Mediterranean ν-Telescopes

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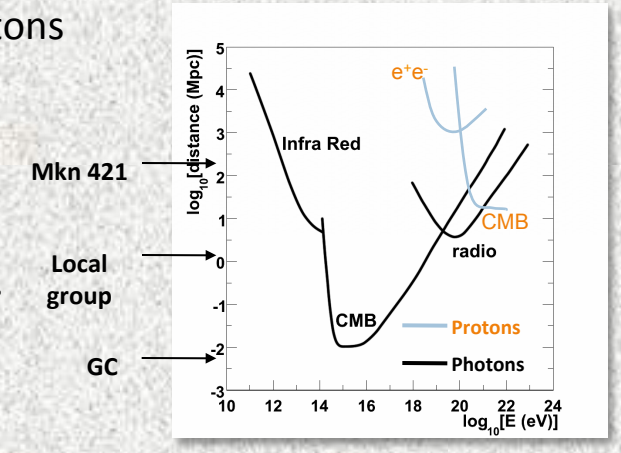
IFIC (CSIC-UV)

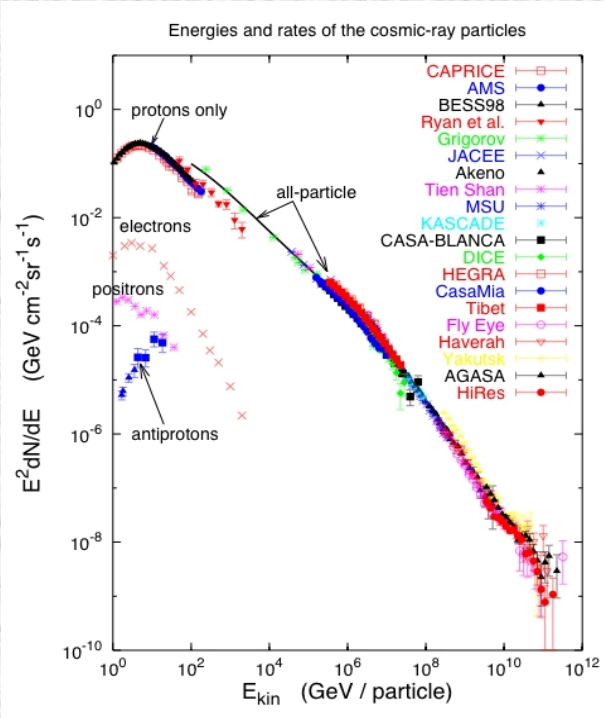
Astroparticle Physics and Cosmology, IFT, UAM, 21-25 October 2013

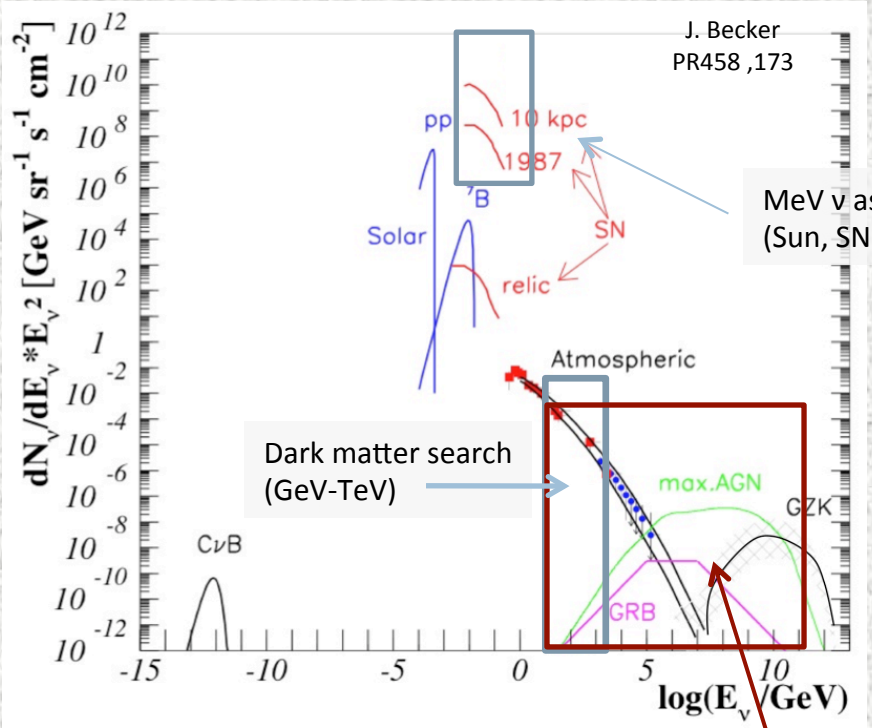
Why neutrino as cosmic messenger?

- Protons are deflected by magnetic fields ($E_p < 10^{19}$ eV) UHE protons interact with the CMB ($E_p > 10^{19}$ eV → 50 Mpc)
- Neutrons decay (~10 kpc at E ~ EeV).
- Photons interact with the EBL (~100 Mpc) and CMB (~10 kpc).
- Neutrinos are neutral, weakly-interacting particles.



Where can HE neutrinos come from?





MeV ν astrophysics (Sun, SN1987A)

Dark matter search (GeV-TeV)

p/N accelerators do exist
Possible sources :
Galactic:
SNRs
Extragalactic:
AGNs, GRBs

but origin still <u>not</u> settled

Accelerated p and nuclei can produce neutrinos:

$$p + A/\gamma \rightarrow \pi^{\pm} + \ldots$$

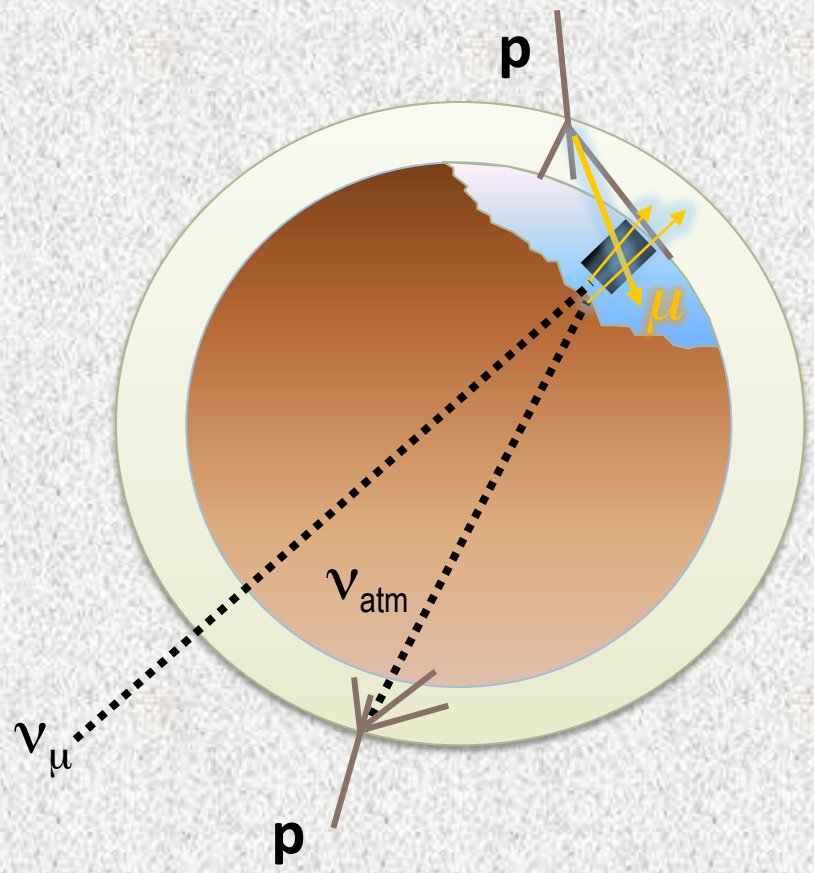
$$\rightarrow \mu^{\pm} + \nu_\mu(\bar{\nu}_\mu) + \ldots$$

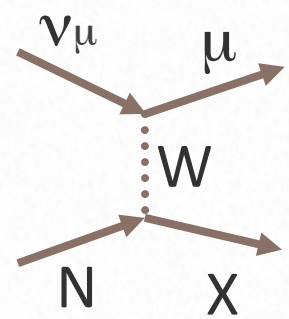
$$\rightarrow e^{\pm} + \nu_e(\bar{\nu}_e) + \nu_\mu(\bar{\nu}_\mu) + \ldots$$

High energy ν Astronomy

Detection techniques exist for $E_\nu \approx 10$ GeV – 10^2 EeV
(10 orders of magnitud same span as radio to X-ray in EM radiation, but at $\lambda < 10^{-14}$ cm)

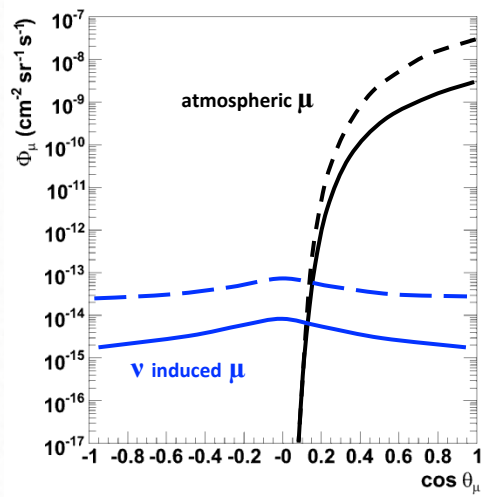
Detection principle

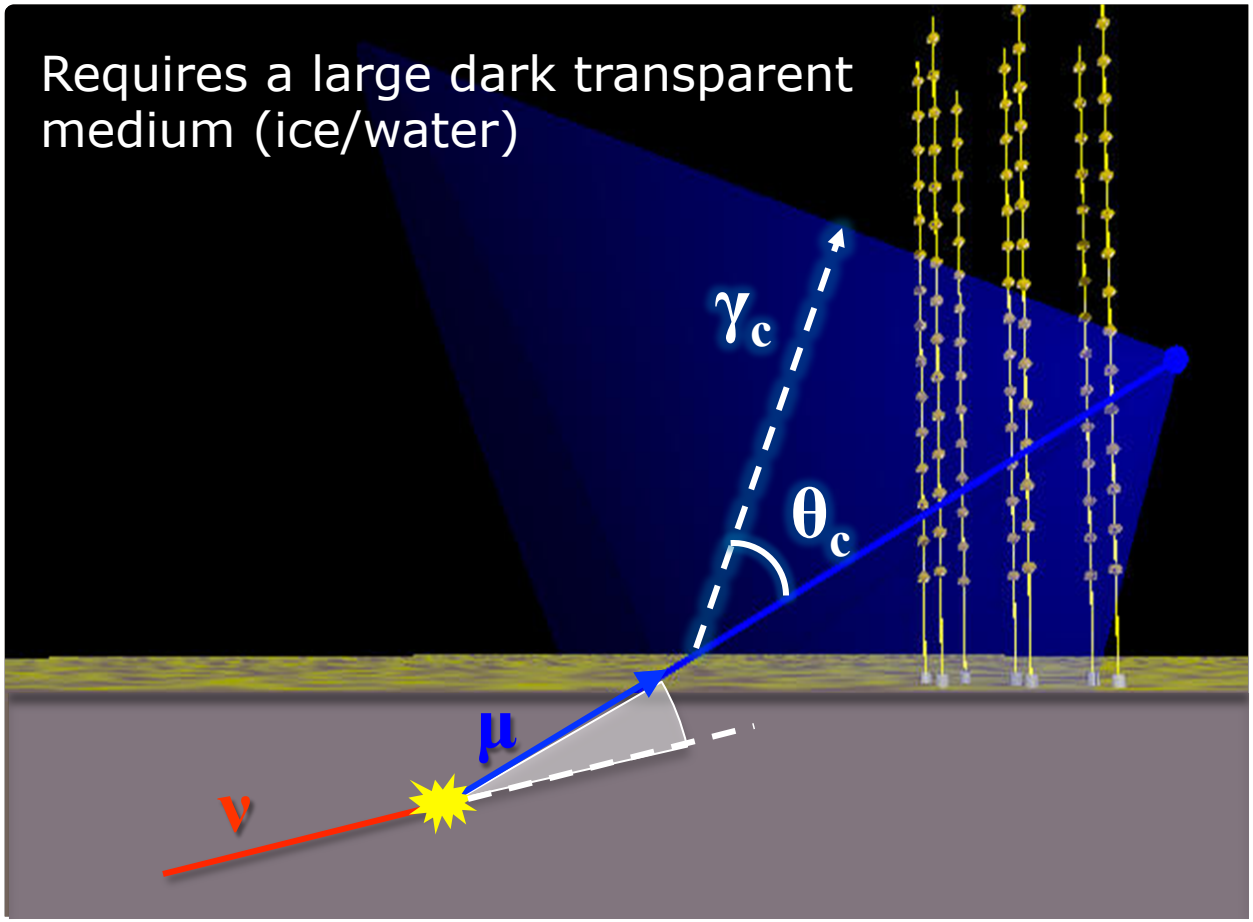




Cosmic neutrinos can interact in the Earth and release a muon

Atmospheric muons and neutrinos can also induce a signal at the detector





Muon neutrinos are well suited for HE detection (cross-section and muon range increase with energy)

Muons emit Cherenkov light collected by a lattice of PMTs.

Other signatures can also be detected.

Long track ⟶ angular resolution

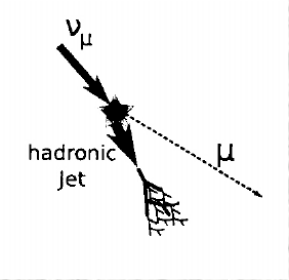
Cherenkov Neutrino detection

Nota Bene: Other possible techniques exist, e.g. via air showers, acoustic and radio emission.

→ Auger → ANITA

Event types

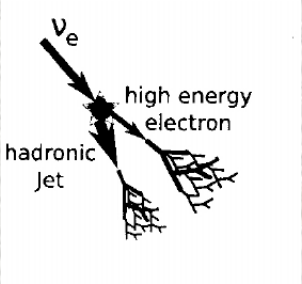
ν_μ charged current

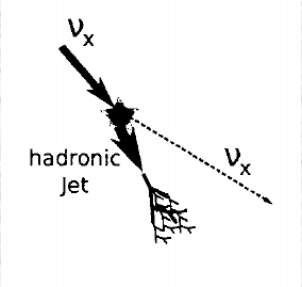


Upgoing muons
μ track length: 1-10 km
(TeV to PeV)
good angular resolution

Downgoing muons
For UHE:
$E_{atm} \sim E^{-3.7}$
$E_{astro} \sim E^{-2}$

ν_e charged current + ν_X neutral current



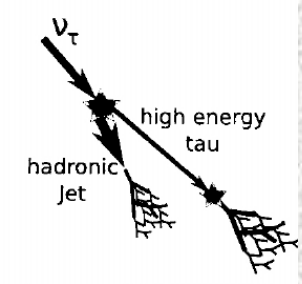


Cascades (EM and hadronic)
Contained events

Light from a small region
(< sensor spacing)

Bad angular resolution
(tens of deg), but
better energy determination

ν_τ charged current

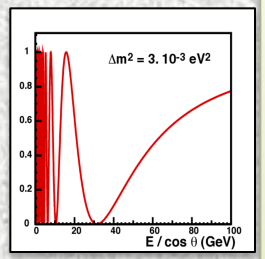


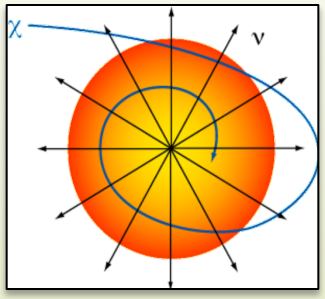
ν_τ not absorbed by Earth, "regenerated" with lower energies.

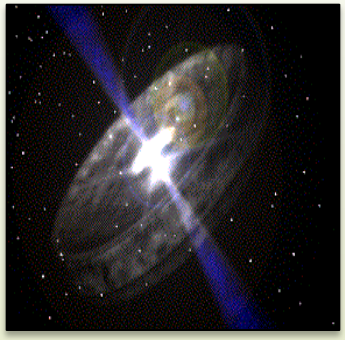
At PeV energies ν_τ can be identified by the production and decay (τ) cascades "double bang"

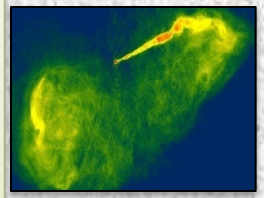
Scientific scope

– Less amount of light
– Lower ranges
– ^{40}K background









?

