# Neutrino searches with ANTARES and KM3NeT



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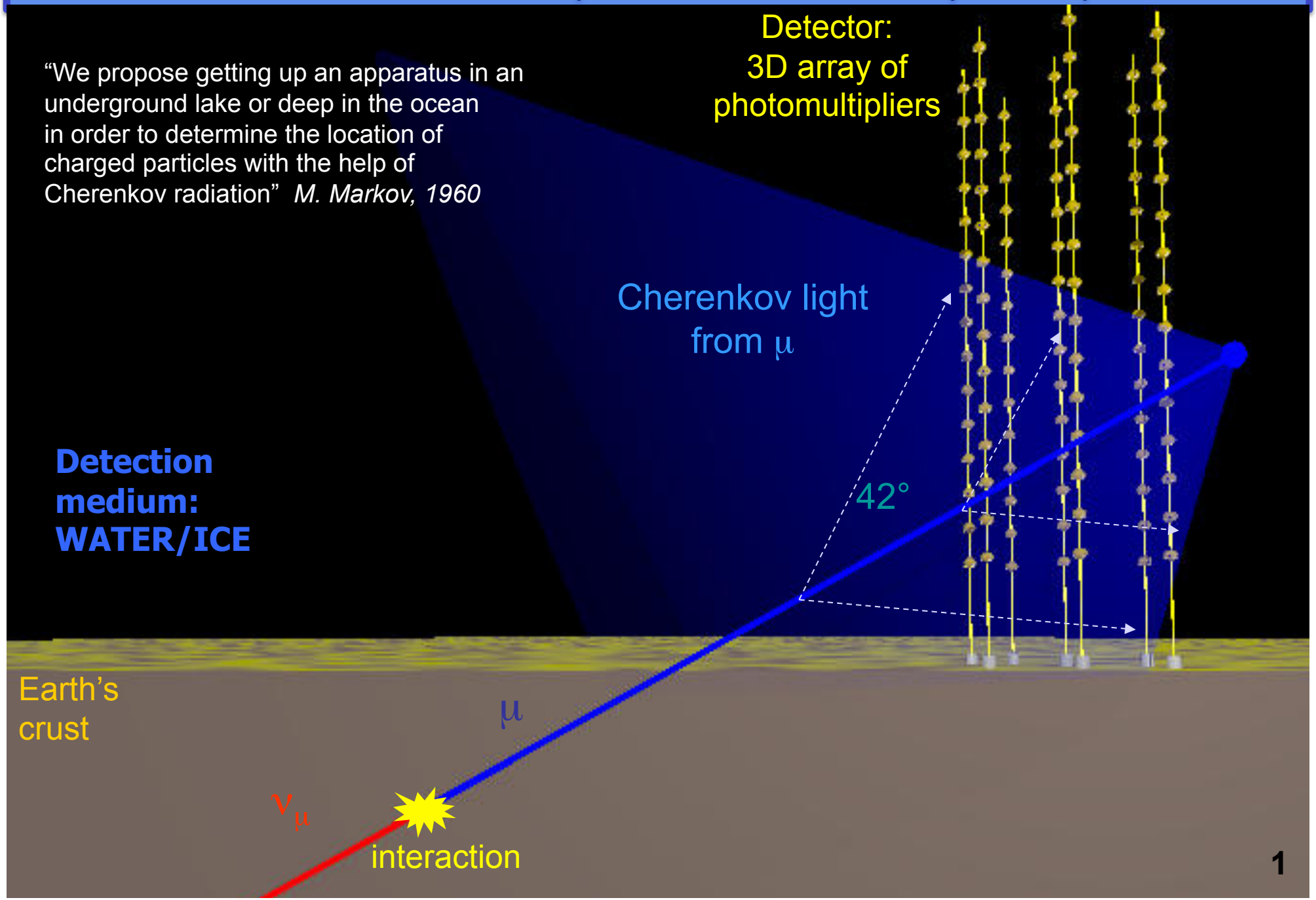
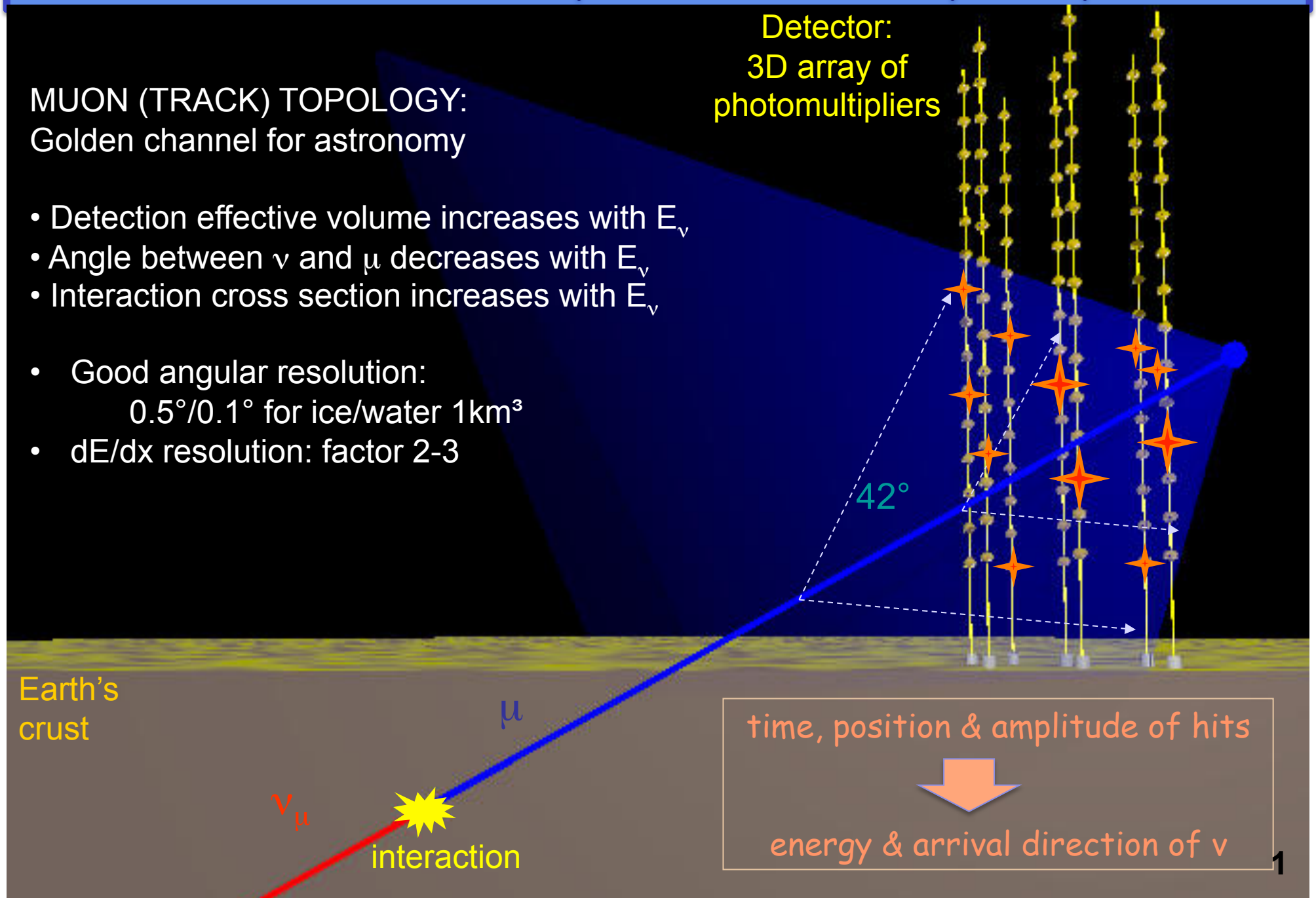
(APC & Université Paris Diderot)
on behalf of
the ANTARES & KM3NeT Collaborations

# Neutrino telescopes: detection principle

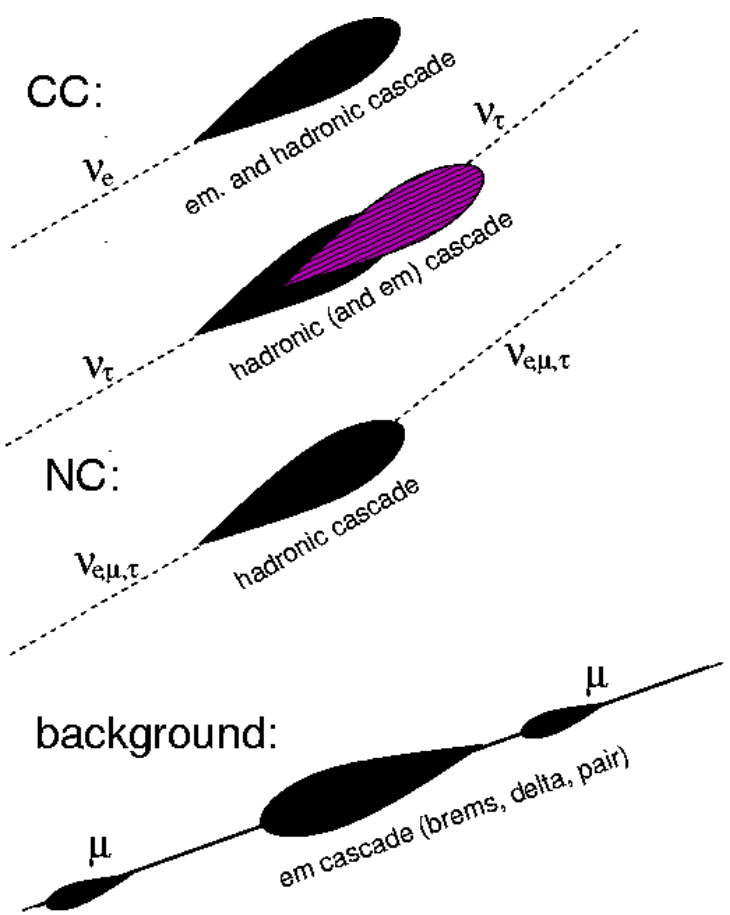


# Neutrino telescopes: detection principle



# Cascade topologies

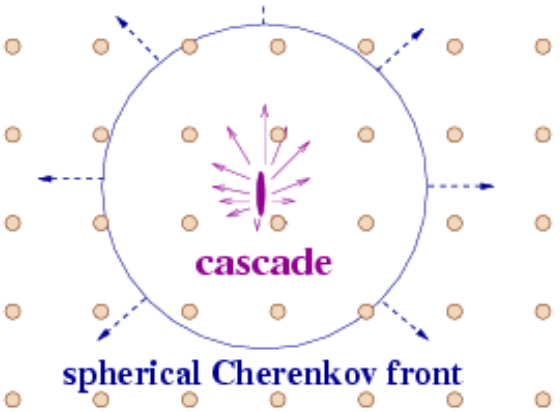
$\nu_e:\nu_\mu:\nu_\tau = 1:2:0$ at source $\xrightarrow{\text{oscillation}}$ $\nu_e:\nu_\mu:\nu_\tau = 1:1:1$ at Earth !

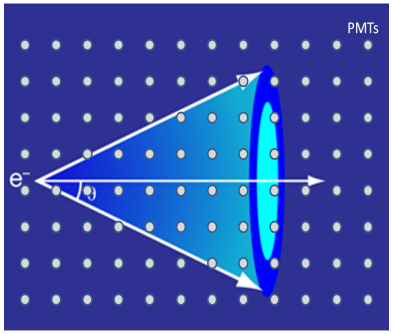



*IceCube discovery channel!*

Generic reconstruction:

Bright Point (+ e Cherenkov cone ?)



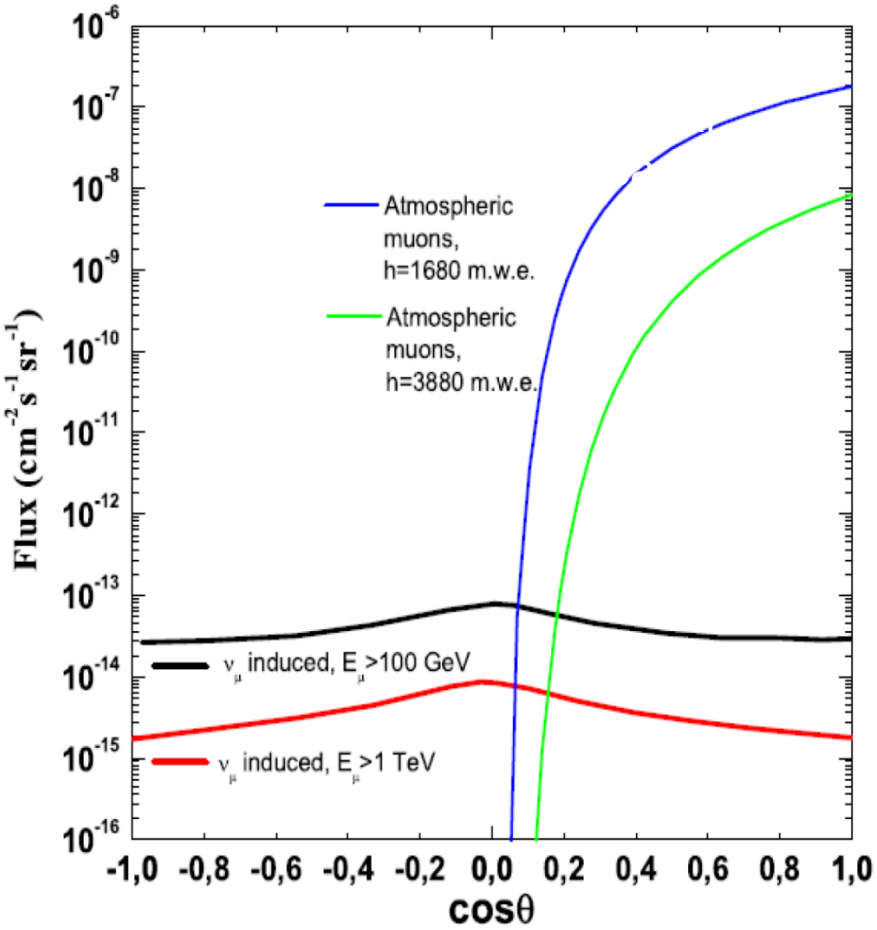

→ Provide sensitivity to all neutrino flavors

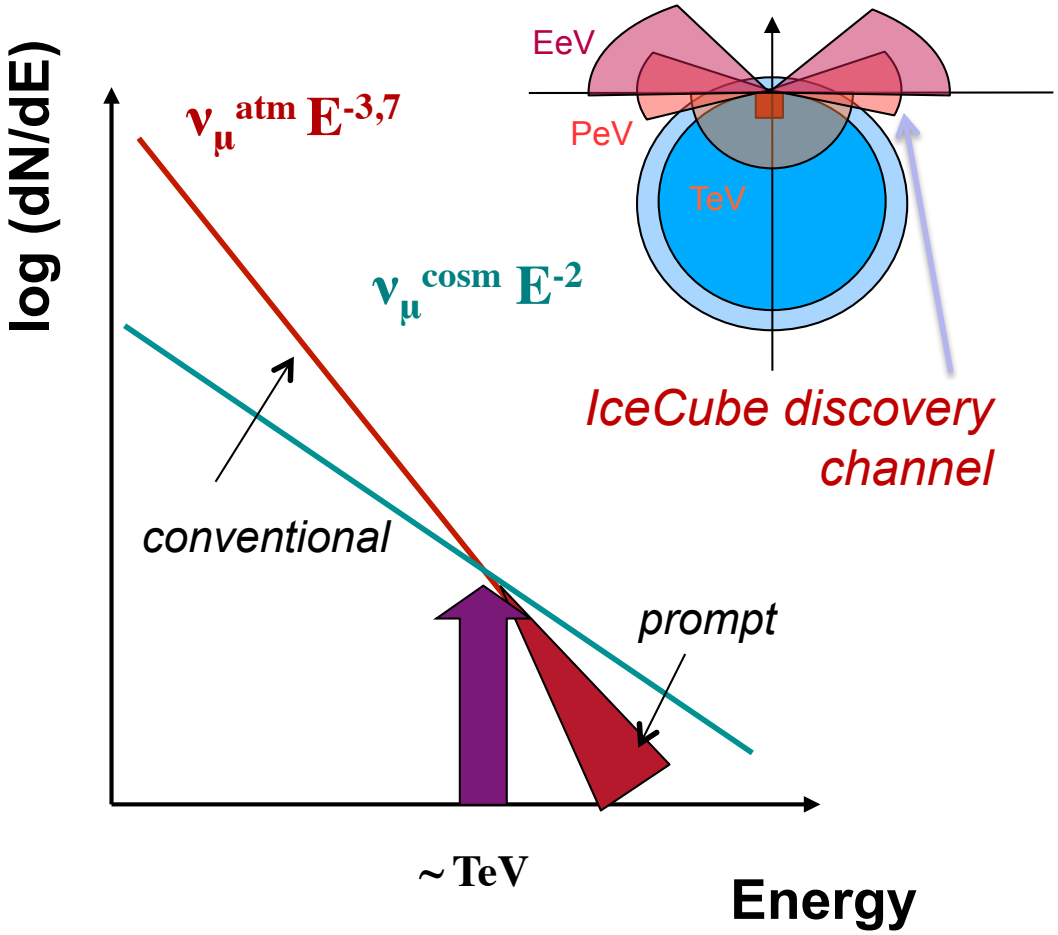
→ Increase overall detector sensitivity

- Angular resolution 10° - 30° / 1°- 5° at 100 TeV for ice / water
- Energy resolution ~ 15%

