Recent results from the ANTARES High Energy Neutrino Telescope. KM3NeT-ARCA status report.

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at the

26th International Workshop
on
Weak Interactions and Neutrinos (WIN2017)

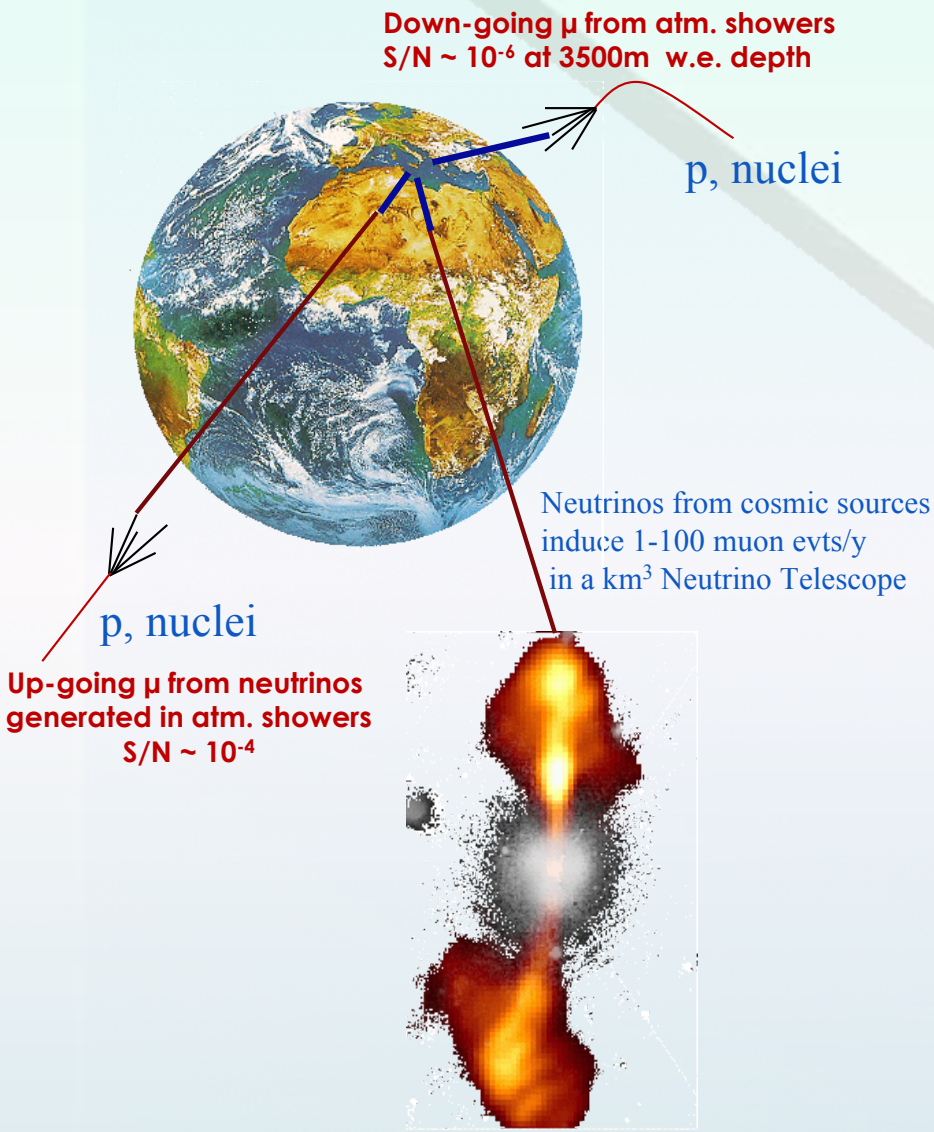
University of California, Irvine

Talk outline

- ANTARES: the 1st undersea Cherenkov detector for High Energy Astrophysical neutrino detection
- The ANTARES main physics goal: search for astrophysical neutrinos
  - Search for a diffuse flux
  - Search for point-like sources
  - Search for "enhanced" diffuse flux
- Indirect search for Dark Matter
  - from the SUN, the Galactic Plane, the Earth
- Transient/multi-messenger studies
- Perspectives for the future
- Conclusions & Summary

Cherenkov ν Telescope: Detection principle

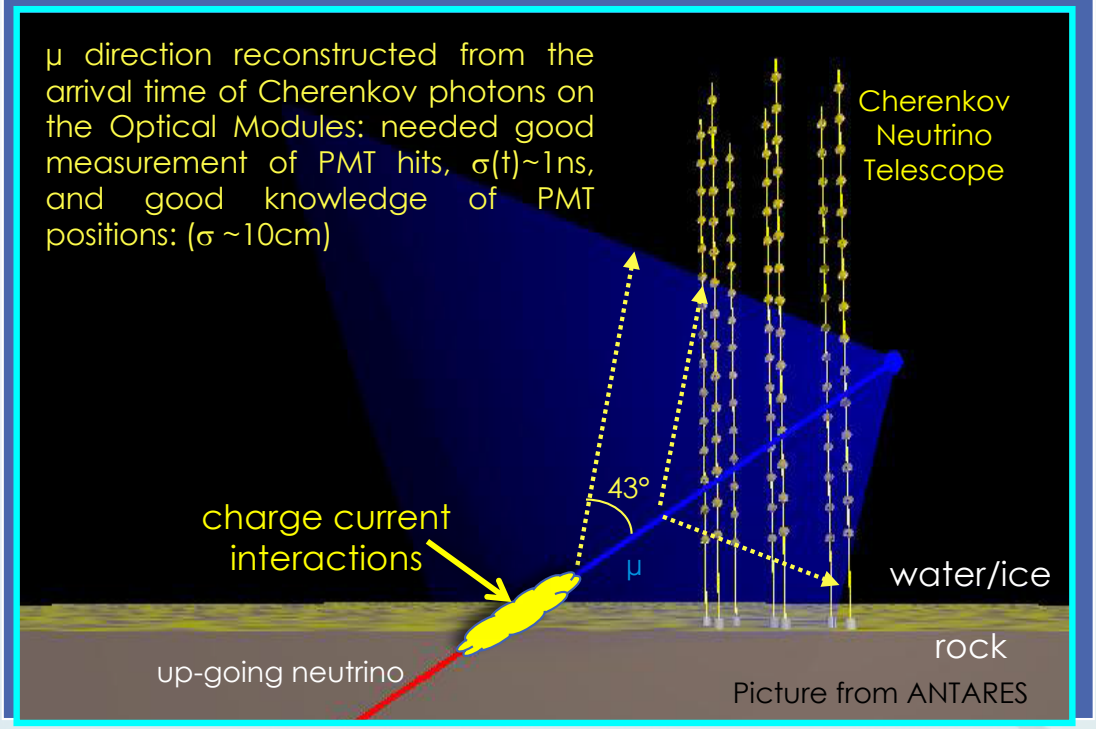
Search for neutrino induced events, mainly $\nu_\mu N \rightarrow \mu X$, deep underwater



- 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

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

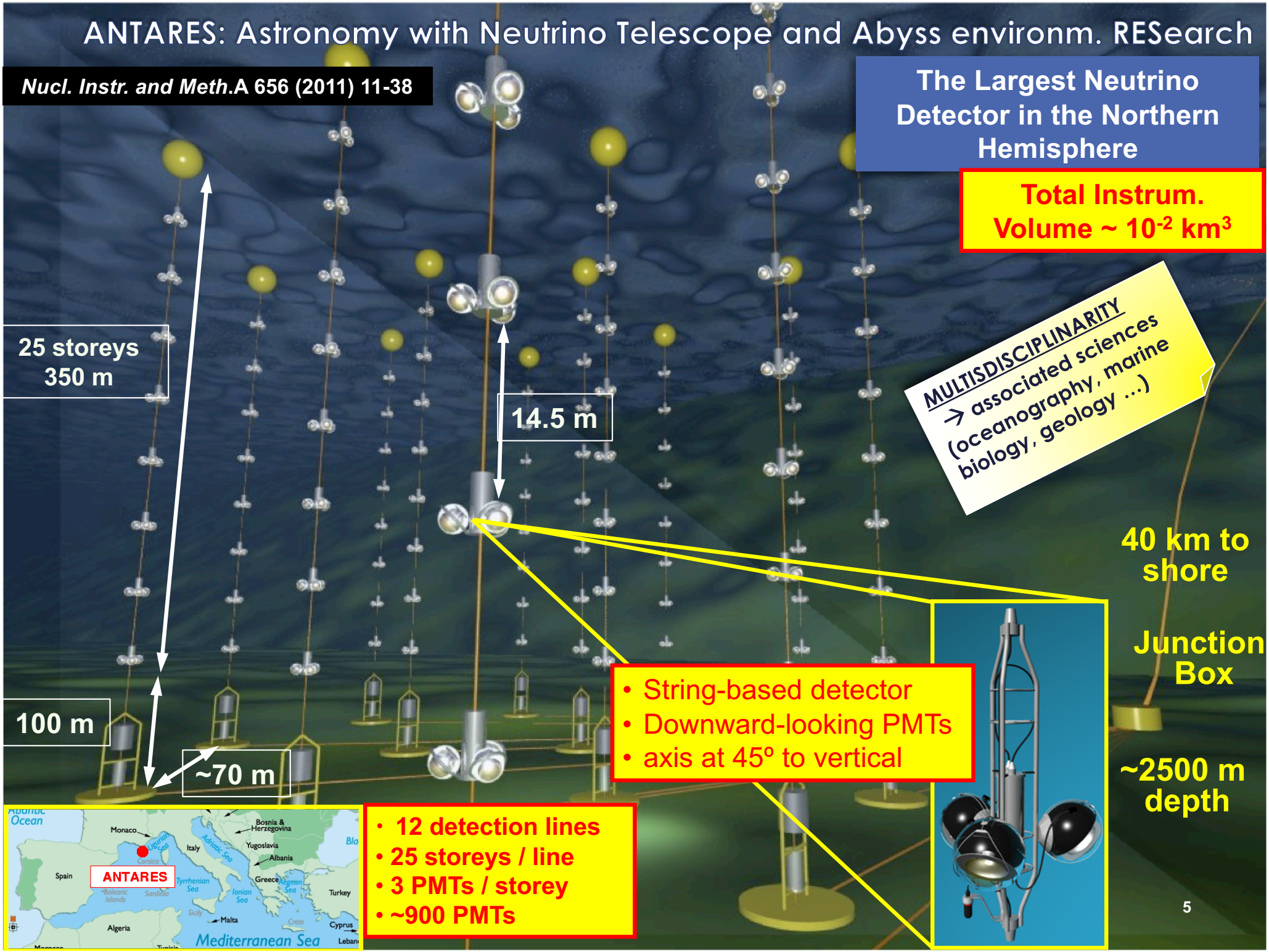


ANTARES: Astronomy with Neutrino Telescope and Abyss environm. RESearch

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

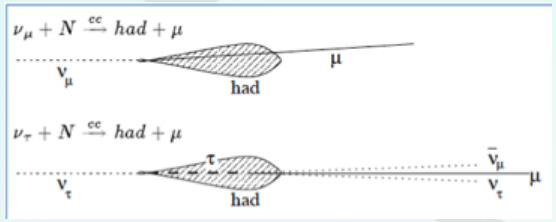
The Largest Neutrino Detector in the Northern Hemisphere

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



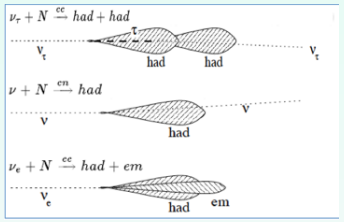
The ANTARES search for point-like ν sources based on two kind of events

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

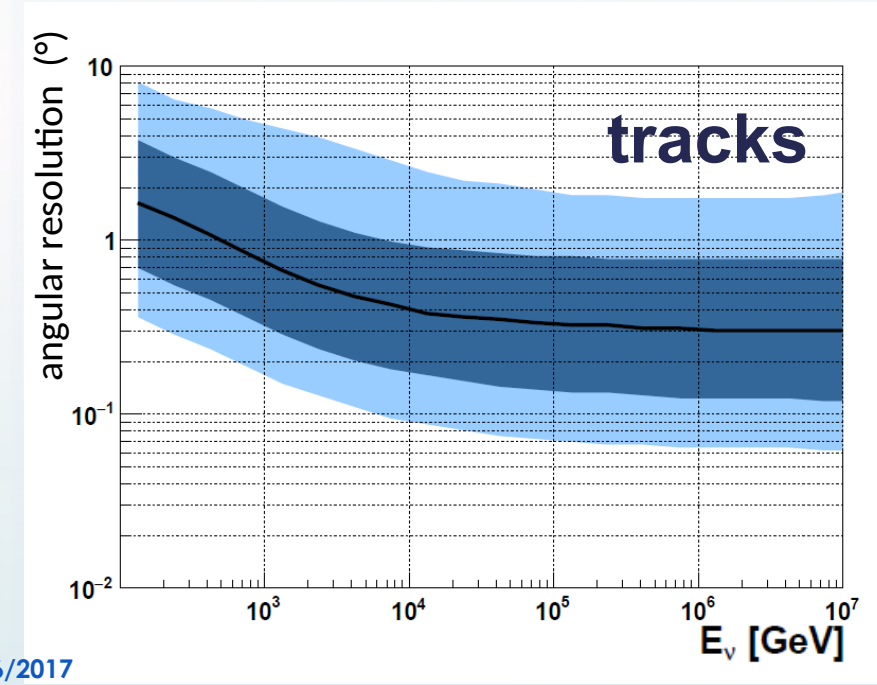


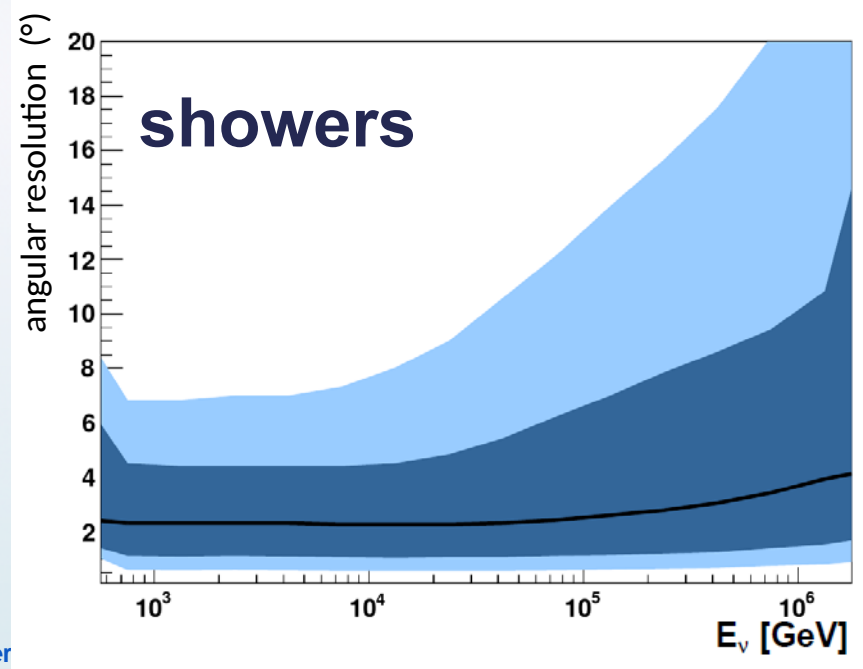
- **Interaction can occur far from the detector providing a large *Effective Volume***
- ***Angular resol.*** $< 0.4°$ **for** $E_\nu > 10\ TeV$
- ***Energy resol.*** **~ factor 3**

