Latest results of the Antares detector and perspectives for KM3NeT/ARCA

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on behalf of the ANTARES and KM3NeT collaborations.

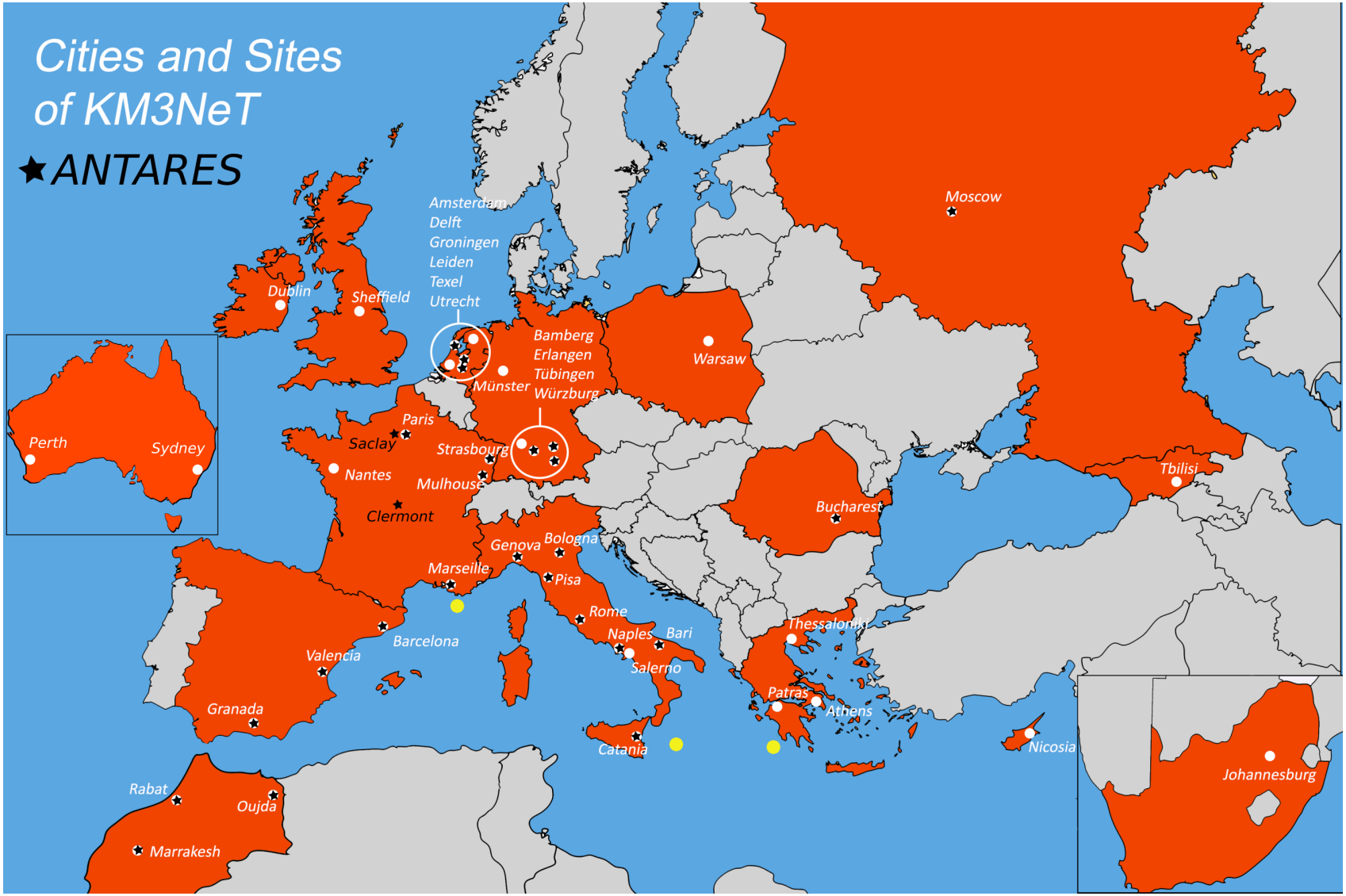
[1]AstroParticule et Cosmologie, Paris

ICHEP, Seoul - July 6, 2018

Outline

ANTARES and KM3NeT Collaborations

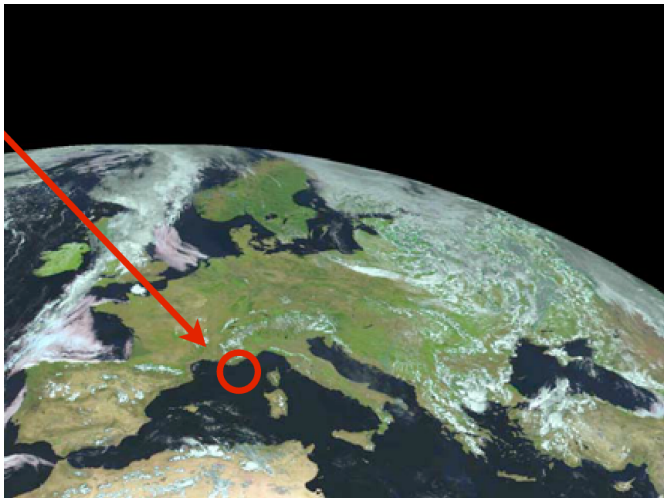
16 countries - more than 40 institutes

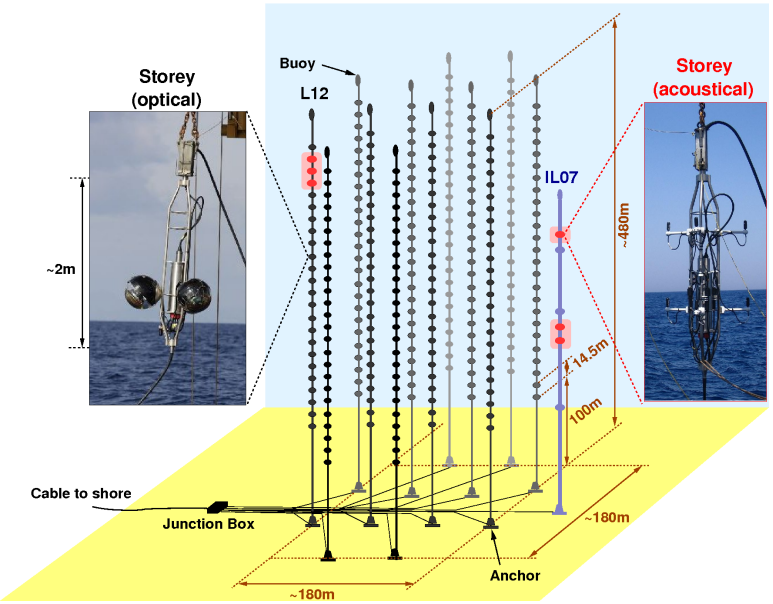


ANTARES Telescope

- neutrino astronomy
- 10 GeV up to 1 TeV
- 40 km off shore
- depth of 2475 m
- 12 lines
- 25 storeys/line
- 3 PMTs/storey
- 885 light detectors

NIMA.656(2011)38
Site studies:
Astropart.Phys.13(2000)
Astropart.Phys.19(2003)
Astropart.Phys.23(2005)

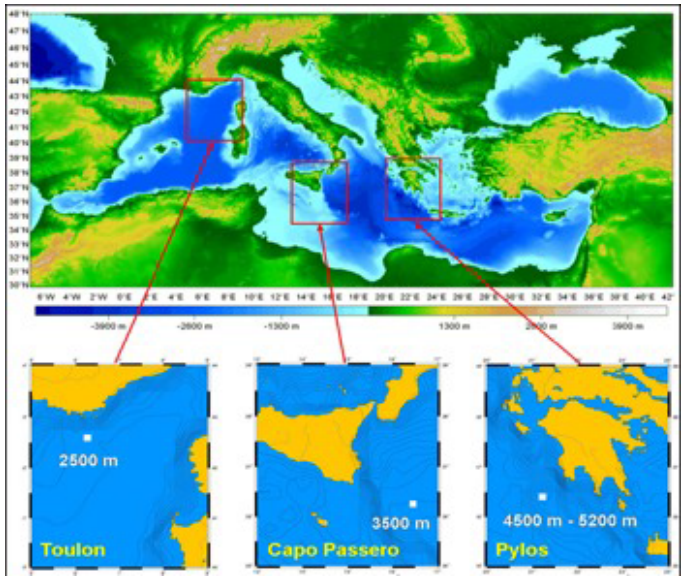


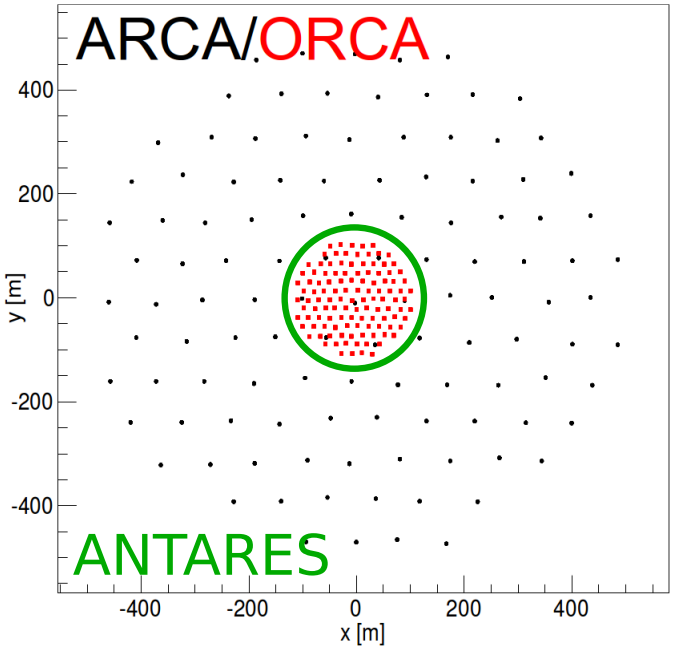


KM3NeT Telescope

- ORCA - Toulon
  - neutrino physics
  - 1 building Block
  - DOM spacing: 9 m
  - 6 Mton - 3 to 50 GeV
  - see M.Circella's presentation
- ARCA - Capo Passero
  - neutrino astronomy
  - 2 building Blocks
  - DOM spacing: 36 m
  - 1 Gton - $>$ 1 TeV
- Pylos site under study
- building block: 115 lines $\times$ 18 DOMs $\times$ 31 PMTs

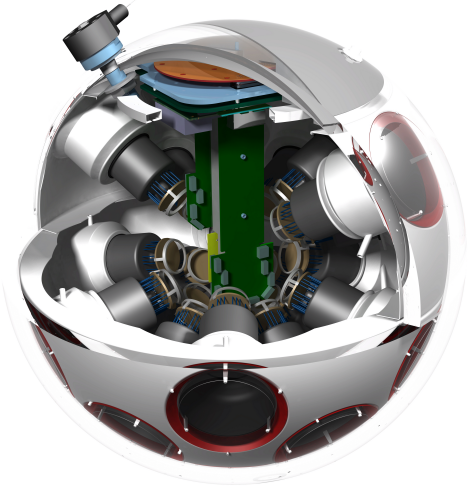
J.Phys.G 43 (8), 084001, 2016

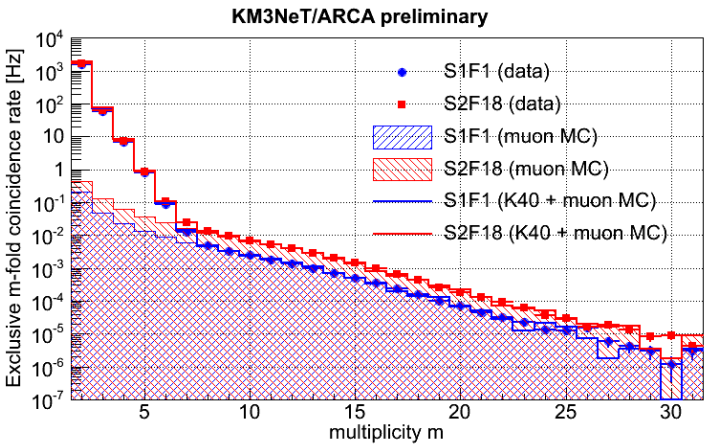


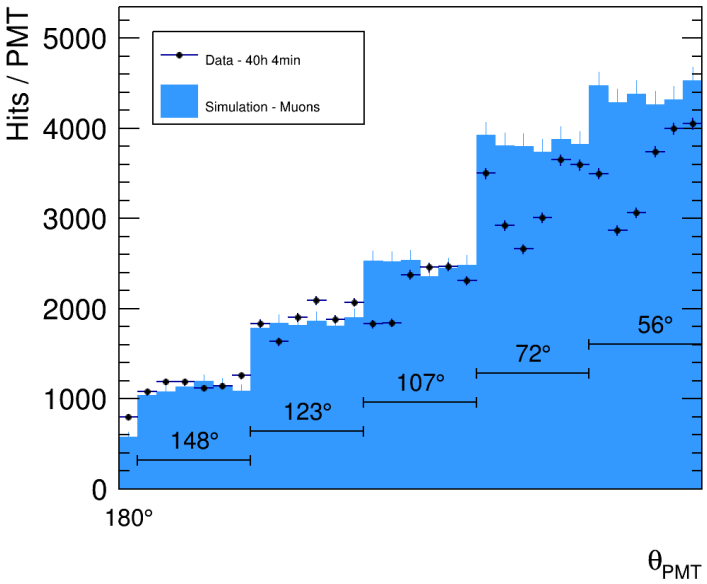


ANTARES and KM3NeT detectors

- 17-inch glass sphere
- ANTARES: 3 10-inch PMTs
- KM3NeT: 31 3-inch PMTs
- larger total photocathode
- pixelization

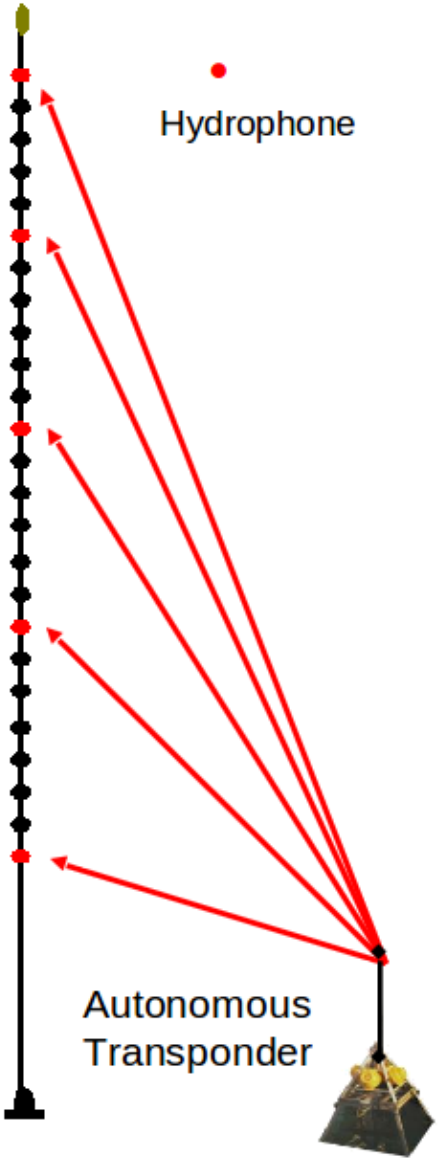


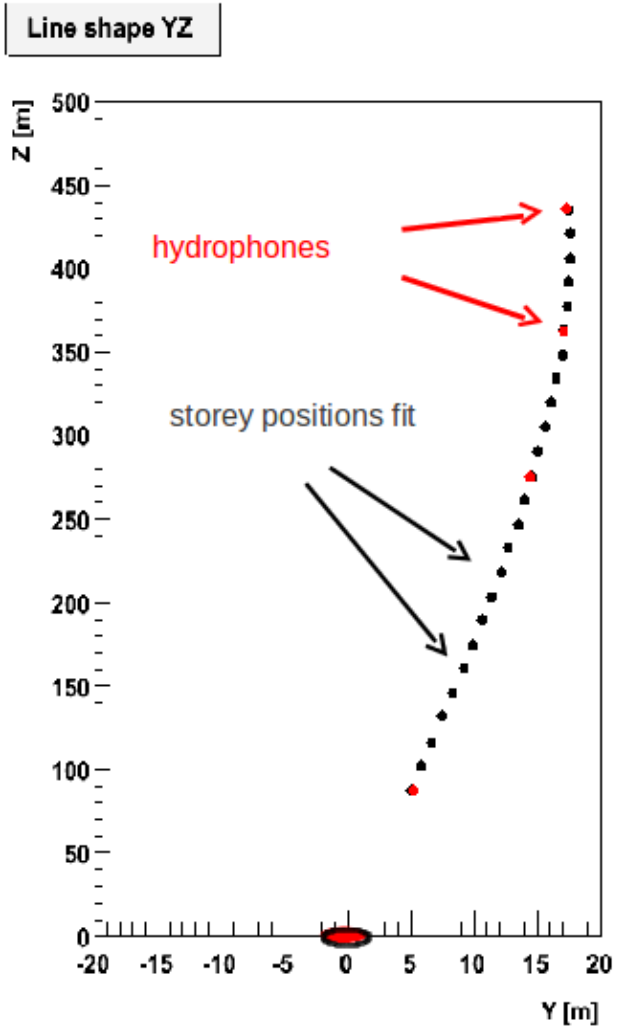




Eur.Phys.J. C (2014) 74:3056
Eur.Phys.J. C (2016) 76:54

Timing and positioning





Positioning

- acoustic
- resolution $< 10\,\mathrm{cm}$

Timing

- LED/laser beacons
- PMT TTS negligible
- resolution of electronics $\sim 0.5\,\mathrm{ns}$

