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# Neutrino astronomy and multi-messenger connections

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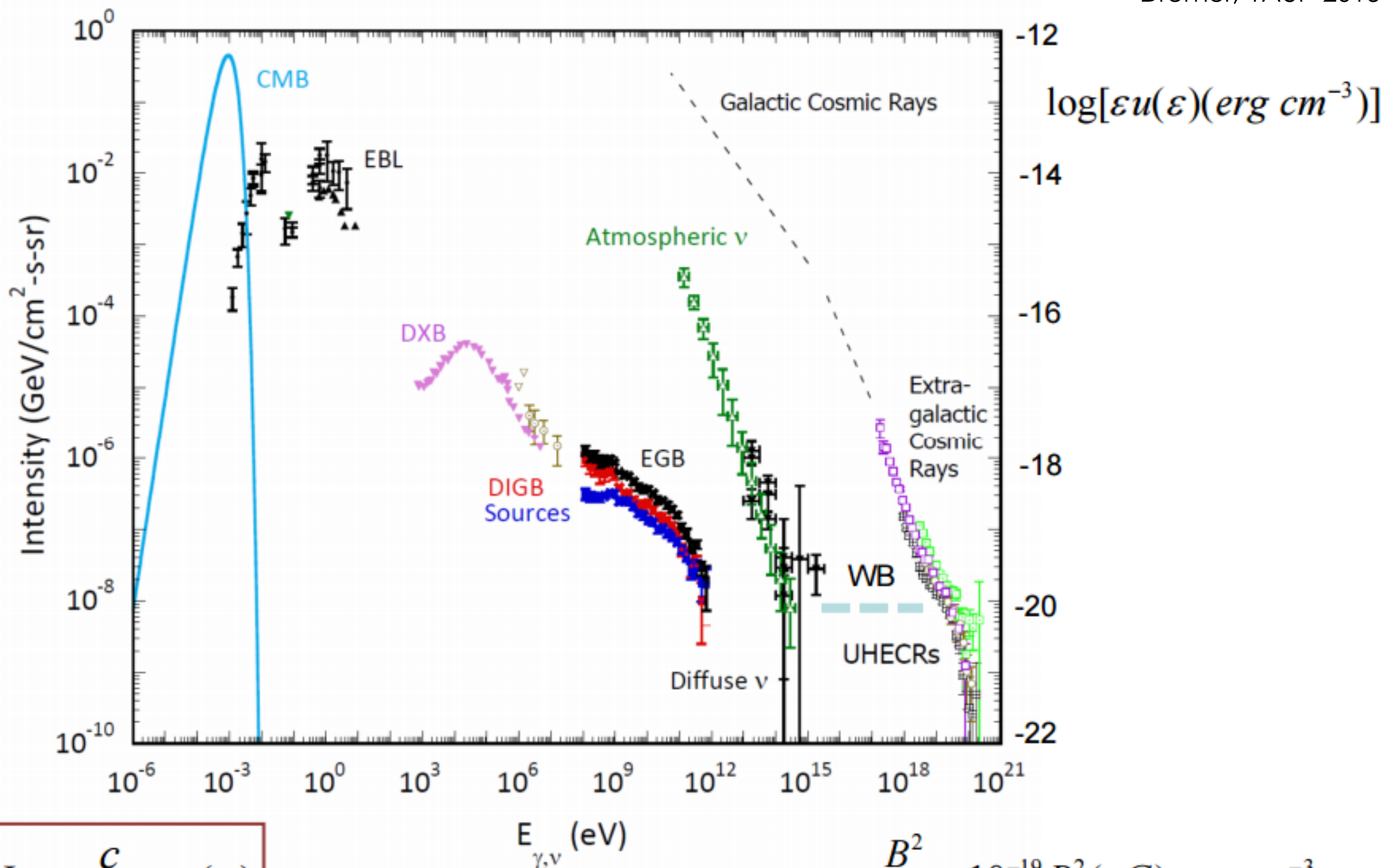
# Outline

- Multi-messenger astronomy
- Cosmic Rays
  - AMS
  - Auger
  - JEM-EUSO
- Neutrino telescopes
  - IceCube
  - ANTARES
  - Multi-messenger connections
  - KM3NeT (ARCA+ORCA)
- Summary

# Diffuse radiation intensities

Dremer, TAUP 2015




$$\varepsilon I_\varepsilon = \frac{c}{4\pi} \varepsilon u(\varepsilon)$$

$$u_B = \frac{B^2}{8\pi} \approx 10^{-19} B^2(nG)\ erg\ cm^{-3}$$

# Multi-messenger approach

- Neutrinos are expected to be produced in the interaction of high energy nucleons with matter or radiation:

Neutrino astronomy

$$N + X \rightarrow \pi^{\pm}(K^{\pm}\ldots) + Y \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu}) + Y$$

$$\downarrow$$

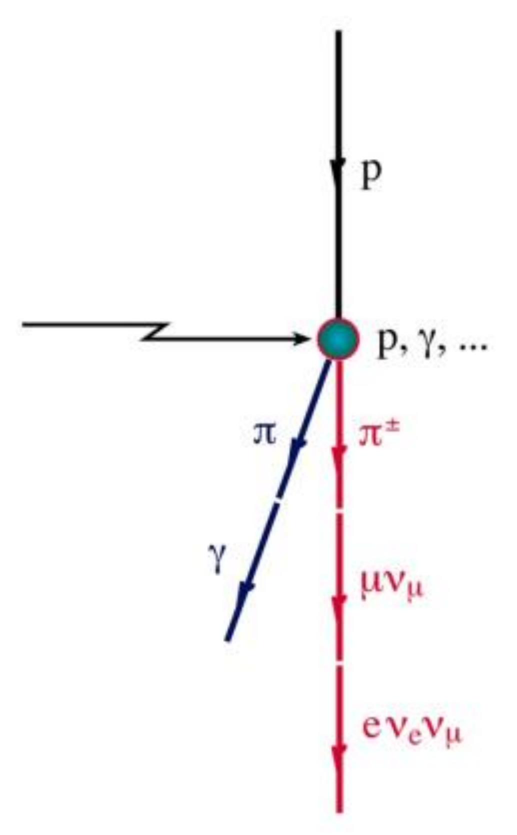
$$e^{\pm} + \bar{\nu}_e(\nu_e) + \bar{\nu}_{\mu}(\nu_{\mu})$$

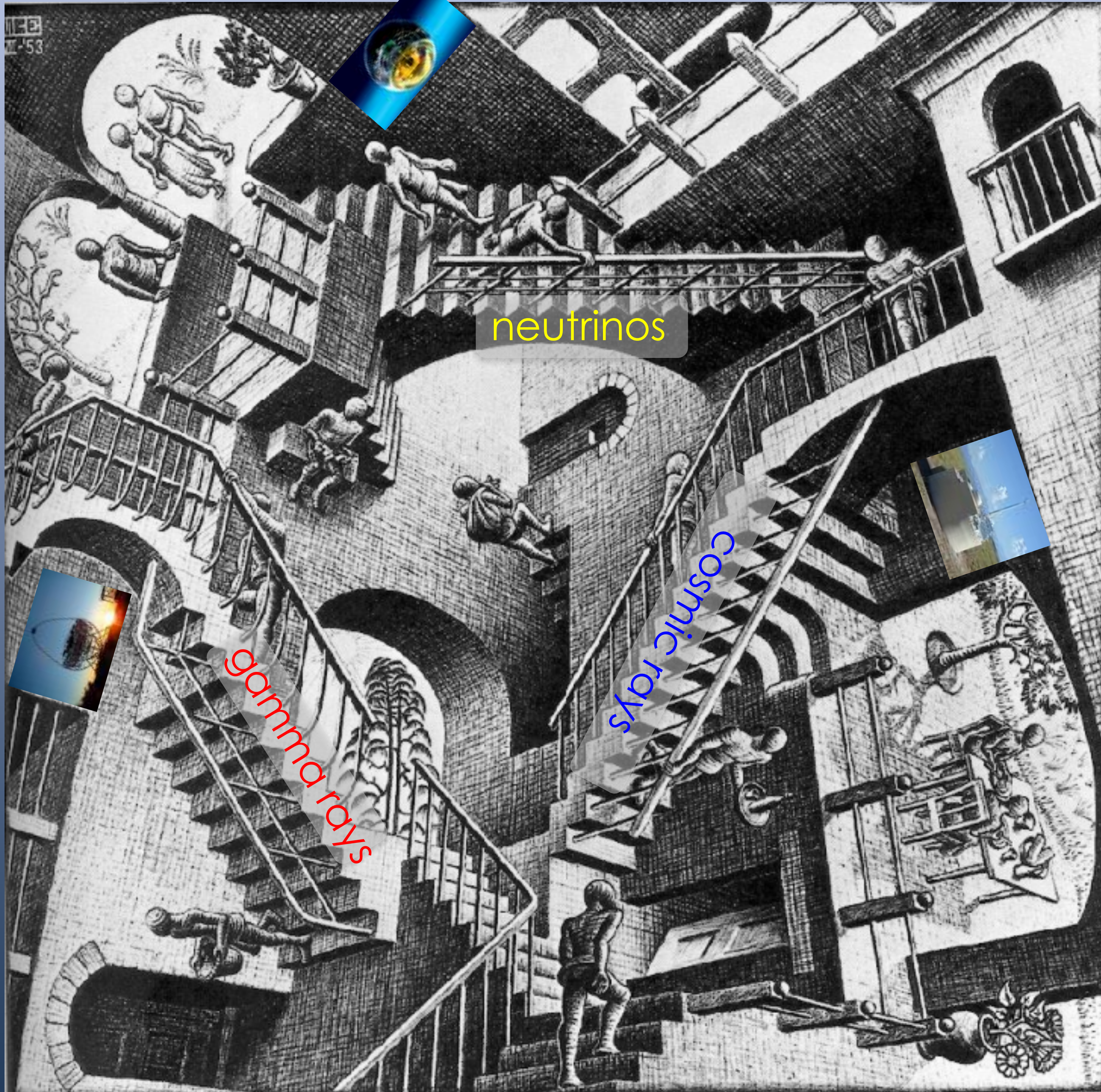
Cosmic rays

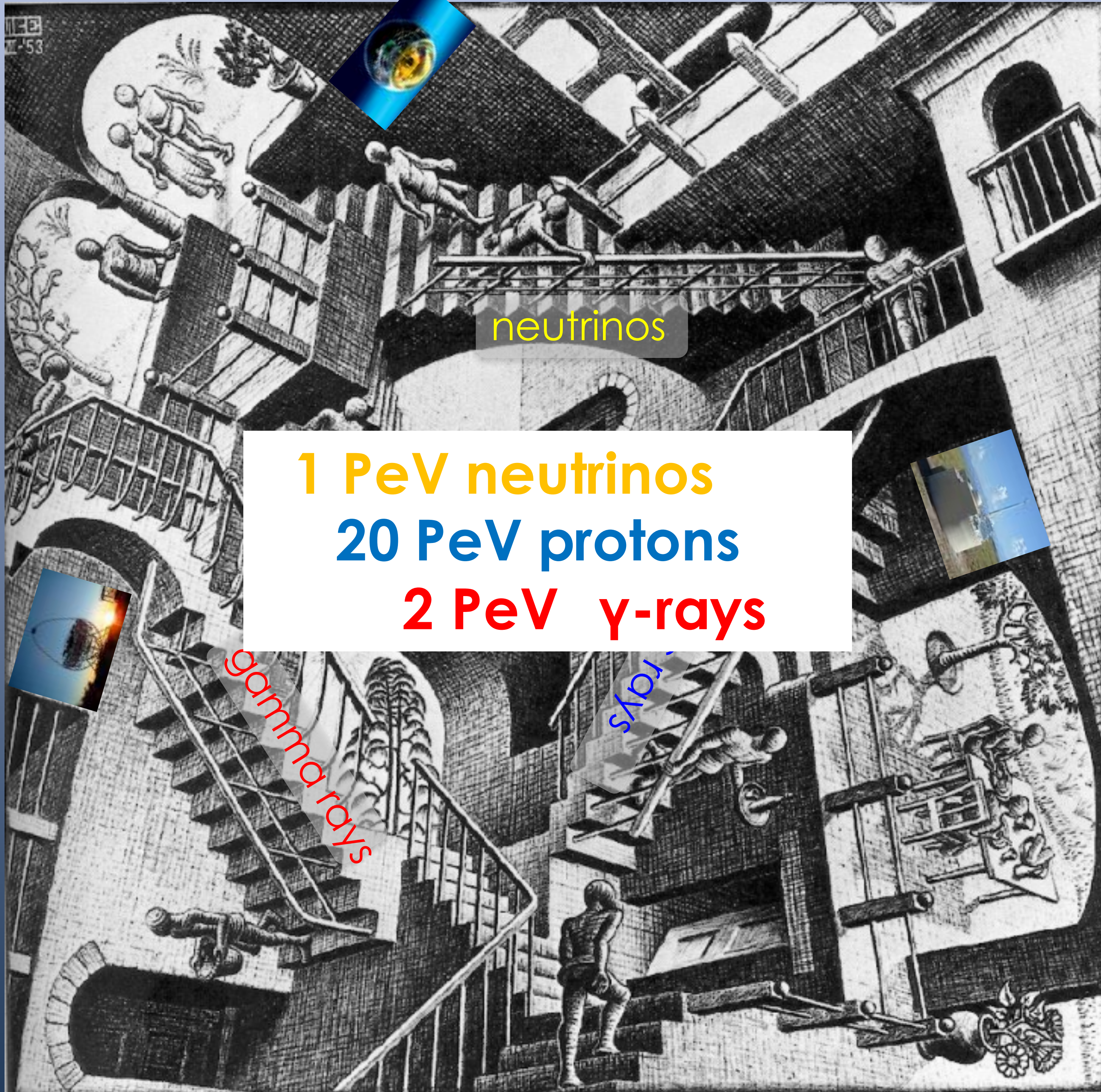
- Gamma rays are also produced in these processes, after the decay of the neutral pion

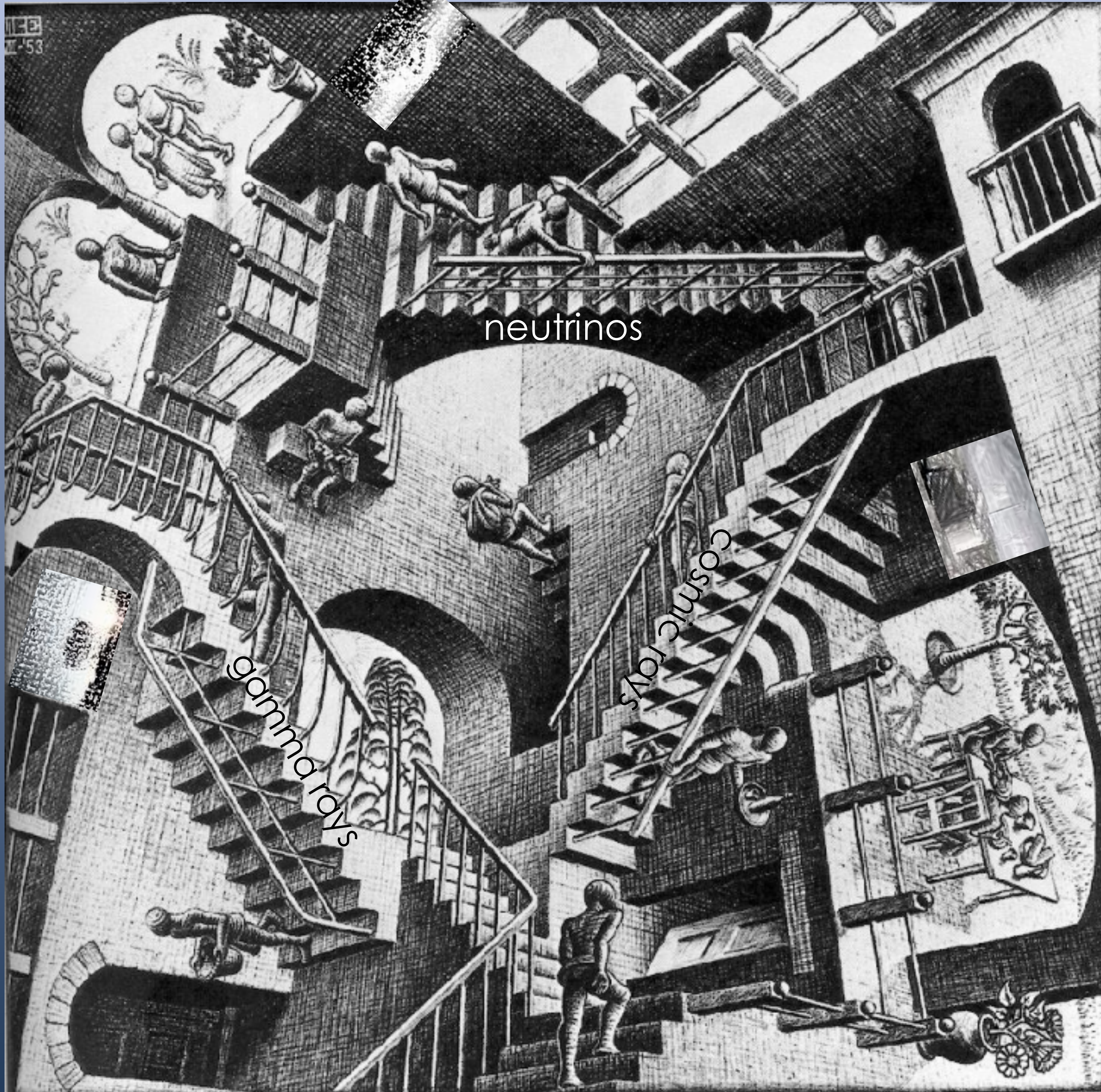
$$N + X \rightarrow \pi^{0} + Y \rightarrow \gamma\ \gamma + Y$$

Gamma ray astronomy




neutrinos
gamma rays
cosmic rays


neutrinos
1 PeV neutrinos
20 PeV protons
2 PeV γ-rays
gamma rays
rays

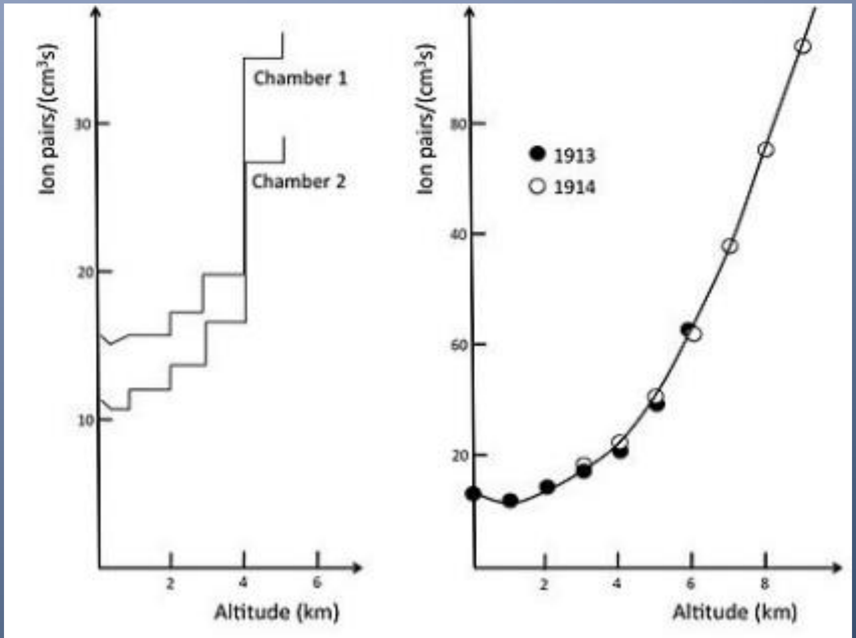

neutrinos
gamma rays
cosmic rays

# Cosmic Rays

# Cosmic origin of CRs

V. Hess' flight (1912)

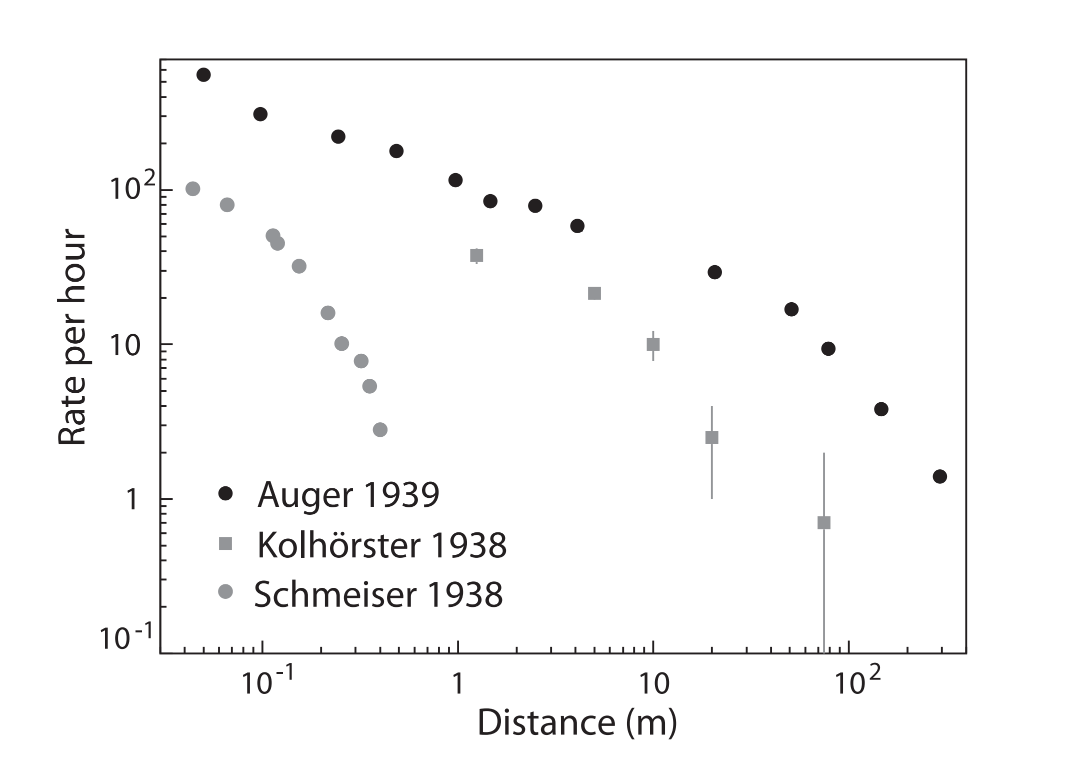
Hess 1912 Kolhorster 1913-14




- Balloon experiments by V. Hess and others showed that the flux of radiation measured at Earth increased with altitude, pointing to the "cosmic" origin of these radiation

# Extended Air Showers (EAS)

- Experiments by Rossi (1934), Schmeiser and Both (1938), Kolhörster (1938) and Auger (1939) proved the existence of simultaneous arrival of particles extending spread over extended areas




Estimated energy: $10^{15}$ eV

"One of the consequences of the extension of the energy spectrum of cosmic rays up to $10^{15}$ eV is that it is actually impossible to imaging a single process able to give a particle such an energy. It seems much more likely that the charged particles which constitute the primary cosmic radiation acquire their energy along electric fields of very great extension "

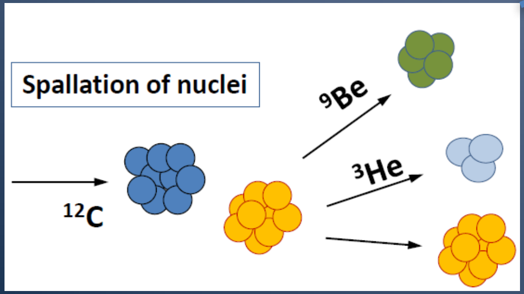
P. Auger, 1939

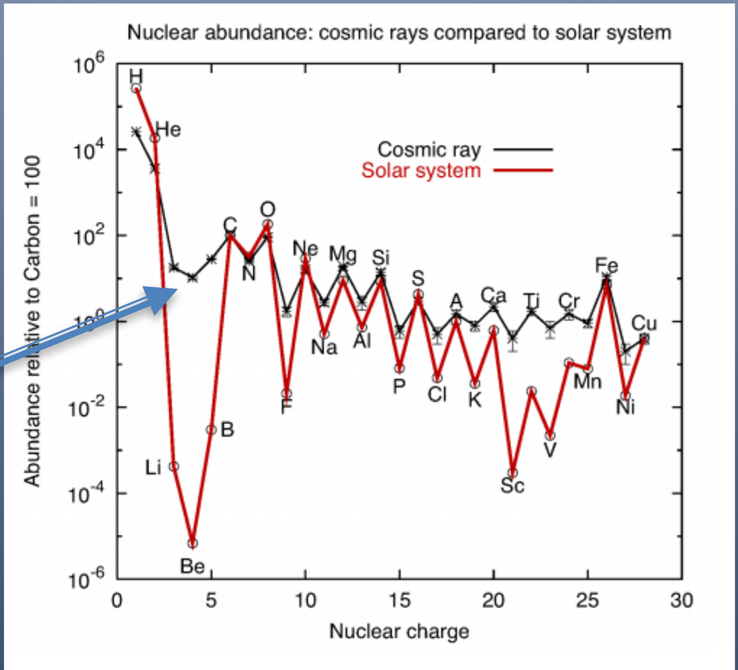
# Questions on CRs

- Origin
- Spatial distribution
- Mass composition
- Spectrum
- Propagation
- Evolution
- Hadronic interactions

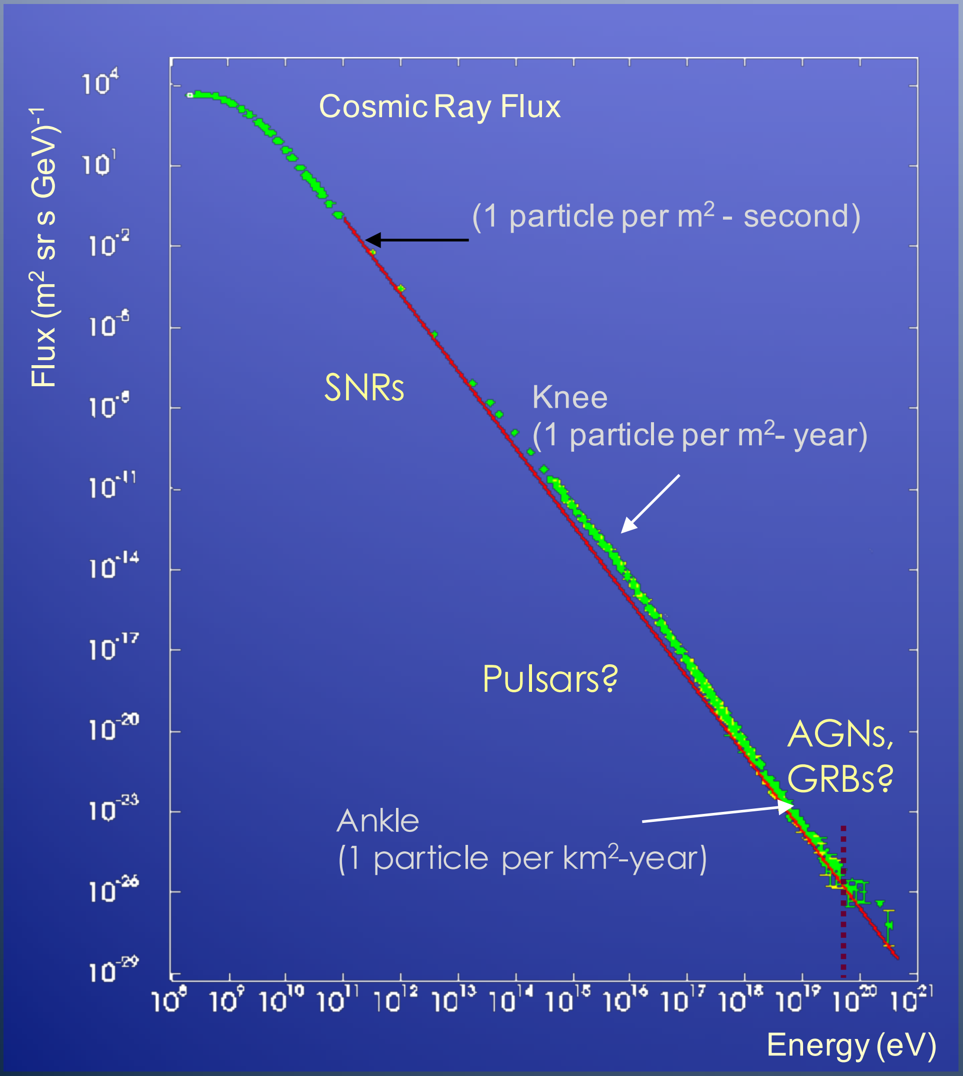
# CR composition

- The question of the CR composition depends very much of the energy. At low energies, similar in general to Solar System abundances (with differences due to spallation)



# CR spectrum




- Cosmic rays follow a power law:

$$\frac{dN}{dE} \propto E^{-\gamma} \begin{cases} \gamma = 2.7 \\ \gamma = 3.0 \\ \gamma = 2.7 \end{cases}$$

the knee

the ankle

- Beyond ~$5\times10^{19}$ eV, the flux should vanish due to the interaction of protons with the CMB (GZK limit).
- High energy neutrinos could give information about the origin of cosmic rays.

# Detection strategies

- Given the wide flux range in intensity and energy, different approaches are needed:
  - Low energy:
    - balloons
    - satellites
  - High energy:
    - ground Cherenkov tanks at ground
    - fluorescence Cherenkov telescopes

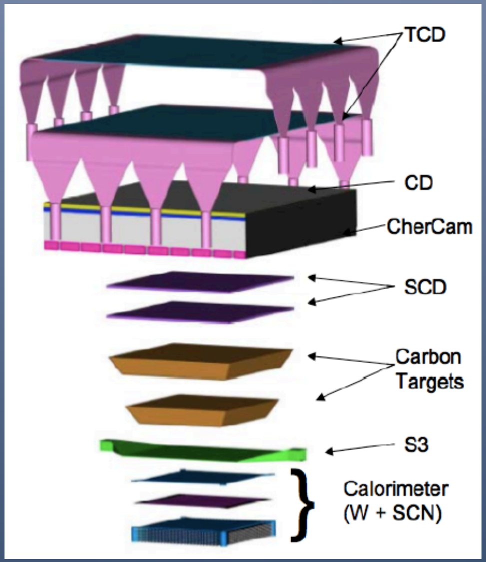
Higher energy →

→ Lower fluxes (bigger detector needed)

→ Wider events (less dense detector needed)

# Balloons

- Balloons are a cheap way for direct measurements of CRs
- Small detector area, suitable for low energy measurements
- Recent examples: CREAM, ATIC

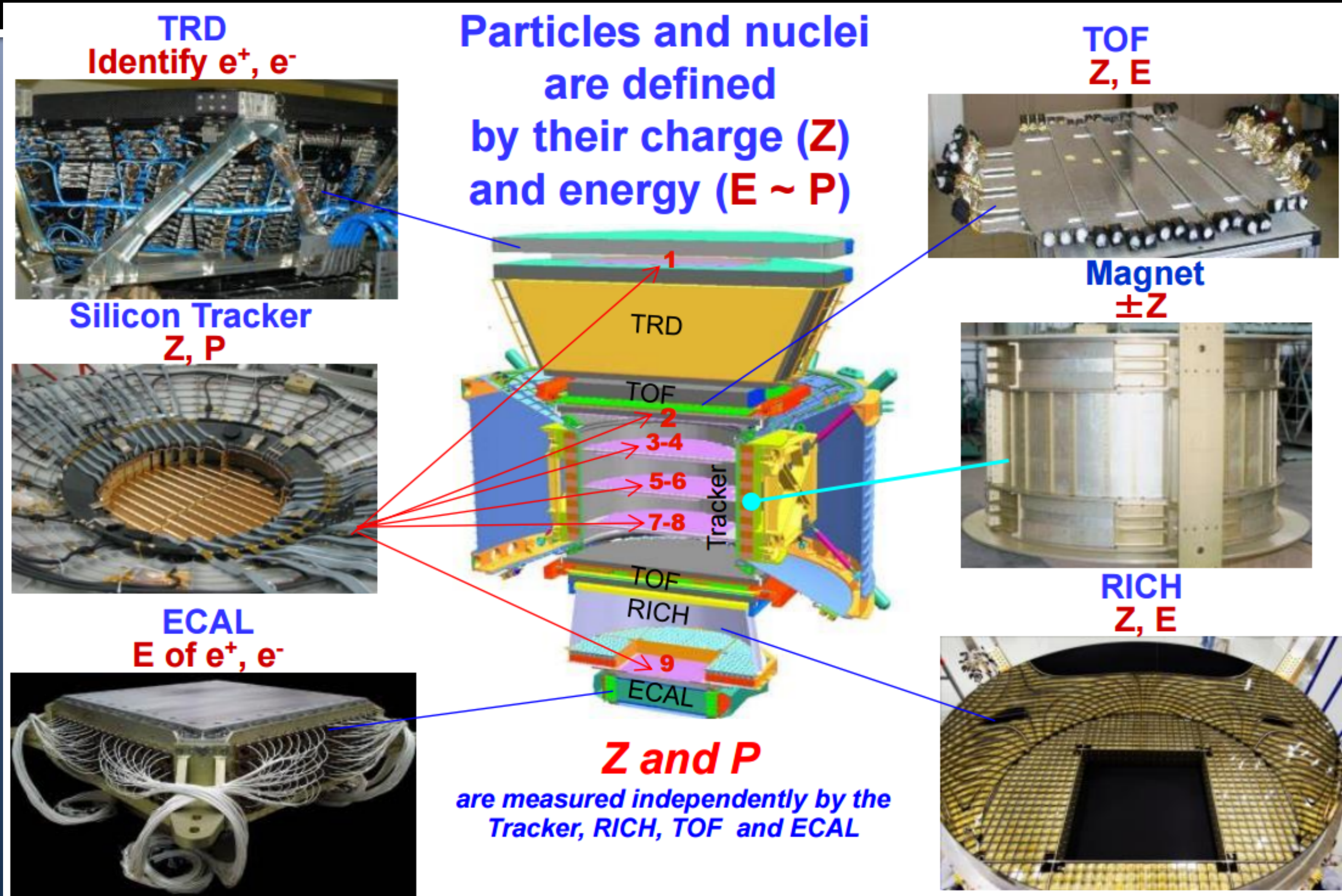



CREAM (Cosmic Ray Energetics and Mass)

- TDCs and scintillators:
  - charge
  - velocity
- Ionization calorimeters:
  - energy

