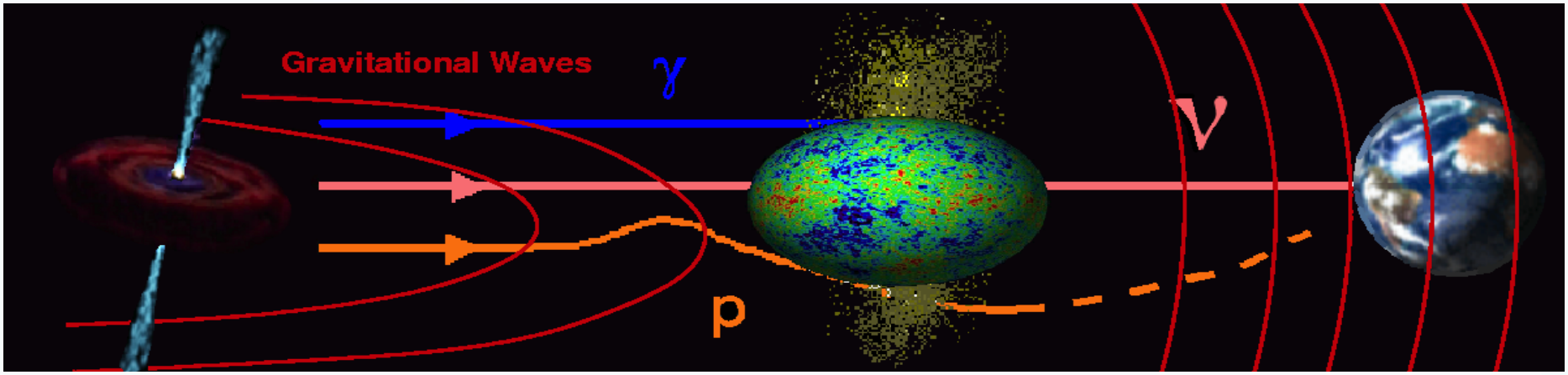
Neutrino Astronomy

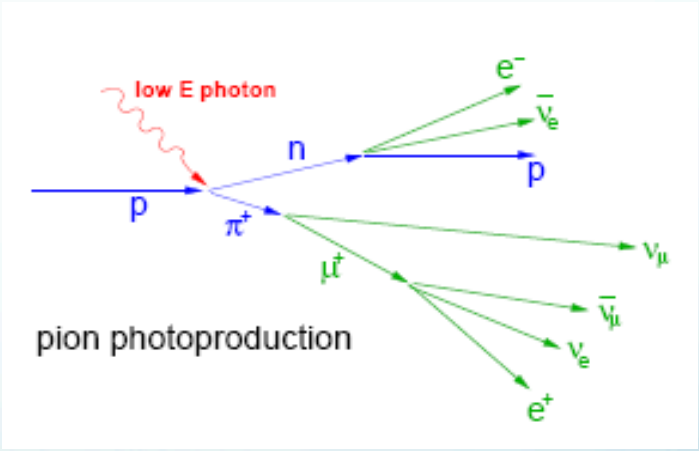
Current status and prospects

Multi-messenger astronomy



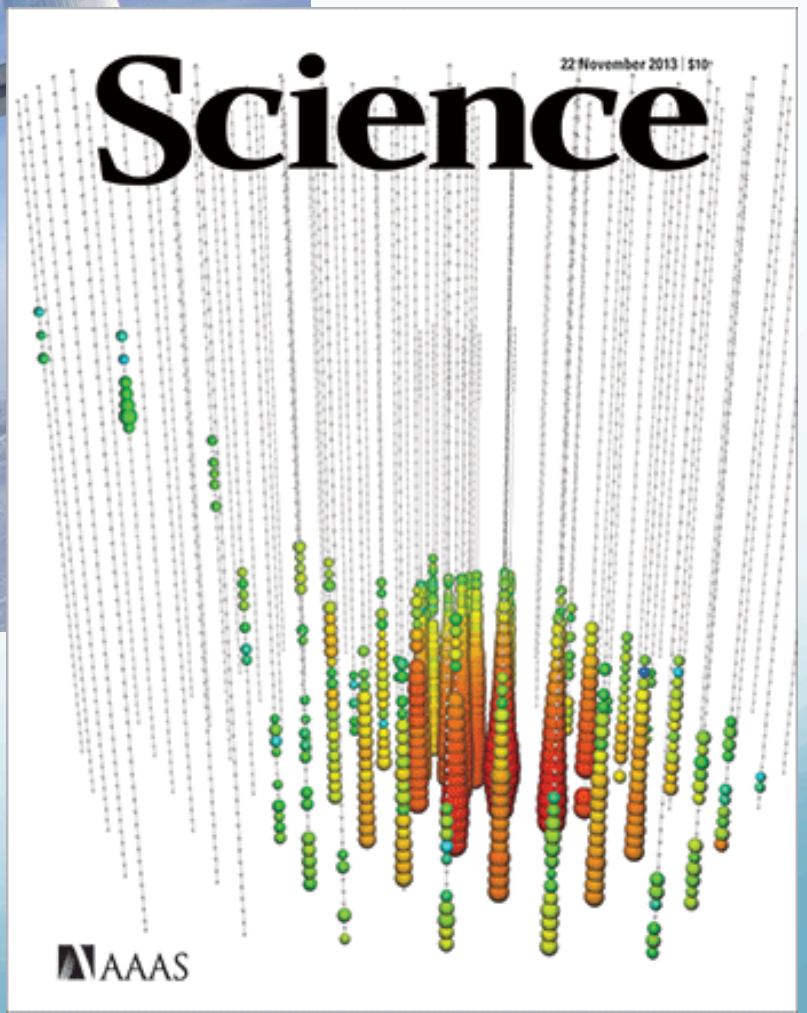
Neutrino

⇒ Transient sources
⇒ Cosmological distances
⇒ Core of astrophysical bodies
⇒ Point source
⇒ Signature of hadronic acceleration



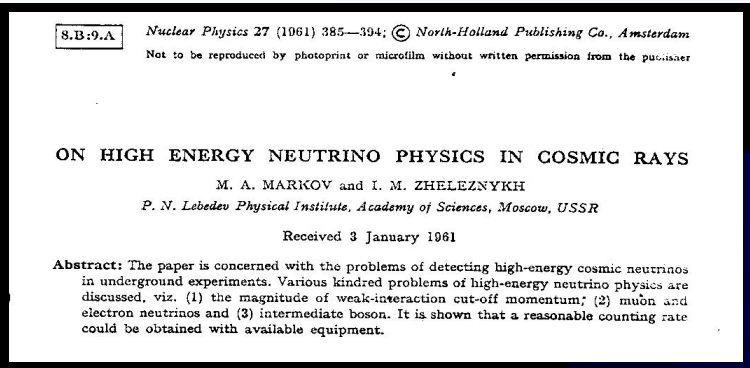
UHECRs + relic photons → Guaranteed source of > PeV neutrinos
→ Alternative techniques (e.g GRAND)

First detection at HE 2013



The field opens after
½ century of technological efforts

Markov idea: muon neutrino



8.B:9.A

Nuclear Physics **27** (1961) 385—394; © *North-Holland Publishing Co., Amsterdam*

ON HIGH ENERGY NEUTRINO PHYSICS IN COSMIC RAYS

M. A. MARKOV and I. M. ZHELEZNYKH

P. N. Lebedev Physical Institute, Academy of Sciences, Moscow, USSR

Received 3 January 1961

Abstract: The paper is concerned with the problems of detecting high-energy cosmic neutrinos in underground experiments. Various kindred problems of high-energy neutrino physics are discussed, viz. (1) the magnitude of weak-interaction cut-off momentum; (2) muon and electron neutrinos and (3) intermediate boson. It is shown that a reasonable counting rate could be obtained with available equipment.

The golden channel ?

Natural radiator is low cost and allows huge instrumented regions
→ Deep sea or lake
→ Deep clear Ice

Detection of Cherenkov light emitted by muons with a 3D array of PMTs

Requires a large (km^3) dark transparent detection medium

$\gamma_{č}$

$\theta_{č}$

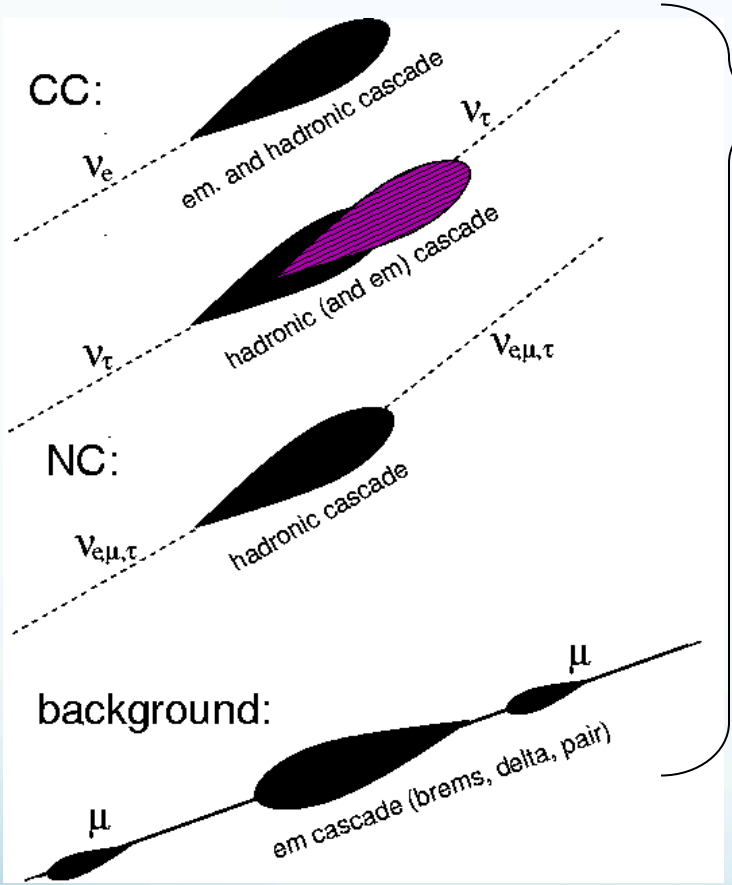
μ

ν

Time, position, amplitude of PMT pulses ⇒ μ trajectory (~ ν < 0.5 °)

Cascade topology

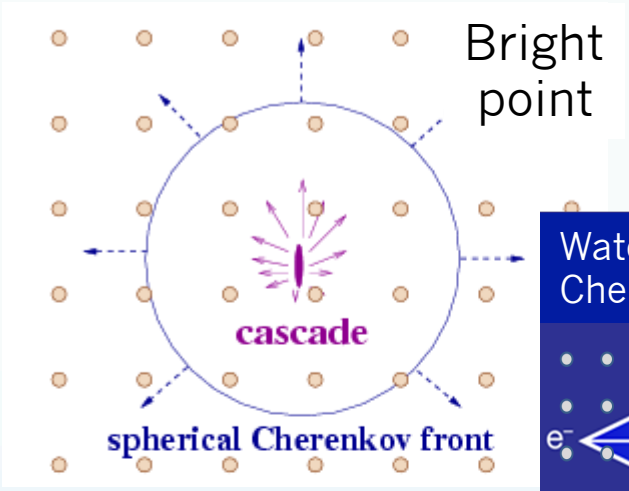
$\nu_e:\nu_\mu:\nu_\tau$ =1:2:0 at source $\xrightarrow{\text{oscillation}}$ $\nu_e:\nu_\mu:\nu_\tau$ =1:1:1 at Earth !

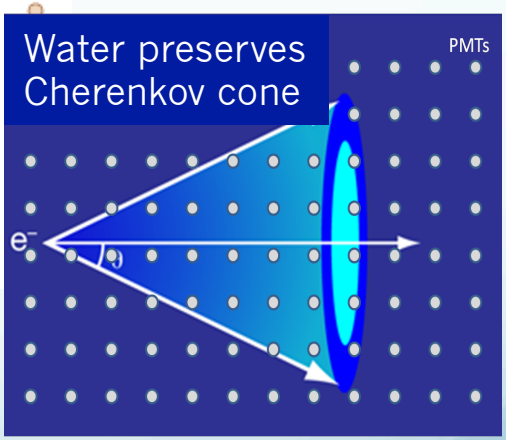


IceCube discovery channel

Use for astronomy in water

Generic reconstruction:



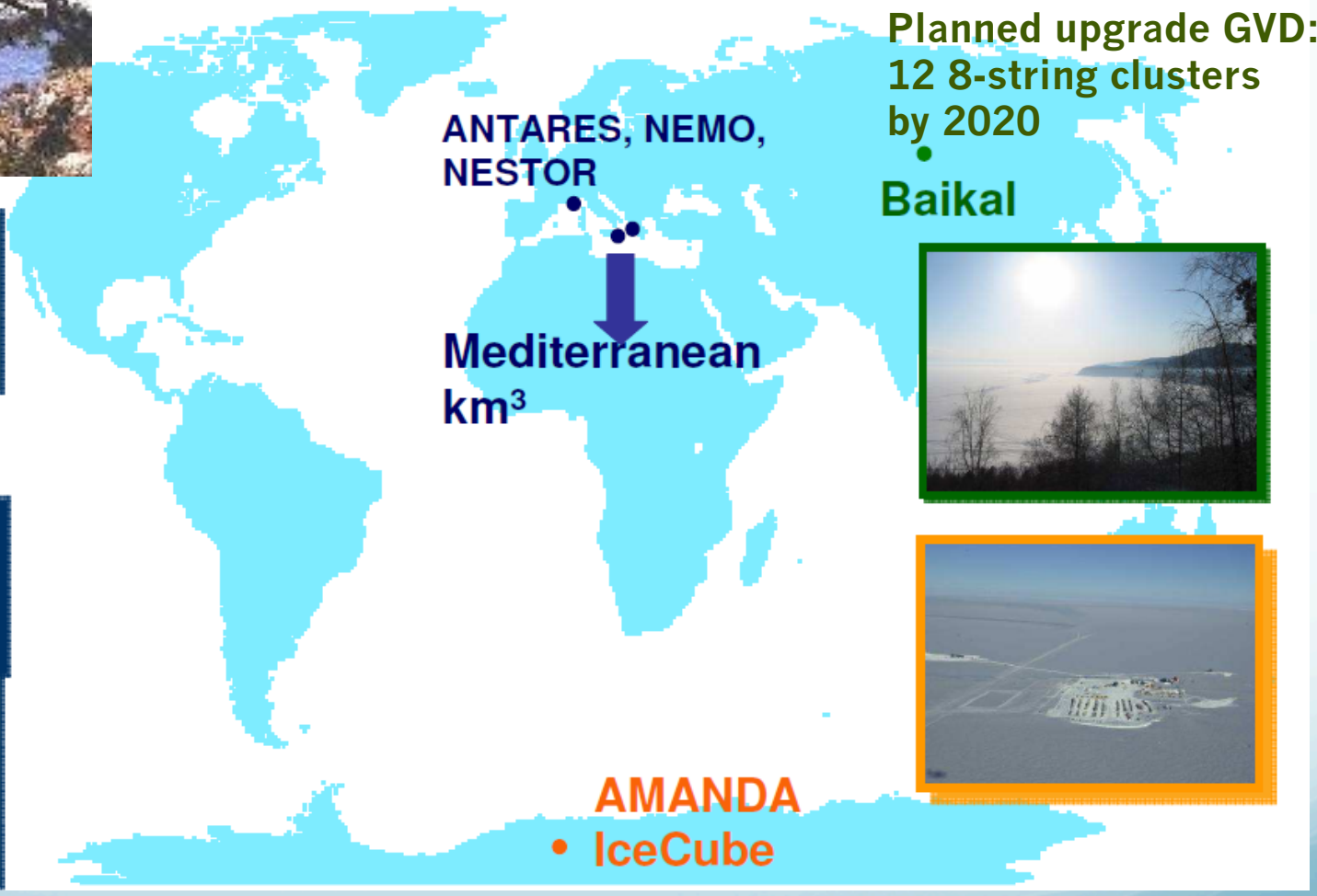


→ Provide sensitivity to all neutrino flavours – Increase overall detector sensitivity

- Angular resolution 10° - 30° / 2°- 5° at 100 TeV for ice / water
- Energy resolution ~ 15%