# Atmospheric background vs. cosmic neutrinos

**Atmospheric muons: shield detector, look downwards, apply veto**

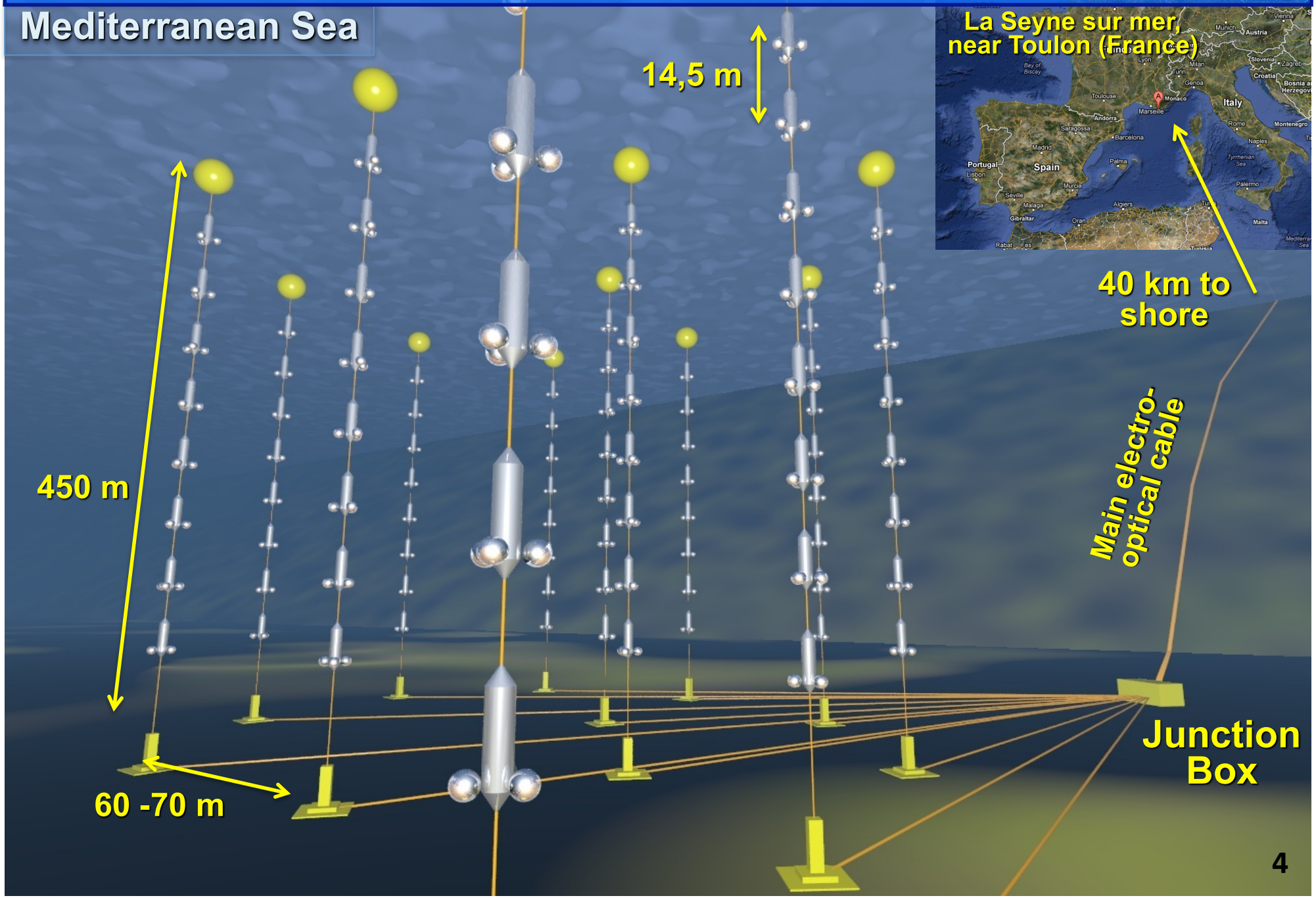



**Atmospheric neutrinos: search for**

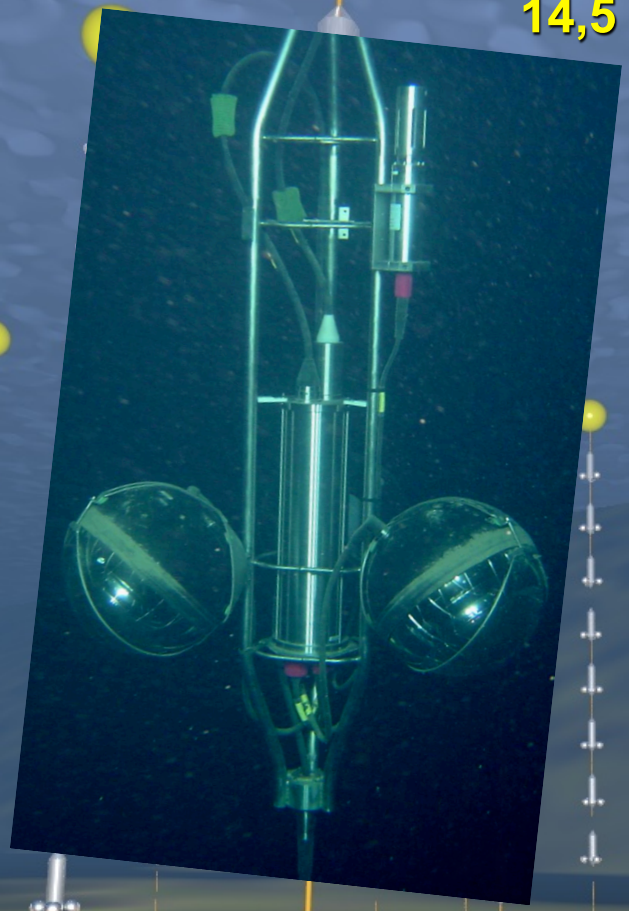
- An excess at High Energy
- Anisotropies, spatial clustering
- Time / space coincidence with other cosmic probes

# The ANTARES neutrino telescope



# The ANTARES neutrino telescope

Mediterranean Sea



14,5 m

450 m

60 -70 m

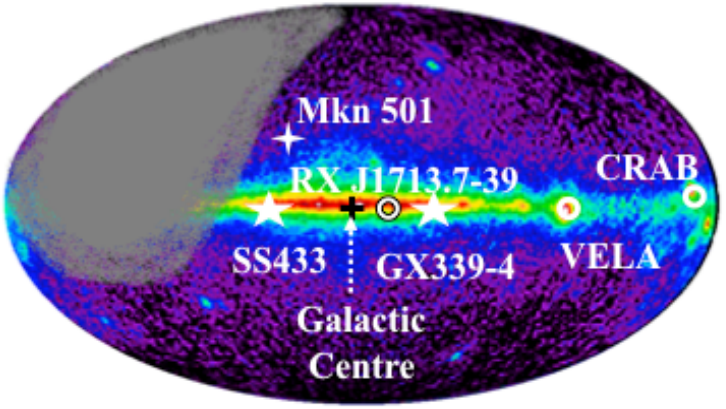

40 km to shore

- 12 lines
- 25 storeys/line
- 3 PMTs / storey
- 885 10" PMTs
- ~15 Mton instrumented volume

+ instrumentation line
+ acoustic array AMADEUS
+ secondary junction box for Earth/marine science

# Neutrino astronomy with ANTARES

- 12-line data taking since 2008;
  physics duty cycle ≈ 85%
  ~5 atmospheric neutrinos/day (upgoing)
  (> 9000 neutrinos detected so far)
- Effective area ≈ 1 m² at 30 TeV
- Visibility: ¾ of the sky, most of the Galactic Plane

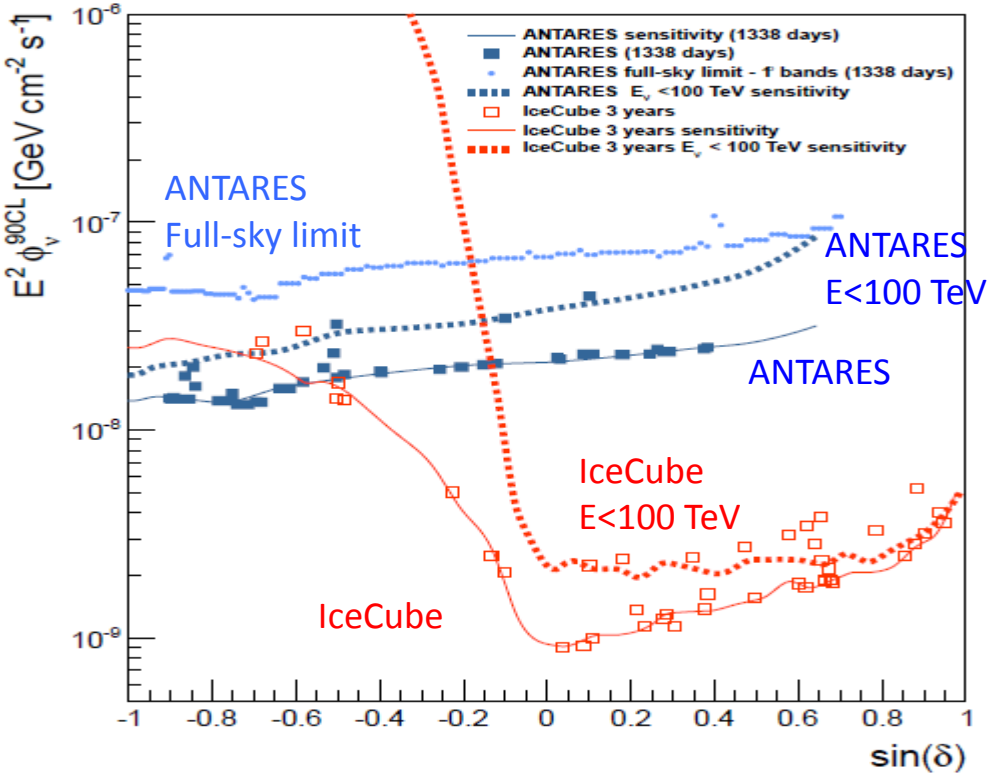



- Latest point source search:
2007-2012 (1338 days of data)

median angular resolution 0.38°
($\nu_\mu$ track-like events)

Hottest spot at 2.2 σ significance
(no associated source)

Good complementarity with IceCube
field of view: most stringent
limits for a large part of the Southern Sky
at E < 100 TeV

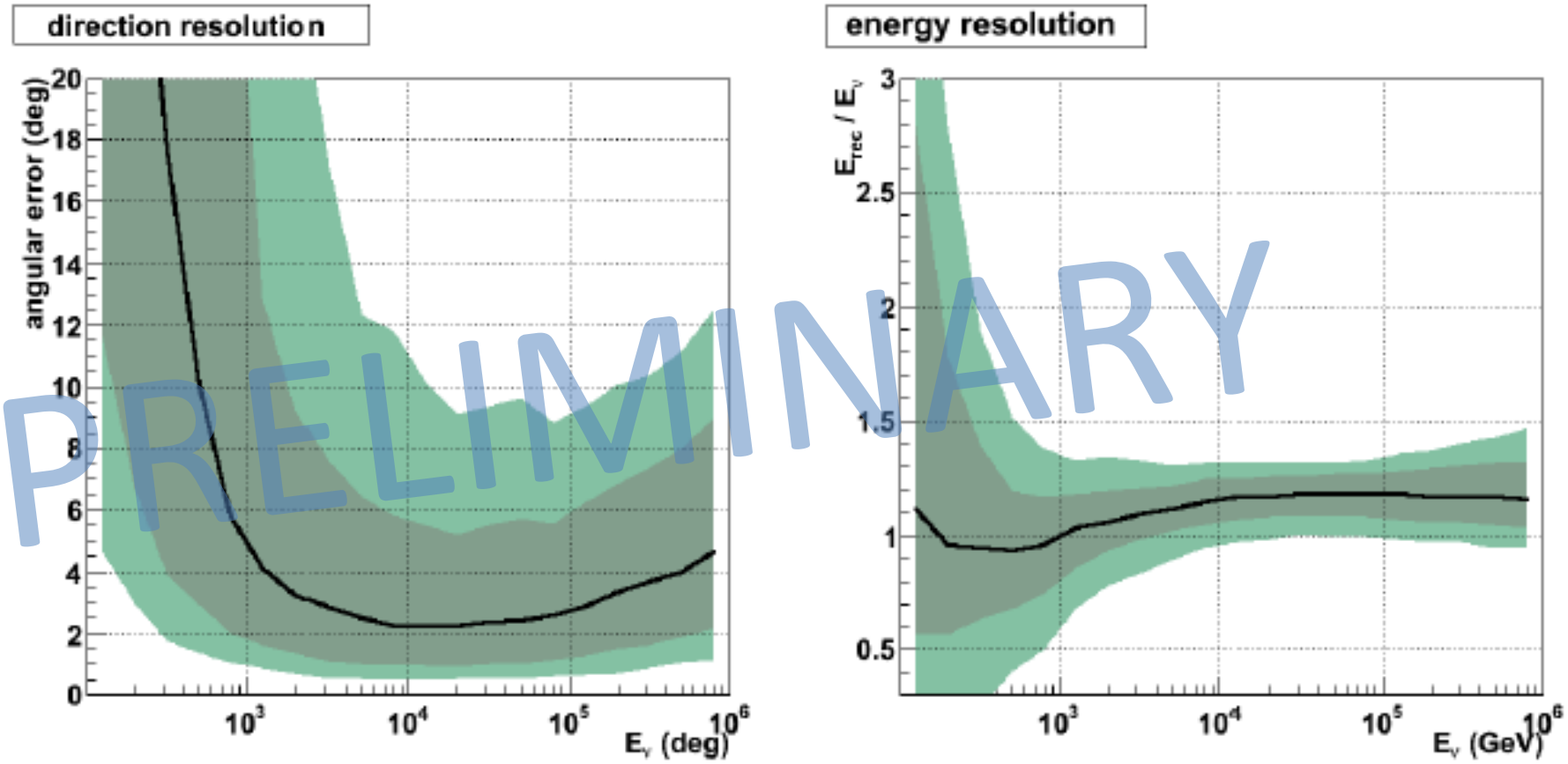




📖 Astrophys. J. Lett. 786:L5 (2014)


Expect further improvment including cascade channel !

