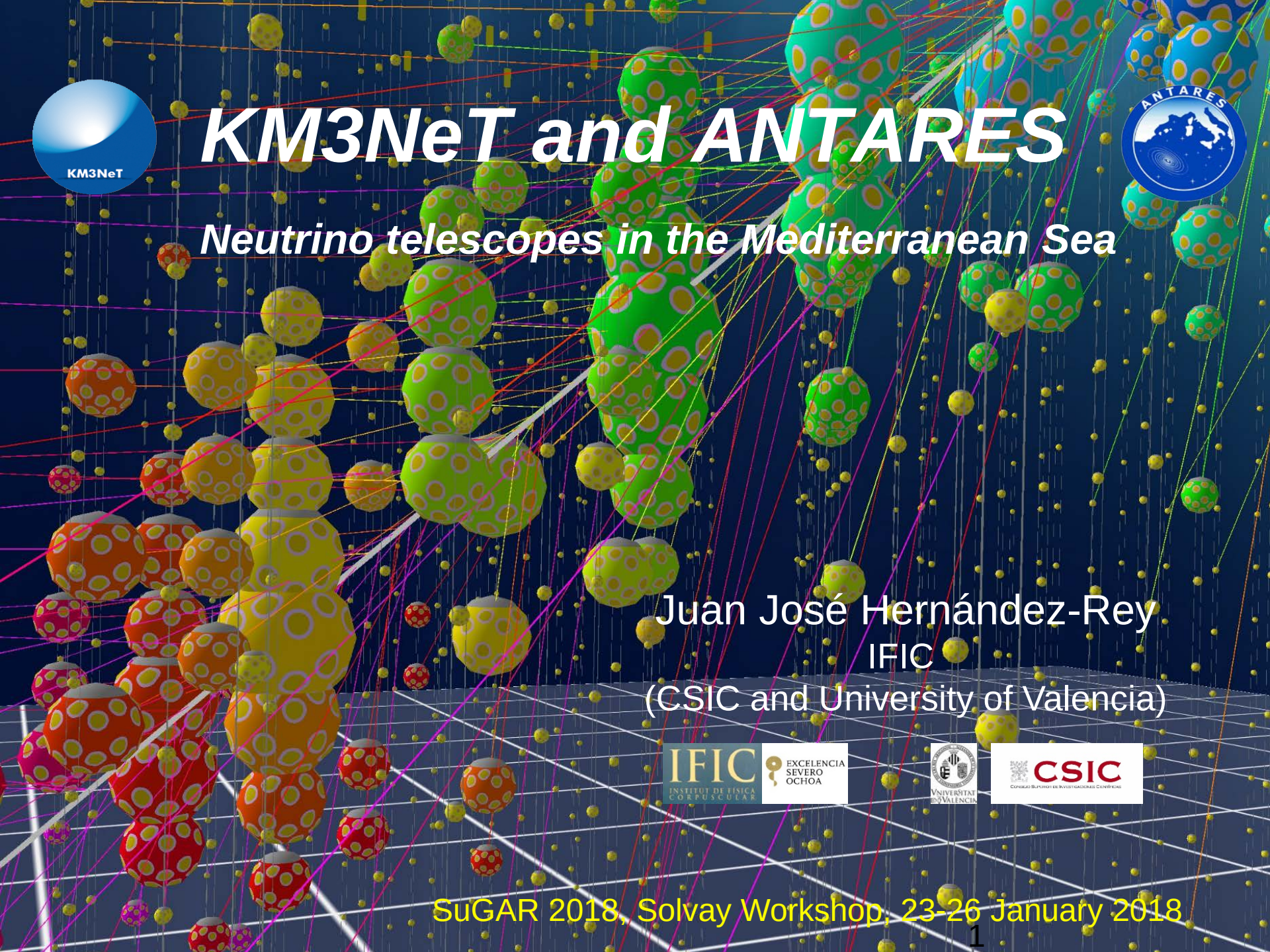


KM3NeT and ANTARES

Neutrino telescopes in the Mediterranean Sea

Juan José Hernández-Rey

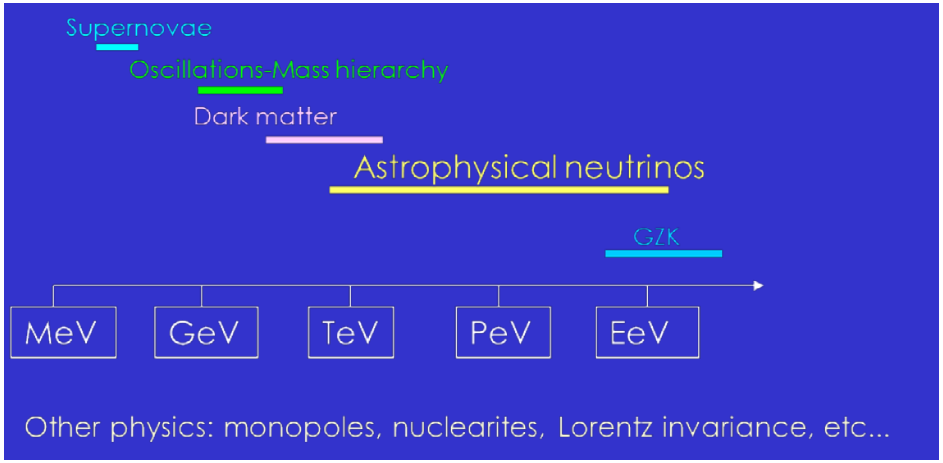
IFIC

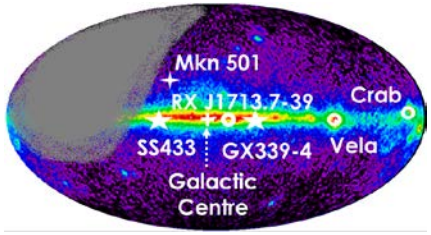
(CSIC and University of Valencia)

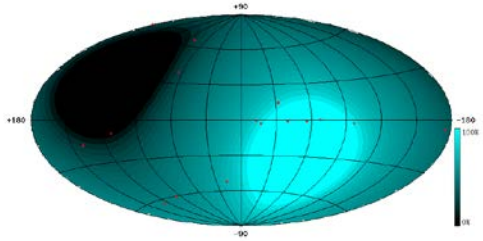
SuGAR 2018, Solvay Workshop, 23-26 January 2018

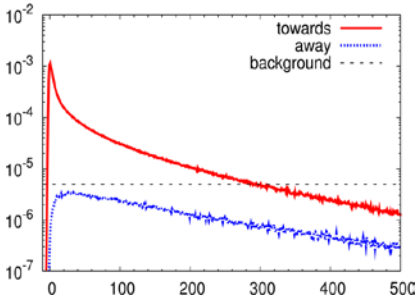
Mediterranean Neutrino Telescopes

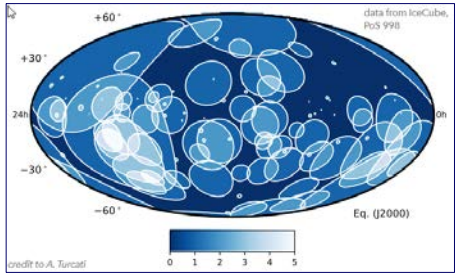
- Physics motivation and Detection principle
  - High energy ν astronomy and neutrino properties
  - Detection: large volume of transparent medium surveyed by photodetectors
- Location:
  - Northern terrestrial hemisphere:
  - Complementary to IceCube
  - Golden channel for southern sky sources. "Milky-Way optimized"
- Medium:
  - Deep Sea water
  - Very small light scattering (good angular resolution)
  - Natural backgrounds (^{40}K and biolum) can be handled.





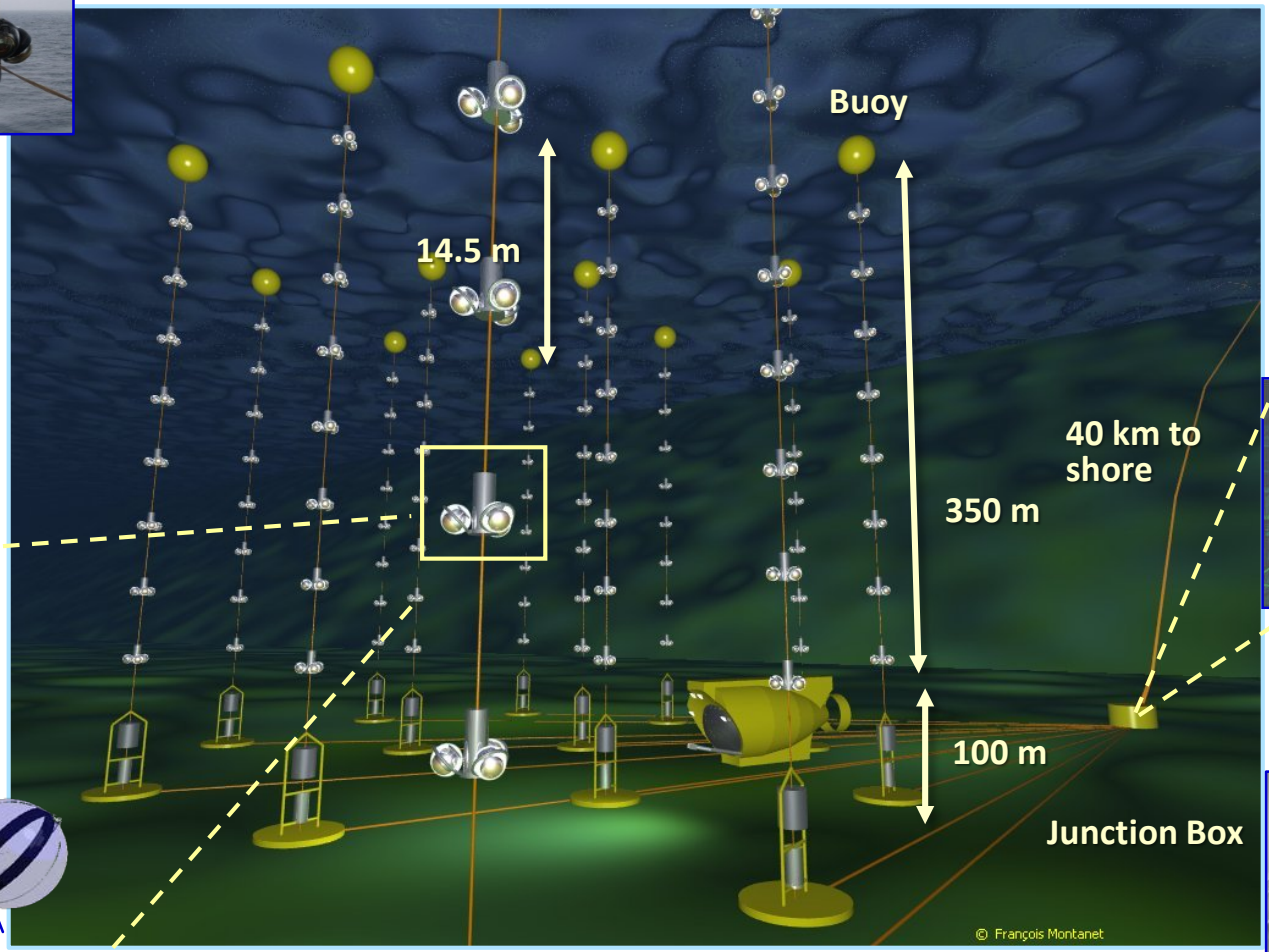






Antares and KM3NeT Collaborations

ANTARES



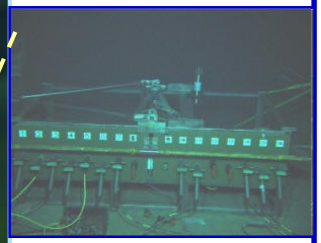
12 lines (885 PMTs)