(TeV) Neutrino telescopes

{ANTARES, BAIKAL, ICECUBE} currently working

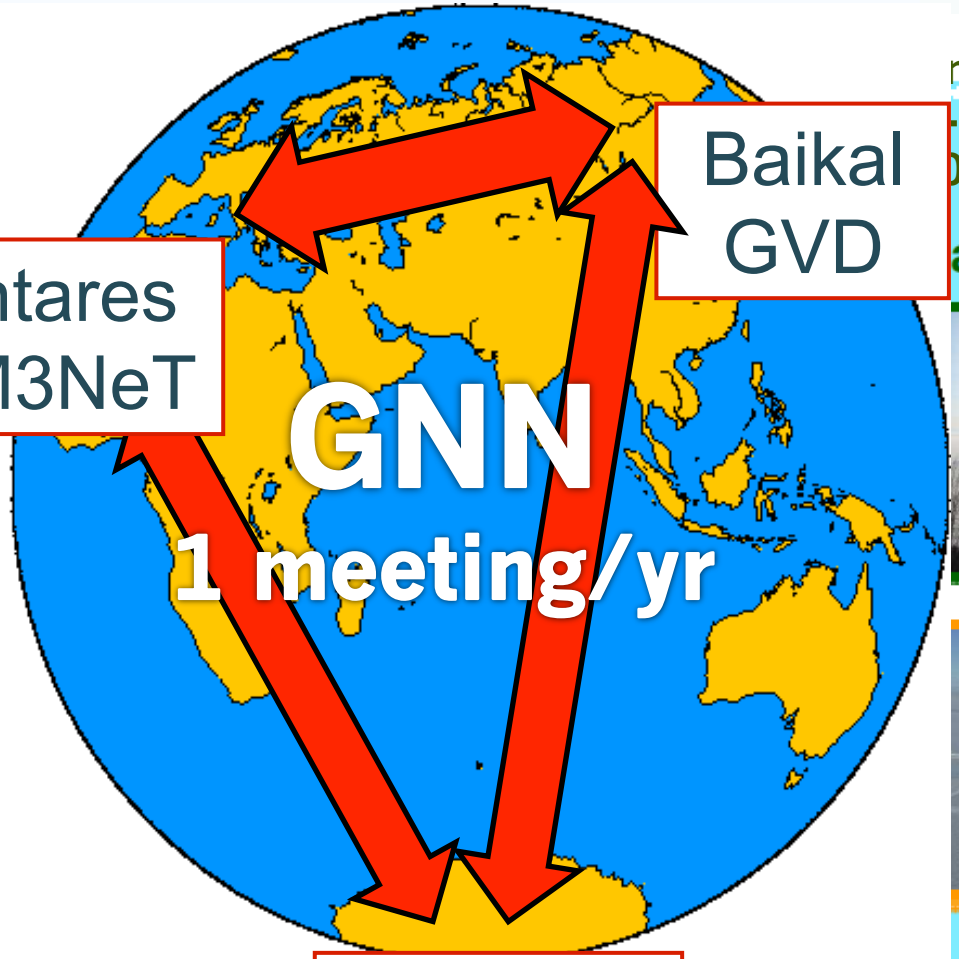


{ANTARES, NEMO, NESTOR} now in KM3NeT collaboration

(TeV) Neutrino telescopes

{ANTARES, BAIKAL, ICECUBE} currently working

Antares
KM3NeT



Baikal
GVD

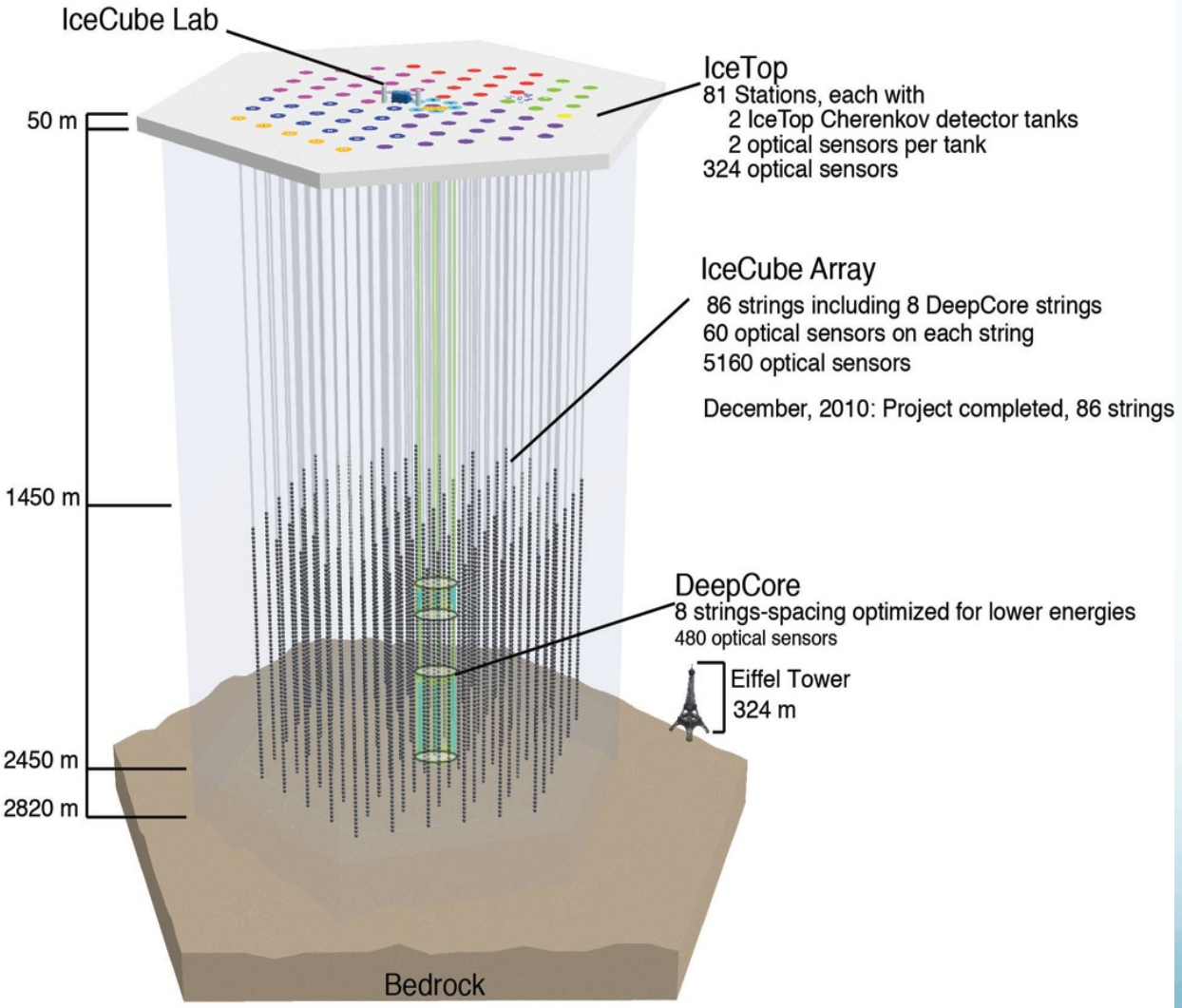
IceCube

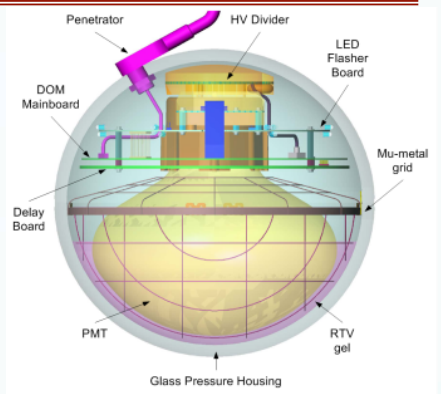
ned upgrade GVD:
-string clusters
020
al

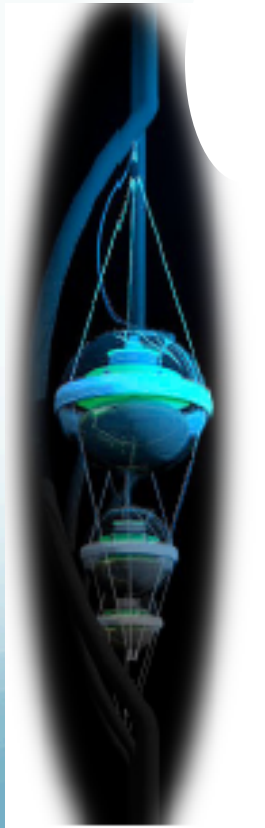
{ANTARES, NEMO, NESTOR} now in KM3NeT collaboration

IceCube: the largest NT in the world

Completed since December 2010.







The ANTARES neutrino telescope

12 line detector completed in May 2008

- 25 storeys / line
- 3 PMTs / storey
- 885 PMTs

Deployed in 2001

14.5 m

40 km

Junction box (since 2002)

Anchor/line socket

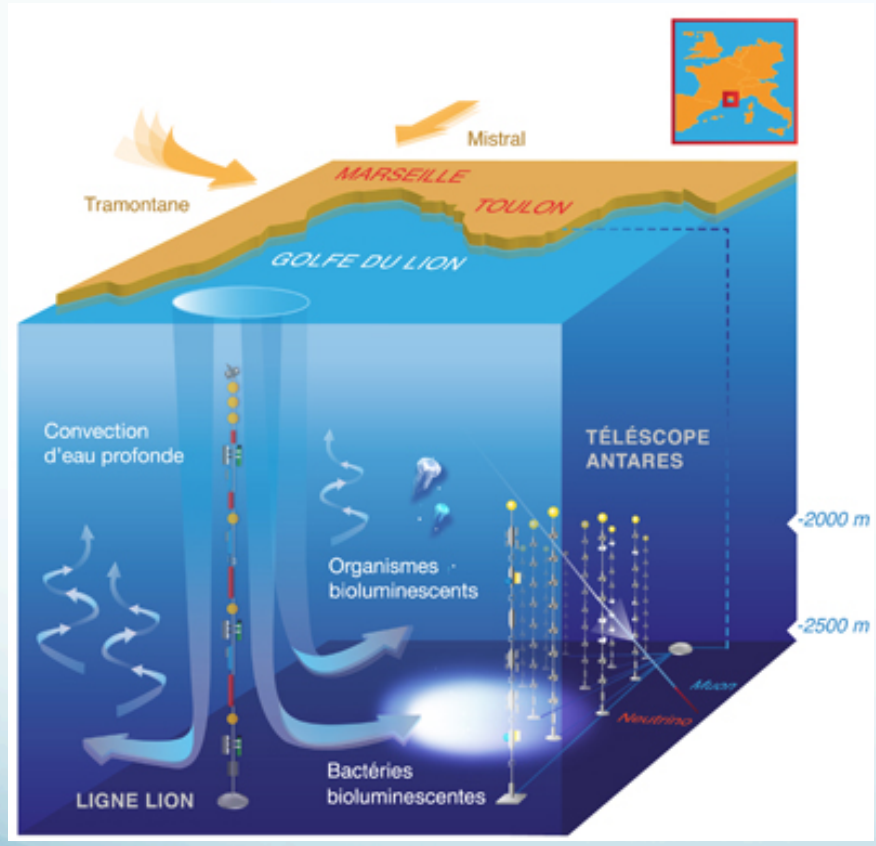
Interlink cables

Interest for deep-sea science

ANTARES awarded "La Recherche Prize" category "Coup de Coeur"

📖 C. Tamburini, S. Escoffier et al., PLoS ONE 8(7) 2013

Deep-sea bioluminescence blooms after dense water formation at the ocean surface



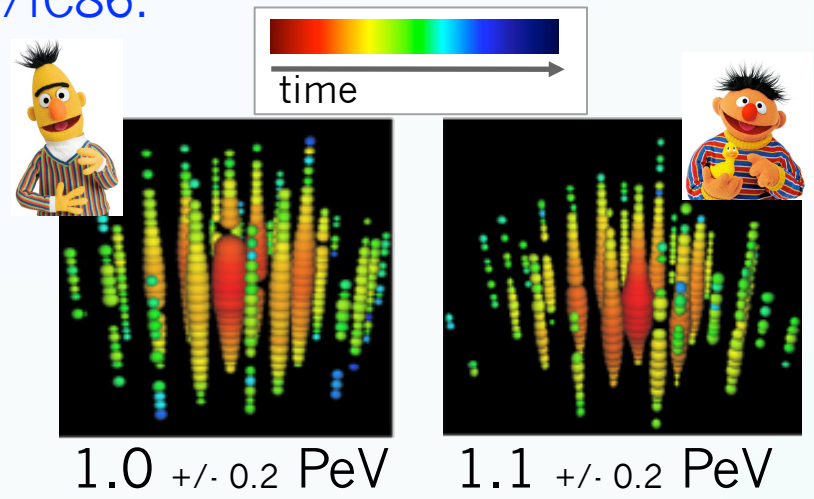
📖 H. van Haren et al., Ocean Dynamics, April 2014, Volume 64, Issue 4, pp 507-517

📖 H. van Harenz et al., Deep-Sea Research I 58 (2011) 875–884

📖 To come: Sperm whale diel behaviour

IceCube Discovery of HE neutrinos

- Two interesting cascade events found in IC79/IC86:
  - analysis targeting GZK neutrinos (~EeV)
  - significance 2.8σ (expected 0.08±0.05)
  - 🕮 Phys. Rev. Lett. 111, 021103 (2013)



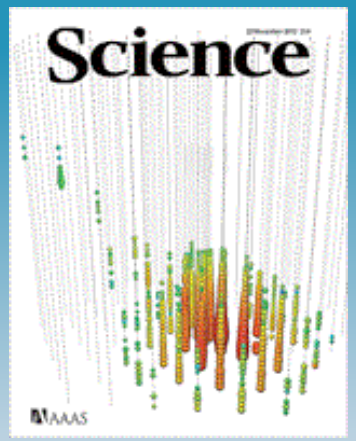
- Re-tuned on high-energy starting events:
  - total deposited charge > 6000 p.e.
  - track-like + shower-like events
  - outer layer used as veto against μ_{atm} & ν_{atm}

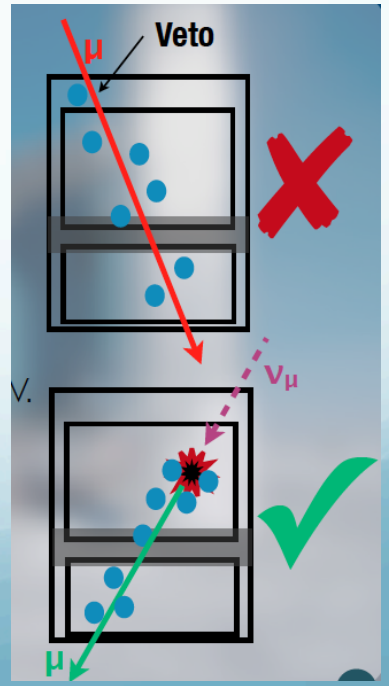
28 events selected (2-year data sample)
11 expected from μ_{atm} & ν_{atm} background:

first signal of high-energy astrophysical neutrinos !
4.1σ stastistical significance

... and a Science cover

High Energy Starting Events (HESE)

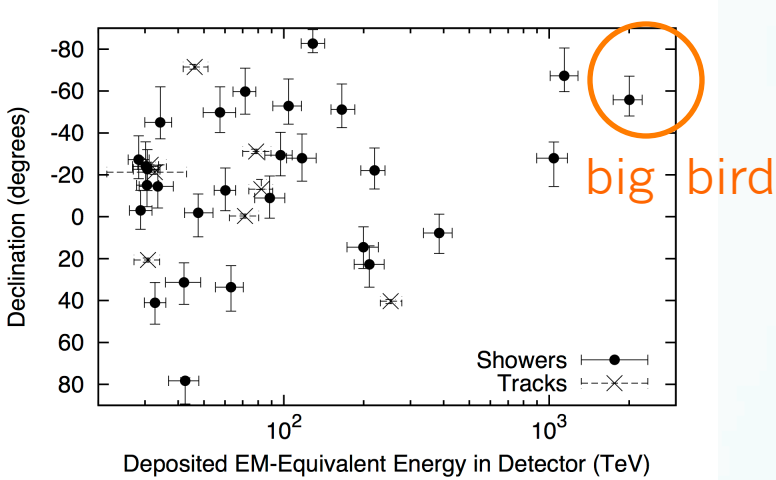




Follow up analysis: the IceCube signal

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

3 year analysis:
37 events
5.7 σ
(📖PRL, 113, 101101, 2014)