- **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*** $\sim 3°$

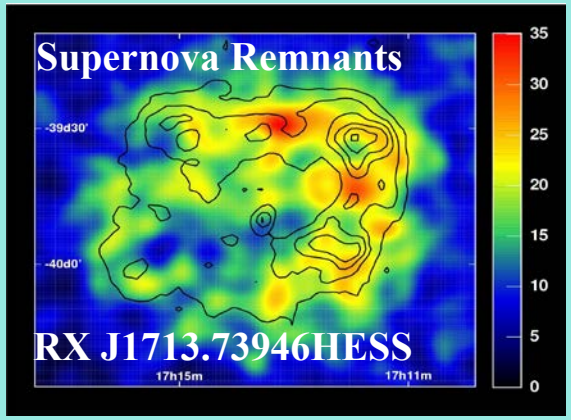


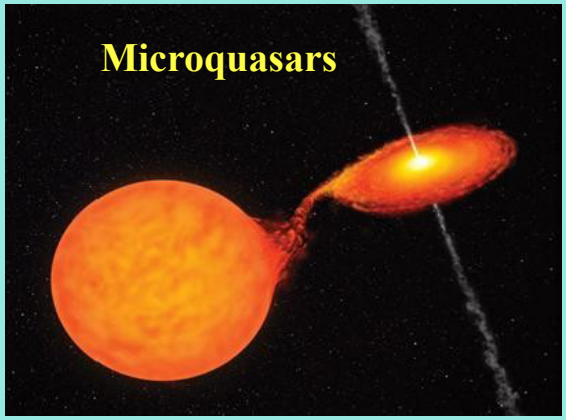


ANTARES physic's goals

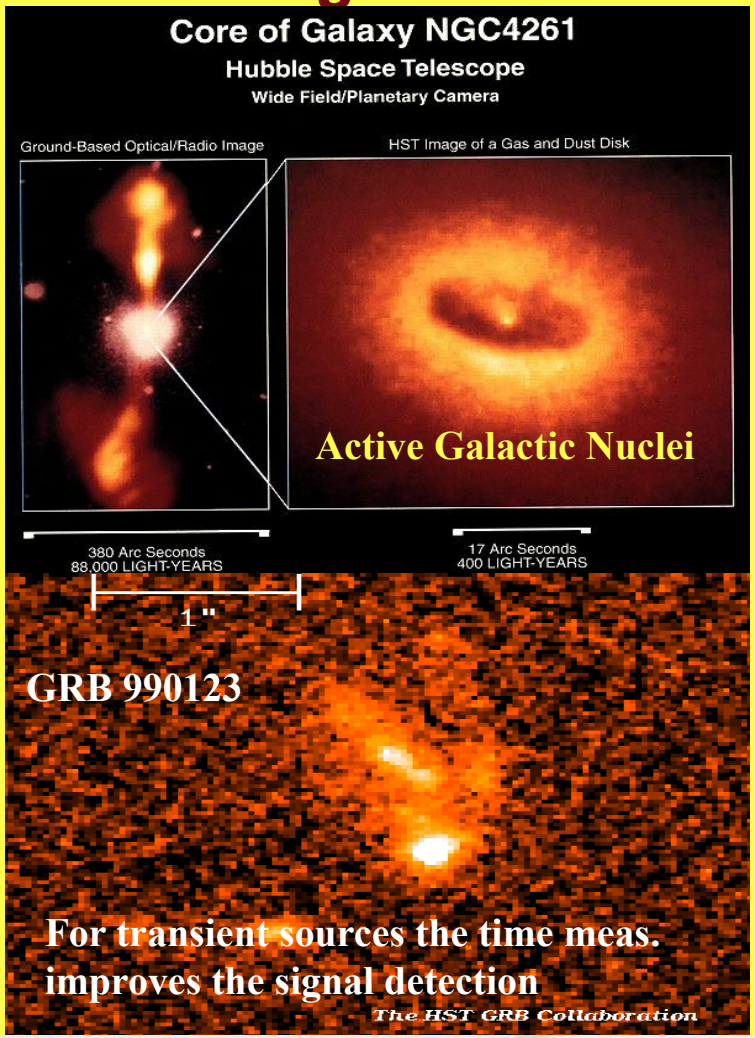
Search for point-like cosmic Neutrino Sources

Galactic





Extragalactic



- Their identification requires a detector with accurate angular reconstruction

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

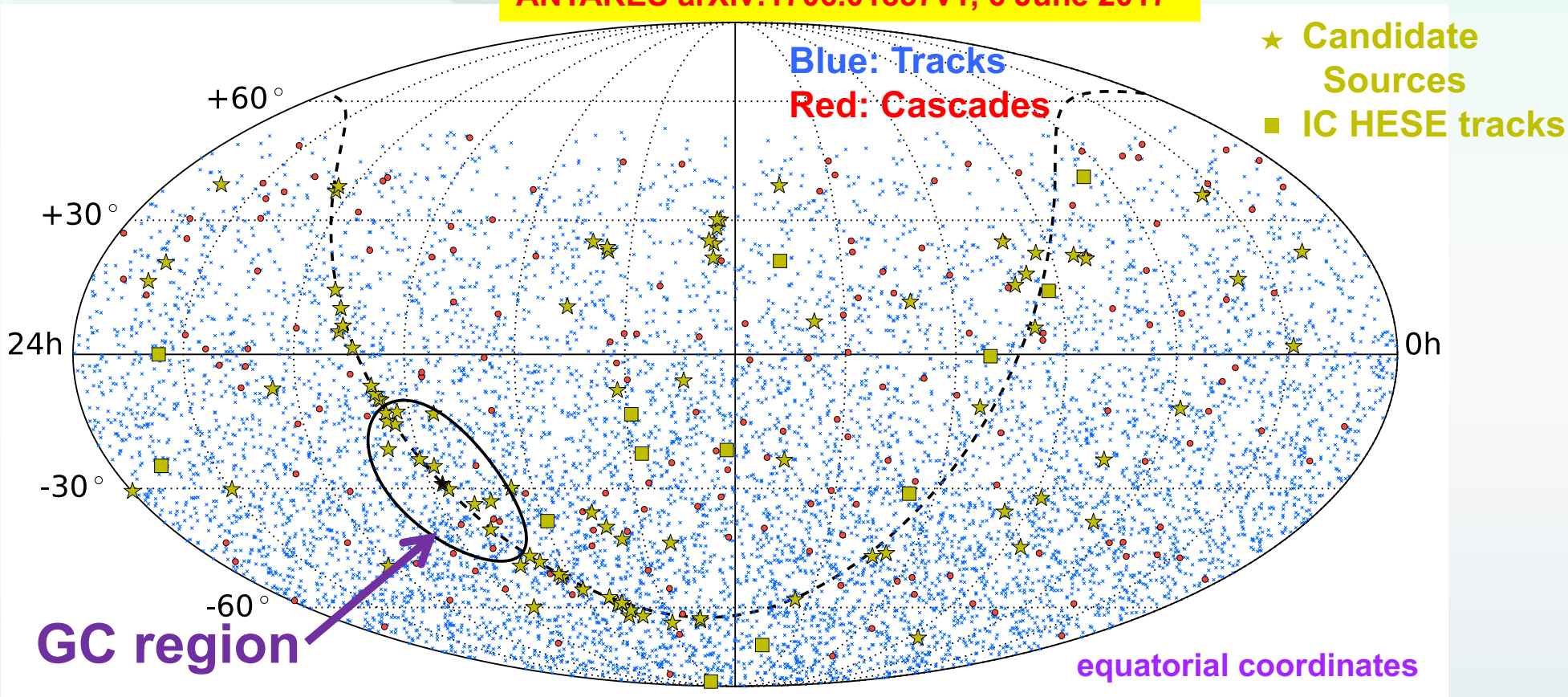
Experimental signal : statistical evidence of an excess of events coming from the same direction

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

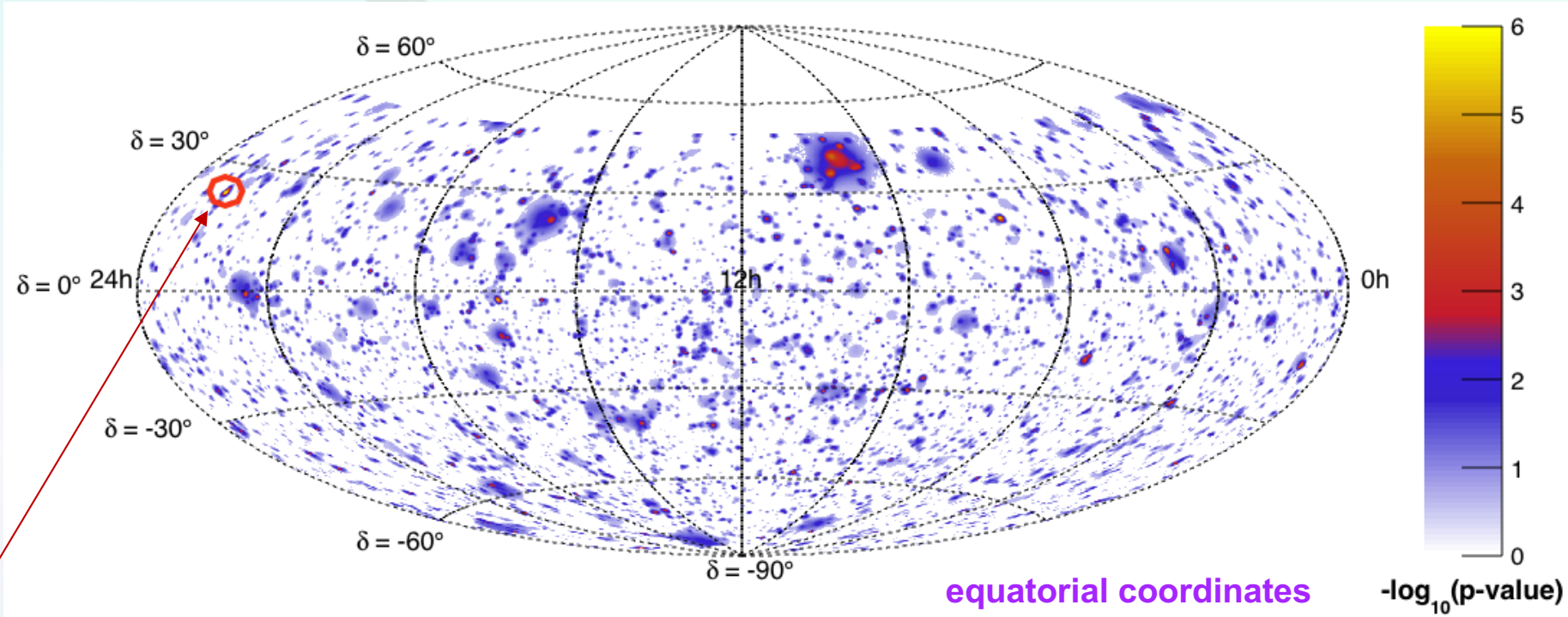


so far …. no significant excess has been found

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

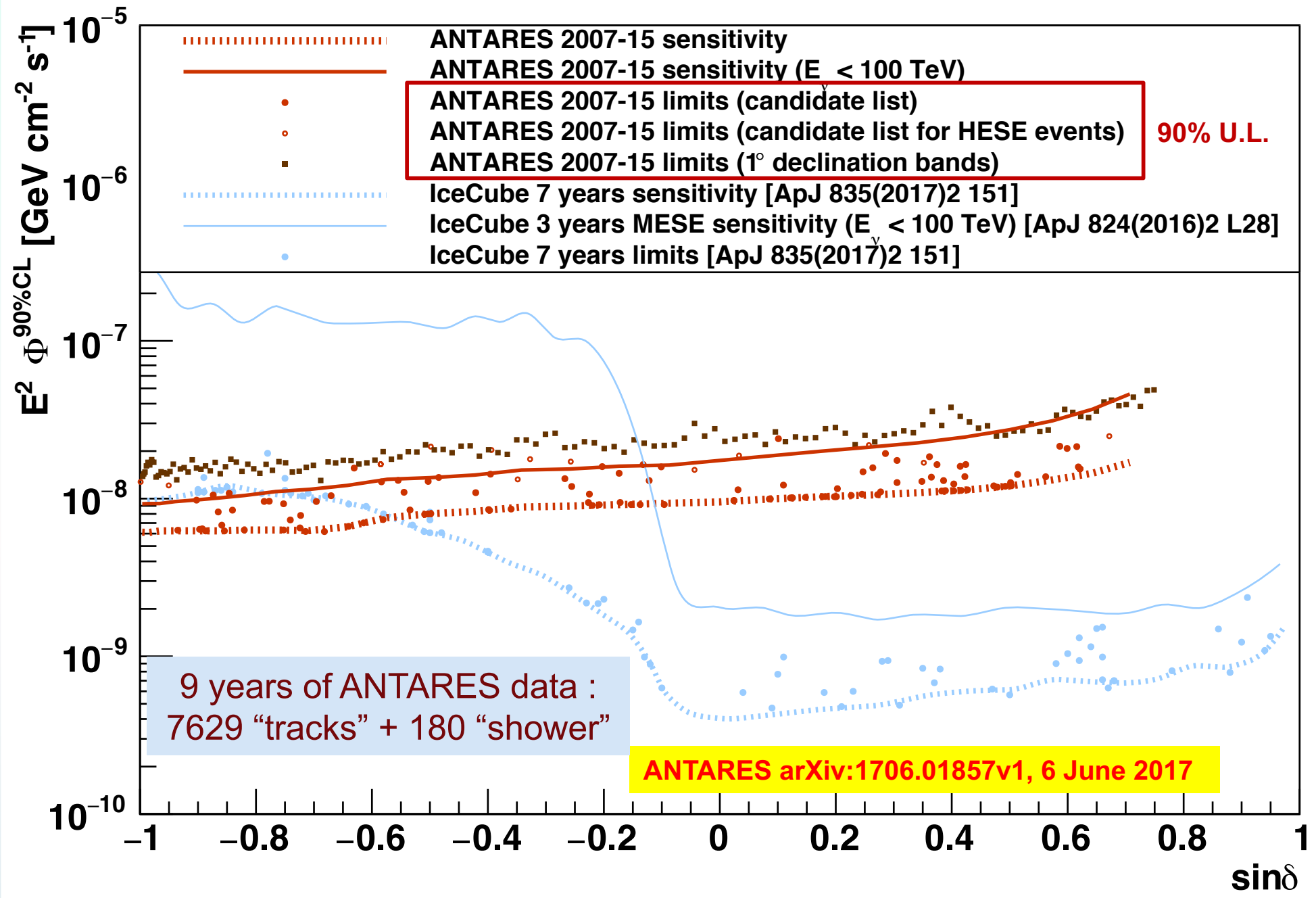
ANTARES arXiv:1706.01857v1, 6 June 2017



The most significant cluster: decl. δ = 23.5⁰, r.a. α = 343.8⁰ has a pre-trial p-value of 3.84×10^{-6}

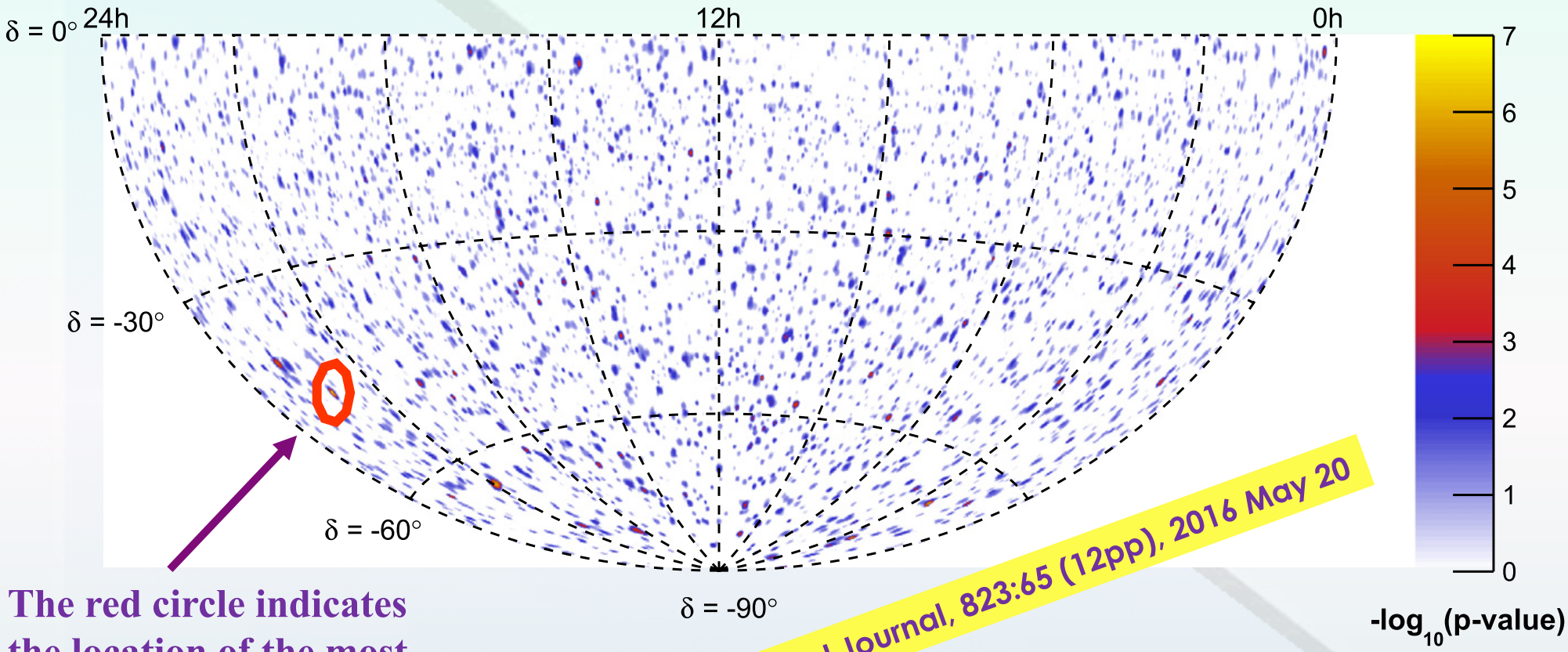
→ U. L. from this sky location $E^2 \frac{d\Phi}{dE} = 3.8 \times 10^{-8}$ GeV cm^{-2} s^{-1}

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.

