IDPASC, Valencia, May 2018

Neutrino Telescopes II

Juande Zornoza (IFIC, UV-CSIC)

Outline

LECTURE 1

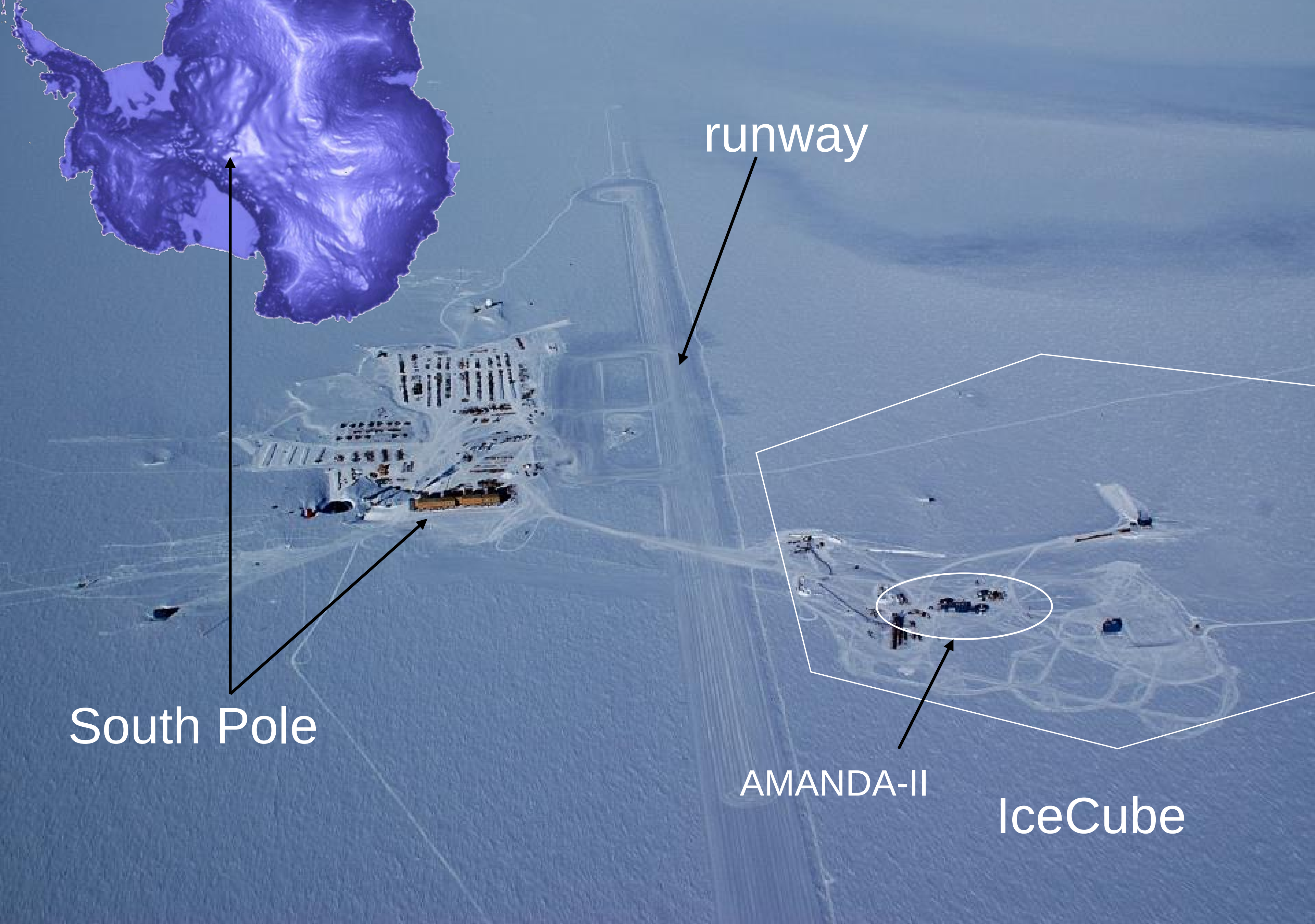
- Introduction to neutrinos
- Scientific motivation
- Signal and background
- Detector design
- Pioneers

LECTURE 2

- Scientific results
  - IceCube
  - ANTARES
- Next future
  - KM3NeT

IceCube

Amundsen-Scott South Pole Station



IceCube

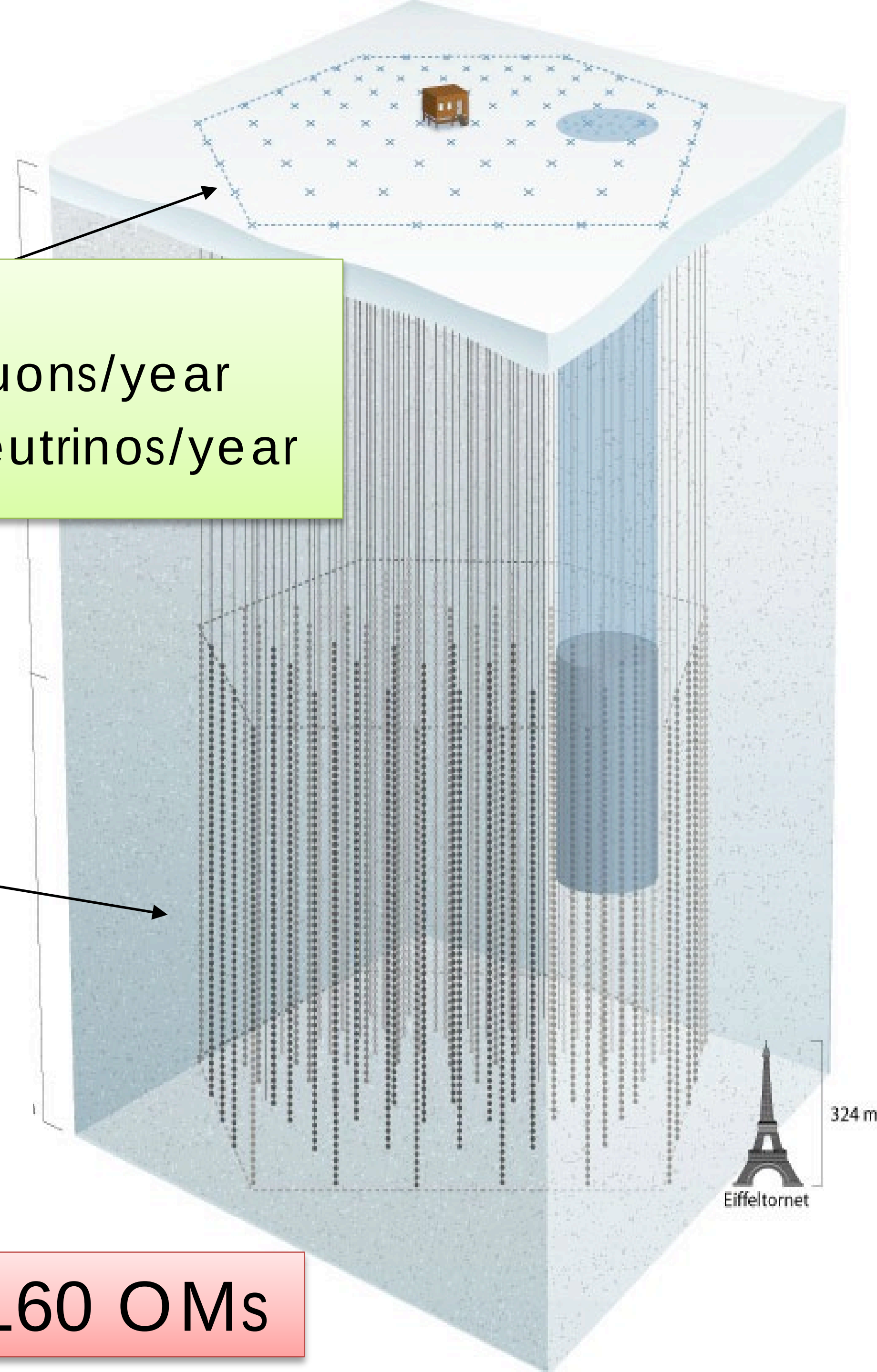
IceTop

80 pairs of ice Cherenkov tanks
Threshold ~ 300 GeV

IC86:

~ 5×10^{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

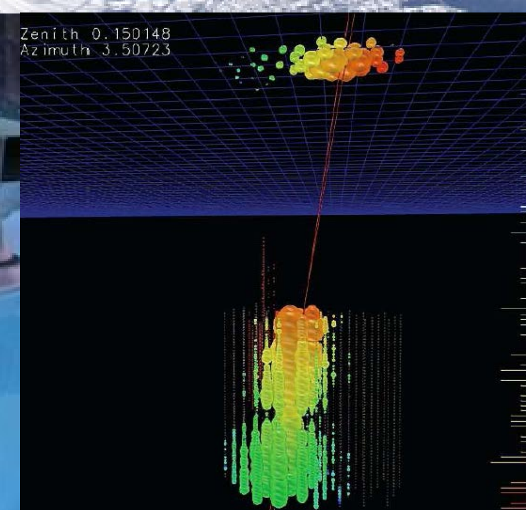
Deep Core

6 strings with 60 HQE OMs
Inner part of the detector

IceCube + Deep Core = 5160 OMs

IceTop

- 80 stations
  - 2 tanks per station
  - 2 DOMs per tank
- Cosmic ray studies
  - 2.8 km altitude
- Use as veto for below ice detector

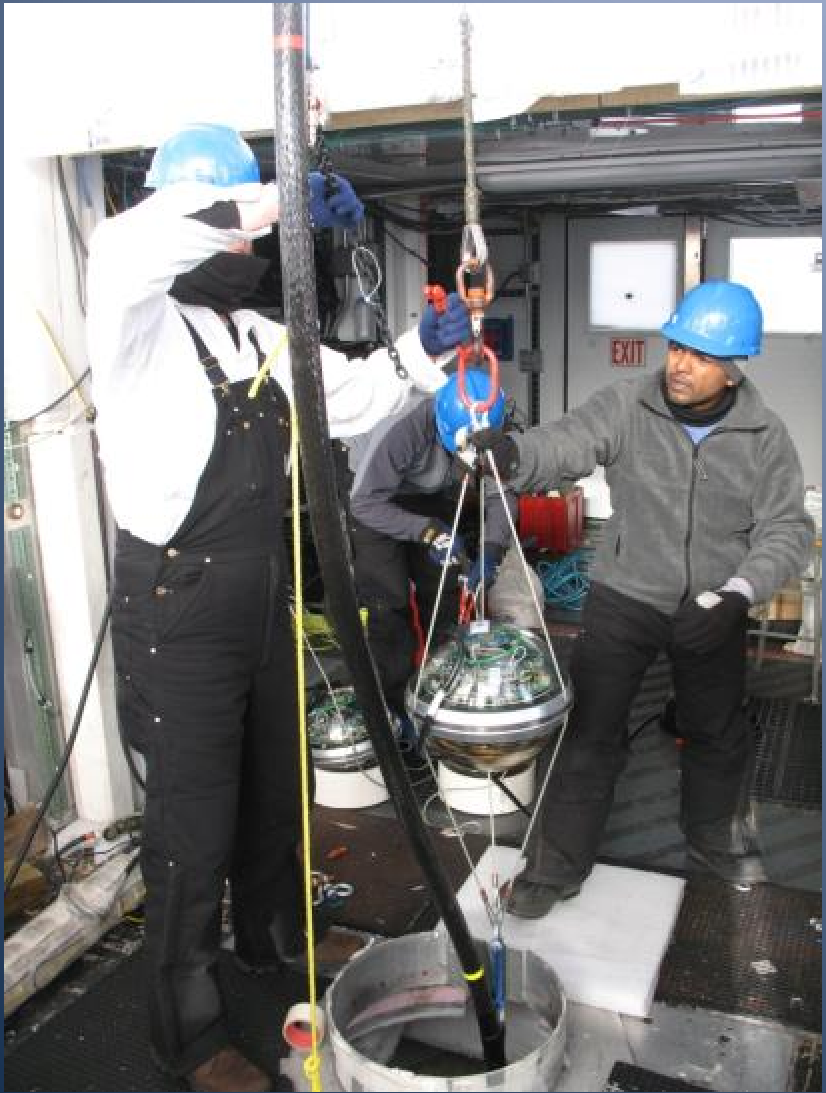


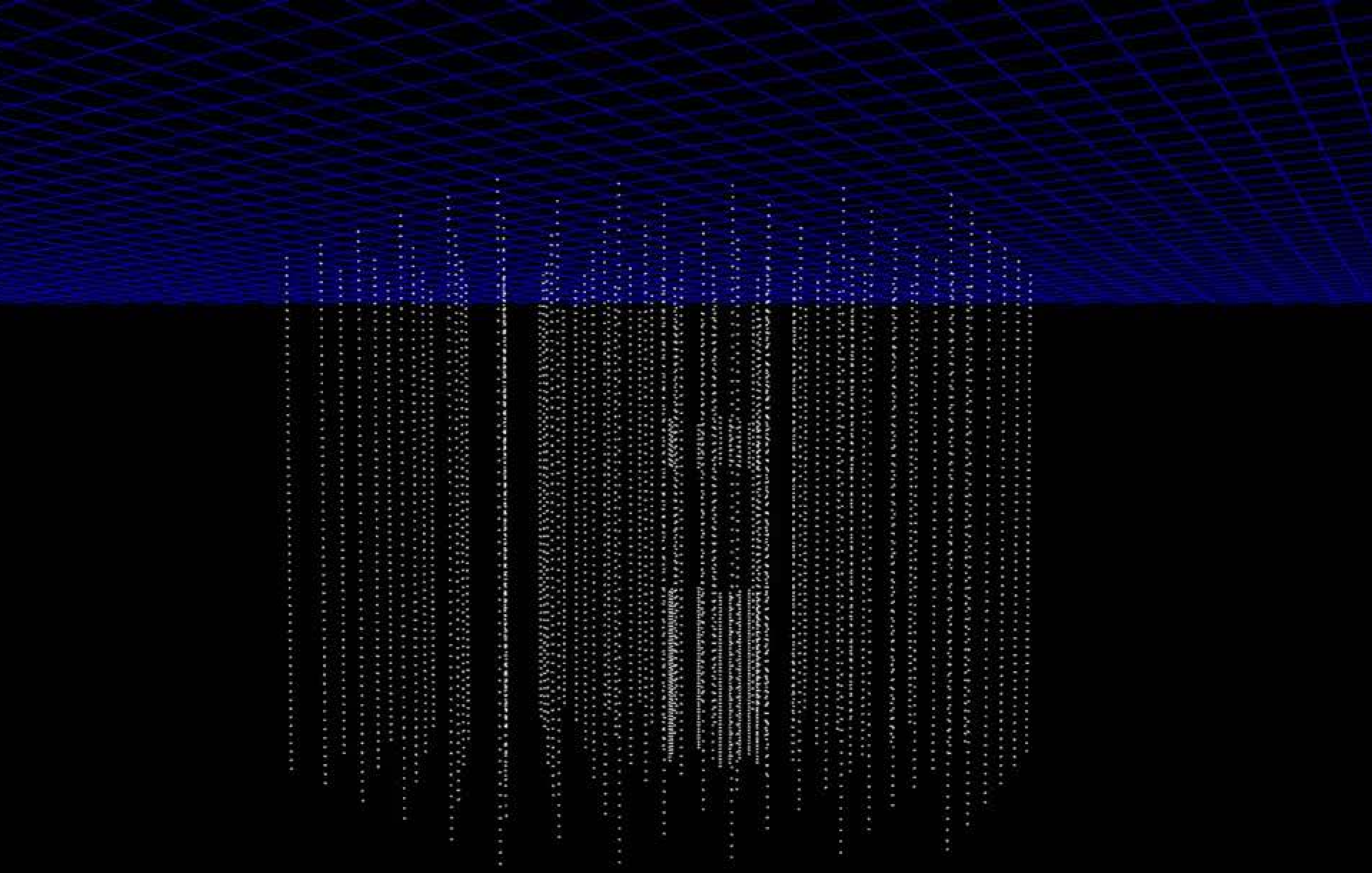

5 megawatt power plant
10^6 kg of drilling equipment

String deployment

about 2 days to drill the 2.5 km hole

String installation

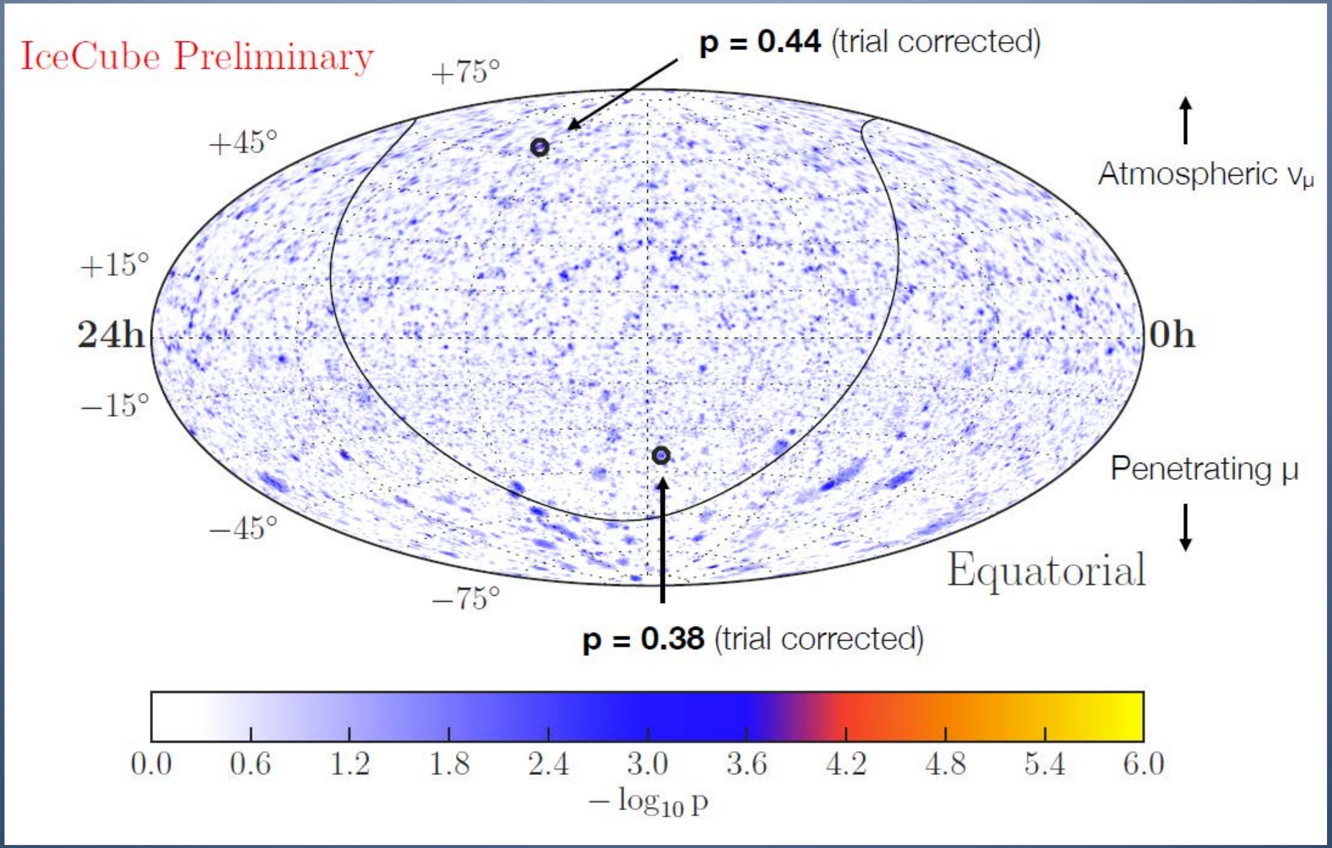




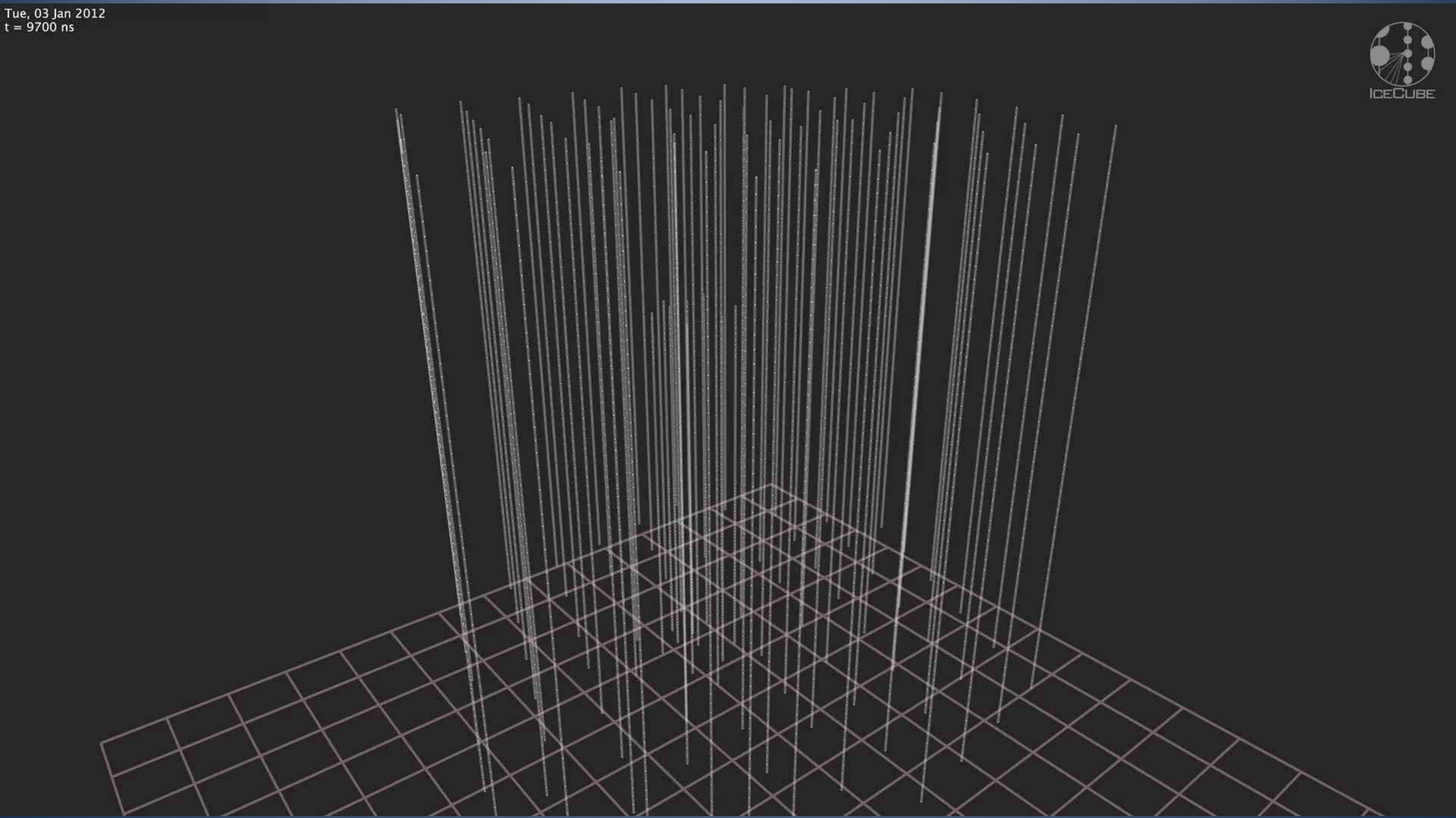
This is just 10 miliseconds

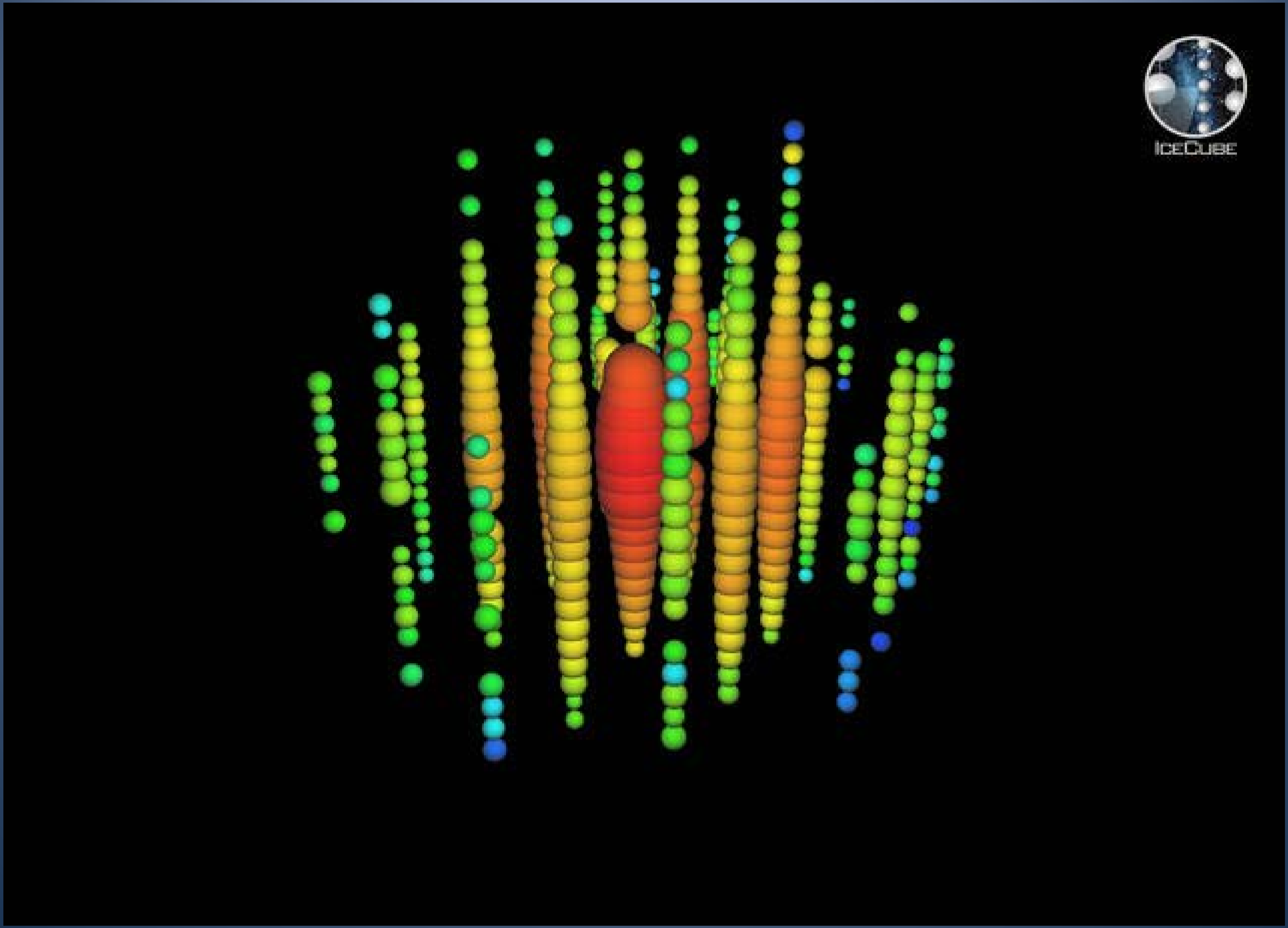
Point Source Search

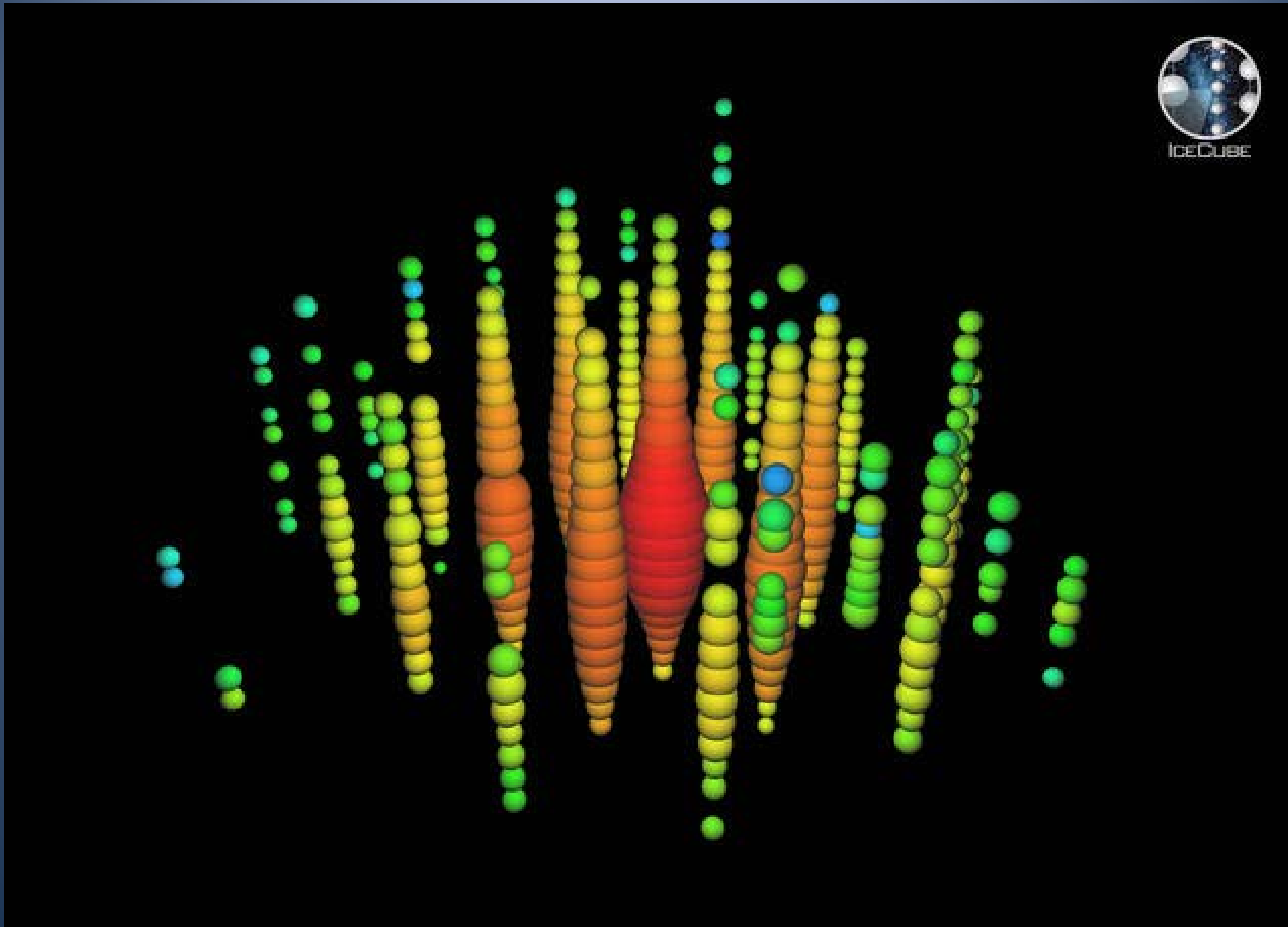
ApJ 835 (2017) 2, 151



Fluctuations compatible with background
Note the different nature of the backgrounds, depending on the hemisphere