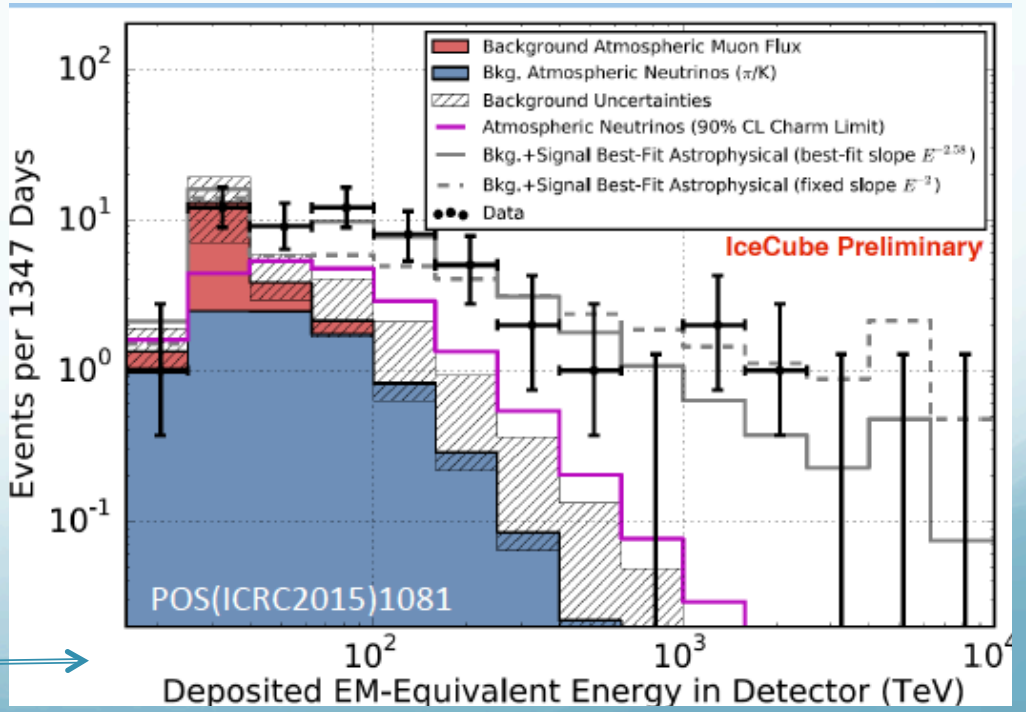


7 ⟹ 9 track-like events
1° angular resolution
muon takes some energy away
total expected background: 11 events

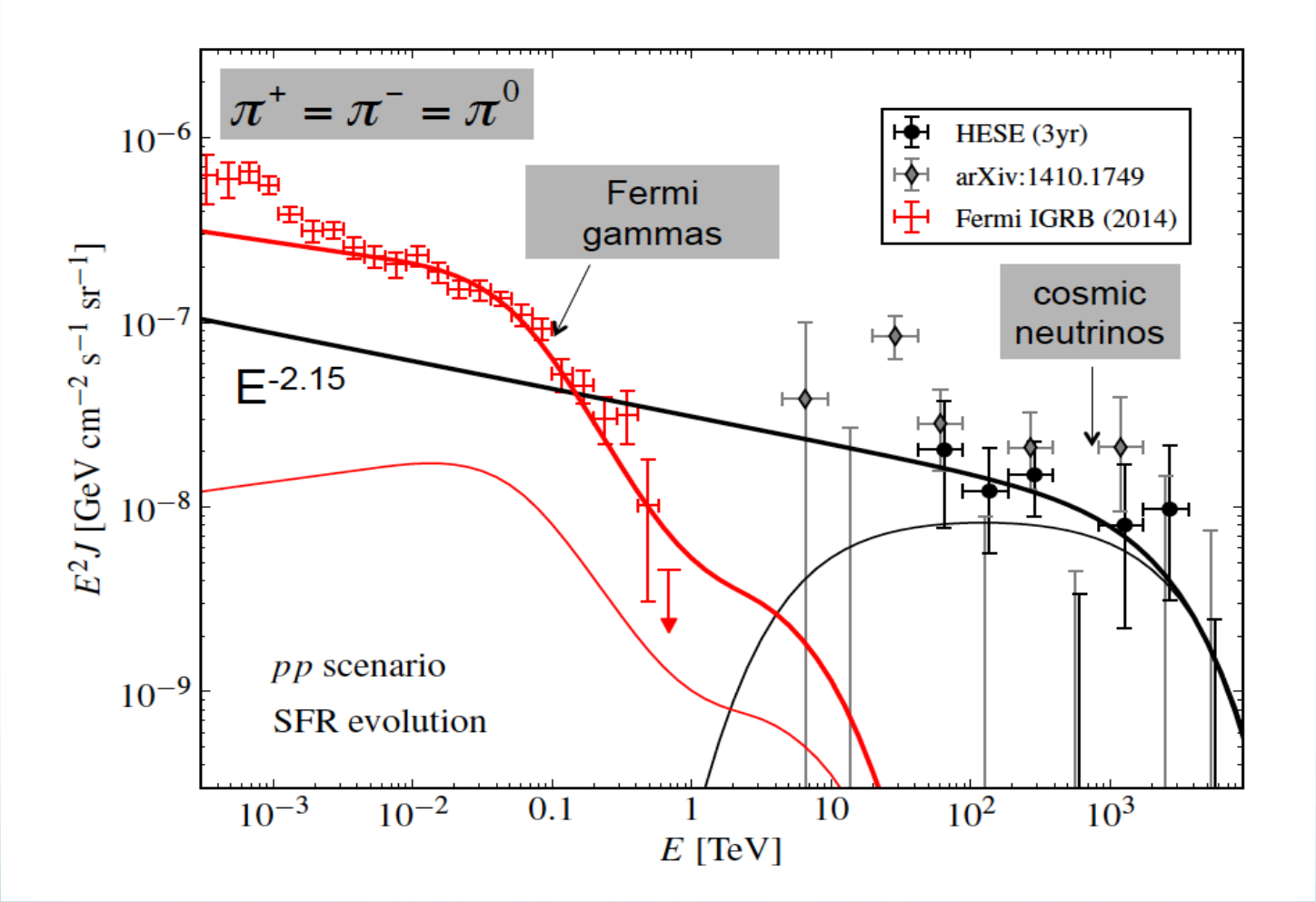
21 ⟹ 28 cascade-like events
10° - 45° angular resolution
15% visible energy reconstruction

highest energy event @ 2 PeV
cutoff at ~2.3 PeV ?

Now 4 years of data (6.5 σ)
Best fit spectral index 2.58



An intense HE neutrino diffuse flux



"Neutrino sources contribute at least 30%–40% of the diffuse gamma-ray background in the 100 GeV range and even ~100%for softer spectra"

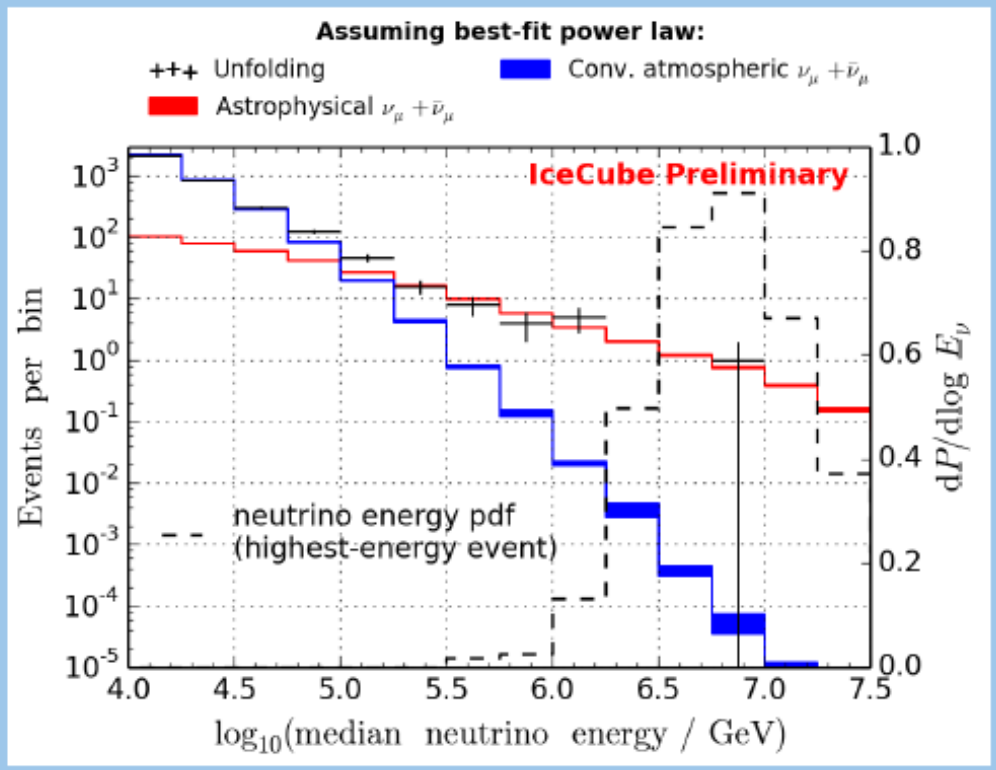
📖 Phys.Rev.D 88 (2013) 121301

The muon channel

- Analysis of up-going track events (northern sky) using 6 years of data, ν_μ charged current only, >100 GeV
- Fit with an unbroken power law

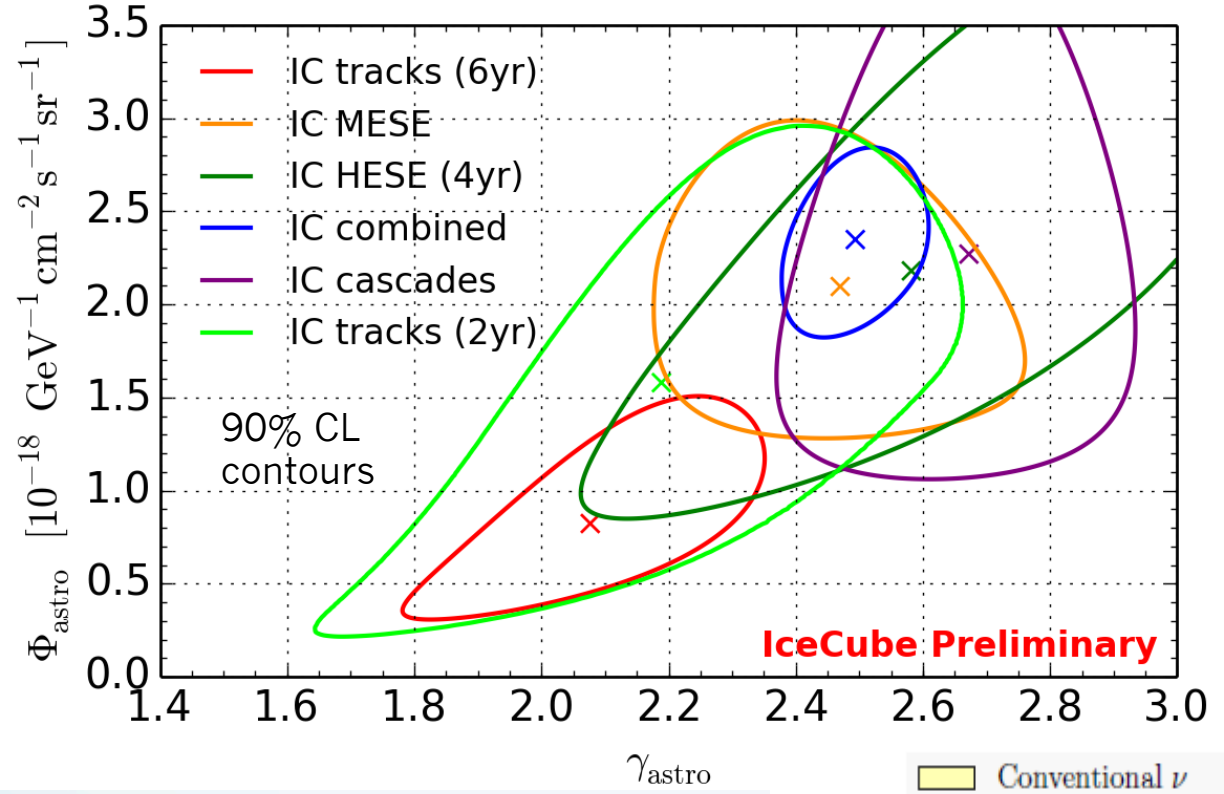
Results:

- Astrophys. norm @100 TeV:
  0.82 +0.3/-0.26 * 10^{-18} GeV cm^{-2} s^{-1} sr^{-1}
- Spectral index:
  γ_{astro} = 2.08 ±0.13
- Energy range:
  220 TeV – 8.3 PeV



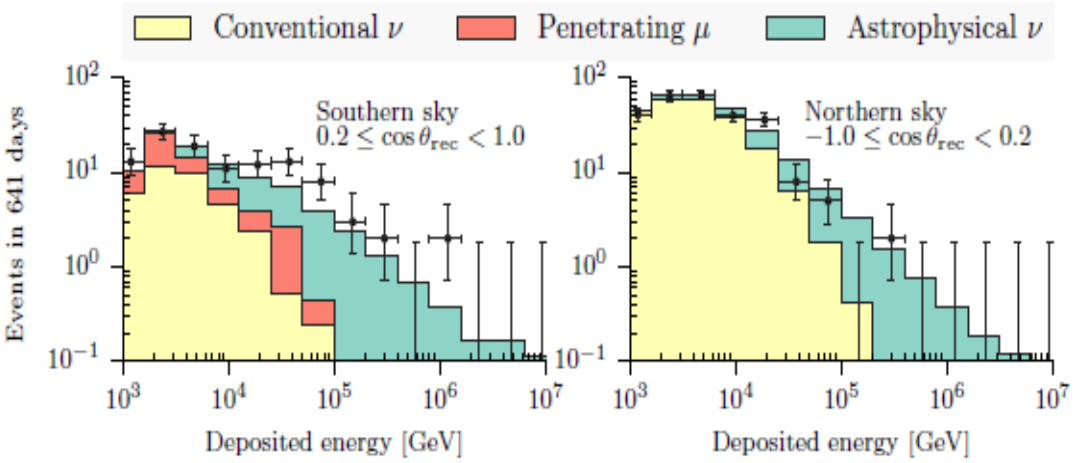
Atmospheric-only hypothesis excluded by 5.9σ

Summary of recent IC results



Results of IC tracks(6yr) and IC combined not compatible at > 3.6 σ level

Medium Energy Starting Events



Indication of spectral break (different energy thresholds) ?

Indication of galactic and extra-galactic contributions (different hemispheres) ?

