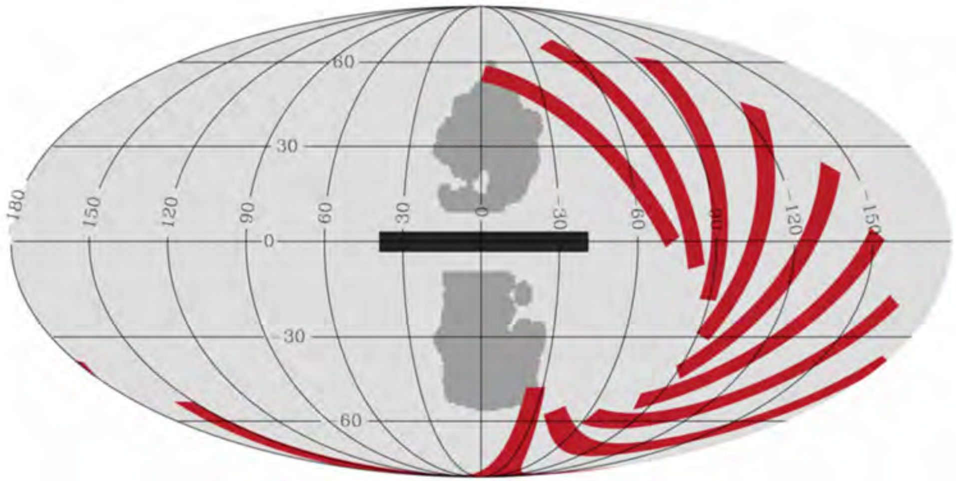
combined upper limits and sensitivities for 9 years data sample (2007-2015) tracks + cascades

The best fit for a single power-law cosmic neutrino spectrum, in terms of per-flavor flux at 100 TeV, is $\phi_0^{1f}(100\ \mathrm{TeV}) = (1.7 \pm 1.0) \cdot 10^{-18}\ \mathrm{GeV^{-1}cm^{-2}s^{-1}sr^{-1}}$ with spectral index $\Gamma = 2.4^{+0.4}_{-0.5}$

Search for neutrinos from the Galactic ridge - 1

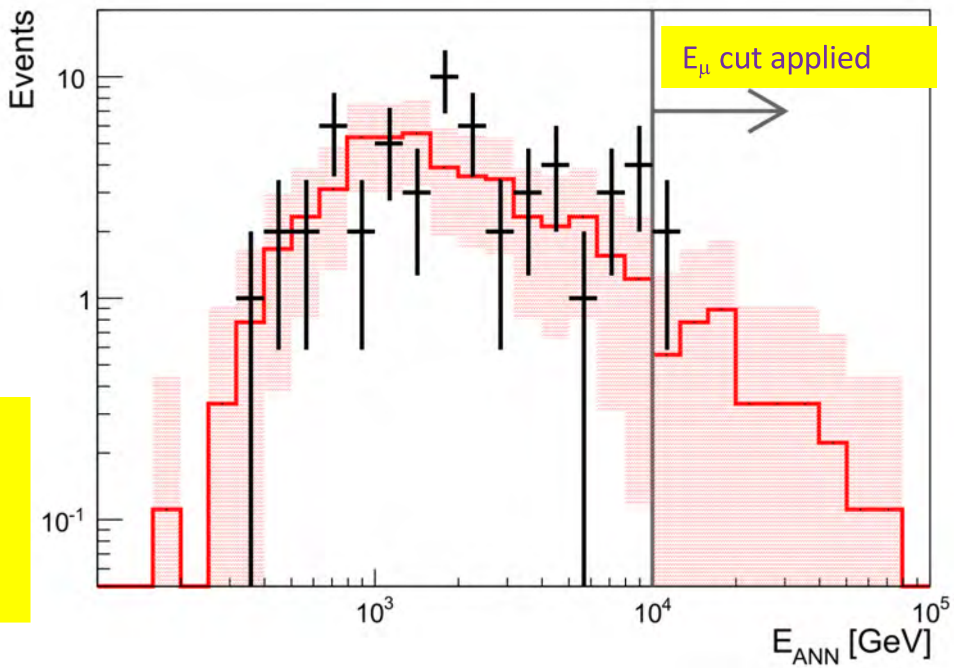
- ν's and γ-rays produced by CR propagation

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



- 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

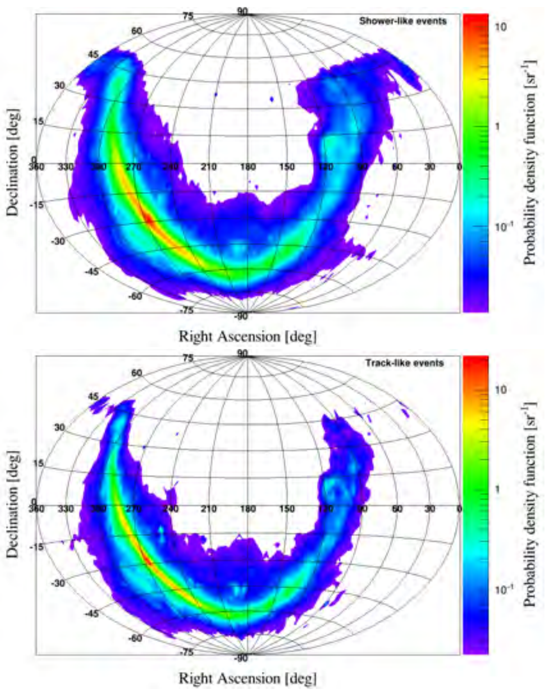


Distribution of the reconstructed E_μ of up-going muons in the Galactic Plane (black crosses) and average of the off-zone regions (red histogram).

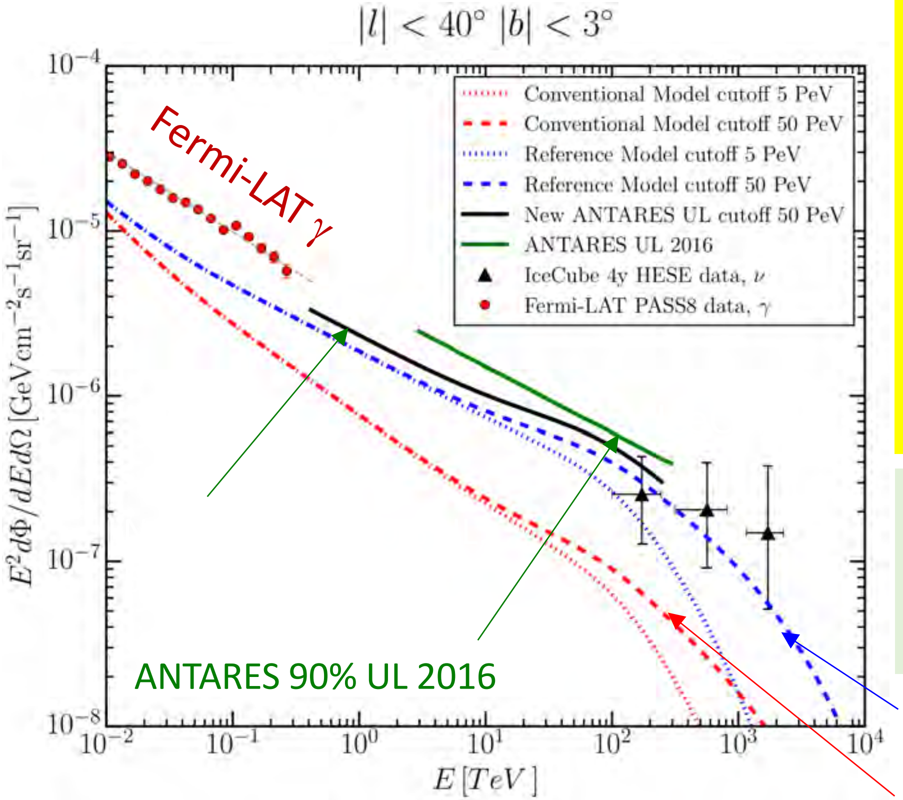
Search for neutrinos from the Galactic plane - 2

New analysis on tracks and showers, based on Maximum Likelihood analysis

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



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 ($\pi^0 \to \gamma\gamma$) well explained above few GeV.

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

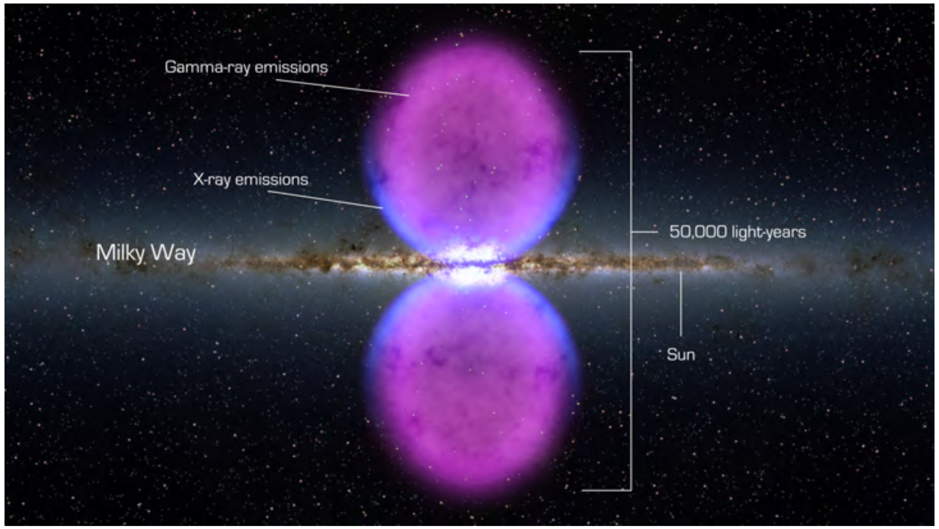
KRA_γ 50PeV cut-off for CR
KRA_γ 5PeV cut-off for CR

KRA_γ assuming a neutrino flux ∝ $E^{-2.5}$ and a CR spectrum with 50 PeV cut-off 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.