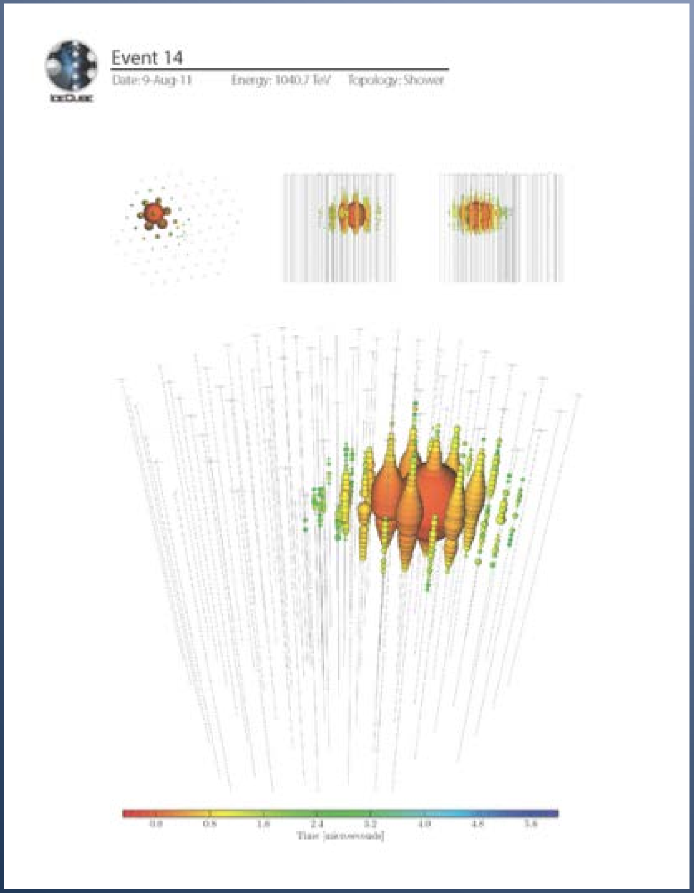

Tue, 03 Jan 2012
t = 9700 ns
ICECUBE

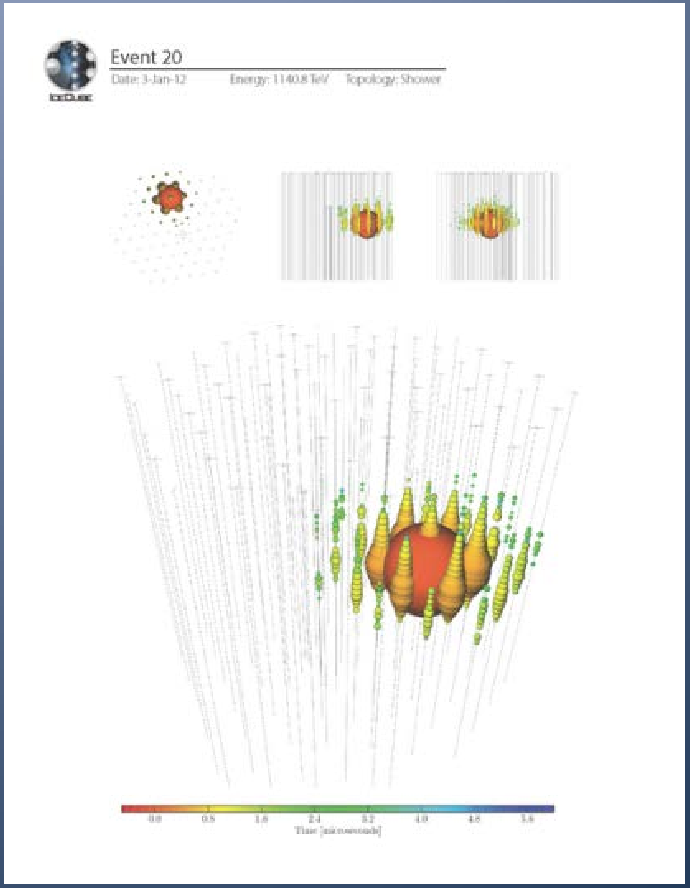

ICECUBE


IceCube

Ernie and Bert

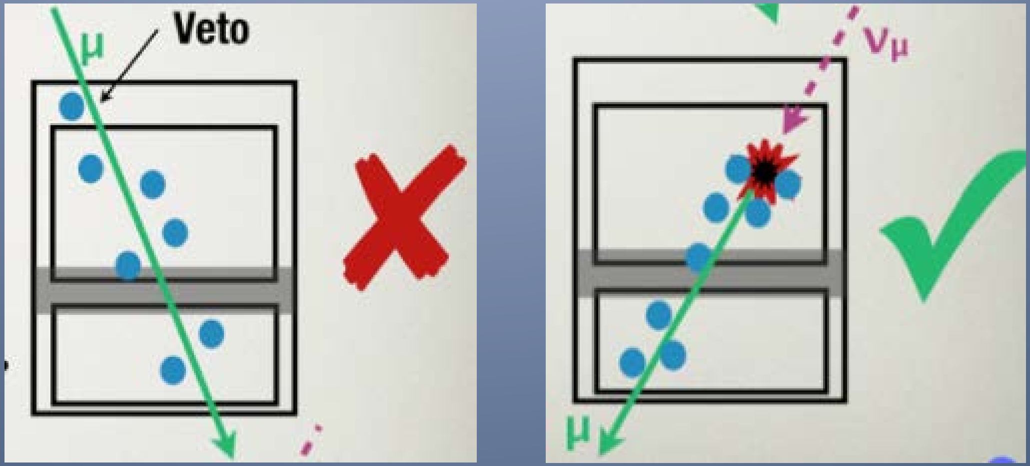
2012: Looking for UHE neutrinos, two events (cascades) appeared with E ~ 1 PeV (0.14 expected, 2.36σ)…



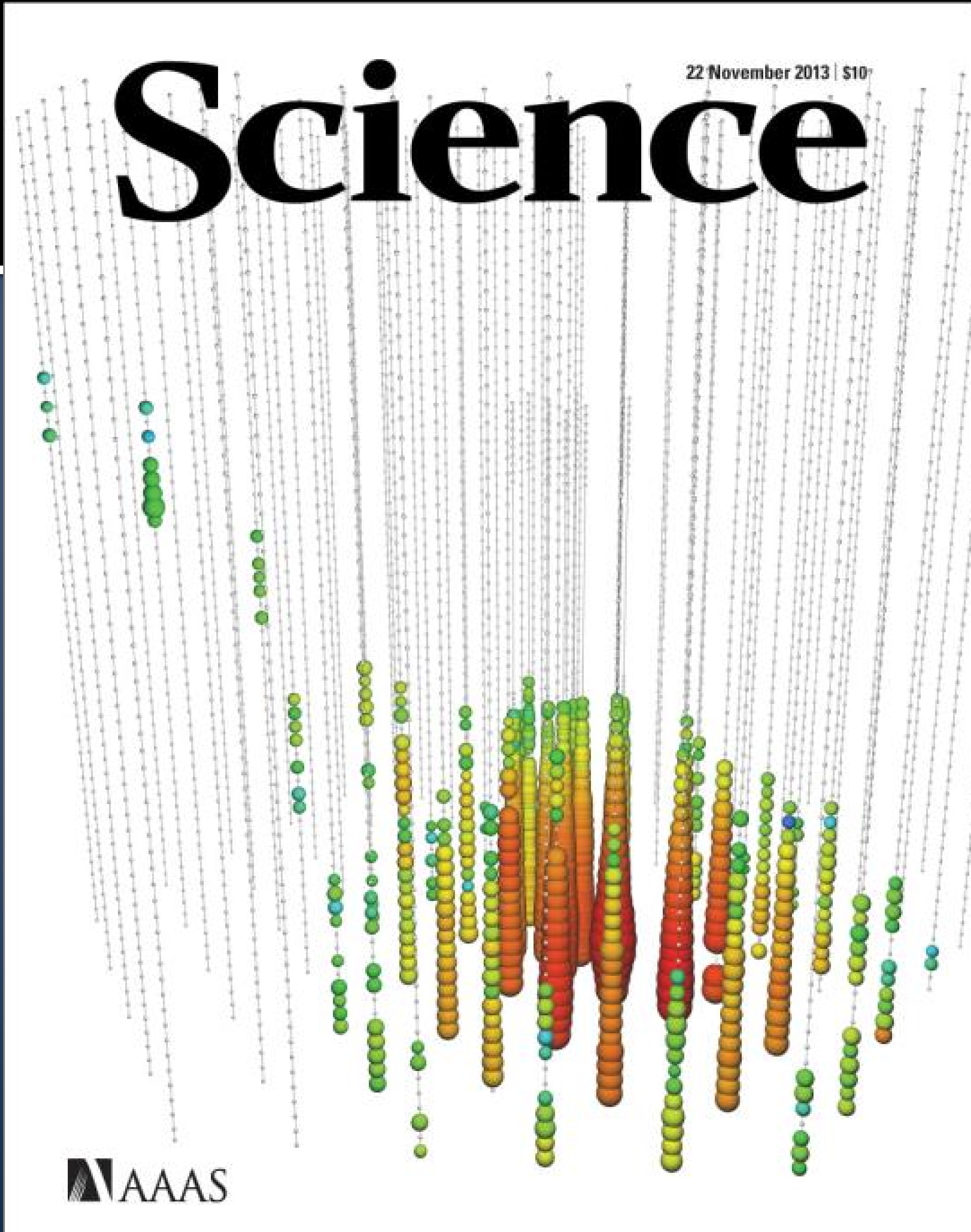


HESE events

- 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 (self-veto)
- Disadvantage: the volume is greatly reduced (only “contained” events)



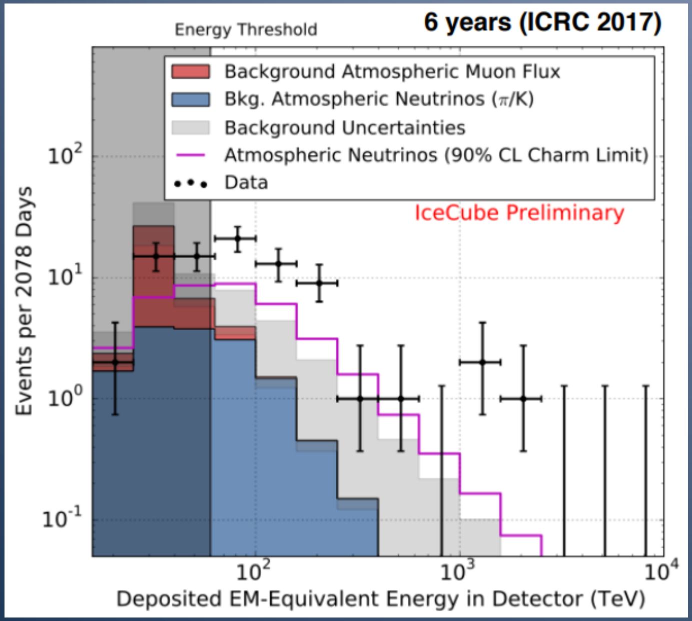
Science 342 (2013) 1242856, 22

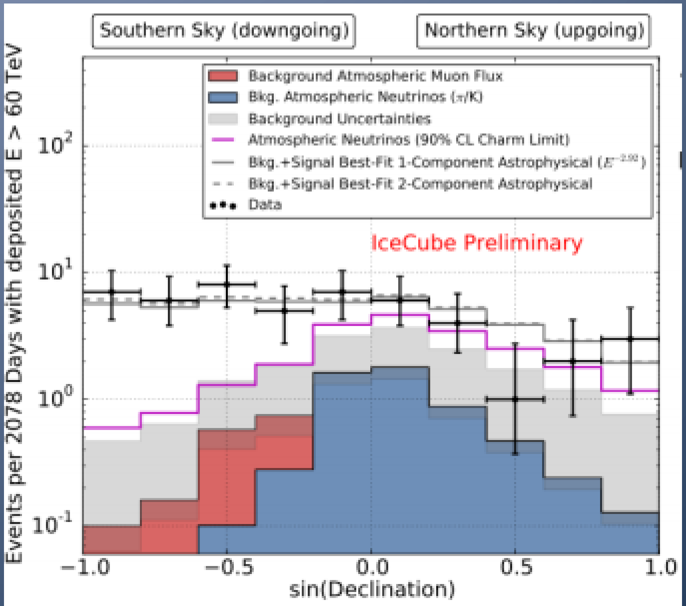
- 28 events in total (including Ernie and Bert)
- Expected background:
  - 6.0±3.4 atm. muons
  - 4.6±1.5 atm. neutrinos
- Significance: 4.9σ

Discovery!

IceCube HESE 6y

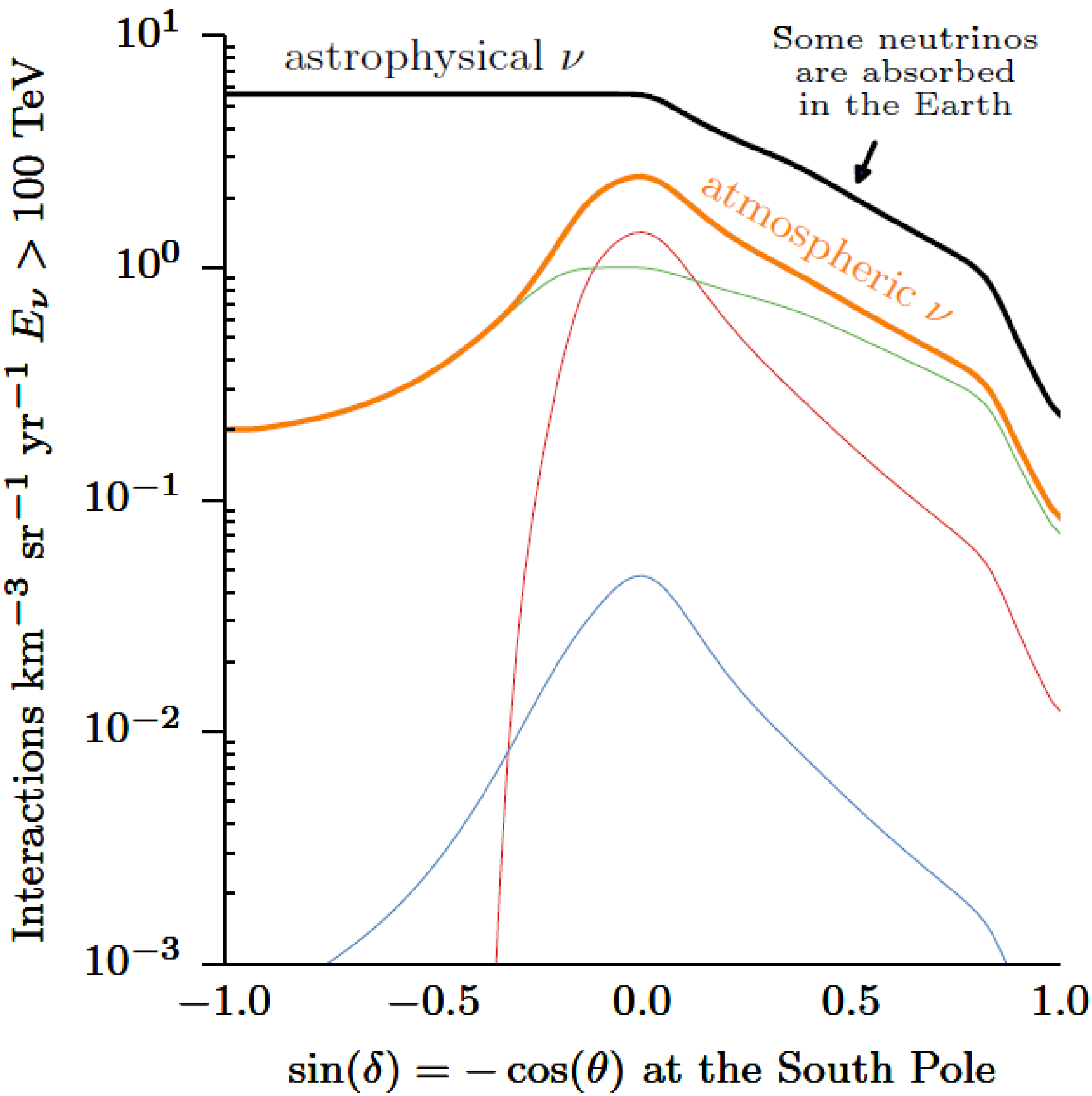
- Six years: 80 events (25±7 atmospheric, >8σ)
- Mostly cascades
- Excess confirmed in other analyses (upgoing ν_μ, MESE…), BUT, with some tensions (spectral index, normalization…)





Zenith distributions

J. van Santen, ICRC 2017

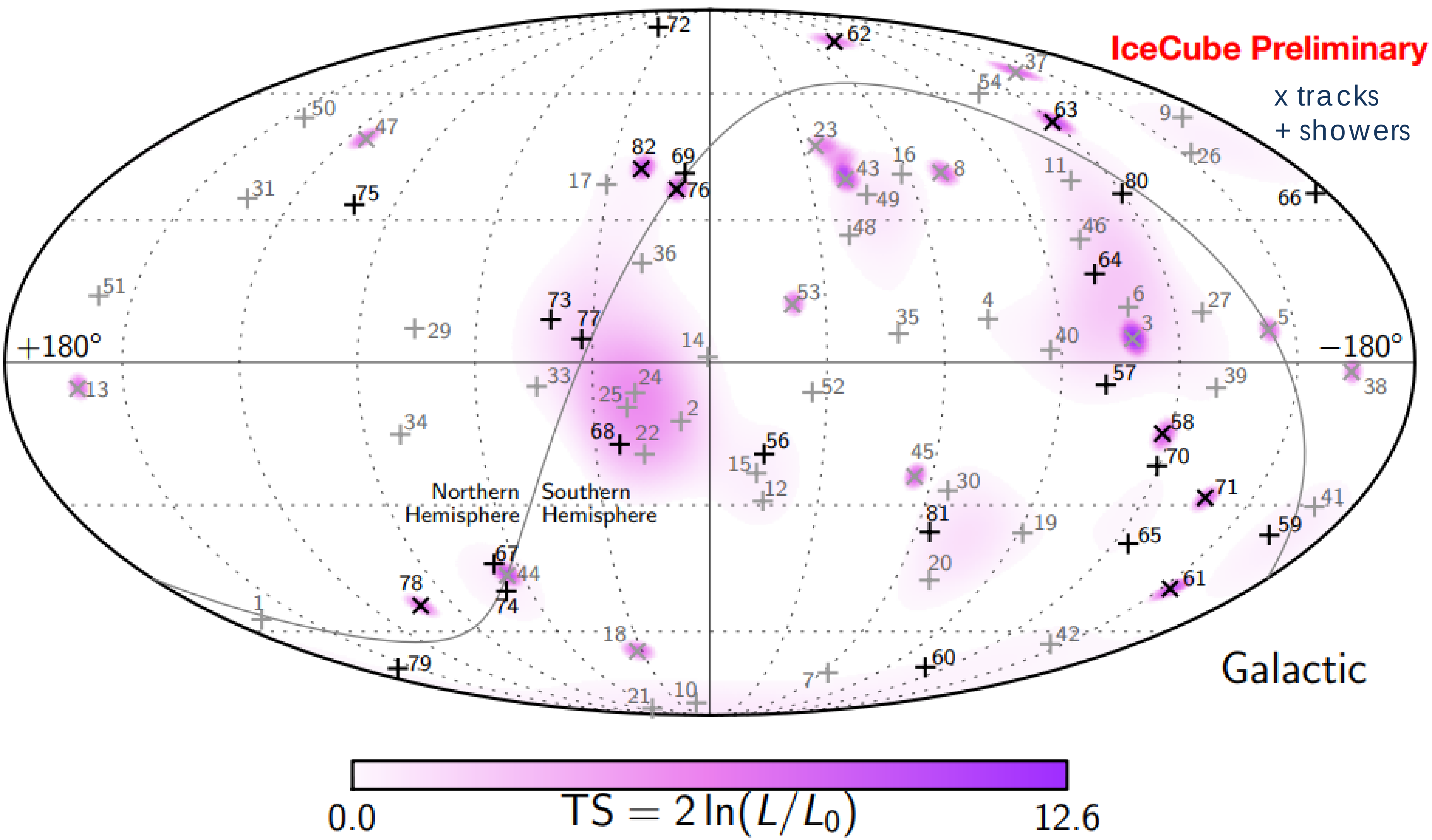


The zenith distributions of high-energy astrophysical and atmospheric neutrinos are fundamentally different.

Schönert, Gaisser, Resconi, Schulz, Phys. Rev. D, 79:043009 (2009)

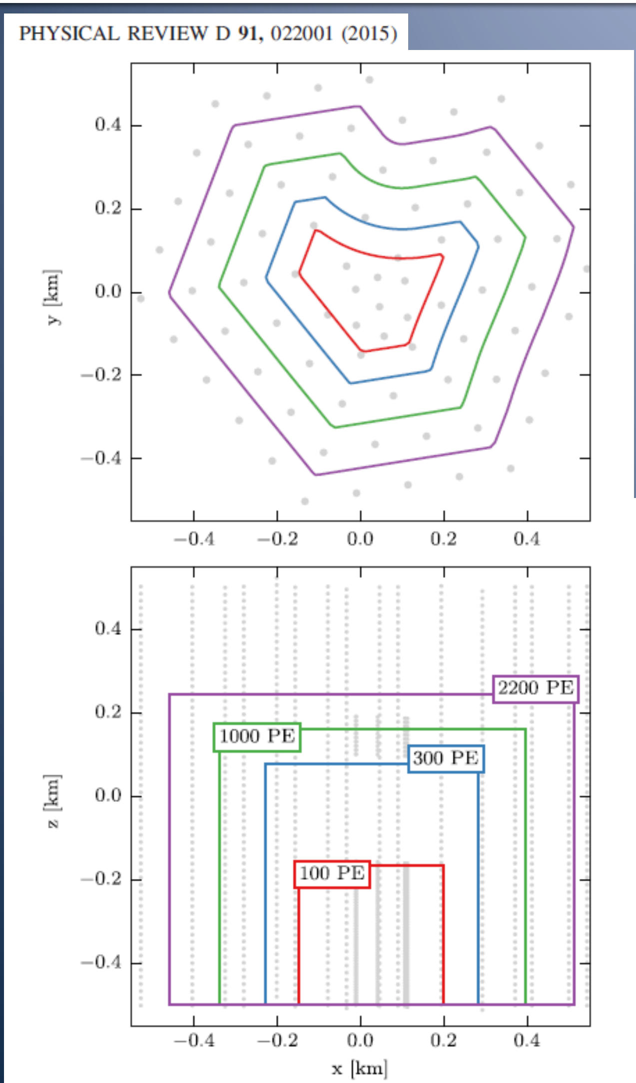
Gaisser, Jero, Karle, van Santen, Phys. Rev. D, 90:023009 (2014)

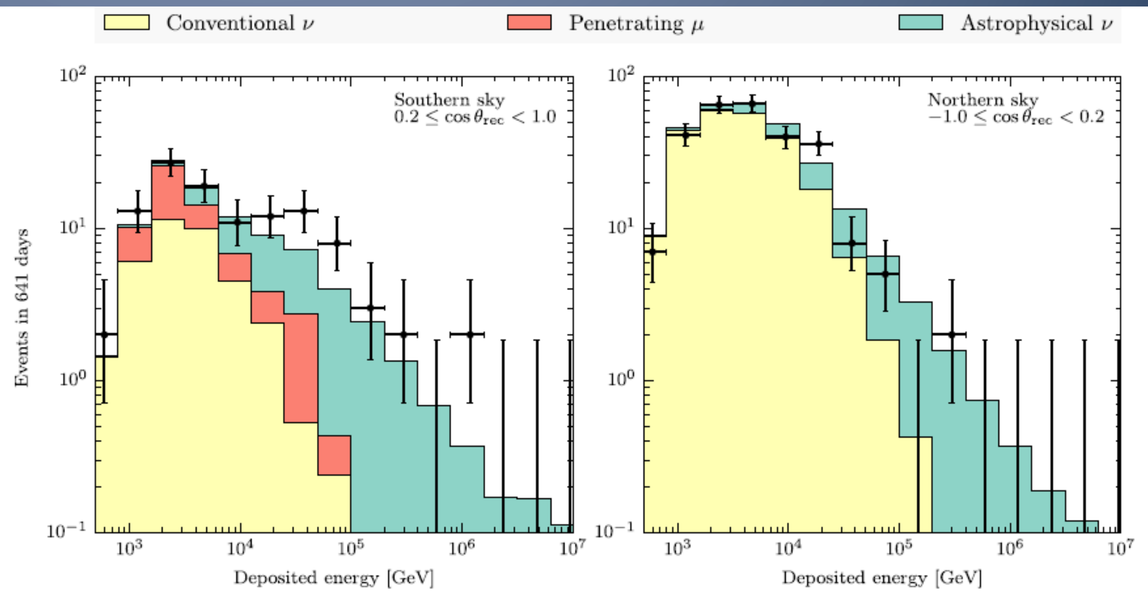
IceCube Skymap (HESE 6y)



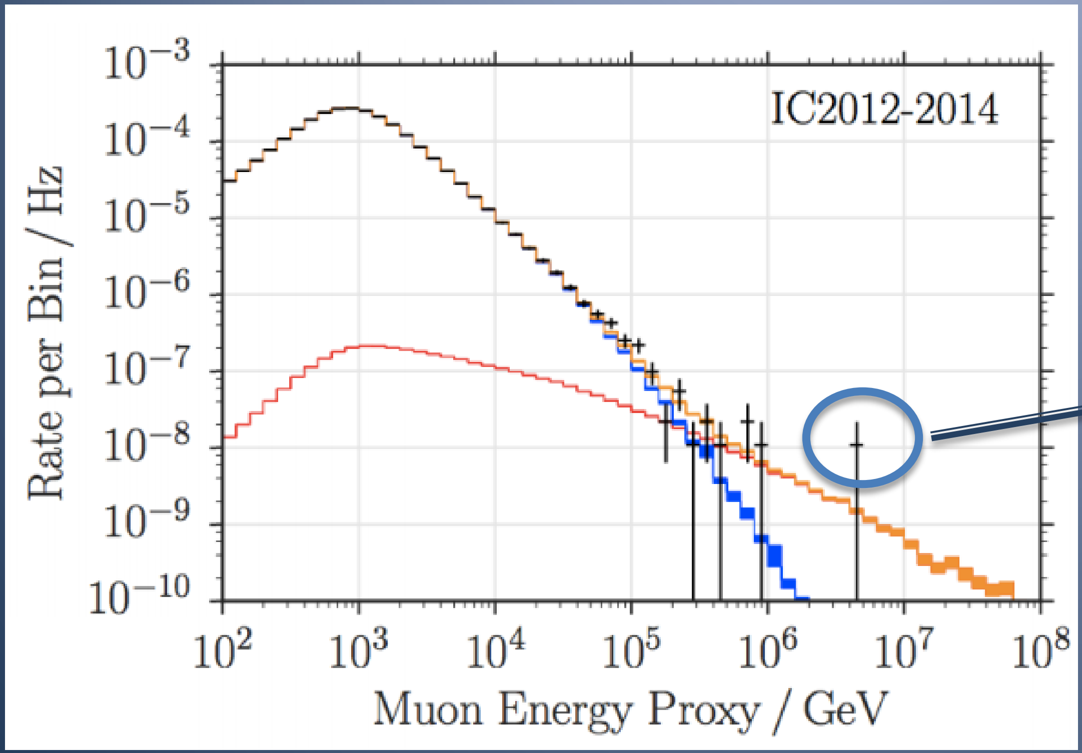
MESE analysis

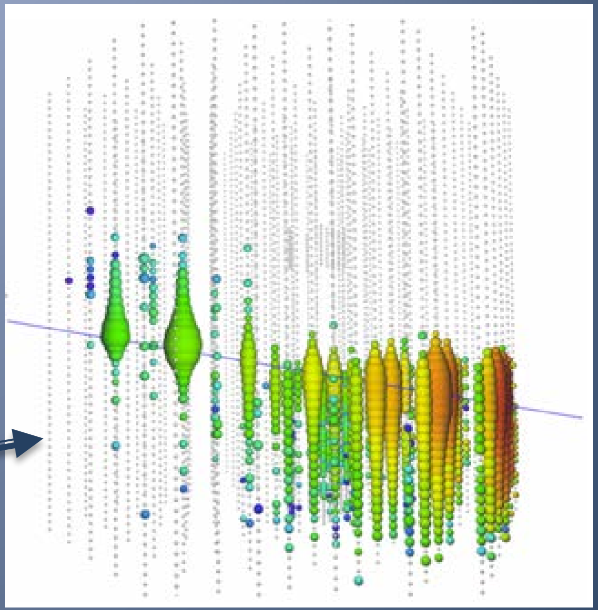
- MESE: Medium Energy Starting Events (>1 TeV)
- Veto condition more restrictive for lower energies
- 641 days: 283 cascades and105 tracks
- Measured spectral index γ= 2.46±0.12 (γ=2 rejected at 99% CL) in the 10-100 TeV range
- Small North/South asymmetry (Galactic flux?)

