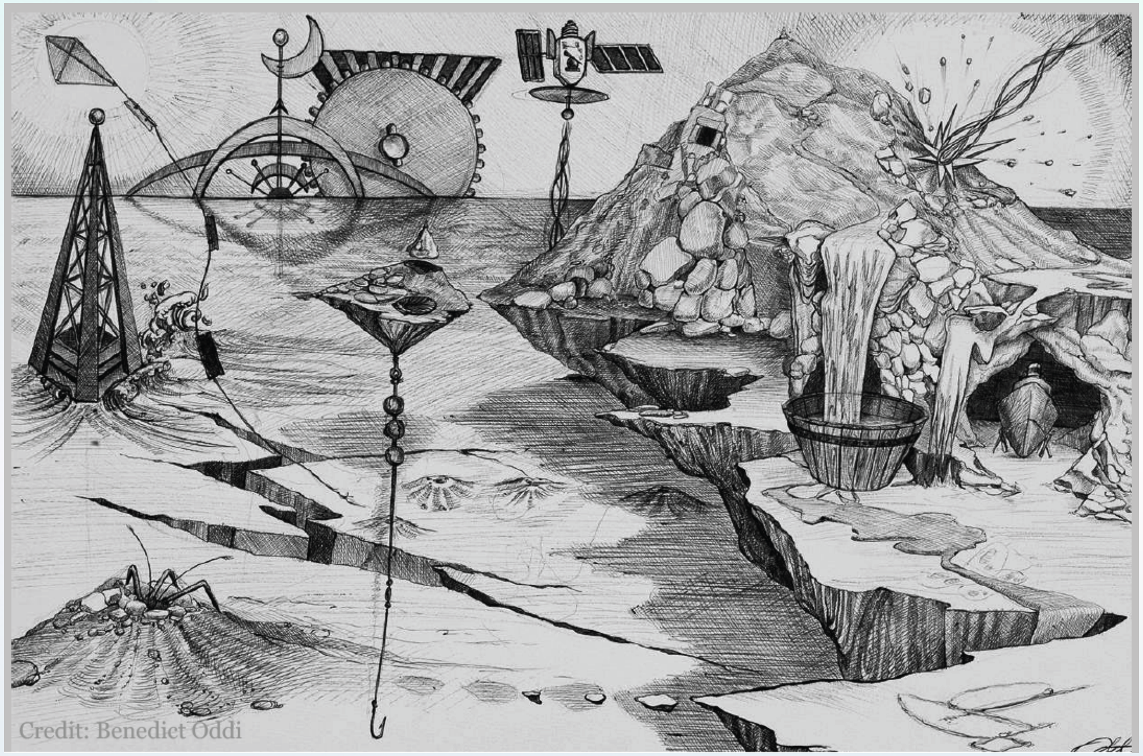
High Energy Astrophysical Neutrino detection in a multi-messenger scenario.



Antonio Capone

Stato e prospettive della Fisica delle Astroparticelle

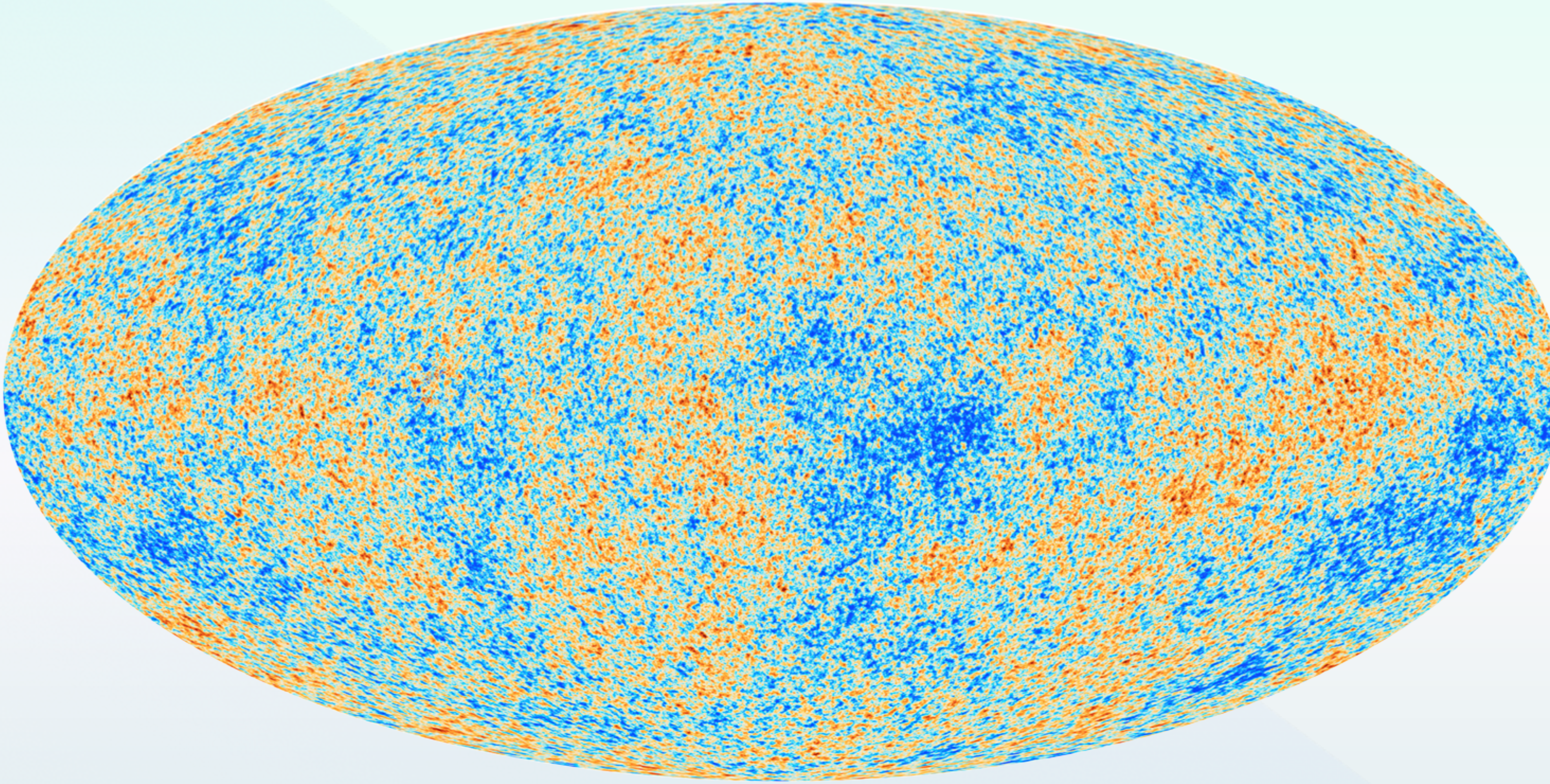
Università "La Sapienza", Roma

Talk outline

- Motivation for High Energy Astrophysical neutrino detection
- IceCube/Gen2, ANTARES/KM3NeT
- Neutrino Telescopes main physics goal: search for astrophysical neutrinos
  - Search for a diffuse flux
  - Search for point-like sources
- Indirect search for Dark Matter
  - from the SUN, the Galactic Plane, the Earth
- Transient/multi-messenger studies
  - Search for GRB
  - Search for transient high intensity gamma sources
  - Search for common CR+neutrino, GW+neutrino, … point like sources
- Perspectives for the future
- Conclusions & Summary

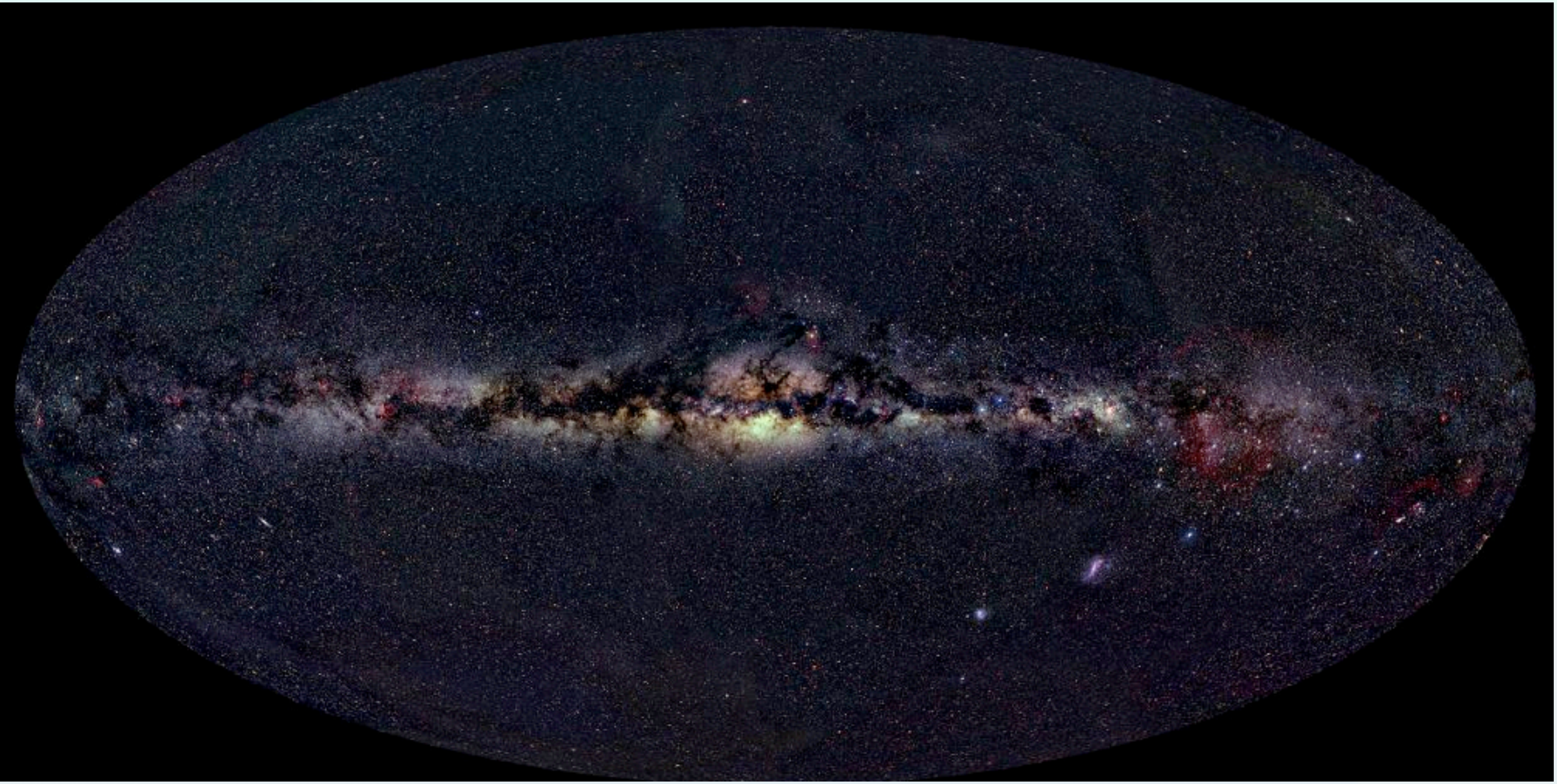
Cosmic Horizons – Microwave Radiation

380.000 years after the Big Bang



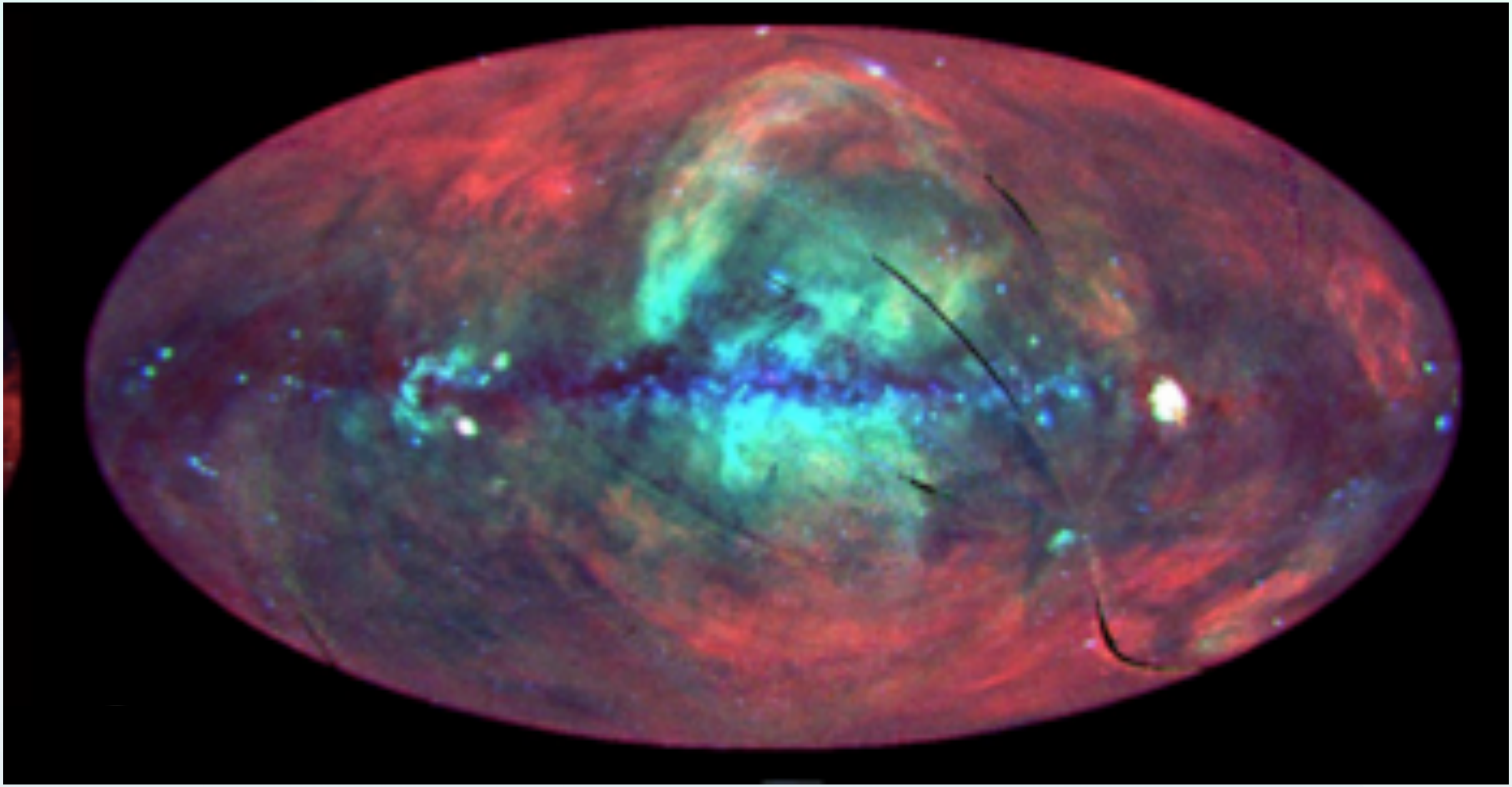
wavelength = 10^{-3} m ⇔ energy = 10^{-4} eV

Cosmic Horizons – Optical Sky



wavelength = 10^{-6} m ⟺ energy = 1 eV

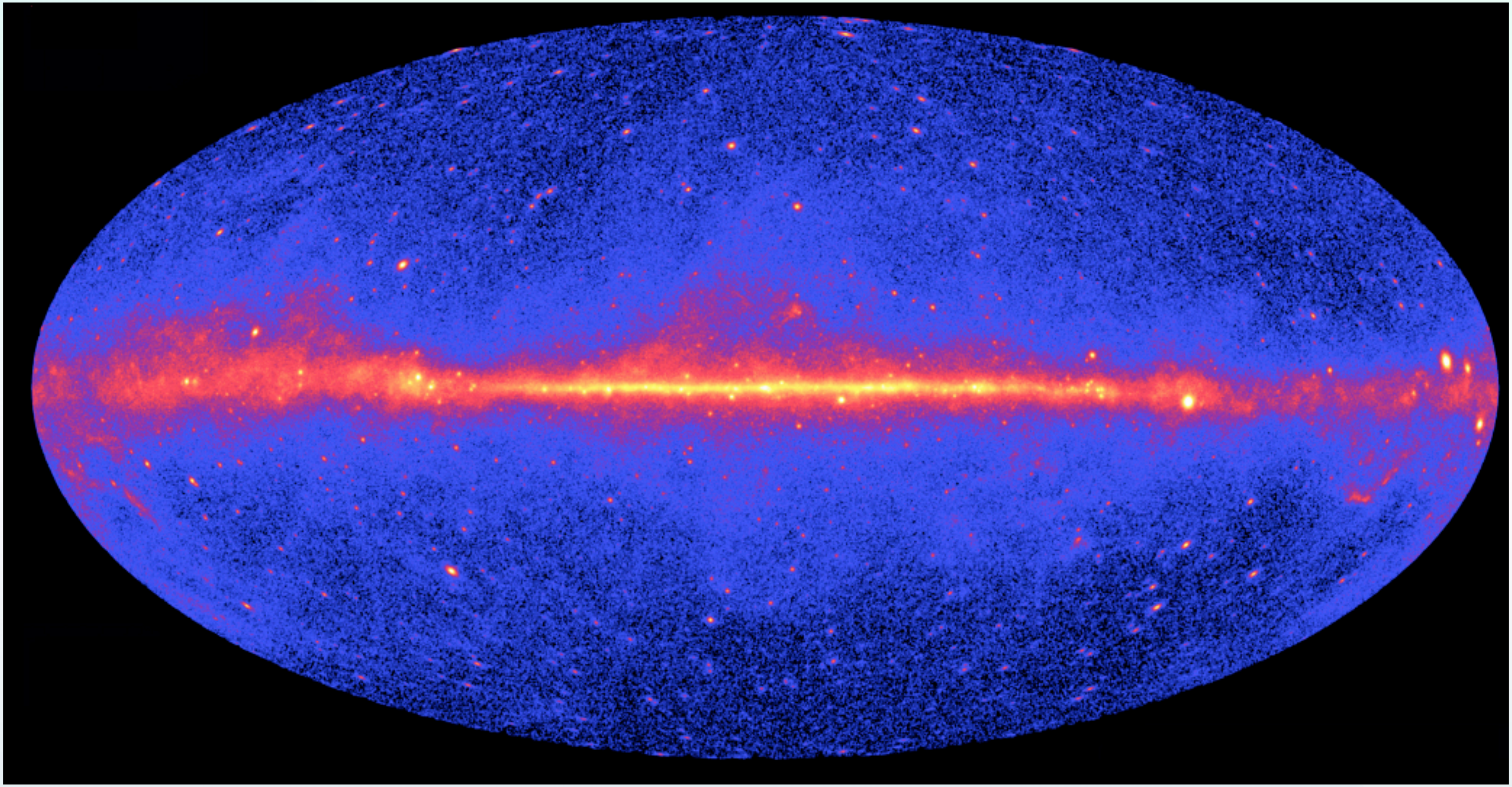
Cosmic Horizons – X ray sky



wavelength ~ 10^{-12} m ⇔ energy ~ 1 keV

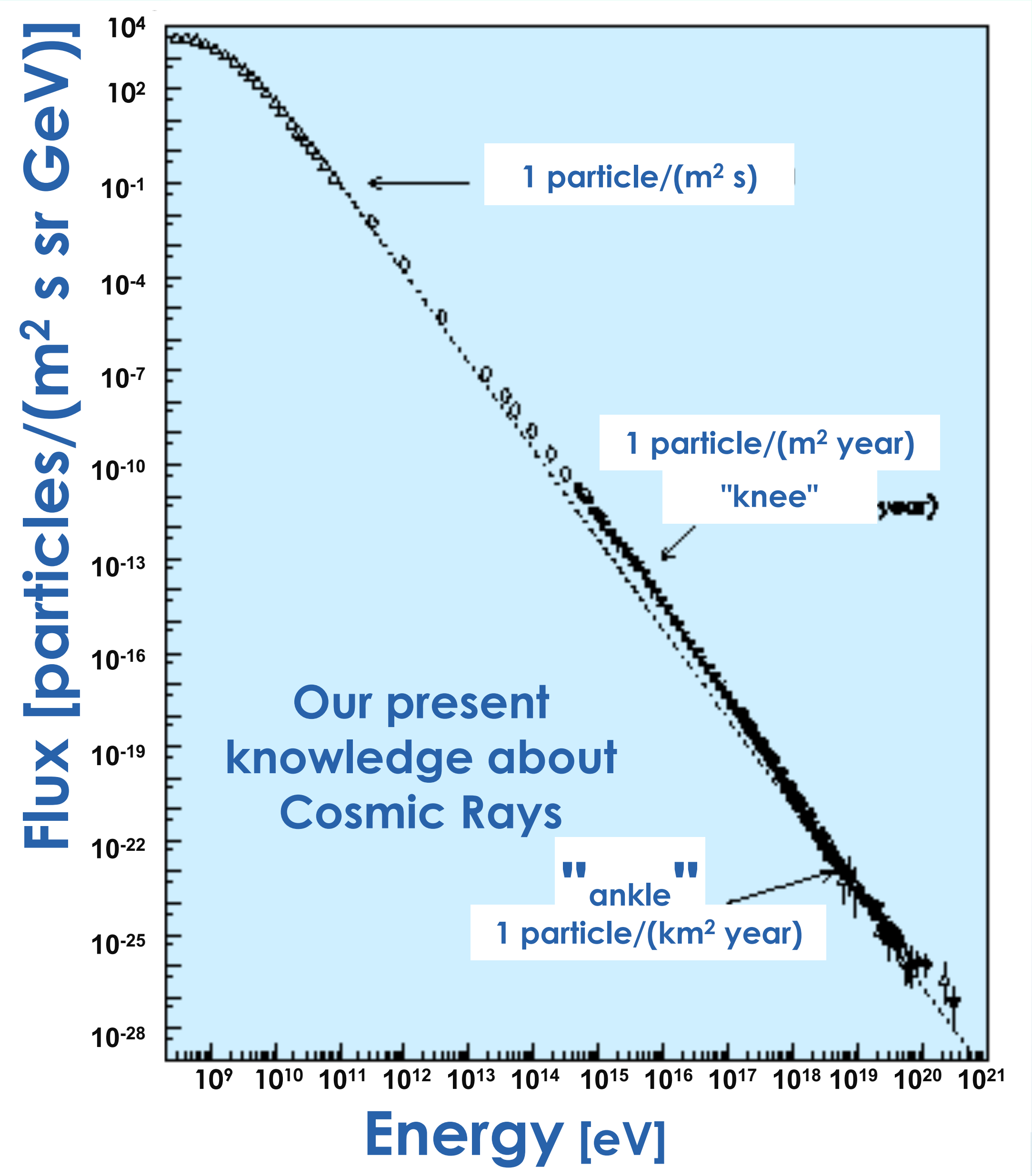
Cosmic Horizons – Gamma Radiation

300.000 years after the Big Bang



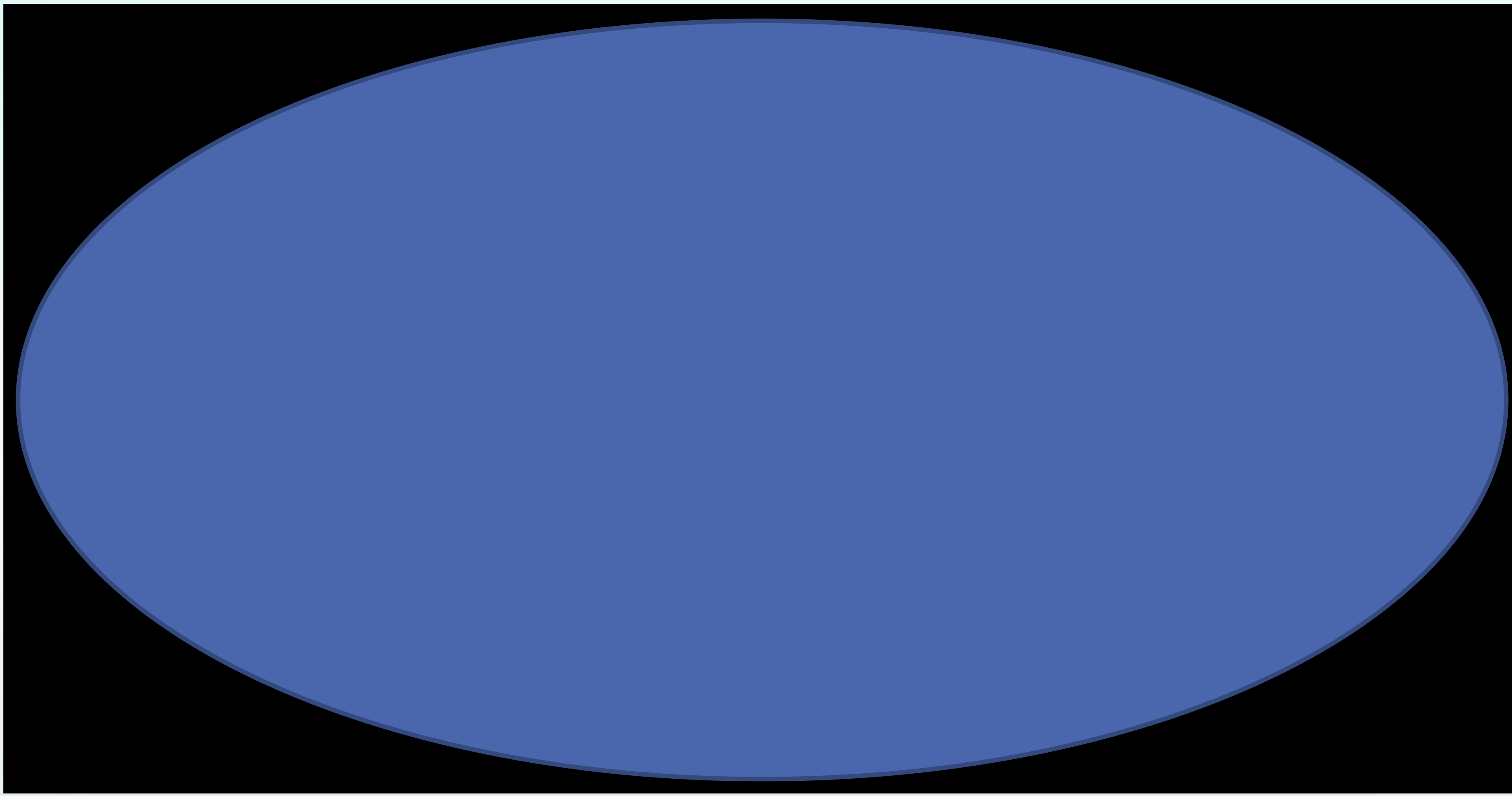
wavelength = 10^{-15} m ⟺ energy = 1 GeV

Cosmic rays spectrum spans over a large energy interval



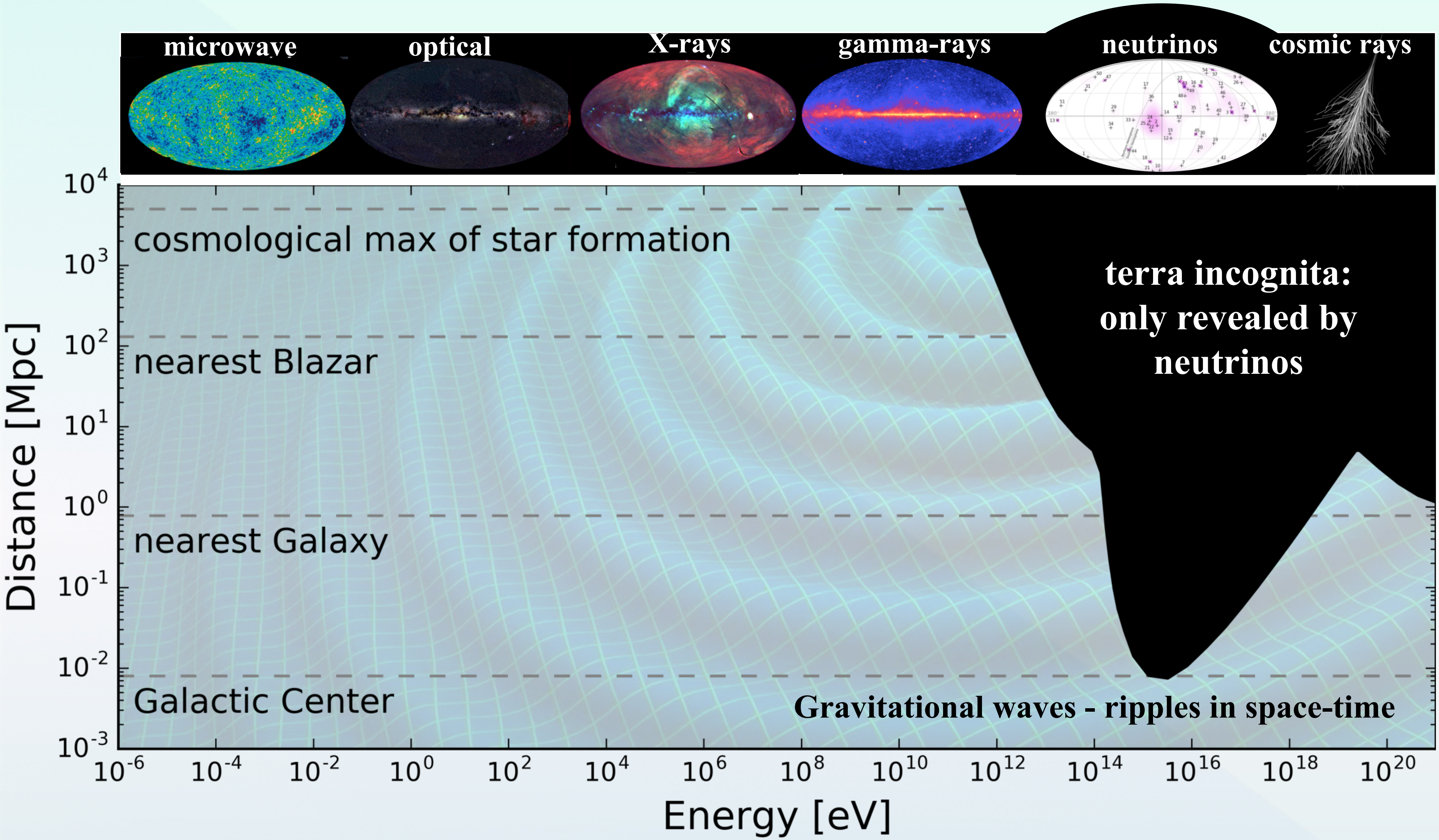
- Observed elementary particles or nuclei carrying a kinetic energy up to 10^{21}eV (like a tennis ball moving at ~150km/h)
- Many open questions:
  - Where they come from ?
  - Which acceleration mechanism ?
  - …

Cosmic Horizons – H.E. Gamma Radiation



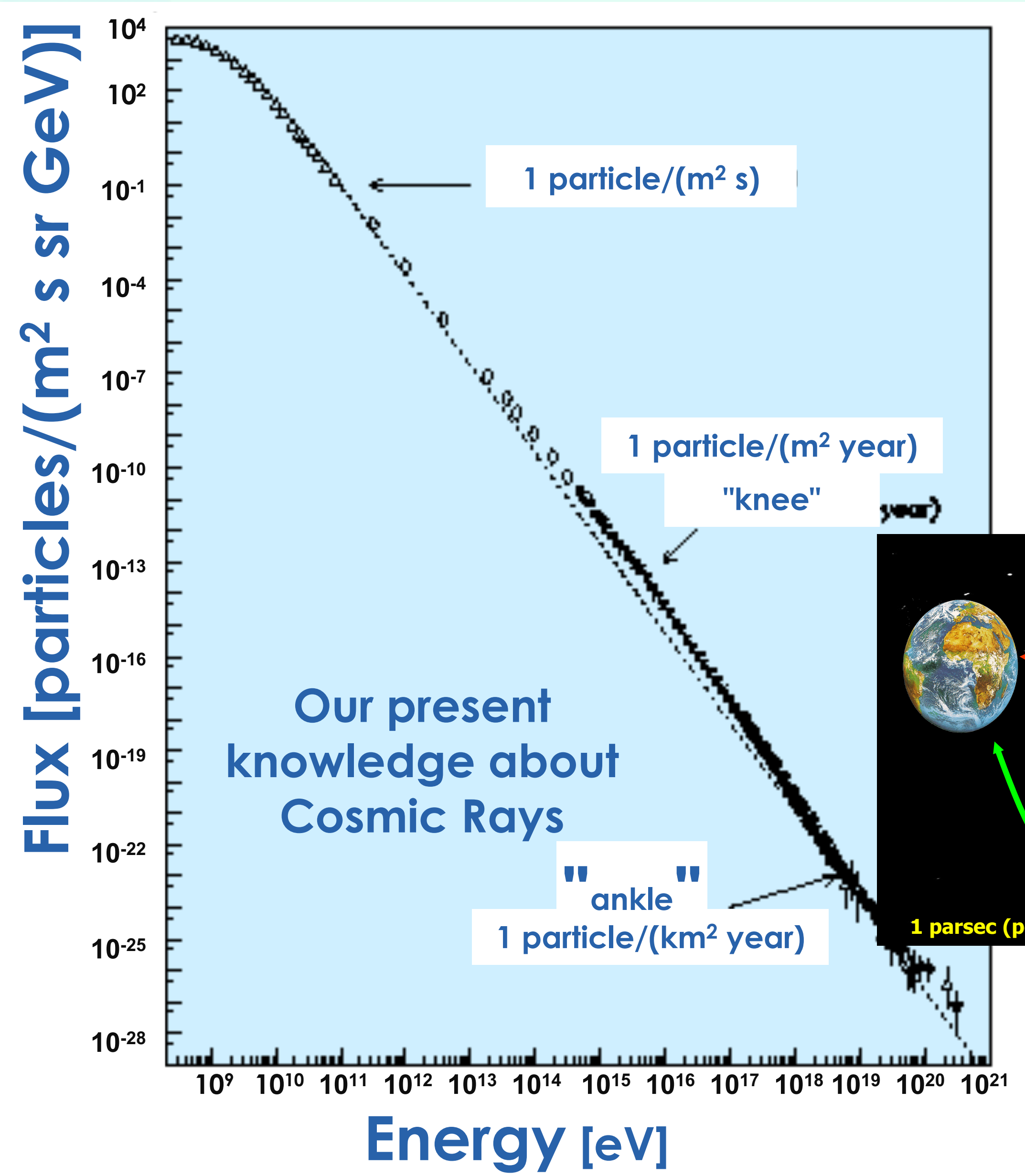
wavelength = 10^{-21} m ⇔ energy = 10^{3} TeV

Multi-Messenger Astronomy



[redacted]

The Universe is transparent for UHE neutrinos !