Neutrinos from "FERMI Bubbles" ??

Search from a Mediterranean Cherenkov ν Telescope

- FERMI detected hard γ emission (E^{-2}) up to 100 GeV in extended "bubbles" around Galactic Center, hard spectrum not compatible with Inverse Compton mechanism, M.Su et al., Ap.J.724 (2010).
- Models involving hadronic processes (e.g. Crocker & Aharonian, PRL 2011) predict significant neutrino fluxes.
- Estimates for the neutrino flux: $\Phi_\nu \approx 0.4 \cdot \Phi_\gamma \Rightarrow \quad E_\nu^2 \frac{dN_{\nu_\mu+\bar{\nu}_\mu}}{dE_\nu} \approx 1.2 \div 2.4 \cdot 10^{-7} GeV\ cm^{-1} s^{-1} sr^{-1} = A_{theory}$
- An exponential energy cut-off could affect the flux $E_\nu^2 \frac{dN_{\nu_\mu+\bar{\nu}_\mu}}{dE_\nu} = A_{theory} e^{-\frac{E}{E_\nu^{cutoff}}}$
- ANTARES, the present Mediterranean ν Telescope, searched for these neutrinos.



Search for a diffuse flux of ν_μ from “FERMI Bubbles”

Compare the neutrino-like events coming from 3 "off-zones" (with the same size and shape as the Fermi Bubbles "on-zone") with the events coming from the Fermi Bubbles

Events selected as up-going and well reconstructed tracks.
Data sample, in the period 2008-2011, includes 806 days

In the 3 off-zones observed:

n_{bkg} = 9, 12 and 12 events

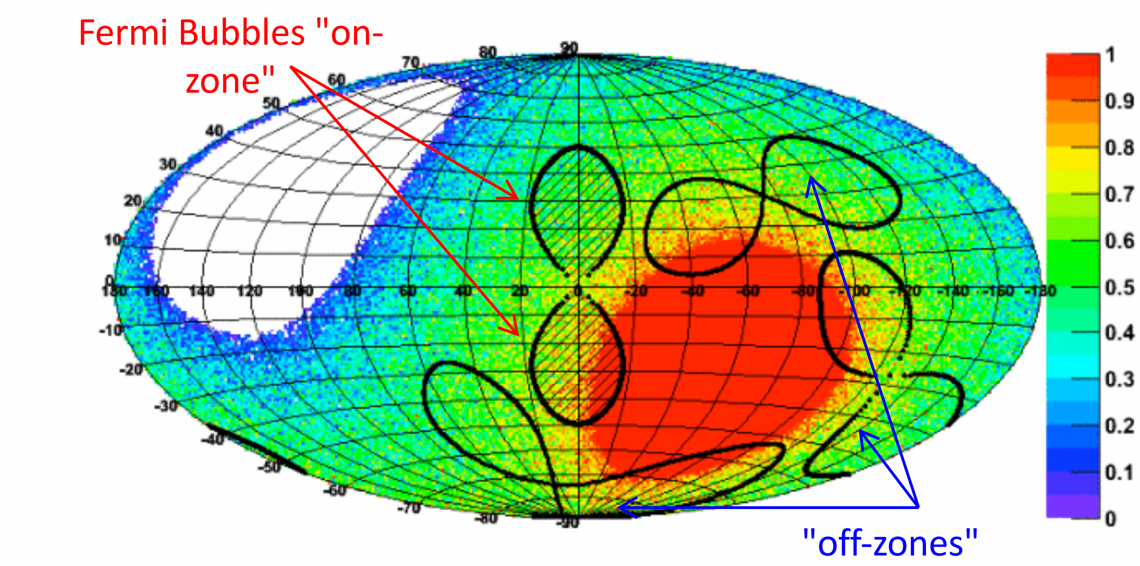
In the Fermi-Bubble **region**

n_{obs} = 16 events (1.2σ excess)

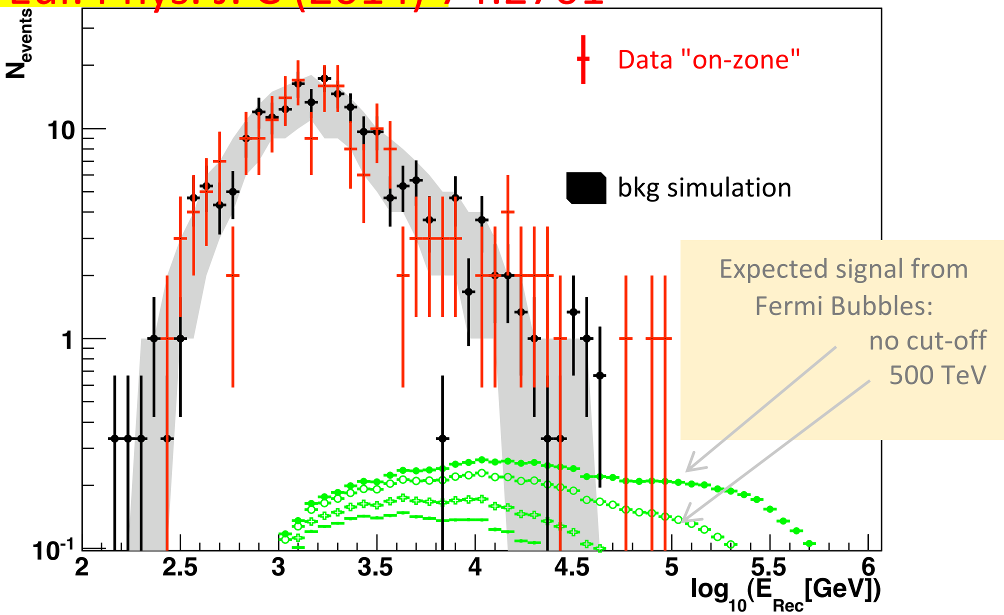
No statistically consistent signal observed.

Assuming no cut-off
$E^2\Phi(E)_{90\%C.L.} = 5.7 \bullet 10^{-7}$ GeV cm^{-2} s^{-1} sr^{-1}

Assuming 500 TeV cut-off
$E^2\Phi(E)_{90\%C.L.} = 8.7 \bullet 10^{-7}$ GeV cm^{-2} s^{-1} sr^{-1}



Eur. Phys. J. C (2014) 74:2701

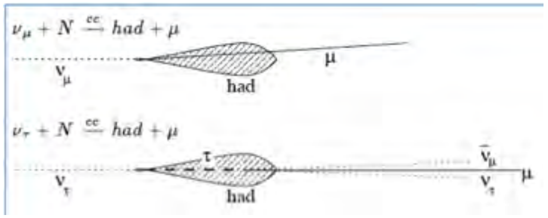


It's mandatory now !!!!

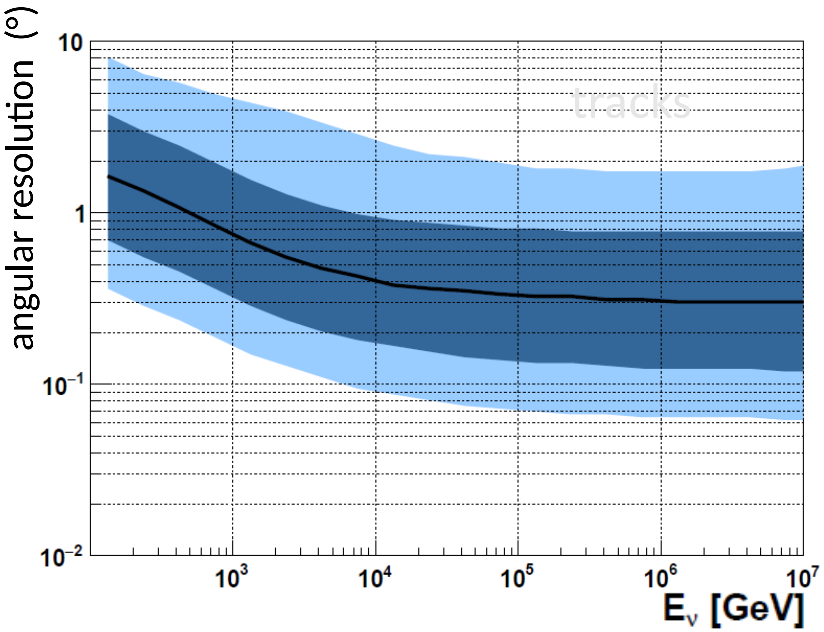
- **To search for neutrino point like sources:**
  - Large size detector required (very small fluxes expected)   (KM3NeT, IceCube phase2)
  - Very good accuracy in angular reconstruction (high background, the irreducible atmospheric background has to be subtracted statistically)
  - Multimessenger analysis

The ANTARES search for point-like ν sources based on two kind of events

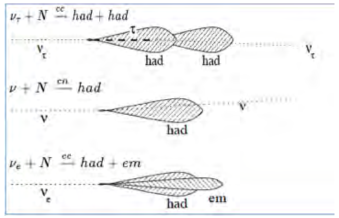
- Tracks: CC ν_μ or $\nu_\tau \rightarrow \mu$