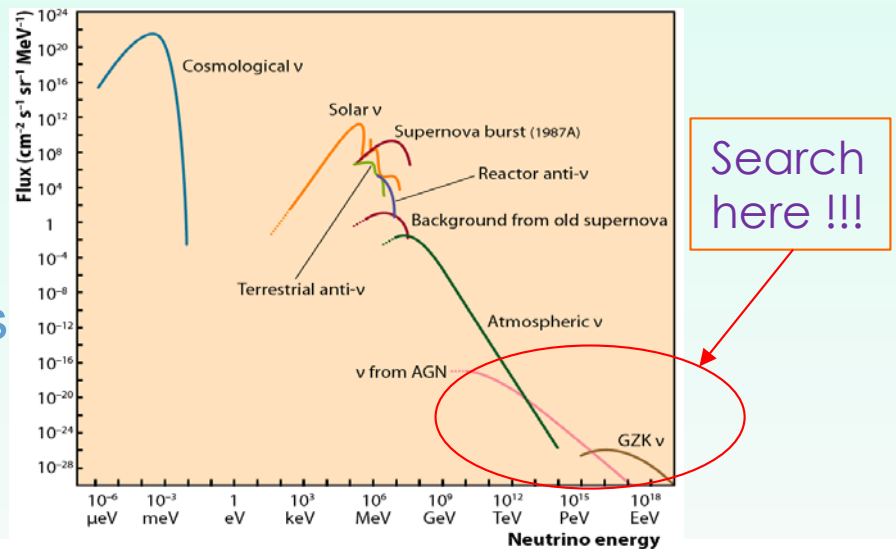


The Astrophysical Journal, 823:65 (12pp), 2016 May 20

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

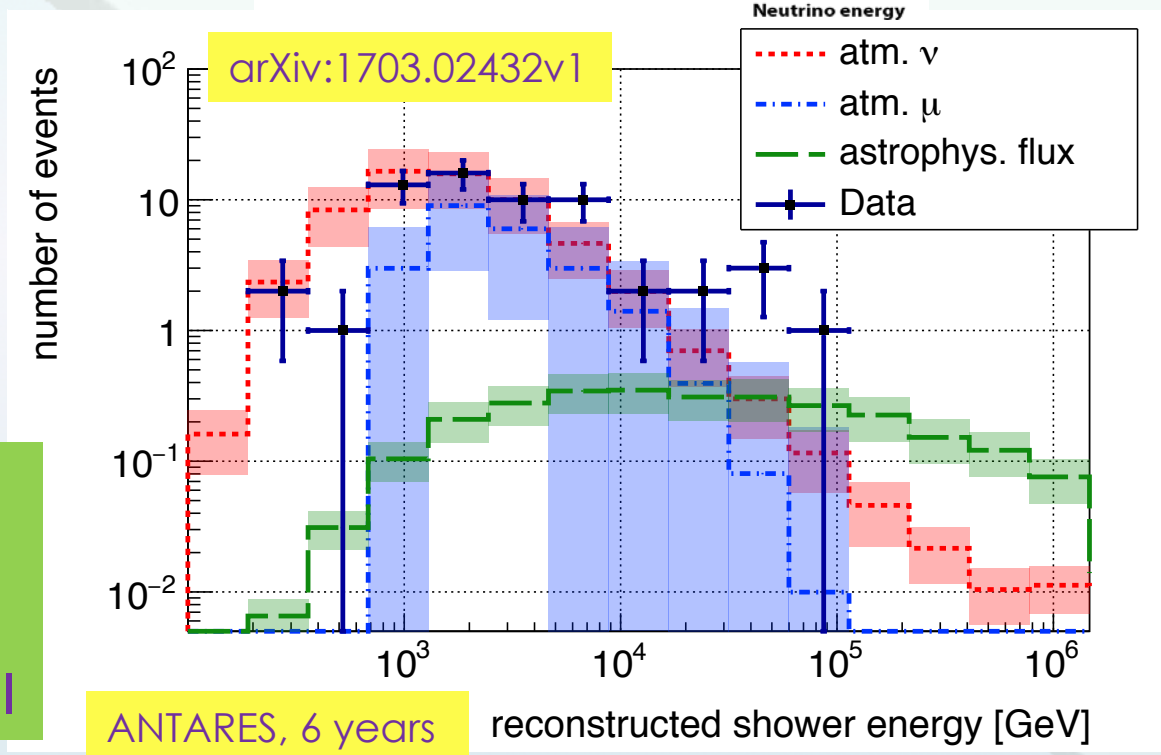
ANTARES Search for Diffuse flux of Cosmic Neutrinos

- 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.

Found 8 "shower events" for 10 TeV<E_{SH}<100 TeV when 5 expected. Compatible with IceCube signal

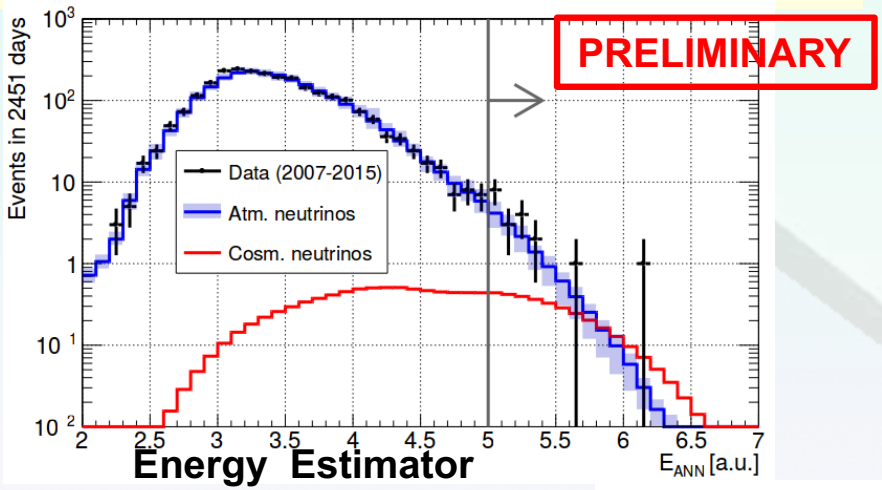


Latest ANTARES results on the search for diffuse ν flux

Tracks

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

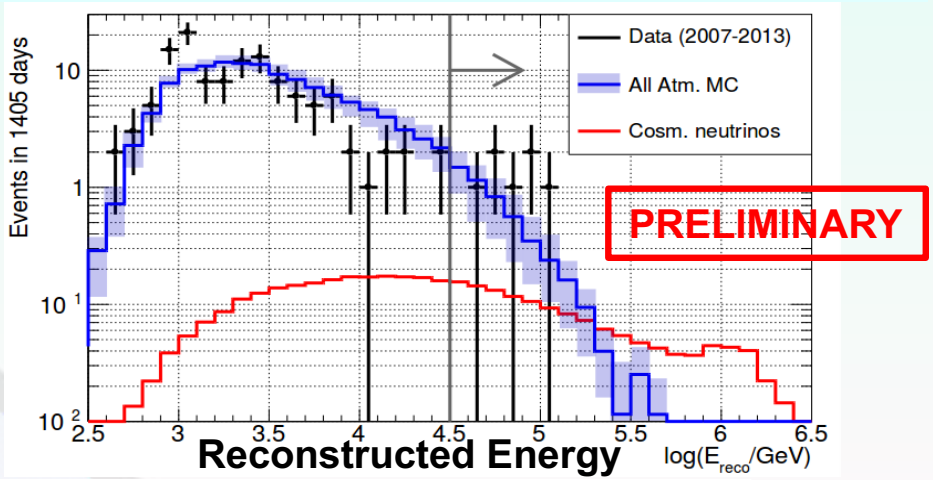
Observed: 19 evts



Cascades

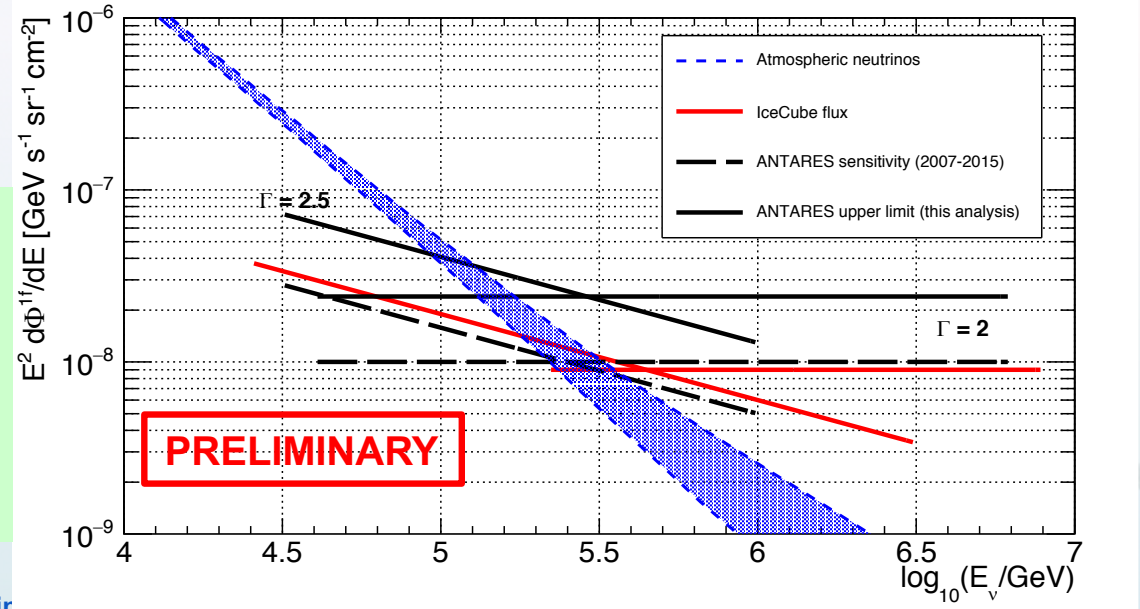
Data: 2007-2013 (1405 live-days)
Above E_{cut}: Bkg: 5 ± 2 evts, IC-like signal: 1.5 evts

Observed: 7 evts



ANTARES

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



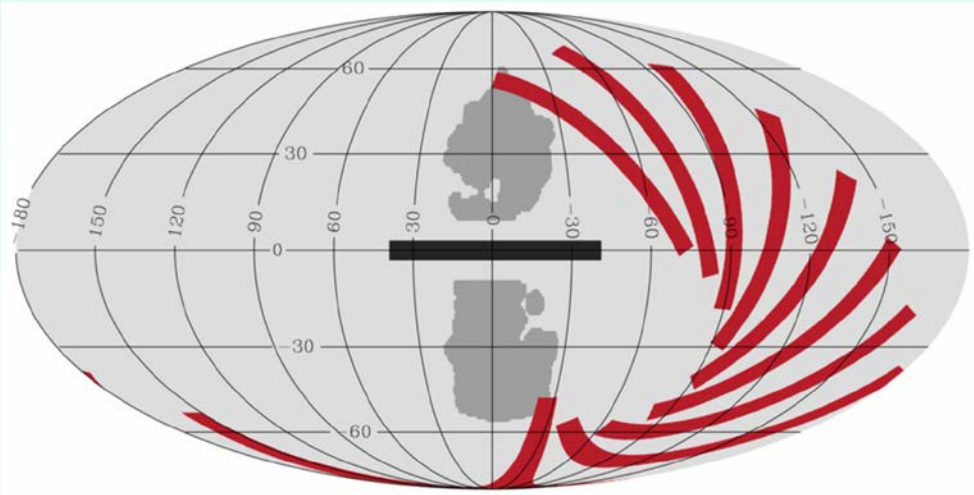
Search for neutrinos from the Galactic ridge - 1

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

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

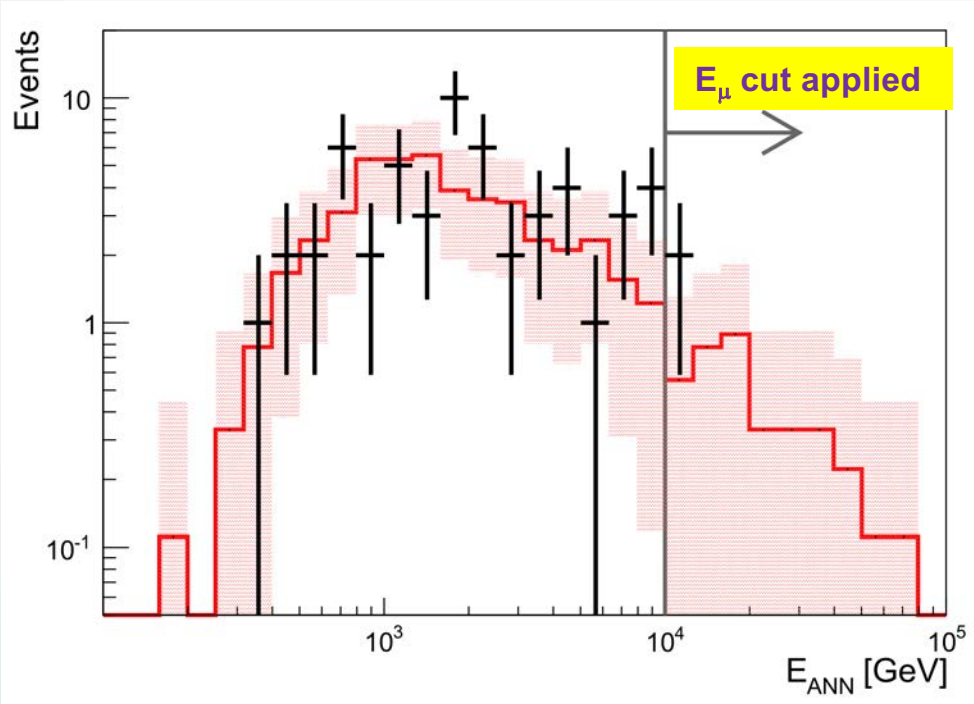
$$\pi^0 \rightarrow \gamma\gamma(EM\ cascade)$$

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



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: $3<E_\nu<300$ TeV

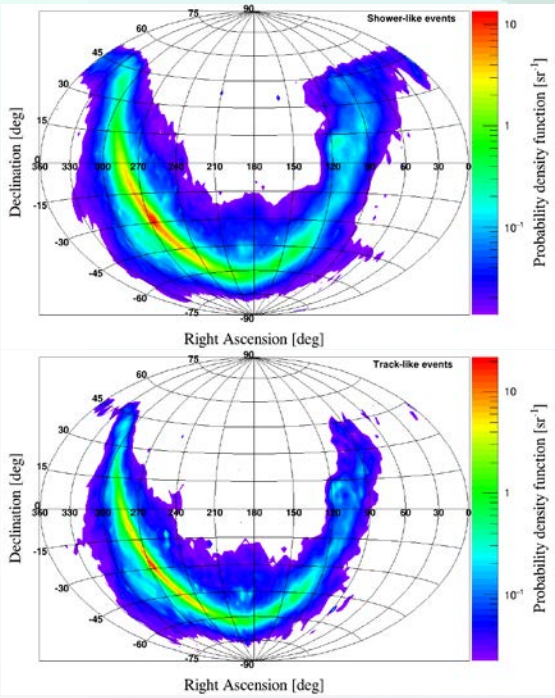


Distribution of the reconstructed E_μ of up-going muons in the Galactic Plane (black crosses) and average of the off-zone regions (red histogram).