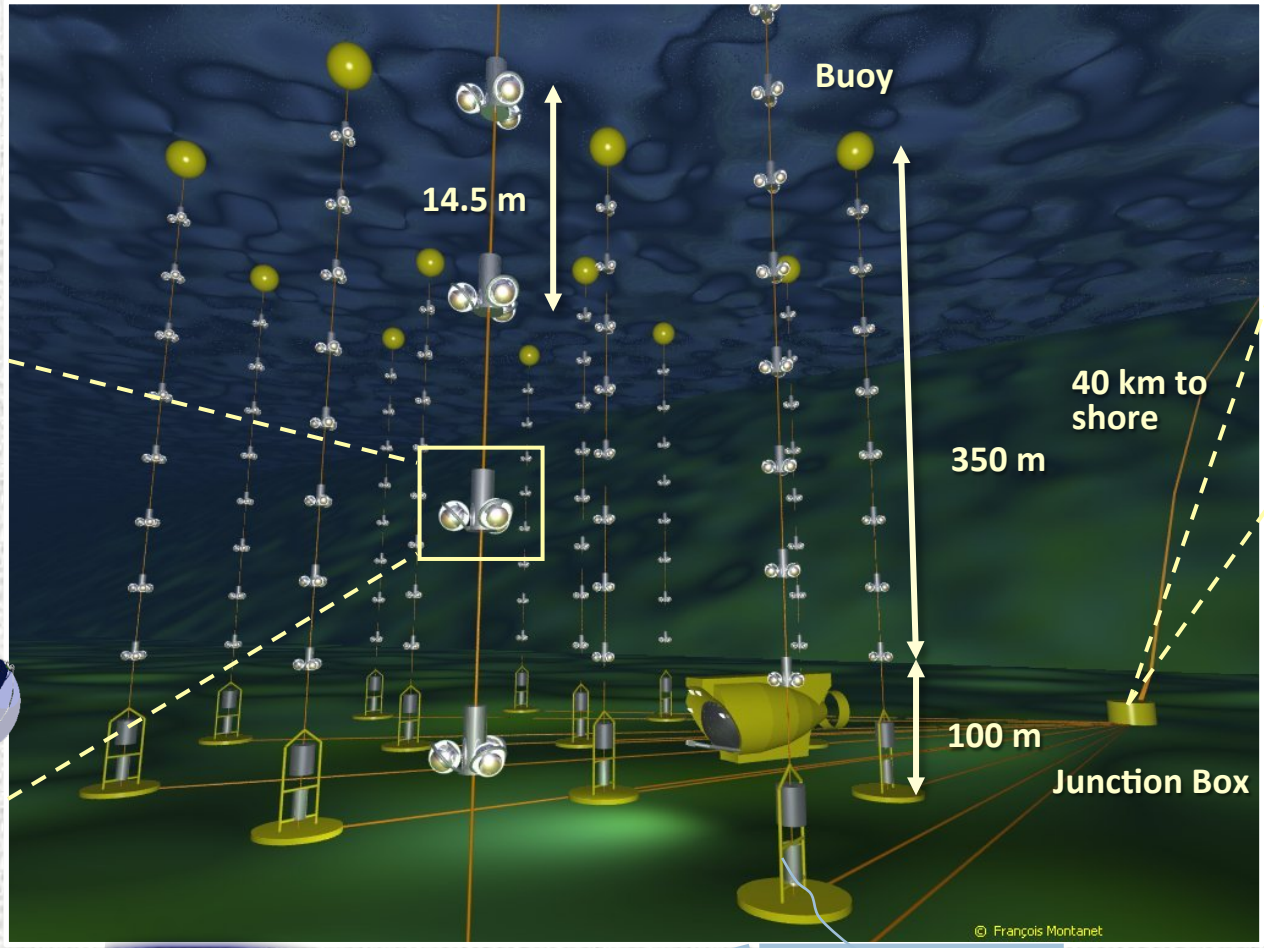
~MeV | GeV-100 GeV | GeV-TeV | TeV-PeV | PeV-EeV | ➢EeV

- High energy astrophysics
- Indirect dark matter search
- Oscillations
- Exotics (monopoles, nuclearites)
- Other ν sources

– Earth opacity
– Decreasing neutrino flux

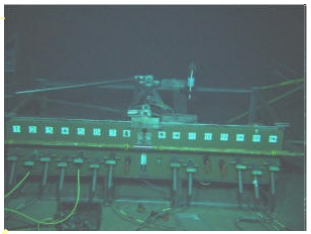
ANTARES

12 lines (885 PMTs)
25 storeys / line
3 PMTs / storey



5-line setup in 2007

Completed in 2008



First undersea ν-telescope

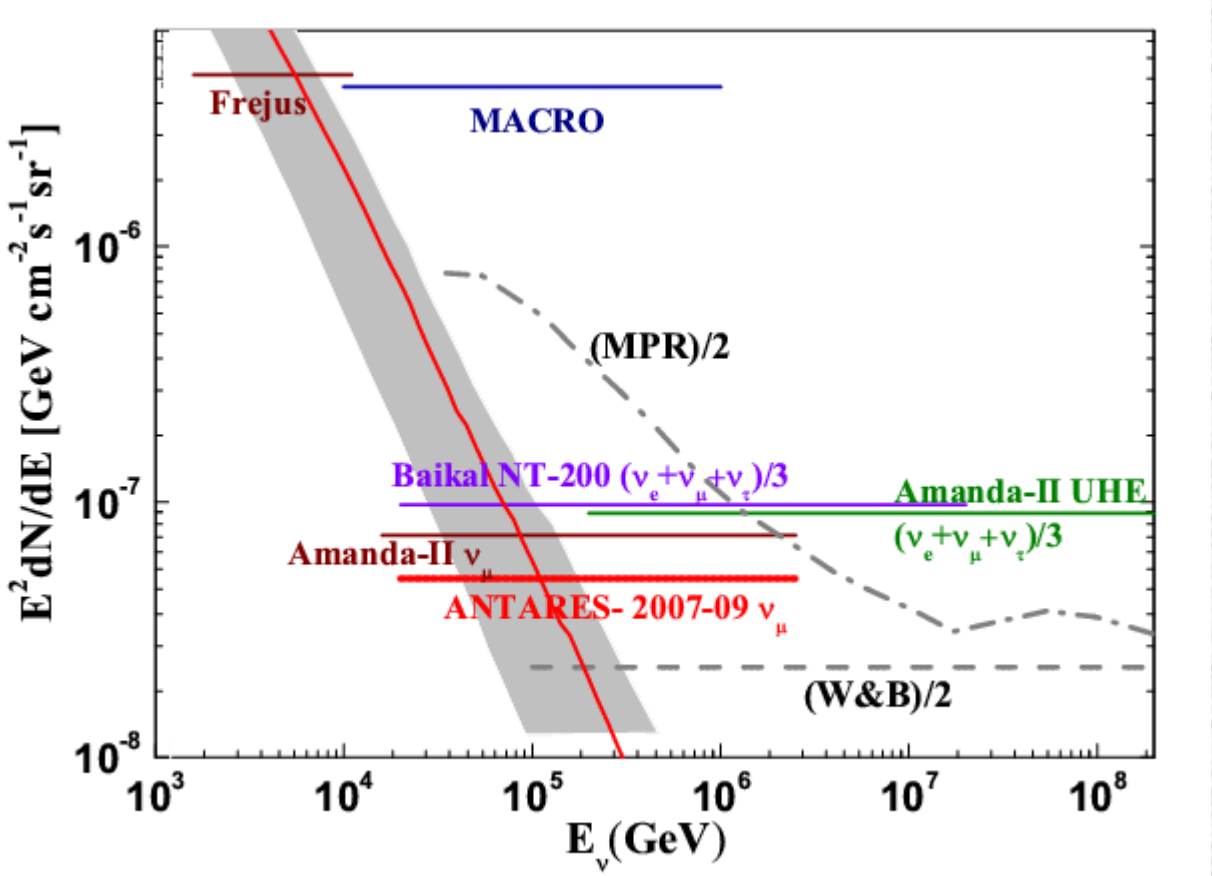
Thorough technical studies:

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

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

ANTARES RESULTS

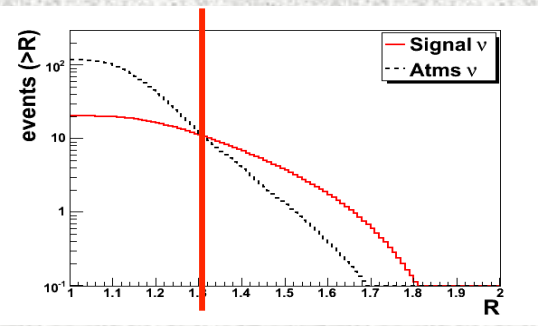
Diffuse ν_μ flux – Upper limits (E^{-2})



885 days

Discards downgoing muons by usual techniques
(zenith angle, track quality, etc)

Background vs. Signal discrimination by energy based on a novel technique: Repetition rate on same OM



$E^2\Phi(E)_{90\%} = 4.7\times10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}

20 TeV<E<2.5 PeV

Phys. Lett. **B696** (2011) 16

Point sources

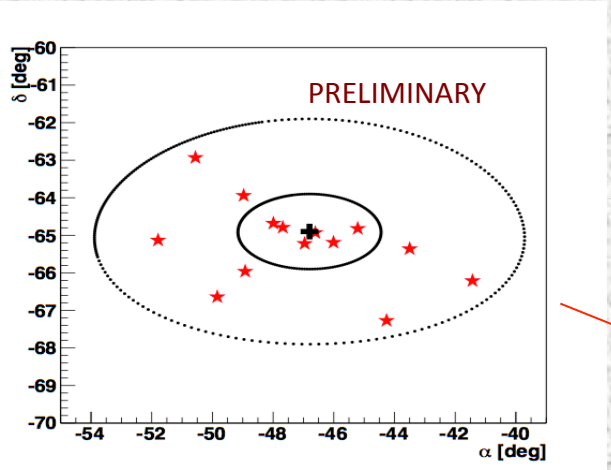
PRELIMINARY

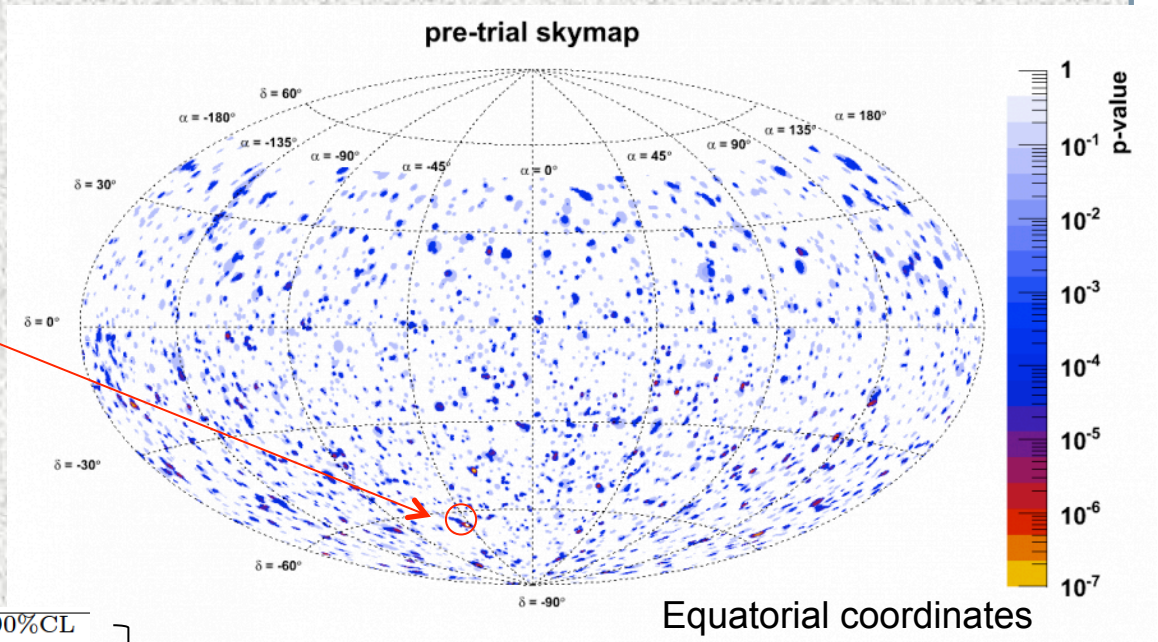
- **Updated search 2007-2012 (1340 days)**

  5516 neutrino candidates (90 % of which being better reconstructed than 1^0)

  Same most significant cluster with 6 additional events: p-value = 2.1% (2.3 σ)

  Compatible with background hypothesis





- Fixed search

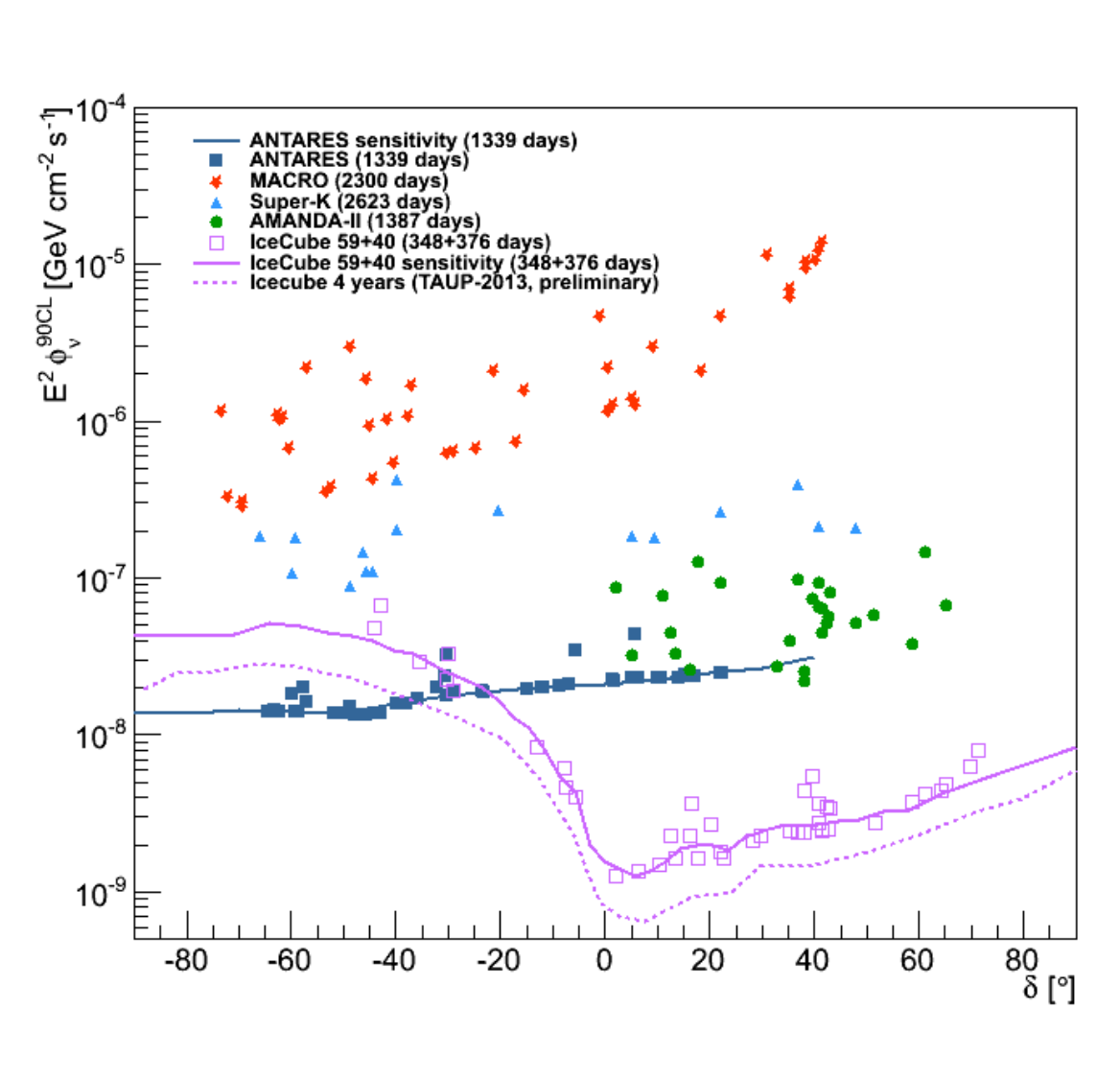
  5 most significant:

source	$\alpha_s[°]$	$\delta_s[°]$	p	$\phi^{90\%CL}$
HESSJ0632+057	98.24	5.81	0.07	4.40
HESSJ1741-302	265.25	-30.20	0.14	3.23
3C279	194.05	-5.79	0.39	3.45
HESSJ1023-575	155.83	-57.76	0.82	2.01
ESO139-G12	264.41	-59.94	0.95	1.82

Limits on normalization factor

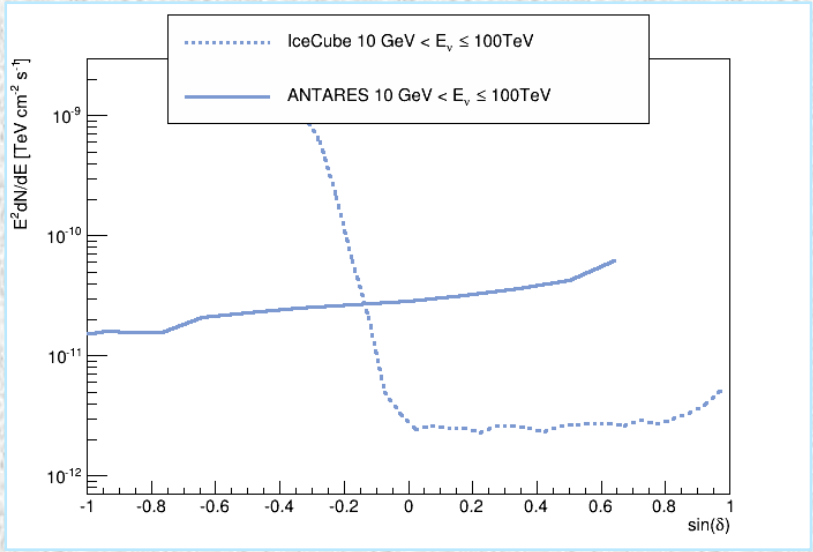
$(E/GeV)^{-2}\ 10^{-8}\ GeV^{-1}\ cm^{-2}\ s^{-1}$