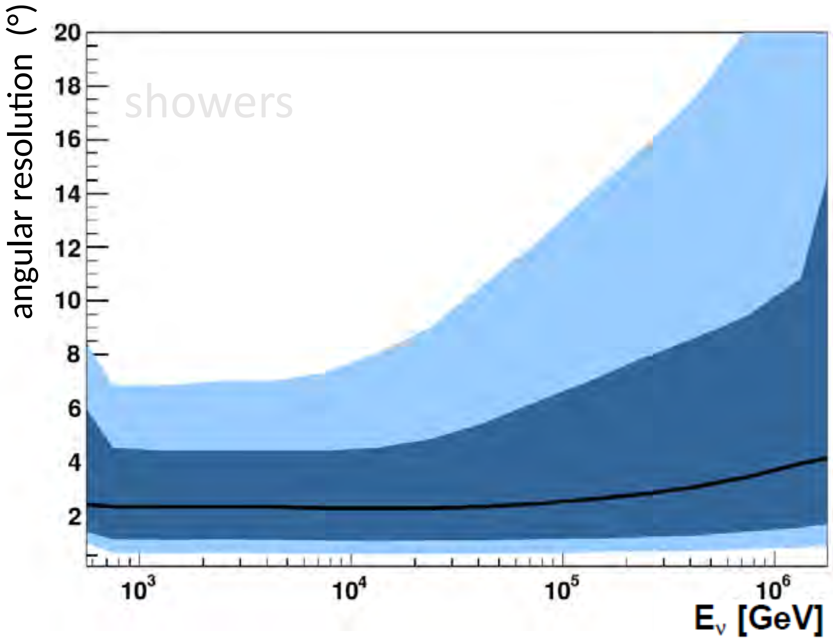
- Interaction can occur far from the detector providing a large *Effective Volume*
- *Angular resol.* $< 0.4°$ for $E_\nu > 10\ TeV$
- *Energy resol.* ~ factor 3



- Electronic or hadronic showers: NC and CC ν_e or $\nu_\tau \rightarrow$ showers



- Events contained in the detector: smaller *Effective Volume,*
- *Energy resolution ~ 5-10%*
- *Median angular resolution* $\sim 3°$

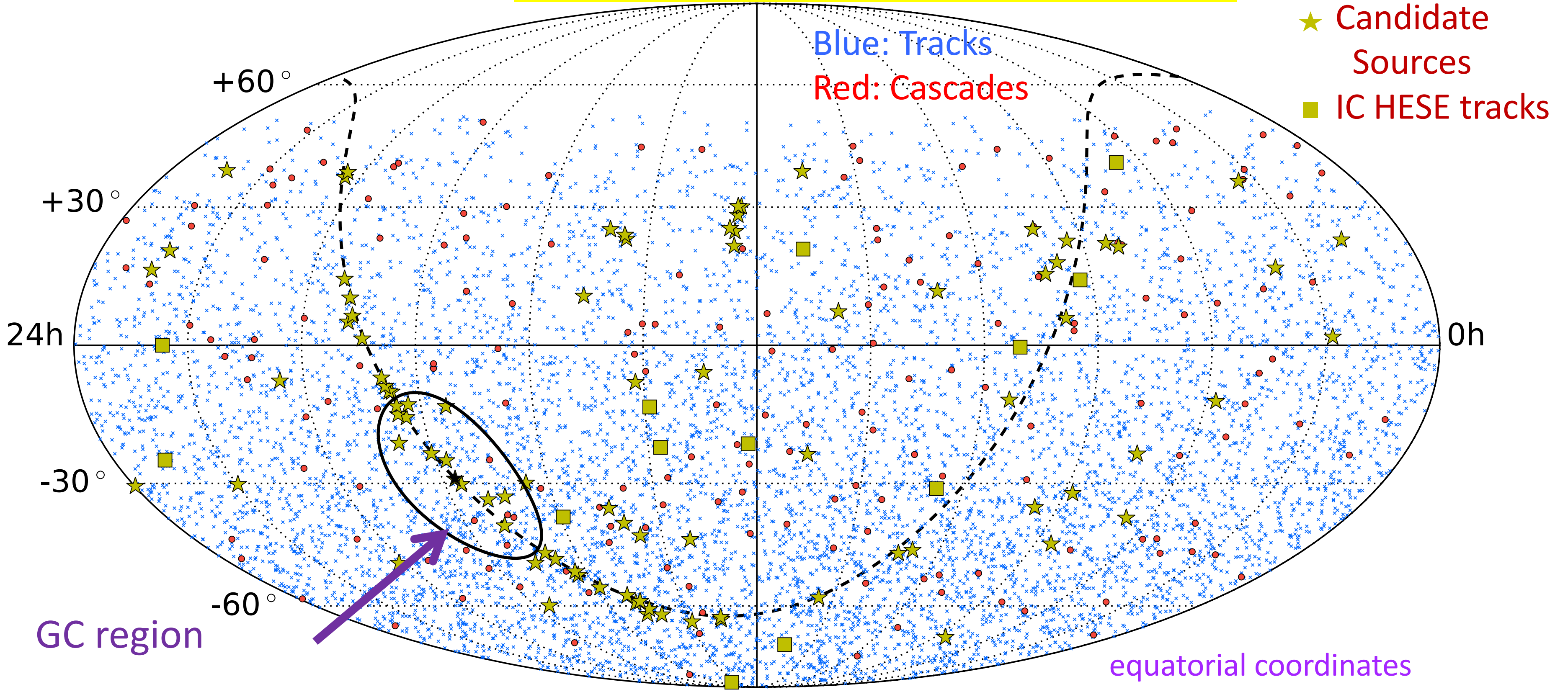


ANTARES Search for point-like cosmic ν Sources

9 years of ANTARES data searching for all neutrino flavours:
7629 “tracks” + 180 “shower” events passed the selection criteria

$$\log\mathcal{L}_{sig+bkg} = \sum_{S=tr.,sh.}\sum_{\tau=S} \log[\mu^{\tau}_{sig}\cdot\mathcal{F}^{\tau}_{sig}(\delta)\cdot\mathcal{P}^{\tau}_{sig,i}(E_i)+\mathcal{N}^{\tau}\cdot\mathcal{B}^{\tau}_{i}\cdot\mathcal{P}^{\tau}_{bkg,i}(E_i)]-\mu_{sig}$$

