DIFI 2018-2022 DIPARTIMENTO DI ECCELLENZA MIUR
UNIVERSITÀ DEGLI STUDI DI GENOVA
INFN Istituto Nazionale di Fisica Nucleare
KM3NeT

High-energy neutrino telescopes and the KM3NeT experiment

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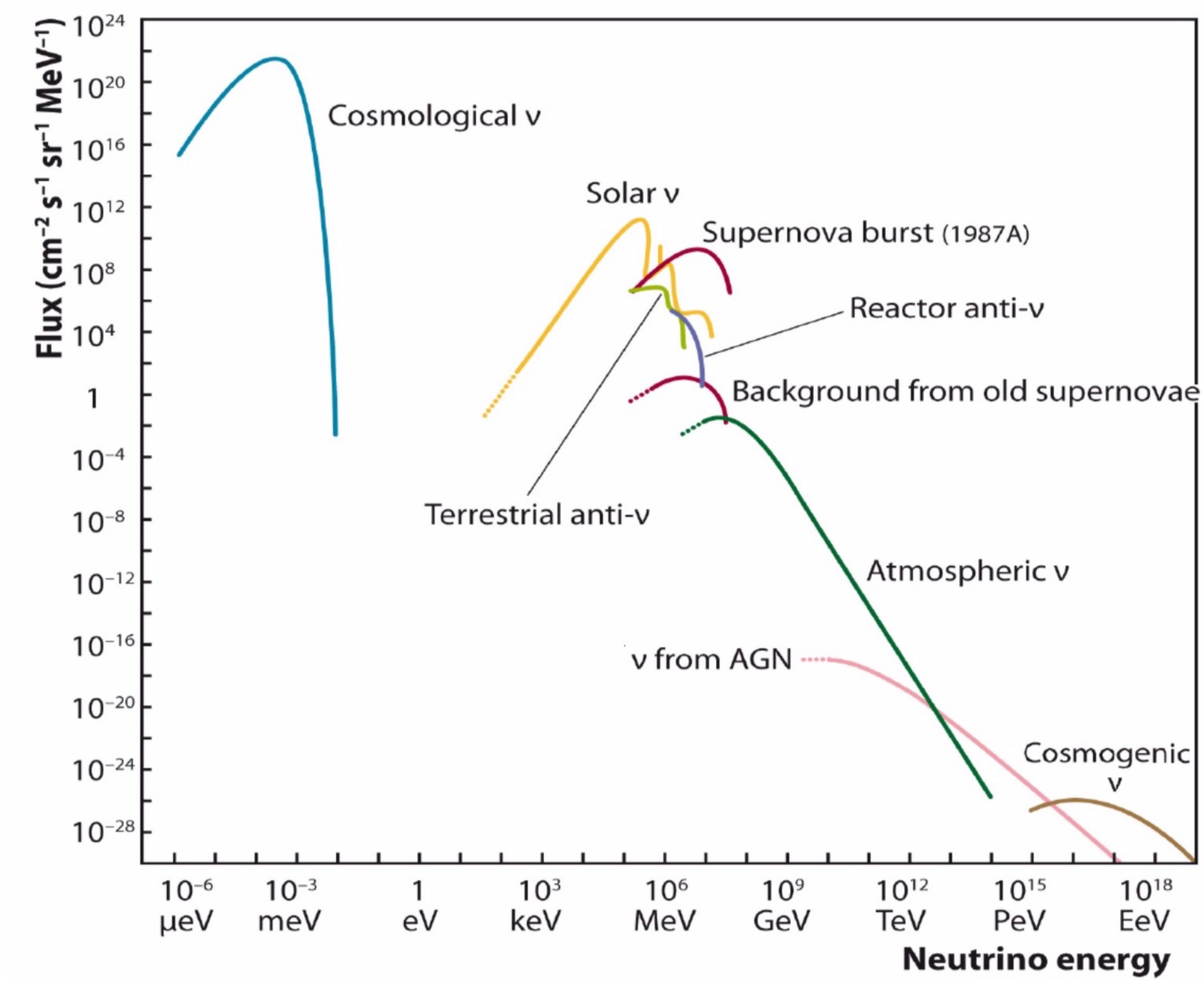
Università degli Studi di Genova – INFN Genova

Credits/Reference: «Probes of Multimessenger Astrophysics», M. Spurio, Springer

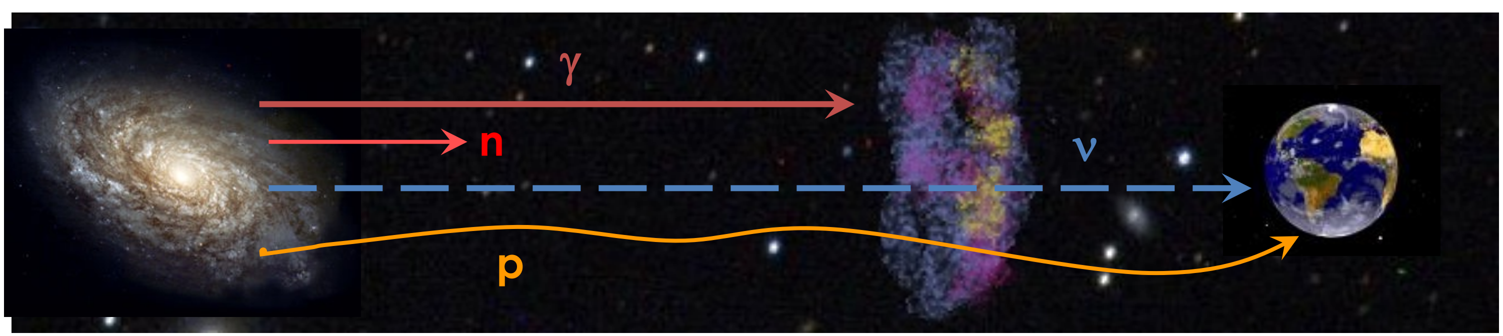
Prologo: Neutrinos from the Cosmos



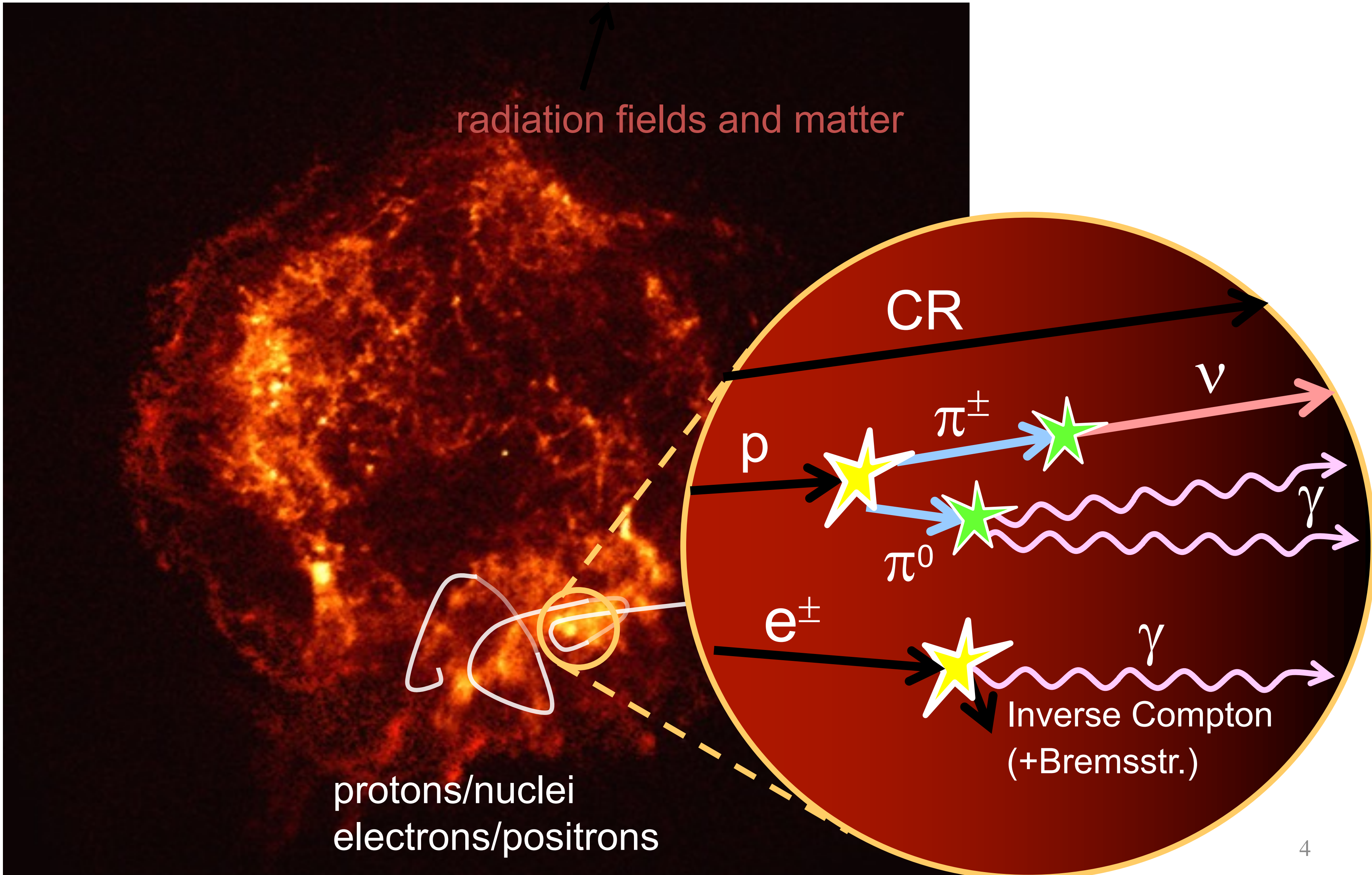
Why HE Neutrino Astronomy?

- **Neutrino Astronomy is a quite recent and very promising experimental field.**

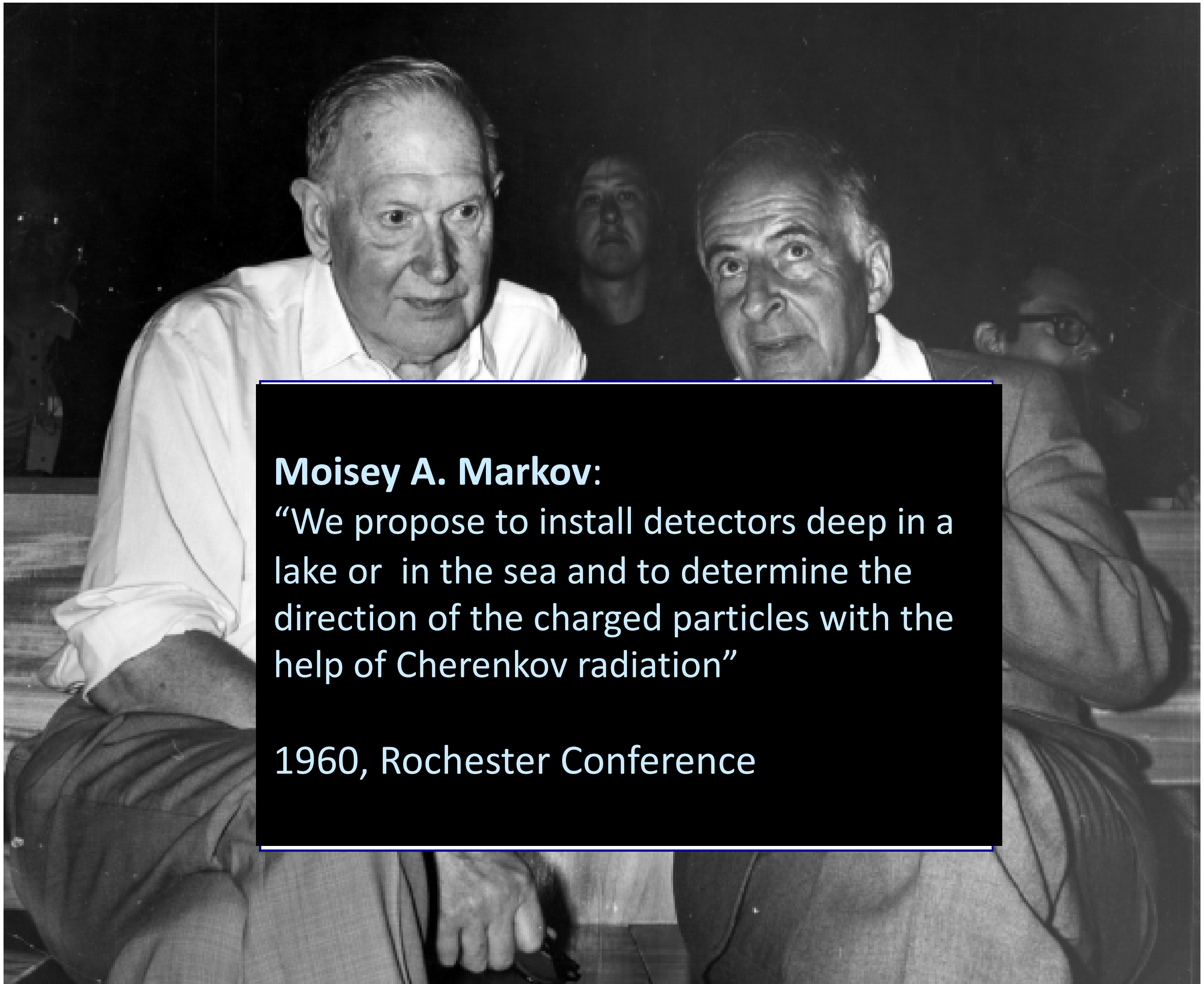
- Advantages:
  - Photons: interact with CMB (r~10 kpc @100 TeV), other radiation fields and matter
  - Protons: interact with CMB (r~10 Mpc@10^{11} GeV) and deflected by magnetic fields ($\Delta\theta>3^{o}$, E<$5\cdot10^{10}$ GeV)
  - Neutrons: are not stable
- Drawback: large detectors (~GTon) are needed.



CRs, γ and ν in cosmic accelerators



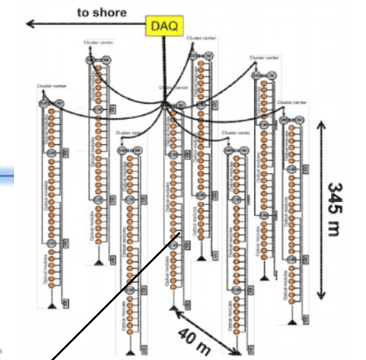
Recipes for a Neutrino Telescope (NT)



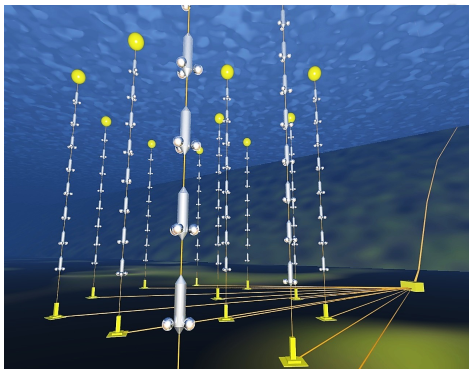
Moisey A. Markov:
"We propose to install detectors deep in a lake or in the sea and to determine the direction of the charged particles with the help of Cherenkov radiation"

1960, Rochester Conference

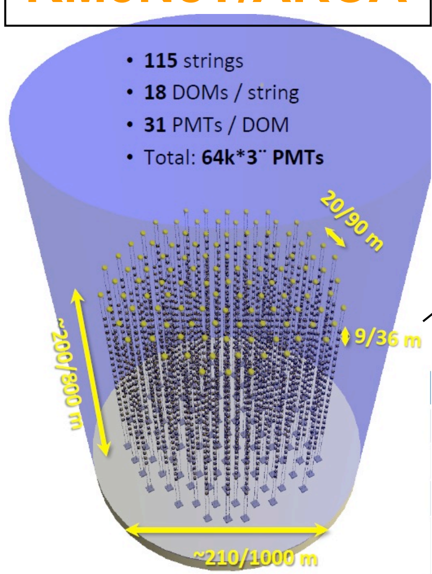
Neutrino telescopes: where ..



ANTARES
KM3NeT/ORCA

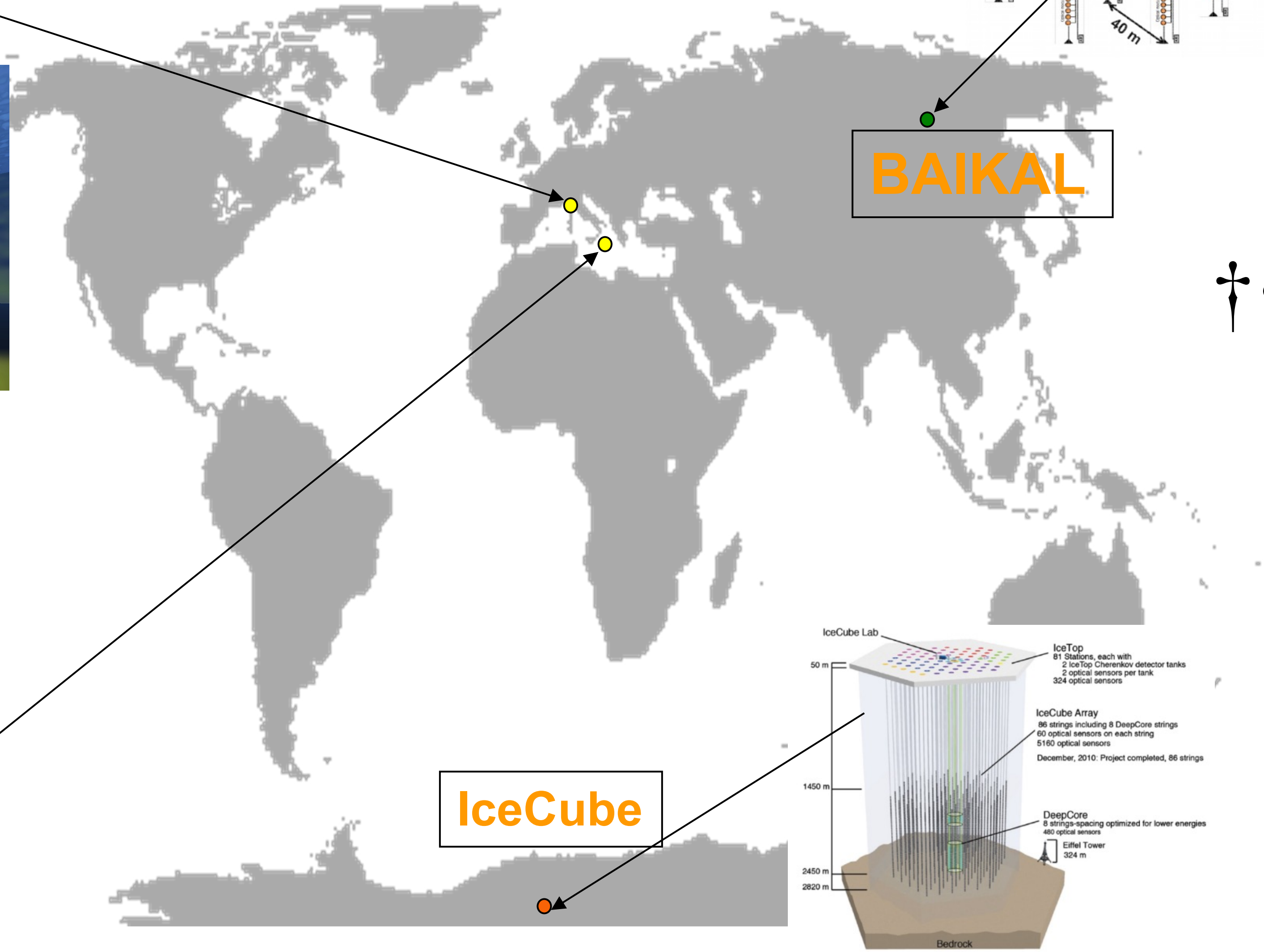


KM3NeT/ARCA

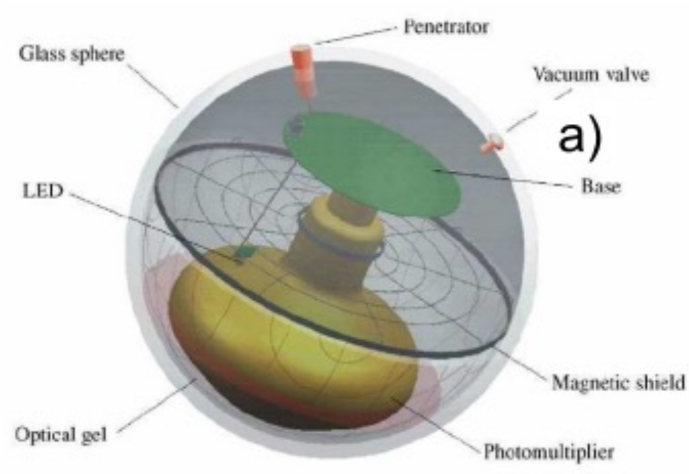


BAIKAL

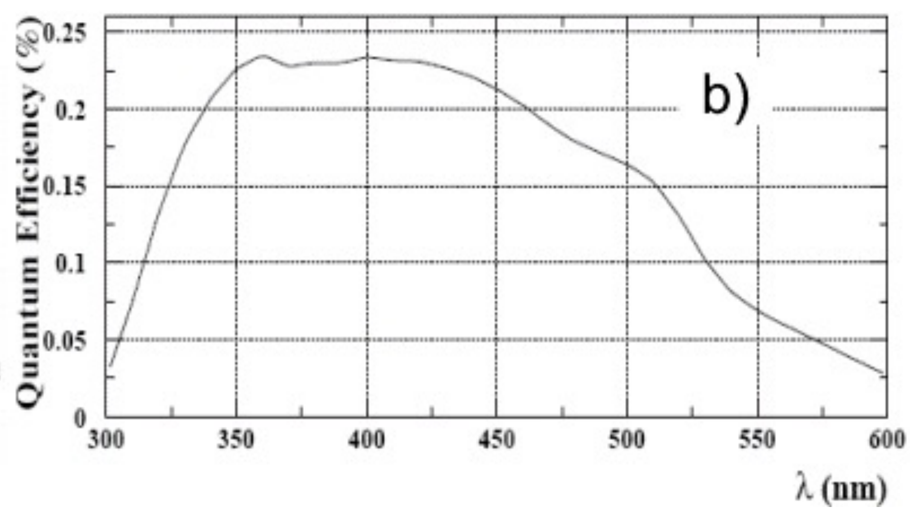
IceCube



«Optical modules» containing PMT(s)

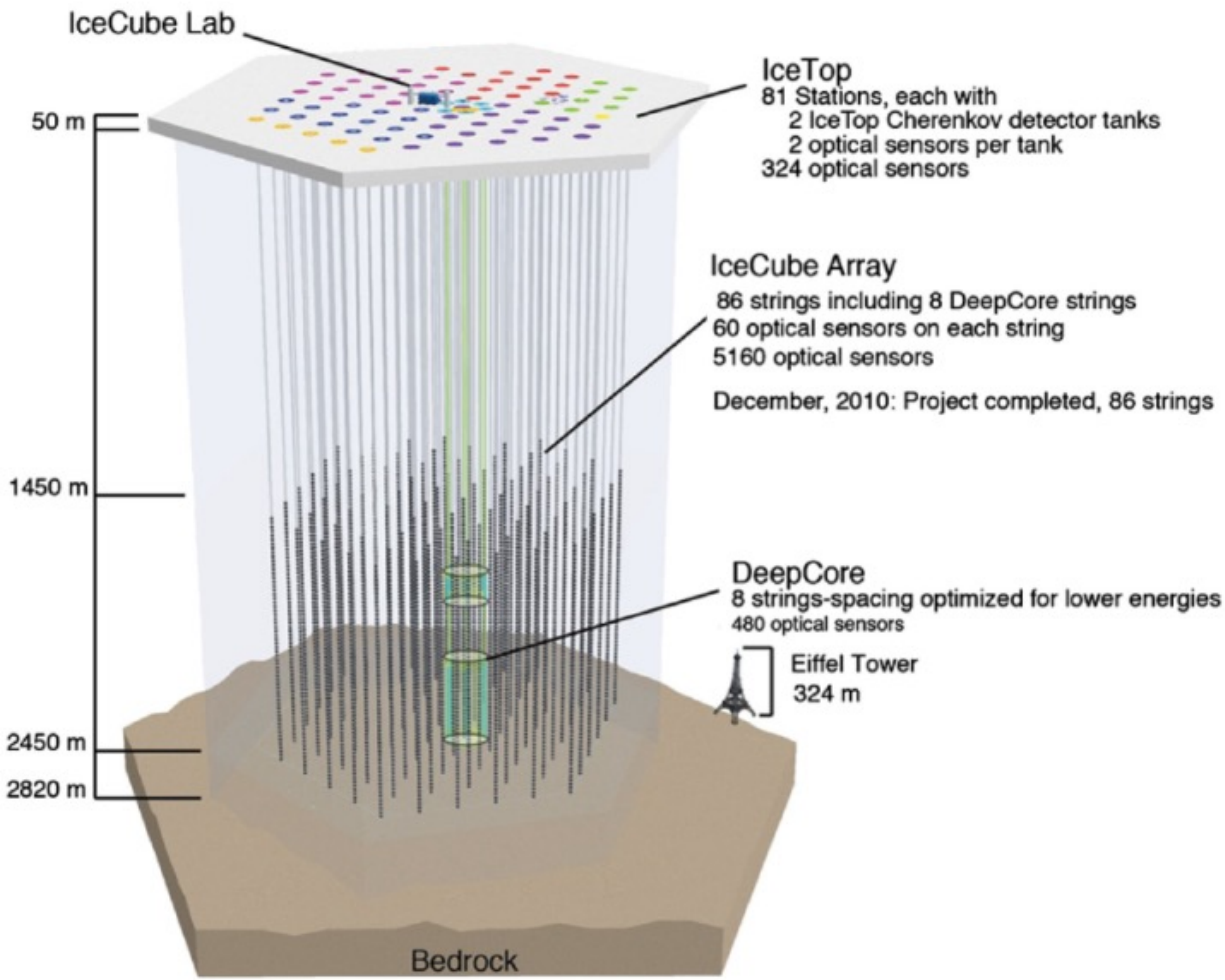


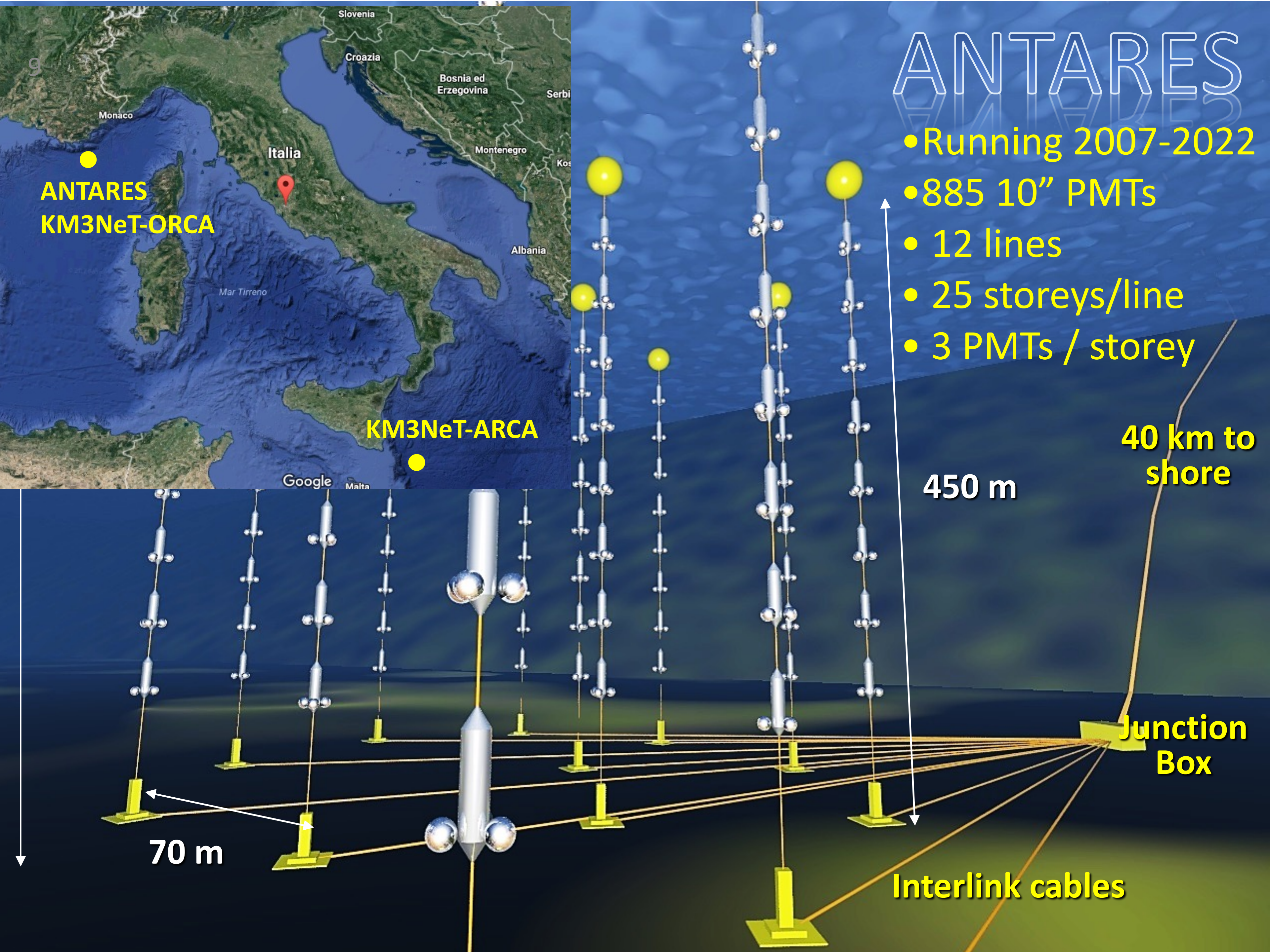
- ANTARES/IC/Baikal option: 1 PMT/OM
- Typical OM efficiency γ→ p.e. : 20%