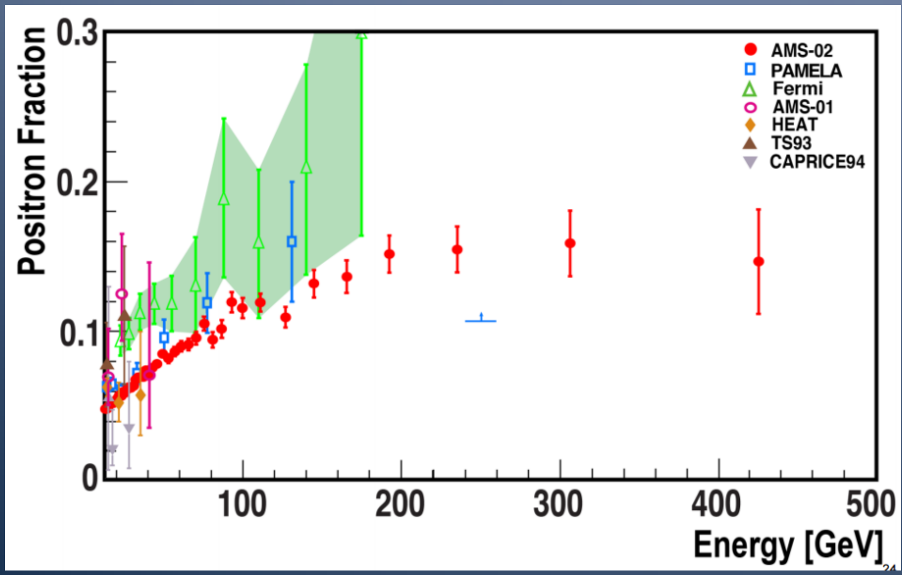
# AMS

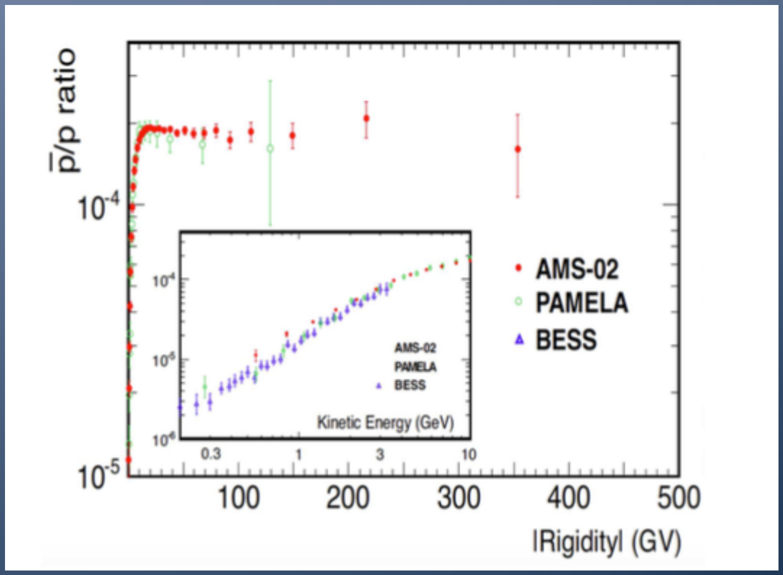
Ting, CERN Days, 2015



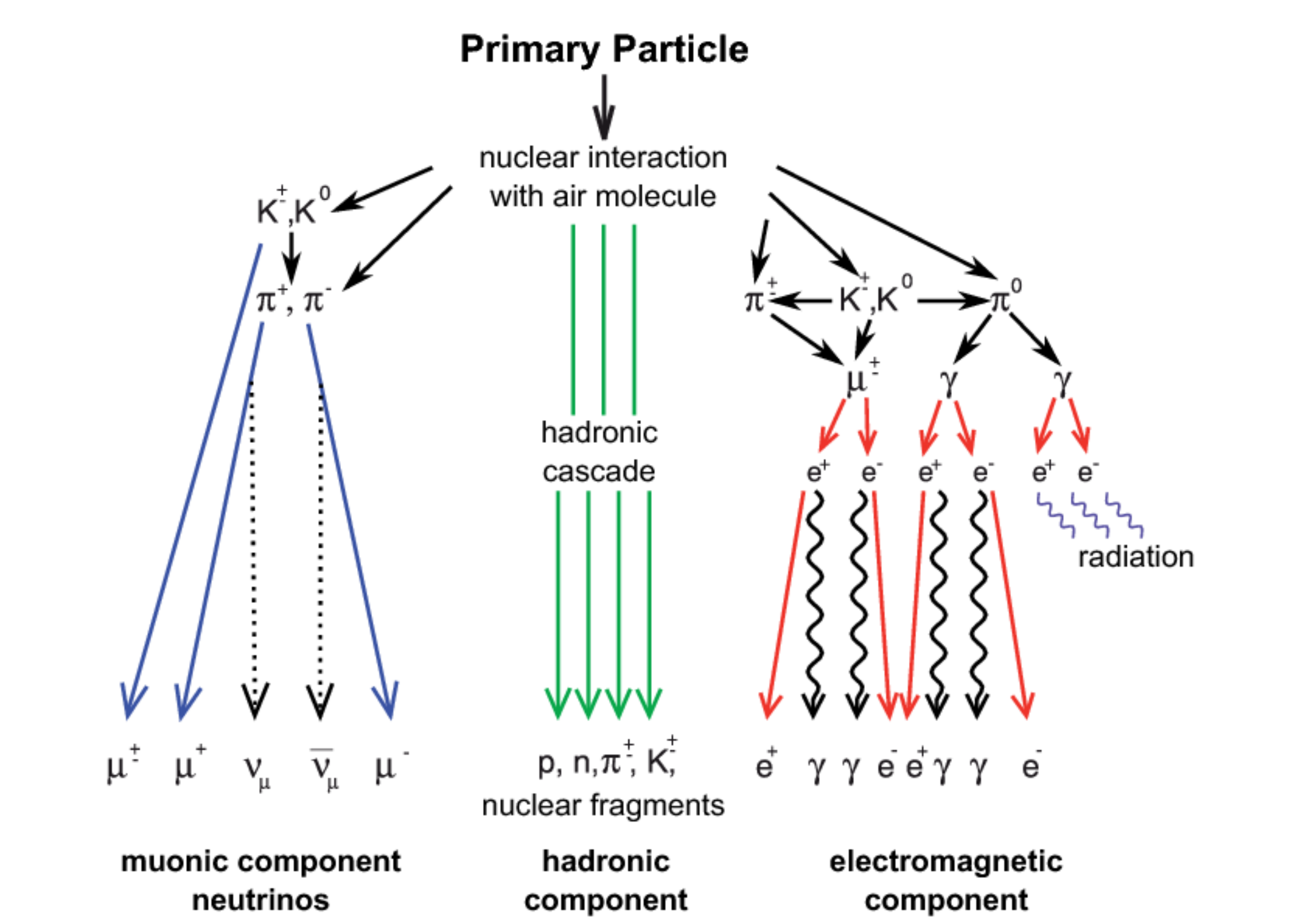
# AMS results

- AMS-02 has confirmed the excess of positrons detected by PAMELA
- Astrophysical explanation (pulsars?) most likely
- Dark matter could be be an explanation, but leptophilic models have to be invoked. Limits from gamma ray detectors neutrino telescopes disagree with this interpretation
- Antiproton/proton ratio compatible with recent secondary production models (but large uncertainties, DM not ruled out)



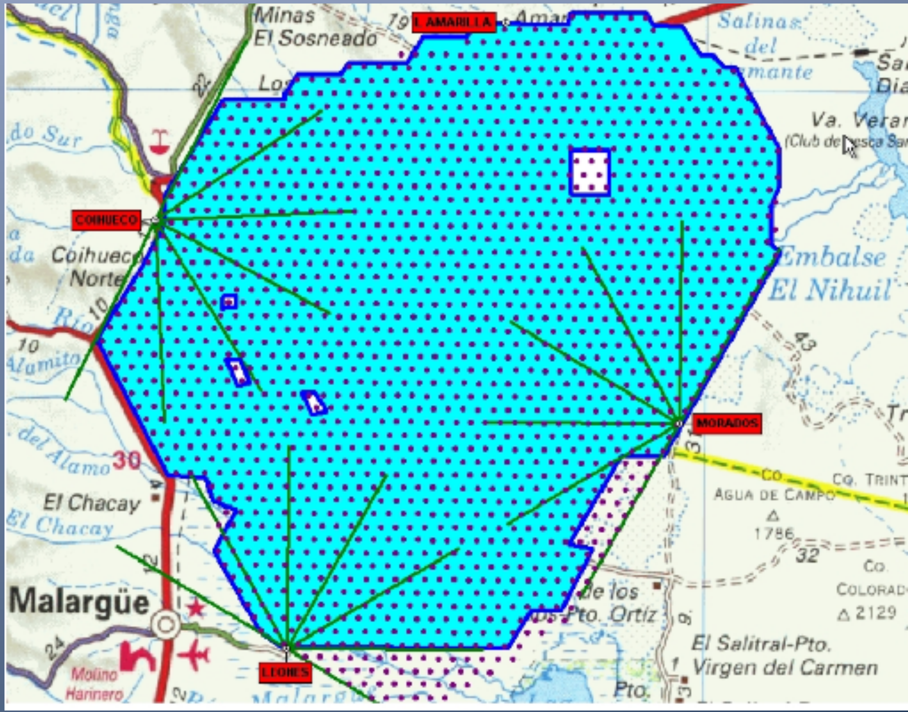



# Detection of EAS



# Auger

- Pierre Auger Observatory (PAO) is located in Malargüe (Argentina)
- Hybrid detection
  - Fluorescence Detectors
  - Surface Detectors
- Detection area: 3,000 km$^2$
- 50,000 km$^2$ sr yr of exposure



# Two types of detectors

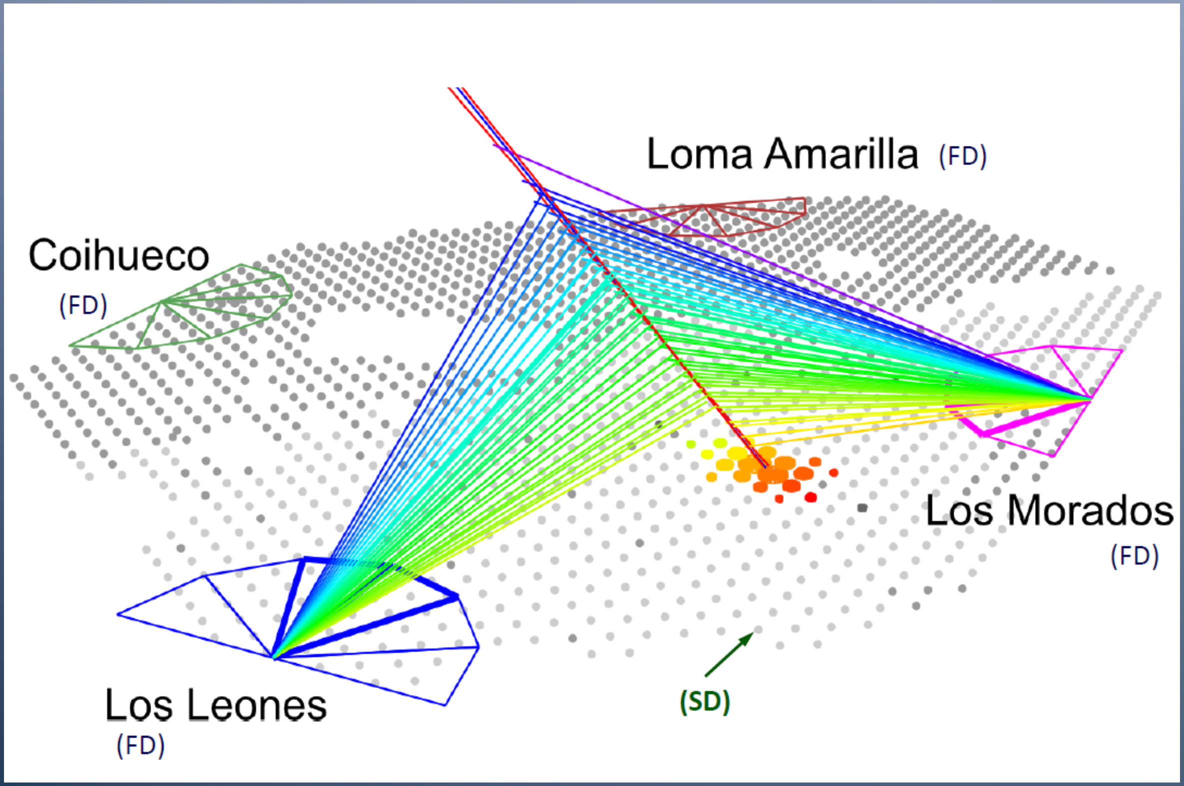
Surface detectors (SDs)

- 1660 Cherenkov tanks
- Hexagonal grid (1.5 km spacing)
- Low energy extension: Infill (61 stations with 0.75 km separation )

Fluorescence detectors (FDs)

- 24 fluorescence telescopes in 4 buildings looking towards SDs
- Low energy extension: HEAT (three additional telescopes looking at Infill, with two operation modes, horizontal and tilted 29° for measuring $X_{max}$ of $10^{17}$eV events)

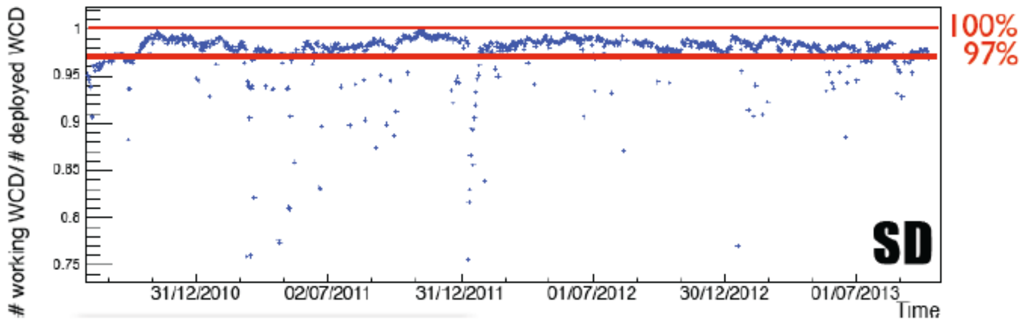
# Hybrid detection

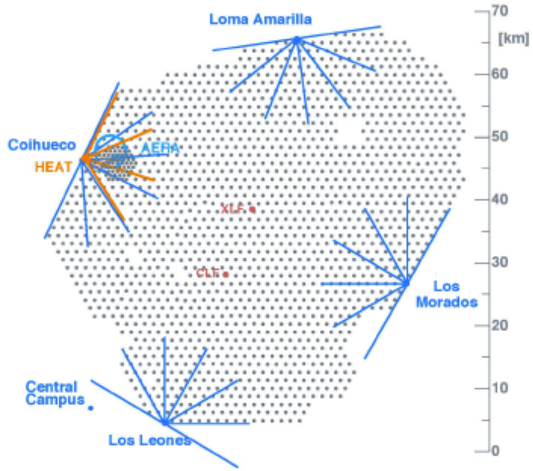



Lateral profile measured with SD
Longitudinal profile measured with FD (10%)

# Auger upgrade: PRIME

Fraction of Cherenkov tanks in operation



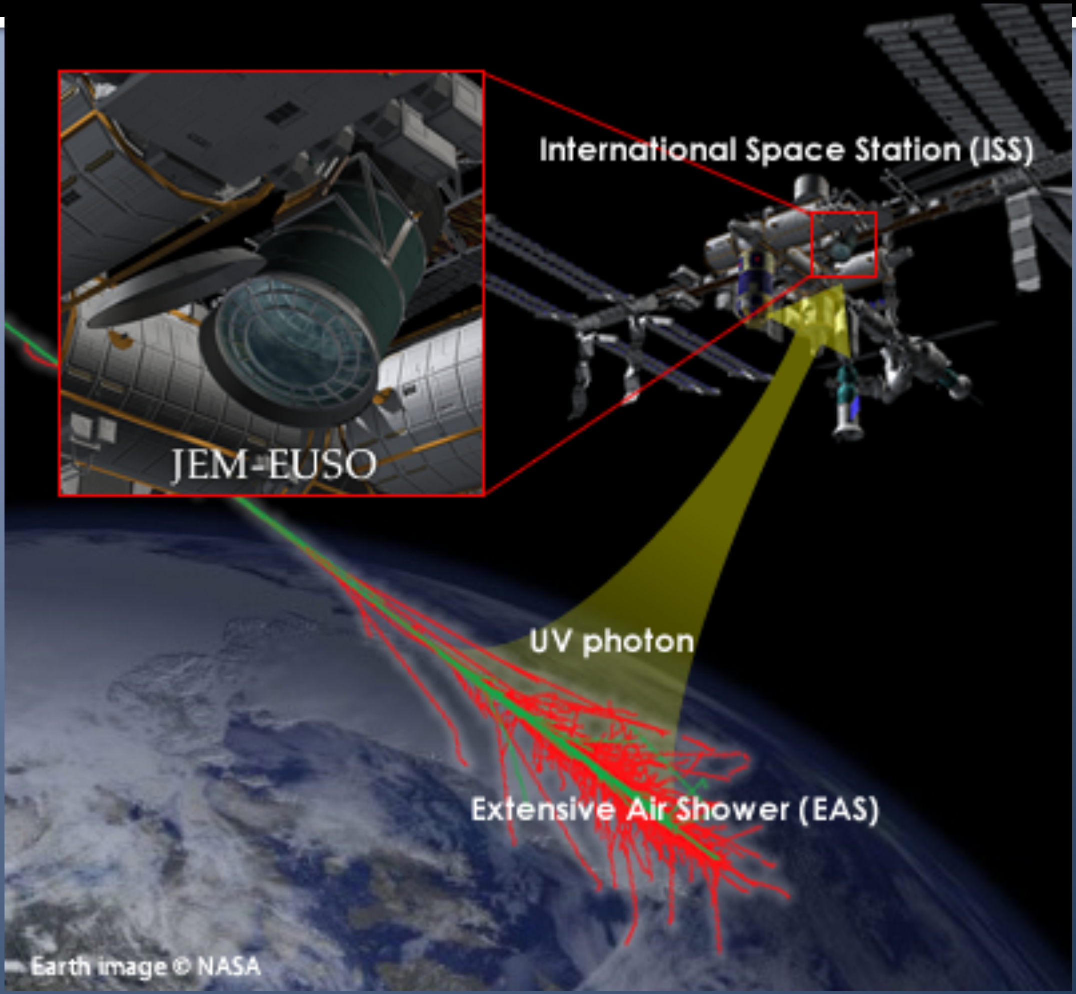




- Auger PRIME – "Primary cosmic Ray Identification through Muons and Electrons"
  - Scintillator on top of the tank to measure directly e.m. shower component
  - WCD measures e.m. + muons
  - Upgrade to:
    - Enhance primary identification
    - Improve shower description
    - Reduce systematic uncertainties

Conceiçao, HEP 2015

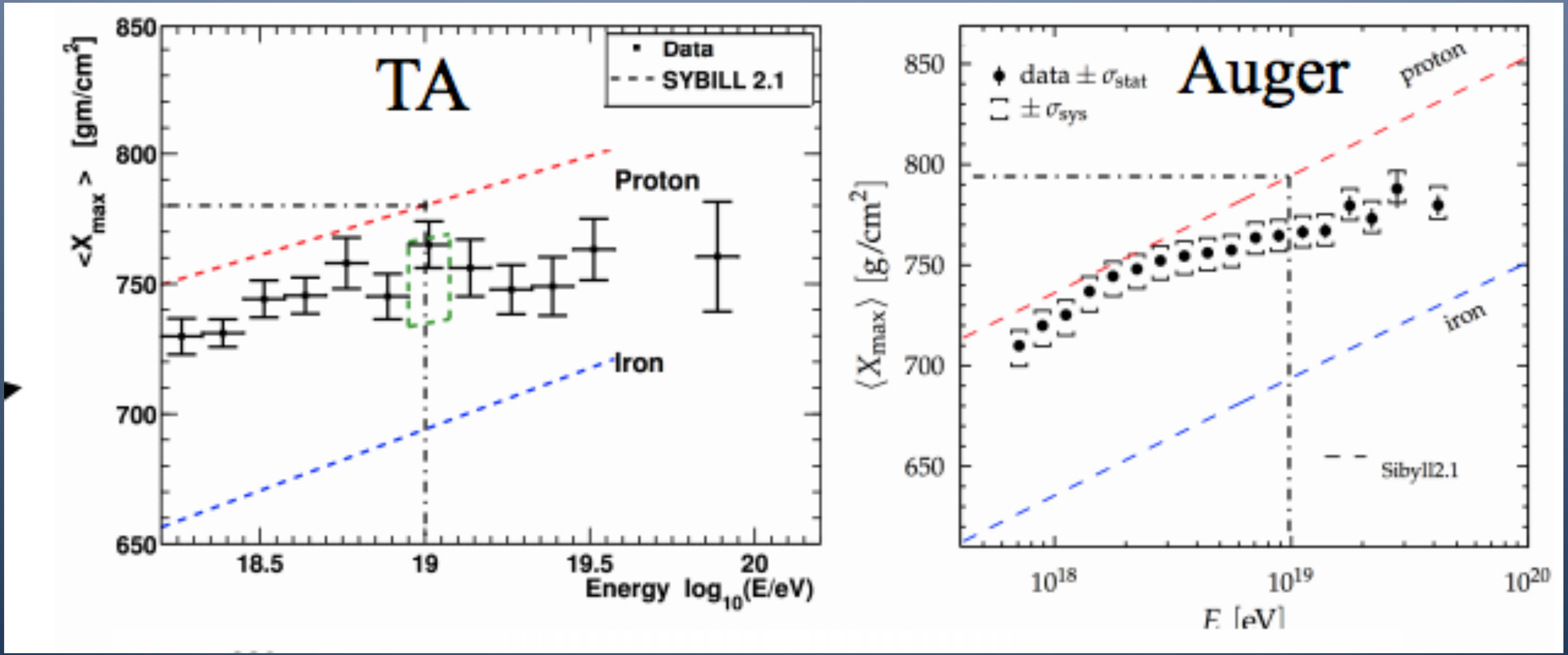
# JEM-EUSO

- In order to detect EHE cosmic rays ($10^{20}$ eV), larger detection volumes are needed

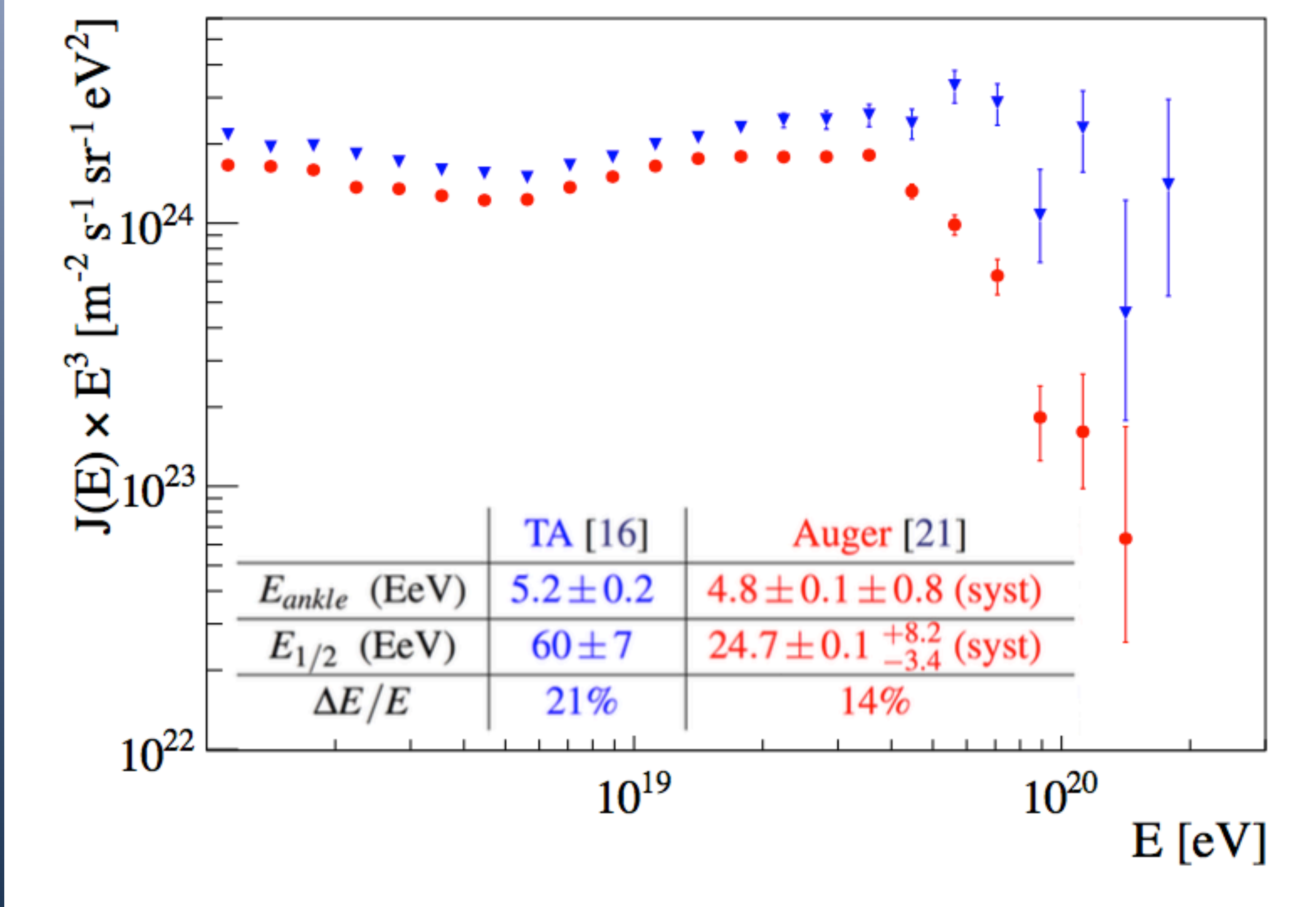


# CR composition at UHE

- Most recent results tend to reconcile TA and Auger results on composition
- Change to heavier composition at UHE



# Spectrum at UHE

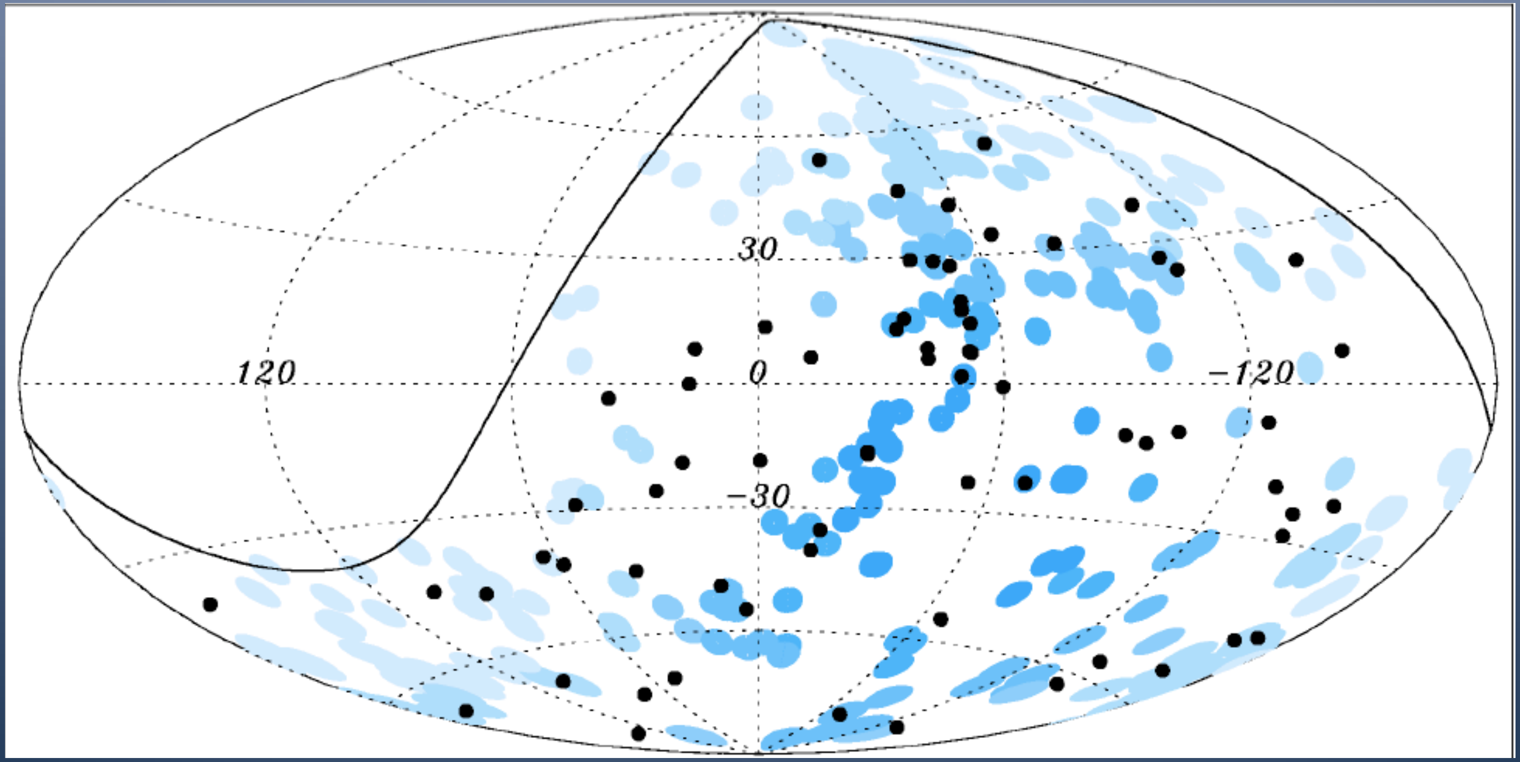


# UHECR Spatial Distribution: Auger

- Correlation with AGN catalogue found… but decreasing with new statistics… (and HiRes favours isotropic distribution)

black: AGN positions

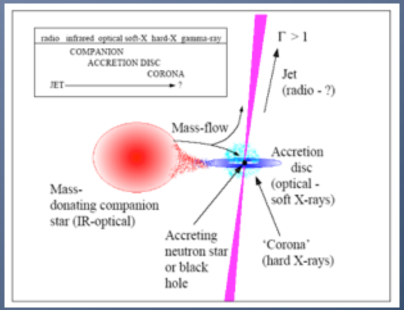
blue UHE events (weighted by visibility)

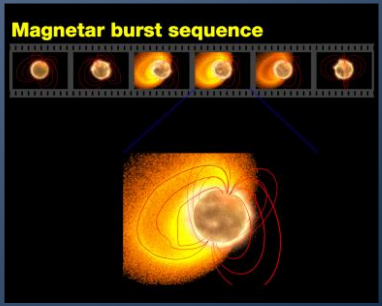


# Sources

# Galactic Sources

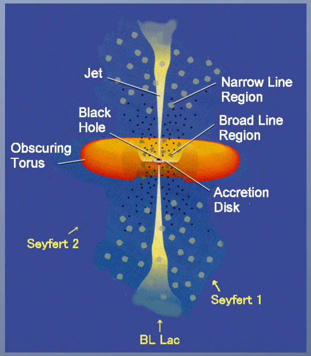
- Supernova remnants
  - Different scenarios: plerions (center filled SNRs), shell-type SNRs, SNRs with energetic pulsars…
- Micro-quasars
  - A compact object (BH or NS) accreting matter from a companion star. Neutrino beams could be produced in the MQ jets
- Magnetars
  - Isolated neutron stars with surface dipole magnetic fields ~$10^{15}$ G, much larger than ordinary pulsars
  - Seismic activity in the surface could induce particle acceleration in the magnetosphere



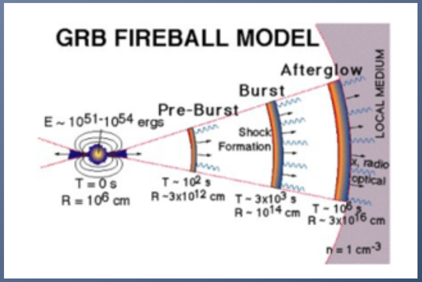



# Extragalactic Sources

- Active galactic nuclei
  - It includes Seyferts, quasars, radio galaxies and blazars
  - Standard model: a super-massive ($10^6$-$10^8$ Mo) black hole towards which large amounts of matter are accreted
  - Time-variable emission would enhance chances of detection



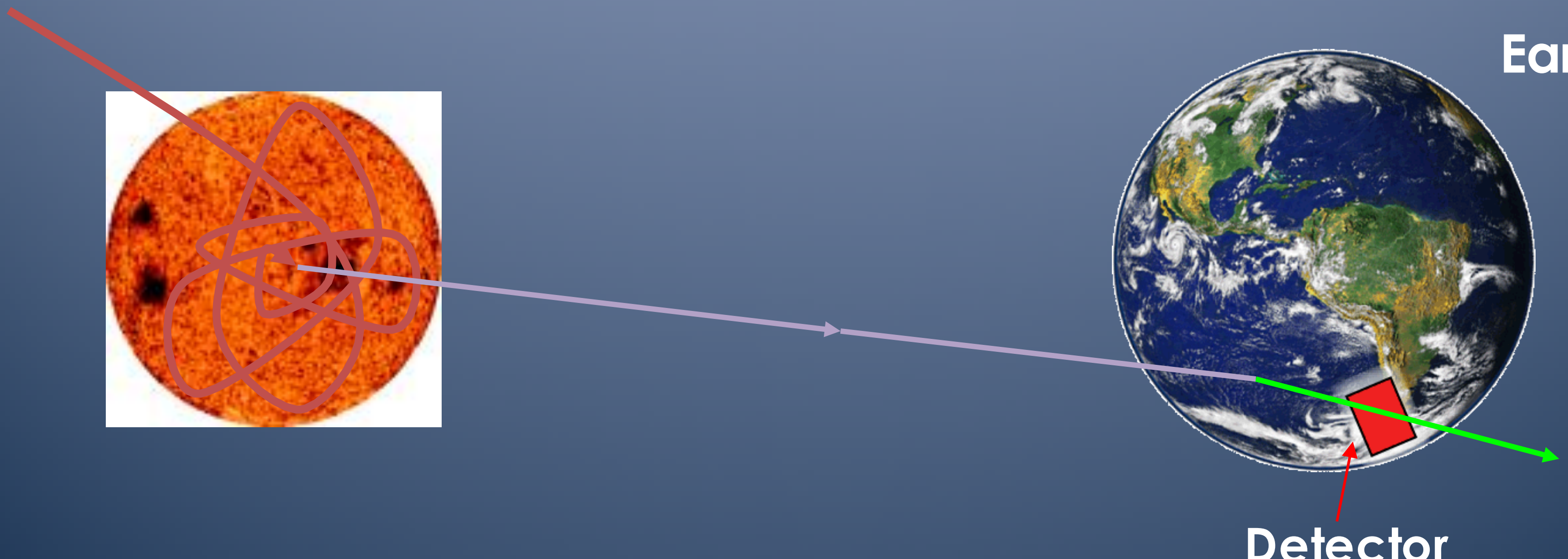

- Gamma-ray bursters
  - GRBs are brief explosions of  rays (often + X-ray, optical and radio) In the fireball model, matter moving at relativistic velocities collides with the surrounding material. The progenitor could be a collapsing super-massive star or NS merging
  - Neutrinos could be produced in several stages: precursor (TeV), main-burst (100 TeV-10 PeV), after-glow (EeV). The time information makes detection almost background free