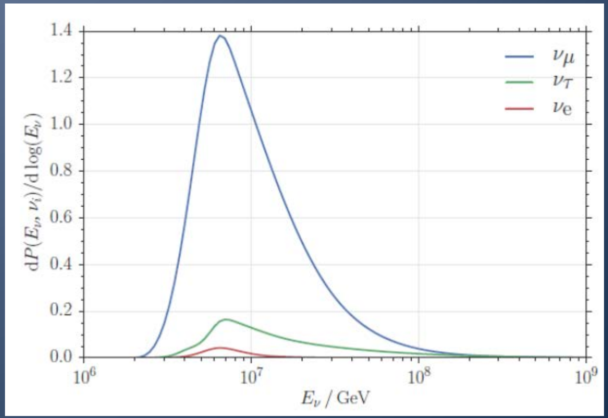




Muon analysis



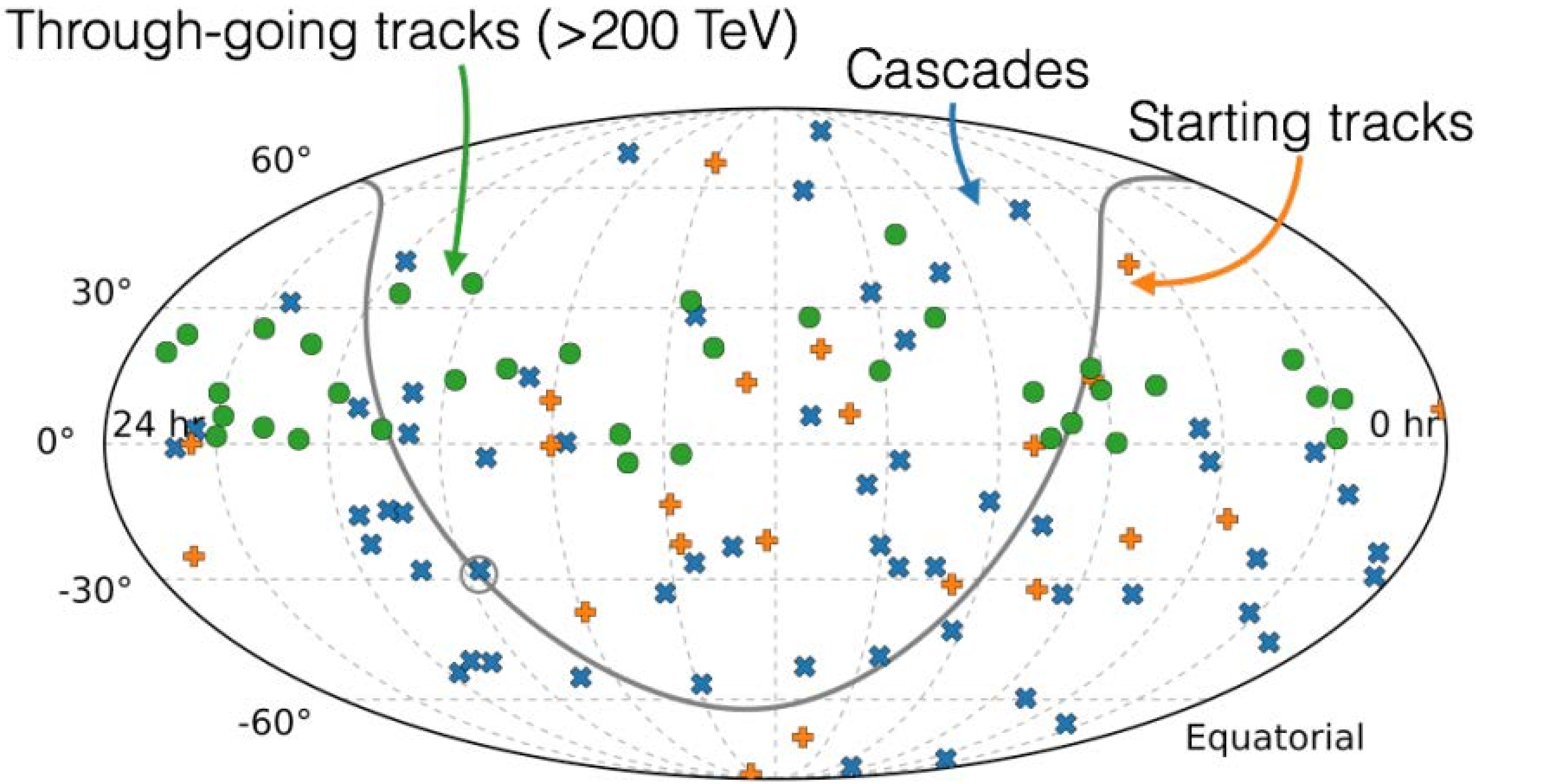




Astrophys.J. 833 (2016) no.1, 3

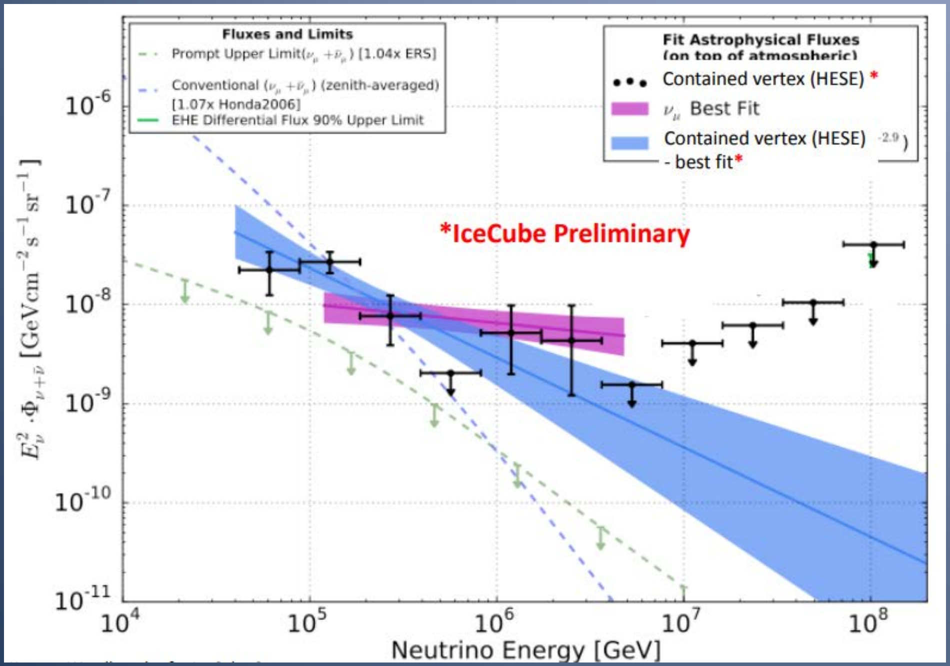
- Only muons, also discovery: 6.7σ
- One muon event with 2.6±0.3 PeV (deposited energy)
- Most probable neutrino energy if E^{-2}: ~7 PeV

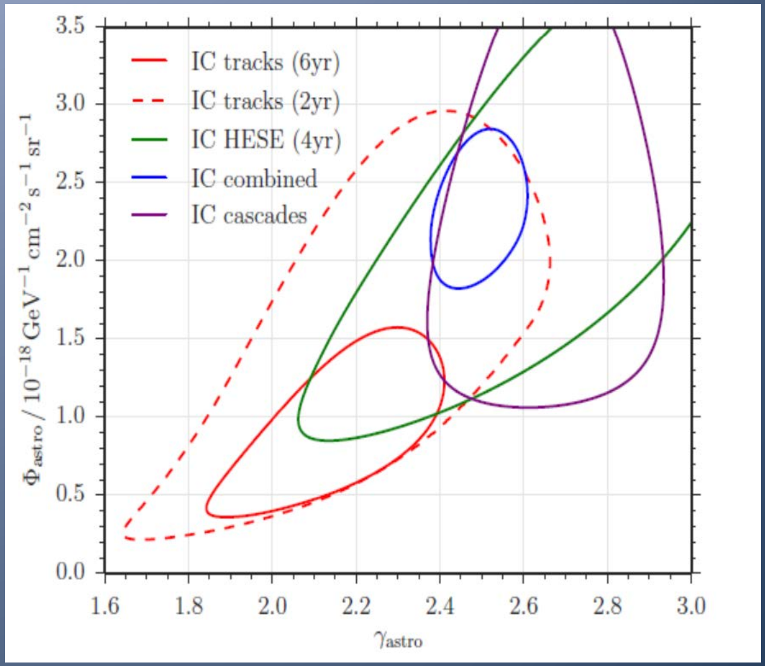
Events E>200 TeV



>50% are cosmic

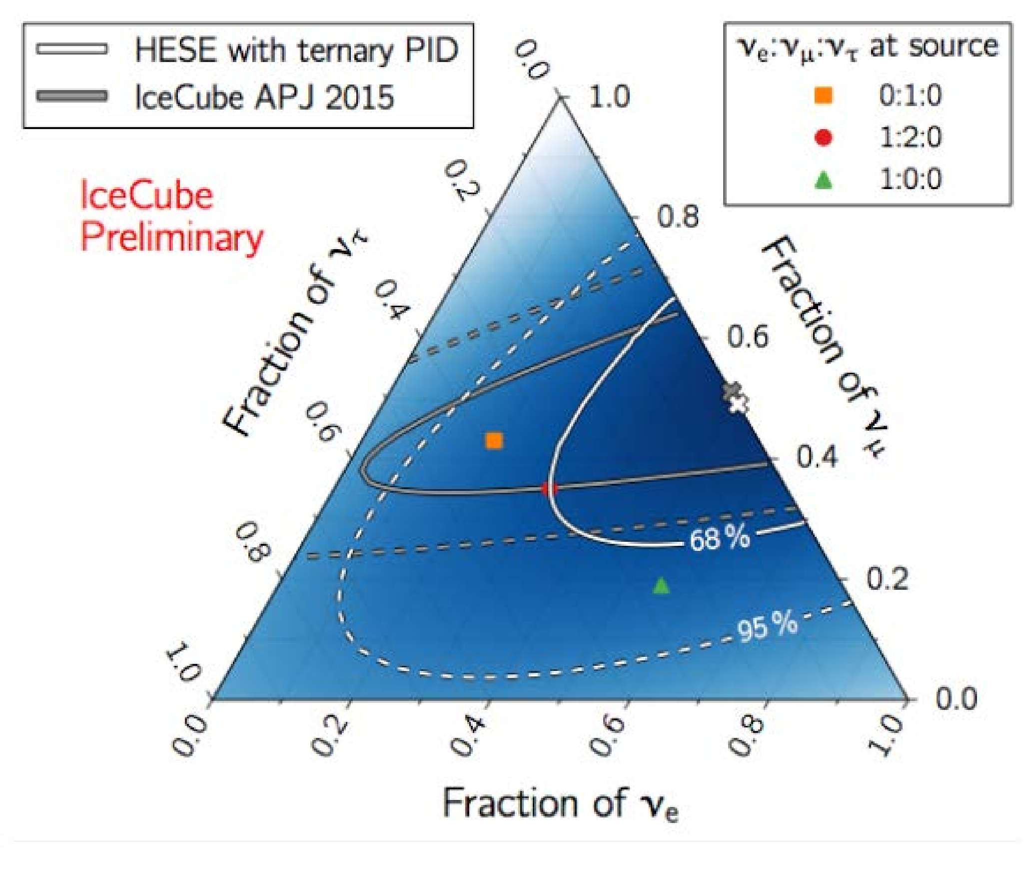
Comparison of analyses





Mild tension between different analysis (channel, sky region, energy)
Different components (extragalactic + some galactic?)

Flavour ratio



muon-suppressed pion decay (0:1:0)
pion & muon decay (1:2:1)
neutron decay (1:0:0)

$f_{\nu_e} = 0.51^{+0.12}_{-0.13}$

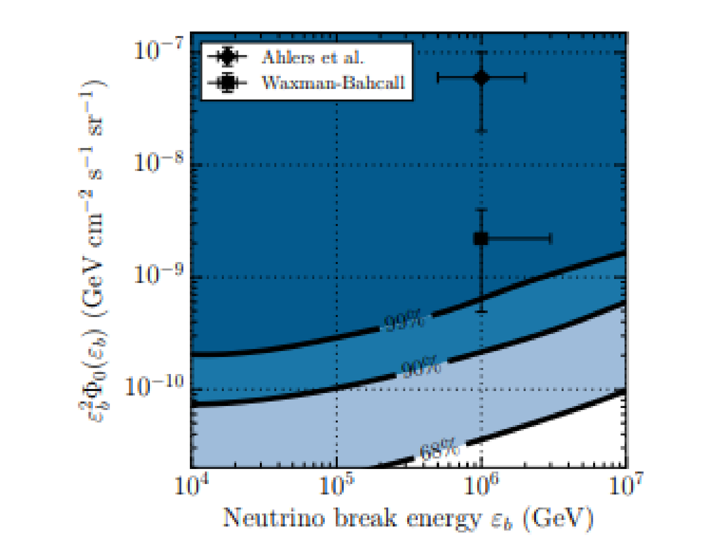
$f_{\nu_\mu} = 0.49^{+0.12}_{-0.13}$

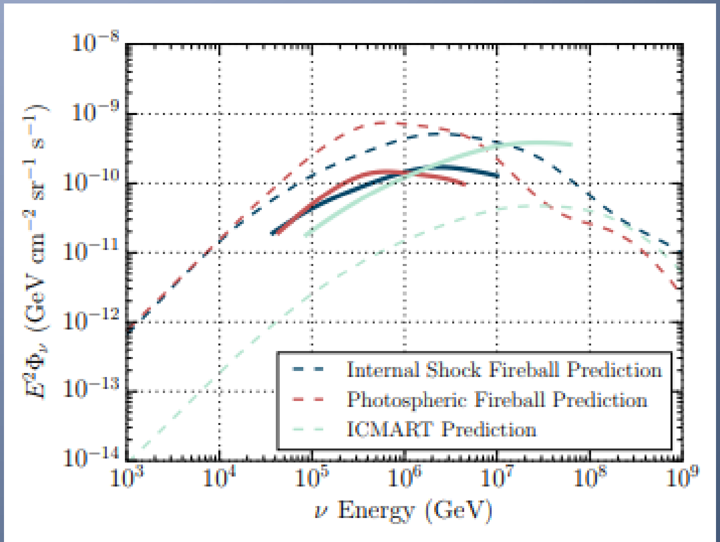
$f_{\nu_\tau} = 0.00^{+0.16}_{-0.00}$

No tau neutrino has been observed, while 2.83 events are expected (not significant, 9% fluctuation)

Gamma Ray Bursts

arXiv:1702.06868





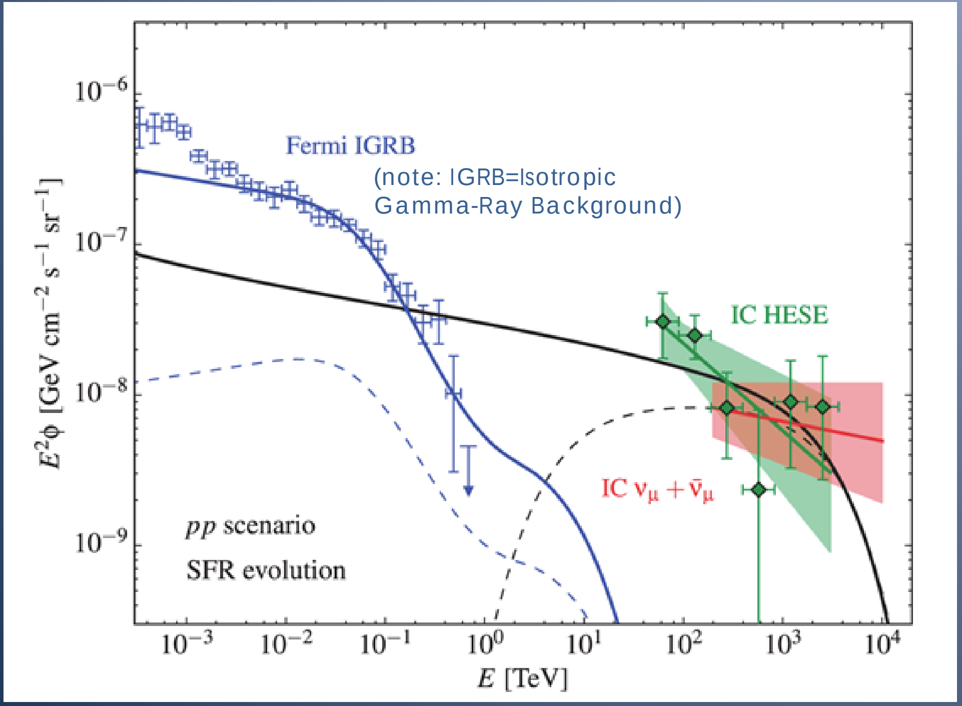
Ahlers et al.: only neutrons contribute
Waxman-Bahcall: protons are allowed to escape and contribute to the UHECR flux

Models using the observed properties of GRBs to predict neutrino fluxes during the prompt gamma emission phase

- 1172 bursts studied
- Number of coincidences compatible with background
- Strong constrains in GRBs models
- Both the internal shock and photospheric fireball models are strongly constrained
- Prompt emission from GRBs can produce only <1% of the observed neutrino flux
- The ICMART model remains beyond the sensitivity of the combined analysis.

Multi-messenger links

Combining Fermi IGRB and IC (HESE and upgoin-muons):

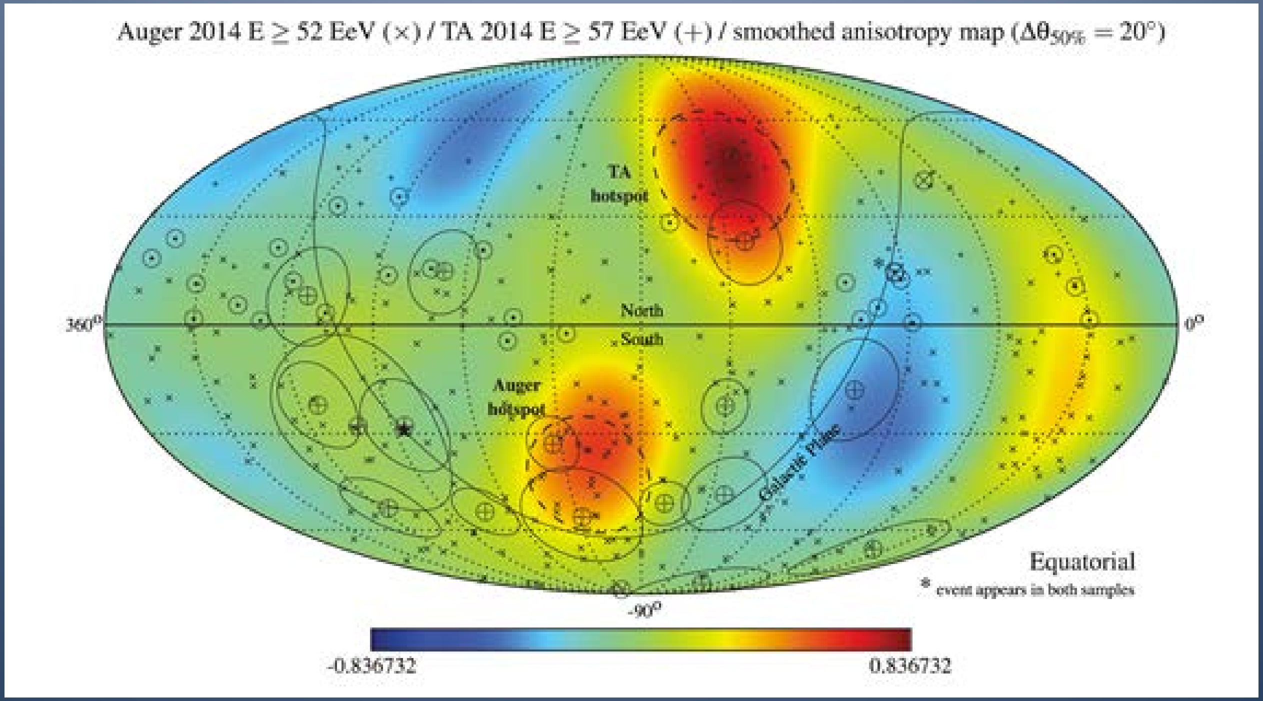


Ahlers and Halzen, PTEP 2017, 12A105

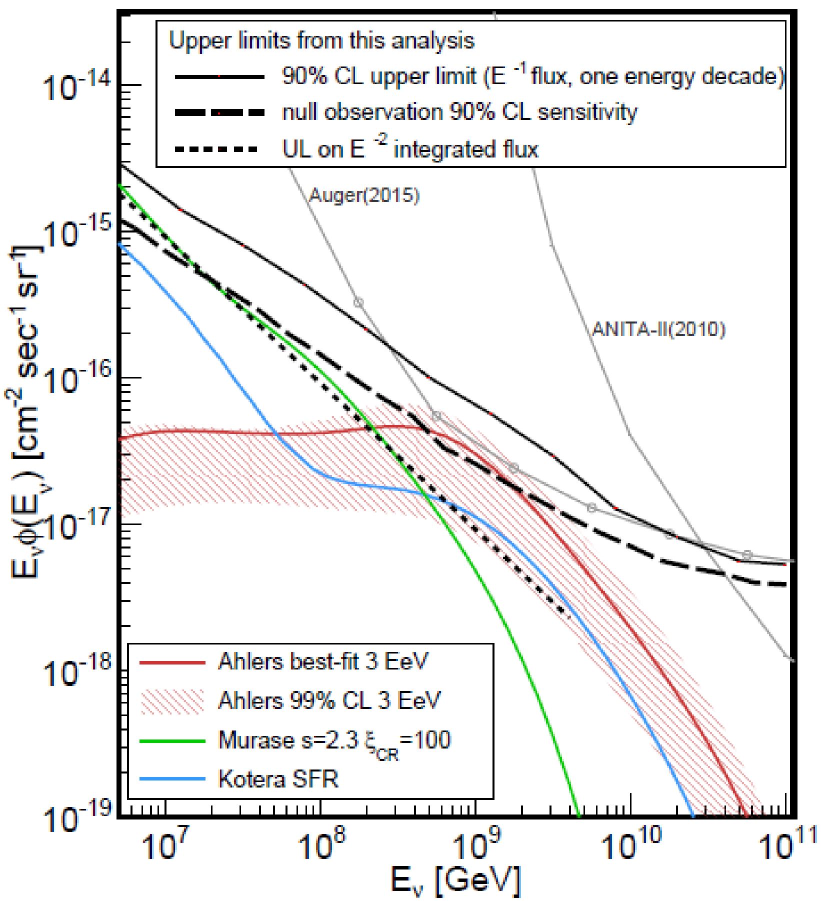
- No gamma events above 10 TeV because they cascade to lower energies (GeV – TeV)
- We can calculate the gamma flux (blue line) corresponding to the IC flux
- It seems that a large fraction (possibly most) of the energy on the non-thermal Universe is produced in hadronic processes

Correlations with Auger and TA UHE events

- A search for correlations with UHE events of Auger and TA has been done
- 318 events with E>50 EeV
- No significant excess has been found
- The interpretation critically depends on the galactic magnetic field and composition which is assumed



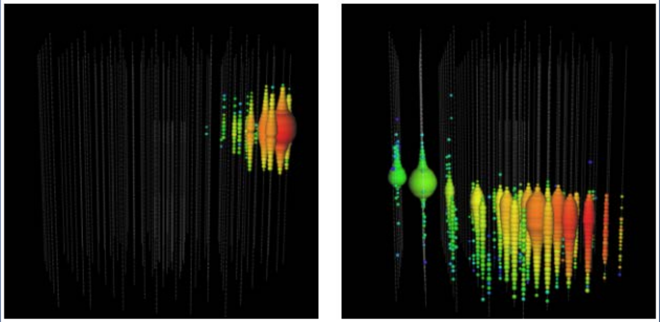
UHE neutrinos



arxiv:1607.05886

7 years of IC data, 2426 live days

$E_\nu > 10^6$ GeV → 2 events



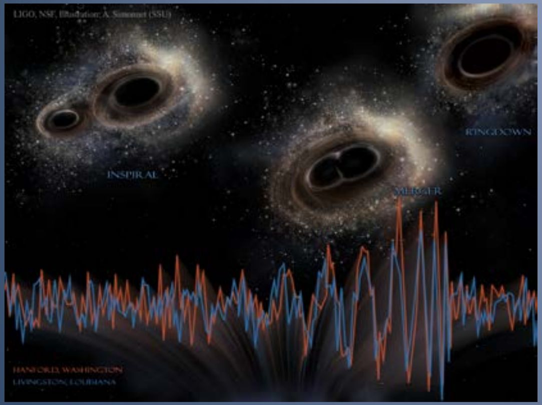
Cosmogenic models

ν Model	Event rate per livetime	p-value	MRF
Kotera *et al.* [37] SFR	$3.6^{+0.5}_{-0.8}$	$22.3^{+10.8}_{-3.9}$%	1.44
Kotera *et al.* [37] FRII	$14.7^{+2.2}_{-2.7}$	<0.1%	0.33
Aloisio *et al.* [38] SFR	$4.8^{+0.7}_{-0.9}$	$7.8^{+6.8}_{-1.8}$%	1.09
Aloisio *et al.* [38] FRII	$24.7^{+3.6}_{-4.6}$	<0.1%	0.20
Yoshida *et al.* [51] $m = 4.0, z_{max} = 4.0$	$7.0^{+1.0}_{-1.0}$	$0.1^{+0.4}_{-0.1}$%	0.37
Ahlers *et al.* [22] best fit, 1 EeV	$2.8^{+0.4}_{-0.4}$	$9.5^{+6.5}_{-1.6}$%	1.17
Ahlers *et al.* [22] best fit, 3 EeV	$4.4^{+0.6}_{-0.7}$	$2.2^{+1.3}_{-0.9}$%	0.66
Ahlers *et al.* [22] best fit, 10 EeV	$5.3^{+0.8}_{-0.8}$	$0.7^{+1.6}_{-0.2}$%	0.48

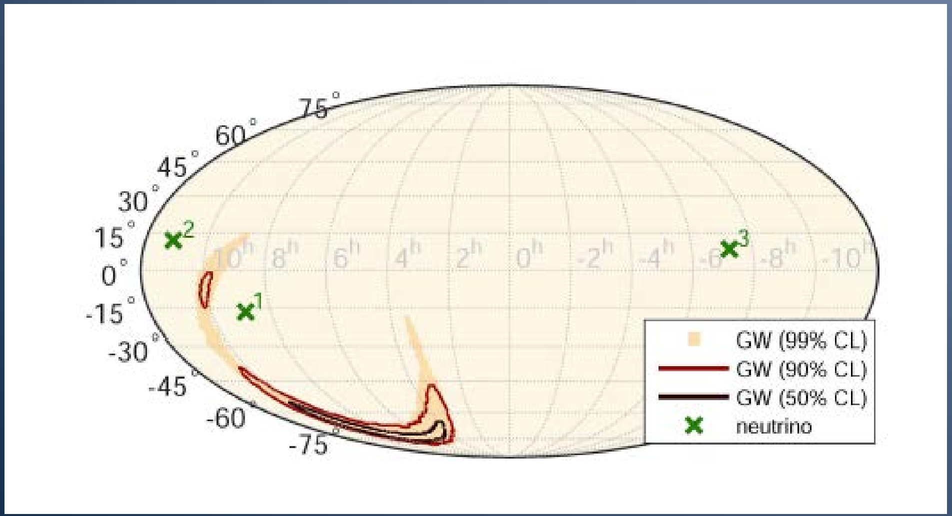
Astrophysical models

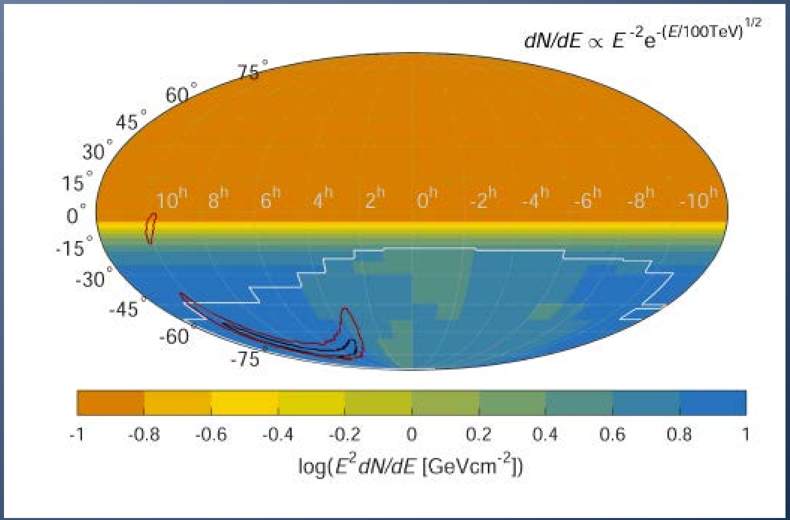
ν Model	Event rate per livetime	p-value	MRF
Murase *et al.* [45] $s = 2.3$, ξ_{CR}=100	$7.4^{+1.1}_{-1.8}$	$2.2^{+9.9}_{-1.4}$%	0.96 ($\xi_{CR} \leq 96$)
Murase *et al.* [45] $s = 2.0$, ξ_{CR}=3	$4.5^{+0.7}_{-0.9}$	$19.9^{+20.2}_{-9.2}$%	1.66 ($\xi_{CR} \leq 5.0$)
Fang *et al.* [48] SFR	$5.5^{+0.8}_{-1.1}$	$7.8^{+14.4}_{-3.7}$%	1.34
Fang *et al.* [48] uniform	$1.2^{+0.2}_{-0.2}$	$54.8^{+1.7}_{-2.7}$%	5.66
Padovani *et al.* [46] $Y_{\nu\gamma} = 0.8$	$37.8^{+5.6}_{-8.3}$	<0.1%	0.19 ($Y_{\nu\gamma} \leq 0.15$)

Gravitational waves



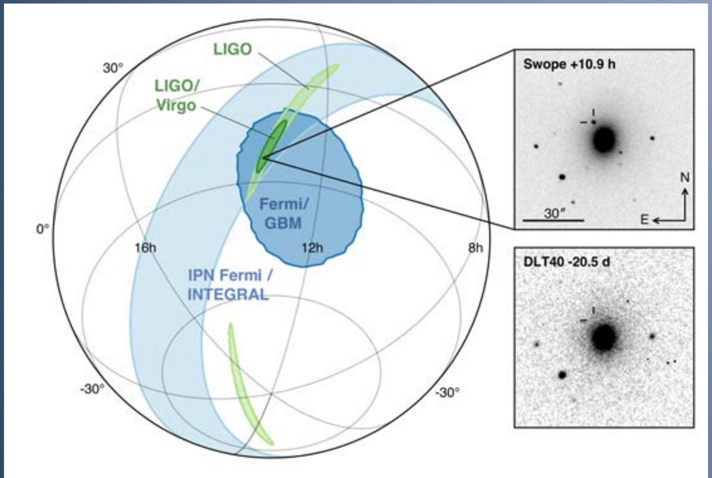
- Neutrino telescopes offer a complete sky coverage and almost continuous data taking: crucial for transient events
- A search for ANTARES and IceCube events correlated in time and space with the GW150916 event has been carried out
  - ANTARES: 0 events
  - IceCube: 3 events (as expected from background)



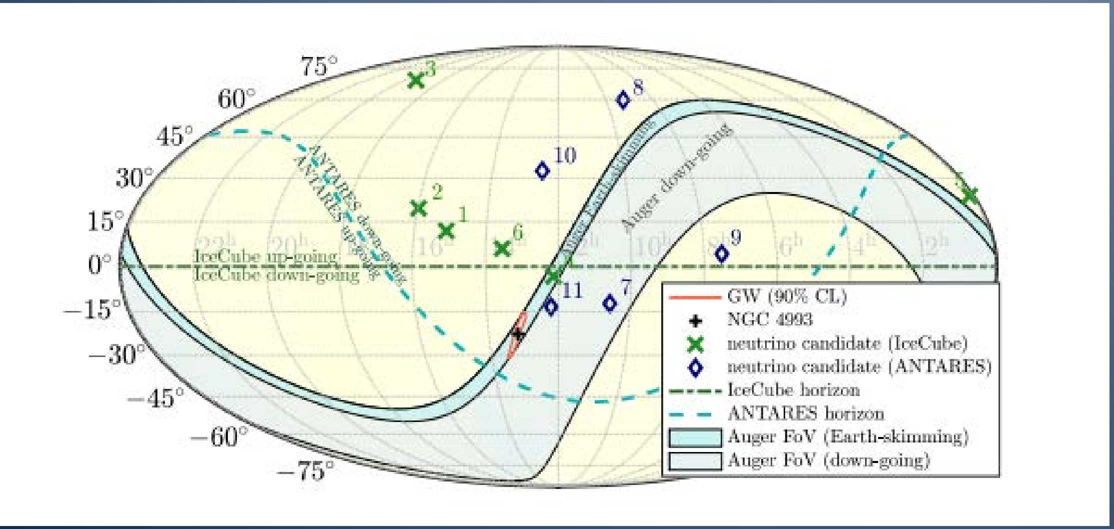


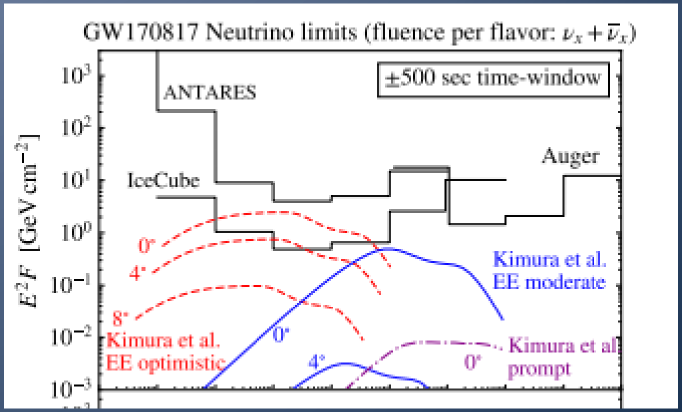
Upper limits in the flux are set

Gravitational waves



- More recent event: GW170817 (neutron star merging)
- Correlation with electromagnetic counterparts observed (GRB)
- Search for neutrinos:
  - ANTARES: 5 events(as expected from background)
  - IceCube: 6 events (as expected from background)
  - Auger: 0 events