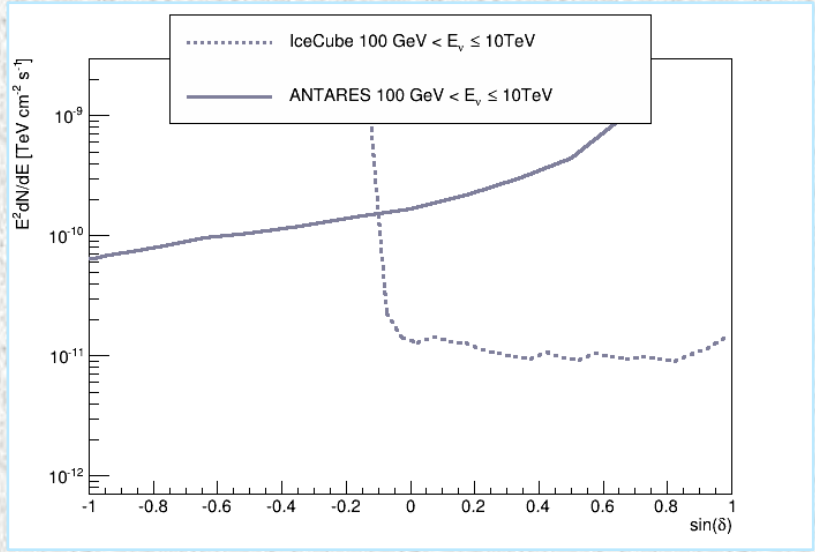
Point Sources

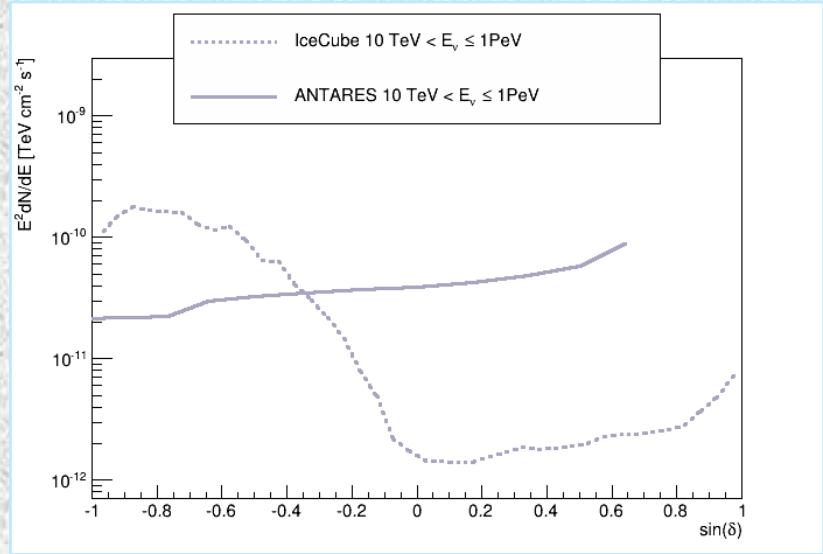


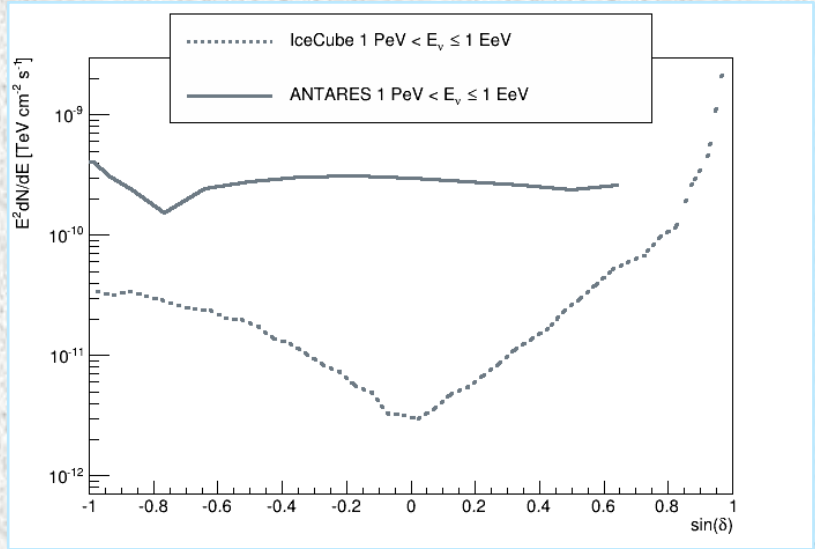
New limits 40 % better than previous result (📖 ApJ. **760** (2012) 53)

PS sensitivity by energy range

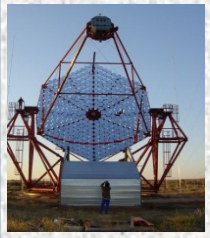


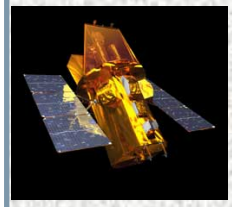






The Multi-messenger Program





GeV-TeV γ-rays
Fermi / HESS…

A&A to be published
JCAP **03** (2013) 006
APJ **760** *(2012) 53*
AP **36** (2012) 204
APJ Lett. **743** (2011) L14

UHECR
Auger

APJ **774** (2013) 19

HE neutrinos

Optic / X-ray
TAROT, ROTSE /
Swift, ZADKO

AP **35** (2012) 530

Gravitational
Waves
Virgo / Ligo

JCAP **06** (2013) 006

A way to better understand the sources and the related physics mechanisms.

A way to increase the detector sensitivities (uncorrelated backgrounds).

Fermi Bubbles

- Excess of γ- (and X-)rays in extended "bubbles" above and below the Galactic Centre. Correlated to the haze seen by WMAP

- Homogenous intensity, hard spectrum (E^{-2}) probably with cutoff.

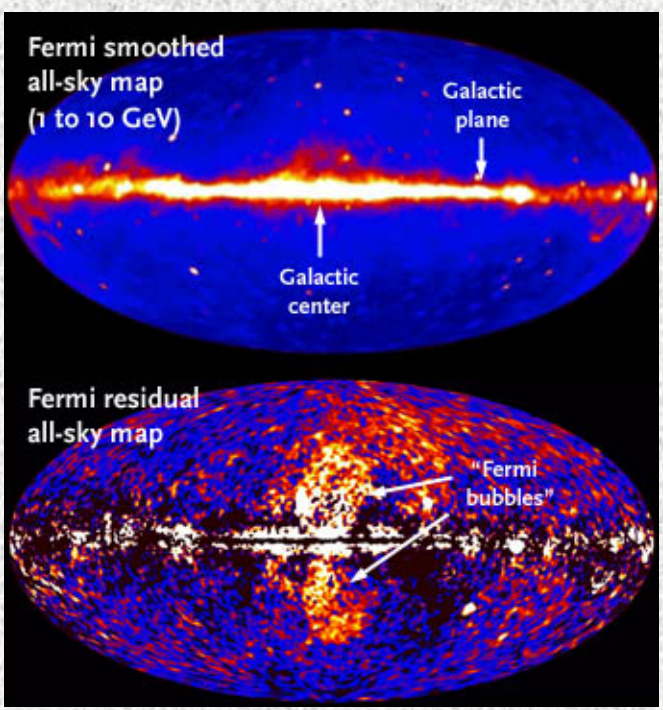
  📖 M. Su et al., Ap. J. 724 (2010)

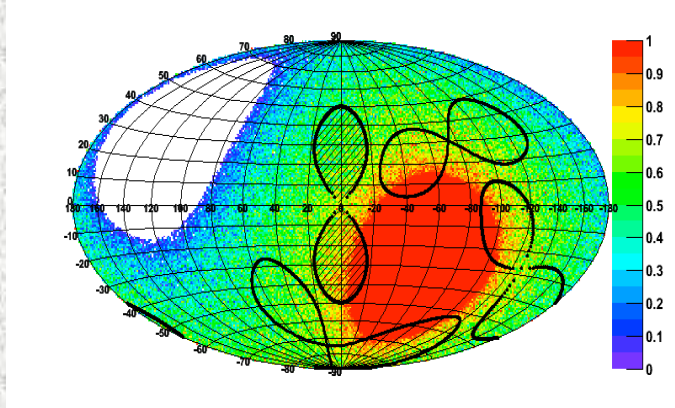
- Origin still unclear

  promising Galactic wind model involves hadronic processes (📖 Crocker & Aharonian, PRL 2011): accelerated cosmic rays interacting with ISM → π → γ,ν $\Phi_\nu \approx 0.4 \times \Phi_\gamma$

- In the field of view of ANTARES

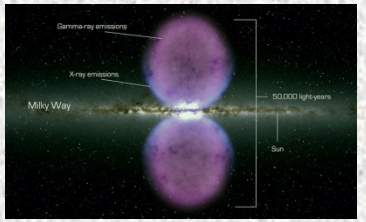
  background estimated from average of 3 non-overlapping "off-zone" data regions (same size, shape and average detector efficiency)





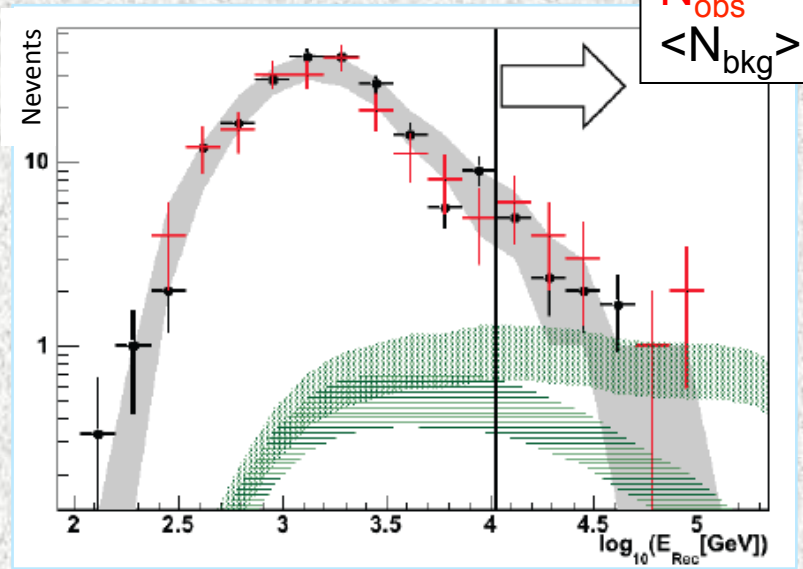
Fermi Bubbles

- 12-line data sample: May 2008 - Dec 2011 (806 days livetime). Only muon neutrinos.
- E_μ estimation based on Artificial Neural Networks procedure.
- Optimization tuned on off-zone background events (MRF).



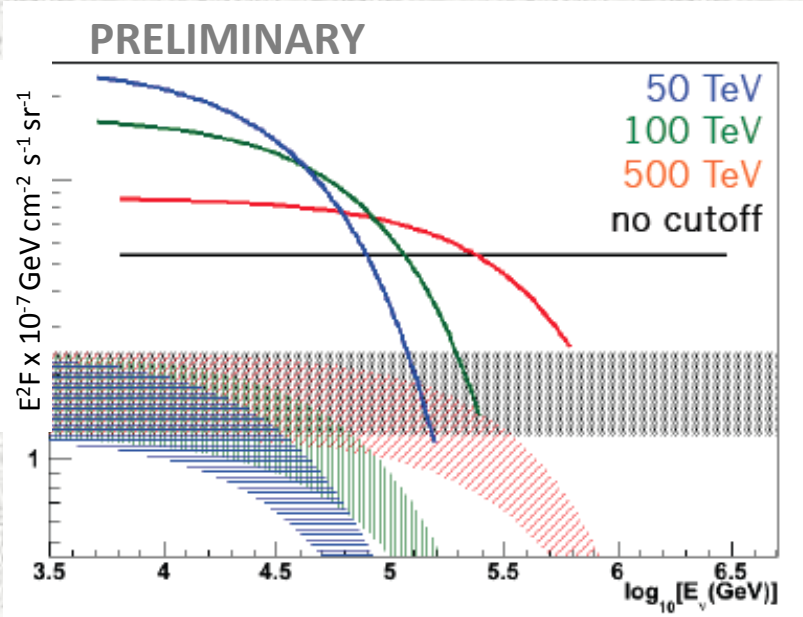
PRELIMINARY

N_{obs} = 16
$\langle N_{bkg} \rangle$ = 11



No significant excess (1.2 σ)

PRELIMINARY



on-zone
off-zone average
expected signal (≠ cutoff, 50TeV cutoff)

Upper limits with respect to different models

65% improvement expected with 2012-2016 data

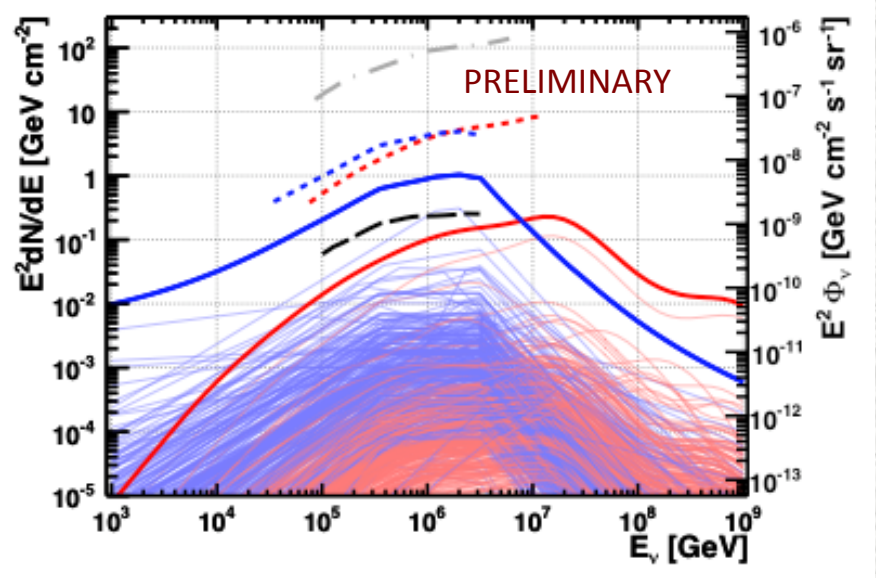
GRB triggered searches

Search for neutrino events in coincidence with observed GRB

- Analysis of GRBs from late 2007 – 2011:
  296 long GRBs,
  Total prompt emission: 6.6 hours
  Information from FERMI/SWIFT/GCN

- GRB simulations of expected neutrino fluence:
  NeuCosmA [📖Hümmer et al. (2010)]
  Guetta [📖Guetta et al. (2004)]

- Quality cut optimized for NeuCosmA & highest signal discovery probability



Grey: first ANTARES limit (40 GRBs, 2007)
📖 JCAP 03(2013) 006

Black: IceCube IC40+59 (215 GRBs)

- No events found within 10° window from GRB
  Expected: 0.48 (Guetta), 0.061(NeuCosmA)

- Dedicated analysis for GRB130427

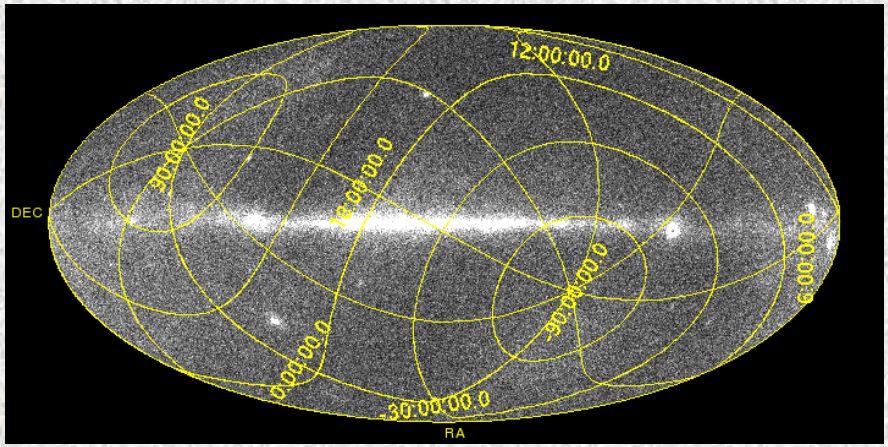
📖 arXiv1307.0304 (to appear in A&A)

Neutrino search from γ-ray flaring blazars

- **Motivation**: γ-ray sky extremely variable
- **Goal:** using the information from γ-ray detectors (Swift, Fermi , HESS) increase discovery potential.
- **Data:** 2008 data (61 days)

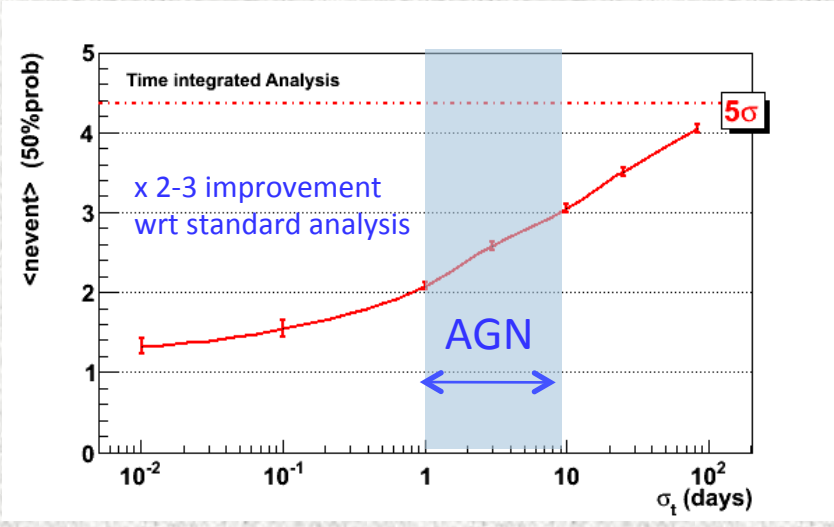
LBAS Catalog (Fermi LAT Bright AGN Sample).