- Starburst galaxies
  - Starburst galaxies are characterized by the existence of regions with a very high star formation rate
  - A galactic scale wind blows out large amounts of mass into the intergalactic medium driven by the collective effect of supernova explosions and massive star winds

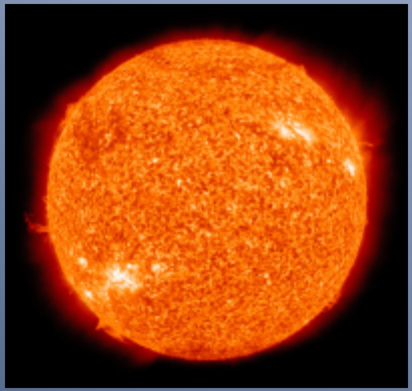
# Dark matter

- WIMPs (neutralinos, KK particles) are among the most popular explanations for dark matter
- They would accumulate in massive objects like the Sun, the Earth or the Galactic Center
- The products of such annhiliations would yield “high energy” neutrinos, which can be detected by neutrino telescopes



# Sources for DM searches

Sun



Galactic Centre

Dwarf galaxies

Earth

Galactic Halo

Galaxy clusters

# Ultra-high energy neutrinos

- Protons interact with cosmic microwave background, which limits its range at high energies (GZK cut-off): p $\gamma_{CMB}$ → $\Delta^+$ → n $\pi^+$ (or p $\pi^0$)

$$\lambda_{\gamma p} = \frac{1}{n_{CMB} \cdot \sigma_{p\gamma_{CMB}}} \cong 10 \text{ Mpc} \ \ @ \ \mathrm{E_p} = 5 \times 10^{19} \text{ eV}$$

- The GZK cut-off also leads to a measurable to neutrinos

$$\pi \to \mu + \nu_\mu \to e + \nu_\mu + \nu_e + \nu_\mu$$

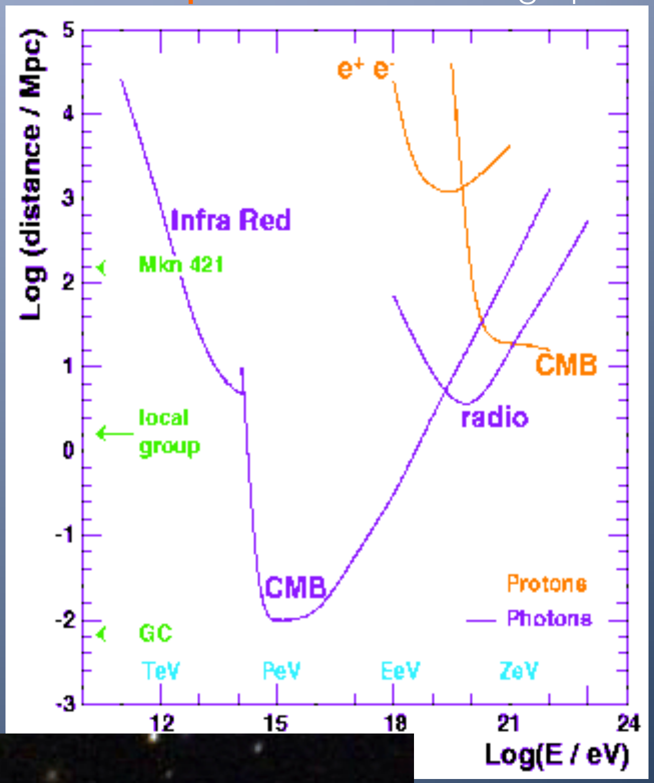
~1 neutrino (E > 2x10$^{18}$ eV) per km$^3$ year

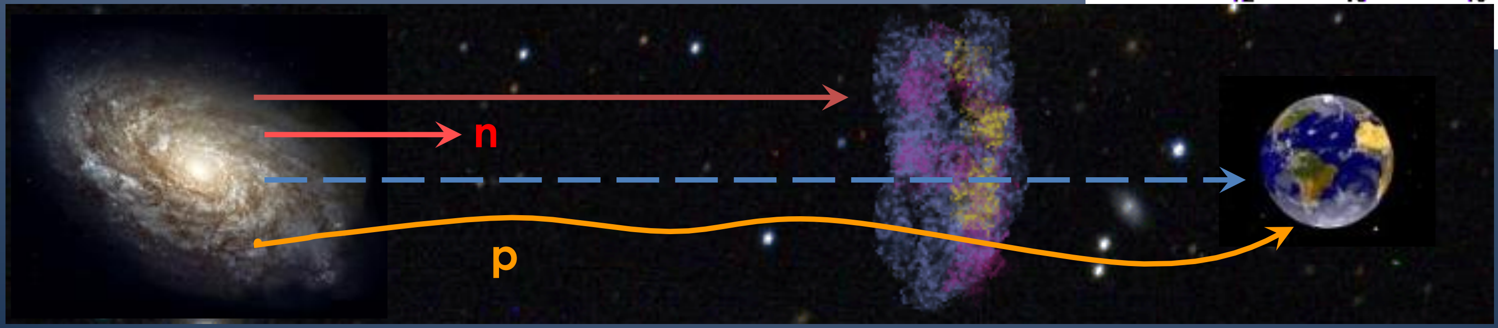
# Neutrino telescopes

# Neutrino Astronomy

- Advantages:
  - Photons: interact with CMB and matter
  - Protons: interact with CMB and are deflected by magnetic fields
- Drawback: large detectors (~GTon) are neded

Photon and proton mean free range path



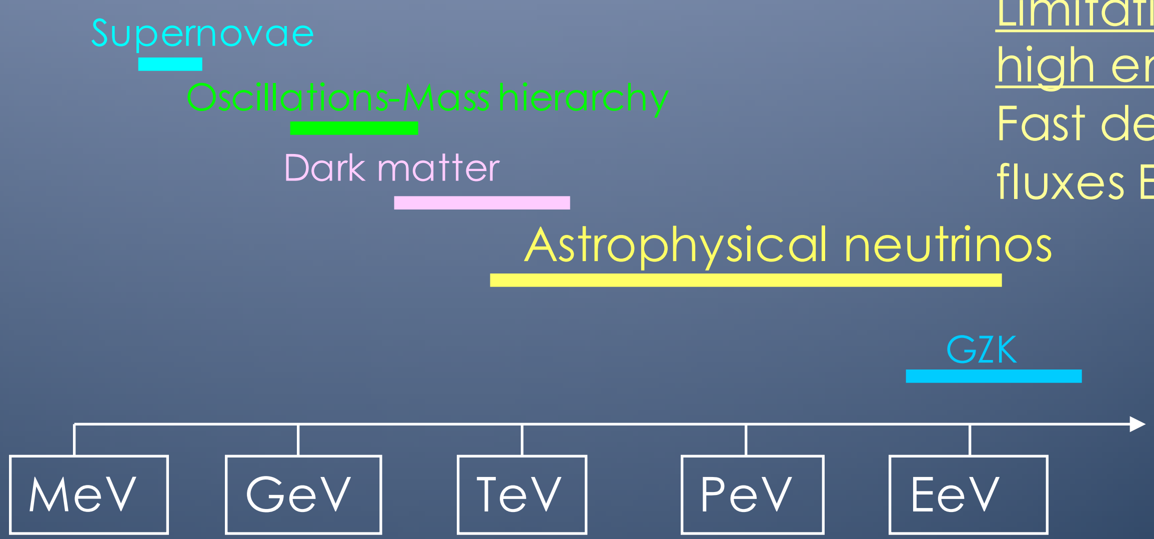
# Scientific Scope

- Origin of cosmic rays
- Hadronic vs. leptonic signatures
- Neutrino mass hierarchy
- Dark matter

Detector size

<u>Limitation at low energies:</u>
-Short muon range
-Low light yield
-$^{40}$K (in water)

Detector density




<u>Limitation at high energies:</u>
Fast decreasing fluxes $E^{-2}$, $E^{-3}$

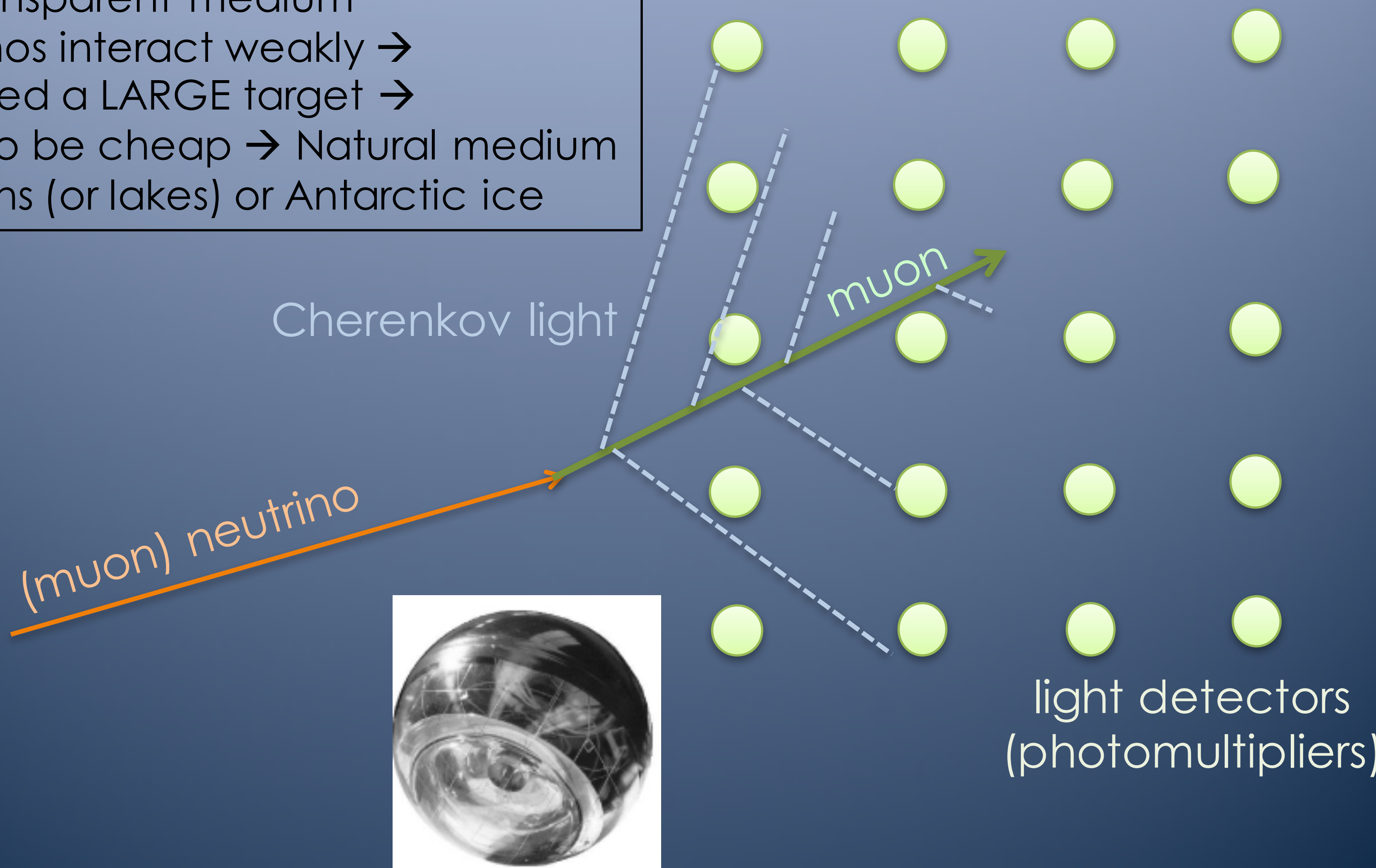
Other physics: monopoles, nuclearites, Lorentz invariance, etc...

# Neutrino detection techniques

- Optical Cherenkov:
  - In Ice: AMANDA, IceCube
  - In water: Baikal, ANTARES, KM3NeT
- Atmospheric showers:
  - On earth: Auger
  - In space: JEM-EUSO
- Radio:
  - On earth: RICE, ARIANNA, LOFAR
  - Balloon: ANITA
- Acoustic:
  - AMADEUS, SPATS

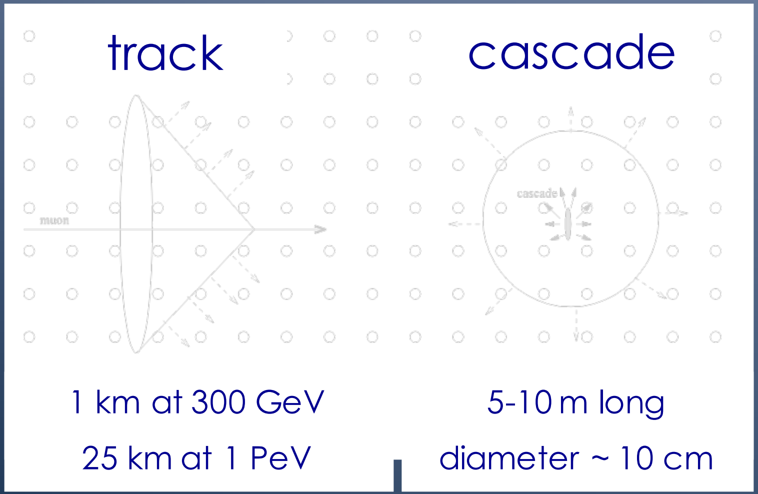
# Detection Principle

Where to put the detector?
1) In a transparent medium
2) Neutrinos interact weakly →
→ We need a LARGE target →
→ It has to be cheap → Natural medium
→ Oceans (or lakes) or Antarctic ice

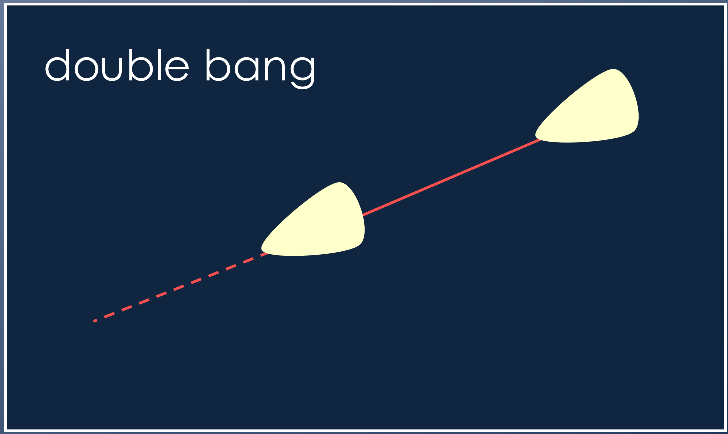


# Other signatures

- Cascades are an important alternative signature: detection of electron and tau neutrinos.
- Also neutral interaction contribute (only hadronic cascade)

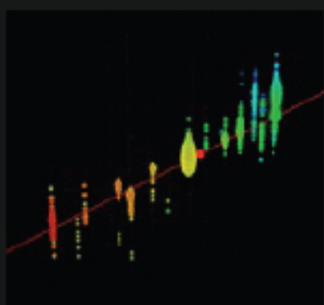



- Clear signature of oscillations.
- ANTARES is too small to detect double bang signature (they are too rare)
- However, cubic-kilometer telescopes could detect them
- Maximum sensitivity at 1-10 PeV



# Channels

## CC Muon Neutrino



$$\nu_\mu + N \rightarrow \mu + X$$

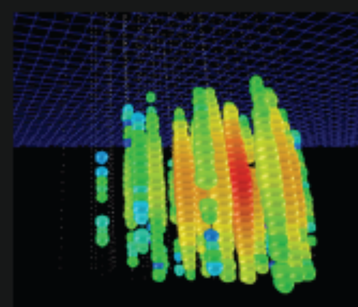
track (data)

factor of $\approx 2$ energy resolution

~~$< 1°$ angular resolution~~

in water: 0.1-0.3 degrees

## Neutral Current / Electron Neutrino



$$\nu_e + N \rightarrow e + X$$

$$\nu_x + N \rightarrow \nu_x + X$$

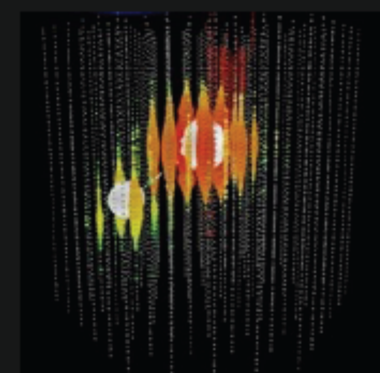
cascade (data)

$\approx \pm 15\%$ deposited energy resolution

~~$\approx 10°$ angular resolution~~

in water: 1-3 degrees!

## CC Tau Neutrino

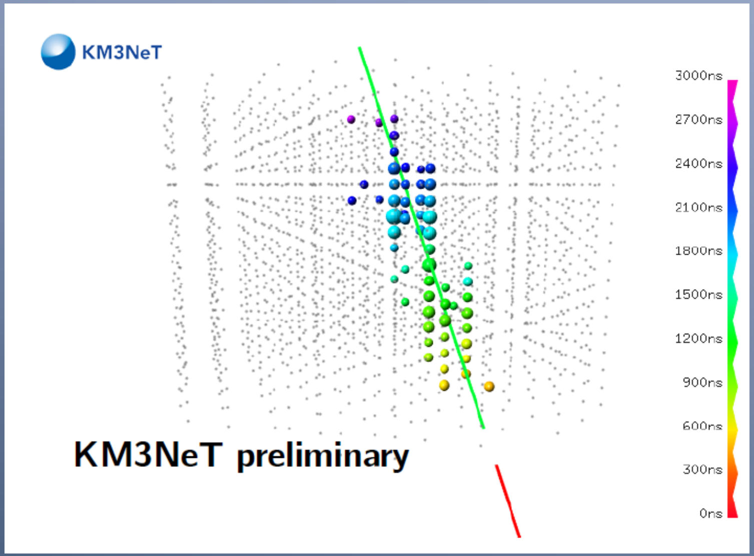



$$\nu_\tau + N \rightarrow \tau + X$$

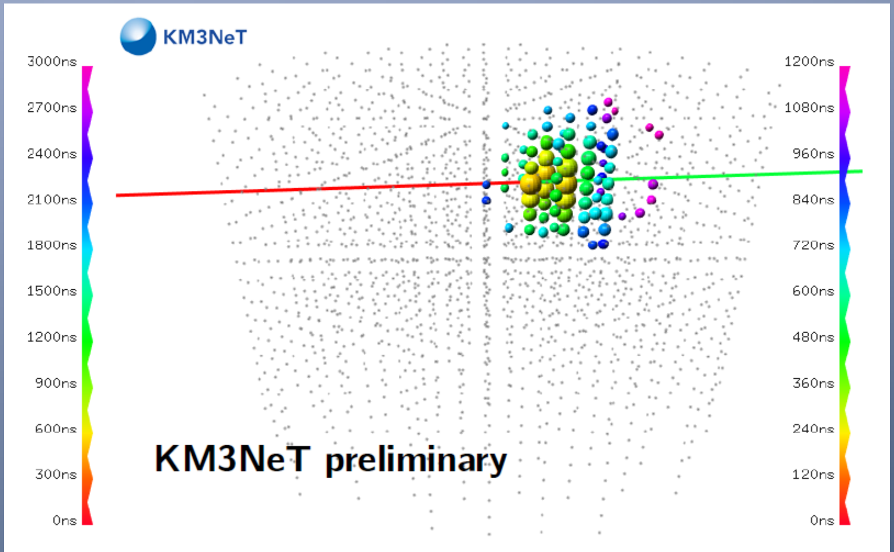
"double-bang" and other signatures (simulation)

(not observed yet)

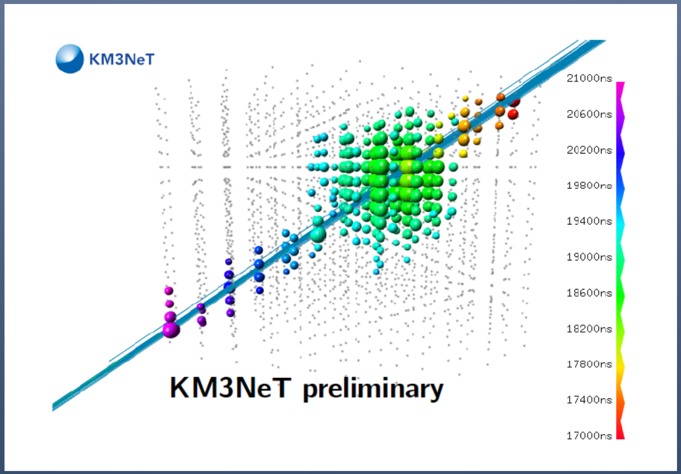
# Channels




track




cascade

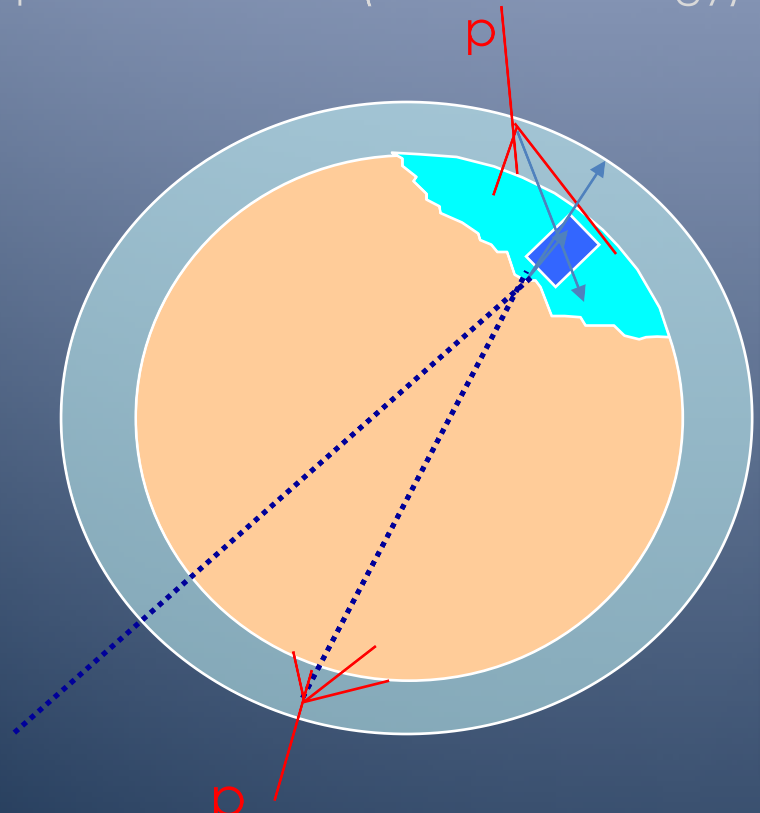


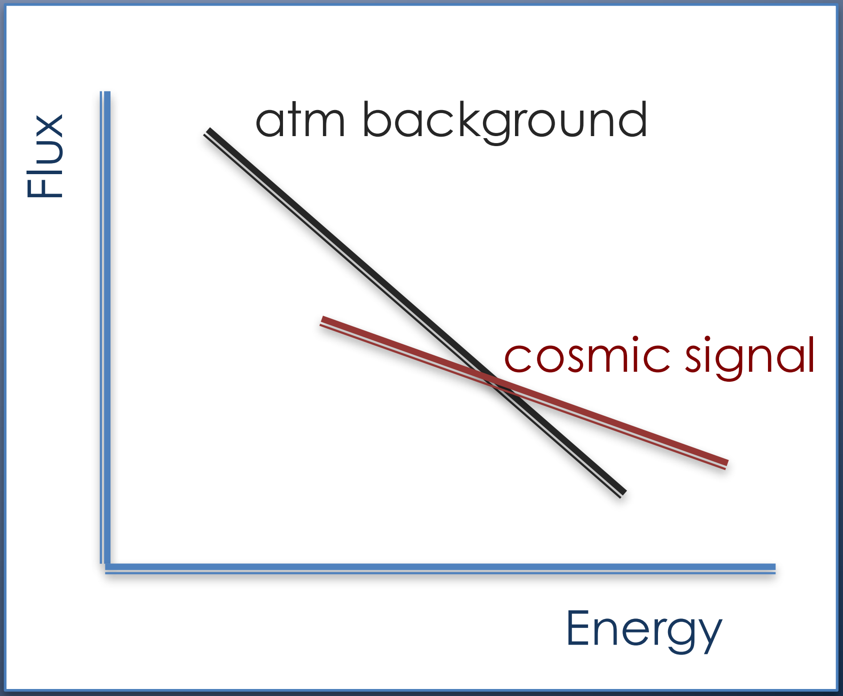

1 PeV atm. nu
+ muon bundle

# Physical Background

- There are two kinds of background:
  - Muons produced by cosmic rays in the atmosphere (→ detector deep in the sea and selection of up-going events)
  - Atmospheric neutrinos (cut in the energy)

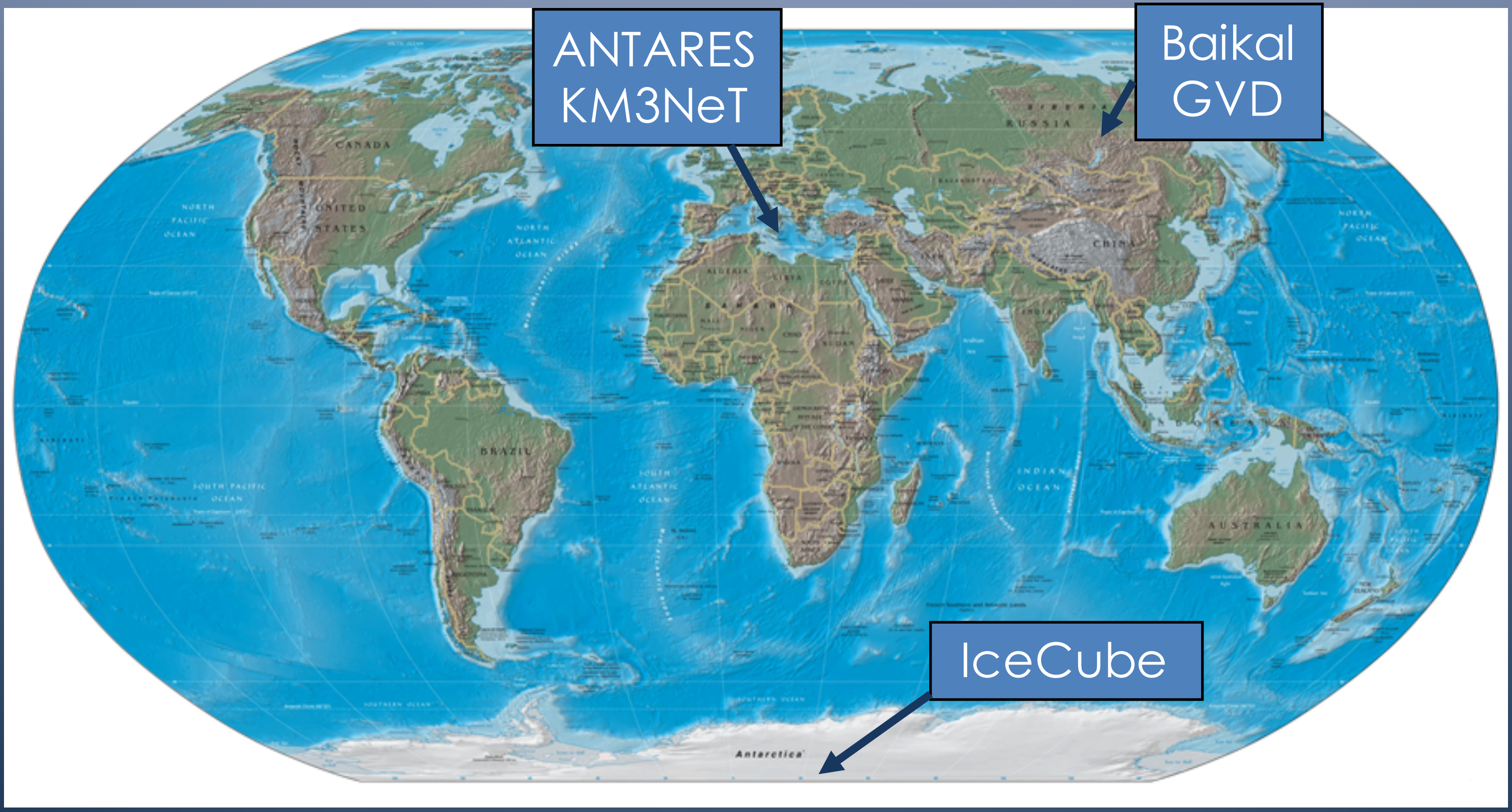
$$p \to \pi^{+}(+K^{+}...) \to \mu^{+} + \nu_{\mu}$$
$$\mapsto e^{+} + \bar{\nu}_{\mu} + \nu_{e}$$



# NTs in the world

- Several projects are working/planned, both in ice and ocean and lakes.

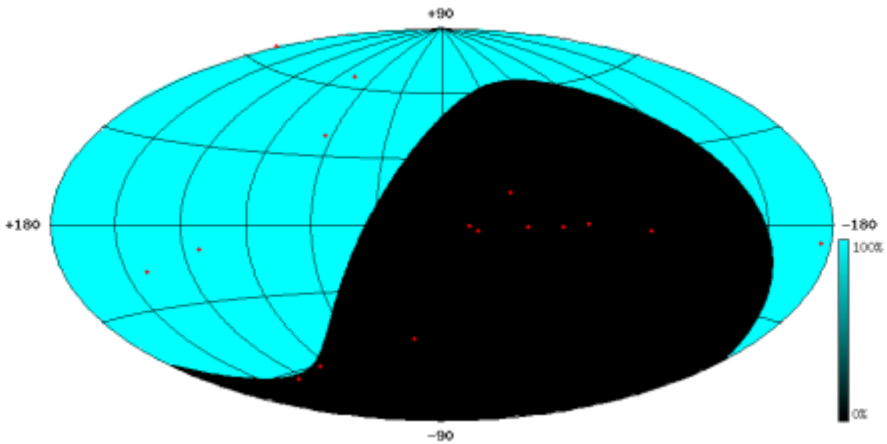


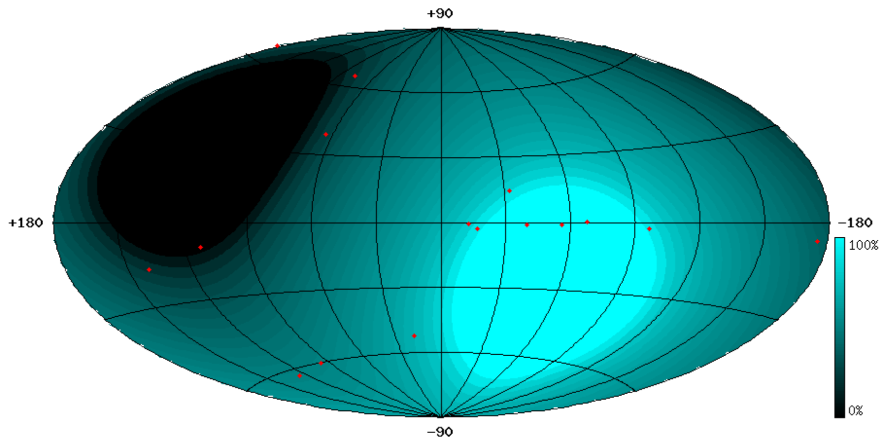
# Water vs Ice

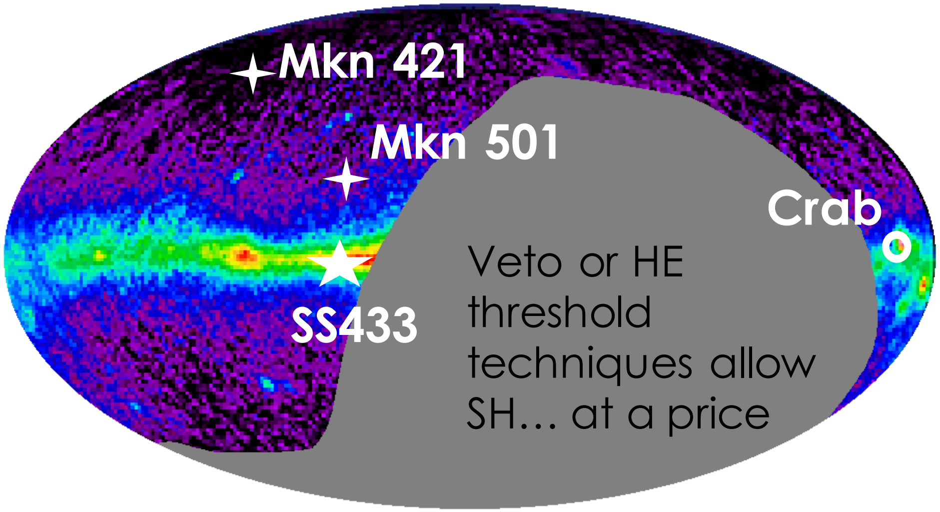
- Very large volumes of medium transparent to Cherenkov light are needed:
  - Ocean, lakes…
  - Antarctic ice
- Advantages of oceans:
  - Larger scattering length better angular resolution
  - Weaker depth-dependence of optical parameters
  - Possibility of recovery
  - Changeable detector geometry
- Advantages of ice:
  - Larger absorption length
  - No bioluminescence, no $^{40}K$ background, no biofouling
  - Easier deployment
  - Lower risk of point-failure
- Anyway, a detector in the Northern Hemisphere in necessary for complete sky coverage (Galactic Center!), and it is only feasible in the ocean.