ANTARES arXiv:1706.01857v1, 6 June 2017

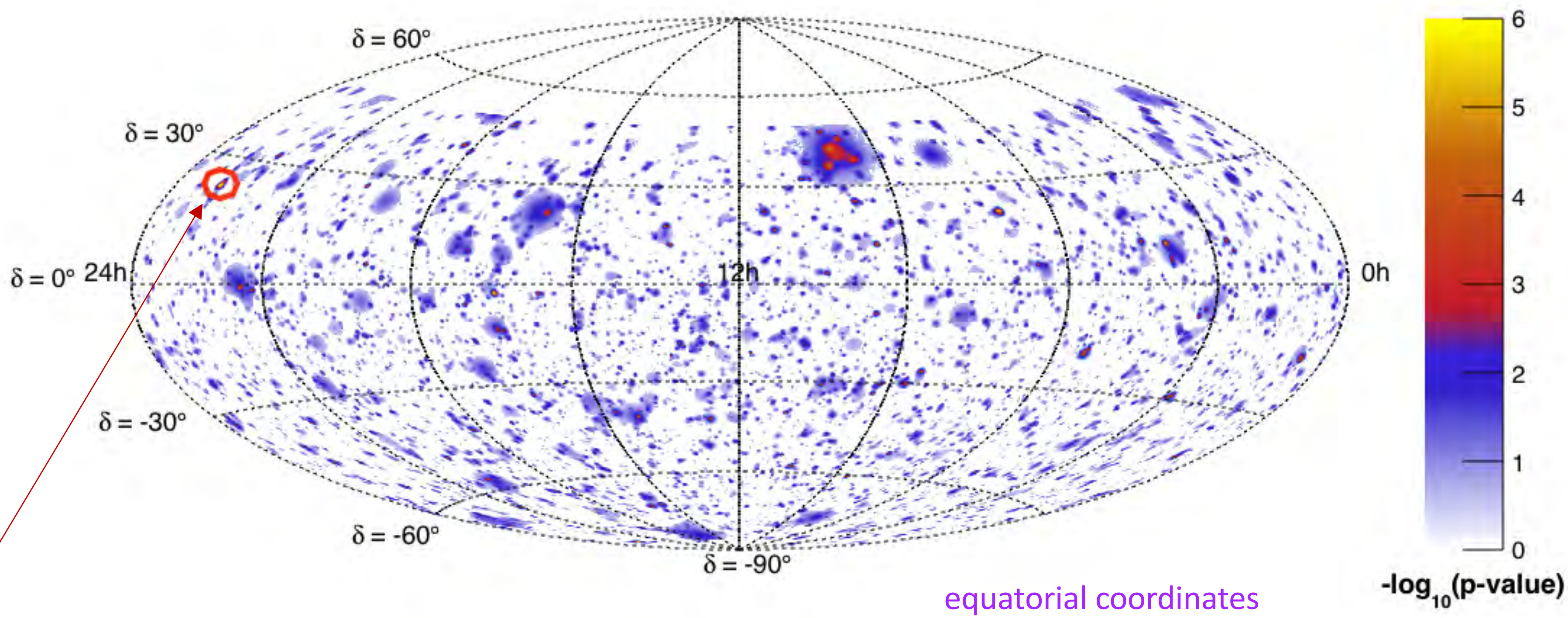


so far …. no significant excess has been found

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

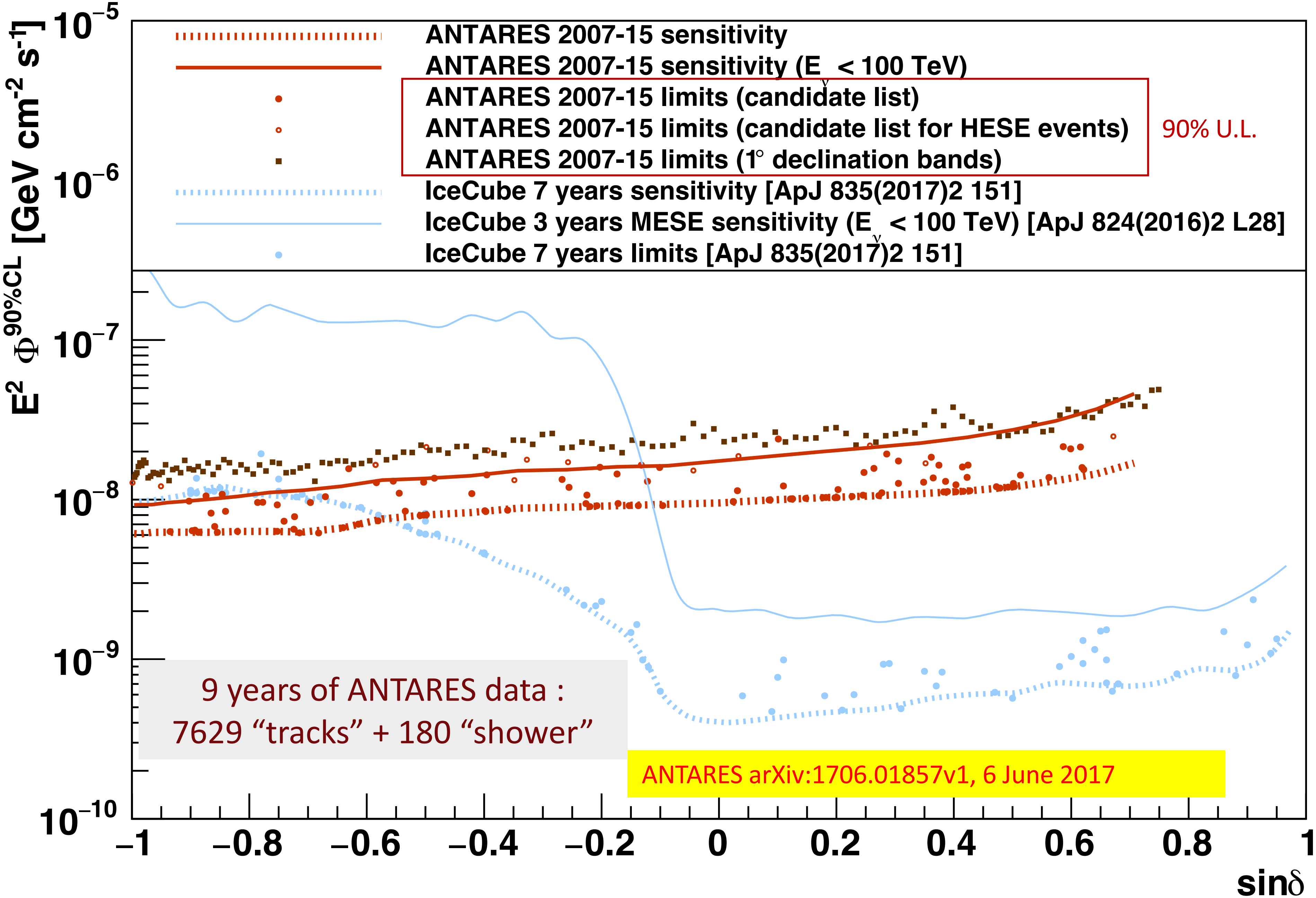


equatorial coordinates

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}

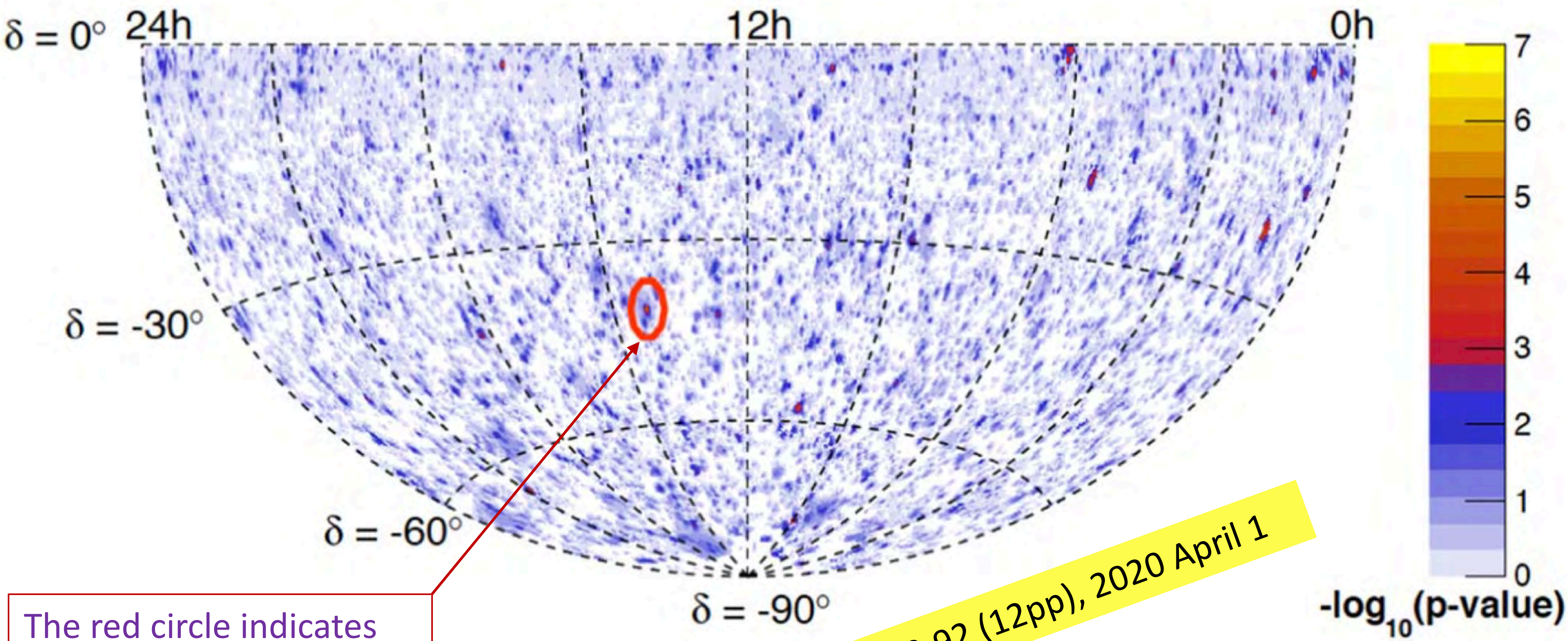
→ U. L. from this sky location $E^2 \frac{d\Phi}{dE} = 3.8 \times 10^{-8}$ GeV cm^{-2} s^{-1}

ANTARES results: “full sky search” of ν sources



Joint IceCube + ANTARES search for ν sources

Skymap of pre-trial p-values for the combined ANTARES (9 years) and IceCube 97 years) point-like sources analysis.