JINST 7 (2012) T08002

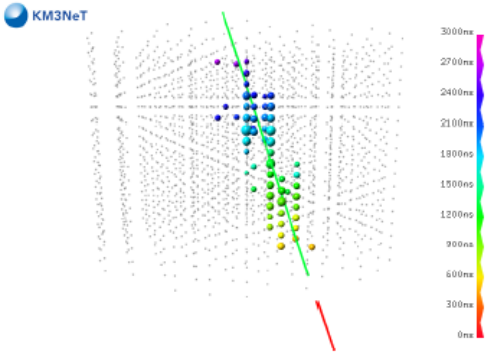
Angular resolution - ANTARES

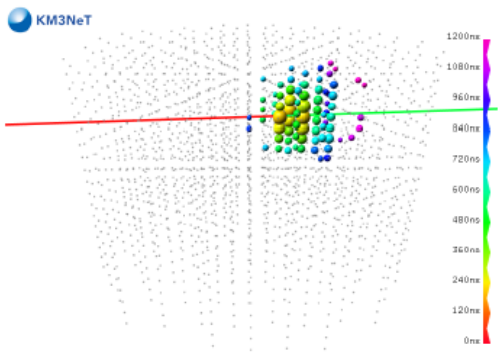
Tracks

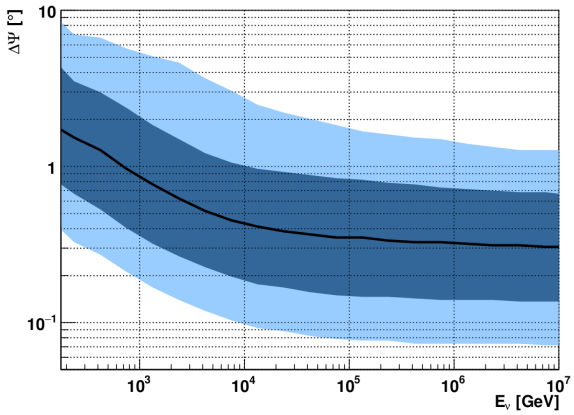
- upgoing track events
- CC - ν_μ
- $< 0.4^\circ$ above $10\,\mathrm{TeV}$

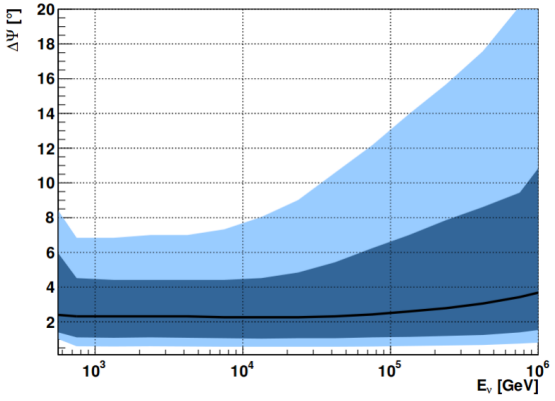
Cascades

- upgoing cascade events
- CC - ν_e, ν_τ, NC
- $< 3^\circ$









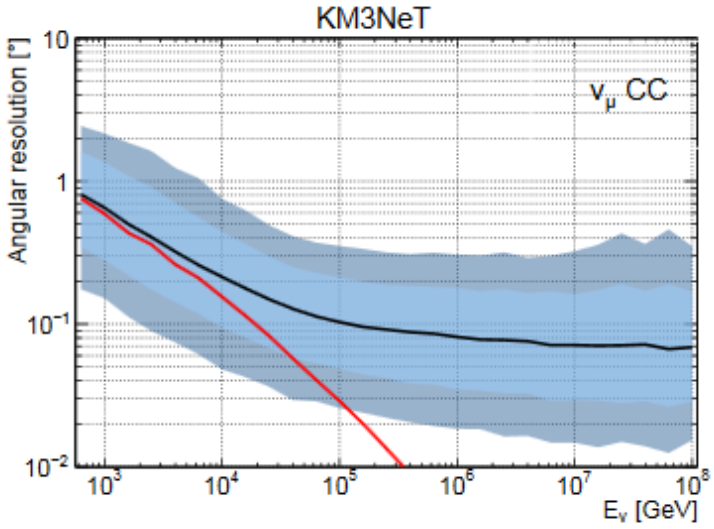
Angular resolution - KM3NeT

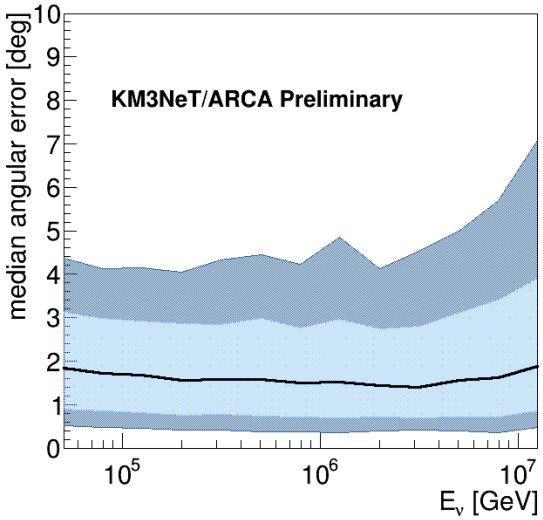
Tracks

- upgoing track events
- CC - ν_μ
- $< 0.2^\circ$ above $10\,\mathrm{TeV}$

Cascades

- upgoing cascade events
- CC - ν_e, ν_τ, NC
- $< 2^\circ$





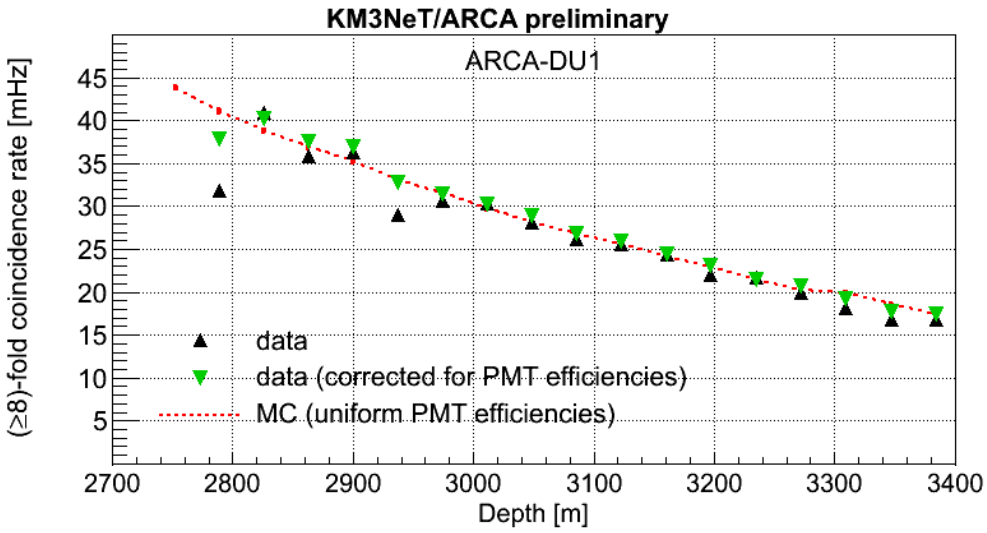
KM3NeT status

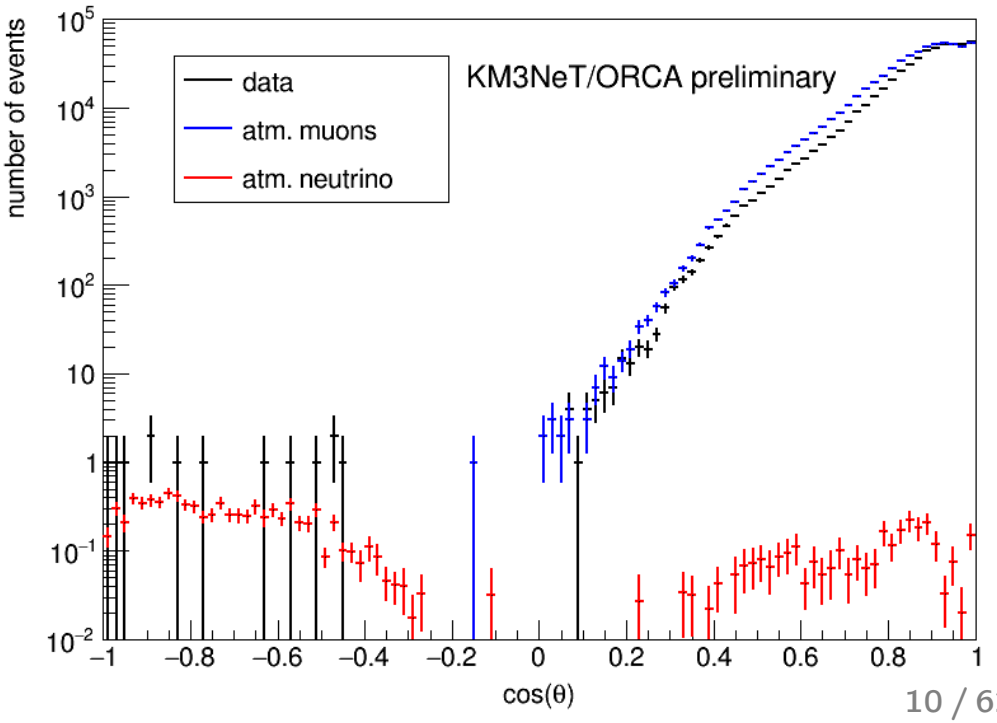
ARCA

- first line in Dec. 2015
- second in May 2016
- currently: seabed network upgrade

ORCA

- first line in Sept. 2017
- currently: main cable replacement





Analysis method

HE neutrinos

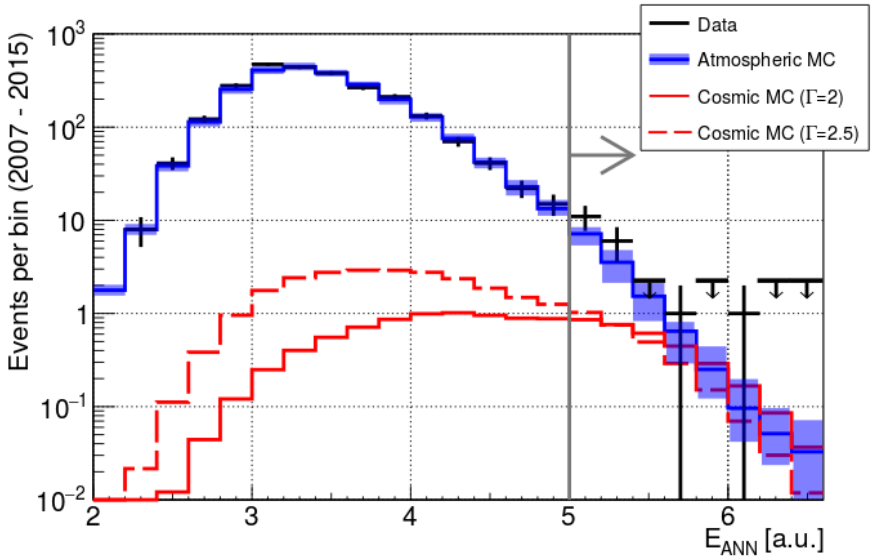
- excess of neutrinos at high energy
  $\rightarrow$ energy estimation
- excess of neutrinos in a direction
  $\rightarrow$ arrival direction
- correlation with other detections
  $\rightarrow$ time and arrival direction

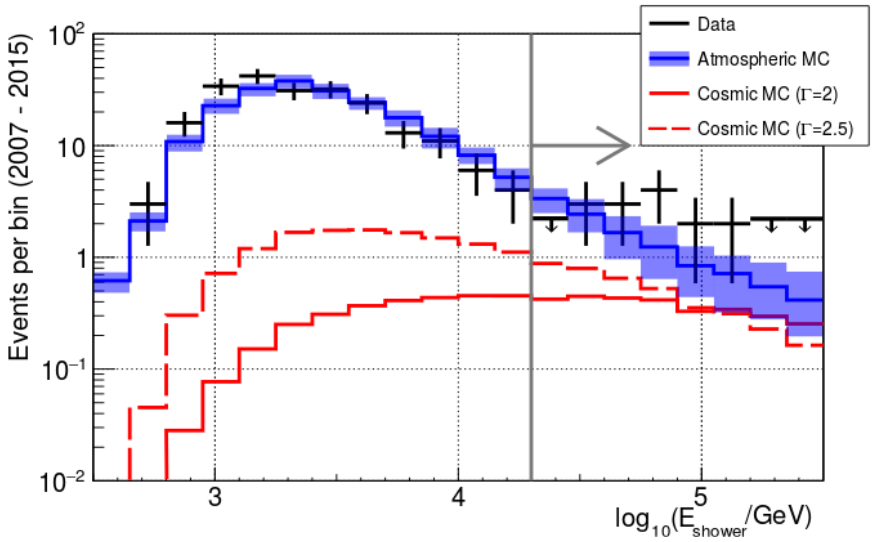
Outline

Diffuse astrophysical flux - ANTARES

2007-2015 results

- ν_μ from unresolved sources
- flux from UHECRs and γ-ray
- $\rho = \frac{dE}{dx}$ as energy estimator
- 2451 days
- tracks:
  $n_{\text{obs}} = 19,\ n_{\text{bkg}} = 13.5,$
  $n_{\text{sig}} = 3 - 3.5$
- cascades:
  $n_{\text{obs}} = 14,\ n_{\text{bkg}} = 10.5,$
  $n_{\text{sig}} = 4$

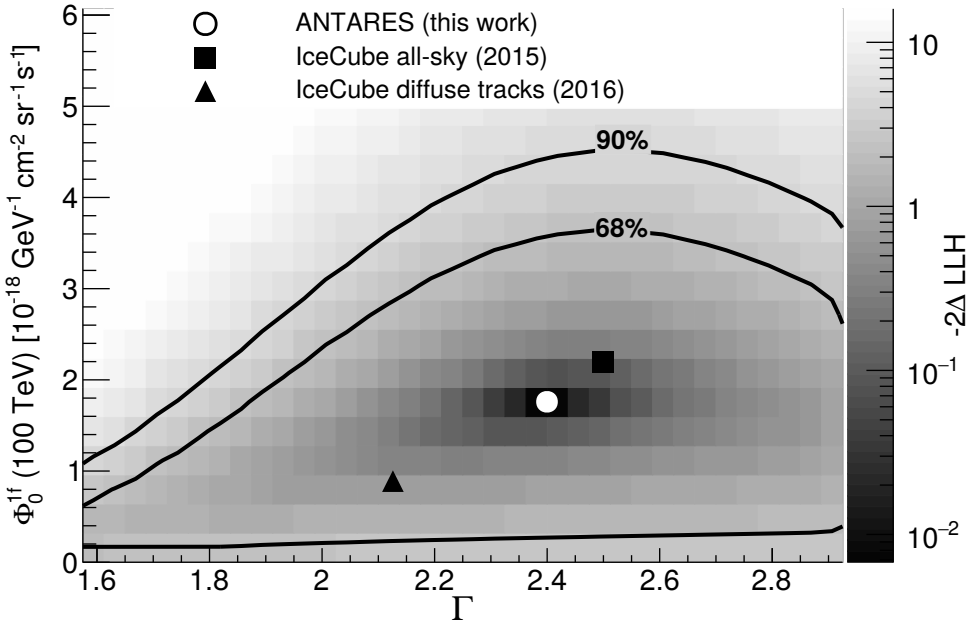




Diffuse astrophysical flux - ANTARES

2007-2015 results

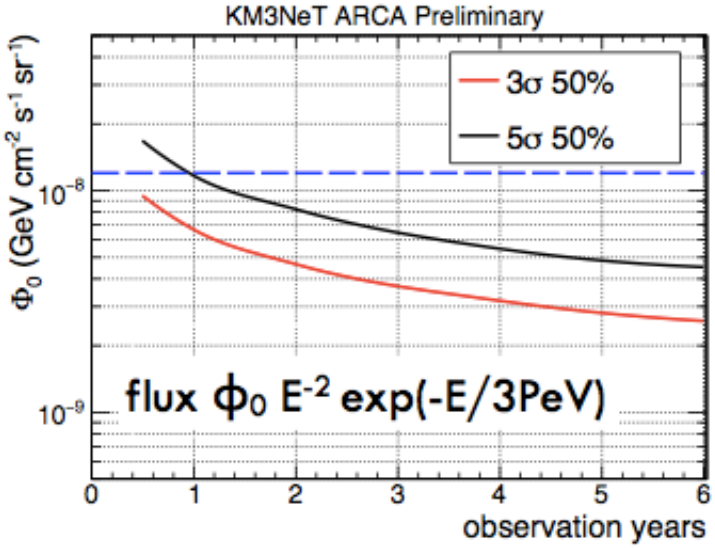
- max likelihood as a function of the spectral index
- 1.6σ post-trial excess
- no signal hypothesis excluded at 85% C.L.
- compatible with IceCube diffuse flux

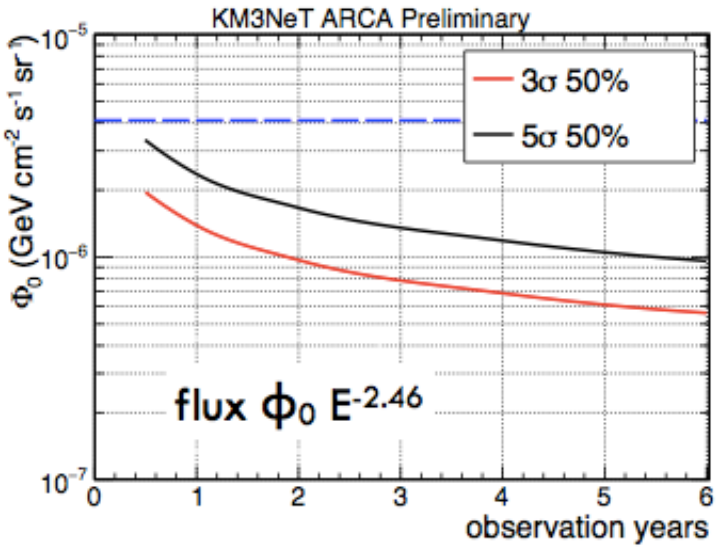


ApJL 853, L7 (2018)