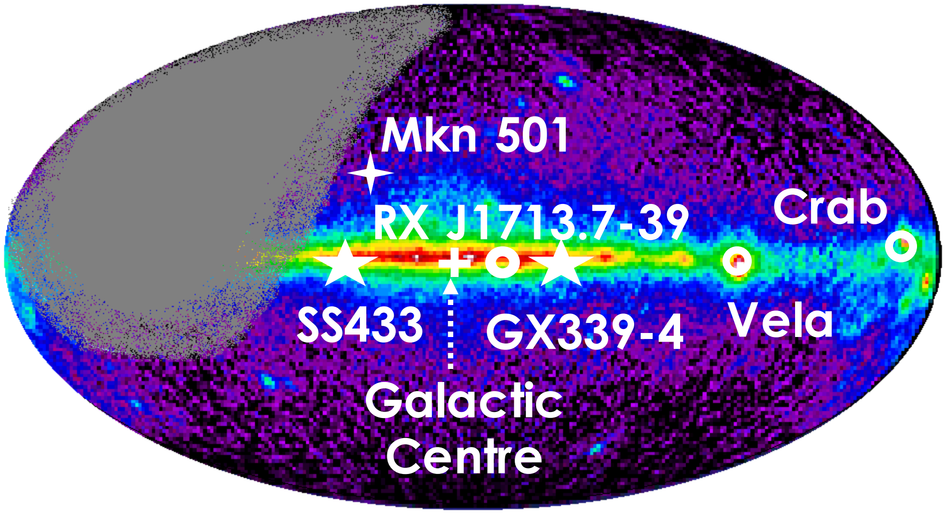
# Regions observed by NTs

| IceCube (South Pole) (ang. res.: 0.5°) | ANTARES/KM3NeT (43° North) (ang. res.: ~0.3°/0.1°) |
|---|---|

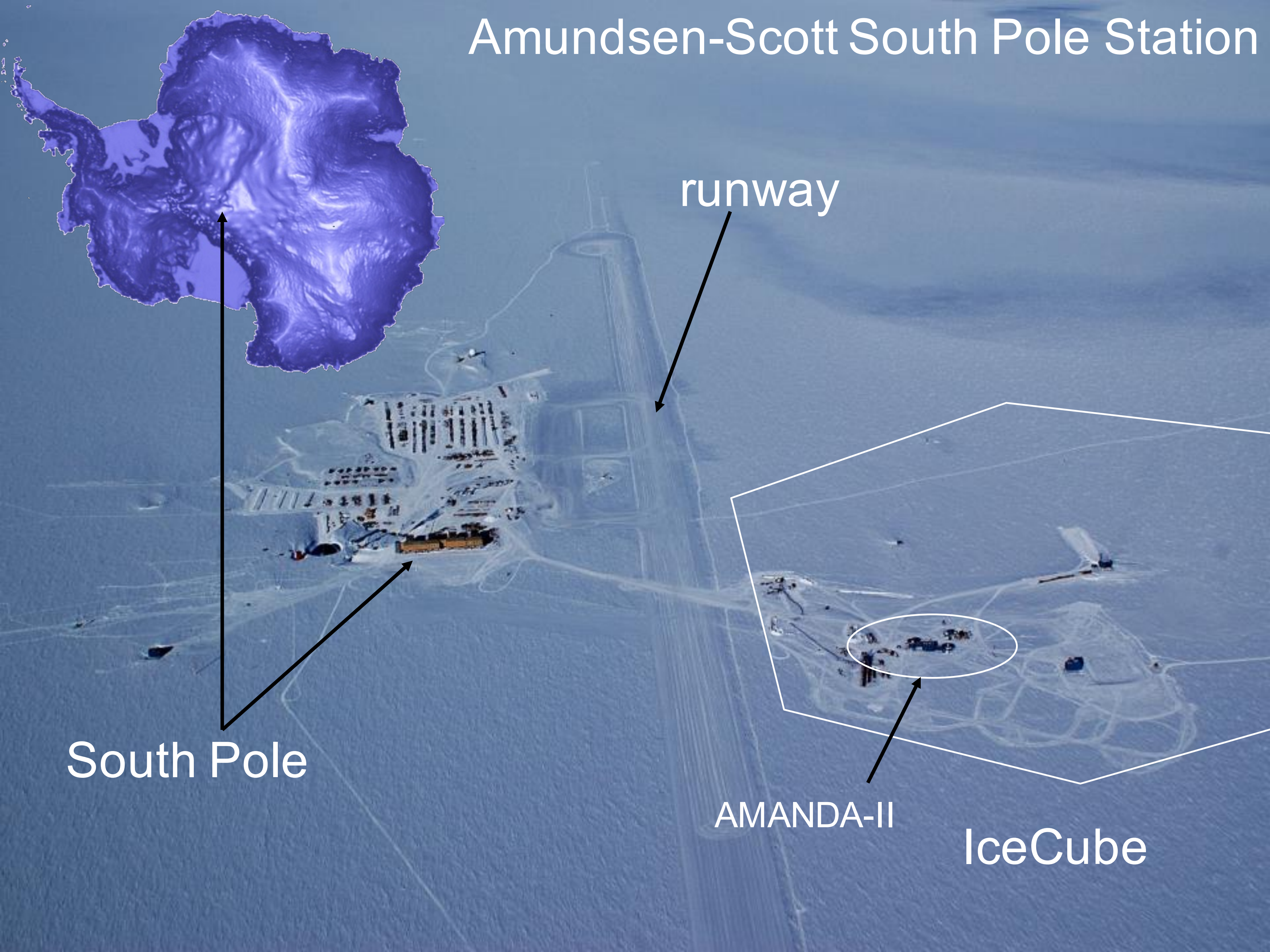


# IceCube



Amundsen-Scott South Pole Station
runway
South Pole
AMANDA-II
IceCube

# IceCube

## IceTop

80 pairs of ice Cherenkov tanks
Threshold ~ 300 GeV

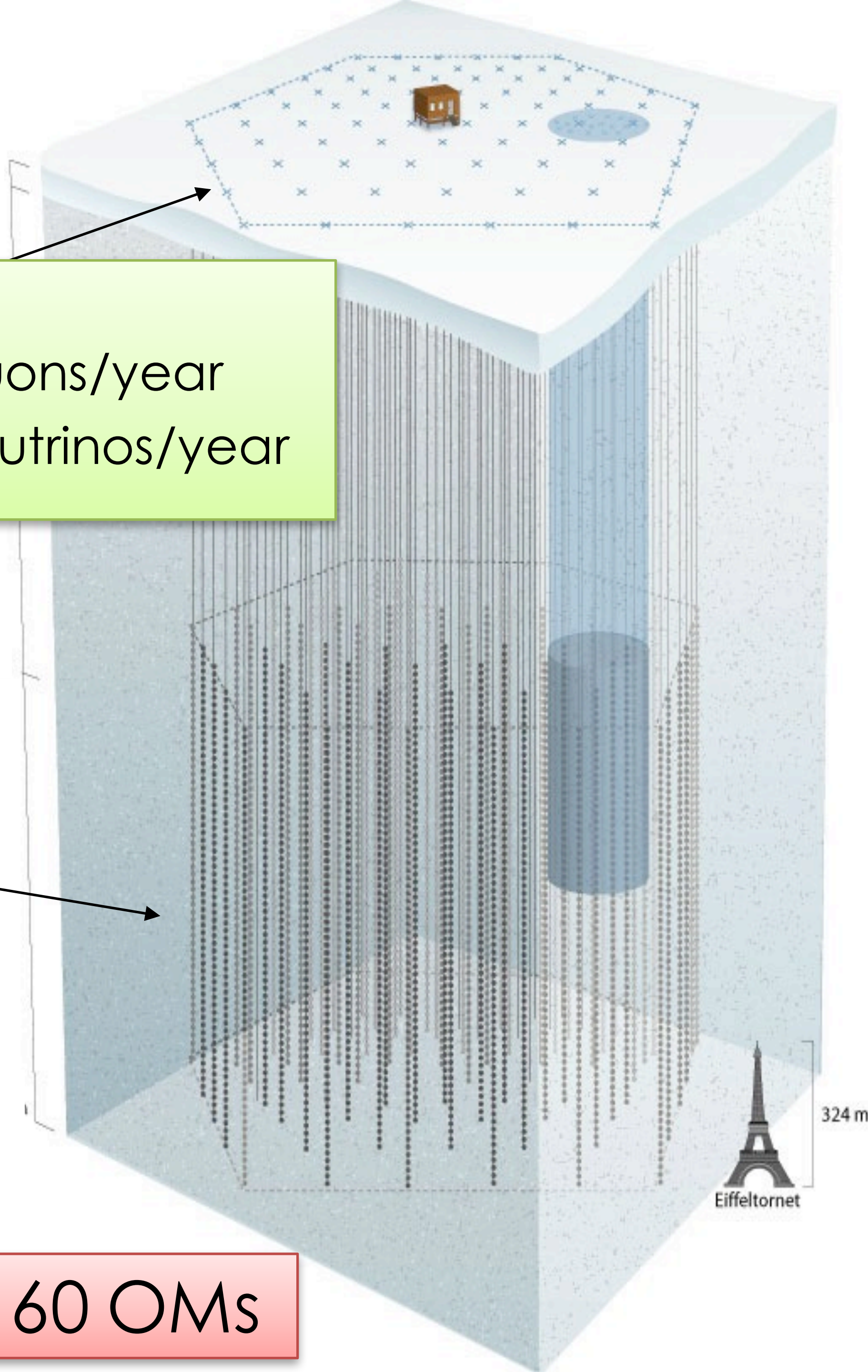
IC86:
~ $5x10^{10}$ muons/year
~ 20,000 neutrinos/year

## IceCube Array

80 strings with 60 OMs
17 m between OMs
125 m between strings
1 $km^3$. A 1-Gton detector

## Deep Core

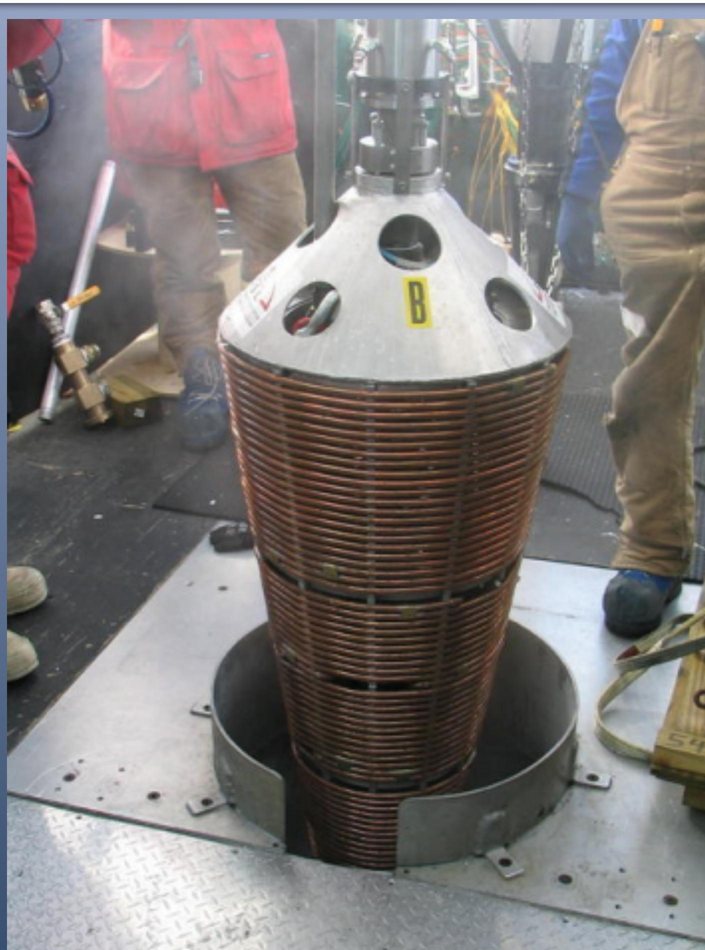
6 strings with 60 HQE OMs
Inner part of the detector




IceCube + Deep Core = 5160 OMs

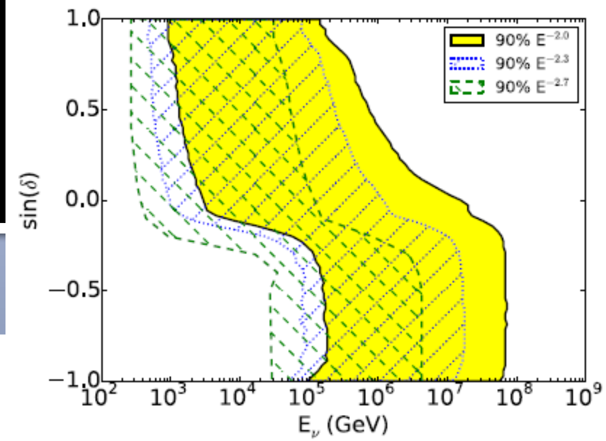

5 megawatt power plant
$10^6$ kg of drilling equipment

# String deployment

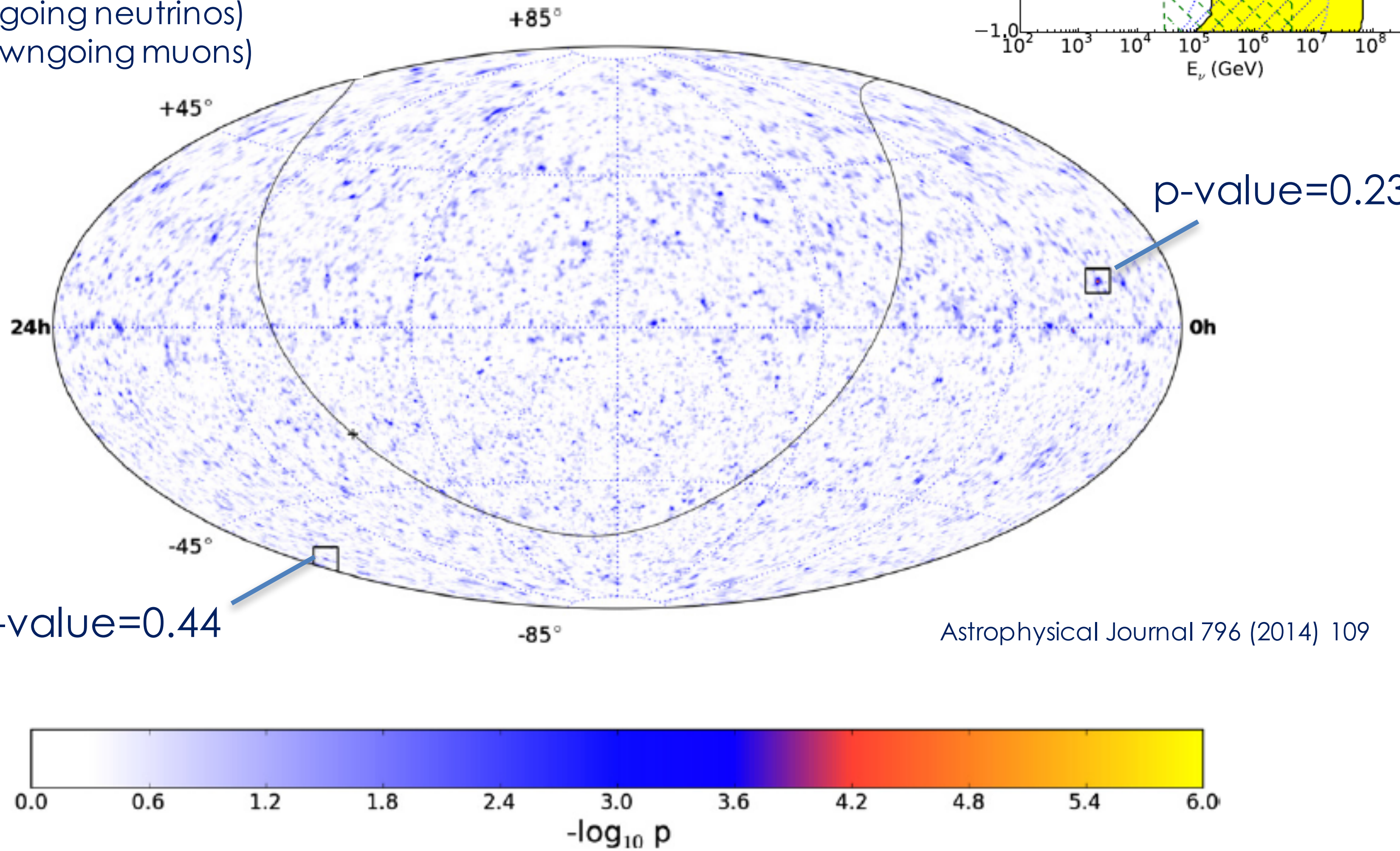



about 2 days to drill the 2.5 km hole

# Point Source Search



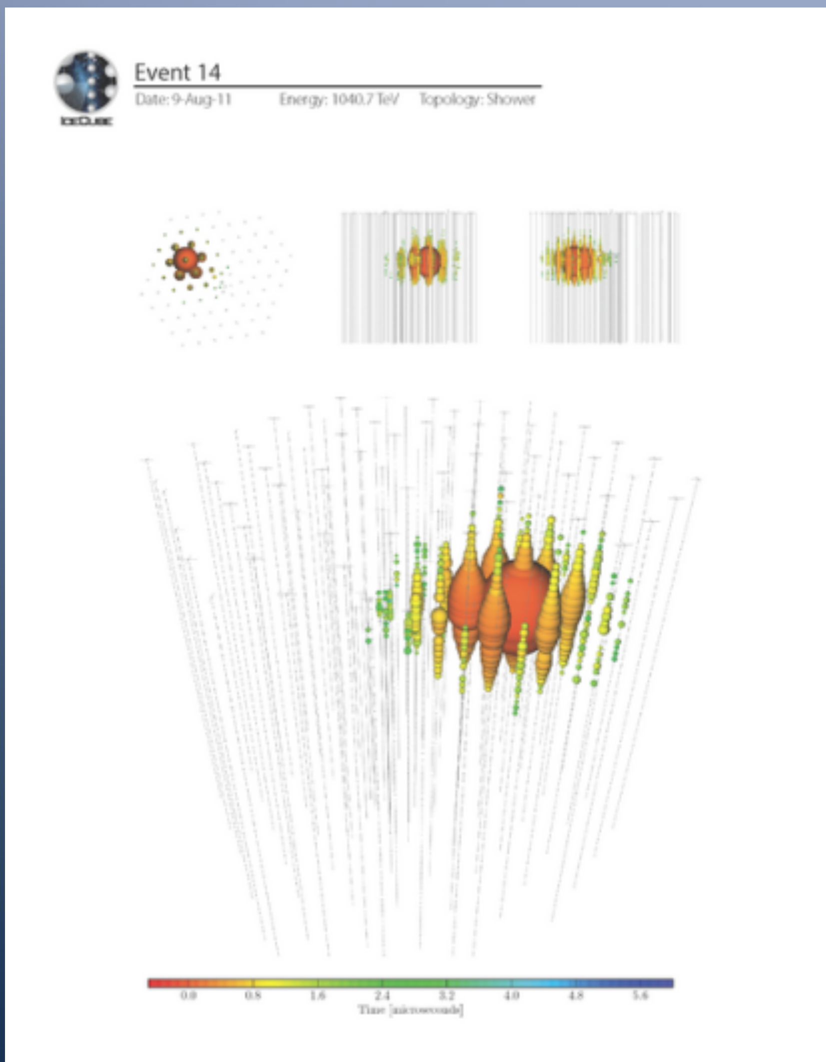

2008-2011 data:
- Livetime 1371 days
- 178k (upgoing neutrinos)
- 216k (downgoing muons)

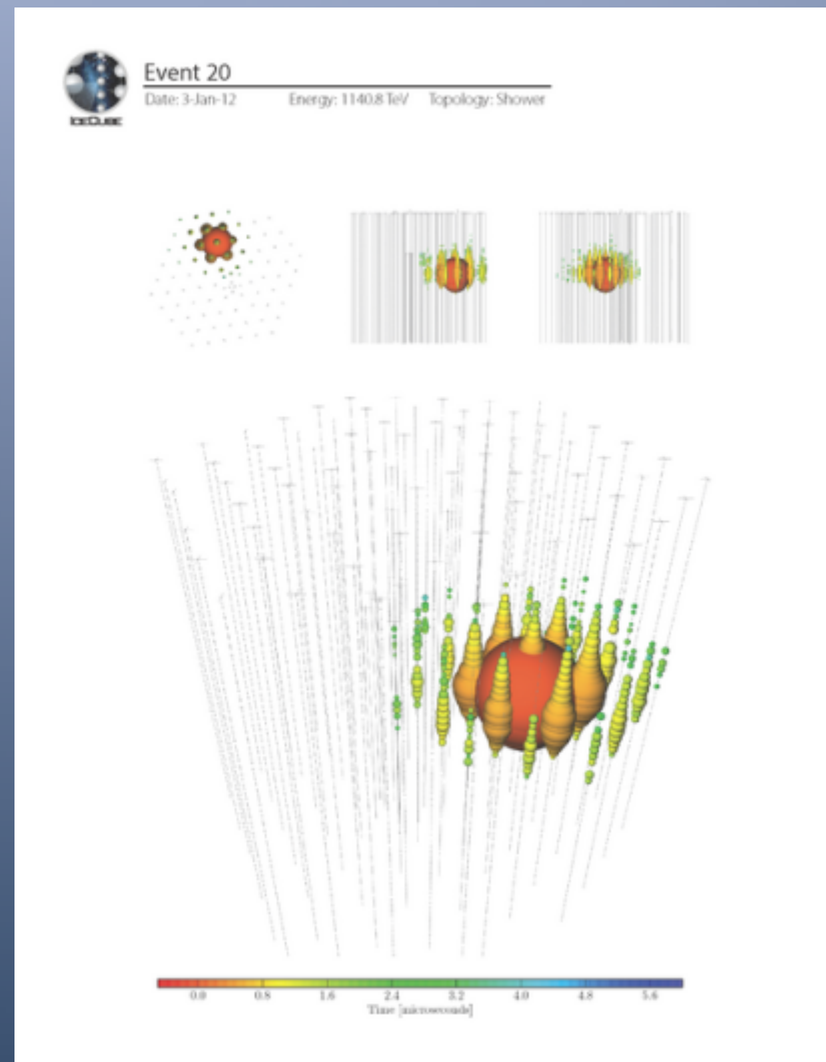



Astrophysical Journal 796 (2014) 109

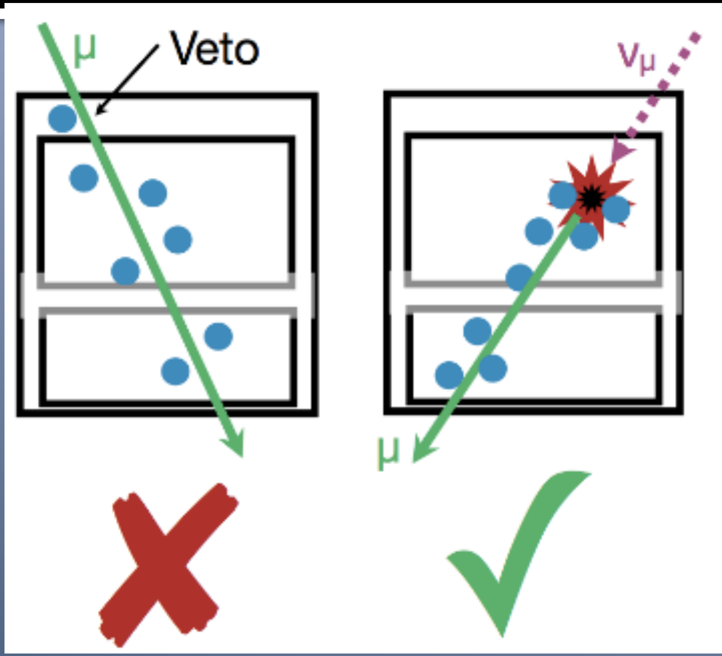
# Ernie and Bert

2012: Looking for UHE neutrinos, two events (cascades) appeared with E ~ 1 PeV (0.14 expected, 2.36σ)…



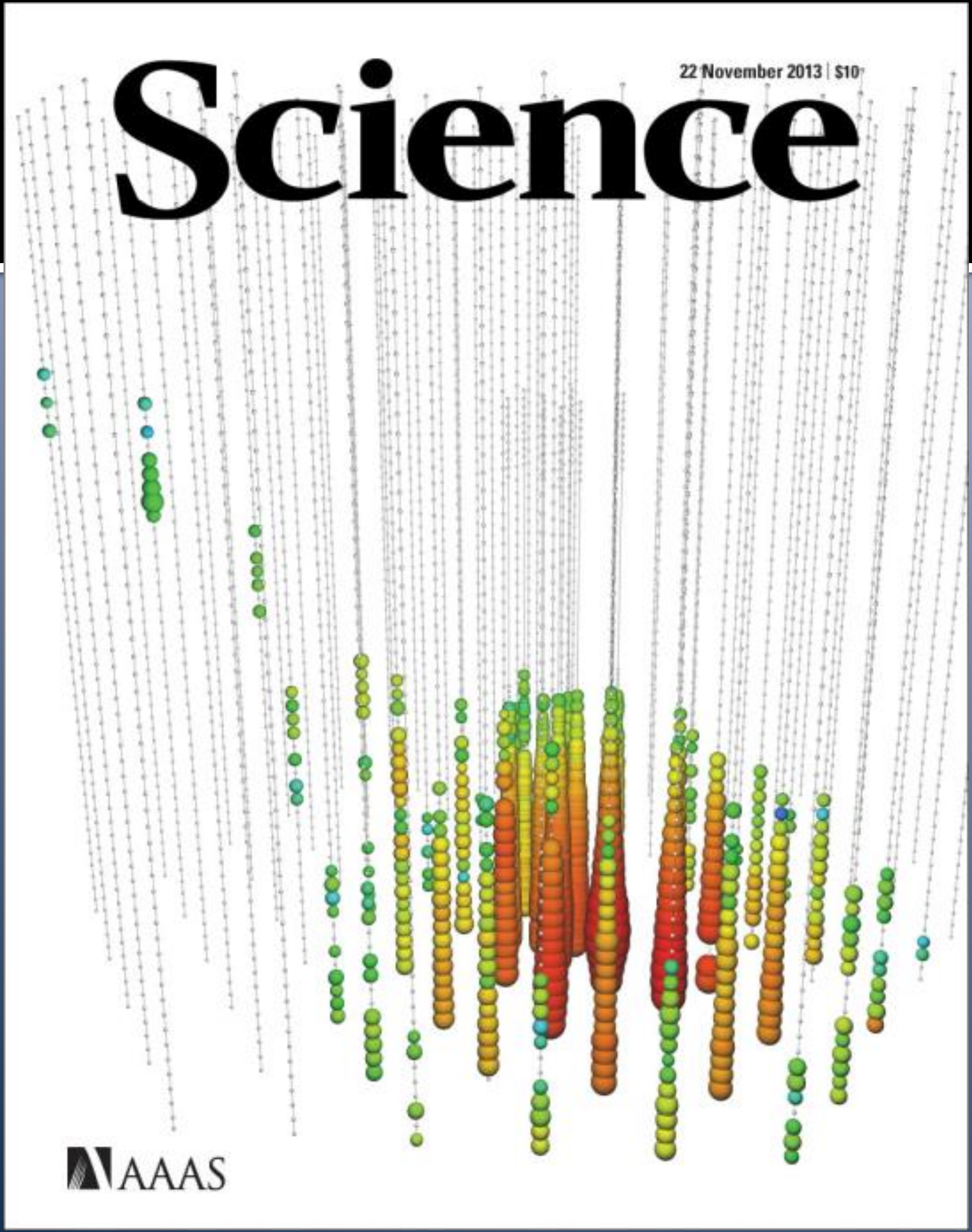



# HESE events




- HESE (High Energy Starting Events): Events of high energy (>30 TeV) starting inside the detector

- This strategy allows to reduce the background due to atmospheric muons because they would have left a signal in the external part of the detector (veto)
- It also helps to filter atmospheric neutrinos, since they are usually accompanied by muons
- Disadvantage: the volume is greatly reduce (only “contained” events)



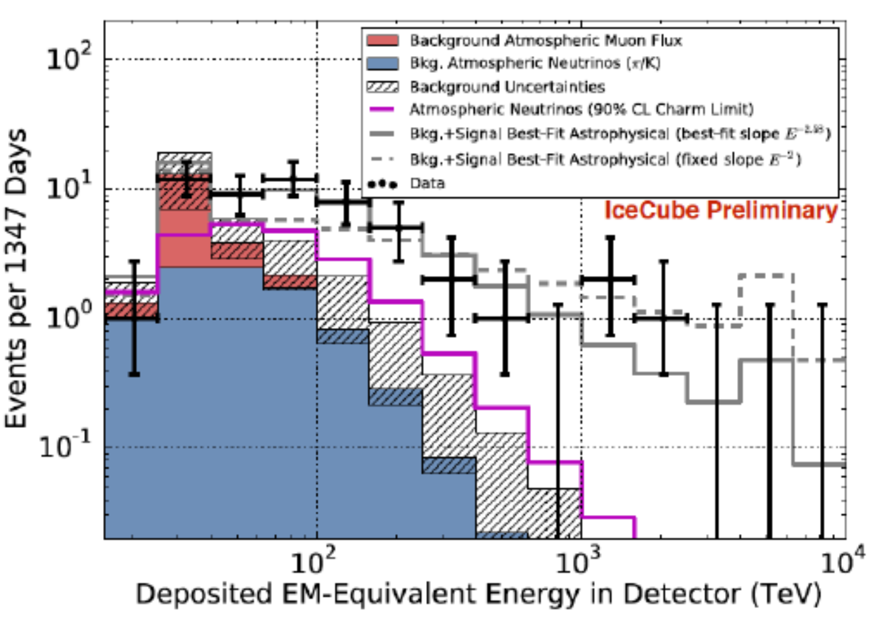

Science 342 (2013) 1242856, 22

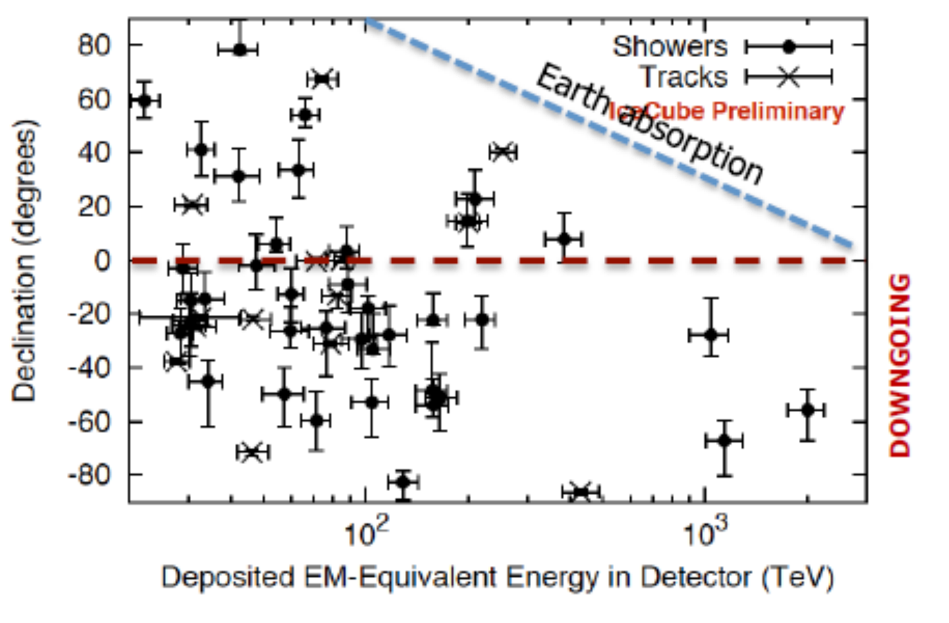
- 28 events in total (including Ernie and Bert)
- Expected background:
  - 6.0±3.4 atm. muons
  - 4.6±1.5 atm. neutrinos
- Significance: 4.9σ

**Discovery!**

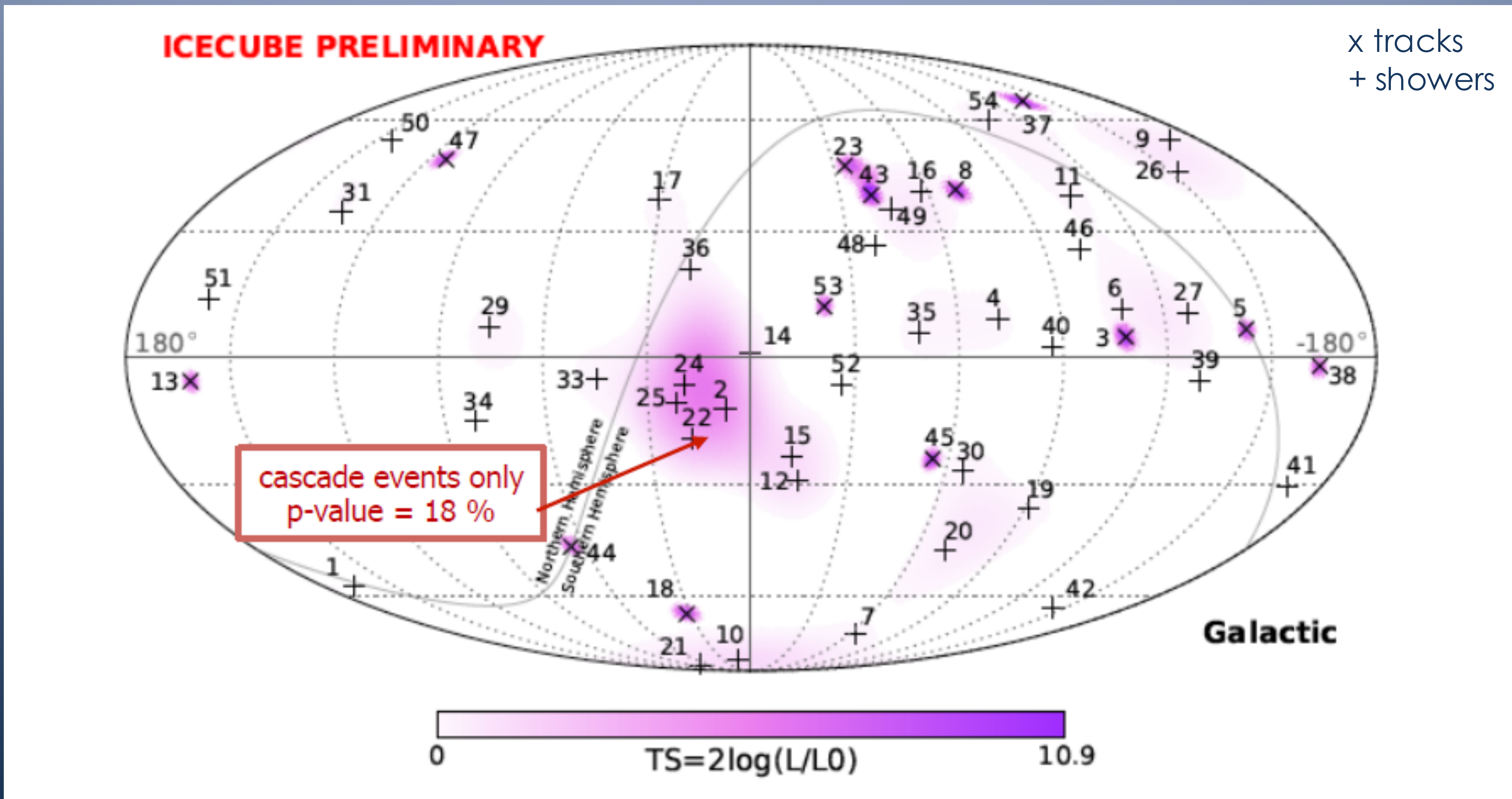
# IceCube HESE 4y

- Four years: 54 events (~7σ)
- Mostly cascades
- Excess confirmed in other analyses (upgoing $\nu_{\mu}$, MESE…), BUT, with some tensions (spectral index, normalization…)