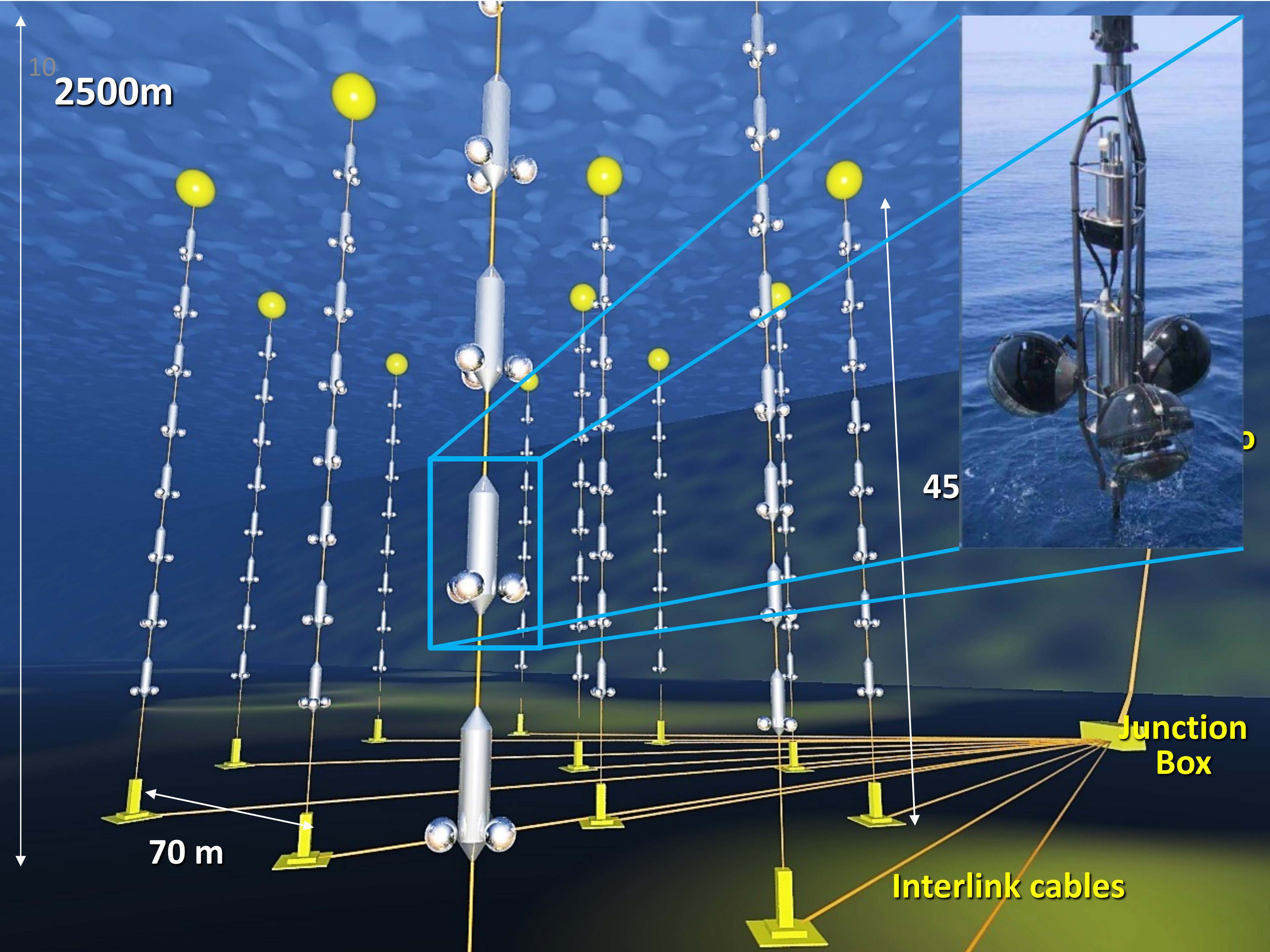


- The KM3NeT (IC-Gen 2?) option: multi-(small) PMTs
- 31 x 3” PMTs in one OM
  - Uniform angular coverage
  - Directional information
  - Digital photon counting
  - Reduced ageing

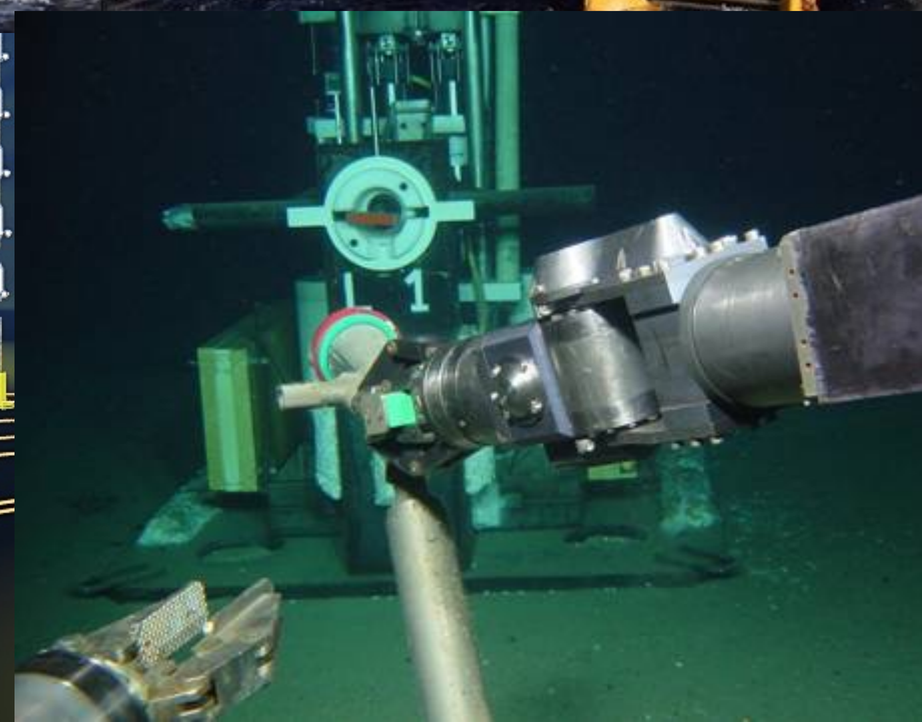
IceCube @South Pole




ANTARES
•Running 2007-2022
•885 10” PMTs
• 12 lines
• 25 storeys/line
• 3 PMTs / storey
Slovenia
Croazia
Bosnia ed Erzegovina
Serbi
Monaco
Italia
Montenegro
Kos
ANTARES
KM3NeT-ORCA
Albania
Mar Tirreno
KM3NeT-ARCA
Google
Malta
450 m
40 km to shore
Junction Box
70 m
Interlink cables


2500m
45
Junction
Box
70 m
Interlink cables


LOXAM

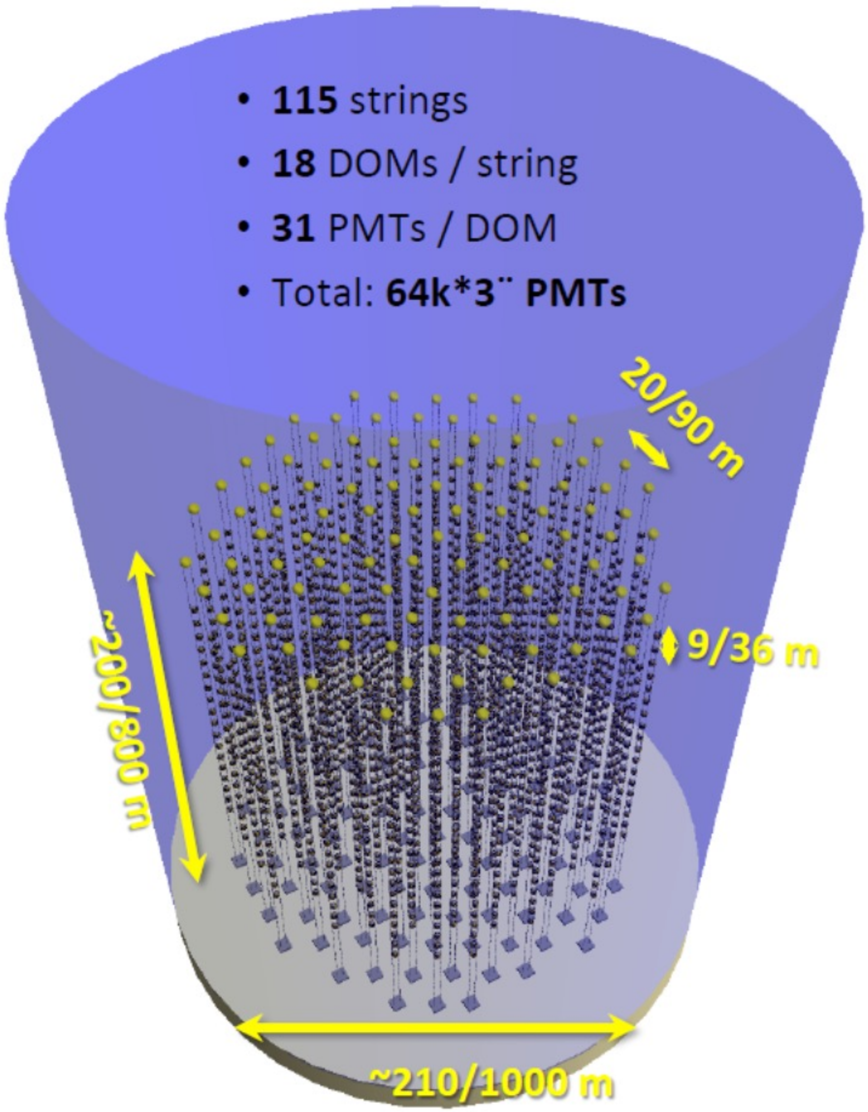
End of ANTARES adventure

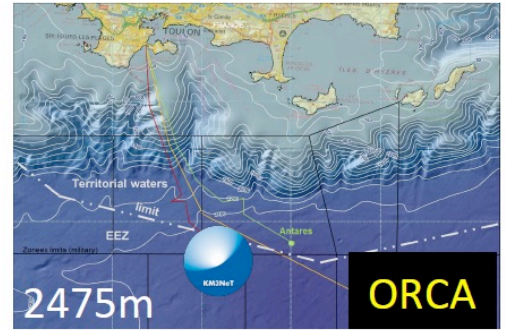
ANTARES has been switched off in Feb 2022 and full recovery of the materials in June 2022.

$\Longrightarrow$ Very competitive physics results. Legacy analyses still in progress. All the data will become public soon.

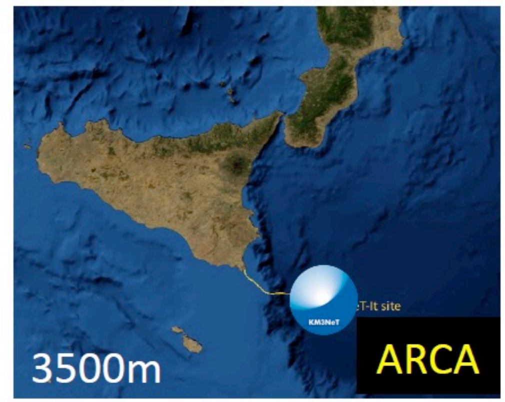
$\Longrightarrow$ KM3NeT adventure

KM3NeT: ARCA/ORCA

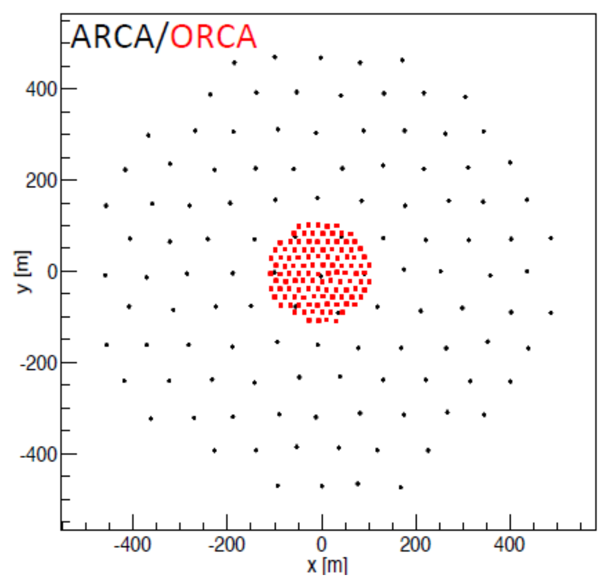




Oscillation **R**esearch with **C**osmics In the **A**byss



Astroparticle **R**esearch with **C**osmics In the **A**byss

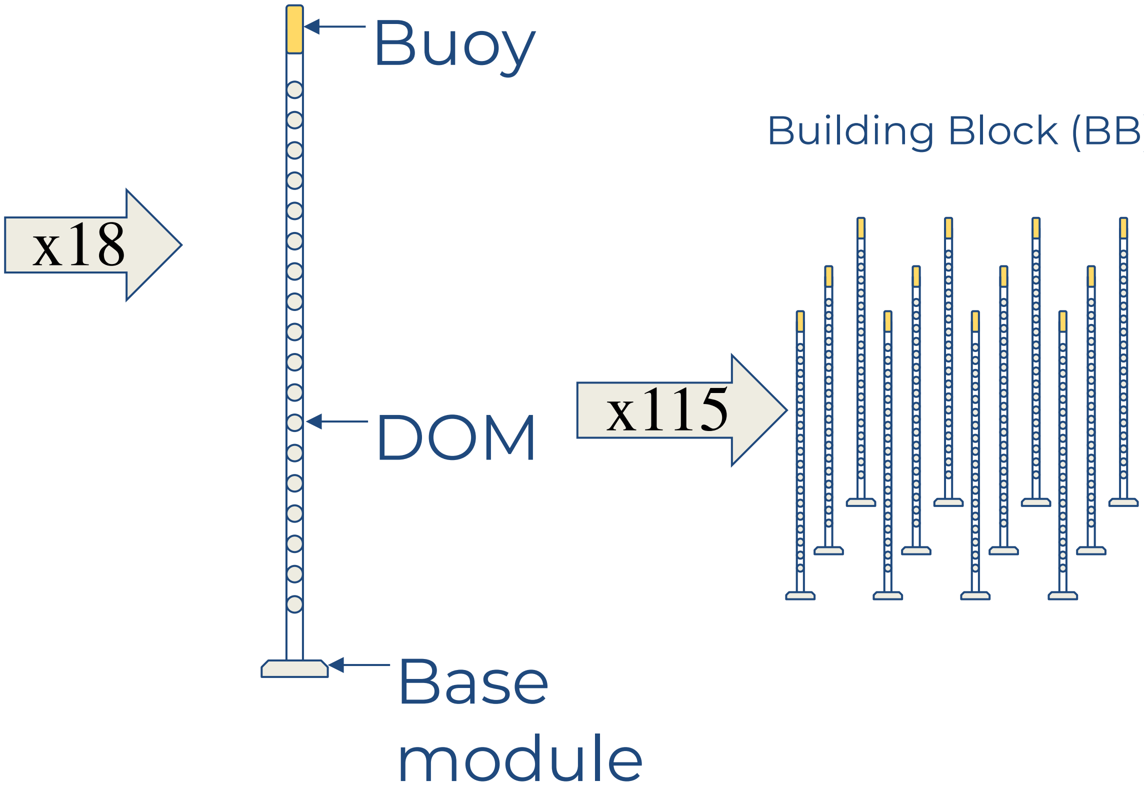


KM3NeT technology

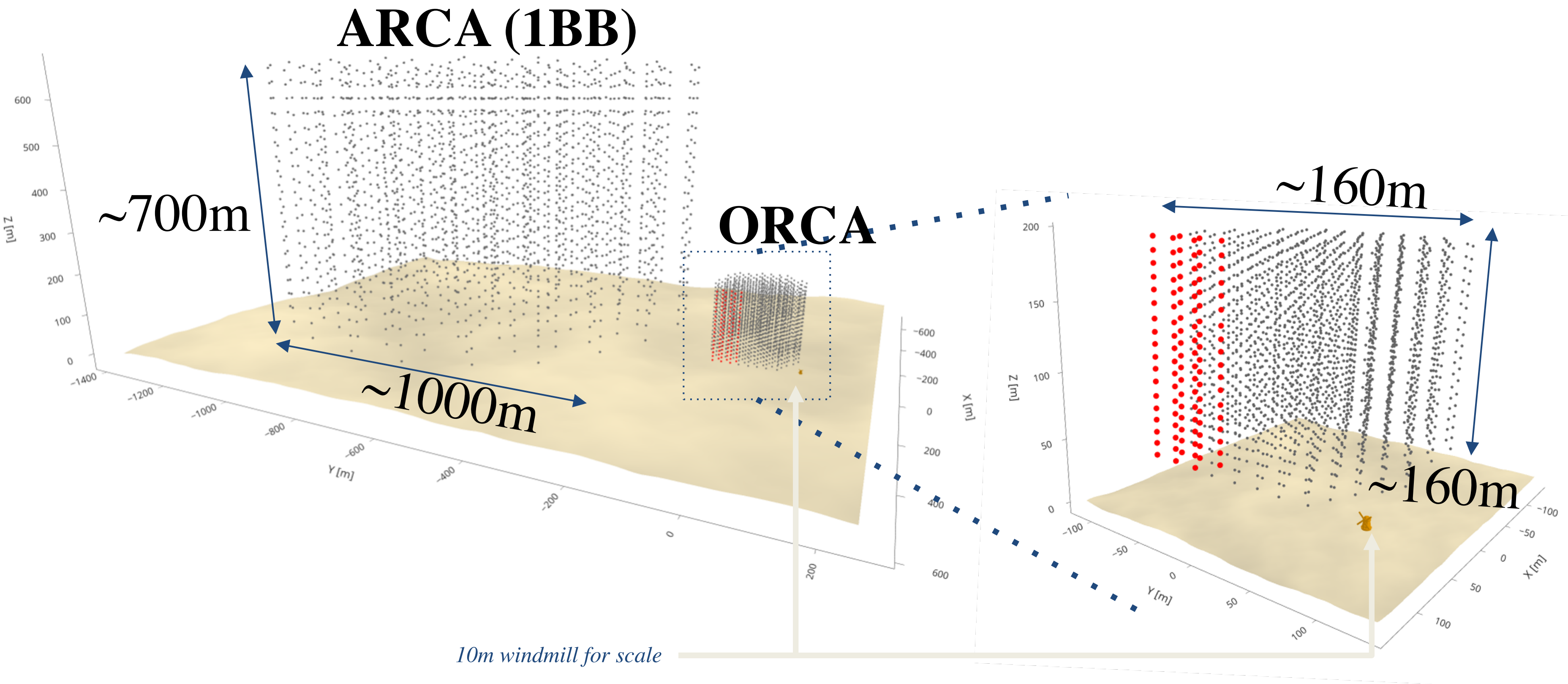
Digital Optical Module (DOM)

- 31x3" PMTs
- ns timing
- ~10 cm spatial positioning

Detection Unit (DU)



ARCA & ORCA

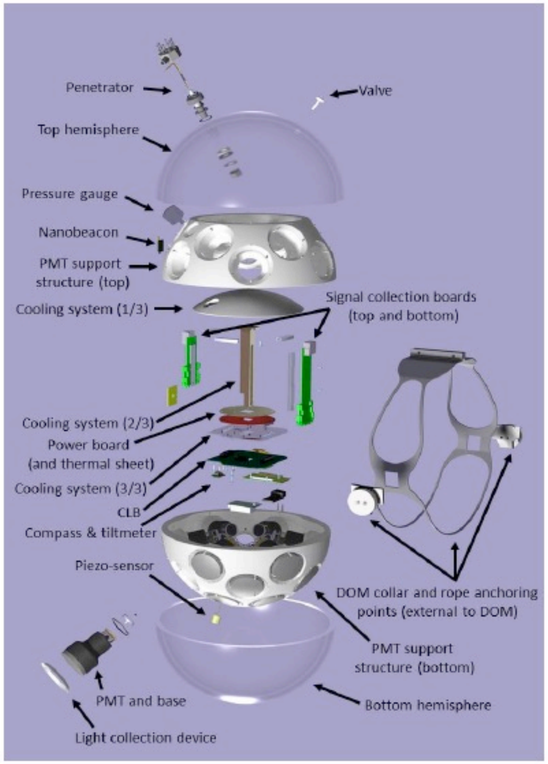


KM3NeT-ARCA
33 DU deployed

KM3NeT-ORCA
28 DU deployed

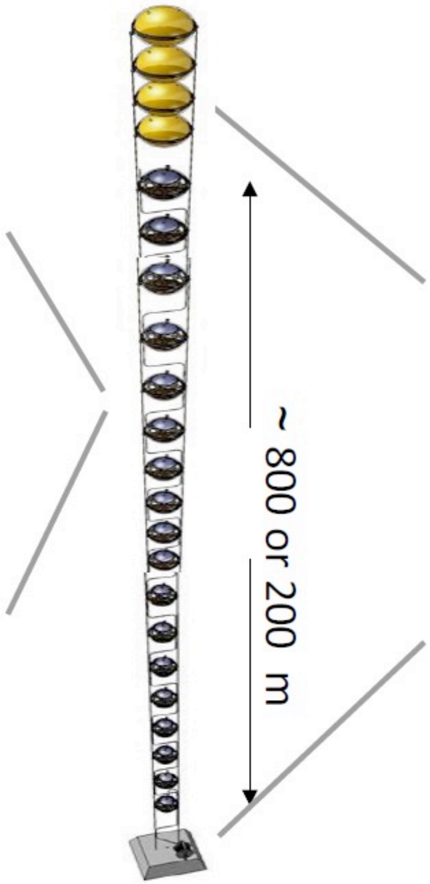
KM3NeT technology

Digital Optical Module



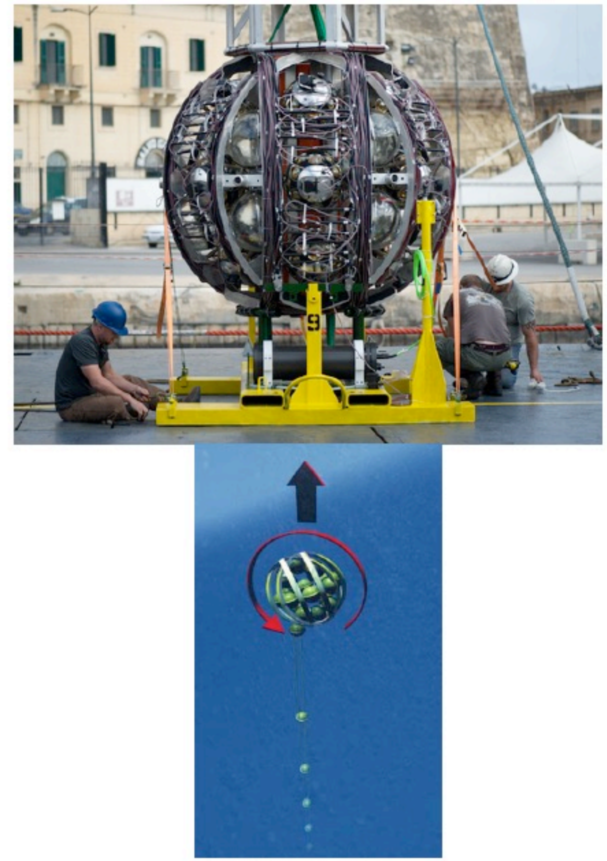
– All data to shore
– Gbit/s on optical fibre
– Hybrid White Rabbit
– LED flasher & acoustic piezo
– Tiltmeter/compass

String



– 2 dyneema ropes
– Oil filled PVC tube
– Low drag
– Low cost

Deployment Vehicle



– Rapid deployment
– Multiple strings/sea campaign
– Autonomous/ROV unfurling
– Reuseable