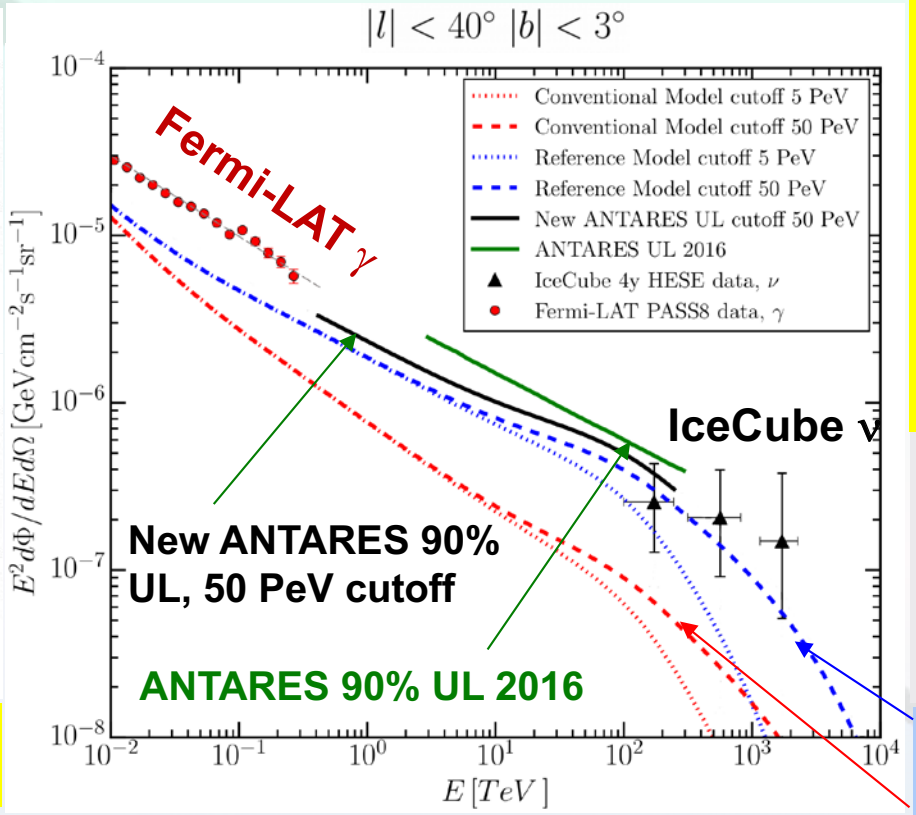
Search for neutrinos from the Galactic plane - 2

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

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

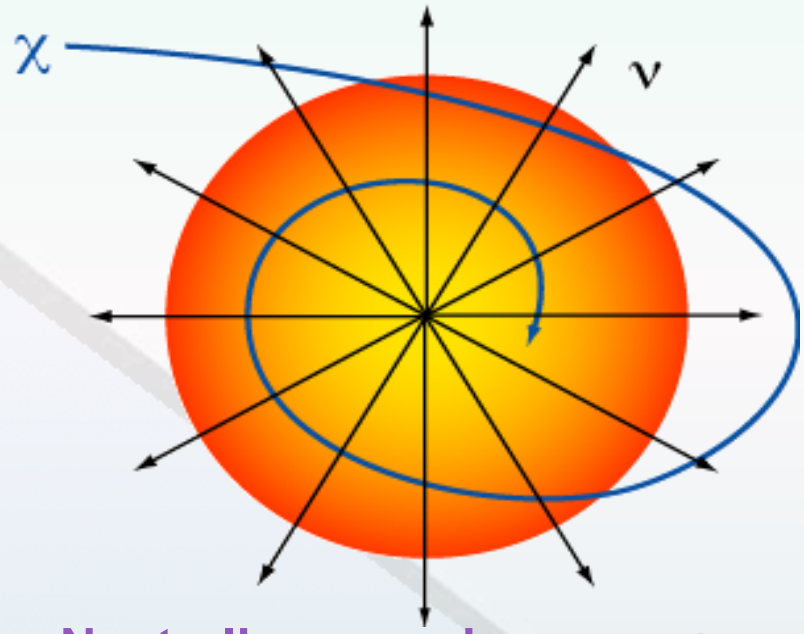
KRA$_\gamma$ 50PeV cut-off for CR
KRA$_\gamma$ 5PeV cut-off for CR

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
- …

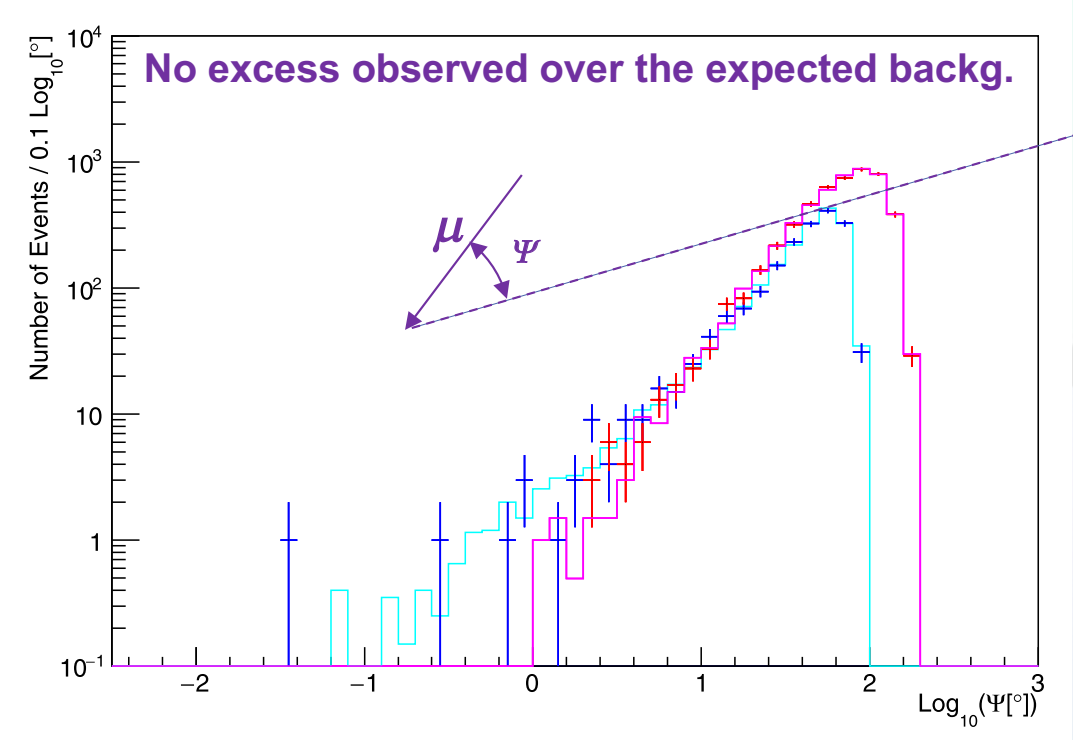


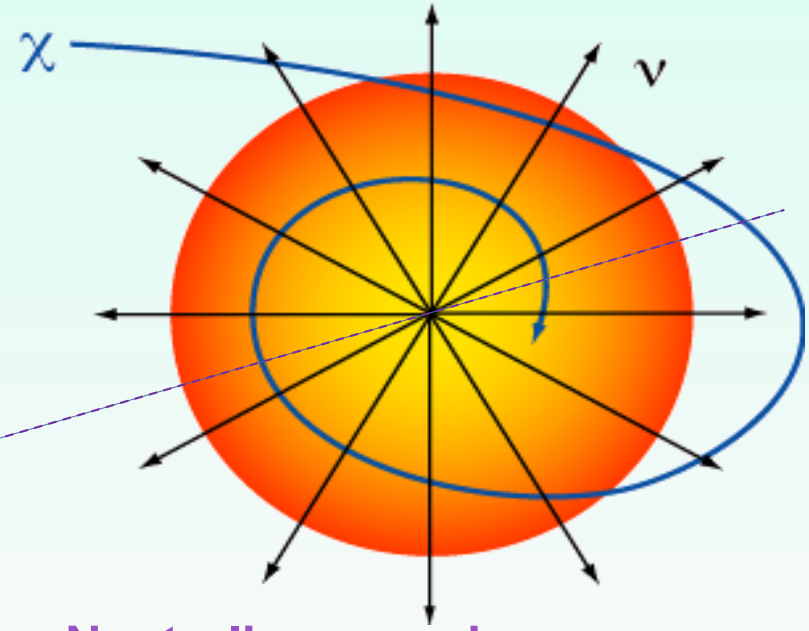
Neutralino search: $\chi\chi \rightarrow \nu$+…

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: $\chi\chi \rightarrow \nu$+…

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

Background
estimated from time-scrambled data.

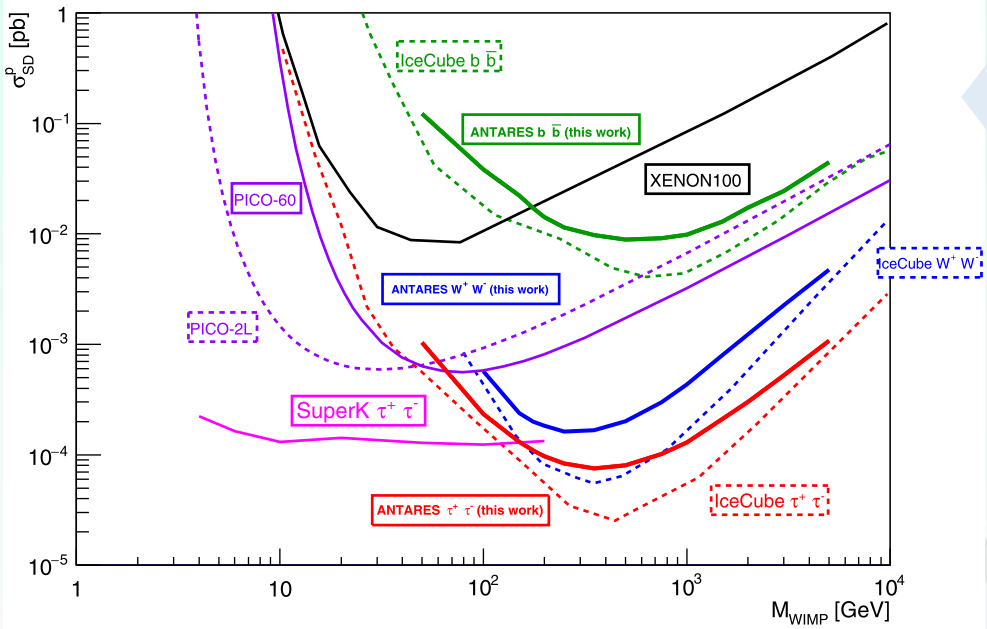
Neutrino fluxes from $WIMP + WIMP \rightarrow \underbrace{b\bar{b}, W^+W^-, \tau^+\tau^-}$ $\rightarrow \bar{\nu}\,\nu + \ldots$

evaluated for 50 GeV/c² < M_{WIMP} < 5 TeV/c²

→ 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

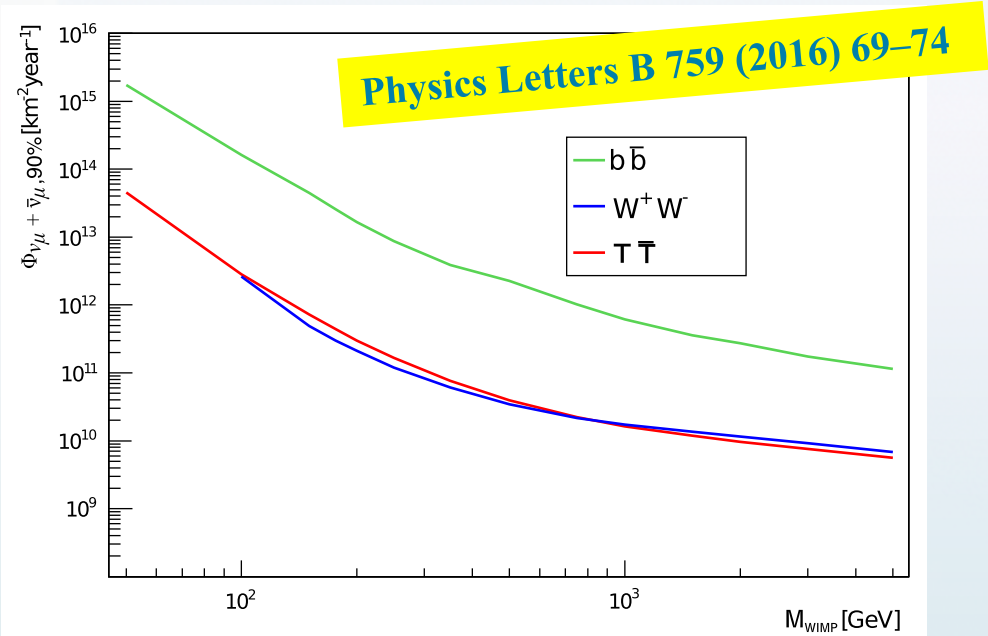


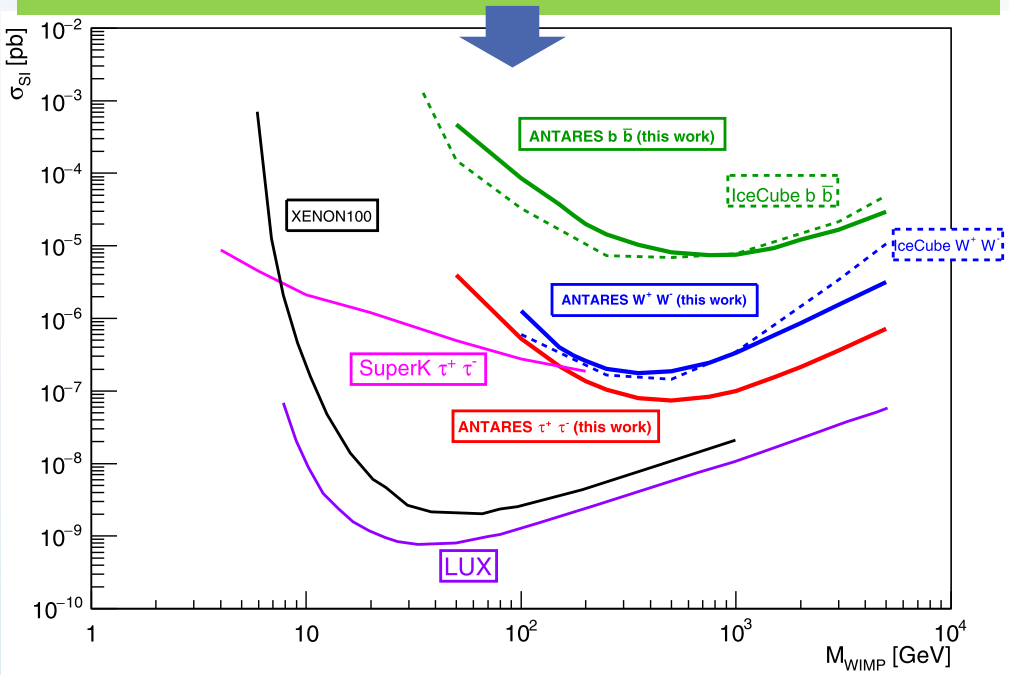
Limits on the **spin-dependent** WIMP-nucleon scattering cross-section as a function of WIMP mass for the bb¯, τ+τ− and W+W− channels.

assumptions:

- **capture and annihilations in equilibrium**
- local D.M. density =0.4 GeV cm^{-3}
- υ^{DM}_{SUN} 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.