📖 Astrop. Phys. **36** (2012) 204



- **Improved search:**
  - 2008-2011 data (750 days)
  - 86 flaring periods 2FGL+Fermi Flare Advocates
  - Allow a lag of ± 5 days for the flares
  - 4 energy spectra considered

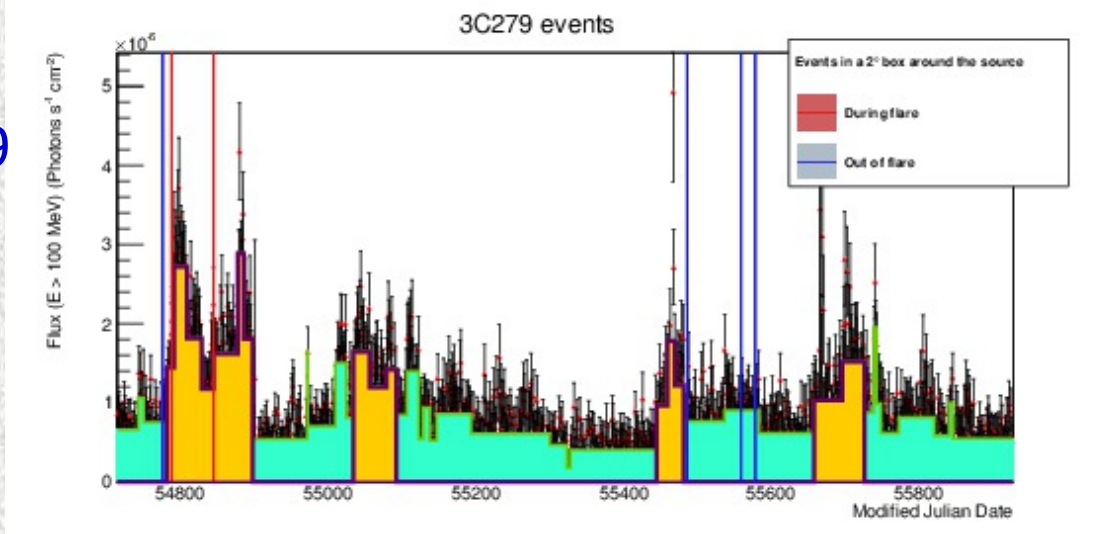
    (E^{-1}, E^{-2}, E^{-1} and cutoff 1TeV, E^{-1} and cutoff 10 TeV).



Events from 3C279

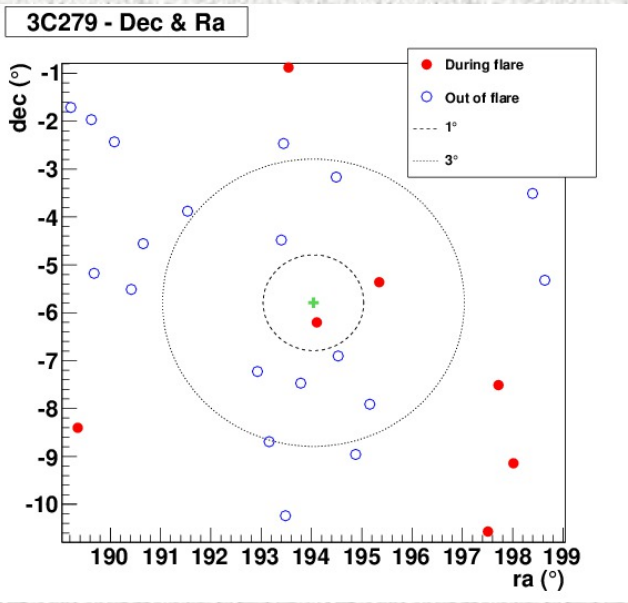
Lowest p-value 10% : 3C279

3C 279 (279 flaring days)
2 events compatible
in time and direction



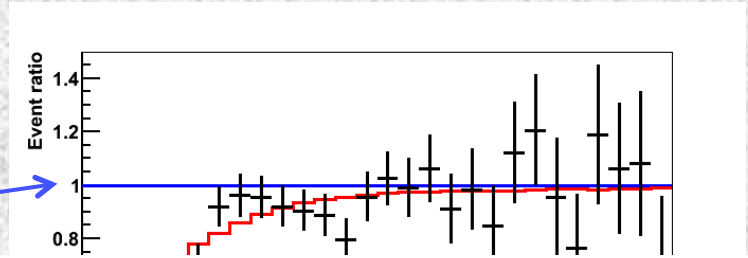
54789 MJD
at 0.5° with high energy
(89 hits, Λ=-4.5)

54845 MJD
at 1.1° lower energy
(52 hits, Λ=-5.45)



Neutrino oscillations

Fraction of events wrt no-oscillation hypothesis



No-oscillations

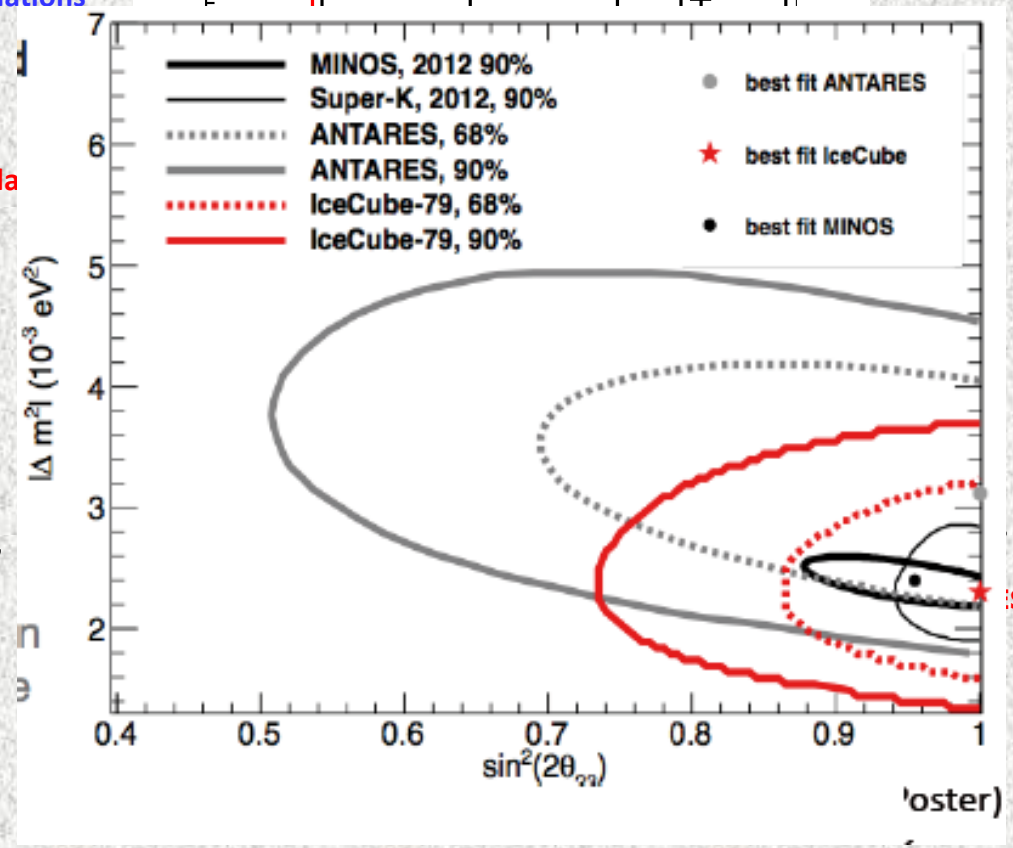
E/L Distribution

E from range:

E(GeV) = (zmax-zmin)/5./cosθ

L=2R cosθ (R – Earth radius)

Fit to oscilla



Δm^2_{32}, $\sin^2 2\theta_{32}$

At 68% CL:

$\Delta m^2 = 2.2 - 4.2\ 10^{-3}\ eV^2$, $\sin^2 2\theta > 0.7$

For maximal mixing:

$\Delta m^2_{32} = (3.1 \pm 0.7) \cdot 10^{-3}\ eV^2$

📖 Phys. Lett. B 714 (2012) 224

Magnetic Monopoles

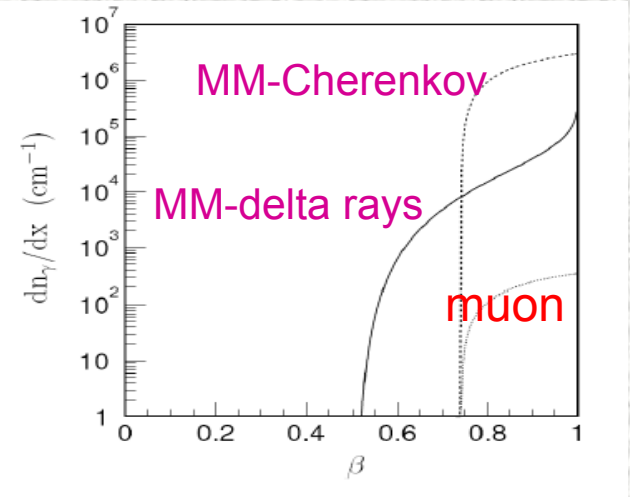
- Required in many models of spontaneous symmetry breaking ('t Hooft, Polyakov)

upgoing ⇒ masses less than ~10^{14} GeV

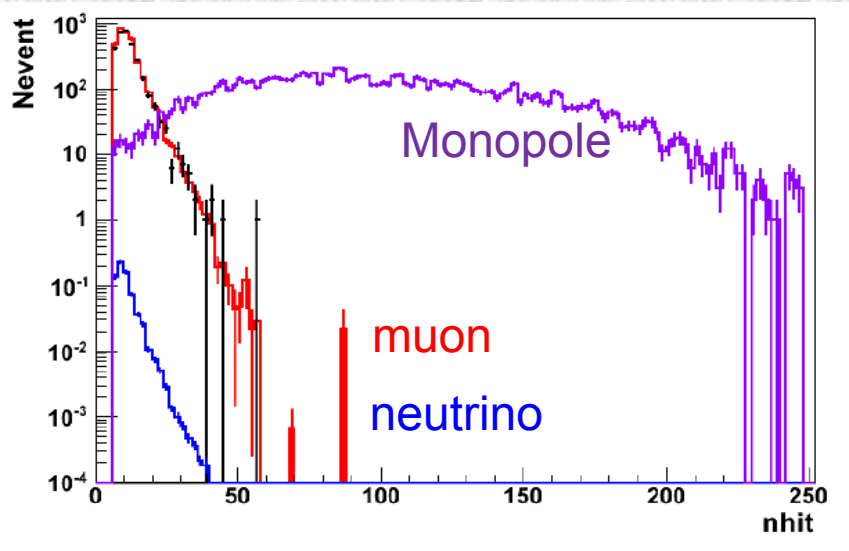
- High photon yield (8.5×10^3 times μ)

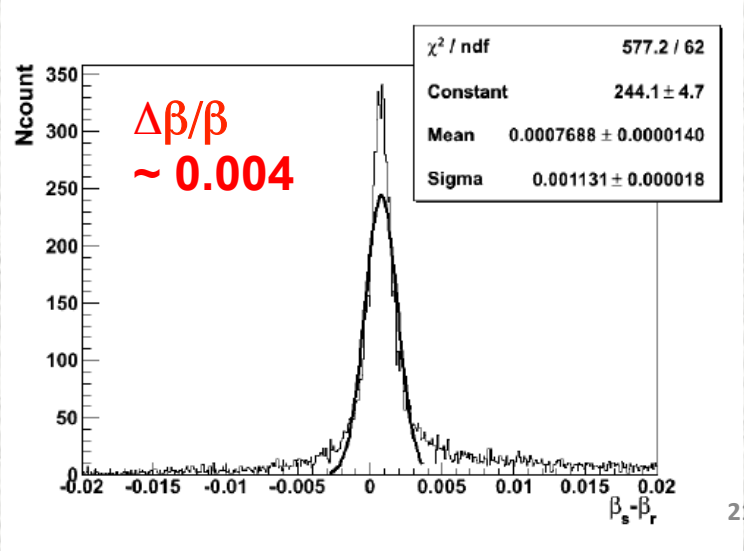
Cherenkov threshold $\beta > 0.74$

secondary δ-rays $\beta \geq 0.5$



- Modified track reconstruction with β free





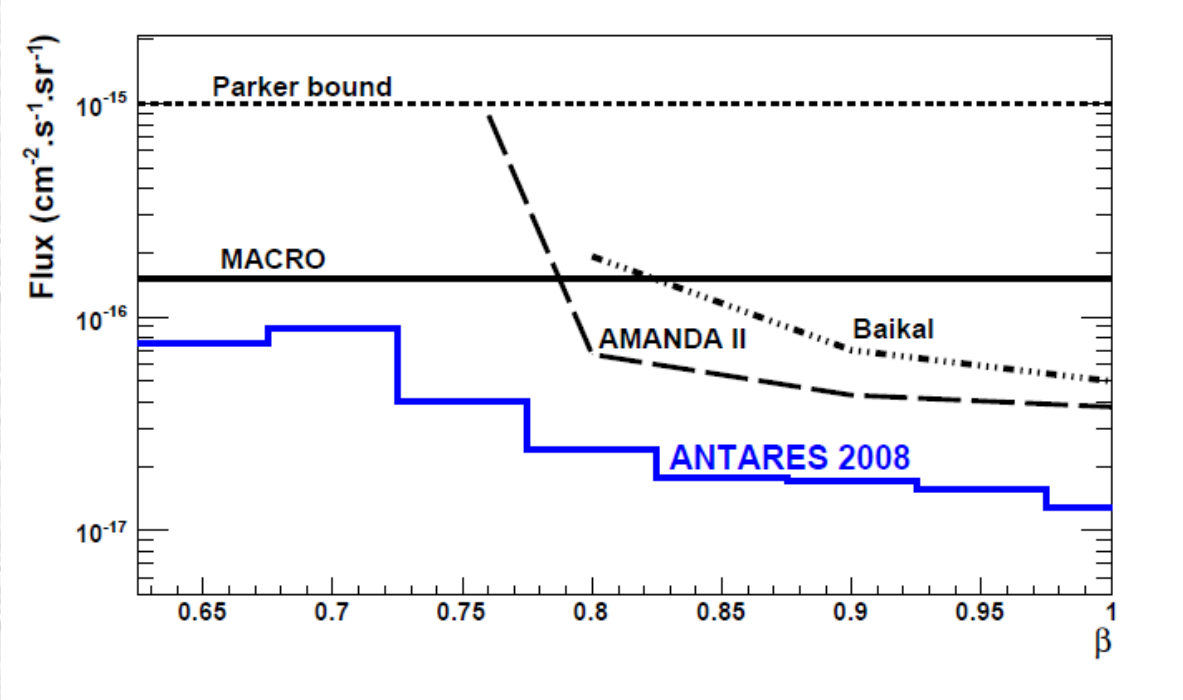
Magnetic Monopoles

Monopoles:

Selection criteria based on:

- Upgoing tracks
- reconstructed velocity

  $\lambda = \log [\chi^2 (\beta=1)/\chi^2 (\beta=\text{free})]$
- number of hits



📖 Astroparticle Physics **35** (2012) 634

Search for Exotics

Nuclearites:

~1 ms to cross the detector

Involve multiple *snapshots*

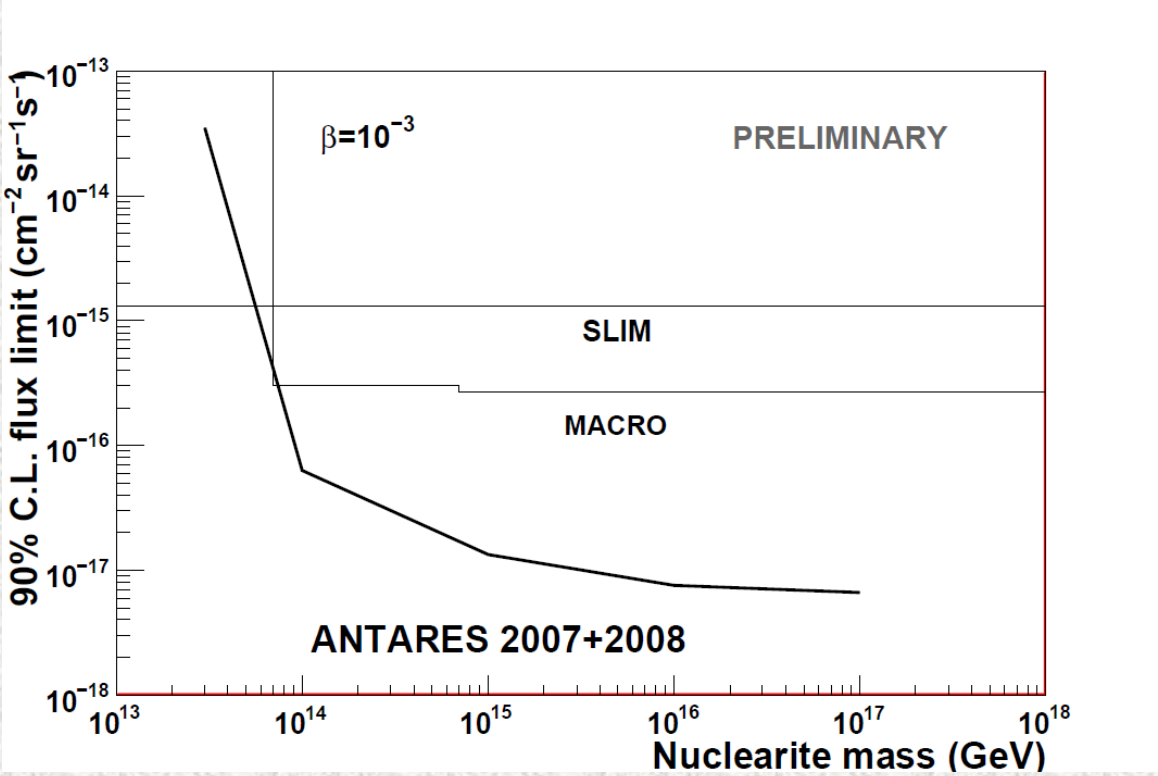
Selection based on:

- downgoing events
- Cuts on duration:

$dt = t_{last\ trigg.} - t_{first}$

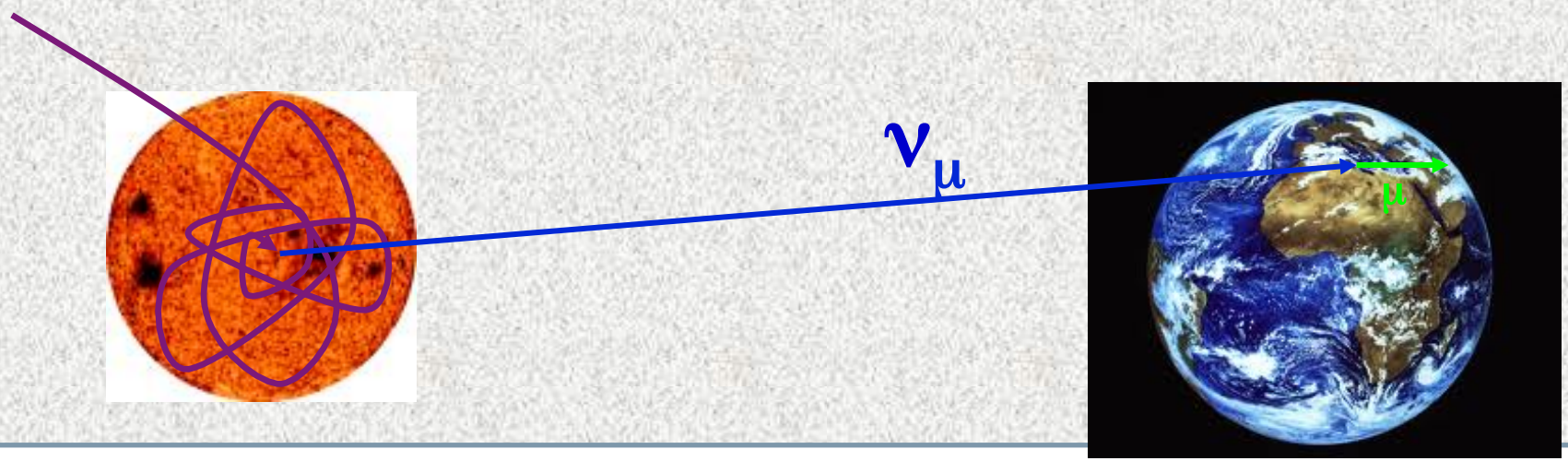
Optimized depending on:
detector layout,
type of trigger
thesholds.

For single snapshot additional cut on **dt.**



Detection of Dark Matter

- WIMPs (neutralinos, KK particles) are among the most popular explanations for dark matter
- They would be accumulated in massive objects like the Sun, the Galactic Centre, dwarf galaxies…
- The products of their annihilations would yield "high energy" neutrinos, which can be detected by neutrino telescopes
- In the Sun a signal would be very clean (compared with gammas from the GC, for instance)
- Sun travel in the Galaxy makes it less sensitive to non-uniformities



Dark matter search

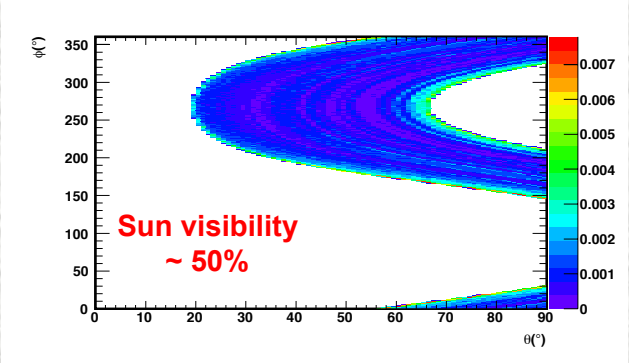
- From the Sun using 2007-2012 data
- 1321 days

(4.5 times more statistics than previous analysis

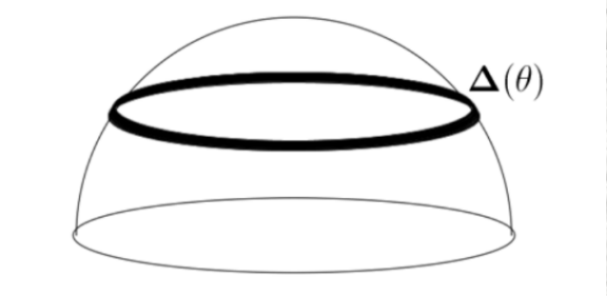
📖 arXiv:1302.6516, soon in JCAP

Year	Lines	Days
2007	5	192
2008	9-12	180
2009	8-12	210
2010	9-12	240
2011	12	275
2012	12	224

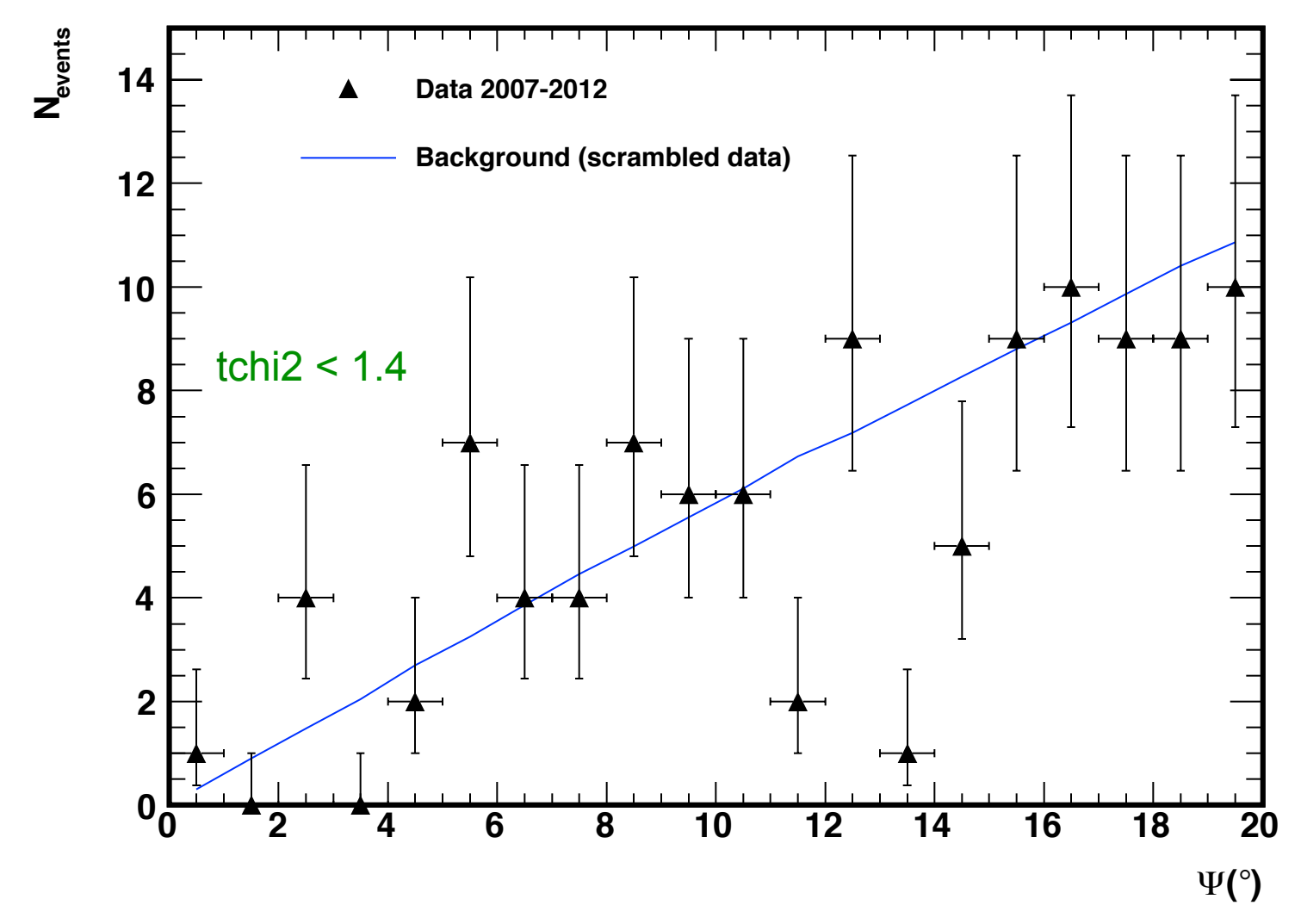
- Events reconstructed on a single line are also used: azimuth angle missing, but "almucantar restriction" good enough to reject background. Sizeable increase of events at low energy.



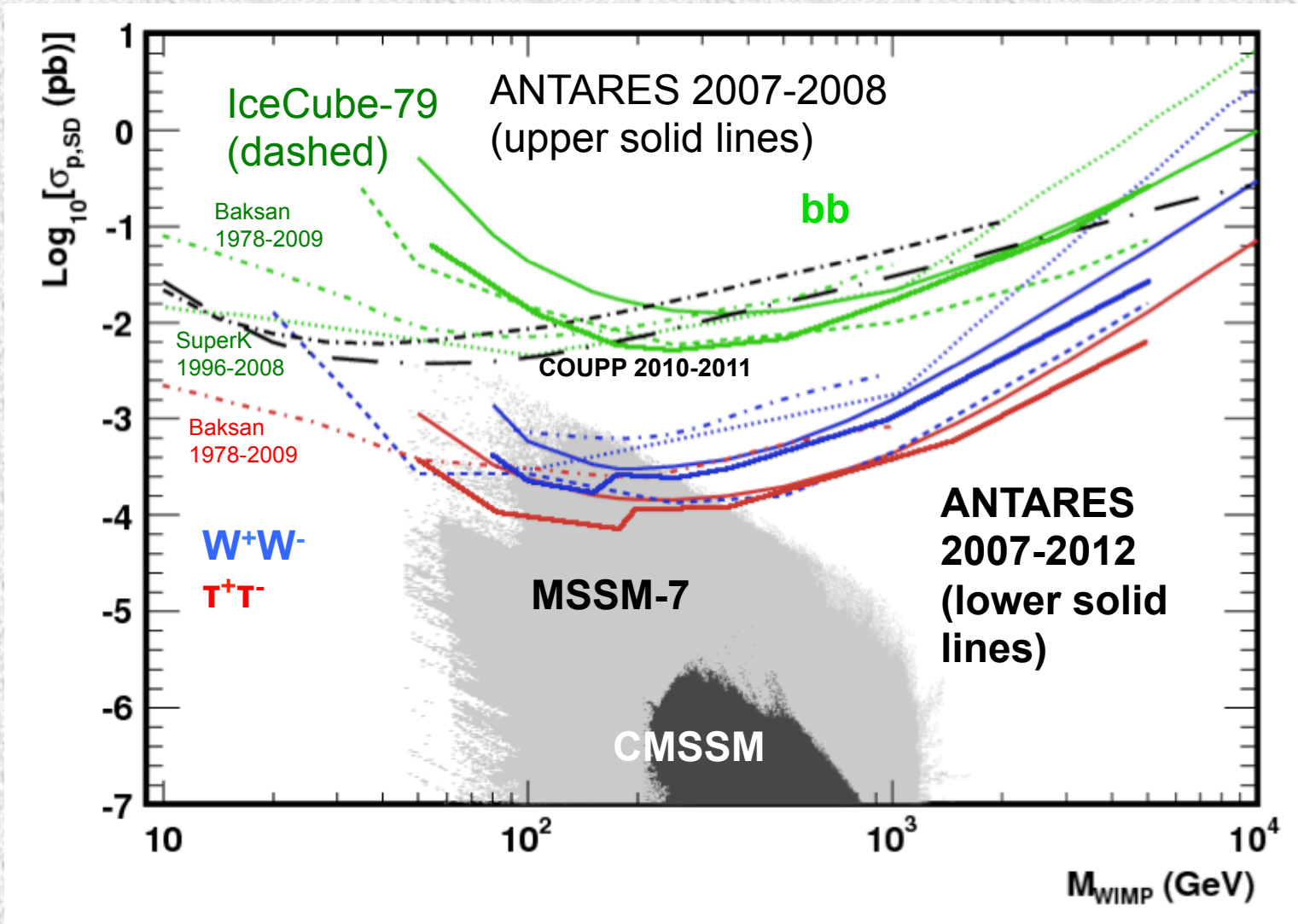
- Theoretical models: adaptive full simulation within the CMSSM and MSSM-7 (including Higgs information plus XENON-100 limits).