- 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 ?
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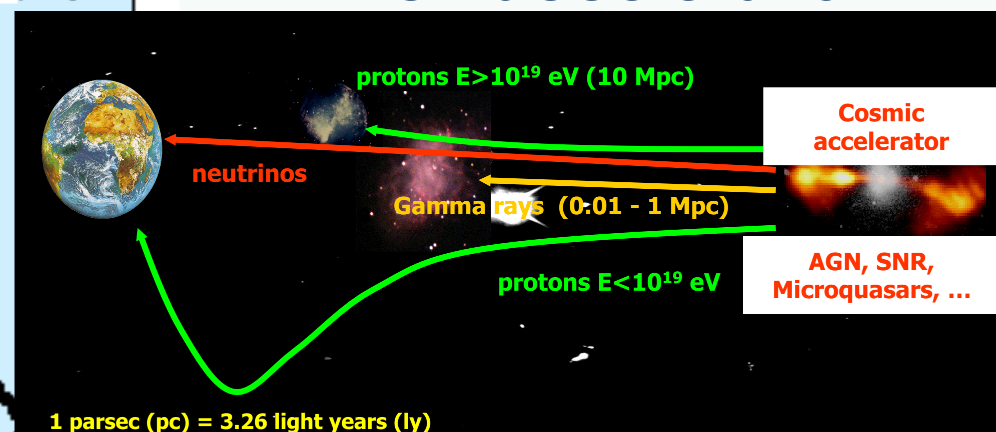
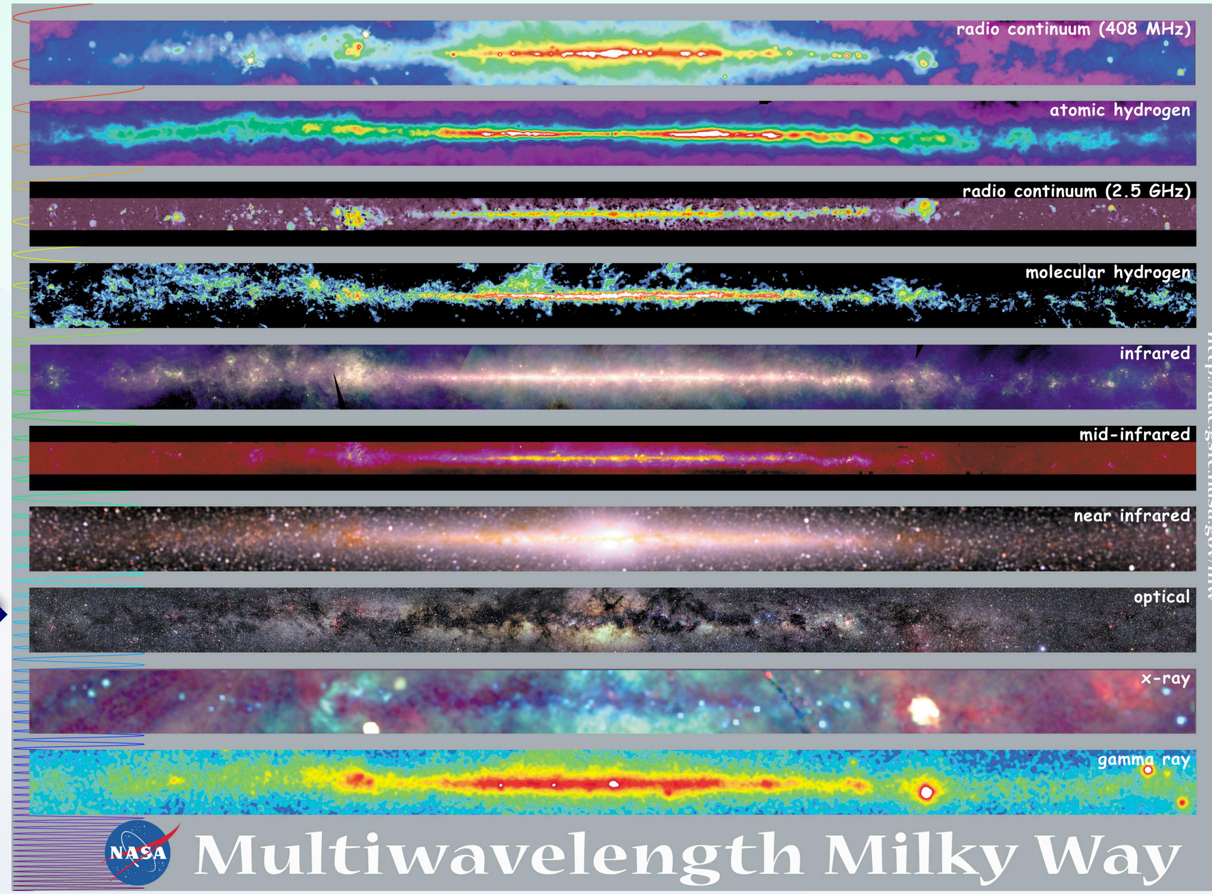


- UHE astrophysical neutrinos will extend the limits of the "visible" Universe.
- Multi-messenger observations

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

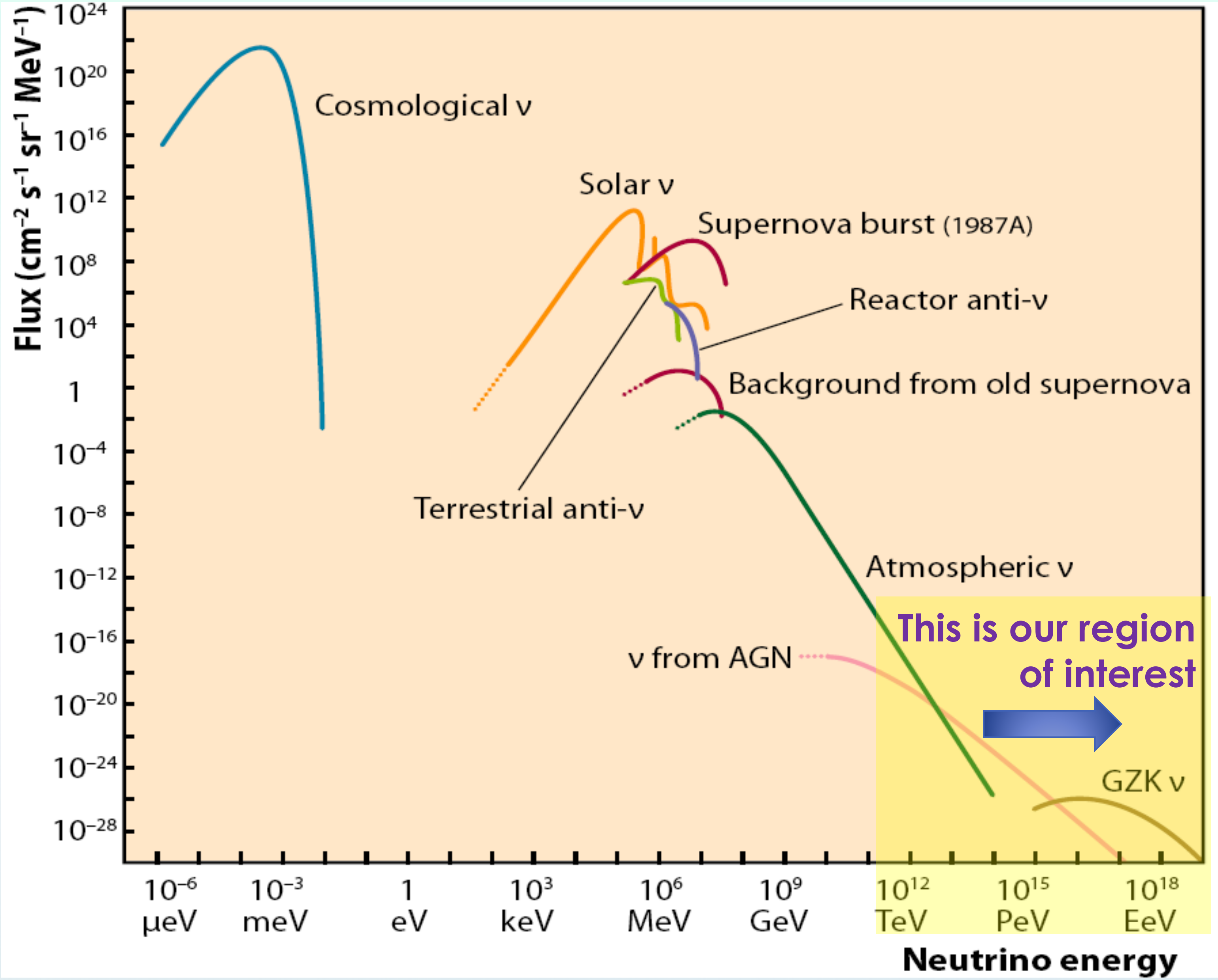


http://mwmw.gsfc.nasa.gov/

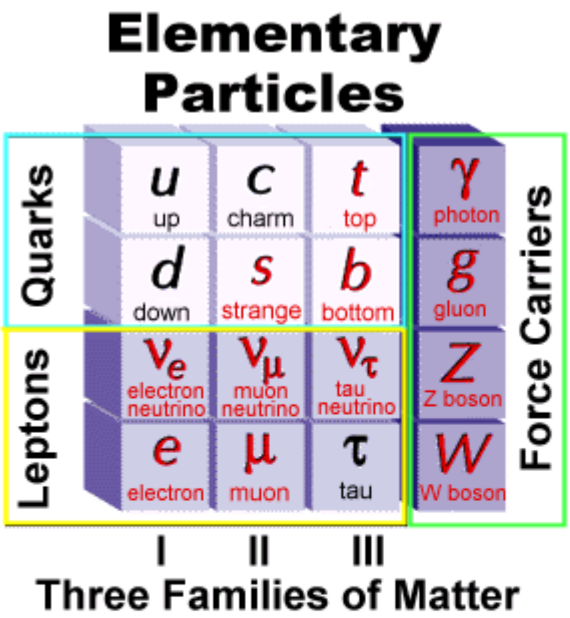
***Galileo Galilei showing the Doge of Venice how to use the telescope* (1858), fresco by Giuseppe Bertini (1825–1898)**

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

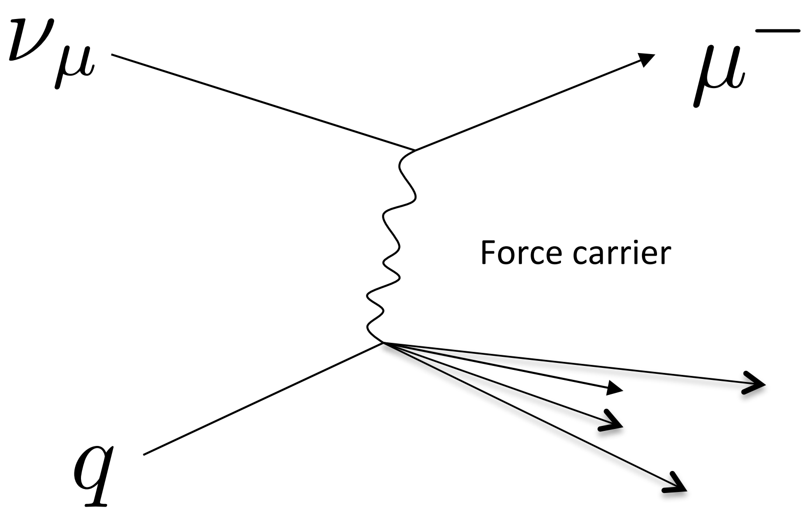
Neutrino fluxes: what do we know/expect ?



Neutrino Interactions - 1



Charged current ν_μ:



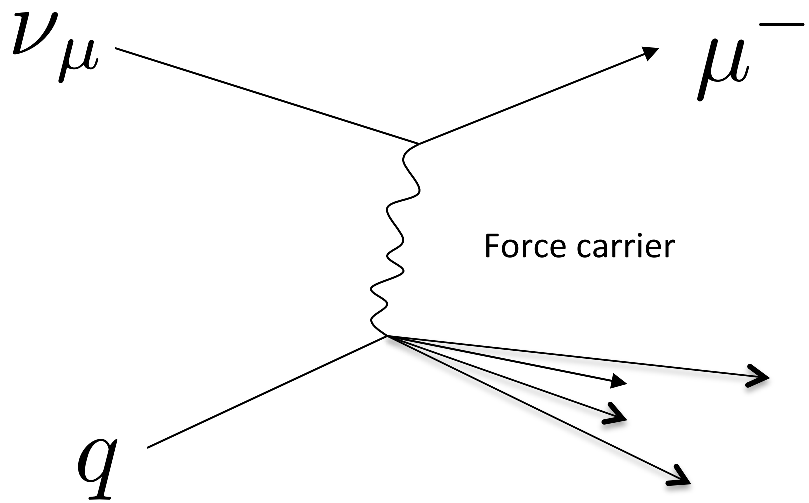
Also charged current $\nu_e \rightarrow e$

and charged current $\nu_\tau \rightarrow \tau$

and neutral current $\nu_\alpha \rightarrow \nu_\alpha$

Neutrino Interactions - 2

Tracks
(because of μ)

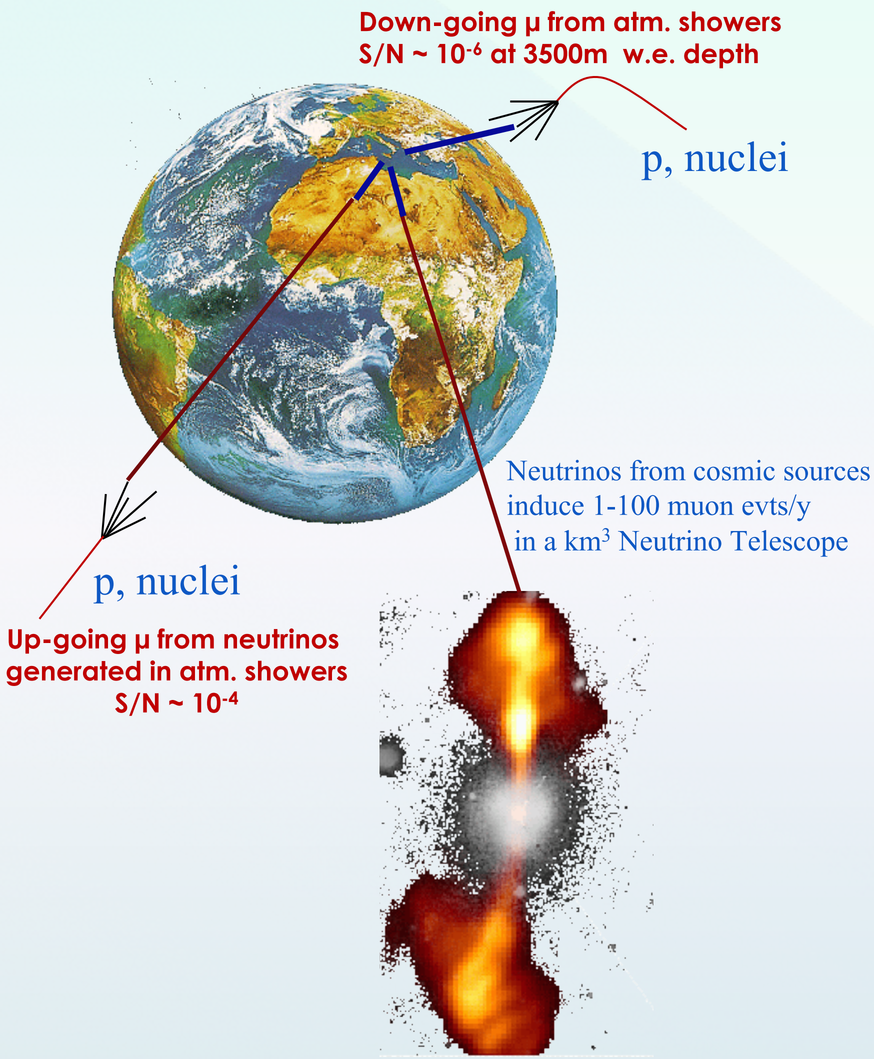


Cascades

$$\text{Also charged current } \nu_e \longrightarrow e$$
$$\text{and charged current } \nu_\tau \longrightarrow \tau$$
$$\text{and neutral current } \nu_\alpha \longrightarrow \nu_\alpha$$

Cherenkov ν Telescope: Detection principle

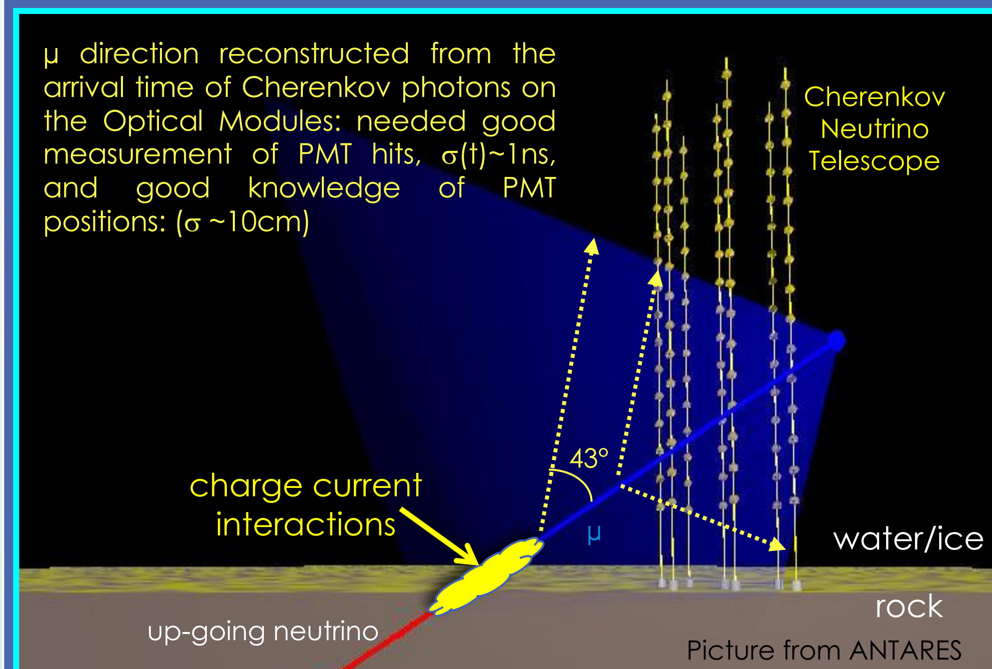
Search for neutrino induced events, mainly $\nu_\mu N \rightarrow \mu X$, deep underwater



- 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

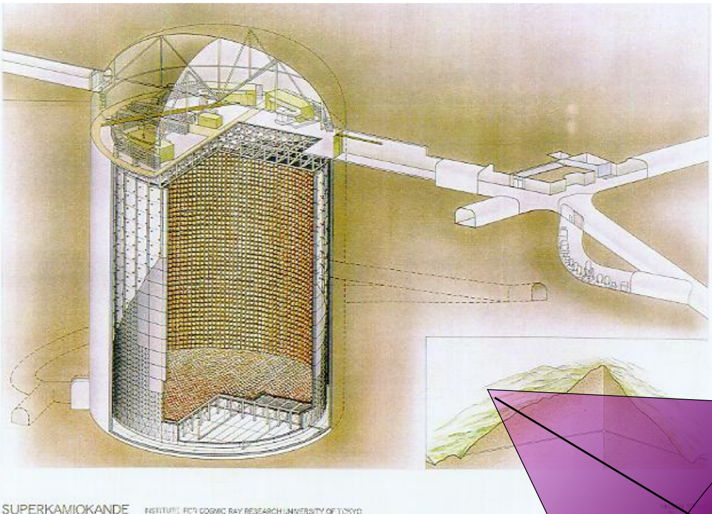
$$For\ E_\nu \geq 1TeV \quad \theta_{\mu\nu} \sim \frac{0.7°}{\sqrt{E_\nu[TeV]}}$$



Detecting neutrinos in H_2O

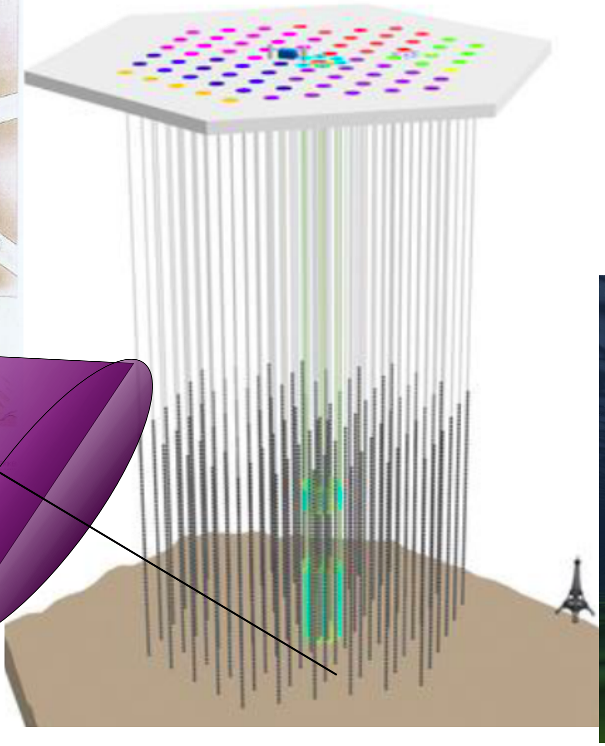
Proposed by Greisen, Reines, Markov in 1960

- DUMAND
- IMB
- Kamiokande
- Baikal
- AMANDA

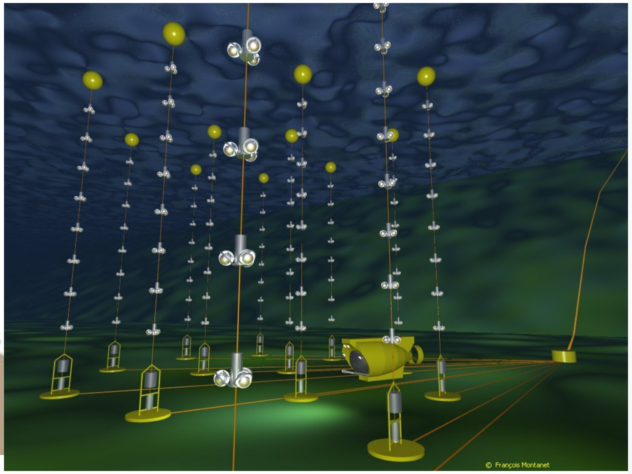


Super-K

SNO



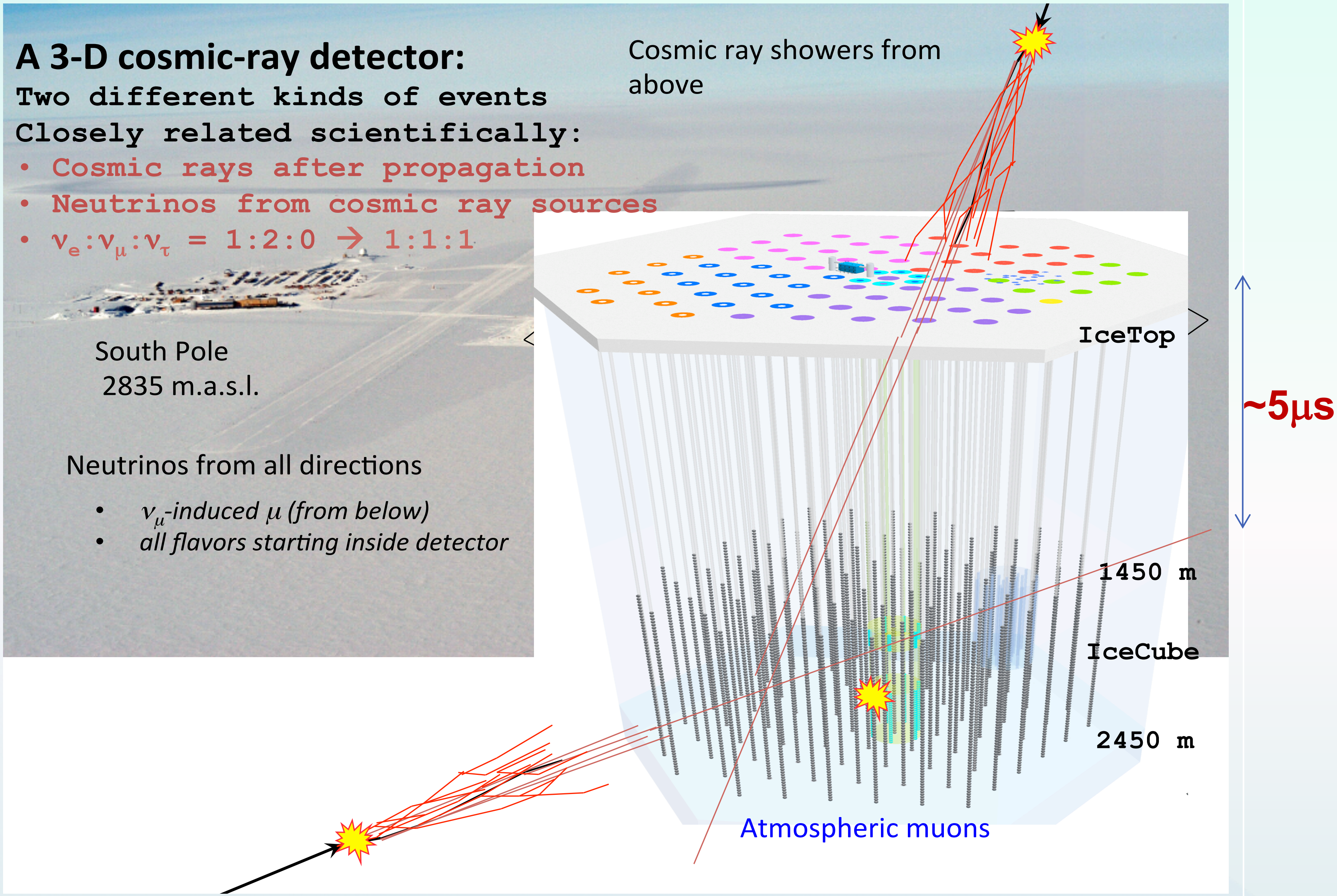
IceCube



ANTARES

Neutrino must interact to be detected

IceCube – The Neutrino Telescope at the South Pole

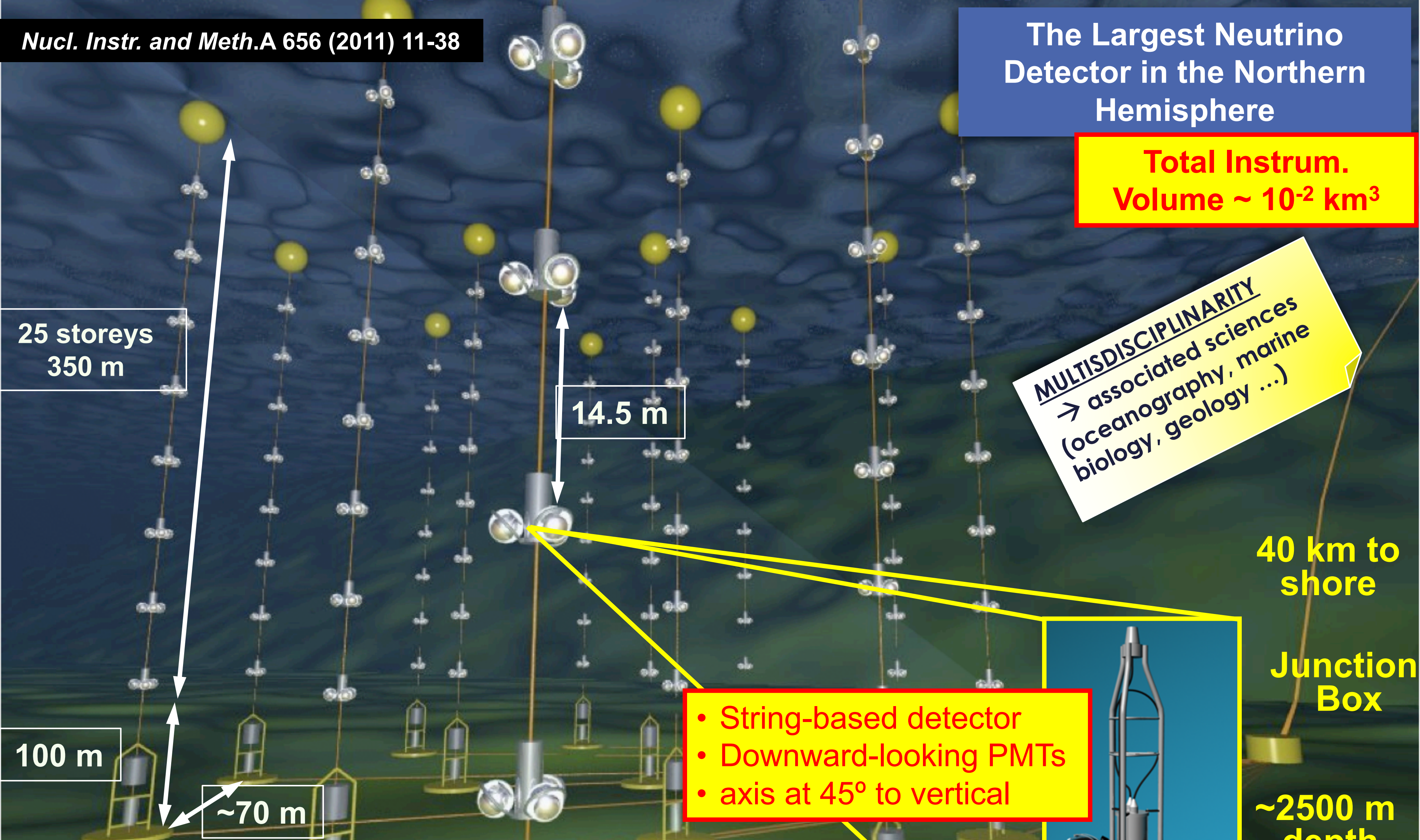


ANTARES: Astronomy with Neutrino Telescope and Abyss environm. RESearch

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

The Largest Neutrino Detector in the Northern Hemisphere

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

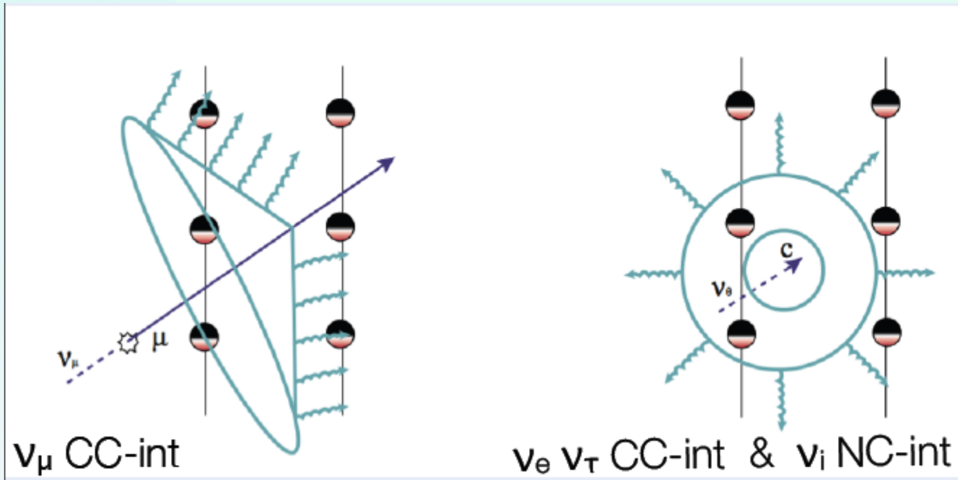


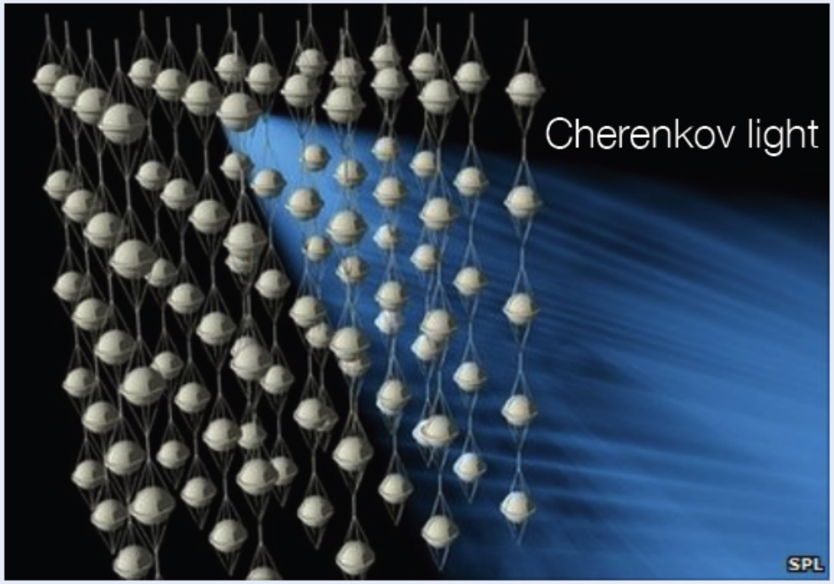
MULTISDISCIPLINARITY → associated sciences (oceanography, marine biology, geology …)