25 storeys / line

3 PMTs / storey

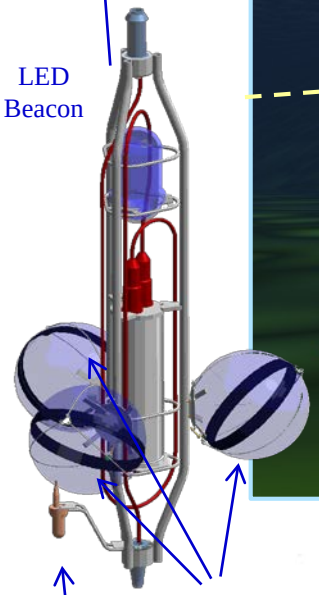
5-line setup in 2007

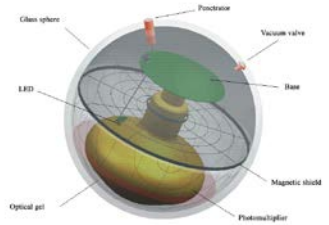
Completed in 2008



Junction Box

Shore station



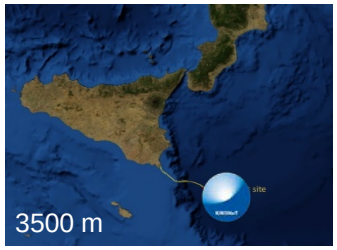


Mediterranean Sea (near Toulon) at **2500 m** depth

NIM **A484** (2002) 369, AP **19** (2003) 253
AP **23** (2005) 131, NIM **A555** (2005) 132
AP **26** (2006) 314, NIM **A570** (2007) 107
NIM **A578** (2007) 498,NIM **A581** (2007) 695
AP **31** (2009) 277, NIM **A622** (2010) 59-73
AP **34** (2011) 539, NIM **A656** (2011) 11

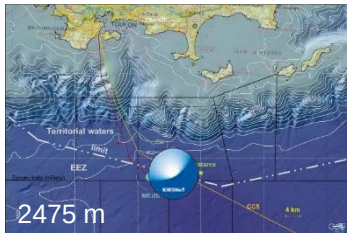
KM3NeT

ARCA
Astroparticle **R**esearch with **C**osmics In the **A**byss



Capo Passero, Sicily, Italy

ORCA
Oscillation **R**esearch with **C**osmics in the **A**byss



Toulon, Var, France

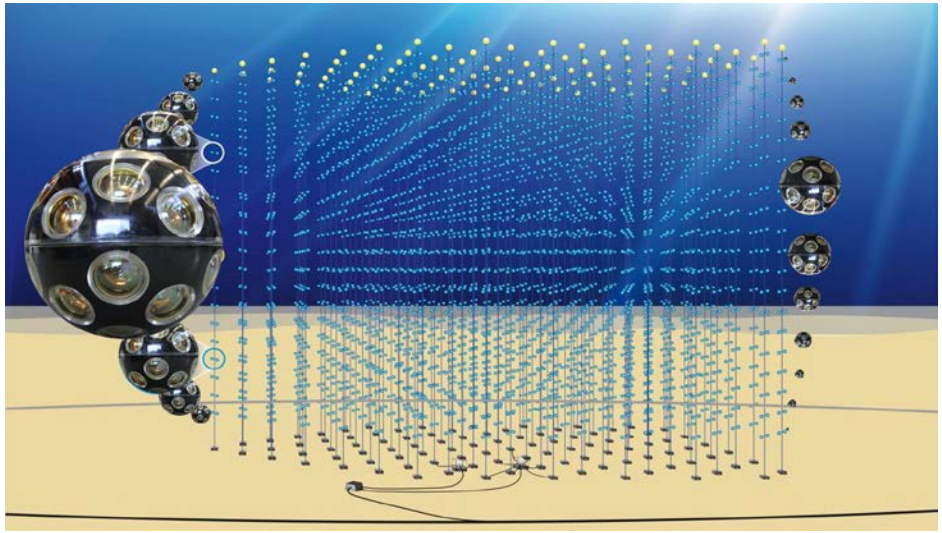
❖ ARCA (Astronomy)

- Building Block:
  - 115 strings
  - 18 DOMs / string
  - 31 PMTs / DOM
  - Total: 64k*3¨ PMTs

❖ ORCA (NMH+ ν properties)

- Same technology, denser layout

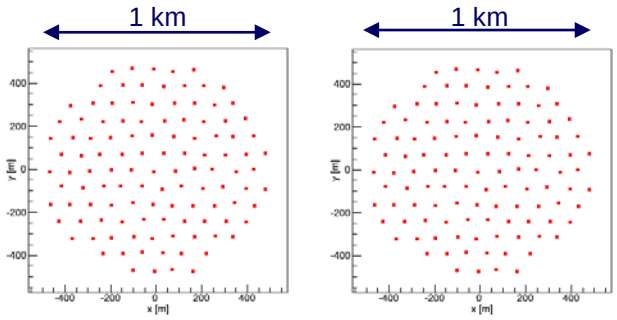
	ORCA	ARCA
String spacing	20 m	90 m
OM spacing	9 m	36 m
Depth	2470 m	3500 m
Instrumented mass	5.7 Mton	0.6*2 Gton



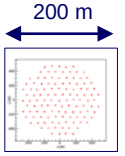
❖ Stages:

- Phase 1: 24 ARCA + 7 ORCA strings (already funded, being deployed)
- KM3NeT 2.0: 2 ARCA +1 ORCA blocks (~50% funded)
- Phase 3: 6 ARCA + 1 ORCA blocks

ARCA



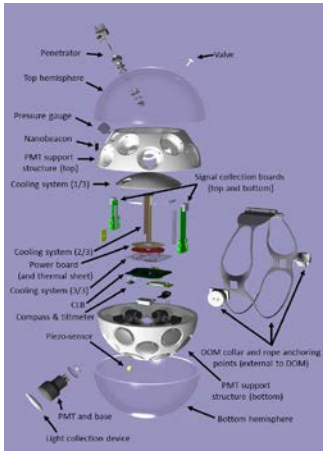
ORCA



KM3NeT Technology

Digital Optical Module

- DOM: 31 3” PMTs
- Digital photon counting
- Directional information
- Wide acceptance angle
- Cost reduction

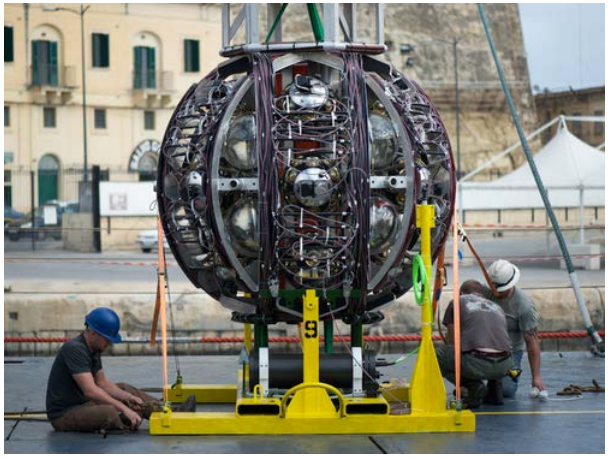


- All data to shore
- Gbit/s on optical fibre
- Hybrid White Rabbit
- LED flasher & hydrophone
- Tiltmeter/compass

String (Detector Unit)

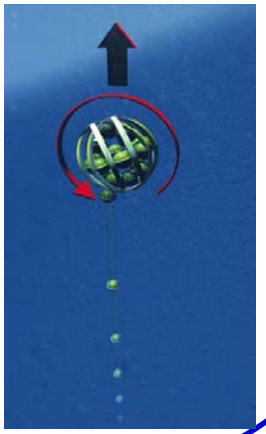
- High modulus polyethylene ropes
- Oil filled PVC tube
- Low drag
- Low cost

Deployment Vehicle



- Rapid deployment
- Multiple strings in one sea campaign

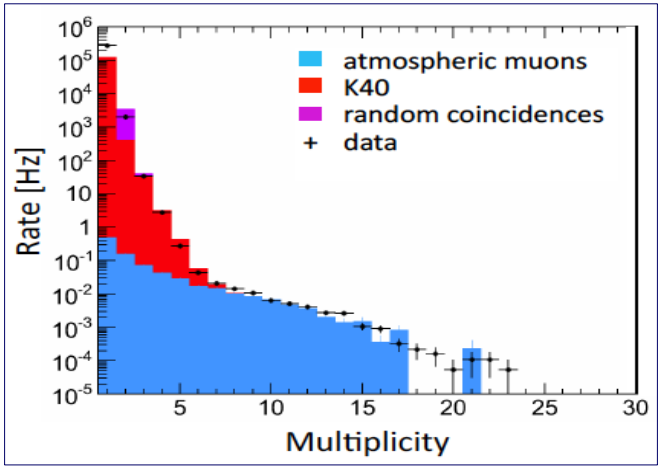
- Unfurling by autonomous ROV
- Reuseable



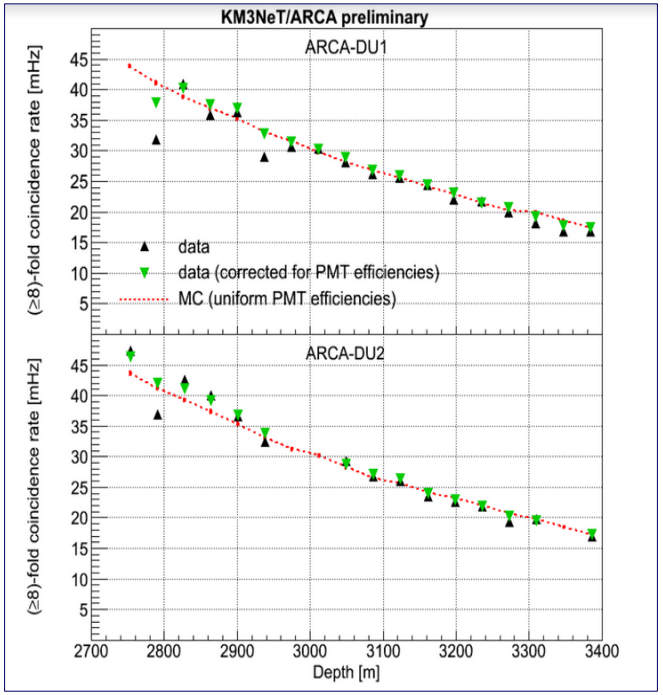
J. Phys. G: Nucl. Part. Phys. 43 (2016) 084001