# Improving resolutions in the cascade channel




Work in progress to reduce angular resolution with cascades

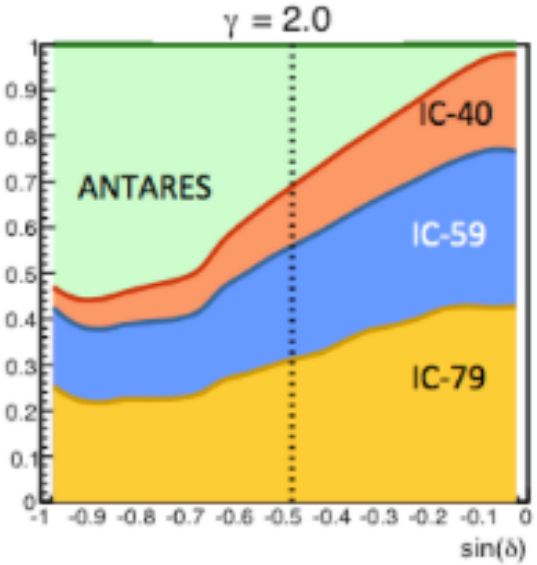
→search for small structures in the sky (including point - sources)

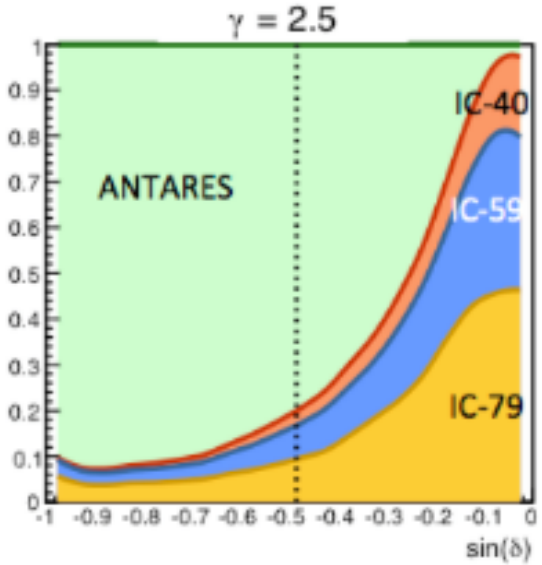
1° achievable with KM3NeT !

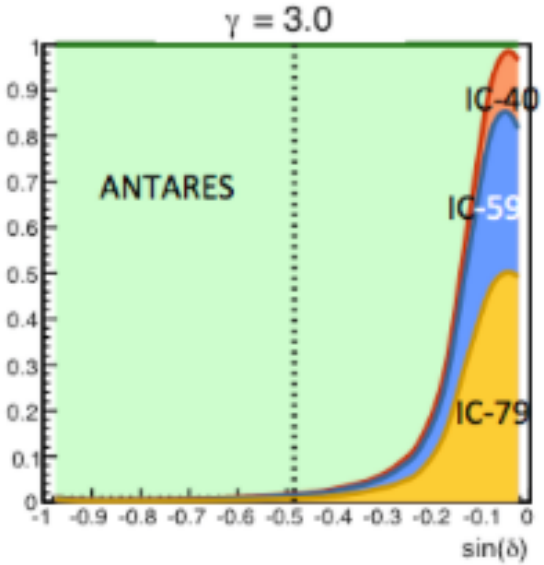
# Joint ANTARES-IceCube search

ANTARES 2007-2012 and the IC40, IC59, and IC79 samples for the Southern Hemisphere

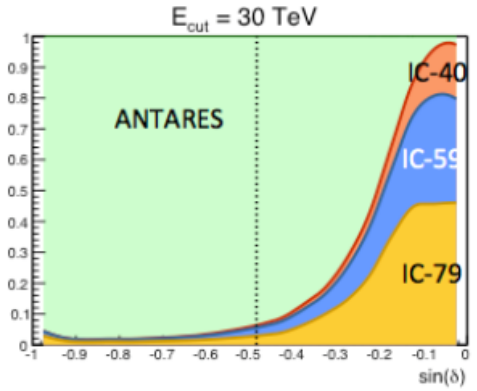
Fraction of signal events which would be detected by each sample ($E^{-\gamma}$):

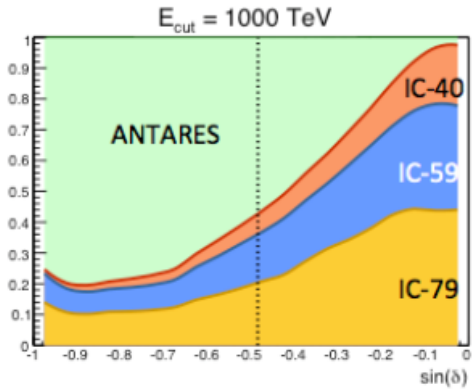


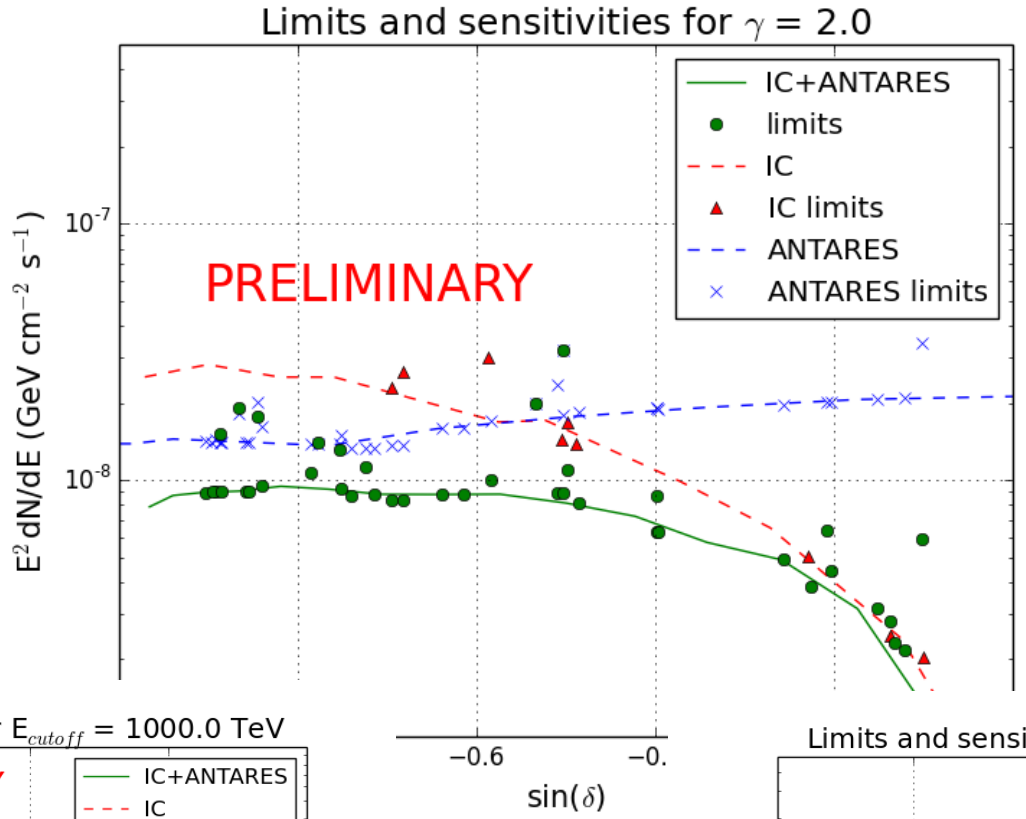

$$\frac{d\Phi}{dE} = \Phi_0 E^{-2} e^{-\sqrt{\frac{E}{E_{cutoff}}}}$$

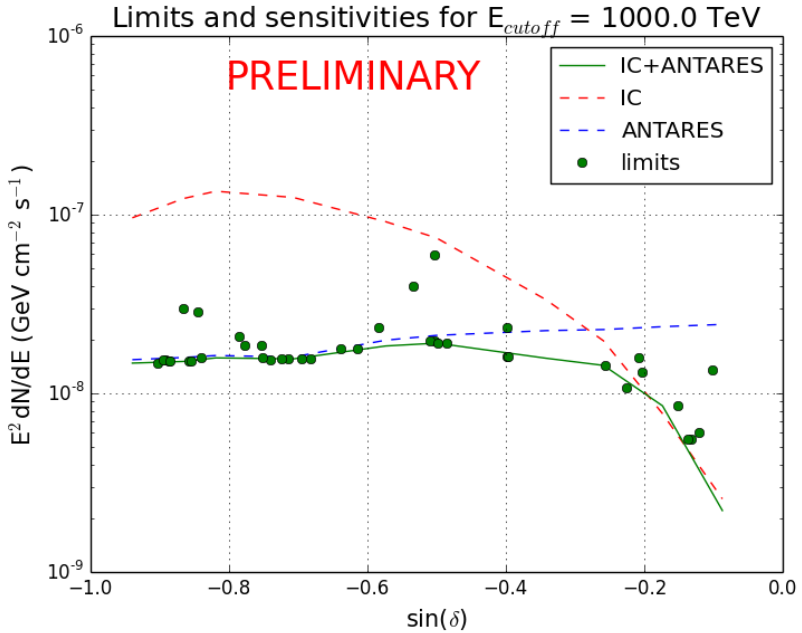


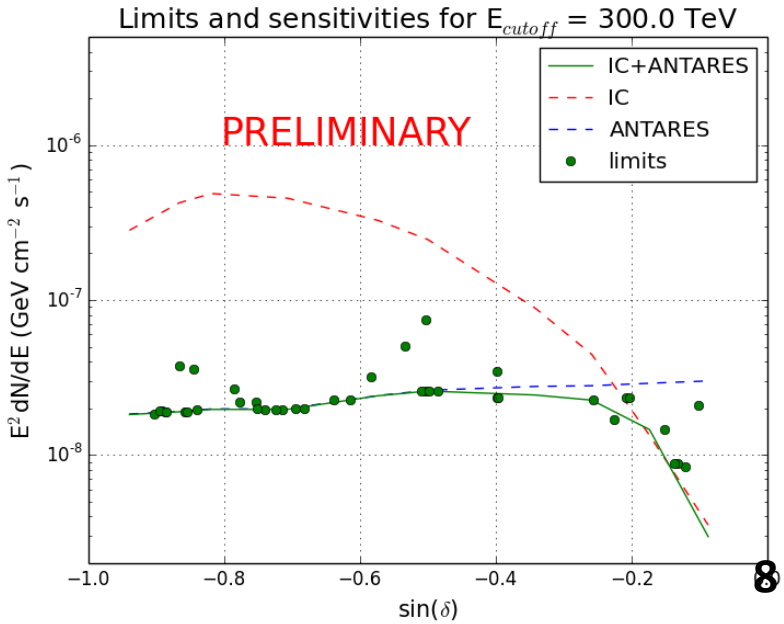



# Joint ANTARES-IceCube search

Joint publication
In preparation



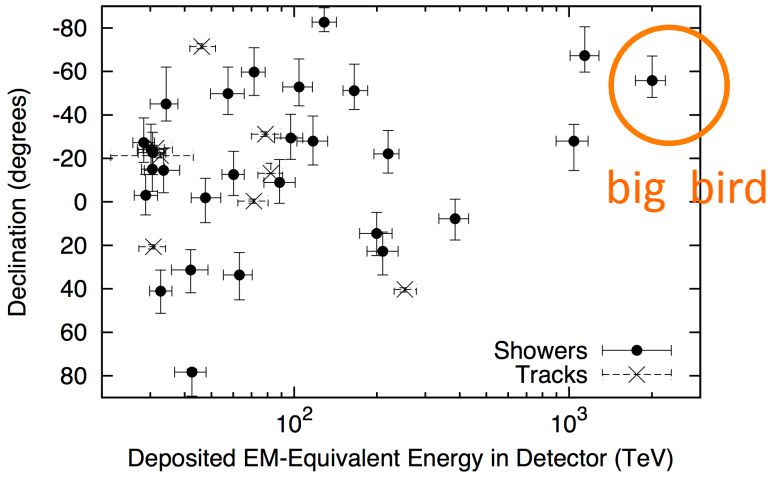



# Diffuse neutrino fluxes: the IceCube signal

**2 year analysis:**
**28 events**
**4.1σ**
*(Science 342, 2013)*

→

**3 year analysis:**
**37 events**
**5.7σ**
*(arXiv:1405.5303, sub.PRL)*




7 → 9 track-like events

1° angular resolution

muon takes some energy away

total expected background: 11 events

21 → 28 cascade-like events

10° - 45° angular resolution

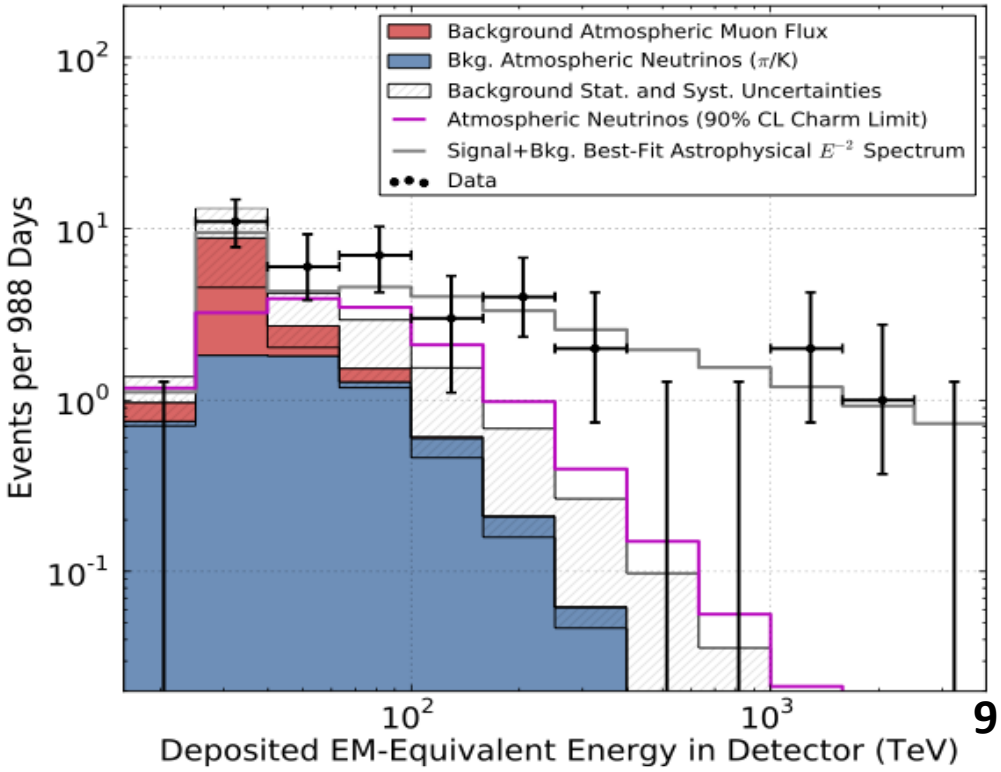
15% visible energy reconstruction

**Best fit (per flavor):**

$0.95 \pm 0.3 \times 10^{-8}\ E^{-2}\ \text{GeV cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$

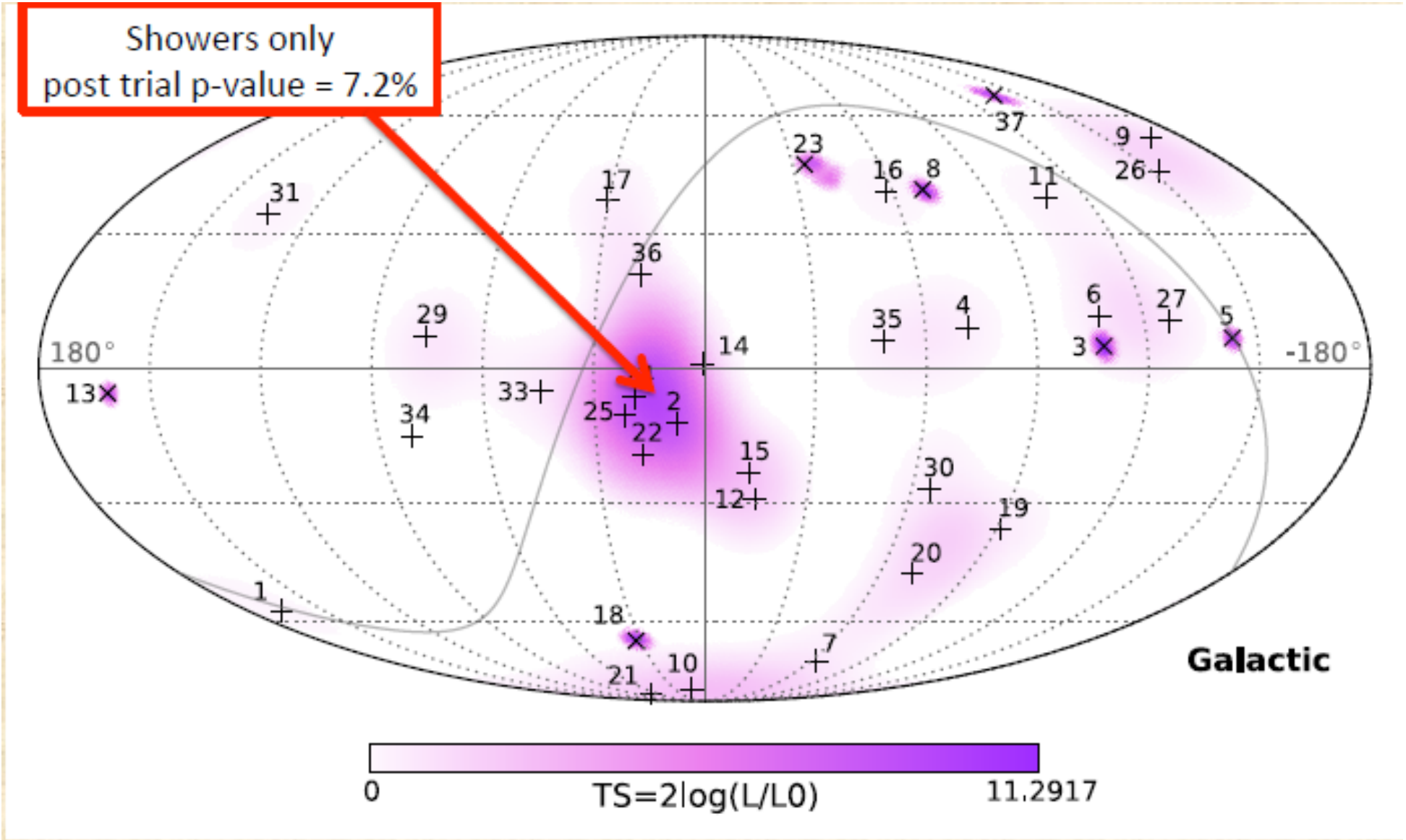
highest energy event @ 2 PeV

cutoff at ~2.3 PeV ?