Building KM3NeT

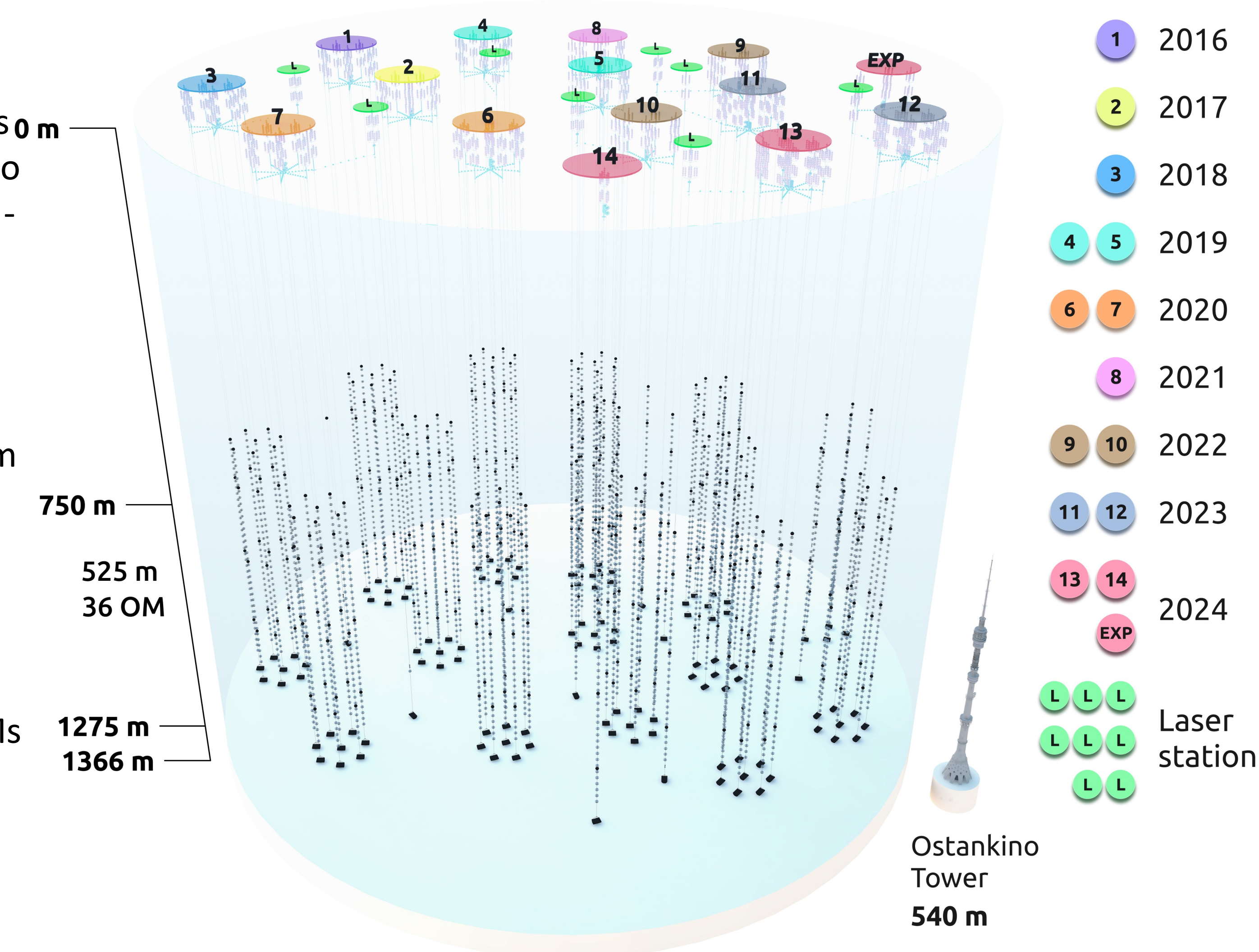
Baikal GVD

Presently detector consists of 110 strings arranged into 14 independent detectors - **clusters**

- 3960 OMs in total

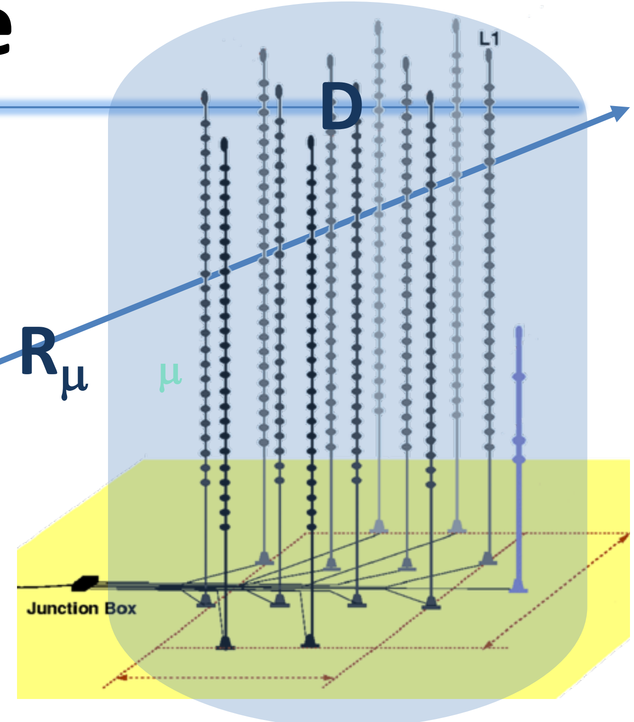
Baikal-GVD cluster:

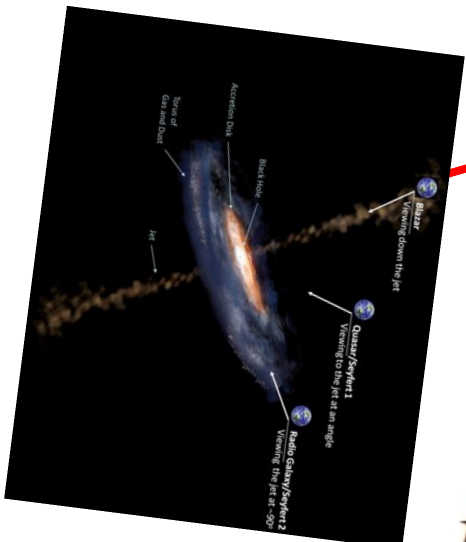
- 8 regular strings, 525 m is instrumented with optical modules (OM)
- 60m radius
- Inter-cluster string carrying lasers, some instrumented with OMs
- Has its own control, trigger and readout systems



Neutrino telescope

- Detector able to measure the ν direction O(<<1°) → only ν_μ
- Instrumented detector: $D<R_\mu$





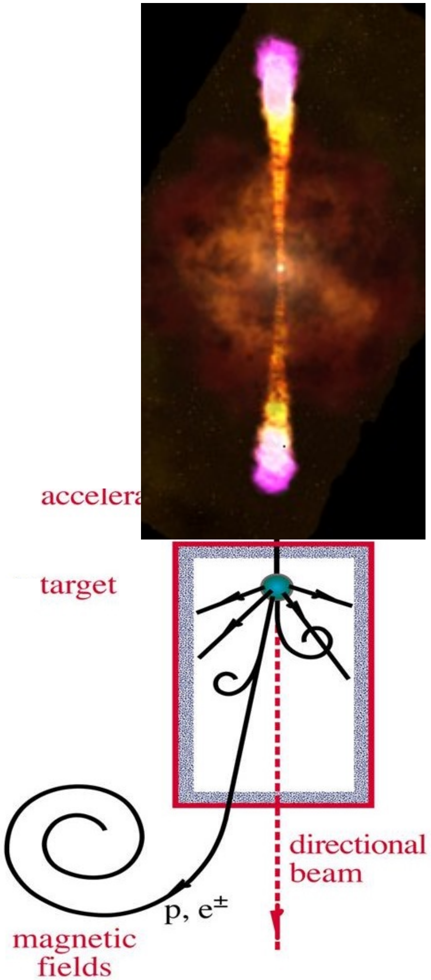
1- PHYSICS: neutrino energy spectrum at source: ν/(cm² s GeV)

Event rate (s^{-1})

$$\frac{N_\nu}{T} = \int \mathrm{d}E_\nu \cdot \frac{\mathrm{d}\Phi_\nu}{\mathrm{d}E_\nu}(E_\nu) \cdot A_\nu^{\mathrm{eff}}(E_\nu)$$

2: INSTRUMENT: ν detection effective area (cm²)

(PHY) Example: a Galactic source



TeV γ-rays and neutrinos can be produced from **hadronic processes**:

$$p + p \rightarrow \pi^{\pm}, \pi^{0}, K^{\pm}, K^{0}, p, n, \ldots$$

Neutral mesons decay in **photons**:

$\pi^{0} \rightarrow \gamma\gamma$

charged mesons decay in **neutrinos**:

$\pi^{+} \rightarrow \nu_{\mu} + \mu^{+}$

$\mu^{+} \rightarrow \bar{\nu}_{\mu} + \nu_{e} + e^{+}$

$\pi^{-} \rightarrow \bar{\nu}_{\mu} + \mu^{-}$

$\mu^{-} \rightarrow \nu_{\mu} + \bar{\nu}_{e} + e^{-}$

$$2\gamma = 6\,\nu$$

(PHY) Effect of neutrino oscillations

- Neutrino flavour ratio at sources

$$\Phi^0(\nu_e):\Phi^0(\nu_\mu):\Phi^0(\nu_\tau) = 1:2:0$$

- Propagation: $P_{\alpha\beta} \equiv P(\nu_\alpha \to \nu_\beta) = \sum_j |U_{\alpha j}|^2 |U_{\beta j}|^2$
- Flavour ratio at Earth:

$$\Phi^T(\nu_e):\Phi^T(\nu_\mu):\Phi^T(\nu_\tau) = 1:1:1$$

- Thus, at Earth:

$$2\gamma = 2\,\nu_\mu \quad \Longleftrightarrow \quad \Phi_\gamma(E) = \Phi_{\nu_\mu}(E) \; {}^*$$

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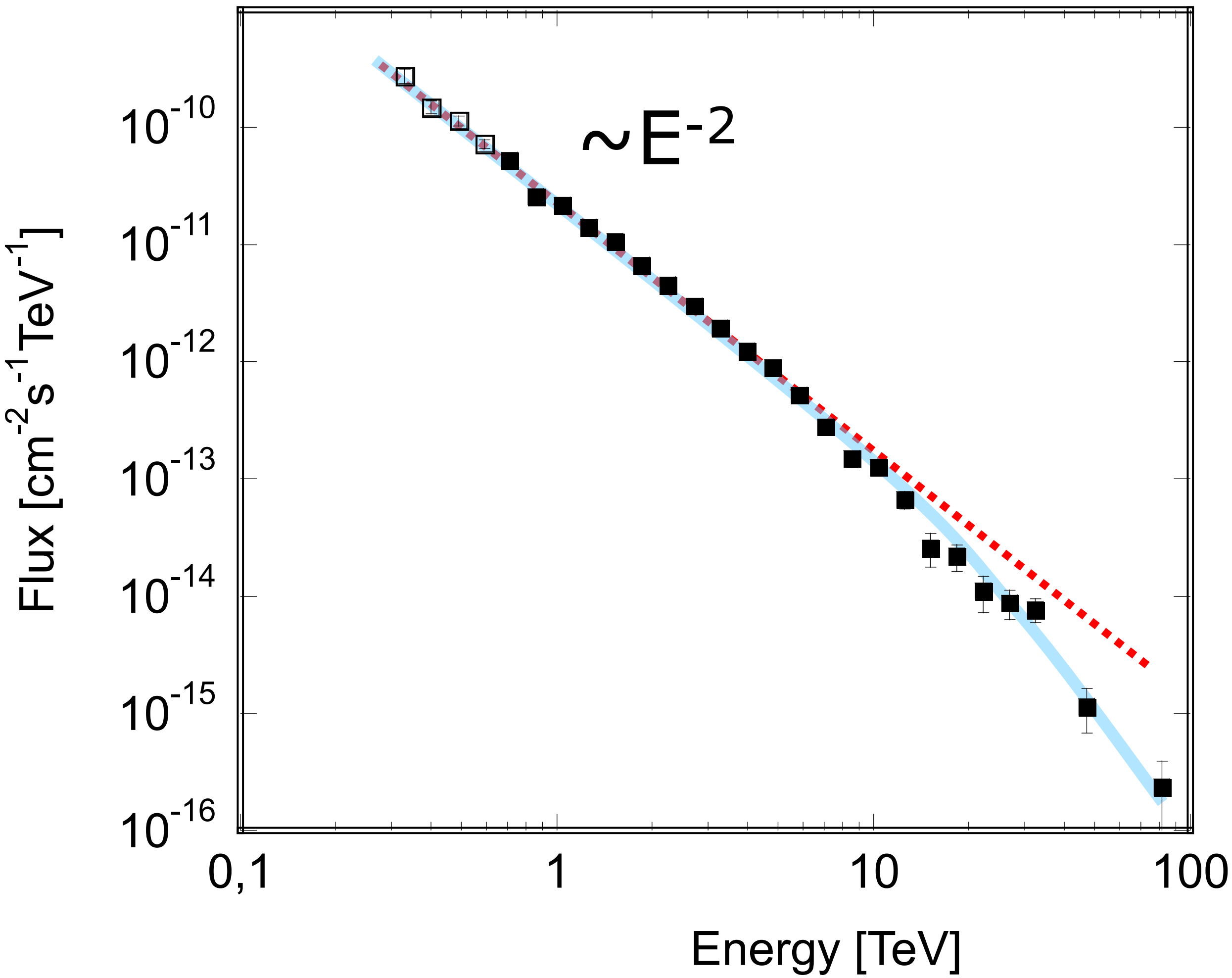
* NOTE: This is not completely correct, at a fixed energy, when decay kinematics are taken into account. See: **C. Mascaretti, F. Vissani, Journal of Cosmology and Astroparticle Physics, 2019(08):004, 2019**

(PHY) A candidate: RX J1713.7-3946

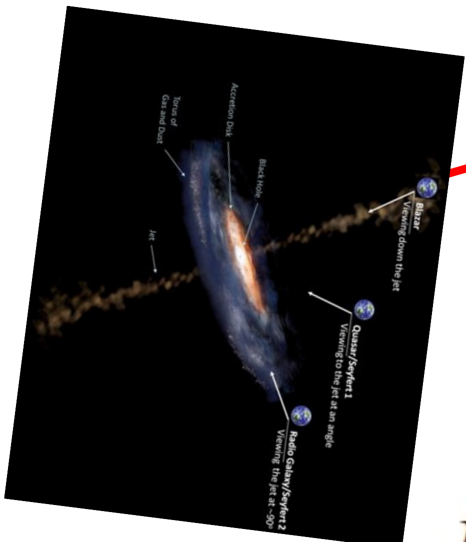


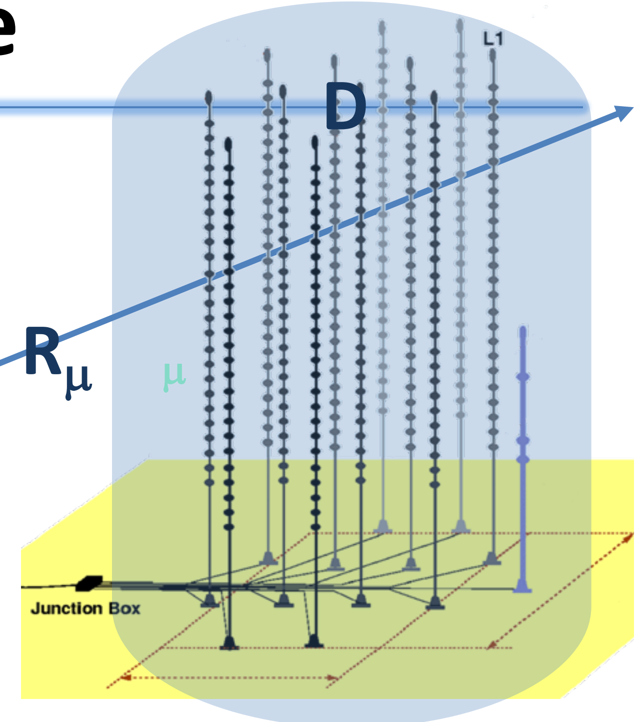
RX J1713.7-3946 seen by HESS (gamma rays)
Supernova remnant

$$E_{\nu,\gamma}^{2}\,\frac{d\Phi_{\nu,\gamma}}{dE_{\nu,\gamma}}=$$
$$=10^{-11}\ \text{TeV cm}^{-2}s^{-1}$$

Neutrino telescope

- Detector able to measure the ν direction O(<<1°) → only ν_μ
- Instrumented detector: $D<R_\mu$





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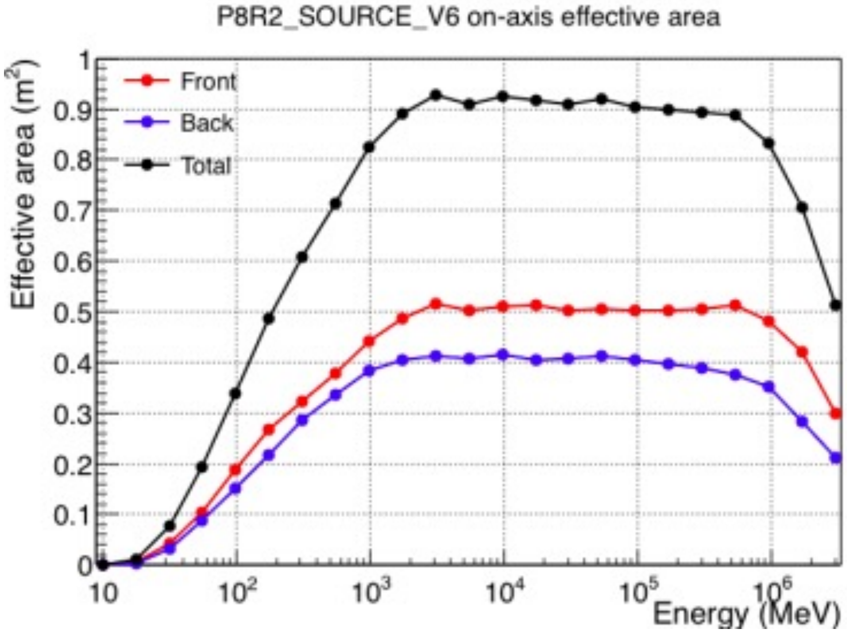
Event rate (s^{-1})

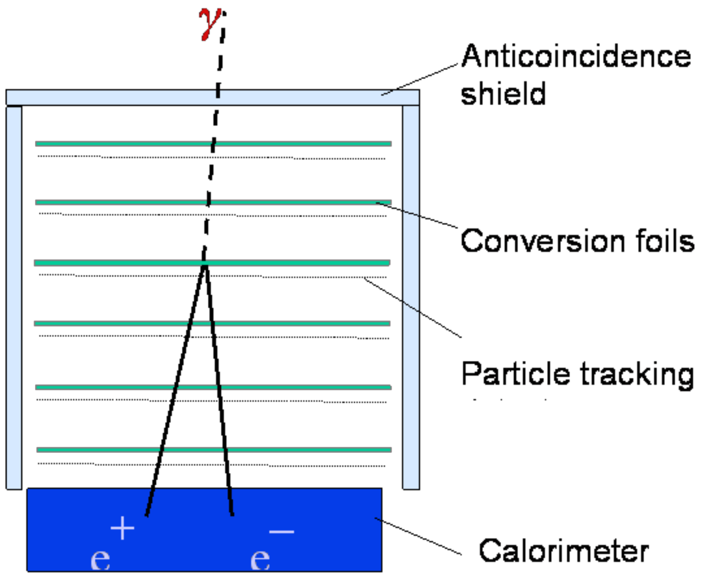
$$\frac{N_\nu}{T} = \int \mathrm{d}E_\nu \cdot \frac{\mathrm{d}\Phi_\nu}{\mathrm{d}E_\nu}(E_\nu) \cdot A_\nu^{\mathrm{eff}}(E_\nu)$$

2: INSTRUMENT: ν detection effective area (cm²)

Effective area (A^{eff}) for a γ-ray experiment



Fermi-LAT *effective area vs. E for normal γ-ray incidence*



Fermi-LAT *= pair-conversion telescope*

- The $\mathbf{A^{eff}}$ is a fundamental quantity: *The number of observed events is the integral over energy of the neutrino flux* [cm^2 s GeV]$^{-1}$ *with* A^{eff} [cm^2]
- **LAT**: Almost 90% of incoming γ-rays are detected **(=converted** into observable particles), if in the correct energy range
- The *A^{eff}* of neutrino telescopes is **very** different!

Neutrino Telescope effective area(s)

- The effective area A^{eff} [m^2] is the **figure-of-merit** of NT
- Number of events: $N_{ev} = \int \frac{dN_\nu}{dE_\nu} \cdot A^{eff}(E) \cdot dE_\nu$
- The NT effective area A^{eff} depends

  - on the outgoing lepton (e, μ or τ)
  - on the neutrino energy
  - on the lepton direction
  - on the specific analysis (efficiency ε)

- Let us specialize for the **muon channel**. The A^{eff} can be written as:

$$A_\nu^{\mathrm{eff}}(E_\nu) = A \cdot P_{\nu\mu}(E_\nu, E_{\mathrm{thr}}^\mu) \cdot \epsilon \cdot e^{-\sigma(E_\nu)\rho N_A Z(\theta)}$$

The quantity A (m^2) is the geometrical area of a detector

Probability of $\nu_\mu \rightarrow \mu$ in the detector

$$A_\nu^{\mathrm{eff}}(E_\nu) = A \cdot P_{\nu\mu}(E_\nu, E_{\mathrm{thr}}^\mu) \cdot \epsilon \cdot e^{-\sigma(E_\nu)\rho N_A Z(\theta)}$$

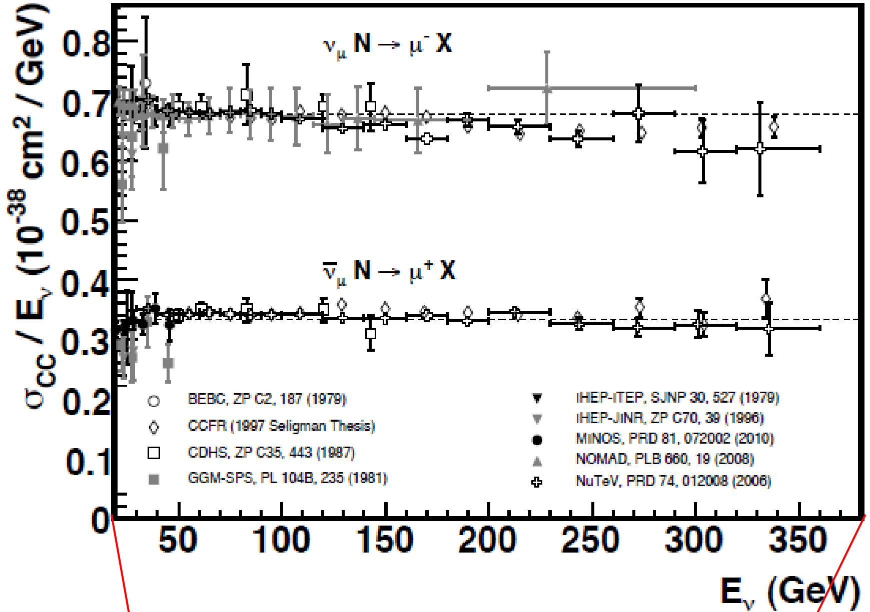
Probability that a ν_μ induces a muon with energy $E>E^\mu_{thr}$ reaches the detector:

$$P_{\nu\mu} = \sigma_{\nu\mu}(cm^2) \times \rho\,(cm^{-3}) \times R(cm)$$

- The ν cross section

$$\sigma_{\nu\mu} \cong 1.5\ 10^{-34} \left(\frac{E}{10\ TeV}\right)^{0.4} (cm^2)$$

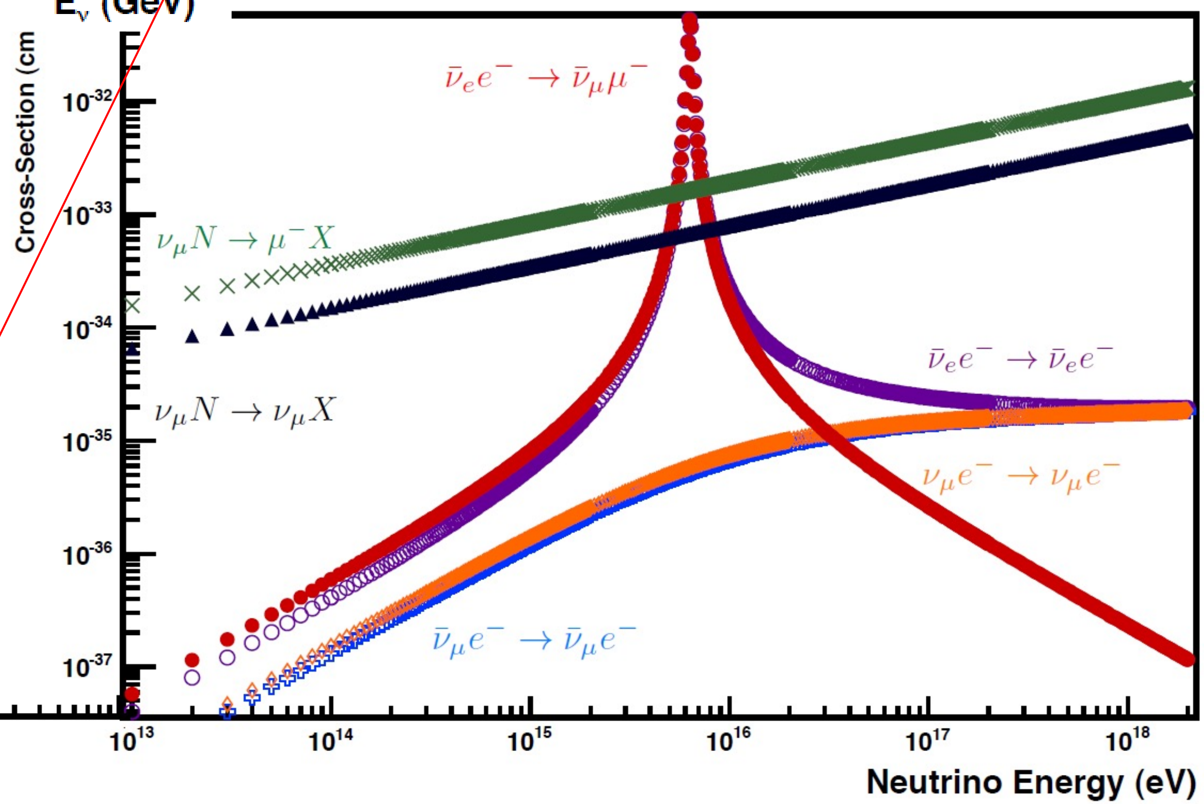
ν cross section



arXiv:1305.7513: J.A. Formaggio, G.P. Zeller
From eV to EeV: Neutrino Cross-Sections Across Energy Scales.