First detection units

- DOM in ANTARES site
  - 2,500 m
  - April 2013
  - Muons from a single DOM
- Mini-string in ARCA site
  - 3,500 m
  - 3 DOMs
  - May 2014
  - Muon reconstruction,angular distribution
- Two full strings in ARCA site
  - Dec 2015 and May 2016
  - Muon reconstruction
  - Muons vs depth



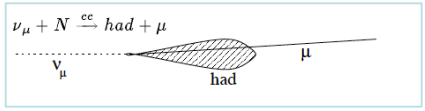
Eur. Phys. J. C (2014) 74:3056



Eur. Phys. J. C (2016) 76:54

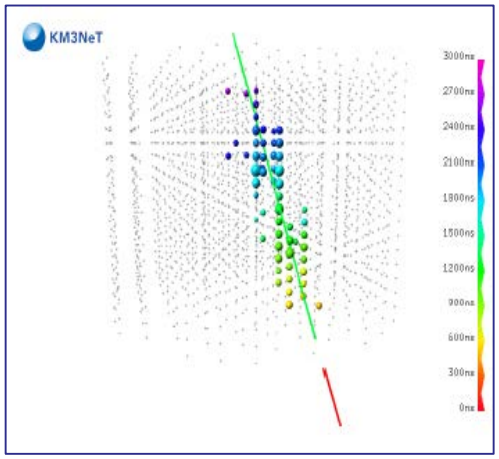
Performance – Track events

CC ν_μ

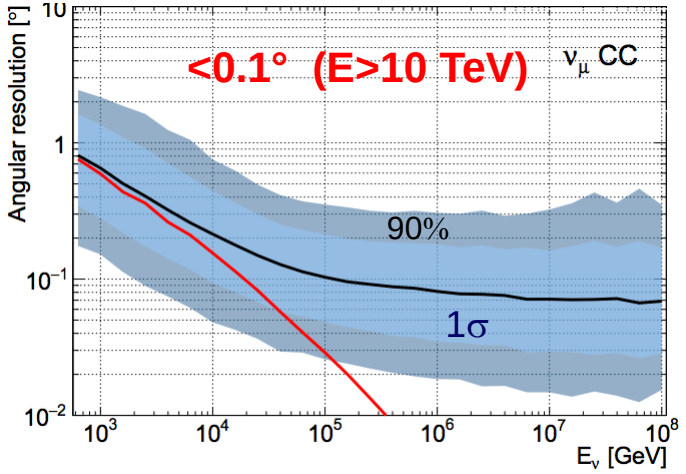


- Golden channel
- High angular accuracy
- Enhanced volume
  (100's m to a few Km muon range)

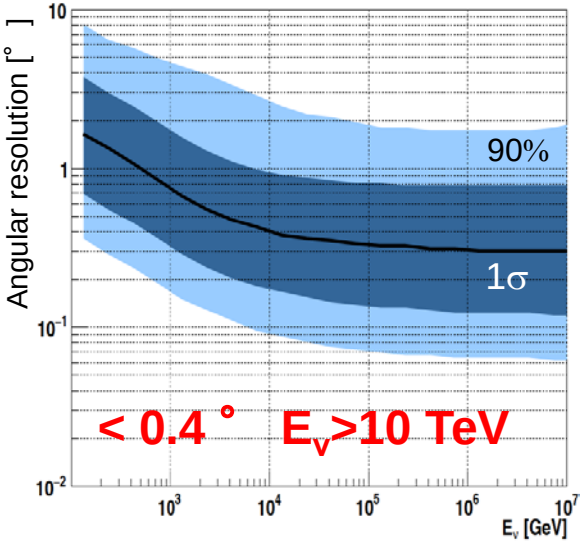
KM3NeT event



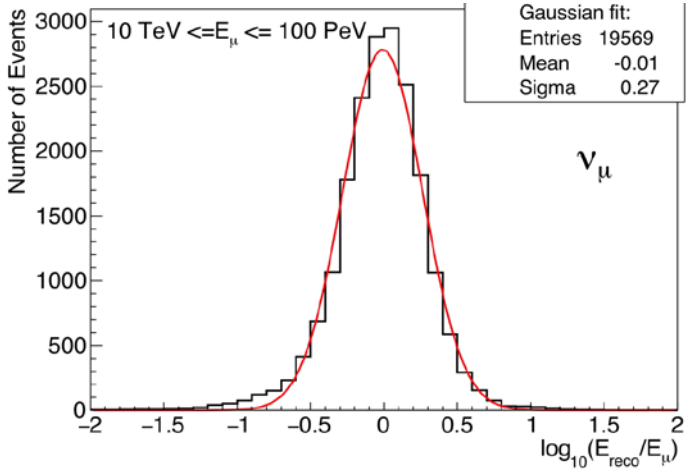
Direction (KM3NeT)



Direction (ANTARES)



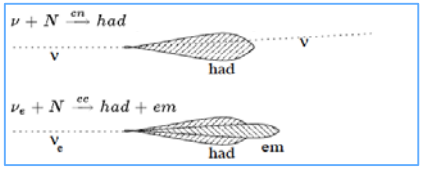
Energy (KM3NeT)



0.3 Log E (E>10 TeV)

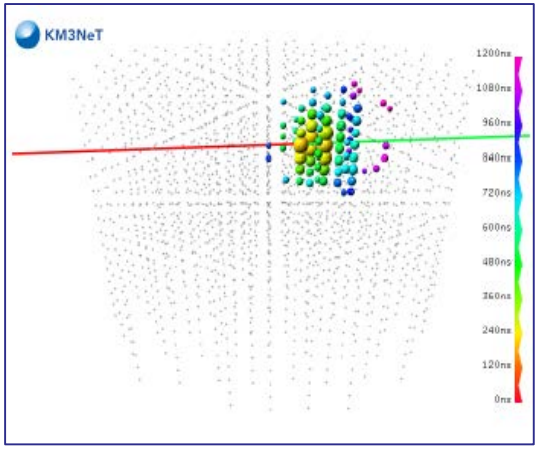
Performance – Shower events

NC ν_{all}
CC ν_e

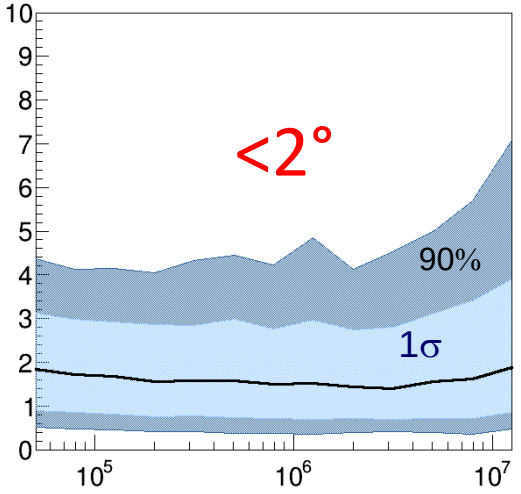


- Good energy reconstruction
- Fair angular resolution (low light scattering in water)

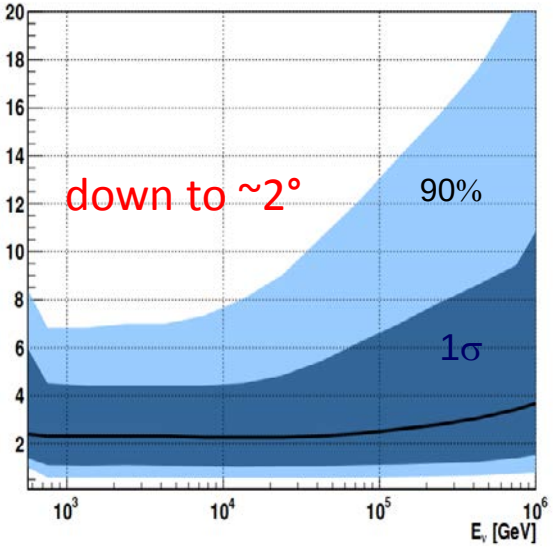
KM3NeT event



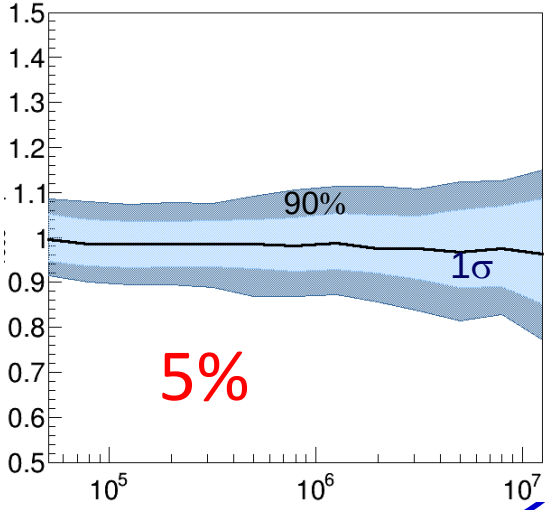
Direction (KM3NeT)



Direction (ANTARES)



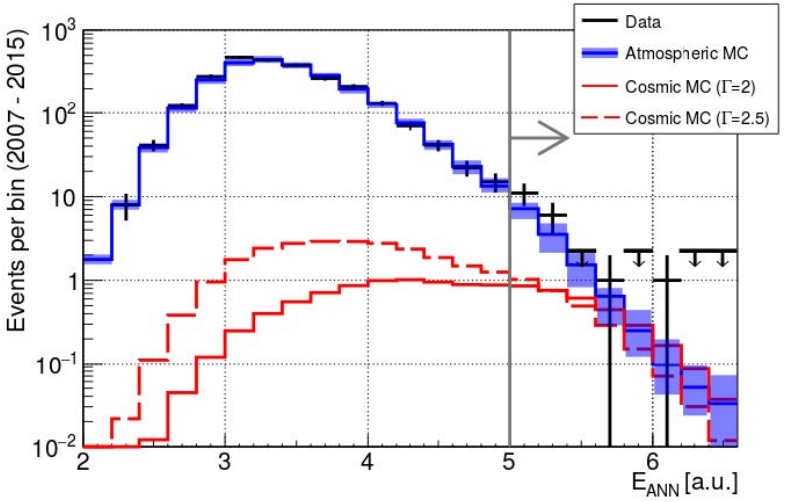
Energy (KM3NeT)