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

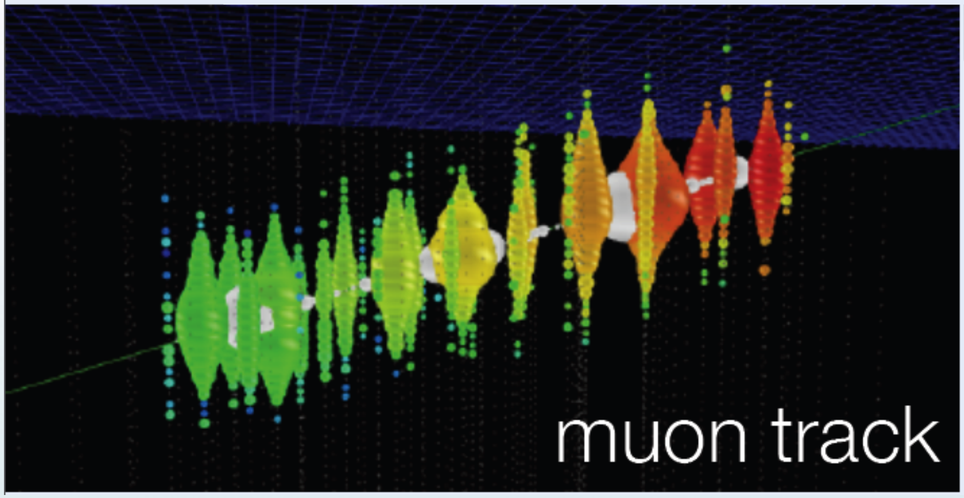
- 12 detection lines
- 25 storeys / line
- 3 PMTs / storey
- ~900 PMTs

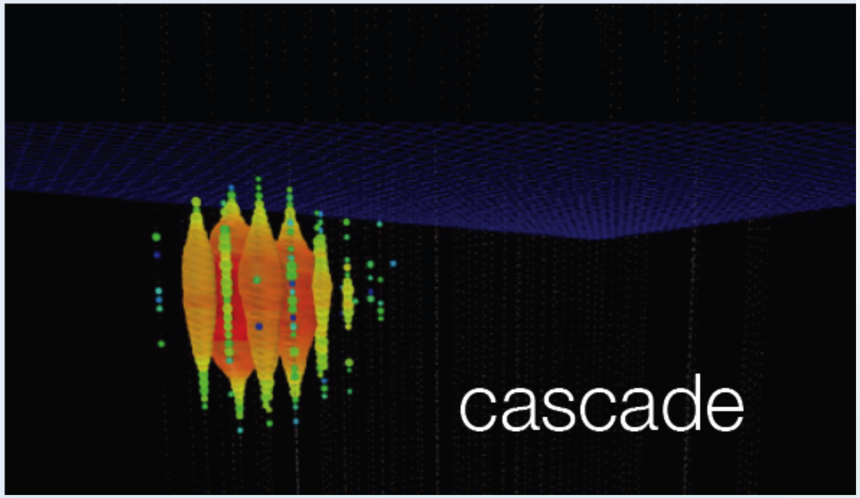
Events in IceCube Detector



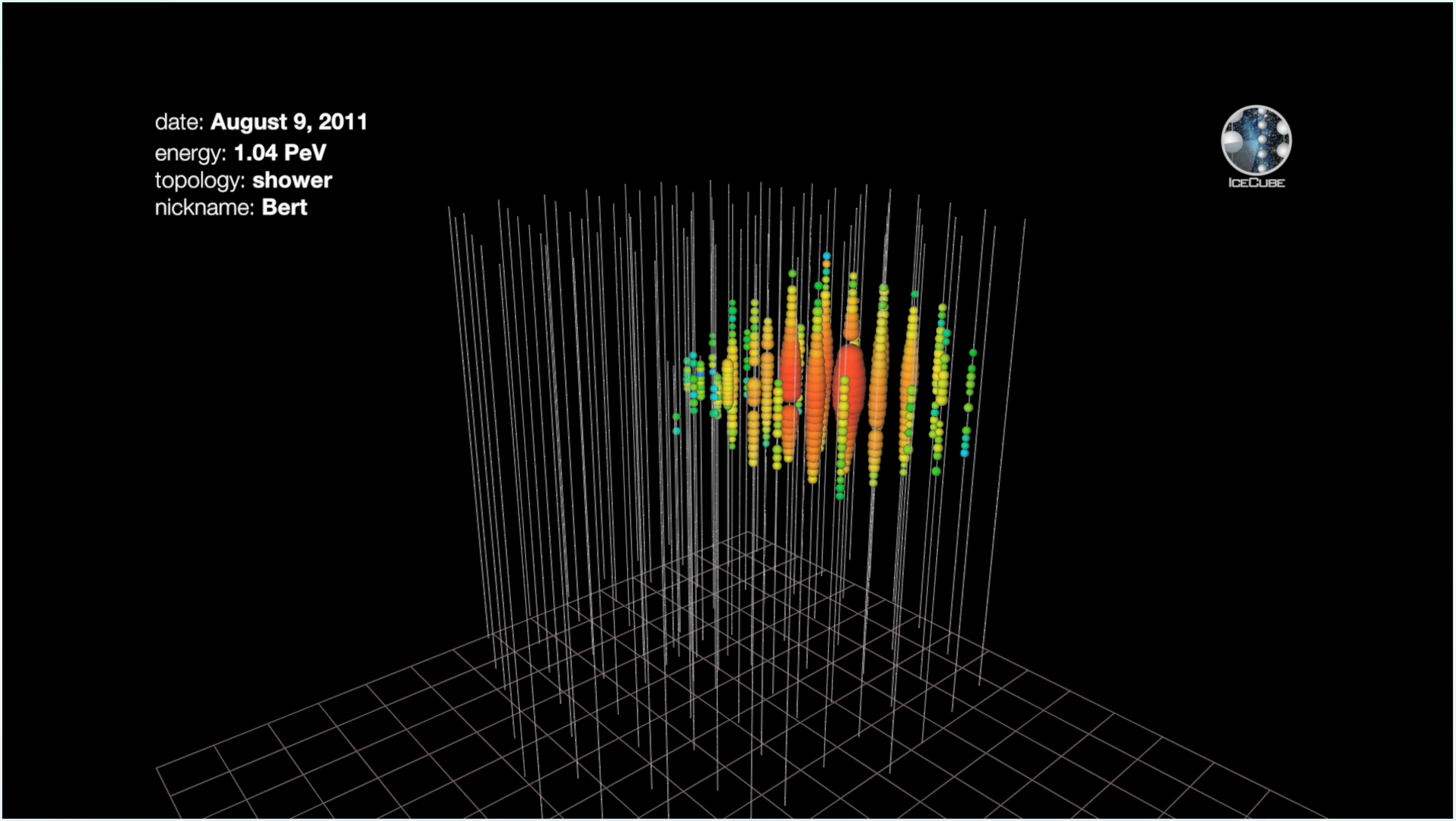


In the event display:
radius ~ number of photons
time ~ red → purple





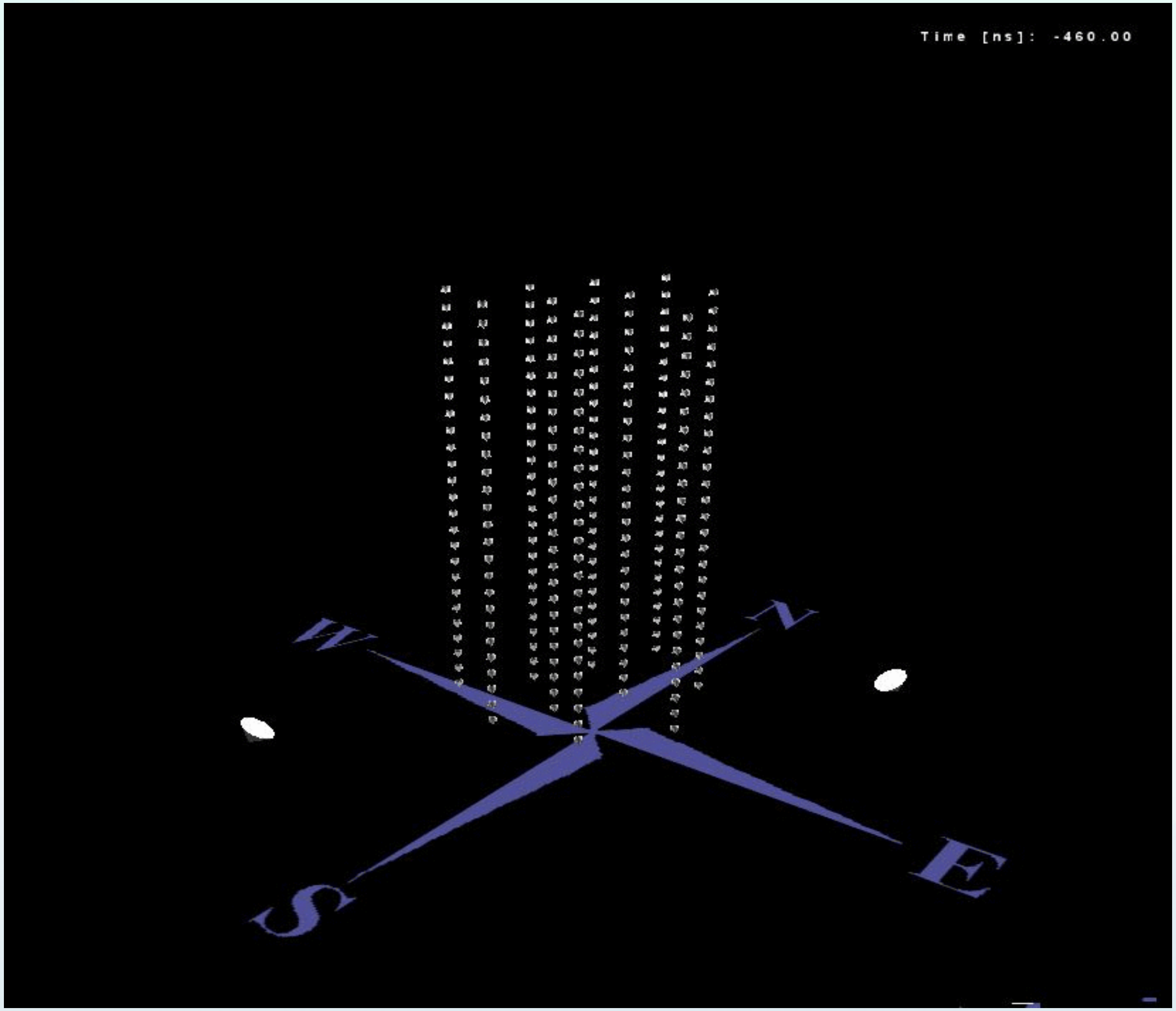
A cosmic neutrino interacts INSIDE IceCube detector



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

Up-going track in ANTARES: a neutrino candidate

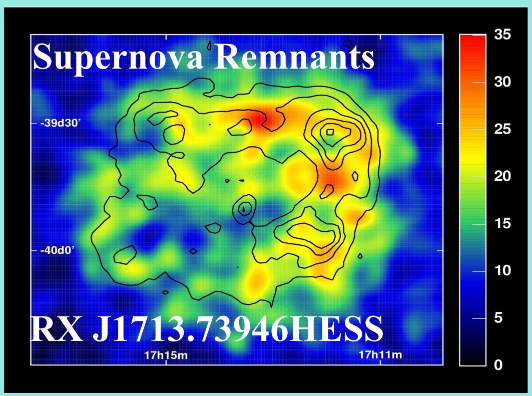
Example of a reconstructed up-going muon (i.e. a neutrino candidate)

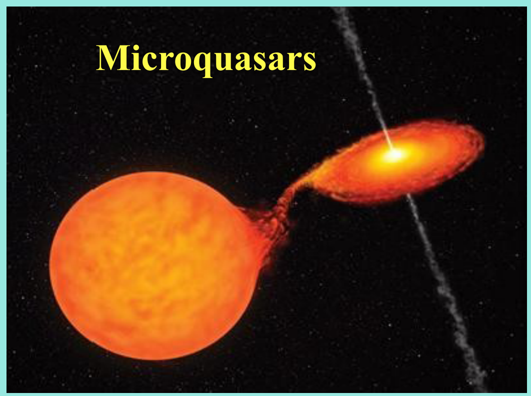


Neutrino Telescope physic's goals

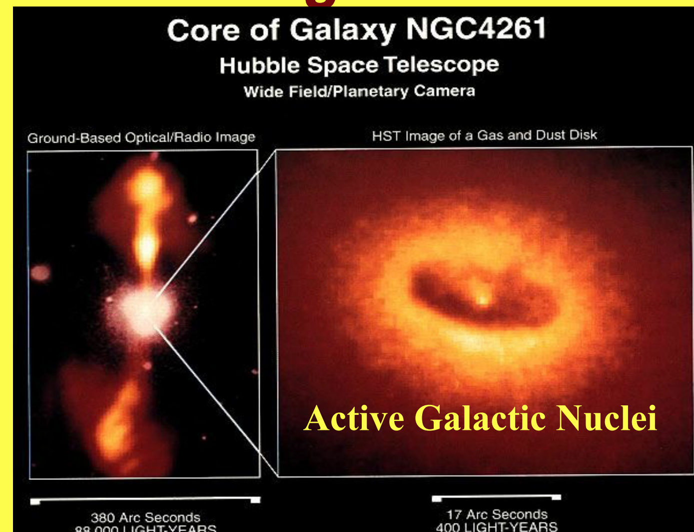
Search for point-like cosmic Neutrino Sources

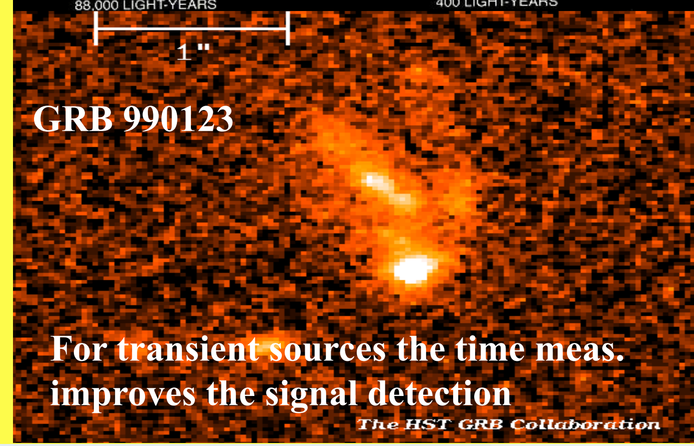
Galactic





Extragalactic





- Their identification requires a detector with accurate angular reconstruction

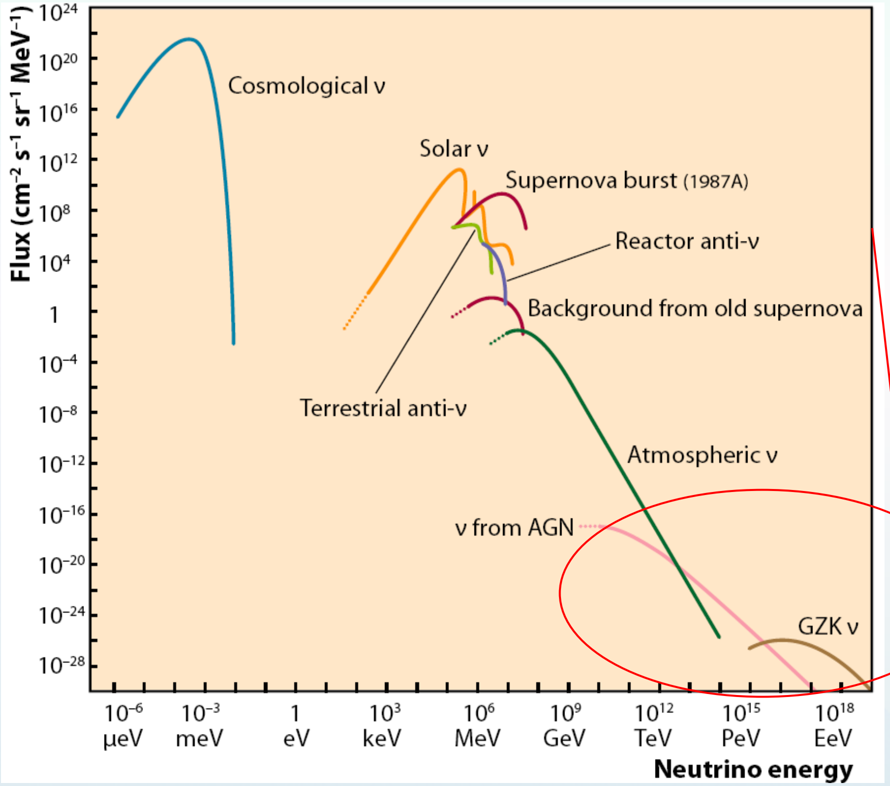
$$\sigma(\vartheta) \leq 0.5° \text{ for } E_\nu \geq 1 TeV$$

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

Neutrino Telescope physic's goal: 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.



Search here !!!

Neutrino Telescope physic's goal

astronomy/astrophysics in a multi-messenger framework

- Search for Coincident event in a restricted time/direction windows with EM/g/GW counterparts (flaring sources, transient events, ...)
- Relaxed energy/direction measurement + transient/ multi-messenger information

IceCube (1 km3 Neutrino Telescope) event statistics

separating signal and “background”

muons detected per year:

• atmospheric*	μ	$\sim 10^{11}$
• atmospheric**	$\nu \rightarrow \mu$	$\sim 10^{5}$
• cosmic	$\nu \rightarrow \mu$	$\sim 10\text{-}10^{2}$

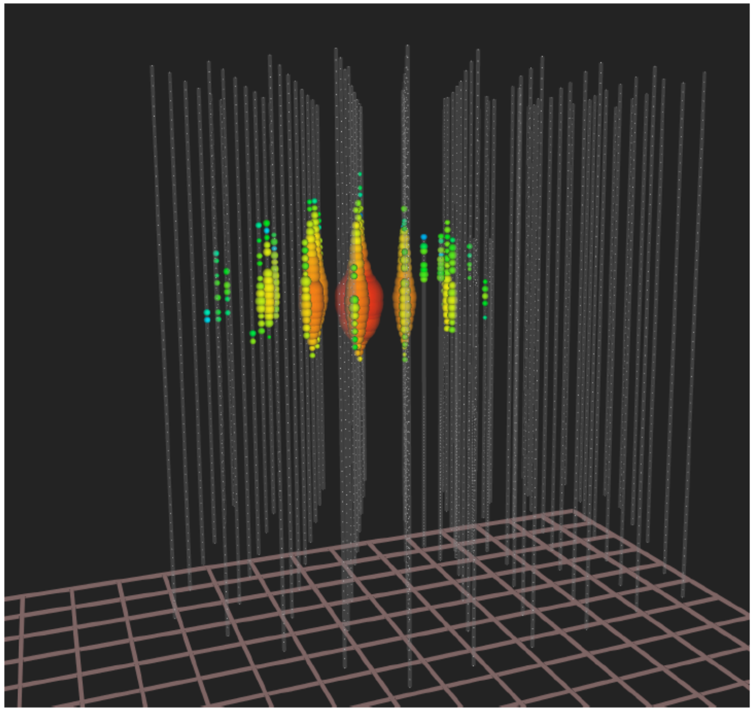
* 3000 per second

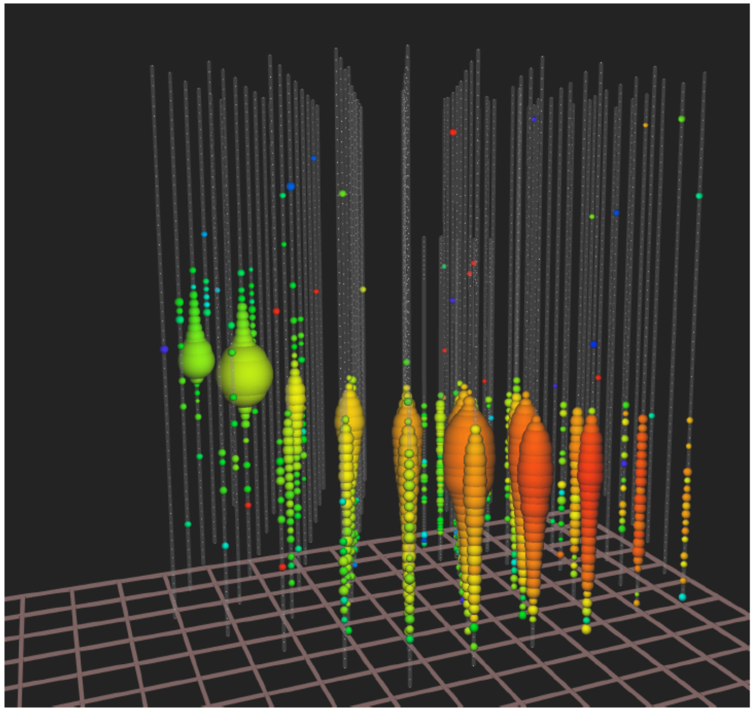
** 1 every 6 minutes

IceCube typical events

isolated neutrinos interacting *inside* the detector (HESE)

up-going muon tracks (UPMU)

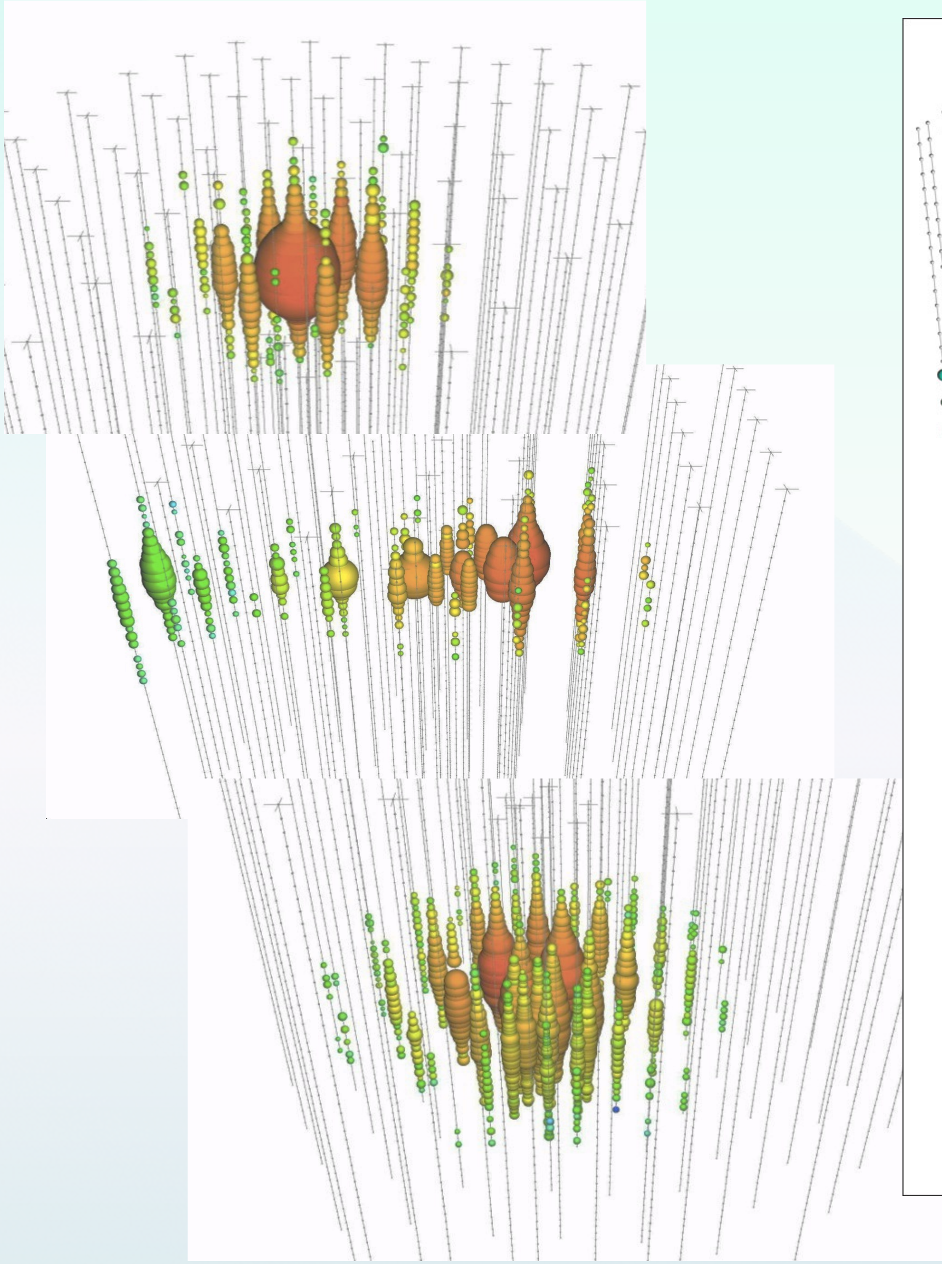


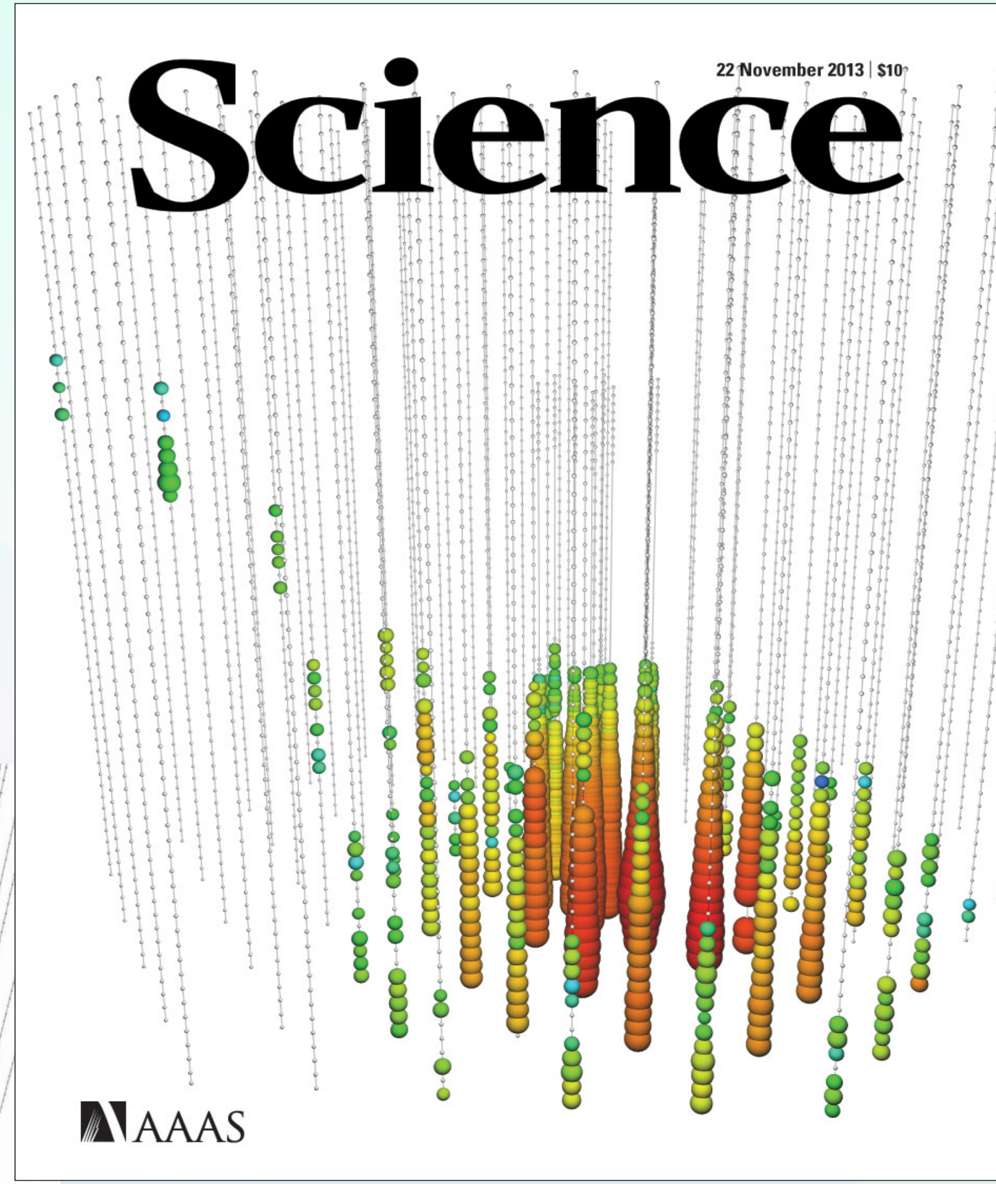


total energy measurement all flavors, all sky

astronomy: angular resolution superior (<0.5^{o})

The great discovery (from IceCube 2013)





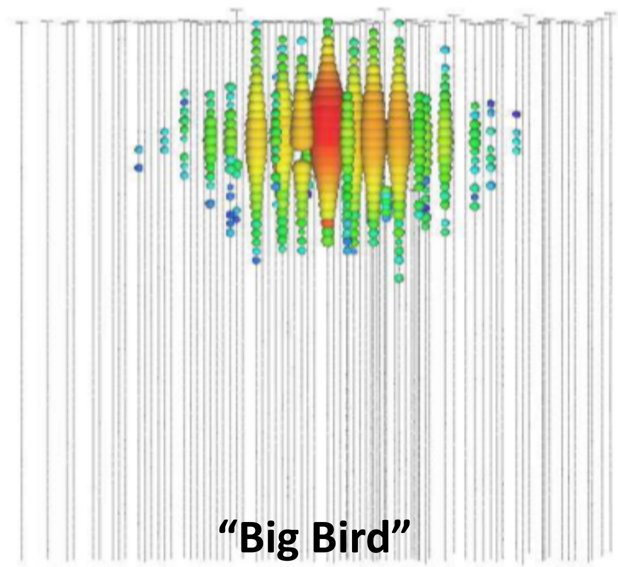
2-year analysis: Science 342, 1242856 (2013)