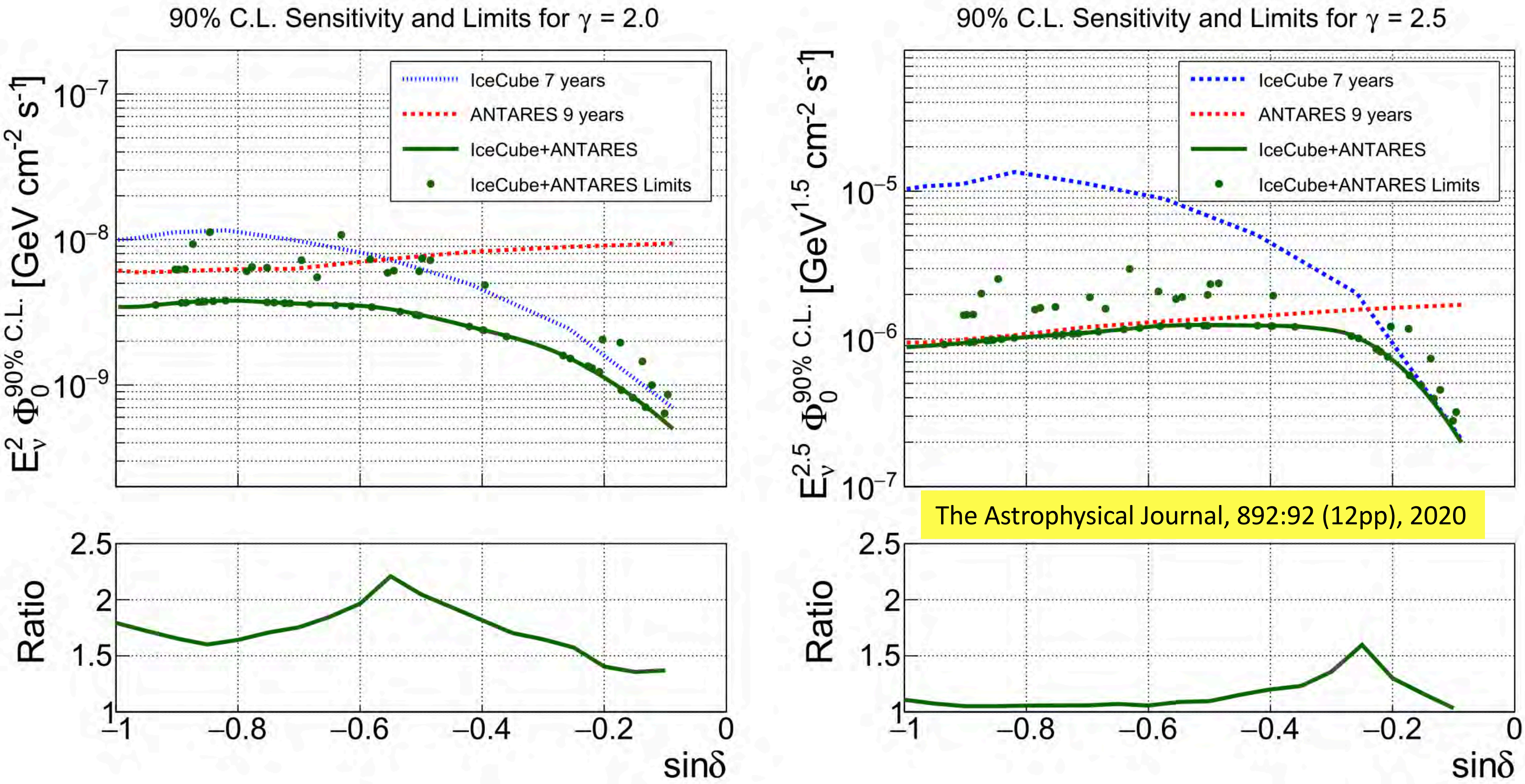


The red circle indicates the location of the most significant cluster: (0.9σ post-trial significance)

The Astrophysical Journal, 892:92 (12pp), 2020 April 1

Joint IceCube + ANTARES search for ν sources

Skymap of pre-trial p-values for the combined ANTARES (9 years) and



upper limits at 90% C.L. on the one-flavor neutrino flux

The Multi-Messenger Search Programme with ANTARES

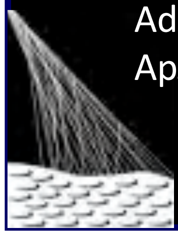
Neutrinos trigger others

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

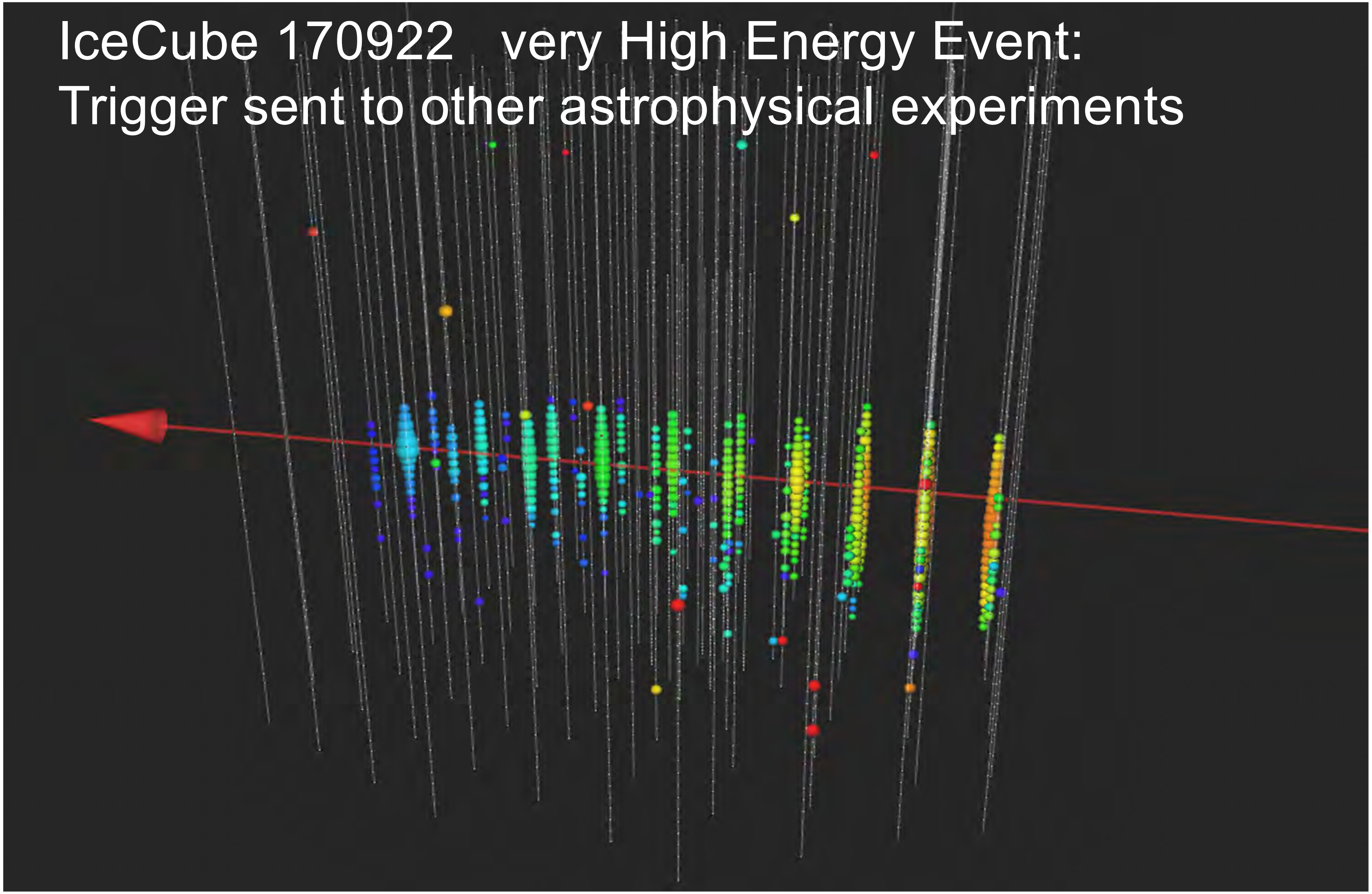
blazars: APP 36 (2012) 304;
μQuasars: JHEAp, 3-4 (2014) 9-7

GCN (Gamma-ray Coordination Network)