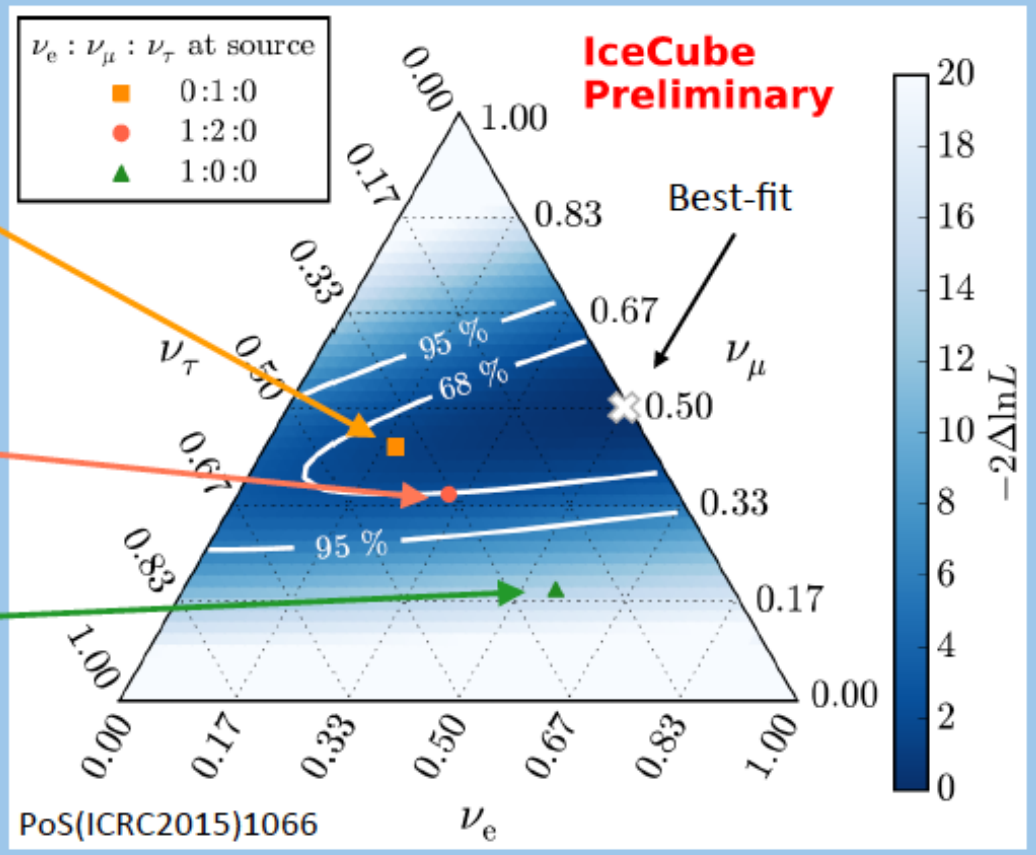
Summary of recent IC results

Flavor composition at Earth useful to constrain production mechanism at the source

Muon-damped pion decay: allowed

Pion decay: allowed

Neutron decay: rejected at 3.7 σ

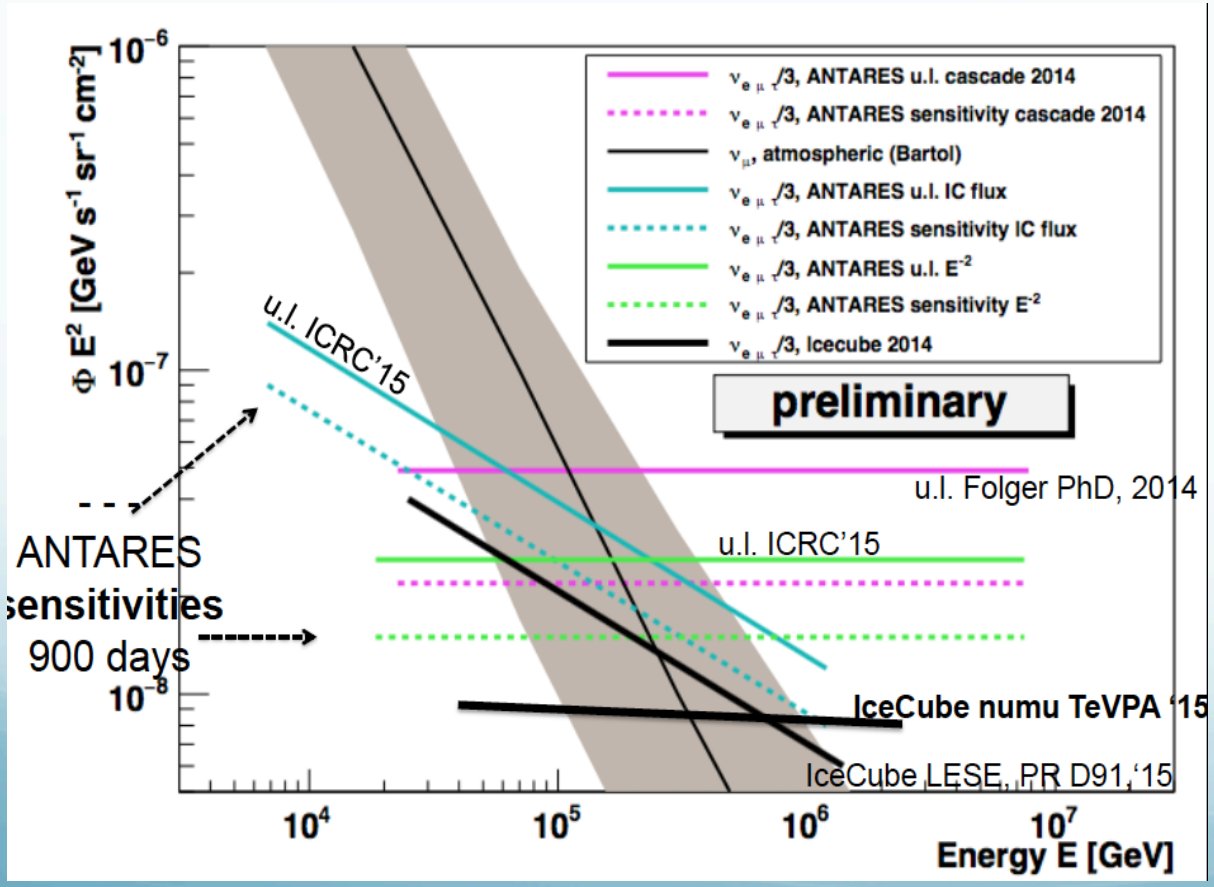


- Contribution of ν_τ nearly unconstrained due to low sensitivity of the ν_τ measurements

ANTARES Diffuse Neutrino Searches

Data sample 2007 – 2013, strong quality cuts (data/MC agreement):
913 days effective lifetime (= about half available sample)
Sensitivity 1.3-2 times IC flux

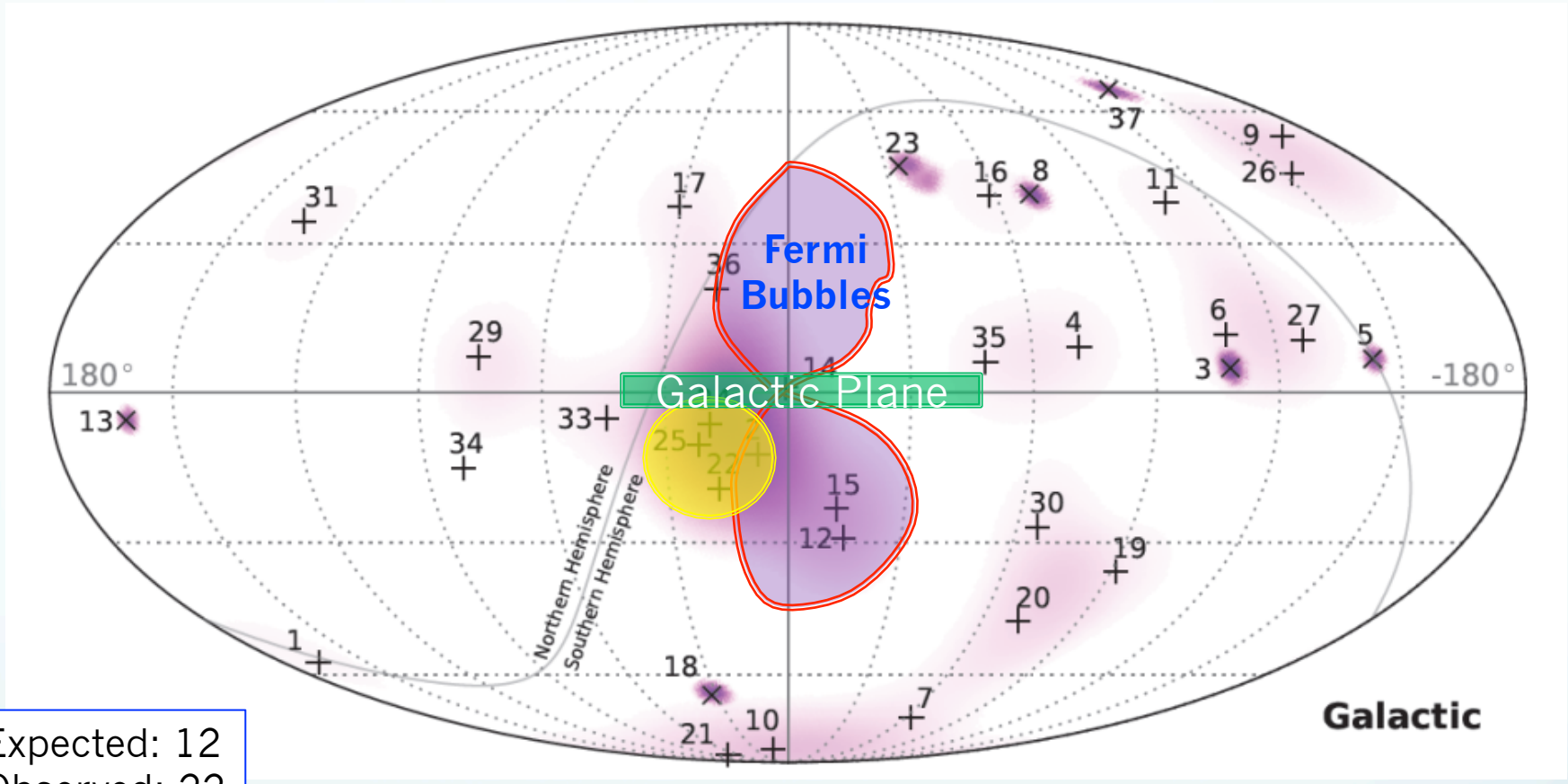
2-steps multivariate analysis: · removal of atmospheric muon background
· track/shower classification



- Expected:
  - 9.5 ± 2.5 bkgd
  - 5.0 ± 1.1 IC flux
- Observed:
  - 12 events
  - 1.75σ excess
- Results:
  - Consistent with bkg
  - Consistent with IC

Sensitivity of ANTARES final sample could reach the IC flux

Reducing the search window

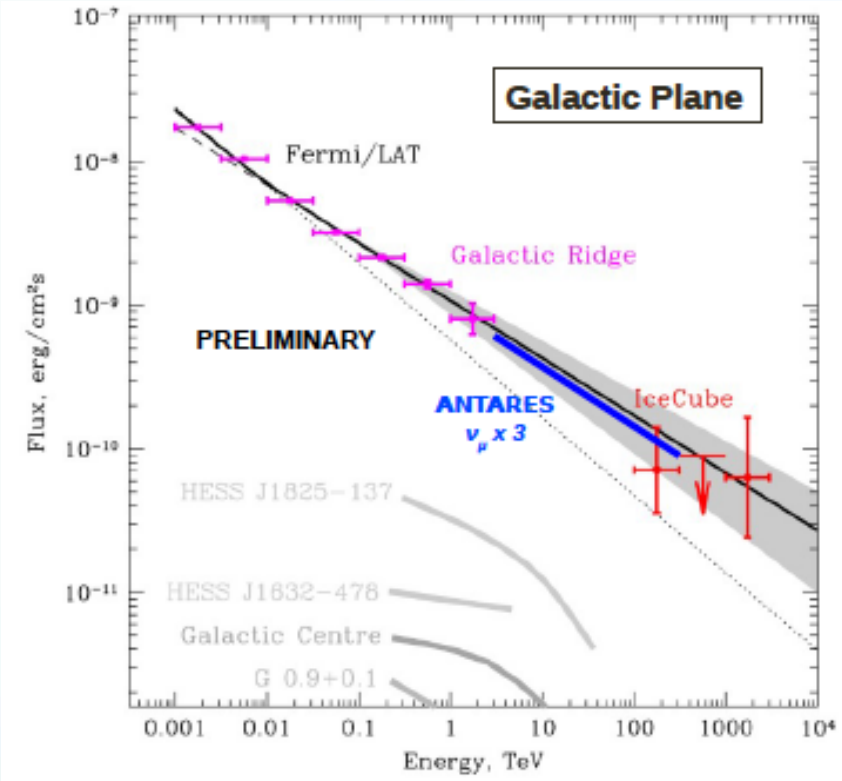


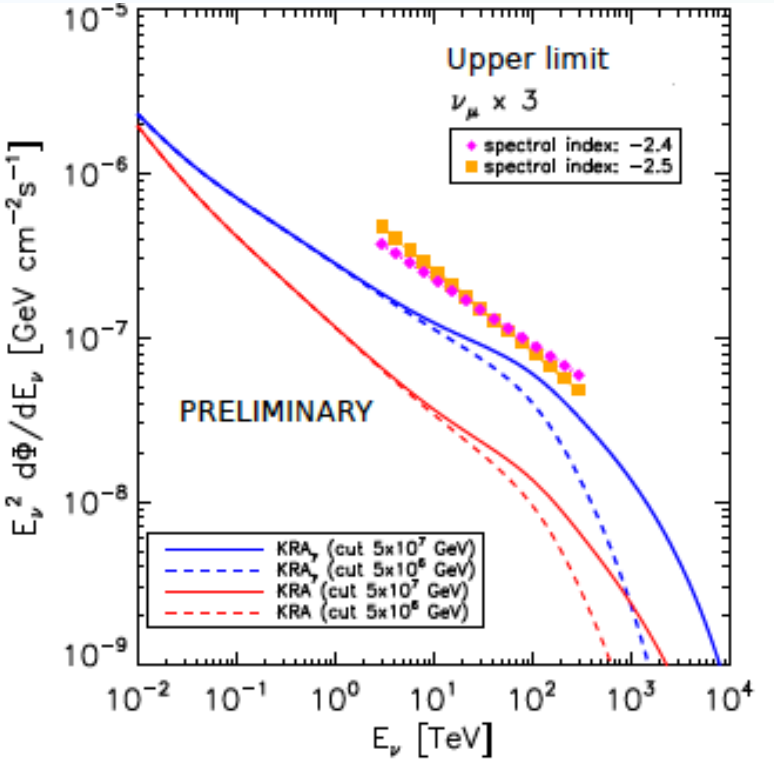
Expected: 12
Observed: 22
1.9 σ excess

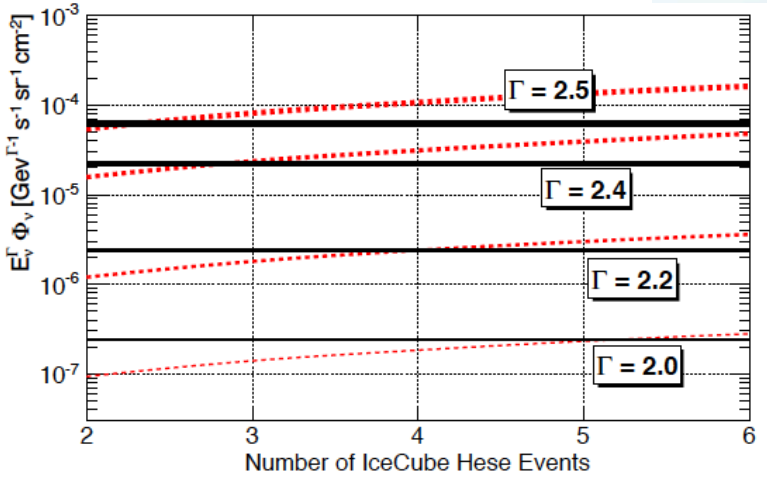
- **Fermi-Bubble region**.
- **Galactic Center region**.
- **IC hot spot.**
  <2 HESE events for G=2.58

➢May 2008- Dec 2013 (1172 days livetime)
Muons only ! Cascades will be soon added

Galactic Ridge

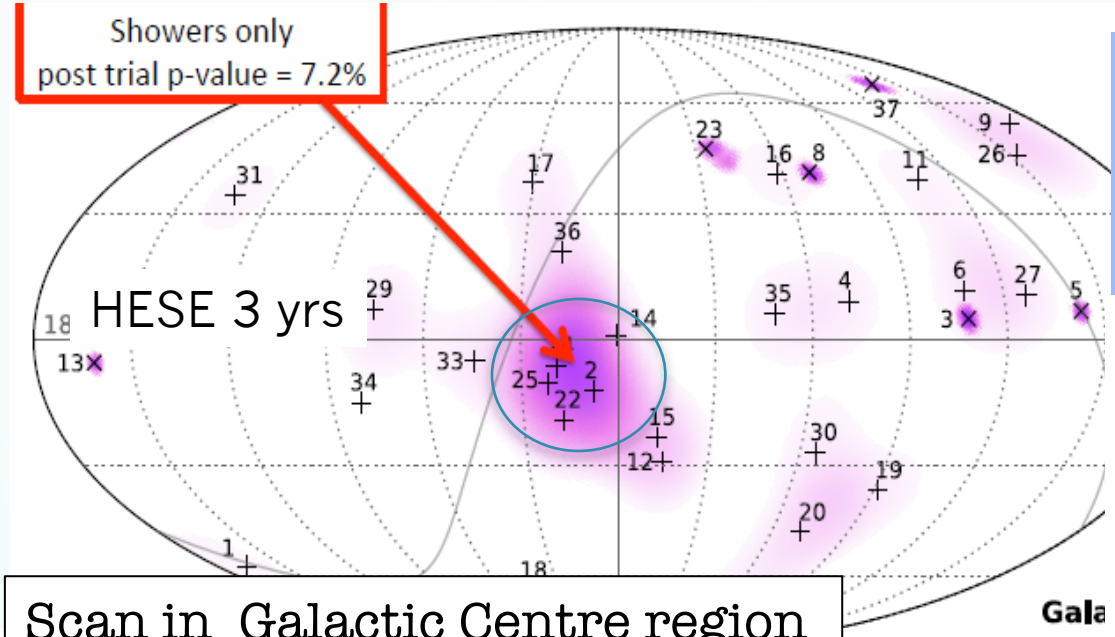




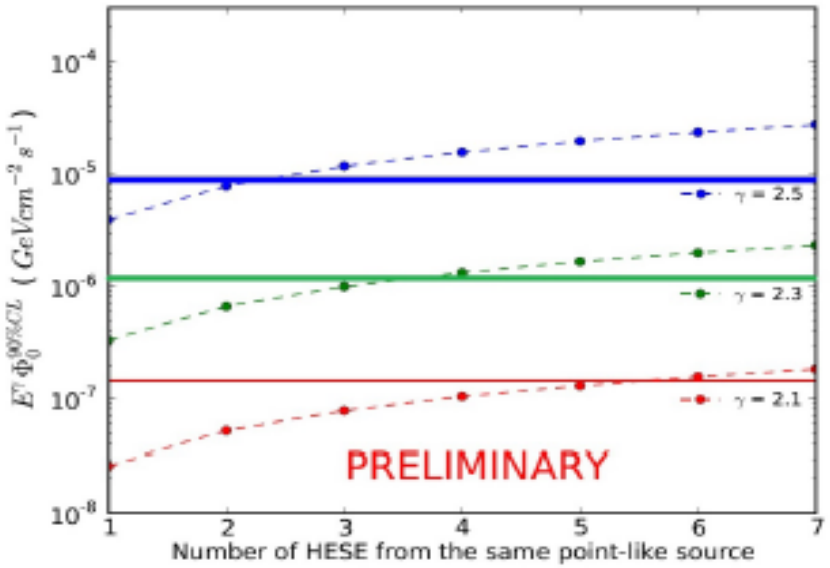


- A. Neronov et al. Phys. Rev. D89, 103002 (2014)
- D. Gaggero et al.,The Astrophysical Journal Letters, 815:L25 (2015)
- ANTARES arXiv:1602.03036, submitted to PLB

A source near the Galactic Center?