# Diffuse neutrino fluxes: the IceCube signal

Hint of clustering near Galactic Center ? … no claim for signal



# A source near the Galctic Center ?

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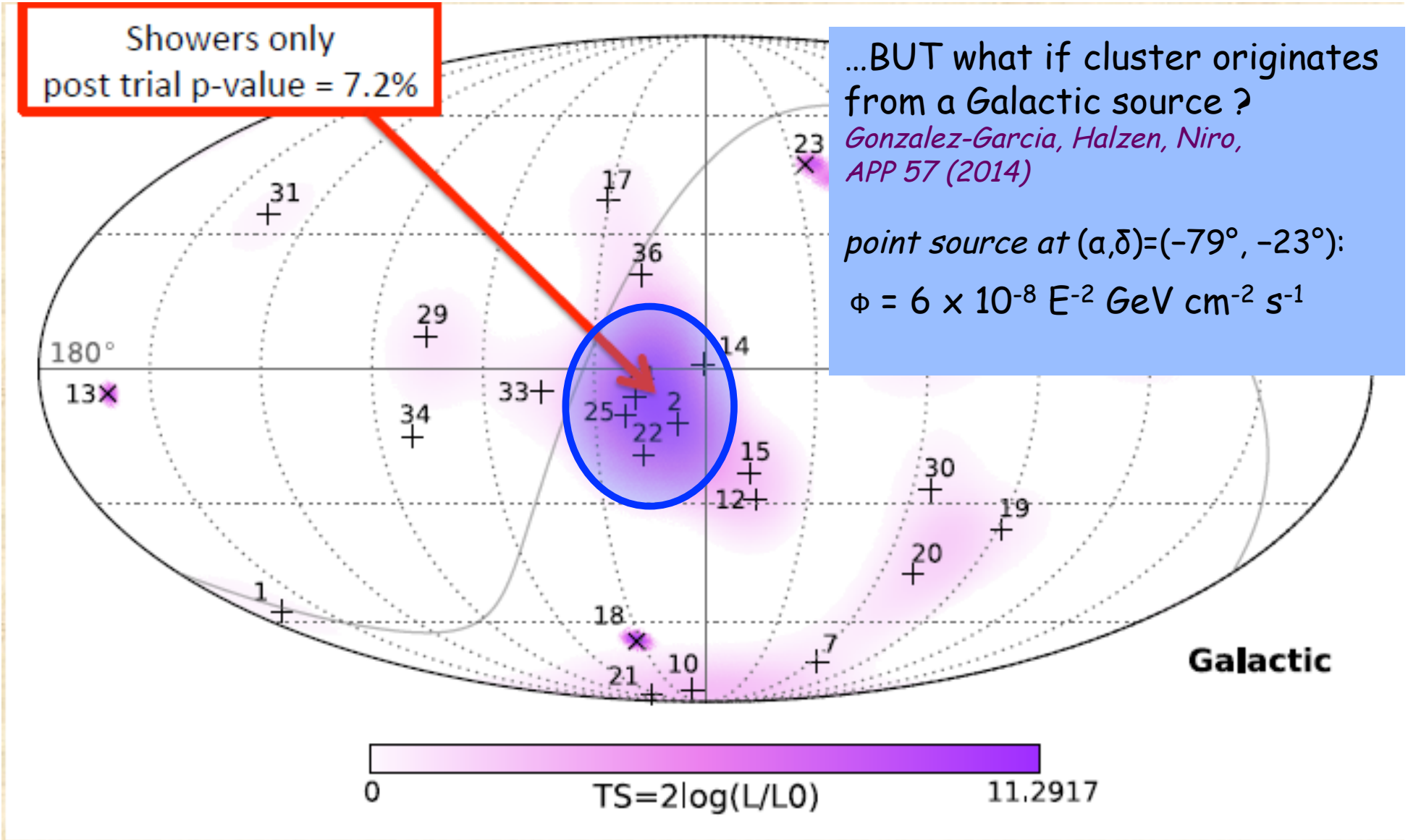



…BUT what if cluster originates from a Galactic source ?
*Gonzalez-Garcia, Halzen, Niro, APP 57 (2014)*

*point source at* (α,δ)=(−79°, −23°):

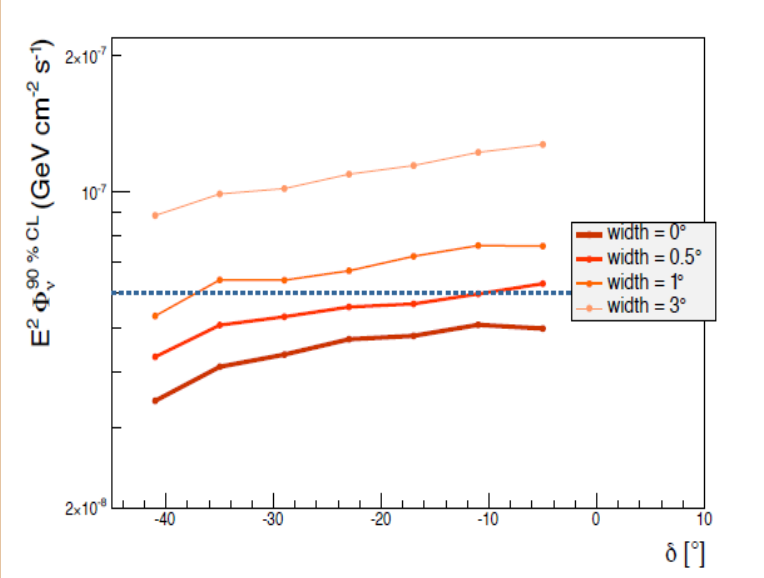
$\Phi = 6 \times 10^{-8}\ E^{-2}\ GeV\ cm^{-2}\ s^{-1}$

# A source near the Galactic Center ?

Hint of clustering near Galactic Center ? … no claim for signal

ANTARES search for neutrino source within 20° around GC:

-scan in declination
- allow for extended sources:
0°, 0.5°, 1°, 3°




ANTARES excludes point source (up to 1° extension) as origin of the IceCube cluster

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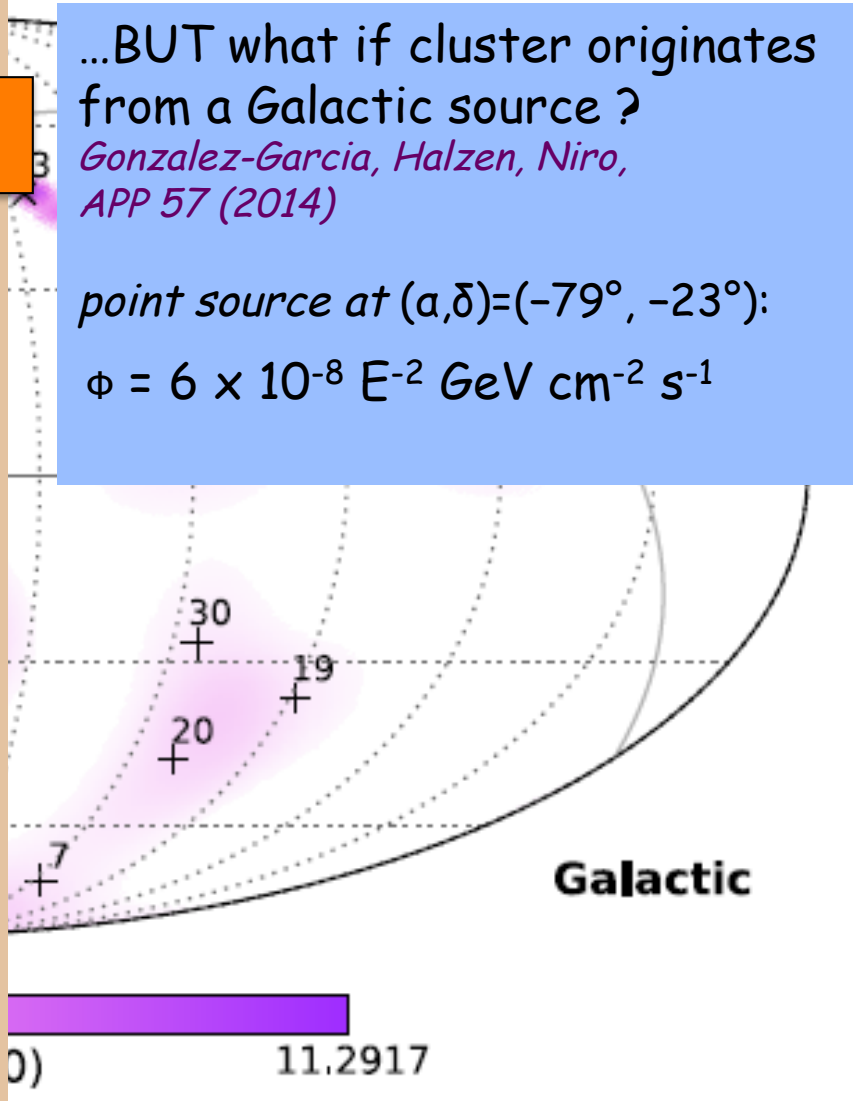
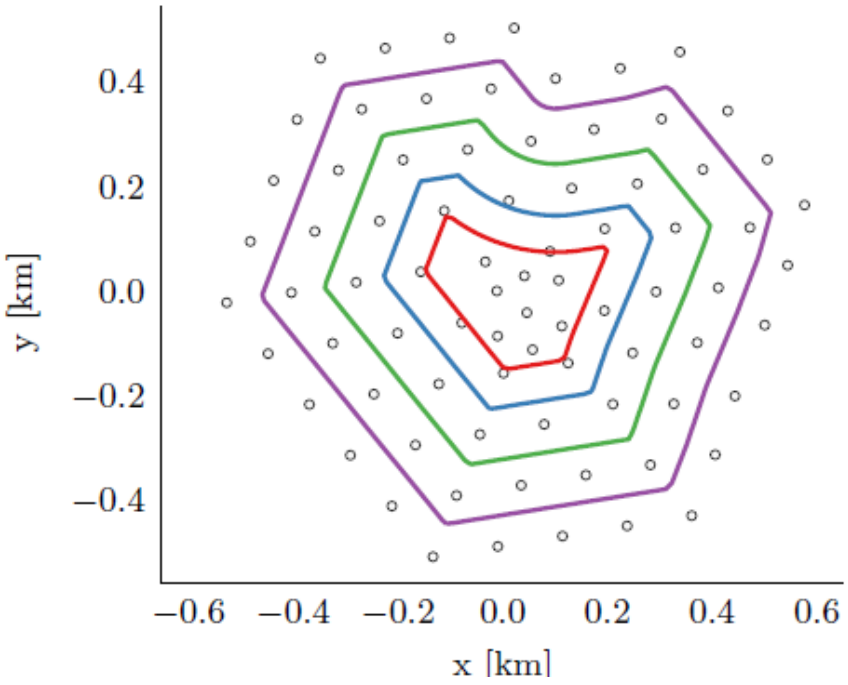
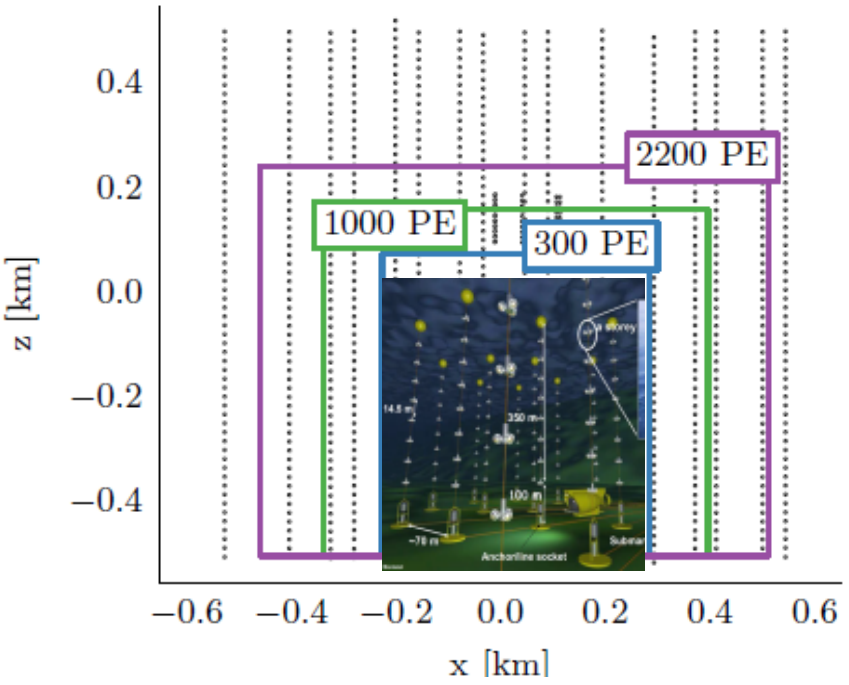


# Latest update from IceCube

**Atmospheric and Astrophysical Neutrinos above 1 TeV Interacting in IceCube**

M. G. Aartsen,[2] M. Ackermann,[47] J. Adams,[15] J. A. Aguilar,[23] M. Ahlers,[28] M. Ahrens,[38] D. Altmann,[22]
T. Anderson,[44] C. Arguelles,[28] T. C. Arlen,[44] J. Auffenberg,[1] X. Bai,[36] S. W. Barwick,[25] V. Baum,[29]
J. J. Beatty,[17,18] J. Becker Tjus,[10] K.-H. Becker,[46] S. BenZvi,[28] P. Berghaus,[47] D. Berley,[16] E. Bernardini,[47]
A. Bernhard,[32] D. Z. Besson,[26] G. Binder,[8,7] D. Bindig,[46] M. Bissok,[1] E. Blaufuss,[16] J. Blumenthal,[1]
D. J. Boersma,[45] C. Bohm,[38] F. Bos,[10] D. Bose,[40] S. Böser,[11] O. Botner,[45] L. Brayeur,[13] H.-P. Bretz,[47]