KM3NeT expectations

- discovery fluxes
- 1 year for E^{-2} spectrum with cut-off
- less than 1 year for $E^{-2.46}$
- blue dashed line: IceCube measured flux (2014)





Phys. Rev. D 89, 062007

Outline

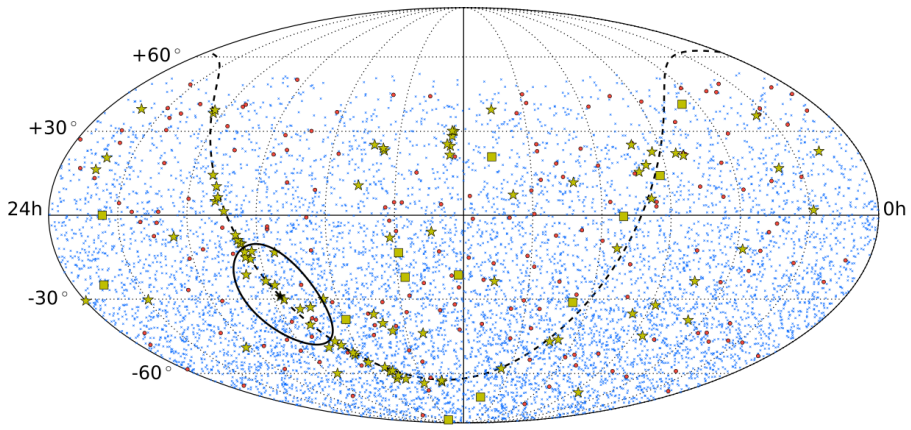
Full sky search - ANTARES

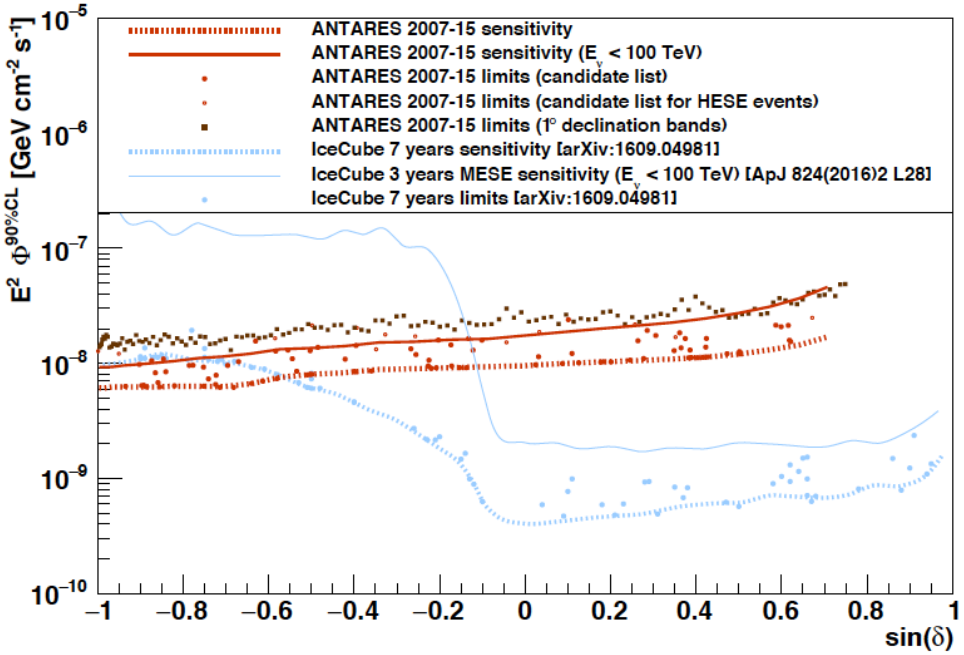
2007-2015 ingredients

- 7629 tracks (blue)
- 180 cascades (red)
- maximum likelihood
- 103 candidate sources
  - ■ pulsars, SNRs, $\cdots$
  - ★ IceCube HESE tracks

2007-2015 results

- best sensitivity for a large part of the southern sky
- excellent sensitivity for $E_\nu < 100\,\mathrm{TeV}$
- no significant excess

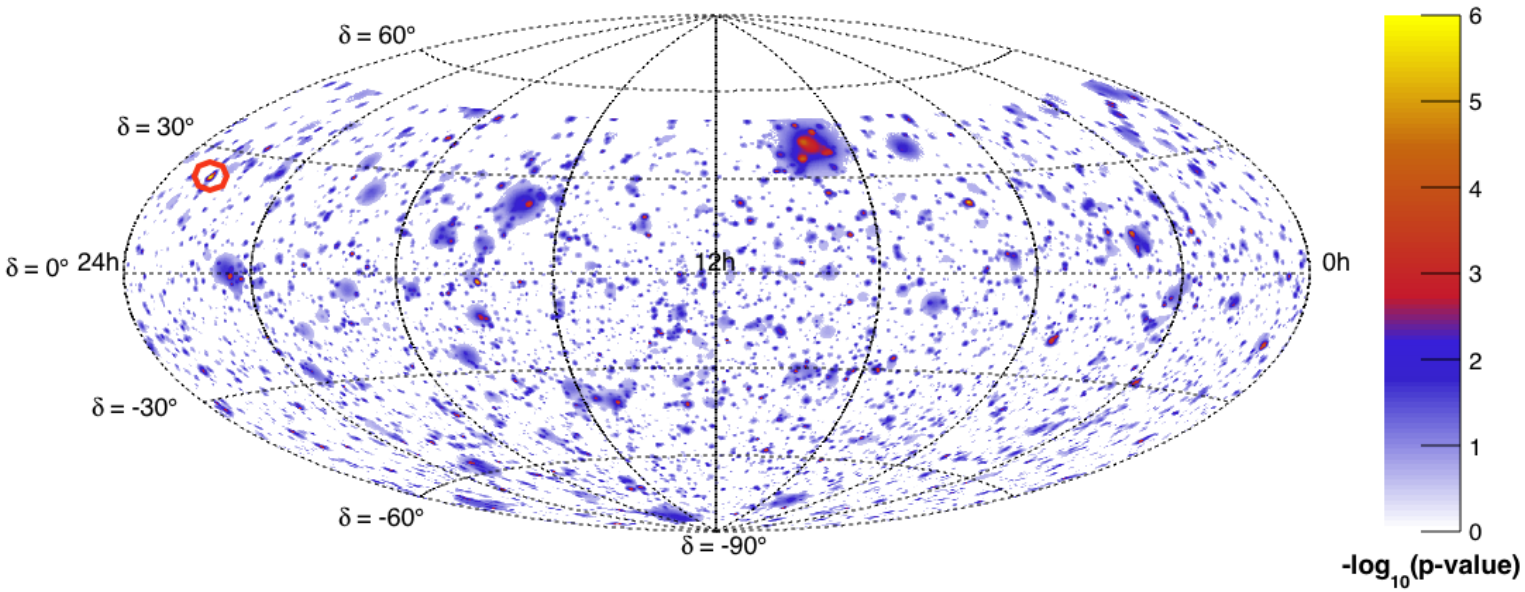




Full sky search - ANTARES

2007-2015 results

- most significant: 1.9σ post-trial

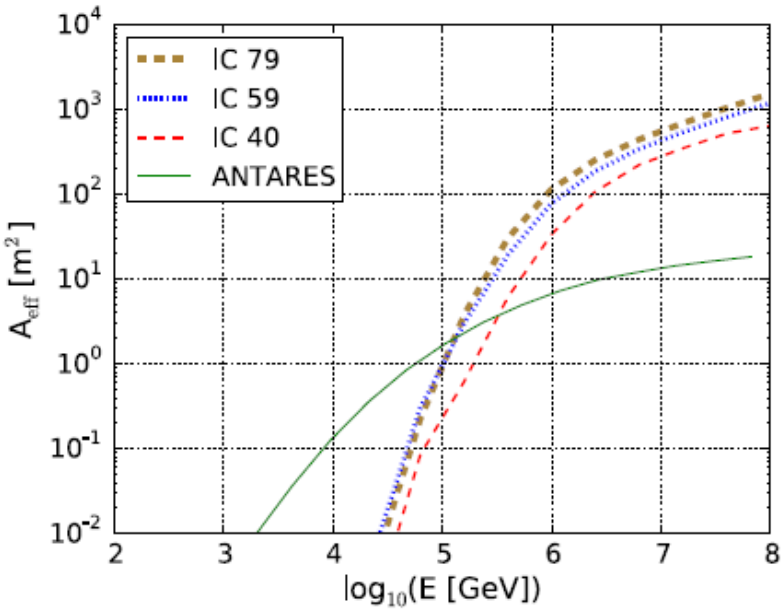


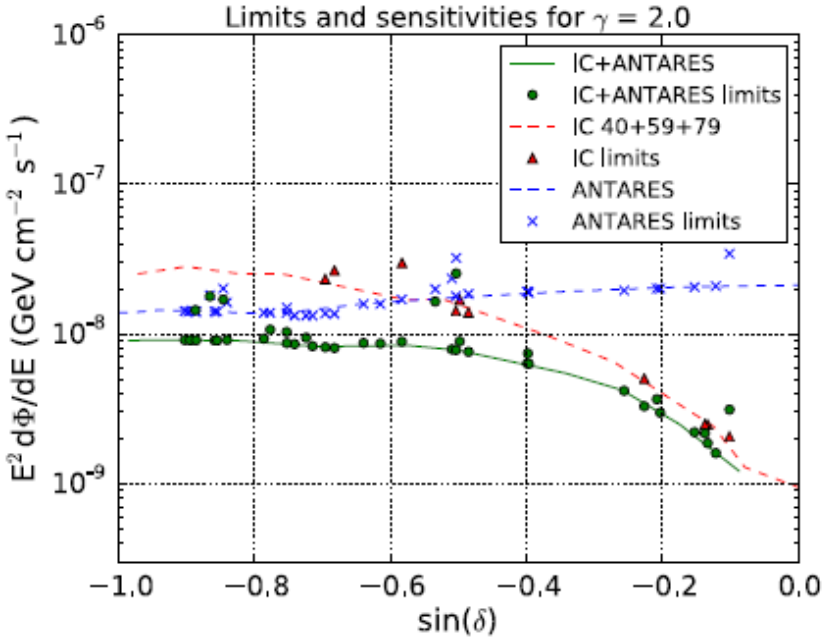
Phys. Rev. D 96, 082001

Full sky search - combined ANTARES-IceCube

2007-2015 results

- IC79 + IC59 + IC40 + 6 years of ANTARES
- effective area for $\delta = 30\,^{\circ}$

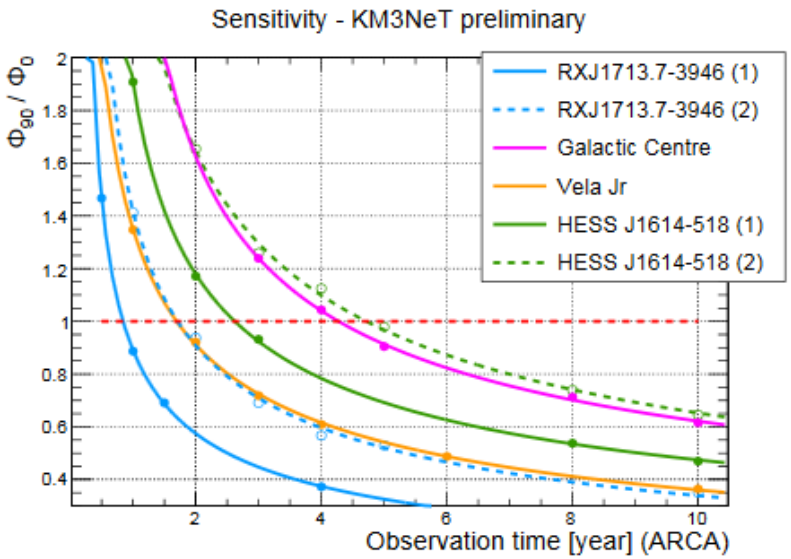


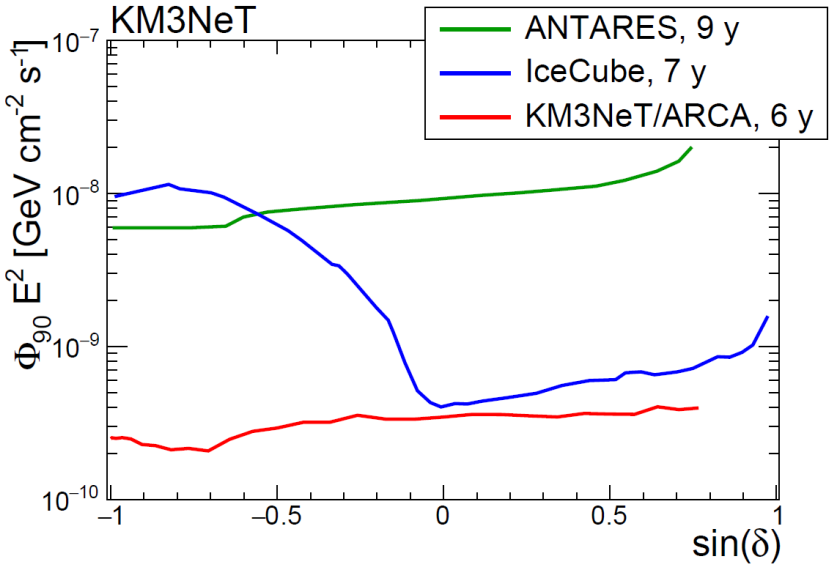


Astrophys.J. 823 (2016) no.1, 65

Full sky search - KM3NeT expectations

- for hadronic scenarii: galactic source detection in a few years
- best sensitivity for southern sky





Galactic plane - ANTARES

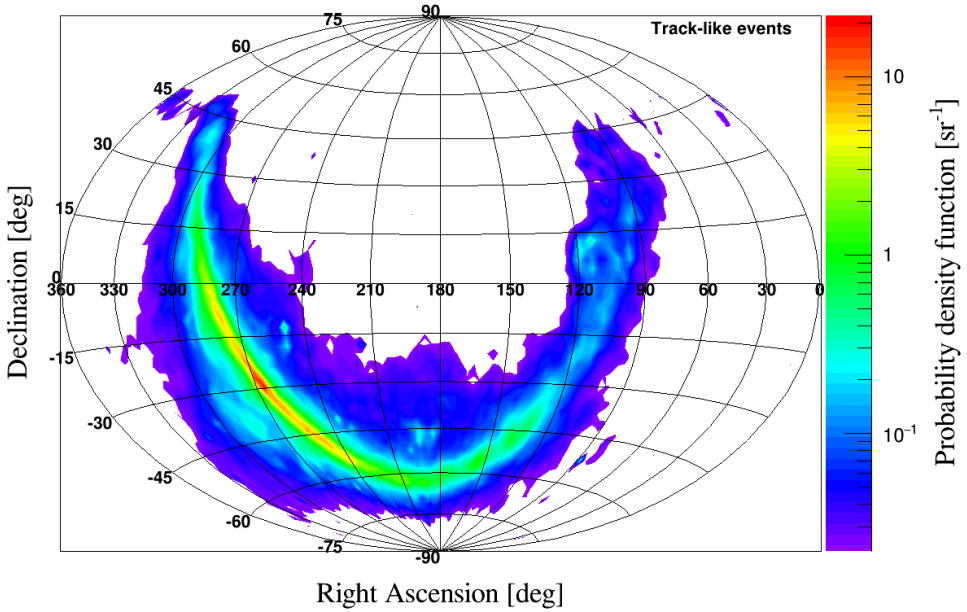
2007-2015 ingredients

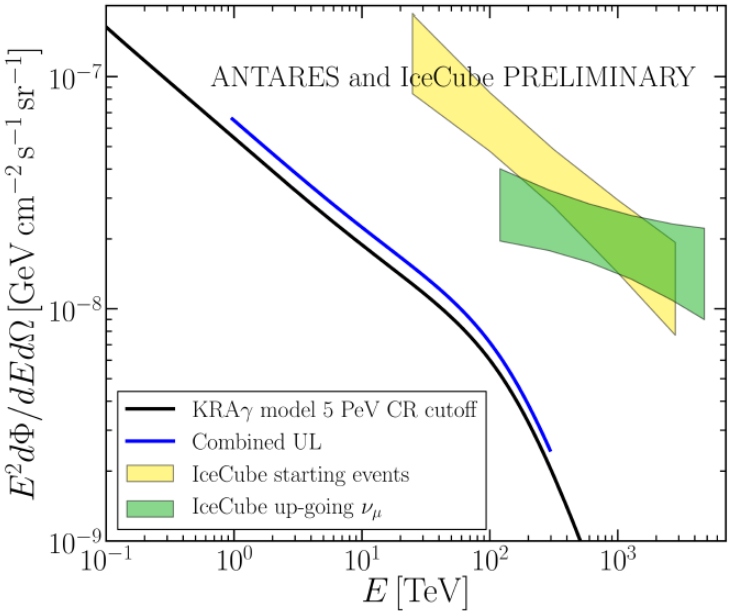
- tracks and cascades
- likelihood approach
- KRA$_\gamma$ model