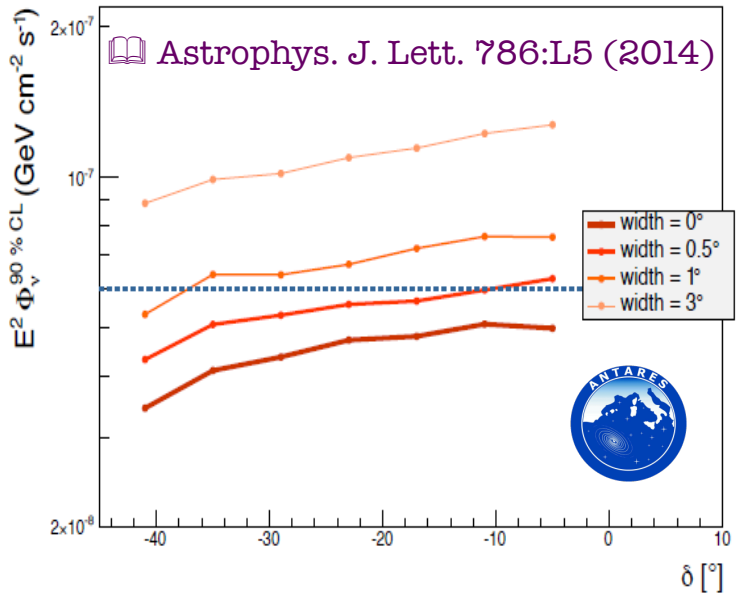
Scan in Galactic Centre region



Hypothesized Galactic Source ?

Point Source at $(\alpha, \delta)=(-79°, -23°)$ as origin of cluster of 6 events.

📖 *Gonzalez-Garcia et al, APP 57 (2014)*



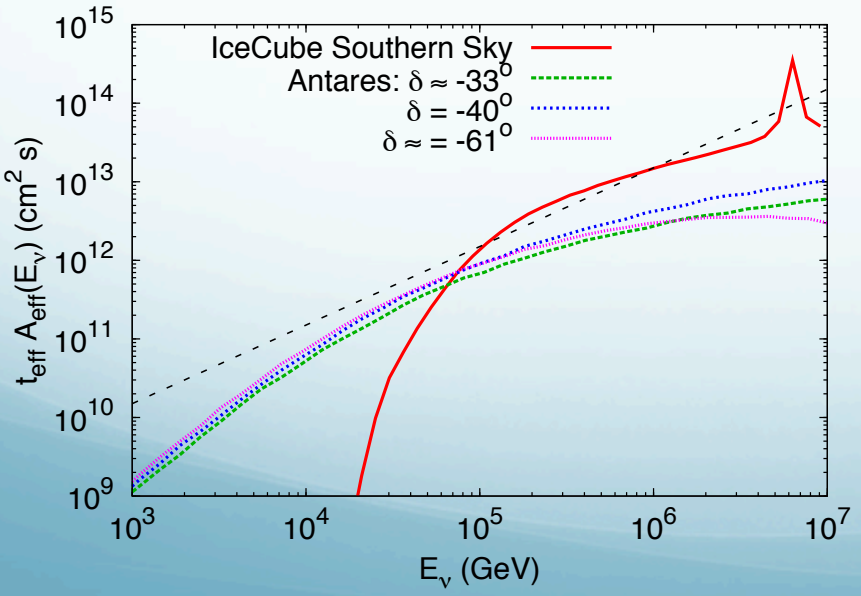
ANTARES rules out any single PS close to the GC with spectral index of -2.5 as having a flux corresponding to more than 2 HESE...

AGNs close to Ernie and Bert?

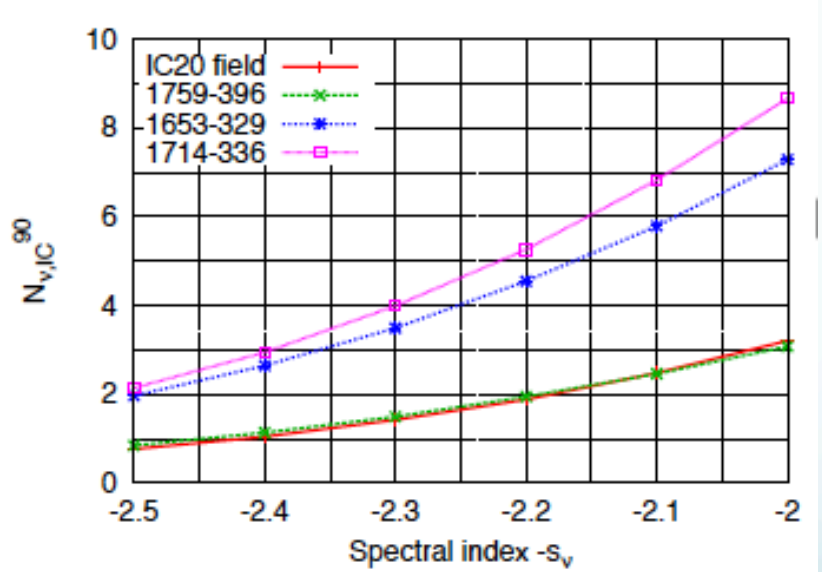
TANAMI collaboration reported observations of 6 bright blazars locally compatible with the 2 first PeV IceCube events IC14 and IC20.

📖 Krauß, F. et al. 2014, A&A, 566, L7

Source	N_{sig}	p	Limit 10^{-8} GeV^{-1} cm^{-2} s^{-1}
0235–618	0	1	1.3
0302–623	0	1	1.3
0308–611	0	1	1.3
1653–329	1.1	0.10	2.9
1714–336	0.9	0.04	3.5
1759–396	0	1	1.4



ANTARES inferred limits



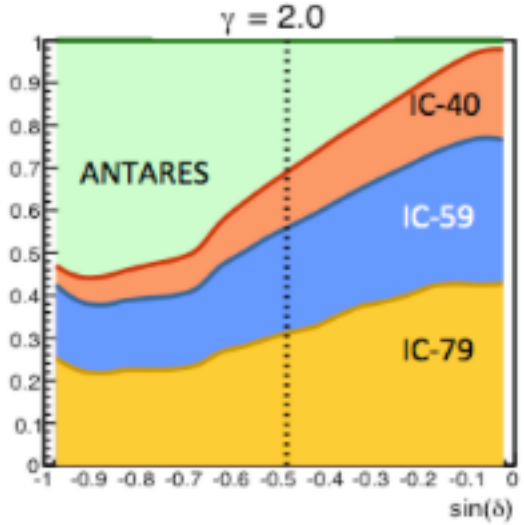
→ Relevant constraints on spectral index of potential source

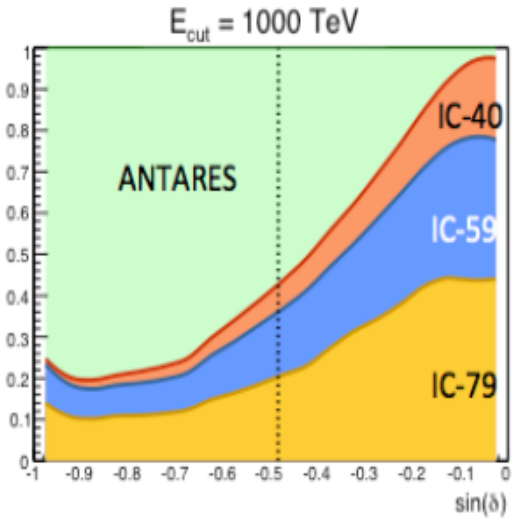
📖 Antares, A&A 576, L8 (2015)

Join ANTARES-IceCube search

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

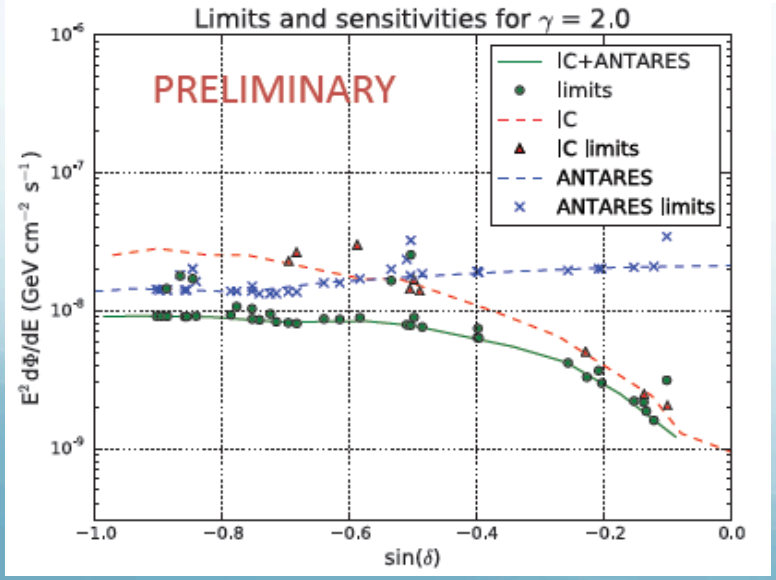
📖 *1511.02149v1 accepted in ApJ*

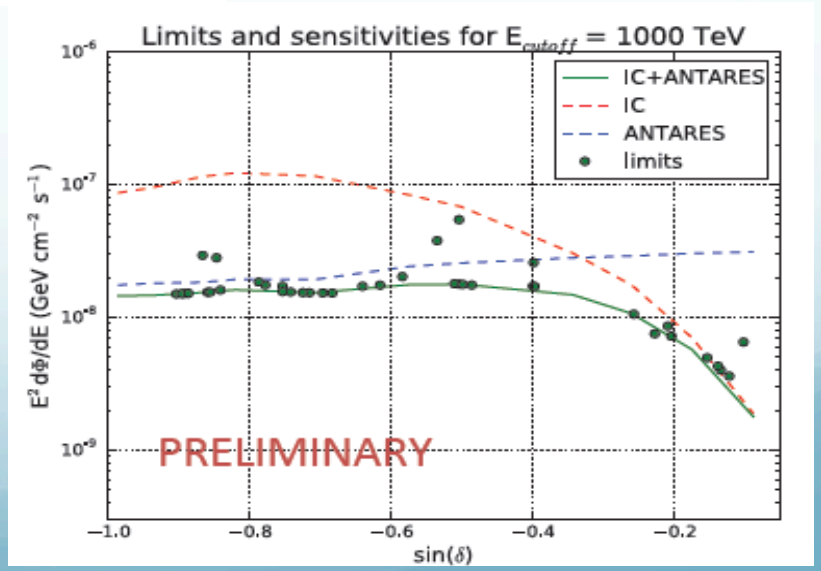




Fraction of signal events which would be detected by each sample ($E^{-\gamma}$):

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

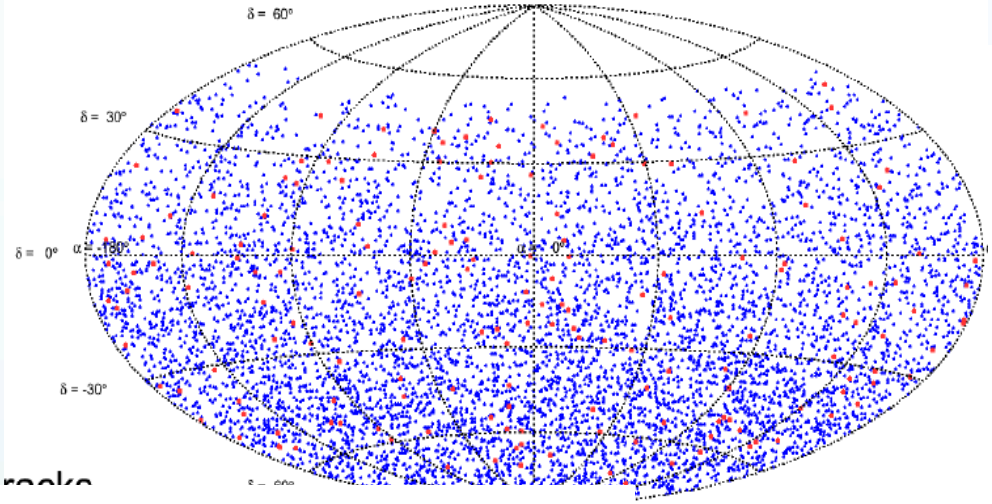


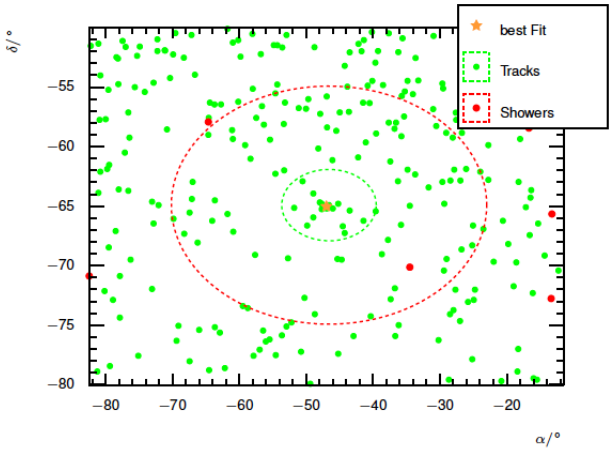


Latest ANTARES PS search

- 1690 days from 2007 to the end of 2013 (including 5-line data also in shower channel)
- contains 6490 muon track candidates and 172 cascade events
- for E^{-2} flux with 1:1:1 flavour composition, shower channel increases signal event rate by 45 %

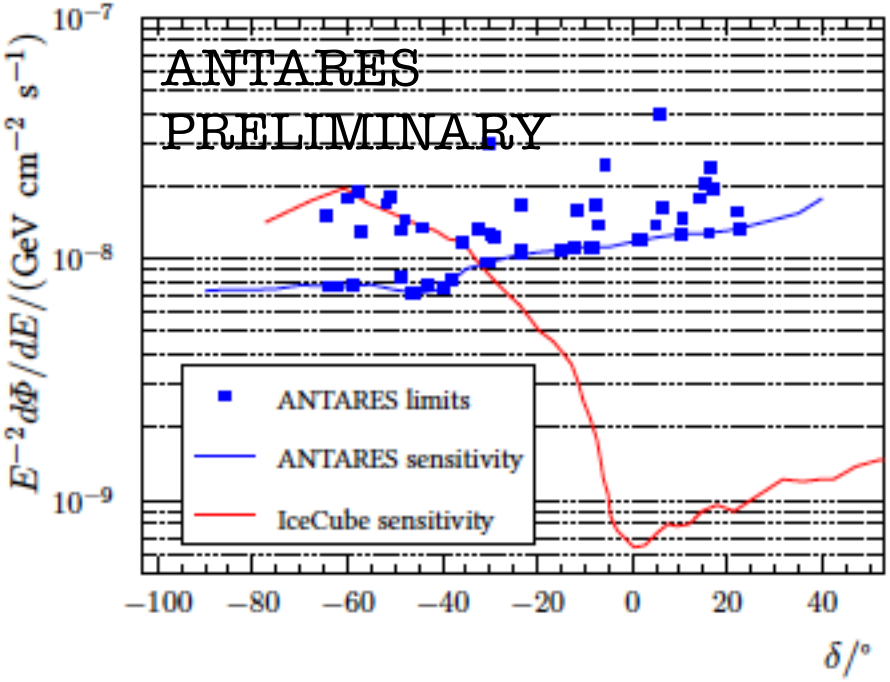
Includes cascades!
(3° median resolution)





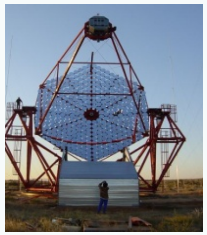
nost significant clus

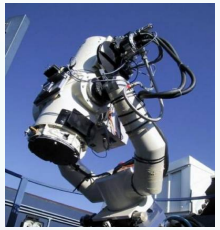
- $\alpha = -47.0°, \delta$
- 17 tracks within
  1 shower within 10°
- NSig = 7.3 + 0.0
  (Tracks + Showers)
- p-value: 0.0418,
  sigma: 2.04

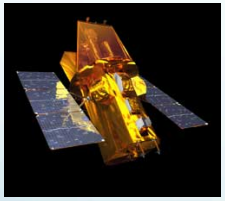


Best limits in Southern Sky in TeV-100TeV range

The Multi-messenger Program







GeV-TeV γ-rays
Fermi / HESS...