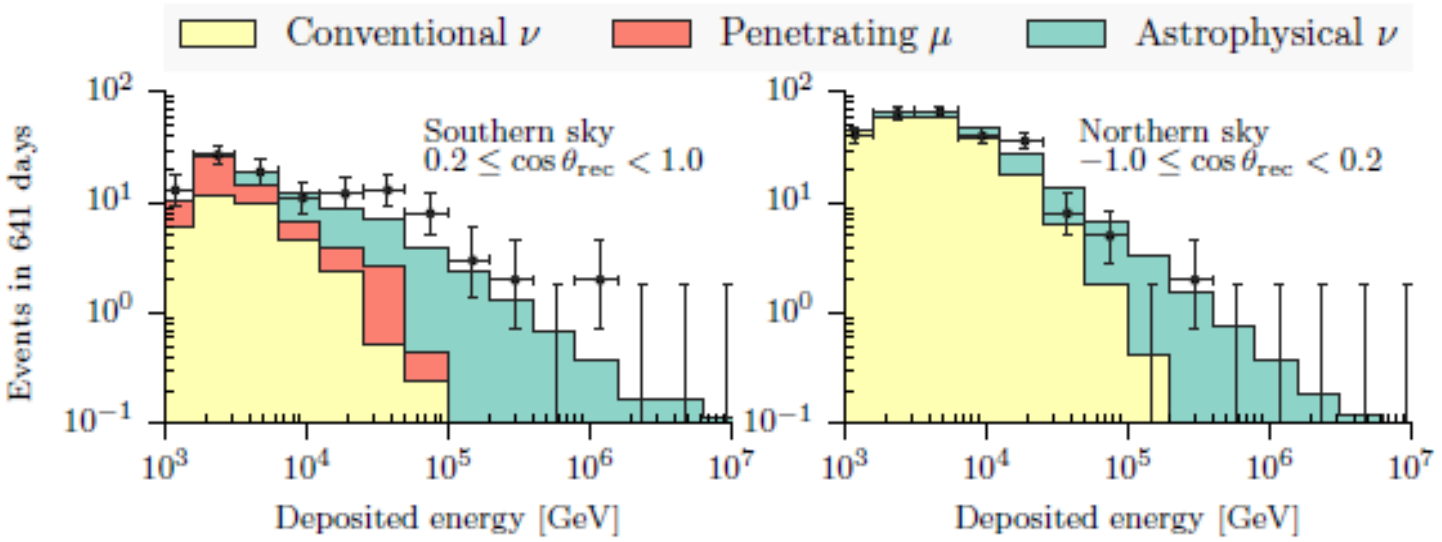


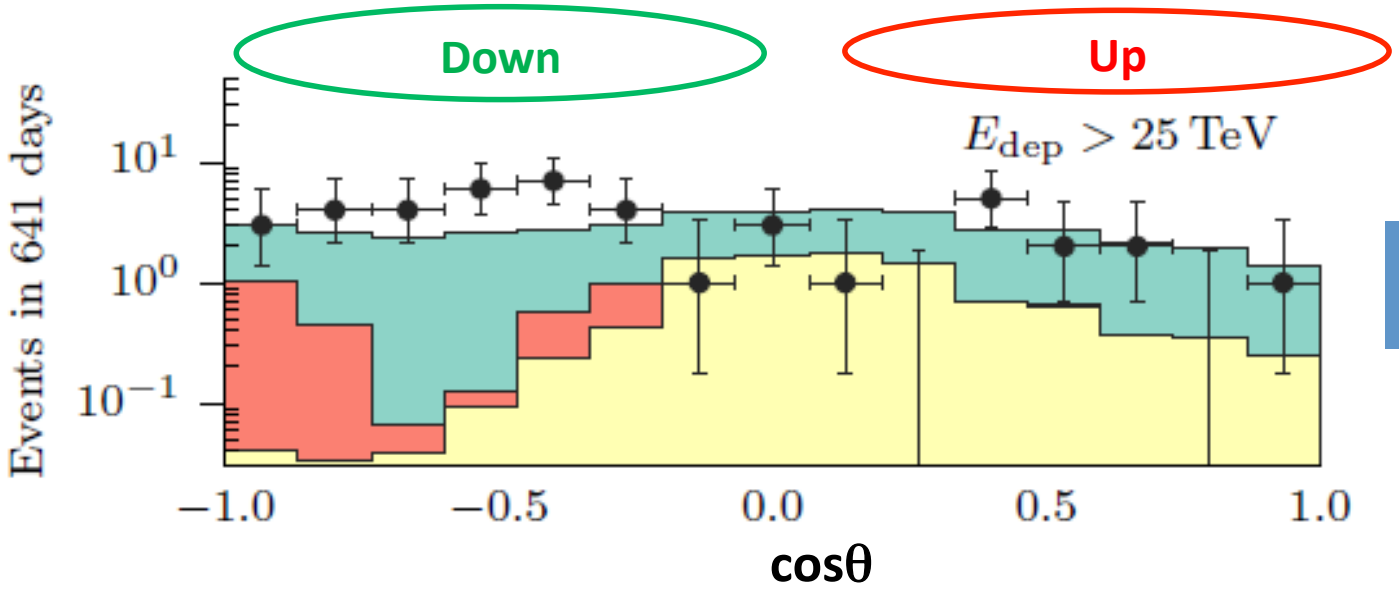




📖 arXiv:1410.1749

Almost to scale

# Latest update from IceCube




Fit of unbroken power law,
→ $E^{-2.46}$
mildly excludes a spectral index of 2

Excess in Southern sky?
Galactic contribution?

# ANTARES current results on diffuse fluxes

## Current flux limits (90% C.L., $E^{-2}$)

❖ Muons (2008-2011) 855 days:

$5.1 \times 10^{-8}\ E^{-2}$ GeVcm$^{-2}$s$^{-1}$sr$^{-1}$

N(obs)=8; N(expected bkgd) = 8.4

❖ Cascades (2008-2012) 1247 days:

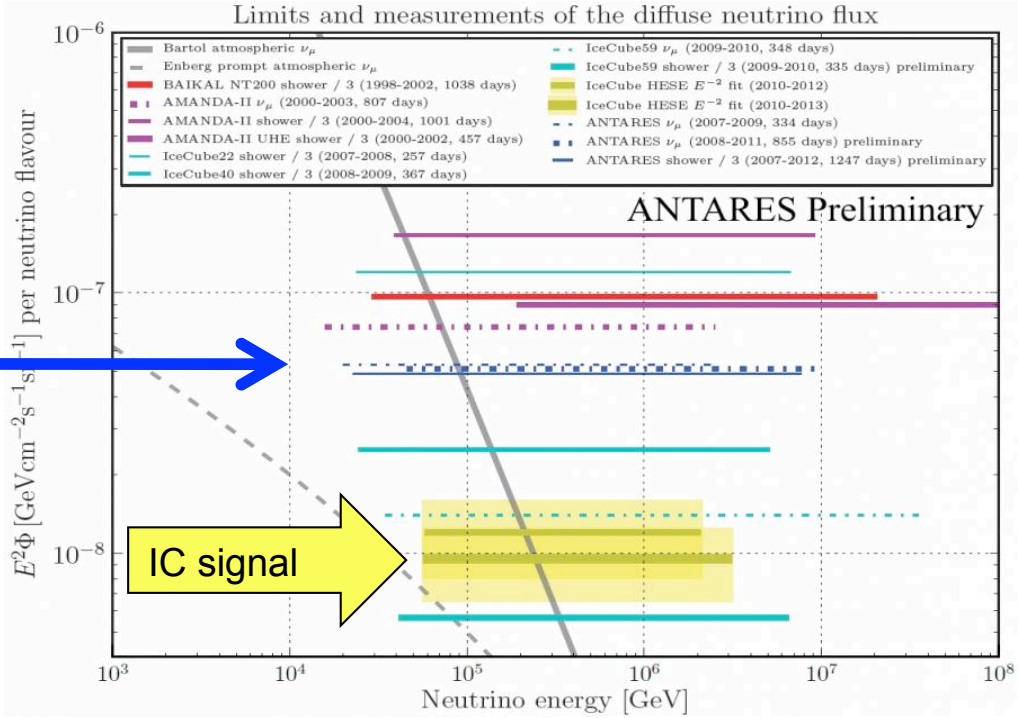
$4.9 \times 10^{-8}\ E^{-2}$ GeVcm$^{-2}$s$^{-1}$sr$^{-1}$ (per flavour)

N(obs)=8; N(expected bkgd) = 4.9

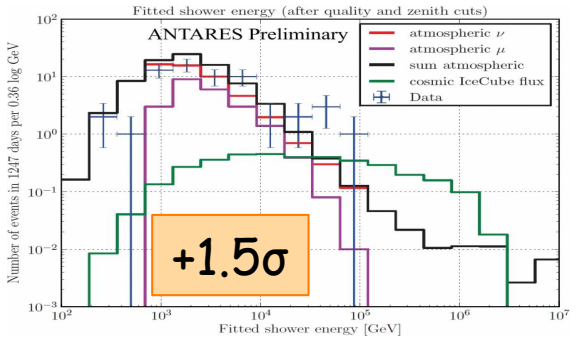
overfluctuation of bkgd ?

…expect 3 events from IC flux…

…multiple hints at Galactic component of cosmic neutrino flux ?

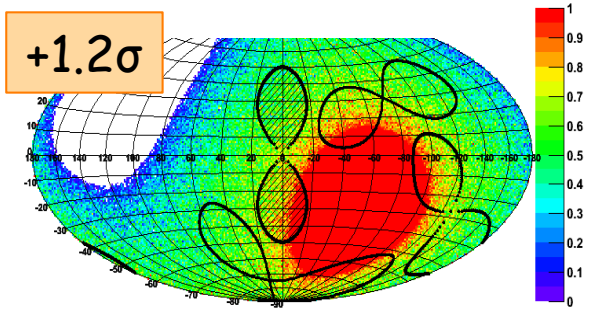



### Diffuse showers



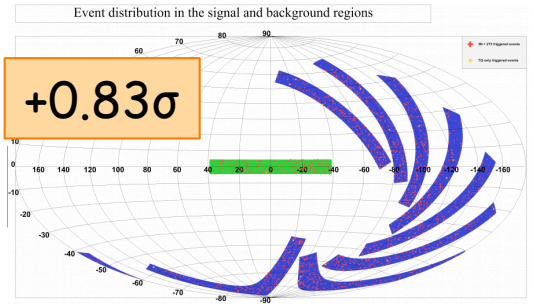

Thesis F. Folger (ECAP)

### Fermi bubbles




Eur. Phys. J. C (2014) 74:2701

### Galactic Plane




Thesis E. Visser (NIKHEF)

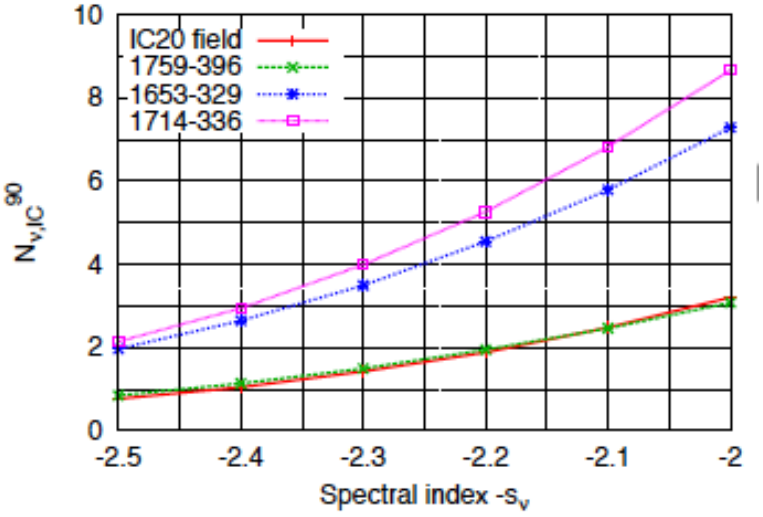
# AGNs responsible for Ernie and Bert ?

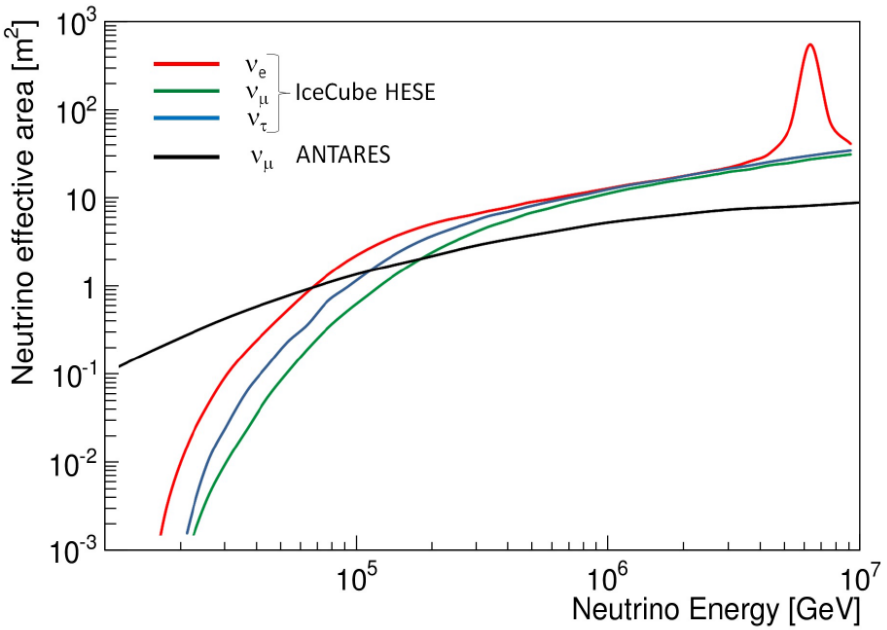
TANAMI collaboration reported observations of 6 bright blazars locally compatible with the 2 first PeV IceCube events IC14 and IC20. 📖 arxXiv:1501.07843

📖 Krauß, F. et al. 2014, A&A, 566, L7

ANTARES limit — number of IC HESE events associated to blazar

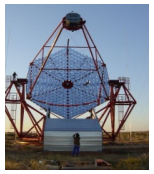
| Source | $N_{sig}$ | $p$ | Limit $10^{-8}$ GeV$^{-1}$ cm$^{-2}$ s$^{-1}$ | $N_{\nu,IC}=1$ | $N_{\nu,IC}=2$ | $N_{\nu,IC}=3$ | $N_{\nu,IC}=4$ |
|---|---|---|---|---|---|---|---|
| 0235–618 | 0 | 1 | 1.3 | -2.4 | -2.1 | -2.0 | -1.9 |
| 0302–623 | 0 | 1 | 1.3 | -2.4 | -2.1 | -2.0 | -1.9 |
| 0308–611 | 0 | 1 | 1.3 | -2.4 | -2.1 | -2.0 | -1.9 |
| 1653–329 | 1.1 | 0.10 | 2.9 | <-2.5 | -2.5 | -2.3 | -2.2 |
| 1714–336 | 0.9 | 0.04 | 3.5 | <-2.5 | -2.5 | -2.3 | -2.2 |
| 1759–396 | 0 | 1 | 1.4 | -2.4 | -2.1 | -2.0 | -1.8 |

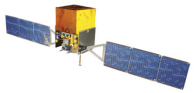



→ Relevant constraints on spectral index of potential source

# Multi-messenger strategies





GeV-TeV γ-rays

(Time &) space coincidences

space coincidences

UHECR

Searches for neutrinos in coincidence with GRBs, blazar flares, microquasars…
2-pt correlation with astrophysical catalogues…