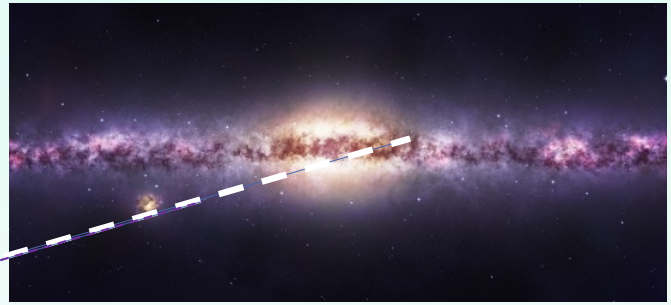
Indirect search for Dark Matter in the Galactic Centre

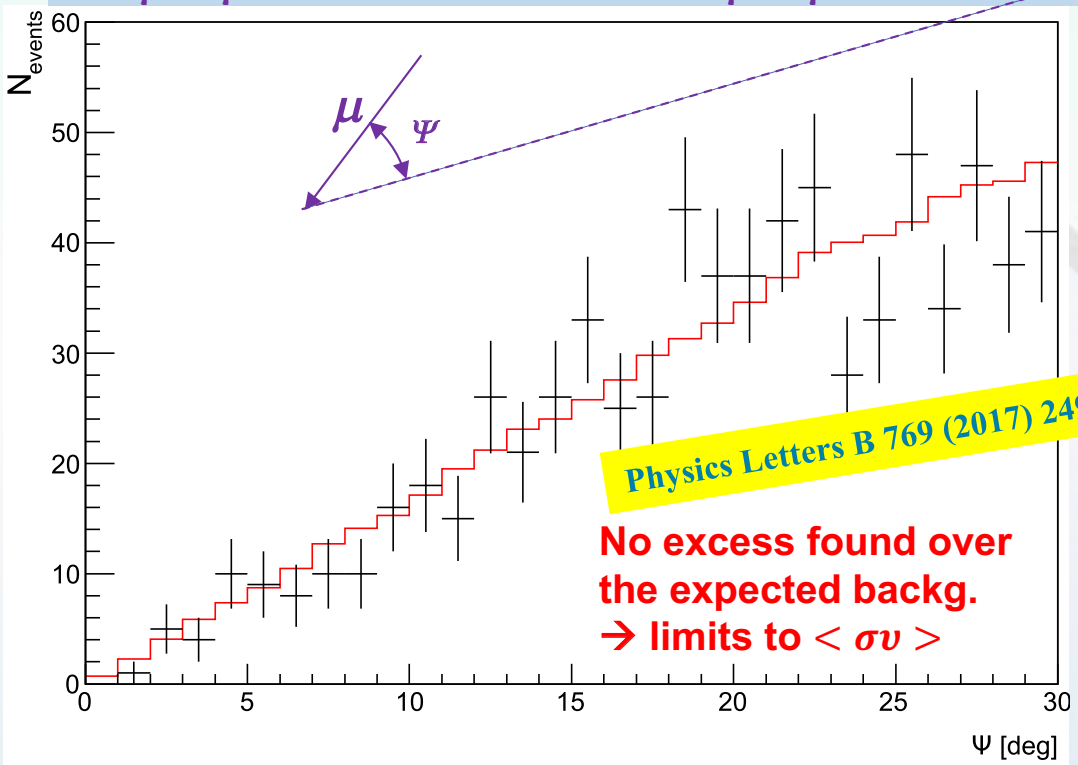
9 years of ANTARES data: 2007-2015 - ANTARES "observes" the G.C > 66% time

Search performed for:

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

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

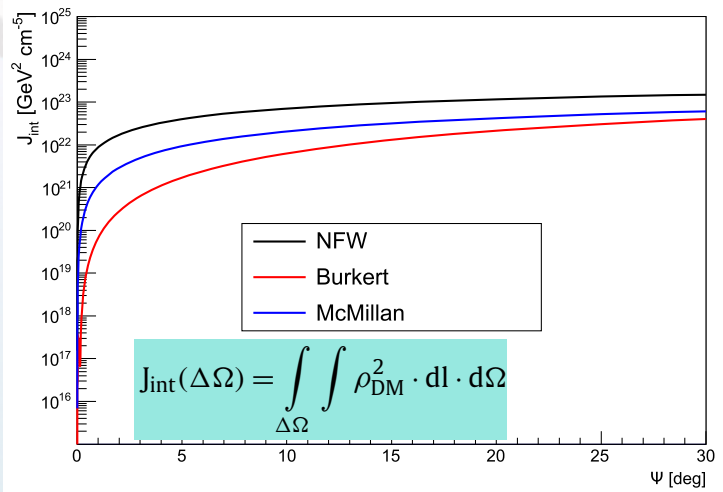




Distribution of measured angles between reconstructed tracks and the Galactic Centre (crosses). The red line describes what is expected from background event.

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/cm³]	$0.471^{+0.048}_{-0.061}$	$0.487^{+0.075}_{-0.088}$	0.390 ± 0.034



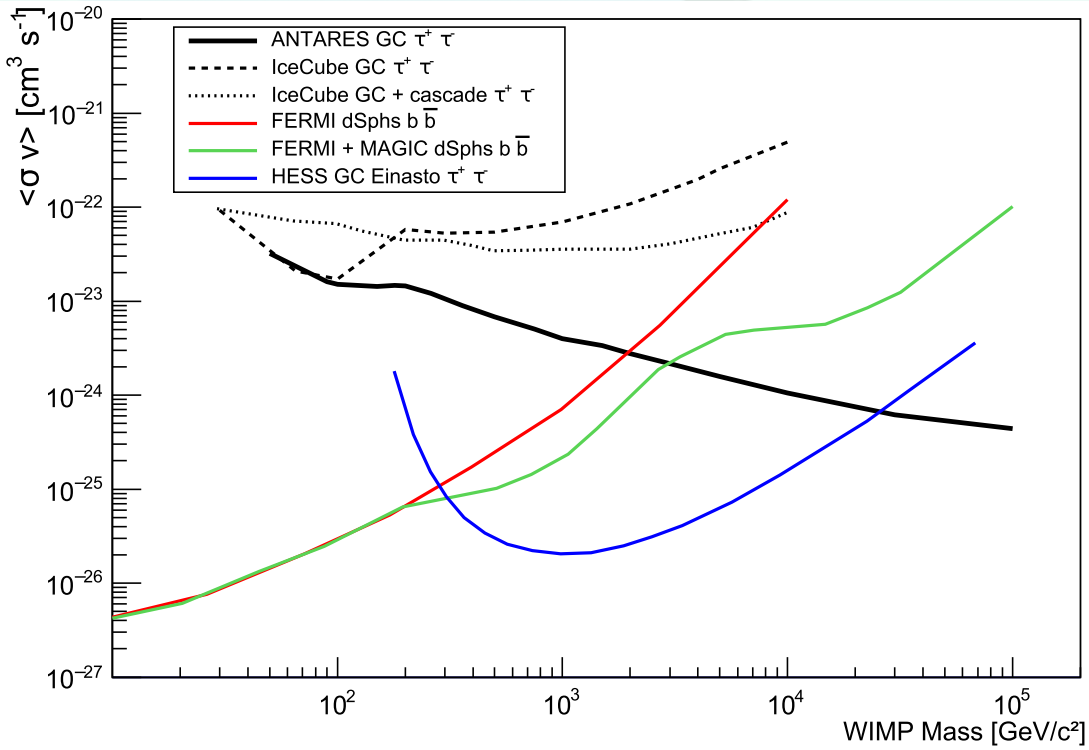
The integrated J-Factor, J_{int}, for a cone-shaped region centred on the G.C. with an opening angle Ψ

Indirect search for Dark Matter in the Galactic Centre

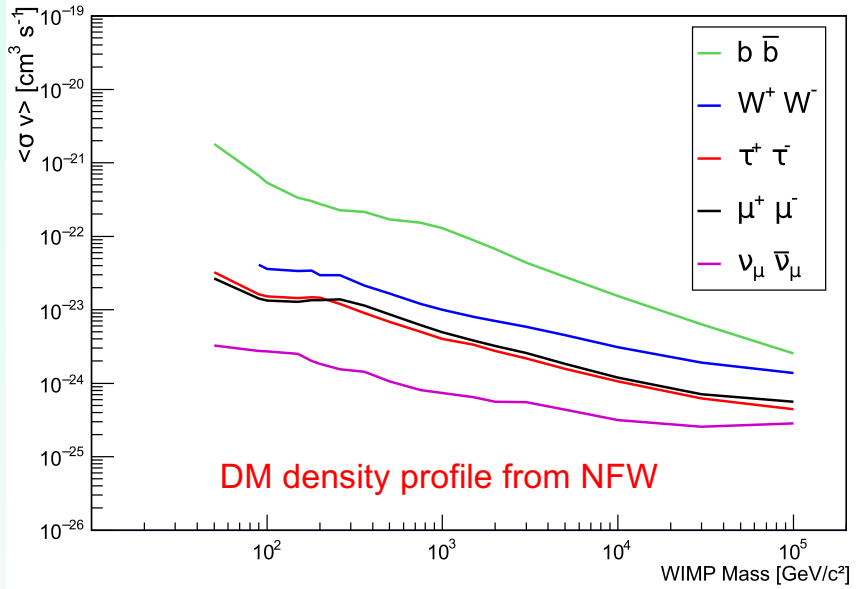
No excess found over the expected background

➡ limits to

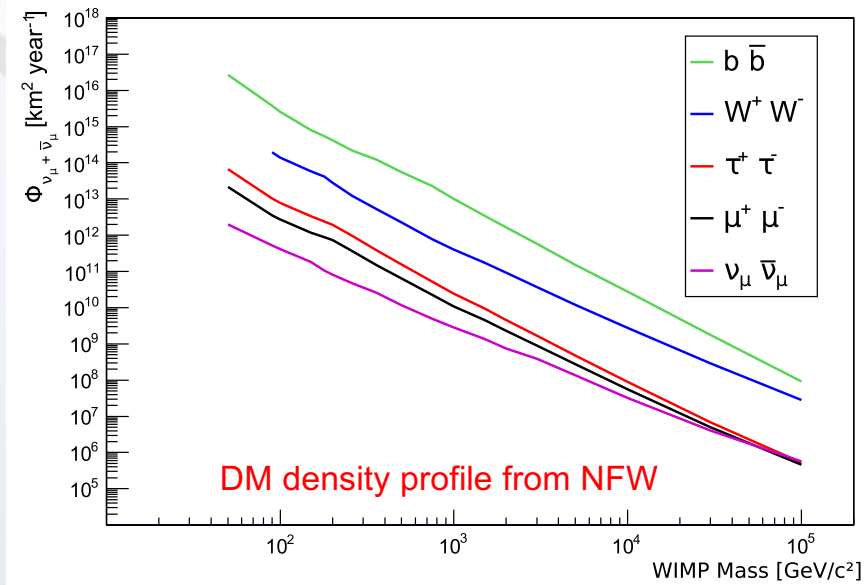
$$\frac{d\Phi_{\nu_\mu+\bar{\nu}_\mu}}{dE_{\nu_\mu+\bar{\nu}_\mu}} = \frac{<\sigma v>}{8\pi M_{WIMP}^2} \cdot \frac{dN_{\nu_\mu+\bar{\nu}_\mu}}{dE_{\nu_\mu+\bar{\nu}_\mu}} \cdot J_{int}(\Delta\Omega)$$



90% C.L. limits on the thermally averaged annihilation cross-section, $\langle\sigma\, v\rangle$, 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 $\langle\sigma v\rangle$ 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 $\upsilon_{WIMP} < \upsilon_{escape}^{Earth}$
- $\boldsymbol{\upsilon_{escape}^{Earth} \sim 14 \frac{km}{s}}$; $\boldsymbol{\upsilon_{WIMP} = \bar{\upsilon}_{270}}$ 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 $\boldsymbol{\sigma_p^{SI}}$
- Fe and Ni most abundant in the Earth → effective capture for $\boldsymbol{M_{WIMP} \sim 50\ GeV}$
- 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:

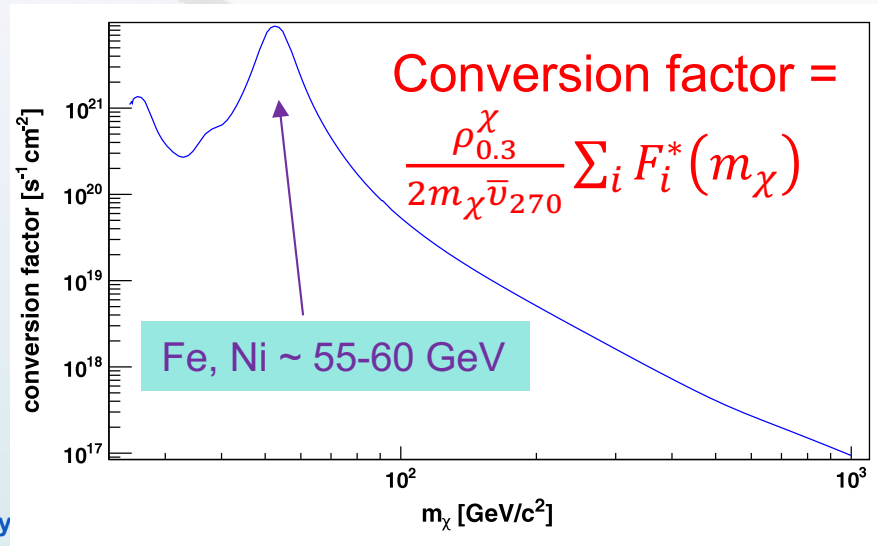
$$\Gamma_A(t_{Earth}) \propto \underbrace{\left[\frac{\sigma_p^{SI}\rho_{0.3}^{\chi}}{m_\chi \bar{\upsilon}_{270}} \sum_i F_i^*(m_\chi)\right]^2}_{C_C^2 \text{ capture factor}} \frac{\langle \sigma_A \upsilon \rangle_{Earth}}{V_{Earth}} \left(\frac{m_\chi}{20\ GeV}\right)^{\frac{3}{2}}$$

C_A annih. factor

Needed to estimate the ν fluxes with WimpSim

$\rho_{0.3}^{\chi}$=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

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

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

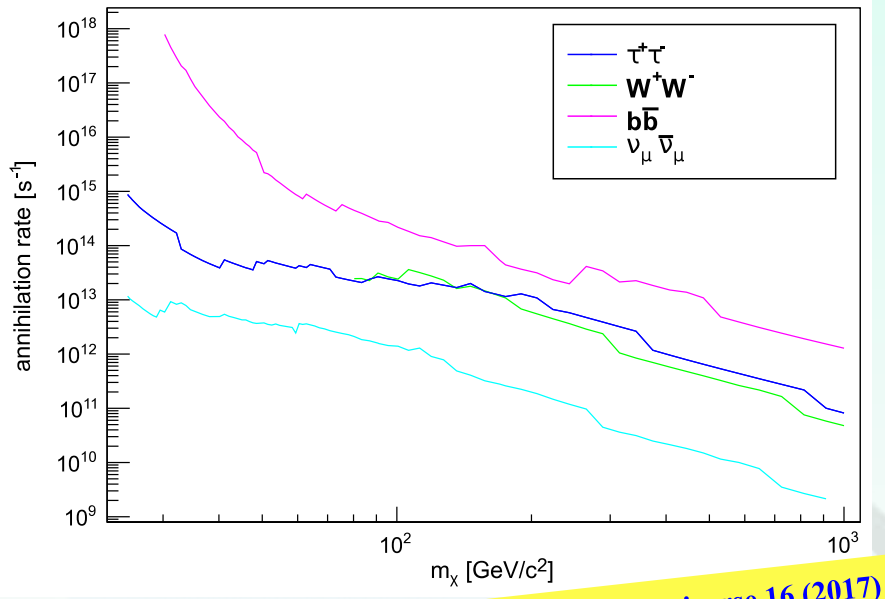
No excess found over the expected background

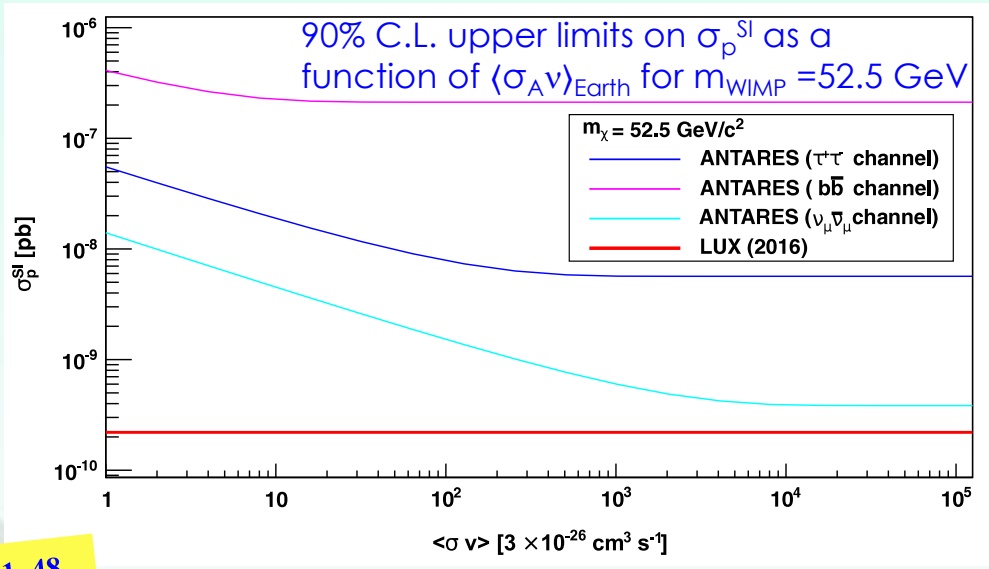
Limits on the WIMP-WIMP annihilation rate in the Earth