IceCube 2013 - High Energy Starting Event Analysis

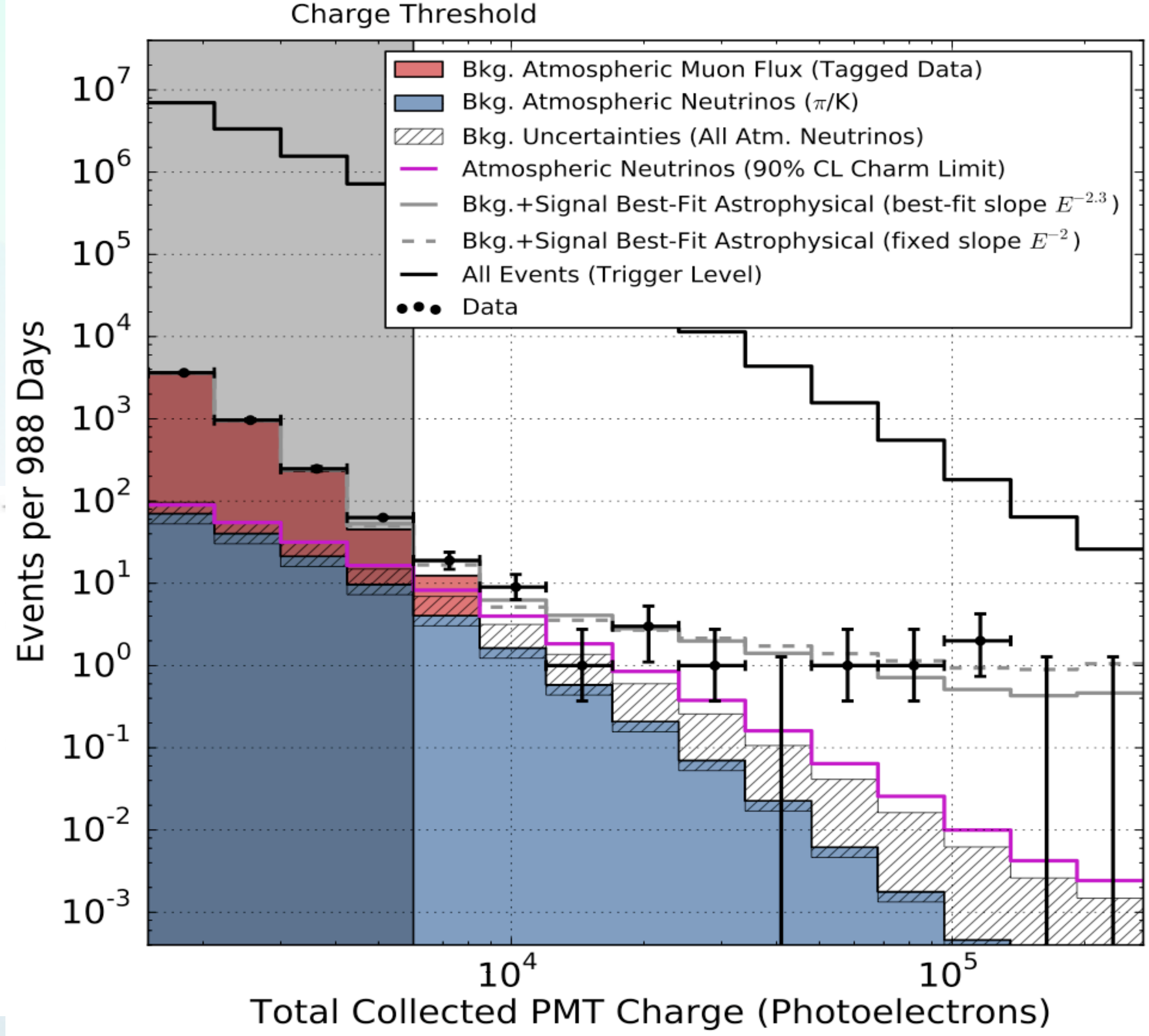
3-Year Analysis
PRL 113, 101101 (2014)

36 events in 3 years

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

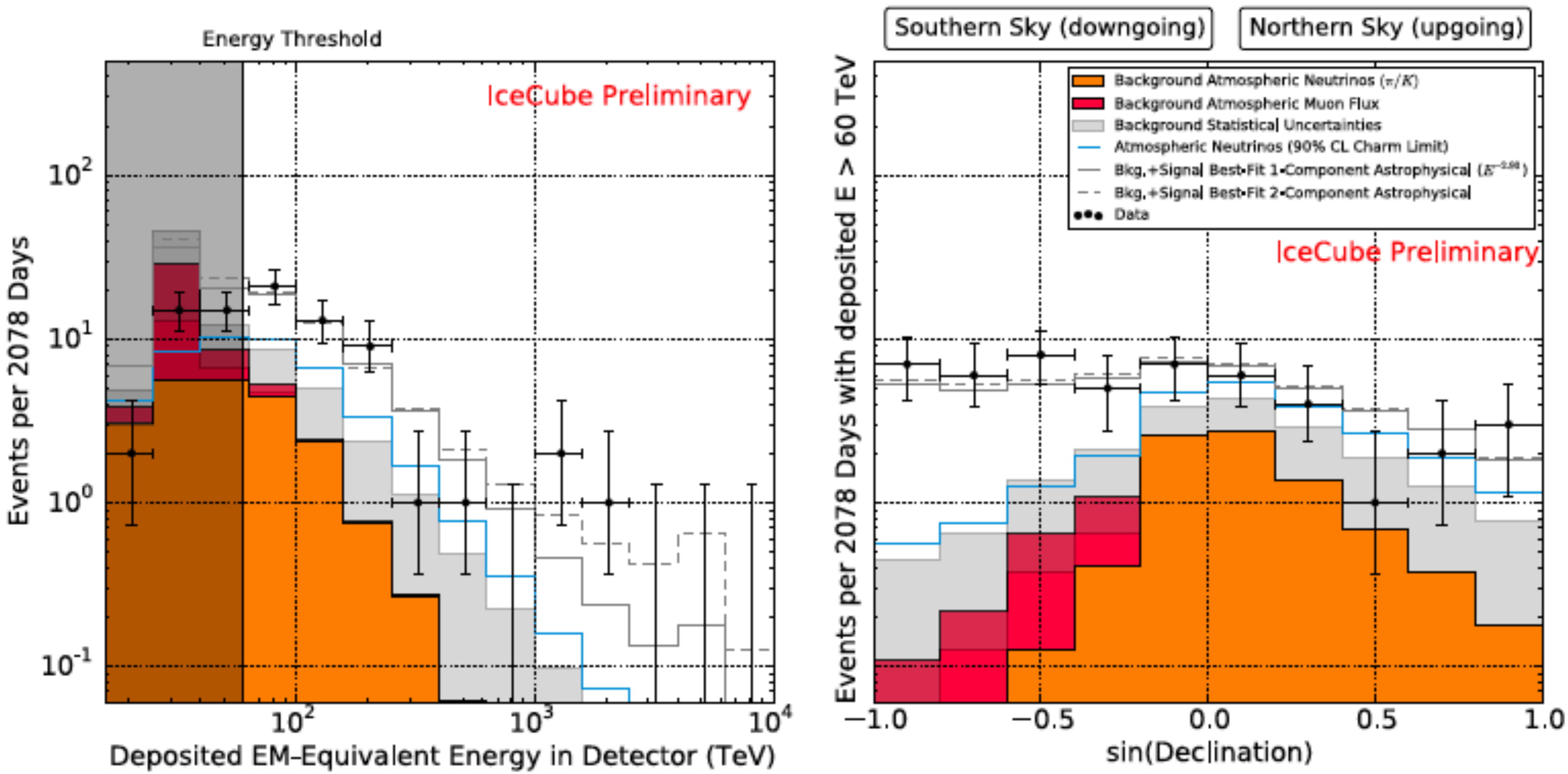


"Big Bird"



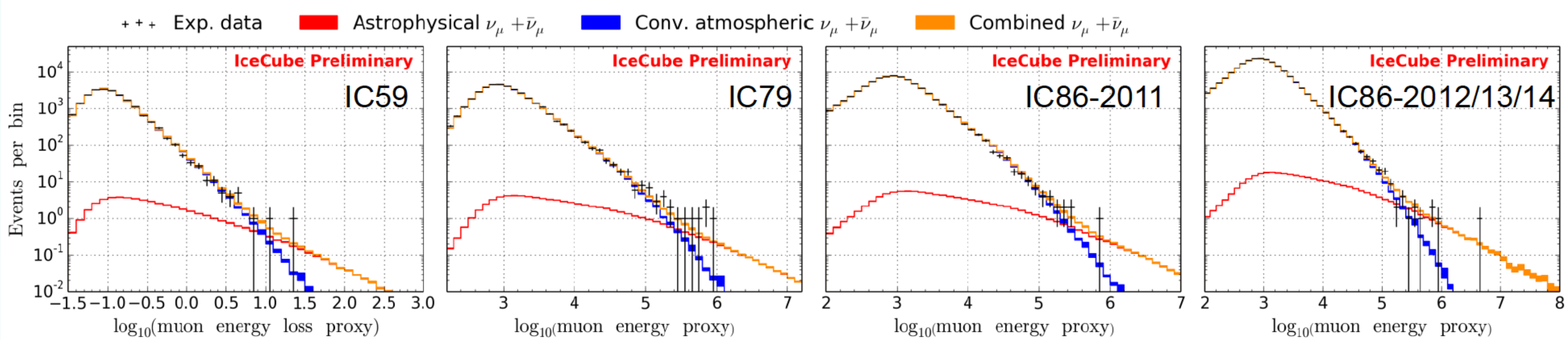
IceCube 2017 - High Energy Starting Event Analysis

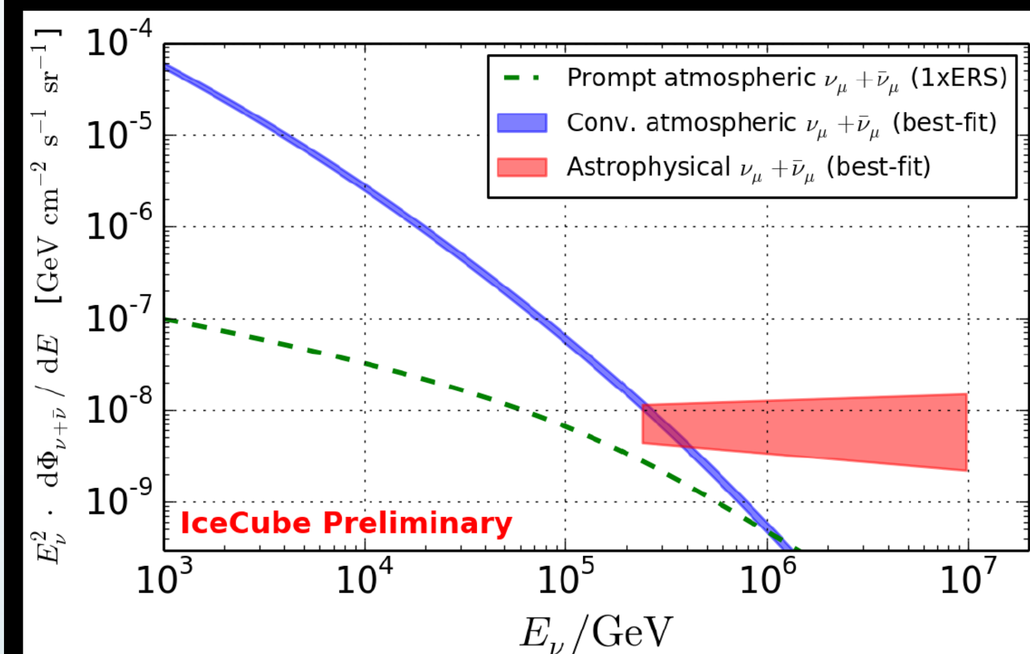
starting events: now 6 years → 8σ



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:

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

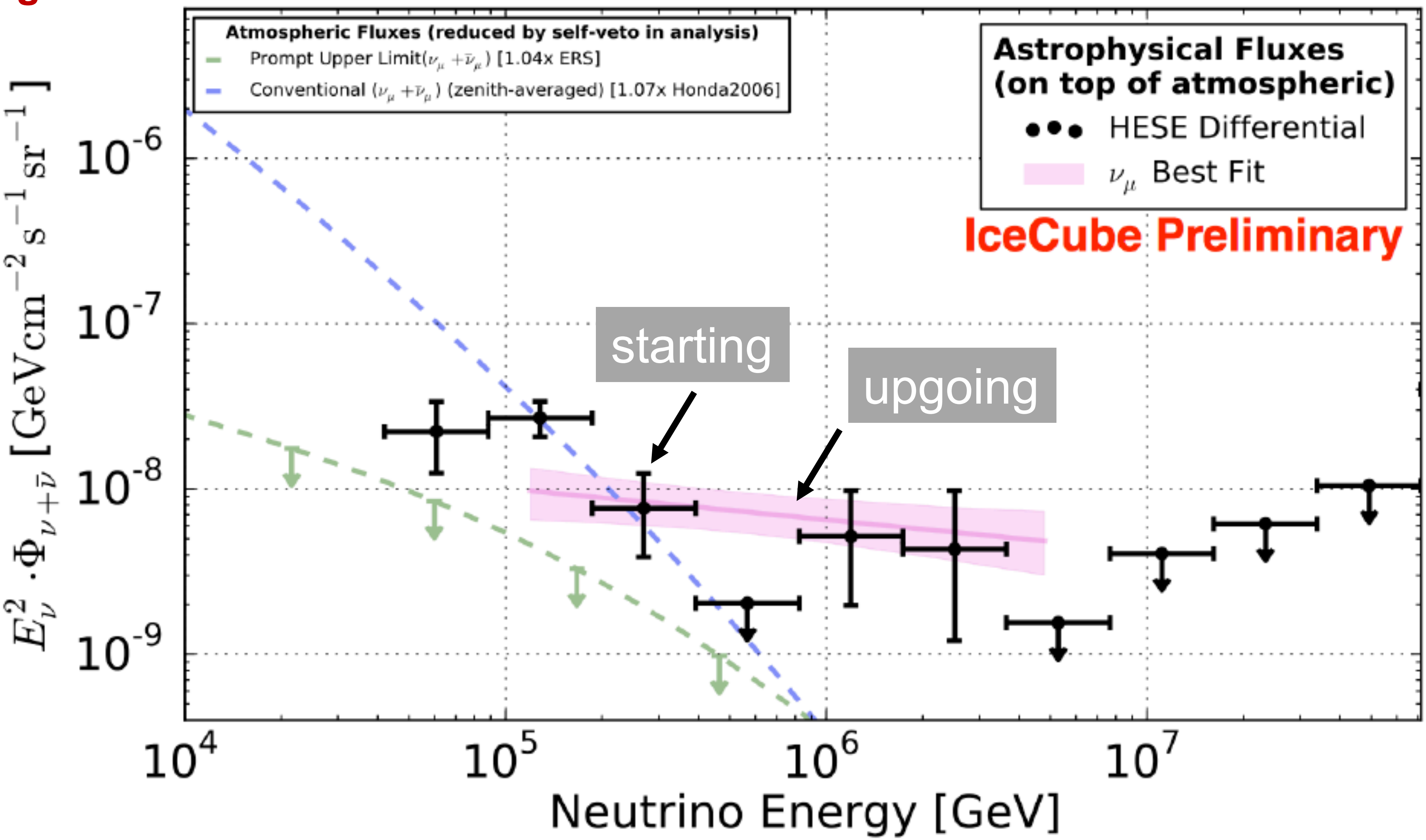
- Energy ranges:

240 TeV – 10 PeV

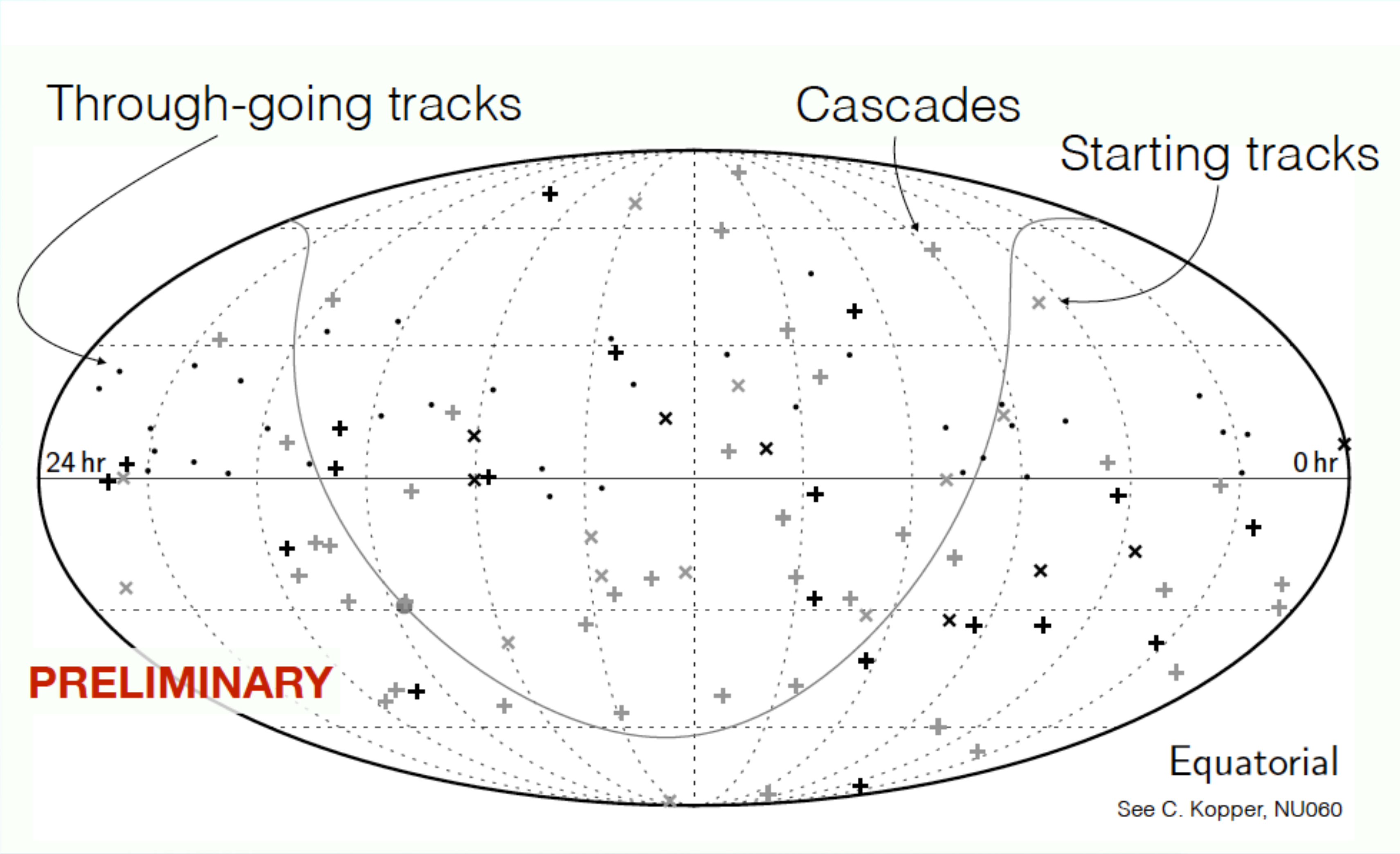
- Atmospheric-only hypothesis excluded by 6.0σ

IceCube 2017

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



Where these neutrinos are coming from ??



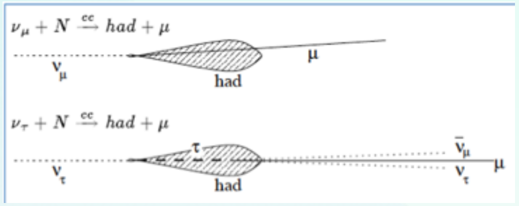
A diffuse flux from extragalactic sources
A subdominant Galactic component cannot be excluded

It's mandatory now !!!!

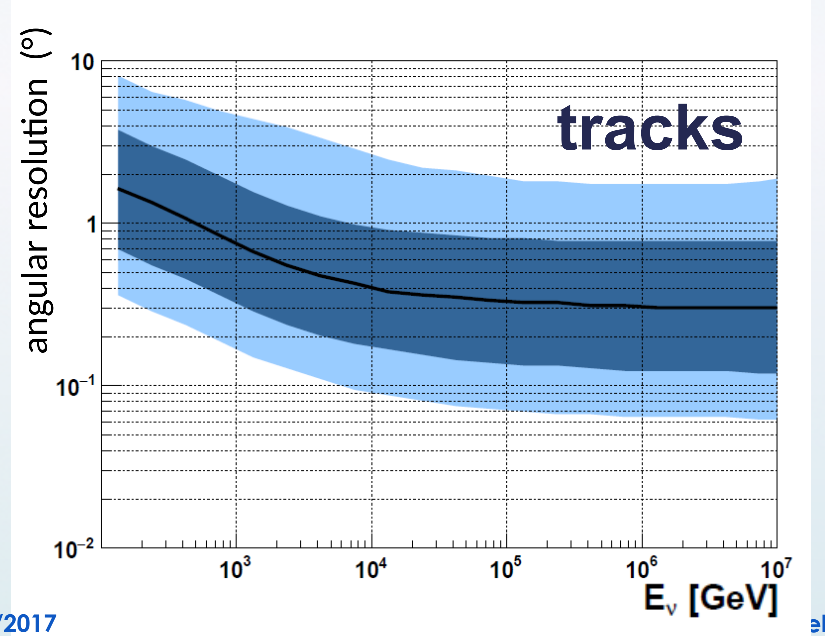
- **Let search for neutrino point like sources:**
  - Large size detector required (very small fluxes expected)
  - Very good accuracy in angular reconstruction (high background, the irreducible atmospheric background has to be subtracted statistically)

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

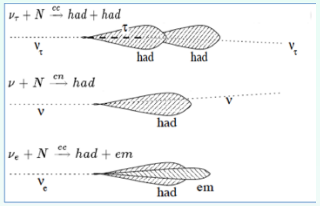
- **Tracks: CC ν_μ or $\nu_\tau \rightarrow \mu$**



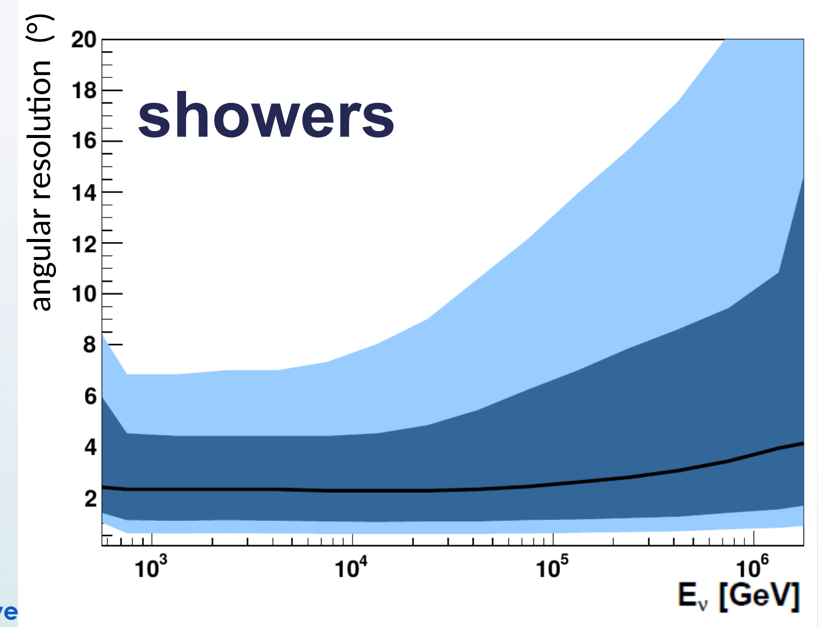
- **Interaction can occur far from the detector providing a large *Effective Volume***
- ***Angular resol.* $< 0.4°$ for $E_\nu > 10\ TeV$**
- ***Energy resol.* ~ factor 3**



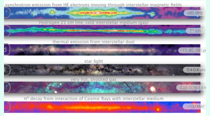
- **Electronic or hadronic showers: NC and CC ν_e or $\nu_\tau \rightarrow$ showers**

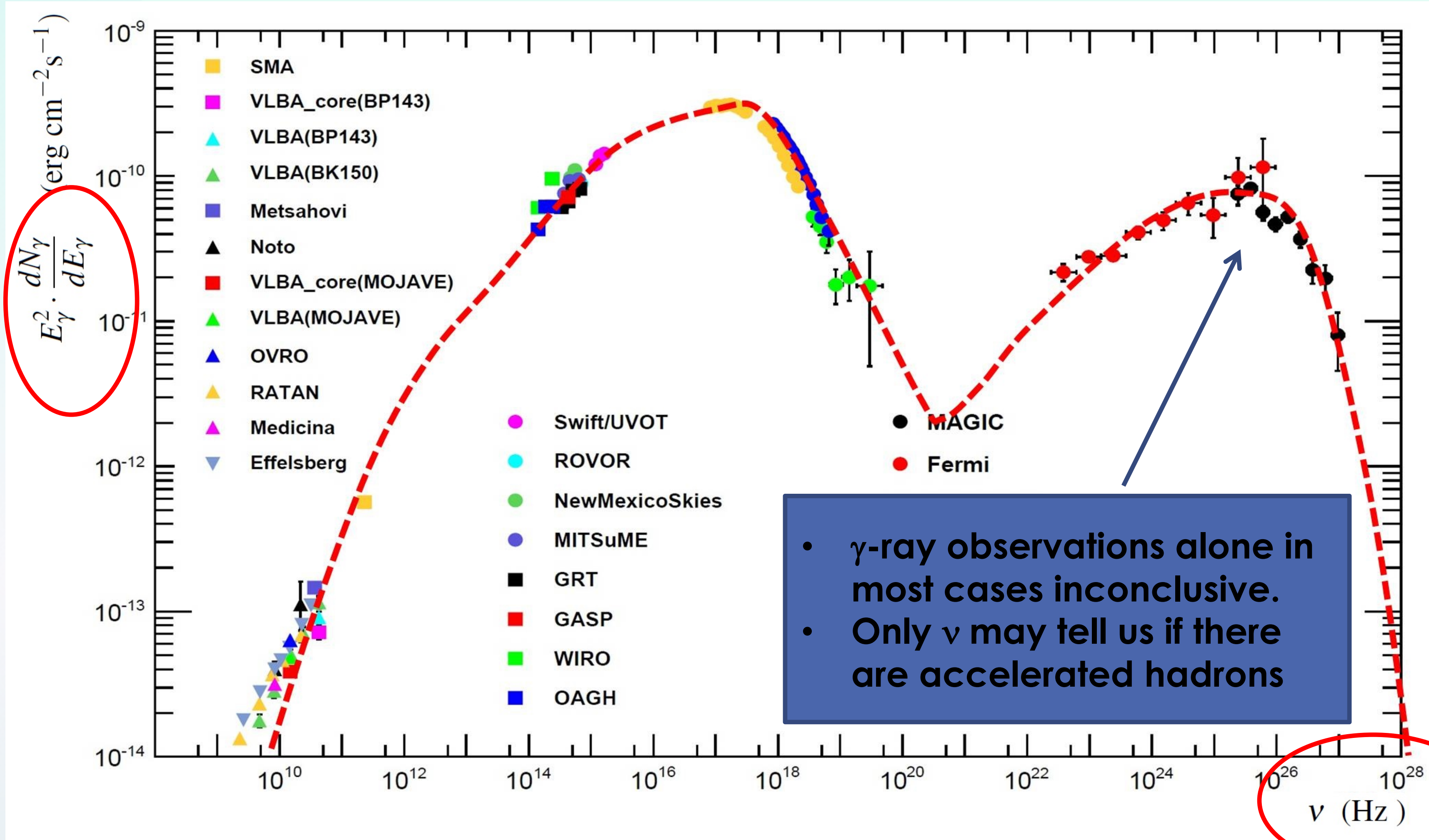


- **Events contained in the detector: smaller *Effective Volume,***
- ***Energy resolution ~ 5-10%***
- ***Median angular resolution* $\sim 3°$**



Multi-wavelength observation: Mrk421
an example

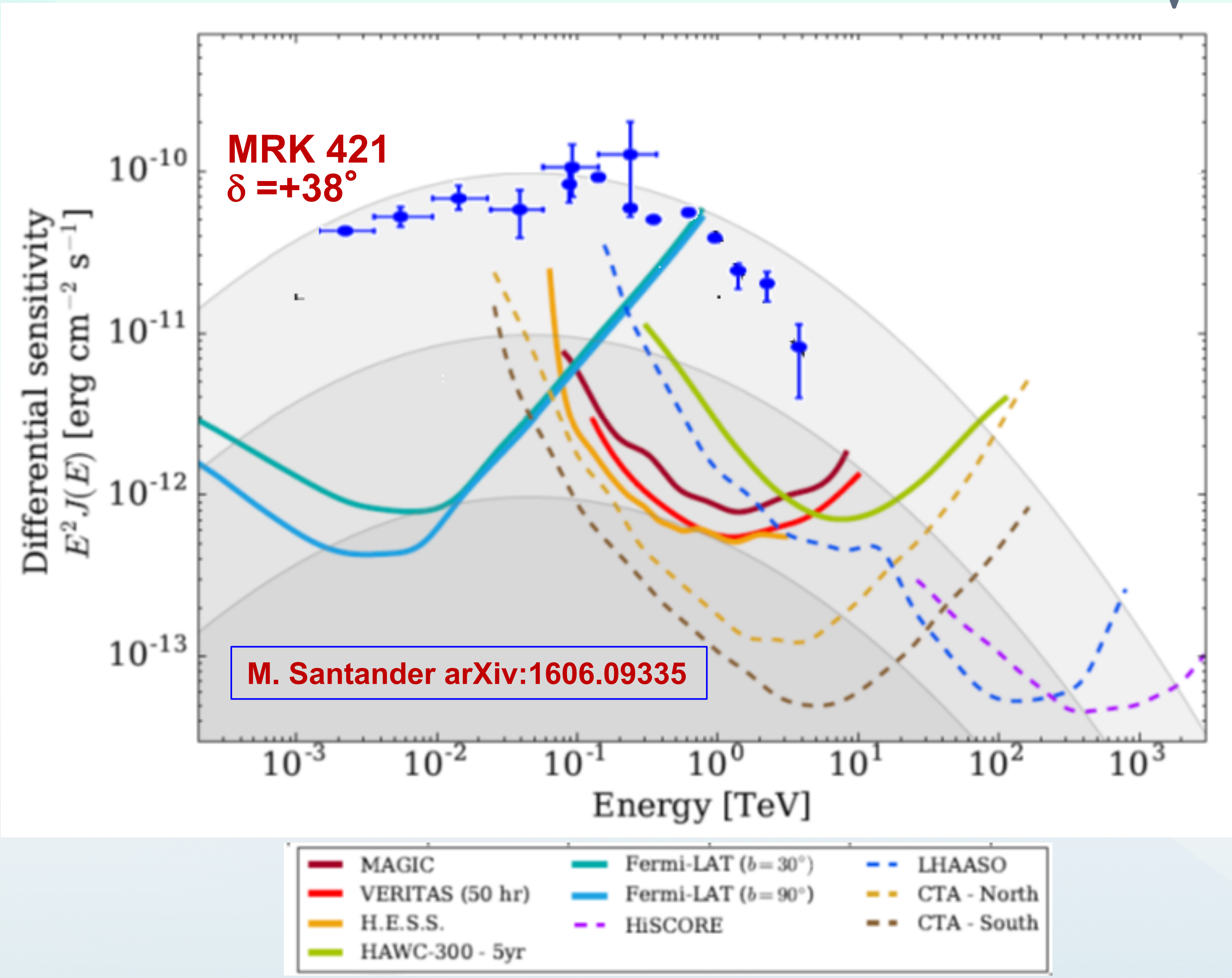




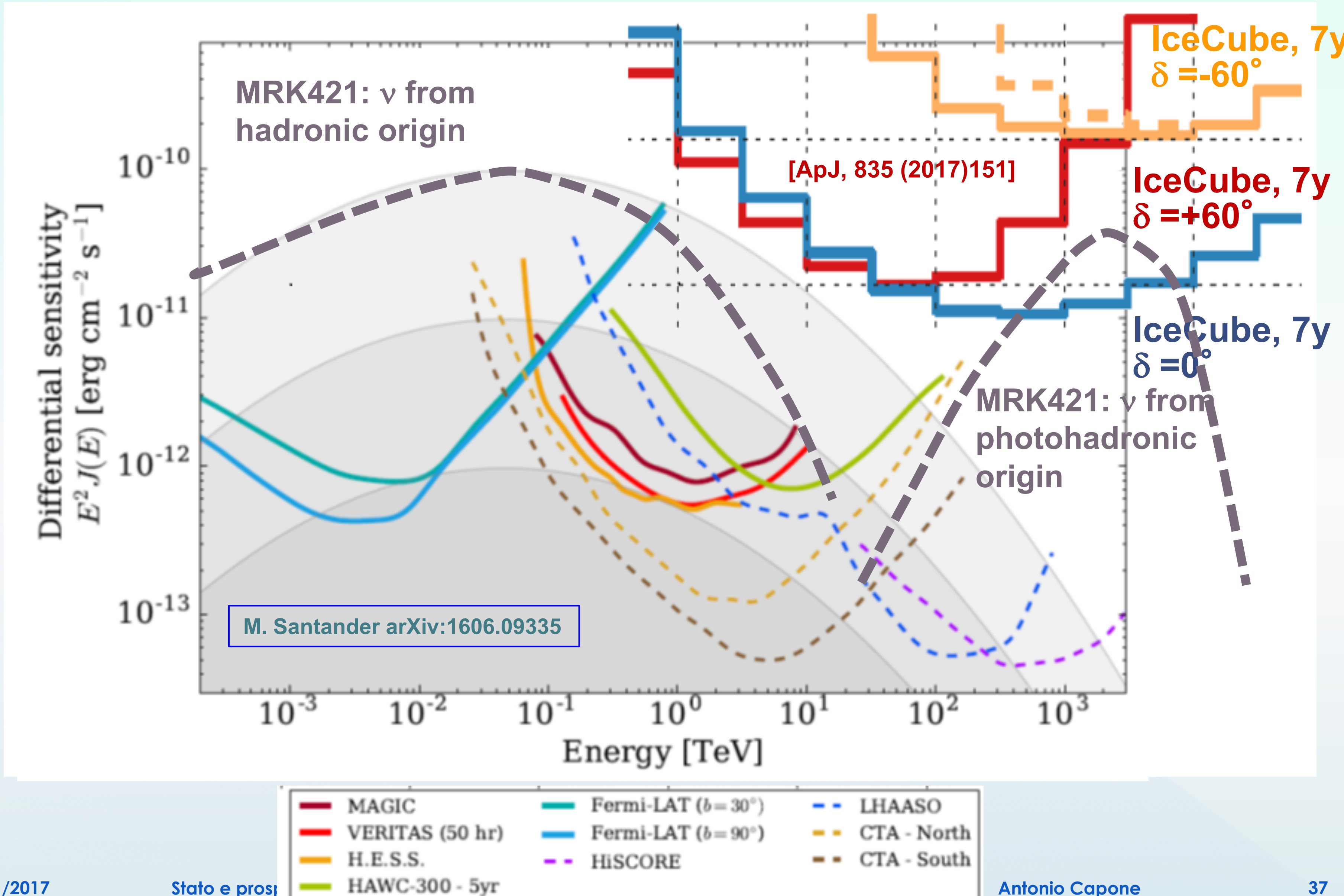
- γ-ray observations alone in most cases inconclusive.
- Only ν may tell us if there are accelerated hadrons