ANTARES-Auger correlation search

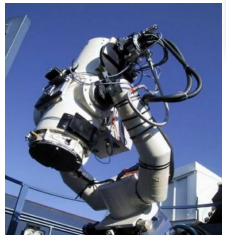
HE neutrinos

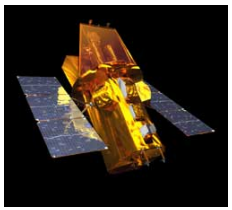
Optic / X-ray

Time & space coincidences

Time & space coincidences

Gravitational Waves

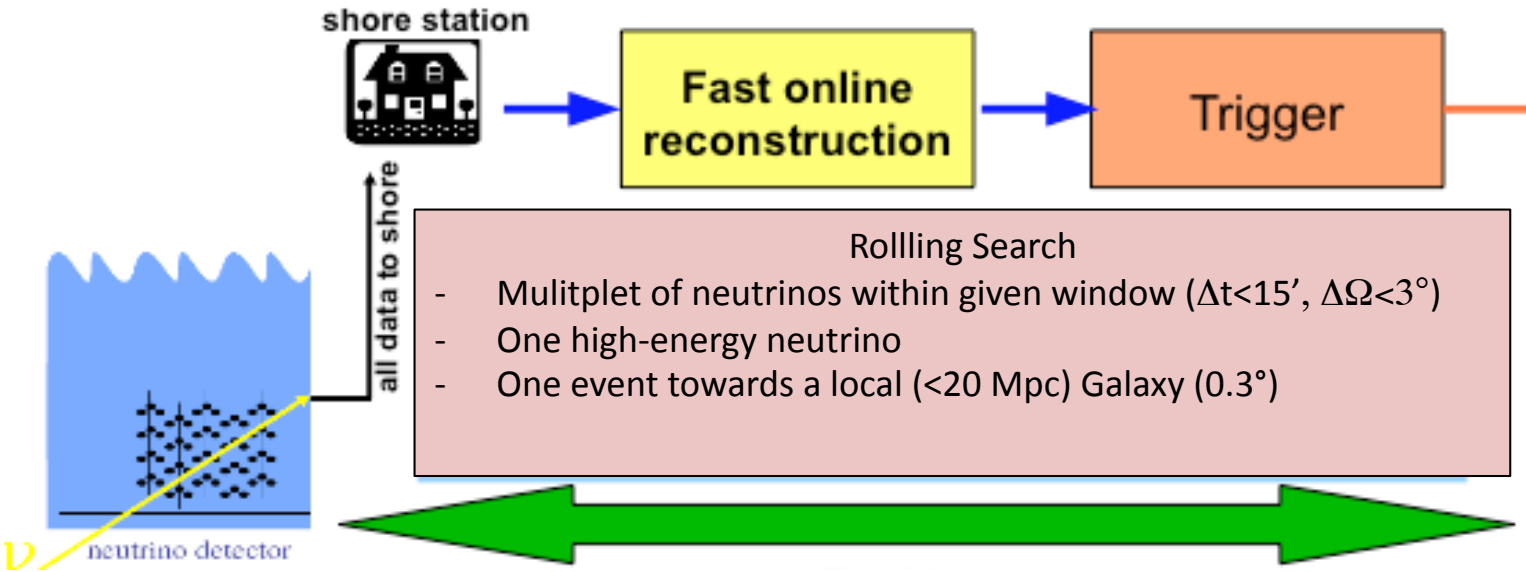




Target of Opportunity programs:
Optical/X-ray follow-up
(TAROT, ROTSE, Swift…)

Joint search for GW+HEN:
ANTARES/VIRGO/LIGO
(data samples 2007 and 2009-2010)
IceCube/VIRGO/LIGO

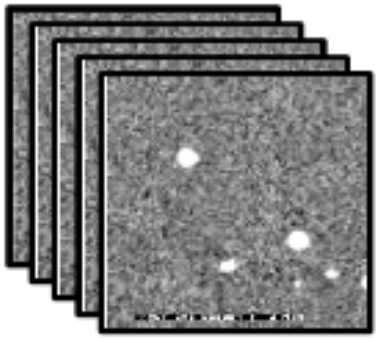
# Alerts and follow-up program: TAToO




Total latency: alert sending (<1s) + repositioning (<10s)

optical telescopes (TAROT/ROTSE/ ZADKO/Skymapper)

- Large sky coverage, high duty cycle
- No hypothesis on the nature of the source
- Sensitivity improved: 1 doublet is 3σ discovery, 1 triplet is 5σ !
- System active since 2009 with optical telescopes, now extended to SWIFT/XRT



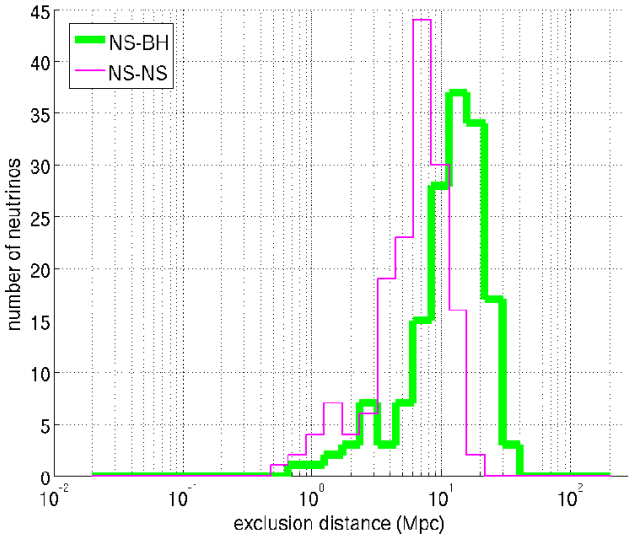
$T_0$, $T_0$ +1, 3, 9 and 27 days

📖 Astropart. Phys. 35 (2012) 530

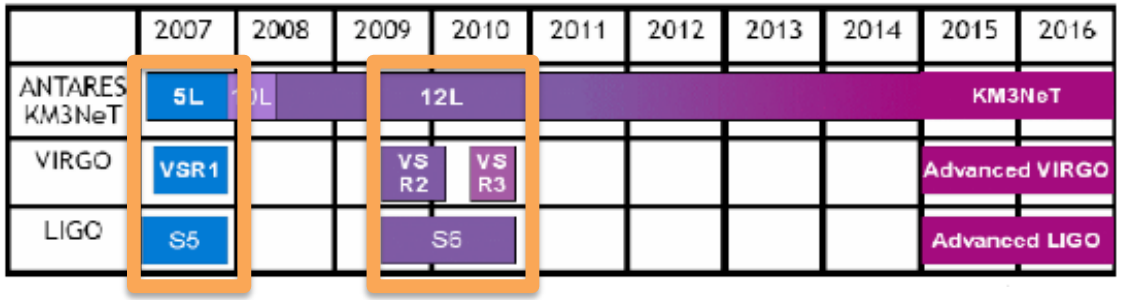
# Other multi-messenger programs

❖ Search for neutrinos in coincidence with gravitational waves: GWHEN

**Main motivations:** - plausible common sources (microquasars, SGR, GRBs)
- discovery potential for hidden sources (e.g. failed GRBs)




Joint collaboration with GW interferometers
VIRGO (Italy) & LIGO (USA)




- GW/HEN common challenge: faint signals on top of abundant noise/background
- Search methodology: combine GW/HEN events lists + search for time coincidences (±500s)

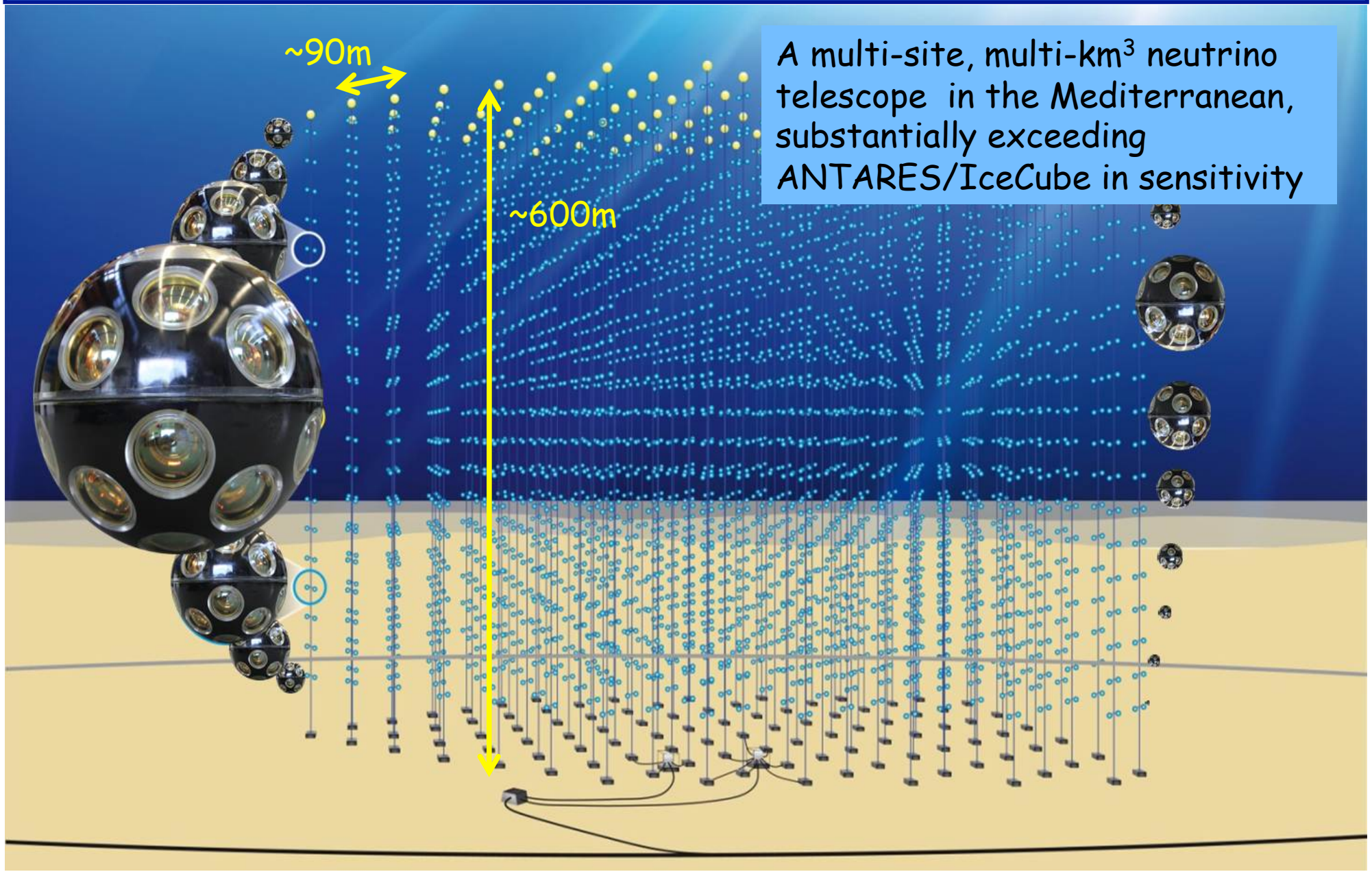
- First analysis completed with 2007 concomitant dataset

No coincidence found ➡ exclusion distances on common GW/HEN emittors

*ANTARES & LIGO & VIRGO Coll., JCAP 2013*

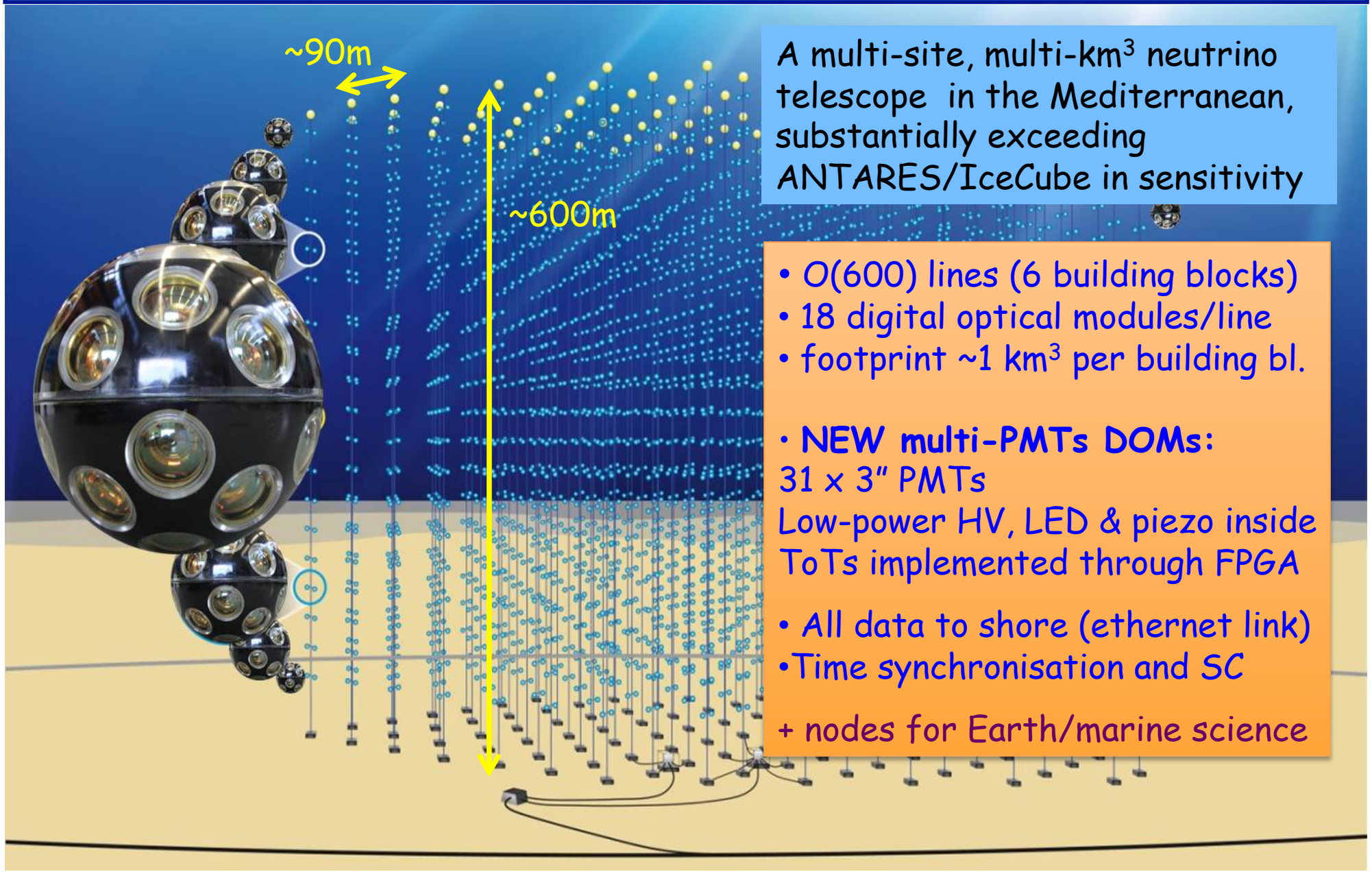
- Analysis of 2009-2010 dataset ongoing

# The next-generation detector: KM3NeT




A multi-site, multi-km$^3$ neutrino telescope in the Mediterranean, substantially exceeding ANTARES/IceCube in sensitivity

# The next-generation detector: KM3NeT




A multi-site, multi-km$^3$ neutrino telescope in the Mediterranean, substantially exceeding ANTARES/IceCube in sensitivity

- O(600) lines (6 building blocks)
- 18 digital optical modules/line
- footprint ~1 km$^3$ per building bl.

- **NEW multi-PMTs DOMs:**
31 x 3" PMTs
Low-power HV, LED & piezo inside
ToTs implemented through FPGA

- All data to shore (ethernet link)
- Time synchronisation and SC

+ nodes for Earth/marine science

# The next-generation detector: KM3NeT

~90m

A multi-site, multi-km$^3$ neutrino telescope in the Mediterranean, substantially exceeding ANTARES/IceCube in sensitivity

Launcher vehicle:
- autonomous unfurling
- rapid deployment (several lines per campaign)
- easy recovery

- O(600) lines (6 building blocks)
- 18 digital optical modules/line
- footprint ~1 km$^3$ per building bl.