Limits on the spin independent WIMP-nucleon cross-section

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

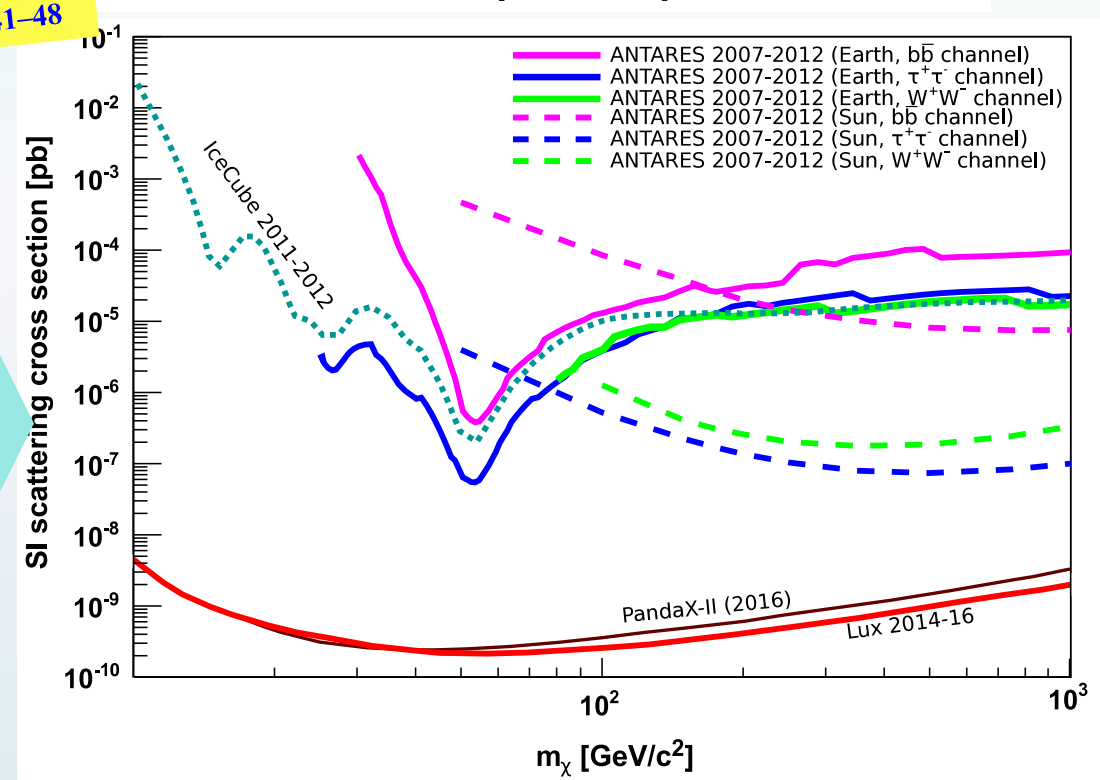
Indirect search for Dark Matter in the Earth





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).



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

ANTARES Multi-messenger program

- **A "common observation" of the same source will allow to better understand the "acceleration mechanisms", the physics inside the source**

- **A "common observation will increase the detector sensitivities**

A long list of activities:

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

- **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:

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

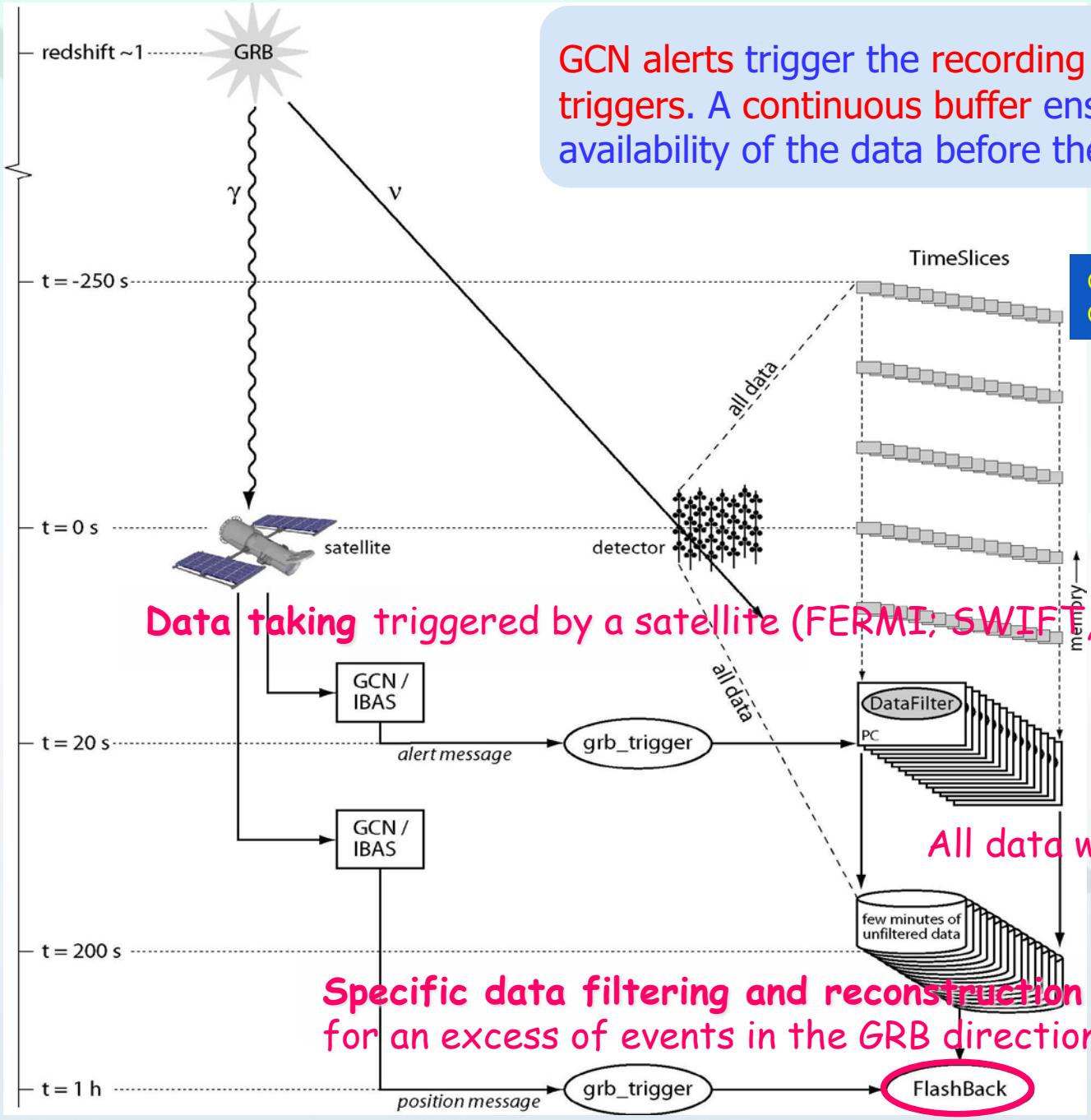
Time-dependent searches:

- **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]**

ANTARES Multi-Messenger program: search for 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



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: some example search for ν from GRB sources

Astronomy & Astrophysics 559, A9 (2013)

2007-2011 data:

- alerts and data from FERMI – SWIFT - GCN
- analysis of 296 long GRBs (total prompt emission 6.6 hours)

Simulation of neutrino fluxes from GRB:

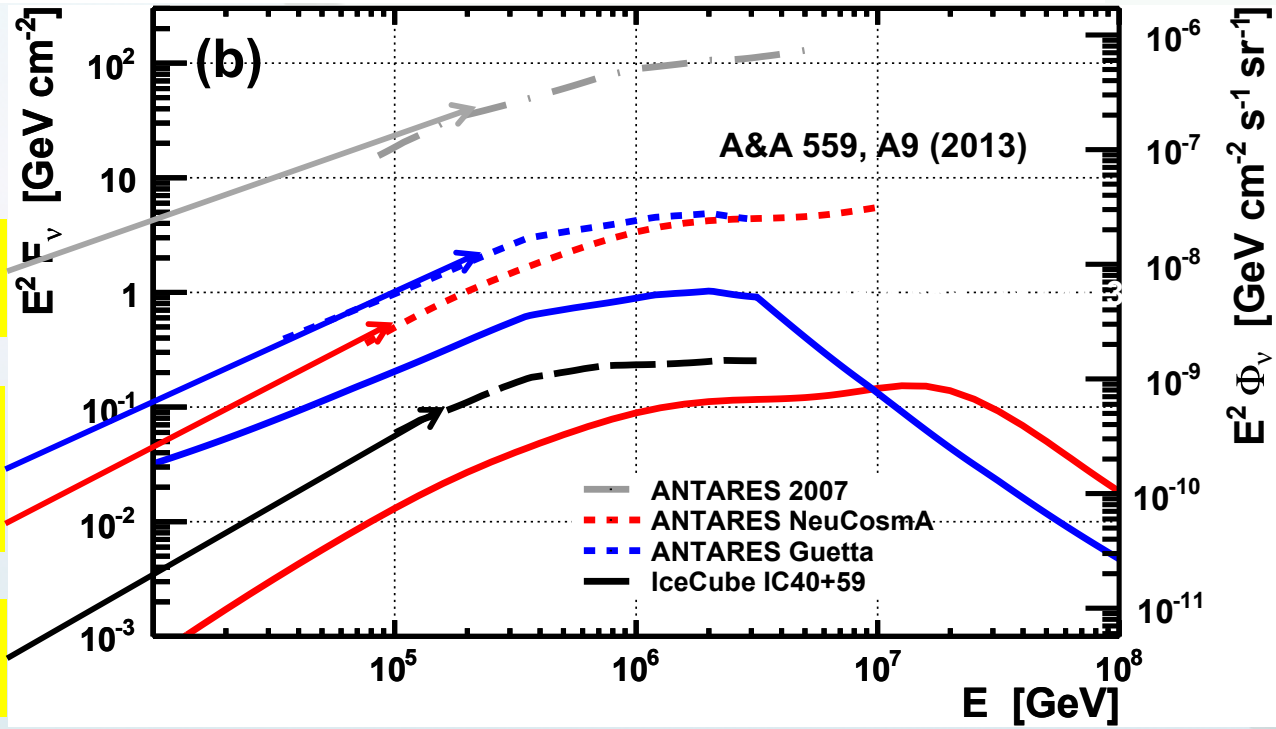
- NeuCosmA (Hümmer et al 2010) → expected 0.061 events
- Guetta (Guetta et al. 2004) → expected 0.48 events
- Expected background 0.051 events

No events found in stacked GRB search within 10° window:

Previous ANTARES result, 40 GRBs JCAP 1303 (2013) 006

ANTARES upper limits 90% C.L. for **Guetta fluxes** **NeuCosmA fluxes**

IceCube upper limits 90% C.L. IC40+59 for 215 GRBs



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)

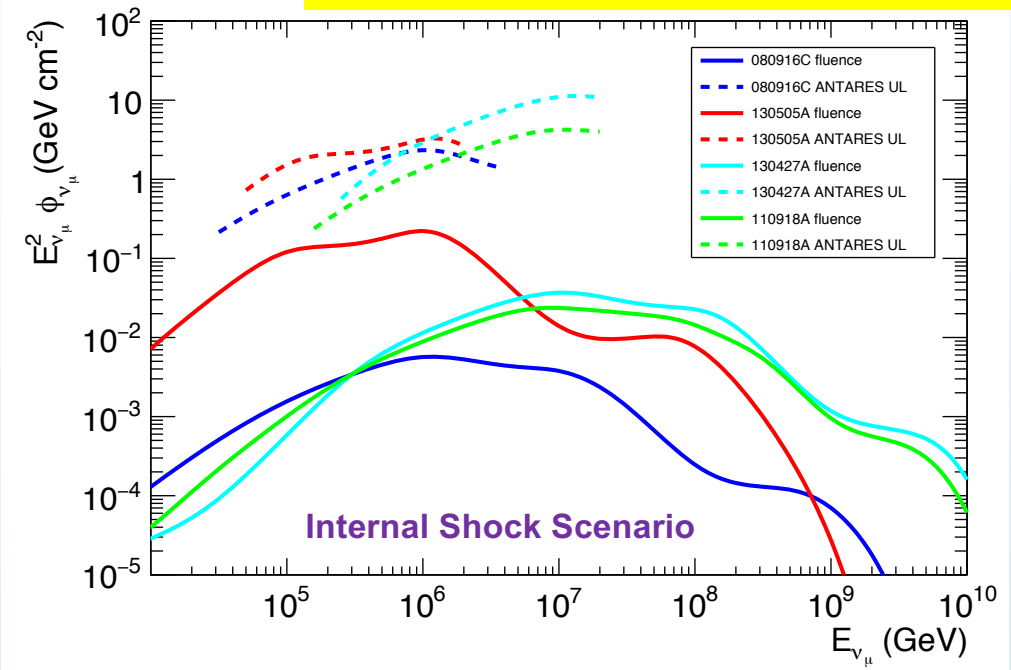
observed between 2008 and 2013.

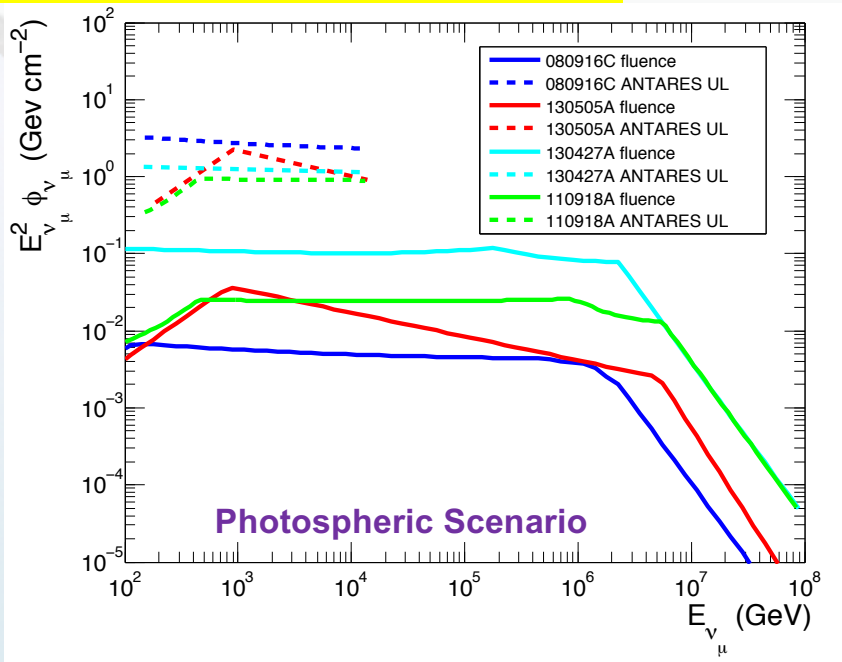
The expected neutrino fluxes evaluated in the framework of:

- **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.