UHECR
Auger

HE neutrinos

Optic / X-ray

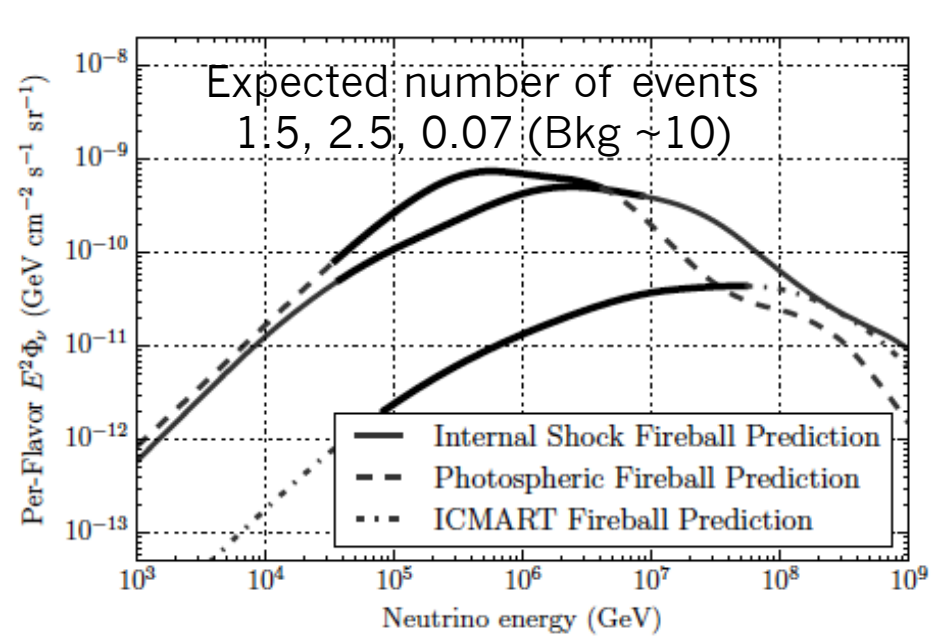
Gravitational Waves
Virgo / Ligo

- A way to better understand the sources and the related physics mechanisms
- A way to increase the detector sensitivities (uncorrelated backgrounds)

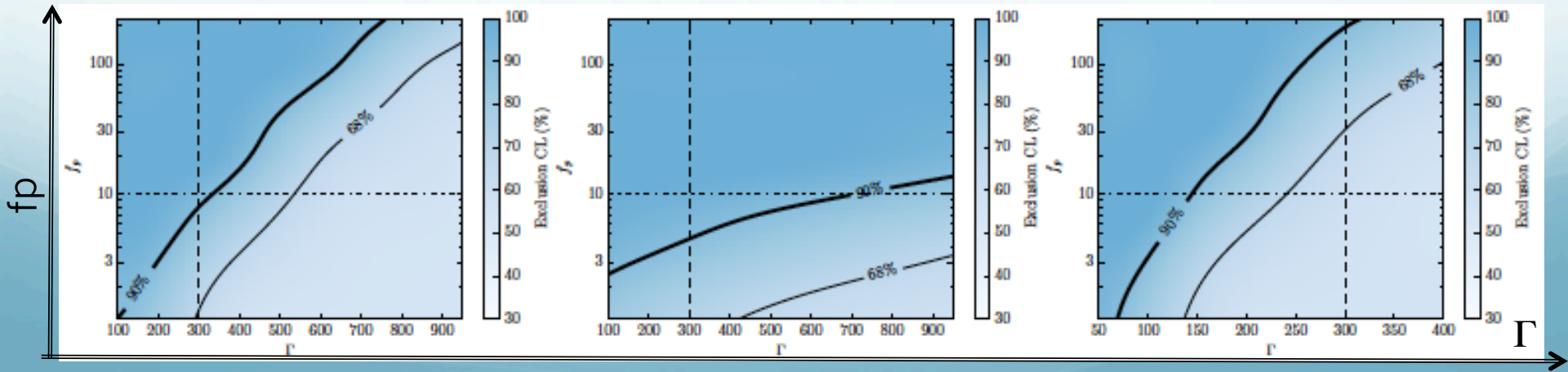
Search for neutrinos from GRB

📖 2015 ApJ 805 L5
4 yrs search 506 observed GRBs (1/2 sky) : tracks

📖 1601.06484v1
3 yrs search 807 GRBs: showers

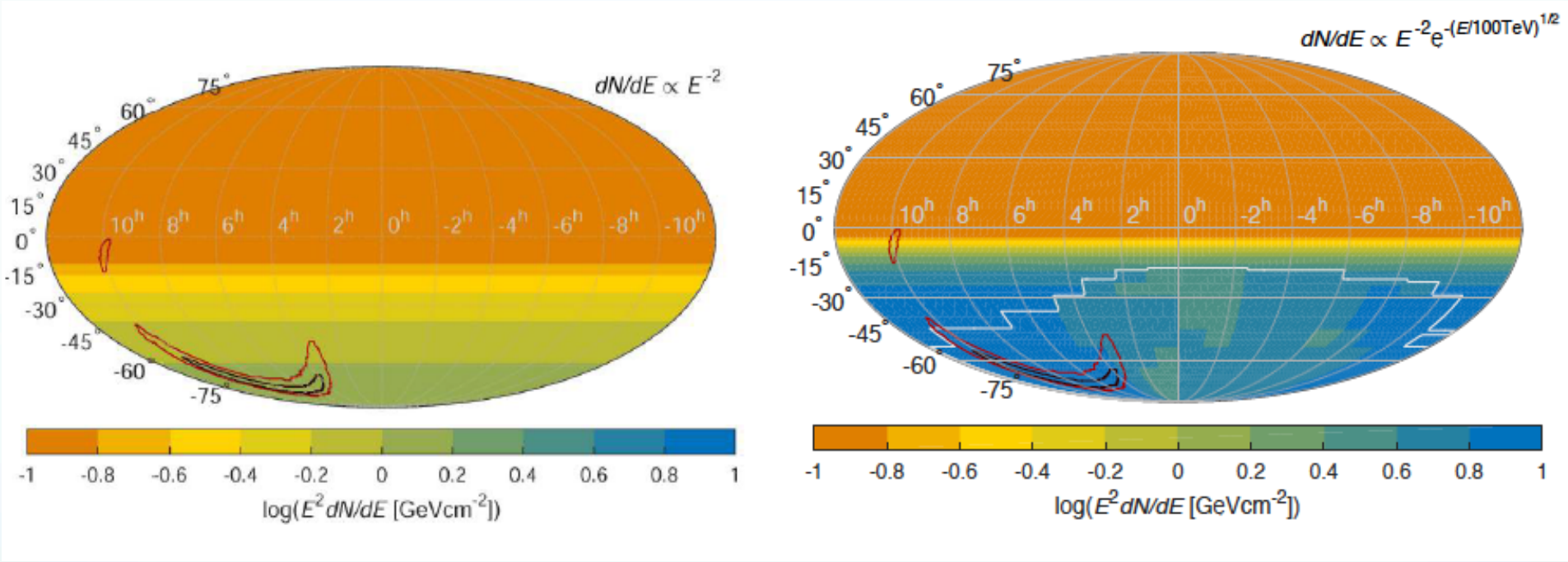


- Prompt emission : no more than 1% of the diffuse astrophysical flux
- Strong constraints on GRBs as source of UHECRs
  Model dependent



GW150914 follow-up

=> (best)Limits on the neutrino spectral fluence (E^{-2} spectrum)



⇒ Limits from ANTARES dominates below O(100 TeV) (white line)

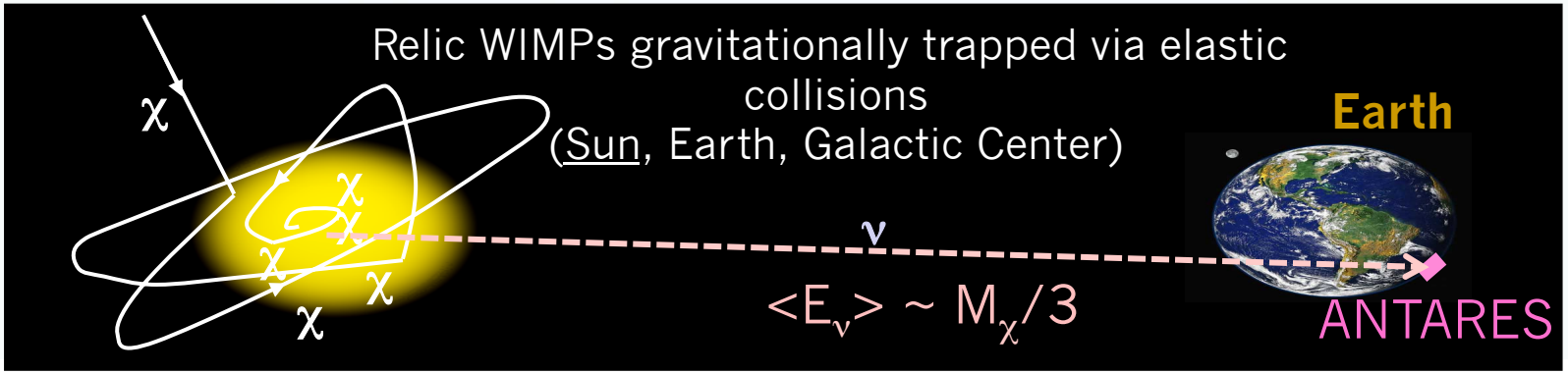
➜ Integrating emission between [100 GeV; 100 PeV] and [100 GeV; 100 TeV]:

$$E^{ul}_{\nu,tot} \sim 10^{52}\text{–}10^{54} \left(\frac{D_{gw}}{410\,\mathrm{Mpc}}\right)^2 \mathrm{erg}$$

Size of GW160914 : 590 deg^2 ANTARES resolution: <0.5 deg^2

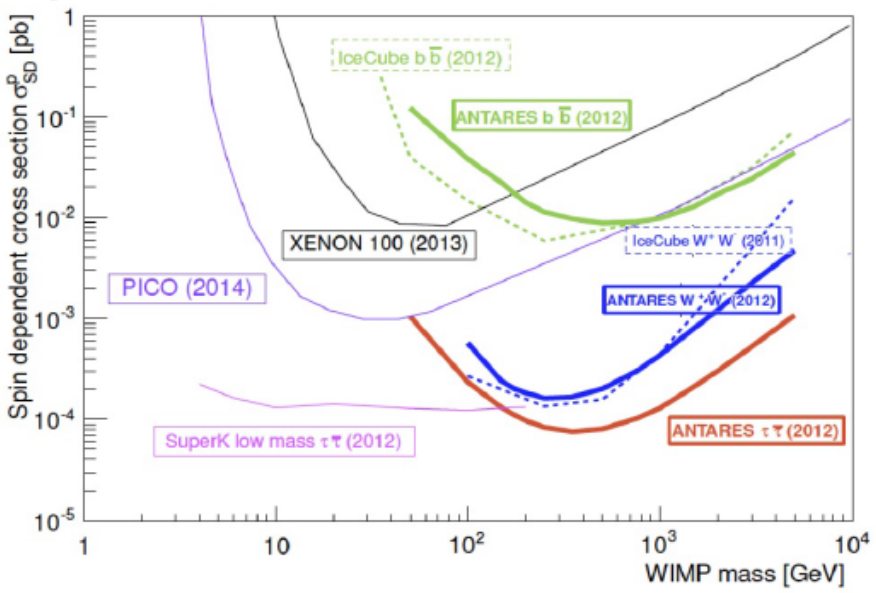
A rapid observation of counterpart would help a better localization for further follow-up