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# KM3NeT: a phased implementation

**PHASE 1:**

**shore and deep-sea infrastucture at Toulon (KM3NeT-Fr)**
**and Capo Passero (KM3NeT-It)**
**+ 31 lines deployed by end 2016**
Proof of feasibility of network of distributed neutrino telescopes

**31 M€**
**FUNDED**
**and**
**ONGOING**

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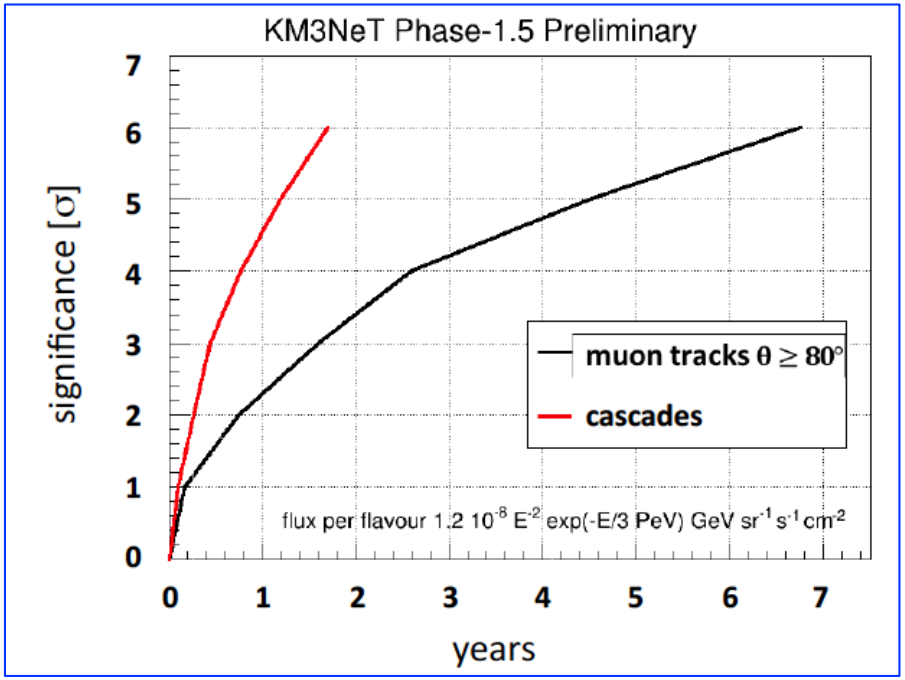
**PHASE 1.5:**

**230 lines (2 building blocks)**
Measurement of IceCube signal

**80-90 M€**
**Letter of Intent**
**in preparation**



# KM3NeT: a phased implementation

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**PHASE 1.5:**
**230 lines (2 building blocks)**
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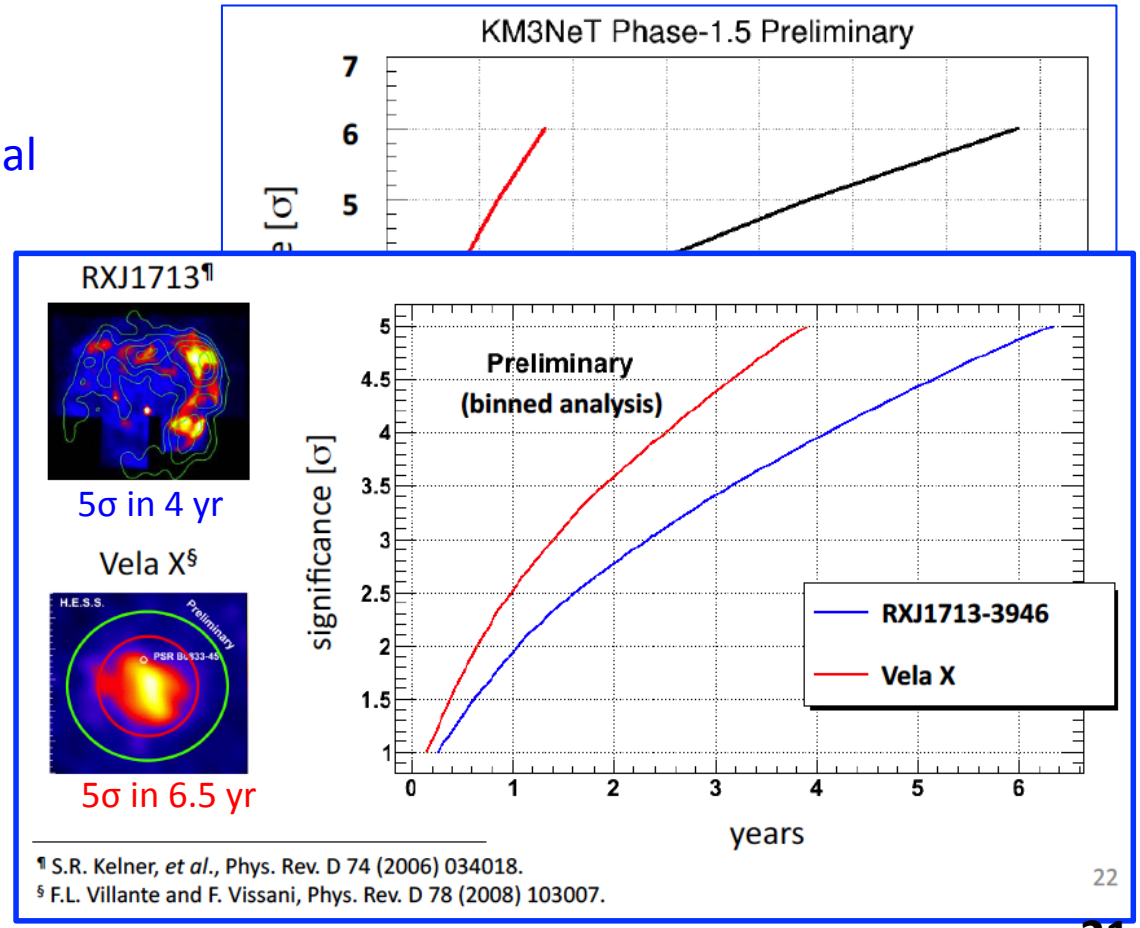
**80-90 M€ Letter of Intent in preparation**

**PHASE 2:**
**600 lines**
**(6 building blocks)**
Neutrino astronomy

**220-250 M€ ESFRI Roadmap**



# Conclusions and perspectives

ANTARES: first undersea neutrino Cherenkov detector

- excellent angular resolution, view of Southern sky, ambitious multi-messenger program
  → competitive sensitivities (especially for Galactic neutrino component)
- improvements still to come: include showers in all analyses (ang. res.→2-3° !)
- will continue taking data until 2016

KM3NeT: phased approach to next-generation neutrino telescope

- prototypes performing well
- deployment of the first detection units in 2015 (Phase 1):

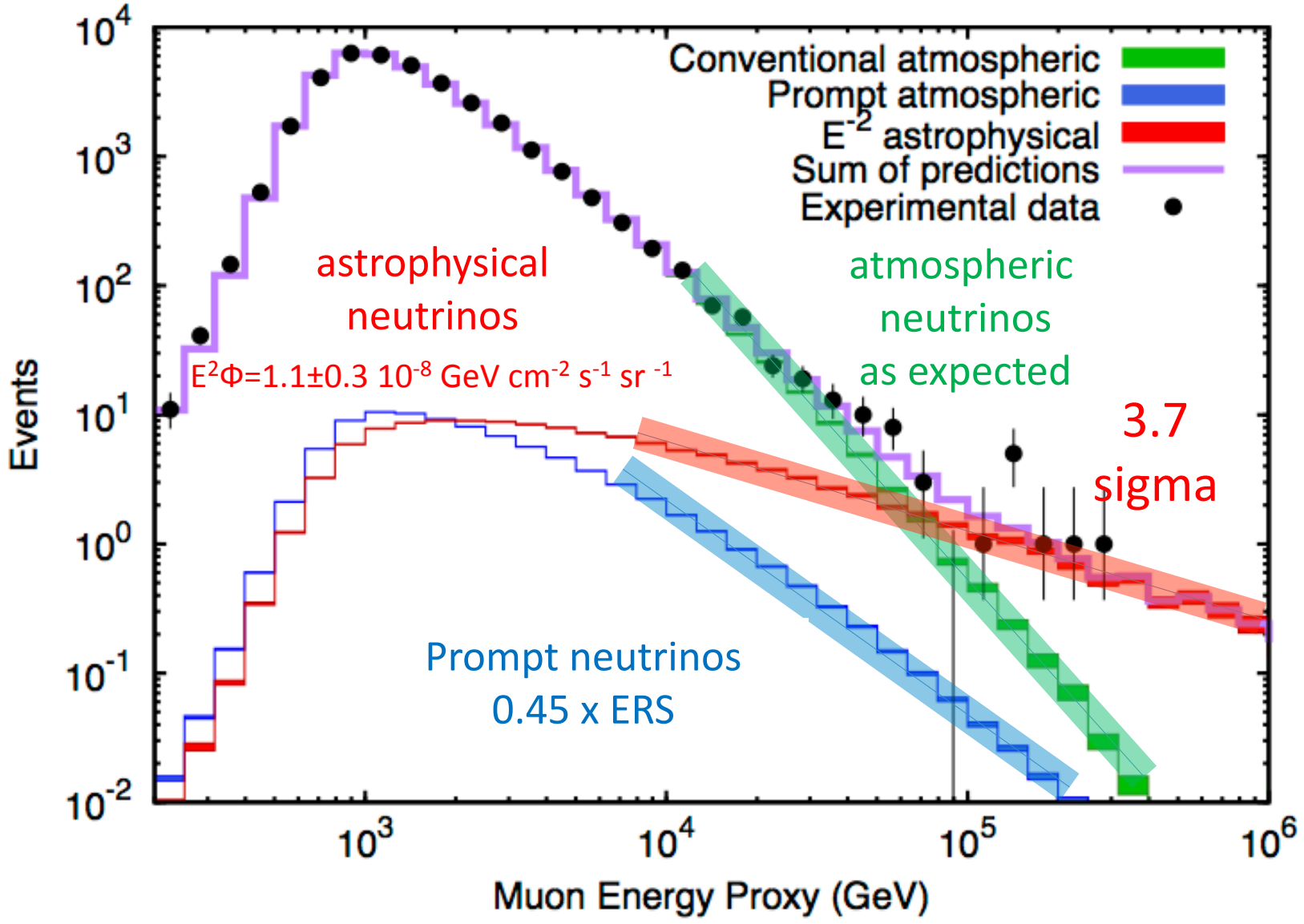
CapoPassero (KM3NeT-It) → **all-flavours HE neutrino astronomy (tracks & showers!)**

Toulon (KM3NeT-Fr) → **ORCA**: opportunity for a quick and cheap (~40M€) measurement of the neutrino mass hierarchy
+ low-energy astronomy program ? (supernovae)

# BACKUP SLIDES

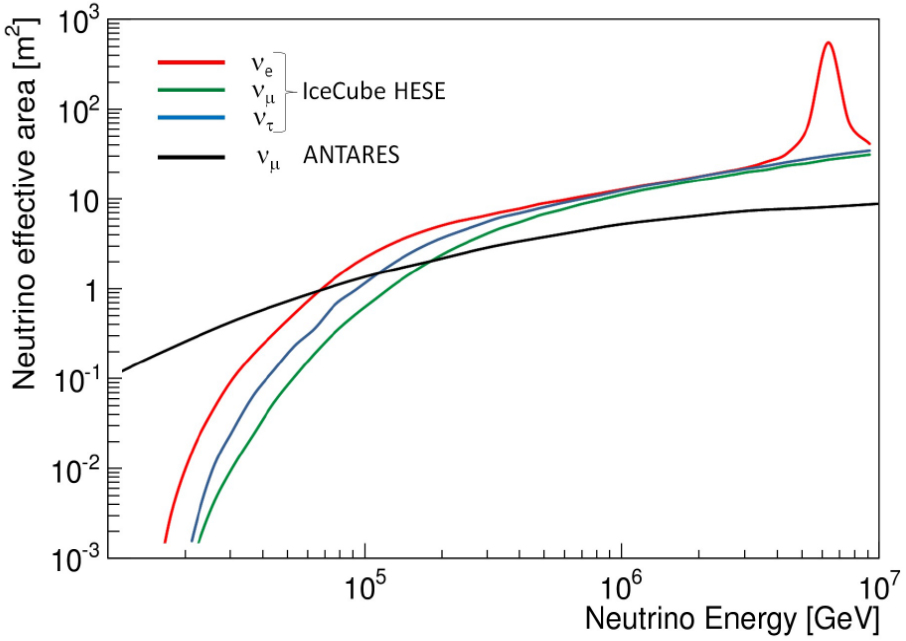
# Diffuse flux now confirmed with muons

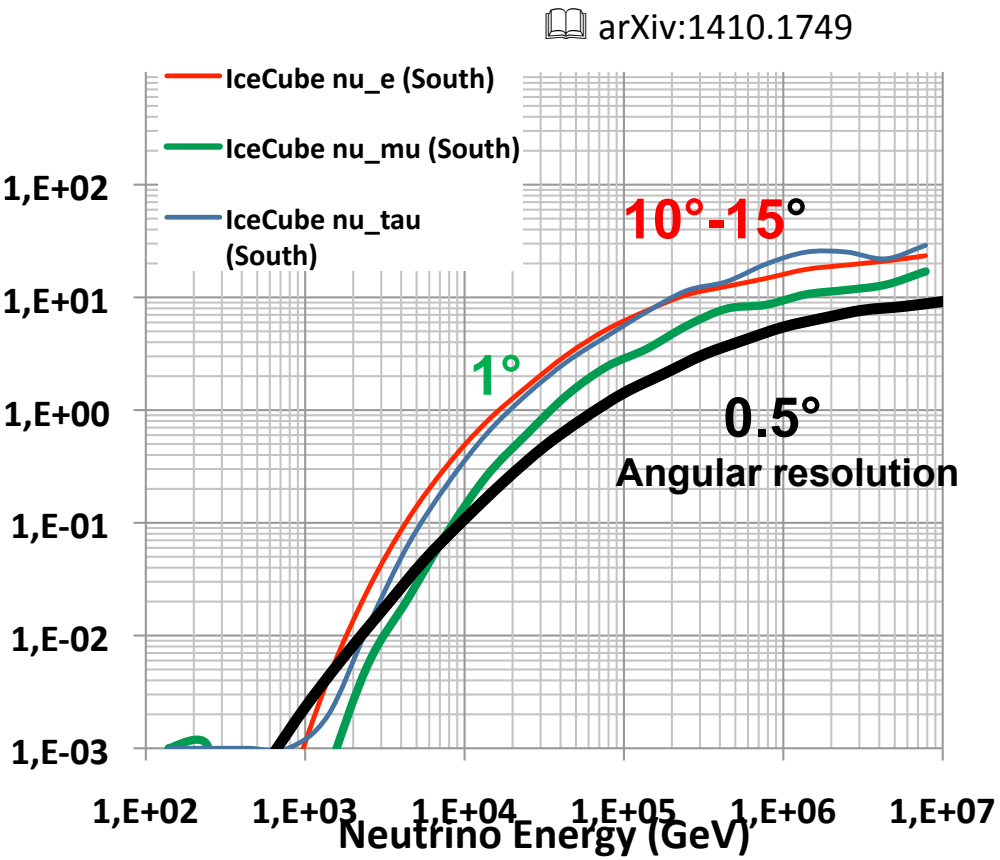
Hint from IC59 (1.8 sigma); now IC79/86-1 upgoing muon neutrinos give 3.7 σ



# IceCube vs. ANTARES $A_{eff}$

IceCube is physically 40 times larger than ANTARES, not effectively !




- IceCube → 4π, high energy sample (Eν > 30 TeV), almost bkg free
- ANTARES → $\nu_\mu$ only Southern Sky only (angular resolution <0.5°)
- ANTARES Aeff > HESE Aeff at Eν < 60 TeV

Future Constraints by ANTARES?