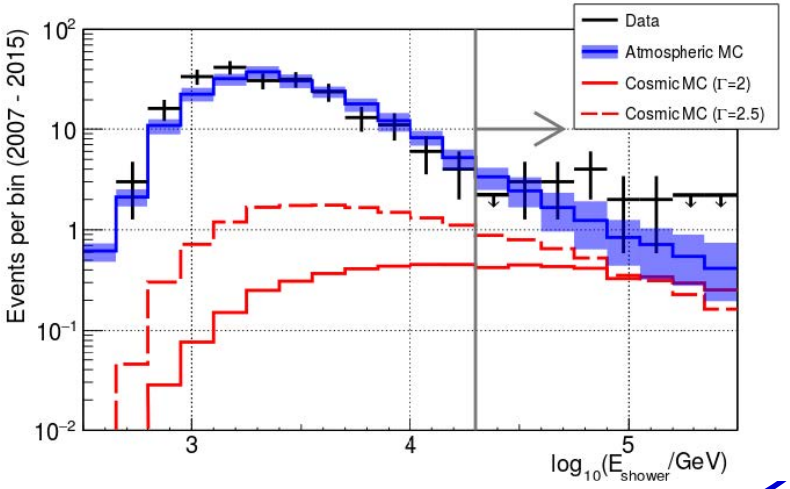
ANTARES – Diffuse Flux Search

- **Sample:**
  - Data collected 2007-2015
  - 2450 days
  - Tracks and showers
    - Tracks: CC: ν_μ
    - Showers: NC: ν_{all} + CC: ν_e , ν_τ
- **Selection:**
  - Event selection
    - $\theta > 90°$ + reconstruction quality parameters (tracks)
  - Energy-based selection by MRF
    - Tracks: Artificial neural networks
- **Methods:**
  - Blinded optimization
    - Energy-related cut
    - Two spectral indexes Γ=2.0 and 2.5
  - Assumptions
    - Isotropic flux
    - Equipartition among 3 flavours
    - Single power law spectrum

Tracks



Showers



Diffuse Flux – Results

- Unblinding:

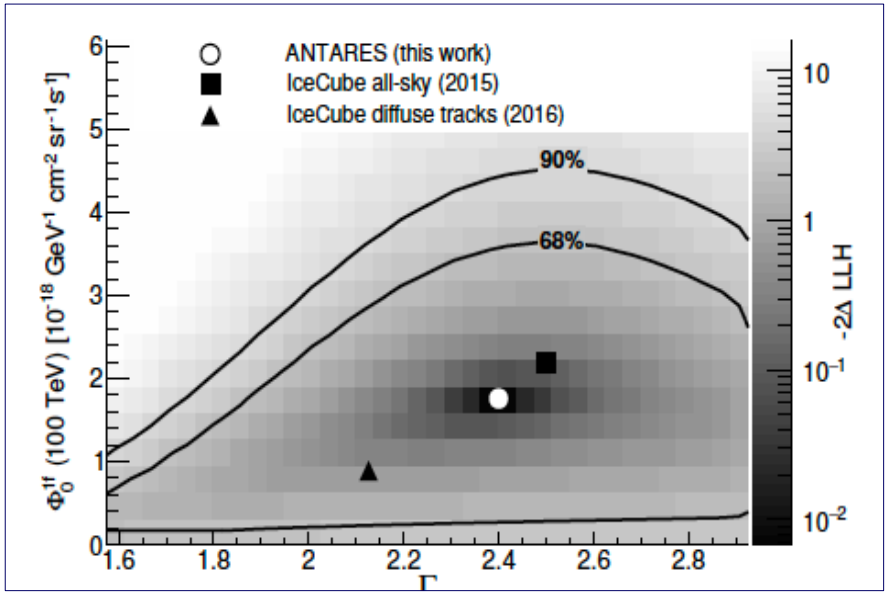
	Events	tracks		showers
Observed:	33 =	19	+	14
Expected:	24 =	13.5	+	10.5

  - Small excess in both samples

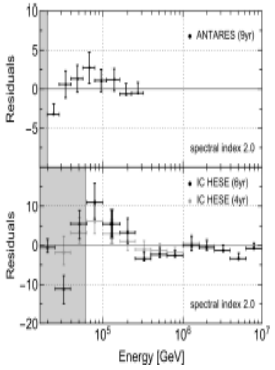
- Best fit (1 flavour flux norm at 100 TeV)

$\Phi_0(100\ \text{TeV}) = (1.7 \pm 1.0) \times 10^{-18}\ \text{GeV}^{-1}\ \text{cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$

Spectral index: $\Gamma = 2.4^{+0.5}_{-0.4}$



- Features:
  - Compatible with IceCube signals
  - Null flux excluded at 1.6σ
    Not very constraining
  - See plot Φ_0 vs Γ



- Chianese et al:
  - Excess at 50 TeV?
  - Single power law?

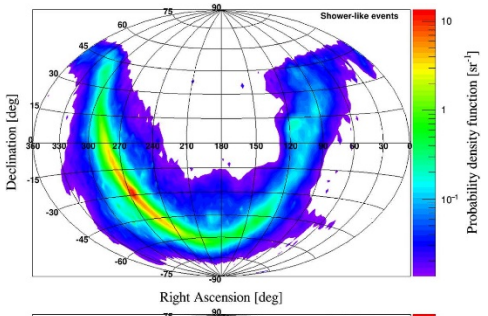
Φ (10^{-18}) GeV^{-1} cm^{-2} s^{-1} sr^{-1}	Γ=2.0	Γ=2.5
sensitivity (90%)	1.2	2.0
upper limit (90%)	4.0	6.8
confidence interval (68%)	0.2 -2.9	0.5 - 5.0

arXiv:1711.07212

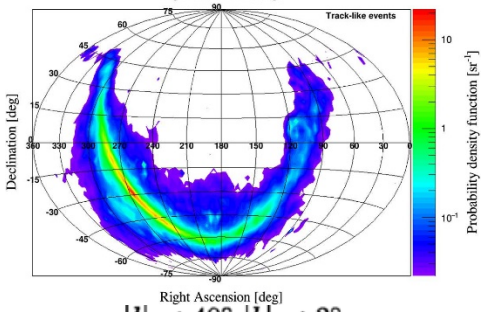
Galactic Plane

- ν's from CR-medium interactions
- KRA_γ model of diffuse gammas
  - CR local features and gamma observations reproduced
- Search strategy:
  - Signal map according to KRA_γ modelling
  - Two ref models: 5 PeV and 50 PeV cutoffs
- Sample:
  - Data collected 2007-2015
  - 7300 Tracks and 208 showers
- Results:
  - No excess of events
  - 90% flux limits for ref models:

    < 1.1 Φ(5 PeV) < 1.2 Φ(50 PeV)
  - Not the source of "spectral anomaly" (IC spectrum in hemispheres)

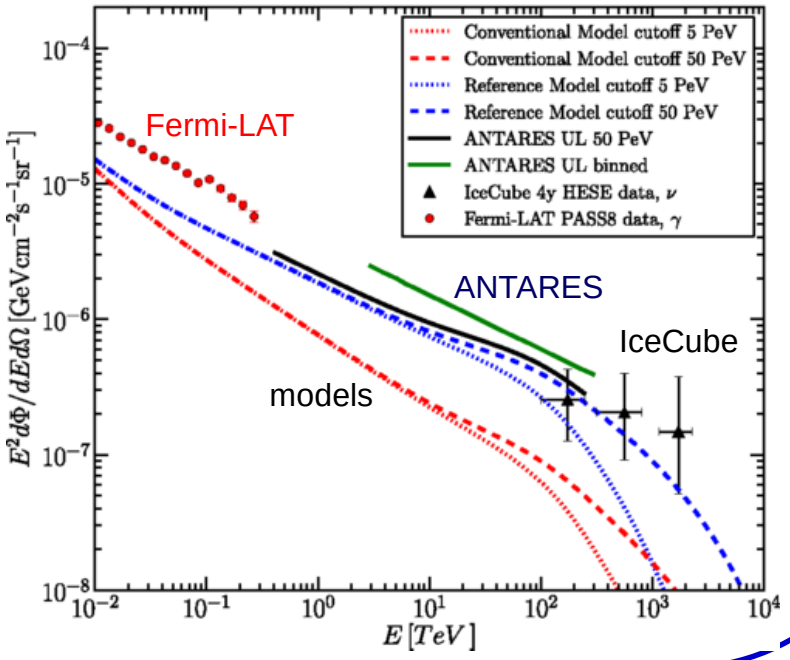


Showers



Tracks

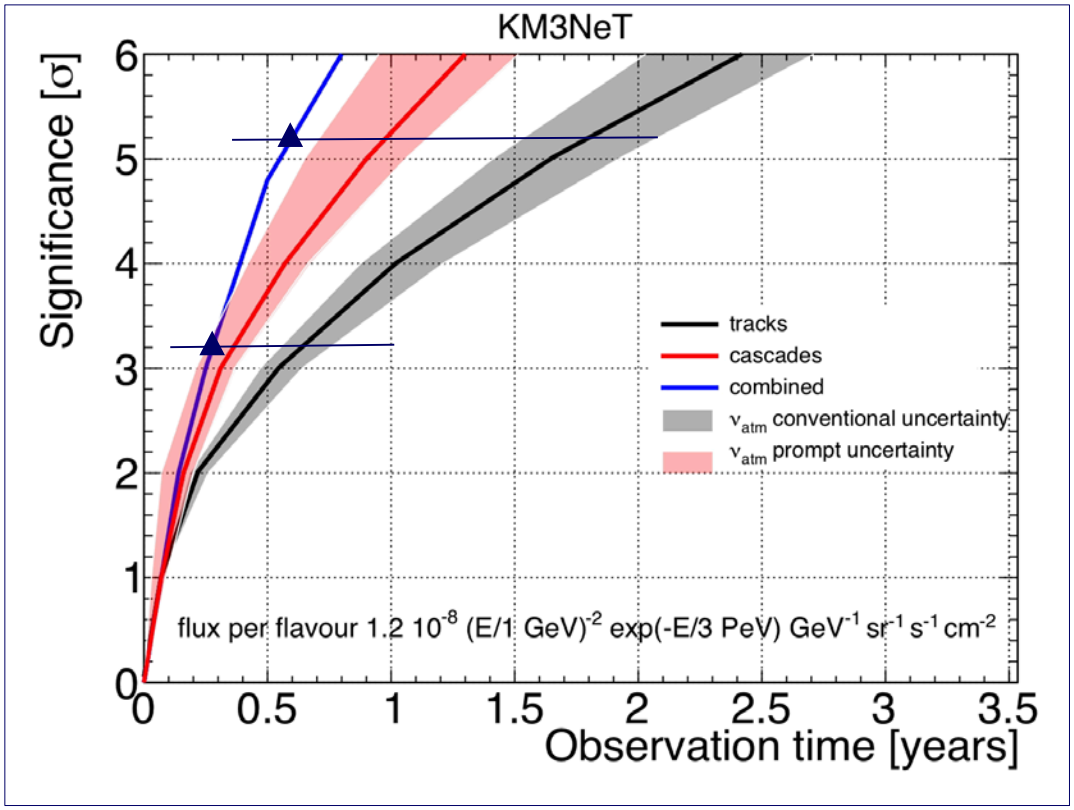
$|l| < 40°$ $|b| < 3°$



Phys. Rev. D **96** 062001 (2017)

Diffuse KM3NeT

- Tracks:
  - Analysis for up-going events based on max. likelihood
  - Pre-cuts on θ_{zen} >80°
  - reconstruction quality parameter and Nhit (proxy for muon energy)
  - 5σ in 1.7 year (IC flux)
- Showers:
  - Containment cut on reconstructed vertex
  - Full sky analysis based on BDT and maximum likelihood.
  - 5σ in 1 year (IC flux)