PDG

$$\frac{d\sigma_{\nu\mu}}{dE_\nu} \cong 0.5\times10^{-35}\,\mathrm{cm^2TeV^{-1}}$$



Probability of $\nu_\mu \rightarrow \mu$ in the detector

$$A_\nu^{\rm eff}(E_\nu) = A \cdot P_{\nu\mu}(E_\nu, E_{\rm thr}^\mu) \cdot \epsilon \cdot e^{-\sigma(E_\nu)\rho N_A Z(\theta)}$$

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$$P_{\nu\mu} = \sigma_{\nu\mu}(cm^2) \times \rho\ (cm^{-3}) \times R(cm)$$

- The ν cross section

$$\sigma_{\nu\mu} \cong 1.5\ 10^{-34} \left(\frac{E}{10\ TeV}\right)^{0.4} (cm^2)$$

- The nucleon number density in ordinary matter

$$\rho \cong 10^{23}\ cm^{-3}\ ;$$

- The muon range for $E_\mu > 1$ TeV:

$$R \cong 10^6\ cm$$

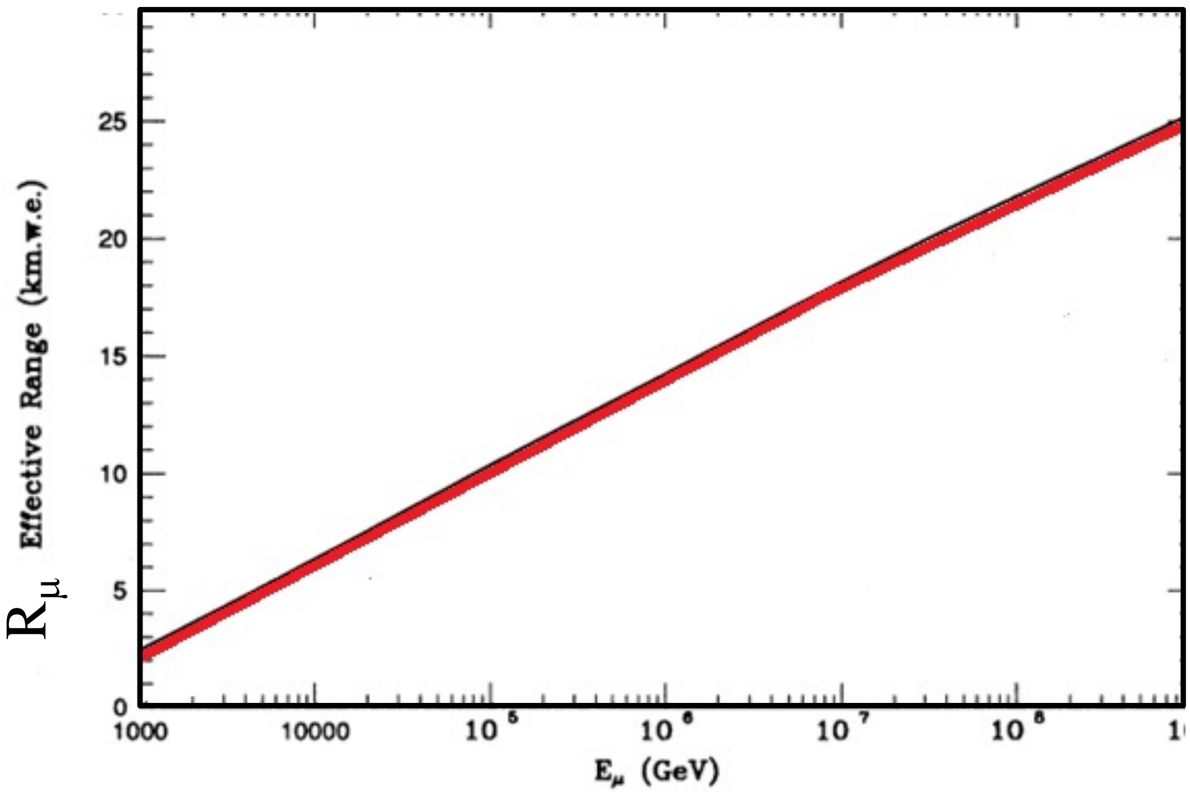
Muon Range

$$-\frac{dE}{dx} = a + bE$$

$$a = 2\,\mathrm{MeV g^{-1} cm^{-2}}\ ;\ b = 4\times10^{-6}\,\mathrm{g^{-1} cm^{-2}}$$

$$a/b = 500\,\mathrm{GeV} = 0.5\,\mathrm{TeV}$$

$$\rightarrow\ R_\mu = \frac{1}{b}\ln\left[1+\frac{E}{a/b}\right] = 2.5\times10^{5}\ln\left[1+2\frac{E}{1\ \mathrm{TeV}}\right]\ [\mathrm{gcm^{-2}}]$$



- **Muon range** (km.w.e.) vs. initial energy E_μ

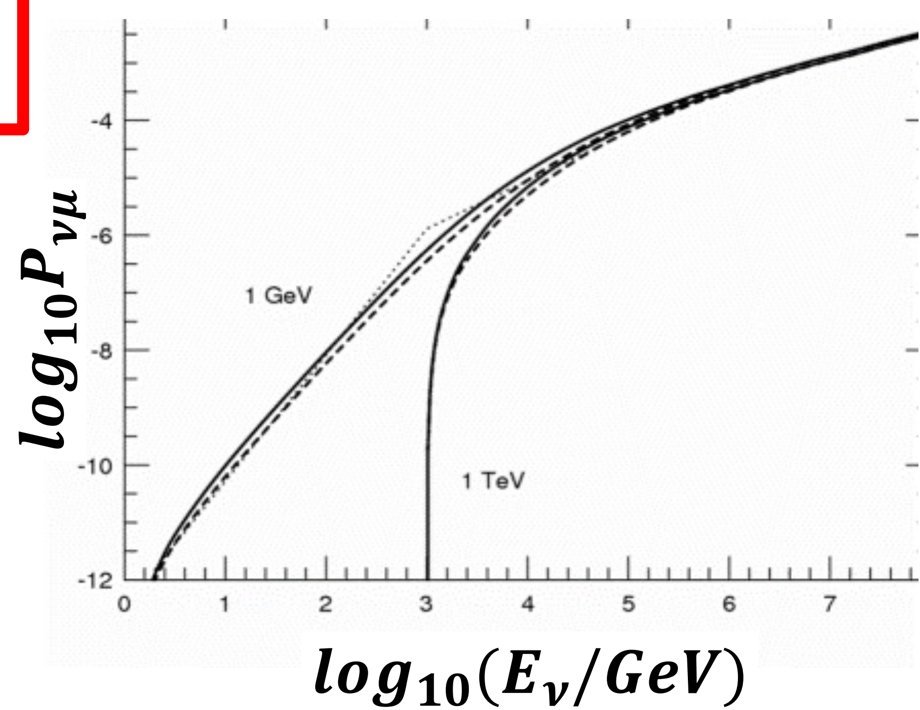
Probability of $\nu_\mu \rightarrow \mu$ in the detector

- By combining the three ingredients, the probability for ν's above the TeV scale to yield a visible muons in a detector is

$$P_{\nu\mu} = \sigma_{\nu\mu}(cm^2)\times \rho\ (cm^{-3})\times R(cm)$$

$$P_{\nu\mu} \cong 4\times 10^{-6} \left(\frac{E}{10\ TeV}\right)^{0.4}$$

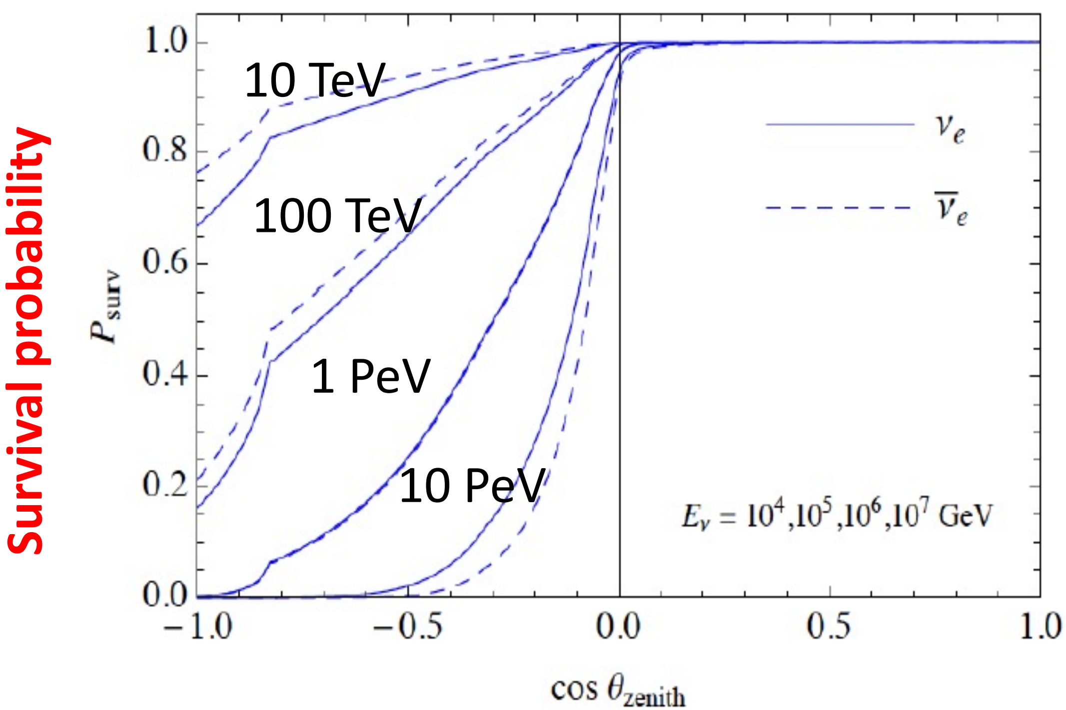
- The plot shows the result of a more detailed computation and for two muon minimum energy

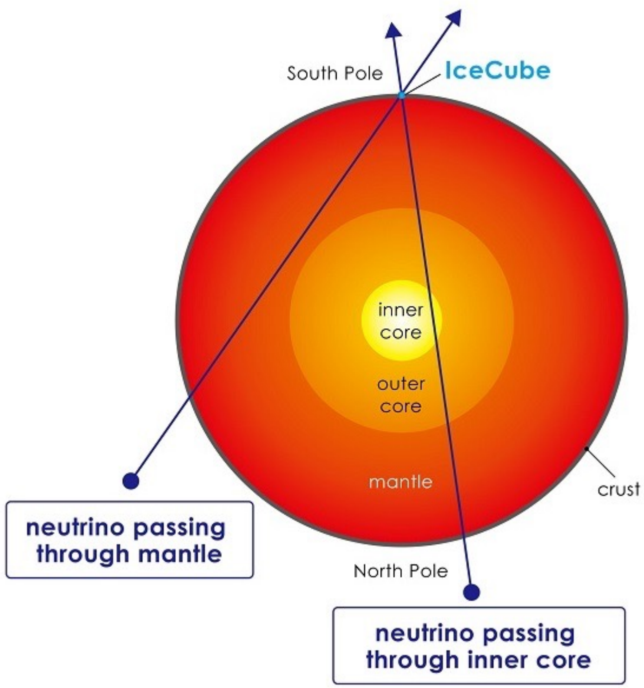


Earth absorption

$$A_\nu^{\text{eff}}(E_\nu) = A \cdot P_{\nu\mu}(E_\nu, E_{\text{thr}}^{\mu}) \cdot \epsilon \cdot e^{-\sigma(E_\nu)\rho N_A Z(\theta)}$$

- Neutrinos can interact in the Earth and get absorbed
- The absorption probability depends on E and zenith angle

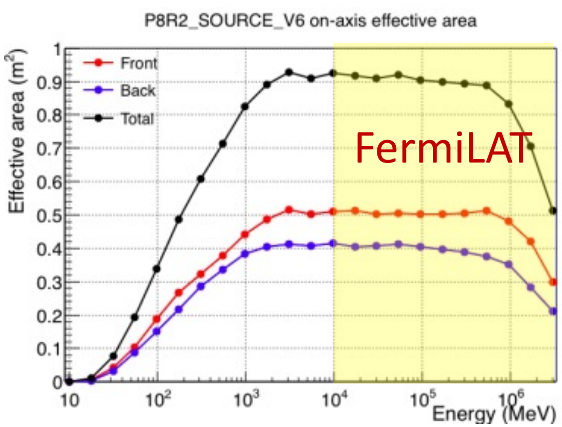


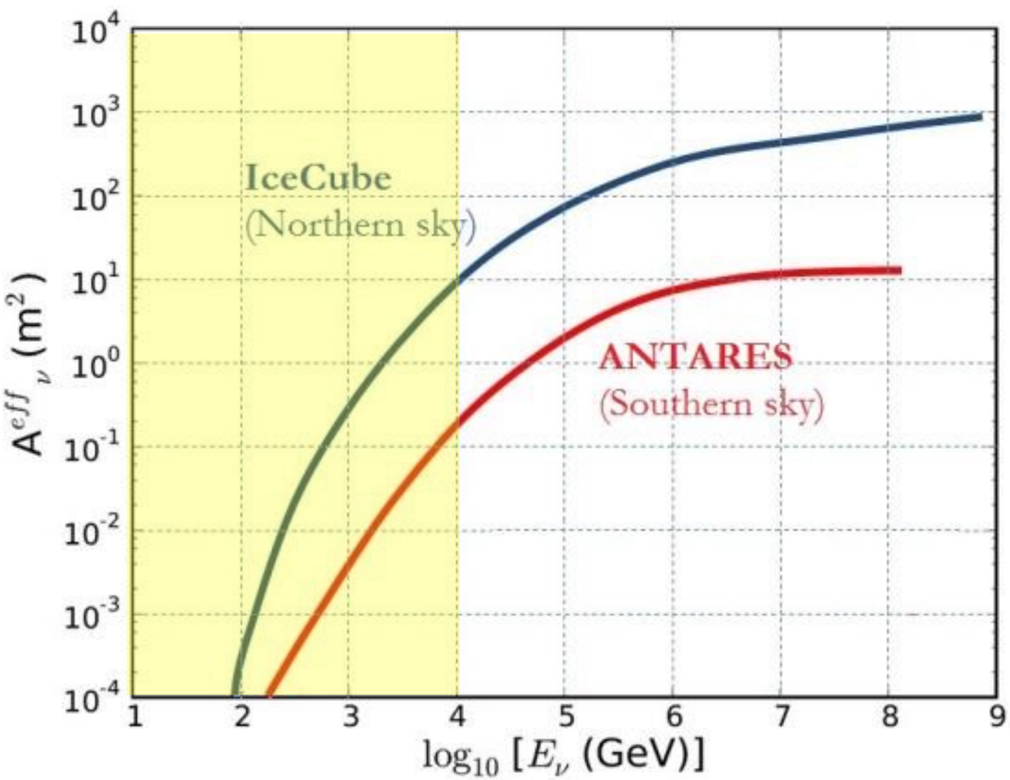


Detector efficiencies

$$A_{\nu}^{\text{eff}}(E_{\nu}) = A \cdot P_{\nu\mu}(E_{\nu}, E_{\text{thr}}^{\mu}) \cdot \epsilon \cdot e^{-\sigma(E_{\nu})\rho N_A Z(\theta)}$$

- Parameter dependent on the analysis
- ANTARES and IceCube A^{eff} for point-like sources (upgoing muons)





Result: Number of events in a 1 km^3

$$\frac{N_\nu}{T} = \int_{1\ \mathrm{TeV}}^{10^3\ \mathrm{TeV}} \mathrm{d}E_\nu \cdot (\Phi_\nu^0 E_\nu^{-2}) \cdot A \cdot \mathrm{P}_{\nu\mu} \cdot \epsilon = 0.5\ 10^{-16} \cdot A \cdot \epsilon\ \ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

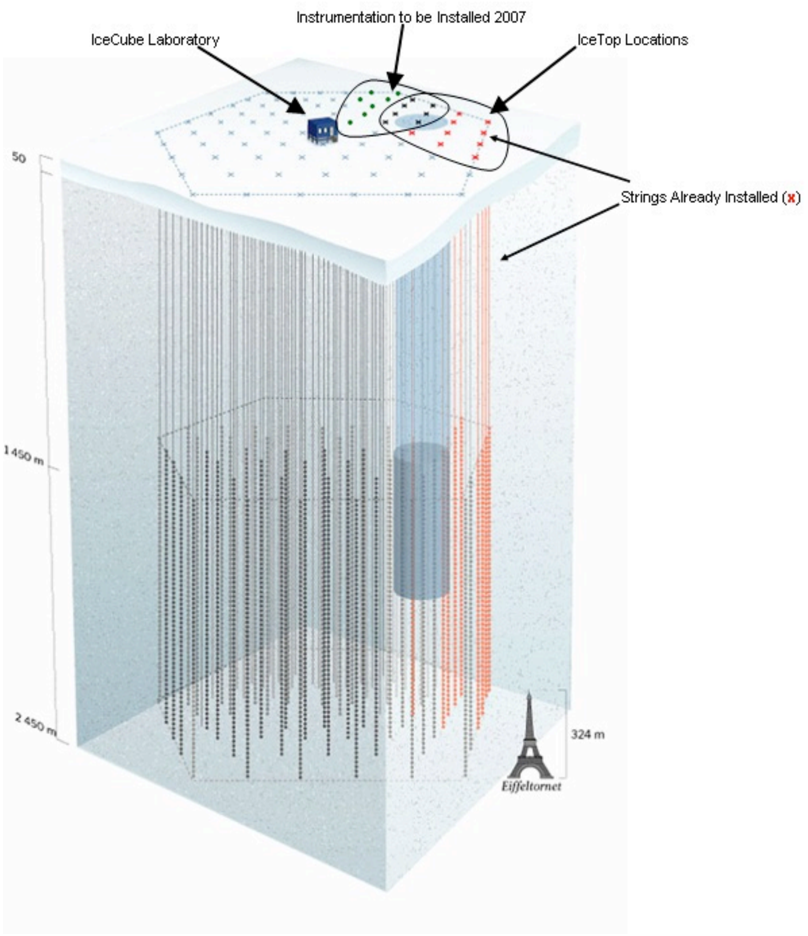
$$E_{\nu,\gamma}^2 \frac{d\Phi_{\nu,\gamma}}{dE_{\nu,\gamma}} = 10^{-11}\ \ \mathrm{TeV\ cm}^{-2} s^{-1}$$

$$T = 3.15 \times 10^7\ s = 1 y$$

$$A = 10^{10}\ \ \mathrm{cm}^2 = 1\,\mathrm{km}^2$$

$$\varepsilon = 1$$

$$P_{\nu\mu} \cong 4 \times 10^{-6} \left(\frac{E}{10\ TeV}\right)^{0.4}$$

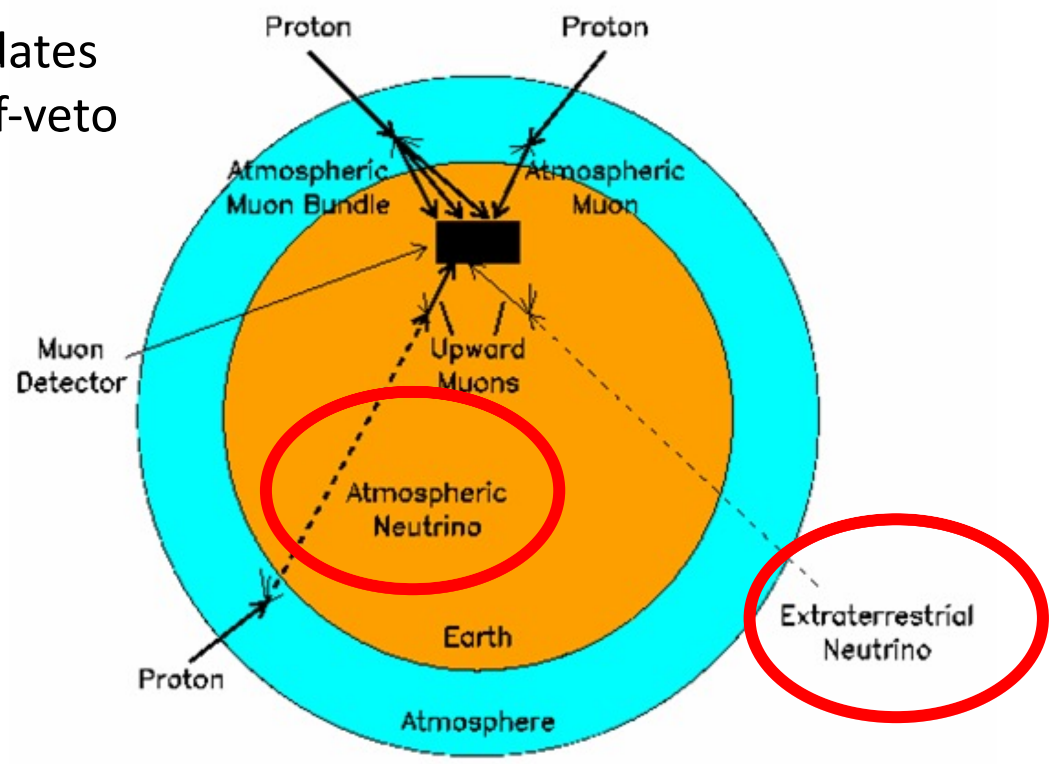


$$N_\mu \approx 1.5\ \mathrm{events/y}$$

NT: signal and background

- **Atmospheric muons** dominate by many order of magnitude the muons induced by neutrinos
- **Atmospheric neutrinos** represent the **irreducible background**
- The selection of **upward-going** particles largely reduces atmospheric μ's
- Large detectors can use part of its internal volume (*fiducial volume*, à la SK) to identify neutrino interactions

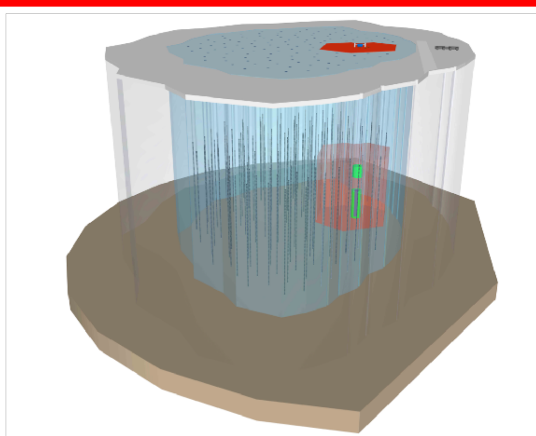
- Atmospheric neutrino candidates can be reduced using the self-veto method

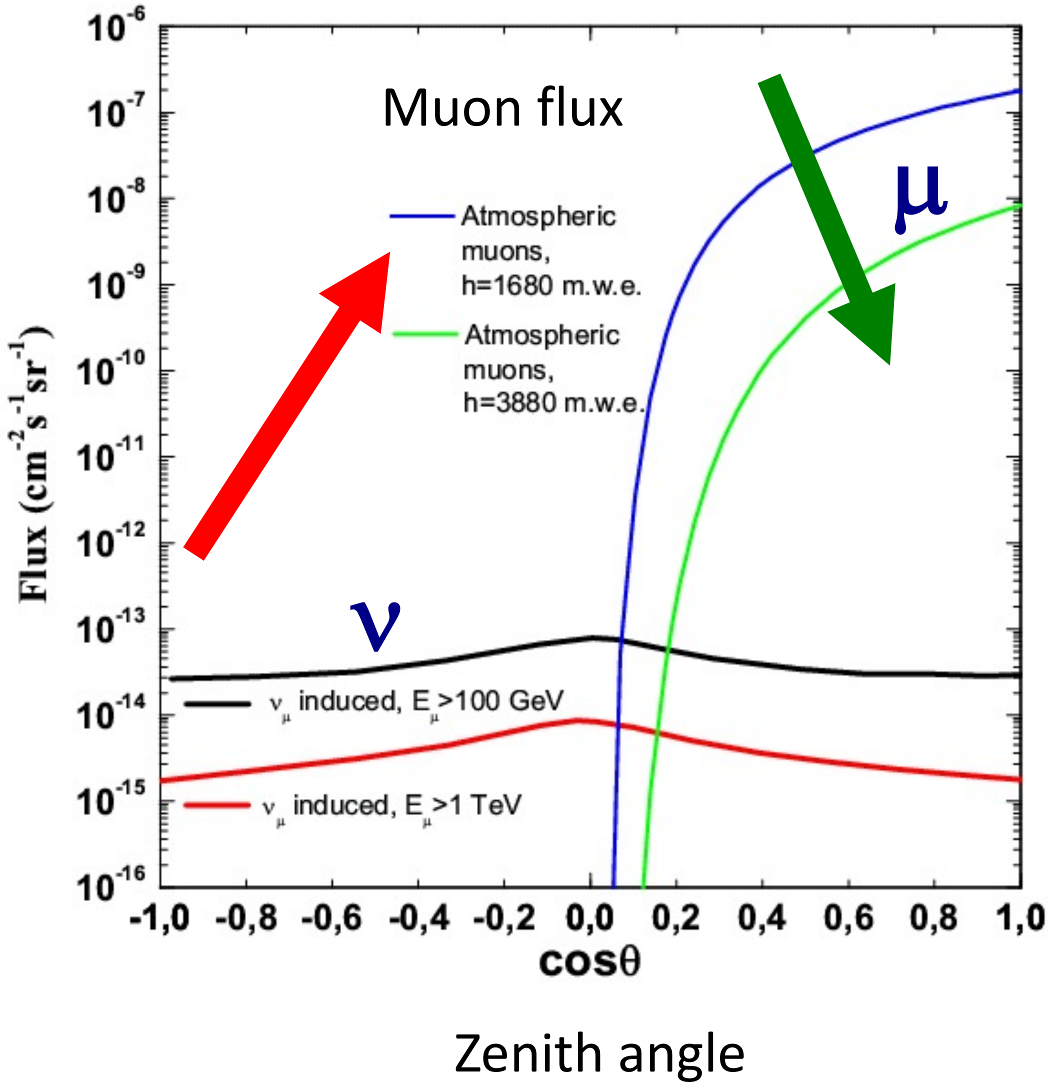


"Deep in a transparent medium"

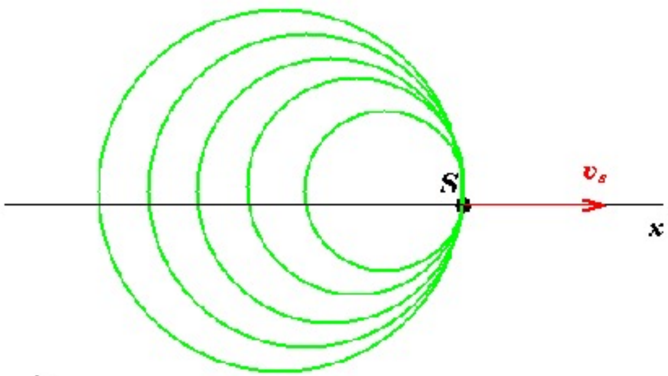
Water or Ice:

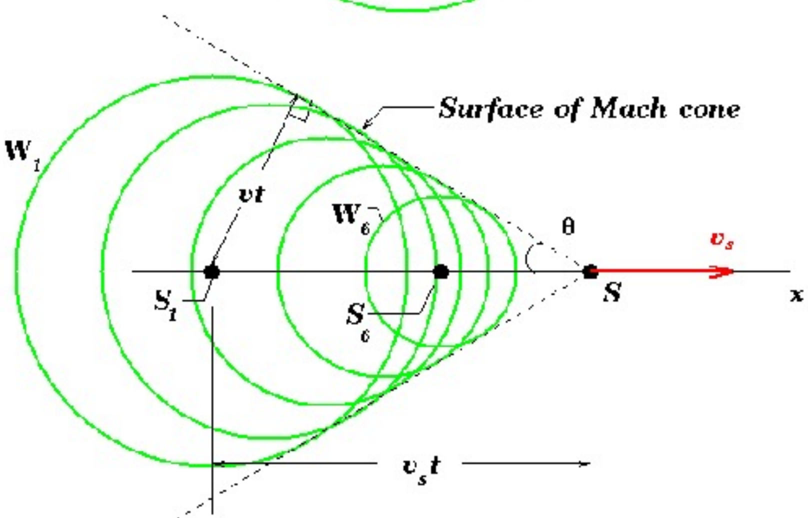
- large (and inexpensive) target for ν interaction
- transparent radiators for Cherenkov light;
- large deep: protection against the cosmic-ray muon background





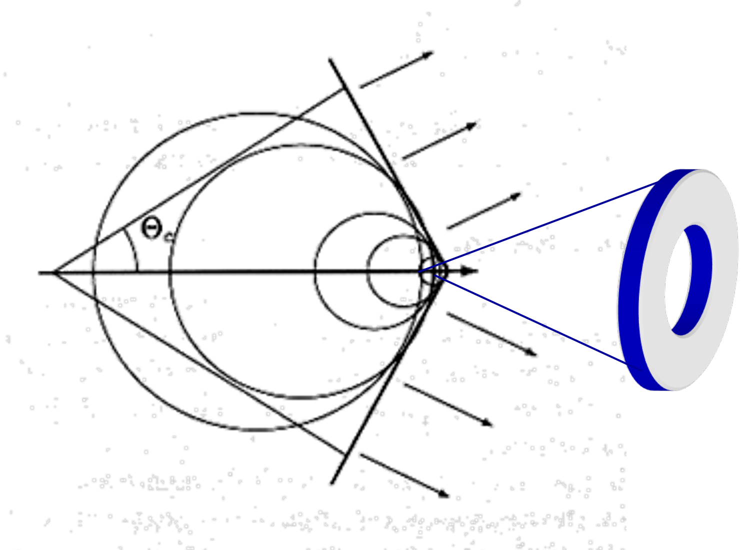
Cherenkov Radiation





- As a charged particle travels, it disrupts the local EM field.
- Radiation is emitted as insulator's electrons restore to equilibrium
- This radiation destructively interfere and no photons are produced.
- However, **when the disruption travels faster than light is propagating through the medium**, the radiation constructively interfere and intensify the observed Cherenkov photons.