2007-2015 results

- limit at 1.2 of KRA$_\gamma$
- 18% max of IC HESE events from GP
- excludes GP diffuse emission as main source of IC spectral anomaly

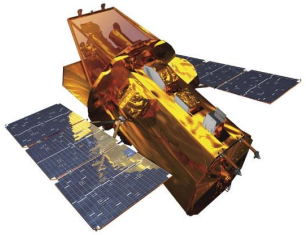
Phys.Rev.D96 (2017) 062001

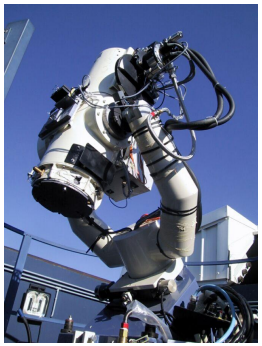




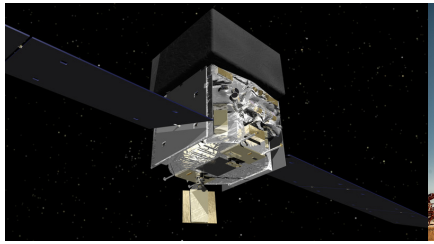
Outline

Multi-messenger - ANTARES





- space/time correlation
- alerts and follow-up



- radio: MWA, Parkes
- visible: TAROT, ZADKO, MASTER, SVOM-GWAC
- X-ray: Swift
- γ-ray: Integral
- GeV-ray: Fermi-LAT
- TeV-ray: HESS, HAWC
- GW: Ligo, VIRGO
- neutrino: IceCube

Alerts and follow-up - ANTARES

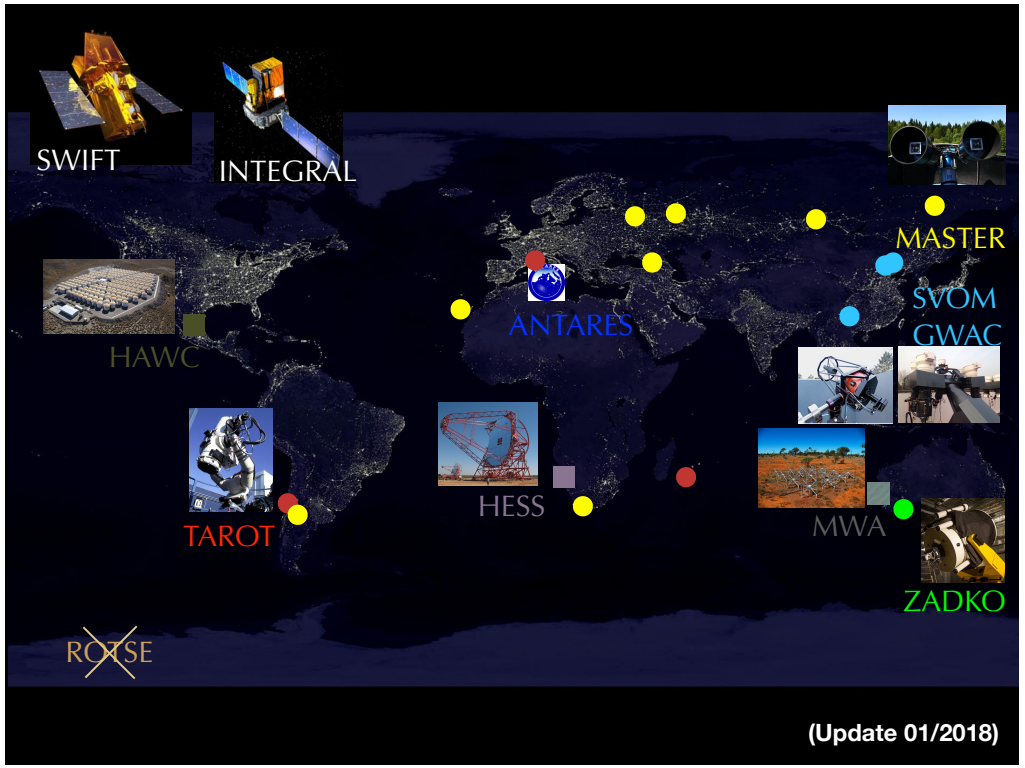
Astropart.Phys.35(2012)530

Procedure

- fast reconstruction
- real time alerts

Triggers

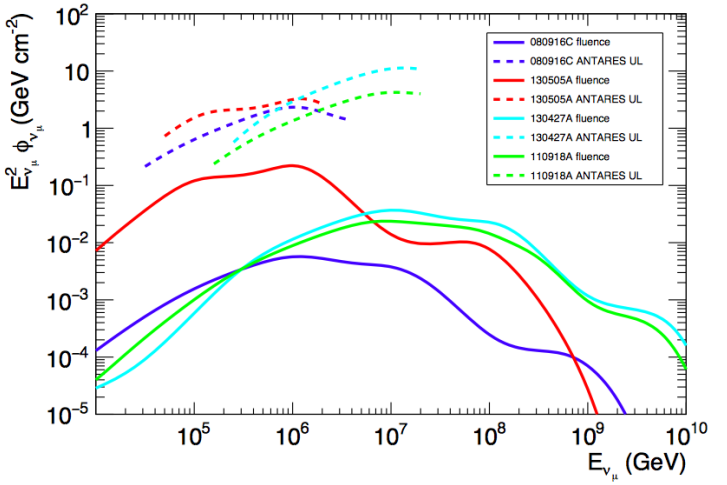
- 2 events (in $3^\circ \times 3^\circ$ and $\Delta t < 15\,\mathrm{min}$)
  1 doublet (3σ evid.), 1 triplet (5σ disc.)
- 1 HE event ($E > 5 - 10\,\mathrm{TeV}$)
- 1 event from local galaxy ($d < 20\,\mathrm{Mpc}$ and $\Delta\Omega < 0.3^\circ$)

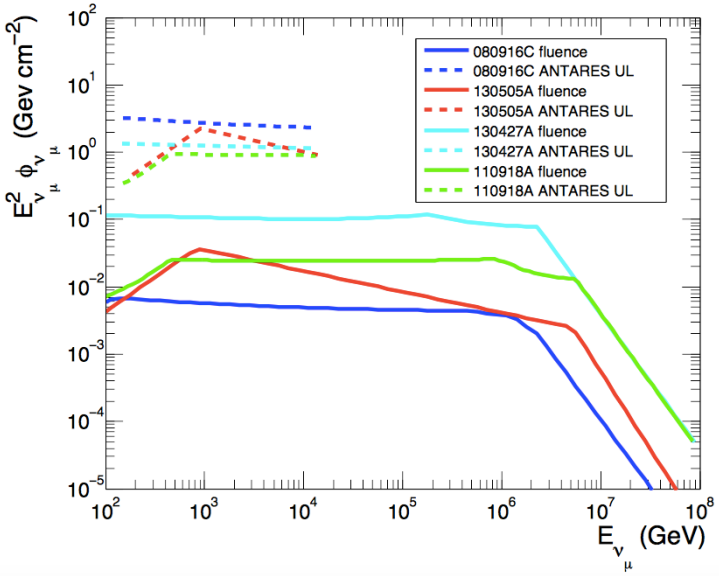


GRB - ANTARES

- neutrino events in coincidence with observed GRB
- data 200 s after GRB trigger
- GRB 080916C, 110918A, 130427A and 130505A
- internal shock model (up)
- photospheric model (down)

MNRAS 469, 906-915 (2017)



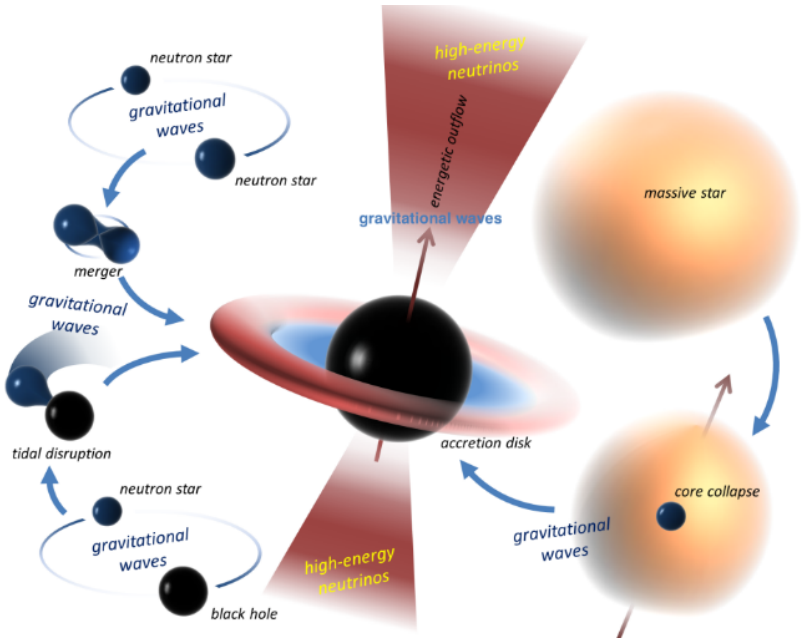


Gravitational waves - ANTARES

- follow-up of GW150914, GW151226, LVT151012, GW170104 and GW170817 (GRB)
- ANTARES, IceCube, LigoSC, VIRGO and Auger

- binary black hole mergers neutrino expected depending on the environments
- neutron star mergers

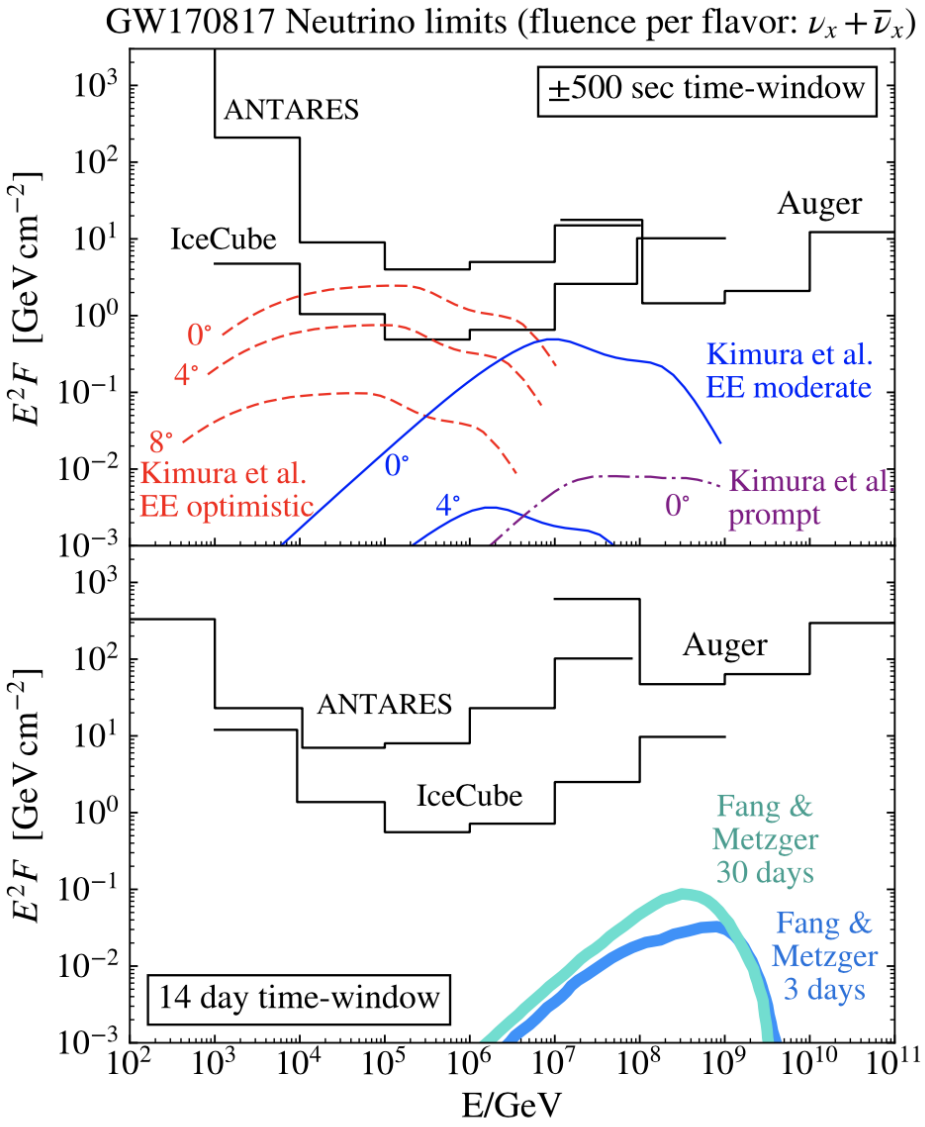
Phys.Rev. D93 (2016), 122010
Phys.Rev. D96 (2017), 022005



Gravitational waves - ANTARES

- GW170817 (GRB)
- neutron star mergers
- $\pm 500\,\mathrm{s}$ time window (prompt emission)
- $14\,\mathrm{d}$ time window (magnetar emission)
- no counterpart

ApJL 850, 2 (2017)



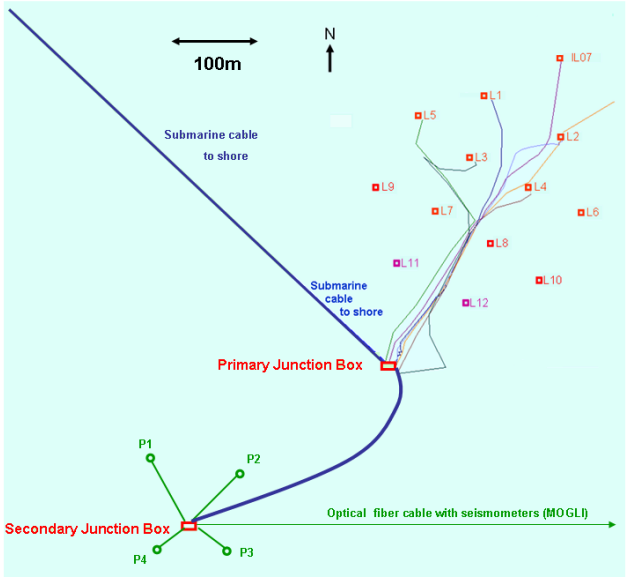
Conclusions and perspectives

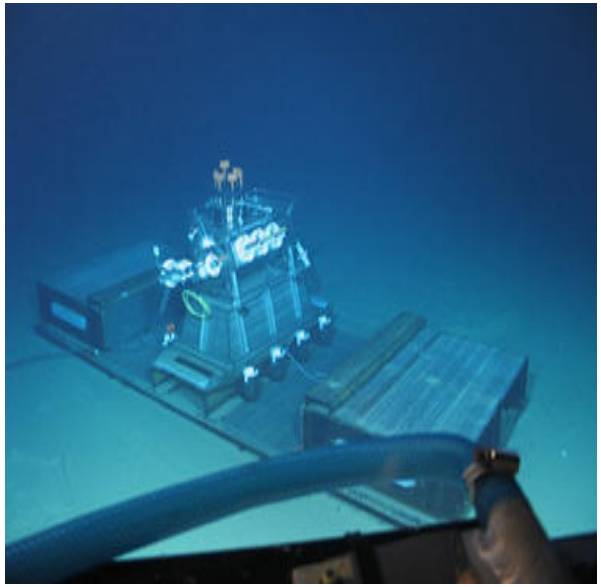
- ANTARES is the current largest neutrino telescope in the northern hemisphere
- Technically, it is a great success
- It has competitive physic results
- There is still a lot to do
- KM3NeT started phase 1
- First lines deployed
- Physics sensitivity will largely be improved

BACK-UP SLIDES

ANTARES Telescope

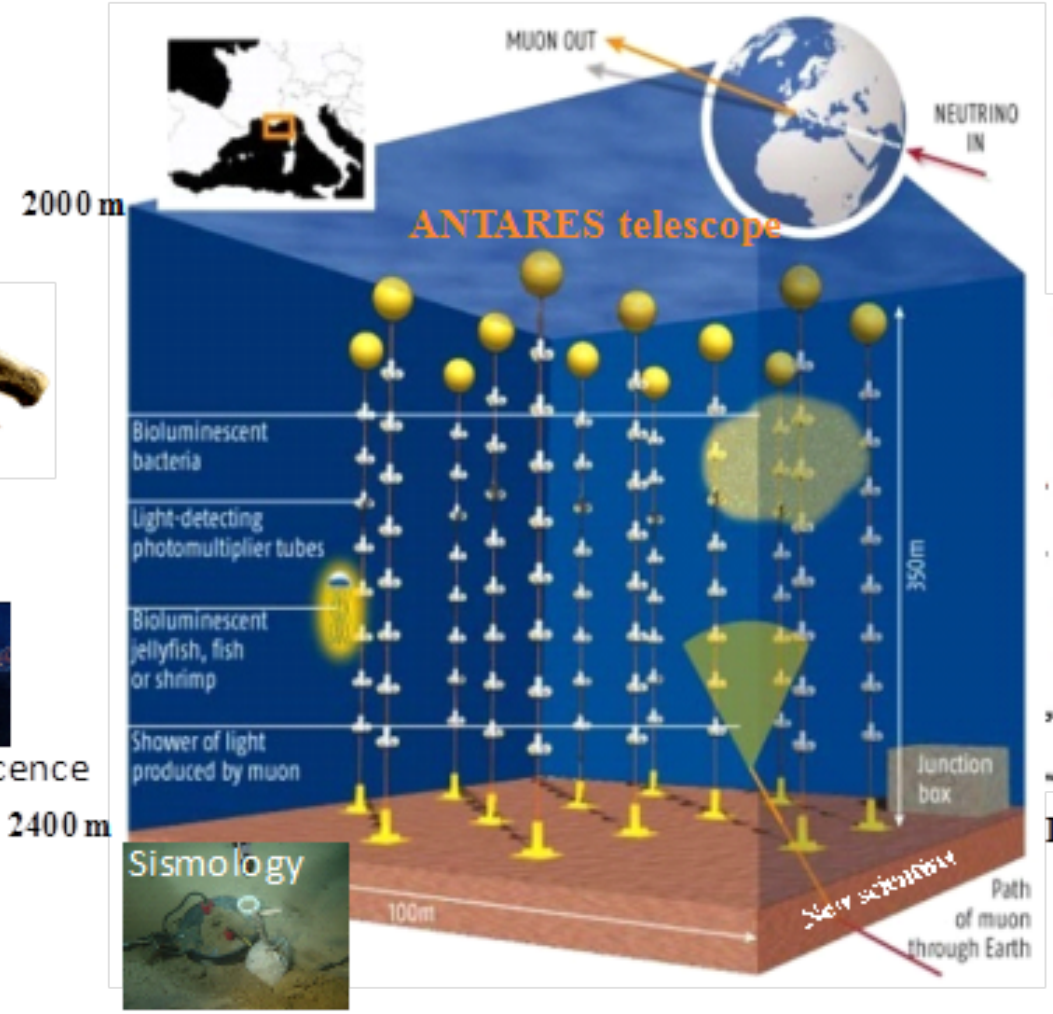
- Junction box: 2001
- 40 km cable: 2002
- line 1, 2: 2006
- line 3, 4, 5: 01/2007
- line 6, 7, 8, 9, 10: 12/2007
- line 11, 12: 05/2008
- Secondary JB: 10/2010
- IL07 → IL13: 2013