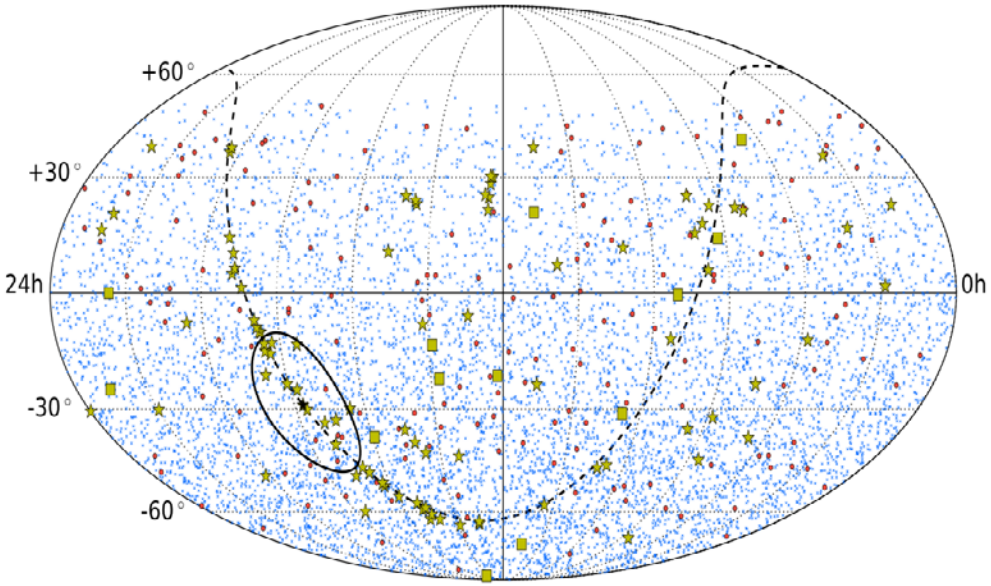


KM3NeT 2.0 can observe (3σ) IceCube signal in 3 months and confirm it (5σ) in six months

Antares Point Sources

❑ Sample:

- ❖ 2007-2015
- ❖ 2424 days of live time
- ❖ 7629 Tracks, 180 Showers (all flavour analysis)



Track
Showers
Source candidate
HESE track

❑ Analysis:

- ❖ *Full-sky Search*
  - 1°x1° squares over ANTARES visible sky
- ❖ *Candidate list Search*
  - 106 objects (pulsars, SNRs, etc.)
  - 13 IceCube HESE tracks
- ❖ *Galactic Centre Region*
  - Ellipse 15°x 20°
  - Test:
    - Spectral indices γ = 2.1, 2.3, 2.5
    - Extension σ = 0.5°, 1.0°, 2.0°
- ❖ *Sagittarius A* location*
  - Extended source. Gaussian profile of various widths: σ = 0°, 0.5°,1.0°, 2.0°)

Full sky

Most significant cluster
(α,δ) = (343.8°, 23.5°)
Post-trial significance:
5.9% or 1.9σ
Upper limit on the neutrino flux:
$E^2 d\phi/dE = 3.8 \times 10^{-8}$ GeV cm^{-2} s^{-1}

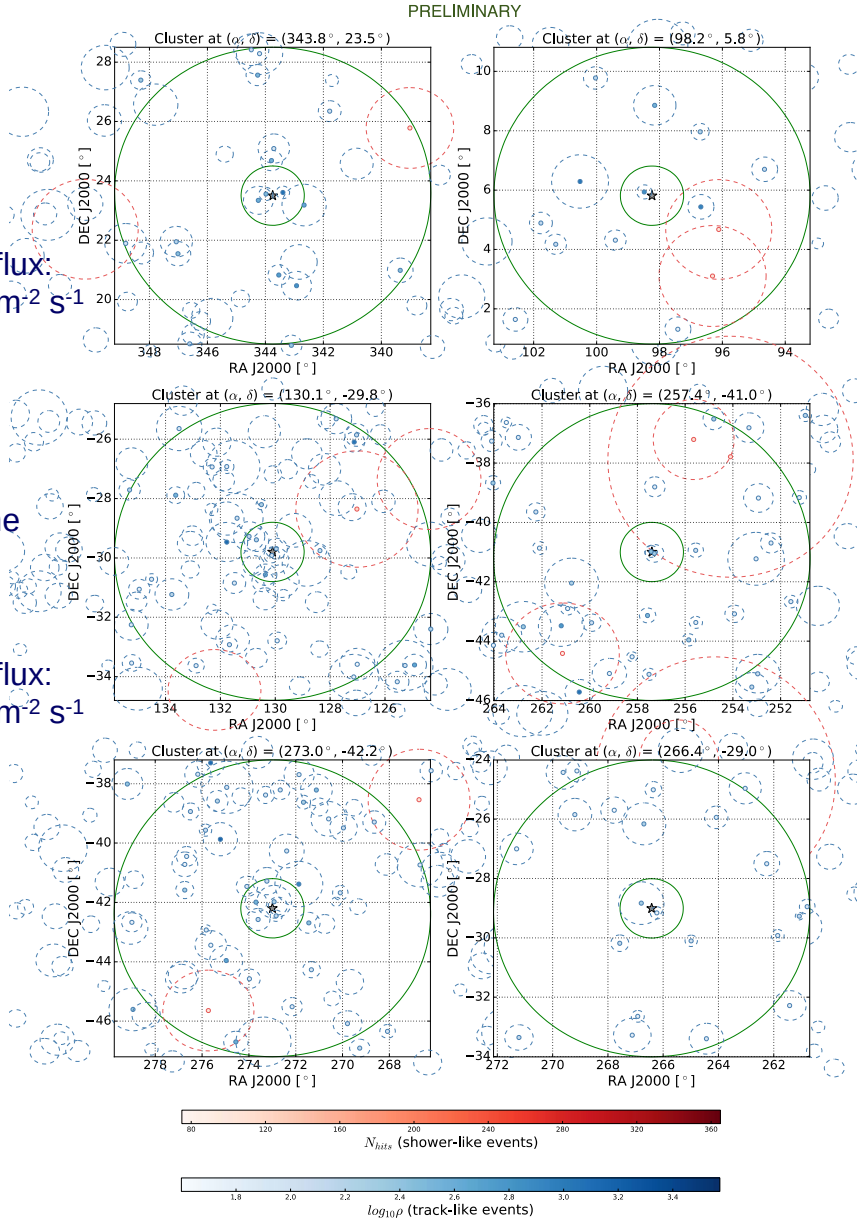
13 HESE tracks

Most significant cluster:
(α,δ) = (130.1°, -29.8°)
at a distance of 1.5° from the HESE track with ID 3
Post-trial significance:
20% or 1.3σ
Upper limit on the neutrino flux:
$E^2 d\phi/dE = 2.1 \times 10^{-8}$ GeV cm^{-2} s^{-1}

Galactic Centre

(γ = 2.1, 2.3, 2.5)
(σ = 0.5°, 1.0°, 2.0°)
(α,δ) = (273.0°, -42.2°)
$E^{-2.5}$ spectrum
point-like source
Post-trial significance:
30% or 1.0σ

PRELIMINARY



Candidate List:

Most significant cluster:
HESSJ0632+057
(α,δ) = (98.24°, 5.81°)
Post-trial significance:
13% or 1.5σ
Upper limit on the neutrino flux:
$E^2 d\phi/dE = 2.4 \times 10^{-8}$ GeV cm^{-2} s^{-1}

Galactic Centre

Spec indices γ = 2.1, 2.3, 2.5
Extension σ = 0.5°, 1.0°, 2.0°
Most significant cluster:
(α,δ) = (257.4°, -41.0°)
for a E^{-2} spectrum + point-like source
Post-trial significance:
60% or 0.5σ

Sagittarius A*:

(α,δ) = (266.42°, -29.01°)
Point-like source (σ = 0°) and
Extended source (σ = 0.5°,1.0°, 2.0°)
Largest excess as point-like
Pre-trial significance:
22% or 1.2σ

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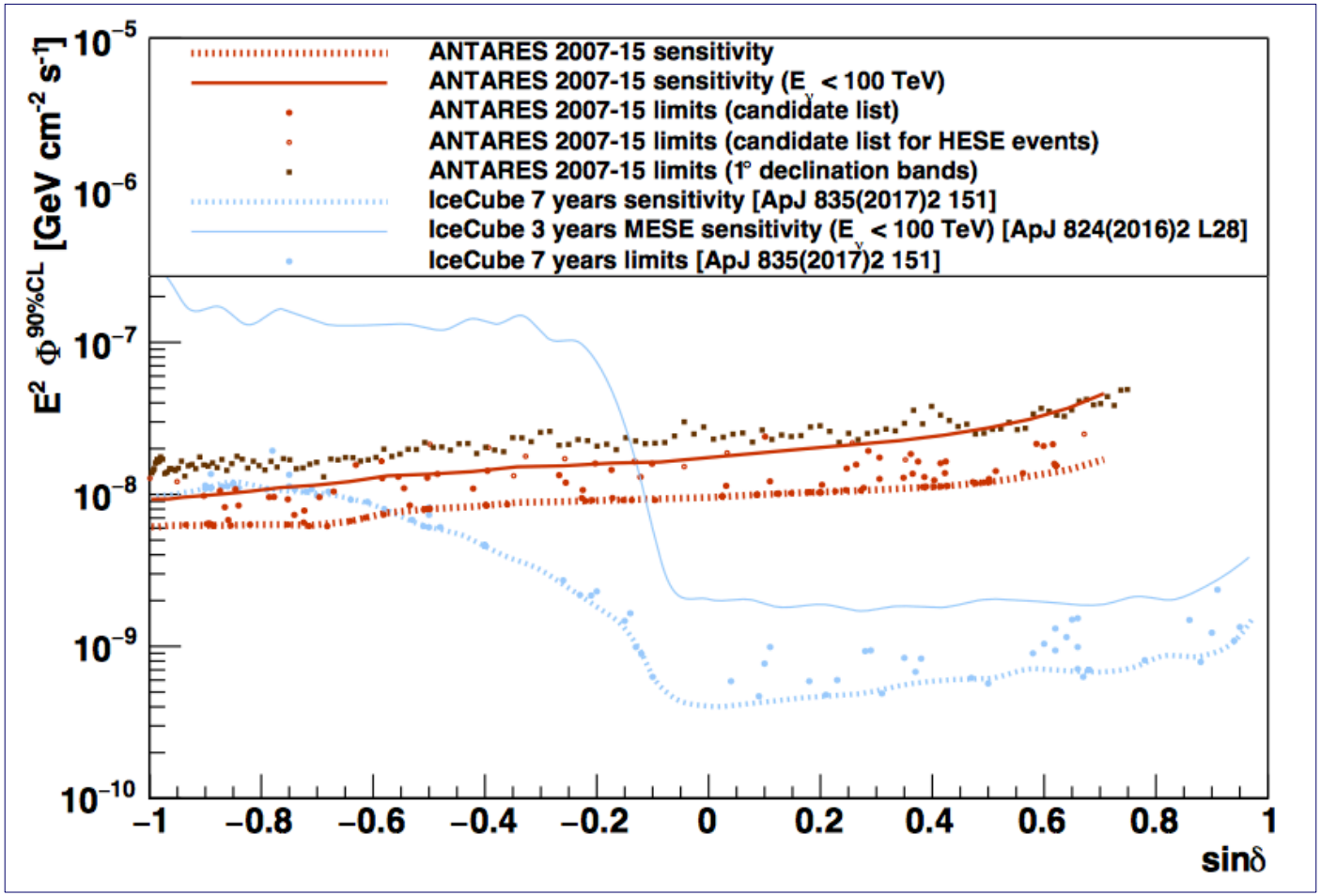
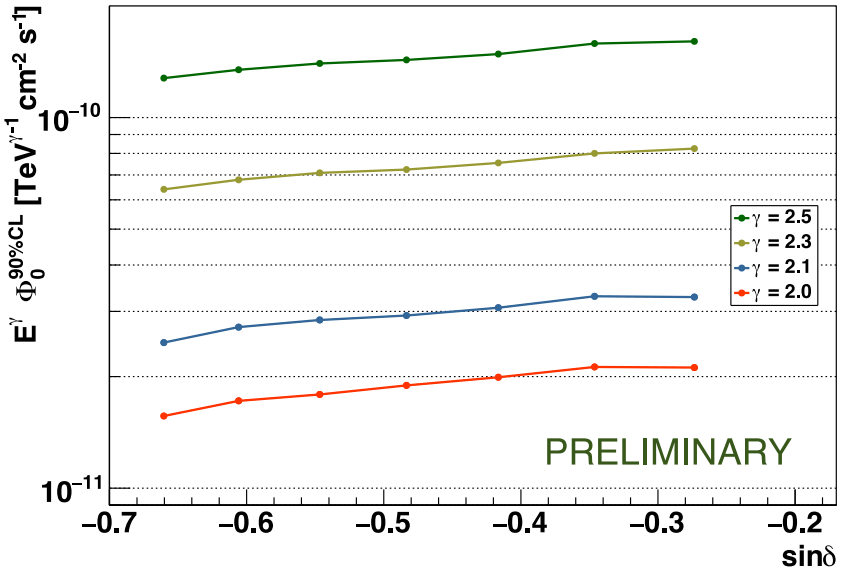
Full-sky and Candidate list searches