ANTARES ⟷ GCN

A&A 559, A9 (2013),
JCAP 1303 (2013) 006

Triggering on Neutrino Telescopes site



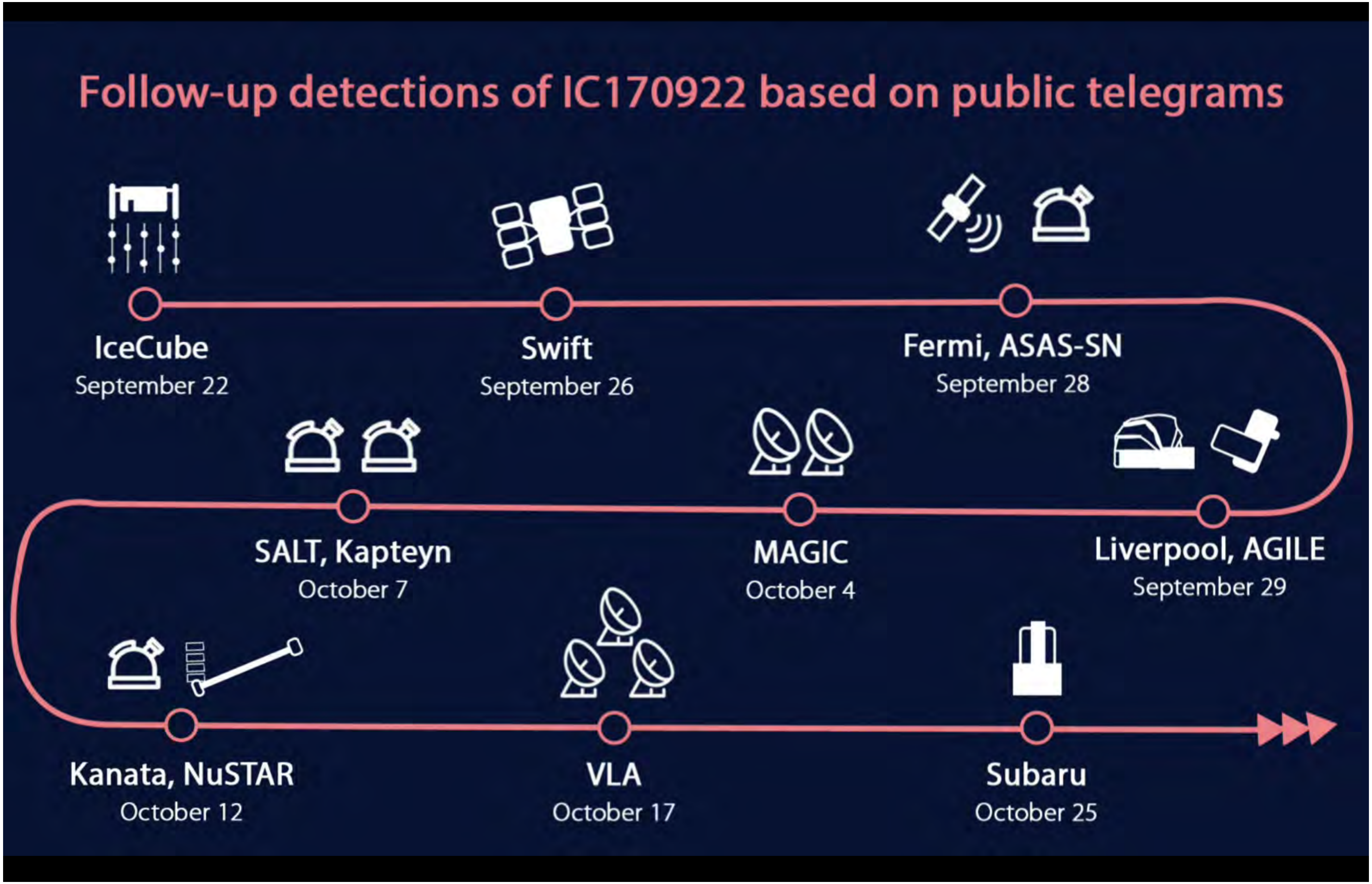
Triggering on Neutrino Telescopes site

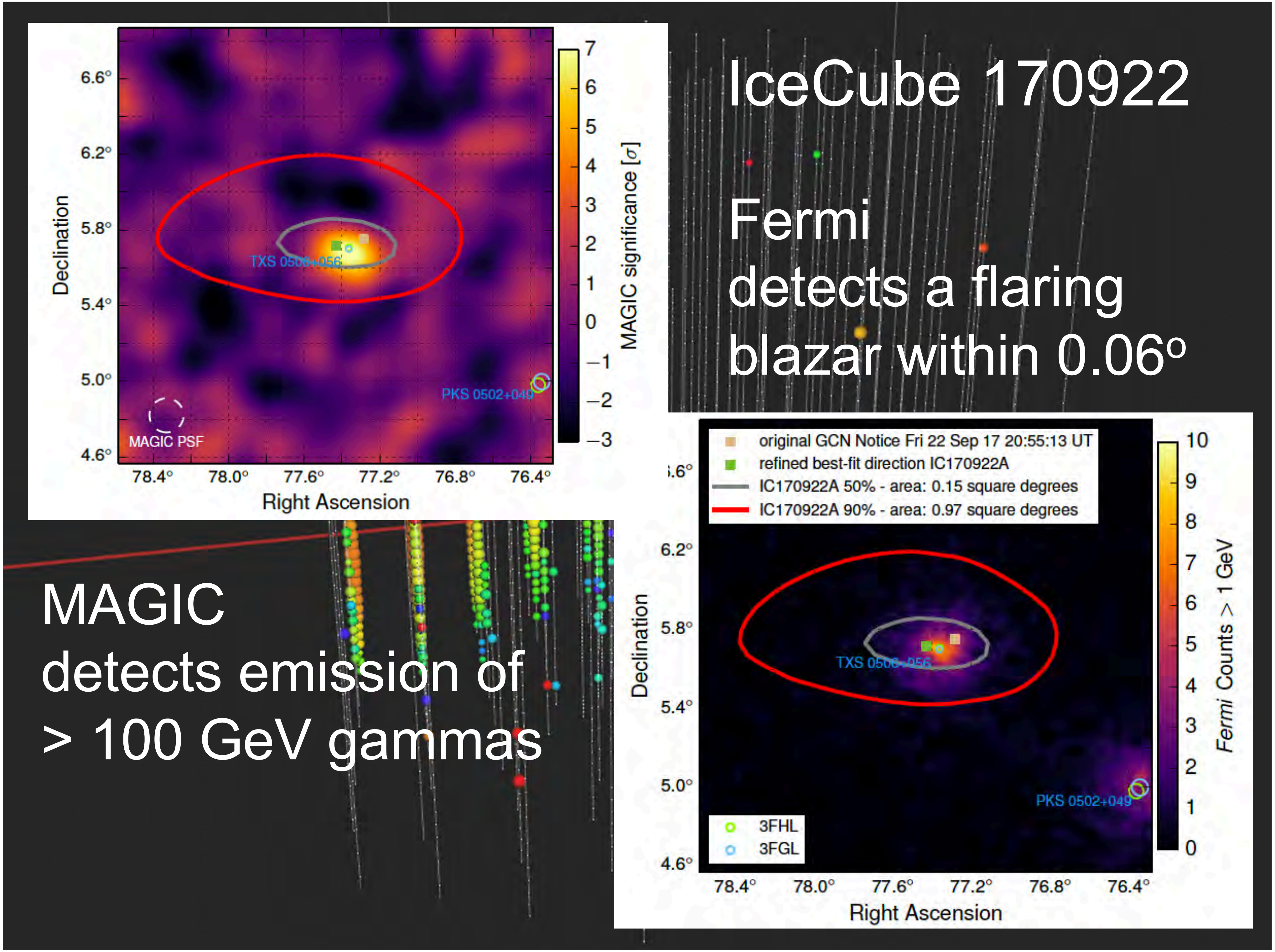
IceCube Trigger

43 seconds after trigger, GCN notice was sent

```
//////////////////////////////////////////////////////////////////////
TITLE:            GCN/AMON NOTICE
NOTICE_DATE:      Fri 22 Sep 17 20:55:13 UT
NOTICE_TYPE:      AMON ICECUBE EHE
RUN_NUM:          130033
EVENT_NUM:        50579430
SRC_RA:            77.2853d {+05h 09m 08s} (J2000),
                   77.5221d {+05h 10m 05s} (current),
                   76.6176d {+05h 06m 28s} (1950)
SRC_DEC:           +5.7517d {+05d 45' 06"} (J2000),
                   +5.7732d {+05d 46' 24"} (current),
                   +5.6888d {+05d 41' 20"} (1950)
SRC_ERROR:        14.99 [arcmin radius, stat+sys, 50% containment]
DISCOVERY_DATE:   18018 TJD;   265 DOY;   17/09/22 (yy/mm/dd)
DISCOVERY_TIME:   75270 SOD {20:54:30.43} UT
REVISION:         0
N_EVENTS:         1 [number of neutrinos]
STREAM:           2
DELTA_T:          0.0000 [sec]
SIGMA_T:          0.0000e+00 [dn]
ENERGY :          1.1998e+02 [TeV]
SIGNALNESS:       5.6507e-01 [dn]
CHARGE:           5784.9552 [pe]
```

Triggering on Neutrino Telescopes site



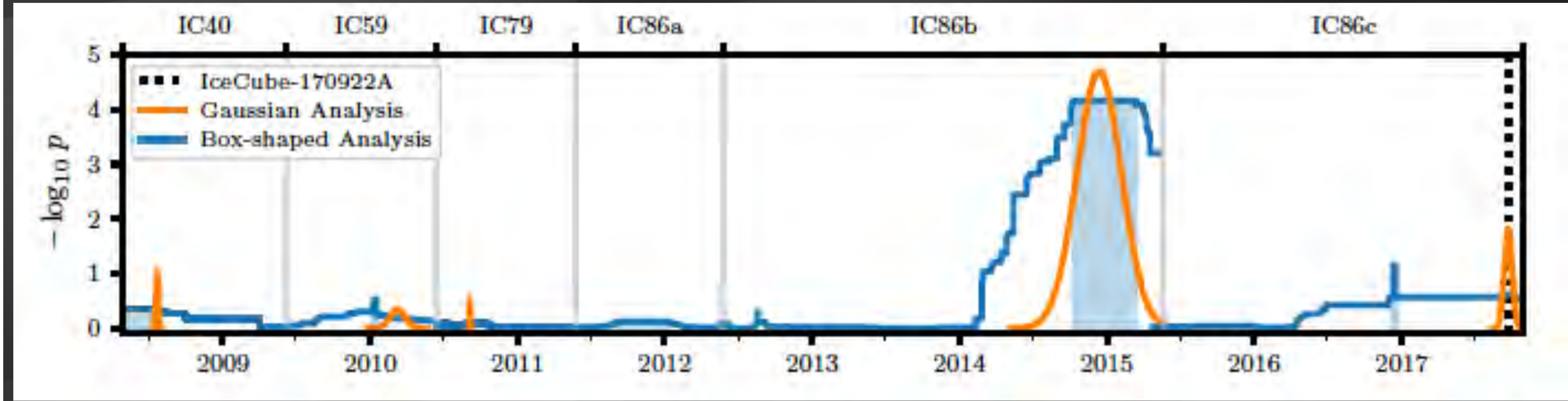


IceCube 170922
Fermi
detects a flaring
blazar within 0.06°
MAGIC
detects emission of
> 100 GeV gammas
6.6°
6.2°
5.8°
5.4°
5.0°
4.6°
Declination
78.4°
78.0°
77.6°
77.2°
76.8°
76.4°
Right Ascension
TXS 0506+056
PKS 0502+049
MAGIC PSF
MAGIC significance [σ]
7
6
5
4
3
2
1
0
−1
−2
−3
original GCN Notice Fri 22 Sep 17 20:55:13 UT
refined best-fit direction IC170922A
IC170922A 50% - area: 0.15 square degrees
IC170922A 90% - area: 0.97 square degrees
3FHL
3FGL
Fermi Counts > 1 GeV
10
9
8
7
6
5
4
3
2
1
0