# IC hotspot: predictions by ANTARES

📖 Spurio, Phys.Rev. D90 (2014) 10, 103004

*Study ongoing*

units: $(\mathrm{GeV\ cm^{-2}\ s^{-1}\ sr^{-1}})$

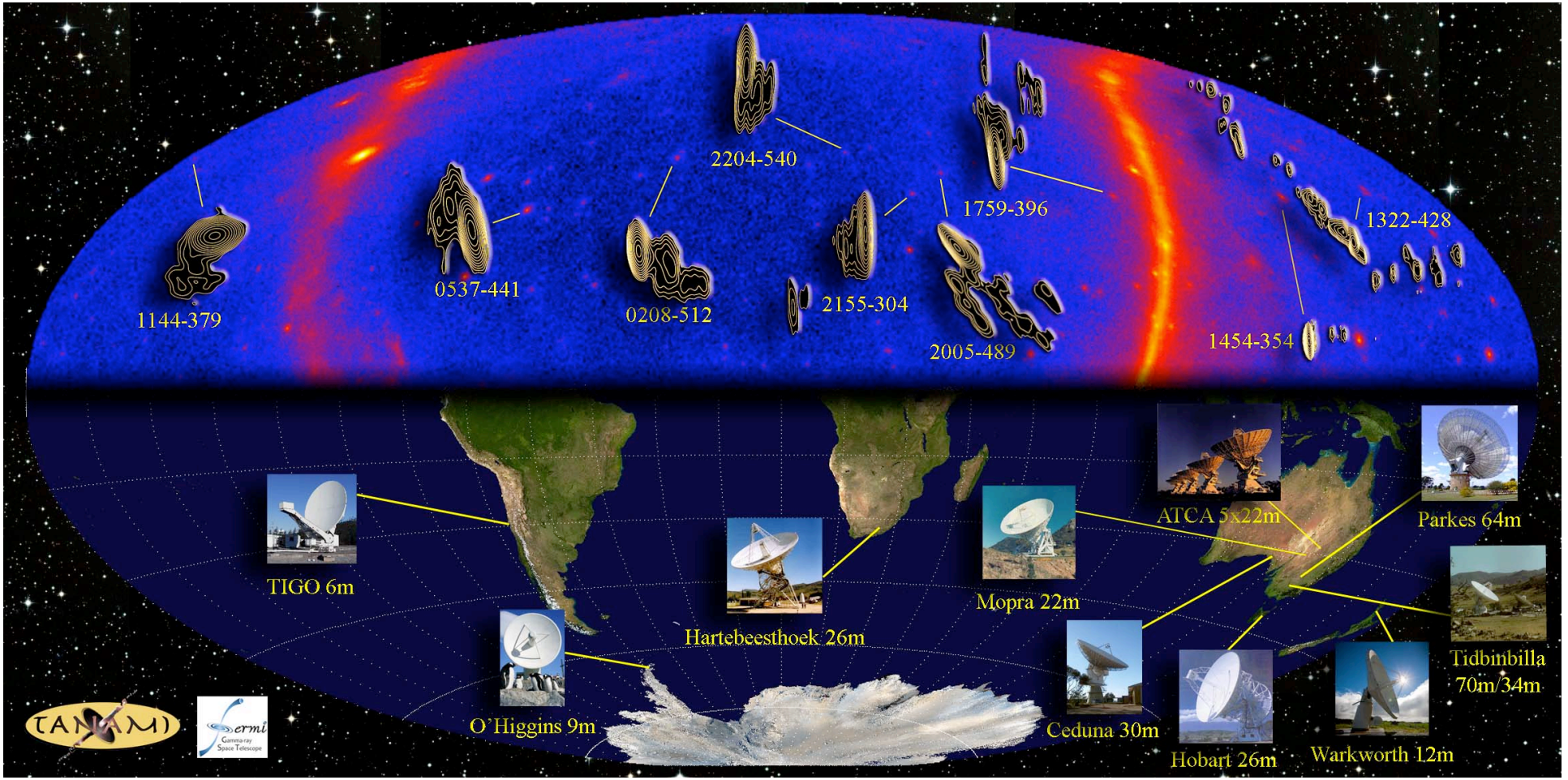
$$\Phi_0^{D',\Gamma} = \left(\frac{n_{\Delta\Omega}}{N_{IC}}\right) \cdot \left(\frac{4\pi}{\Delta\Omega}\right) \cdot \Phi_0^{D,\Gamma}$$

| $\Delta\Omega$ (sr) | $\Gamma =$ | $n_{\Delta\Omega}=3$ | $n_{\Delta\Omega}=4$ | $n_{\Delta\Omega}=5$ | $n_{\Delta\Omega}=6$ | ANTARES sensitivity |
|---|---|---|---|---|---|---|
| 0.06 | 2.0 | $3.5\ 10^{-7}$ | $4.6\ 10^{-7}$ | $5.8\ 10^{-7}$ | $7.0\ 10^{-7}$ | $3.1\ 10^{-7}$ |
| 8° | 2.2 | $4.5\ 10^{-6}$ | $6.0\ 10^{-6}$ | $7.5\ 10^{-6}$ | $9.0\ 10^{-6}$ | $3.6\ 10^{-6}$ |
| | 2.3 | $1.7\ 10^{-5}$ | $2.2\ 10^{-5}$ | $2.8\ 10^{-5}$ | $3.3\ 10^{-5}$ | $1.1\ 10^{-5}$ |
| | 2.4 | $5.9\ 10^{-5}$ | $7.8\ 10^{-5}$ | $9.8\ 10^{-5}$ | $1.2\ 10^{-4}$ | $3.4\ 10^{-5}$ |
| 0.38 | 2.0 | $5.4\ 10^{-8}$ | $7.3\ 10^{-8}$ | $9.1\ 10^{-8}$ | $1.1\ 10^{-7}$ | $3.1\ 10^{-7}$ |
| 20° | 2.2 | $7.1\ 10^{-7}$ | $9.4\ 10^{-7}$ | $1.2\ 10^{-6}$ | $1.4\ 10^{-6}$ | $3.6\ 10^{-6}$ |
| | 2.3 | $2.6\ 10^{-6}$ | $3.6\ 10^{-6}$ | $4.4\ 10^{-6}$ | $5.2\ 10^{-6}$ | $1.1\ 10^{-5}$ |
| | 2.4 | $9.3\ 10^{-6}$ | $1.2\ 10^{-5}$ | $1.5\ 10^{-5}$ | $1.9\ 10^{-5}$ | $3.4\ 10^{-5}$ |

- Model yielding $n_{\Delta\Omega}>2$ events within $\Delta\Omega = 0.06$ sr (= 8°) can be excluded by ANTARES for any $E^{-\Gamma}$ spectrum with an analysis similar to that already done on Fermi Bubbles (muons only).

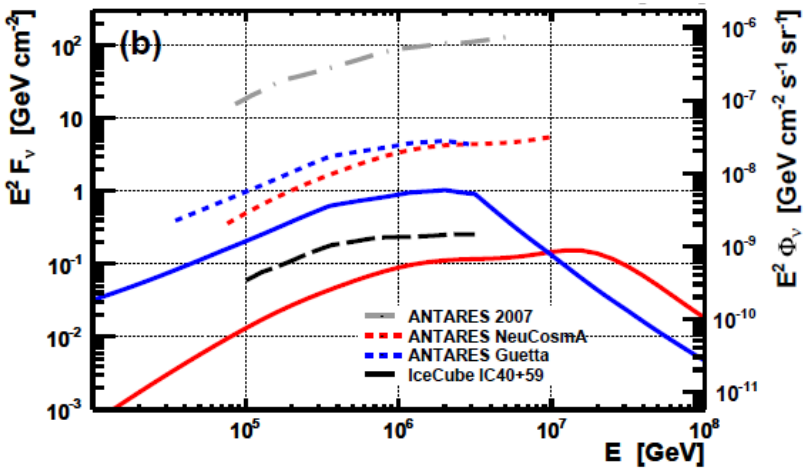
**TANAMI**

TANAMI (Tracking Active Galactic Nuclei with Austral Milliarcsecond Interferometry) is a multiwavelength program to monitor relativistic jets in active galactic nuclei (AGN) of the Southern Sky. TANAMI consists of 1) a VLBI core program targeting the parsec-scale structures of blazars, radio galaxies and other types of AGN, 2) complementary radio spectral and light-curve monitoring programs with ATCA and the Ceduna telescope, and 3) higher-energy multiwavelength observations with REM, *Swift*, *XMM-Newton*, *Suzaku*, *INTEGRAL*, *Fermi*/LAT and other telescopes. Currently, TANAMI is monitoring about 90 jets including many sources found by *Fermi* to be flaring at gamma-rays.



# Examples of multi-messenger searches

- 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)]
- No events found within 10° window from GRB
Expected: 0.48 (Guetta), 0.061(NeuCosmA)
- Dedicated analysis for GRB130427




Search with 40 blazars

- 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).

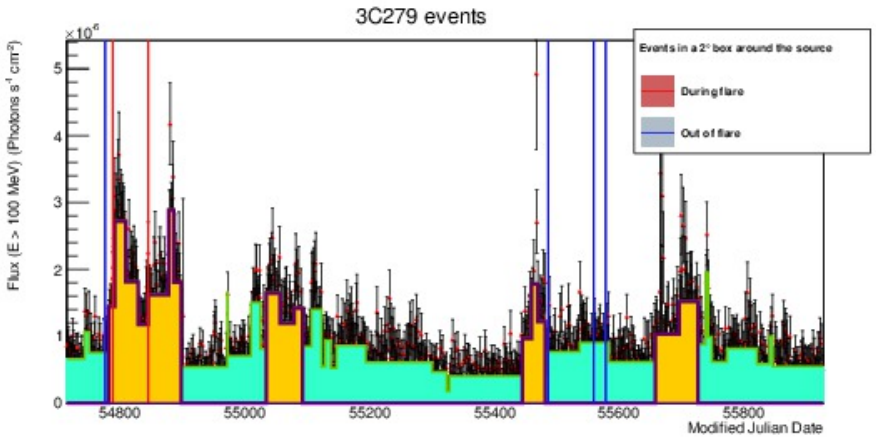
- MDP optimization on Lambda quality cut only.
- Improved likelihood with energy proxy (Nhits)

Separate optimization for 6 most significant flares

3C 279 (279 flaring days)

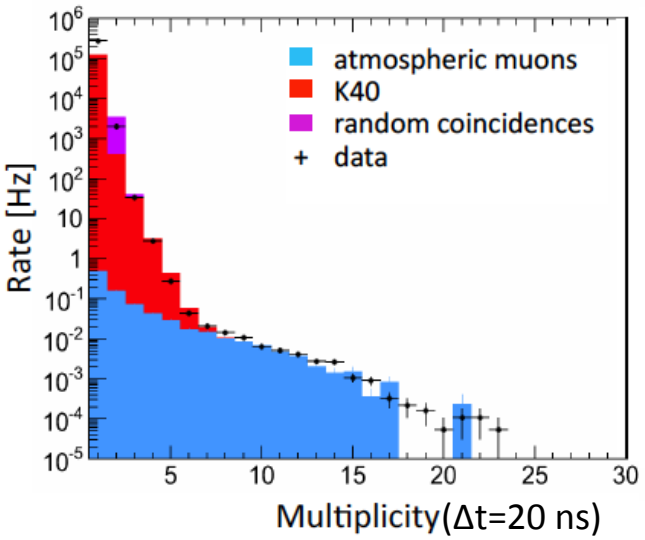
2 events compatible in time and direction

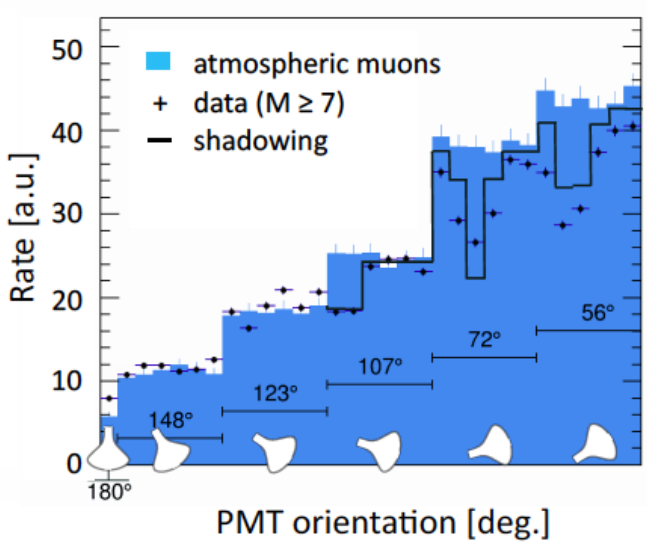
- Lowest p-value (10%) for 3C279



# KM3NeT: status of Phase-1

April 2013: First DOM installed on ANTARES instrumented line (KM3NeT-Fr)




Validates photon counting & directionality performances

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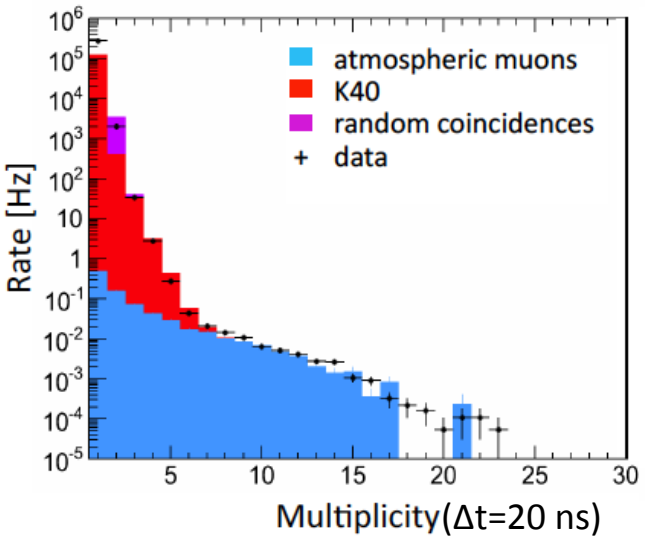
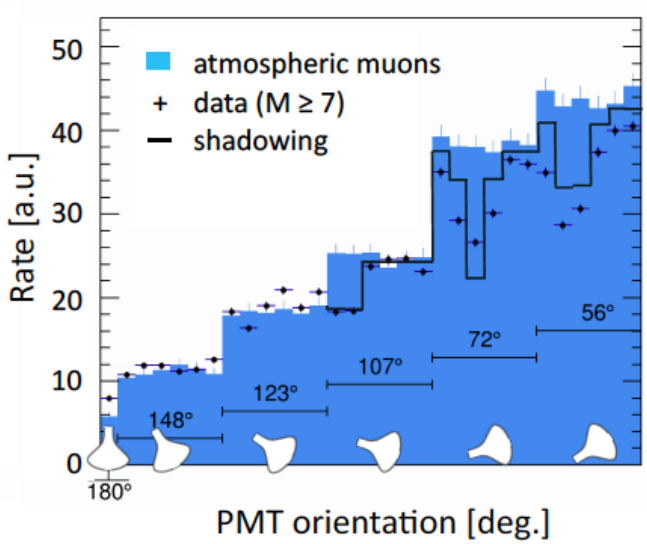



Validates photon counting & directionality performances

$^{40}$K

e$^-$ (β decay)

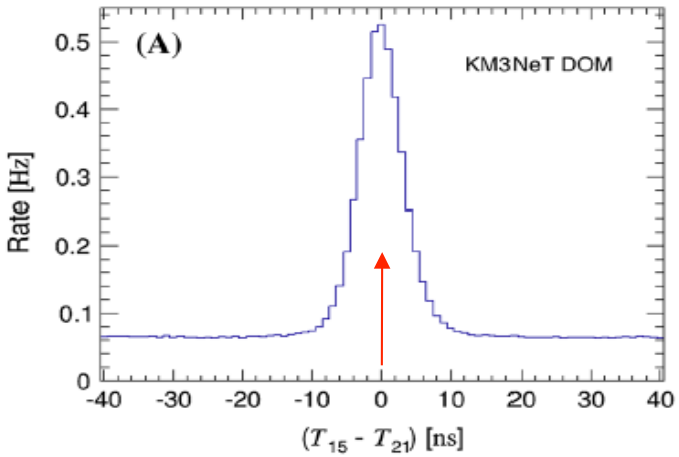
Up to 150 Cherenkov photons per decay; stable $^{40}$K concentration

$^{40}$Ca

$^{40}$K decay provides intra-DOM time calibration:

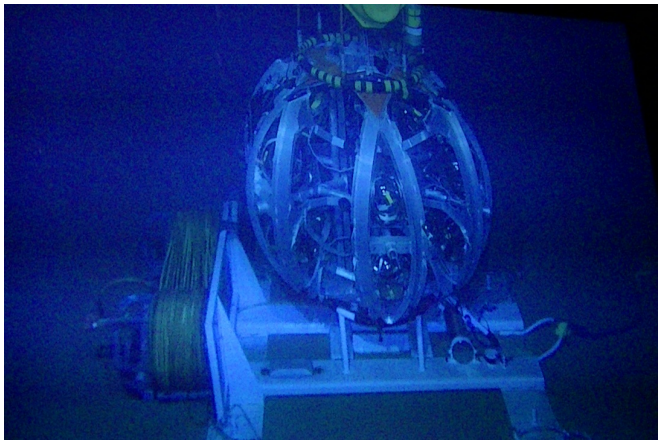
(coincidence rate ~5 Hz on neighbouring PMTs)


📖 Eur. Phys. J. C (2014) 74:3056

# KM3NeT: status of Phase-1

May 2014: prototype deployed at KM3NeT-It



Reduced-size detection unit (DU) with 3 DOMs, equipped with Vertical Electro-Optical Cable

- First benchmark of DU integration and deployment
- Smooth operation and data taking

📖 *Paper in preparation!*