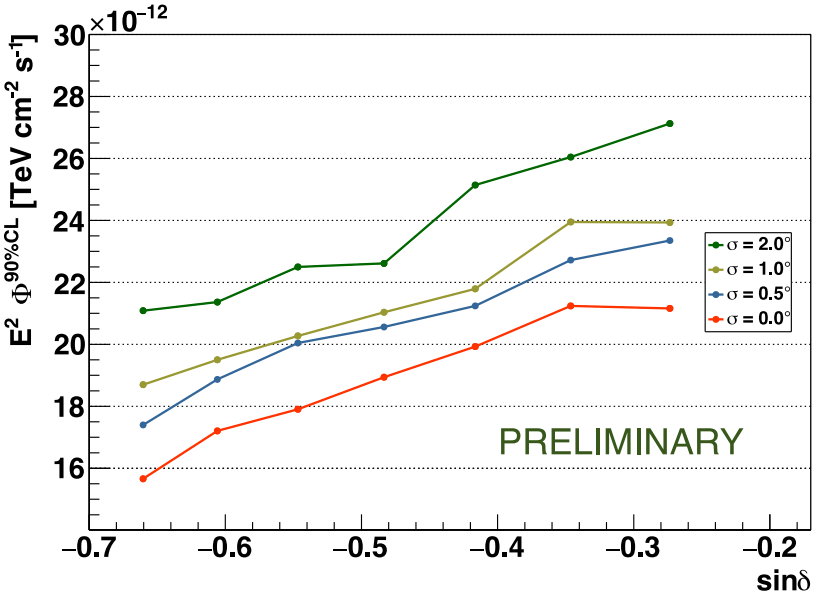
Sensitivities and upper limits at a 90% C.L. on the signal flux from the Full-sky and the Candidate list searches



Galactic Centre Region

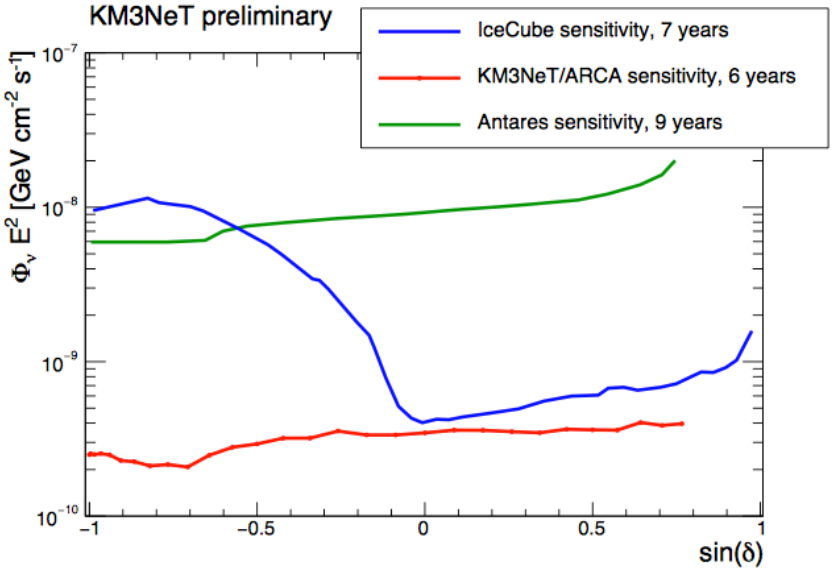
90% C.L. upper limits of the search restricted to the region around the origin of the galactic coordinates at (α,δ) = (266.40°,-28.94°) assuming different spectral indices for the neutrino flux (left) and different source extensions for γ= 2 (right).



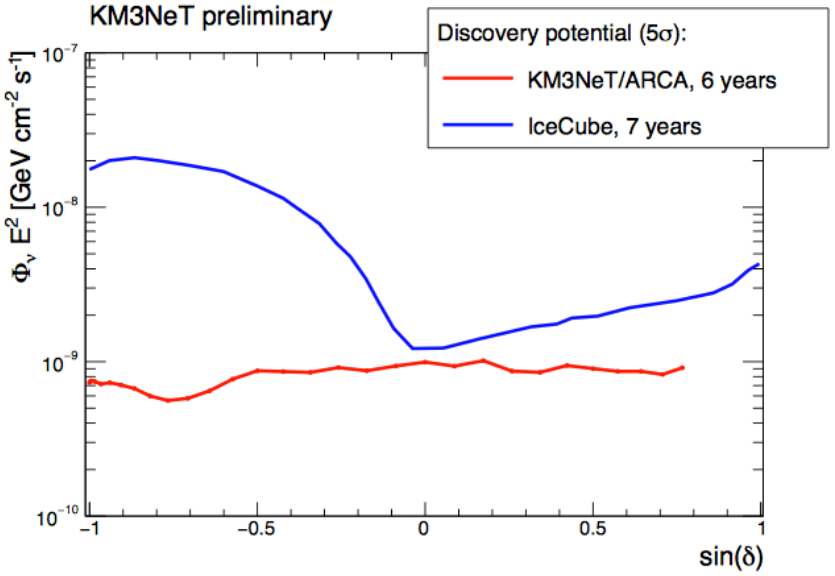


KM3NeT/ARCA Expectations (E^{-2} Spectrum)

Sensitivity



Discovery potential



KM3NeT/ARCA point sources

- Only up-going track events

(estimated contribution from cascades from previous analyses ~ 20%)

- Discovery fluxes for:
  - Generic point-like source with spectrum $\propto E^{-2}$
- Benchmark fluxes from candidate Galactic neutrino sources
  - Expected neutrino fluxes estimated from the observed ɣ-ray spectra following [1]

    (RXJ1713.7-3946(1) from [2])
  - Assumptions:
    - Hadronic scenario for the ɣ-ray production
    - Transparent sources

Source	δ	extension	Φ_0	Γ	E_{cut}	β
RX J1713.7-3946 (1)	-39.77°	0.6°	1.68	1.72	2.1	0.5
RX J1713.7-3946 (2)	-39.77°	0.6°	0.89	2.06	8.04	1
Vela X	-45.6°	0.8°	0.72	1.36	7	1
Vela Jr	-46.36°	1°	1.30	1.87	4.5	1
HESSJ1614-518 (1)	-51.82°	0.42°	0.26	2.42	-	-
HESSJ1614-518 (2)	-51.82°	0.42°	0.51	2	3.71	0.5
Galactic Centre	-28.87°	0.45°	0.25	2.3	85.53	0.5

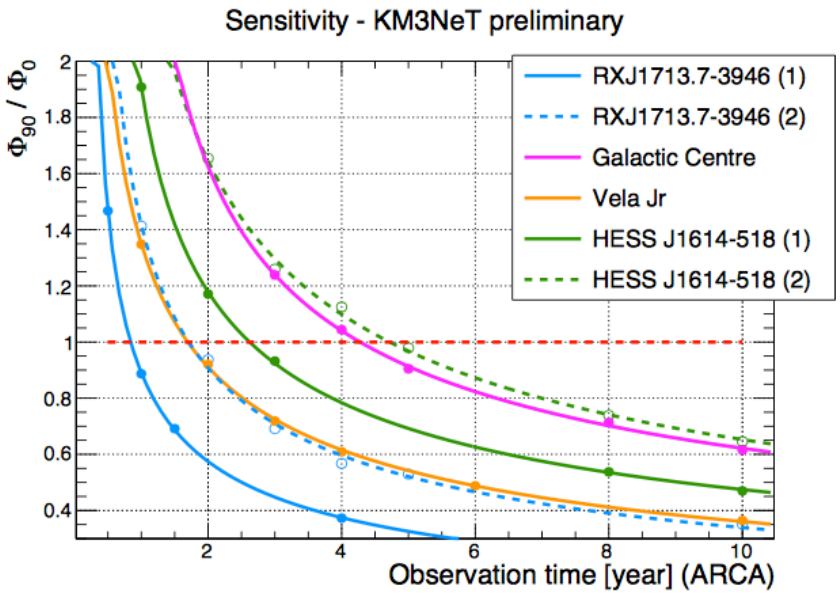
$$\Phi_\nu(E) = \Phi_0 \, E^{-\Gamma} \, exp(-(E/E_{cut})^\beta) \; \mathrm{TeV}^{-1}\,\mathrm{s}^{-1}\,\mathrm{cm}^{-2}$$

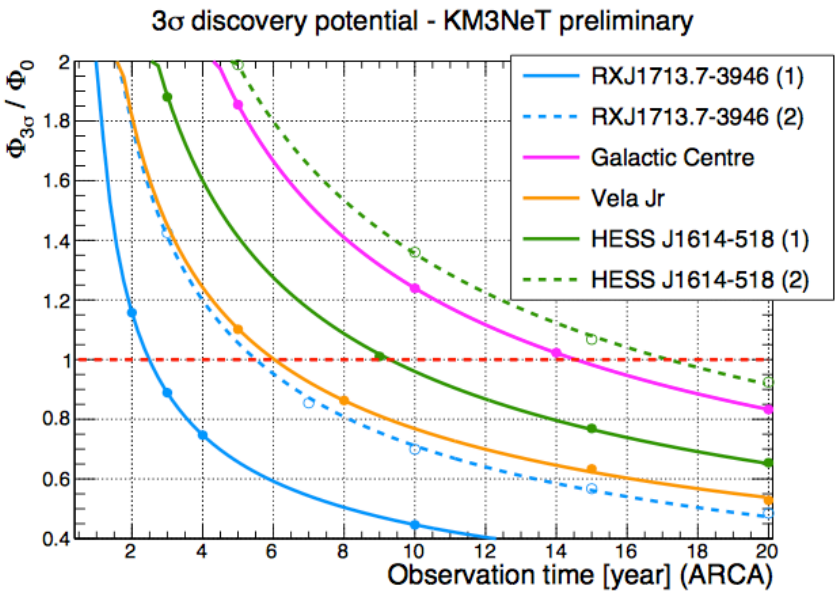
Φ_0 [10^{-11} TeV^{-1} s^{-1} cm^{-2}]