Dark matter indirect searches



Sun

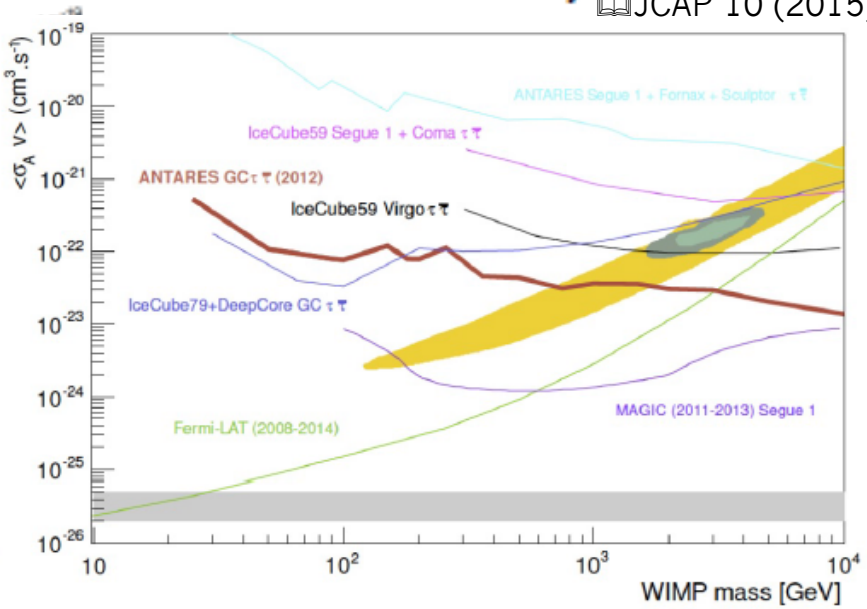
📖 arXiv:1603.02228



- Limits in the spin-dependent Wimp-nucleon cross section

Galaxy

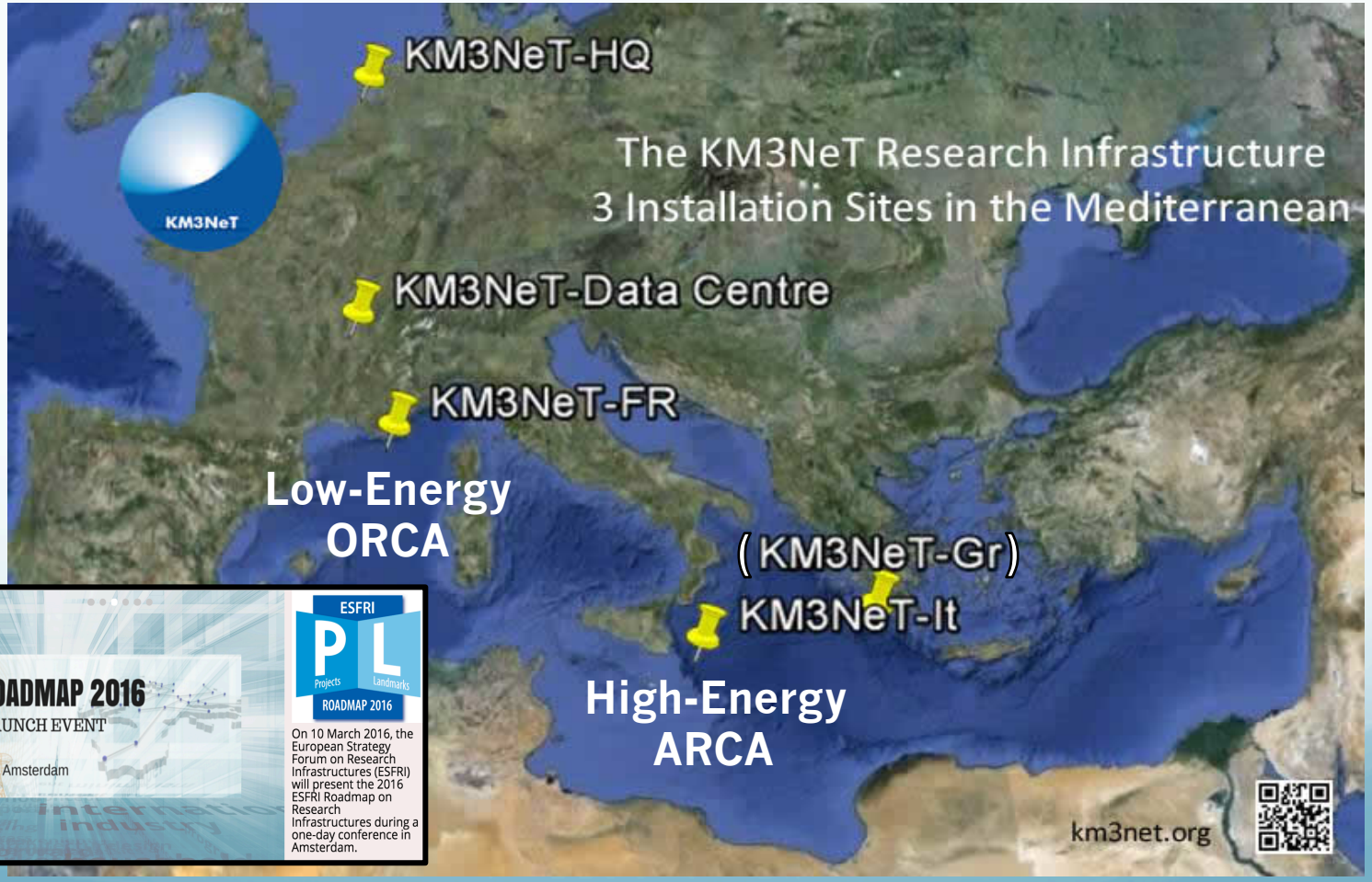
📖 JCAP 10 (2015) 068



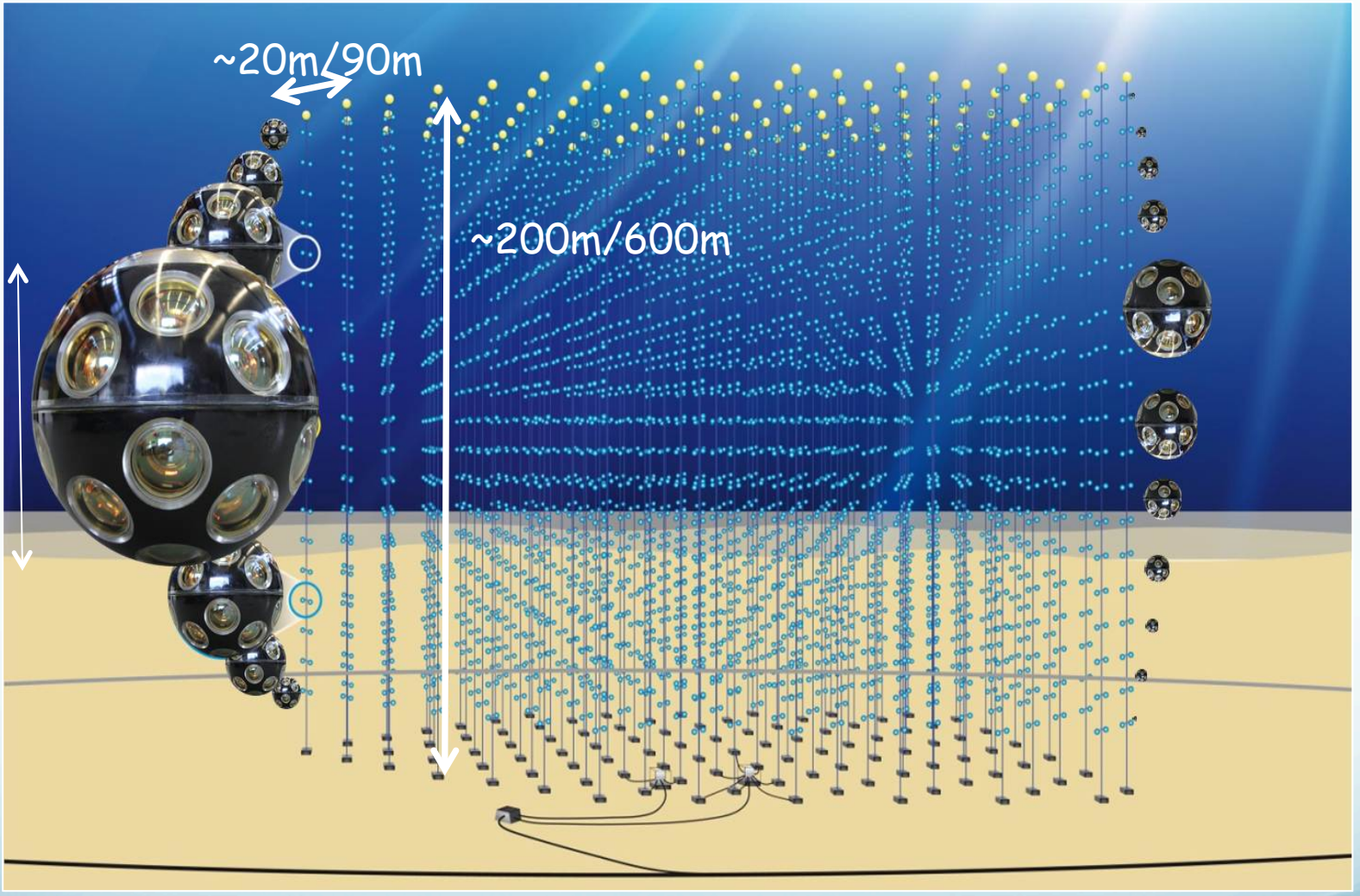
- Limits on the Wimp self annihilation cross section

KM3NeT: Next generation detectors

KM3NeT is a distributed research infrastructure with 2 main physics topics:
Low-Energy studies of atmospheric neutrinos – High-Energy search for cosmic neutrinos
Single Collaboration -- Single Technology



Detector technology

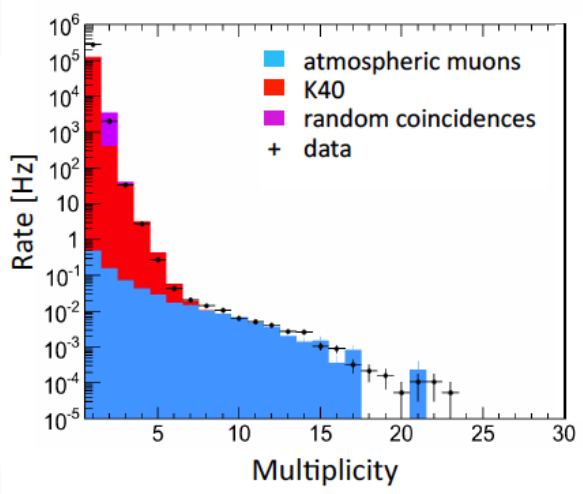


- 31 3” PMTs
- Digital photon counting
- Directional information

- Wide angle of view
- More photocathode than 1 ANTARES storey
- Cost reduction wrt ANTARES

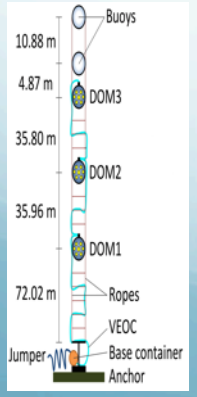
KM3NeT Prototypes

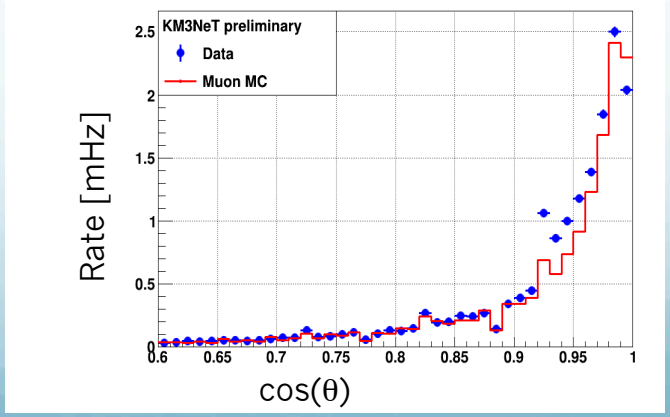
1) Optical Module deployed at Antares, April 2013 (2500 m)



📖 Eur. Phys. J. C (2014) 74:3056

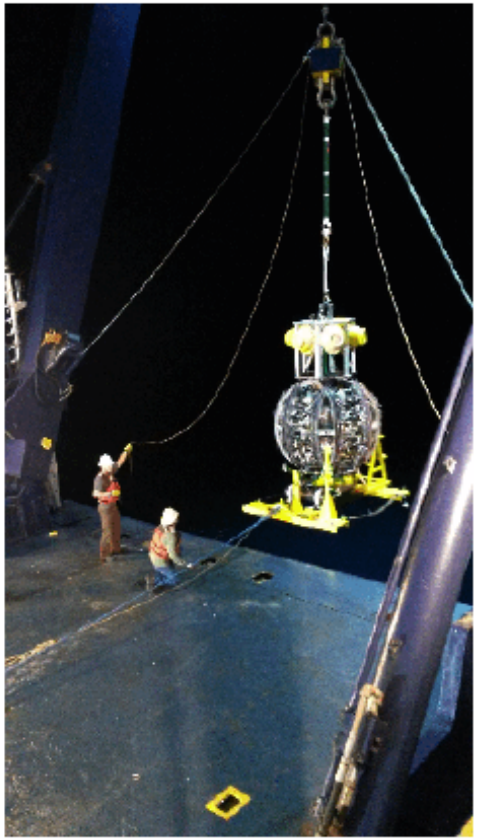
2) Mini string deployed at Capo Passero, May 2014 (3500 m)



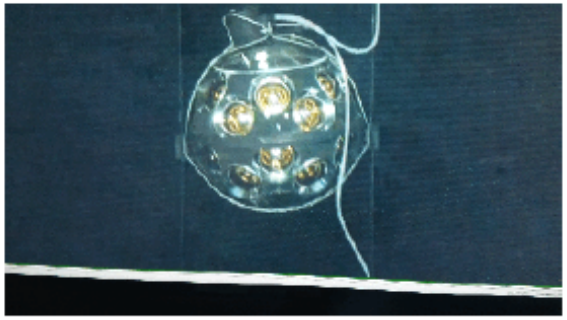


📖 arXiv:1510.01561 Accepted by Eur. Phys. J. C

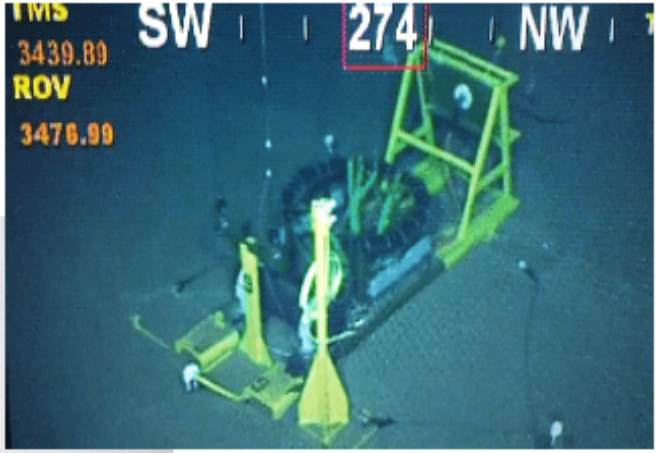
A first string working



04/12/2015
Laid on seabed
Unfurled
Powered on
Taking data !



First reconstructed μ seen!



A phased implementation

PHASE 1:

Shore and deep-sea infrastructure at KM3NeT-Fr & KM3NeT-It

31 lines deployed by end 2016 (**3-4 x ANTARES sensitivity**)

Proof of feasibility of network of distributed neutrino telescopes and more?

31 M€ FUNDED ONGOING

2016 PHASE 2:

ARCA 230 lines (2 building blocks)