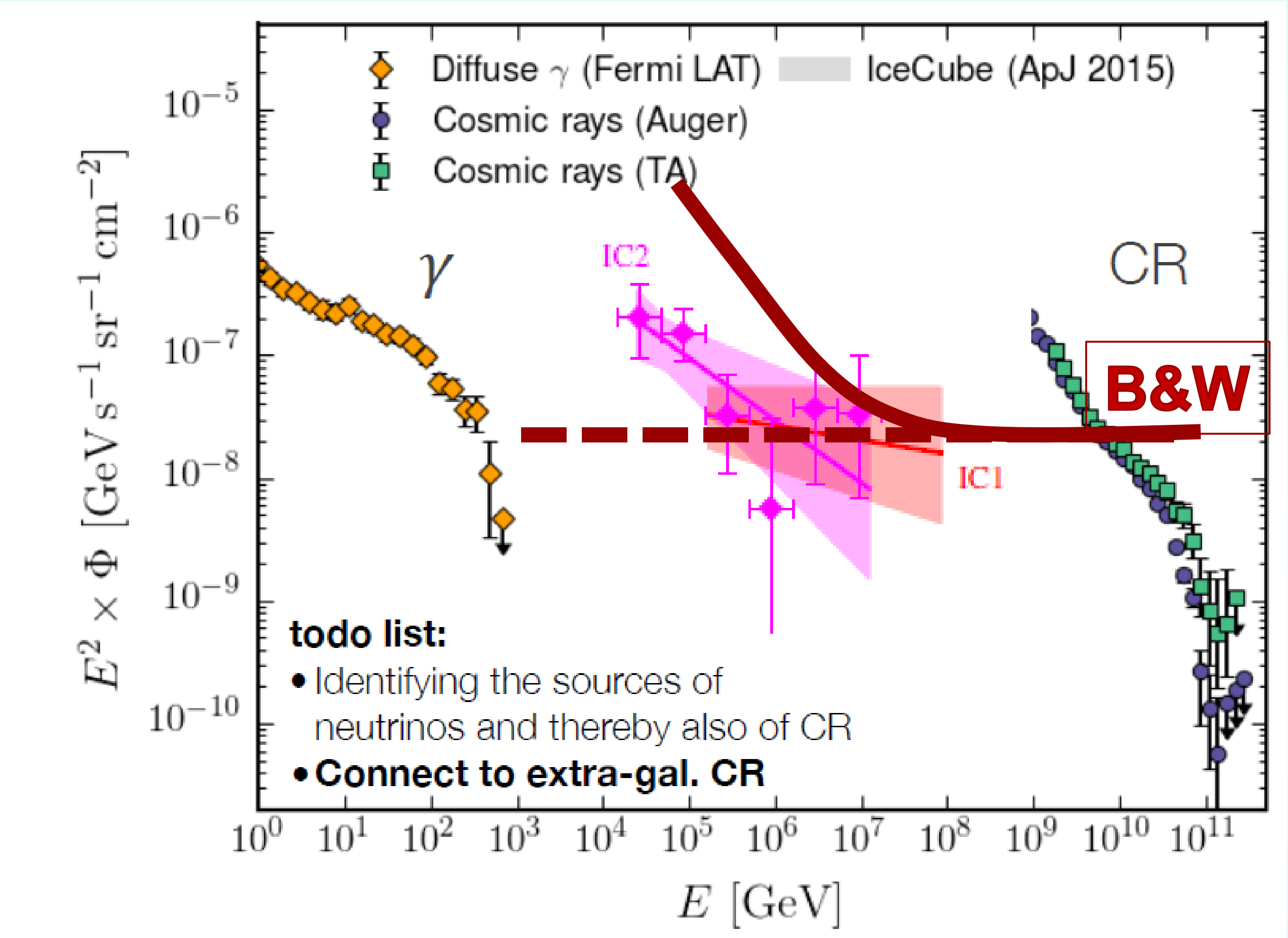
Extensive multi-wavelength measurements showing the spectral energy distribution (SED) of Markarian 421 from observations made in 2009. The dashed line is a fit of the data with a leptonic model. Abdo et al. ApJ 736(2011) 131 for the references to the data

γ and ν discovery potential



From multiwavelenght to multimesenger: γ and ν discovery potential



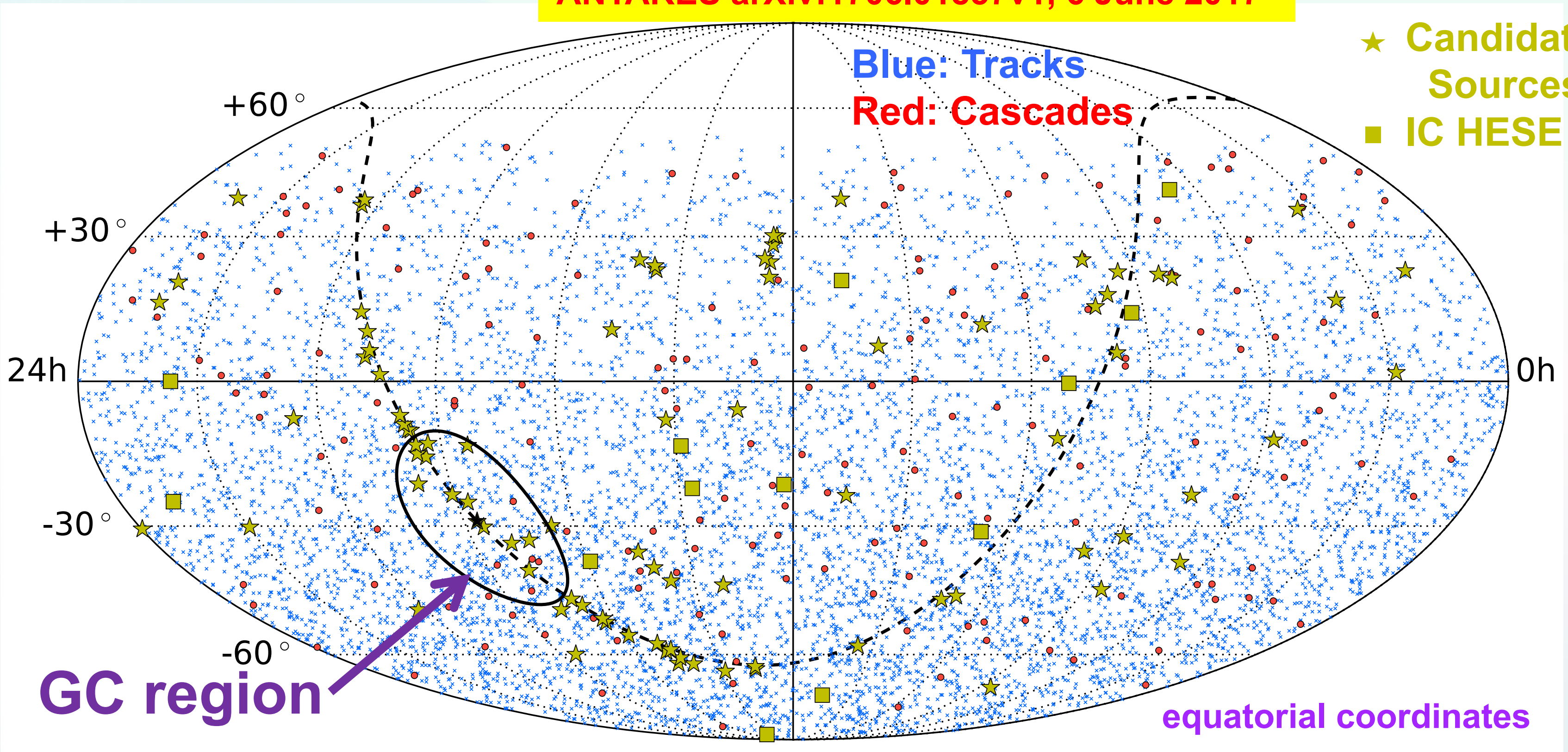

Diffuse γ (Fermi LAT)
IceCube (ApJ 2015)
Cosmic rays (Auger)
Cosmic rays (TA)
γ
IC2
IC1
CR
B&W
todo list:
• Identifying the sources of neutrinos and thereby also of CR
• Connect to extra-gal. CR
$E^2 \times \Phi$ [GeV s^{-1} sr^{-1} cm^{-2}]
E [GeV]

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

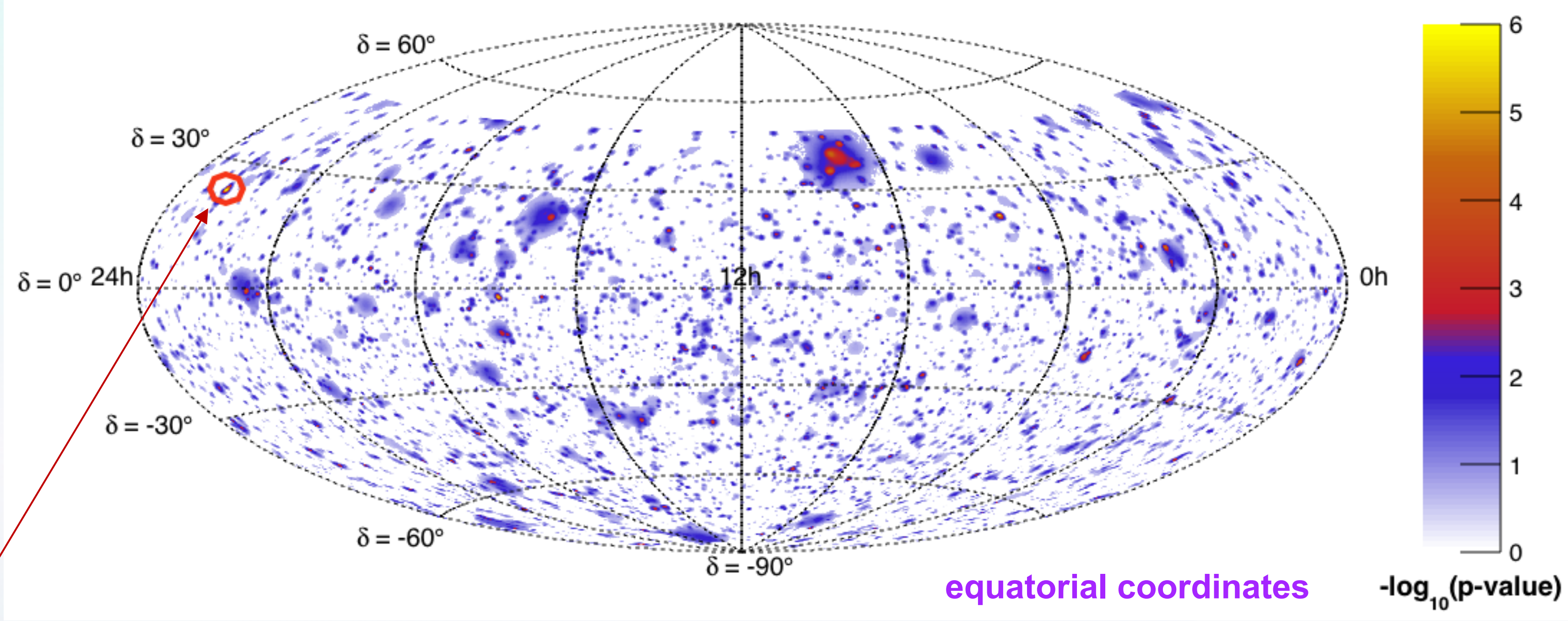


so far …. no significant excess has been found

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

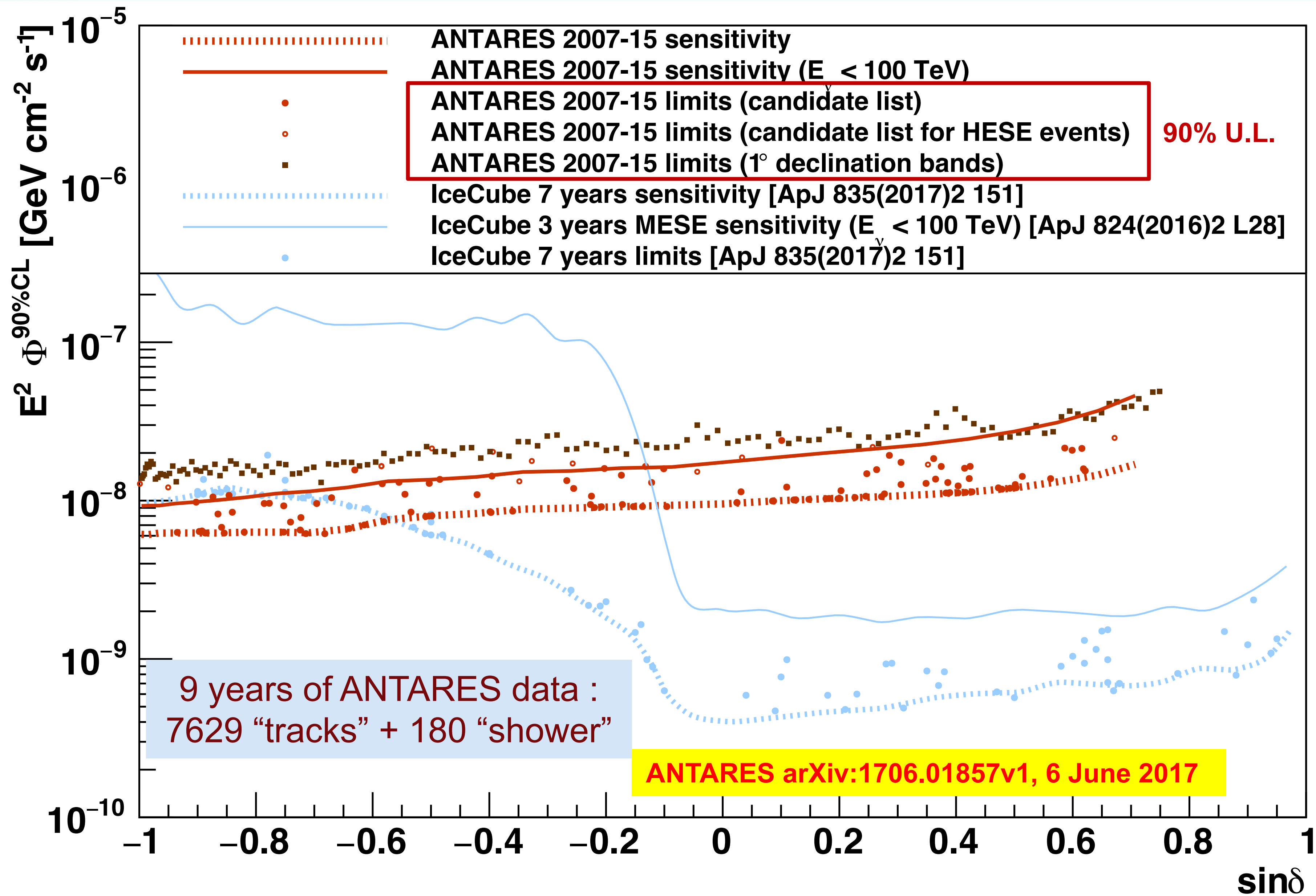
ANTARES arXiv:1706.01857v1, 6 June 2017



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}

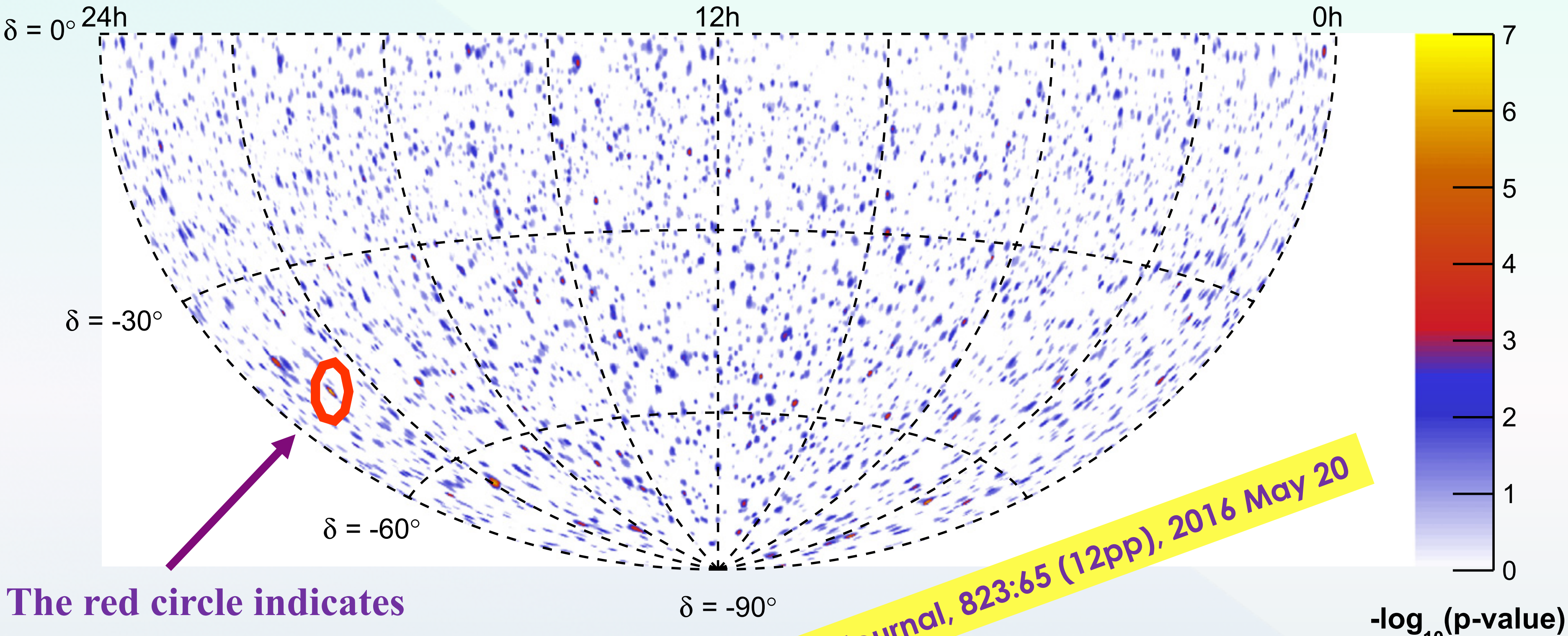
→ U. L. from this sky location $E^2 \frac{d\Phi}{dE} = 3.8 \times 10^{-8}$ GeV cm^{-2} s^{-1}

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 2007/12 and IceCube 40, 59, 79 point-source analyses.



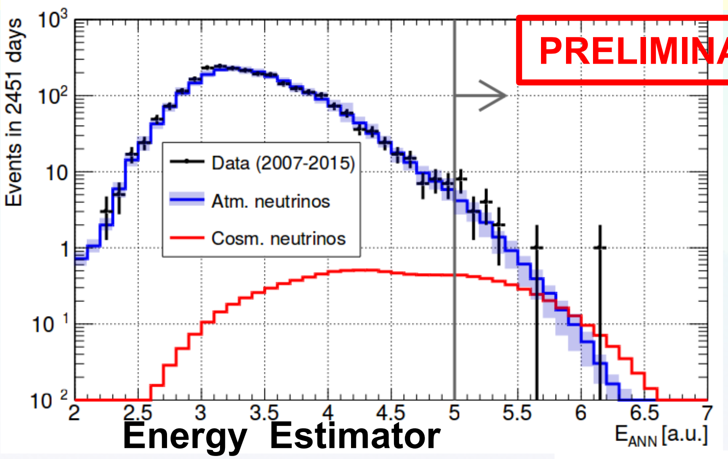
The red circle indicates the location of the most significant cluster: (0.7σ post-trial significance)

The Astrophysical Journal, 823:65 (12pp), 2016 May 20

Latest ANTARES results on the search for diffuse ν flux

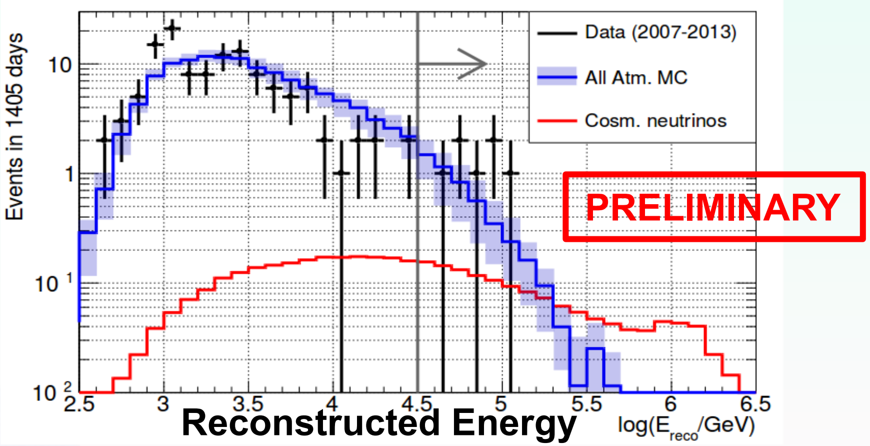
Tracks

Data: 2007-2015 (2451 live-days)
Above E_{cut}: Bkg: 13.5 ± 3 evts, IC-like signal: 3 evts
Observed: 19 evts



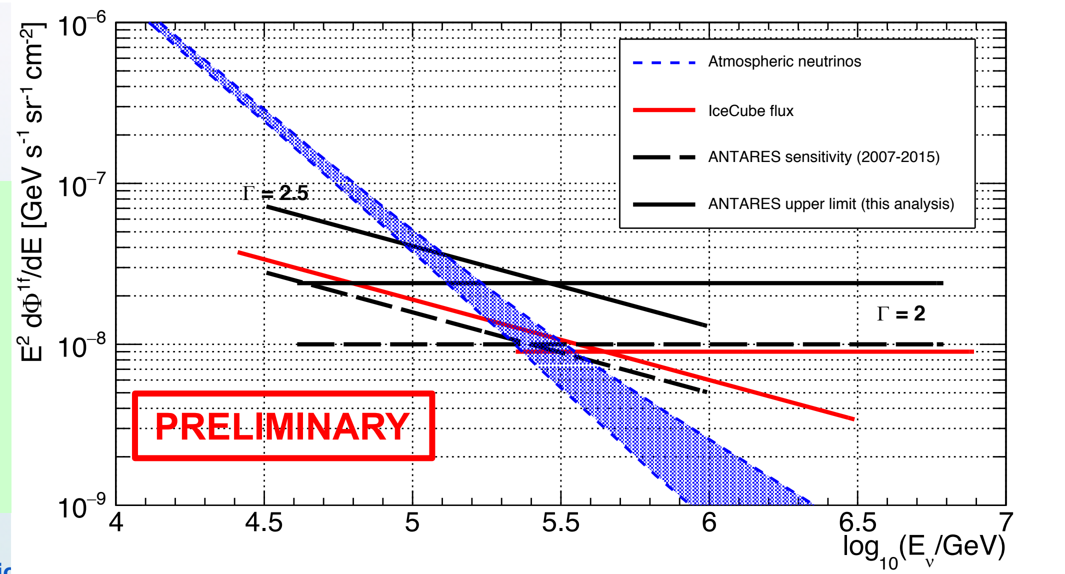
Cascades

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



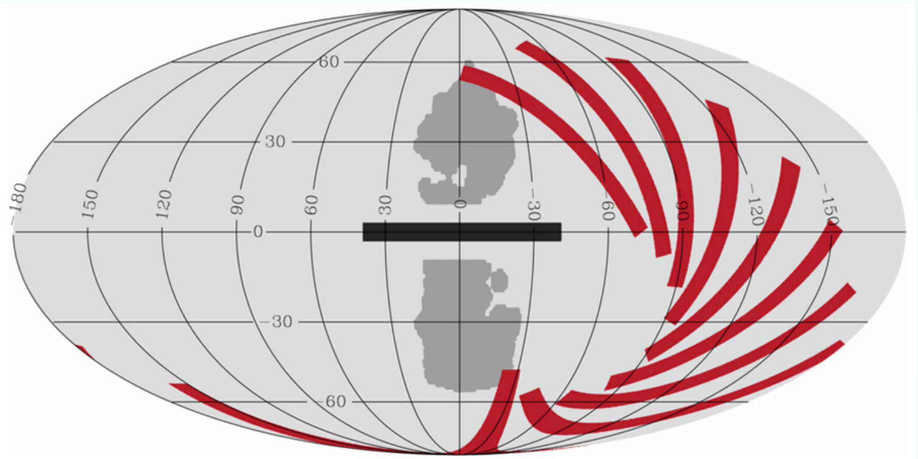
Search for neutrinos from the Galactic ridge - 1

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

$$p_{CR} + p_{ISM} \rightarrow \pi^0 \pi^\pm \ldots$$

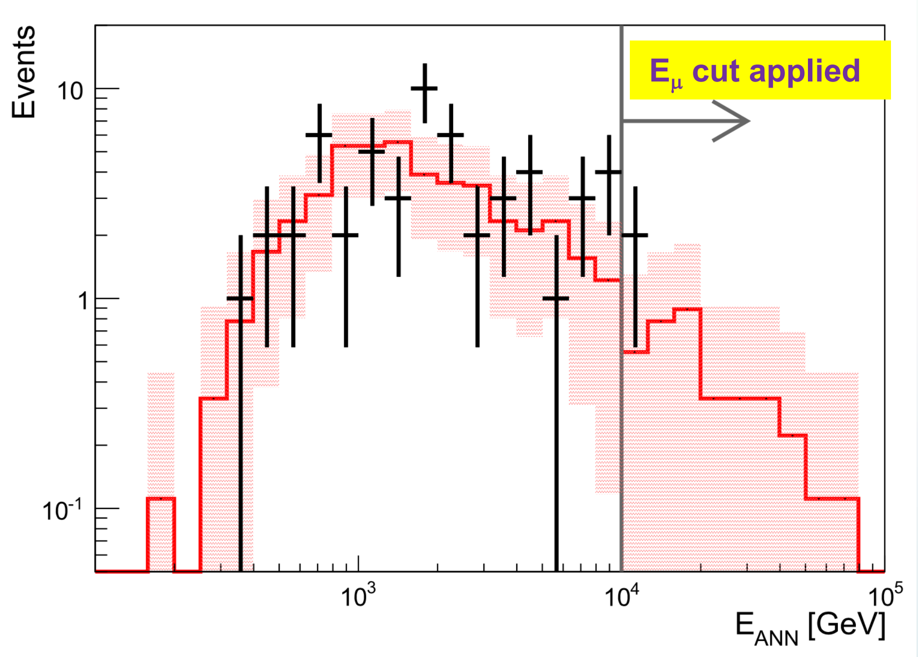
$$\pi^0 \rightarrow \boldsymbol{\gamma\gamma(EM\ cascade)}$$

$$\pi^\pm \rightarrow \boldsymbol{\nu_\mu, \nu_e} \ldots$$



Physics Letters B 760 (2016) 143–148

- 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

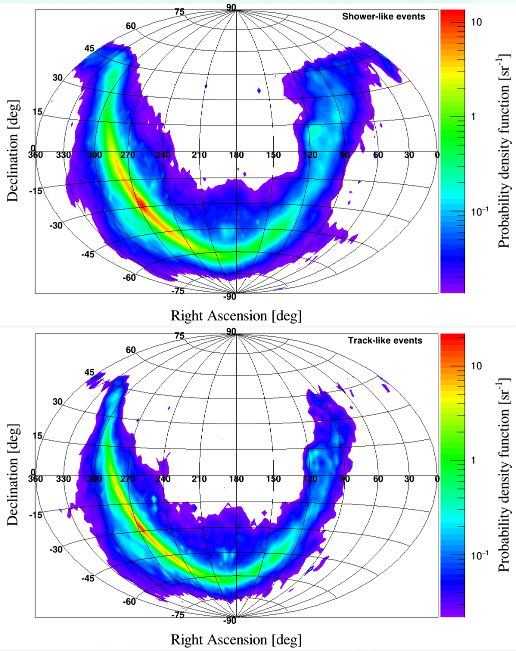


Distribution of the reconstructed E_μ of up-going muons in the Galactic Plane (black crosses) and average of the off-zone regions (red histogram).

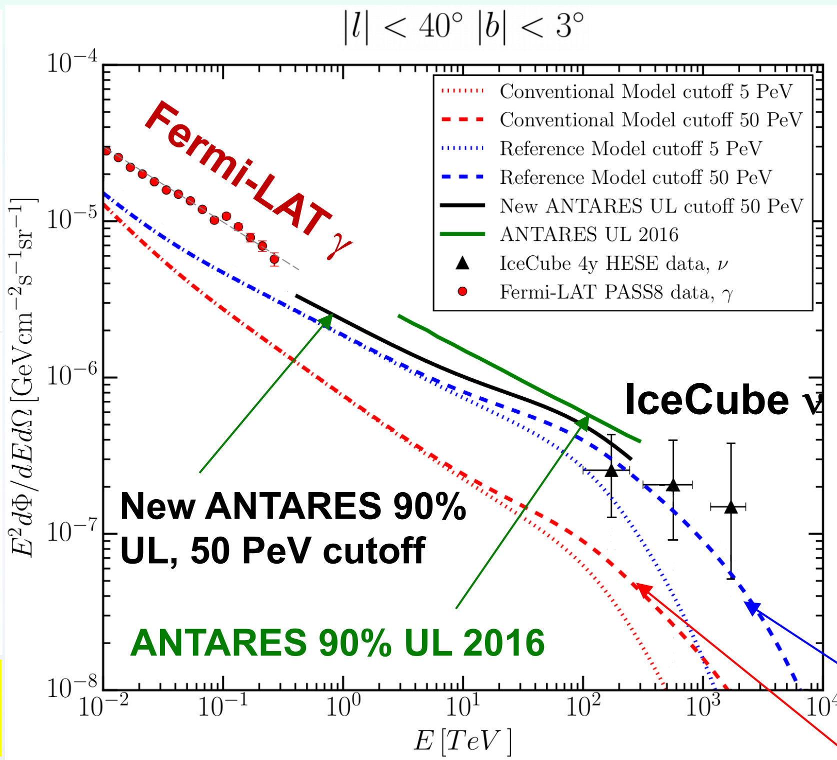
Search for neutrinos from the Galactic plane - 2

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

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



ANTARES arXiv:1705.00497v1
1 May 2017



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

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

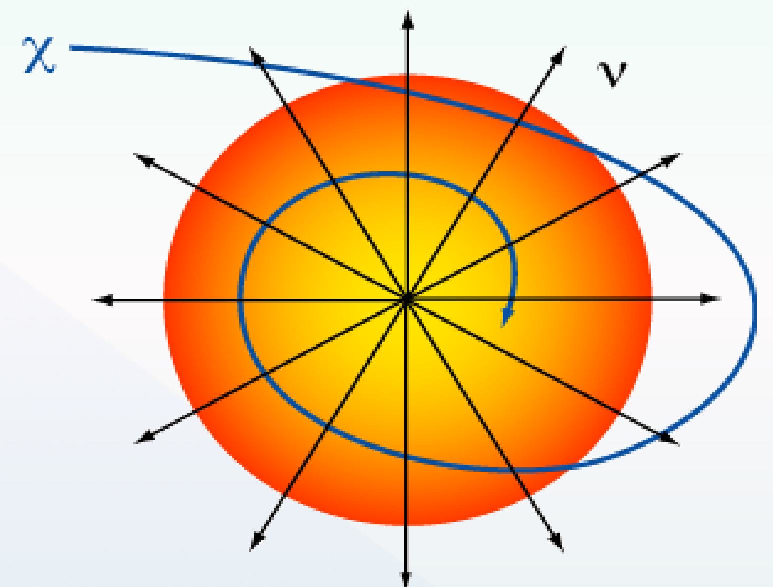
KRA$_\gamma$ 50PeV cut-off for CR
KRA$_\gamma$ 5PeV cut-off for CR

KRA$_\gamma$ assuming a neutrino flux $\propto E^{-2.5}$ and a CR spectrum with 50 PeV cut-off can explain ~20% of the IceCube observed HESE.
ANTARES, with an good visibility of the Galactic Plane well suited to observe these fluxes or to put competitive limits: no signal found → set 90%C.L. upper limits.