[1] F. Vissani, Astr. Phys. 26 (2006) 310

[2] S. R. Kelner, Phys. Rev. D 74 (2006), 063007

KM3NeT/ARCA Expectations (Galactic sources)



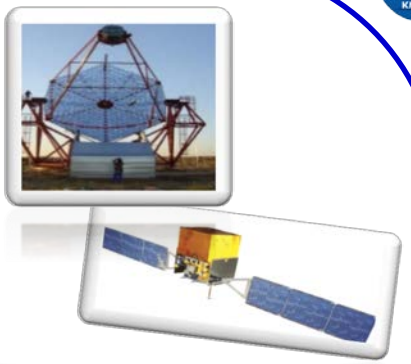


Multimessenger Programme

- Advantages:
  - A-priori interesting sources or events
  - Reduced background:
    - Uncorrelated between techniques
    - Transient/short time events
    - Spatial location
  - Fully exploit the ν telescopes features:
    - Continuous monitoring
    - Wide angle survey
    - High efficiency, low latency (all-data-to-shore, fast reconstruction)
- Send and receive alerts:
  - Alerts from:
    - Flaring AGNs, X-ray binaries
    - GRBs, FRBs
    - Gravitational waves
    - SN Ib,c
  - Alerts sent out if:
    - High energy neutrino
    - Multiplets
    - Preferred direction

GeV-TeV γ-rays

Fermi, HESS, HAWC



Radio-Visible-X

MWA, SUPERB
TAROT, ZADKO, MASTER
Swift

UHE Cosmic rays

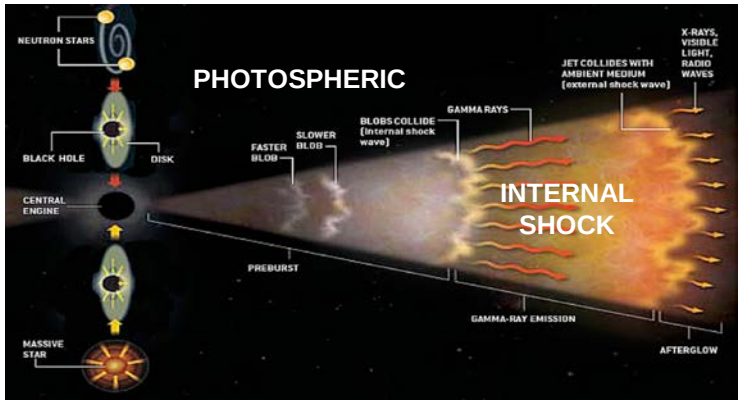
Auger, TA

Gravitational waves

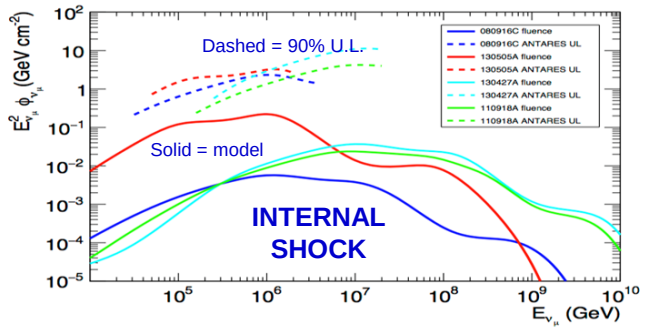
LIGO-VIRGO-EGO

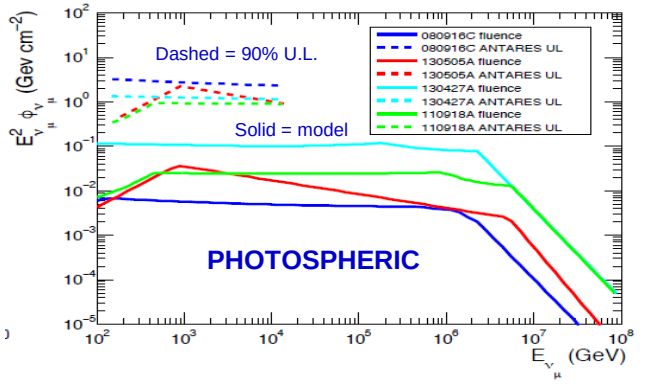
Gamma-ray Bursts

- Individual Search
  - 4 bright GRBs (2008-2013)
  - Two scenarios:
    - Photospheric
    - Internal shock
  - Optimization and limits for each scenario
  - Reasonable parameters to derive spectra (Γ= 316 and f_p = 10)



- Source stacking
  - Long GRBs: T90 ≥ 2 s;
  - Gamma-ray spectrum is well constrained
  - ANTARES 2008-2016 (upgoing events)
  - 462 sources
  - No events in coincidence.
    - Limits on the GRB quasi-diffuse emission and constraints on the baryonic content of the jet





MNRAS(2017) 469 (1): 906-915

Eur. Phys. J. C (2017) 77: 20

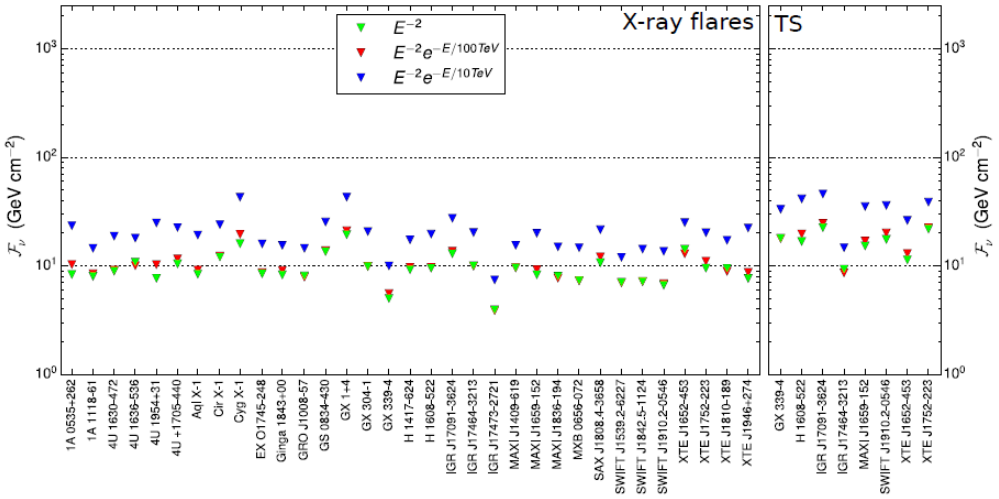
Flaring X-ray Binaries

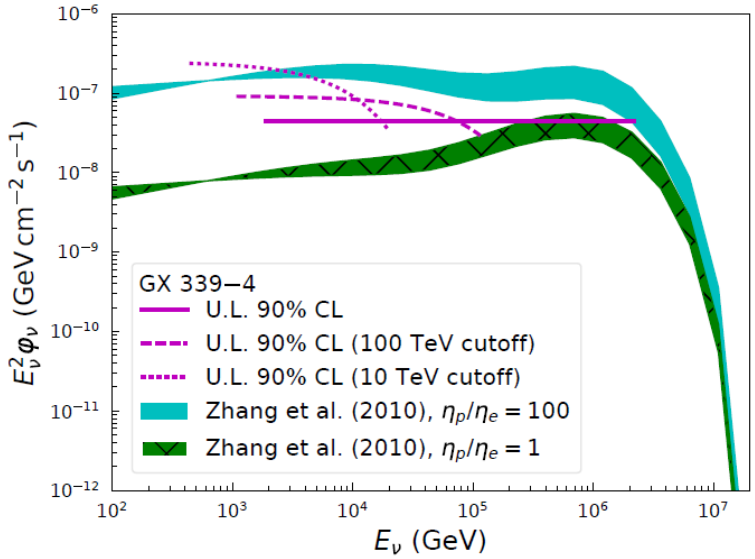
- X-Ray Binaries:
  NS/BH + companion Star
  - Accretion produces outflows
  - Wide-angle shocks but also relativistic jets (μ-quasars)
  - Outbursts often observed
  - GeV-TeV γ emission observed
  - Possible hadronic acceleration

- Flaring periods
  - ANTARES 2008-2012 data
  - 33 XRB sources (8 during hardness transitions periods)
  - Flares from light curves (Swift/BAT, RXTE/ASM, MAXI)
  - No neutrino signal

1(3) events in 1°(3°) cone for GX 1+4 during flare, but post-trial prob 72%

  - Translated into neutrino fluency (flux x time) upper limits

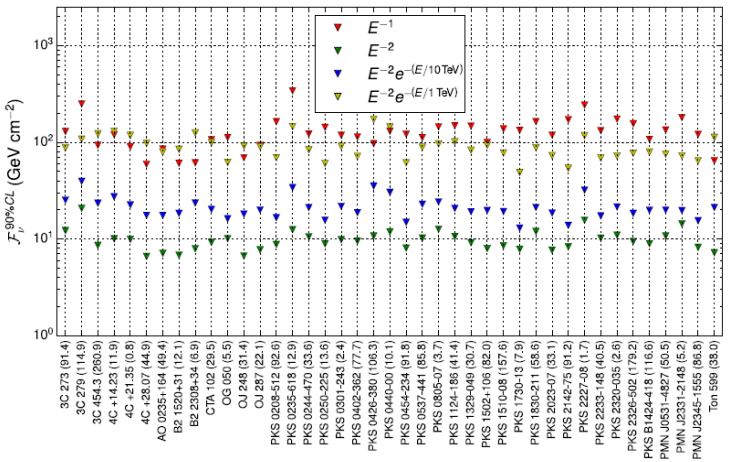




Some micro-quasar models are constrained

Flaring Blazars

- Blazars and extragalactic flares:
  - AGN with relativistic jets
  - High variability in gamma-rays
  - Neutrinos if hadronic acceleration
  - Look for neutrinos in coincidence wth flaring periods