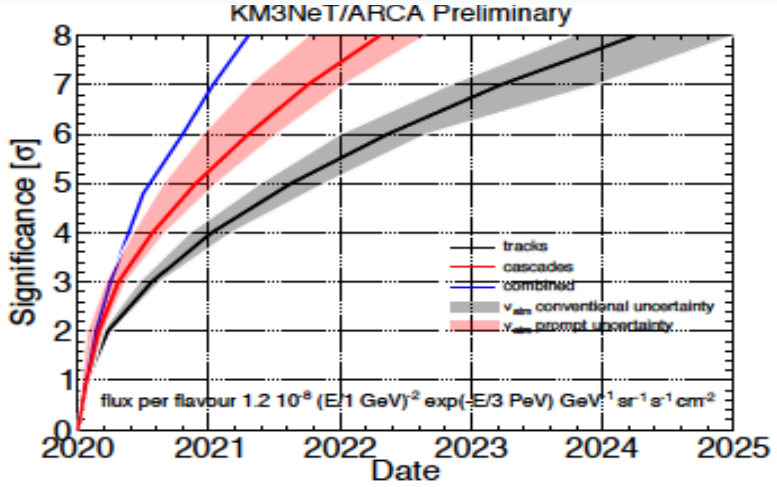
Investigation of IceCube signal

ORCA *115 lines (1 building block)*

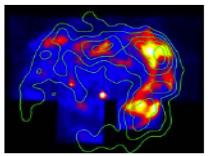
Oscillations studies

Letter of Intent
arXiv:1601.07459

Phase	Total costs (cumulative) M€
1	31
2.0	125
3	220–250

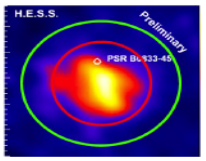


RXJ1713¶

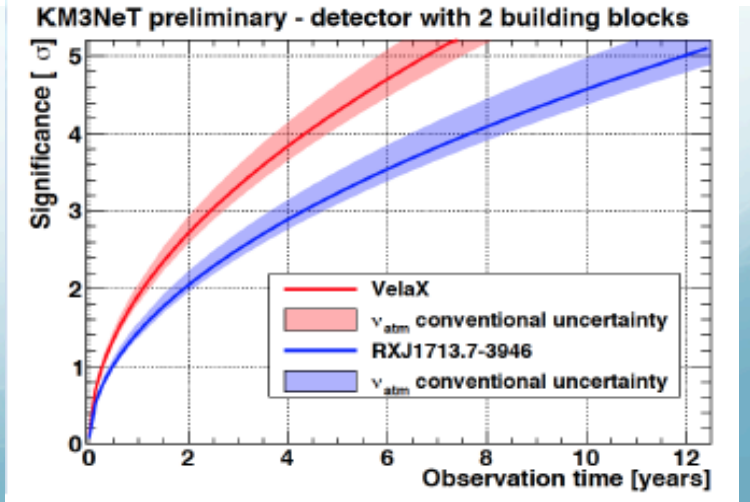


S.R. Kelner, *et al*

Vela X§



Villante & Vissani



2020 KM3NeT 3.0: 6 blocks

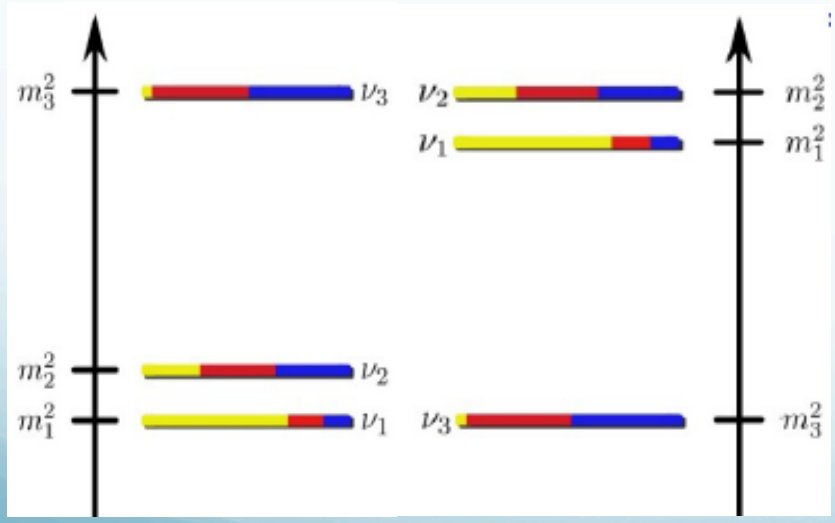
Neutrino Mass Hierarchy

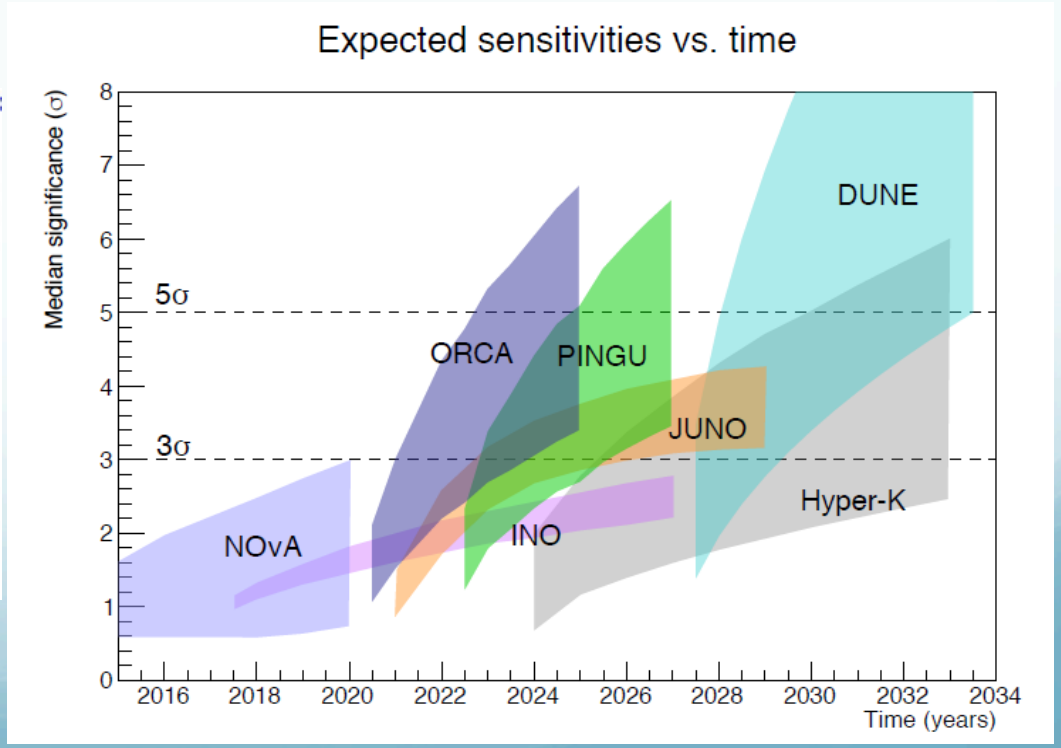
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Atmospheric $\theta_A \sim 45°$ | Reactor $\theta_{13} \sim 9°$ | Solar $\theta_\odot \sim 30°$ | Majorana

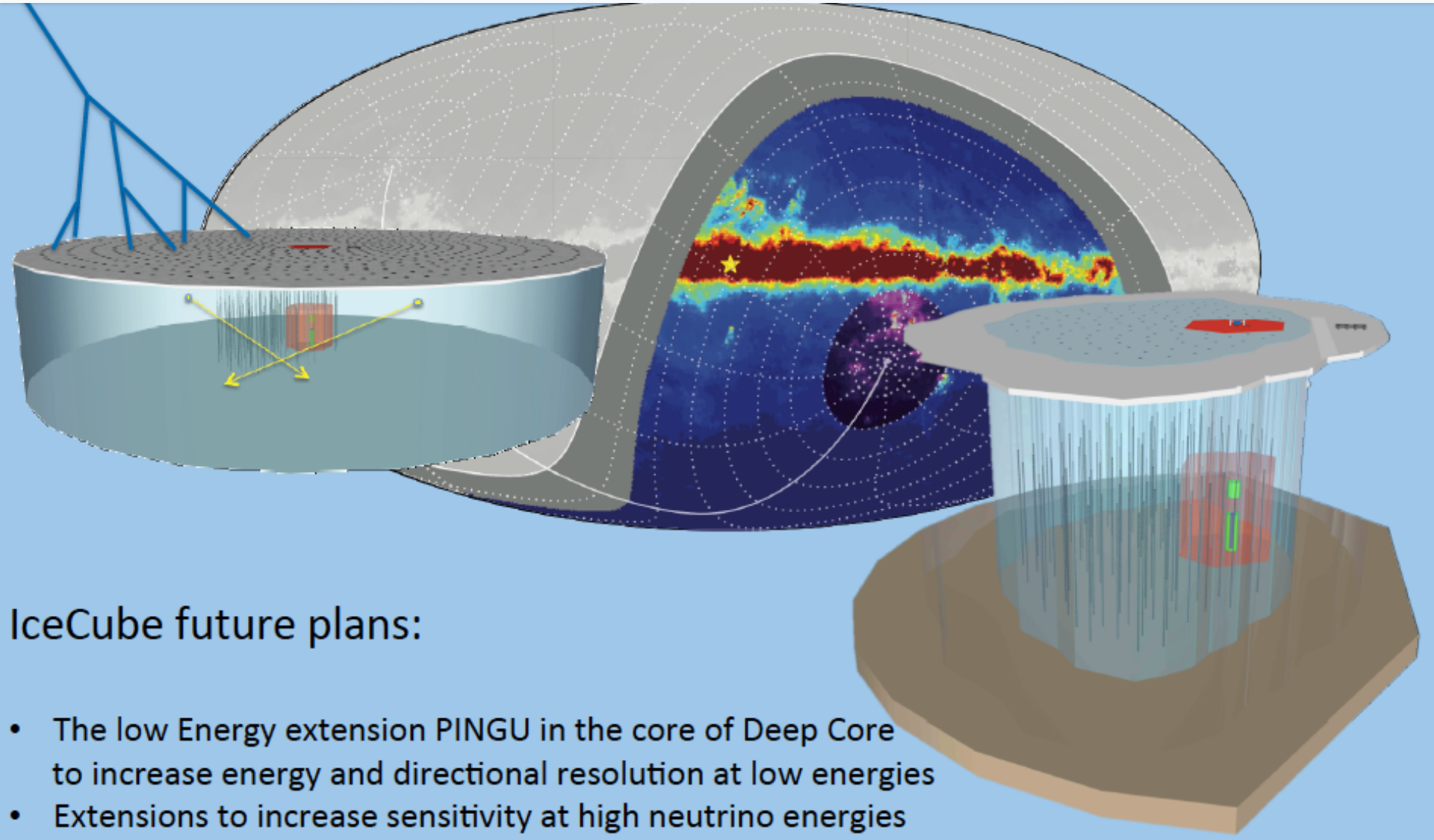
↓

CP violating phase δ_{CP}





IceCube planned extensions



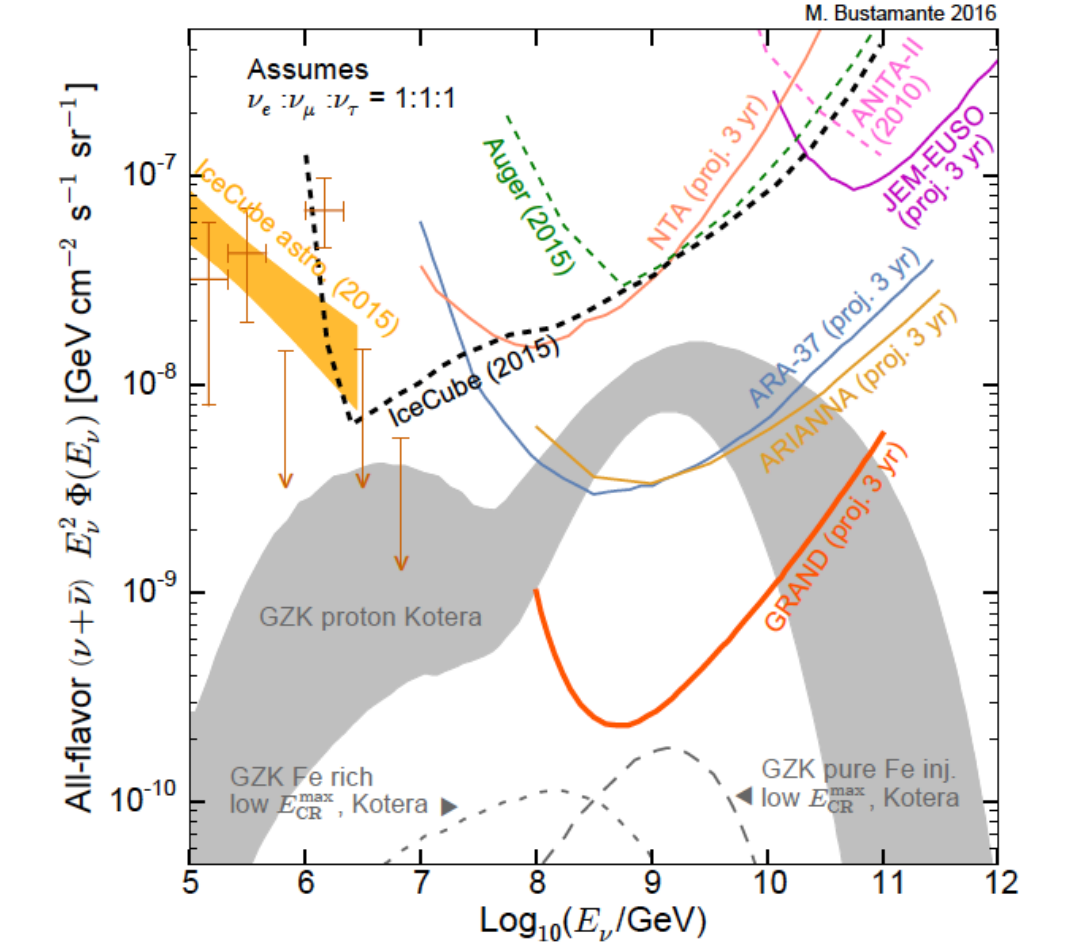
IceCube future plans:

- The low Energy extension PINGU in the core of Deep Core to increase energy and directional resolution at low energies
- Extensions to increase sensitivity at high neutrino energies

No construction before 2020 (funding process)

Quest for Cosmogenic neutrinos

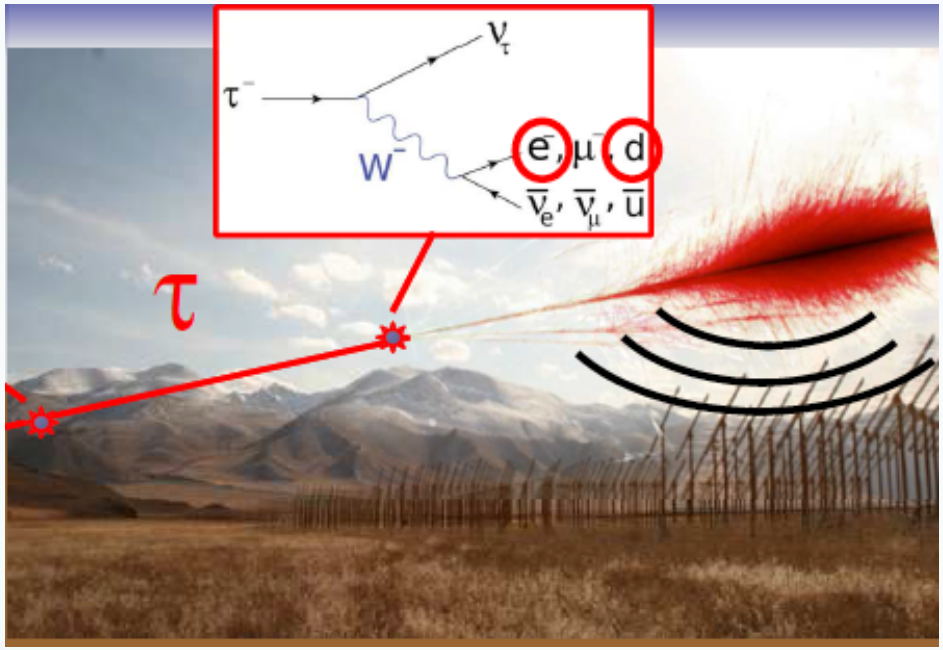
- They are sensitive to the UHECR composition (fewer ν's if nuclei)
- They probe the high-redshift UHECR evolution
- Probe ν properties at previously unexplored energies



Proton-induced GZK neutrinos in the reach of radio arrays in the coming years
e.g.
ARA – ARIANNA

If no cosmogenic neutrino
→ Constraints on GRBs as source of UHCRs and neutrinos

The GRAND project

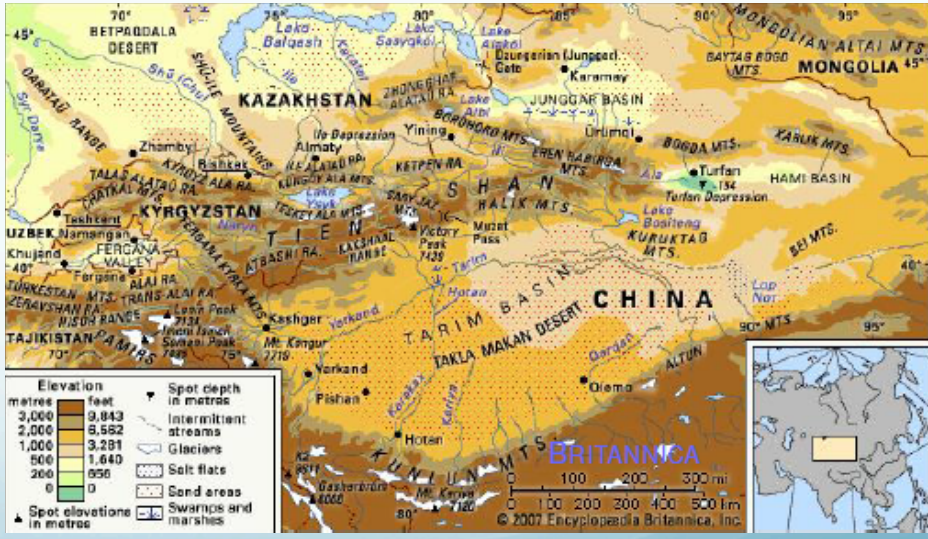


Based on various R&D studies
CODALEMA, TREND-50...

Goal achieved:
autonomous EAS detection with radio antennas is possible

Collaboration avec AUGER/AERA)

- Possible timeline:
  - 2016: GRANDproto + proposal
  - 2018: engineering array of $\mathcal{O}\left(1000\ \mathrm{km}^2\right)$
  - 2021: start building full array



200k antennas over 200 000 km² In West China (<200€/antennas)

Summary and perspectives

- IceCube has just opened the field of neutrino astronomy suggesting a higher level of hadronic activity in the non-thermal universe than previously though.

  → Exciting times ahead !

- Sources remain to be identified.

- ANTARES: first undersea Cherenkov detector
  - Excellent angular resolution, view of Southern sky, competitive sensitivities
  - Improvements still to come: include showers in all analyses
  - Taking data until superseded by KM3NeT in 2017

- KM3NeT: phased approach to next-generation neutrino telescope by 2020
  - Letter of Intent available
  - Prototypes performing well
  - Deployment of the first detection unit (Phase 1).
  - **ARCA → HE neutrino astronomy (tracks & showers)**
  - **ORCA for the measurement of NMH**

- **IceCube continues data taking + planned extension (PeV)**

- **Radio : promising techniques for > PeV detection**

ESFRI P L Projects Landmarks ROADMAP 2016

On 10 March 2016, the European Strategy Forum on Research Infrastructures (ESFRI) will present the 2016 ESFRI Roadmap on Research Infrastructures during a one-day conference in Amsterdam.