… 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
- …

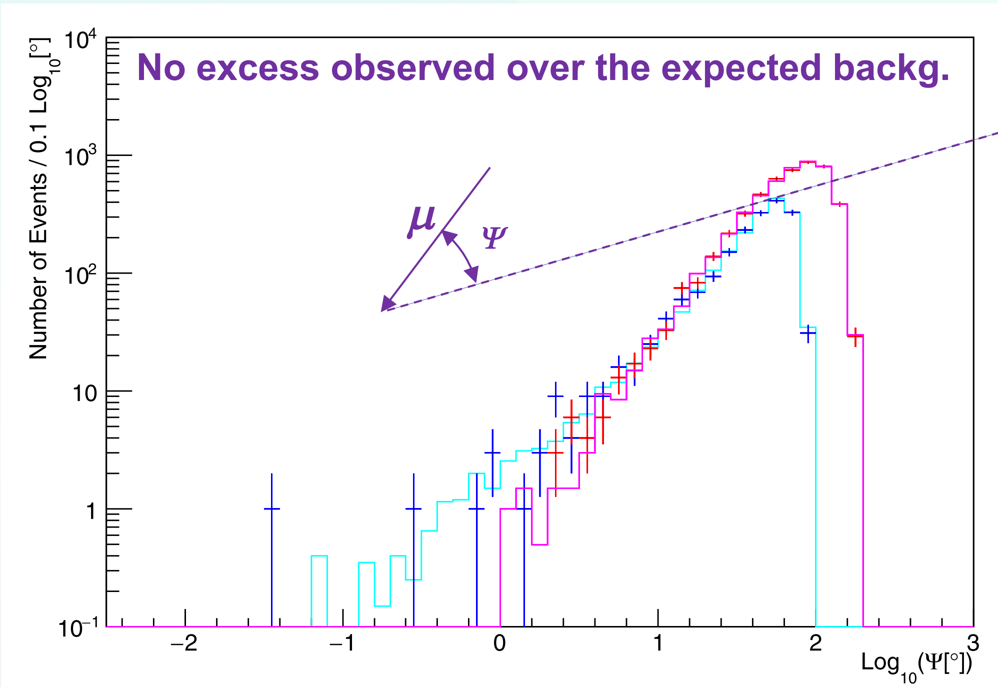


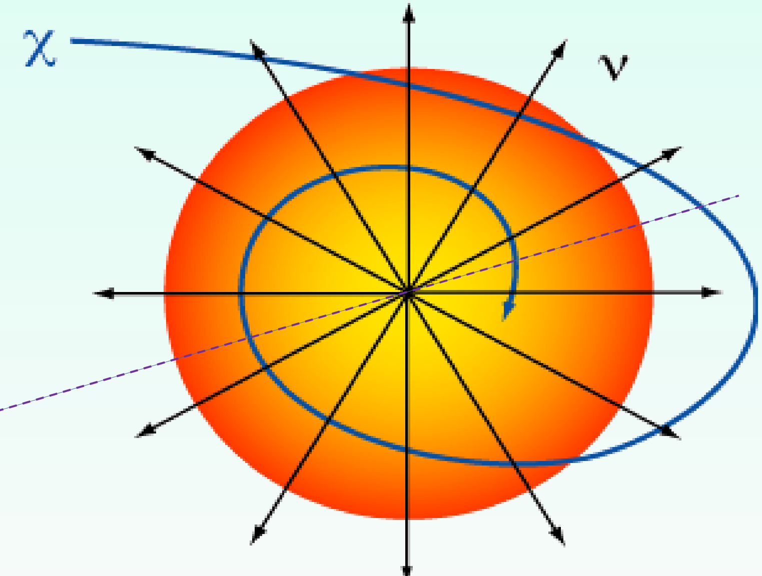
Neutralino search: $\chi\chi \rightarrow \nu + \ldots$

Indirect search for Dark Matter in the Sun

6 years of ANTARES data: 2007-2012

Distribution of the angular distance between reconstructed the track direction of events and the Sun position for two different track reconstruction algorithms in order to maximize the event reconstruction for single line and multi-lines events.





Neutralino search: $\chi\chi \rightarrow \nu + \ldots$

Neutrino spectrum
from WIMPSIM (M. Blennow, J. Edsjö, T. Ohlsson, J. Cosmol. Astropart. Phys. 0801 (2008) 021.)

Background
estimated from time-scrambled data.

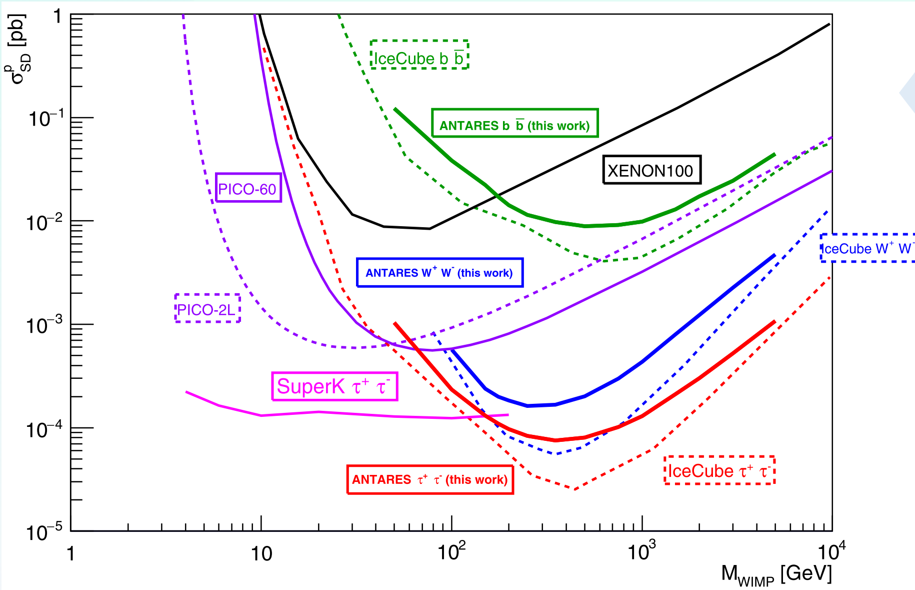
Neutrino fluxes from $WIMP + WIMP \rightarrow b\bar{b}, W^+W^-, \tau^+\tau^-$ $\rightarrow \bar{\nu}\,\nu + \ldots$

evaluated for 50 GeV/c^2 < M$_{WIMP}$ < 5 TeV/c^2

→ limits to ν fluxes and to WIMP-nucleon cross sections

Indirect search for Dark Matter in the Sun

No excess observed over the expected background: evaluate 90% C.L. upper limits for expected signal

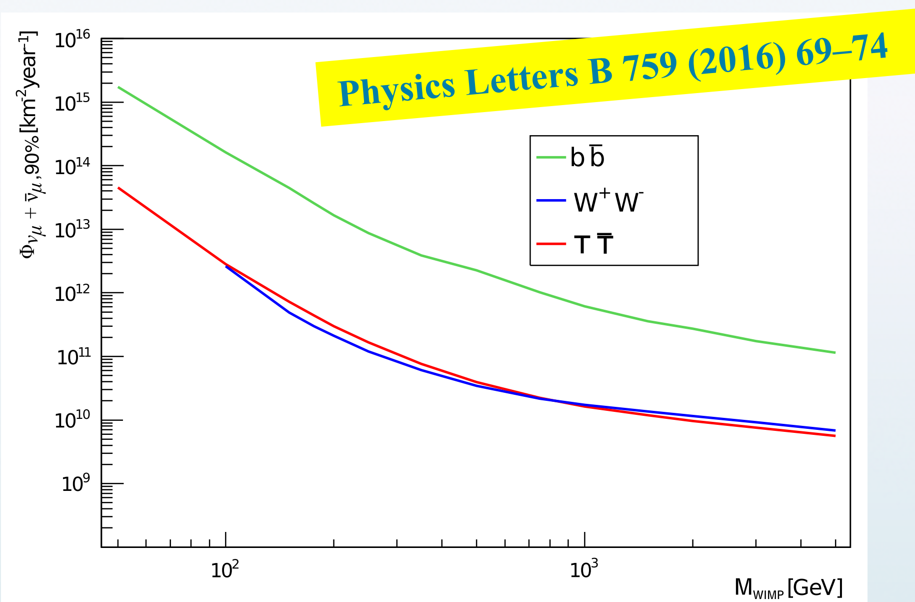


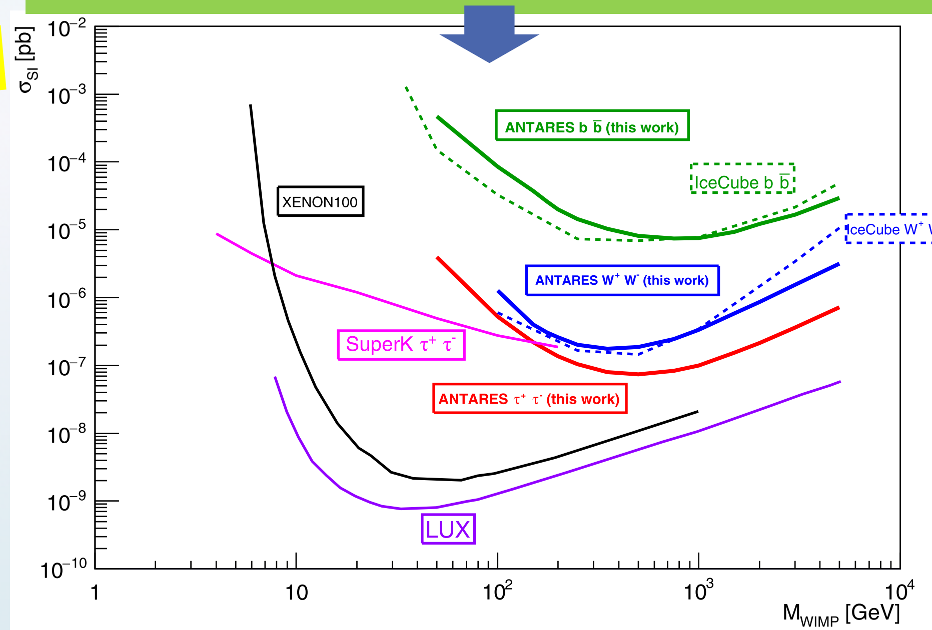
Limits on the **spin-dependent** WIMP-nucleon scattering cross-section as a function of WIMP mass for the bb ̄, τ+τ− and W+W− channels.

assumptions:

- **capture and annihilations in equilibrium**
- local D.M. density =0.4 GeV cm^{-3}
- v_{SUN}^{DM} according to Maxwell distr. 270 km s^{-1} r,m.s.

Limits on the **spin-independent** WIMP-nucleon scattering cross-section as a function of WIMP mass for the different channels considered.





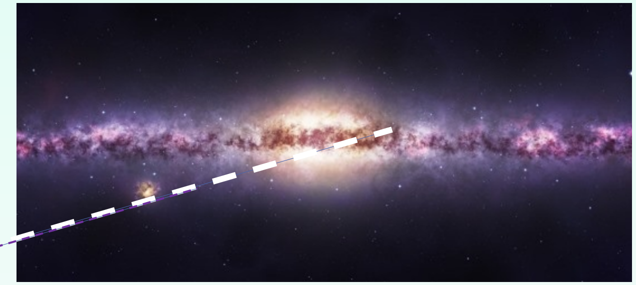
Indirect search for Dark Matter in the Galactic Centre

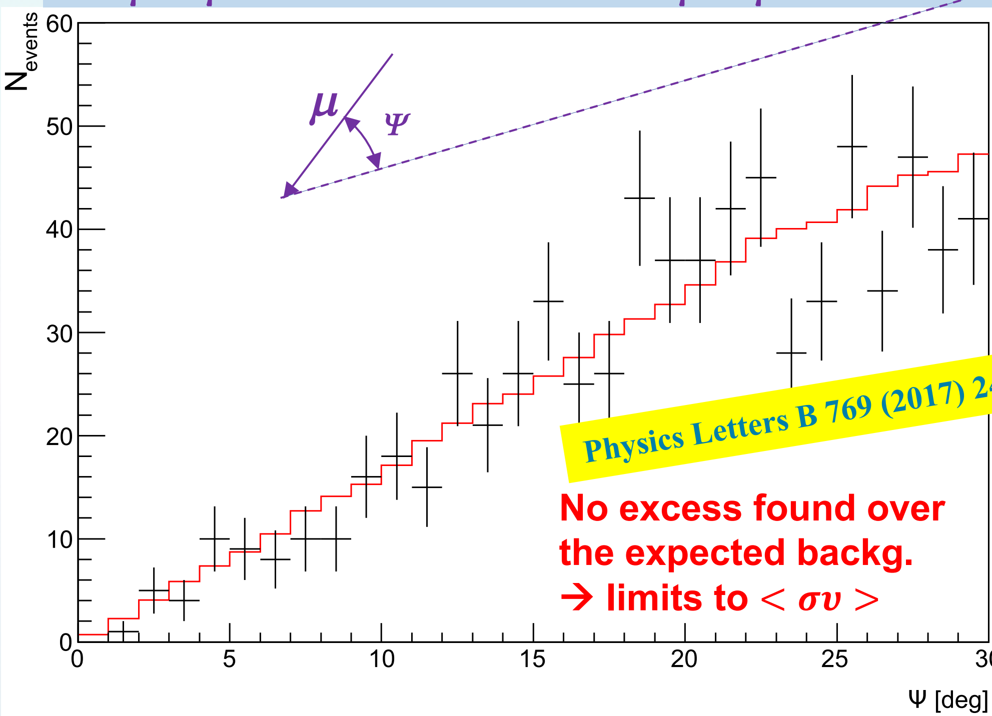
9 years of ANTARES data: 2007-2015 - ANTARES "observes" the G.C > 66% time

Search performed for:

- **50 GeV/c² < M_{WIMP} < 100 TeV/c²**
- $WIMP + WIMP \rightarrow b\bar{b}, W^+W^-, \tau^+\tau^-, \mu^+\mu^-, \nu\bar{\nu}$

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

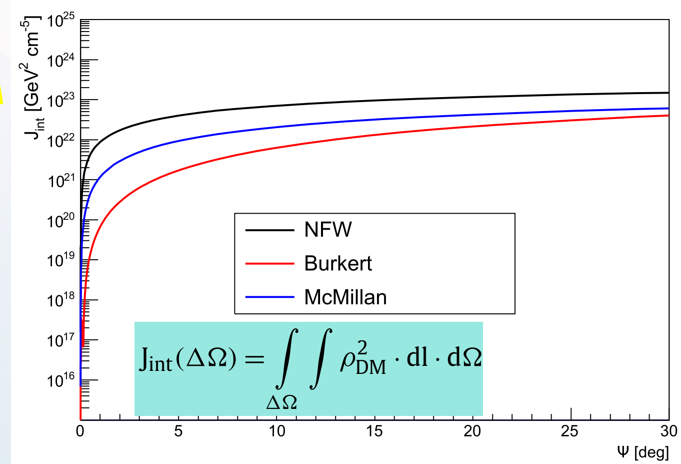




Distribution of measured angles between reconstructed tracks and the Galactic Centre (crosses). The red line describes what is expected from background event.

The expected ν flux depends on the DM distribution around the GC.
3 halo models have been considered

Parameter	NFW	Burkert	McMillan
r_s [kpc]	$16.1^{+17.0}_{-7.8}$	$9.26^{+5.6}_{-4.2}$	17.6 ± 7.5
ρ_{local} [GeV/cm^3]	$0.471^{+0.048}_{-0.061}$	$0.487^{+0.075}_{-0.088}$	0.390 ± 0.034



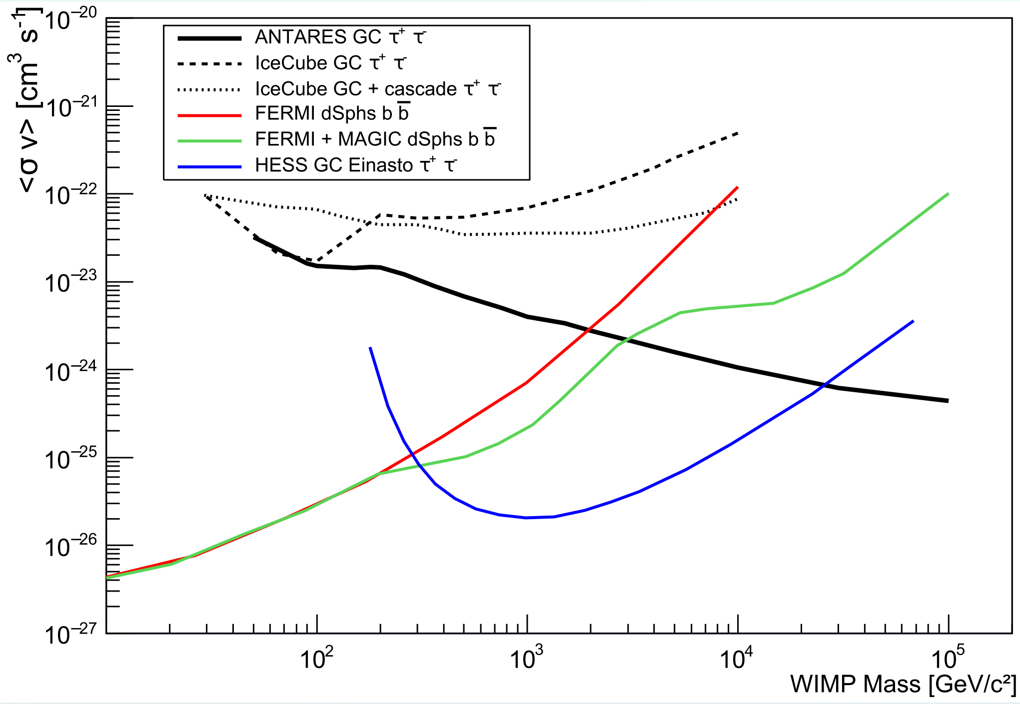
The integrated J-Factor, J_{int} , for a cone-shaped region centred on the G.C. with an opening angle Ψ

Indirect search for Dark Matter in the Galactic Centre

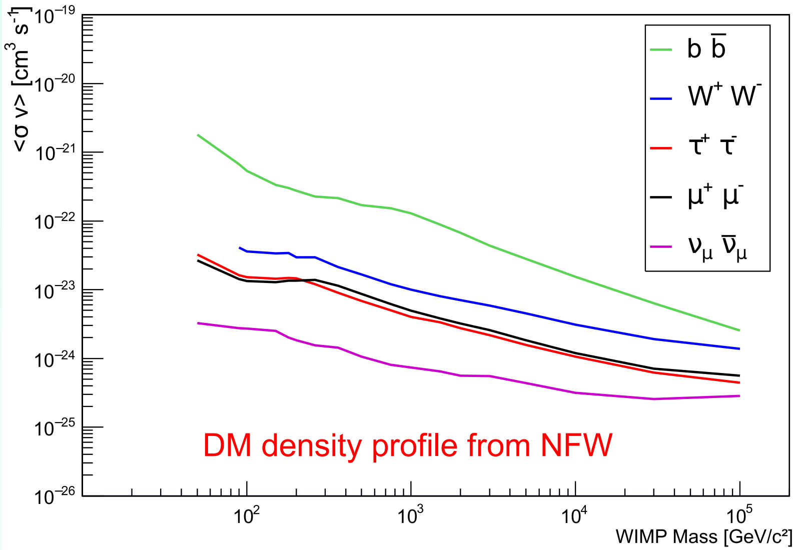
No excess found over the expected background

➡ limits to

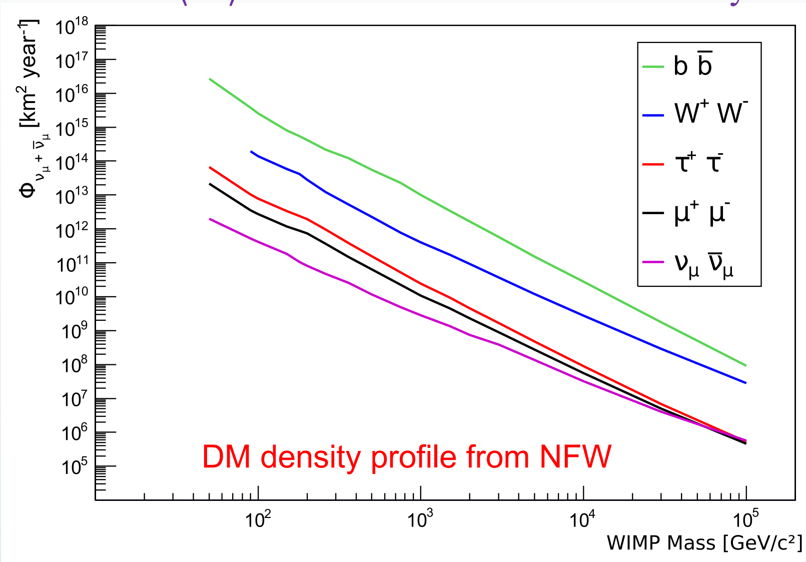
$$\frac{d\Phi_{\nu_\mu+\bar{\nu}_\mu}}{dE_{\nu_\mu+\bar{\nu}_\mu}} = \frac{<\sigma v>}{8\pi M^2_{WIMP}} \cdot \frac{dN_{\nu_\mu+\bar{\nu}_\mu}}{dE_{\nu_\mu+\bar{\nu}_\mu}} \cdot J_{int}(\Delta\Omega)$$



90% C.L. limits on the thermally averaged annihilation cross-section, ⟨σ v⟩, as a function of M_{WIMP}. The results from IceCube and ANTARES were obtained with the NFW profile.



90% C.L. limits on the thermally averaged annihilation cross-section ⟨σv⟩ from WIMP annihil. in the Milky Way



90% C.L. upper limits on the neutrino flux from WIMP annihilations in the Milky Way.

Indirect search for Dark Matter in the Earth

- WIMPS can be gravitationally bound to the Earth if $v_{WIMP} < v_{escape}^{Earth}$
- $v_{escape}^{Earth} \sim 14\,\frac{km}{s}$; $v_{WIMP} = \bar{v}_{270}$ following a Maxwell-Boltzmann distr. with r.m.s. velocity 270 km/s ➝ only a small fraction of WIMPS captured on the Earth.
- WIMPS-nucleons collision described by spin-independent cross section σ_p^{SI}
- Fe and Ni most abundant in the Earth → effective capture for $M_{WIMP} \sim 50\ GeV$
- In the Earth the capture ($\Gamma_C(t)$) and annihilation ($\Gamma_A(t)$) rates would reach the equilibrium in $\tau \sim 10^{11}$ y >> Earth age ($t_{Earth} = 4.5\ 10^9$ y)
- In these conditions:

$$\Gamma_A(t_{Earth}) \propto \left[\frac{\sigma_p^{SI}\rho_{0.3}^{\chi}}{m_\chi \bar{v}_{270}} \sum_i F_i^*(m_\chi)\right]^2 \frac{\langle\sigma_A v\rangle_{Earth}}{V_{Earth}} \left(\frac{m_\chi}{20\ GeV}\right)^{\frac{3}{2}}$$

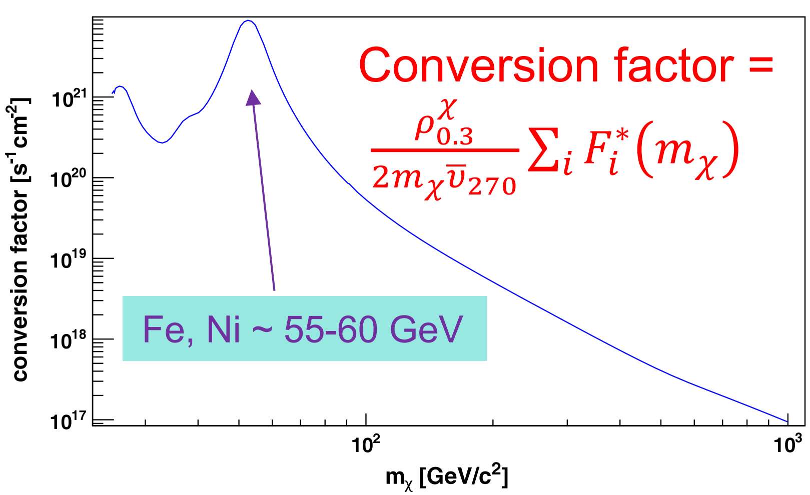
Needed to estimate the ν fluxes with WimpSim

C_C^2 capture factor

C_A annih. factor

$\rho_{0.3}^{\chi}$=0.3 GeV/cm³
Local D.M. density

the capture is very effective when $m_{WIMP} \sim m_{target}$



ANTARES, Physics of the Dark Universe 16 (2017) 41–48

Indirect search for Dark Matter in the Earth

6 years of ANTARES data: 2007-2012

$25\ \mathrm{GeV/c^2} < M_{WIMP} < 1\ \mathrm{TeV/c^2}$

$$WIMP + WIMP \rightarrow b\bar{b}, W^+W^-, \tau^+\tau^-, \nu\bar{\nu}$$

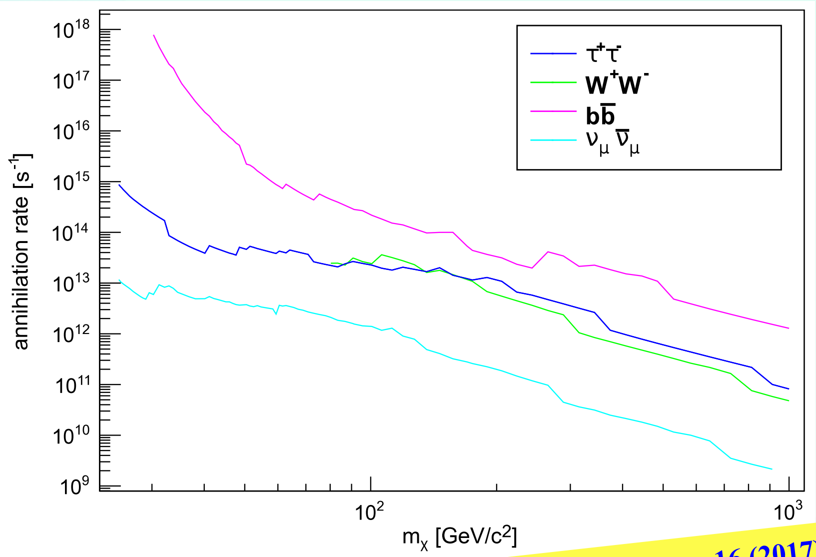
No excess found over the expected background

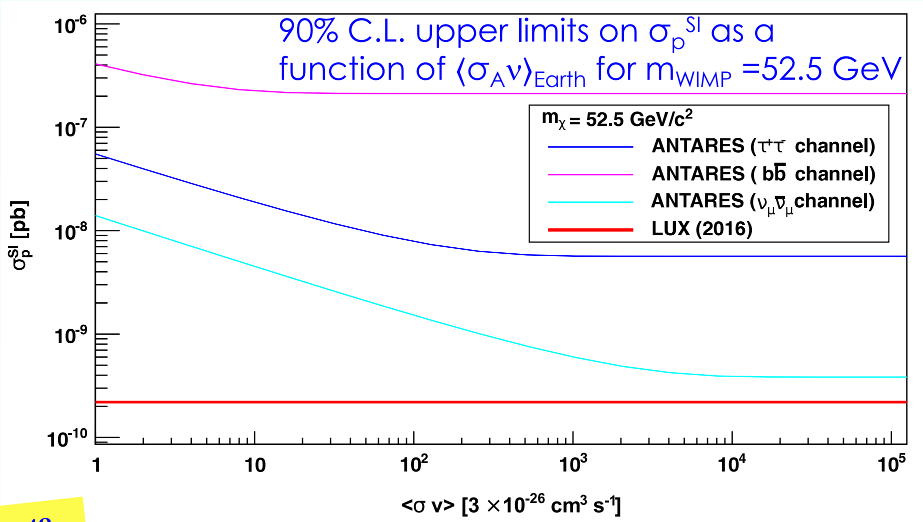
Limits on the WIMP-WIMP annihilation rate in the Earth

Limits on the spin independent WIMP-nucleon cross-section

ANTARES, Physics of the Dark Universe 16 (2017) 41–48

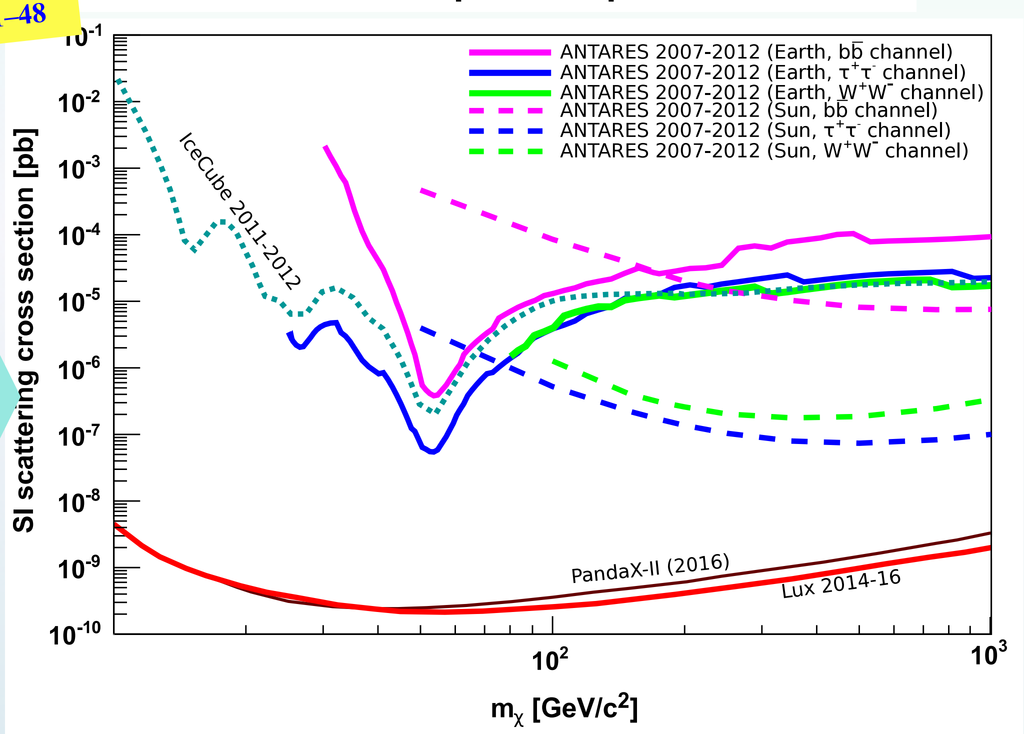
Indirect search for Dark Matter in the Earth





ANTARES, Physics of the Dark Universe 16 (2017) 41–48

90% C.L. upper limits on σ_p^{SI} as a function of the WIMP mass for ANTARES 2007–2012 (Earth) and ANTARES 2007–2012 (Sun), assuming $\langle\sigma_A v\rangle_{Earth} = 3 \cdot 10^{-26}$ cm^3 s^{-1} and WIMP pair annihilation to 100% into either $\tau^+ \tau^-$ (blue), $W^+ W^-$ (green) or $b\bar{b}$ (purple).