Sea and earth sciences

Bioluminescence



Biogeochemistry

Oceanography

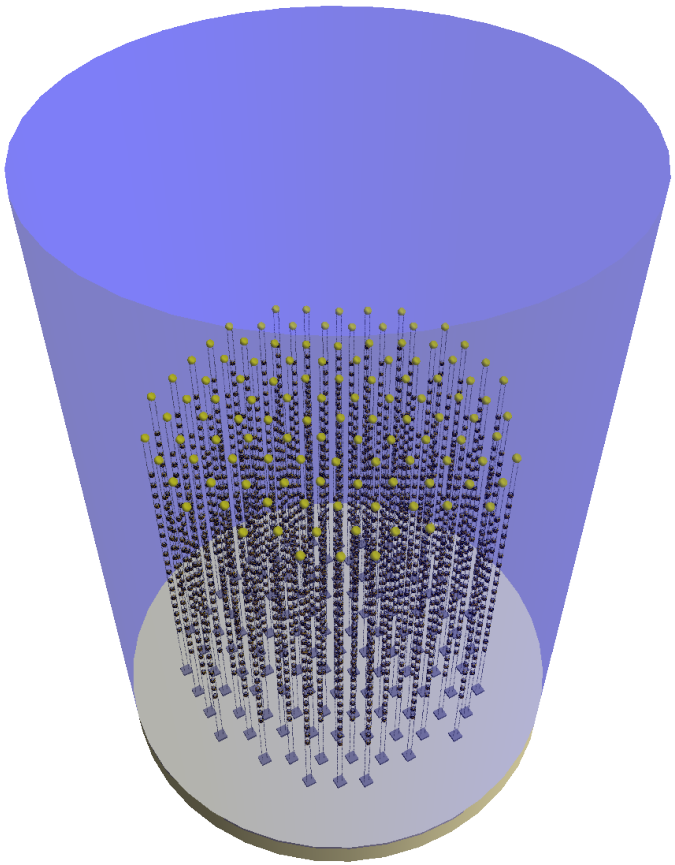
Microbial ecology

Environmental research

C.Tamburini et al., PLoS ONE 8(7): e67523
H.van Haren et al., Deep-Sea Research I 58(2011)875

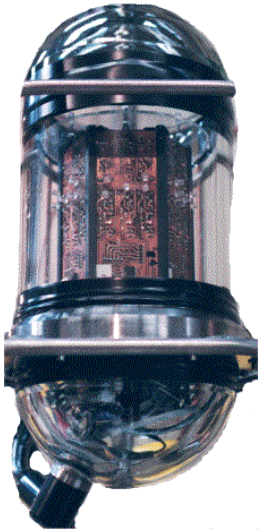
KM3NeT Telescope

- 1 building block
- 115 lines
- 18 digital optical modules (DOM) per line
- 31 PMTs per DOM
- 64k PMTs

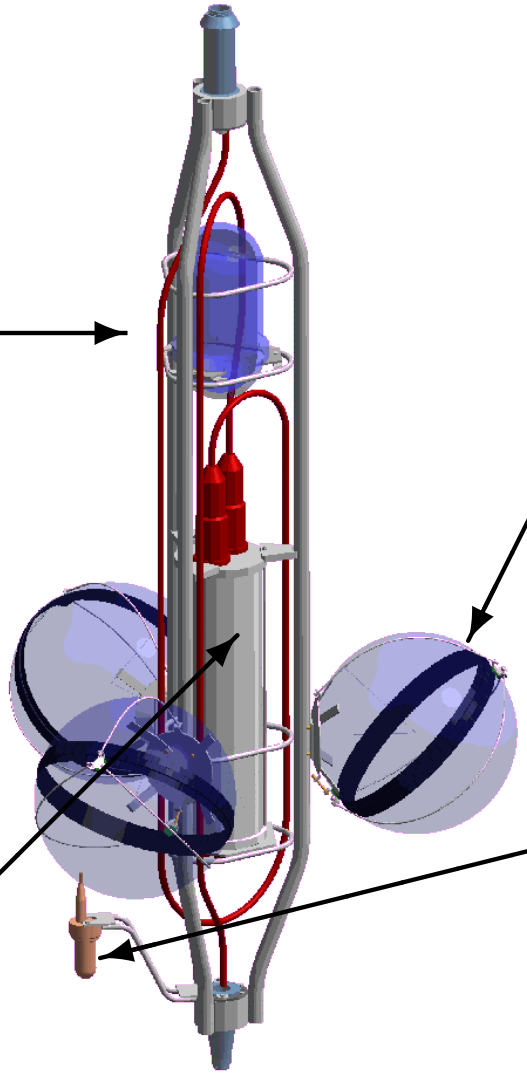


ANTARES storey

Optical Beacon:
blue LEDs
timing calibration
NIMA.578(2007)498

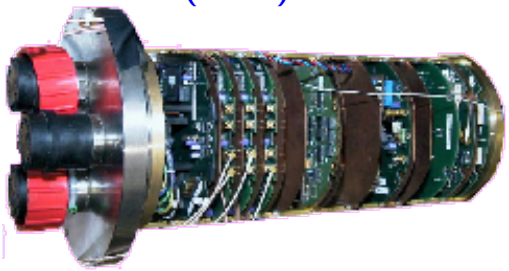


Titanium frame:
support structure



Optical Module (OM):
10"Hamamatsu PMT
17"glass sphere
NIM A484 (2002) 369
NIM A555 (2005) 132

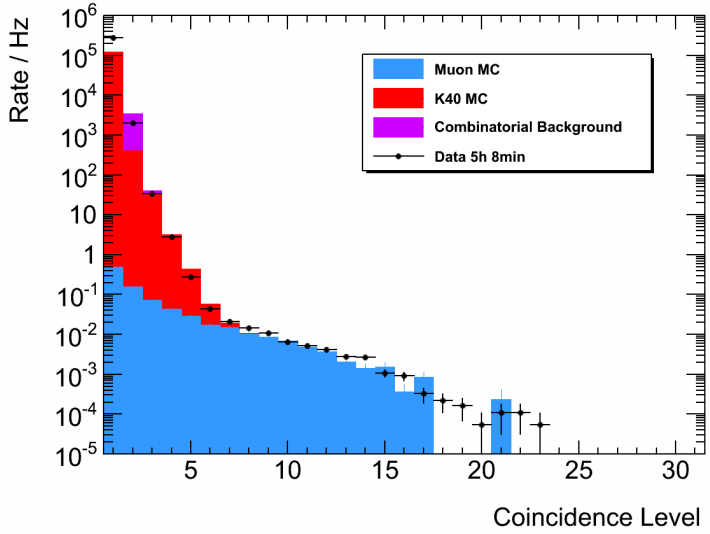
Local Control Module:
ASIC, DAQ/SC
Clock, power, $\cdots$
NIMA 622 (2010) 59-73

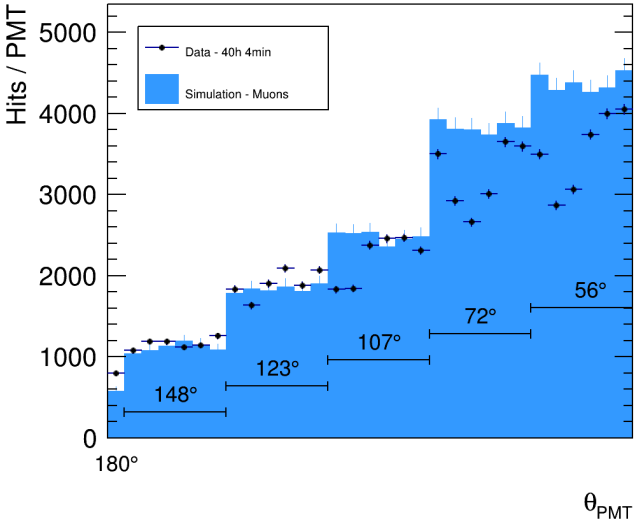


Hydrophone:
acoustic positioning
JINST 7 T08002

KM3NeT prototype optical module

- deployed on IL13 in 04/13
- in operation
- muon identification
- arrival direction sensitivity



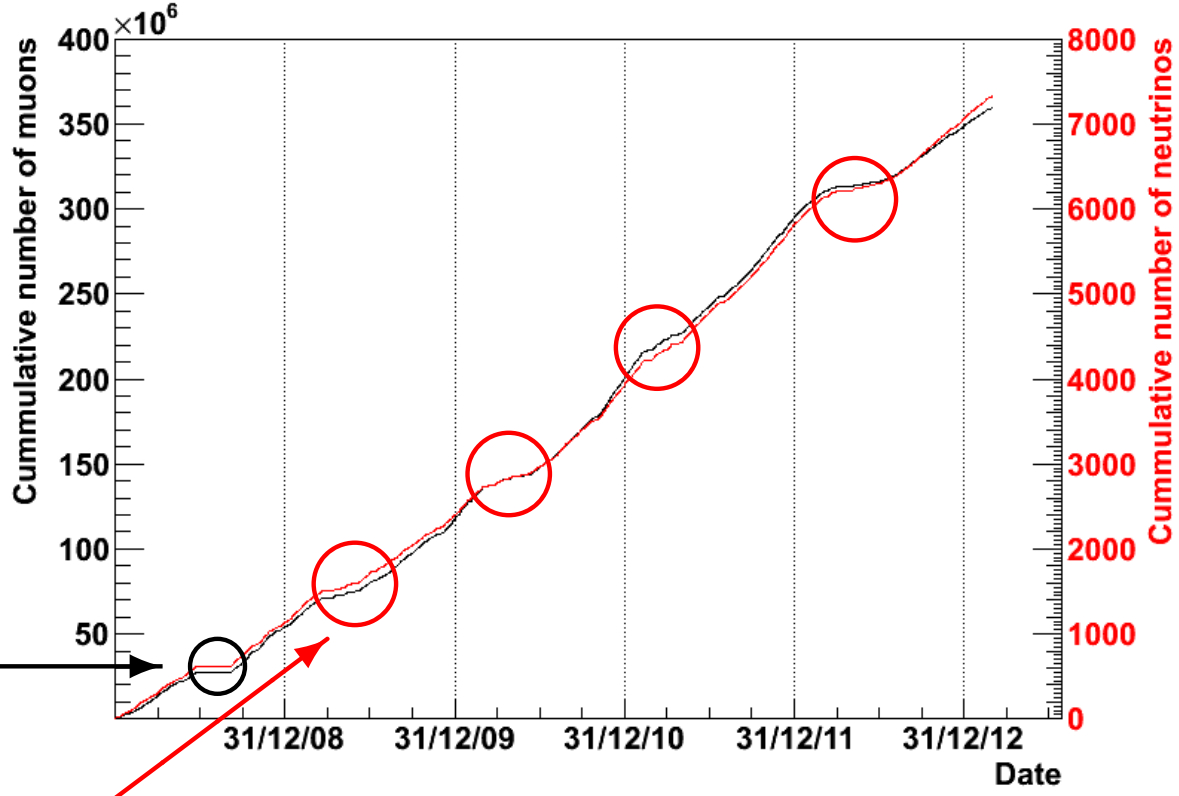


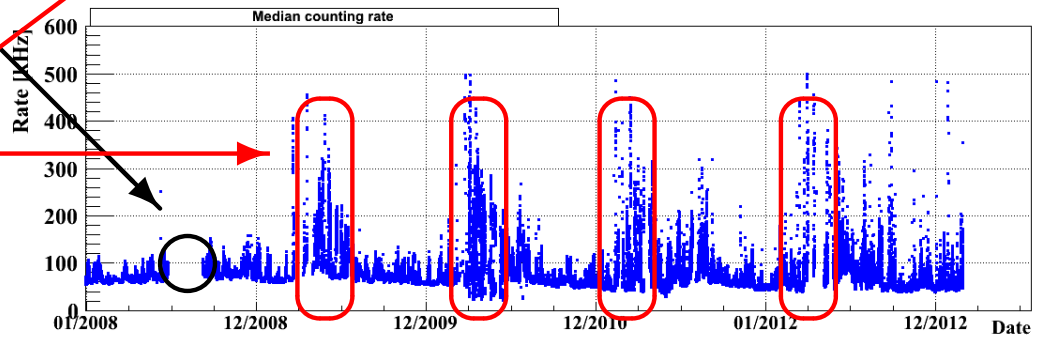
Data taking

since 2008:
12 lines
0.85 duty cycle

cable failure

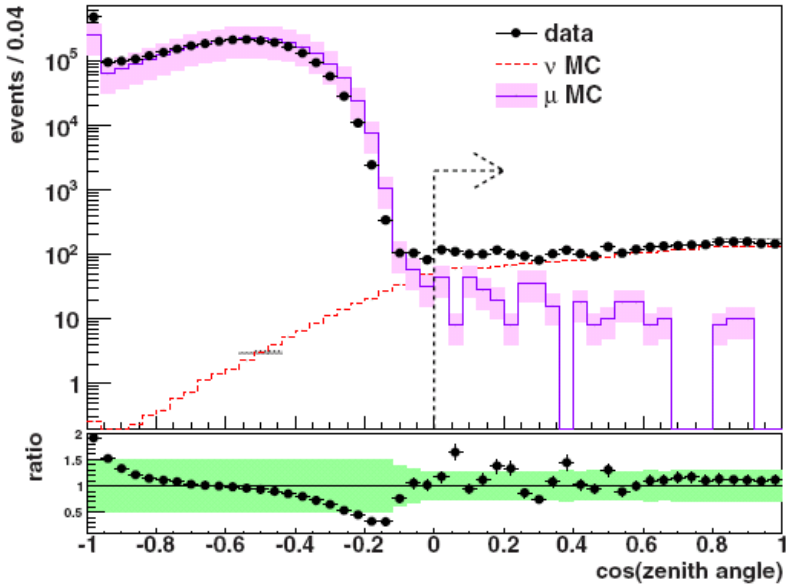
springs:
bio-luminescence

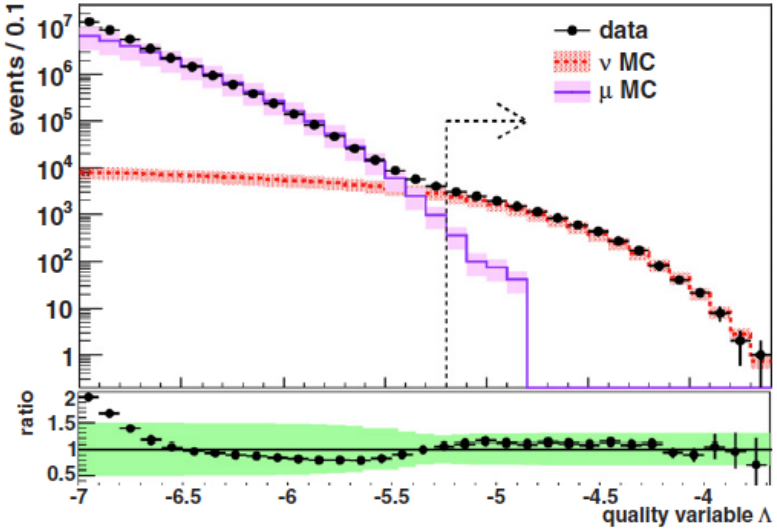




Track reconstruction - ANTARES

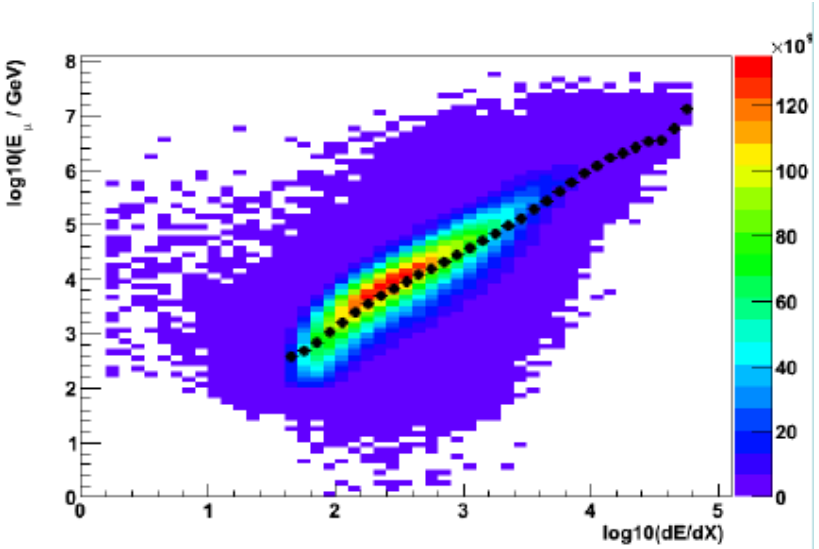
- time and position
- likelihood maximization (Λ)
- cut on θ (atm. muons)
- cut on Λ (misrec. muons)
- median resolution $\sim 0.3°$
- $\sim 1.5\,\nu \cdot \mathrm{day}^{-1}$
  more than 9000 so far
- visibility: $\frac{3}{4}$ of the sky
  most of galactic plane
  including galactic center