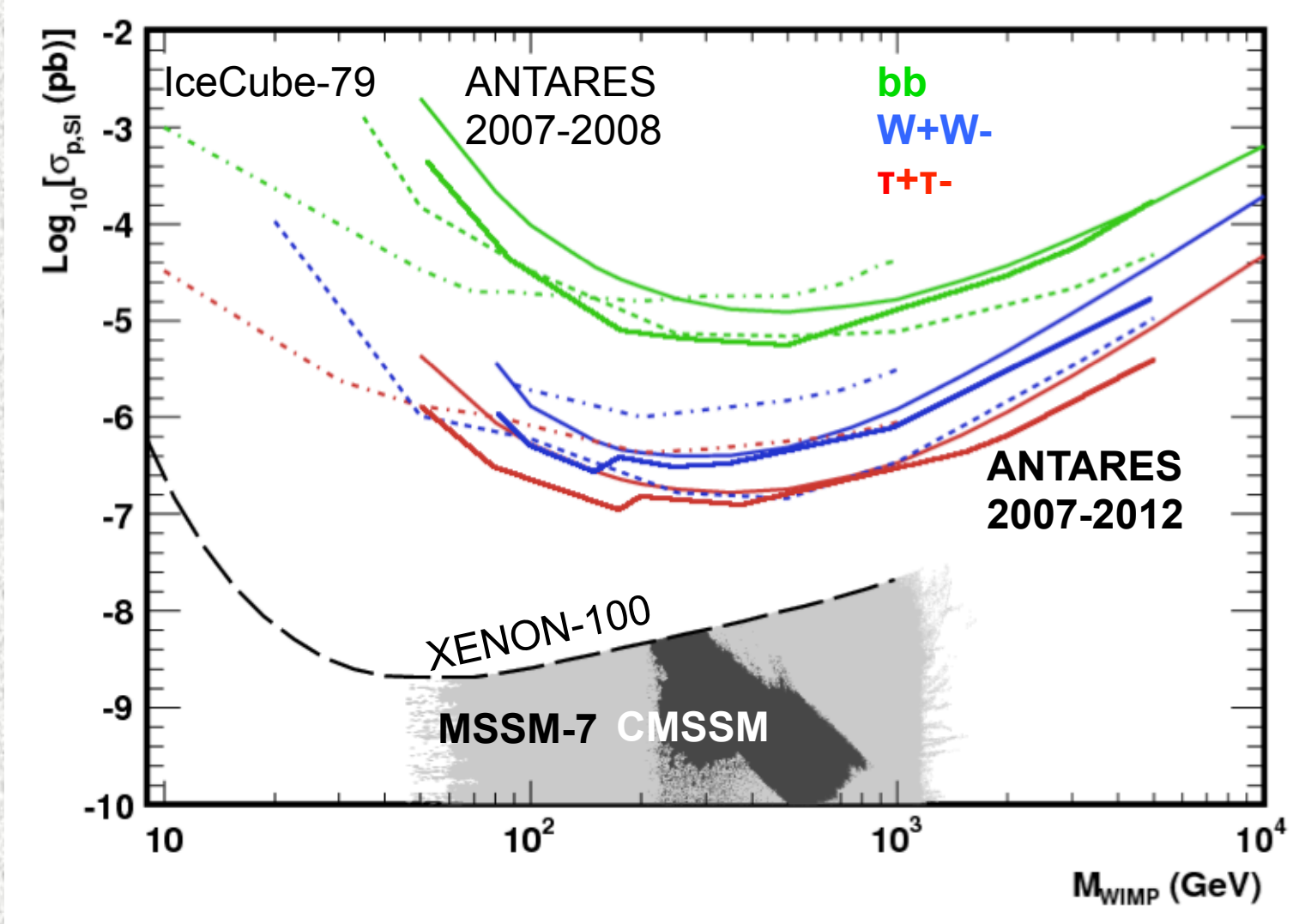
Unblinded - BBFIT Multiline (differential)



Spin-dependent cross-section limits

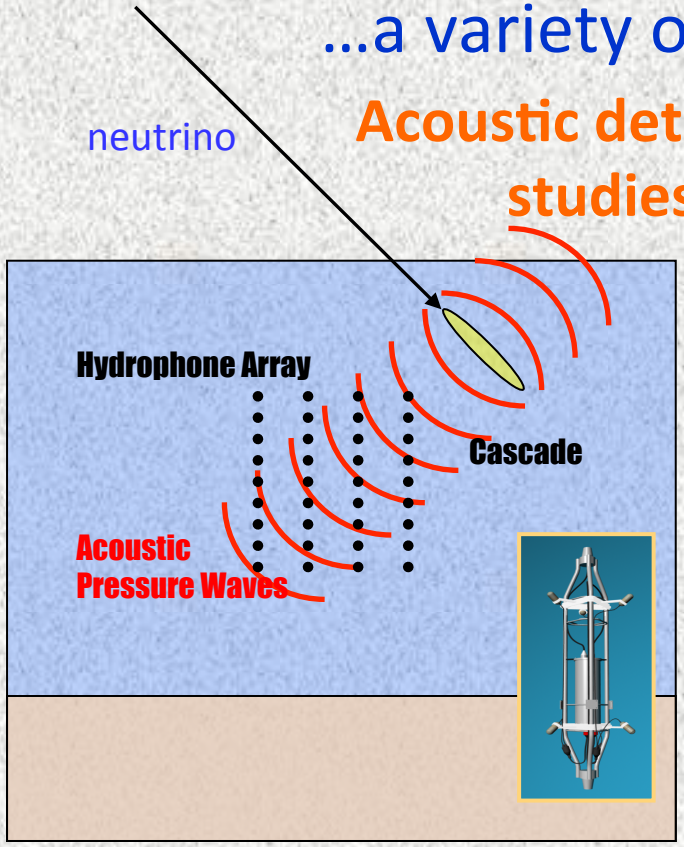


Spin-independent cross-section limits



...a variety of other scientific activities

Acoustic detection studies



Marine Biology

The Economist

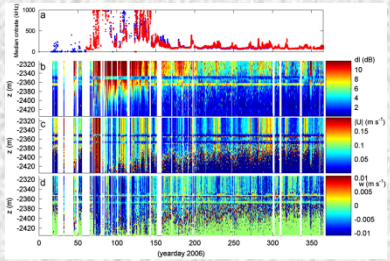
Hang on, that's not a neutrino

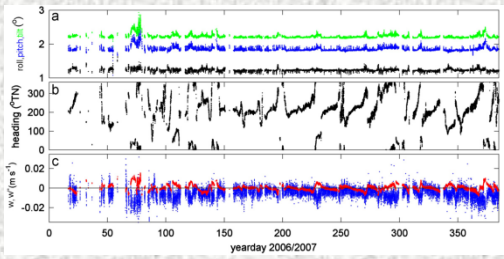
Dec 1st 2010, 16:10 by J.P.

Tweet 21 Like 230

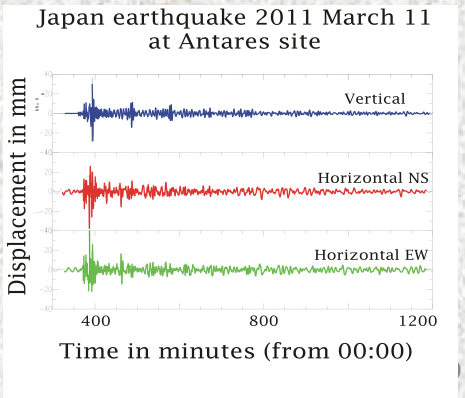
PHYSICISTS are often accused by the public and other scientists of spending inordinate sums on fancy kit that does little apart from merely satisfying human curiosity. Besides stressing that there is nothing mere about knowledge, the boffins will typically respond by trotting out a long list of blue-sky projects that yielded serendipitous results, from microwave ovens to the internet. They can also offer plenty of examples of how their own research has aided colleagues in other fields, from climate science to, somewhat more improbably, marine biology.

Sea Sciences





Geoscience



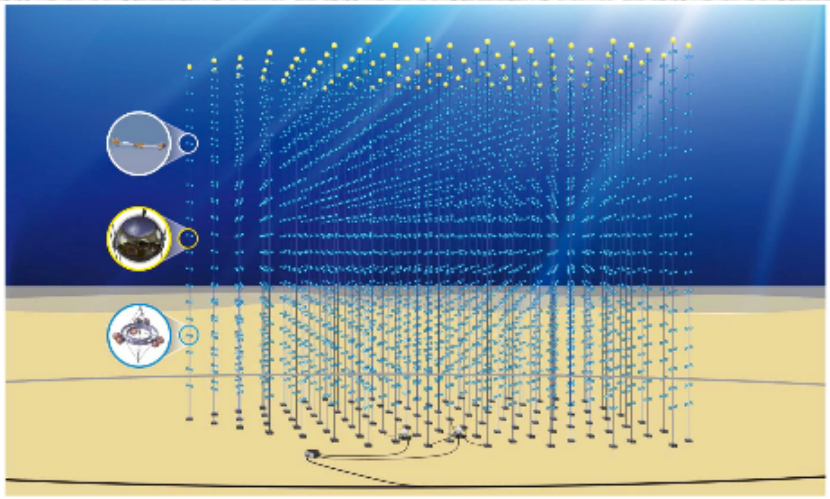
Summary so far…

KM3NeT

- Central physics goals:
  - Neutrino Astronomy under the Mediterranean Sea.
  - Investigate neutrino "point sources" in the 100 GeV-100 TeV energy range.
  - Focus on Galactic sources. Complement IceCube field of view.
  - Exceed IceCube sensitivity
- Implementation requirements:
  - Construction time ≤5 years
  - Operation over at least 10 years without "major maintenance"

KM3NeT

- 40 Institutes in 10 European countries.
- Design Study funded by the EU VIth Framework Program
- Conceptual Design Report and Technical Design Report released.
- Preparatory Phase funded by EU VIIth Framework Program.. Ended in 2012.
- 40 M€ available for the first phase.



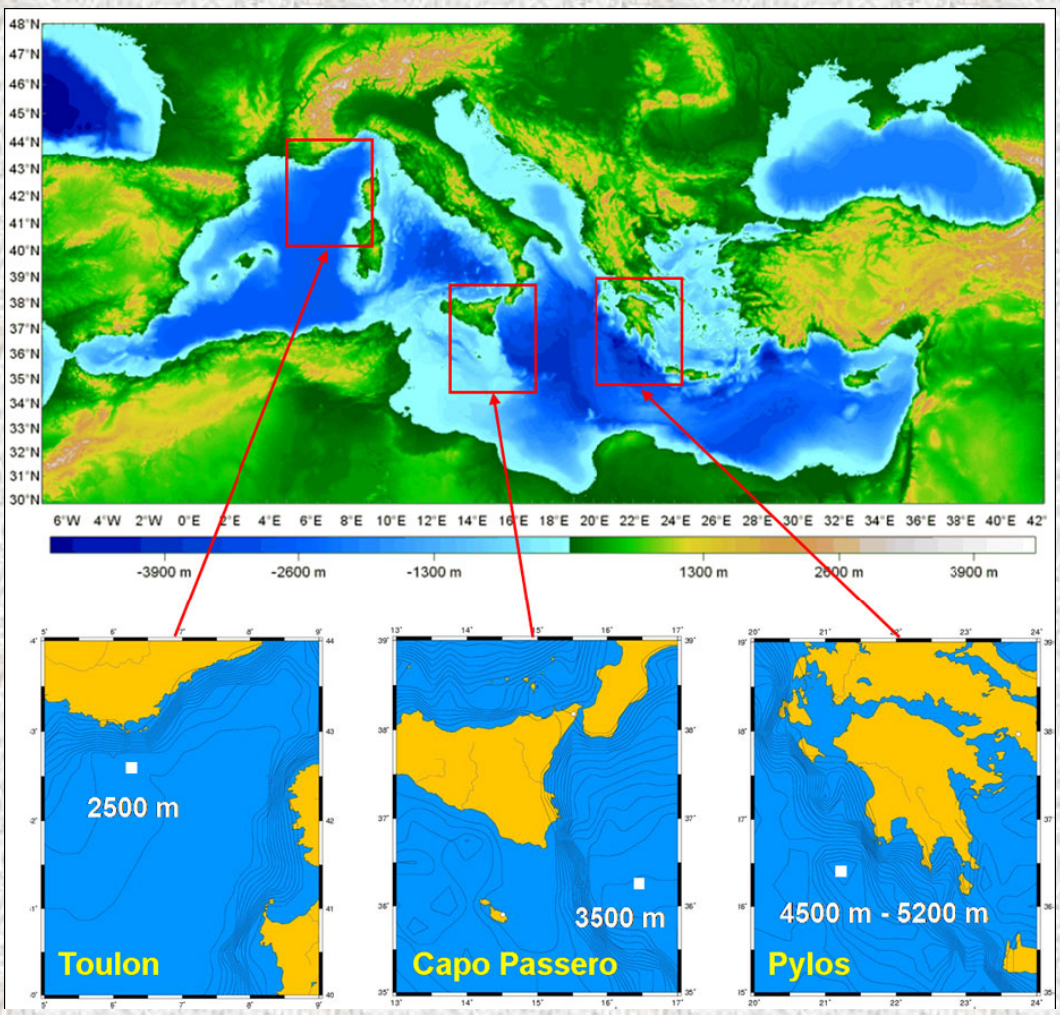
KM3NeT Sites

- KM3NeT-France: Toulon

  KM3NeT-Italy: Capo Passero

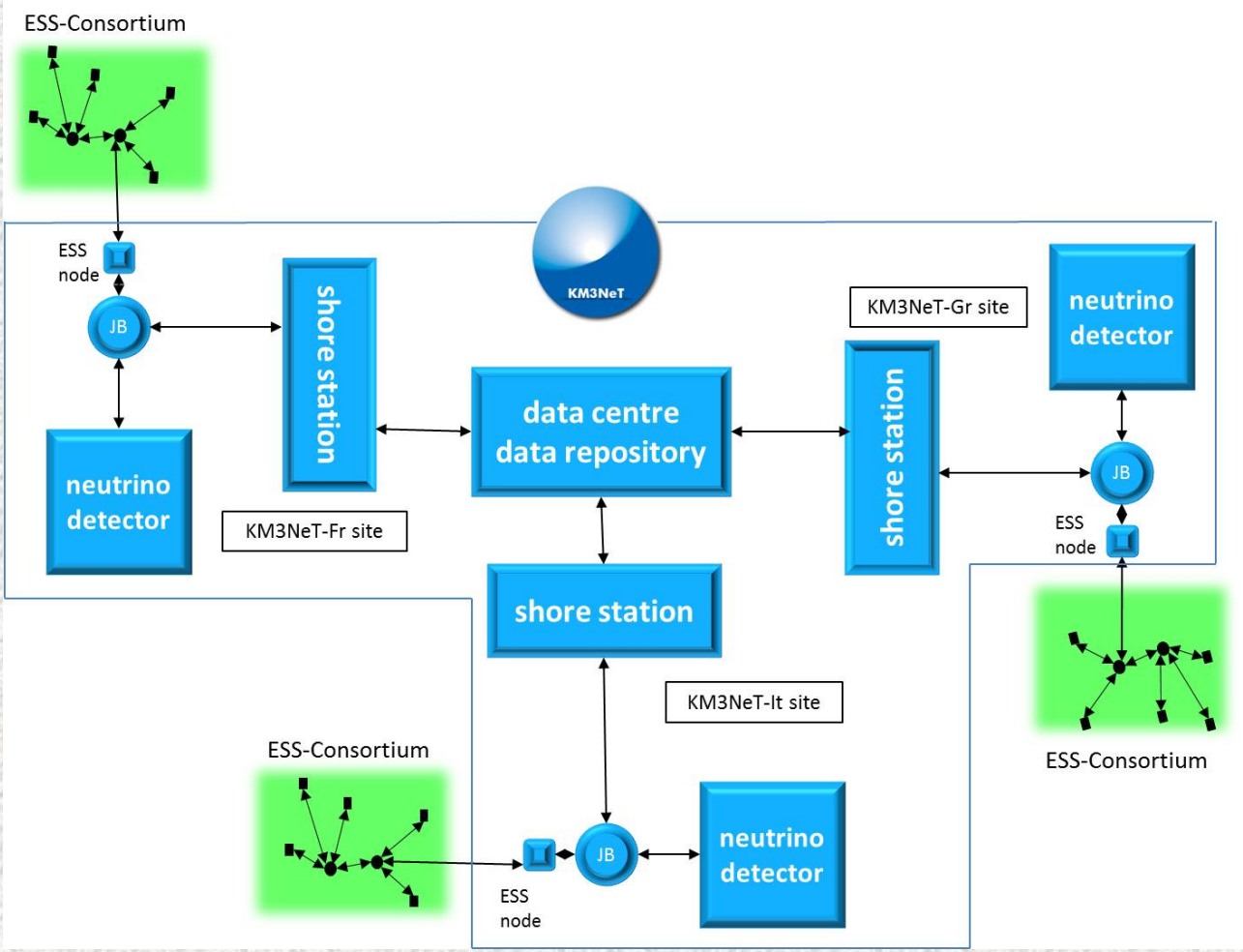
  KM3NeT-Greece: Pylos

- Long-term site characterisation measurements performed



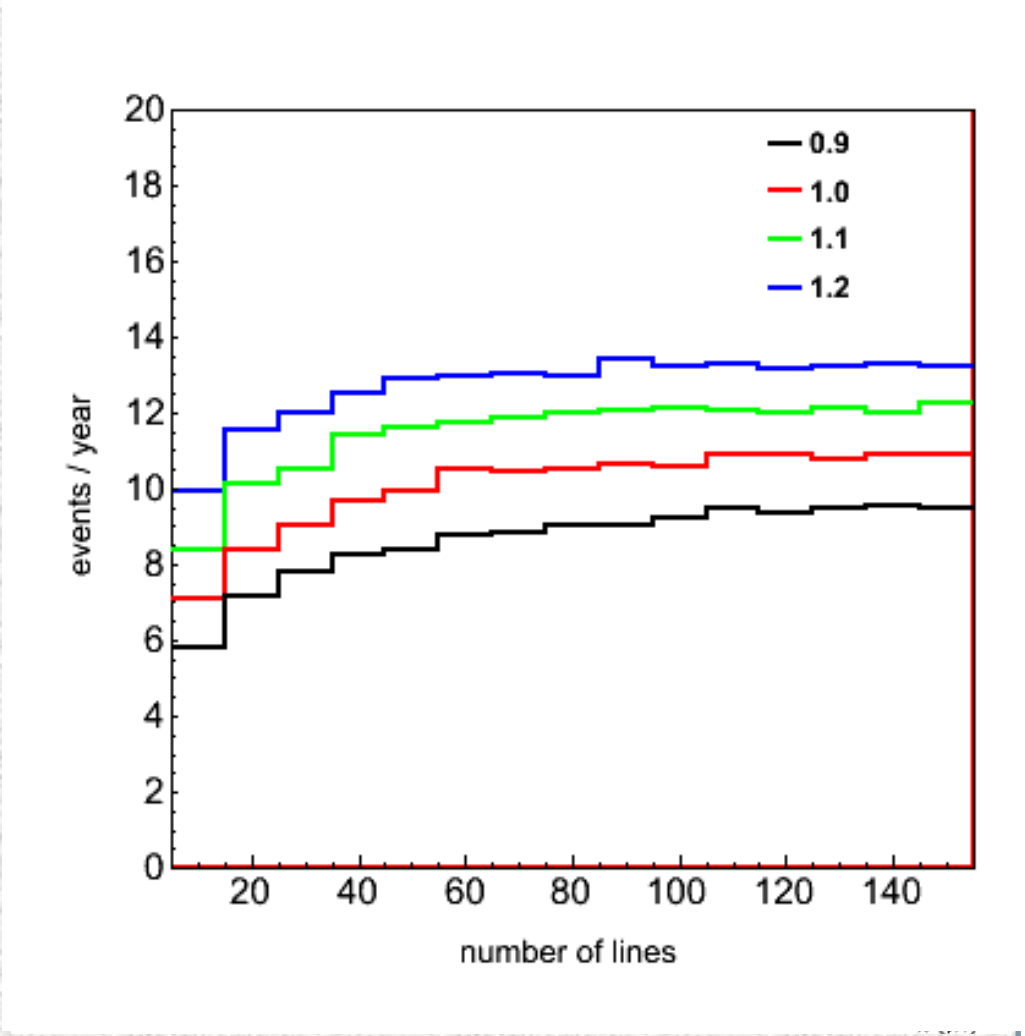
Distributed Research Infrastructure

- Centrally managed
- Common hardware
- Common software, data handling, operation and control.
- Sites in France, Greece, Italy
- Consistent with funding structure (regional sources)