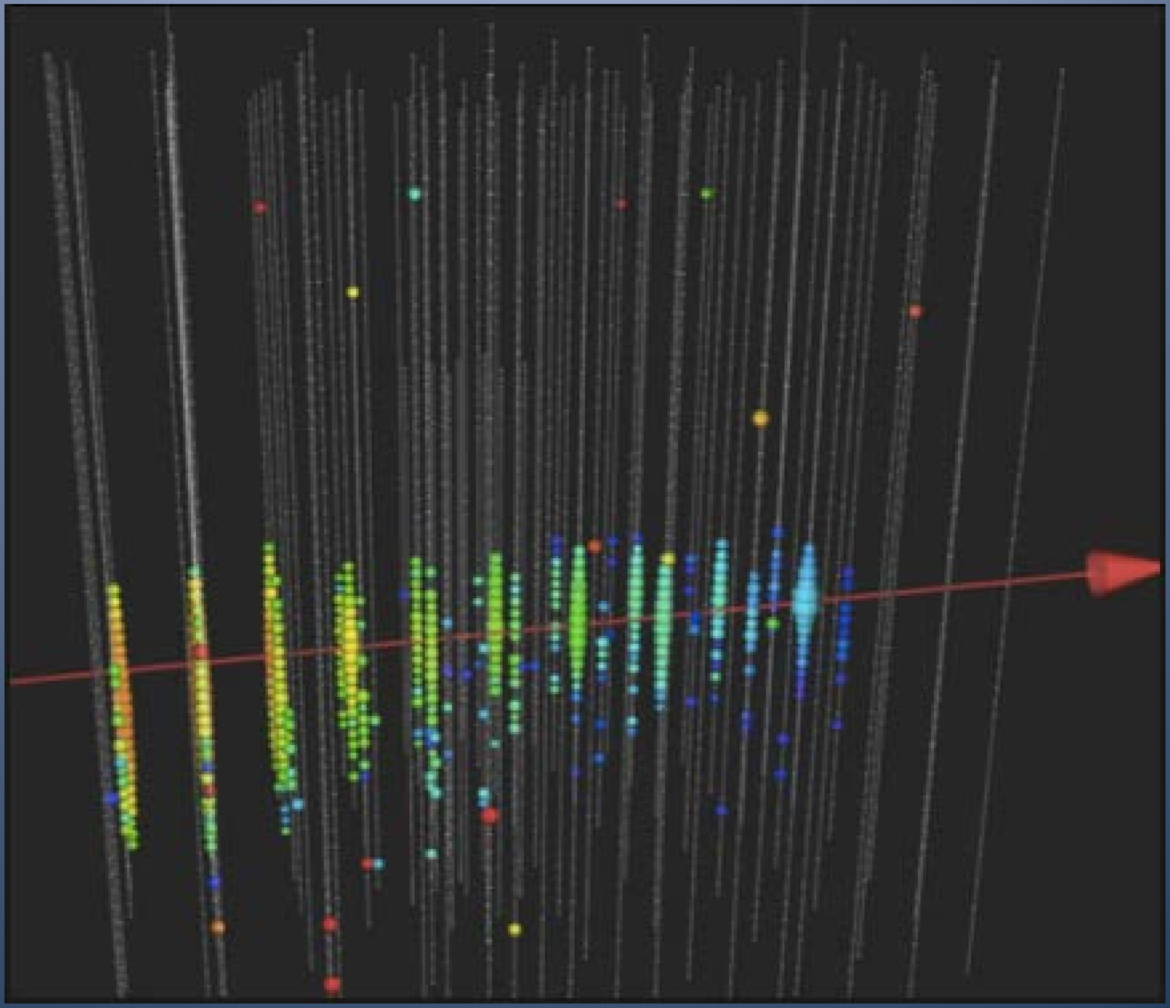




Upper limits on the fluence are set, which constrain the tilt angle

IceCube 170922A

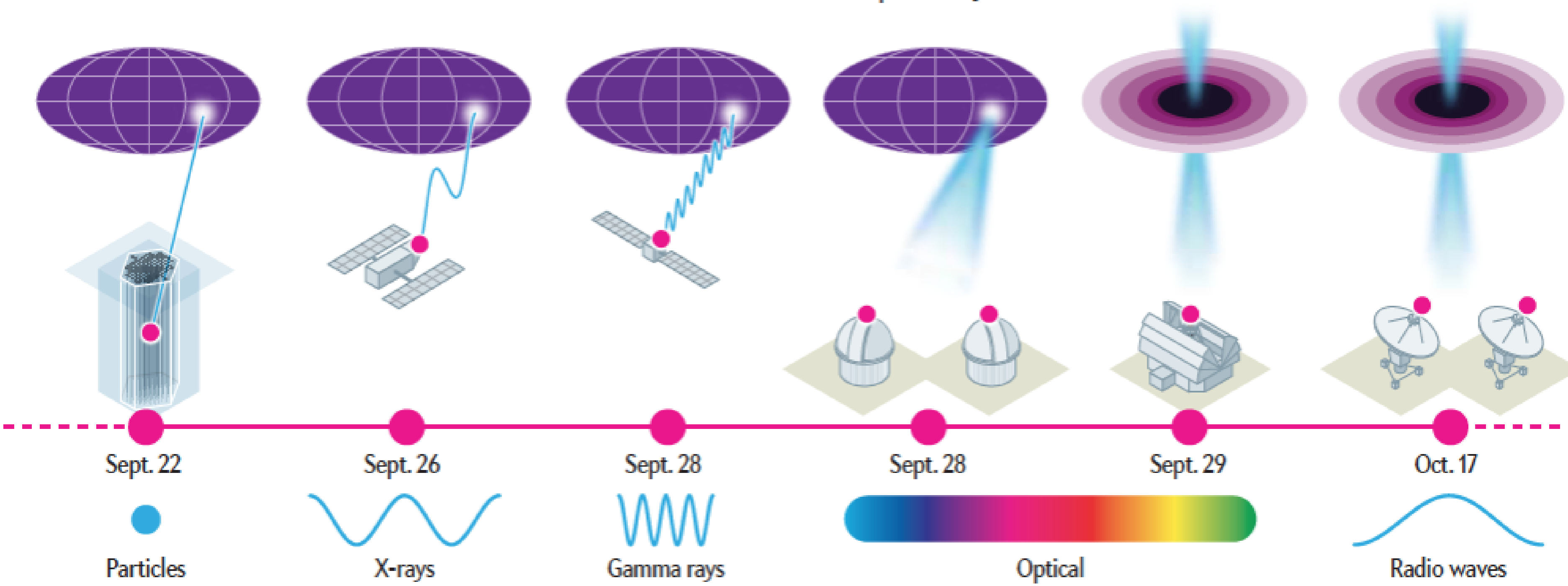
Zenith: 95.7º
RA: 77.43
dec: 5.72
Muon deposited energy around 20 TeV.



Many Messengers

Over three and a half weeks in 2017, astronomers observed the same celestial event—what they believe to be a flare-up from matter falling into a supermassive black hole—through multiple wavelengths of light, as well as particles called neutrinos. The combined observations offer scientists much more information about these mysterious phenomena than any measurement alone.

1. First, the IceCube Neutrino Observatory at the South Pole detected a high-energy neutrino and issued an alert.
2. The orbiting Swift x-ray telescope reported finding nine sources of x-rays coming from the same area of the sky as the neutrino.
3. Two days later the Fermi space telescope identified gamma rays coming from one of the same sources Swift found.
4. A network of ground-based optical telescopes called ASAS-SN announced that this source had been brightening over the past 50 days.
5. Another optical telescope found evidence that the source was a blazar—a huge black hole emitting jets as it swallowed mass.
6. The Very Large Array in New Mexico, observing in radio light, confirmed that the source of all these signals was a jet from a blazar.



Finkbeiner (Scientific American)

IceCube 170922A follow-up

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Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

ATel #10791; *Yasuyuki T. Tanaka (Hiroshima University), Sara Buson (NASA/GSFC), Daniel Kocevski (NASA/MSFC) on behalf of the Fermi-LAT collaboration*
on 28 Sep 2017; 10:10 UT
Credential Certification: David J. Thompson (David.J.Thompson@nasa.gov)

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Optical Spectrum of TXS 0506+056 (possible counterpart to IceCube-170922A)

ATel #10799; *I. A. Steele (Liverpool JMU)*
on 29 Sep 2017; 13:00 UT
Credential Certification: Iain Steele (iainsteele@mac.com)

First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

ATel #10817; *Razmik Mirzoyan for the MAGIC Collaboration*
on 4 Oct 2017; 17:17 UT
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

Subjects: Optical, Gamma Ray, >GeV, TeV, VHE, UHE, Neutrinos, AGN, Blazar

Referred to by ATel #: 10830, 10833, 10838, 10840, 10844, 10845

AGILE confirmation of gamma-ray activity from the IceCube-170922A error region

ATel #10801; *F. Lucarelli (SSDC/ASI and INAF/OAR), G. Piano (INAF/IAPS), C. Pittori, F. Verrecchia (SSDC/ASI and INAF/OAR), M. Tavani (INAF/IAPS, and Univ. Roma Tor Vergata), A. Bulgarelli (INAF/IASF-Bo), P. Munar-Adrover, G. Minervini, A. Ursi (INAF/IAPS), S. Vercellone (INAF/OA-Brera), I. Donnarumma (ASI), V. Fioretti, A. Zoli (INAF/IASF-Bo), E. Striani (CIFS and INAF/IAPS), M. Cardillo (INAF/OA-Arcetri and INAF/IAPS), F. Gianotti, M. Trifoglio (INAF/IASF-Bo), A. Giuliani, S. Mereghetti, P. Caraveo, F. Perotti (INAF/IASF-Mi), A. Chen (Wits University), A. Argan, E. Costa, E. Del Monte, Y. Evangelista, M. Feroci, F. Lazzarotto, I. Lapshov, L. Pacciani, P. Soffitta, S. Sabatini, V. Vittorini (INAF/IAPS), G. Pucella, M. Rapisarda (ENEA-Frascati), G. Di Cocco, F. Fuschino, M. Galli, C. Labanti, M. Marisaldi (INAF/IASF-Bo), A. Pellizzoni, M. Pilia, A. Trois (INAF/OA-Cagliari), G. Barbiellini, F. Vallazza (INFN Trieste), F. Longo (Univ. Trieste ... Prest ... ttaneo, ... miggian ... aoletti ... mi, L.*

First multimessenger fruit for HE neutrinos + EM!

...56, ... ows increased optical activity

ATel #10794; *A. Franckowiak (DESY), K. Z. Stanek, C. S. Kochanek, T. A. Thompson (OSU), T. W.-S. Holoien, B. J. Shappee (Carnegie Observatories), J. L. Prieto (Diego Portales; MAS), Subo Dong (KIAA-PKU)*
on 28 Sep 2017; 18:00 UT
Credential Certification: Krzysztof Stanek (stanek.32@osu.edu)

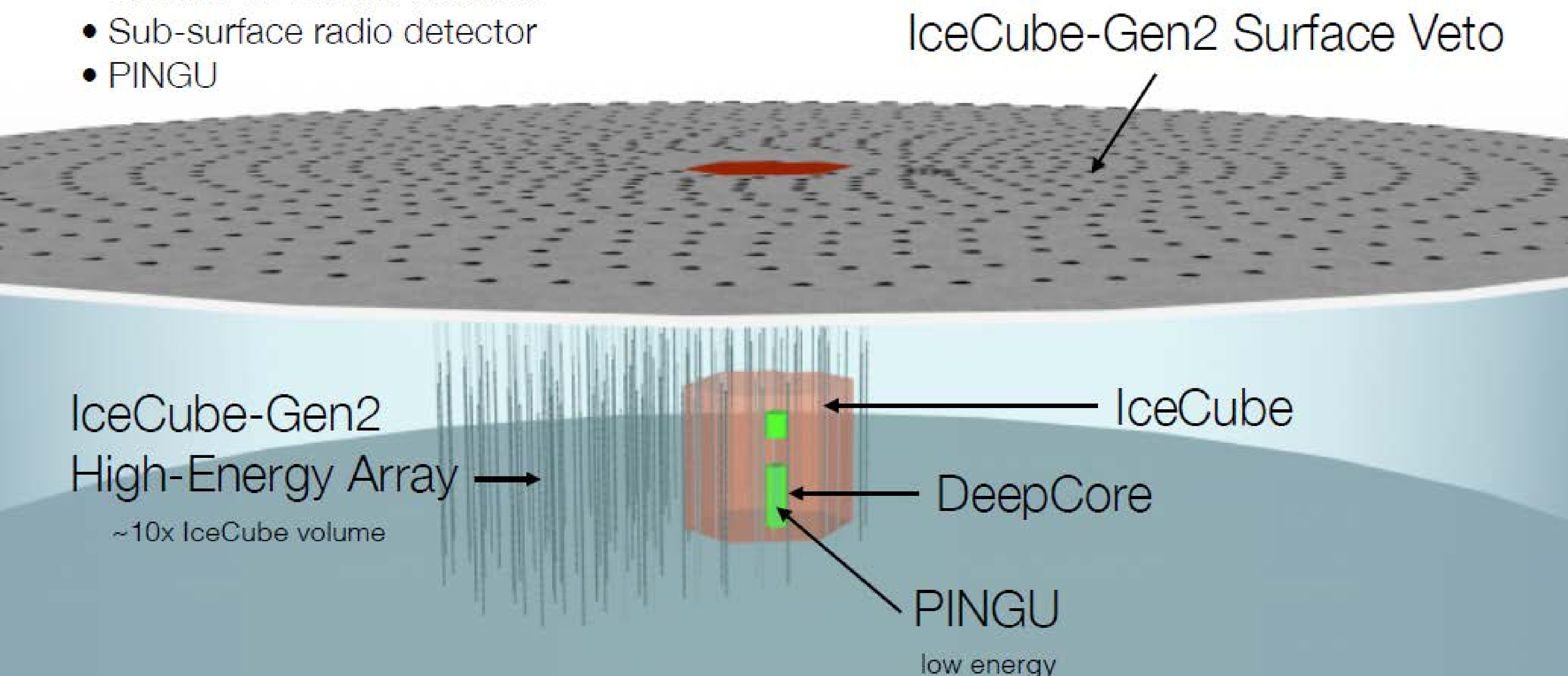
VLA Radio Observations of the blazar TXS 0506+056 associated with the IceCube-170922A neutrino event

ATel #10861; *A. J. Tetarenko, G. R. Sivakoff (UAlberta), A. E. Kimball (NRAO), and J. C.A. Miller-Jones (Curtin-ICRAR)*
on 17 Oct 2017; 14:08 UT
Credential Certification: Alexandra Tetarenko (tetarenk@ualberta.ca)

Subjects: Radio, Neutrinos, AGN, Blazar, Quasar

IceCube Gen2

Multi-component observatory:
- IceCube-Gen2 High-Energy Array
- Surface air shower detector
- Sub-surface radio detector
- PINGU

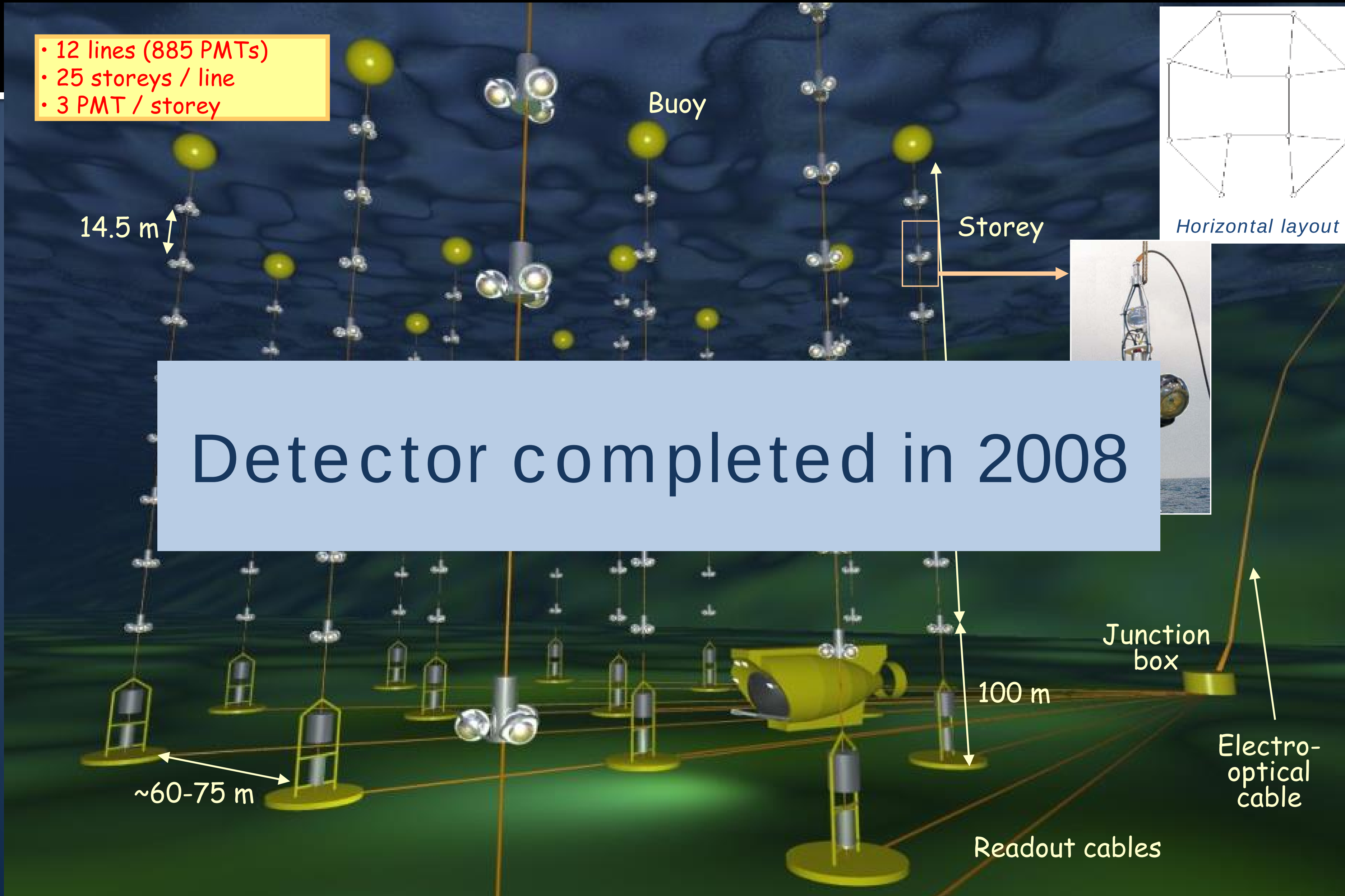


J. van Santen ICRC 2017

ANTARES

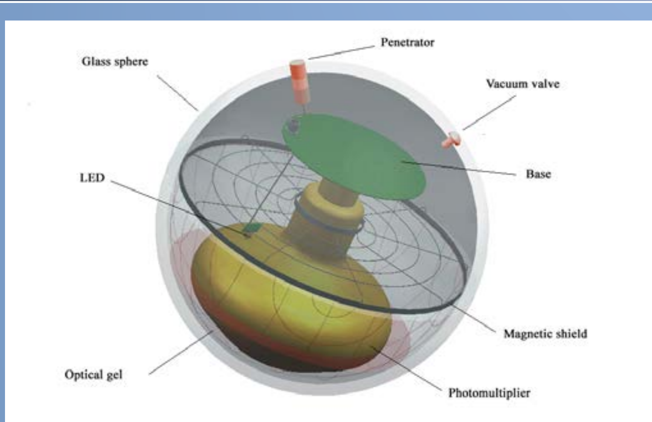
ANTARES and KM3NeT Collaborations

The ANTARES Detector



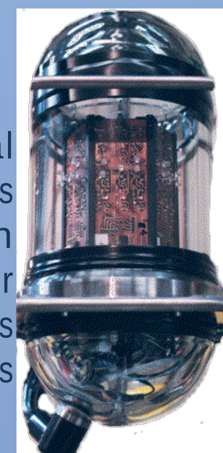
Detector completed in 2008

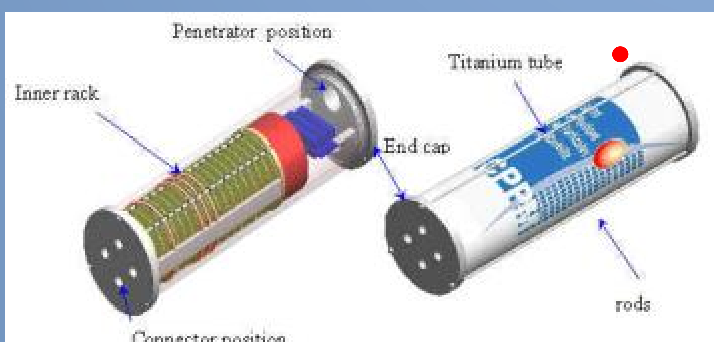
Detector Elements



The Optical Module contains a 10” PMT and its electronics

The Optical Beacons allows timing calibration and water properties measurements





The Local Control Module contains electronics for signal processing

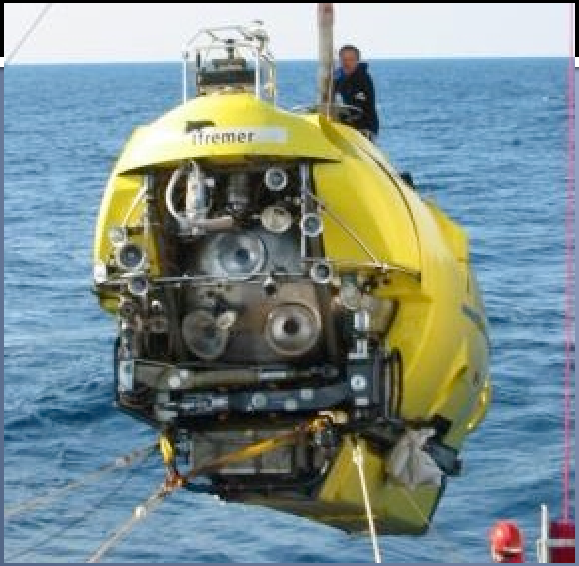
It receives power from shore station and distributes it to the lines. Data and control signals are also transmitted via the JB.

It provides power and data link between the shore station and the detector (40 km long)

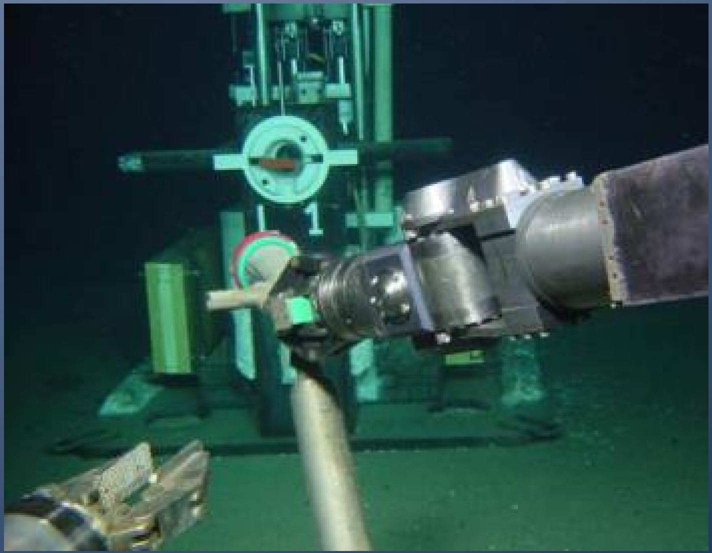
Deployment

Connection

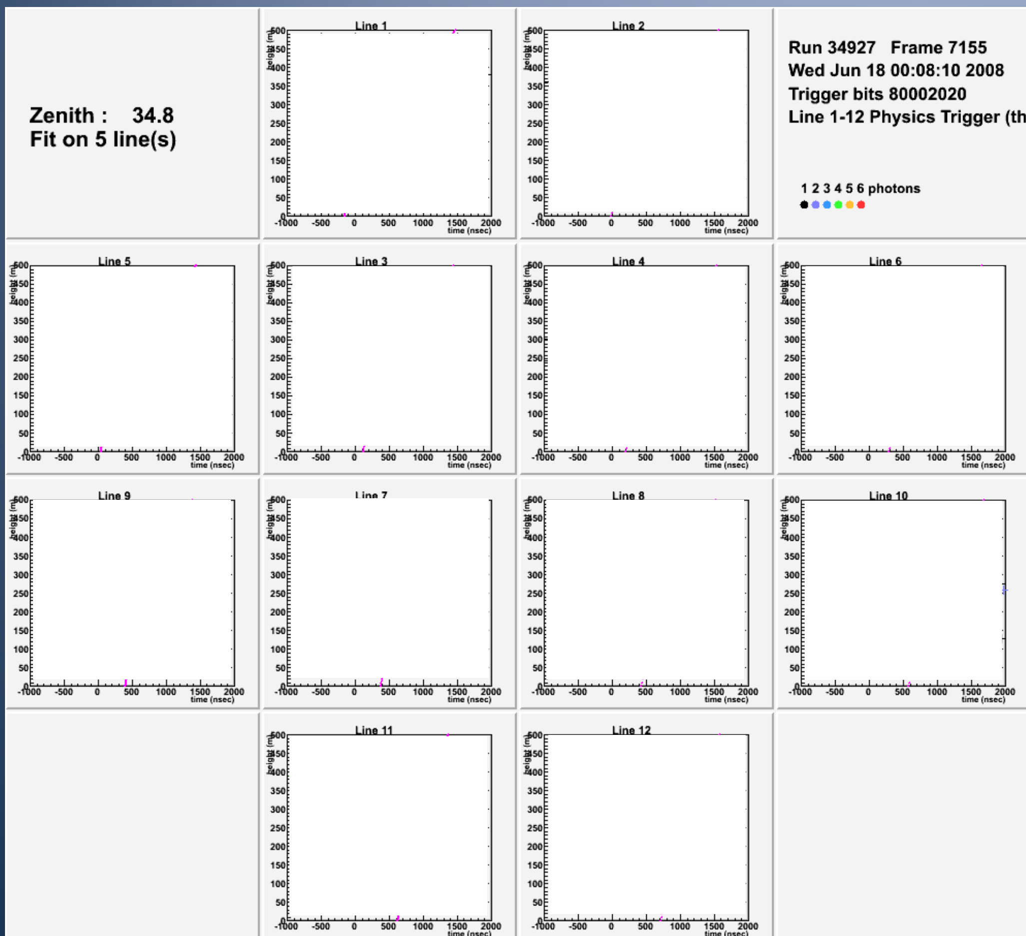
Nautile (manned)



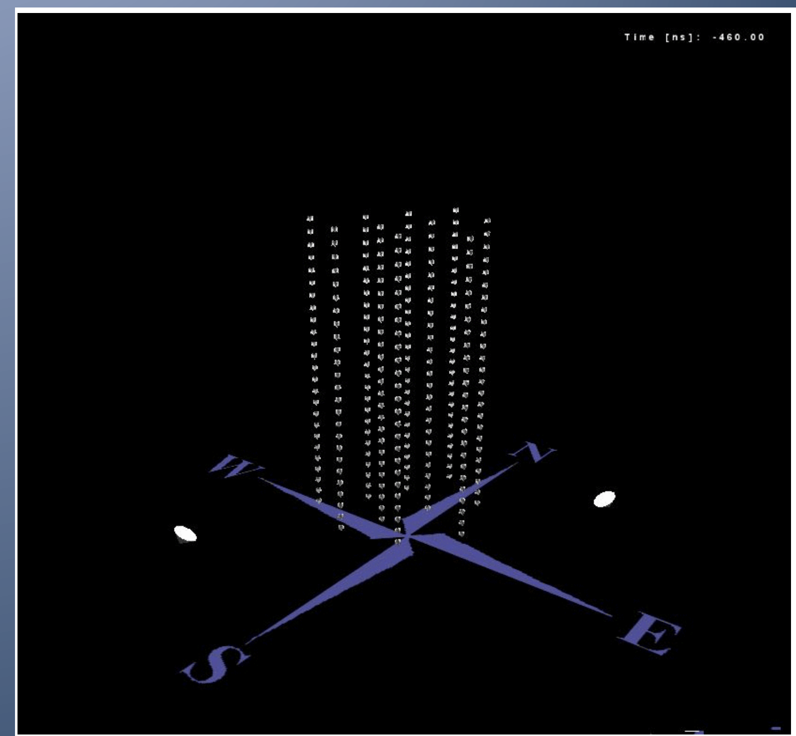
Victor (ROV)



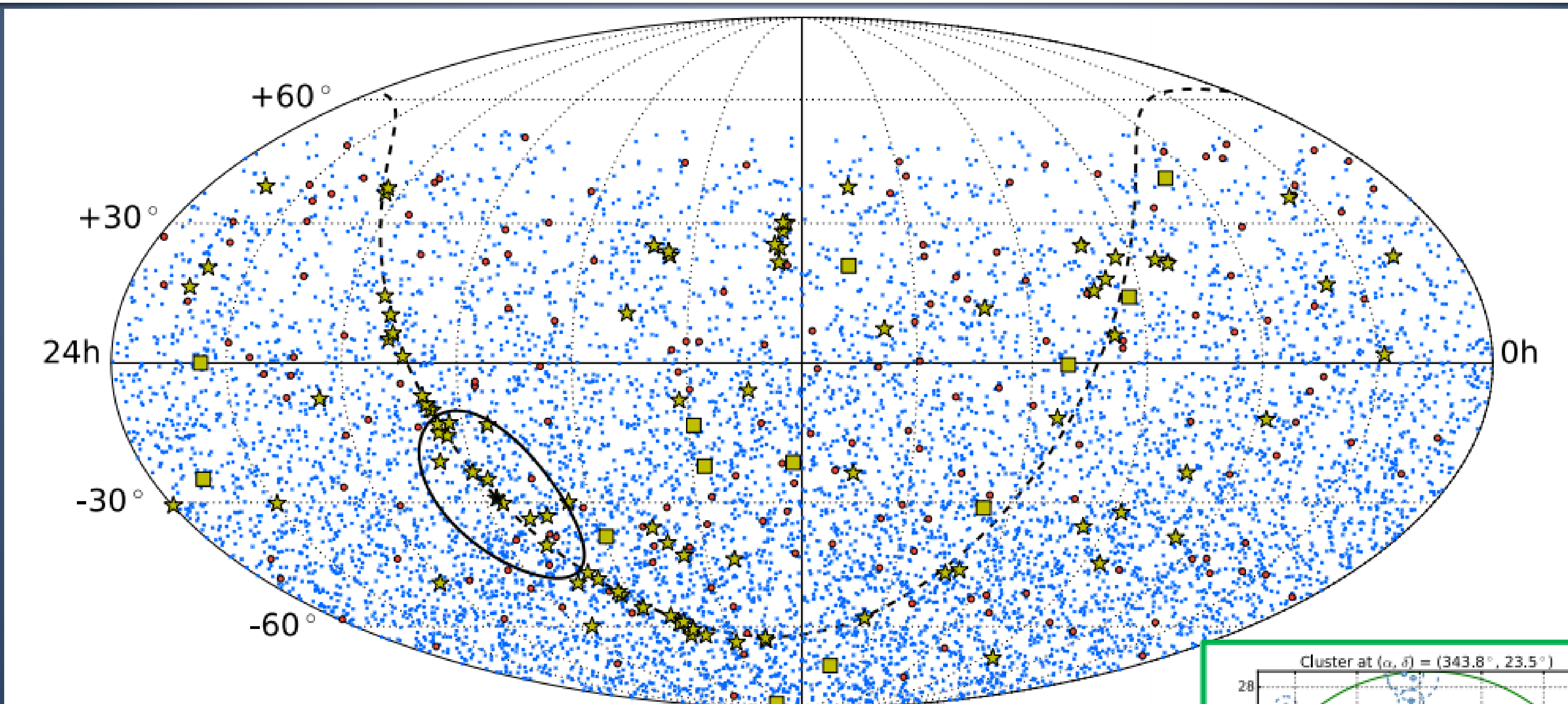
Neutrino candidate



reconstructed up-going muon (i.e. a neutrino candidate) detected in 6/12 detector lines:



Neutrino sky



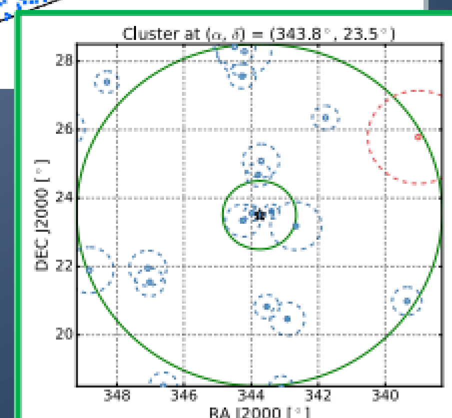
X Track
Cascade
Source candidate
HESE track (IC)

Data: 2007-2015

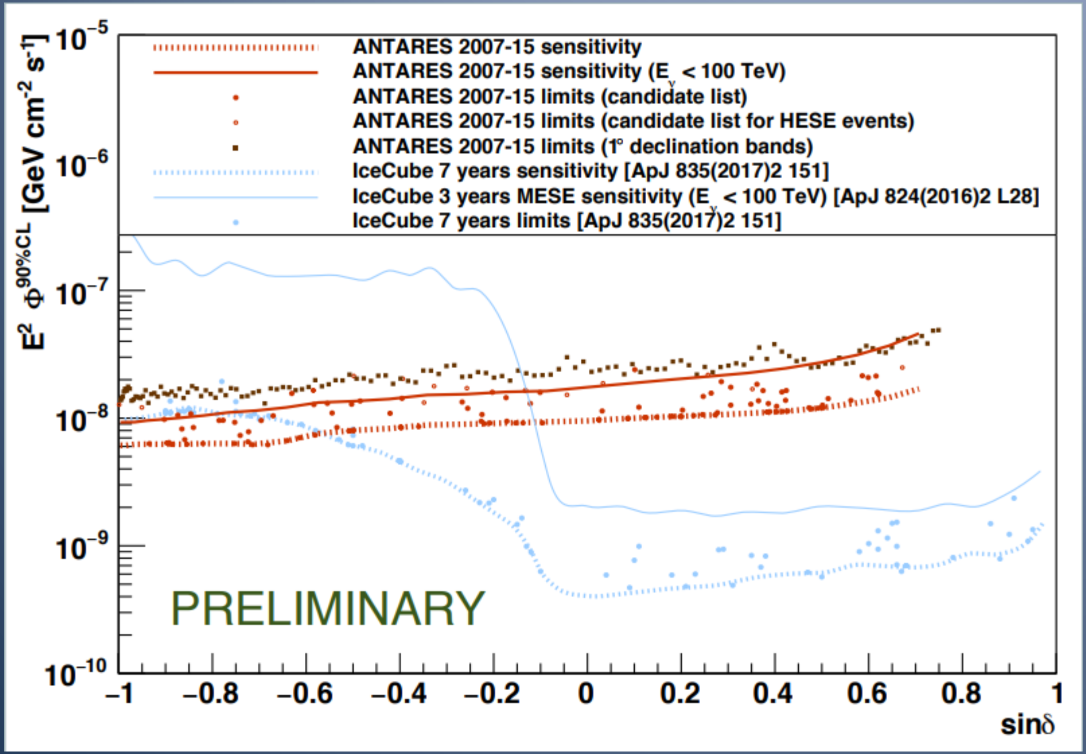
7629 tracks **180 showers**

Cascades can be used in point source searches by undersea detectors!