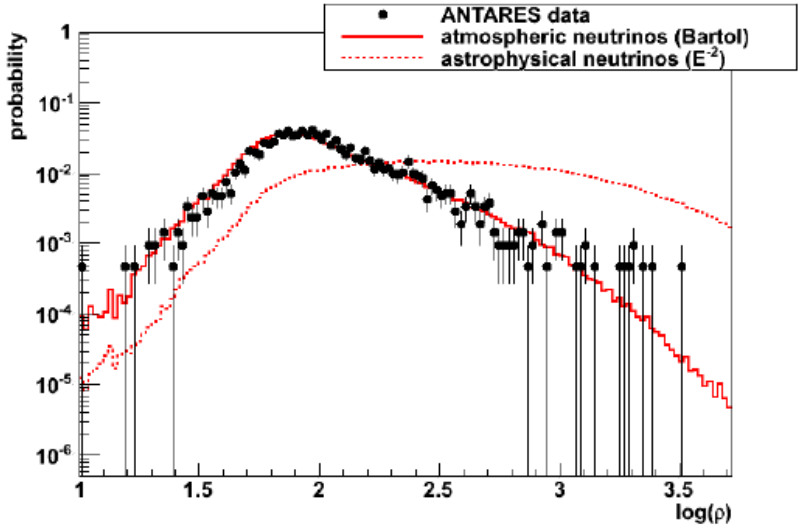




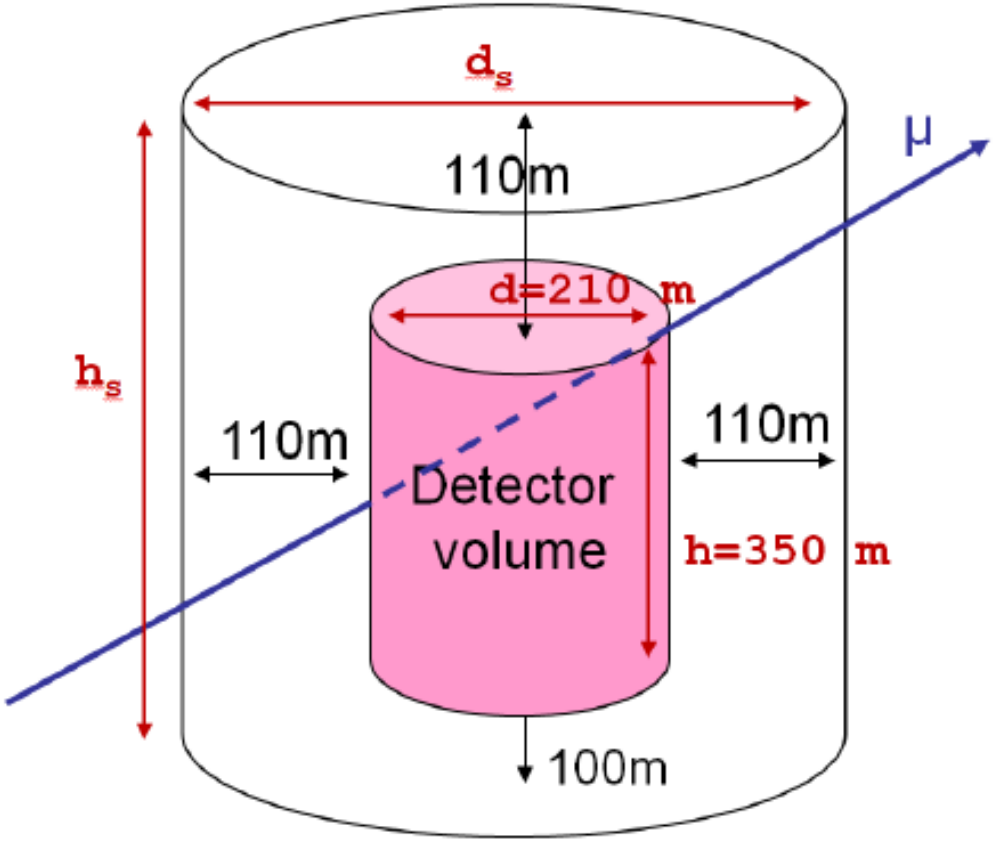
Energy reconstruction - ANTARES

- $\rho = \frac{dE}{dx} \propto E, \ \frac{dE}{dx} \sim \frac{\sum_{i=1}^{hits} Q_i}{\epsilon(\vec{x}) L_\mu(\vec{x})}$
- $\epsilon(\vec{x}) = \sum_{i=1}^{OM} \frac{\alpha_i(\theta_i)}{r_i} e^{-\frac{r_i}{L_{abs}}}$
- $L_\mu(\vec{x})$: muon track
- larger fiducial volume
- proportionality via simulation
- resolution
  muons: $\log E \sim 0.45$
  neutrinos: $\log E \sim 0.7$
- no large systematic errors
- other methods:
  likelihood maximization
  neural network
  hit repetition





Fiducial volume



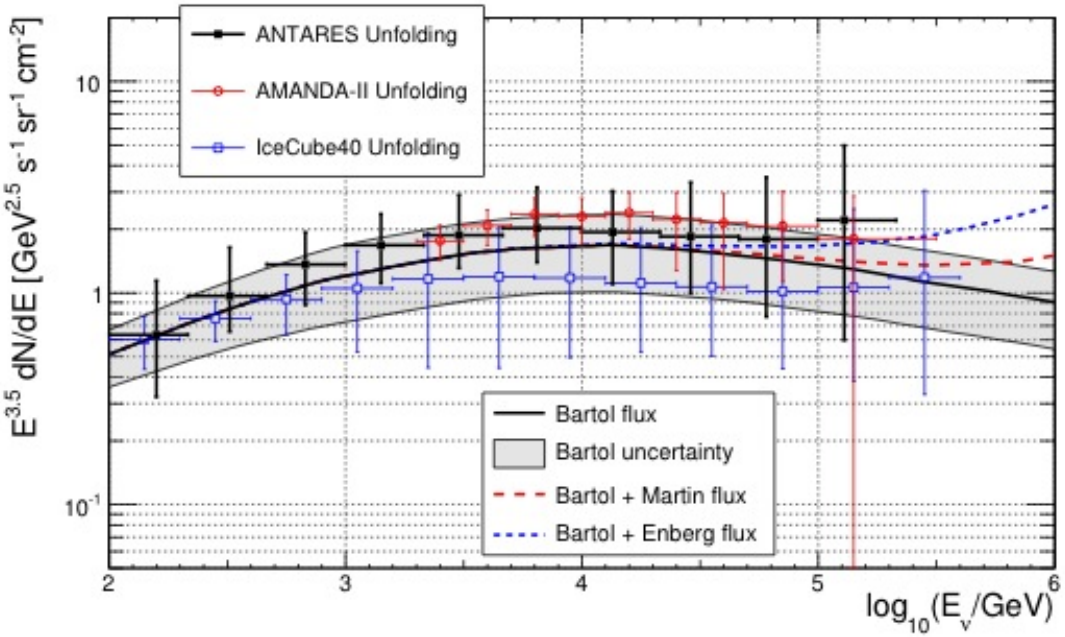
Atmospheric muon neutrino flux - ANTARES

Cuts

- $\pi/2 < \theta < \pi$
- $\Lambda > -5.2$
- ang. uncert. $< 1^\circ$

Data selection

01/2008→12/2011
misrec. muons $< 0.3\%$
ν rate: $1.7\,\nu \cdot \mathrm{day}^{-1}$



Spectrum

- average over zenith angle: $[\pi/2; \pi]$
- correction factor: 3% at 100 GeV, 40% at 100 TeV

Diffuse astrophysical flux - ANTARES

Theory

- ν_μ from unresolved sources
- flux from UHECRs and γ-ray

$E_\nu^2 \Phi_\nu < \frac{4.5}{2} \cdot 10^{-8}\,\mathrm{GeV} \cdot \mathrm{cm}^{-2} \cdot \mathrm{s}^{-1} \cdot \mathrm{sr}^{-1}$

Method

- $\rho = \frac{dE}{dx}$ as energy estimator
- ρ for discrimination between atm. and astrophys. ν
- blinding procedure on MC
- Model Rejection Factor
- unblinding on data

Cuts

- $\theta > 100°$, $N_{\text{hit}} > 60$, $N_{\text{line}} \geq 2$
- $\Lambda(N_{\text{hit}})$
- misrec. muon $< 1\,\mathrm{evt} \cdot \mathrm{yr}^{-1}$

Waxman & Bahcall, Phys.Rev.D59(1998)023002

Feldman & cousins, Phys.Rev.D57(1998)3873

Diffuse astrophysical flux - ANTARES

Theory

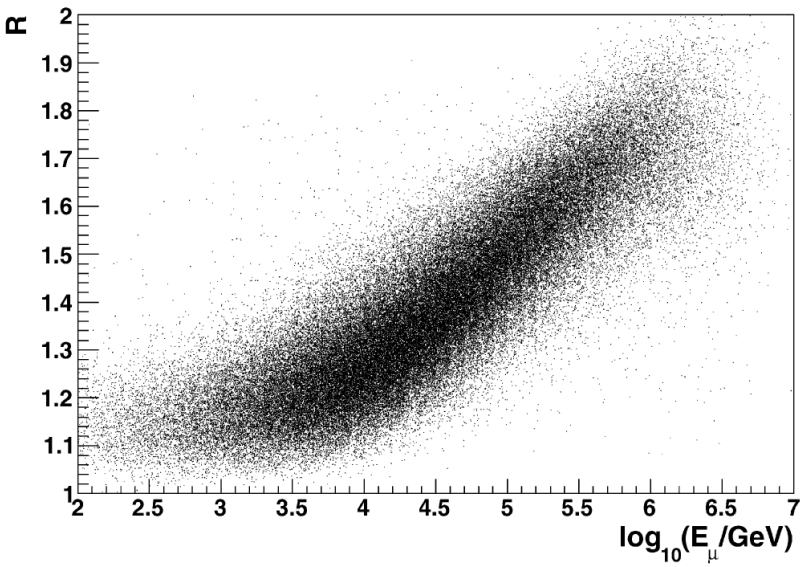
- from unresolved sources
- flux from UHECRs and γ-ray
- $E_\nu^2 \Phi_\nu < \frac{4.5}{2} \cdot 10^{-8}\,\mathrm{GeV} \cdot \mathrm{cm}^{-2} \cdot \mathrm{s}^{-1} \cdot \mathrm{sr}^{-1}$

Method

- energy est.: hit repetition R
- $R = \frac{\Sigma R_i}{N_{OM}}$ for discrimination
- blinding procedure on MC
- unblinding on data
- Model Rejection Factor

Waxman & Bahcall, Phys.Rev.D59(1998)023002

Feldman & cousins, Phys.Rev.D57(1998)3873



Cuts

- $\theta > 100°$, $N_{hit} > 60$, $N_{line} \geq 2$
- $\Lambda(N_{hit})$
- mis-reconstructed muon contamination $< 1\,\mathrm{evt} \cdot \mathrm{yr}^{-1}$

Diffuse astrophysical flux - ANTARES

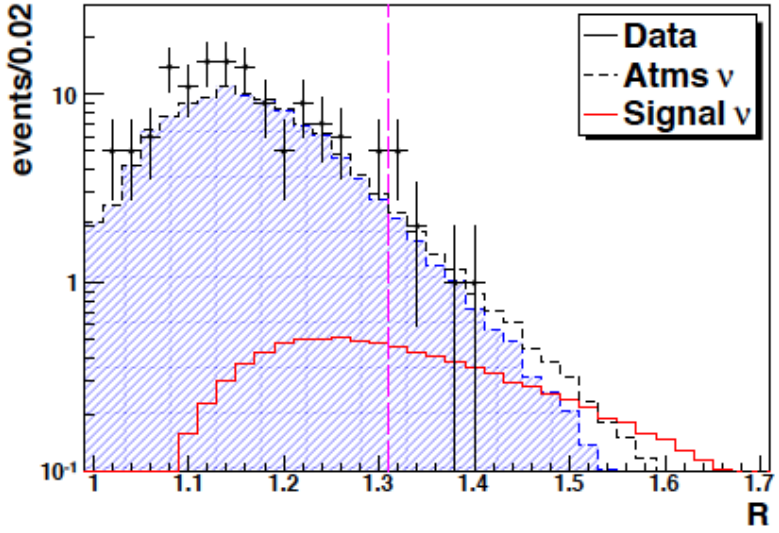
2008-2009 results

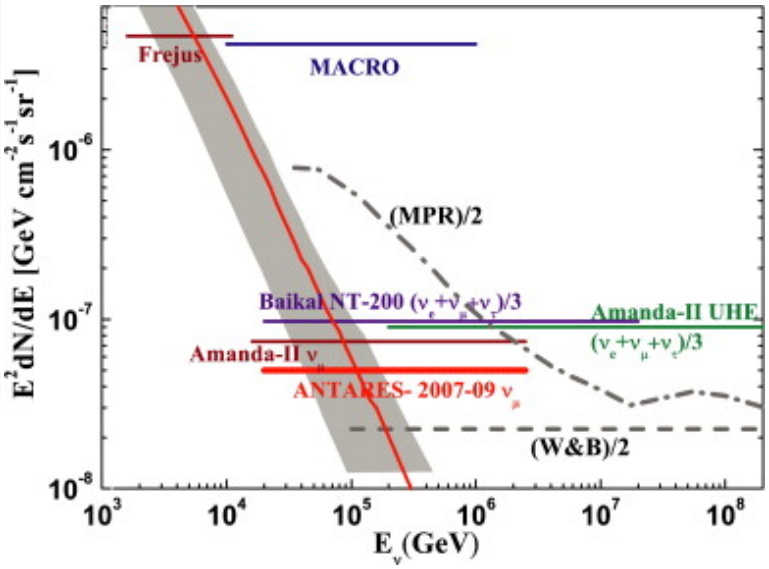
- 334 days
- energy est.: hit repetition
- $n_{\text{obs}} = 9,\ n_{\text{bkg}} = 10.7 \pm 2.0$
- sensitivity:

  $E^2\Phi = 7.0 \cdot 10^{-8}\ \text{GeV} \cdot \text{cm}^{-2} \cdot \text{s}^{-1} \cdot \text{sr}^{-1}$
- upper limit:

  $E^2\Phi^{90\%\text{CL}} = 5.3 \cdot 10^{-8}\ \text{GeV} \cdot \text{cm}^{-2} \cdot \text{s}^{-1} \cdot \text{sr}^{-1}$

Physics Letters B, 696(2011)16





Diffuse astrophysical flux - ANTARES

results with the first data set

Physics Letters B, 696(2011)16

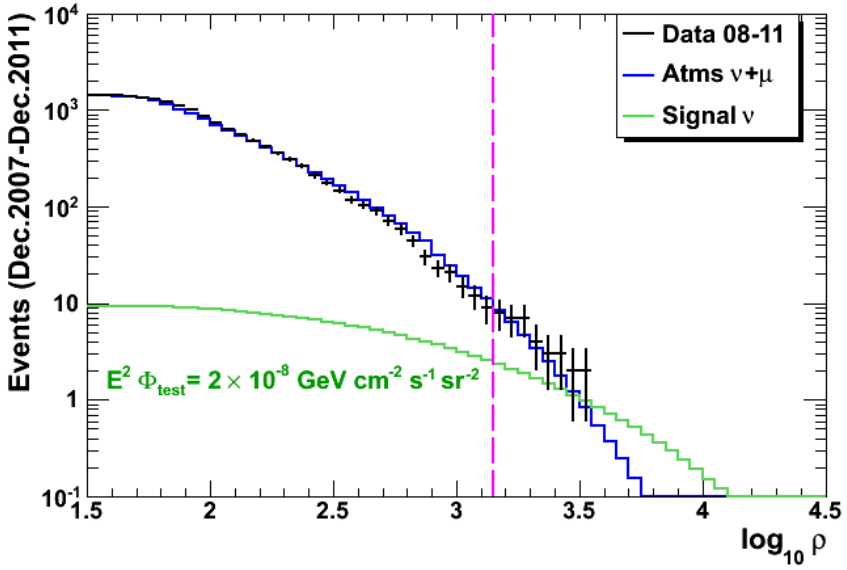
2008-2011 results

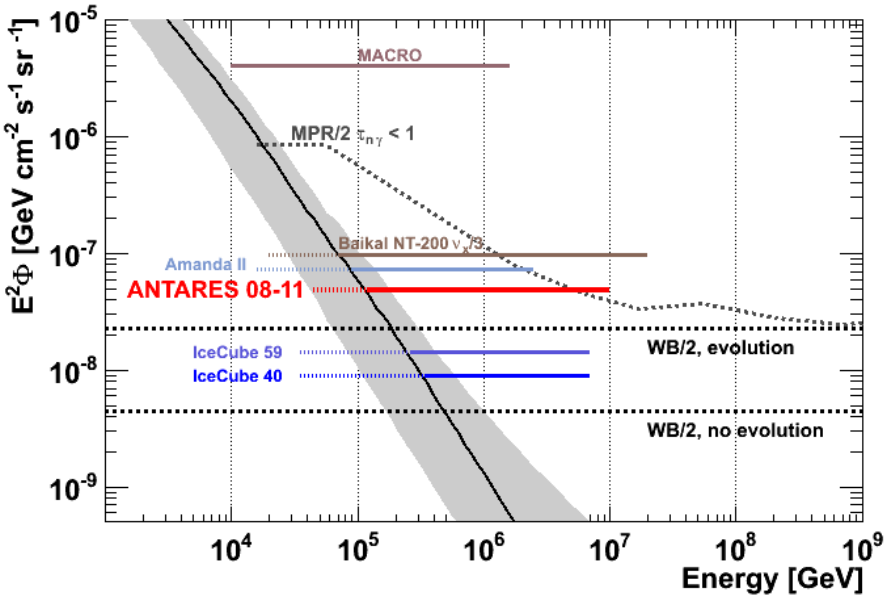
- 855 days
- $n_{\text{obs}} = 8$, $n_{\text{bkg}} = 8.4$, $n_{\text{sig}} = 2.3$
- sensitivity:

$$E^2\Phi = 4.7 \cdot 10^{-8}\ \mathrm{GeV} \cdot \mathrm{cm}^{-2} \cdot \mathrm{s}^{-1} \cdot \mathrm{sr}^{-1}$$