Cherenkov light yield (Frank-Tamm)



- Number of Cherenkov photons in a transparent medium, with $\beta n(\lambda) > 1$
- Dominant photon emission in the blue-UV band (the range in which water/ice are most transparent):
- The Frank-Tamm formula gives

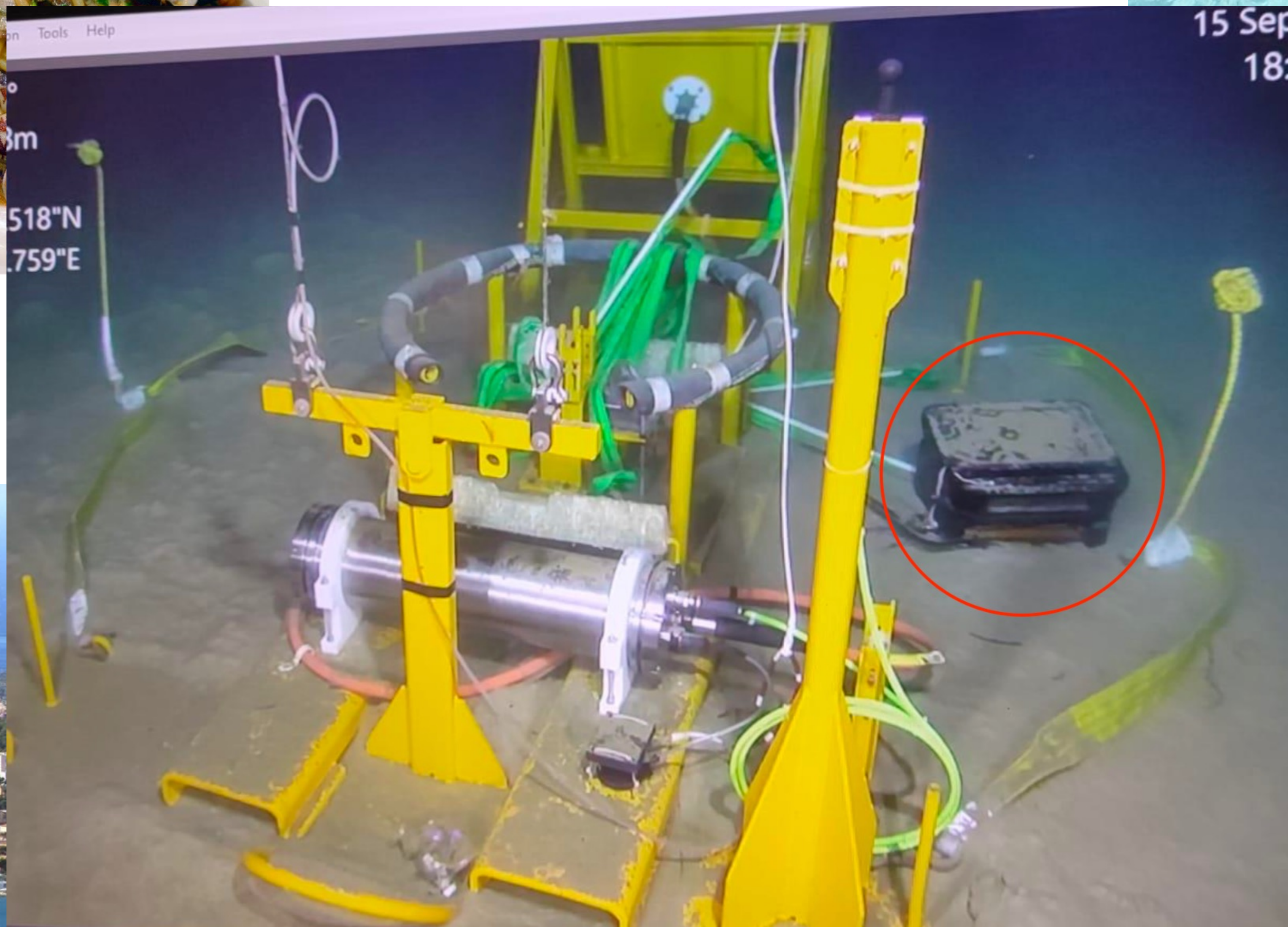
$$\frac{d^2N}{dx d\lambda} = \frac{4\pi^2 e^2}{hc\lambda^2}\left(1 - \frac{c^2}{v^2 n_\lambda^2}\right)$$

- **EXERCIZE**: Compute the Cherenkov angle and the number of photons in water (n=1.33) in the range 300-600 nm for a β=1 particle.
- **A**: θ=42° ; N_C = 300/ cm

Difference between ice…

… and Mediterranean water

… and Mediterranean water



4. water/ice properties

Cherenkov photons can reach one (or many) **PMT(s)** in an **Optical Module (OM)** and produce a signal.

Water/ice characterized by two quantities (depending on photon wavelength λ)

- ***absorption length, a(λ)***, of the order of 50 m (ice better than water). The absorption reduces the number of photons arriving on OMs.
- ***scattering length, b(λ)***, (water better than ice). The scattering reduces the number of photons arriving in time. It worsening the reconstruction capability.

- Usually, instruments measure the ***absorption*** and the ***attenuation*** length $c(\lambda)$ (the combination of scattering and absorption), where

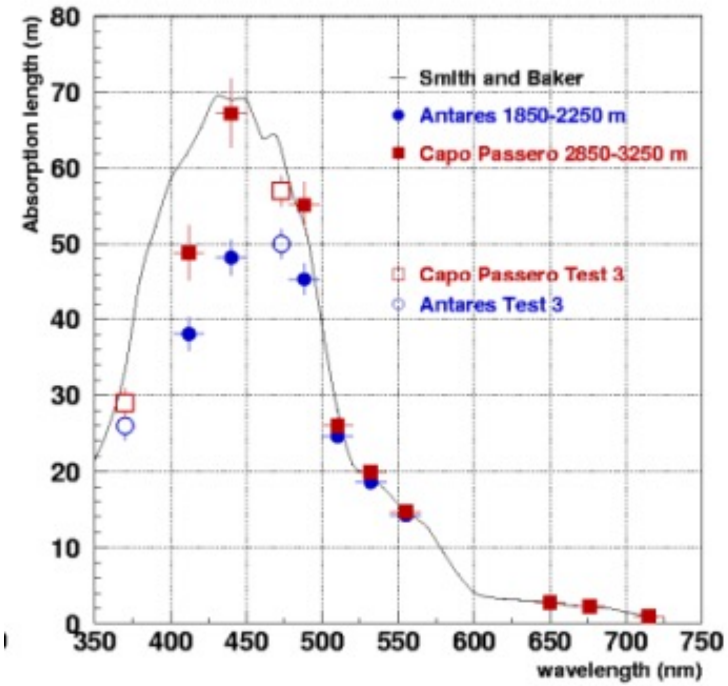
$$c(\lambda) = a(\lambda) + b(\lambda) \ [m^{-1}]$$

- The attenuation at a distance x is thus:

$$\mathrm{I}(x, \lambda) = I_o e^{-x \cdot c(\lambda)}$$

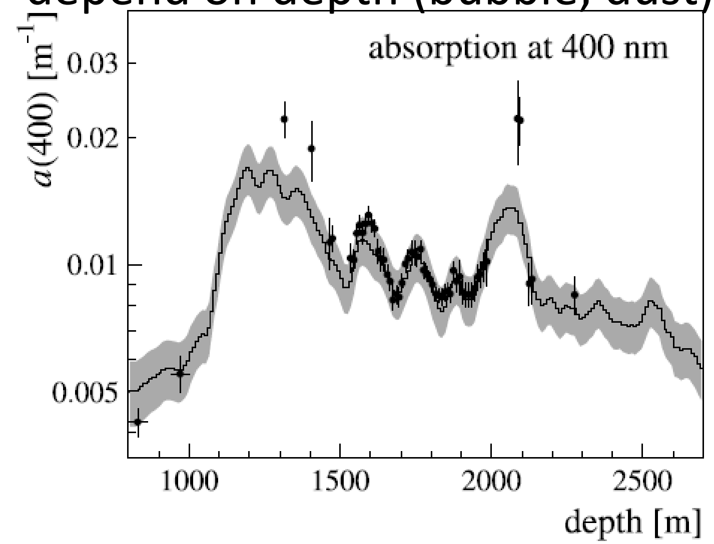
Water/ice properties

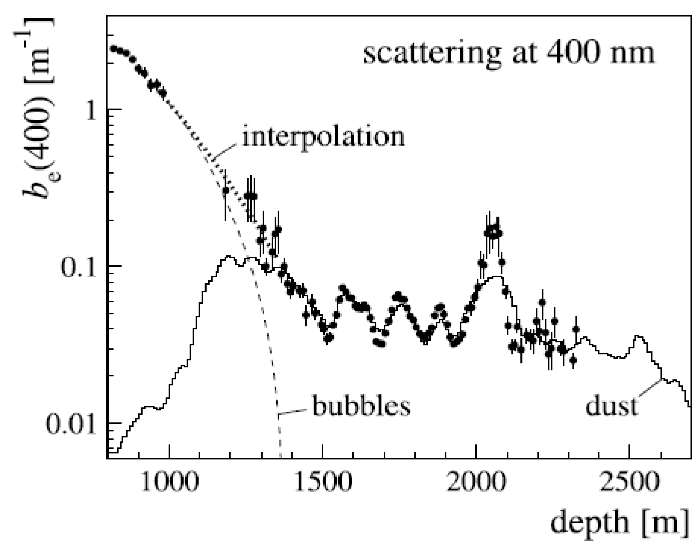
- The water is an homogeneous medium
- The medium properties changes with location (+ seasonal, depth)



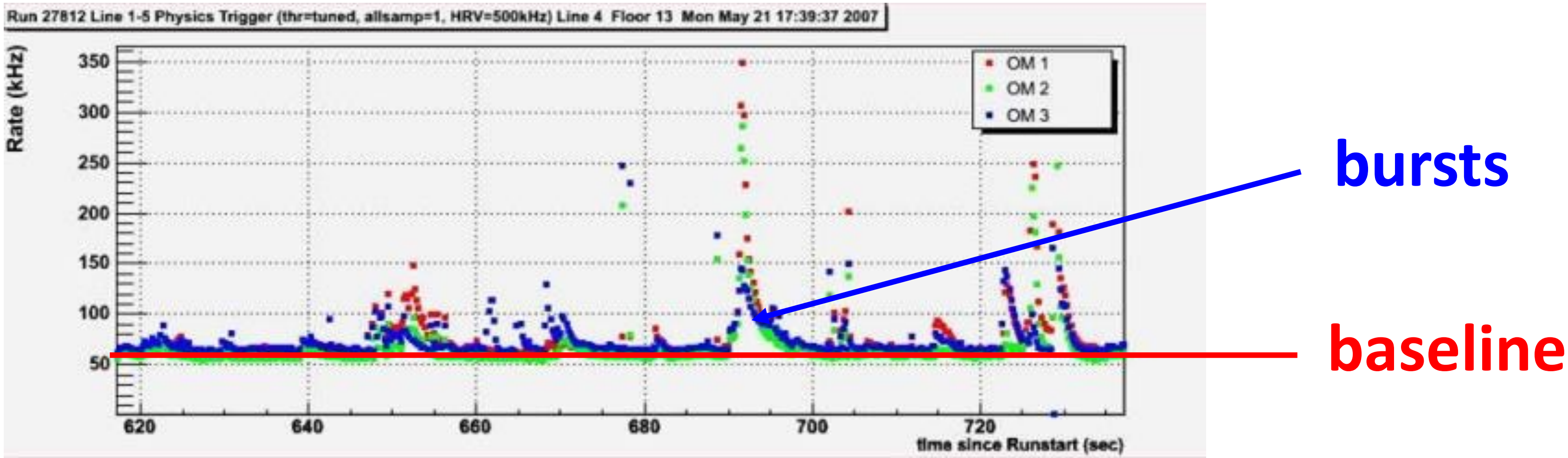
$a^{-1}(\lambda)$ vs. wavelength for different sites (ANTARES, KM3/ARCA)

- Ice: Absorption/scattering depend on depth (bubble, dust)





Optical background in water



Baseline:

^{40}K decays + bacteria luminescence

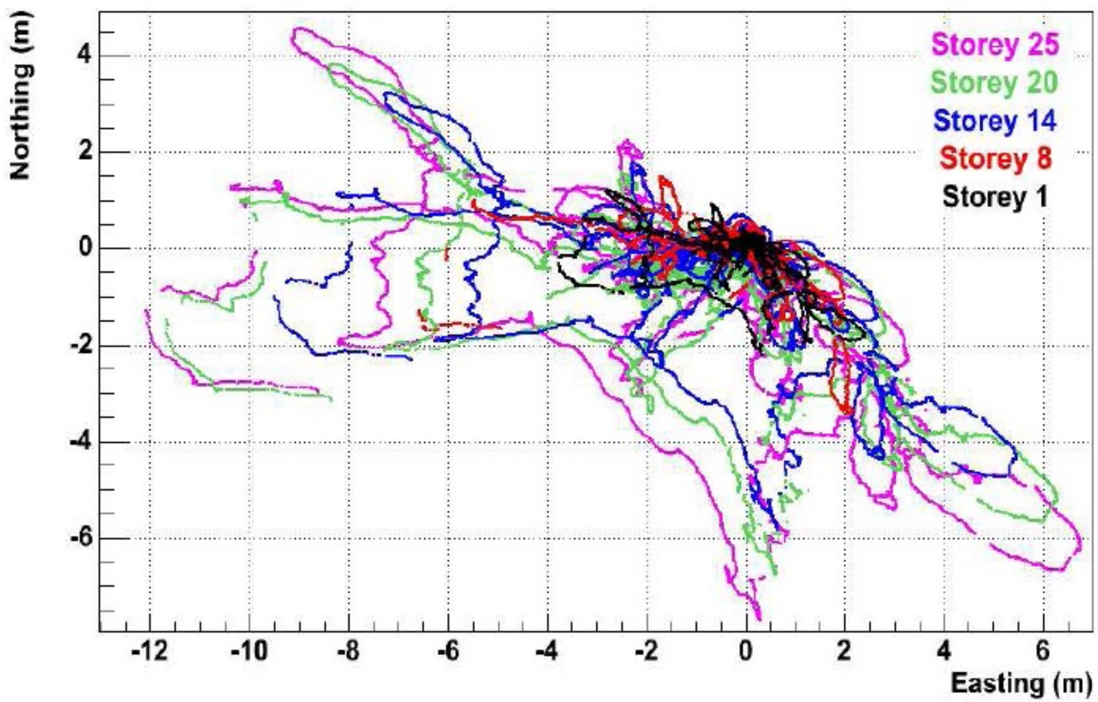
Bioluminescence bursts:

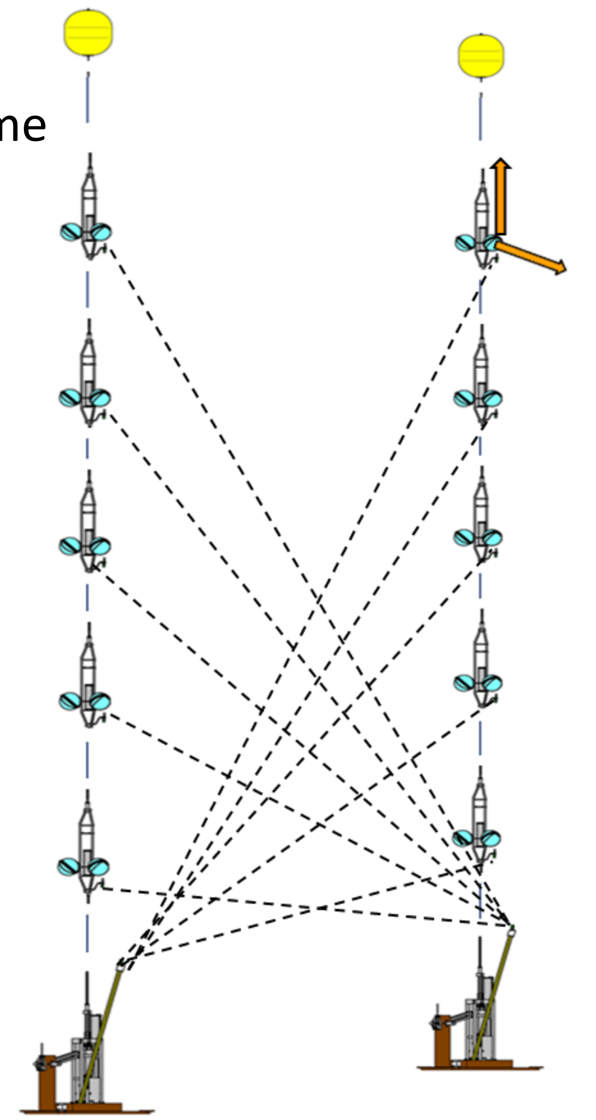
Animal species which emit light by flashes, spontaneous or stimulated around the detector.

- Periodical
- Correlated with water speed

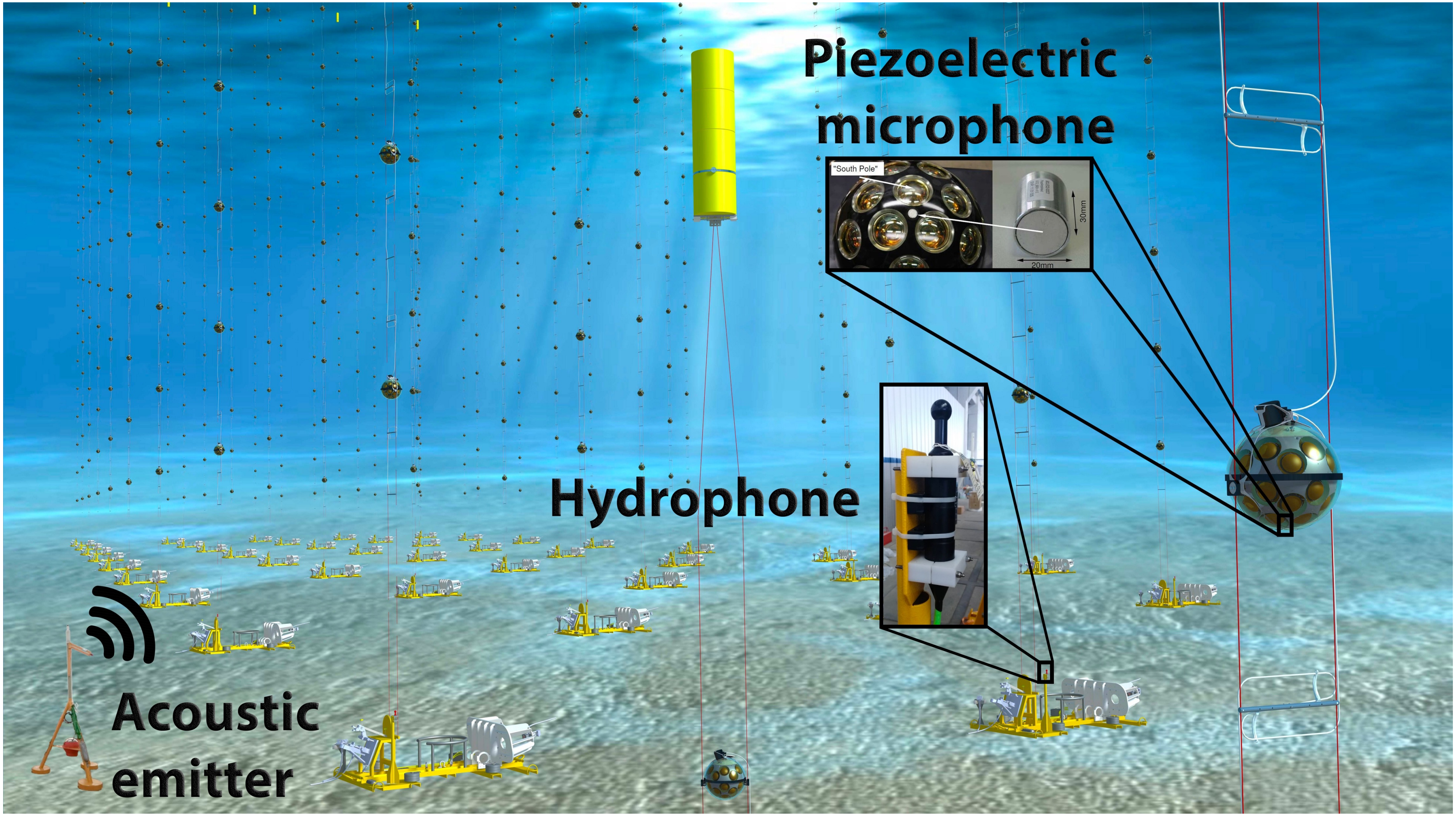
9. Detector positioning

- $\Delta r<10$ cm accuracy on individual OM position
- Acoustic system monitoring the OM position vs. time
- Additional devices provide independent sound velocity measurements
- Figures: ANTARES Data

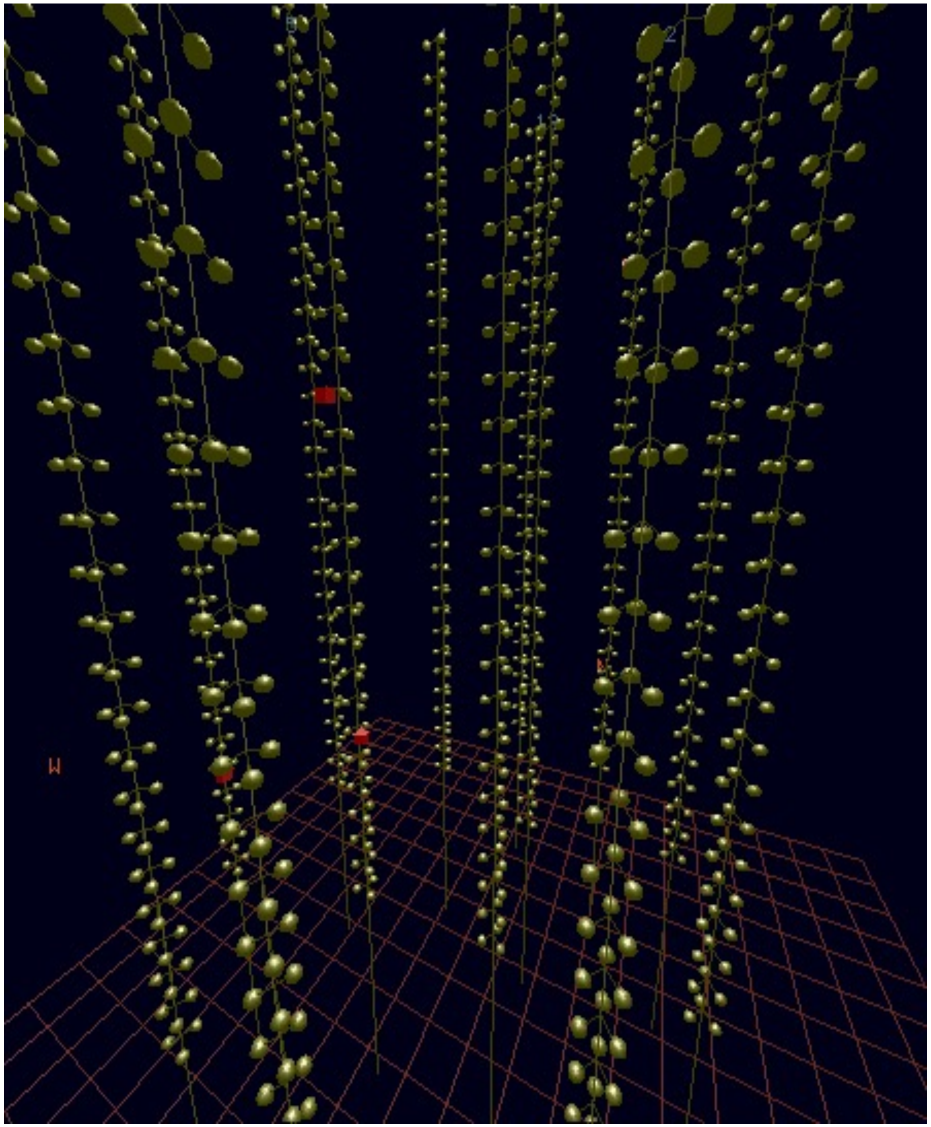




Detector positioning



Tracks and cascades



- ❑ Reconstructed from time-space correlation between ***hits***.
- ❑ energy reconstructed from ***hits*** number and amplitudes

Track channel (CC ν_μ)

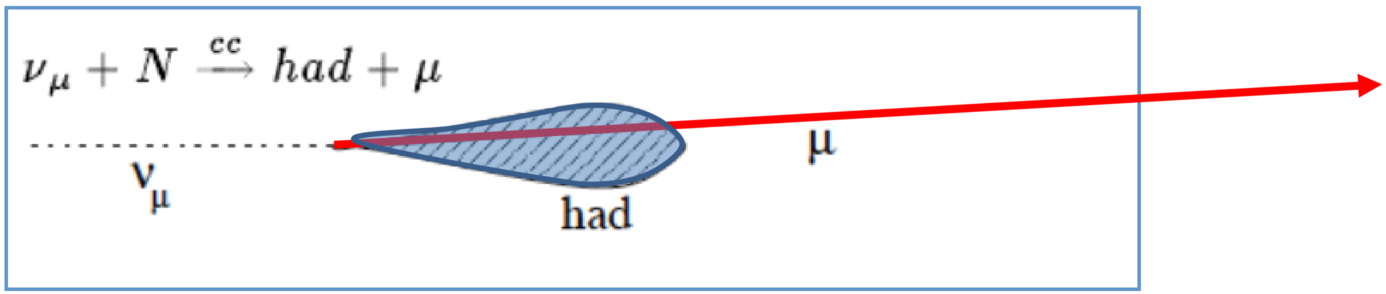
- Long pattern in the detector
- Cherenkov photons are correlated in space and time

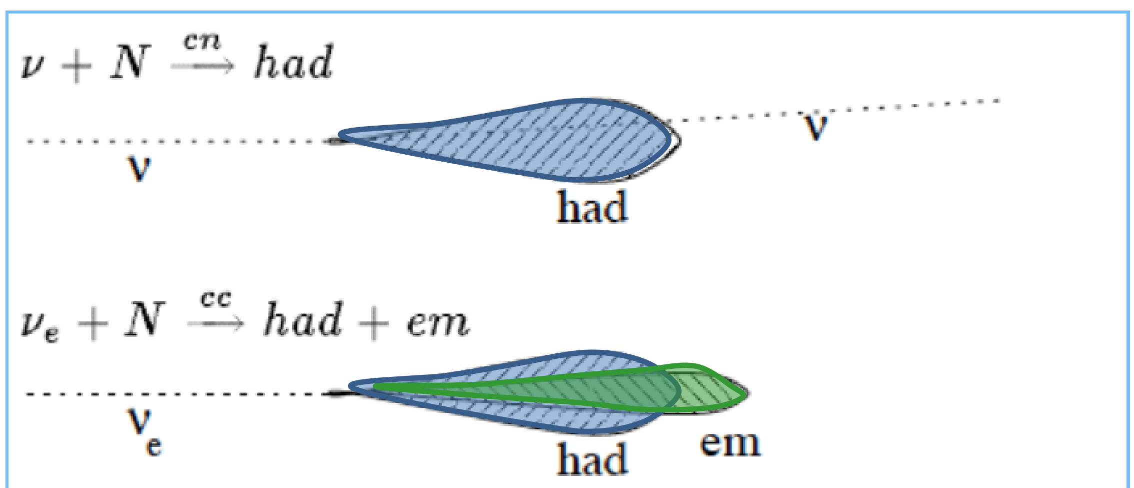
Cascades/shower (CC ν_e+ NC)

- Short pattern (point like)

Tracks and cascades

- ν_μ **yield tracks**
  - Better direction estimate (the muon collinear with the neutrino)
- ν_e, ν_τ **CC + NC**: yield **cascades** (or **showers**)
  - Better energy measurement (energy dissipated in the detector)



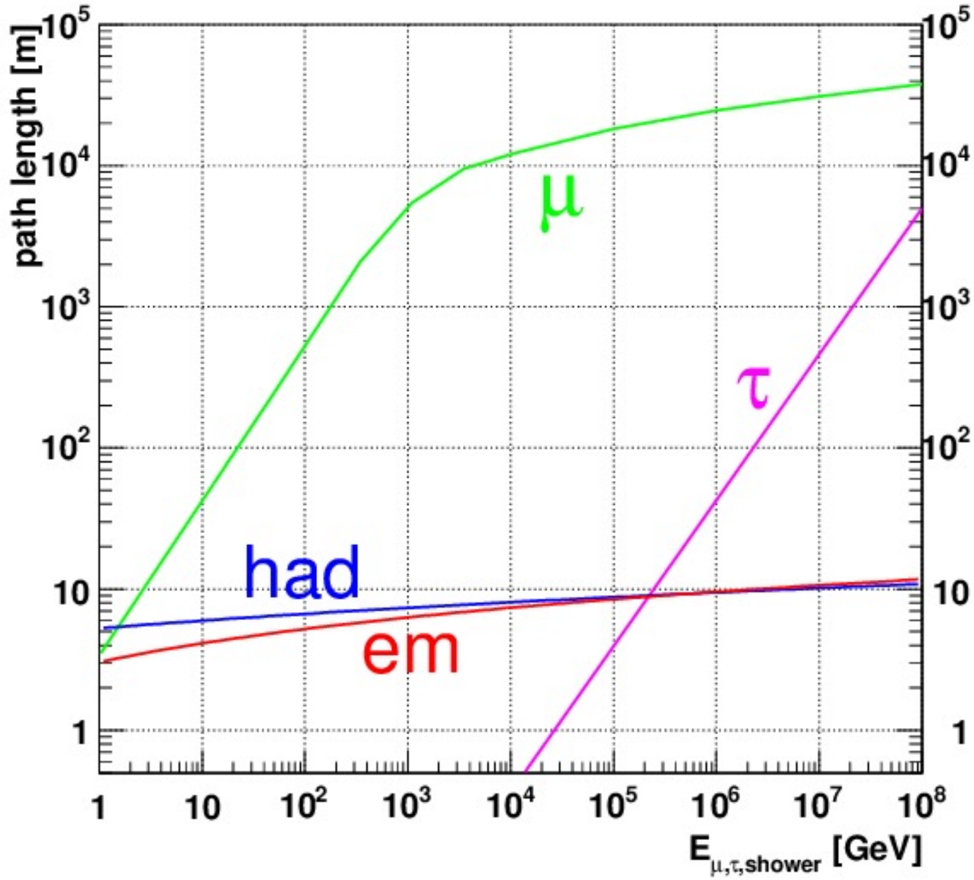


Path length (m) of tracks/cascades

Figure: Path length of leptons from ν CC interactions in water vs. energy.