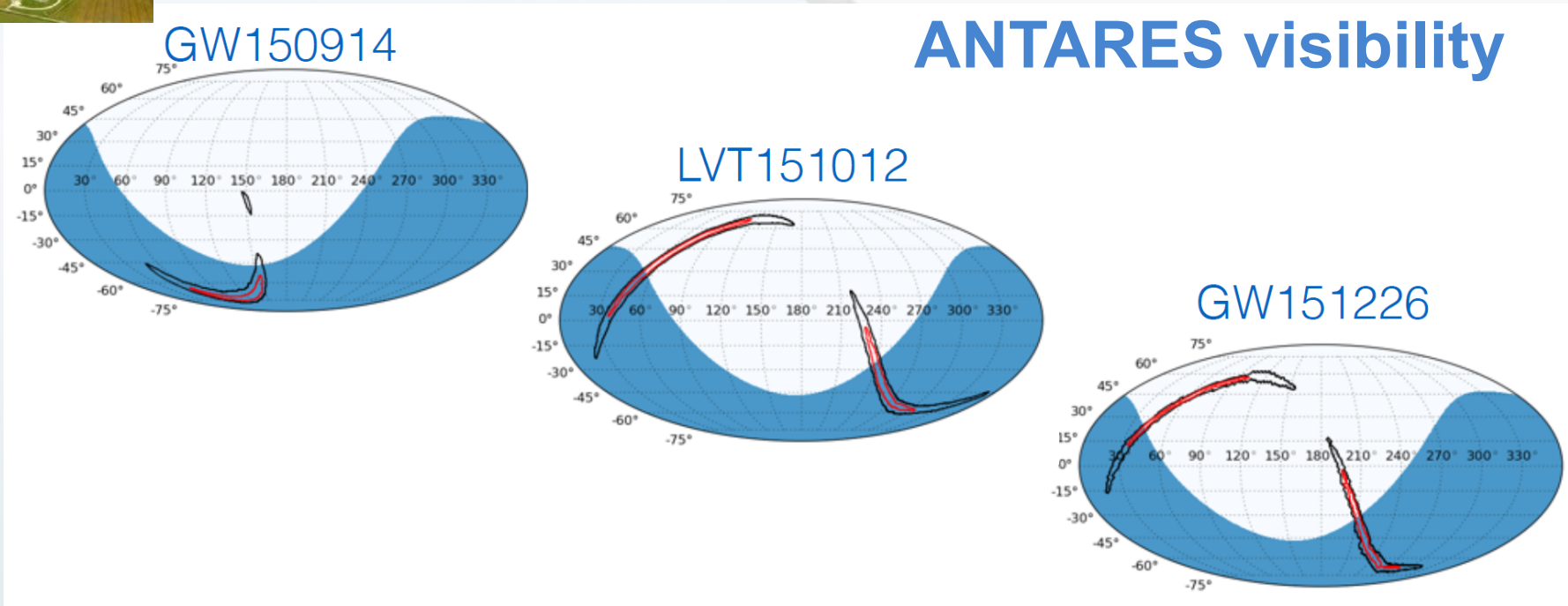




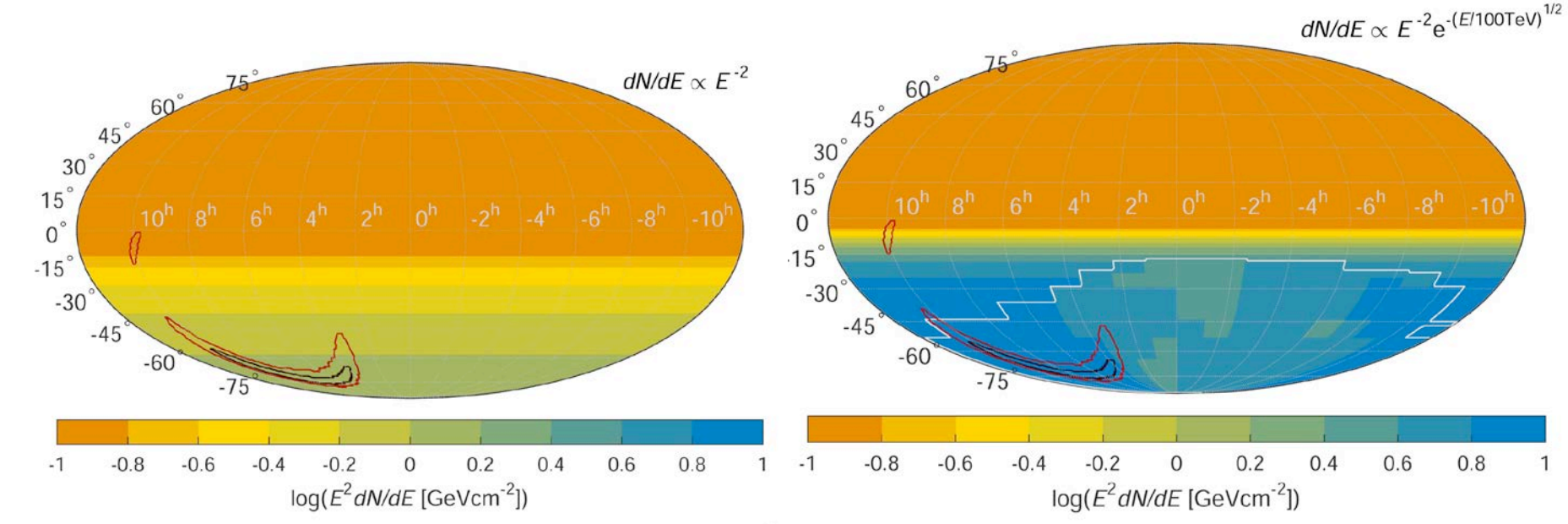
ANTARES Multi-messenger program
ν follow-up of GW sources - 1

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 $E\nu < 100$ TeV
- U.L. from IC dominated above 100 TeV
- Size of GW150914 : 590 deg^2 ANTARES resolution: <0.5 deg^2
- Limits on total energy radiated in neutrinos: <10% GW
- Future: Receive / send alerts in real time

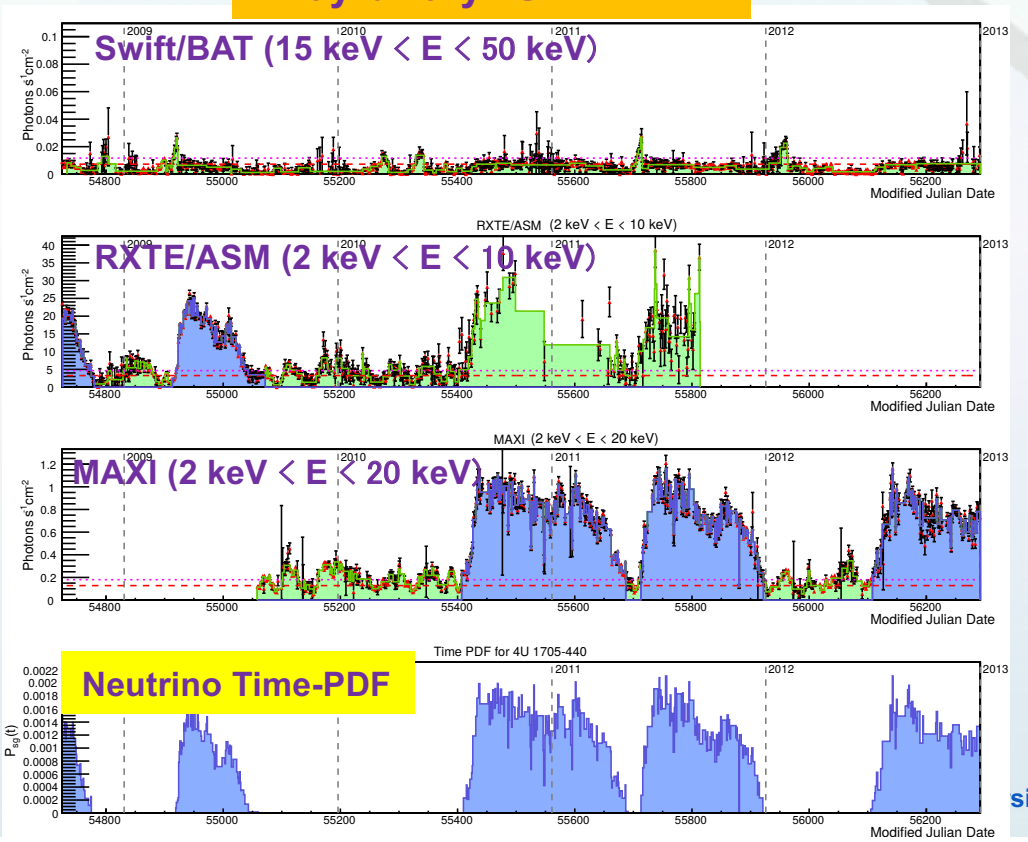
ANTARES Multi-messenger program

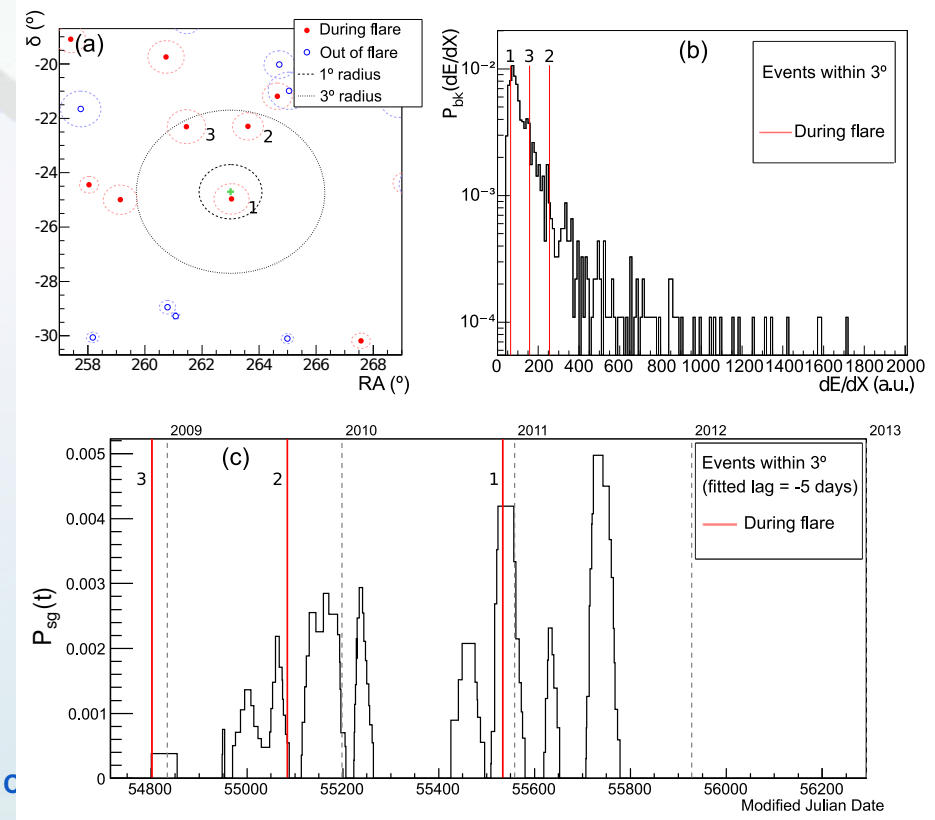
ν associated with GeV and TeV γ-ray flaring blazars and X-ray binaries

- 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



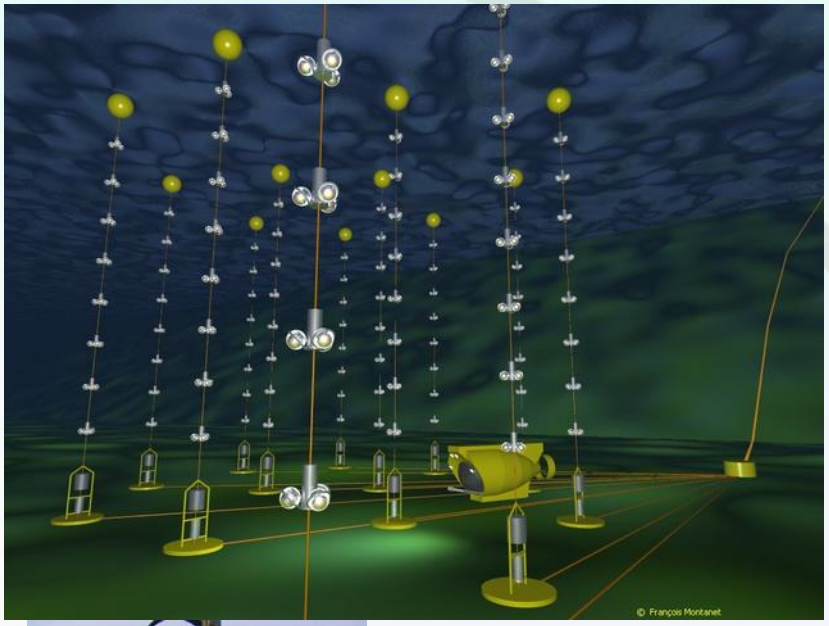


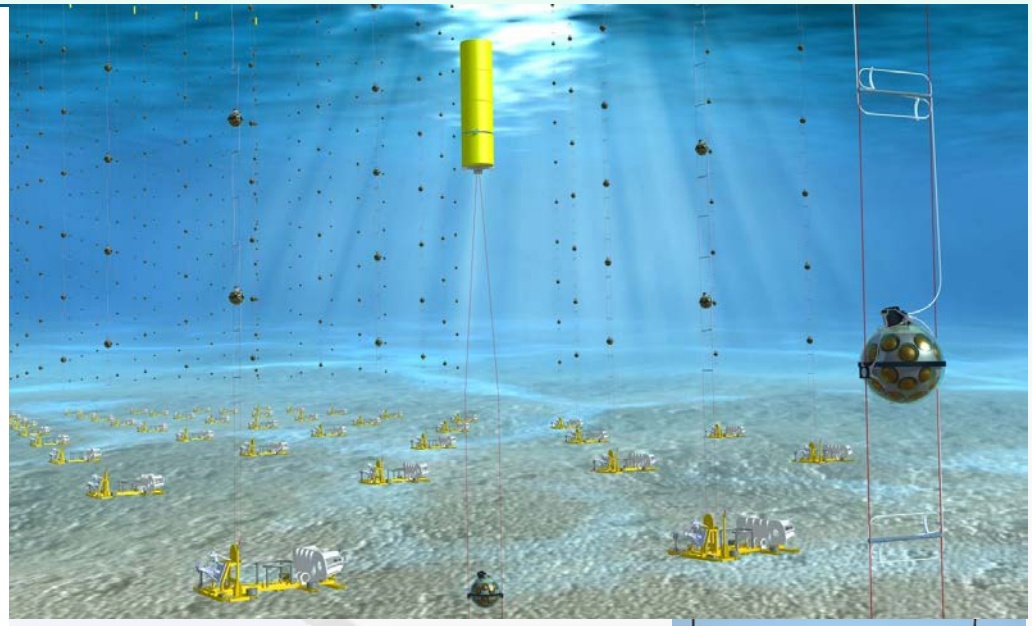
The future of Neutrino Astronomy in the Mediterranean Sea

ANTARES → KM3NeT

12 Lines, 885 OM

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

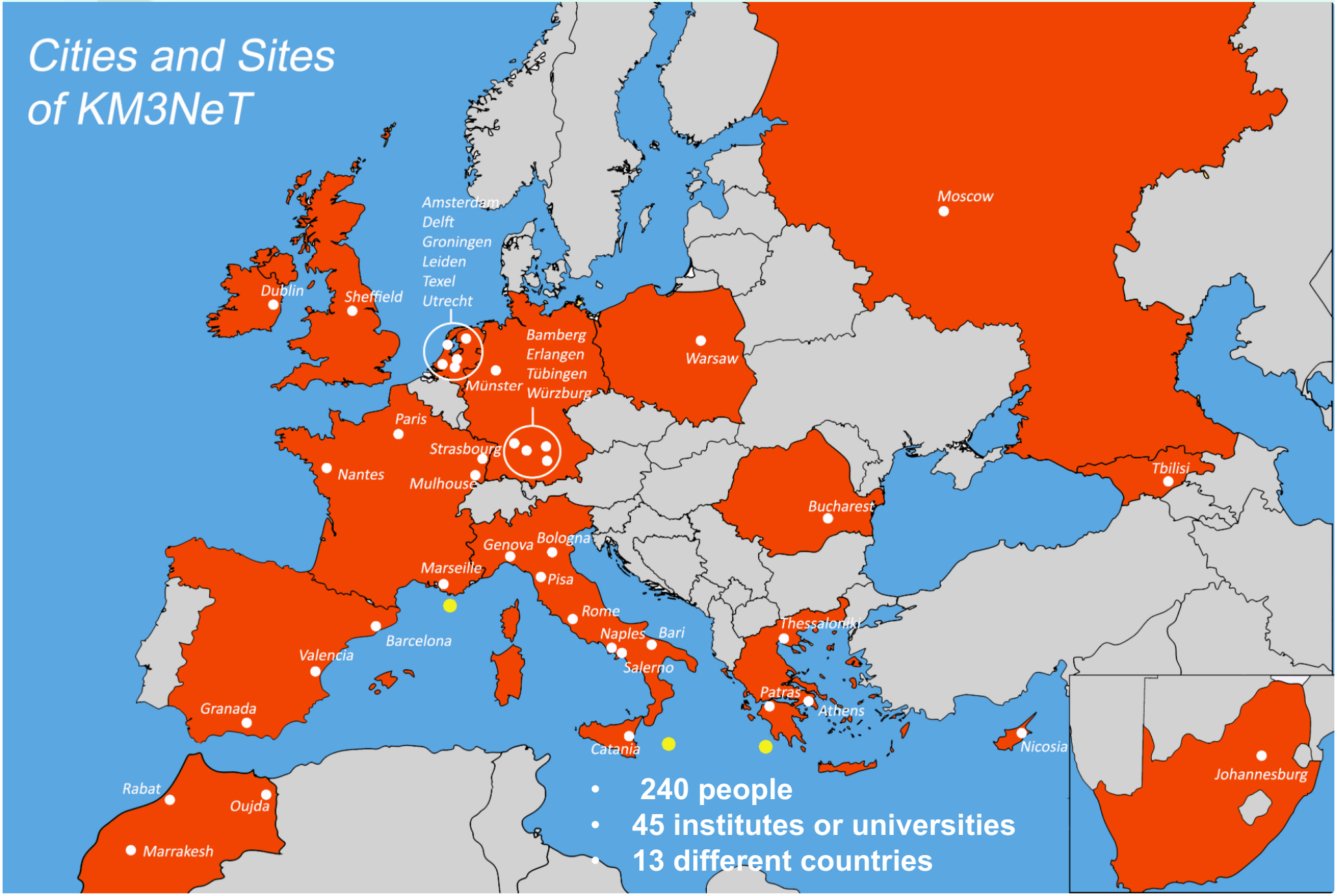




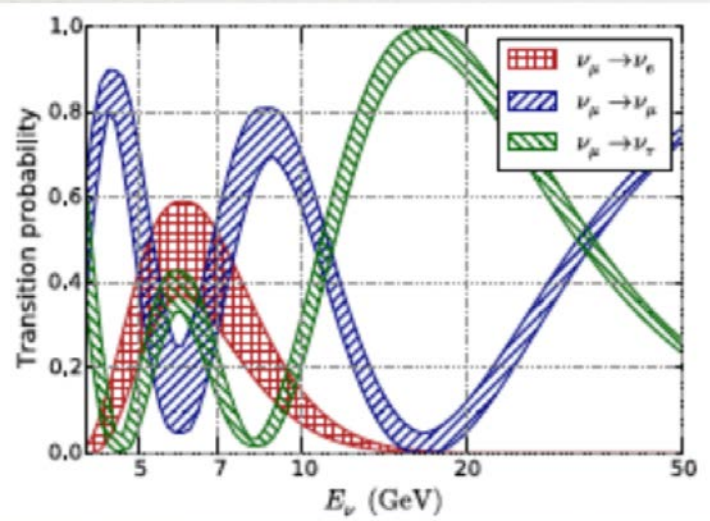
Basic active element:
Digital Optical Module
31 x 3” PMTs