Most significant cluster:1.9σ

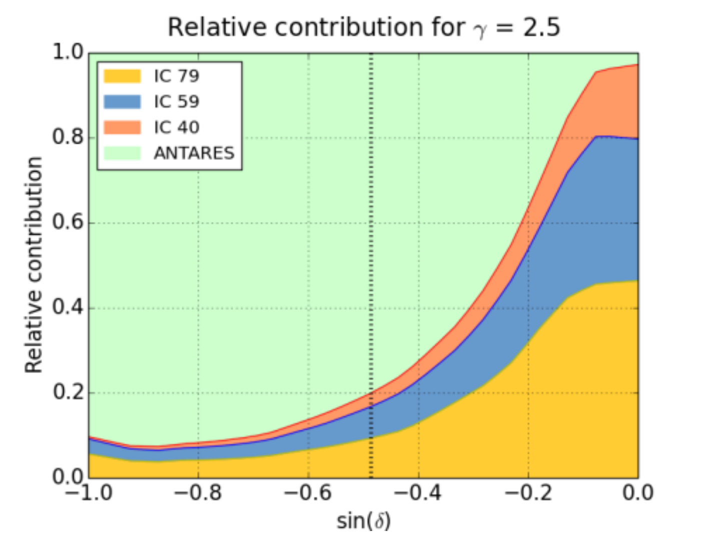


Flux limits

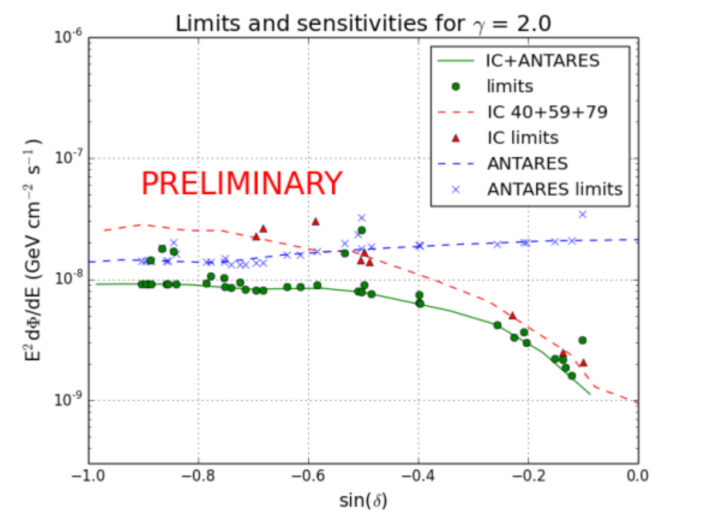


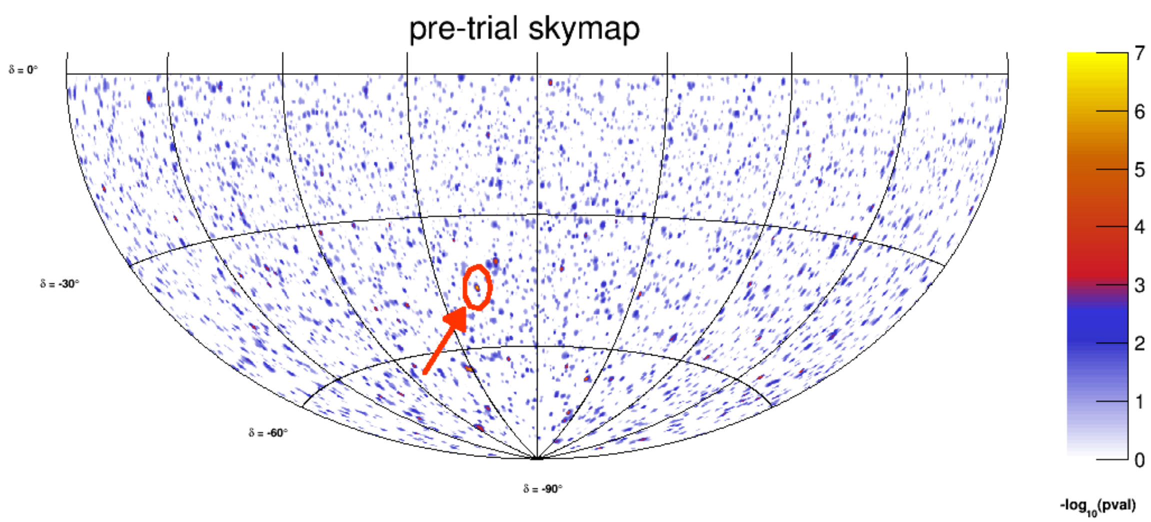
- Best limits for TeV-PeV energies in the Southern Hemisphere

ANTARES+IceCube Combined



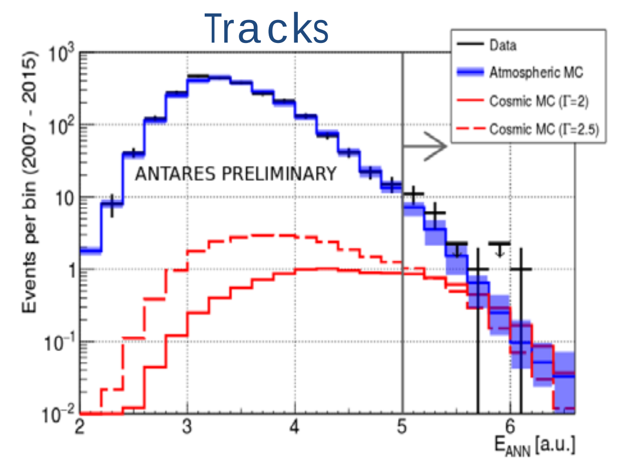
- An analysis has been done looking for point sources combining ANTARES and IceCube data
- There is an improvement in the declination region corresponding to the crossing of sensitivities (it depends on the spectral index and a potential energy cutoff)
- Data (ANTARES 6y + IceCube 3y) has been unblinded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

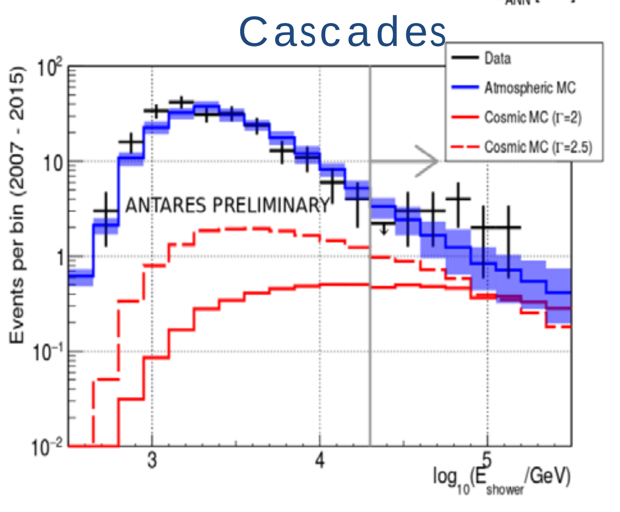




Diffuse flux

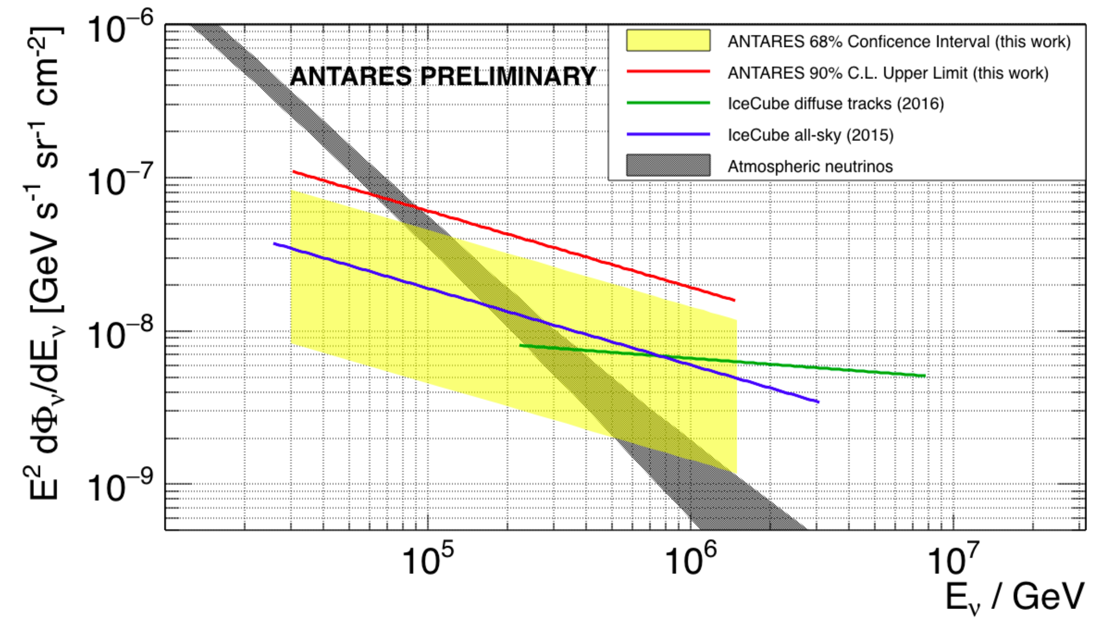
Reminder: no directional information, discrimination made by selecting high energy events



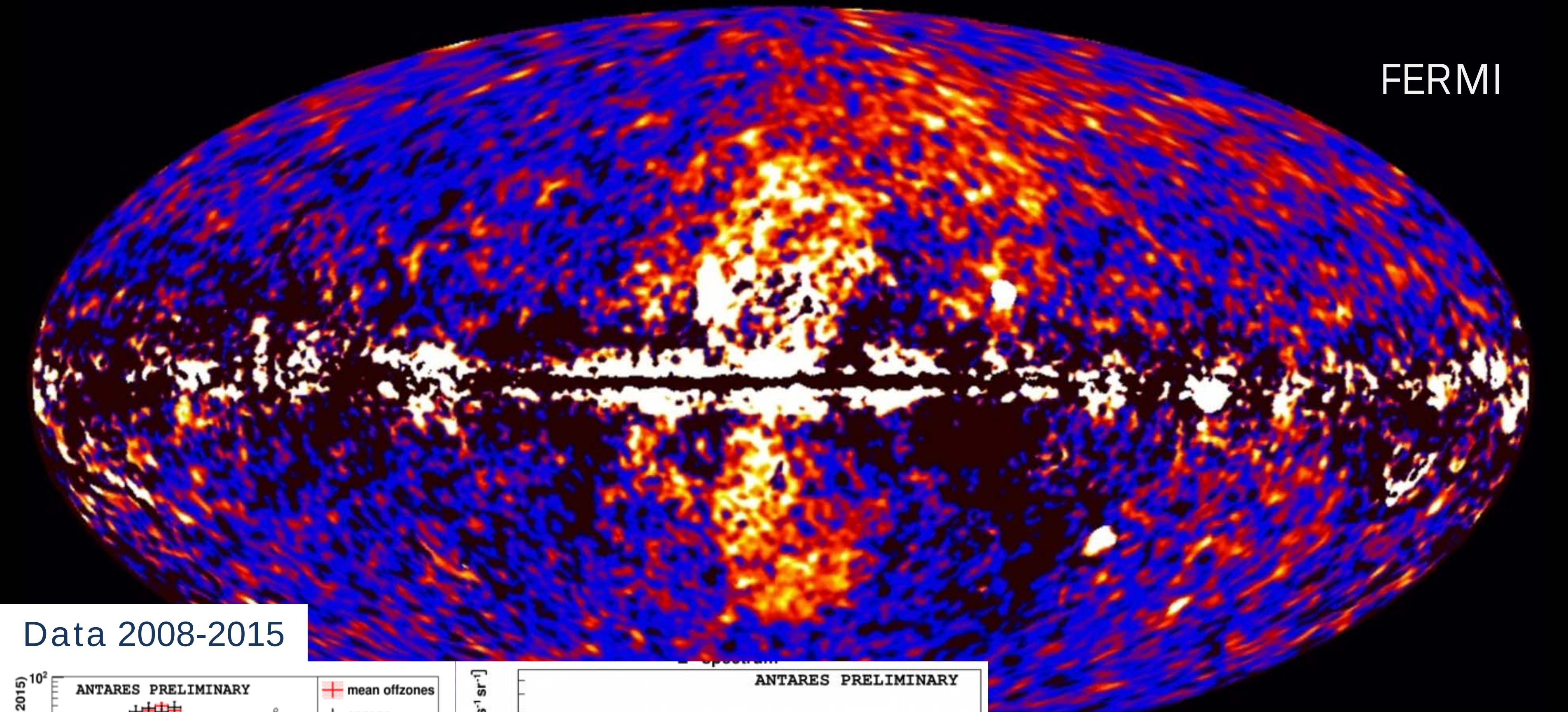


Tracks & Cascades

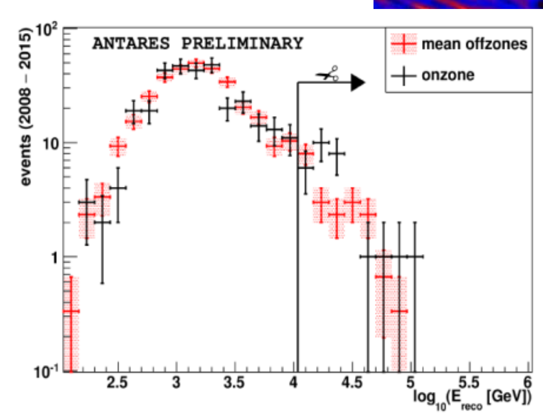
- Data: 2008-2015 (2451 live days)
- 33 observed events above E_{cut}
- 24 ± 7 expected background events
- 8 expected from IceCube flux

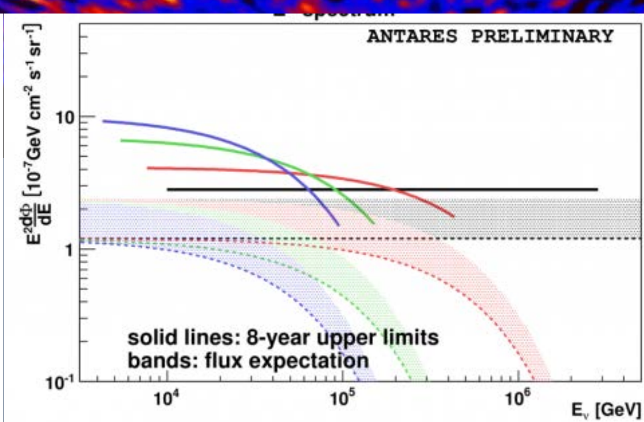


Fermi Bubbles



Data 2008-2015





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

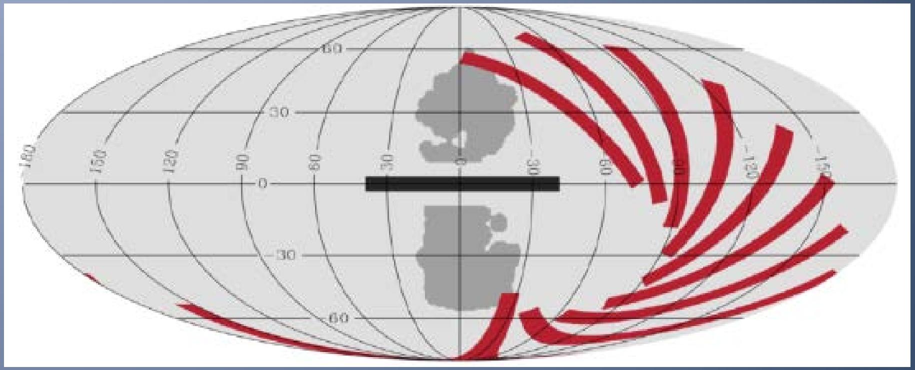
N_{bg} (OFF) = 19.7bg events

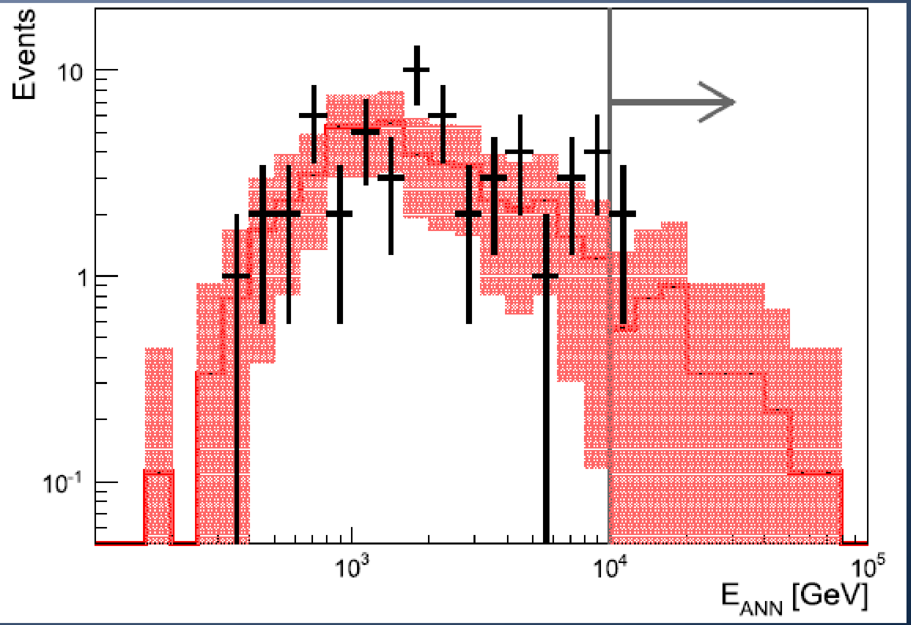
N_{obs} = 28 events

Galactic Ridge

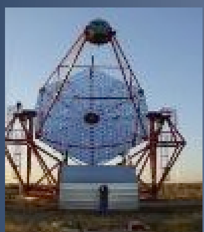
arXiv:1602.03036

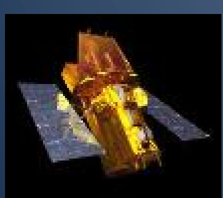
- Neutrinos could be produced in by the interaction of cosmic rays with the interstellar medium
- Search region:
  - |l|<30º
  - |b|<4º
- Data set: 2007-2013
- No excess found





Multimessenger





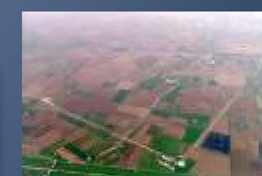
GeV-TeV γ-rays
Fermi / HESS,
HAWC…

UHECR
Auger

High energy
neutrinos

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

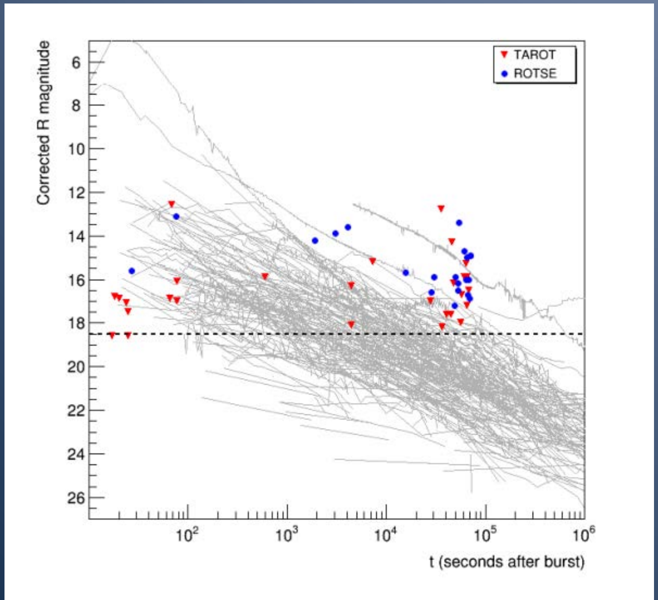
Gravitational
Waves
Virgo / Ligo

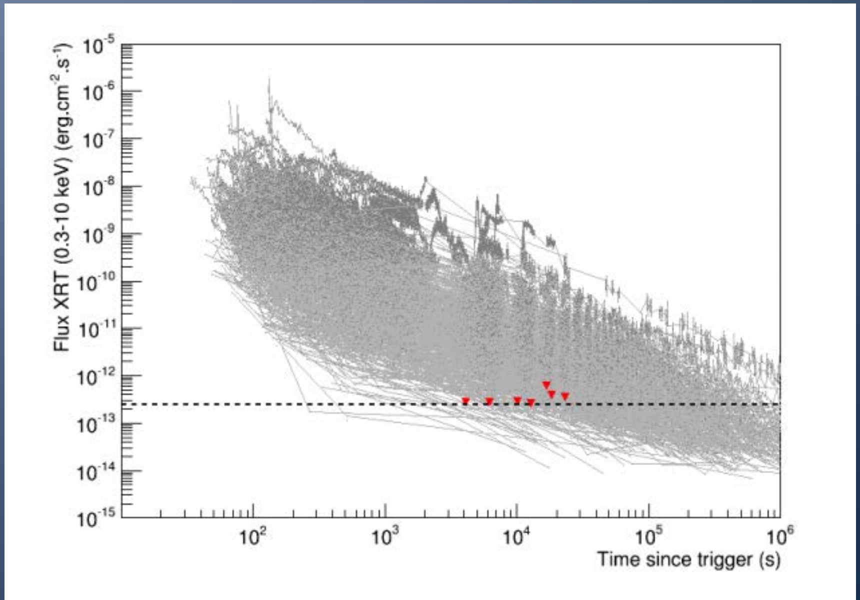


- It increases the chances of detection
  - Common sources for different messengers
  - Backgrounds and systematics non correlated

TAToO

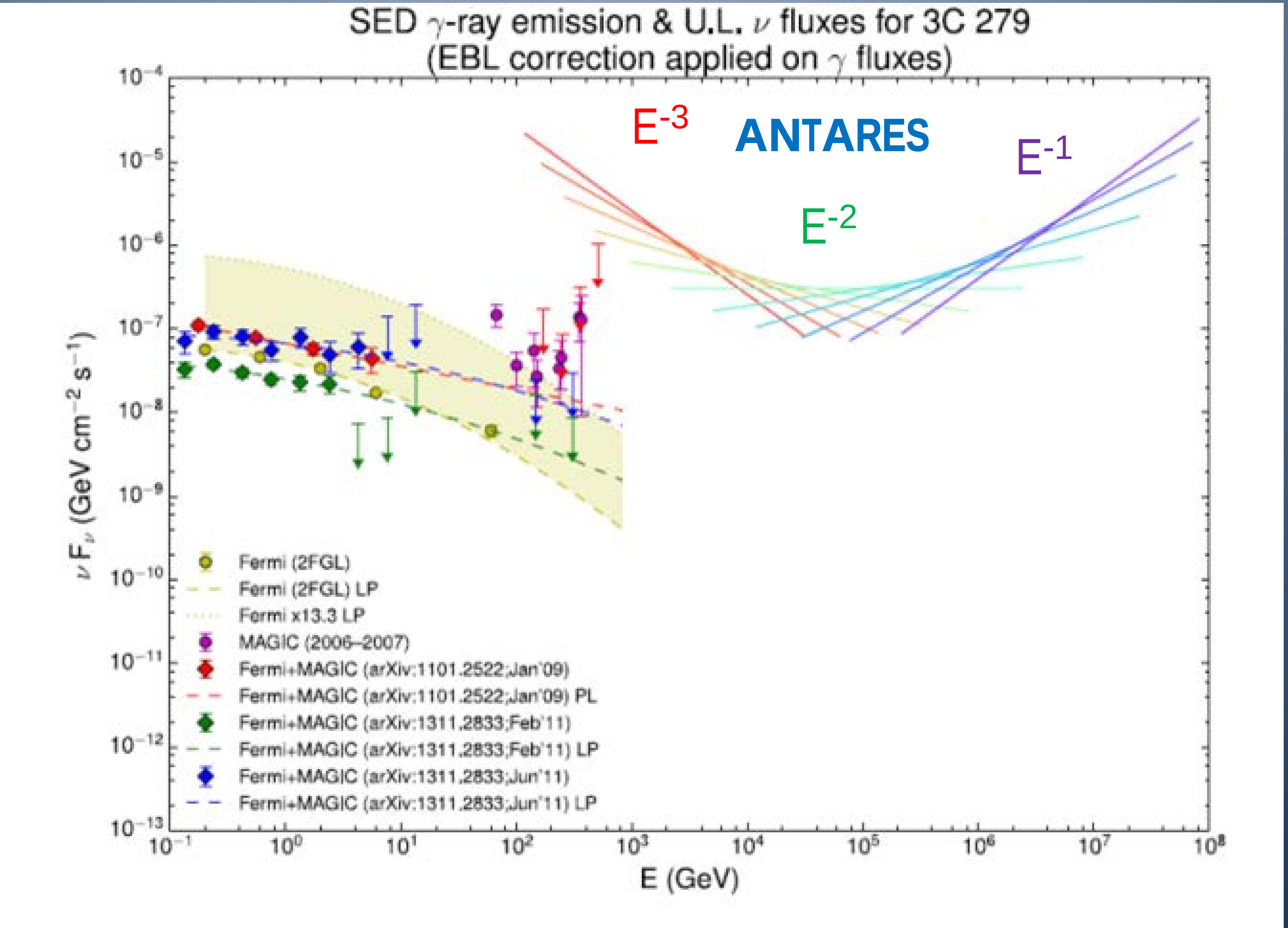
- Target of Opportunities Program:
  - Alerts sent to TAROT and ROTSE (optical) and Swift-XRT (X-rays)
  - Several trigger conditions (doublets, high energy single events, directional triggers)
  - Alerts followed up: 42 alerts of optical and 7 tof X-rays
  - Very quick reaction: 3-5 seconds





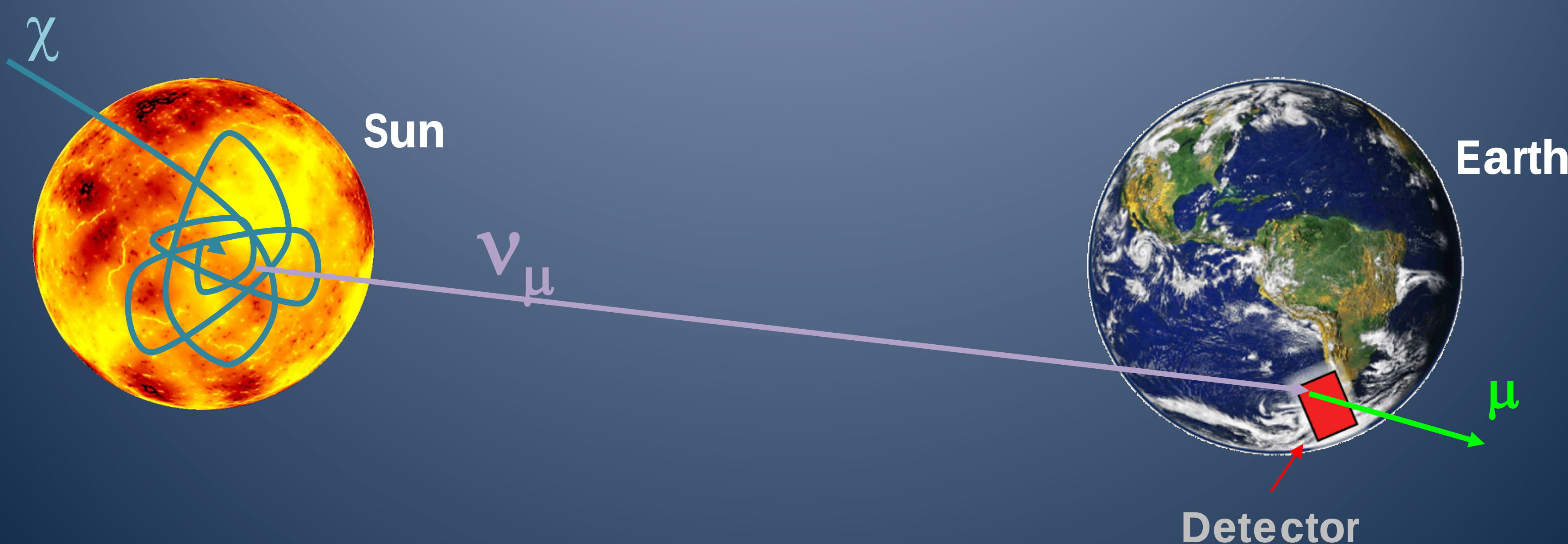
Correlation with blazars

- Search for neutrino events correlated with high activity state
- 1 correlation (3C279) out of 48 cases