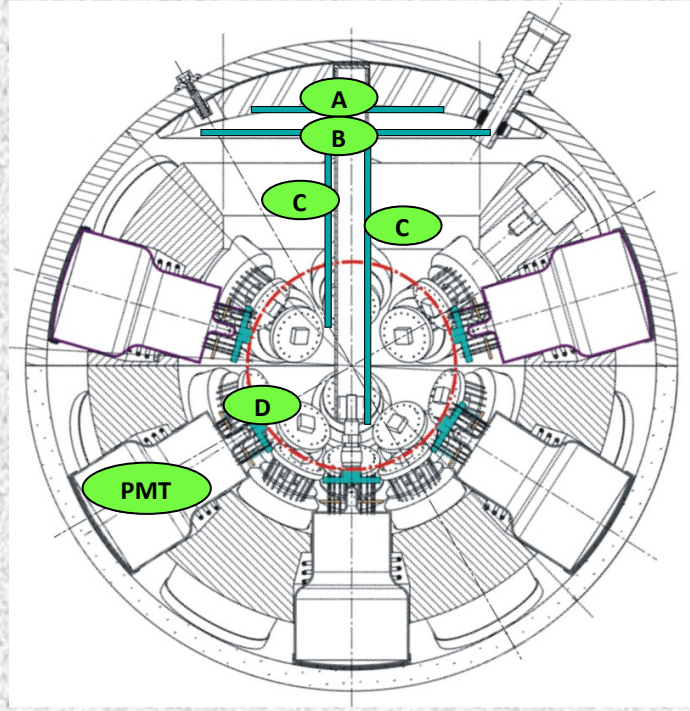
The building block concept

- Building block:
  - 115 detection units
  - Segmentation enforced by technical reasons
  - Sensitivity for muons independent of block size above ~75 strings
  - One block ~ half IceCube
- Geometry parameters optimised for galactic sources (E cut-off)
- Technical feasibility verified
- KM3NeT includes 6 building blocks



OM with many small PMTs

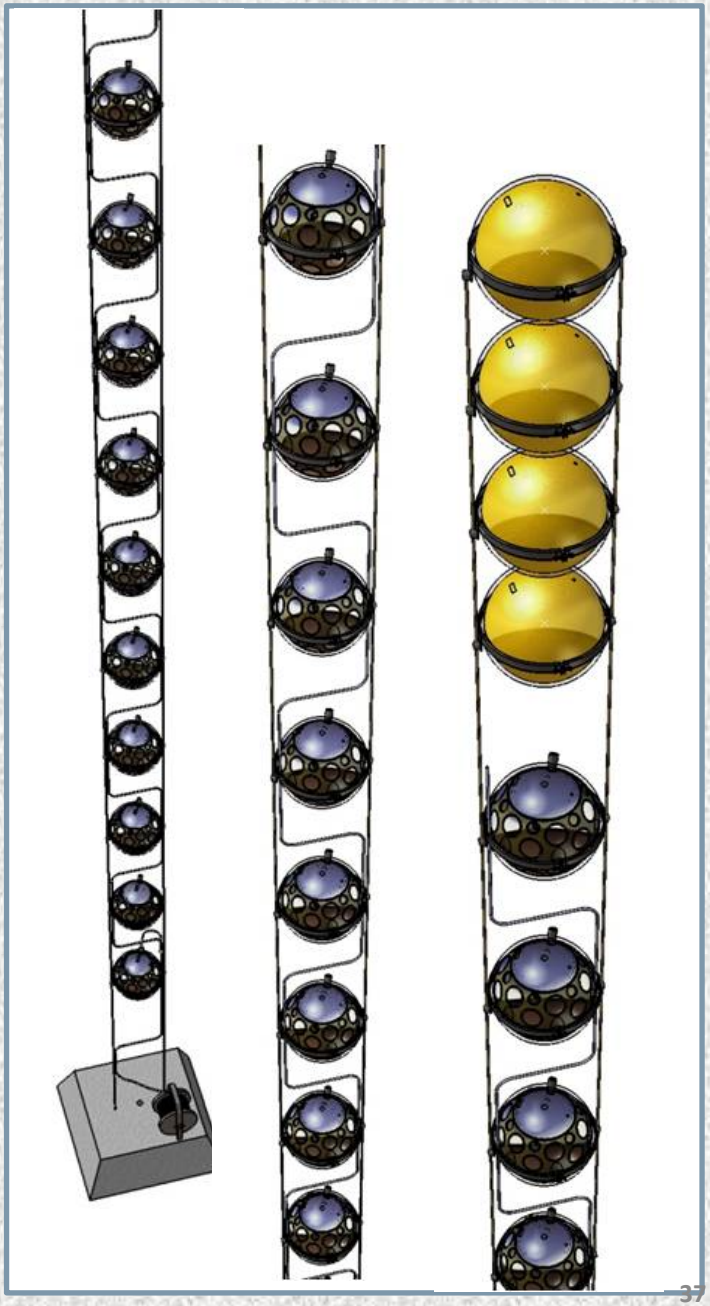
- 31 3-inch PMTs in 17-inch glass sphere (cathode area~ 3x10" PMTs)
  - 19 in lower, 12 in upper hemisphere
  - Suspended by plastic structure
- 31 PMT bases (total ~140 mW) **(D)**
- Front-end electronics **(B,C)**
- Al cooling shield and stem **(A)**
- Single penetrator



- Increased photocathode area
  - 1 KM3NeT DOM = 3 ANTARES OMs
  - Reduces numbers of penetrations/connectors (expensive & risky)
  - Reduces number of optical modules (expensive)
- 1-vs.-2 photo-electron separation
  - Better sensitivity to coincidences / background suppression
  - Information at online data filter level
- Directionality
  - Additional input to reconstruction and veto algorithms
  - Identification of downgoing events (PMTs are also looking upwards)
  - Reduction of random background (K40, bioluminescence)

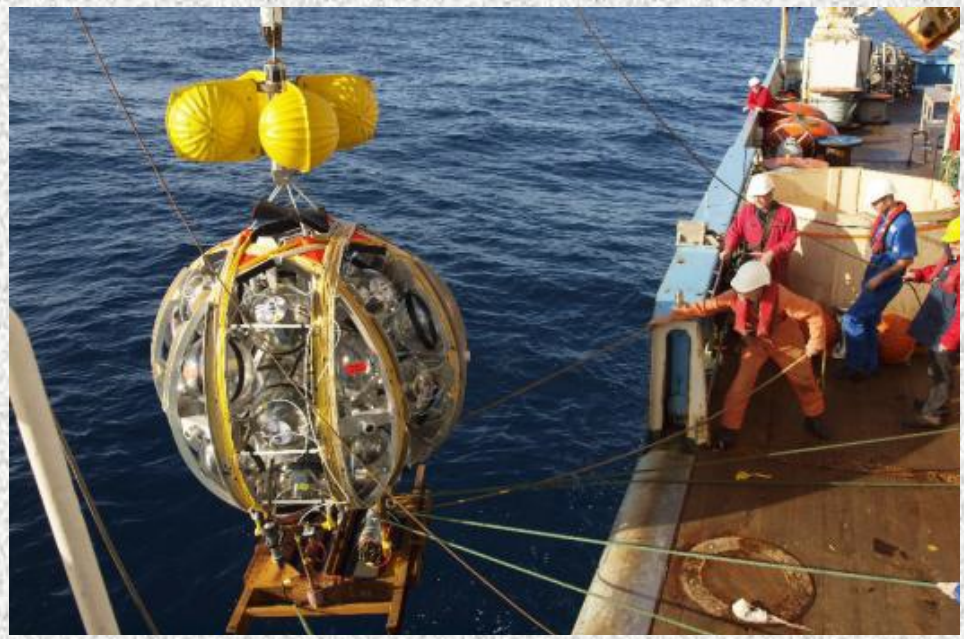
Strings as detector units

- Mooring line:
  - Buoy (probably syntactic foam)
  - 2 Dyneema© ropes (4 mm diameter)
  - 18 storeys (one OM each), 30-36m distance, 100m anchor-first storey
- Electro-optical backbone (VEOC):
  - Flexible hose ~ 6mm diameter
  - Oil-filled
  - fibres and copper wires
  - At each storey: connection to 1 fibre+2 wires
  - Break out box with fuses at each storey: One single pressure transition



Deployment strategy

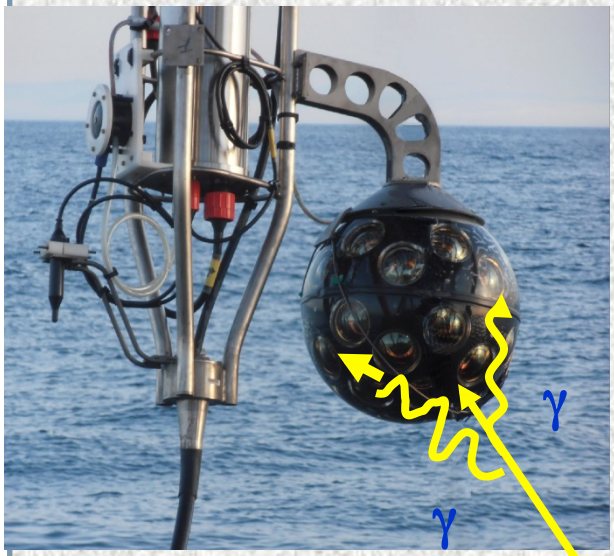
- Compact package self-unfurling
  - Eases logistics (in particular in case of several assembly lines)
  - Speeds up and eases deployment; several units can be deployed in one operation
  - Self-unfurling concepts is being thoroughly tested and verified
- Connection to seabed network by ROV



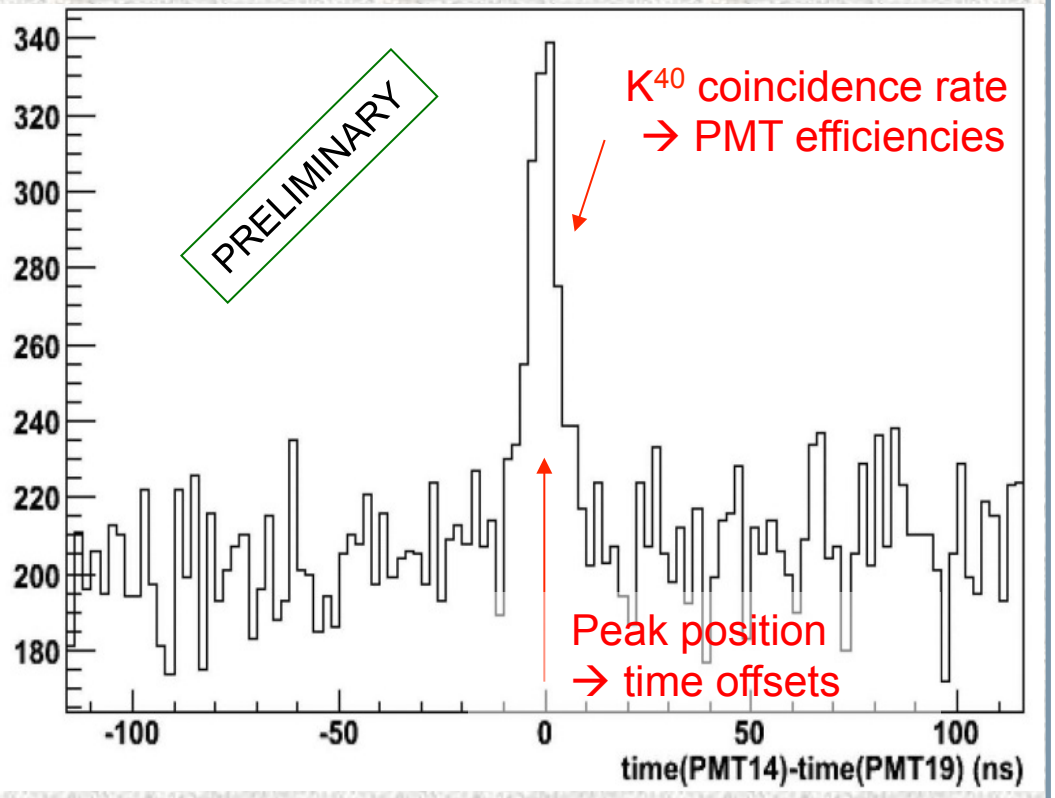
"String compactification"

- First successful test in December 2009
- Further tests in April 2013

PP-DOM: K40 Coincidences

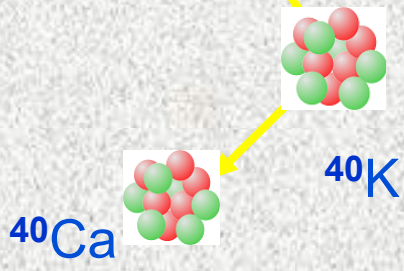


Coincidence rate on 2 adjacent PMTs



e^- (β decay)

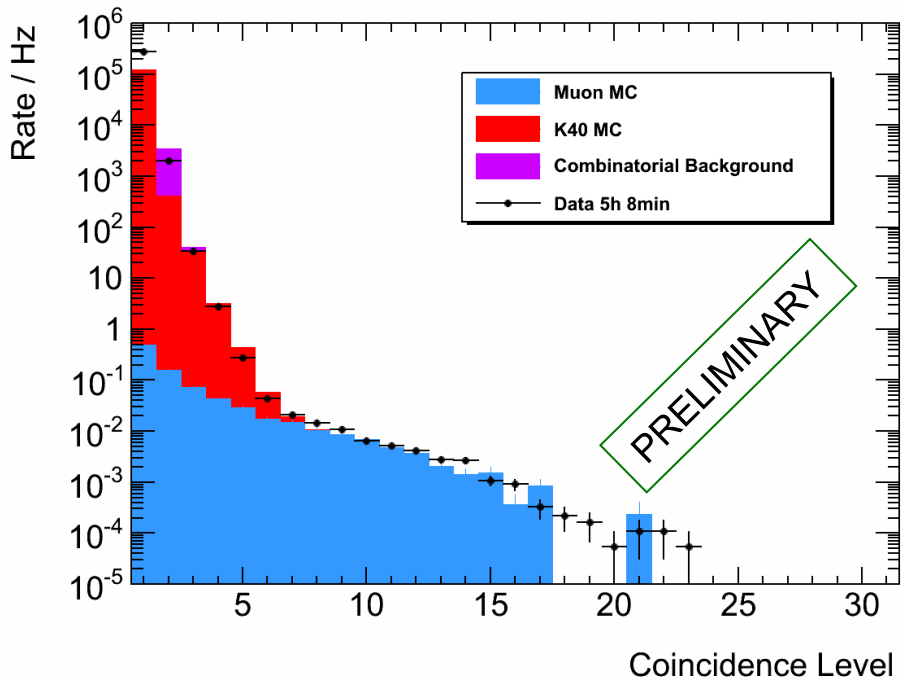
Up to 150 Cherenkov photons per decay

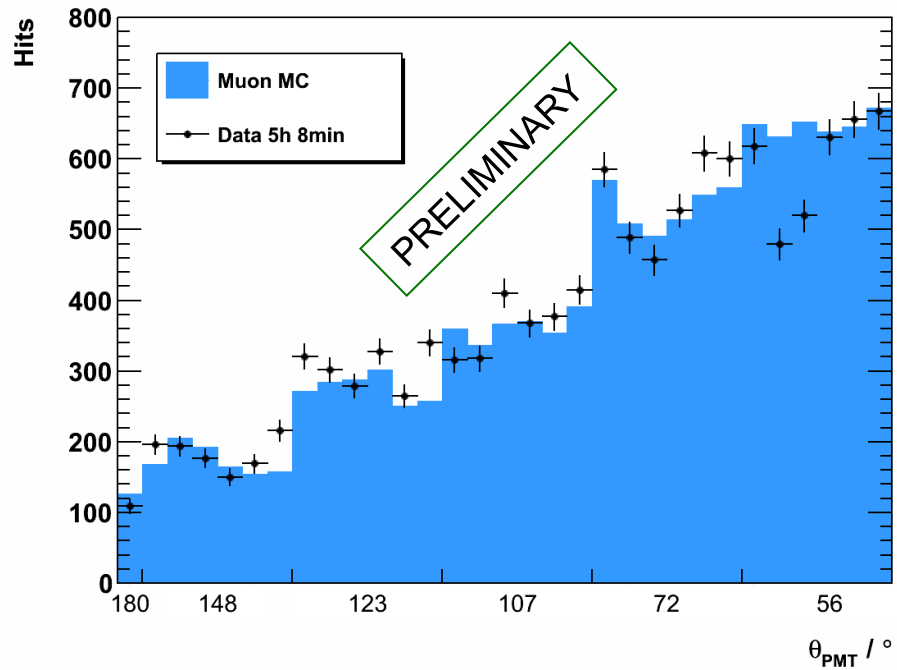


Concentration of ^{40}K is stable
(coincidence rate ~5 Hz on adjacent PMTs)