- upper limit:

$$E^2\Phi^{90\%\mathrm{CL}} = 4.8 \cdot 10^{-8}\ \mathrm{GeV} \cdot \mathrm{cm}^{-2} \cdot \mathrm{s}^{-1} \cdot \mathrm{sr}^{-1}$$





Likelihood maximization - ANTARES

Principle

Search for an excess of signal over background with an unbinned maximum likelihood

Cuts

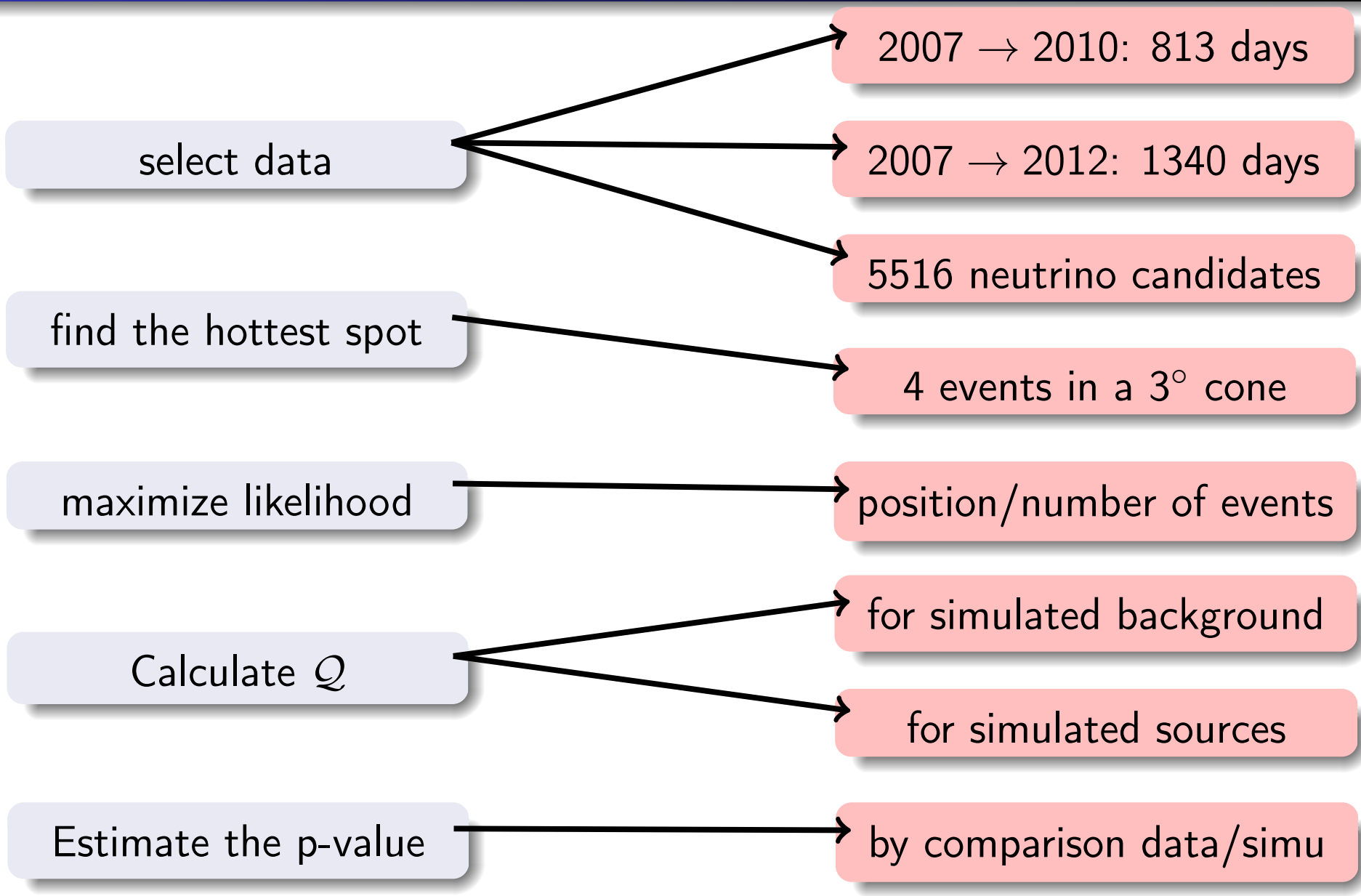
$\pi/2 < \theta < \pi$, quality $\Lambda > -5.2$, angular uncertainty $< 1^\circ$

$$\log \mathcal{L}_{\mathrm{s+b}} = \sum_{i=1}^{\mathrm{events}} \log \left[\mu_{\mathrm{sig}} \times F(\beta_{\mathrm{i}}(\alpha_{\mathrm{s}}, \delta_{\mathrm{s}})) \times \mathcal{N}(N_{\mathrm{hits}}^{\mathrm{i,sig}}) + \mathcal{B}_{\mathrm{i}} \times \mathcal{N}(N_{\mathrm{hits}}^{\mathrm{i,bkg}}) \right]$$

- μ_{sig}: mean number of detected events emitted by the source
- F: point spread function
- $\mathcal{B}_{\mathrm{i}}$: background parametrization α uniform δ from data
- $\mathcal{N}$: probability to reconstruct an event with N_{hits}

Test statistic: $\mathcal{Q} = \log \mathcal{L}_{\mathrm{s+b}}^{\mathrm{max}} - \log \mathcal{L}_{\mathrm{b}}$

Full sky search - ANTARES



Model Rejection Factor

- perform an unbiased optimization of the final event selection
- parameters characterizing the source flux spectrum are known
  $\rightarrow$ signal hypothesis
- optimization for the best sensitivity (minimization of the source flux normalization)
  $\rightarrow$ at a given confidence level $1 - \alpha$
- MRP: optimize cuts to minimize the flux limit assuming no signal

Model Rejection Factor

- for one cut: estimate μ_b and μ_s
  μ_b from Poisson distribution
  μ_s from theoretical flux $A\Phi(E)$
  $\mu_s = \int A\Phi(E)\epsilon(E)dE$
  with $\epsilon(E)$ the detector response
- data unblinding:
  $MRF = \frac{\mu(n_{obs},\mu_b)}{\mu_s} = \frac{\bar{\mu}(n_{obs},\mu_b)}{\mu_s}$ with
  n_{obs} = number of observed events
  $\mu(n_{obs}, \mu_b)$ = event upper limit (data)
  $\bar{\mu}(n_{obs}, \mu_b)$ = average upper limit (simu)
  limit on flux normalization: $A_{lim} = A \times MRF$
- minimize A_{lim} according to the cuts

Average upper limit

- simulated atmospheric neutrinos
- experiments with no signal and n_b background event
- $\bar{\mu}(n_\mathrm{obs}, \mu_\mathrm{b}) = \sum_{n_\mathrm{obs}=0}^{+\infty} \mu(n_\mathrm{obs}, \mu_\mathrm{b}) \frac{n_\mathrm{b}^{n_\mathrm{obs}}}{n_\mathrm{obs}!} e^{-n_\mathrm{b}}$
- $\mu(n_\mathrm{obs}, \mu_\mathrm{b})$ from Feldman-Cousins
- allows to minimize the MRF and find the optimal cut!

Bayesian method

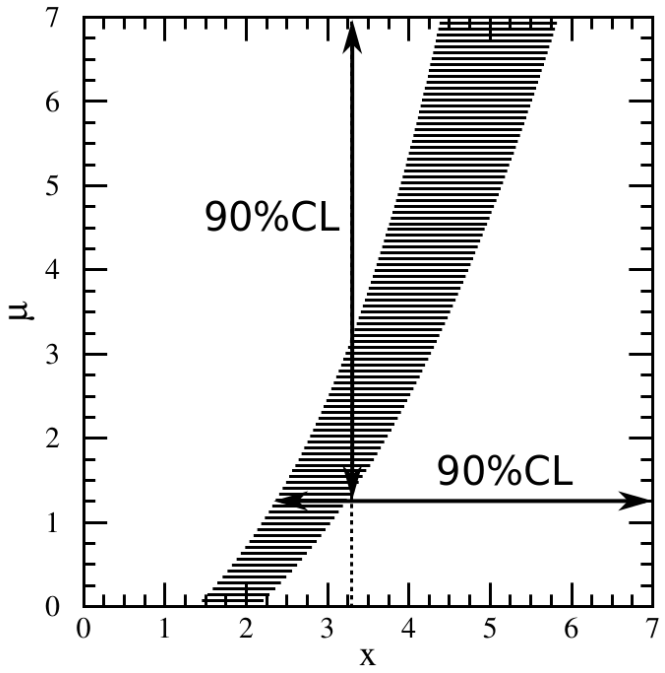
Bayesian

- $p(A|B) = p(B|A)\frac{p(A)}{p(B)}$
- posterior as a function of prior
- problem with non informative prior

Neyman construction

Classical

- $p(x|\mu) = (\mu + b)^x \exp(-(\mu + b))/x!$
- μ is the mean number of signal
- b is the background
- x the number of events
- for each μ, we look for the acceptance region: $p(x \in [x_1, +\infty]) = 0.9$
- the upper limit is given by $p(\mu \in [\mu_1, +\infty]) = 0.9$
- the sensitivity is found for $x = 0$
- problem: unphysical intervals (empty set)



Feldman-Cousins method

Modified Neyman

- same procedure for acceptance interval
- for each *mu* signal $\rightarrow p(x|\mu)$
- for each $x \rightarrow p(x|\mu_{\text{best}})$ (likelihood max)
- $R = \frac{p(x|\mu)}{p(x|\mu_{\text{best}})}$
- decreasing order on R: add x to the acceptance region until $p(x|\mu)$ reaches 90%

n	$P(n\|\mu)$	μ_{best}	$P(n\|\mu_{\text{best}})$	R	rank	U.L.	central
0	0.030	0.	0.050	0.607	6		
1	0.106	0.	0.149	0.708	5	√	√
2	0.185	0.	0.224	0.826	3	√	√
3	0.216	0.	0.224	0.963	2	√	√
4	0.189	1.	0.195	0.966	1	√	√
5	0.132	2.	0.175	0.753	4	√	√
6	0.077	3.	0.161	0.480	7	√	√
7	0.039	4.	0.149	0.259		√	√
8	0.017	5.	0.140	0.121		√	
9	0.007	6.	0.132	0.050		√	
10	0.002	7.	0.125	0.018		√	
11	0.001	8.	0.119	0.006		√	

Alerts and follow-up - ANTARES

Characteristics

- precision of 0.5° ($E > 1\,\mathrm{TeV}$)
- reconstruction latency $< 5\,\mathrm{s}$
- alert latency $< 10\,\mathrm{s}$
- slewing latency $< 5\,\mathrm{s}$
- High duty cycle (large sky coverage)
- no hypothesis on the source nature

Data

- 02/09 $\rightarrow$ 12/12
- tuned for 2 per month (83 alerts)
- 12 alerts with good follow-up
- no 2ν trigger

prompt observation - GRB

- 6 images: $3\,\mathrm{min}$ exposition
- 30 images: $1\,\mathrm{min}$ exposition

Delayed observations - ccSNe

- 6 images: $3\,\mathrm{min}$ exposition
- day $+1 \rightarrow +7$, $+9$, $+15$, $+27$, $+45$, $+60$

Alerts and follow-up - ANTARES

- limiting magnitude ($\frac{S}{N} > 5$)
- No transient optical counterpart associated to a neutrino detection (model independant) to date

neutrino ID	delay (day)	lim mag	Gal ext
ANT100123A	0.64	12	0.2
ANT100302A	1.01	15.7	0.2
ANT100725A	$8.7e^{-4}$	14.5	0.3
ANT100922A	$4.7e^{-2}$	14.0	0.5
ANT101211A	0.5	15.1	0.1
ANT110409A	$3.0e^{-3}$	18.1	6.7
ANT110529A	$5.2e^{-3}$	15.6	1.2
ANT110613A	$7.8e^{-4}$	17.0	2.3
ANT120730	$2.4e^{-4}$	17.6	0.2
ANT120907	$2.9e^{-4}$	16.9	0.2
ANT121010	$2.8e^{-4}$	18.6	0.1
ANT121206	$3.1e^{-4}$	16.9	0.2

Flaring sources - ANTARES

Method

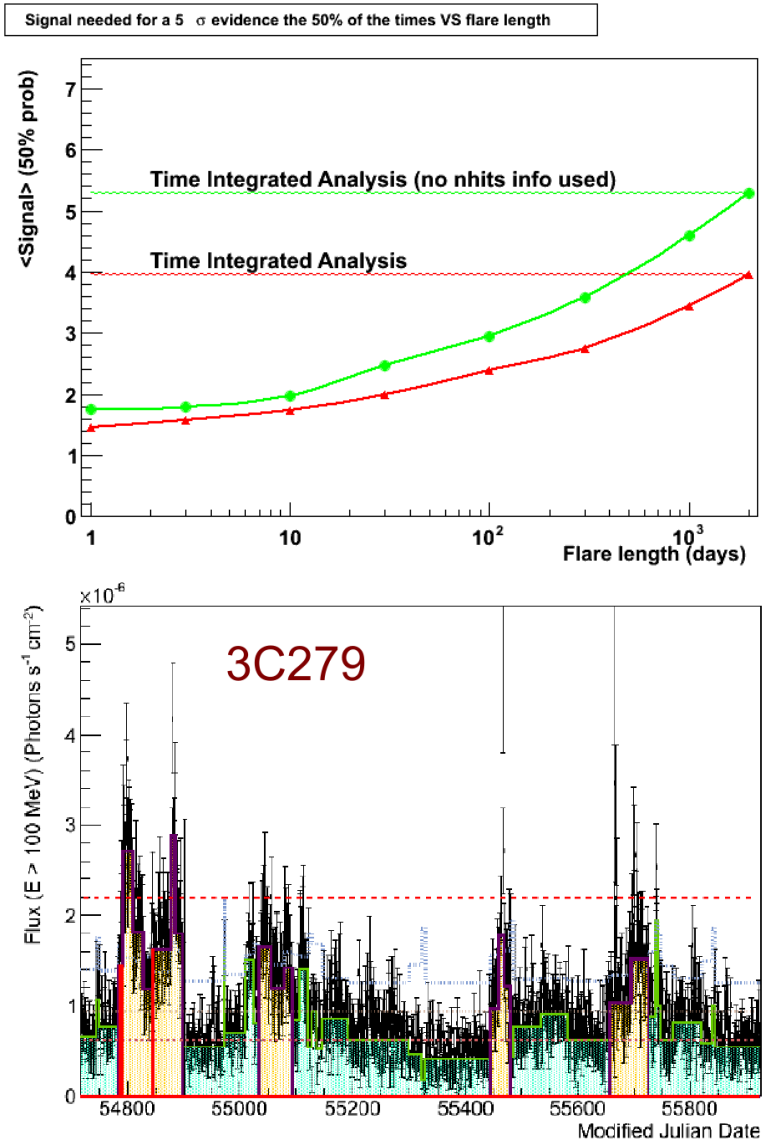
- from Fermi catalog
- γ-ray light curve
- likelihood maximization

10 Blazars - 2008

- 1 event in coincidence with 3C279 ($< 0.56°$)
- post-trial p-value $p = 0.10$

41 Blazars - 2008→2011

- 2 events in coincidence (3C279)
- post-trial p-value: $p = 0.12$
- background compatible