Calculated using a parameterization.

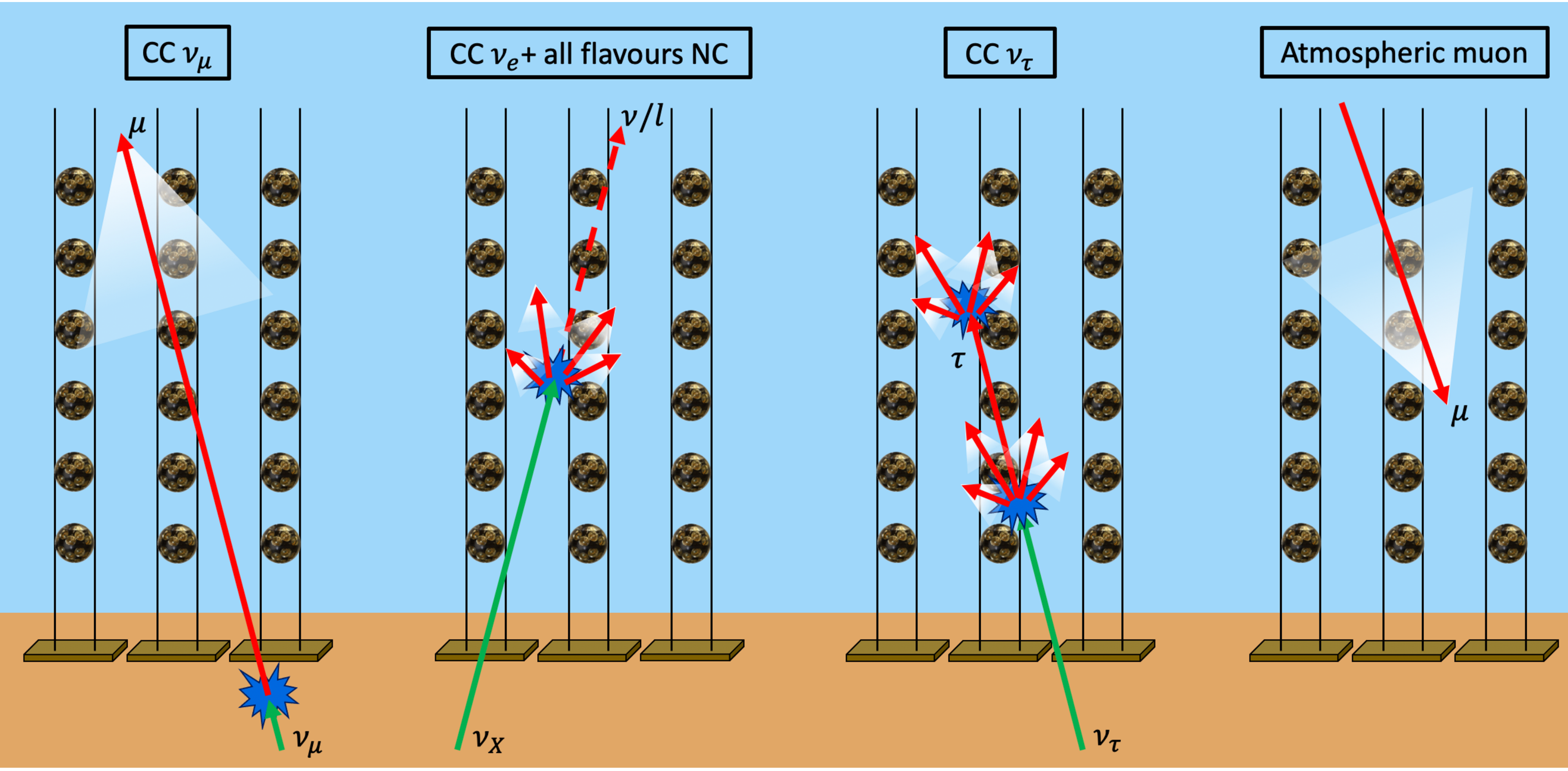
- **Muons** (CC interactions)
- taus (CC interactions)
- electromagnetic showers
- hadronic showers



- Muons can reach the detector also if produced very far
- «em» and «had» showers are almost point-like in the scale of the detector sizes

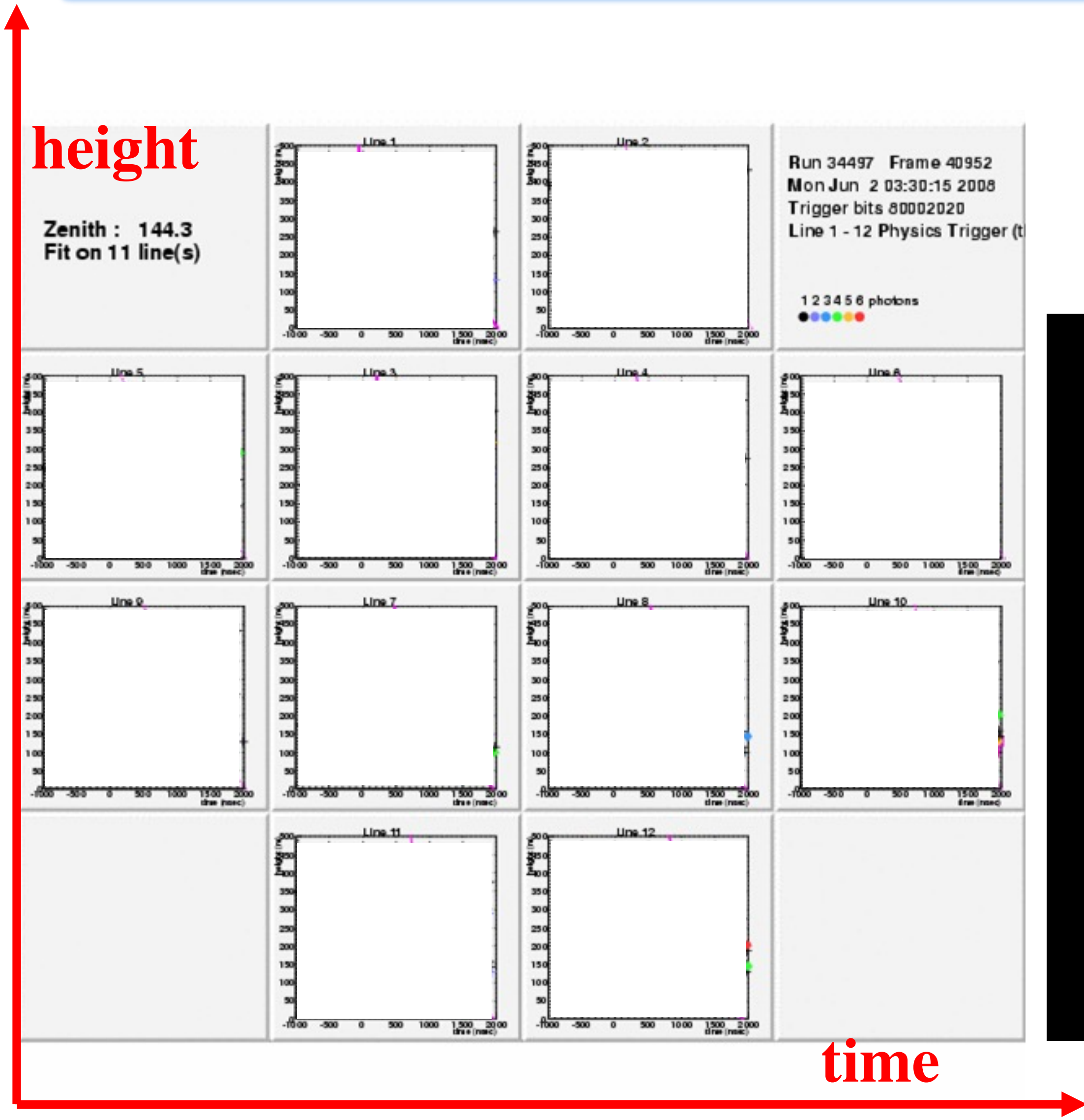
- In a certain energy window, τ can produce **«double bang»** events (never identified so far!)
  - One «had» shower + τ track at the neutrino vertex
  - One «had» shower at the tau decay vertex

Signature in a neutrino telescope

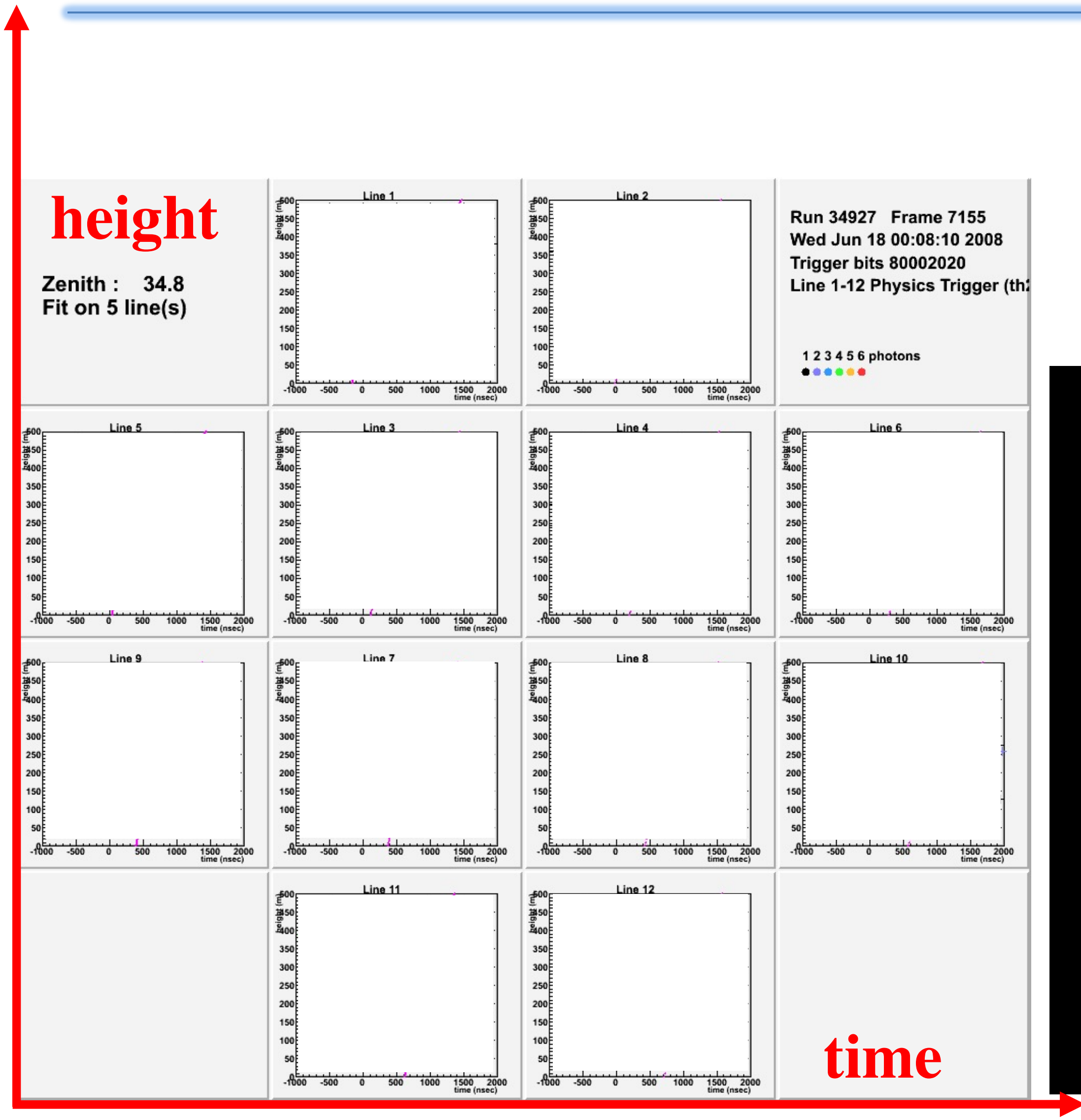


ANTARES: atmospheric muons

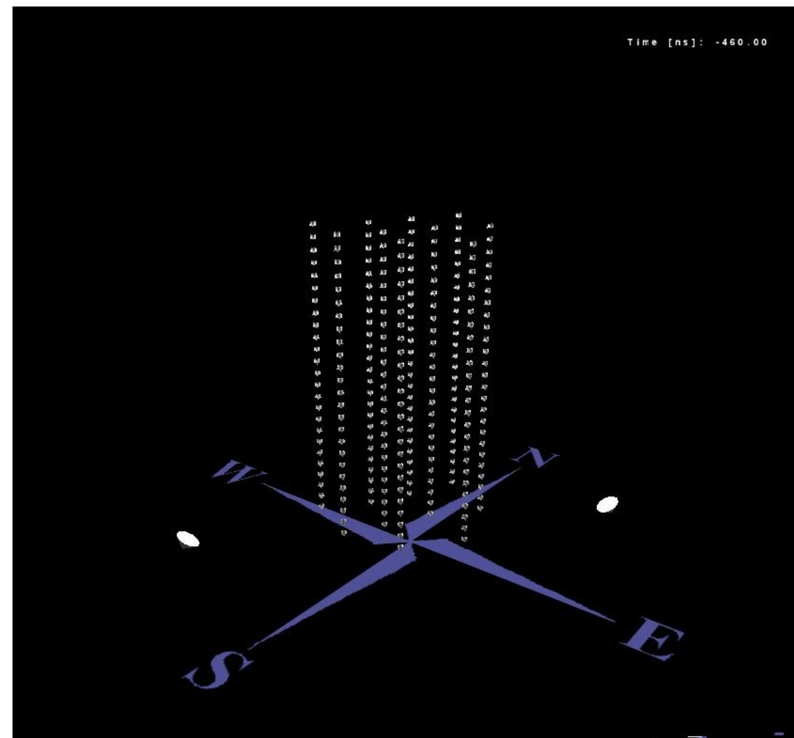
Example of a reconstructed down-going muon in ANTARES detected in all 12 detector lines:



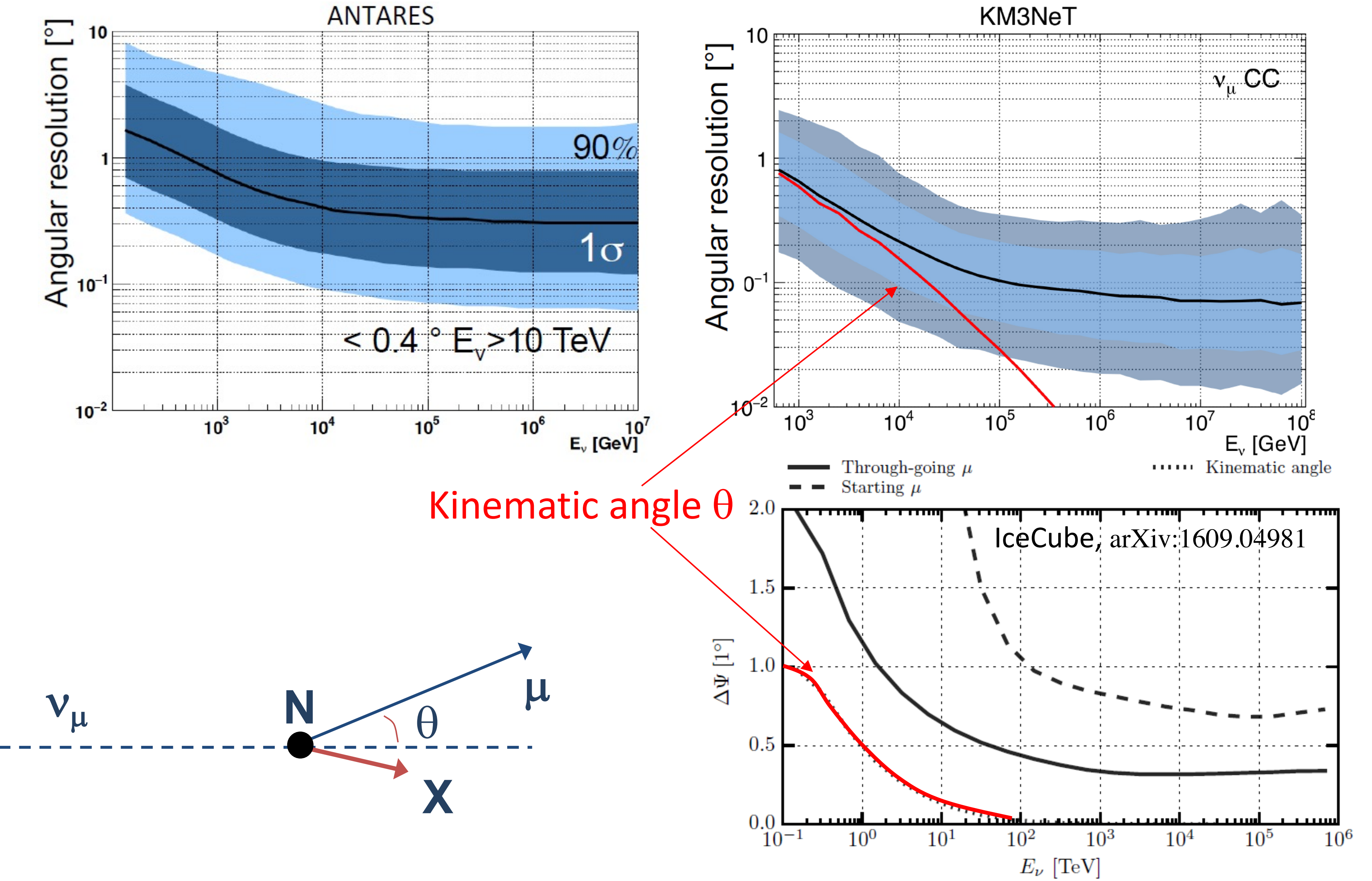
ANTARES: ν-induced muon



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

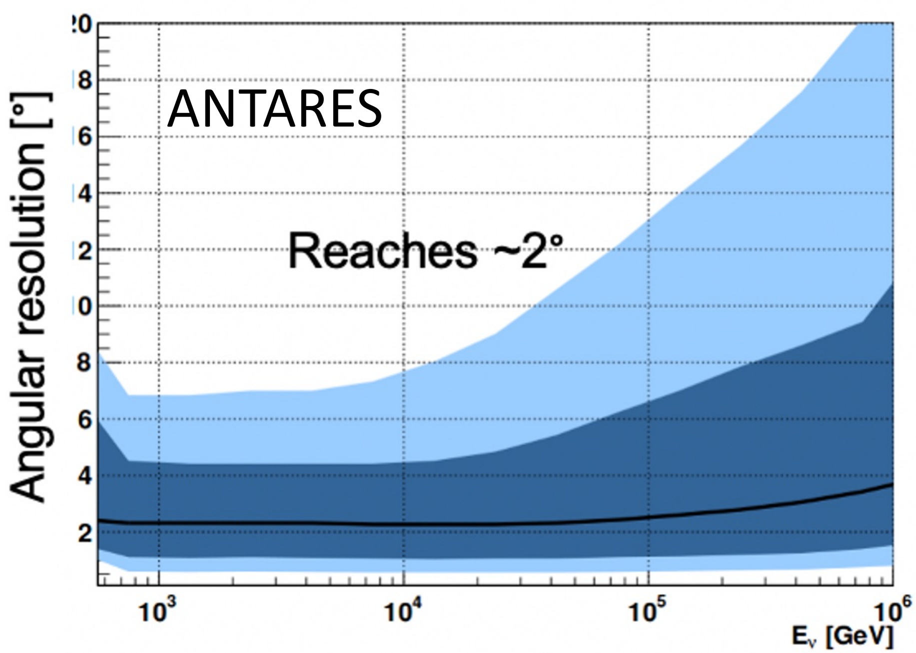


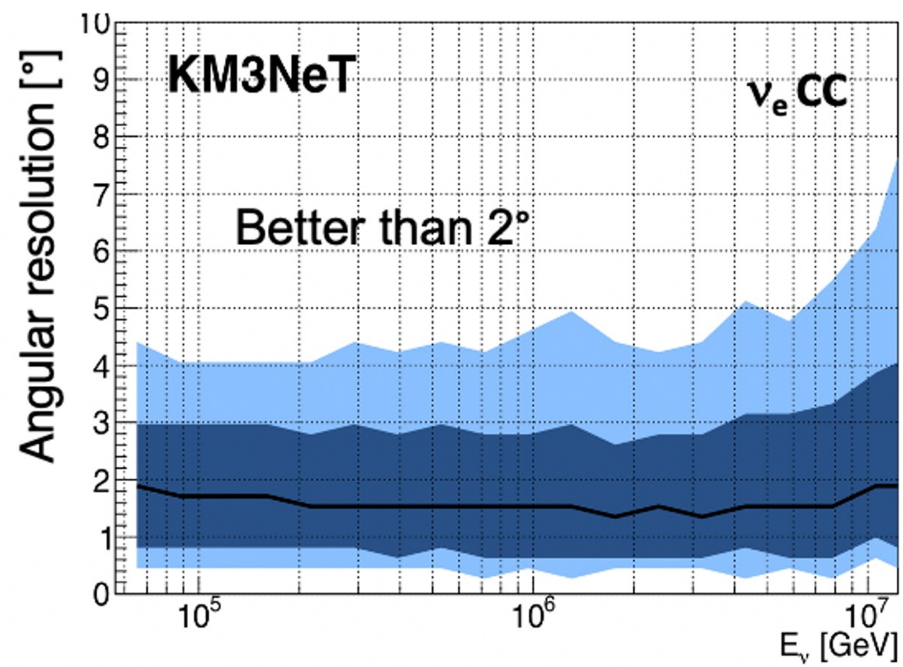
Angular resolution for ν_μ



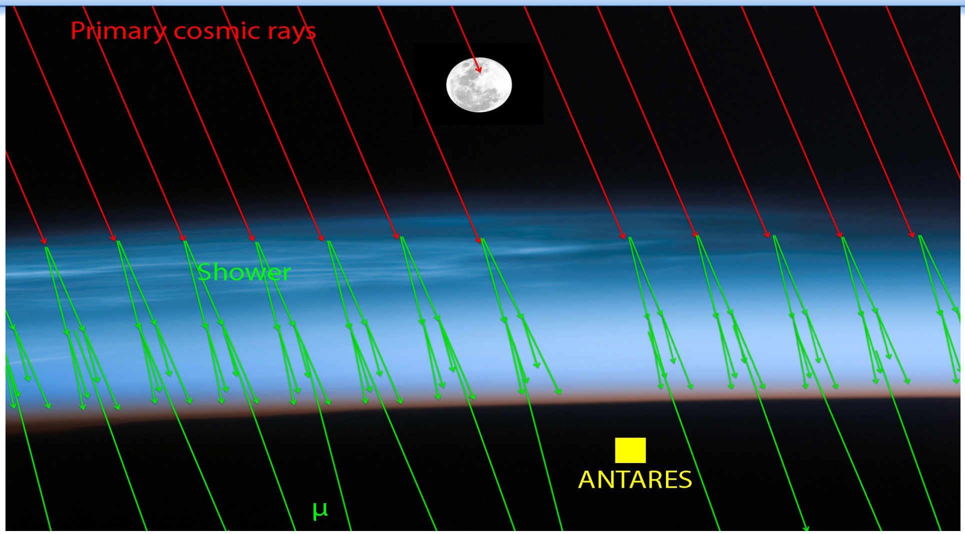
Angular resolution for cascades

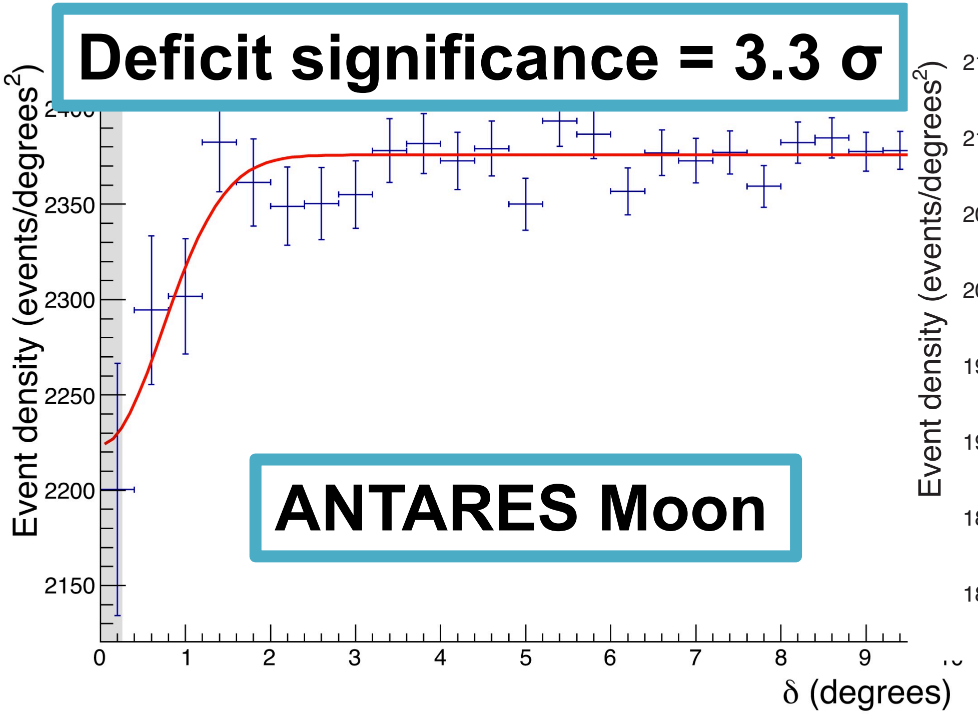
- Electromagnetic/hadronics cascades develop within ~10 m
- Very short tracks, poor ***angular resolution*** (depends on the detector. Ranges from few degrees to 15º-20º)
- Energy resolution much better (large fraction of the ν energy released in secondaries)