PPM–DOM deployed in
ANTARES instrumentation line

PPM-DOM: Atmospheric muons





Number of coincident hits in a DOM

>5 coincidences within 20ns ⇒ reduced K40 contribution, dominated by atmospheric muons

Zenith angle of hit PMTs in events with more than 6 coincident hits

More upper PMTs in multi-hit events ⇒ directional information from single storey

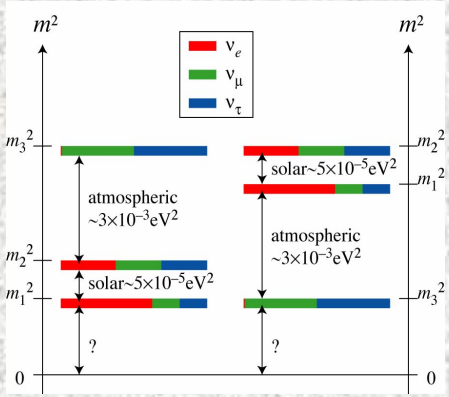
A detour? ORCA

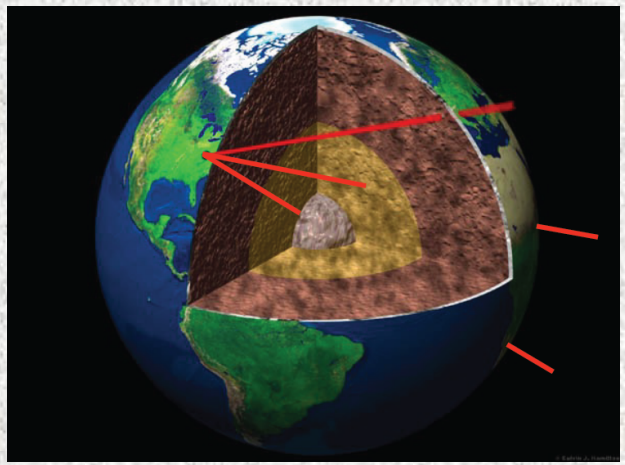
Mass hierarchy with atmospheric neutrinos?

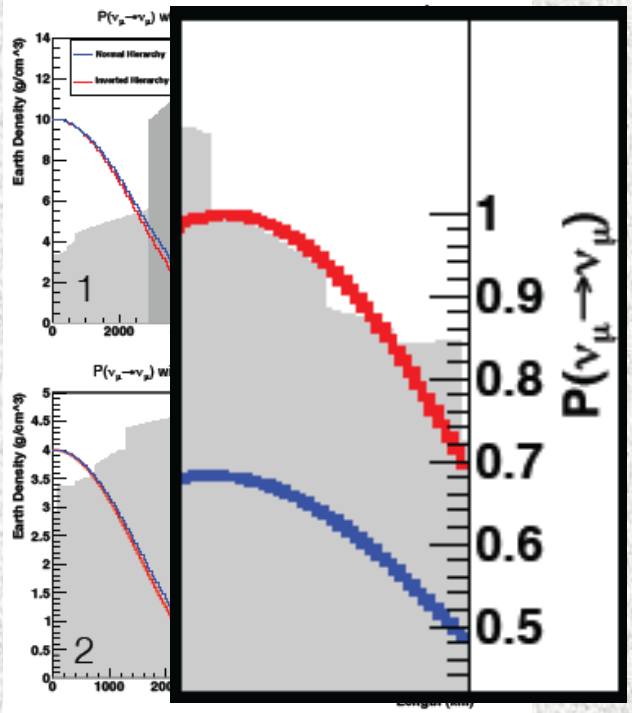
- MSW effect in Earth induces $\nu/\overline{\nu}$ difference in oscillations.
- Resonance around $E_\nu \approx 3 - 10$ GeV ($L = D_{earth}$, $\rho \approx 4–13$ g/cm^3)
- Could be measurable since at these energies:

$$\sigma(\nu) \approx 2\sigma(\overline{\nu})$$

- Differences in the (E_ν, $\cos\theta_\nu$) plane between normal and inverted hierarchies







ORCA

- If feasible, it is worth doing it → study group.
- Caveat: agreed KM3NeT technology, must be used, only minor changes (e.g. length of strings, distance, connection techniques)
- Given the funding profile, decision should be taken soon.
- An (scalable) example of detector has been studied:
  - 50 strings, 20 OMs each
  - 31 3-inch PMTs / OM
  - 20 m horizontal distance
  - 6 m vertical distance
  - Instrumented volume: 1.75 Mton water

- Not only "can we see low energy events?",
- Long list of questions:
  - What are the trigger/event selection efficiencies?
  - How and how efficiently can we separate different event classes?
  - How can we reconstruct these events and what resolutions can we reach on E_ν and θ ?
  - How can we control the backgrounds?
  - What are the dominant systematic effects and how can we control them?
  - What precision of calibration is needed and how can it be achieved?

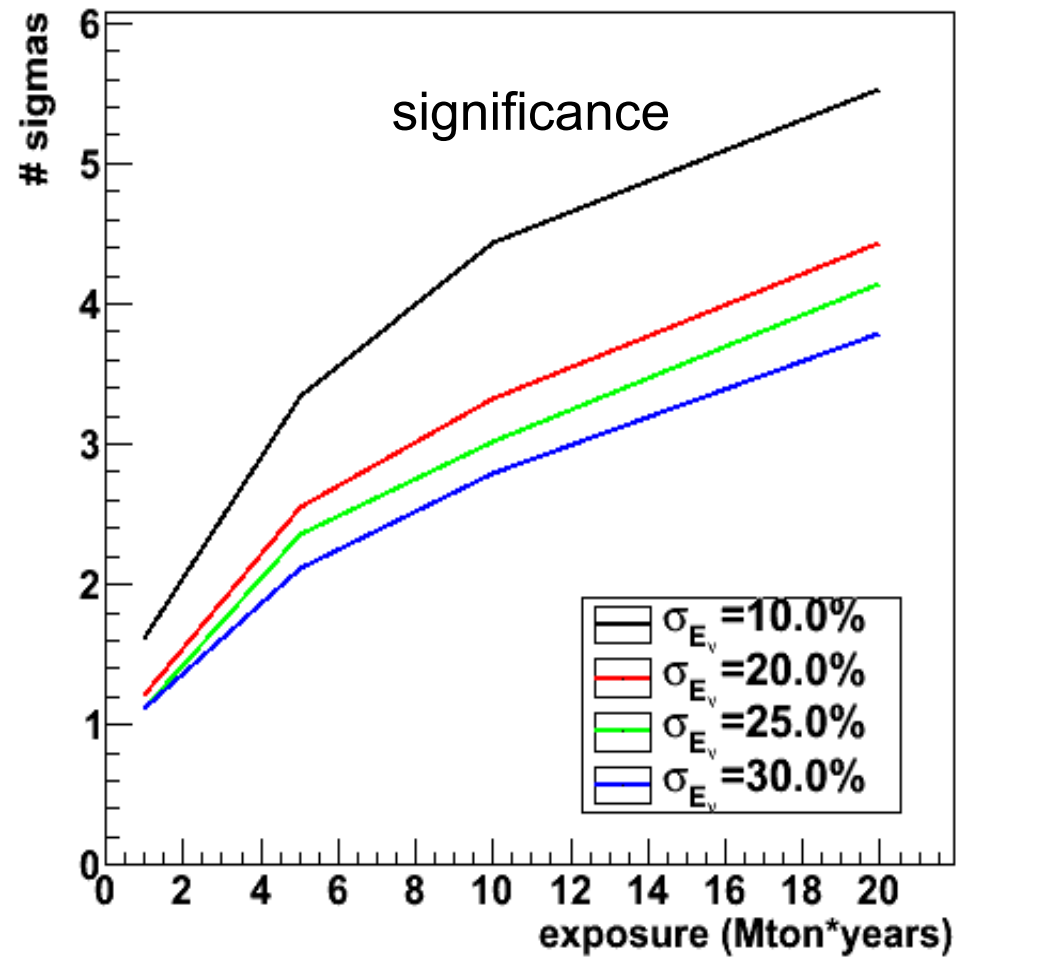
ORCA

All the questions above are still under investigation.

Results of a toy analysis:

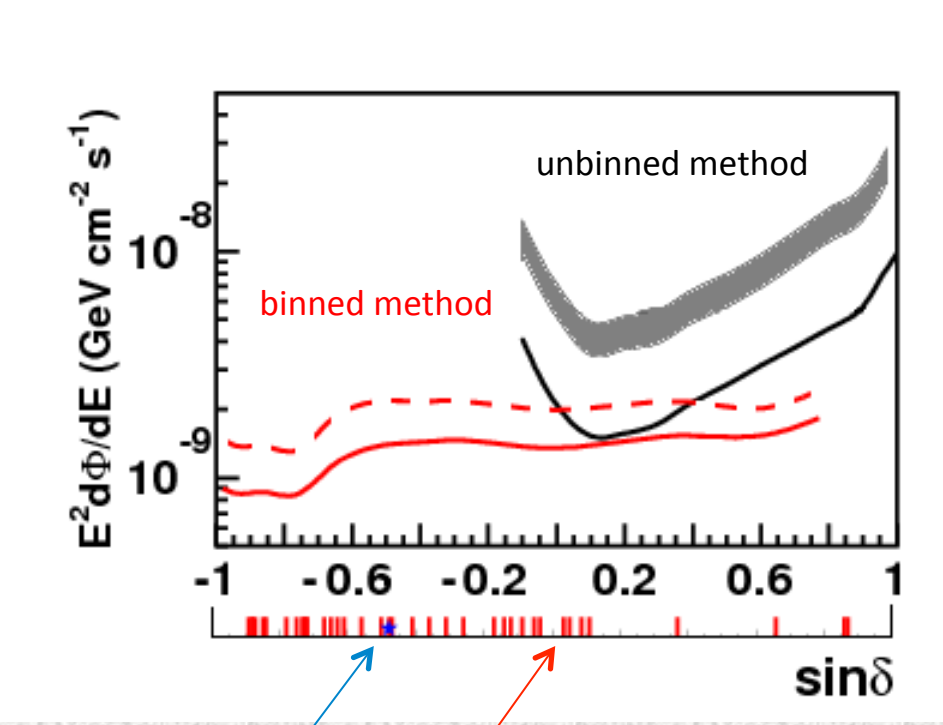
Experimental determination of mass hierarchy at 4-5σ level requires ~20 Mton-years

Improved determination of Δm^2_{23} and θ_{23} seems possible



KM3NeT Performances

Sensitivity and discovery fluxes for point like sources (E^{-2} spectrum) for 1 year of observation time



IceCube discovery 5σ 50% 2.5÷3.5 above sensitivity flux.

IceCube sensitivity 90%CL

KM3NeT discovery 5σ 50%

KM3NeT sensitivity 90%CL

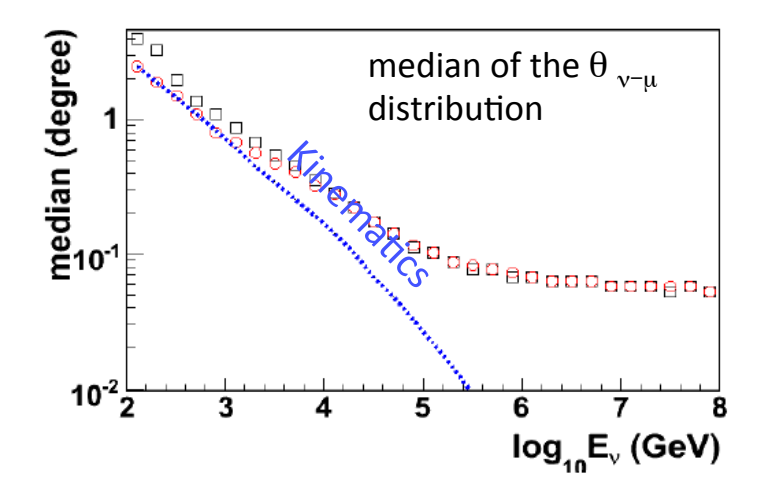
★ Galactic Centre

Observed Galactic TeV-γ sources (SNR, unidentified, microquasars)

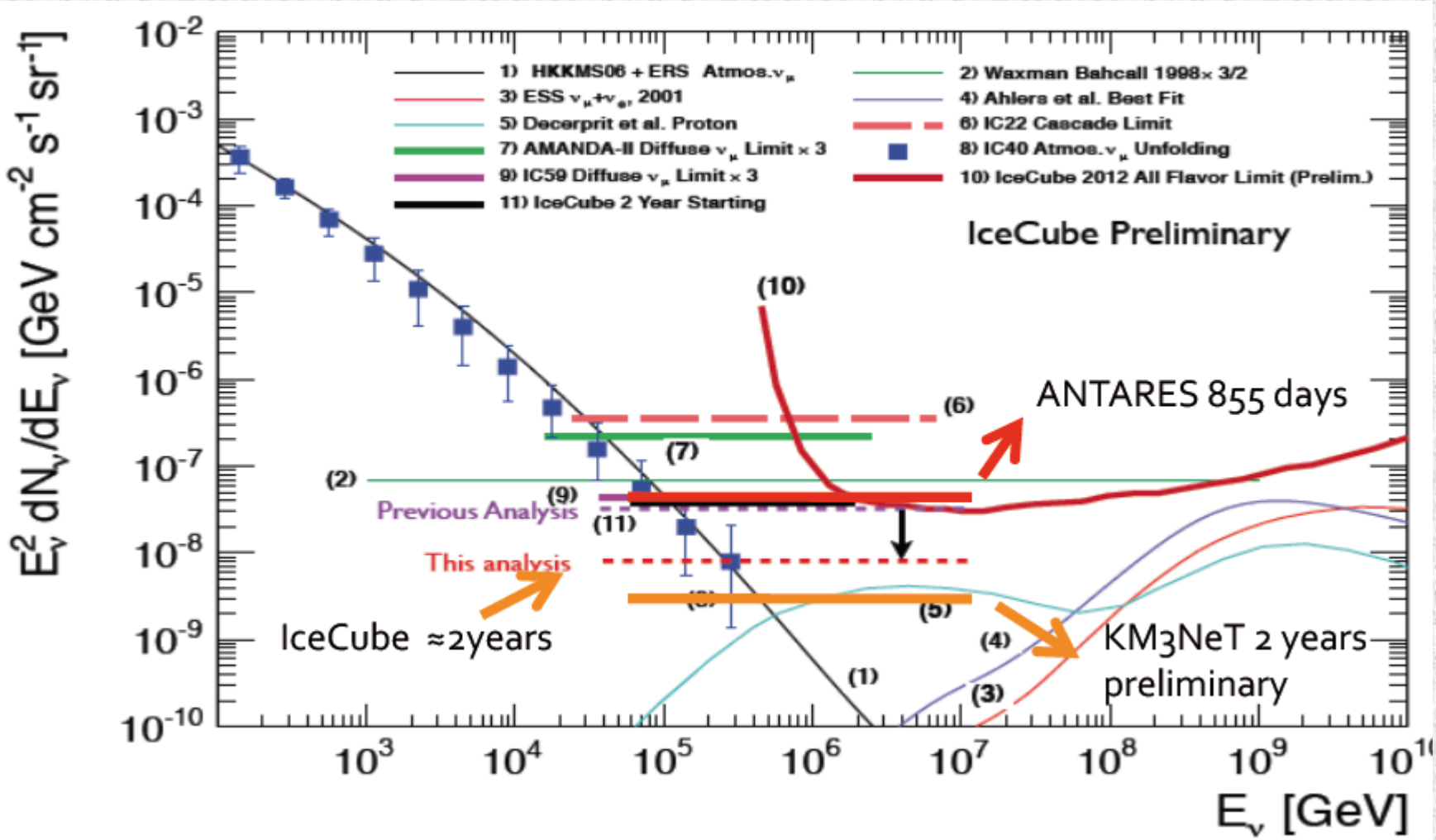
F. Aharonian et al. Rep. Prog. Phys. (2008)

Abdo et al., MILAGRO, Astrophys. J. 658 L33-L36 (2007)

Detector resolution



Diffuse fluxes



Summary

- The physics case of neutrino telescopes and their technical feasibility are beyond doubt. The struggle is now to reach the required sensitivity.
- IceCube is operating smoothly and providing unprecedented sensitivities. Hints of a signal have been observed, the tip of the iceberg!
- ANTARES is taking data in its final configuration since 2008 and providing physics results.
- The initiatives for a Med-Sea neutrino telescope (Antares, NEMO and NESTOR) have joined forces to build KM3NeT. Funding is available to start the first phase.
- The opportunity of low energy cherenkov detectors (PINGU, ORCA) is under study. They could become an interesting option soon.