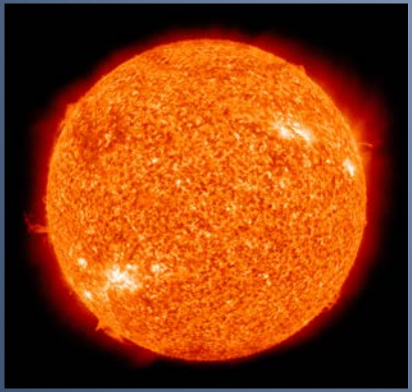
Dark matter detection in NTs

- 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 Centre
- The products of such annihilations would yield "high energy" neutrinos, which can be detected by neutrino telescopes



Dark matter sources

Sun



Galactic Centre

Dwarf galaxies

Earth

Galactic Halo

Galaxy clusters

Sun: $\sigma_{\chi N}$

Differential neutrino flux is related with the annihilation rate as:

$$\frac{d\phi_\nu}{dE_\nu} = \frac{\Gamma}{4\pi d^2}\,\frac{dN_\nu}{dE_\nu},$$

If we assume equilibrium between capture and annihilation in the Sun:

$$\Gamma \simeq \frac{C_\otimes}{2}.$$

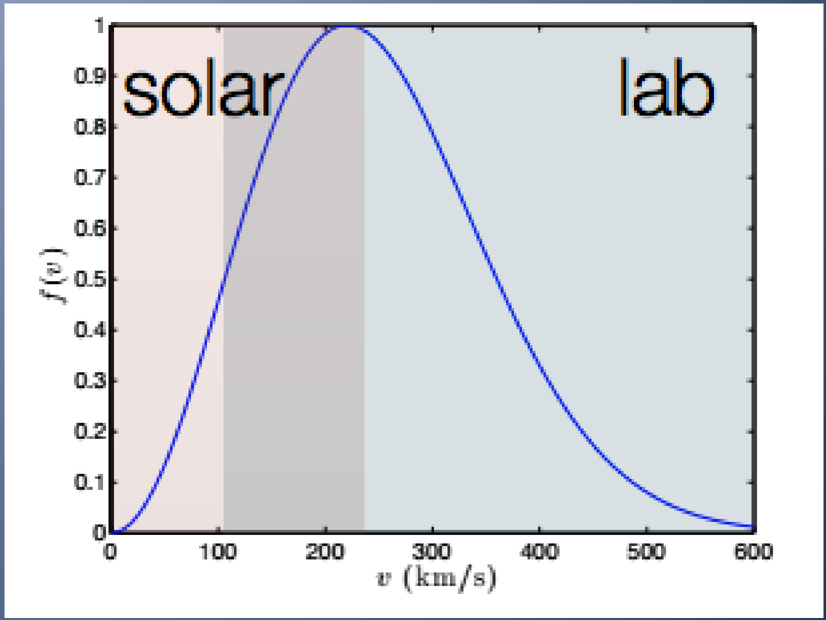
where the capture rate can be expressed as:

$$C_\otimes \simeq 3.35\times 10^{18}\mathrm{s}^{-1} \times \left(\frac{\rho_{\mathrm{local}}}{0.3\,GeV\cdot cm^{-3}}\right) \times \left(\frac{270\,\mathrm{km}\cdot\mathrm{s}^{-1}}{v_{\mathrm{local}}}\right) \times \left(\frac{\sigma_{H,SD}}{10^{-6}\,\mathrm{pb}}\right) \times \left(\frac{TeV}{M_{\mathrm{WIMP}}}\right)^2,$$

Velocity distributions in the Galactic Halo

- Neutrino telescopes (for searches in the Sun) complementary to direct searches
  - low velocity: easier to capture in the Sun
  - high velocity: large recoils easier at high velocities

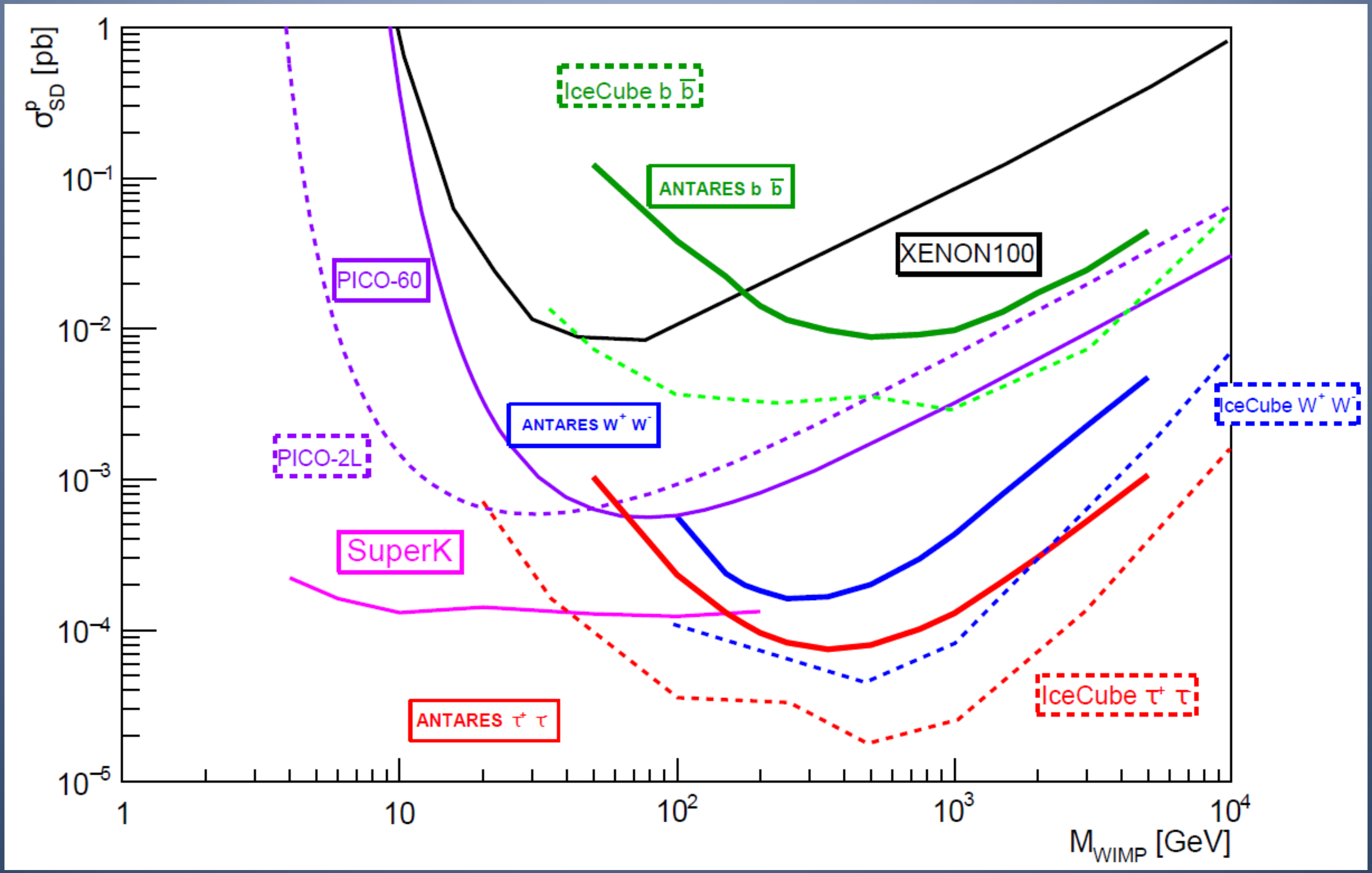
$$f(u) = \sqrt{\frac{3}{2\pi}}\frac{u}{v_\odot v_{\rm rms}}\left(\exp\left(-\frac{3(u-v_\odot)^2}{2v_{\rm rms}^2}\right) - \exp\left(-\frac{3(u+v_\odot)^2}{2v_{\rm rms}^2}\right)\right)$$



Typically Maxwell distribution of velocities is assumed

Other v distributions: <20% change in C
Choi et al. JCAP 1405 (2014) 049

The Sun



Neutrino telescopes: best tool for spin-*dependent* cross section (WIMP-nucleon)

Rate calculation

- Gamma rays, neutrinos:

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, \psi, \theta, \Delta\Omega) = \boxed{\frac{1}{4\pi} \frac{\langle\sigma_{\text{ann}} v\rangle}{2m_\chi^2} \frac{dN_\gamma^i}{dE_\gamma}} \boxed{\int_0^{\Delta\Omega} d\Omega \int_{\text{l.o.s}} \rho^2(r(s, \psi, \theta))ds.}$$

Particle Physics

Dark matter distribution (J-factor)

- Cosmic rays:
  - propagation more complex

$$-\mathcal{K}(E)\cdot\nabla^2 n_f - \frac{\partial}{\partial E}\left(b(E,\vec{x})\, n_f\right) + \frac{\partial}{\partial z}\left(\text{sign}(z)\, V_{\text{conv}}\, n_f\right) = Q(E,\vec{x}) - 2h\,\delta(z)\,\Gamma\, n_f$$

Density profiles

Cirelli et al., 1012.4515v4

$$\text{NFW}: \quad \rho_{\rm NFW}(r) = \rho_s \frac{r_s}{r}\left(1+\frac{r}{r_s}\right)^{-2}$$

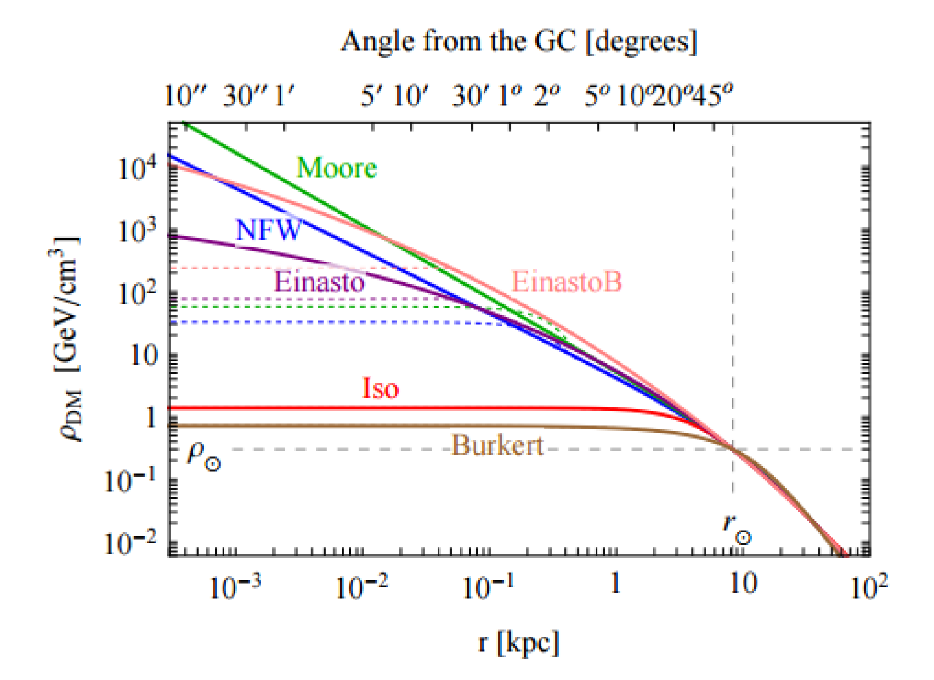
$$\text{Einasto}: \quad \rho_{\rm Ein}(r) = \rho_s \exp\left\{-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^{\alpha}-1\right]\right\}$$

$$\text{Isothermal}: \quad \rho_{\rm Iso}(r) = \frac{\rho_s}{1+(r/r_s)^2}$$

$$\text{Burkert}: \quad \rho_{\rm Bur}(r) = \frac{\rho_s}{(1+r/r_s)(1+(r/r_s)^2)}$$

$$\text{Moore}: \quad \rho_{\rm Moo}(r) = \rho_s \left(\frac{r_s}{r}\right)^{1.16}\left(1+\frac{r}{r_s}\right)^{-1.84}$$

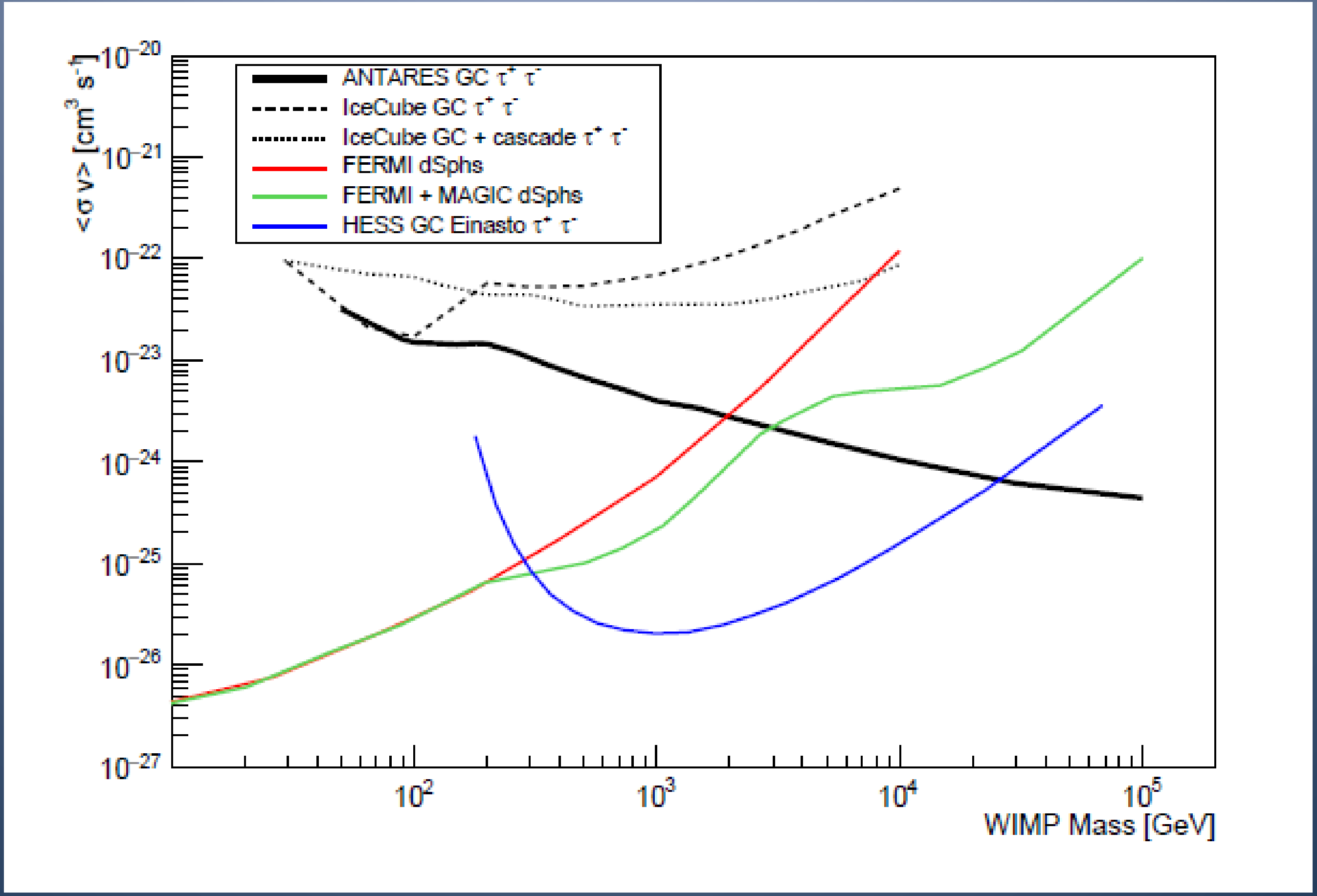
DM halo	α	r_s [kpc]	ρ_s [GeV/cm^3]
NFW	–	24.42	0.184
Einasto	0.17	28.44	0.033
EinastoB	0.11	35.24	0.021
Isothermal	–	4.38	1.387
Burkert	–	12.67	0.712
Moore	–	30.28	0.105



- Several profiles available on the market

Dark Matter: Galactic Center

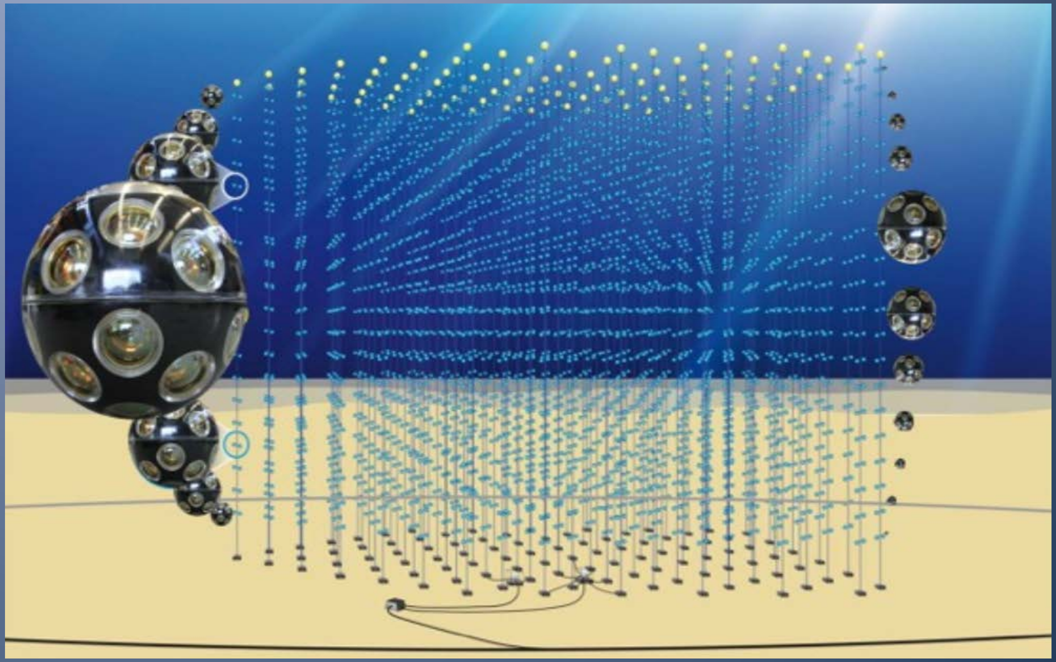
In the Galactic Centre: limits on annihilation cross section



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 (and two more in May 2016)

Phases

PHASE 1:

- Already funded
- 30 lines (24 in Italy, 6 in France)
- Proof of feasibility and first science results

PHASE 2.0:

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

PHASE 3: FINAL CONFIGURATION

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

ORCA and ARCA

- Same technology

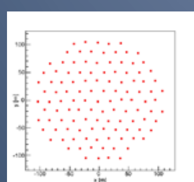
ARCA

ORCA

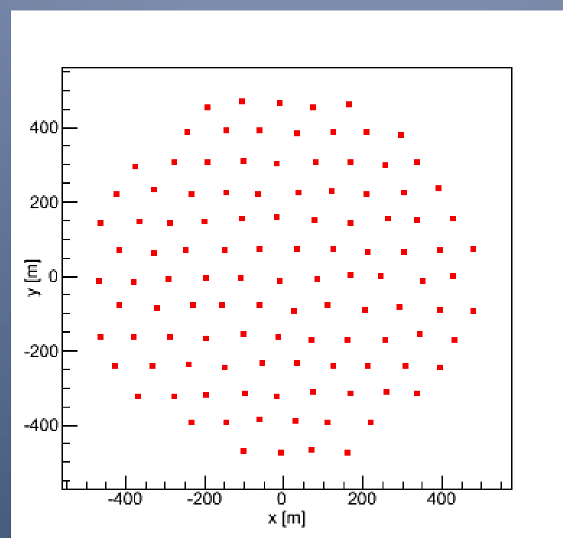
1 km

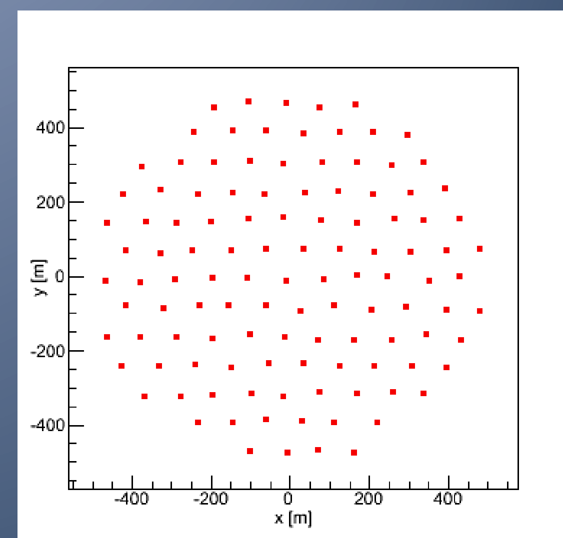
1 km

200 m



France

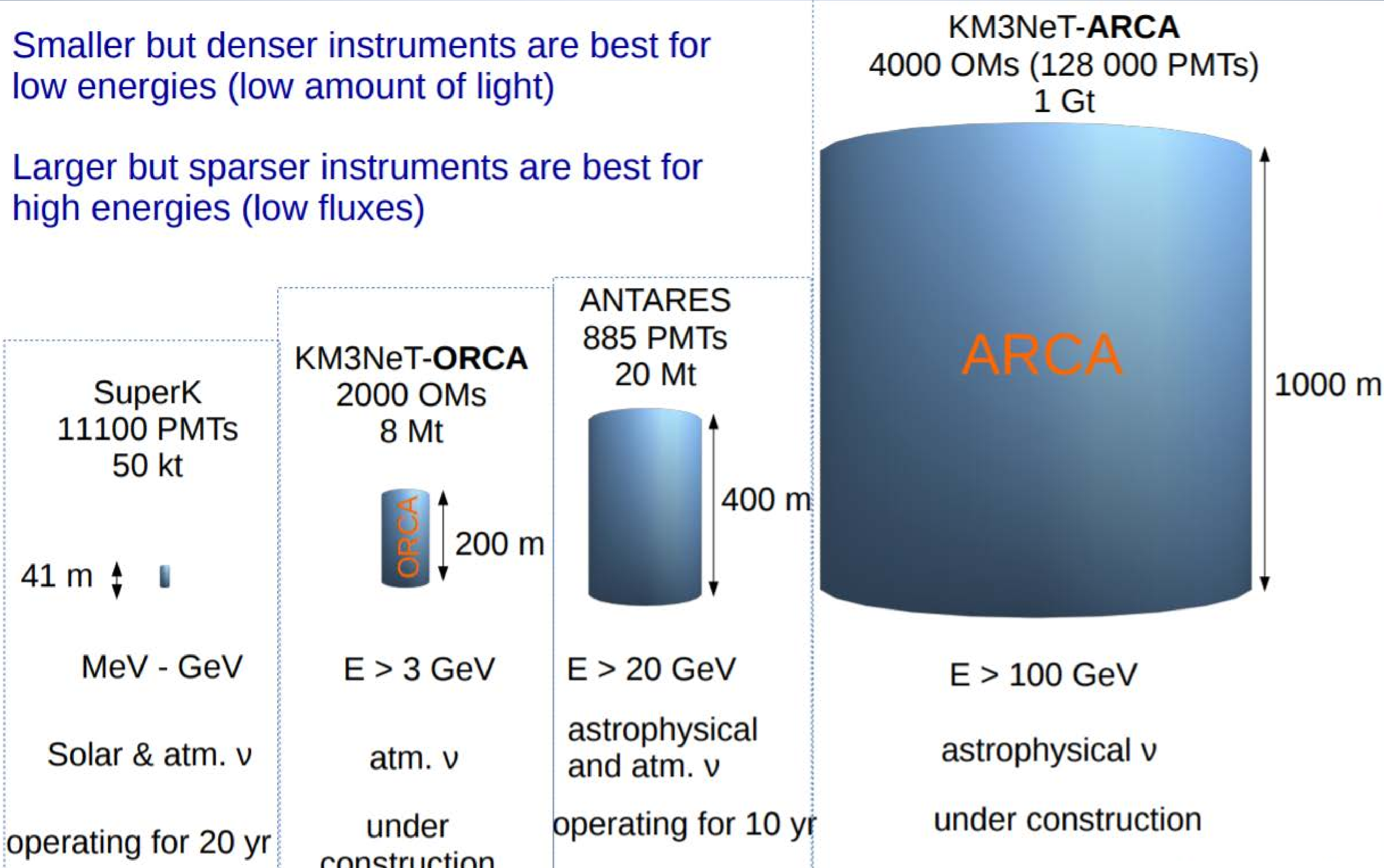




Italy

Smaller but denser instruments are best for low energies (low amount of light)

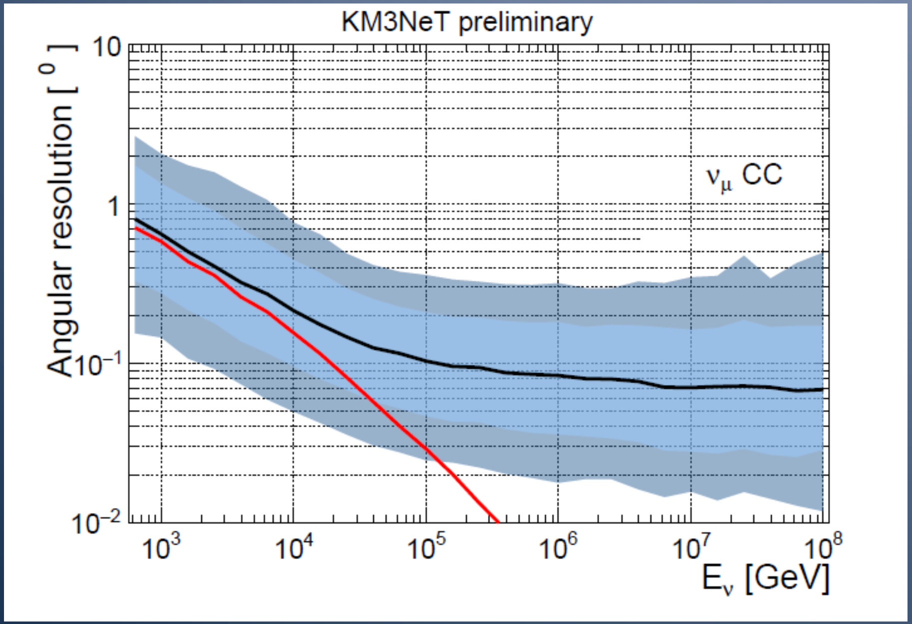
Larger but sparser instruments are best for high energies (low fluxes)



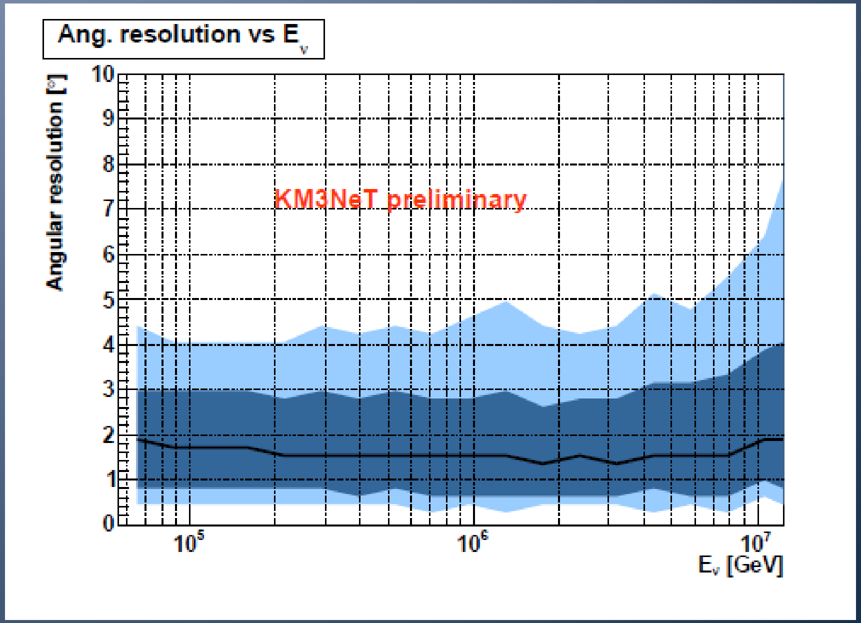
ARCA performance (I)

- Angular resolution
  - For tracks: ~0.1-0.2 degrees
  - For cascades: < 2 degrees:

Tracks



Cascades



1 TeV cascade

Red: direct light

Blue: scattered light

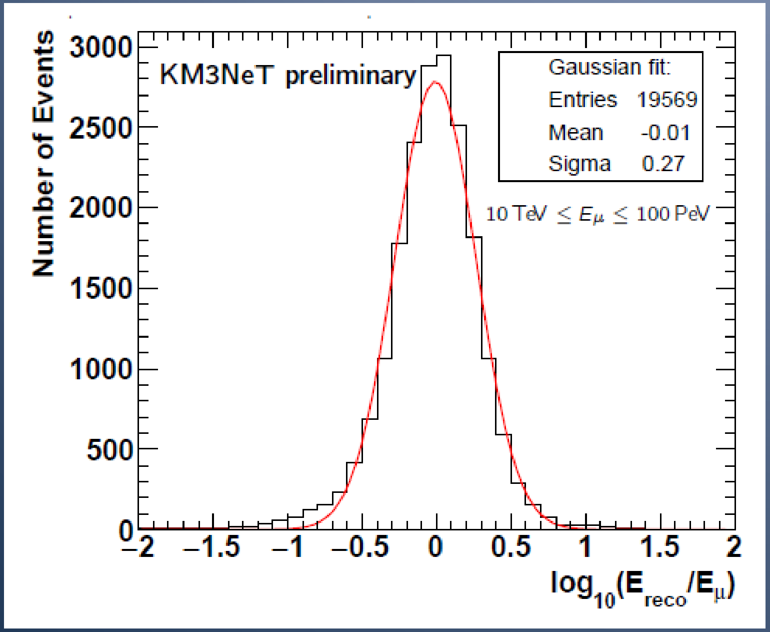
Water

Ice

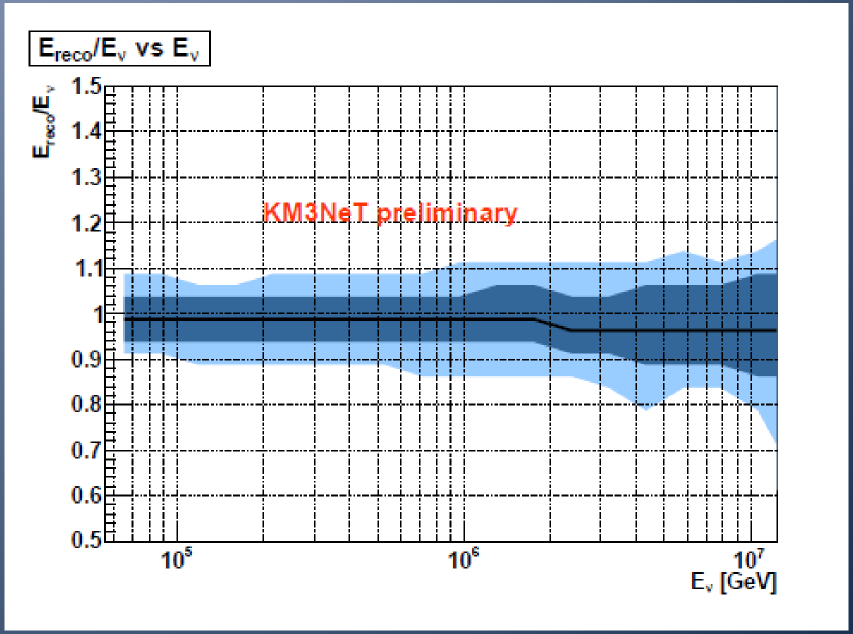
ARCA performance (II)

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

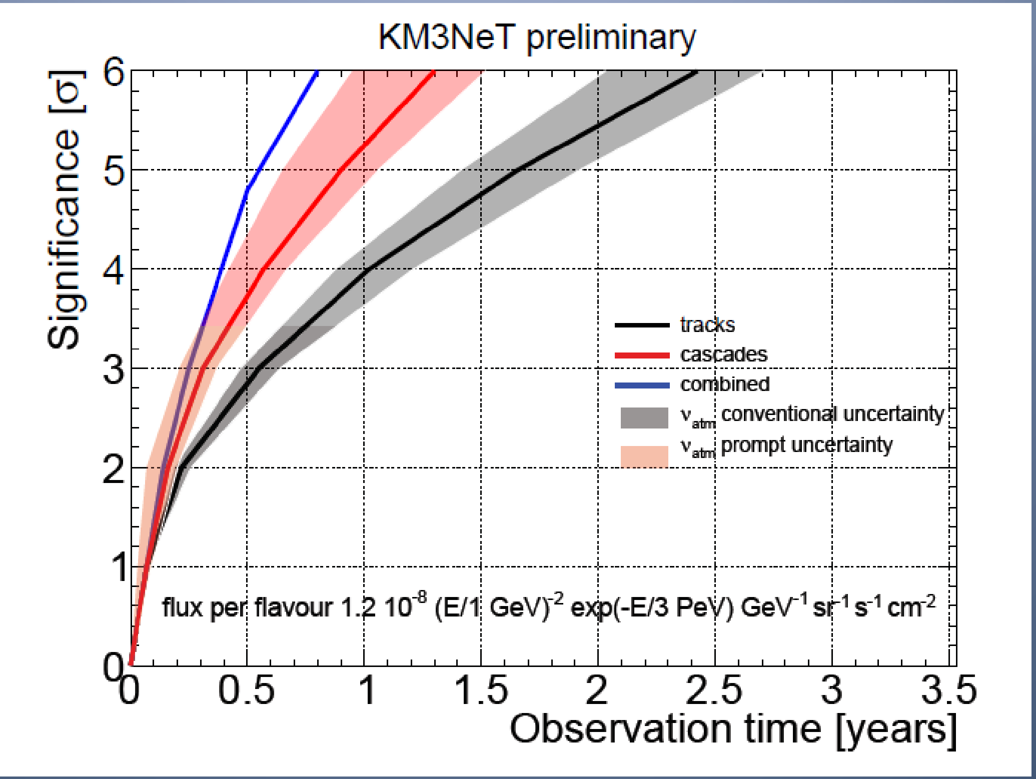
Tracks



Cascades



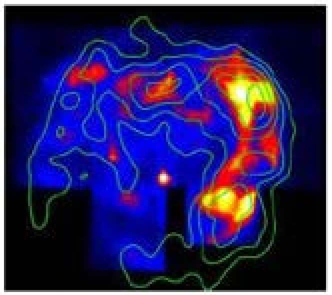
ARCA: sensitivity to diffuse fluxes



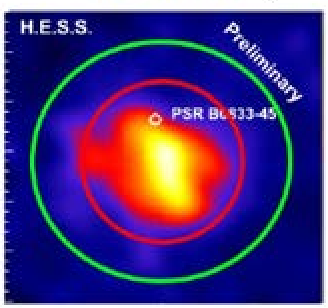
Significance as a function of time for the detection of a diffuse flux of neutrinos corresponding to the signal reported by IceCube, for cascade-like events (red line) and track-like events (black line). The blue line indicates the result of the combined analysis.