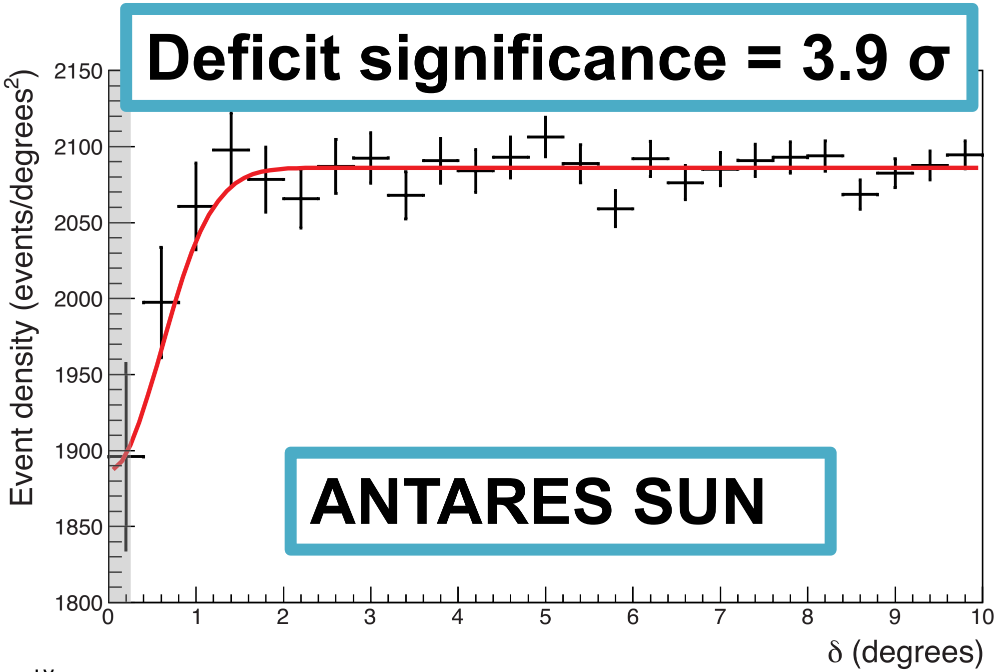




Calibration – Moon/Sun shadow

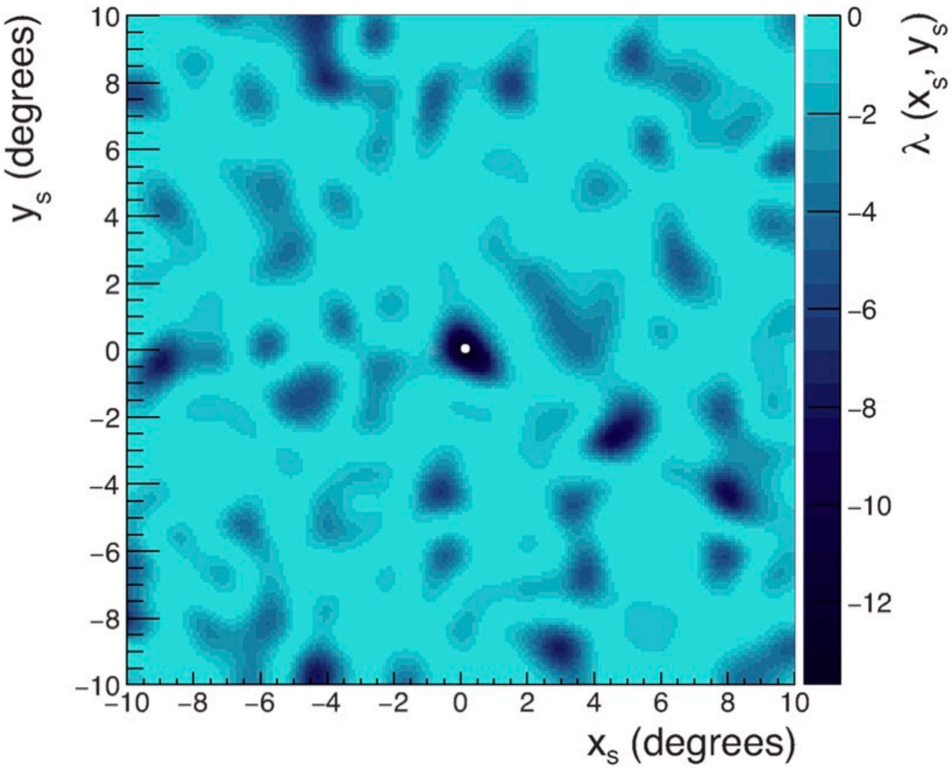


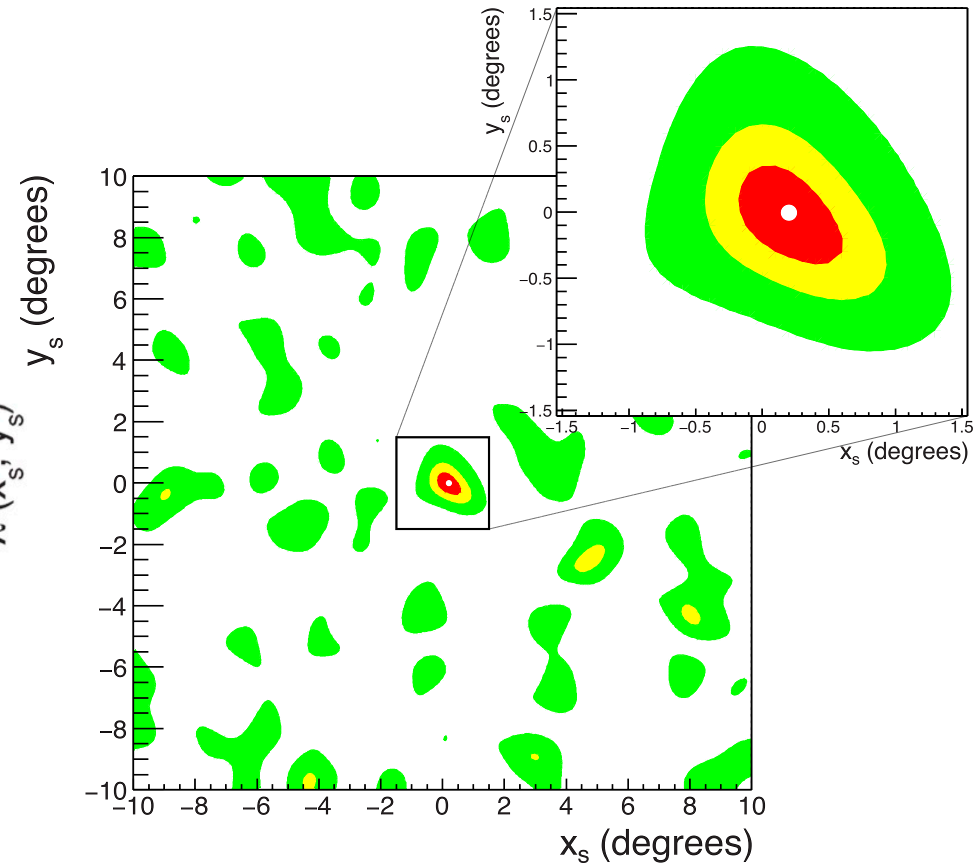




Calibration – Moon/Sun shadow

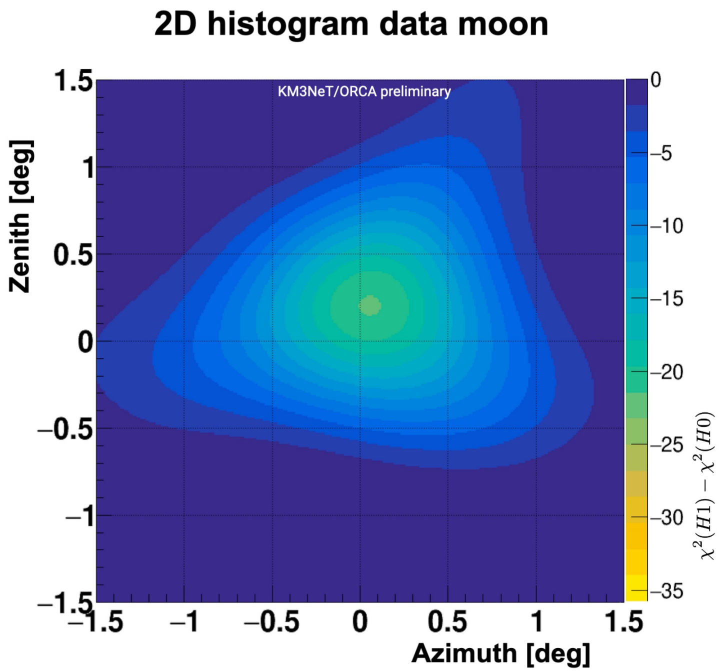
ANTARES SUN

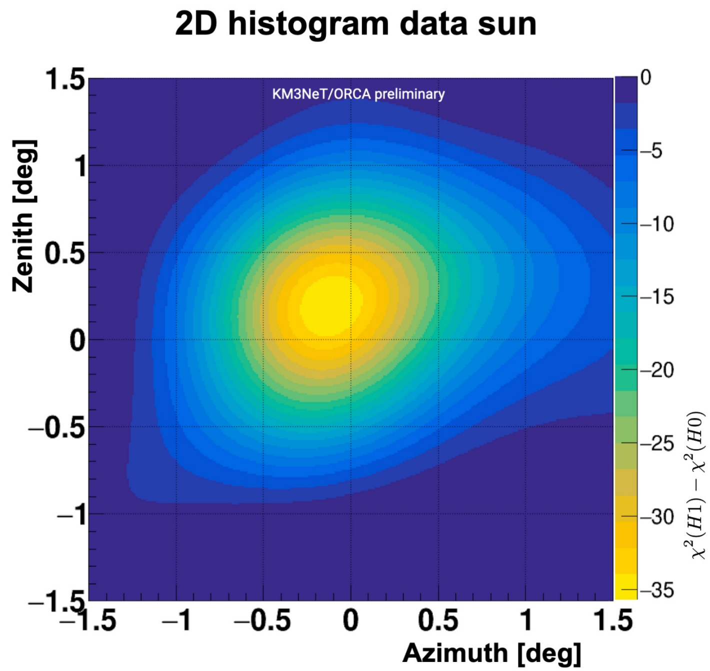




Calibration – Moon/Sun shadow

KM3NeT



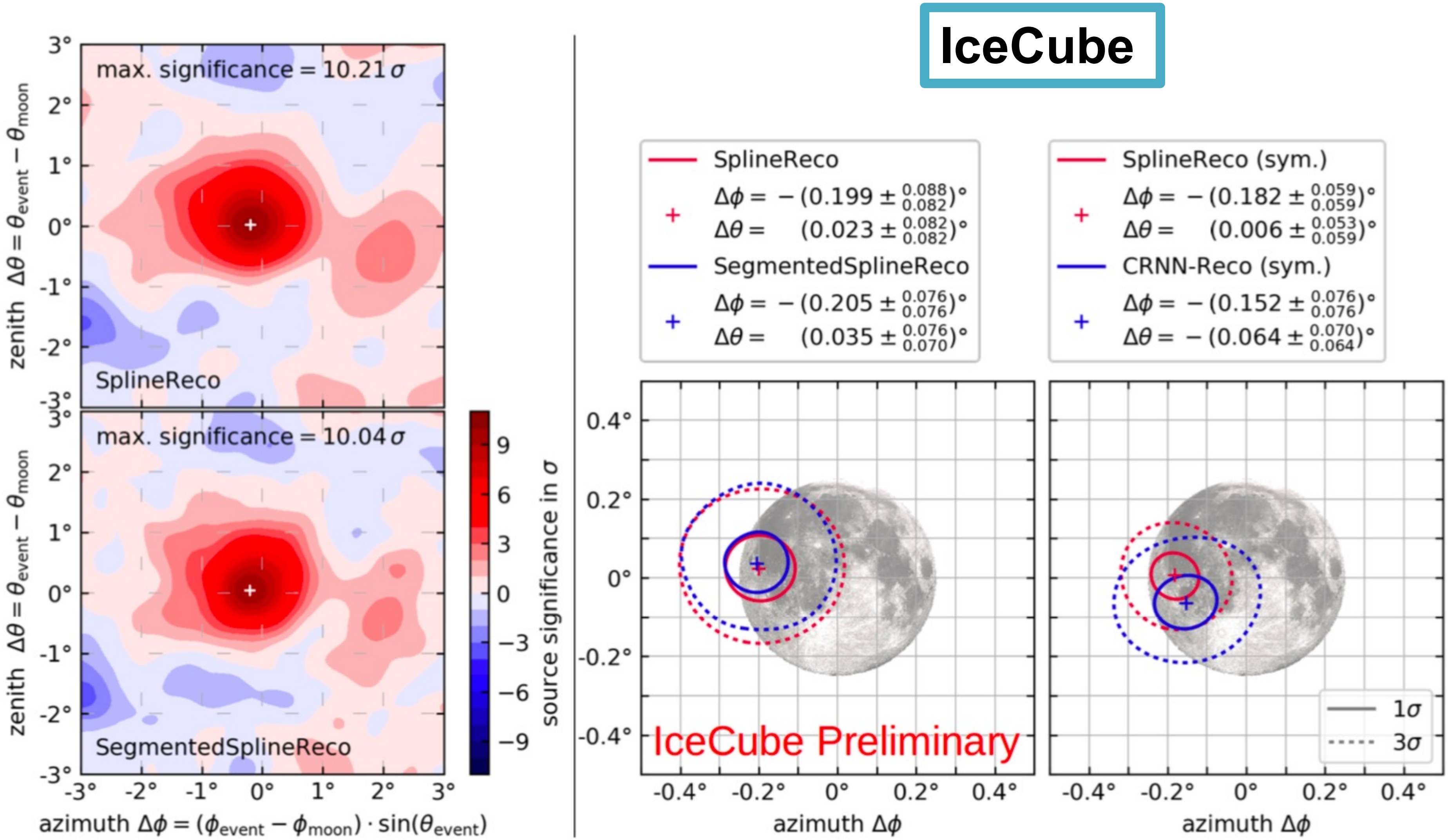


KM3NeT ORCA 13 months data taking

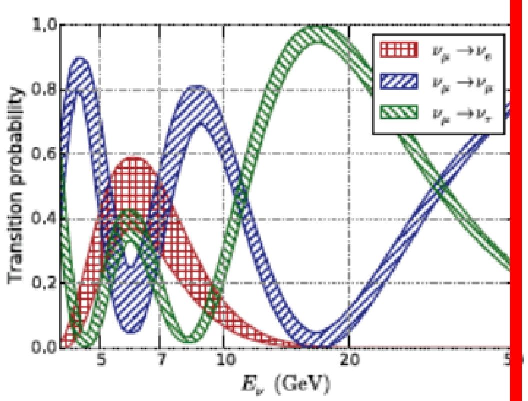
Significance = 4.4 σ
Angular resolution = 0.54°+/-0.13° deg

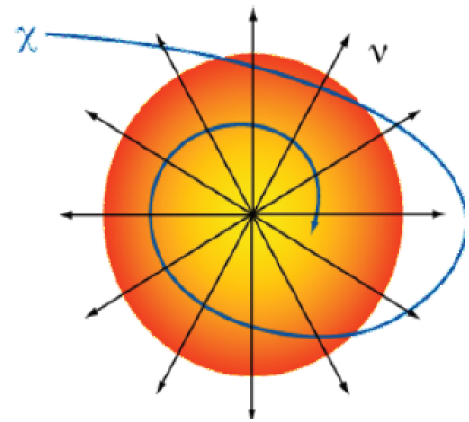
Significance = 5.7 σ
Angular resolution = 0.59°+/-0.10° deg

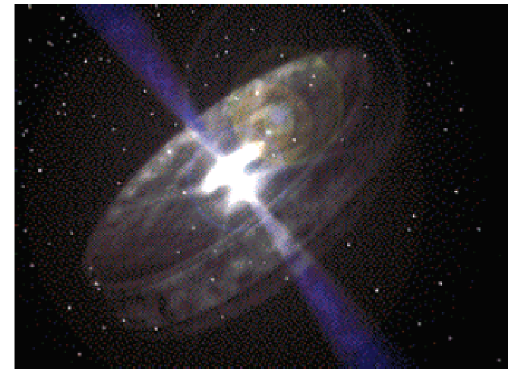
Calibration – Moon/Sun shadow



The Science case







Low Energy	Medium Energy	High Energy
MeV < E_ν < 100 GeV	10 GeV < E_ν < 1 TeV	E_ν > 1 TeV

ν Oscillations
ν Mass hierarchy
Supernova

Dark matter search
Monopoles, nuclearites,…

ν from extra-terrestrial sources

Origin and production mechanism of HE CR

KM3NeT-ORCA ANTARES KM3NeT-ARCA

DeepCore GVD, IceCube

Detecting cosmic neutrinos

Method 1) Measuring an excess of events from a given direction (**point-sources**).

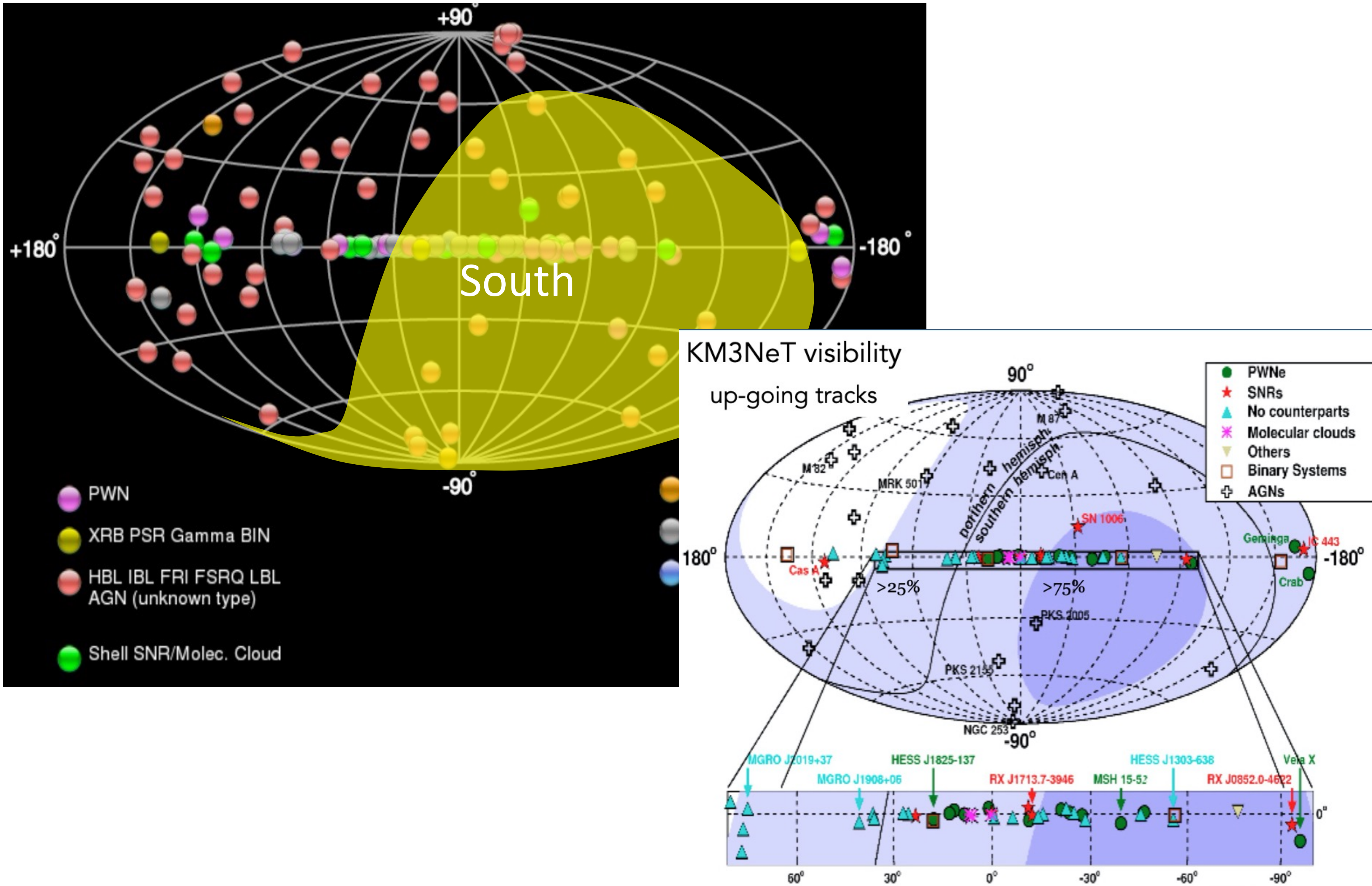
- mainly ν_μ and upgoing events

Method 2) Measure an excess of high-energy events with respect to the background (**diffuse**).

- All flavors. Tracks, showers and partially contained events.

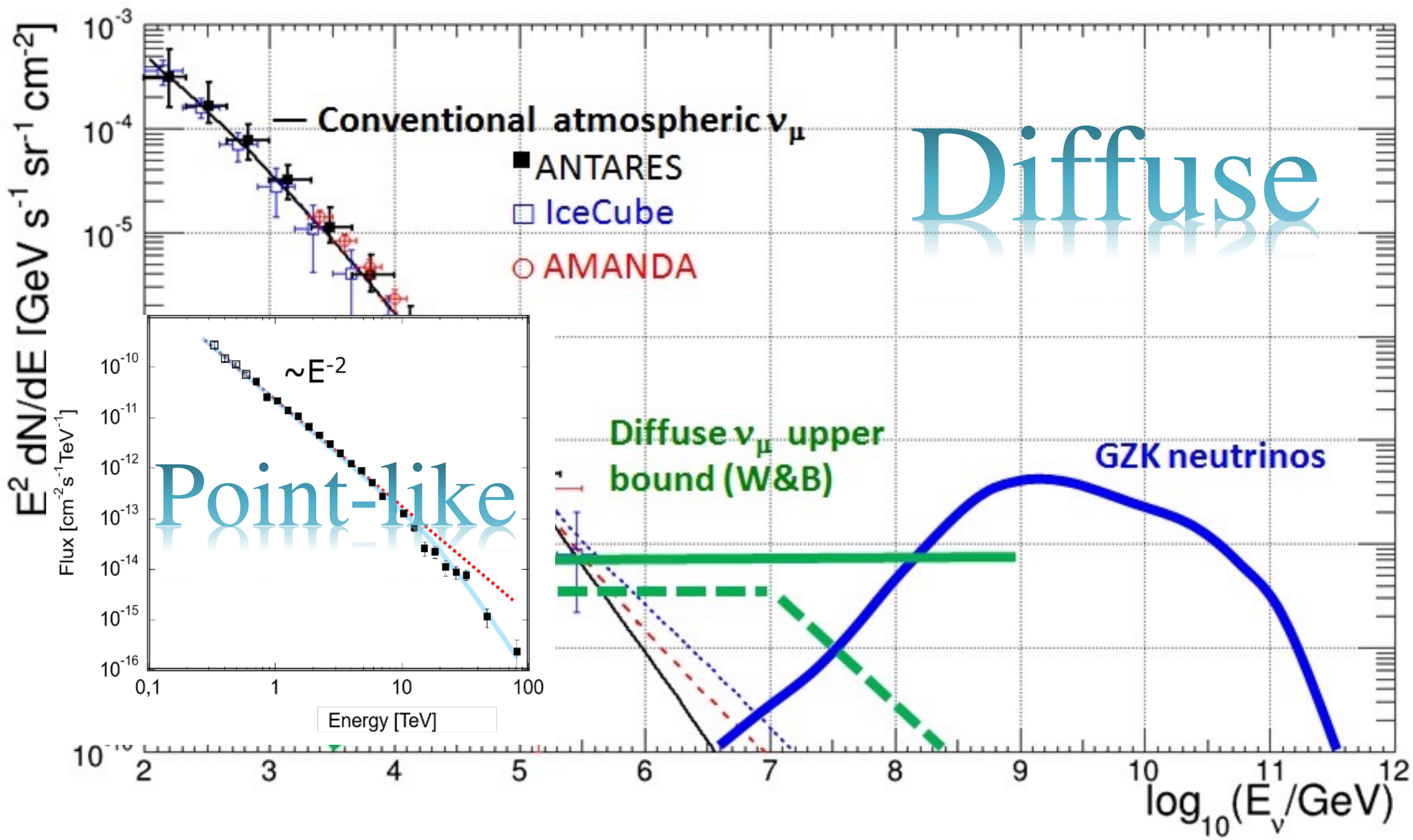
Point Sources: catalog of TeV γ-rays

http://tevcat.uchicago.edu/



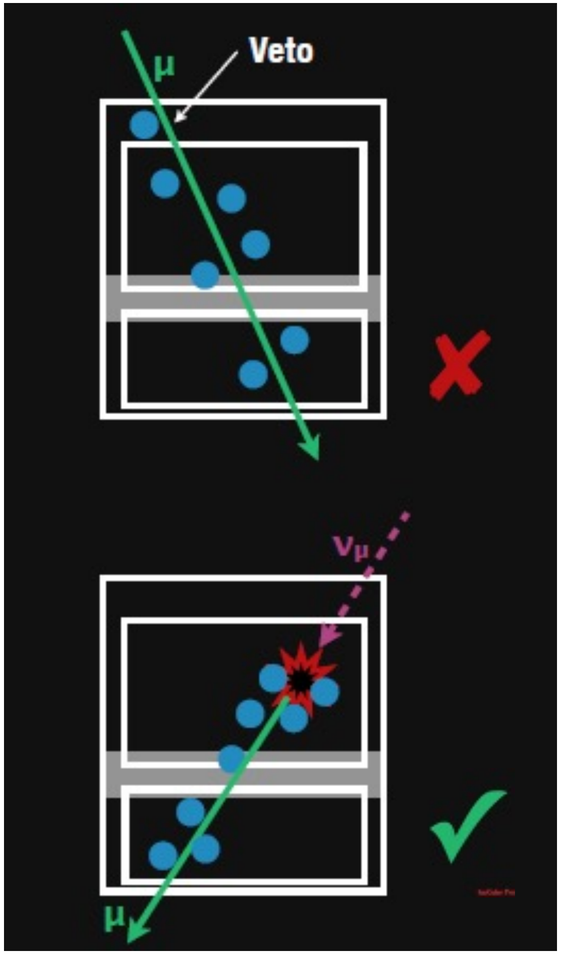
13. The energy range optimization

- Astrophysics neutrinos: from 10^2 to 10^{12} GeV (10 orders of magnitude)
- Detectors optimized to cover a given energy range (as wide as possible)
- Grid size (distance between OMs)