25 Gev/c^2 < M_{WIMP} < 1 Tev/c^2

The Multi-Messenger Search Programme with ANTARES

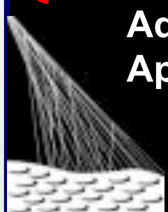
Neutrinos trigger others

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

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

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

GCN (Gamma-ray Coordination Network)

ANTARES ⟺ GCN

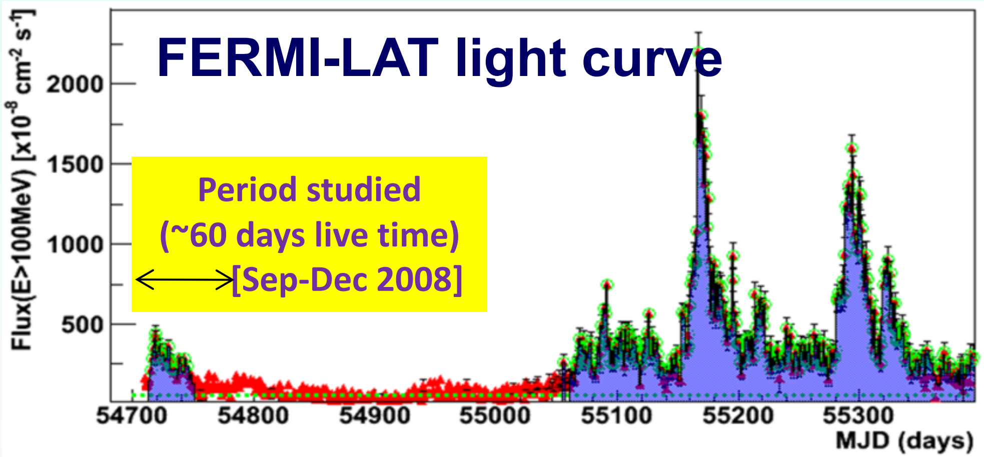
A&A 559, A9 (2013),
JCAP 1303 (2013) 006

Search for ν from flaring AGN - 2008

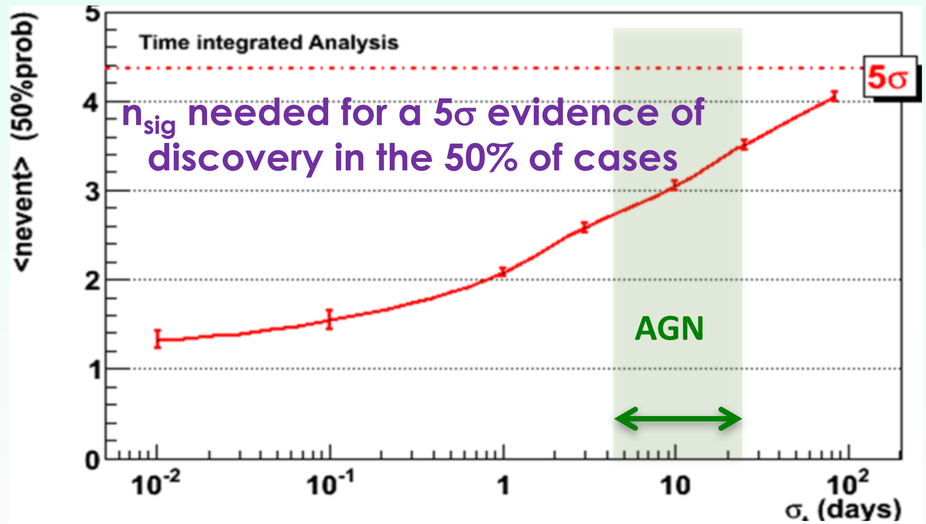
ν emission from γ-flaring blazars

Astropart. Phys. 36 (2012) 204–210, arXiv:1111.3473 [astro-ph.HE]

ANTARES ⟷ FERMI



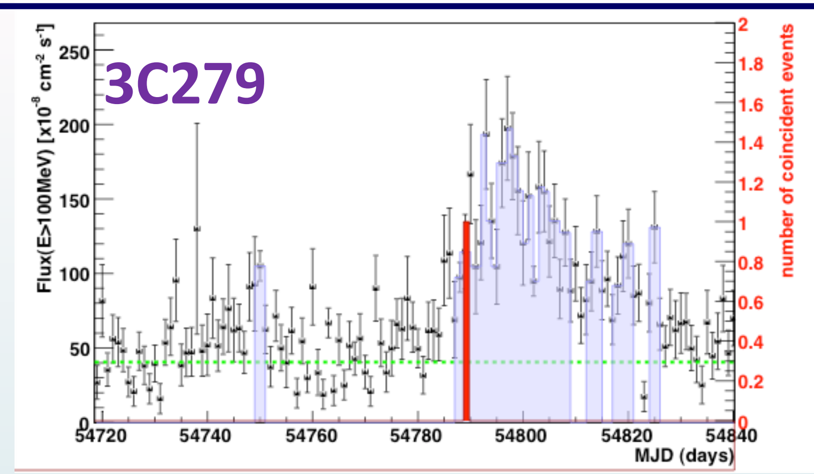
10 sources selected from the FERMI/LAT catalogue, showing a large variability (flaring state) in the period studied for this analysis.



Performance of the time-dependent analysis

RESULTS

- **1 neutrino candidate event compatible with the time/space distribution (Δα=0.56°) of 3C279 with probability (p-value) = 1% (but post trial probability = 10%)**
- **Fluence Upper Limits**
- **RESULTS ARE VERY PROMISING, new analisys going on with 2008-2011 FERMI data**



Search for ν from flaring AGN – 2008-2011

[40 sources, 86 flaring periods] (ANTARES ⟷ FERMI)

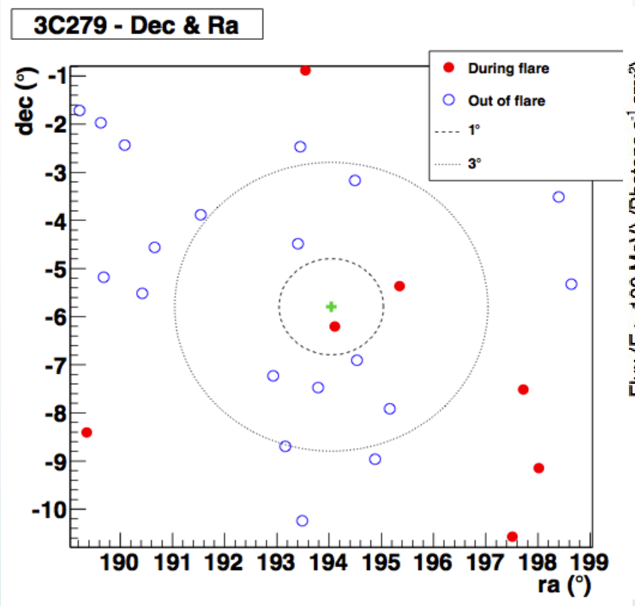
...to be extended to IACT blazars (HESS, MAGIC, VERITAS)

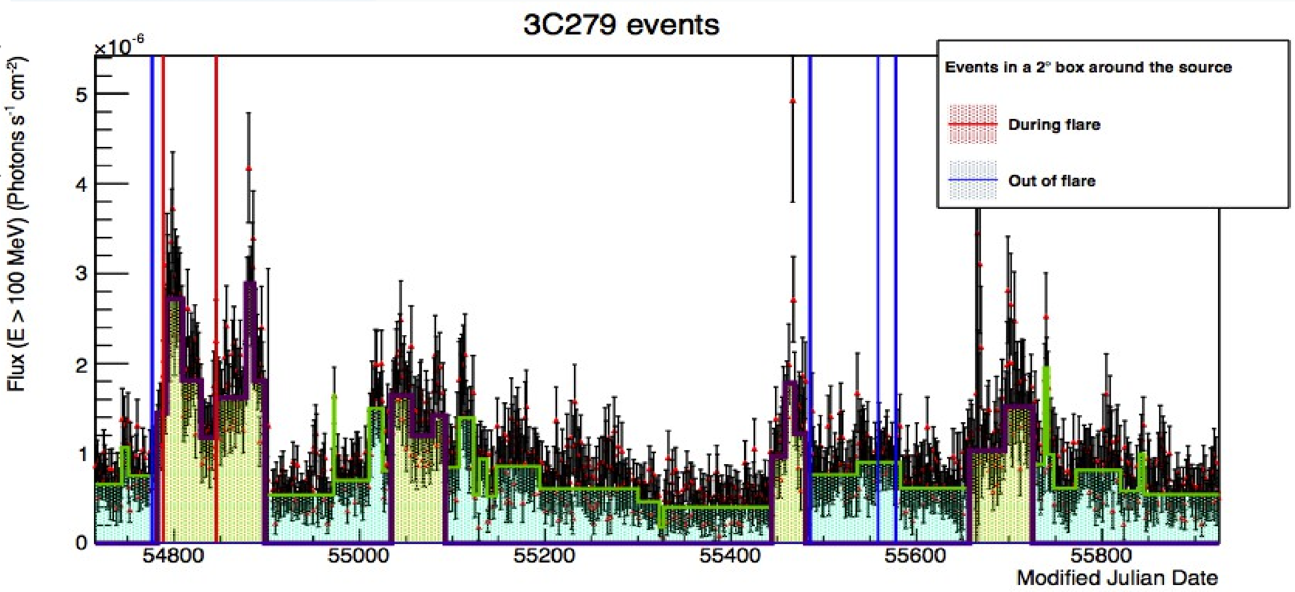
PRELIMINARY

6 specially significant flares

p-values (Pre-trial/Post-trial)				
Source	E^{-1}	E^{-2}	$E^{-2} exp^{-E/10TeV}$	$E^{-2} exp^{-E/1TeV}$
3C 279	**0.17%/9.91%**	0.33%/14.5%	5.31%/73.5%	6.68%/89.4%
PKS 1124-186	1.94%/54.3%	**1.07%/41.29%**	1.68%/55.1%	3.85%/82.2%
PKS 1830-211	2.67%/69.5%	**1.43%/52.8%**	3.08%/72.6%	6.64%/91.6%
3C 454.3	**3.53%/67.7%**	—	—	—
4C +21.35	**3.68%/68.9%**	—	5.31%/73.5%%	—
CTA 102	—	**4.62%/86.5%**	—	—

(—) Those cases have a fitted signal $n_{sig} \lesssim 0.001$ and p-value∼100%

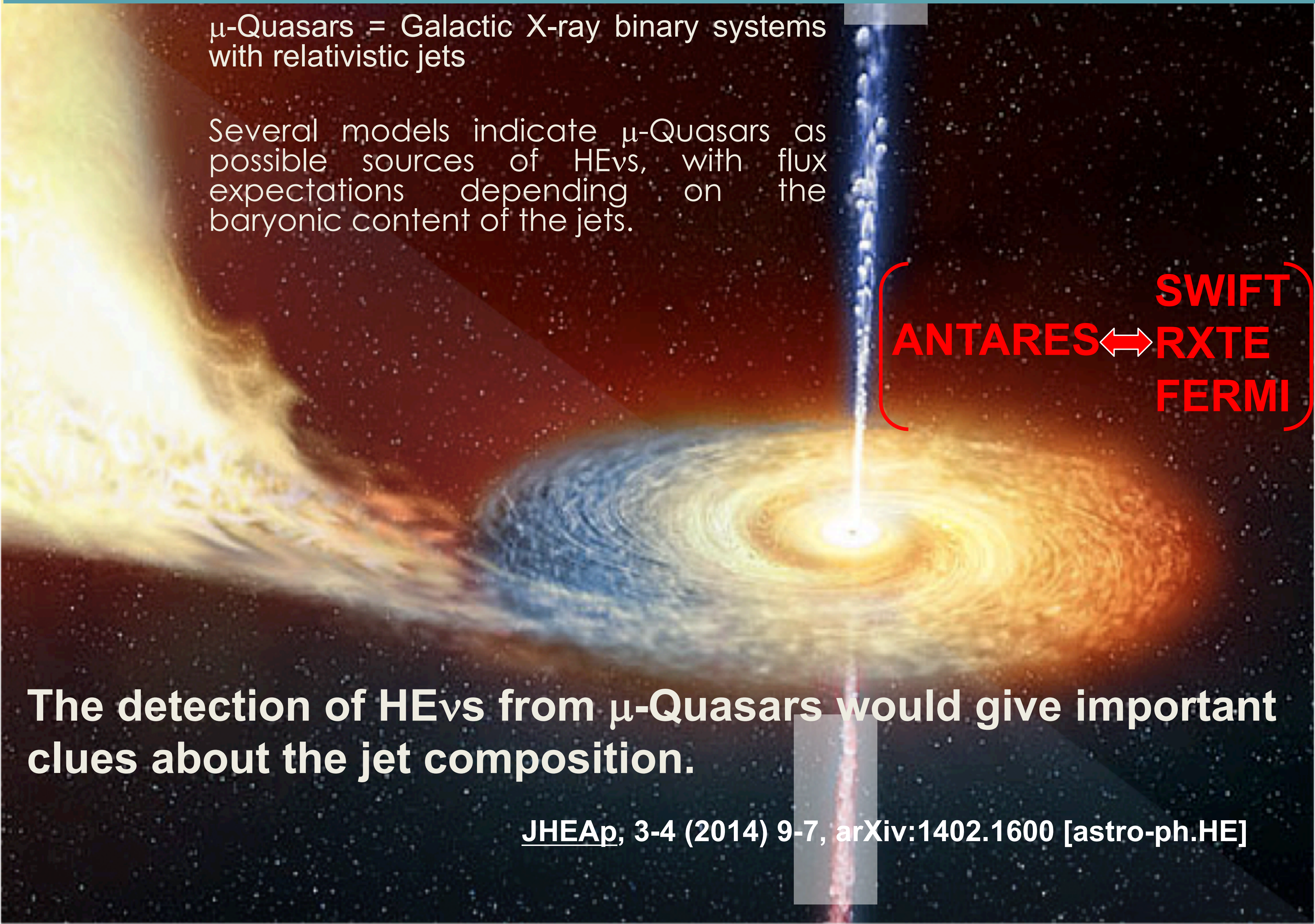




ANTARES and ν from μ-Quasars

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.

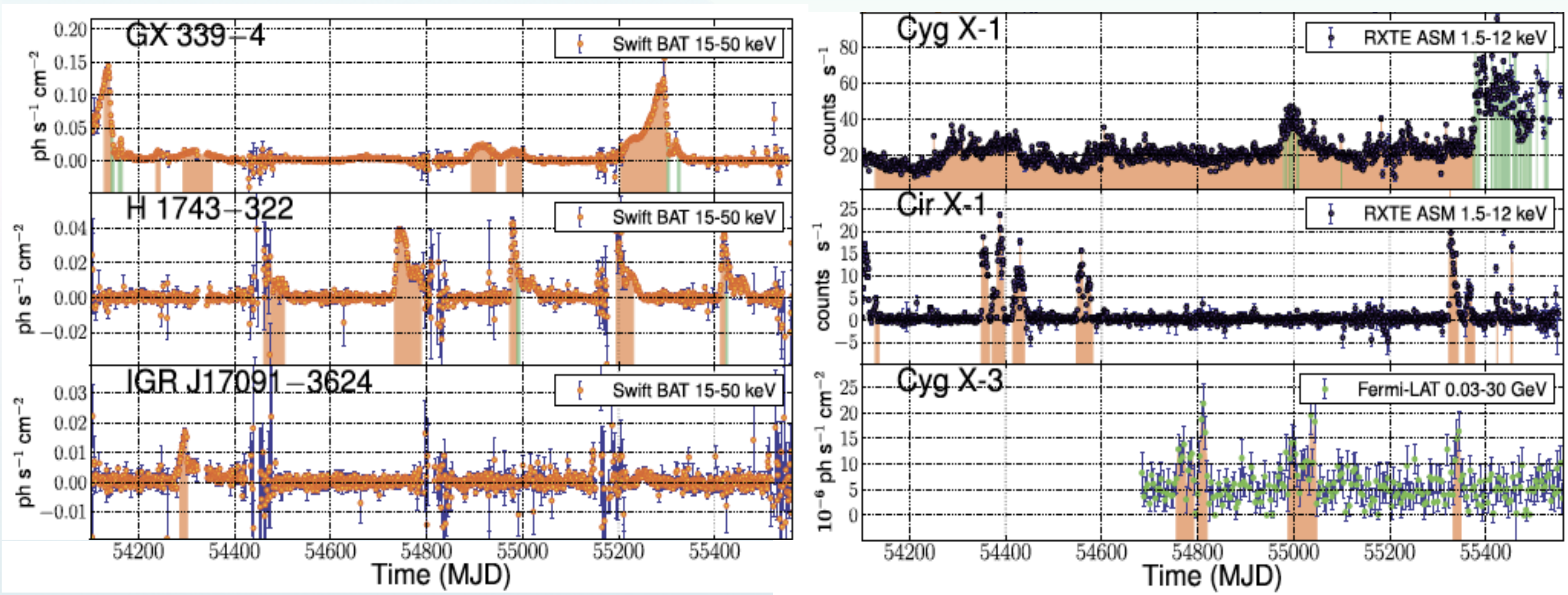
JHEAp, 3-4 (2014) 9-7, arXiv:1402.1600 [astro-ph.HE]

ANTARES and ν from μ-Quasars

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

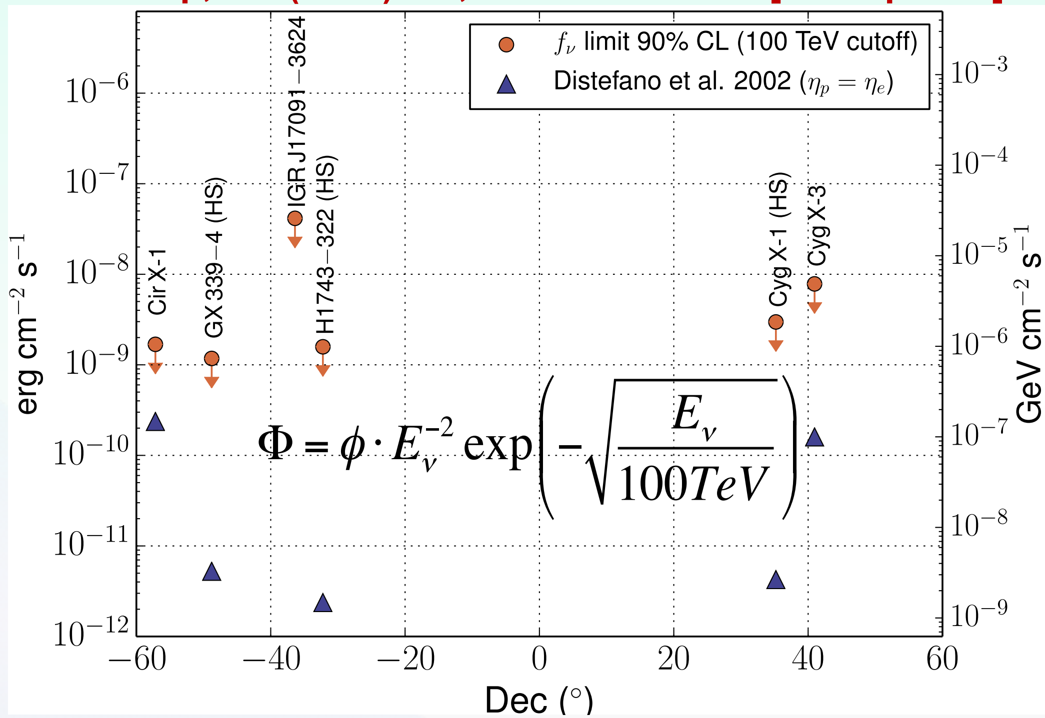
- **in the ANTARES visible sky;**
- **showing an outburst in the period 2007-2010.**

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

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



$$\Phi = \phi \cdot E_\nu^{-2} \exp\left(-\sqrt{\frac{E_\nu}{100TeV}}\right)$$

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

[systematic uncertainties included]

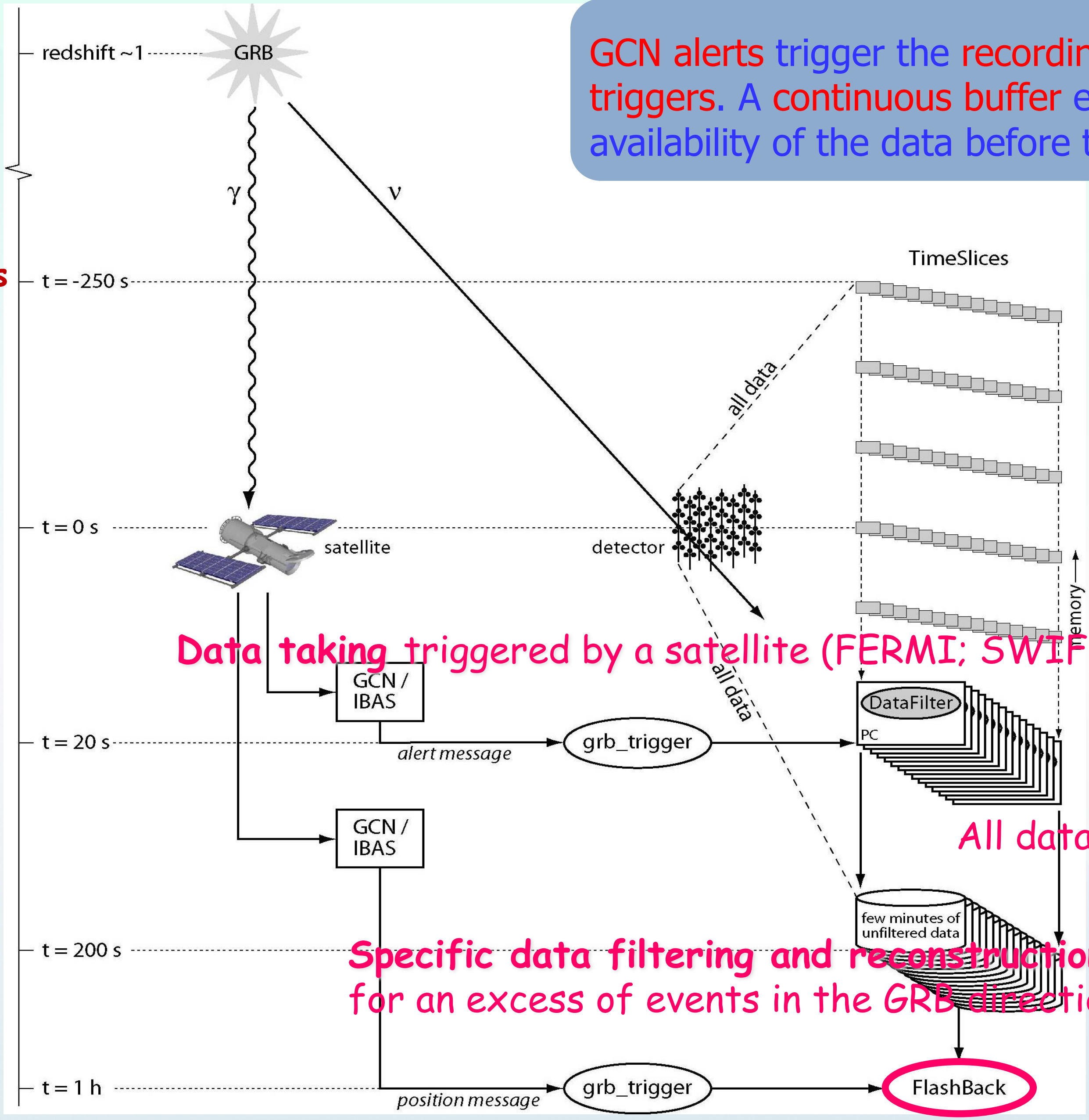
…assuming a neutrino spectrum following:
- a power-law
- a power-law with expo. cut-off

→ **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 ν 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)

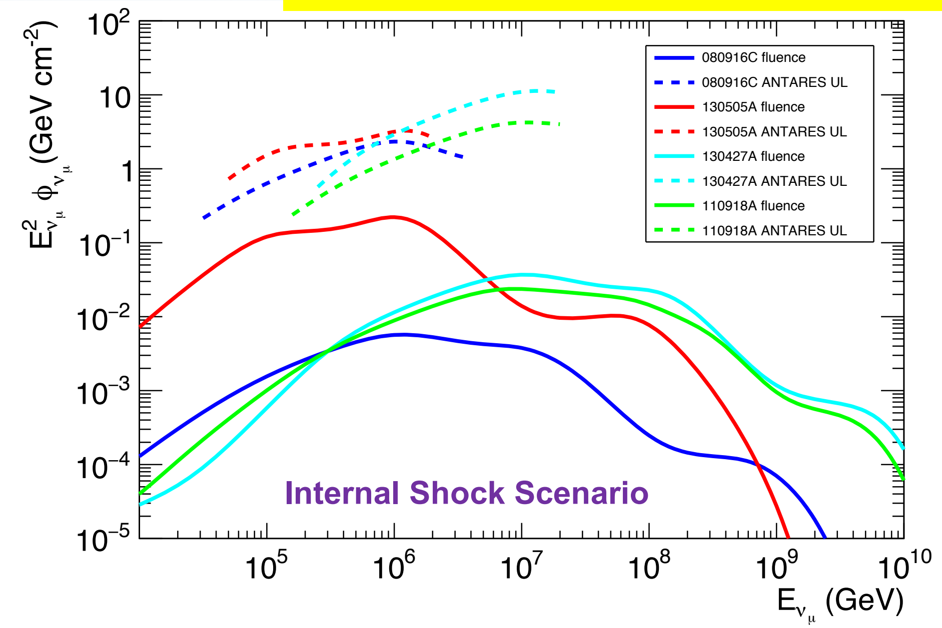
observed between 2008 and 2013.

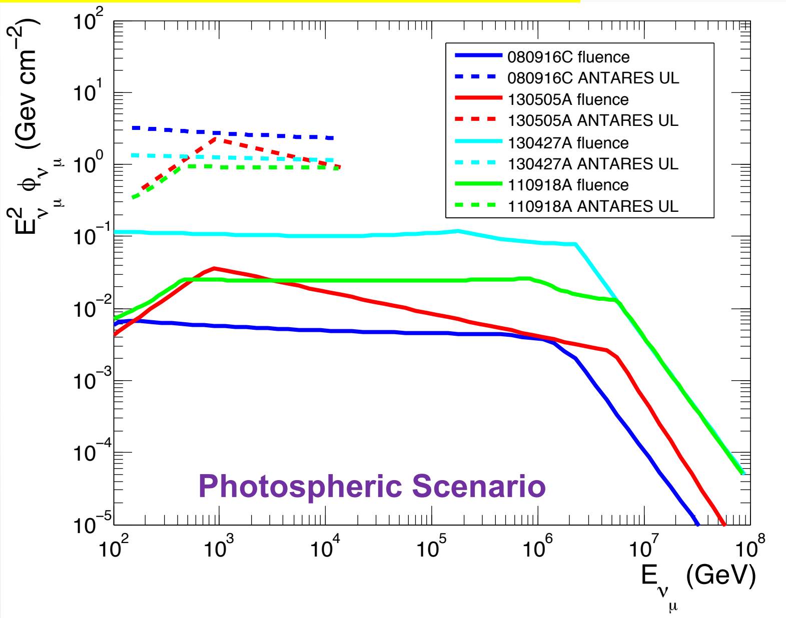
The expected neutrino fluxes evaluated in the framework of:

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

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

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

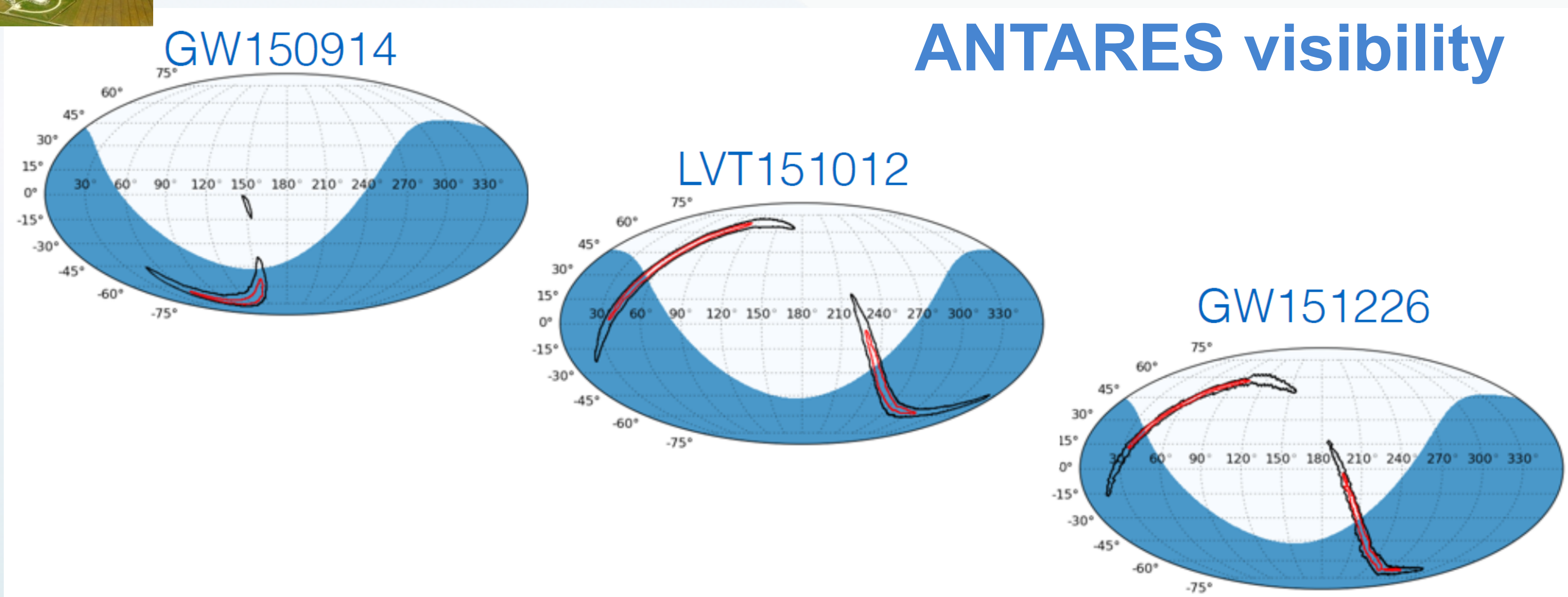




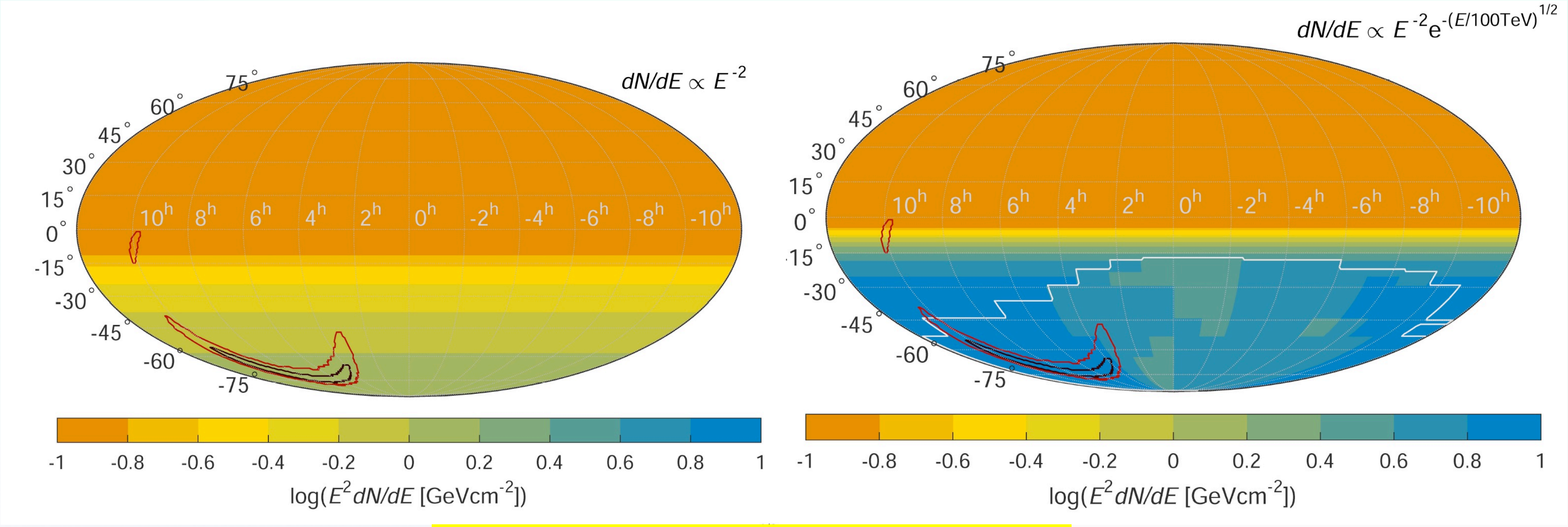
ANTARES Multi-messenger program
ν follow-up of GW sources - 1

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

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



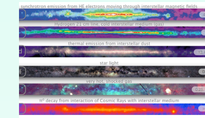
A joint ANTARES/IceCube/LigoSC/Virgo analysis performed as “Neutrino follow-up” of GW150914