Astropart.Phys.36(2012)204

Flaring sources - ANTARES

6 Microquasars

- associated to jet acceleration
- interesting period from light curves

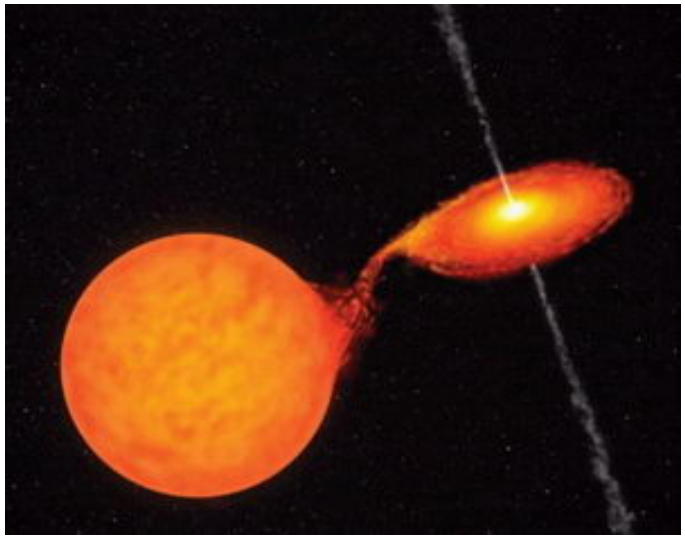
neutrinos

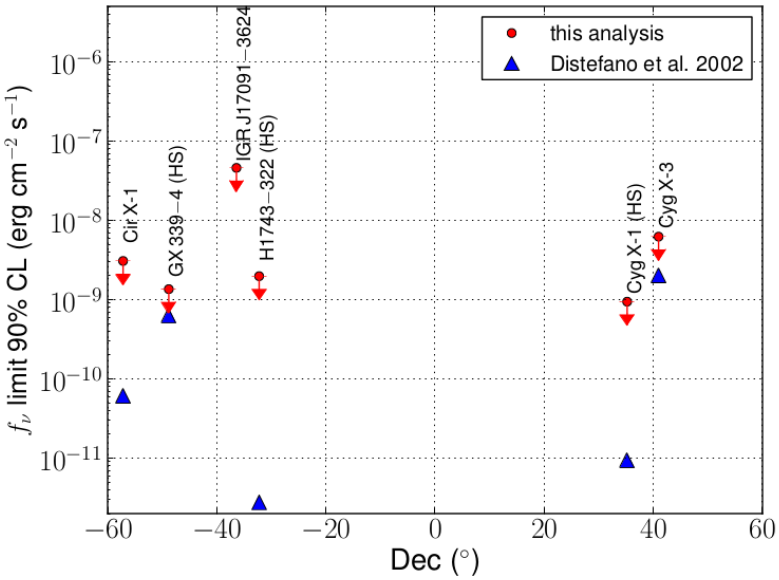
- 2007→2010: 813 days
- in the outbursting periods

Method and results

- likelihood maximization
- no coincidence
- flux limit assuming $E_\nu^{-2} e^{-\frac{E_\nu}{100\ \mathrm{TeV}}}$

Levinson, Waxman (2001) - DiStefano et al. (2002)



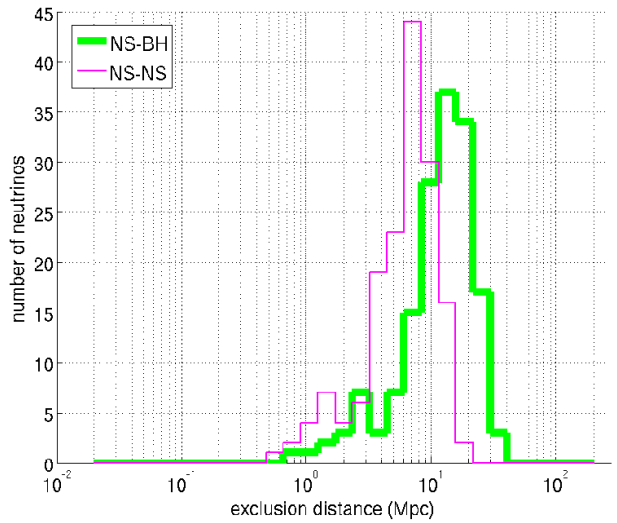


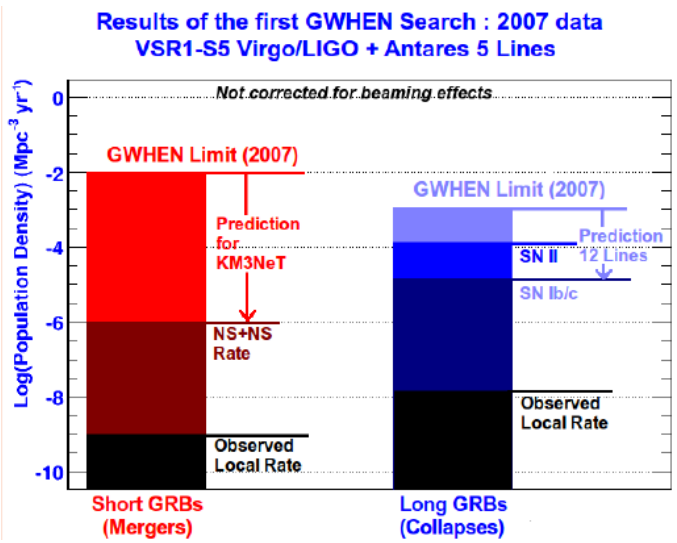
Gravitational waves

Results

- No coincidence found
- exclusion distances on common GW/HEN emitters
- Analysis of 2009-2010 dataset ongoing

JCAP.06(2013)008

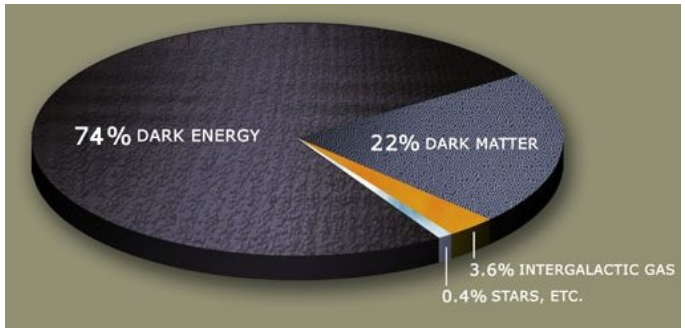


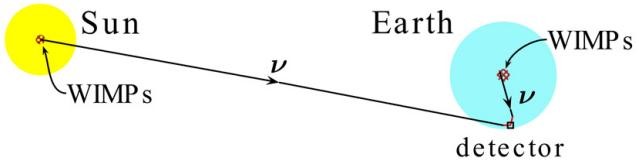


Dark matter indirect search

Properties

- galaxies, clusters, CMB, Weak lensing, LSS formation
- non baryonic matter
- no electromagnetic or strong interaction
- WIMP model (SUSY $\rightarrow$ neutralino)





Indirect search

- WIMPs gravitationally trapped (elastic collisions)
- Earth, Sun, Galactic center
- self-annihilation (c-b-t quarks, τ lepton, W-Z-H bosons)
- clear signature from sun

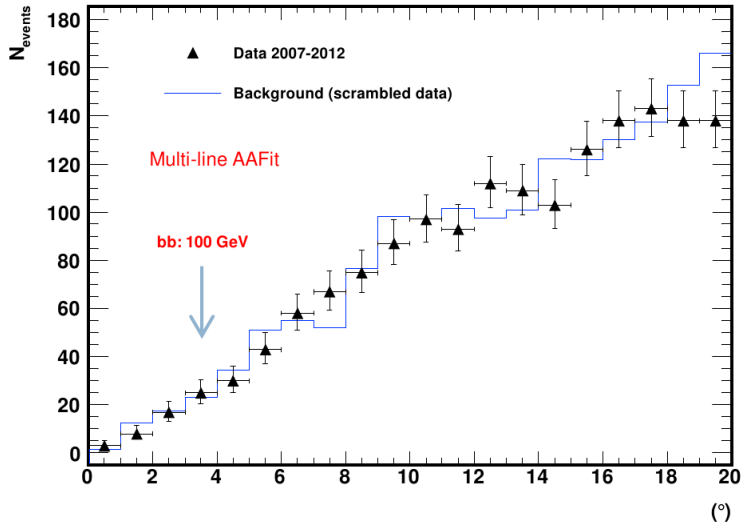
Dark matter indirect search - ANTARES

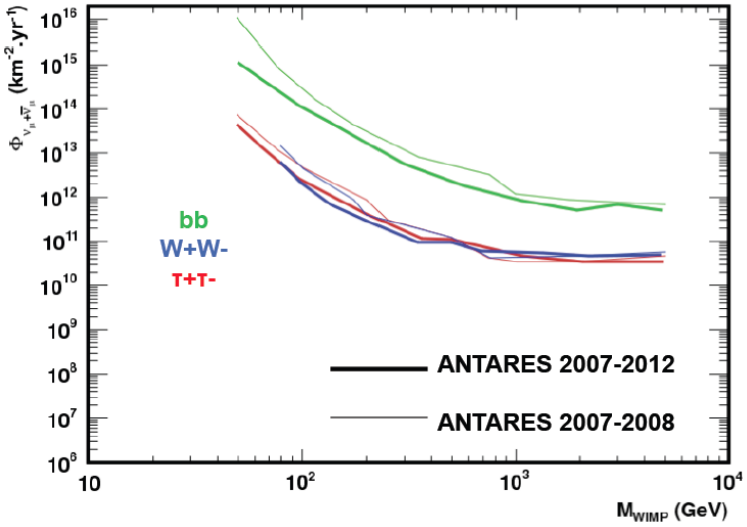
Method

- cuts: $N_{\text{hits}} \geq 5$, $N_{\text{lines}} \geq 2$
- reconstruction: χ^2 minimization (quality Q)
- background $\rightarrow$ scrambled data
- Q_{cut} and Ψ_{cut} (ang dist to sun) optimization: neutrino flux

2007-2012 results

- 1321 days
- single line events included
- no significant excess

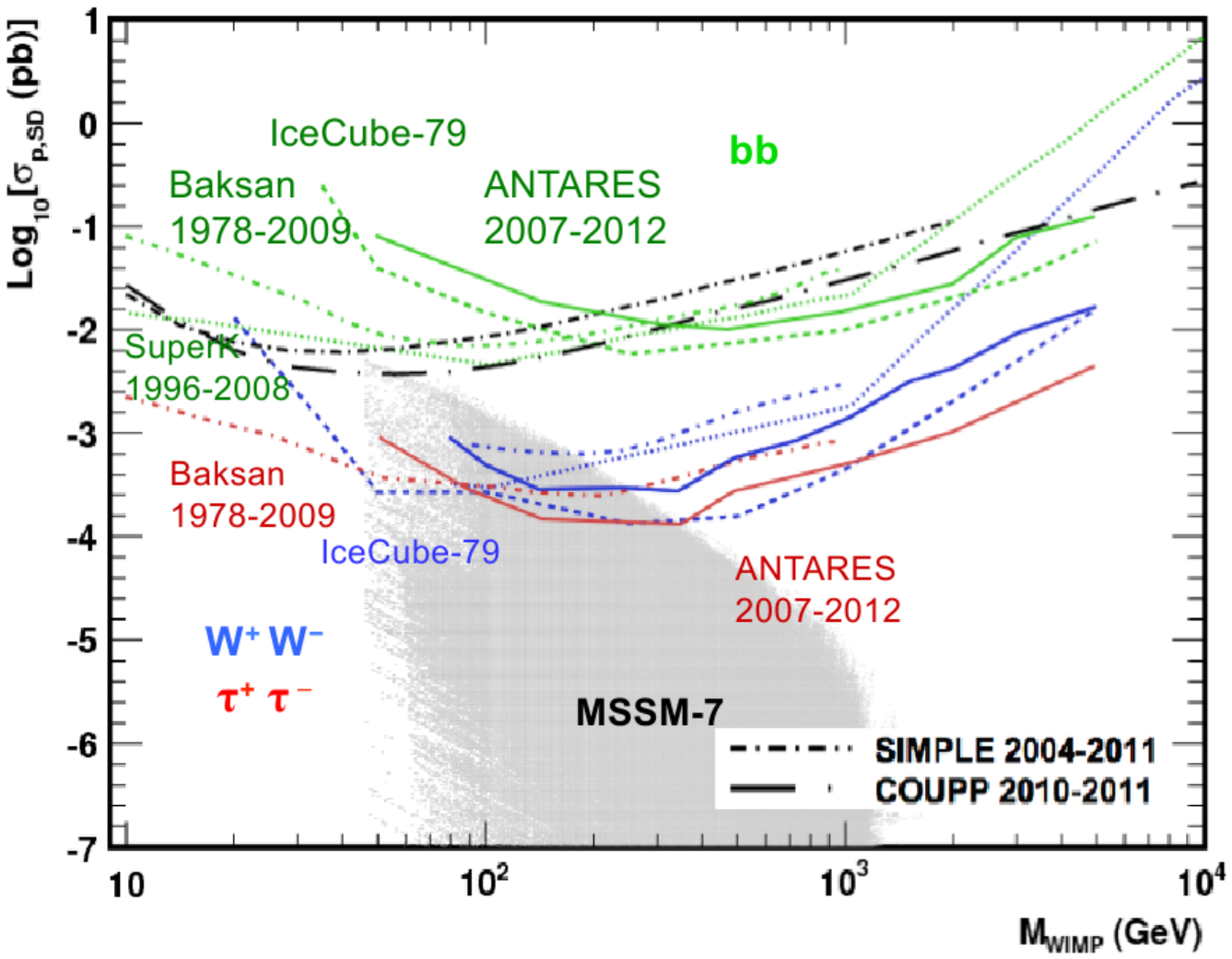




$\rightarrow$ derive a limit on the flux as a function of M_{WIMP}

Dark matter indirect search - ANTARES

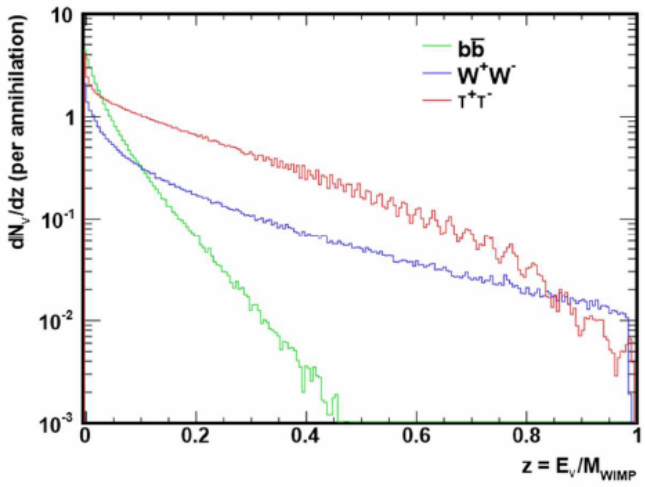
Limit on the WIMP-proton cross section for spin dependent model



Dark matter indirect search - ANTARES

Properties

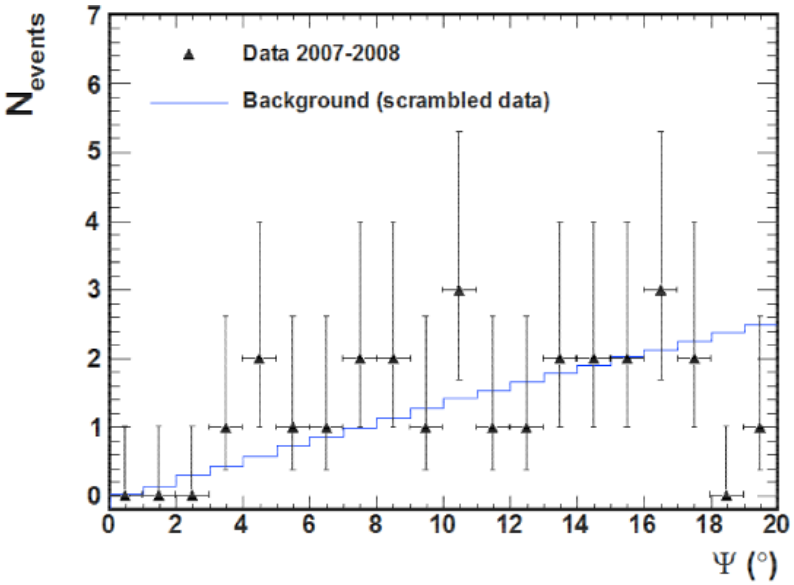
- for a 350 GeV WIMP
- $b\bar{b}$ (soft), $\tau^+\tau^-$ (hard), W^+W^- (hard) channels
- depends on $\sigma_{\mathrm{WIMP-p}}$ but not on v_{WIMP} distribution

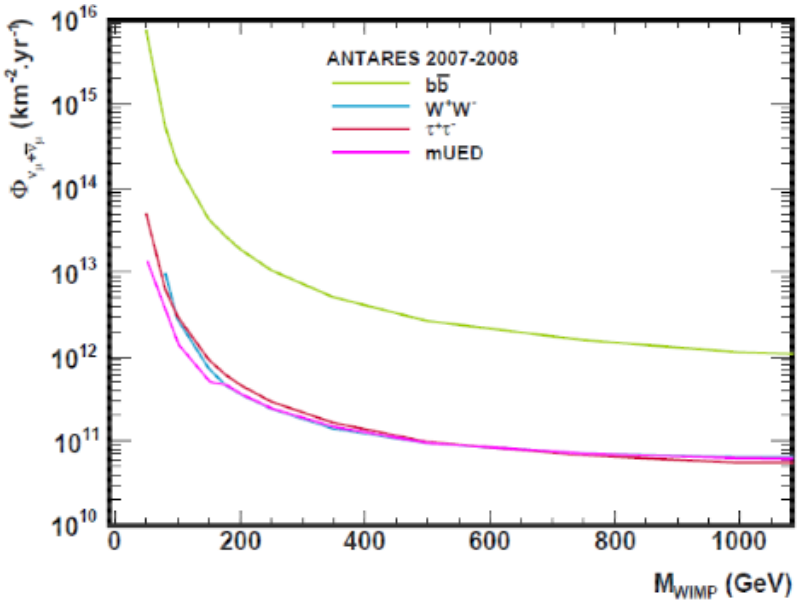


Dark matter indirect search - ANTARES

2007-2008 results

- 295 days
- 27 events within 20° from sun
- no significant excess





Dark matter indirect search - ANTARES

KM3NeT expectations

Better than ANTARES but not than IceCube (deep core)