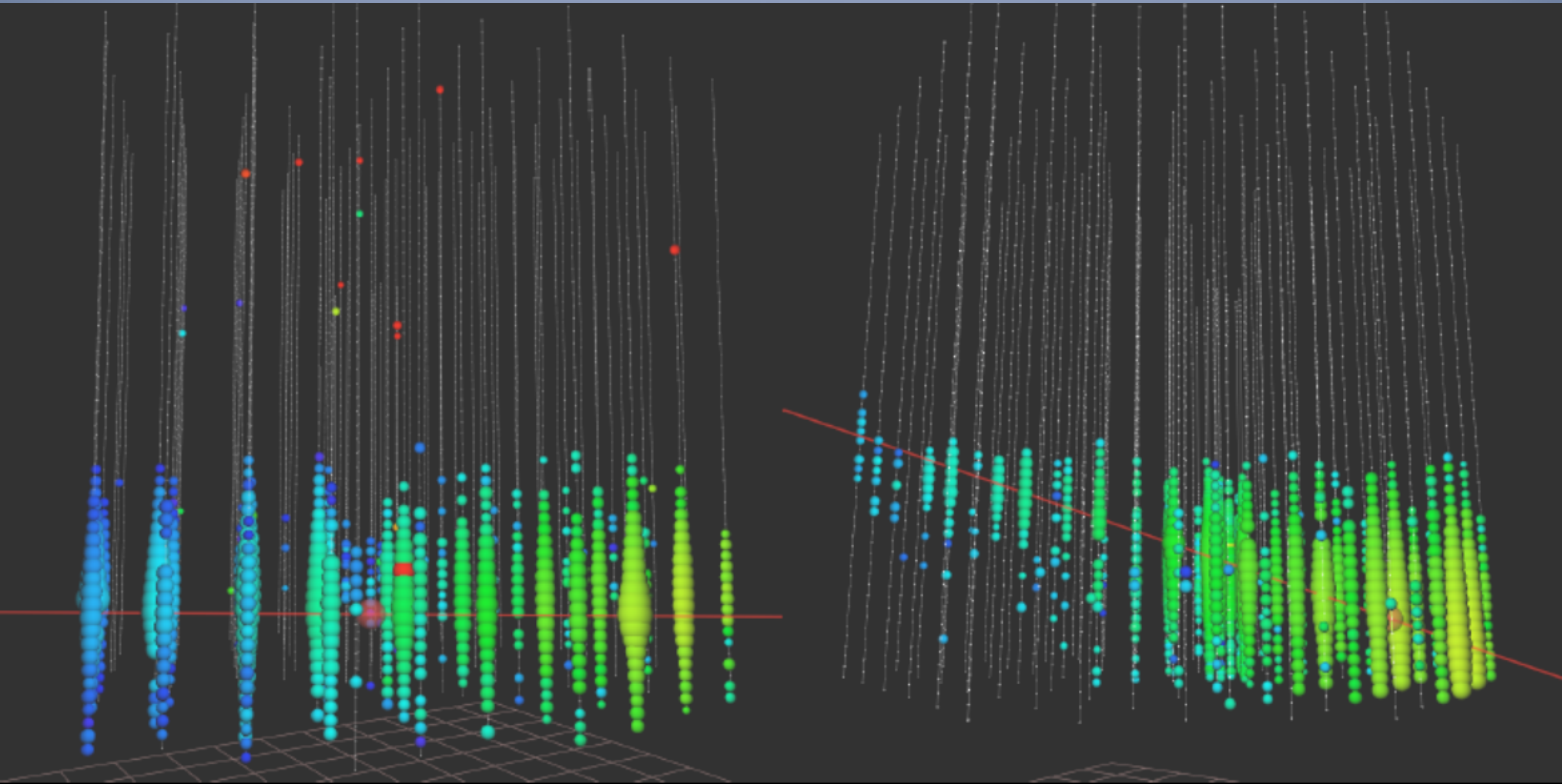



# IceCube Skymap (HESE 4y)

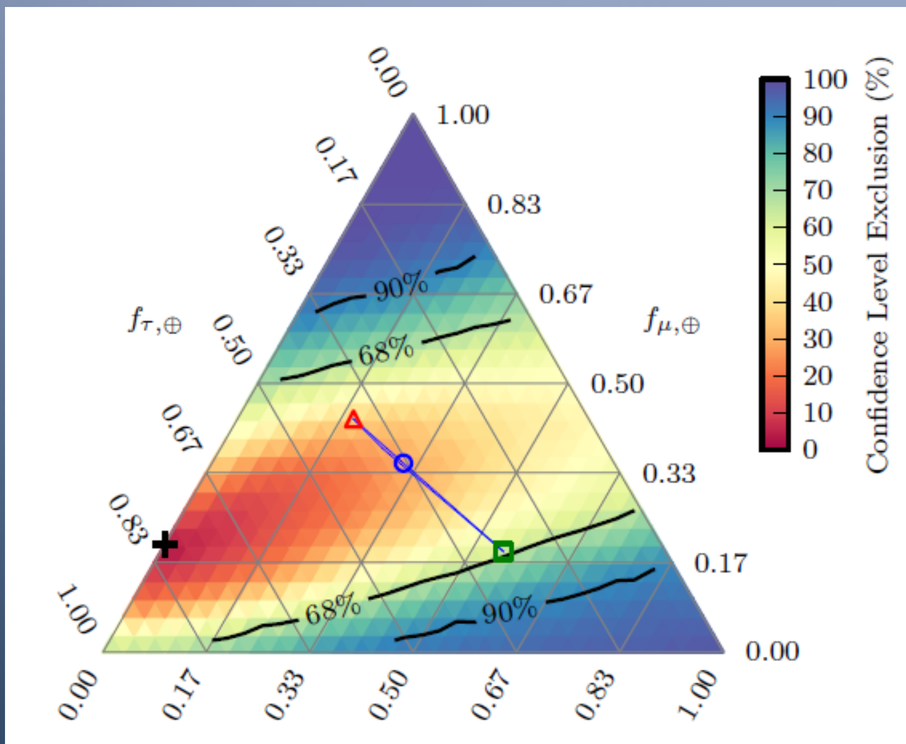


# Diffuse flux

- Highest energy observed in muon: 560 TeV → 1 PeV neutrino



# Flavour ratios



arXiv:1502.03376

- muon-suppressed pion decay (0:1:0)
- pion & muon decay (1:2:1)
- neutron decay (1:0:0)
- best fit (0:0.2:0.8)

- 3 year sample
- 129 showers and 8 tracks (superset of HESE sample)
- Best fit:

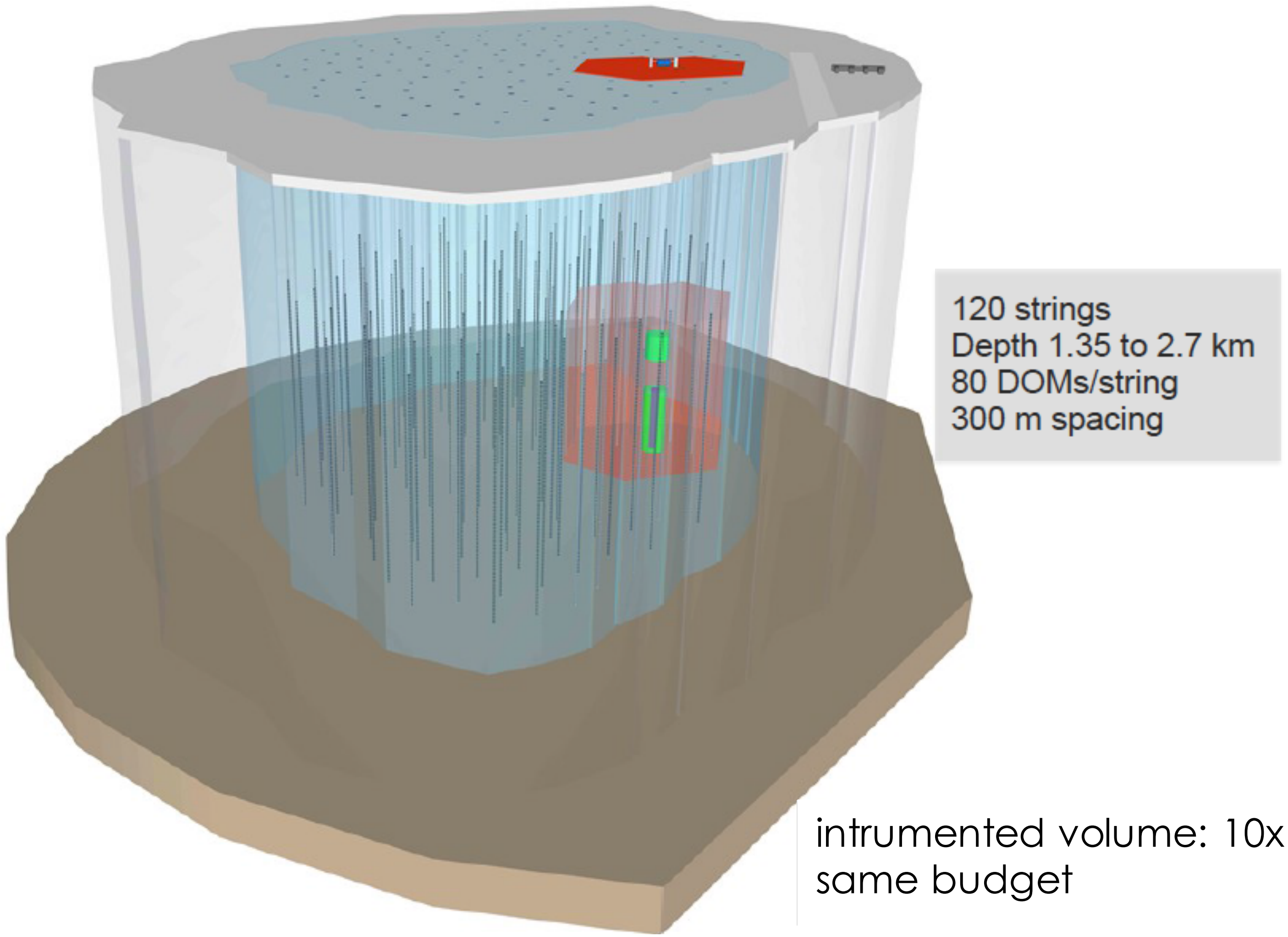
$$\gamma \ = \ 2.6 \pm 0.15$$

$$\Phi_0 \ = \ (2.3 \pm 0.4) \times 10^{-18} \, \mathrm{GeV}^{-1} \, \mathrm{s}^{-1} \, \mathrm{cm}^{-2} \, \mathrm{sr}^{-1}$$

(spectrum with HE cutoff also disfavoured)

- Best composition at Earth is (0:0.2:0.8), but the limits are compatible with all compostions possible under averaged oscillations

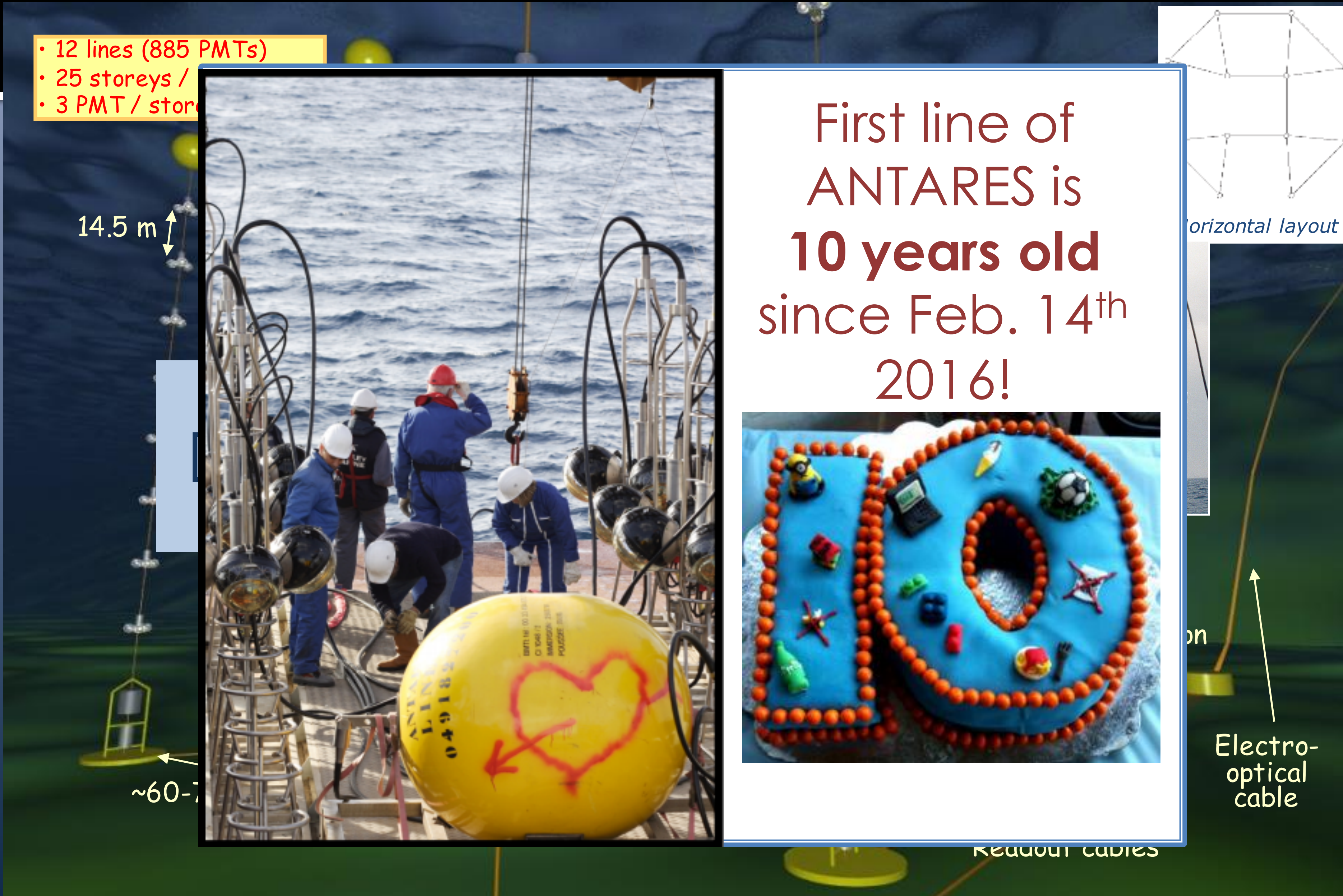
# IceCube-Gen2




intrumented volume: 10xIC
same budget

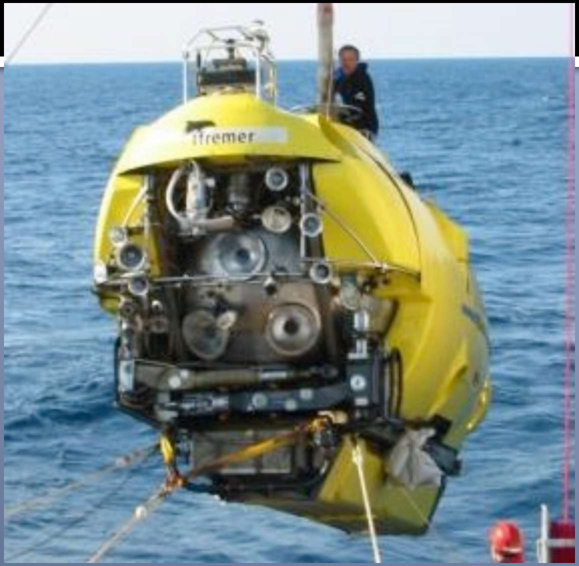
# ANTARES

# The ANTARES Detector



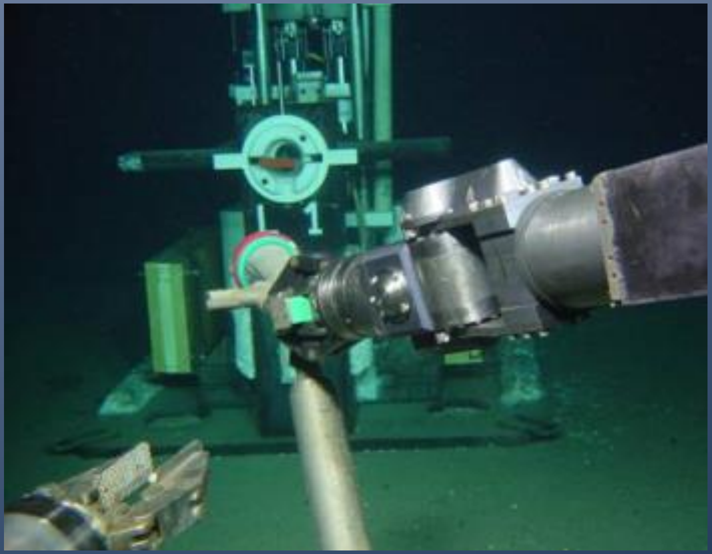
# Connection

Nautile (manned)



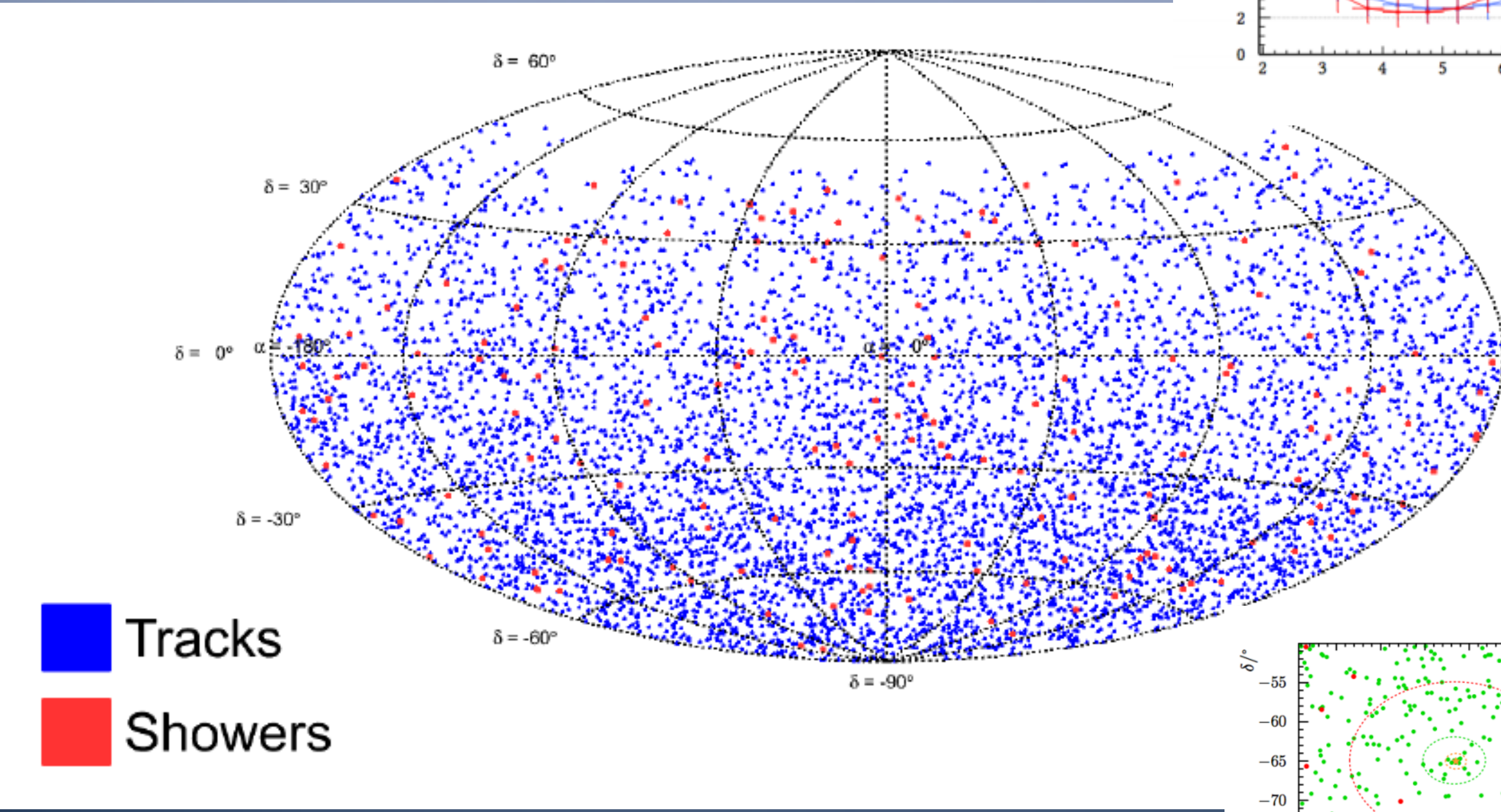


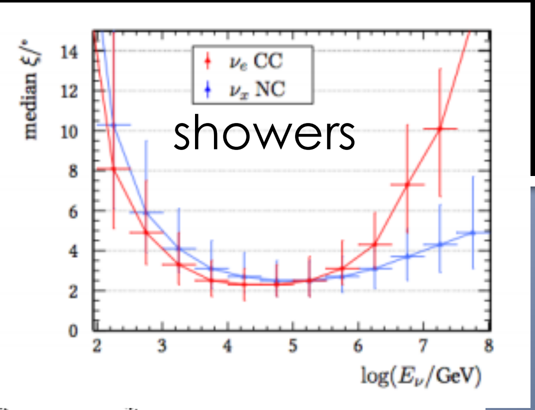
Victor (ROV)

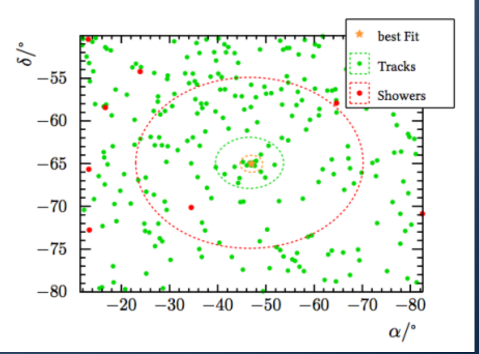


# Neutrino candidate

# ANTARES Skymap



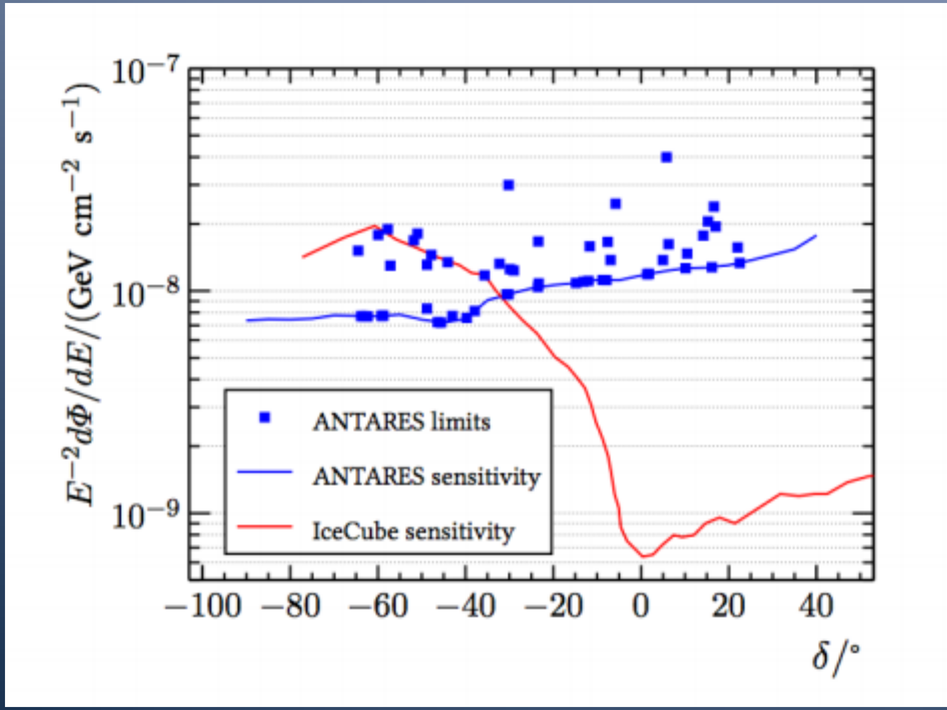




most significant cluster at (α, δ) = (−47°, −65°), 2.0 sigmas

# Flux limits

<u>Candidate search</u>

- Best limits for TeV-PeV energies in the Southern Hemisphere
- IceCube threshold for SH is ~1 PeV

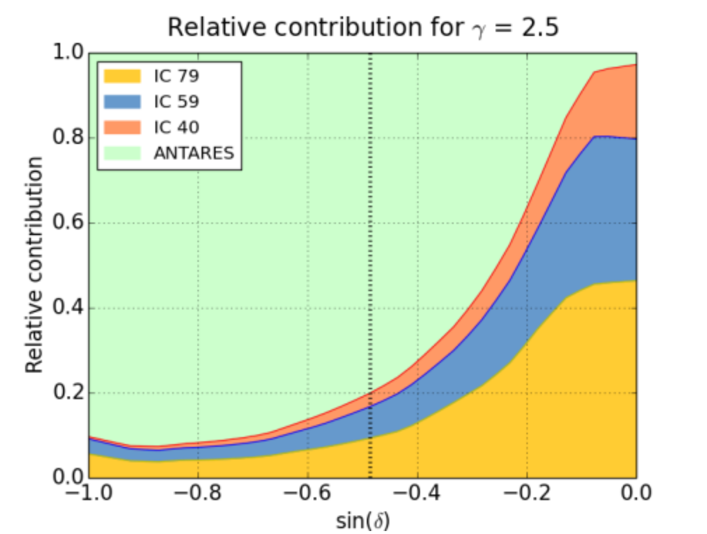



<u>Search on IC tracks</u>

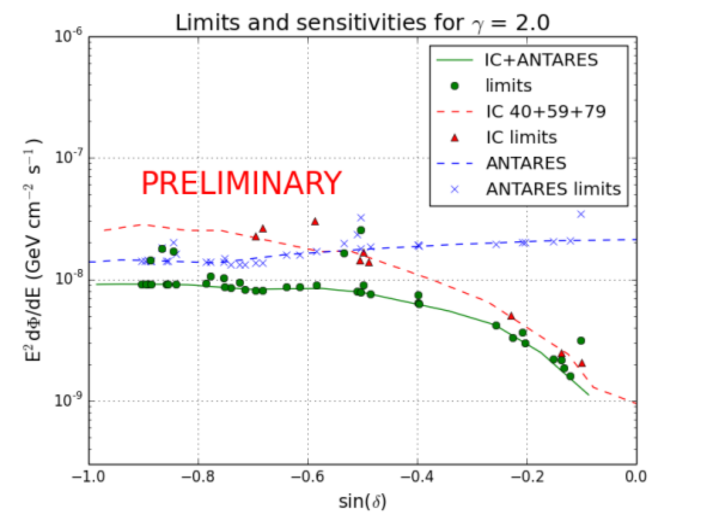
- Most significant case at (a, δ) = (130.7°, −29.5°)
  - ID 3, with original (a, δ) = (127.9°, −31.2°)
  - ns: 5.3 (tracks) + 0.6 (cascades)

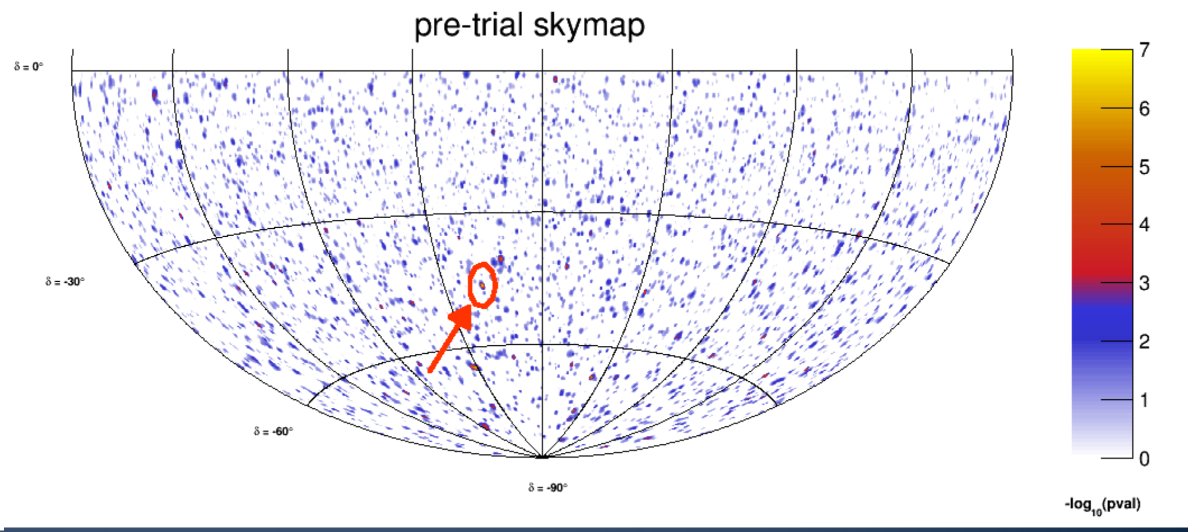
| ID | RA (°) | DEC (°) | $\Phi^{90\%}$ (GeVcm$^{-2}$s$^{-1}$) |
|---|---|---|---|
| 3 | 127.9 | -31.2 | 4.30E-08 |
| 5 | 110.6 | -0.4 | 3.30E-08 |
| 8 | 182.4 | -21.2 | 1.50E-08 |
| 13 | 67.9 | 40.3 | 2.30E-08 |
| 18 | -14.4 | 24.8 | 5.20E-08 |
| 23 | -151.3 | -13.2 | 1.80E-08 |
| 28 | 164.8 | -71.5 | 1.70E-08 |
| 37 | 167.3 | 20.7 | 1.70E-08 |

# ANTARES+IceCube Combined

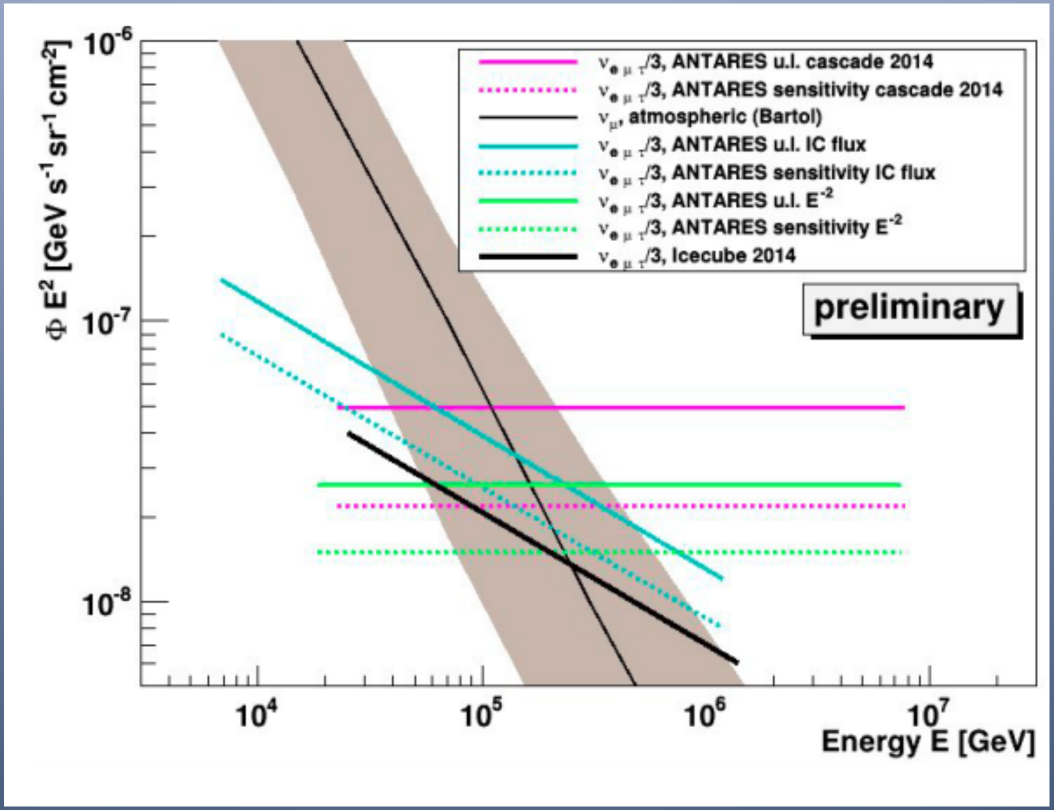



- An analysis has been done looking for point sources combining ANTARES and IceCube data
- There is an improvement in the declination region corresponding to the crossing of sensitivities (it depends on the spectral index and a potential energy cutoff)
- Data (ANTARES 6y + IceCube 3y) has been unblinded and a common skymap produced (no excess found)



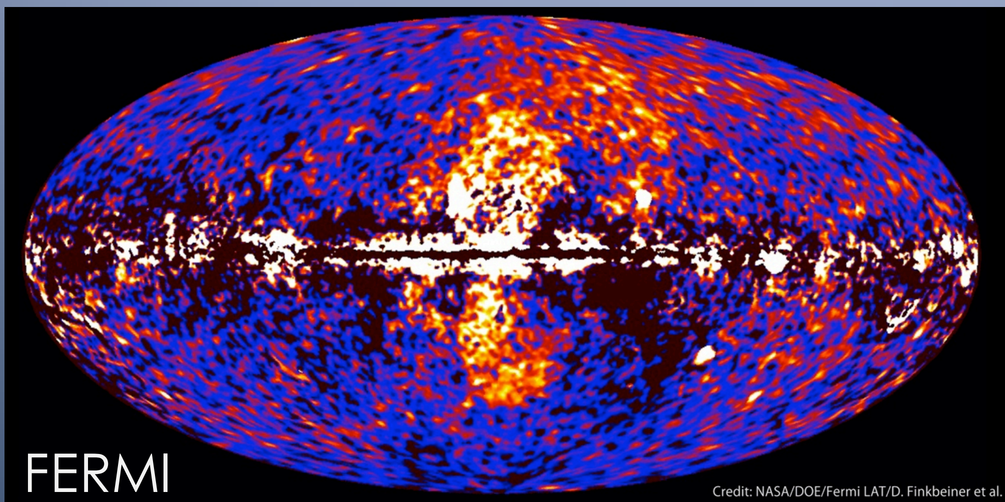
# Diffuse fluxes




- Expected:
  - background: 9.5 ± 2.5 events
  - IC flux: 5.0 ± 1.1 events
- Observed: 12 events