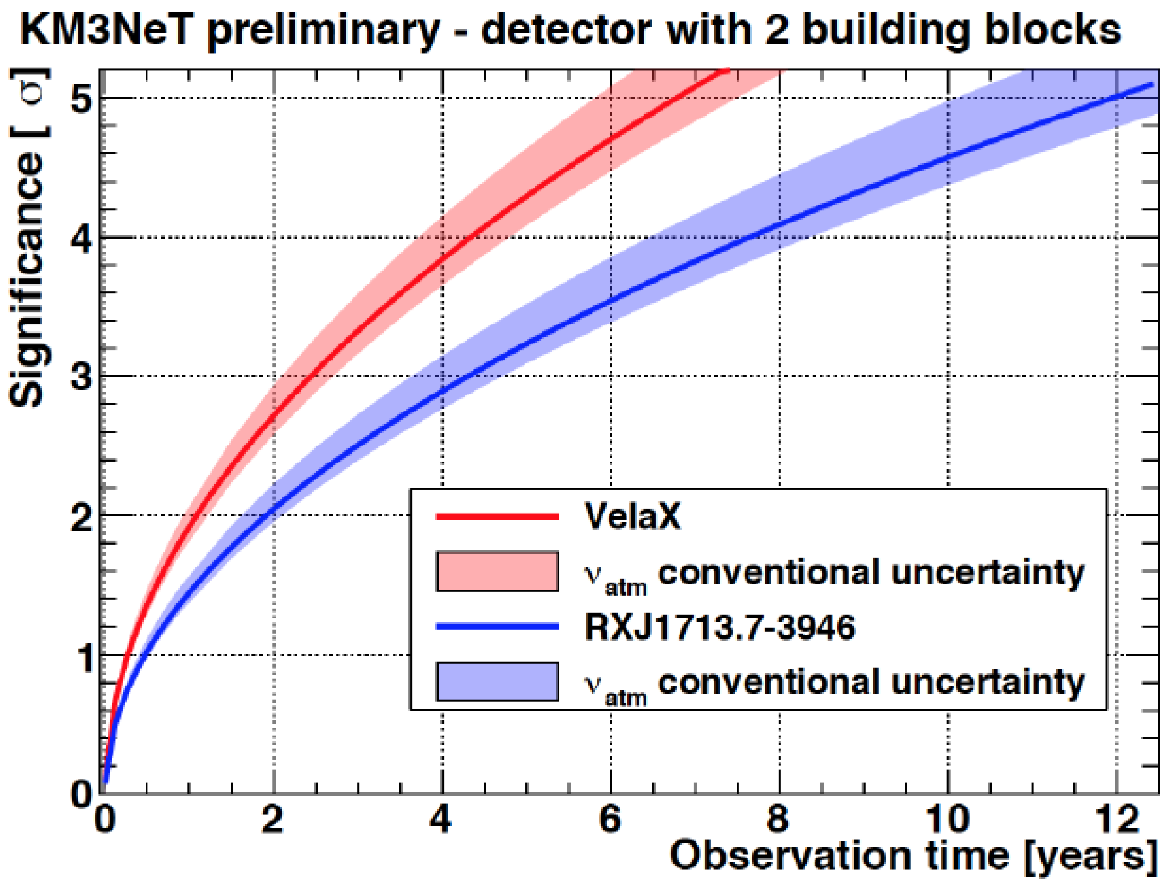
ARCA: sensitivity to point sources

RXJ1713[¶] (SNR)



Vela X[§] (PWN)

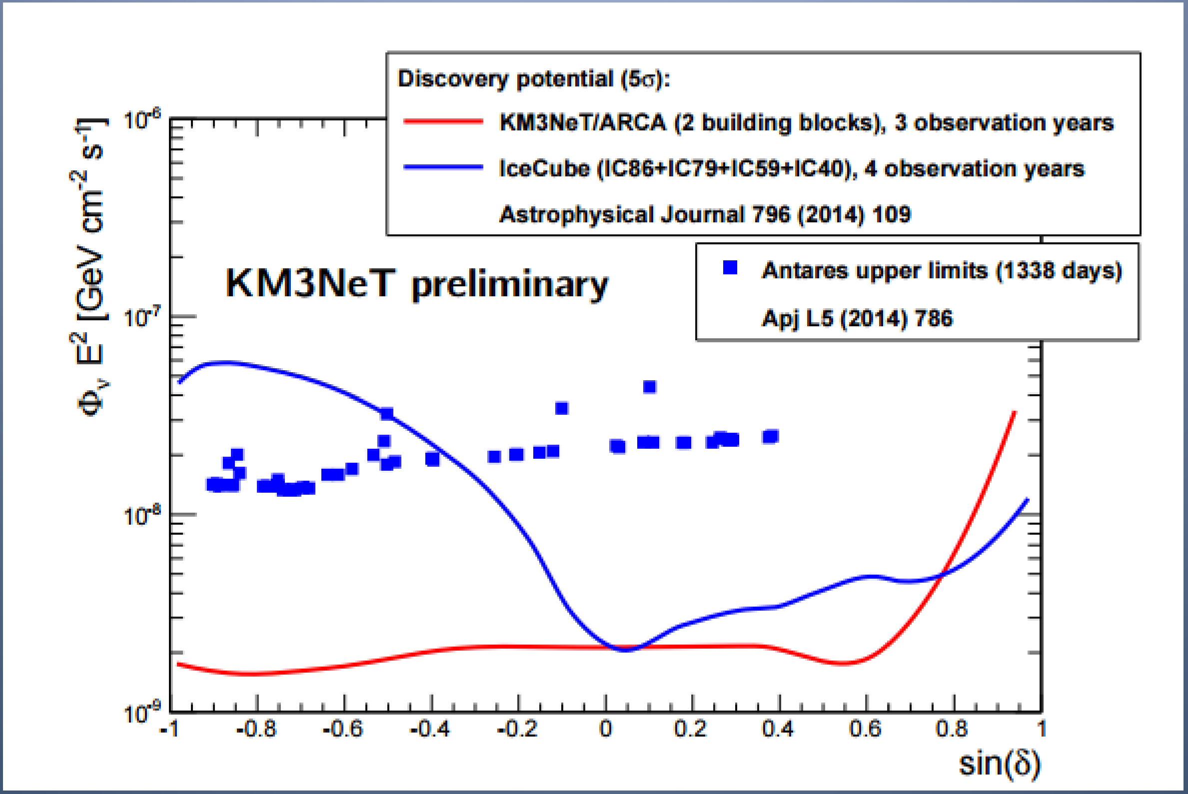




¶ S.R. Kelner, *et al.*, Phys. Rev. D 74 (2006) 034018.

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

ARCA: sensitivity to point sources

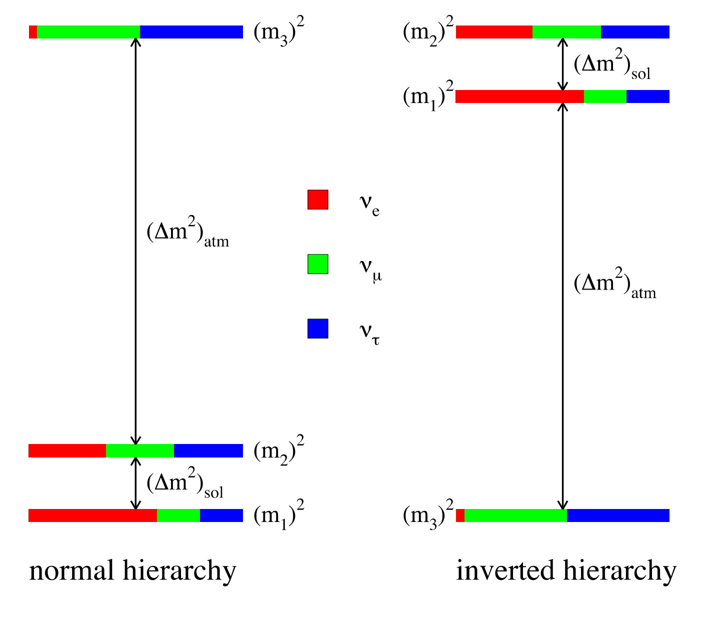


- KM3NeT/ARCA 5σ discovery potential as a function of the source declination (red line) for one neutrino flavour, for point-like sources with a spectrum $\propto E^{-2}$ and 3 years of data-taking

ORCA and PINGU

Introduction

- Neutrino mass ordering 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
  - $0\nu\beta\beta$ experiments



NMO in ORCA

- In matter, the sign of Δm^2_{13} is revealed through the CC interactions of ν_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

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

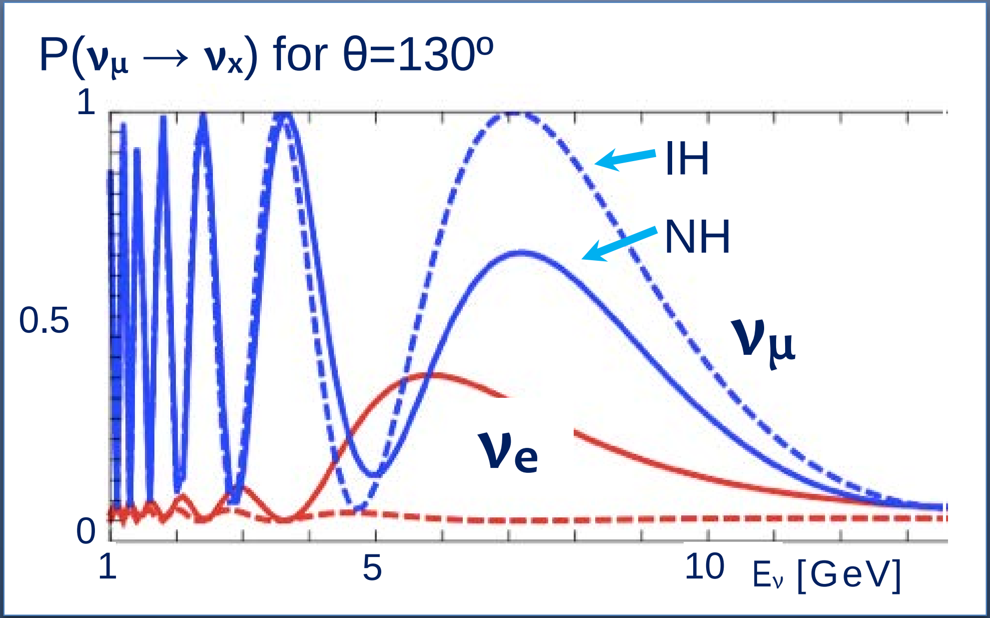
E_{res}~7 GeV for mantle
E_{res}~3 GeV for core

MH with atmospheric neutrinos

- Matter effect in Earth induces ν/anti-ν difference in oscillations
- Examples: PINGU, ORCA, INO (iron tracking calorimeter)
- First maximum for $\nu_\mu \rightarrow \nu_\mu$ is at 12 GeV for $L=D_{earth}$
- Could be measurable since at these energies:

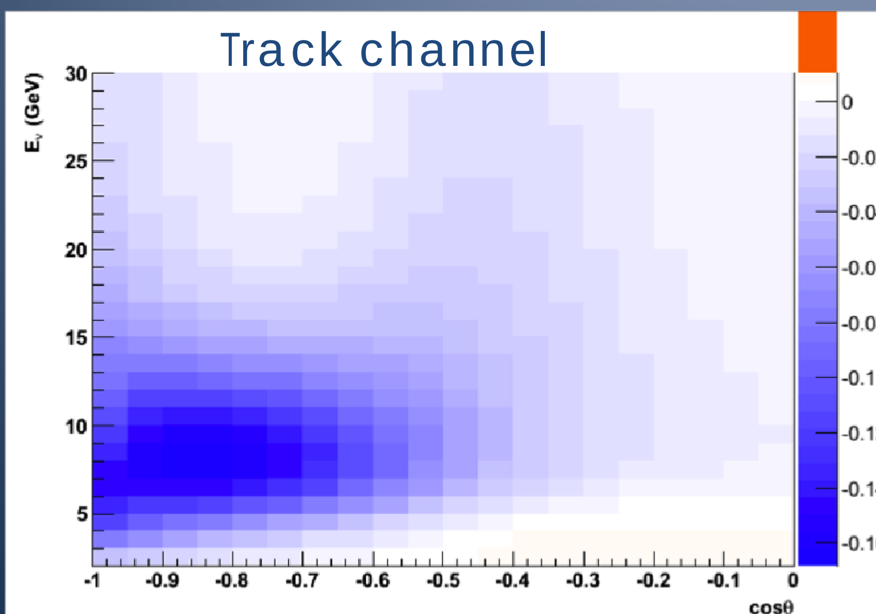
$$\sigma(\nu) \approx 2\sigma(\overline{\nu})$$

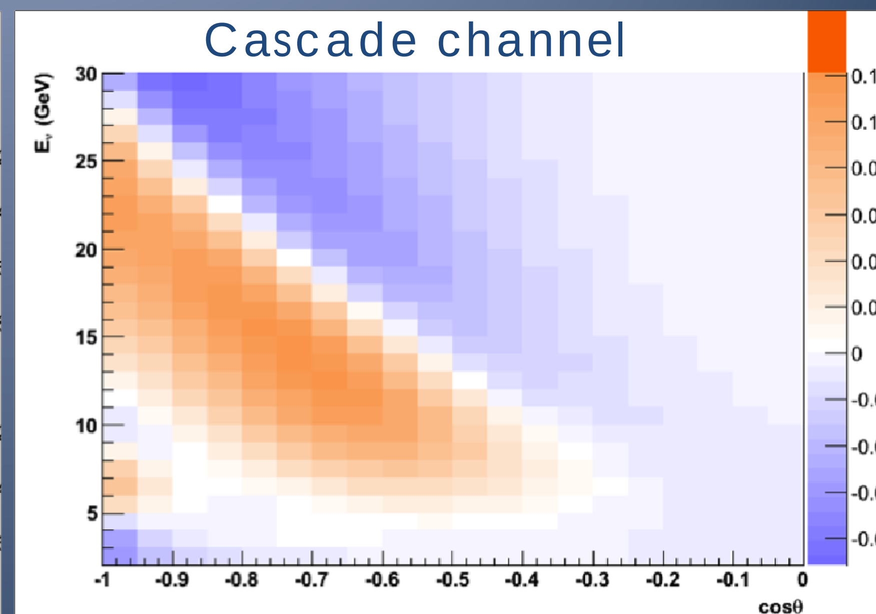
- Differences in the (E_ν, $\cos\theta_\nu$) plane



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

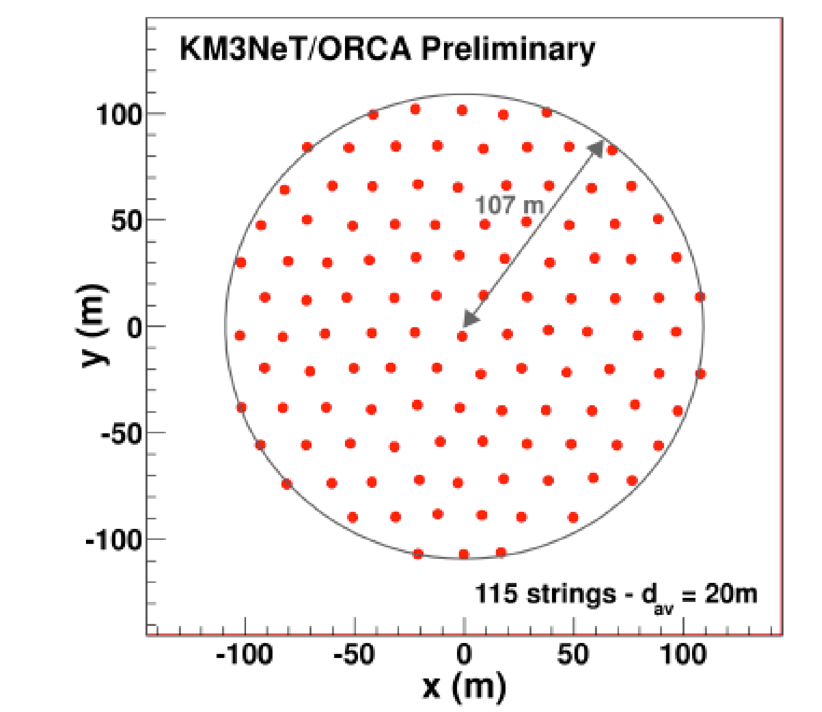




$$A' = (N_{IH} - N_{NH}) / N_{NH}$$

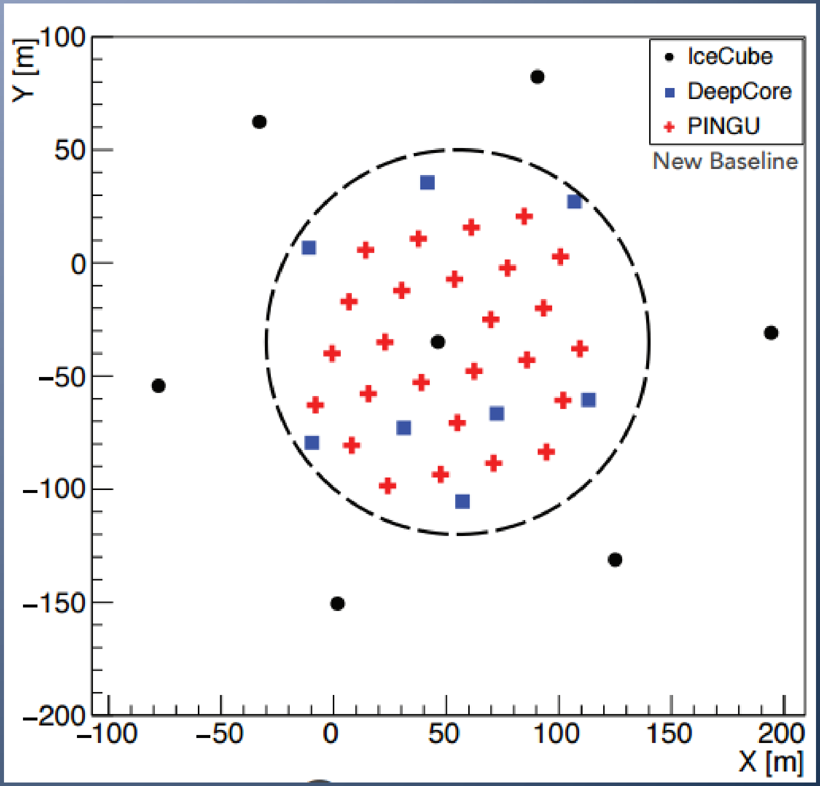
ORCA

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



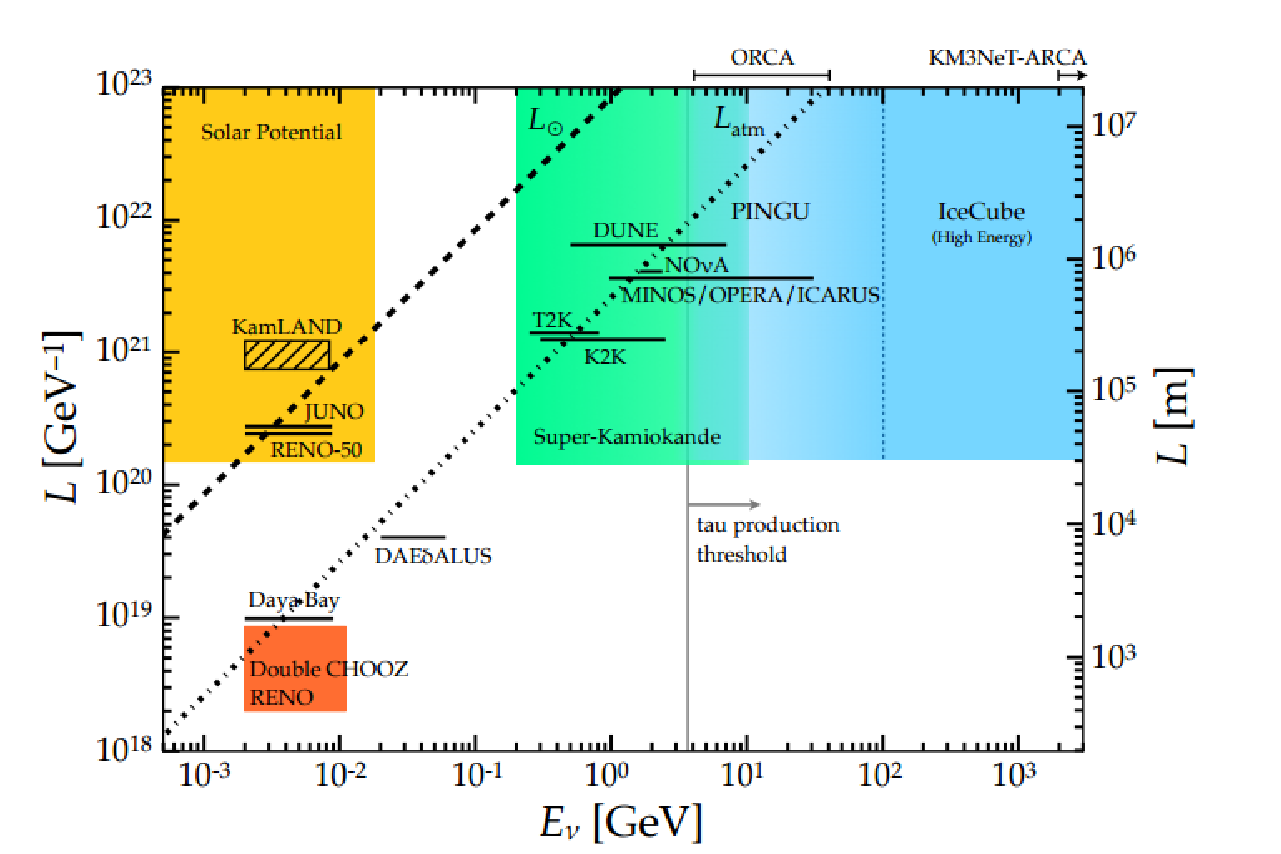
PINGU

- New configuration proposed:
- 26 strings with 192 OMs each (deployable in two seasons)
- 1.5 m DOM-DOM spacing
- Instrumented volume 6 Mton
- Multi-PMT DOM considered as a new option



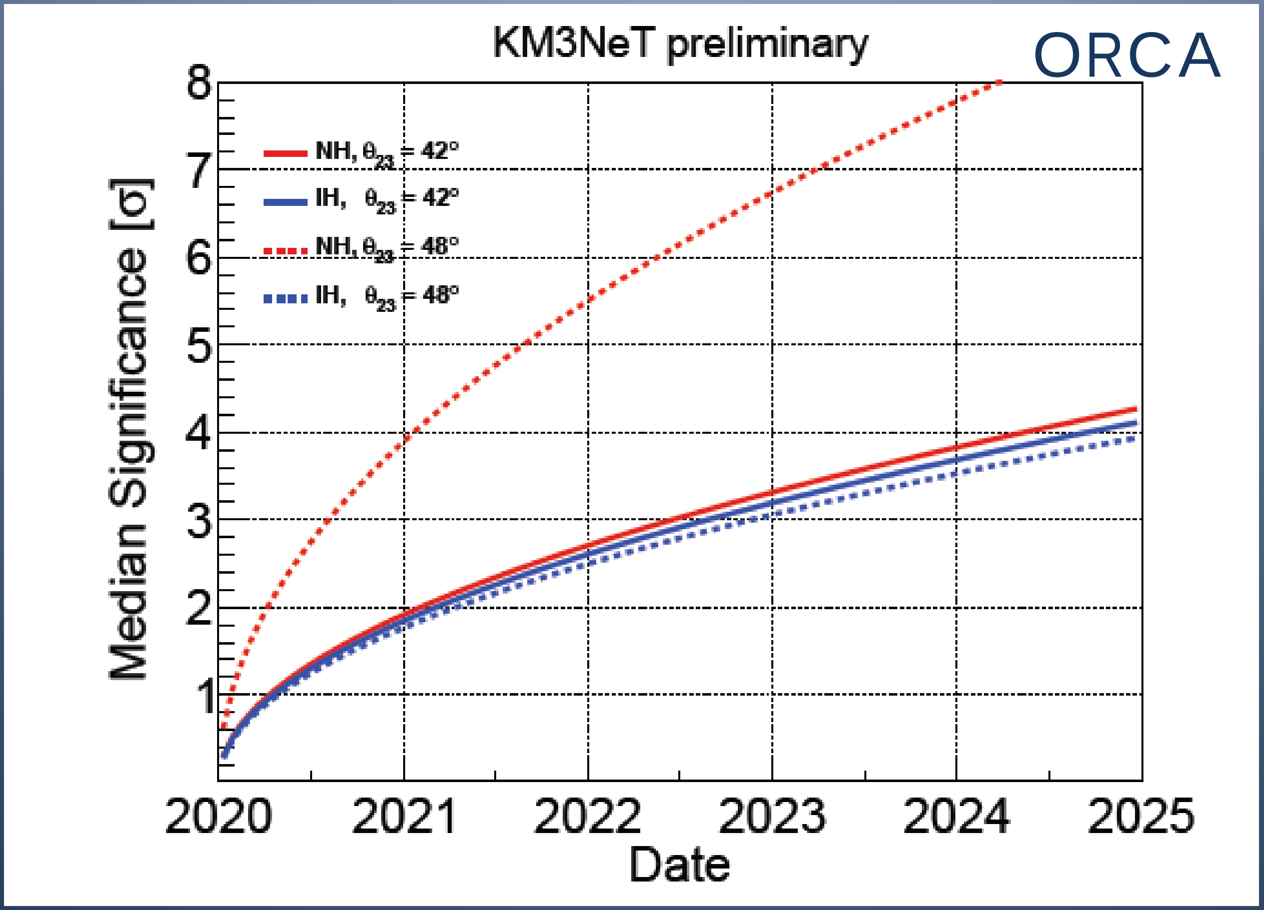
Baseline

- ORCA/PINGU would study oscillations in a different energy/baseline range



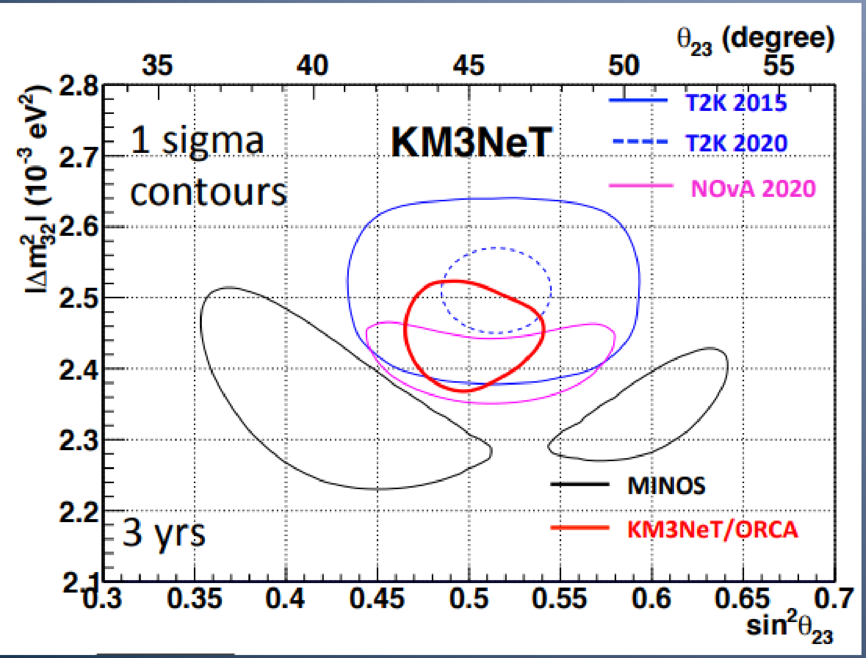
arXiv:1607.0267

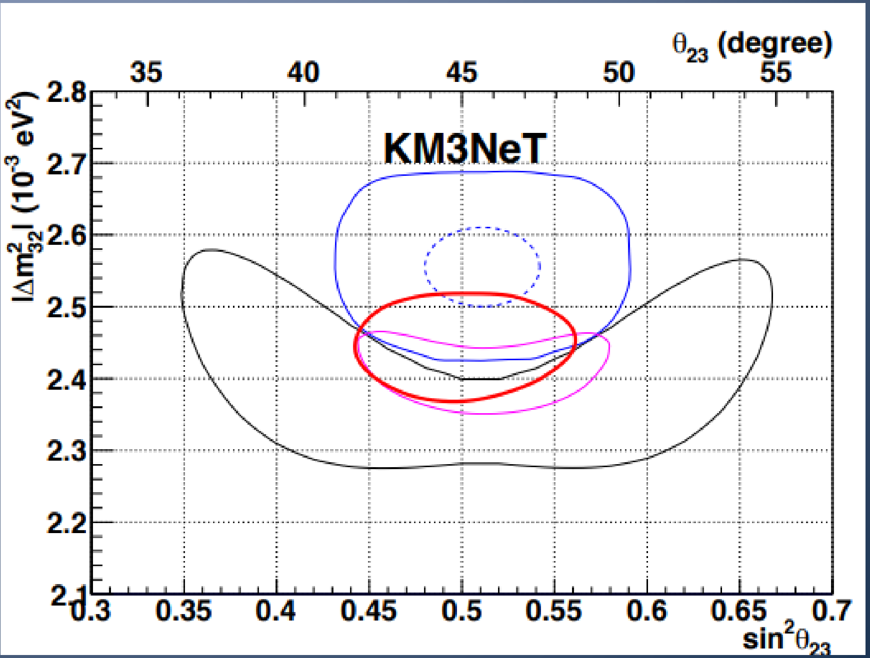
Sensitivity to NMO (ORCA)