multiwavelength campaign launched by IC 170922

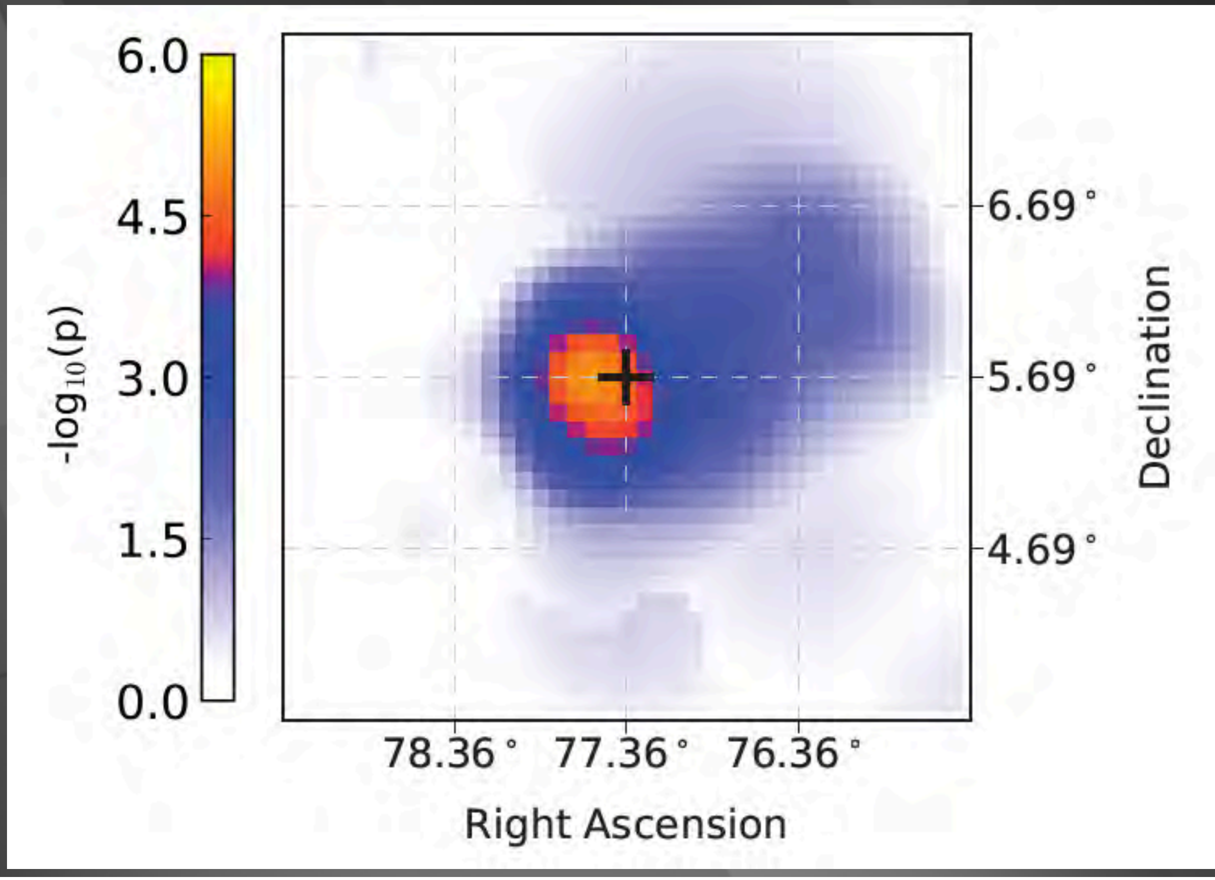
IceCube, *Fermi* –LAT, MAGIC, Agile, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, KISO, Liverpool, Subaru, *Swift*, VLA, VERITAS

- neutrino: time 22.09.17, 20:54:31 UTC
  energy 290 TeV
  direction RA 77.43° Dec 5.72°
- Fermi-LAT: flaring blazar within 0.06° (7x steady flux)
- MAGIC: TeV source in follow-up observations
- follow-up by 12 more telescopes
- → IceCube archival data (without look-elsewhere effect)
- → Fermi-LAT archival data



search in archival IceCube data:

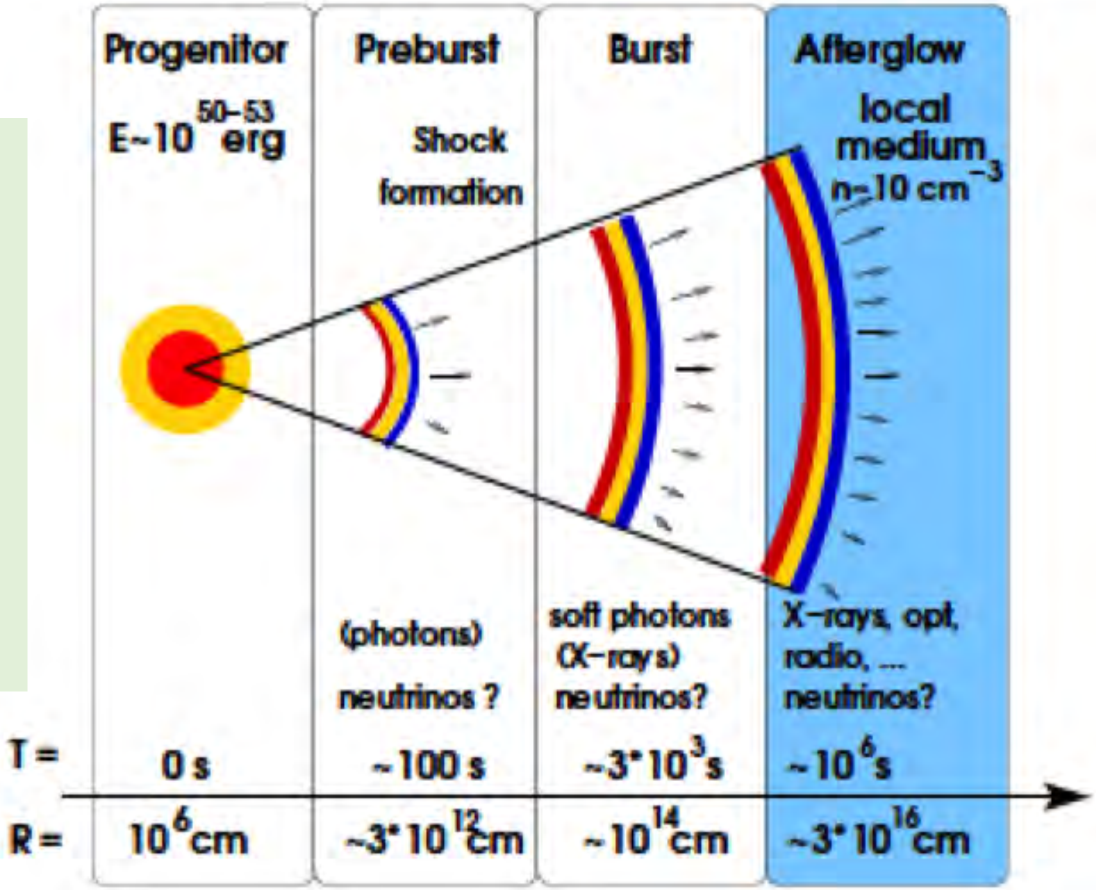
- 150 day flare in December 2014 of 19 events (bkg <6)
- 10^{-5} bkg. probability
- spectrum $E^{-2.1}$



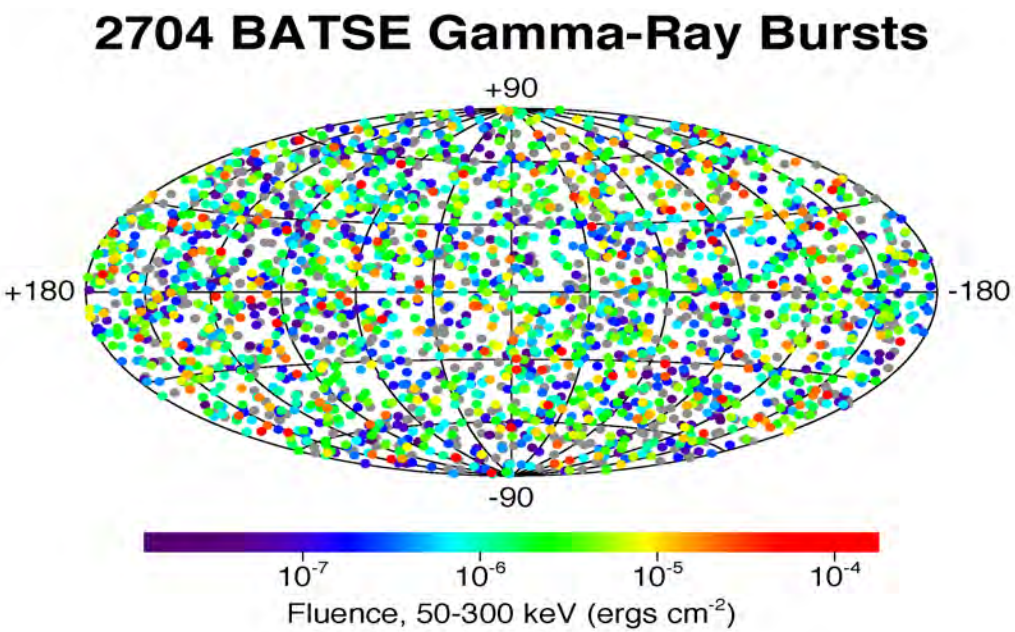
ν from sources of GRBs

GRBs are the brightest gamma ray sources in the Universe lasting from a few milliseconds to several minutes. With a total luminosity, under the hypothesis of isotropic emission, of about $L_{GRB} = 10^{51}$ erg/s, these sources are four orders of magnitude brighter than Active Galactic Nuclei, the most luminous steady sources in the sky, with luminosity ranging from:

$L_{AGN} = 10^{44}$ erg/s to $LAGN = 10^{47}$ erg/s.