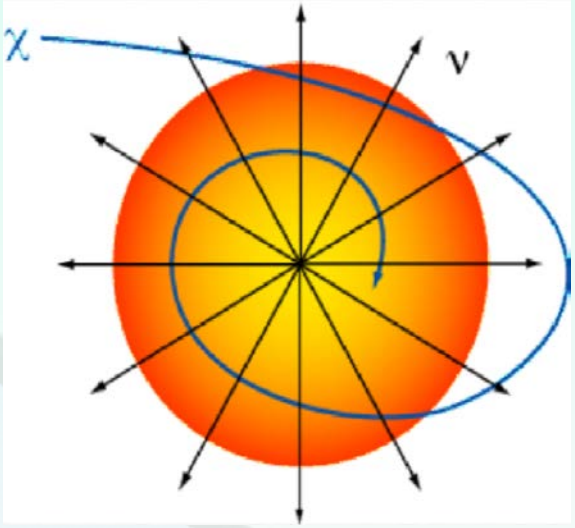
18 OMs/line

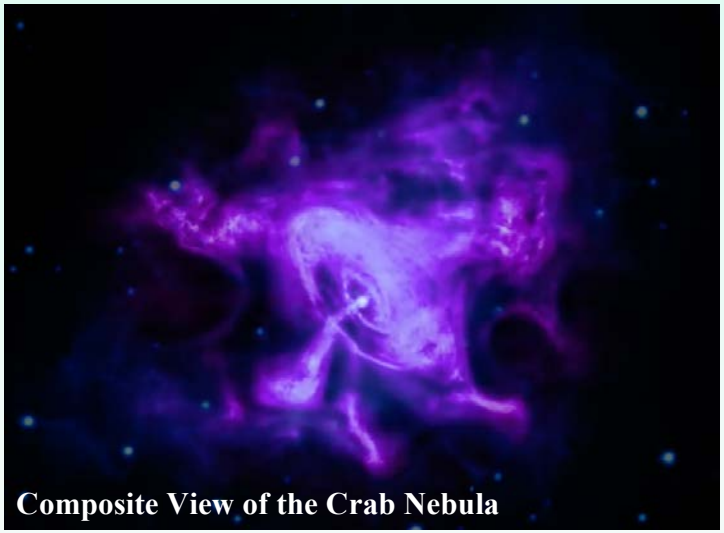
KM3NeT - Collaboration



KM3NeT Neutrino Telescope science scopes



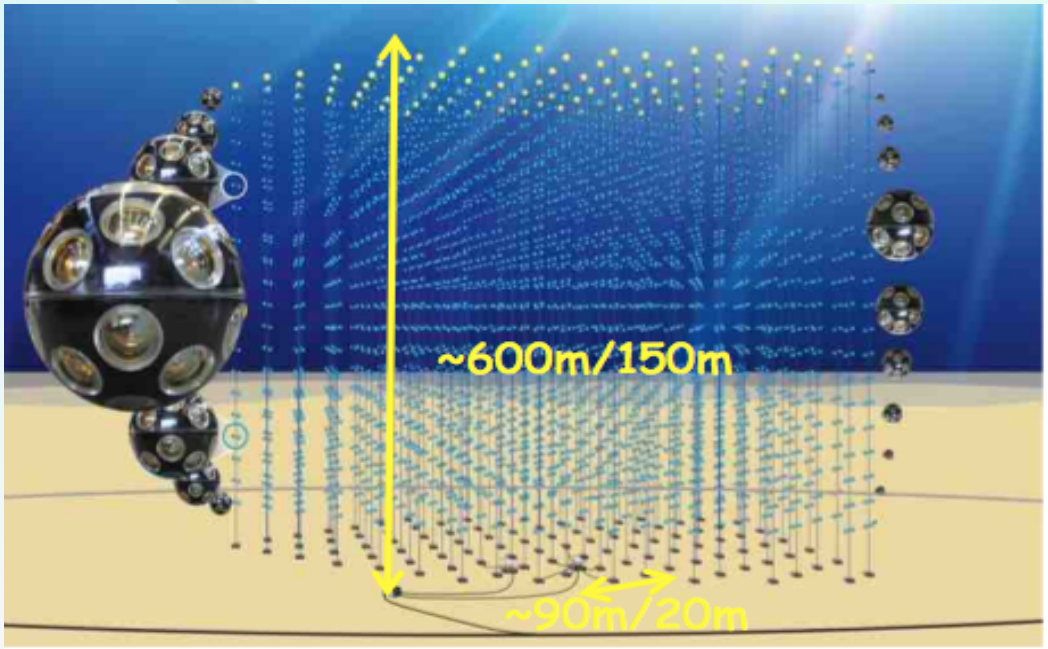


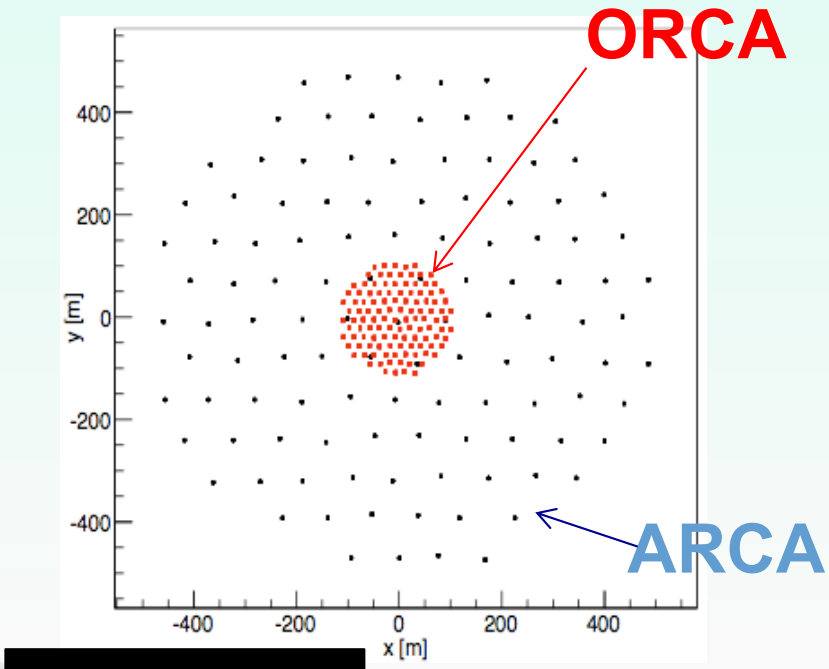


Low Energy	Medium Energy	High Energy
MeV < E_ν < 100 GeV	M eV < E_ν < 100 GeV	E_ν > 1 TeV
- Neutrino Oscillations - Neut. Mass Hierarchy - Sterile neutrinos - Neut. From Supernovae	- Dark Matter search - Monopoles - Nuclearites	- Neutrinos from extra-terrestrial sources - Origin and production mechanism of HE CR
KM3NeT-ORCA	ANTARES	KM3NeT-ARCA

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

KM3NeT Building Blocks





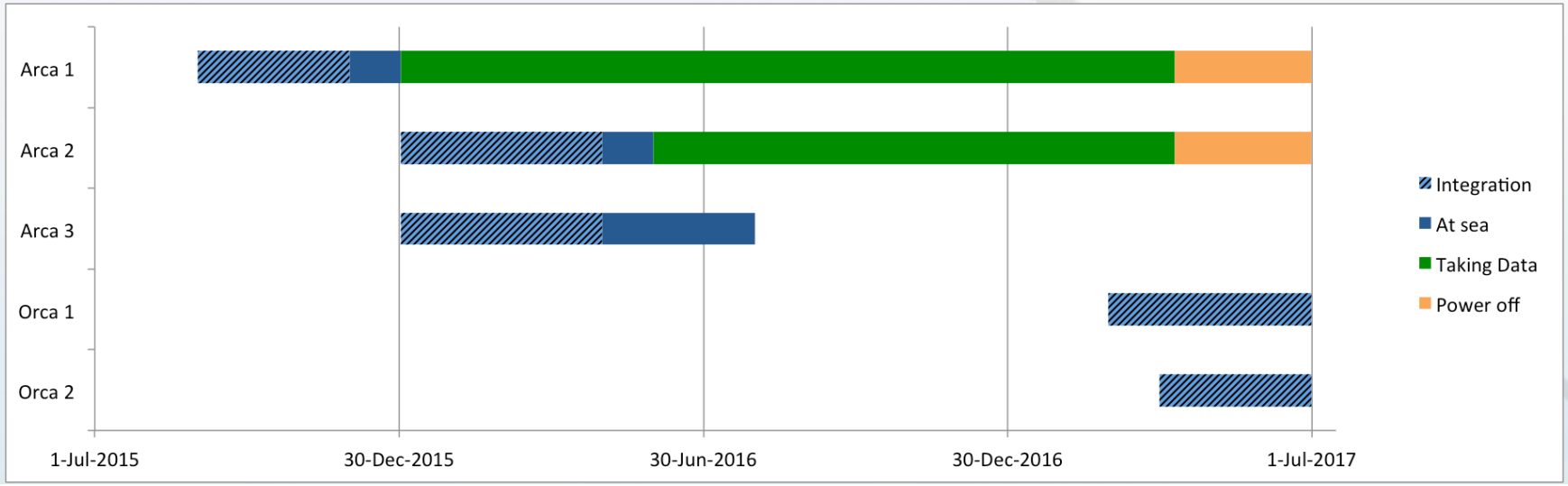
	ARCA	ORCA
Location	Italy – Capo Passero	France - Toulon
Detector Lines distance	90m	20m
DOM spacing	36m	9m
Instrumented mass	500Mton	5,7 Mton

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**

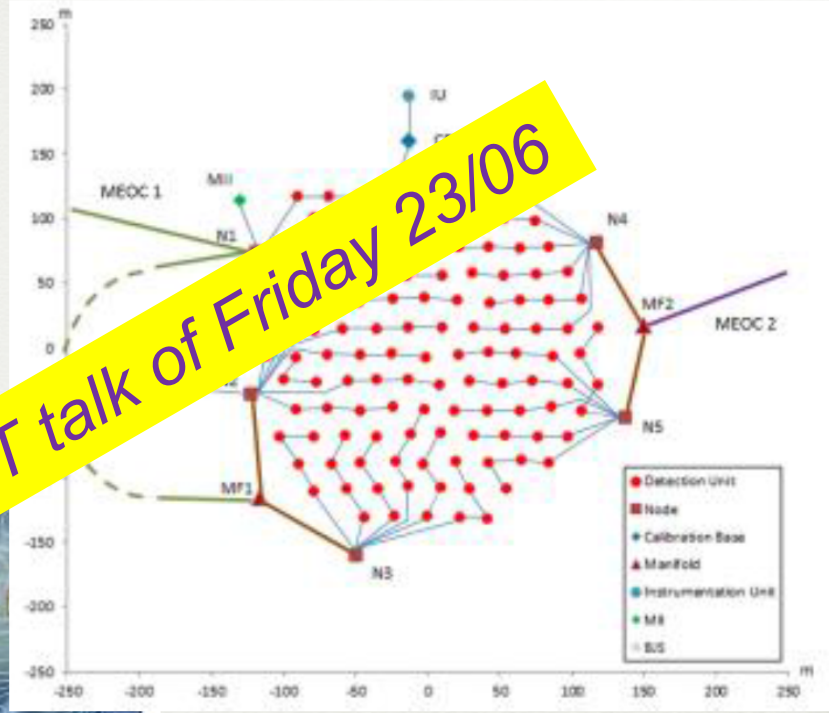


The future of Neutrino Astronomy in the Mediterranean Sea

KM3NeT ORCA

ORCA detector:

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



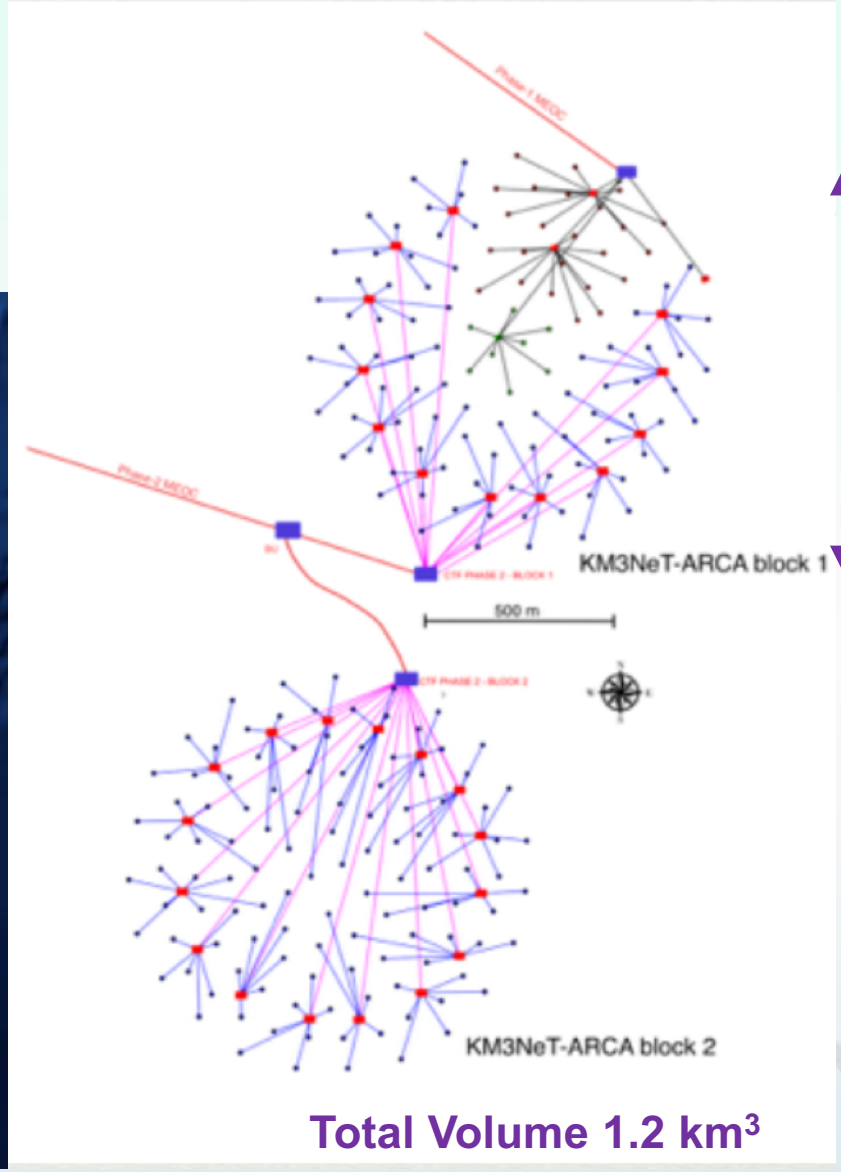
See Simon BOURRET talk of Friday 23/06

- ➡ 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

Total Volume 1.2 km^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.