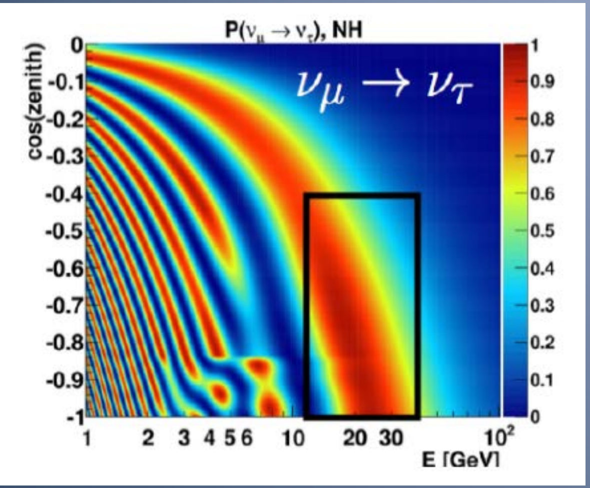
Sensitivity to Δm^2_{23} and $\sin^2\theta_{23}$

- Precision: 2-3% for Δm^2_{23} and 4-10% for $\sin^2\theta_{23}$ → competitive with sensitivity of NOvA and T2K by 2020

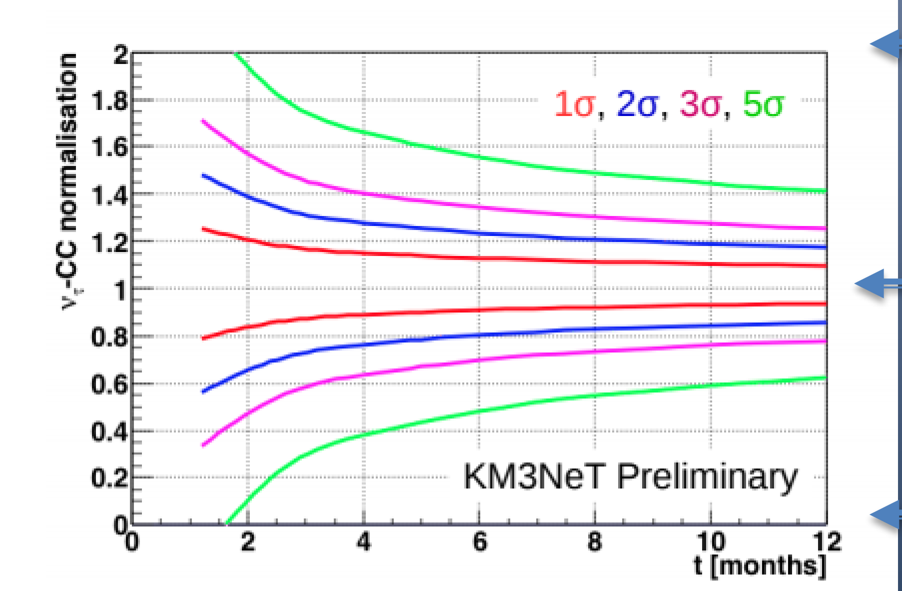




Unitarity with tau neutrinos



- About 3000 ν_τ/year (CC) in ORCA → test on unitarity
- In one year, rates constrained to 10% (world data precision now at 30%)



excess of tau neutrinos

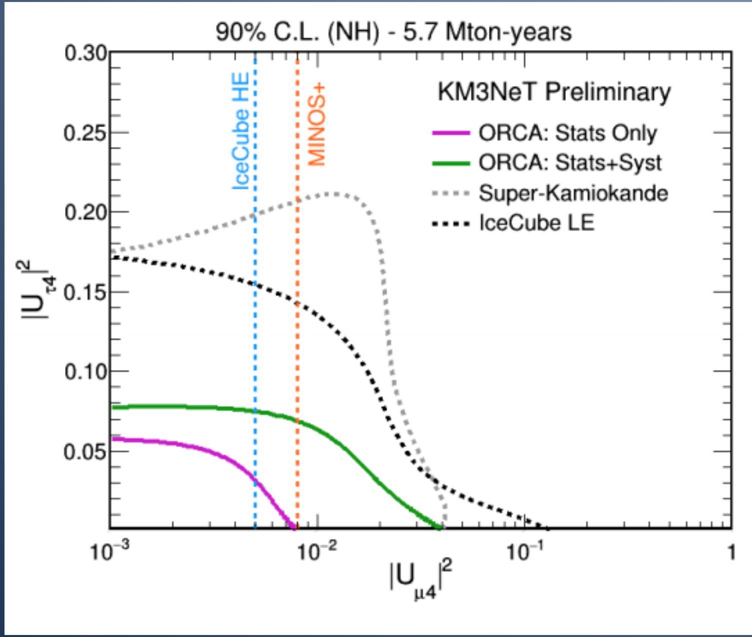
unitarity

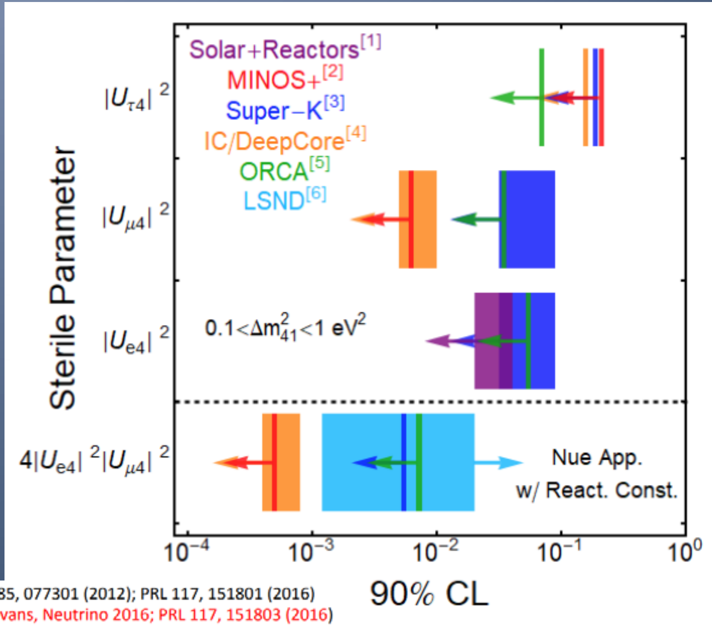
no appearance of tau neutrinos

Light sterile neutrinos

- After only one year, factor two of improvement in sensitivity for $U_{\tau 4}$ wrt SuperK and IceCube

$$H_{sterile} = U \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & \frac{\Delta m^2_{21}}{2E} & 0 & 0 \\ 0 & 0 & \frac{\Delta m^2_{31}}{2E} & 0 \\ 0 & 0 & 0 & \frac{\Delta m^2_{41}}{2E} \end{pmatrix} U^\dagger \pm \sqrt{2} G_F \begin{pmatrix} n_e & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & n_n \end{pmatrix}$$



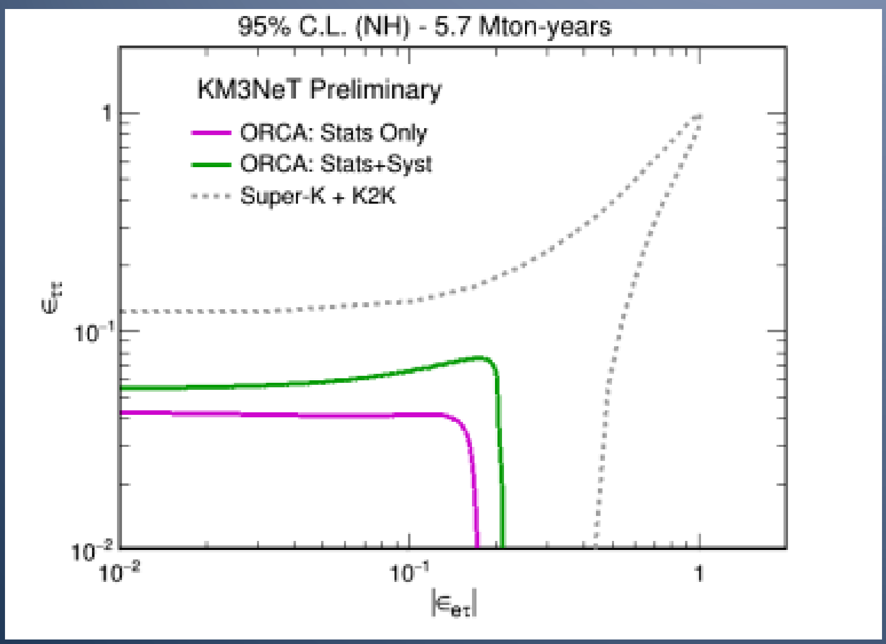


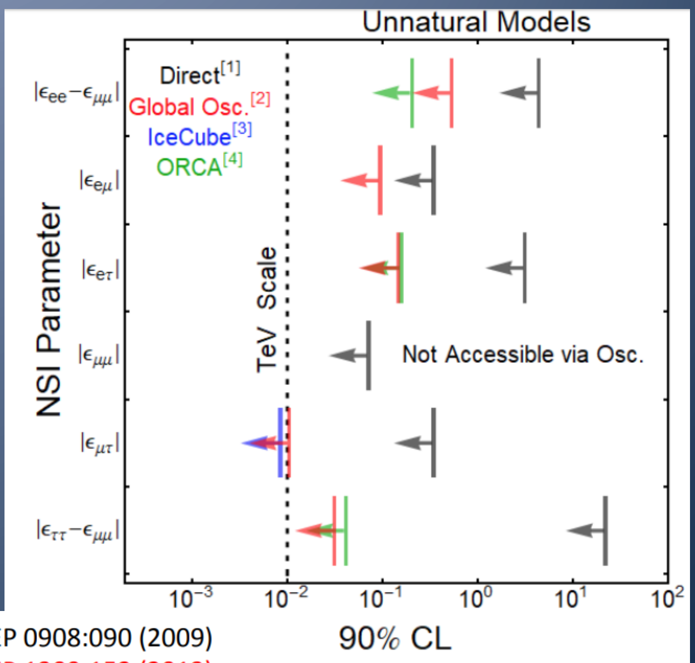
[1] PRD 85, 077301 (2012); PRL 117, 151801 (2016)
[2] J. J. Evans, Neutrino 2016; PRL 117, 151803 (2016)
[3] Phys. Rev. D 91, 052019 (2015)
[4] PRL 117, 071801 (2016); arXiv:1702.05160 (2017)
[5] KM3NeT-ORCA Preliminary
[6] Phys. Rev. D 64, 112007 (2001)

Non-standard interactions

- Effects of non-standard interactions could be observable in ORCA, with limits competitive from oscillations and more than factor 10 better direct

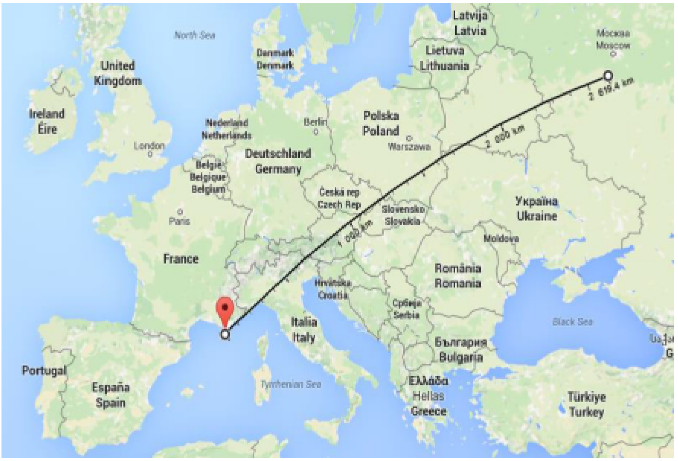
$$H_{NSI} = U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m^2_{21}}{2E} & 0 \\ 0 & 0 & \frac{\Delta m^2_{31}}{2E} \end{pmatrix} U^\dagger \pm \sqrt{2} G_F n_e \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}$$





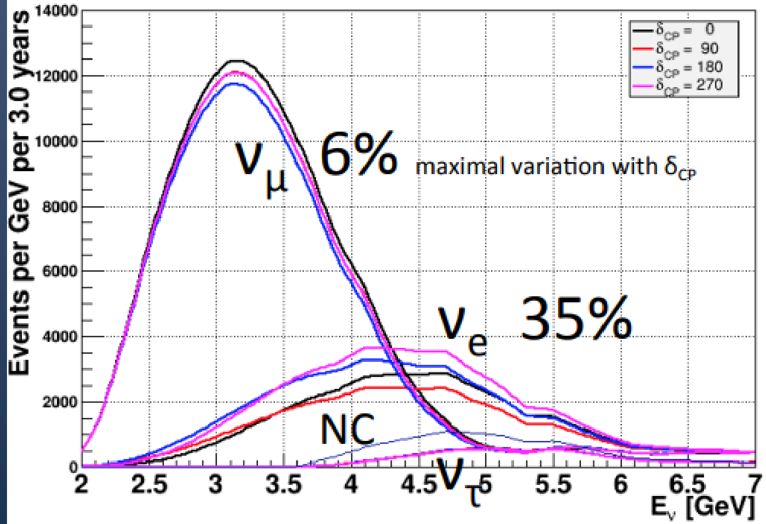
[1] JHEP 0908:090 (2009)
[2] JHEP 1309:152 (2013)
[3] arXiv:1709.07079 [hep-ex]
[4] KM3NeT-ORCA Preliminary

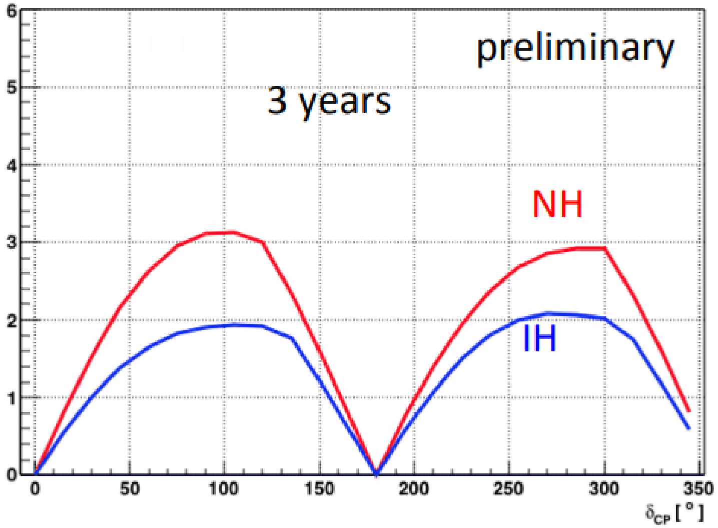
P2O: Protvino to ORCA



- -U70 accelerator in Protvino (near Moscow), E=70 GeV
- -Proposed intensity upgrade
  P = **450 kW** ➔ up to **4.10^{20} POT / year**

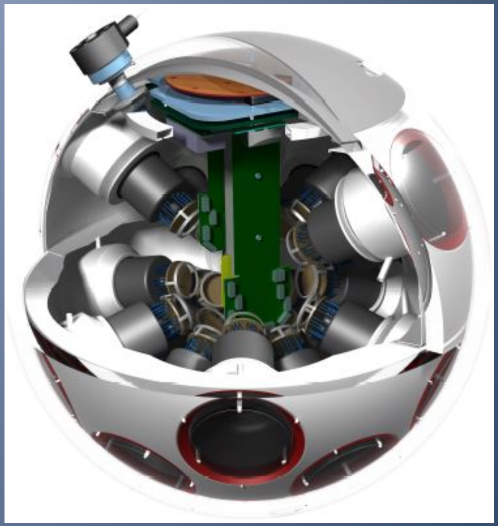
- -ν_e appearance at **L = 2600 km**
- -Target energy range : **3-8 GeV**
- -Optimal baseline for separating NMH from δ_{CP}



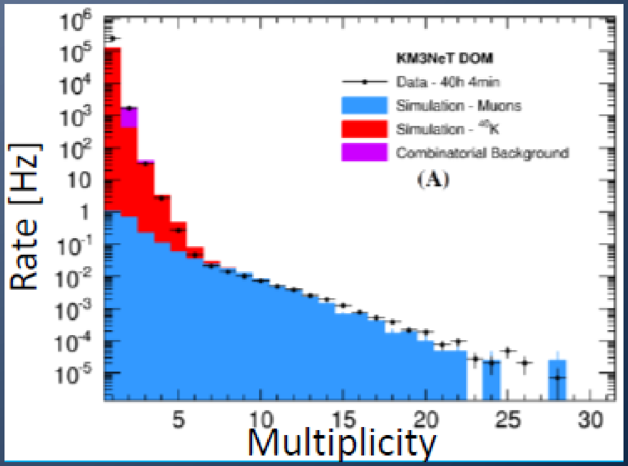


KM3NeT Optical Modules

- (Multi-PMT) Optical Module
  - 31 x 3” PMTs
  - diametre: 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

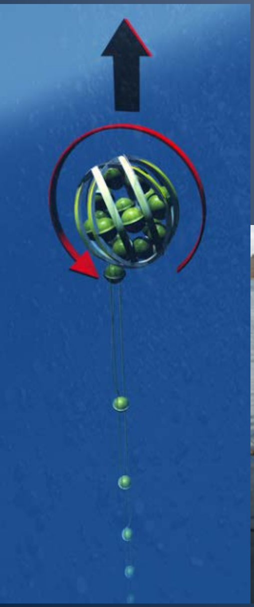


- Prototype at ANTARES intrumentation line since April 2013
- Ref: Eur. Phys. C. (2014) 74:3056

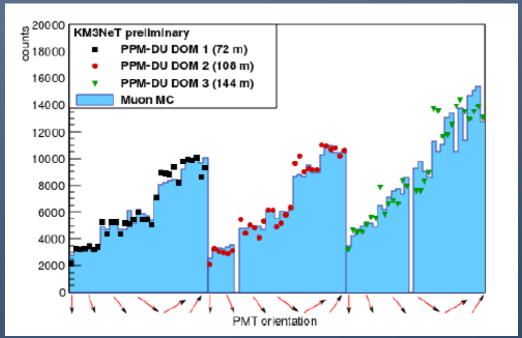


KM3NeT Detector Units

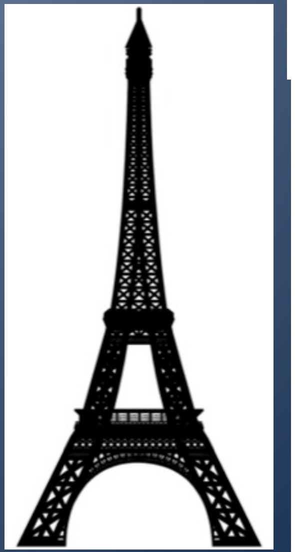
- Detector Units (strings)
  - 18 DOMs, separated vertically by: 6 m (ORCA) or 36 m (ARCA)
  - anchored at sea floor by a dead weight
  - kept vertical by buoys
  - 115 DUs = 1 building block
- Deployable with launching vehicle:
  - fast
  - recoverable
  - safe
  - less dependent on weather conditions



Prototype installed at Capo Passero since May 2014



ARCA



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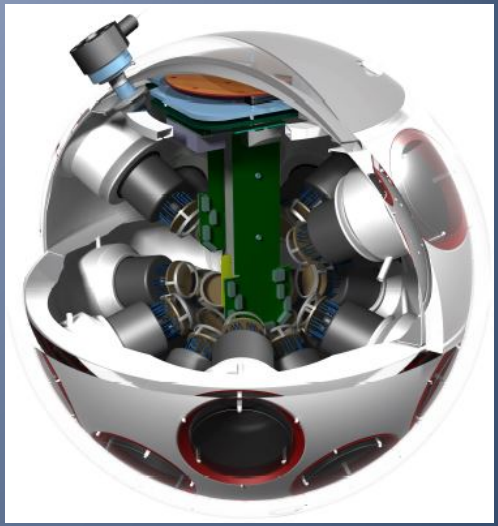

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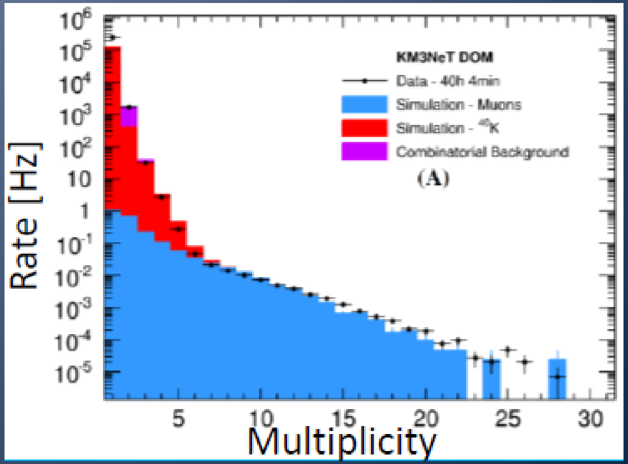

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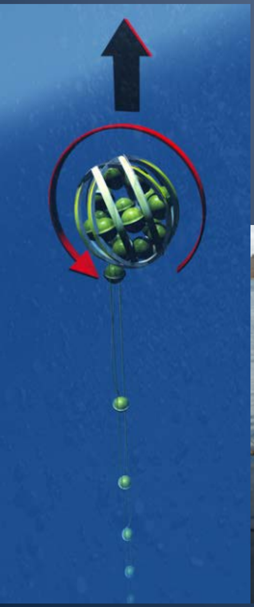

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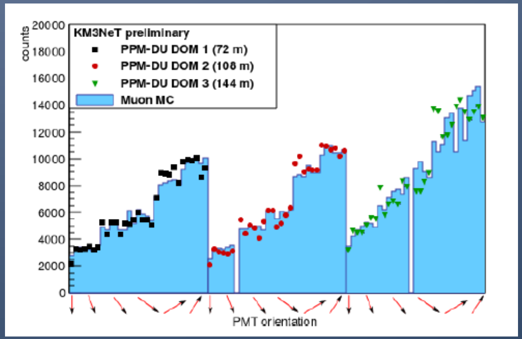
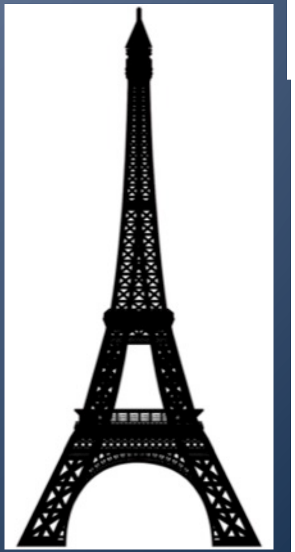
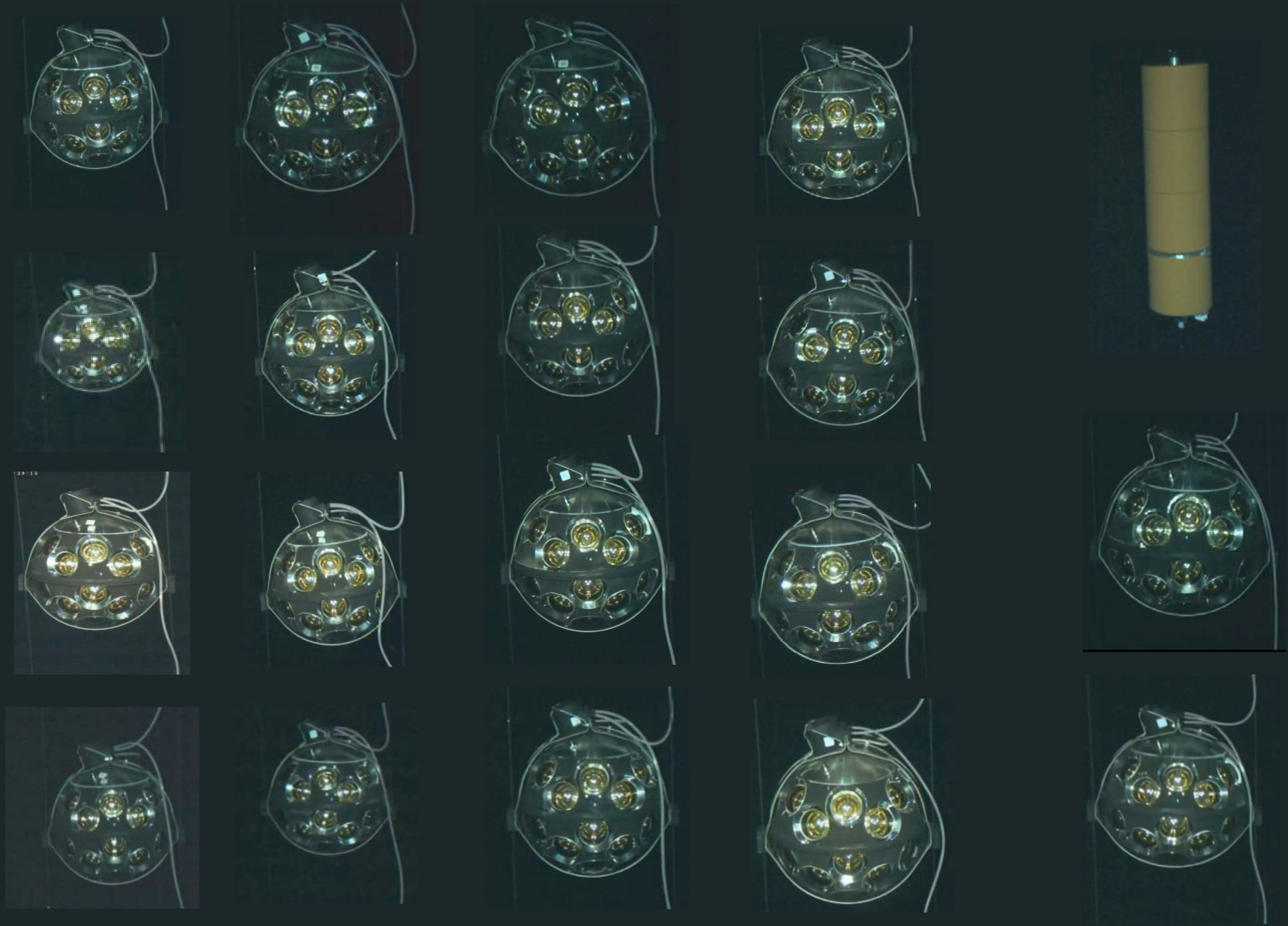


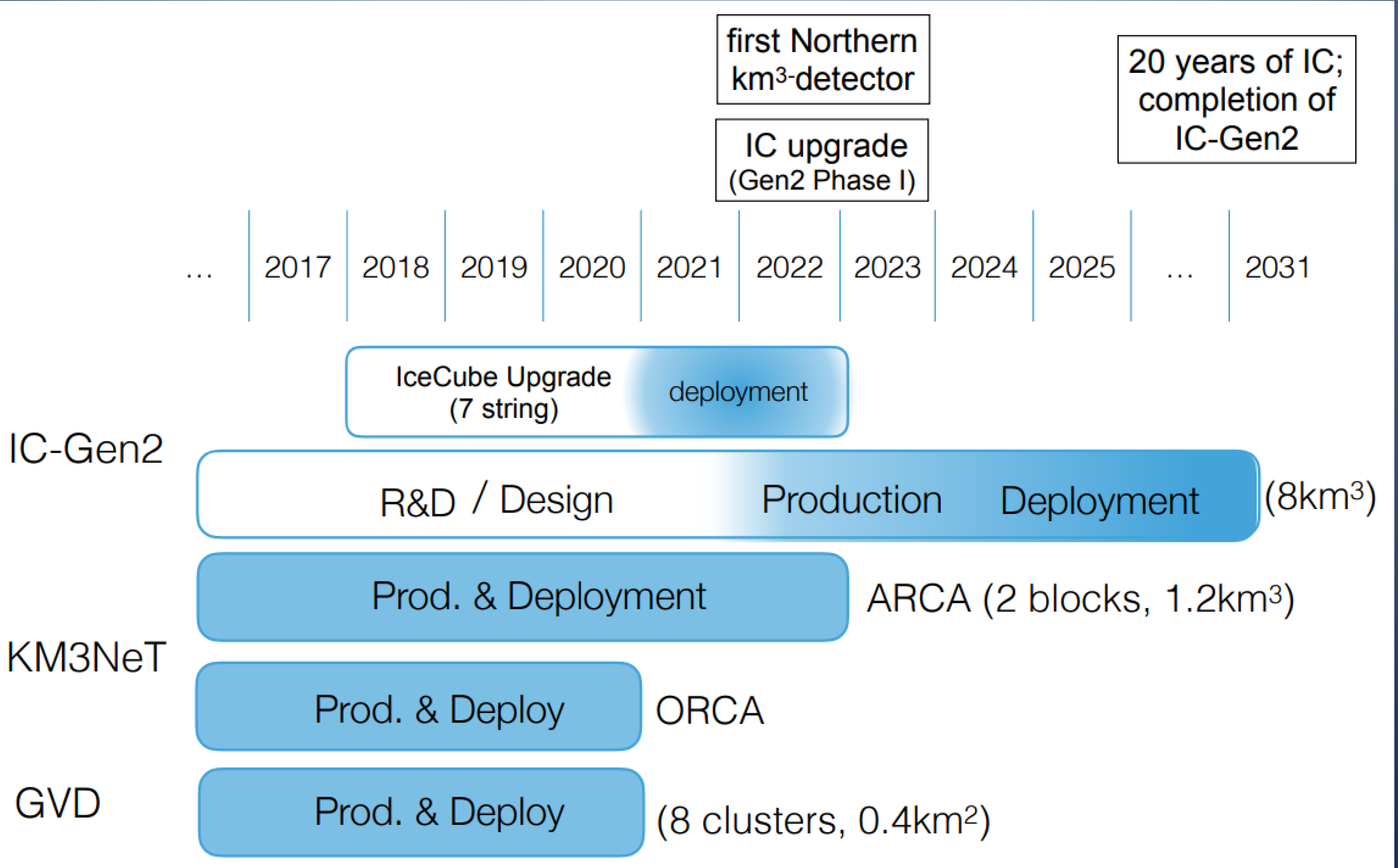
ARCA



First KM3NeT line in situ



The future



M. Kowalski, SUGAR 2018

Summary

- 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
- First prototypes of KM3NeT already installed and plans for IceCube Gen2 taking shape
- Rich physics harvest already gathered, but much more to come...

Thanks for your attention!