- Consistent with background and IC flux

# Fermi Bubbles

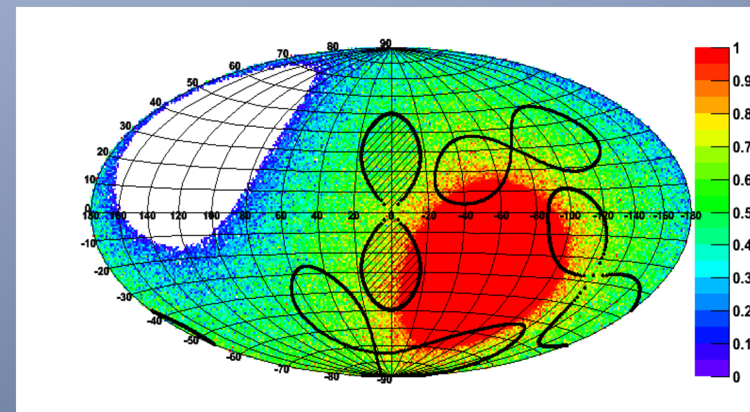



The origin is not clear: if due to CRs, neutrinos would be produced

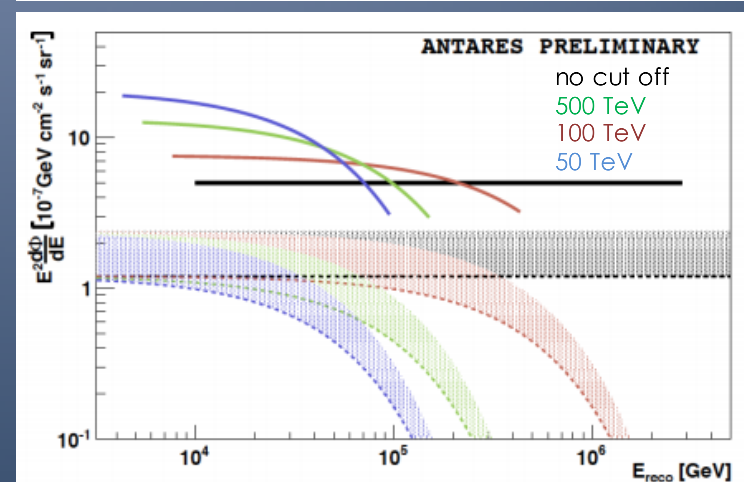
$$E^{2.18}\frac{d\Phi_\gamma(E_\gamma)}{dE_\gamma} = 0.5-1.0 \cdot 10^{-6}\mathrm{GeV}^{1.18}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$$

C. Lunardini, S. Razzaque, and L. Yang, arXiv1504.07033

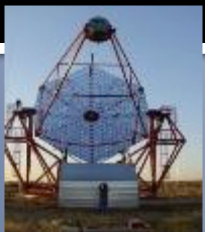
$$\Phi_\nu(E_\nu) = 0.36\ \Phi_\gamma(E_\gamma)$$

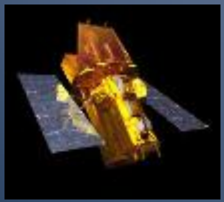


$N_{bg}$ (OFF) = 33/3=11 events
$N_{obs}$ = 16 events



# Multimessenger





GeV-TeV γ-rays
Fermi / HESS,
HAWC

- JCAP 03(2013) 006
- A&A 559 (2013) A9
- JCAP 05 (2014) 001

UHECR
Auger

- APJ 774 (2013) 19

High energy
neutrinos

Optical / X-rays
TAROT, ROTSE /
Swift, ZADKO,
MASTER

- APP 36 (2012) 204
- A&A 559 (2013) A9

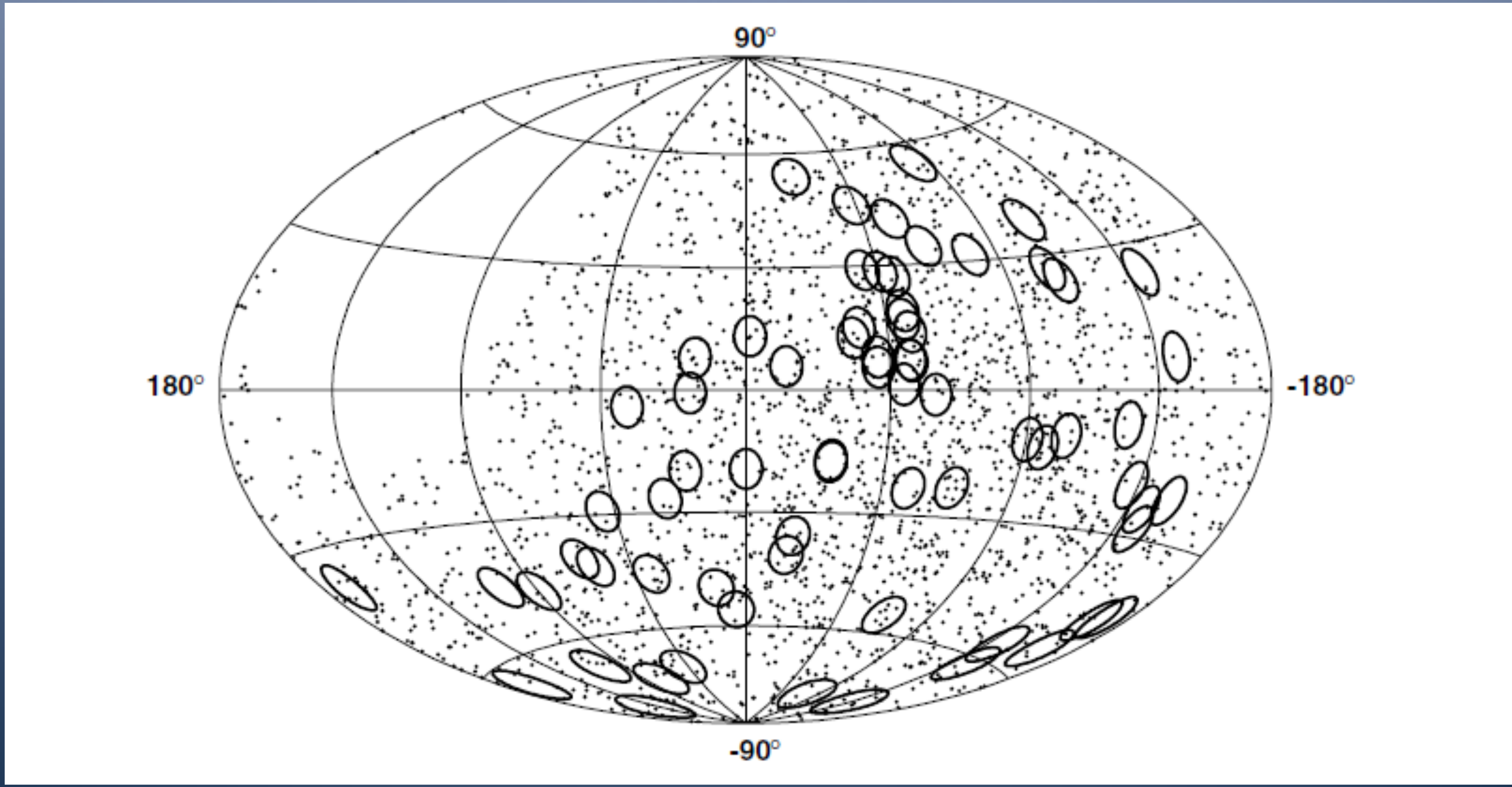
Gravitational
Waves
Virgo / Ligo

- JCAP 06 (2013) 008
- arxiv: 1602.05411

- It increases the chances of detection
  - Common sources for different messengers
  - Backgrounds and systematics non-correlated
  - MoUs signed with each collaboration

# Correlations with Auger

- Stacked search using bins of 4.9 degrees (radius)
- No correlation has been found (290 ev. observed vs 301.5 ev. expected from bg)
- Interpretation dependent on the composition and magnetic fields assumed



# Gravitational waves

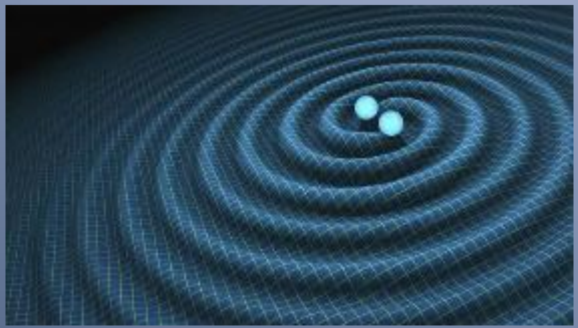
## High-energy Neutrino follow-up search of Gravitational Wave Event GW150914 with ANTARES and IceCube


S. Adrián-Martínez,[1] A. Albert,[2] M. André,[3] G. Anton,[4] M. Ardid,[1] J.-J. Aubert,[5] T. Avgitas,[6] B. Baret,[6] J. Barrios-Martí,[7] S. Basa,[8] V. Bertin,[5] S. Biagi,[9] R. Bormuth,[10,11] M.C. Bouwhuis,[10] R. Bruijn,[10,12] J. Brunner,[5] J. Busto,[5] A. Capone,[13,14] L. Caramete,[15] J. Carr,[5] S. Celli,[13,14] T. Chiarusi,[16] M. Circella,[17] A. Coleiro,[6] R. Coniglione,[9] H. Costantini,[5] P. Coyle,[5] A. Creusot,[6] A. Deschamps,[18] G. De Bonis,[13,14] C. Distefano,[9] C. Donzaud,[6,19] D. Dornic,[5] D. Drouhin,[2] T. Eberl,[4] I. El Bojaddaini,[20] D. Elsässer,[21] A. Enzenhöfer,[4] K. Fehn,[4] I. Felis,[22] L.A. Fusco,[23,16] S. Galatà,[6] P. Gay,[24,25] S. Geißelsöder,[4] K. Geyer,[4] V. Giordano,[26] A. Gleixner,[4] H. Glotin,[27,28] R. Gracia-Ruiz,[6] K. Graf,[4] S. Hallmann,[4] H. van Haren,[29] A.J. Heijboer,[10] Y. Hello,[18] J.J. Hernández-Rey,[7] J. Hößl,[4] J. Hofestädt,[4] C. Hugon,[30,31] G. Illuminati,[13,14] C.W James,[4] M. de Jong,[10,11] M. Jongen,[10] M. Kadler,[21] O. Kalekin,[4] U. Katz,[4] D. Kießling,[4] A. Kouchner,[6,28] M. Kreter,[21] I. Kreykenbohm,[32] V. Kulikovskiy,[9,33] C. Lachaud,[6] R. Lahmann,[4] D. Lefèvre,[34] E. Leonora,[26,35] S. Loucatos,[36,6] M. Marcelin,[8] A. Margiotta,[23,16] A. Marinelli,[37,38] J.A. Martínez-Mora,[1] A. Mathieu,[5] K. Melis,[12] T. Michael,[10] P. Migliozzi,[39] A. Moussa,[20] C. Mueller,[21] E. Nezri,[8] G.E. Păvălaş,[15] C. Pellegrino,[23,16] C. Perrina,[13,14] P. Piattelli,[9] V. Popa,[15] T. Pradier,[40] C. Racca,[2] G. Riccobene,[9] K. Roensch,[4] M. Saldaña,[1] D. F. E. Samtleben,[10,11] M. Sanguineti,[30,31] P. Sapienza,[9] J. Schnabel,[4] F. Schüssler,[36] T. Seitz,[4] C. Sieger,[4] M. Spurio,[23,16] Th. Stolarczyk,[36] A. Sánchez-Losa,[7,41] M. Taiuti,[30,31] A. Trovato,[9] M. Tselengidou,[4] D. Turpin,[5] C. Tönnis,[7] B. Vallage,[36,25] C. Vallée,[5] V. Van Elewyck,[6] D. Vivolo,[39,42] S. Wagner,[4] J. Wilms,[32] J.D. Zornoza,[7] and J. Zúñiga[7]

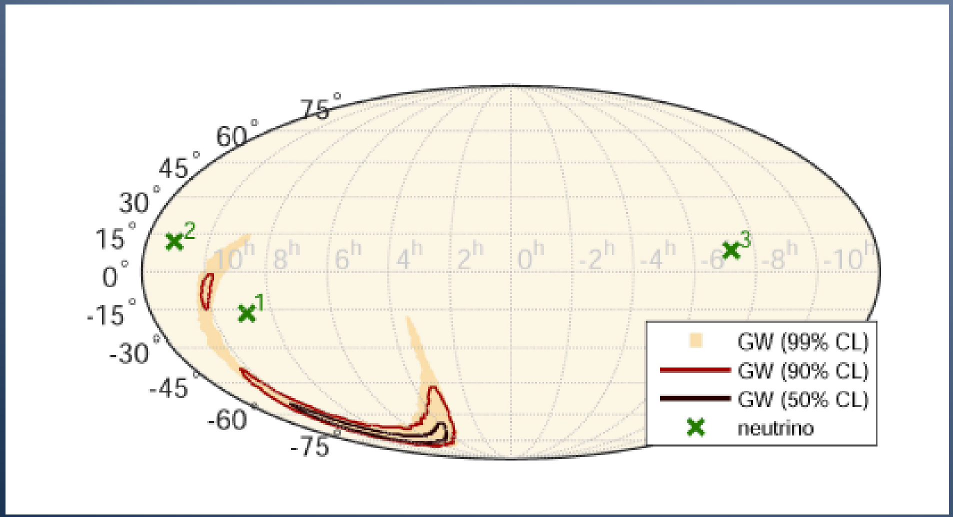
(The ANTARES Collaboration)

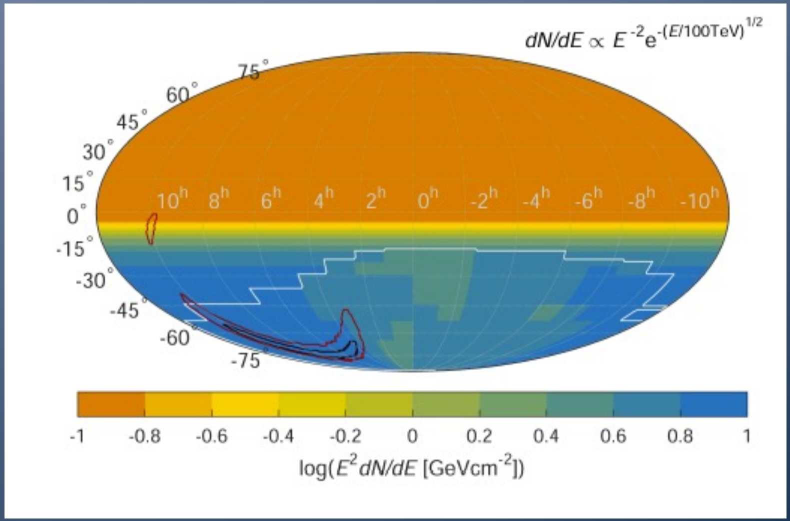
M. G. Aartsen,[44] K. Abraham,[74] M. Ackermann,[91] J. Adams,[58] J. A. Aguilar,[54] M. Ahlers,[71] M. Ahrens,[81] D. Altmann,[4] T. Anderson,[87] I. Ansseau,[54] G. Anton,[4] M. Archinger,[72] C. Arguelles,[56] T. C. Arlen,[87]

# Gravitational waves



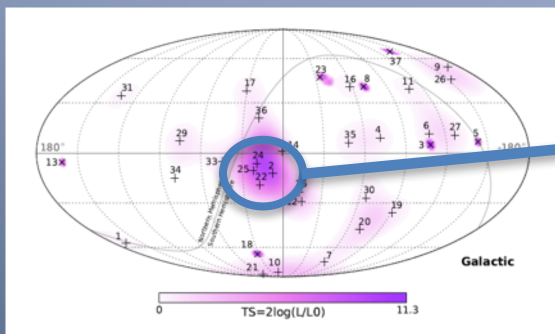
- Neutrino telescopes offer a complete sky coverage and almost continuous data taking: crucial for transient events
- A search for ANTARES and IceCube events correlated in time and space with the GW150916 event has been carried out
  - ANTARES: 0 events
  - IceCube: 3 events (as expected from background)

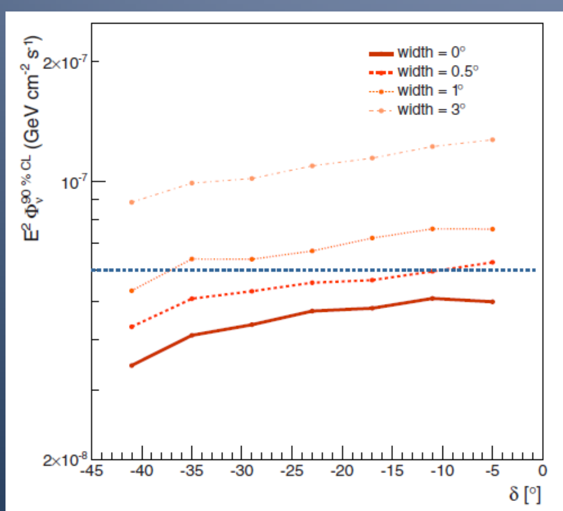



Upper limits in the flux are set

# ANTARES on IceCube signal (I)




THE ASTROPHYSICAL JOURNAL LETTERS, 786:L5 (5pp), 2014

- What can ANTARES say about this? (seven events in the HESE analysis close to the GC)
- In arXiv:1310.7194 (González-García, Halzen, Niro), it is proposed to come from a point source with flux $6 \times 10^{-8}$ GeV $cm^{-2}$ $s^{-1}$.
- ANTARES data allows to reject this possibility (it is not a point-like source) at the flux proposed there and limits depending on the size of the source are set

# ANTARES on IceCube signal (II)

A&A 566, L7 (2014)
DOI: 10.1051/0004-6361/201424219

Astronomy & Astrophysics

LETTER TO THE EDITOR

**TANAMI blazars in the IceCube PeV-neutrino fields★**

F. Krauß[1,2], M. Kadler[2], K. Mannheim[2], R. Schulz[1,2], J. Trüstedt[1,2], J. Wilms[1], R. Ojha[3,4,5], E. Ros[6,7,8], G. Anton[9], W. Baumgartner[3], T. Beuchert[1,2], J. Blanchard[10], C. Bürkel[1,2], B. Carpenter[5], T. Eberl[9], P. G. Edwards[11],

*Astronomy & Astrophysics* manuscript no. antares_tanami_aa
January 16, 2015


LETTER TO THE EDITOR

**ANTARES Constrains a Blazar Origin of Two IceCube PeV Neutrino Events**

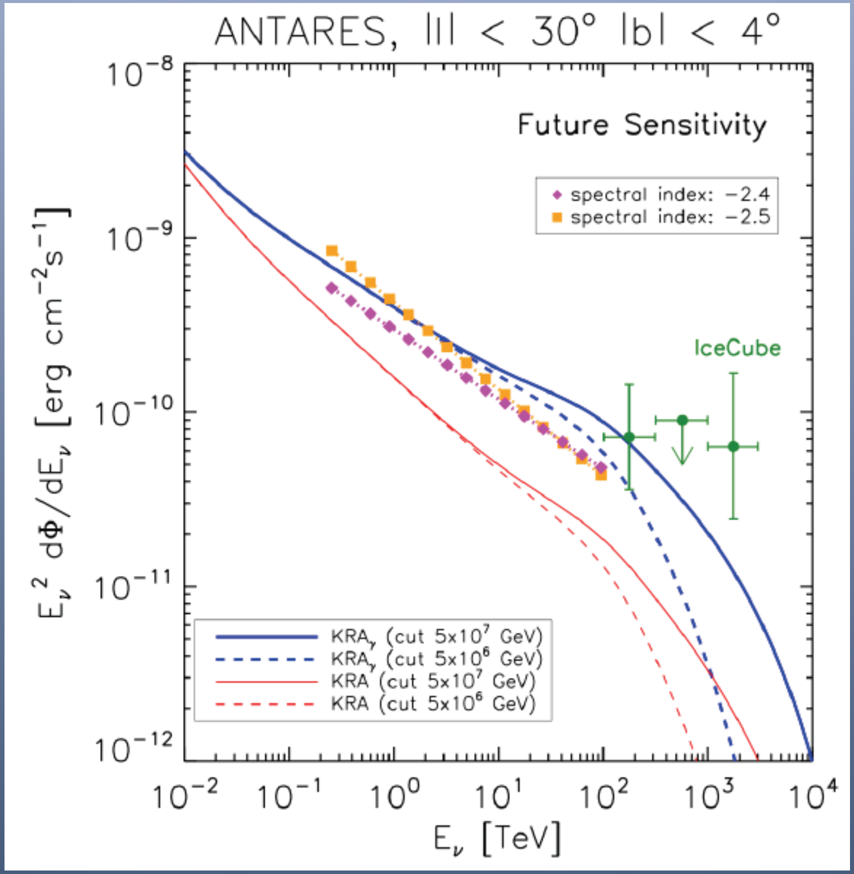
The ANTARES Collaboration: S. Adrián-Martínez[1], A. Albert[2], M. André[3], G. Anton[5], M. Ardid[1], J.-J. Aubert[6], B. Baret[7], J. Barrios[8], S. Basa[9], V. Bertin[6], S. Biagi[23], C. Bogazzi[12], R. Bormuth[12, 13], M. Bou-Cabo[1],

- TANAMI collaboration has shown that the two first PeV events of the IC HESE analysis are consistent with the integrated energy output of six blazars positionally coincident with these events
- The analysis by ANTARES shows that each of the two blazars to be predicted to be the most bright has a signal flux fitted by the LH corresponding to about one ANTARES event (the other four have no associated event)

arXiv:1501.07843
accepted by A&A Letters

| Source | Cat. Name | $F_\gamma$ [GeV cm$^{-2}$ s$^{-1}$] | $N_{\nu_e}$ | IC |
|---|---|---|---|---|
| 0235−618 | PKS 0235−618 | $\left(6.2^{+3.1}_{-3.1}\right)\times10^{-8}$ | $0.19^{+0.04}_{-0.04}$ | 20, 7 |
| 0302−623 | PKS 0302−623 | $\left(2.1^{+0.4}_{-0.4}\right)\times10^{-8}$ | $0.06^{+0.01}_{-0.01}$ | 20 |
| 0308−611 | PKS 0308−611 | $\left(4.7^{+1.8}_{-1.8}\right)\times10^{-8}$ | $0.14^{+0.05}_{-0.05}$ | 20 |
| 1653−329 | Swift J1656.3−3302 | $\left(2.8^{+0.3}_{-0.3}\right)\times10^{-7}$ | $0.86^{+0.10}_{-0.10}$ | 14, 2, 25 |
| 1714−336 | TXS 1714−336 | $\left(1.5^{+0.3}_{-0.4}\right)\times10^{-7}$ | $0.46^{+0.10}_{-0.12}$ | 14,2,25 |
| 1759−396 | MRC 1759−396 | $\left(7.5^{+1.9}_{-1.9}\right)\times10^{-8}$ | $0.23^{+0.50}_{-0.40}$ | 14, 2, 15, 25 |

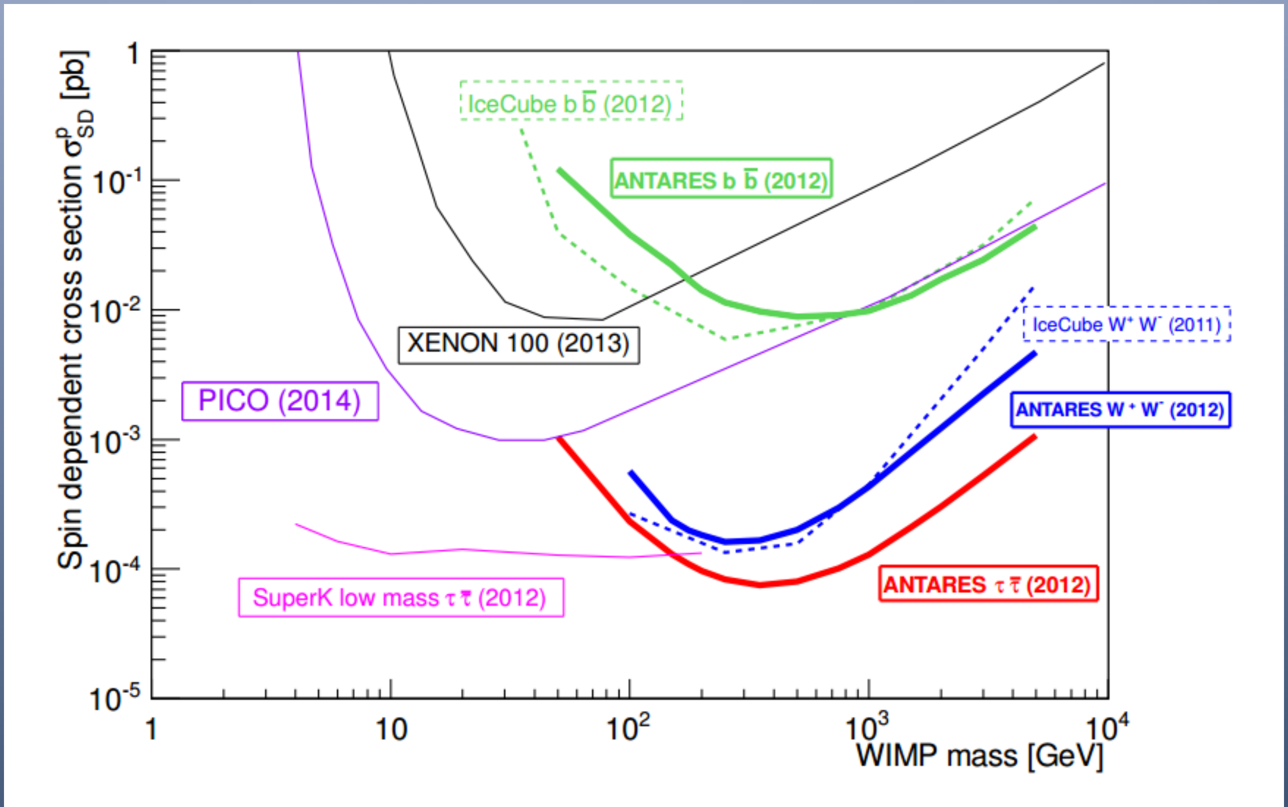
# ANTARES on IceCube signal (III)




Gaggero, Grasso, Marinelli, Urbano, Valli, arxiv/1504.00227 subm. to Phys.Rev.Lett.

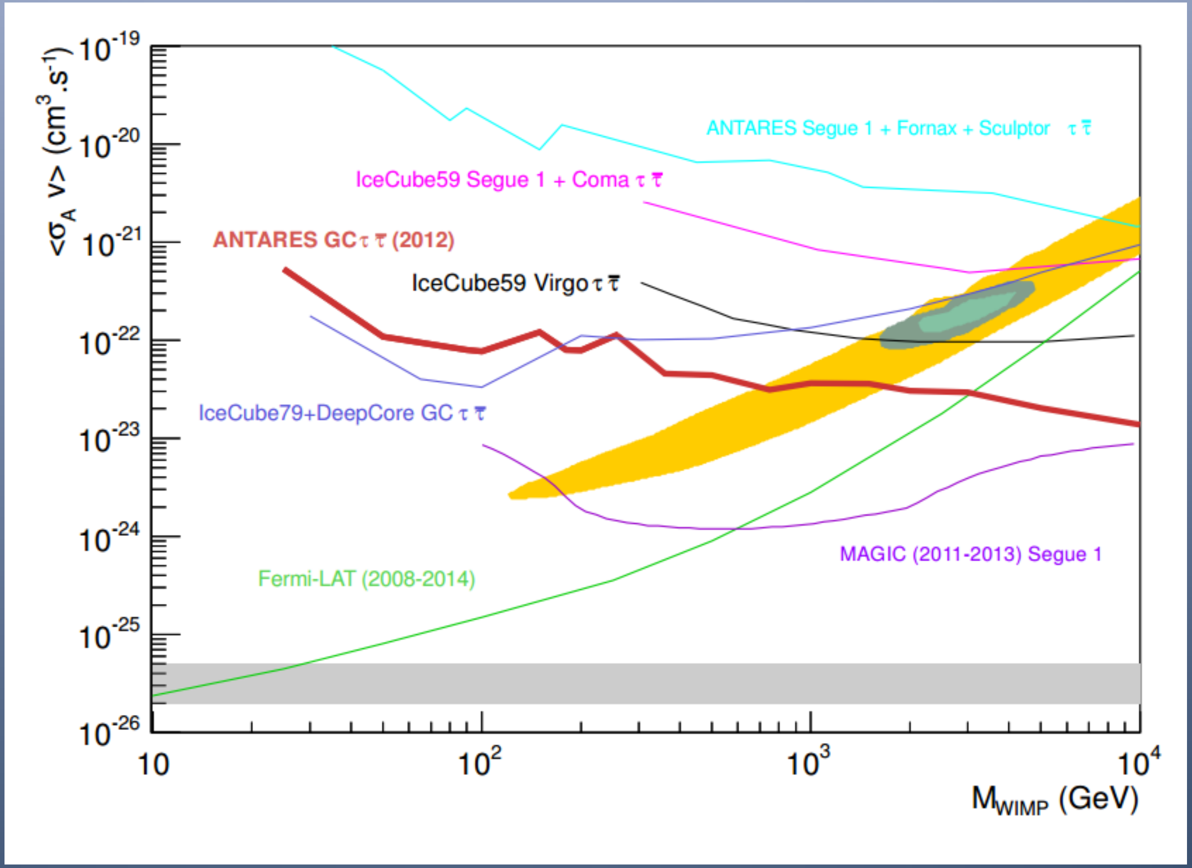
Model to explain both MILAGRO/HESS and FERMI-LAT observations: Galactocentric radial dependence of diffusion scaling

# Dark Matter: Sun




- Neutrino telescopes:
  - Best results for spin-dependent WIMP-nucleon cross section
  - No significant astrophysical backgrounds

# Galactic center

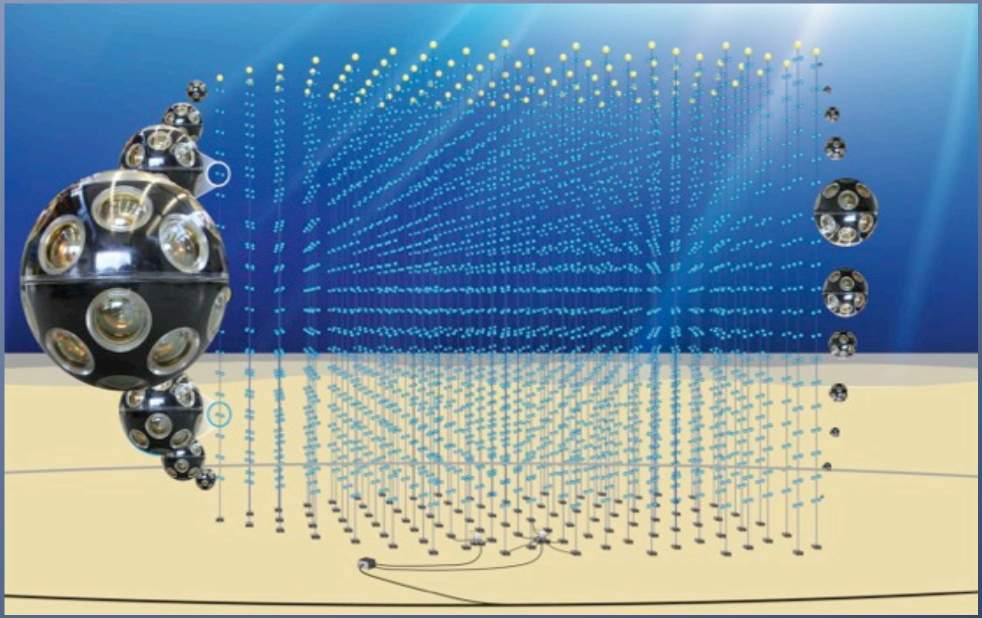



- ANTARES:
  - Better visibility than IceCube for the Galactic Centre

# KM3NeT

# KM3NeT

- KM3NeT is a common project to construct neutrino telescope in the Mediterranean with an instrumented volume of several cubic kilometers
- It will also be a platform for experiments on sea science, oceanography, geophysics, etc.
- 240 groups of Astroparticle Physics and Sea Science from 12 countries are involved
- New groups very welcome! (UGR just joined)



- Prototype lines have already been installed
- The first KM3NeT line has been installed in December 2015

# Phases

**PHASE 1:**

31 M€ (already secured)

- Already funded
- 31 lines (24 in Italy, 7 in France) to be deployed in 2015- early 2017
- Proof of feasibility and first science results