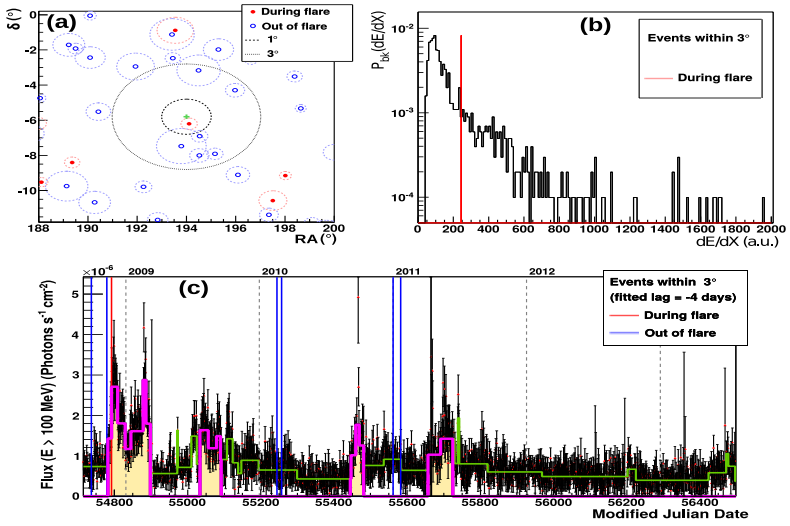


- Flaring periods:
  - ANTARES 2008-2012 (1044 days)
  - FermiLAT: 41 Blazars (33 FSRQs+7 BL Lacs + 1 unknown)
  - IACTs: 7 TeV flares (HESS, MAGIC, VERITAS)
  - All coincident neutrinos compatible with background. Fluency limits
  - Most significant: 3C279. One neutrino event coincident with large flare.

    p-value 3.3%, post-trial: 67%
  - Soon to come:

    ANTARES 2008-2016 data (2413 days) with tracks and showers

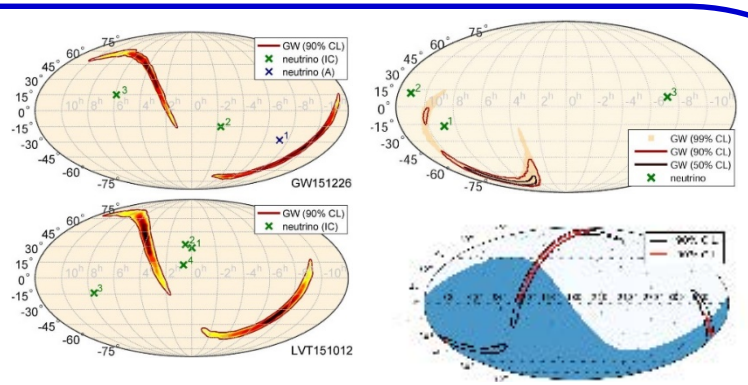
3C279

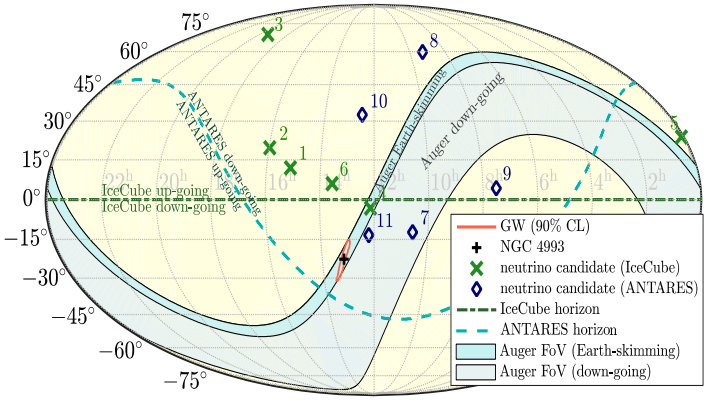


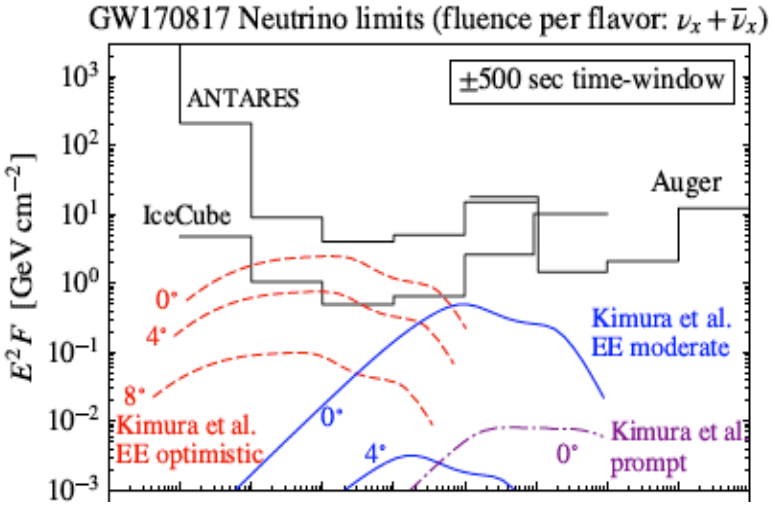
Gravitational Waves

- Search ν in coincidence with:
  - BBH's: GW150914, LVT151012, GW151226, GW170104
  - BNS: GW170817
- Search features:
  - Most recent reconstruction (offline search advantage).
  - ± 500 s around GW time
  - Individual optimization (3σ detection if event within 90% GW contour)
  - Combined IceCube-Antares analyses
- No coincident events found
  - GW151226 (1 event)
  - GW170817 (5 events/downgoing)
  - Upper limit on fluences:

    $E_{iso} < 10^{51} – 10^{54}$ erg





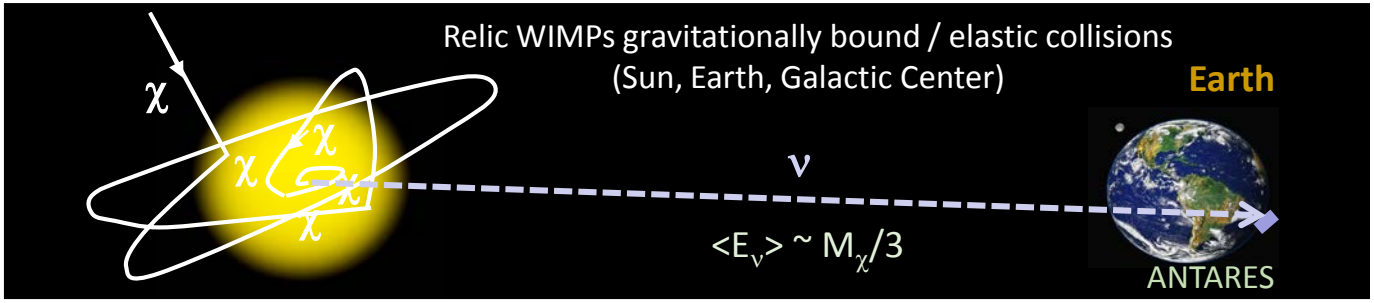


Phys. Rev. D 93, 122010 (2016)

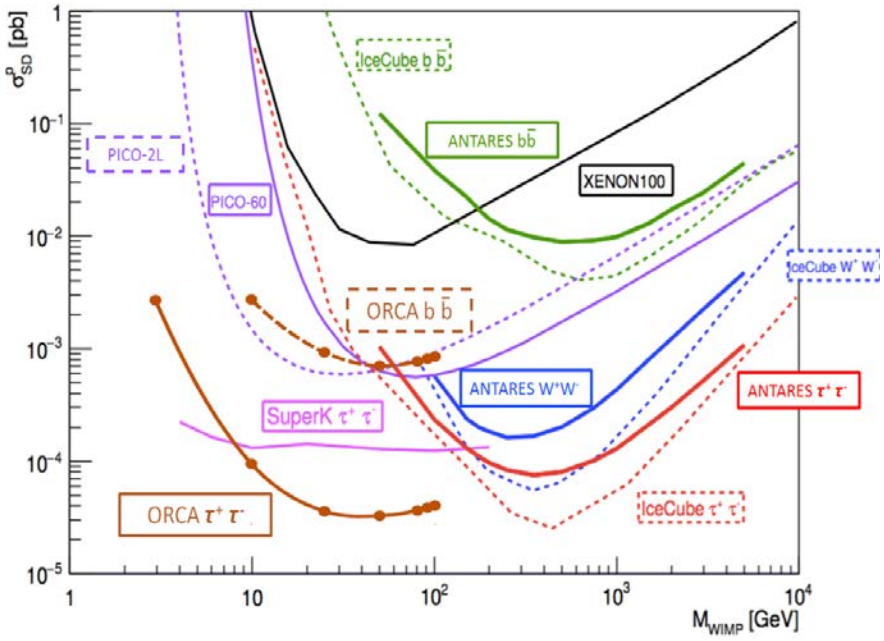
Phys. Rev. D 96 022005 (2017)

ApJ Letters 850:L35 (2017

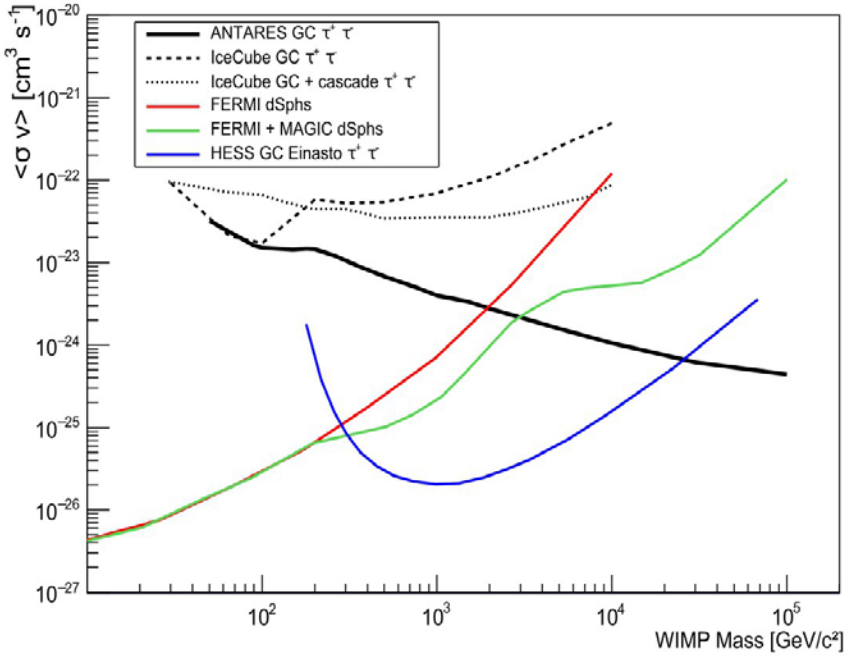
Dark matter annihilation (as a source of CRs)



Sun – spin-dependent cross section



Galactic Centre



Phys.Lett. B759(2016) 69-74

Phys. Let. B 769 (2017) 249

Summary

- ANTARES:
  - 10 year experience. Thousands of ν's reconstructed (tracks and showers). Excellent resolution (down to 2° for showers!)
  - Diffuse flux: a small excess at high energy compatible with a cosmic signal
  - Point sources: best limits for southern sky Galactic sources (E< 100 TeV)
  - A lively and vibrant multi-messenger programme search. We need a larger detector!

- KM3NeT:
  - On the move!
    - 2 ARCA and 1 ORCA strings in water (teething problems, soon to be fixed)
  - KM3NeT 2.0:
    - ESFRI Roadmap 2016, APPEC European Strategy 2017
    - ARCA : high-resolution follow up of IceCube flux (5σ within 1 yr)
    - ORCA : Measure neutrino mass hierarchy (3σ in 4 years)
  - Strings in production…

END