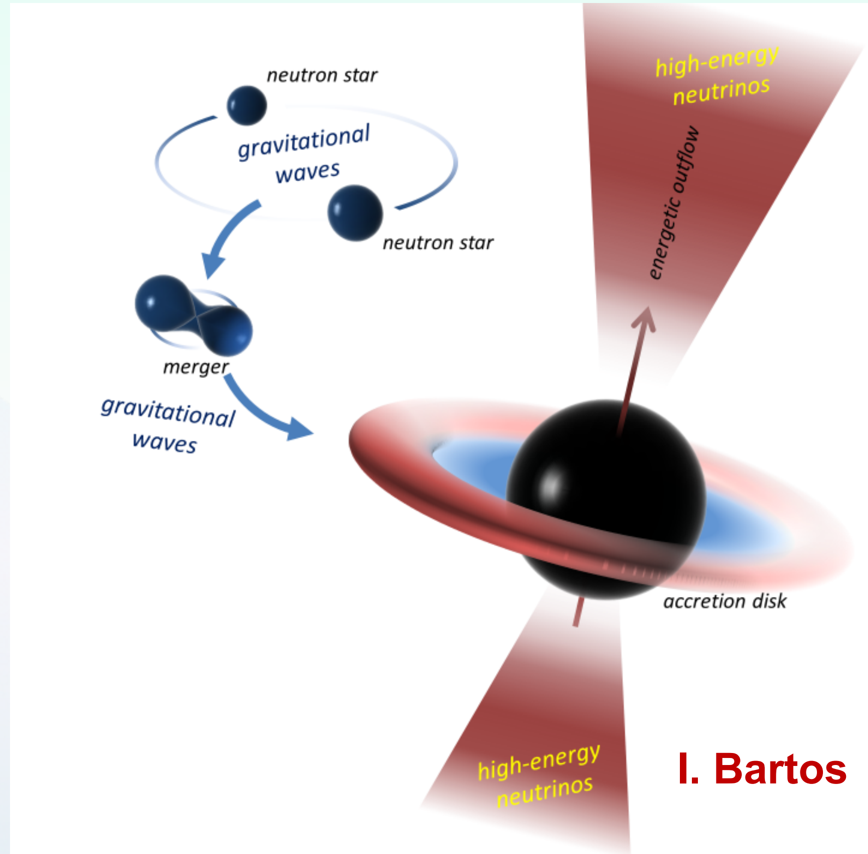
Phys.Rev. D93 (2016), 122010

- No ANTARES events in ±500 s from the GW time (0.015 expected)
- Limits from ANTARES dominates for Eν < 100 TeV
- U.L. from IC dominated above 100 TeV
- Size of GW150914 : 590 deg² ANTARES resolution: <0.5 deg²
- Limits on total energy radiated in neutrinos: <10% GW
- Future: Receive / send alerts in real time

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

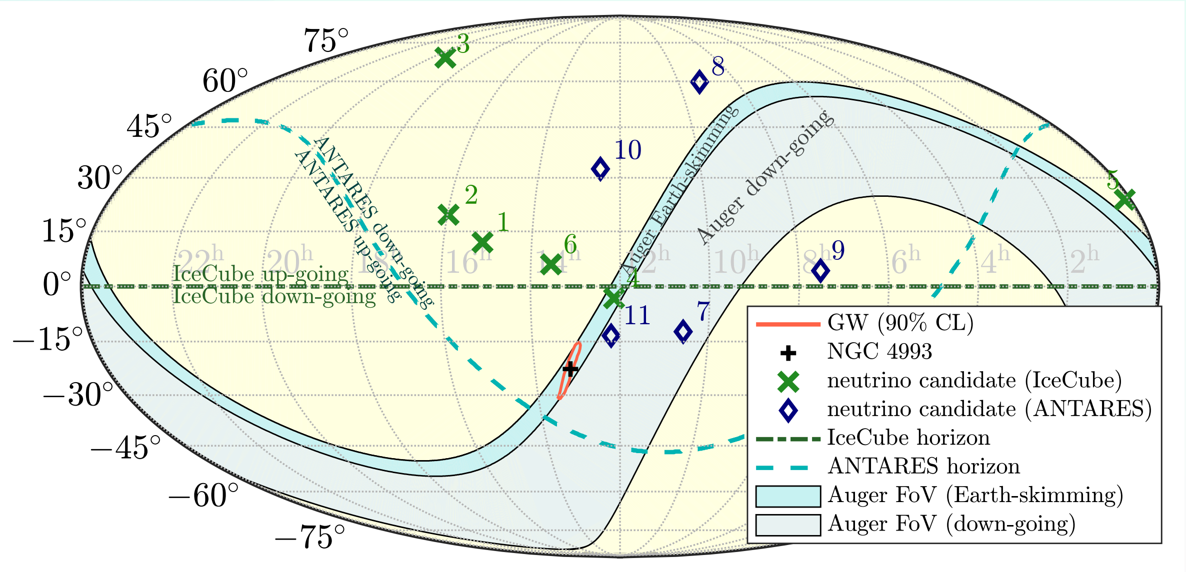


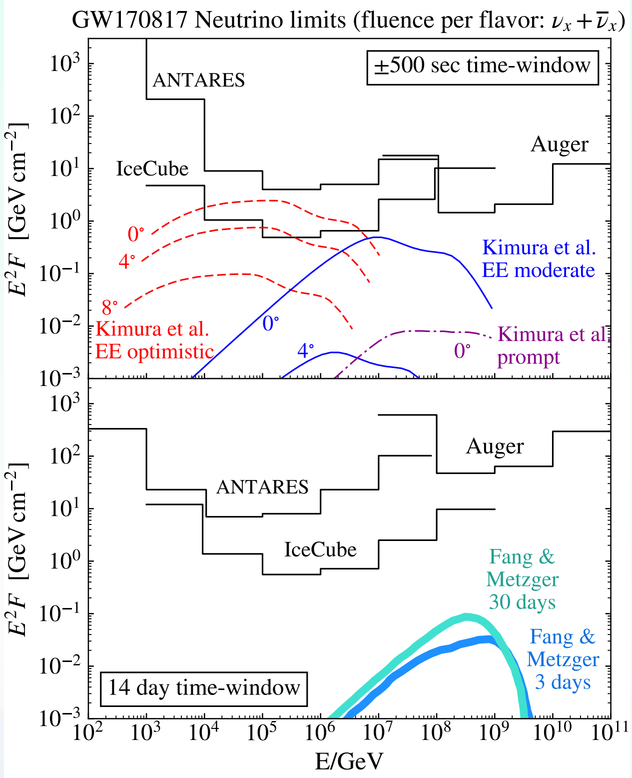
- A rich variety of phenomena in the case of NS-NS merging
- GW standard "sirene"
- Neutrinos ν
- EM counterpart
  - Fast emission (GRB)
    - Beamed emission
    - Afterglow (X-ray,…)
  - Kilonova (*)
    - Isotropic emission
    - Neutron-rich ejecta
  - Radio emission
- UHECR's acceleration?



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

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





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

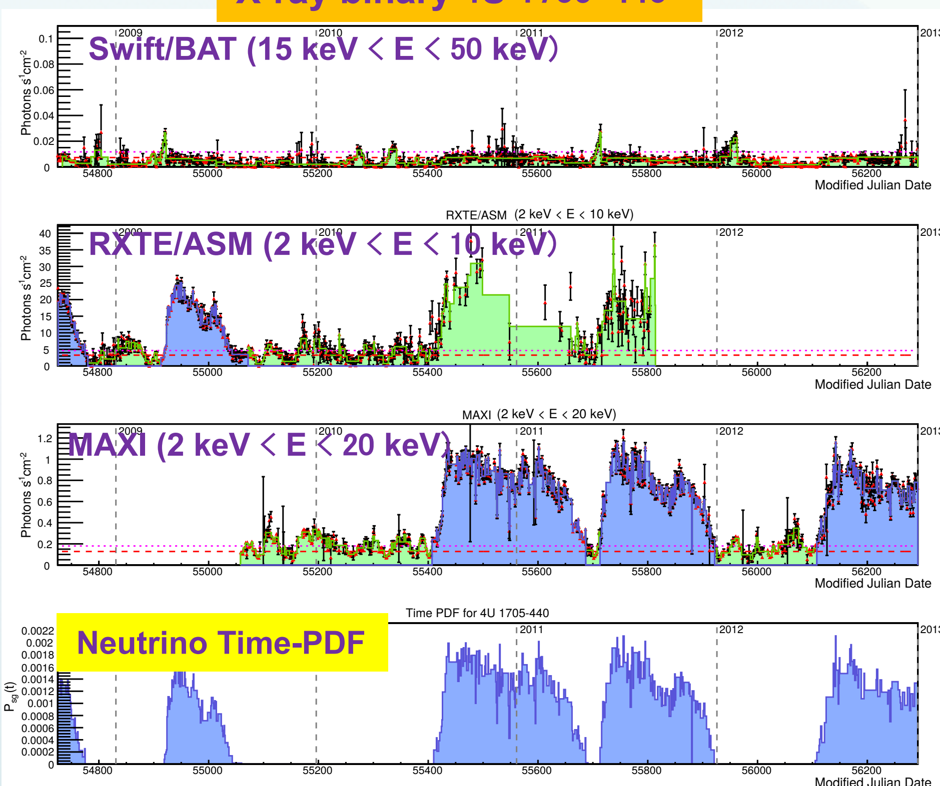
ANTARES Multi-messenger program

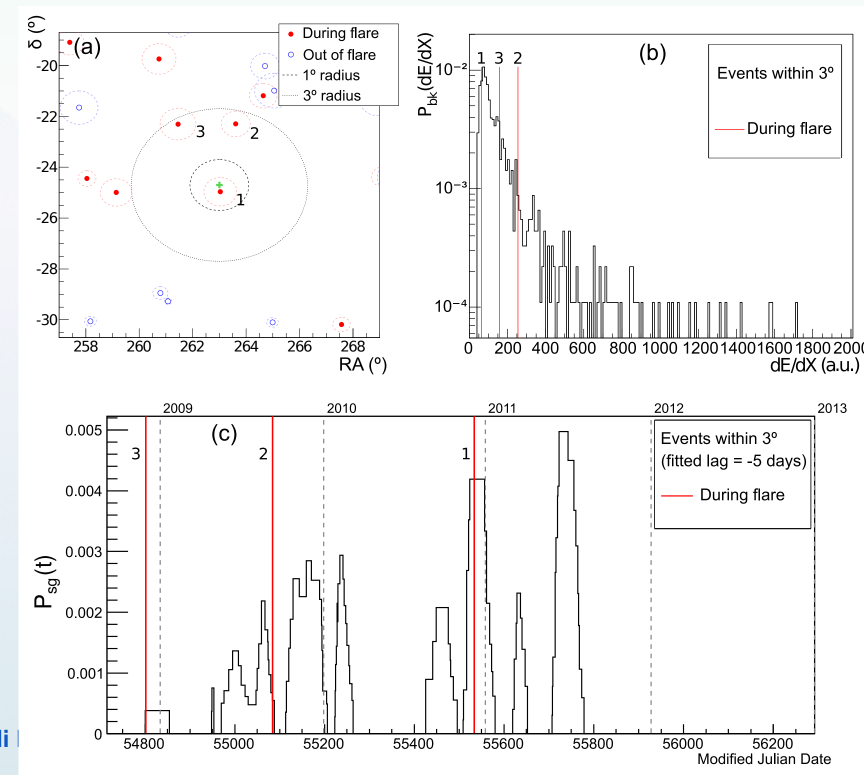
ν associated with GeV and TeV γ-ray flaring blazars and X-ray binaries

- 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



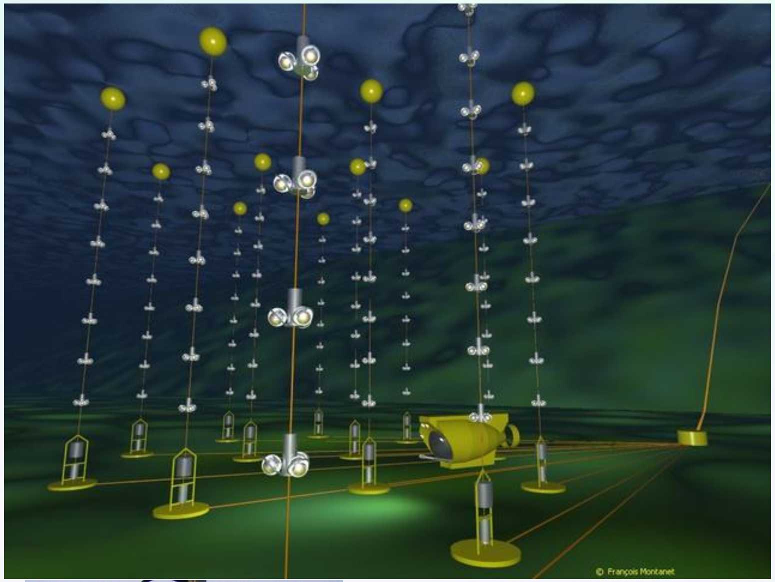


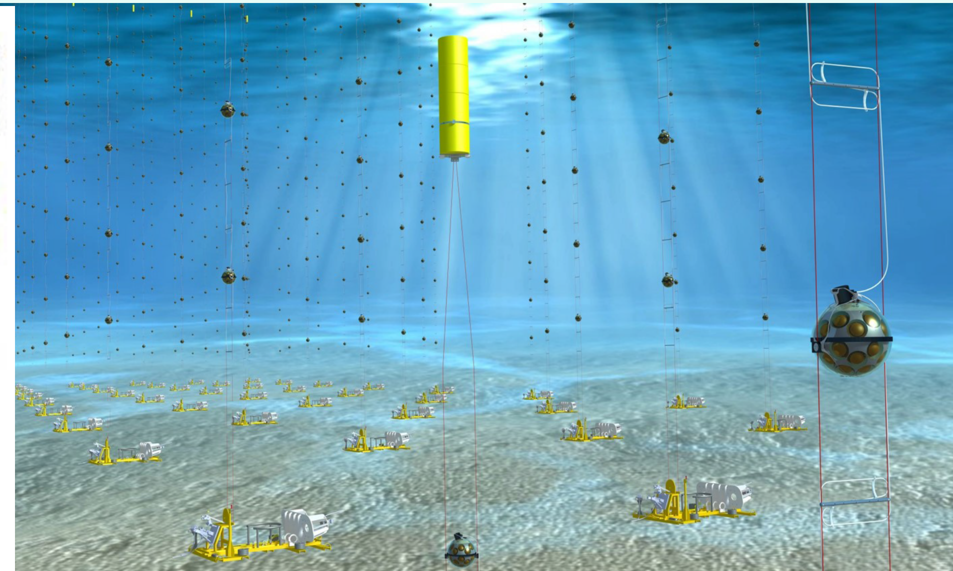
The future of Neutrino Astronomy in the Mediterranean Sea

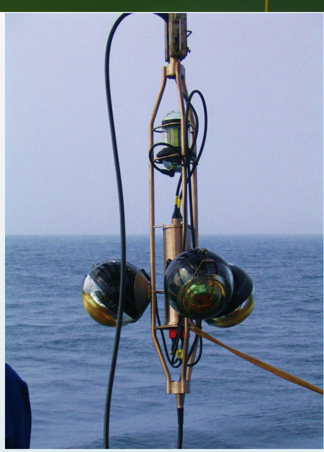
ANTARES → KM3NeT

12 Lines, 885 OM

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



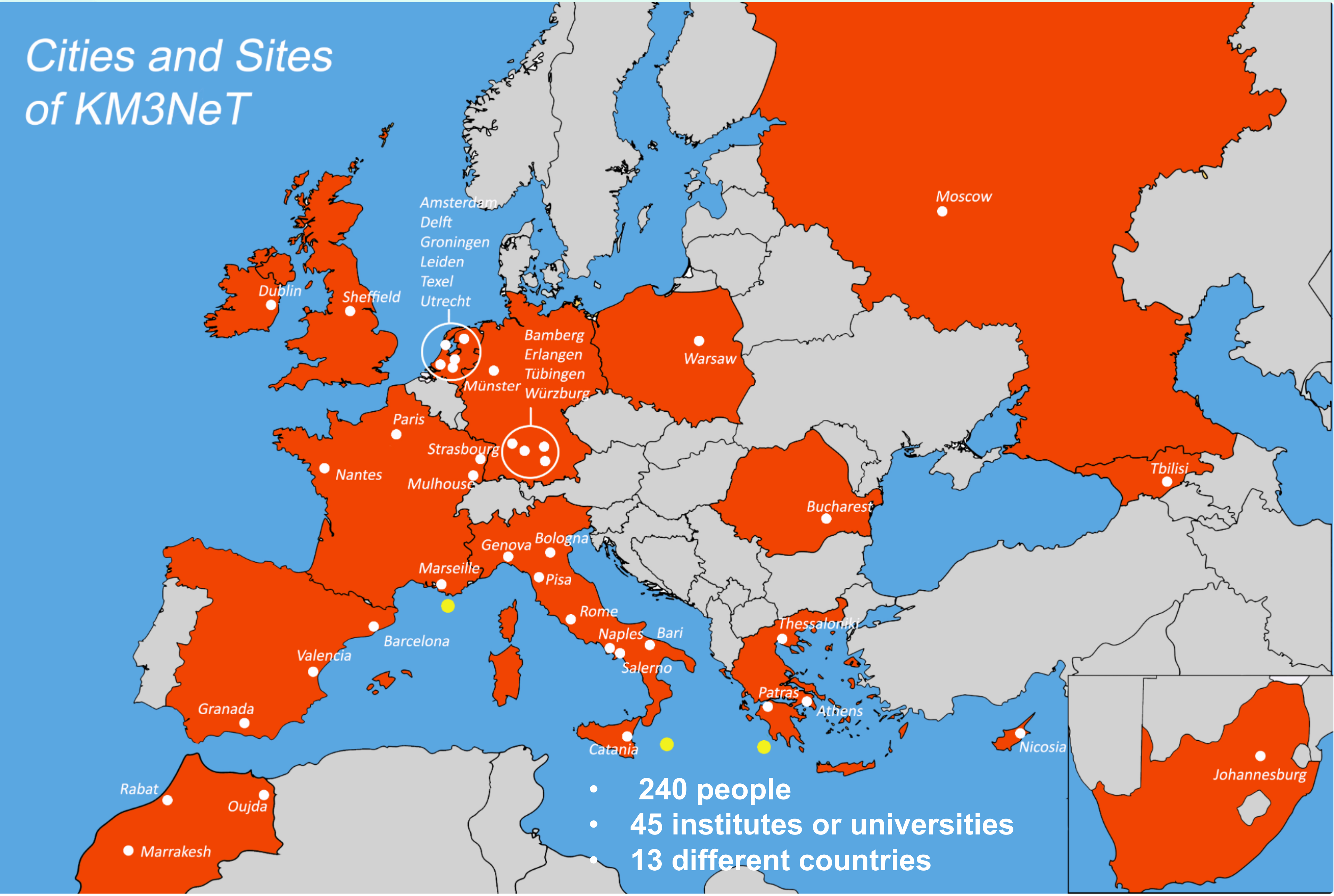




Basic active element:
Digital Optical Module
31 x 3” PMTs

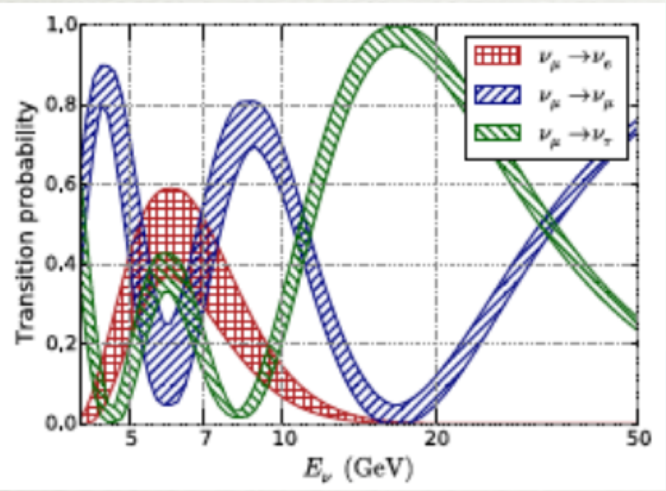
18 OMs/line

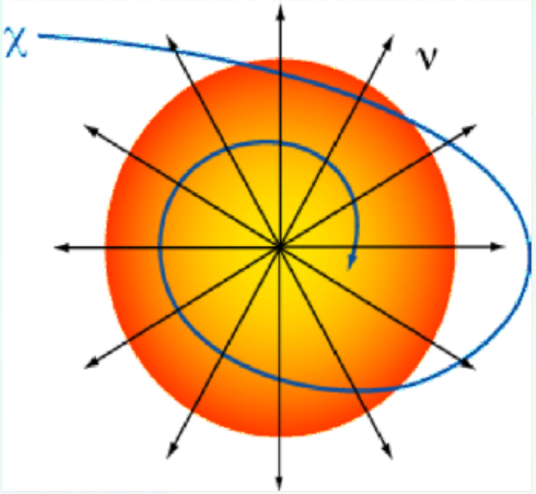
KM3NeT - Collaboration



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

KM3NeT Neutrino Telescope science scopes





Composite View of the Crab Nebula

Low Energy	Medium Energy	High Energy
MeV < E_ν < 100 GeV	M eV < E_ν < 100 GeV	E_ν > 1 TeV

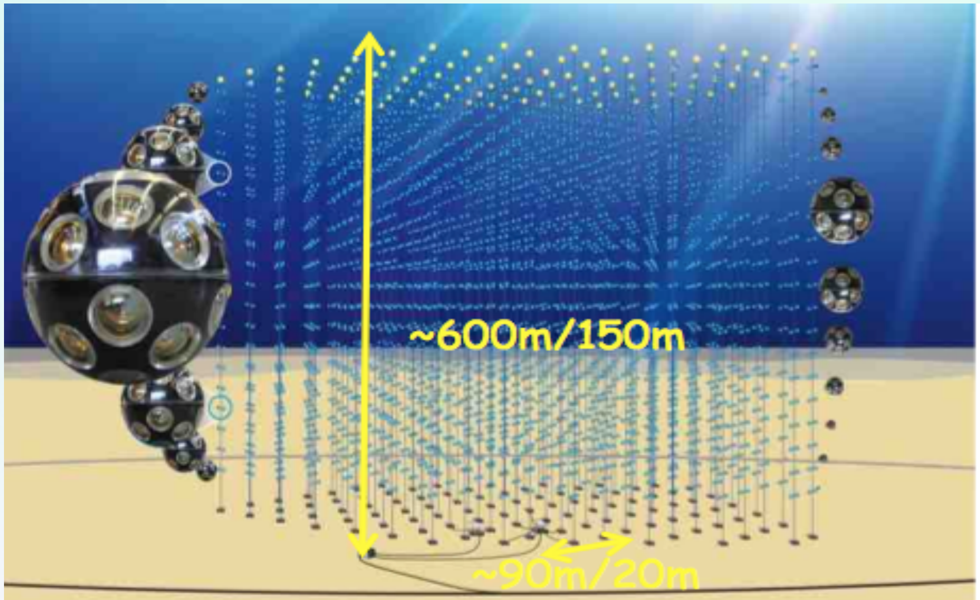
- Neutrino Oscillations
- Neut. Mass Hierarchy
- Sterile neutrinos
- Neut. From Supernovae

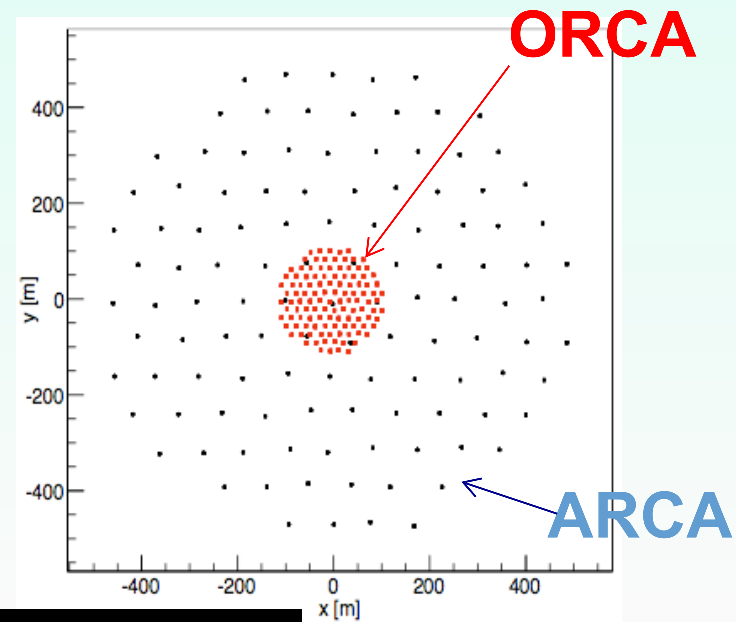
- Dark Matter search
- Monopoles
- Nuclearites

- Neutrinos from extra-terrestrial sources
- Origin and production mechanism of HE CR

… and synergies with Sea-Sciences: oceanography, biology, seismology, …

KM3NeT Building Blocks





[redacted]

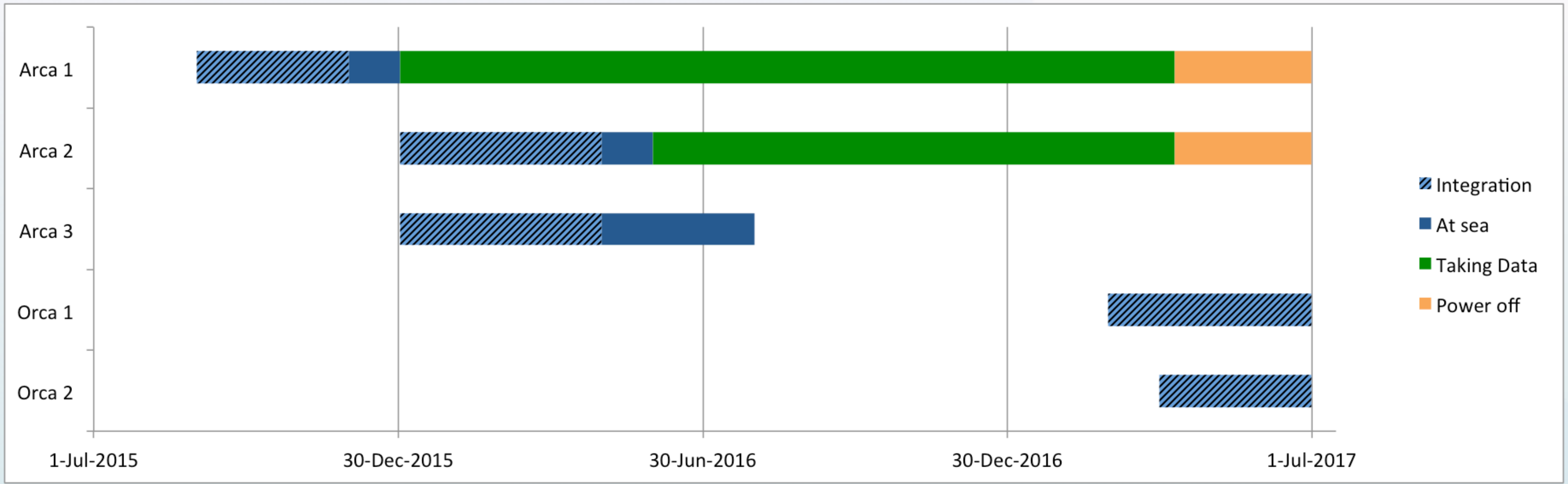
	ARCA	ORCA
Location	Italy – Capo Passero	France - Toulon
Detector Lines distance	90m	20m
DOM spacing	36m	9m
Instrumented mass	500Mton	5,7 Mton

KM3NeT phased implementation

Phase	Building Blocks		Number of DUs		Phisics Goals		Status	
	ARCA	ORCA	ARCA	ORCA	ARCA	ORCA	ARCA	ORCA
1	0.2	0.06	24	7	Proof of feasibility and first science results. Joined analysis with ANTARES.		Fully funded. First 2 DUs acquiring data in Capo Passero.	
2.0	2	1	230	115	Study of the IceCube signal.	Determination of neutrino mass hyerarchy.	Not yet funded.	Not yet funded.
3	6	1	690	115	All flavour neutrino astronomy.			

L.O.I. KM3NeT ARCA and ORCA

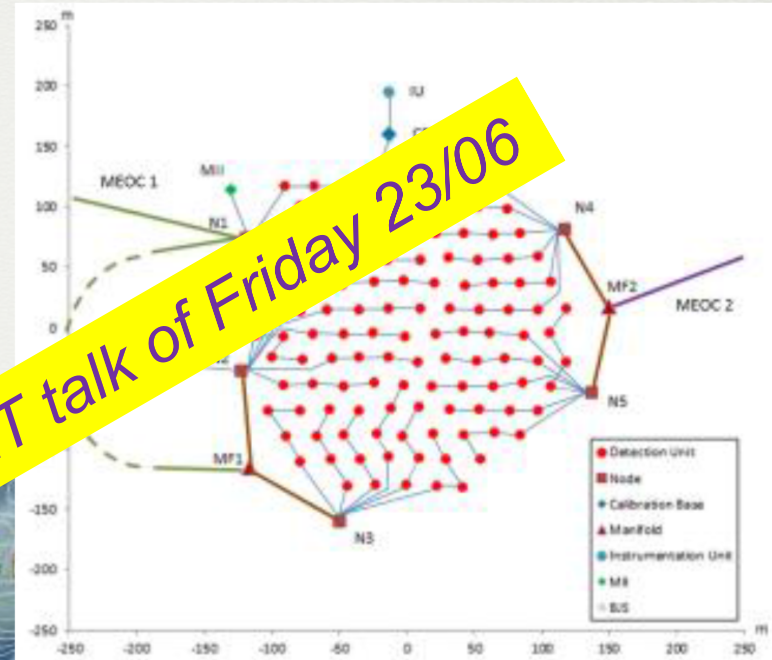
- **J. Phys. G43 (2016) n. 8, 084001**
- **arXiv: 1601.07459**



The future of Neutrino Astronomy in the Mediterranean Sea

KM3NeT ORCA

ORCA detector:
- 115 lines
- 20 m horizontal spacing
- 9 m vertical DOM spacing
- 18 DOMs / string
- ~6 Mt instrumented volume



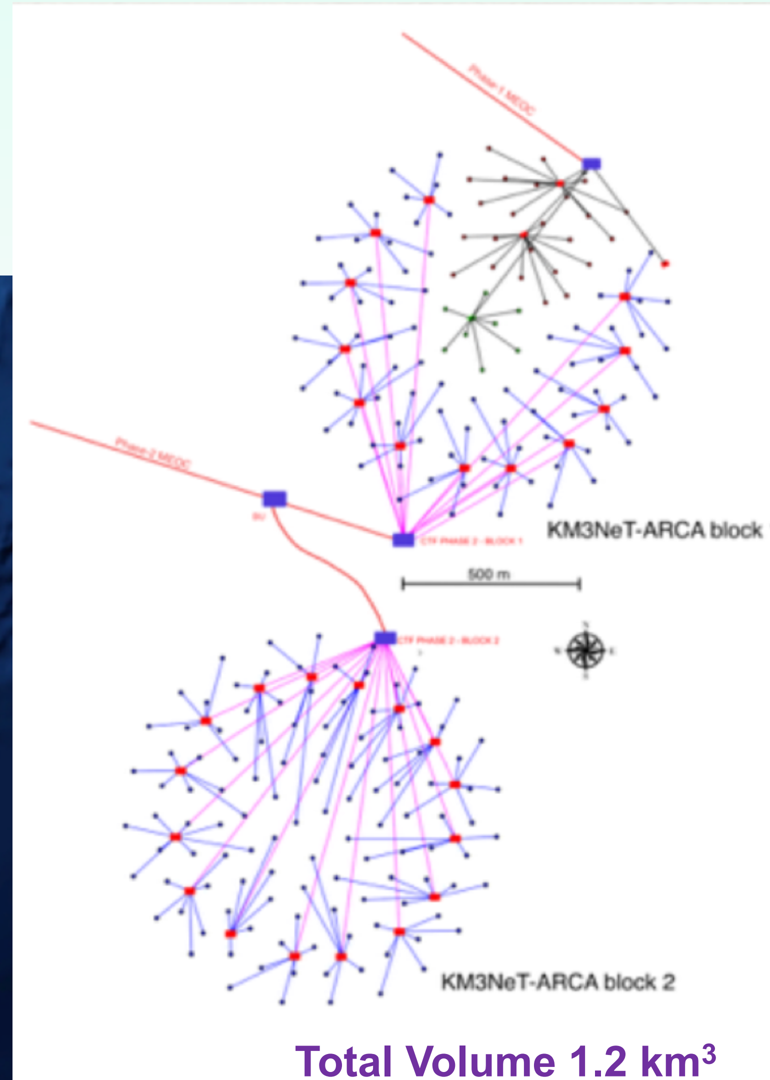
See Simon BOURRET talk of Friday 23/06

- ➡ Located closed to ANTARES at a depth of ~2475m
- ➡ Shore station La Seyne sur Mer
- ➡ Infrastructure already deployed
- ➡ 2 new ORCA lines will be deployed before summer

KM3NeT-ARCA

ARCA detector

- **ARCA: 2 blocks**
- **115 strings/block**
- **90m horizontal spacing**
- **18 Optical Modules/strings**
- **36m vertical spacing**



~1km^3

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.