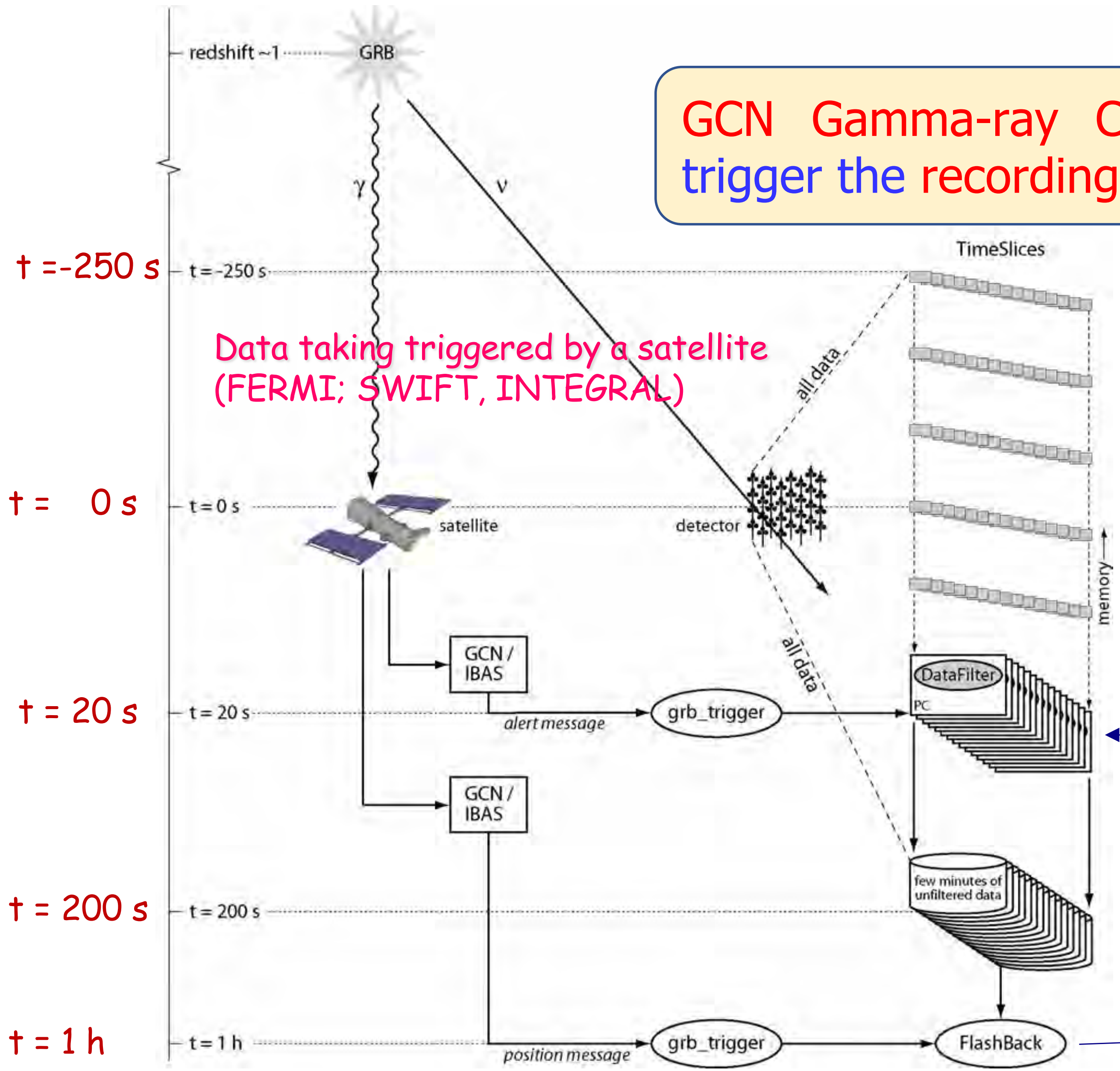
Schematic view of the GRB fireball model. The three phases of the GRB development are displayed together with characteristic times and dimensions.



Map of observed GRB in galactic coordinates: the plane of the Milky Way galaxy is along the horizontal line at the middle of the figure. The burst locations are color-coded based on the fluence, which is the energy flux of the burst integrated over the total duration of the event.

A Multi-Messenger Search for ν from GRBs

GCN Gamma-ray Coordination Network) alerts trigger the recording of all the low level triggers.



A continuous buffer ensures the availability of the data before the alert

All data written to disk

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

disk

Multi-Messenger Search for ν from GRB

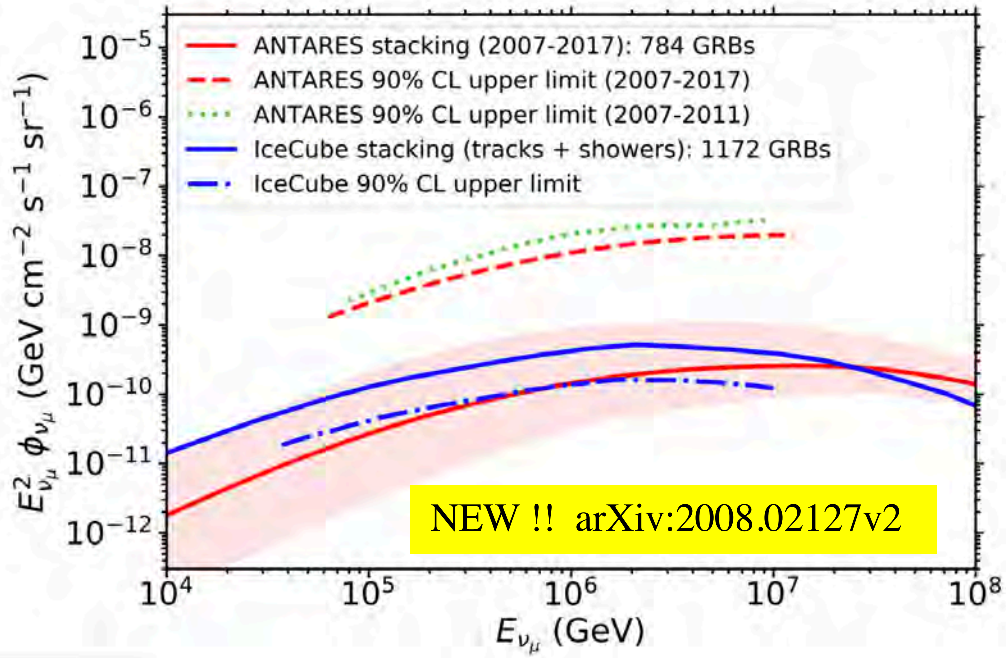
GRBs: intense flashes of high-energy electromagnetic radiation observed isotropically in the sky. If hadrons are accelerated in GRBs, following the pγ interactions both ν and γ are expected.

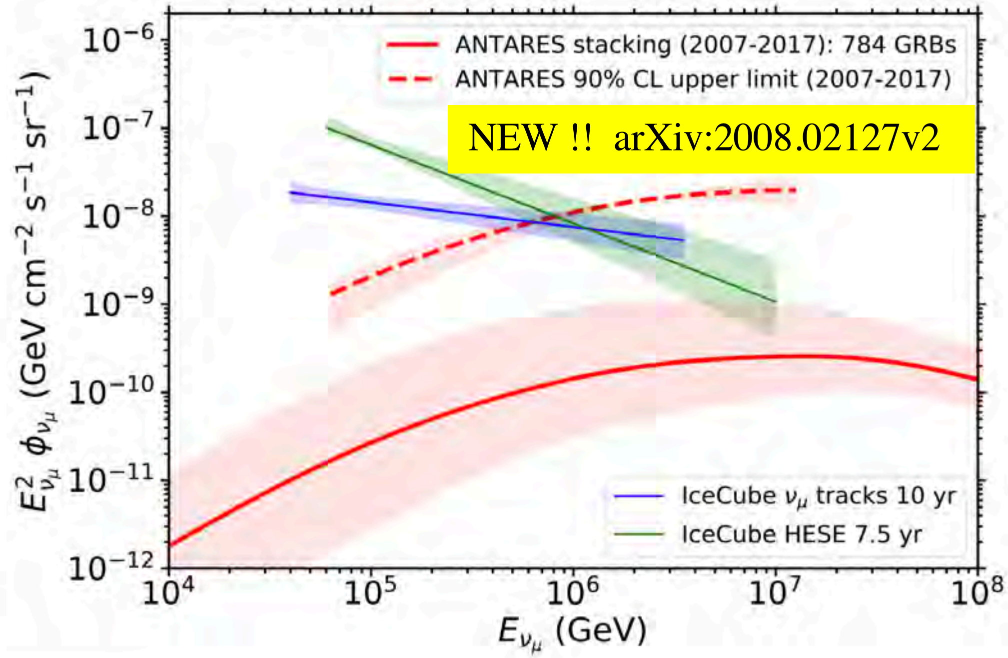
Search for neutrinos in coincidence with GRBs occurred in the period 2007-2017.

784 long GRBs (T_{90} >2 s) selected out of FERMI/SWIFT catalogues, below ANTARES horizon at the trigger time. NeuCosmA software used to evaluate individual ν fluxes.

Total ν fluence from GRBs stacking and the contribution to the diffuse ν flux evaluated

No neutrino events are found in spatial and temporal coincidence with the GRB sample





GRBs are not the main contributors to the observed IceCube diffuse n flux below Eν ~ 1 PeV

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
- Detailed study of **extended** regions (Galactic plane, Fermi Bubbles)
  - no ν_μ excess from the Galactic ridge/IC hot spot
- A large **multi-messenger** effort
  - EM radiation: radio (MWA), optical, X-ray, γ-rays (LAT,IACTs)
  - Gravitational Wave observatories and IceCube
- ANTARES contribute to the indirect searches for **Dark Matter**
  - Most competitive limits for spin-dependent cross-section
  - Competitive $<\sigma v>$ limits from the Galactic centre
- **KM3NeT-Arca** Neutrino Telescope under construction will soon be able to observe the neutrino sky with unprecedented sensitivities.