**PHASE 2.0:**

95 M€

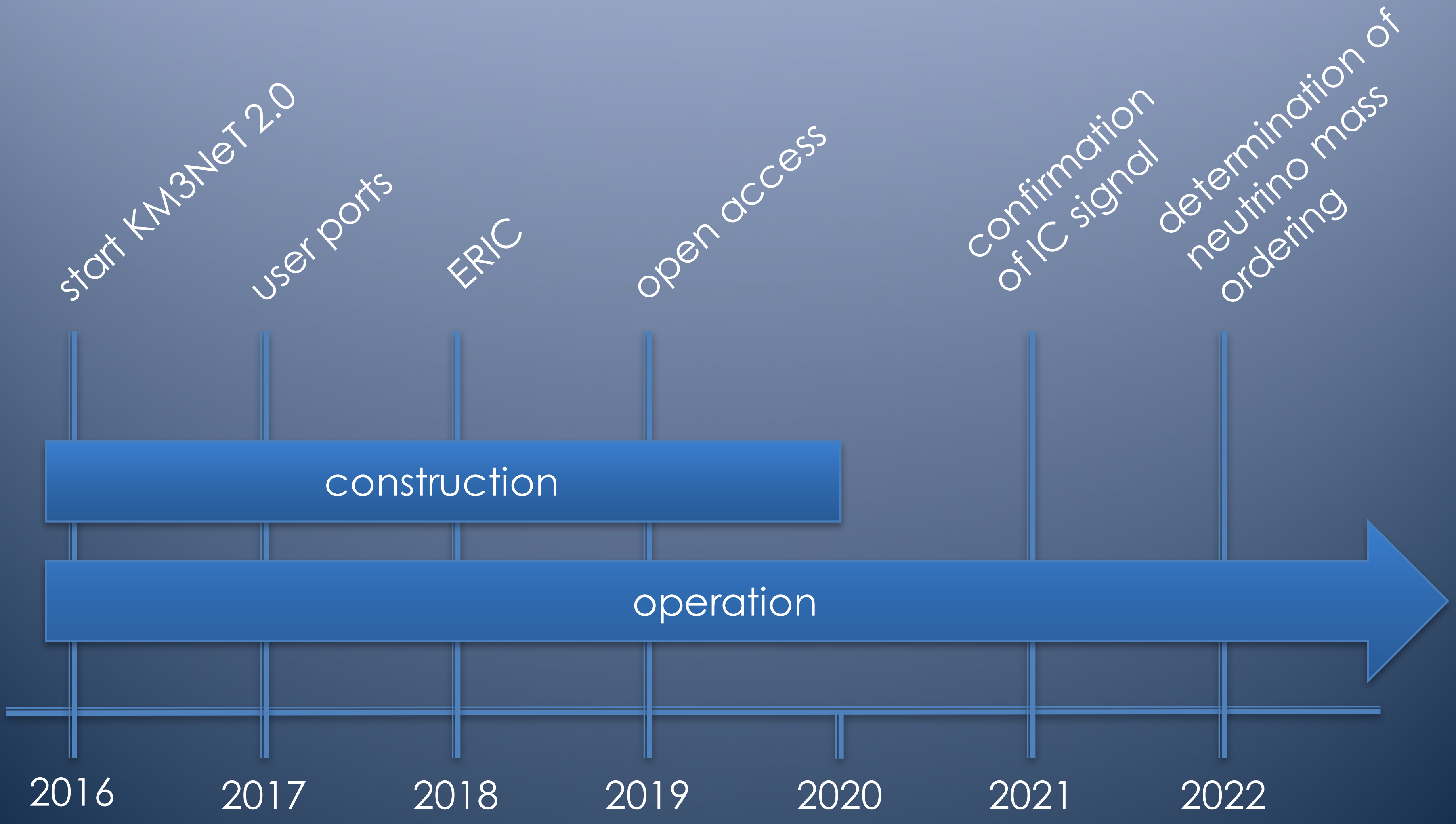
- ***ARCA*** (Astroparticle Research with Cosmic Rays)
  - Test IceCube signal
  - Italy
  - 2x115 lines
  - Sparse configuration
- ***ORCA*** (Oscillation Research with Cosmic Rays)
  - Mass hierarchy (and DM)
  - France
  - 115 lines
  - Dense configuration

**PHASE 3: FINAL CONFIGURATION**

95-125 M€

- 6x115 lines (in total)
- Neutrino astronomy including Galactic sources

# KM3NeT time line

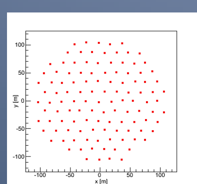


# ORCA and ARCA

- Same technology

ORCA

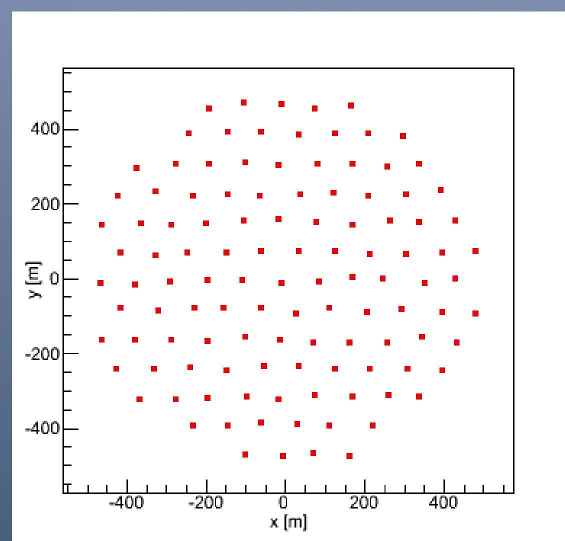
200 m



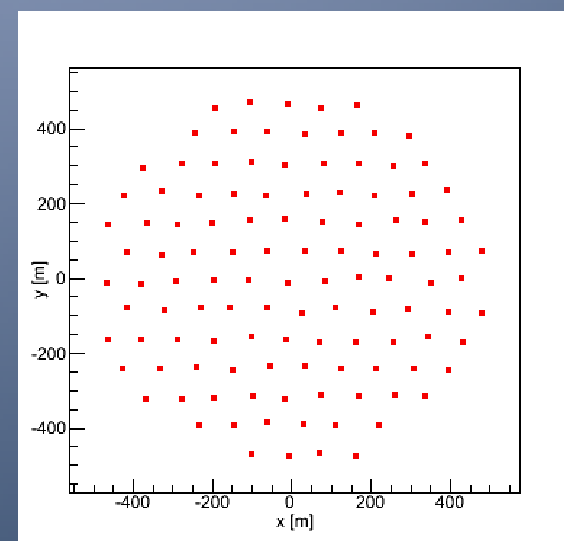
France

ARCA

1 km

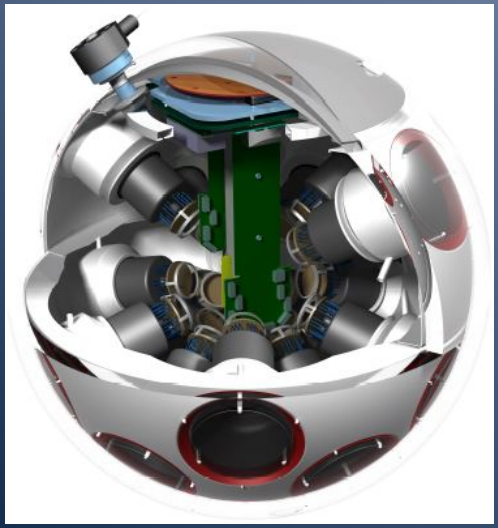



1 km



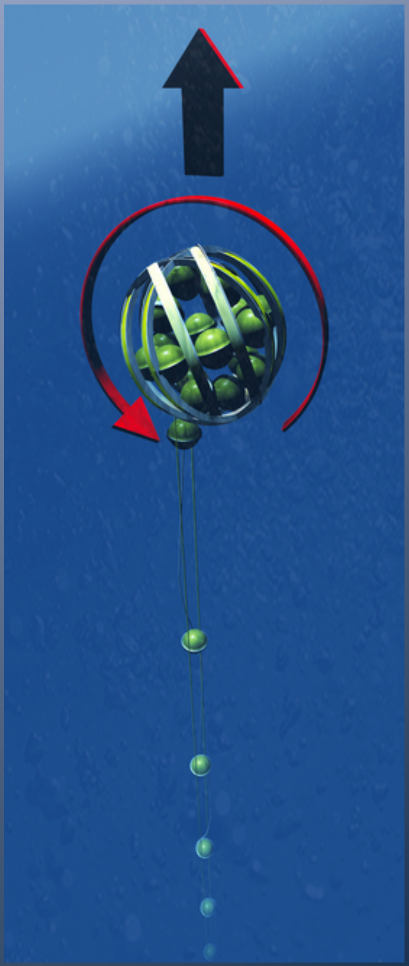

Italy

# KM3NeT Optical Modules



- (Multi-PMT) Optical Module
  - 31 x 3" PMTs
  - diameter: 17''
  - low power requirements
  - "full" module: no additional electronics vessel needed
  - uniform angular coverage
  - information of the arrival direction of photons
  - better rejection of background

- Detector Units (strings)
  - 18 DOMs, separated vertically by: 6 m (ORCA) or 36 m (ARCA)
  - anchored at sea floor by a dead weight
  - kept vertical by buoys
  - 115 DUs = 1 building block



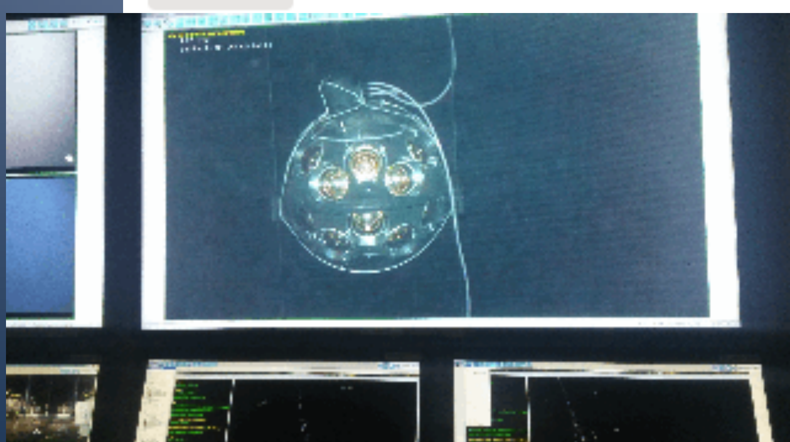
# First KM3NeT Line!

**Instalada la primera línea de detección del telescopio de neutrinos KM3NeT**

Enviado por Isidoro.Garcia@ific.uv.es en Vie, 04/12/2015 - 10:33

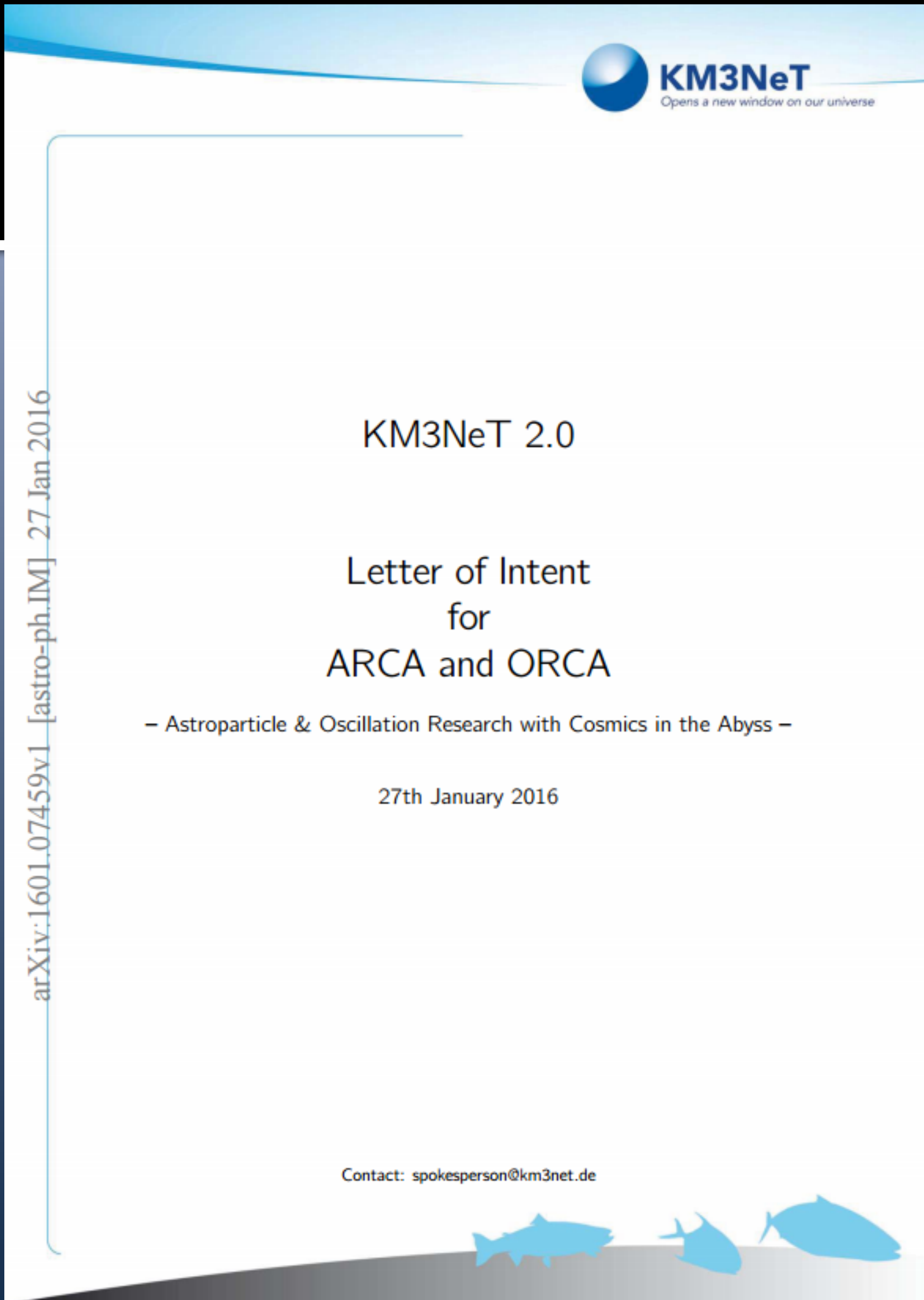
Este jueves se ha dado un paso crucial en la construcción del que será el mayor telescopio de neutrinos del mundo, KM3NeT. La colaboración internacional del experimento ha instalado la primera línea de detección frente a las costas de Capo Passero, cerca de Sicilia (Italia). El Instituto de Física Corpuscular (IFIC, CSIC-UV) ha contribuido de forma importante al éxito de este primer paso en la construcción de KM3NeT.

Leer más



# Letter of Intent

- Crucial step to show to the community the level of maturity of the project
- Crucial to ourselves to converge on the evaluation of the performance of the detector
- Now sent to J. Phys. G.
- arXiv:1601.07459


KM3NeT
Opens a new window on our universe

arXiv:1601.07459v1 [astro-ph.IM] 27 Jan 2016

KM3NeT 2.0

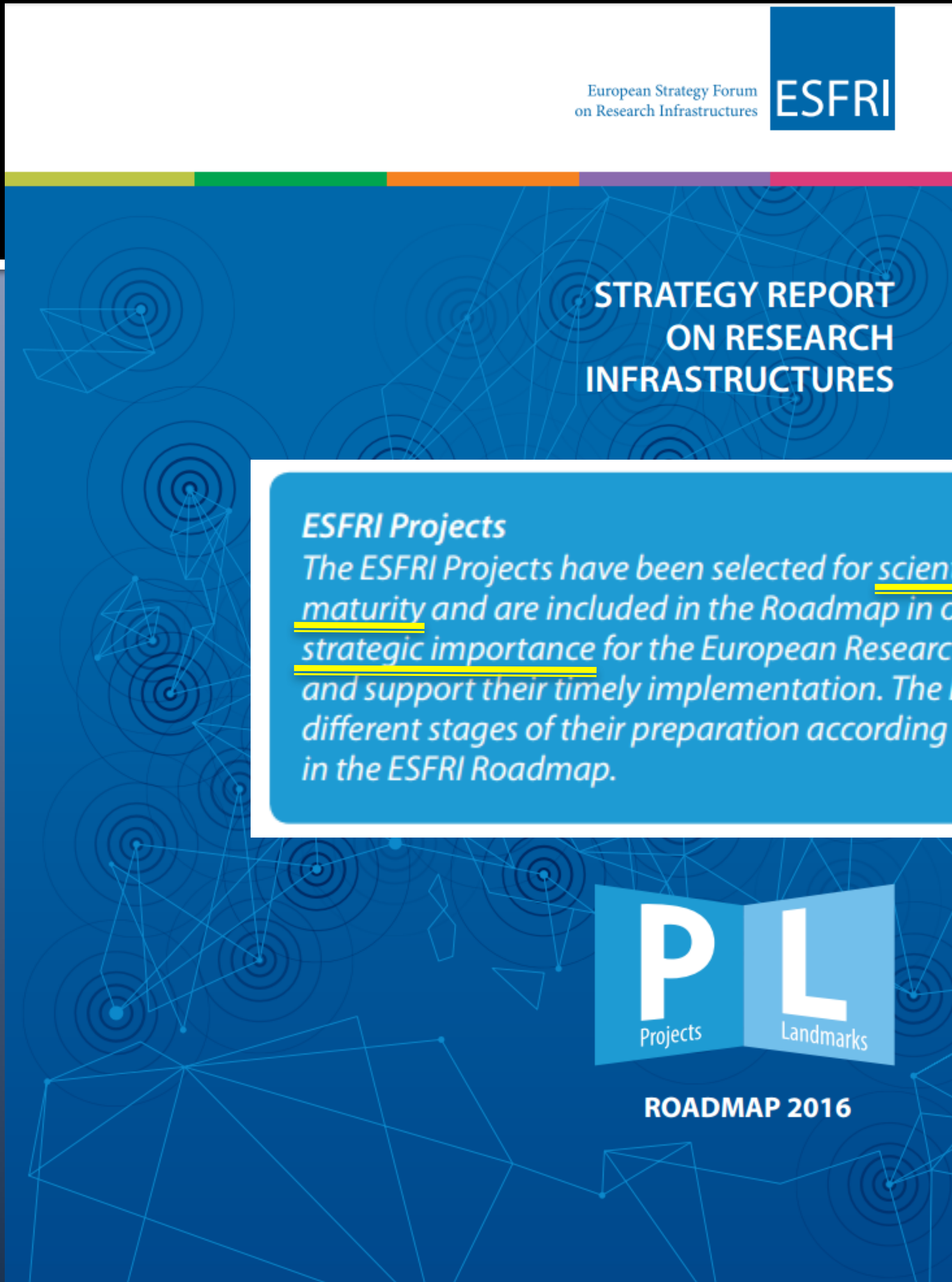
Letter of Intent
for
ARCA and ORCA

– Astroparticle & Oscillation Research with Cosmics in the Abyss –

27th January 2016

Contact: spokesperson@km3net.de

# KM3NeT in the ESFRI list




***ESFRI Projects***
*The ESFRI Projects have been selected for scientific excellence and maturity and are included in the Roadmap in order to underline their strategic importance for the European Research Infrastructure system and support their timely implementation. The ESFRI Projects can be at different stages of their preparation according to the date of inclusion in the ESFRI Roadmap.*

## KM3NeT 2.0

**KM3 Neutrino Telescope 2.0: Astroparticle & Oscillations Research with Cosmics in the Abyss**

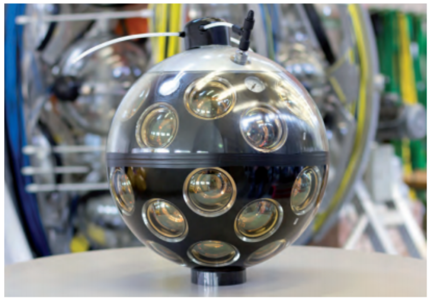
*A network of neutrino telescopes in the Mediterranean Sea for astroparticle and oscillations research*

**Description**

typical energies observed in cosmic rays. Neutrinos are ideal for observing the highest-energy phenomena in the Universe and, in particular, pinpointing the hitherto unknown sources of cosmic rays.

The IceCube neutrino telescope at the South Pole has detected a flux of cosmic neutrinos which is assumed to have its origin in extragalactic sources. They might be the same sources that produce the flux of the highest energy gamma rays observed, for instance, by H.E.S.S.

the first time. The phase one of the project has led to the engineering of the modular detector and to construction of the final prototypes. The resubmission of KM3NeT 2.0 redefines the previous project and adopts it to the scientific and technological progress which has been made in the last years. It is effectively under construction as a first set of the new detectors is being deployed at this time.



**TYPE**: distributed
**COORDINATING COUNTRIES**: NL
**PROSPECTIVE MEMBER COUNTRIES**: EL, FR, IT, NL

**PARTICIPANTS**: CY, DE, ES, IE, PL, RO, UK

**TIMELINE**
- ESFRI Roadmap entry: 2006, 2016
- Preparation phase: 2008-2014
- Construction phase: 2016-2020
- Operation start: 2020

**ESTIMATED COSTS**
- Capital value: 137 M€
- Preparation: 45 M€
- Construction: 92 M€
- Operation: 3 M€/year

**HEADQUARTERS**
KM3NeT-HQ
Amsterdam Science Park
Amsterdam
The Netherlands

**WEBSITE**
http://www.km3net.org/

THE NETHERLANDS

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# ESFRI Roadmap 2016

## ESFRI PROJECTS

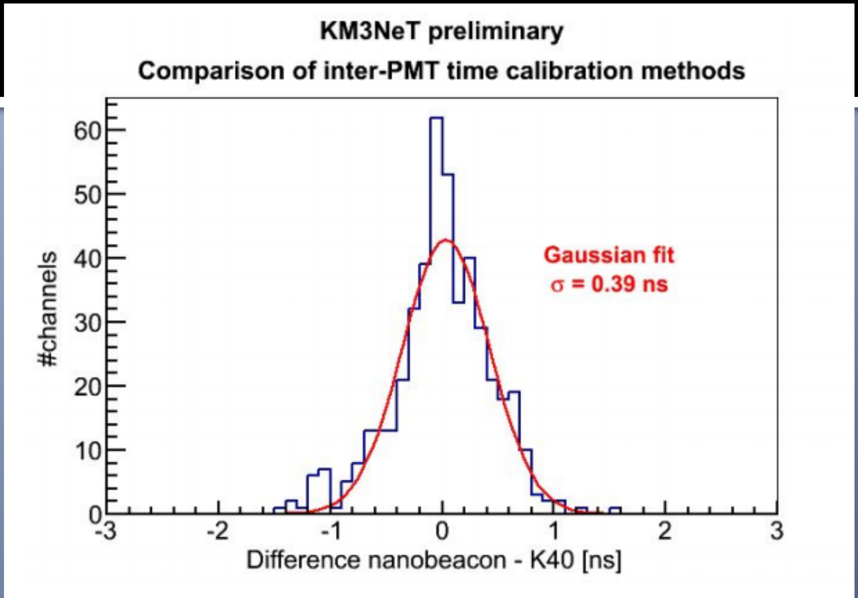
| | NAME | FULL NAME | ROADMAP ENTRY (YEAR) | OPERATION (YEAR) | LEGAL STATUS (AS OF 10 MARCH 2016) | CONSTRUCTION COSTS (M€) | OPERATIONAL ANNUAL BUDGET (M€/YEAR) |
|---|---|---|---|---|---|---|---|
| PHYSICAL SCIENCES & ENGINEERING | **CTA** | Cherenkov Telescope Array | 2008 | 2023* | | 297 | 20 |
| | **EST** | European Solar Telescope | **2016** | 2026* | | 200 | 9 |
| | **KM3NeT 2.0** | KM3 Neutrino Telescope 2.0: Astroparticle & Oscillations Research with Cosmics in the Abyss | **2016** | 2020* | | 92 | 3 |

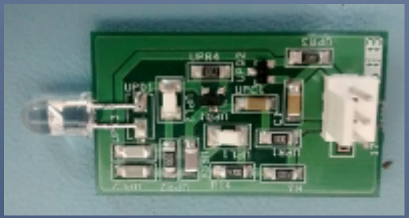
# Relevance of the ESFRI Roadmap

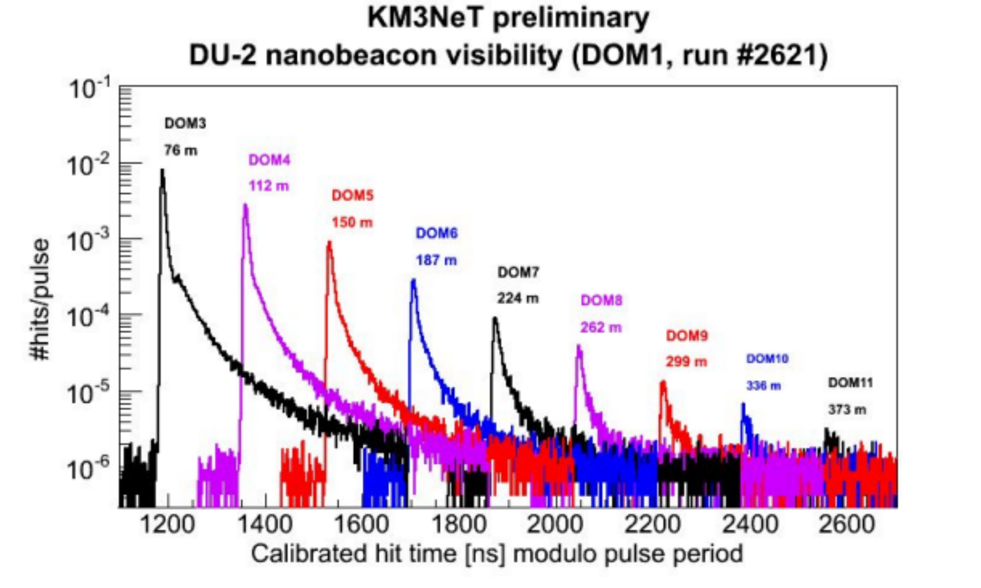
- The inclusion in the ESFRI Roadmap list is a **seal of quality**
- Concerning funding:
  - **FEDER** funds for scientific infrastructures can **only** be used in project in the **ESFRI list**
  - According to **RIS3** rules, FEDER funds can only be used in regions where the infrastructure is **NOT located** (provided it is shown that this investment help to the region development)

# Nanobeacons

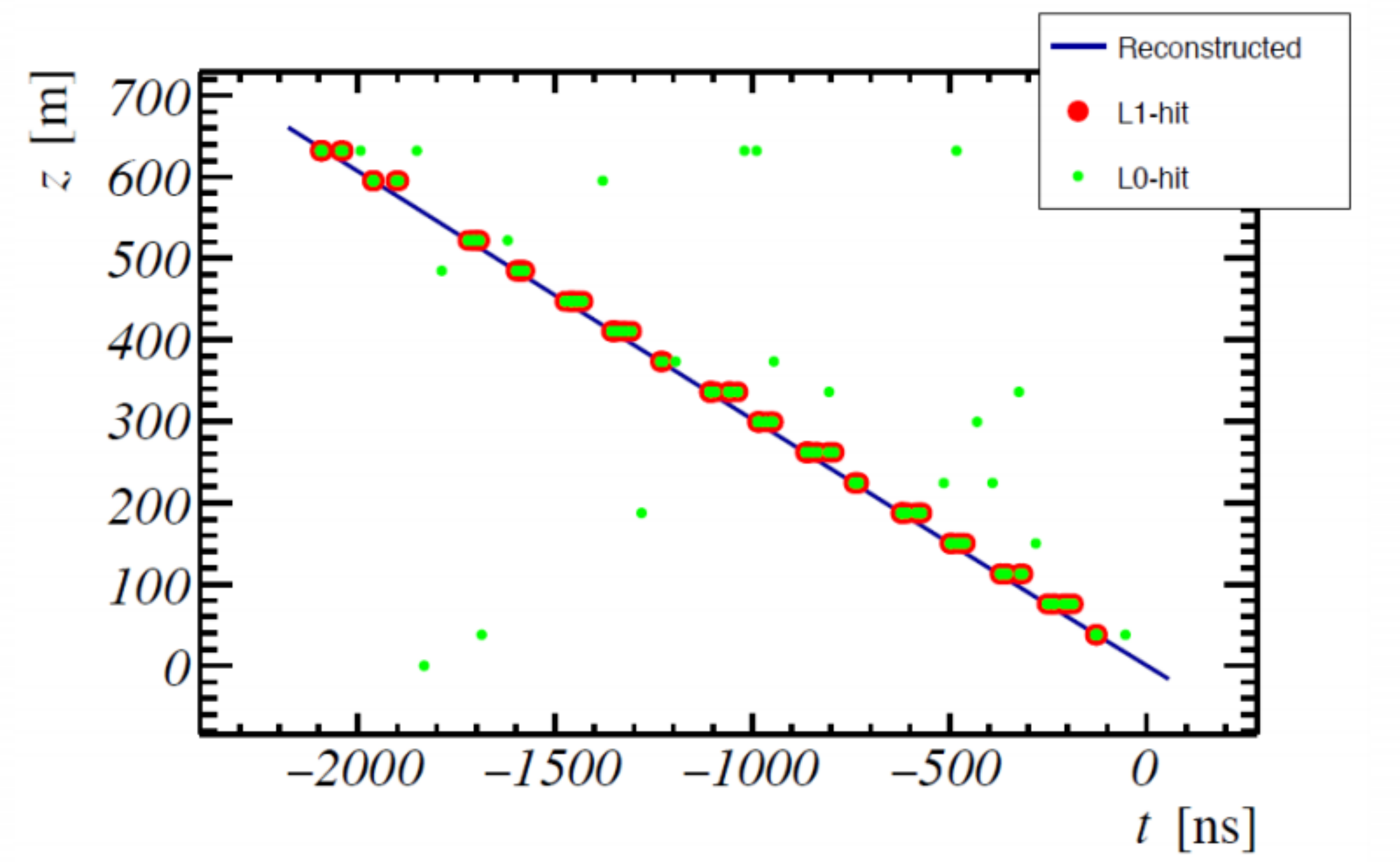
- One pulsed LED in each DOM, pointing upwards, for time calibration and measurements of water optical properties





# First data

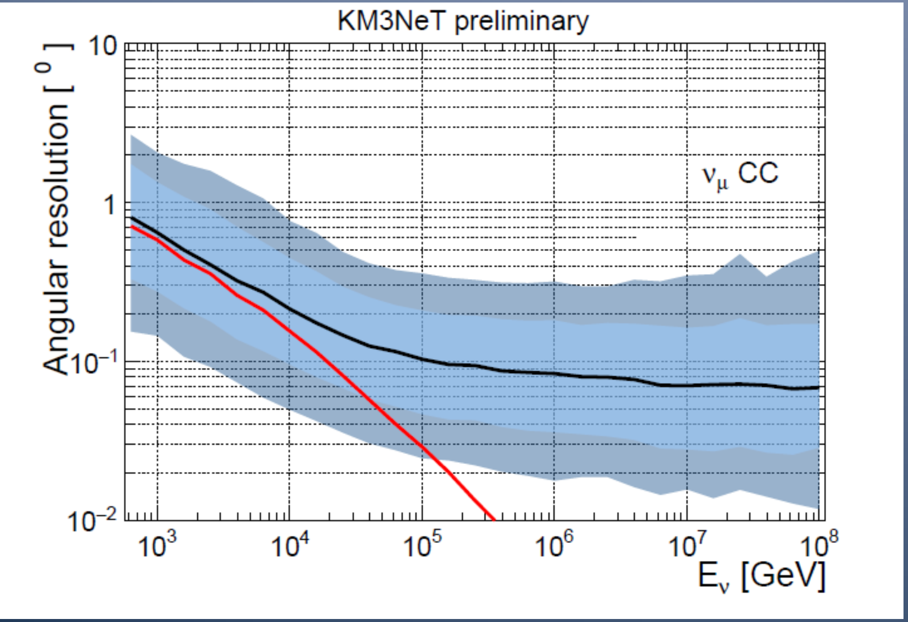



- Downgoing track. Reconstructed zenith angle: 0.89 deg

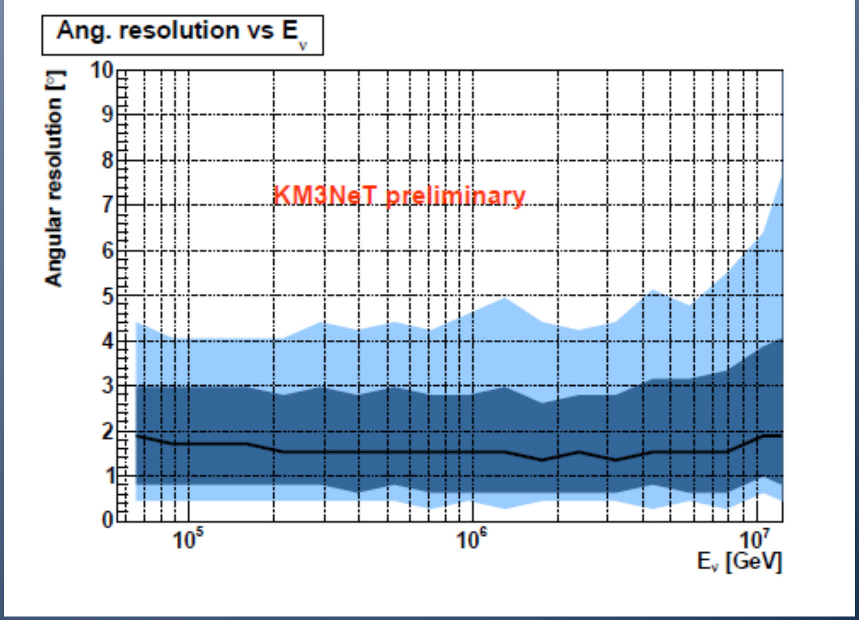
# ARCA performance (I)

- Water: best angular resolution
  - For tracks: ~0.1-0.2 degrees
  - For cascades: < 2 degrees:

Tracks



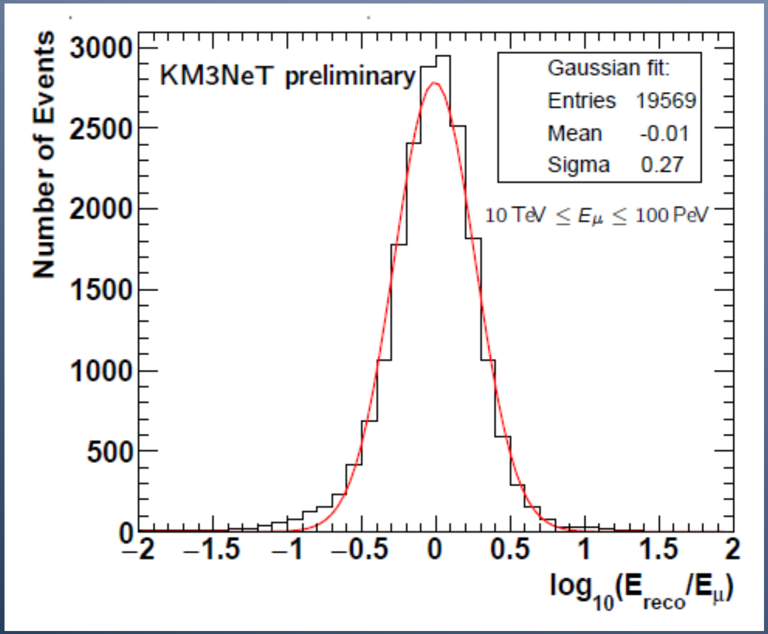

Cascades



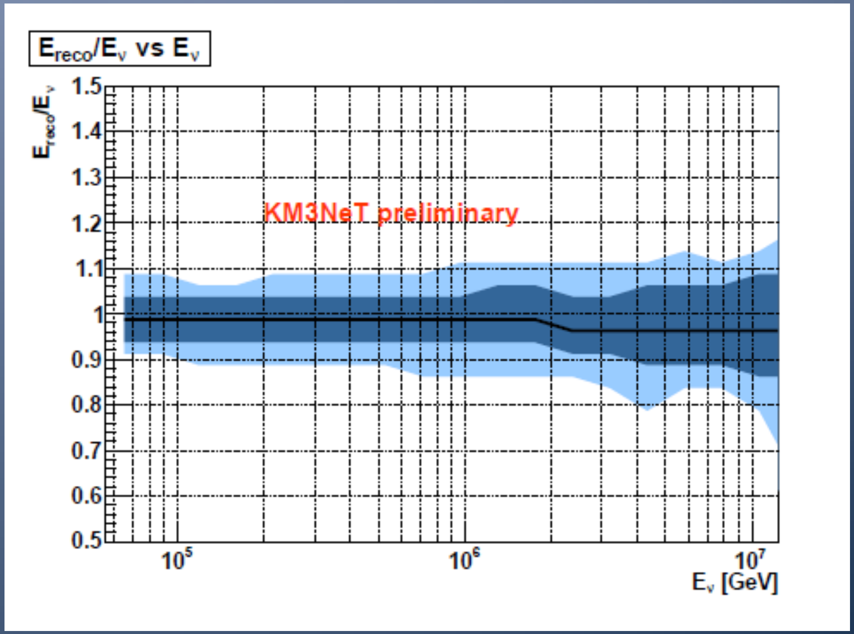
# ARCA performance (II)

- Energy resolution (1σ):
  - ~0.27 in $Log_{10}(E_\mu)$ for tracks
  - 5%-10% for contained cascades

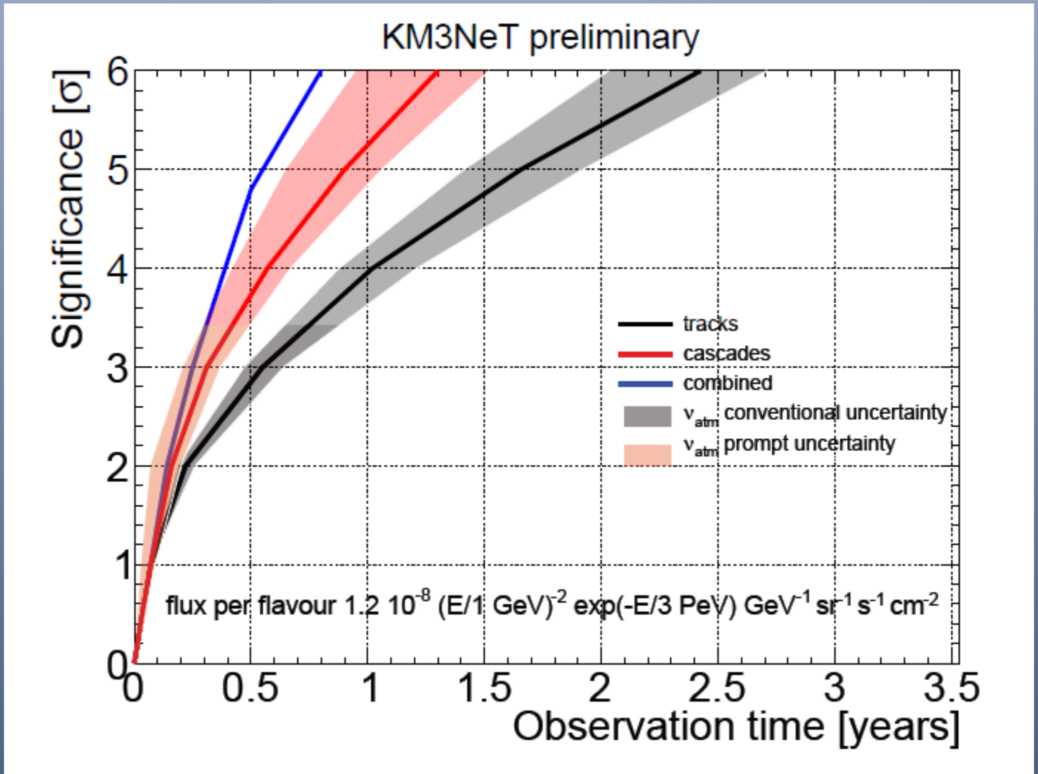
Tracks




Cascades



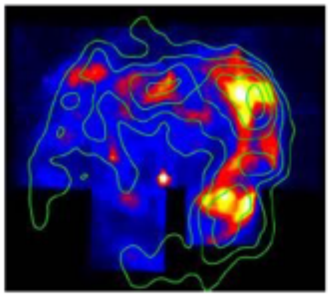
# ARCA: sensitivity to diffuse fluxes



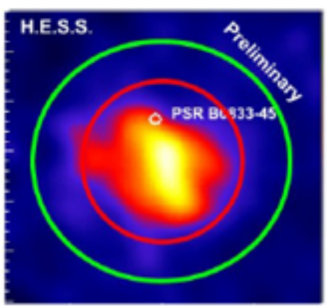

Significance as a function of time for the detection of a diffuse flux of neutrinos corresponding to the signal reported by IceCube, for cascade-like events (red line) and track-like events (black line). The blue line indicates the result of the combined analysis.

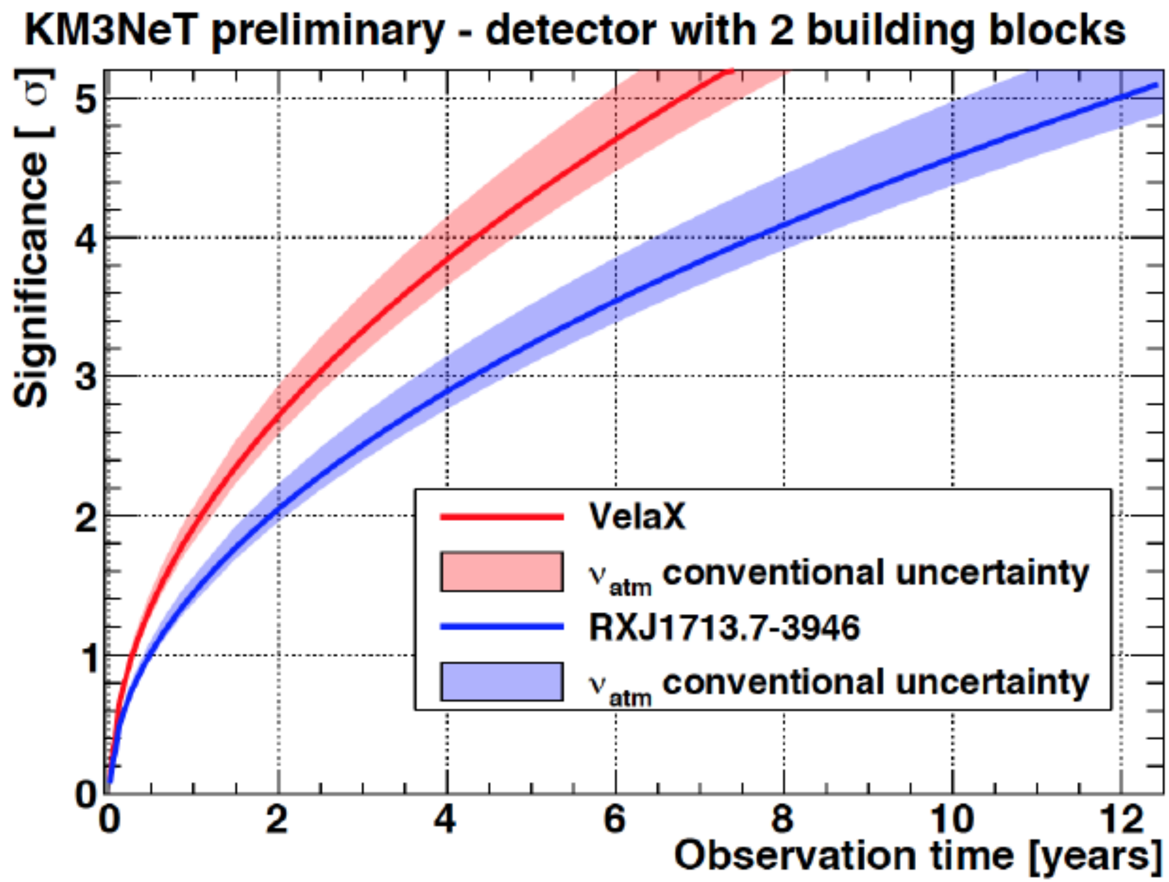
# ARCA: sensitivity to point sources

RXJ1713[¶] (SNR)



Vela X[§] (PWN)

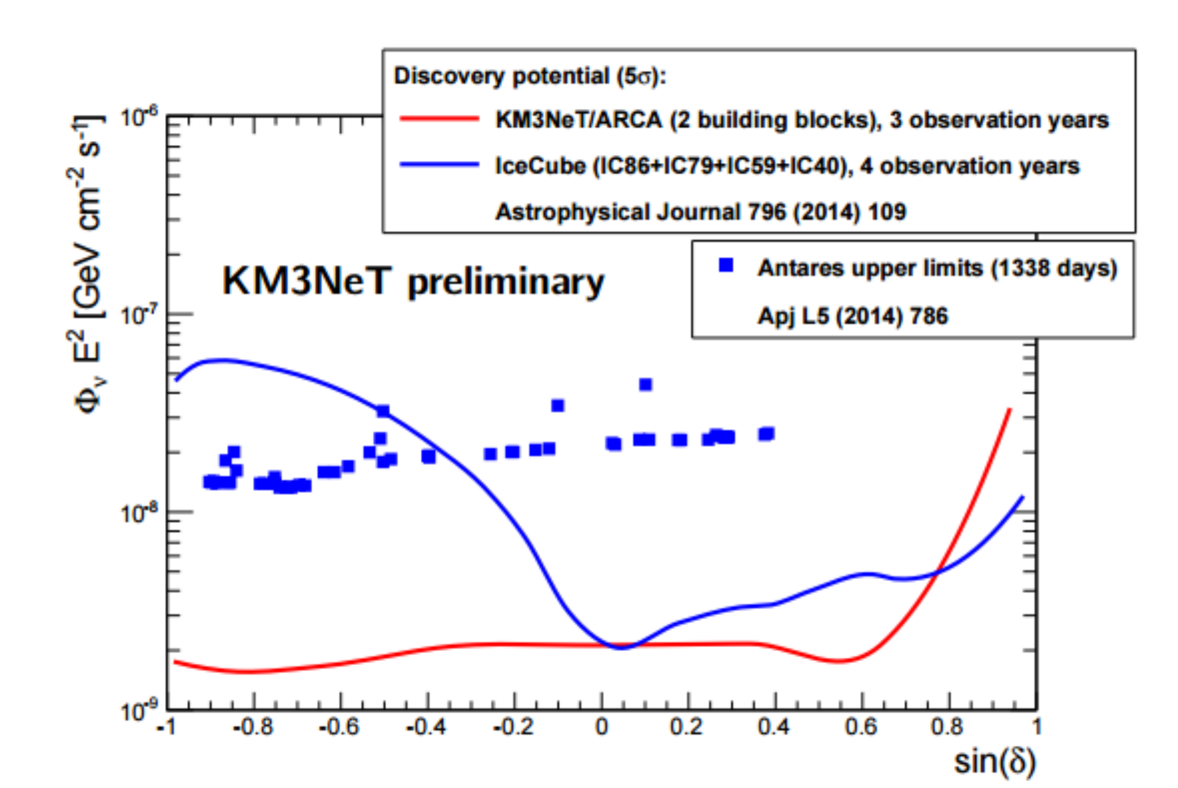



¶ S.R. Kelner, *et al.*, Phys. Rev. D 74 (2006) 034018.

§ F.L. Villante and F. Vissani, Phys. Rev. D 78 (2008) 103007.

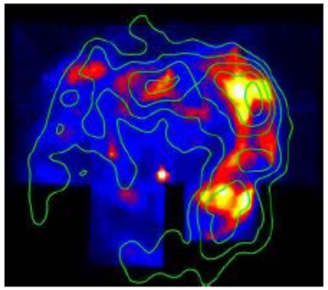
# ARCA: sensitivity to point sources



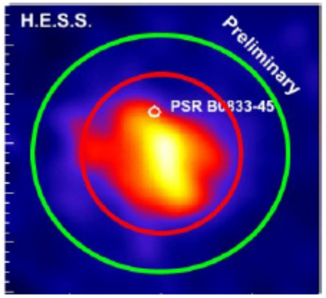

- KM3NeT/ARCA 5σ discovery potential as a function of the source declination (red line) for one neutrino flavour, for point-like sources with a spectrum $\propto E^{-2}$ and 3 years of data-taking

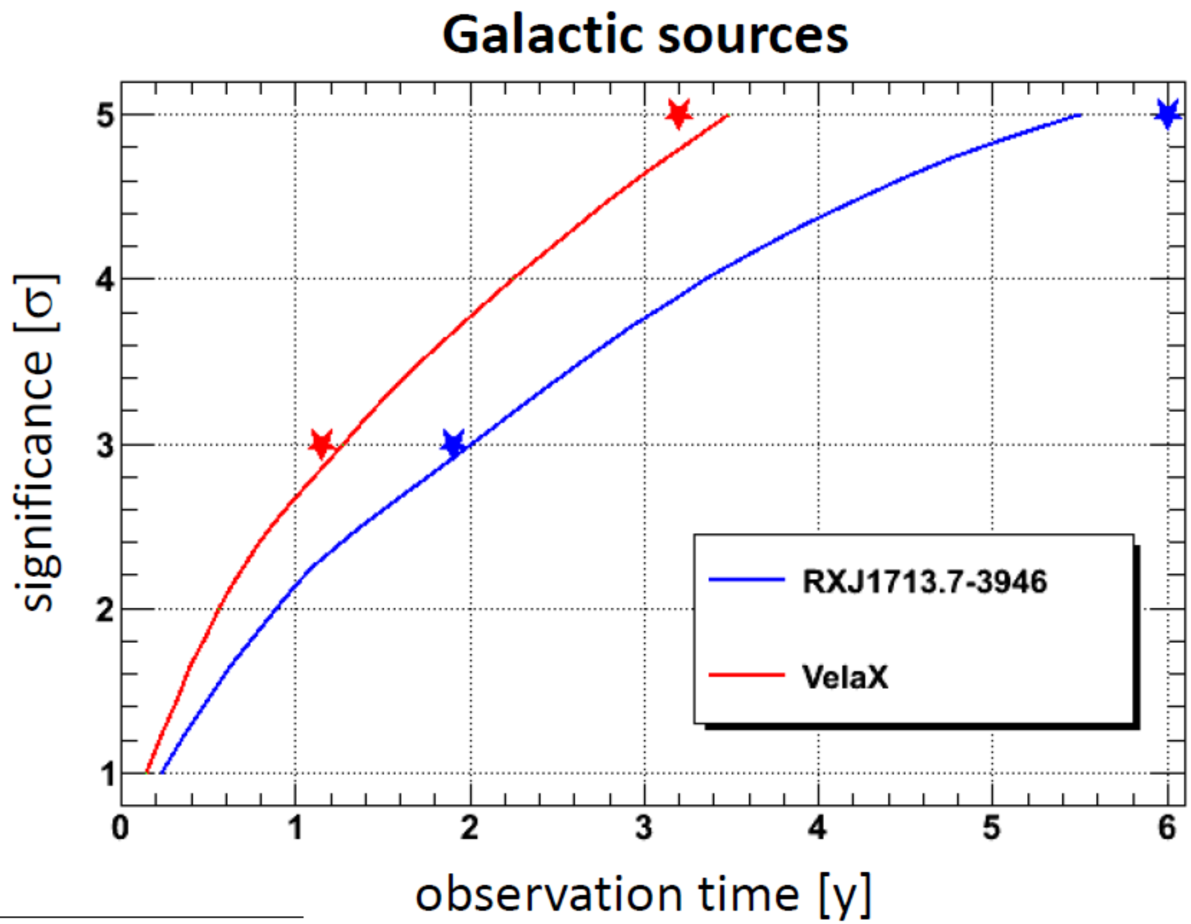
# Phase 3

RXJ1713[¶] (SNR)



Vela X[§] (PWN)



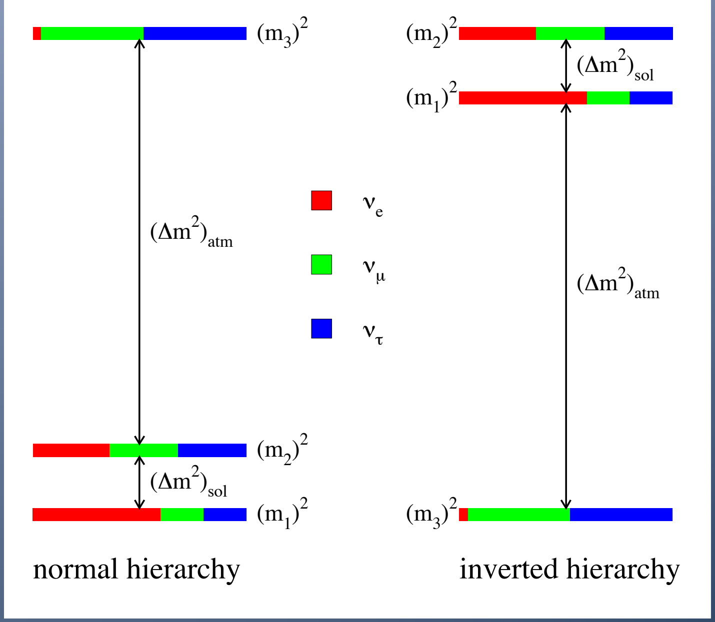

[¶] S.R. Kelner, *et al.*, Phys. Rev. D 74 (2006) 034018.

[§] F.L. Villante and F. Vissani, Phys. Rev. D 78 (2008) 103007.

# ORCA

# Introduction

- Neutrino mass hierarchy is one of the most relevant unknowns in Particle Physics
  - constrain theoretical models to explain the origin of mass in leptonic sector
- Impact on potential performance of next-generation experiments for
  - CP-phase measurement
  - absolute value of neutrino masses
  - 0νββexperiments



# NMH in ORCA

- In matter, the sign of $\Delta m^2_{13}$ is revealed through the CC interactions of $\nu_e$ with electrons

$$P^m_{3\nu}(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\,\sin^2 2\theta^m_{13}\,\sin^2\left(\frac{\Delta^m m^2_{31}\,L}{4E_\nu}\right),$$

$$\sin^2 2\theta^m_{13} \equiv \sin^2 2\theta_{13}\left(\frac{\Delta m^2_{31}}{\Delta^m m^2_{31}}\right)^2$$

$$\Delta^m m^2_{31} \equiv \sqrt{(\Delta m^2_{31}\,\cos 2\theta_{13} - 2\,E_\nu A)^2 + (\Delta m^2_{31}\,\sin 2\theta_{13})^2},$$

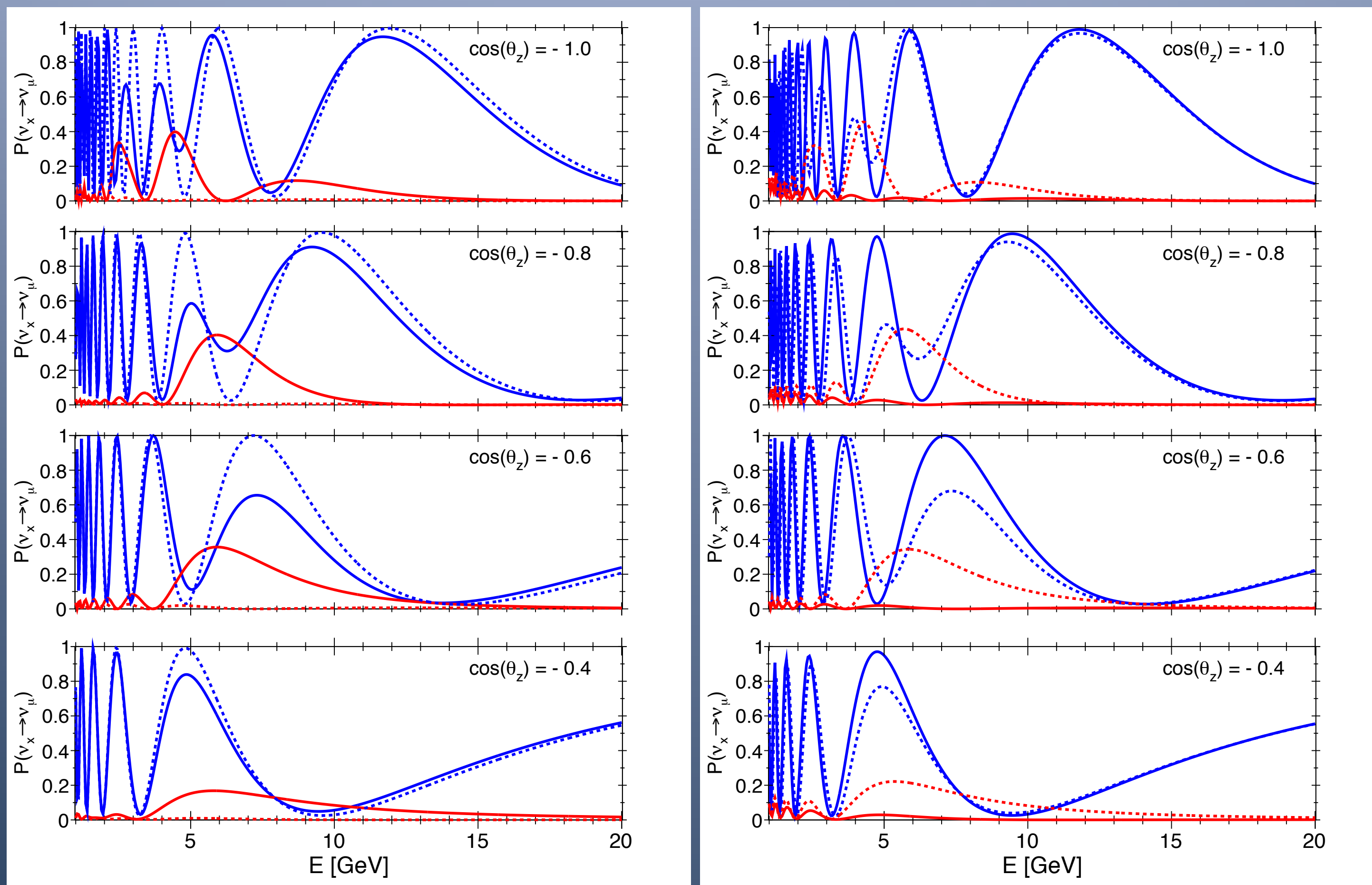
- Resonance condition is met for NH (IH) in the neutrino (anti-neutrino) channel when

$$E_{\rm res} \equiv \frac{\Delta m^2_{31}\,\cos 2\theta_{13}}{2\,\sqrt{2}\,G_F\,N_e} \simeq 7\,{\rm GeV}\left(\frac{4.5\,{\rm g/cm^3}}{\rho}\right)\left(\frac{\Delta m^2_{31}}{2.4\times 10^{-3}\,{\rm eV^2}}\right)\cos 2\theta_{13}$$

$E_{res}$~7 GeV for mantle
$E_{res}$~3 GeV for core

# Oscillation probabilities

Neutrinos    Antineutrinos

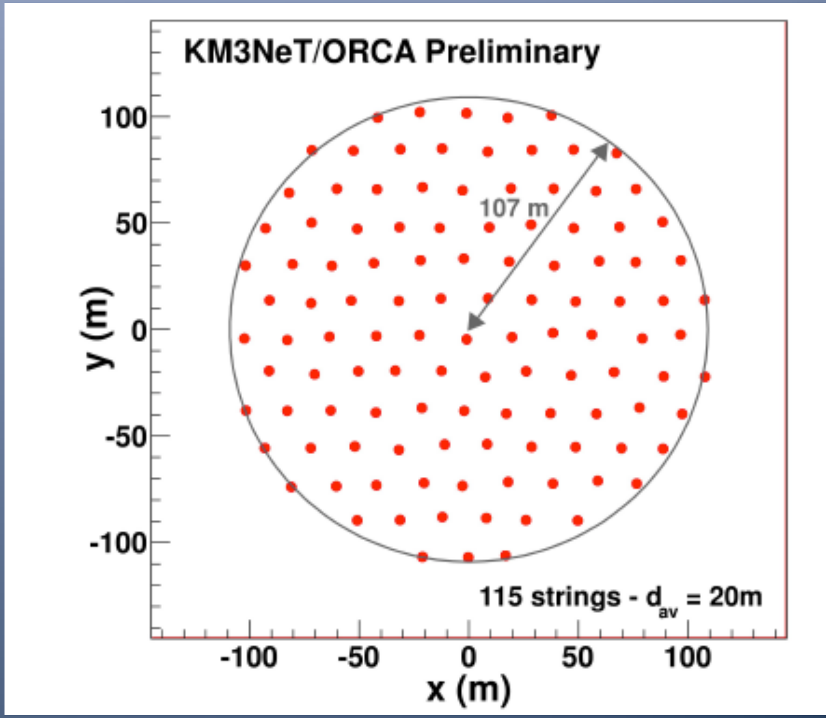



$\nu_\mu \to \nu_\mu$ (blue lines) and $\nu_e \to \nu_\mu$ (red lines) a

solid: NH
dashed: IH

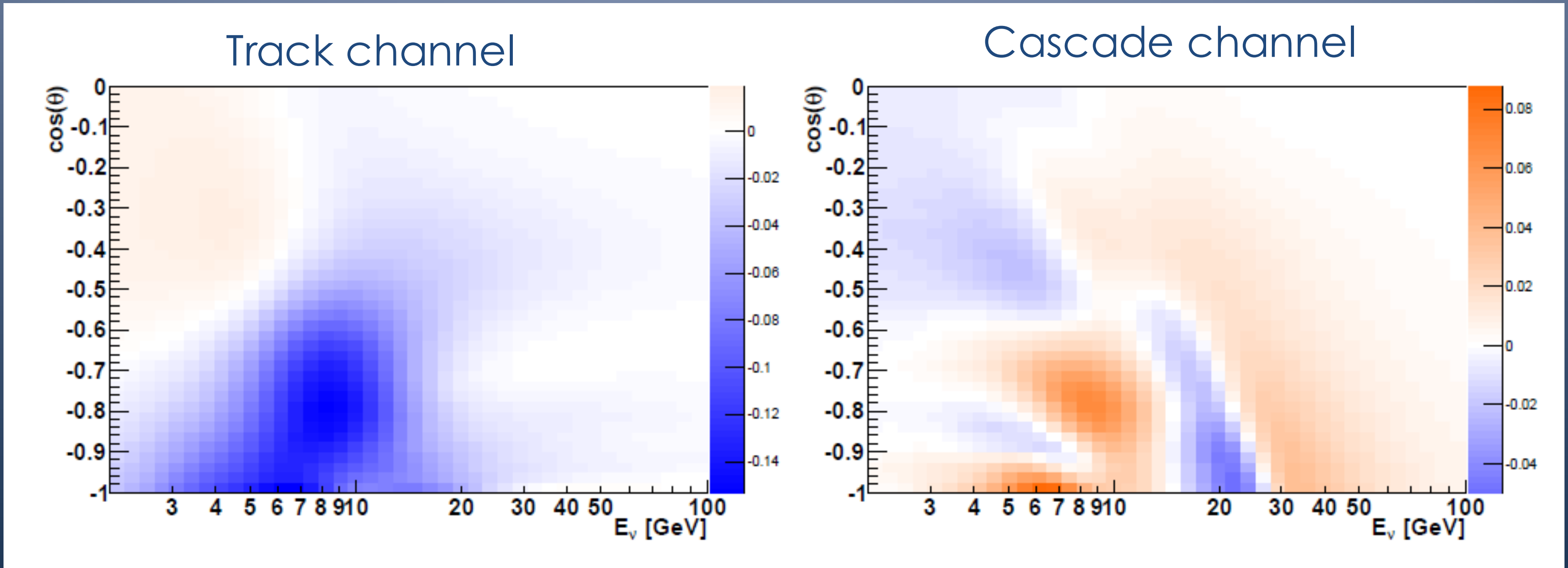
# ORCA

- The proposed ORCA detector consists of 2070 OMs (with multi-PMTs)
- 18 OMs/line, 9 m spaced
- Instrumented volume 5.8 Mton



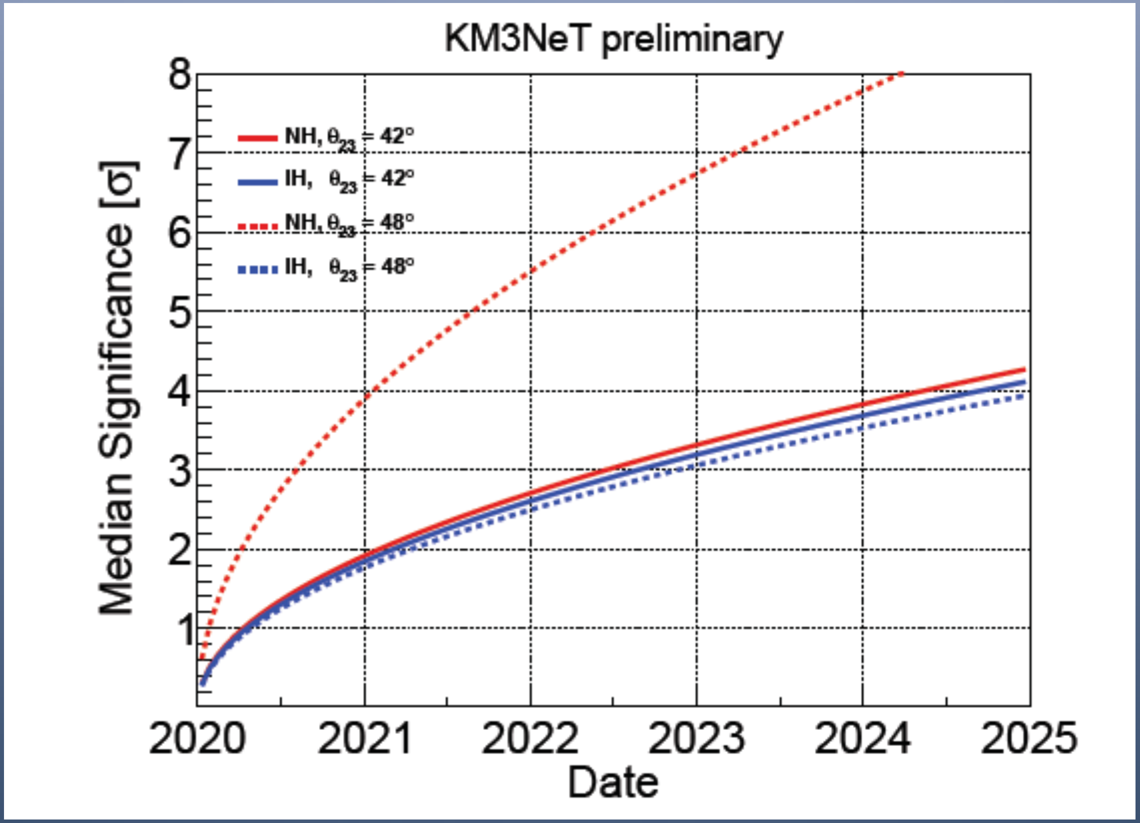
# Oscillograms

- Finite angular/energy resolutions, uncertainties in oscillation parameters, etc. blur quite a lot the "theoretical" oscillograms, but it still seems to be enough signal




$A' = (N_{IH} - N_{NH}) / N_{NH}$

# Sensitivity to NMH



# Phase 1 status

- First line deployed in December 2015
- 2015-2017: installation of 31 lines
  - 24 à la ARCA in the Italian site
  - 7 à la ORCA in the French site

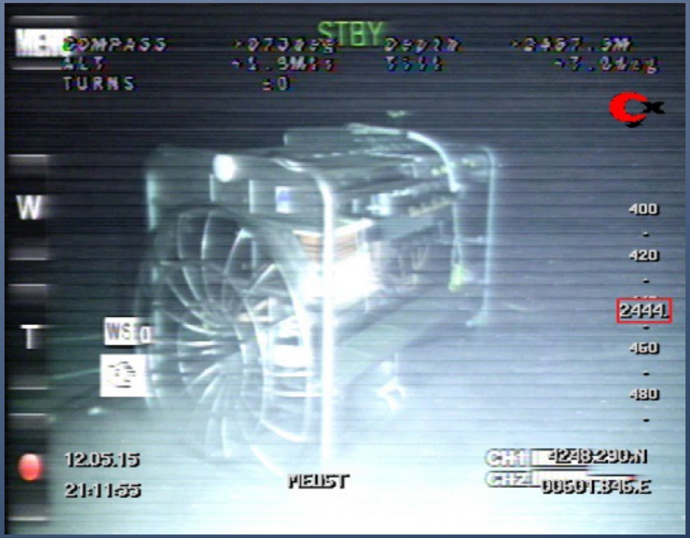
LOMs ready for deployment

DOMs during tests @ NIKHEF

DOMs in dark room @ CPPM

# Phase 1 status

- KM3NeT-It:
  - one primary node and two secondary nodes were connected in summer 2015
  - deployment of DU3 and DU4 planned for May 2016
- KM3NeT-Fr:
  - deployment of cable during this week (April 2016)
  - node to be deployed in May 2016
  - qualification of ORCA in spring 2016
  - deployment of first ORCA line planned for early summer

# Construction plans

- DOM integration:
  - Target production speed: 3-5 DOMs/week/site
  - Four sites preparing massive DOM integration (NIKHEF, Erlangen, Naples, Catania). Strasbourg preparing to join.
- DU integration:
  - Target speed: faster than 1 DU/month/site
  - Three sites preparing for DU integration (NIKEF, CPPM, Naples). Catania will join.

# Summary (I)

- A new era of extended multi-messenger astronomy is starting
- Cosmic rays, more than one century after their discovery, still bring many interesting questions
- Neutrino astronomy is a extraordinary tool for both Astroparticle and Particle Physics
- IceCube has found the first evidence for a cosmic neutrino signal
- ANTARES has showed the feasibility of the technique in water
- ANTARES, although quite smaller, has produced a very rich scientific results and is able to say a lot about the IceCube signal

# Summary (II)

- First KM3NeT line constructed, to be deployed in the following weeks
- KM3NeT-ARCA will take advantage of the Mediterranean:
  - medium: best angular resolution
  - location: best visibility of our Galaxy

with the appropriate size for (all-flavour!) neutrino astronomy and improved technology (multi-PMTs)

- KM3NeT-ORCA is an extraordinary opportunity for the first measurement of the neutrino mass hierarchy in terms of timescale and budget
- Multi-messenger astronomy has a lot to offer…

# Thanks for your attention!