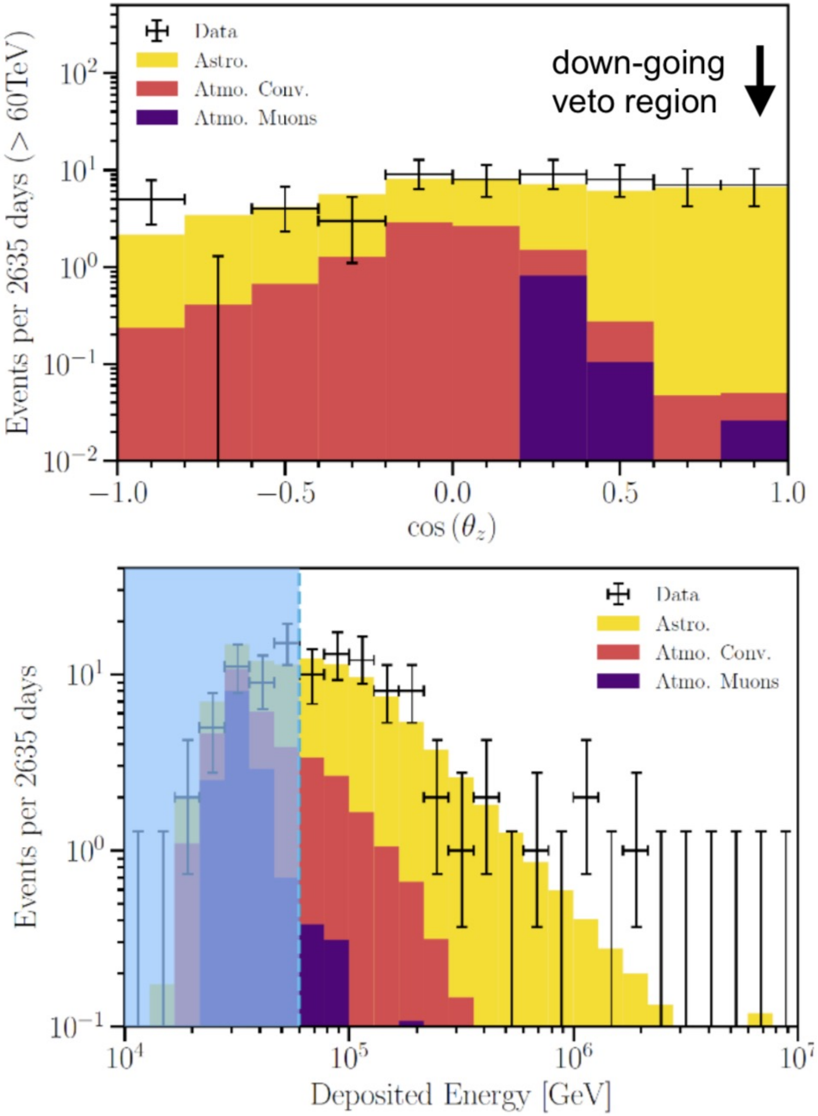


Excess of HE starting events (HESE)

- High Energy Starting Events (HESE) in IceCube
- Events selected in a restricted fiducial volume (SK-like)
- Mostly showers with poor angular determination (>10°)



Excess of HE starting events (HESE)

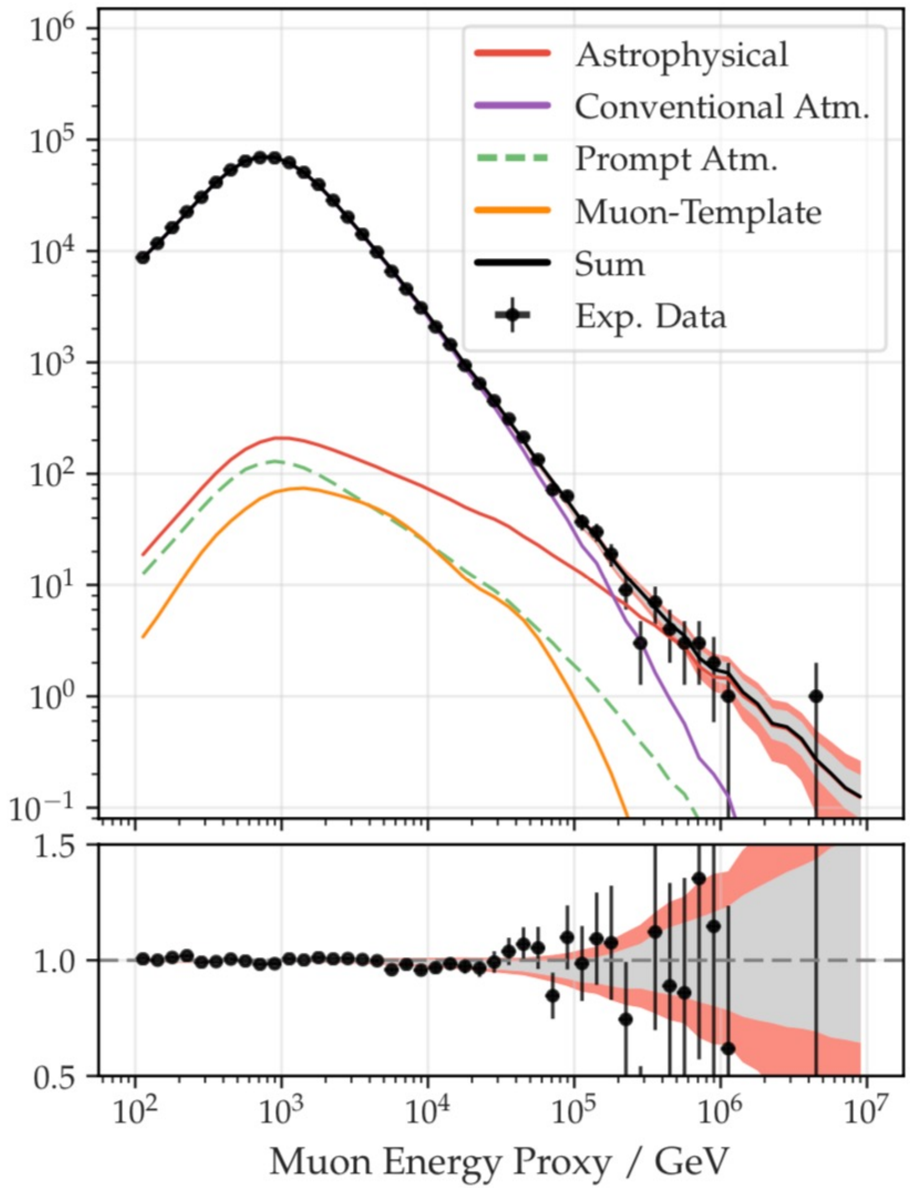


PRD (2021), https://arxiv.org/abs/2011.03545 7

7.5 years of data

Astrophysical neutrino spectrum is compatible with an unbroken power law, with a preferred spectral index of 2.87+0.20–0.19 for the 68.3 % confidence interval.

Diffuse measurement with through-going northern tracks



- 5.6 σ rejection of background-only hypothesis (in addition to >5 σ from 7.5 yrs HESE)
- Astrophysical neutrinos measured with two interaction and detection methods: tracks and cascades
- Measured between 15 TeV and 5 PeV
- Spectral index: 2.37 ± 0.09

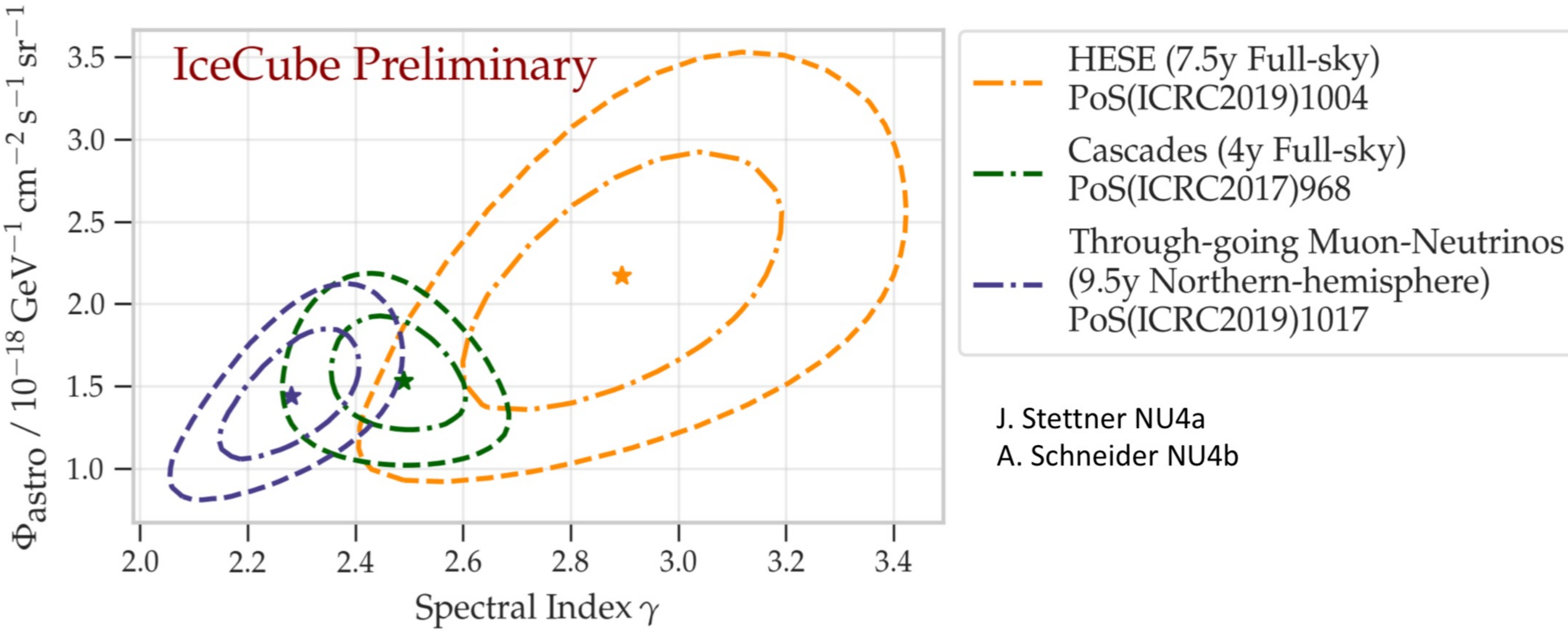
9.5 years of experimental data

https://arxiv.org/abs/2111.10299

The IceCube spectral anomaly

- A ~3σ discrepancy between sample using the same $\Phi_\nu = \Phi_o E^{-\Gamma}$
- Harder spectrum (Γ~ 2.3) in the Northern Hemisphere
- Softer spectrum in the Southern (Γ~ 2.5-2.9)

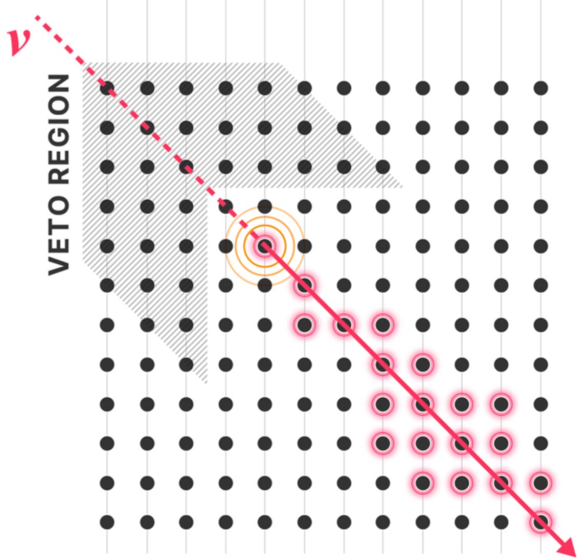
Single power law astrophysical neutrino spectrum



J. Stettner NU4a
A. Schneider NU4b

The IceCube spectral anomaly

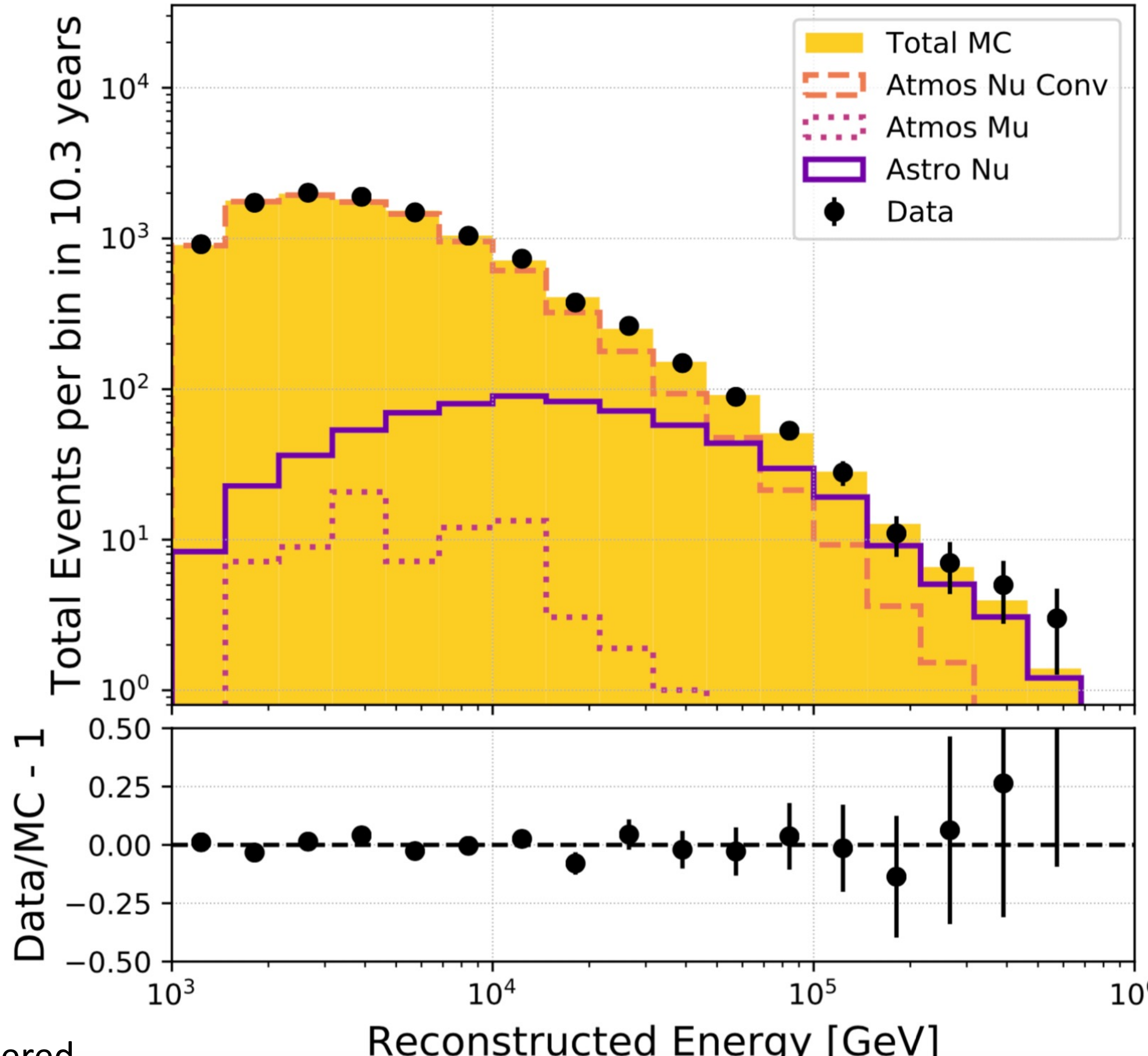
Enhanced Starting Tracks



Selection of 10.3 years

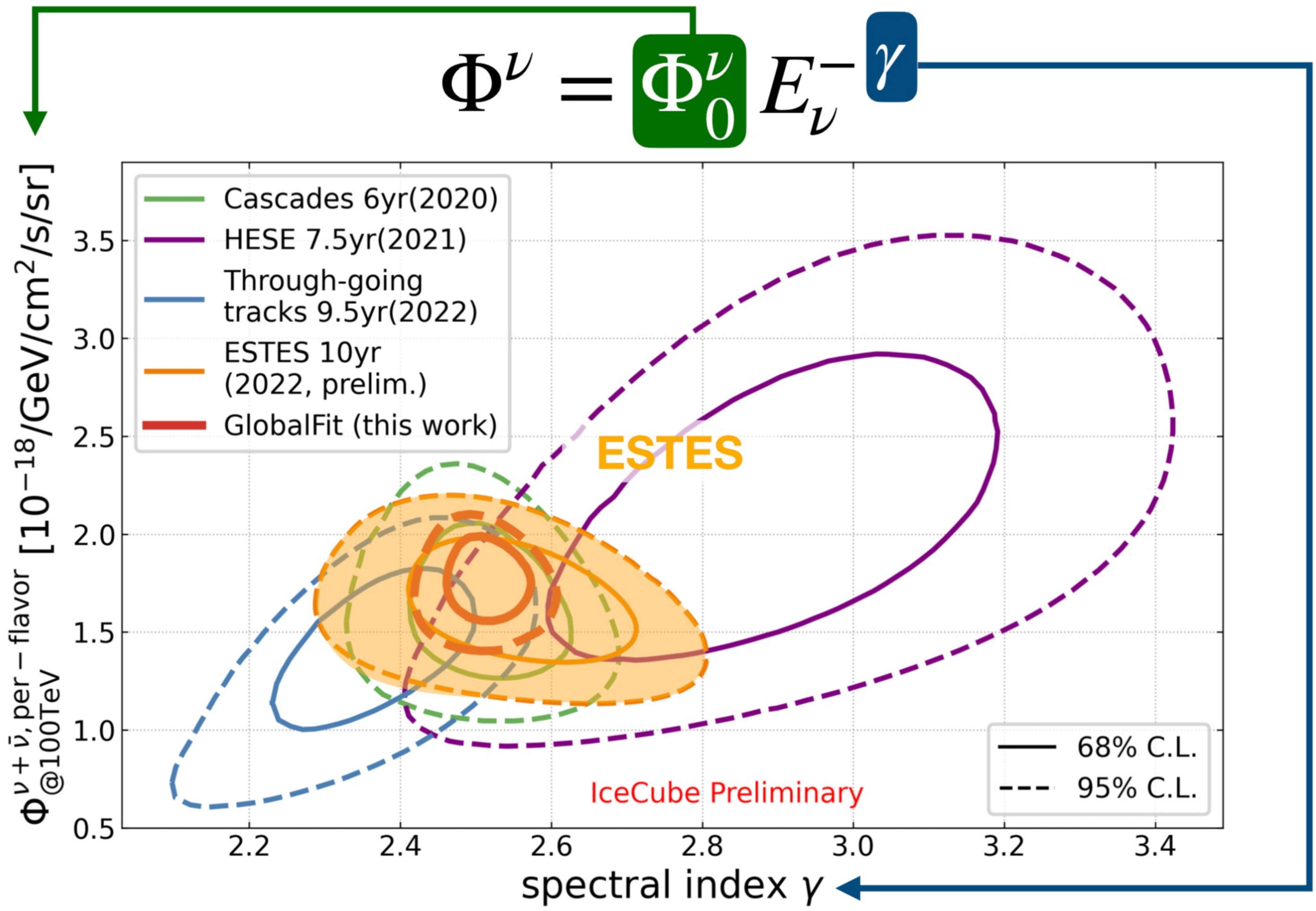
Energy range: 3 - 550 TeV

Spectrum: $E^{-2.58}$



Dynamic veto region allows atmospheric muons and neutrinos to be efficiently filtered

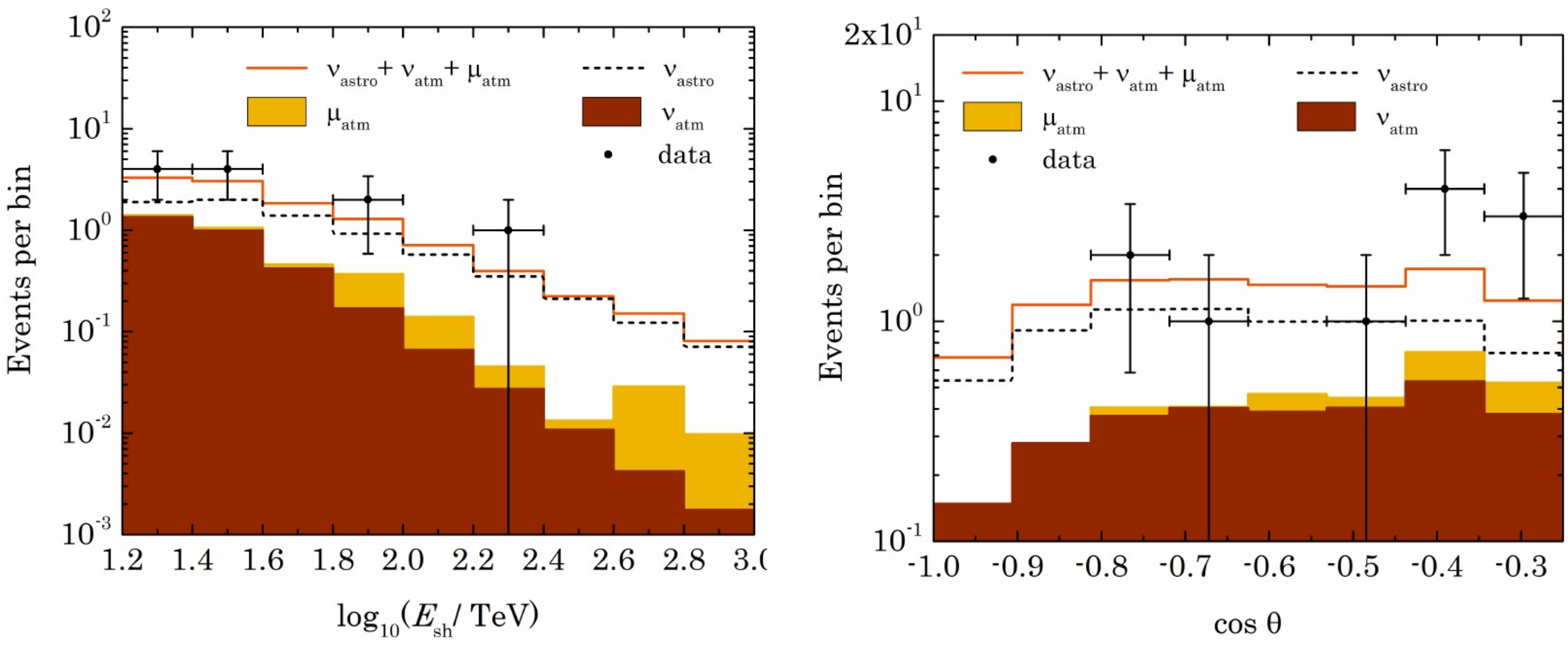
The IceCube spectral anomaly



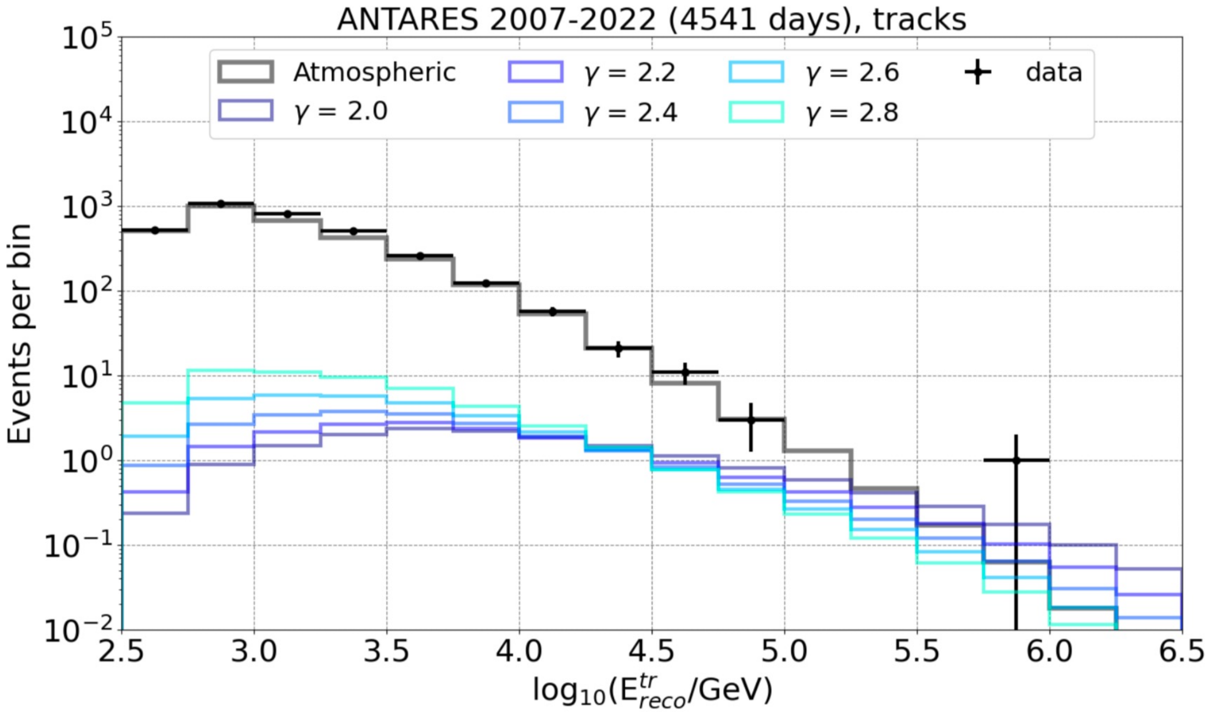
The IceCube spectral anomaly

Baikal GVD

Significance of diffuse flux in upward-going events: 3.05σ

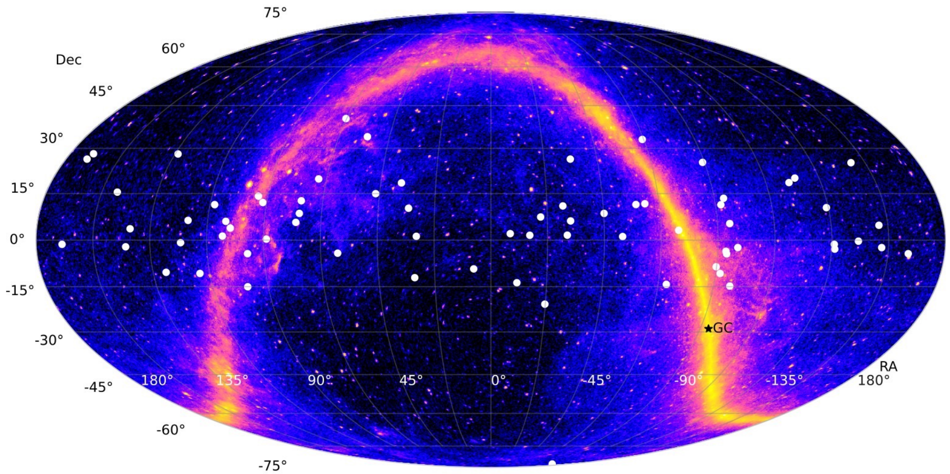


The IceCube spectral anomaly

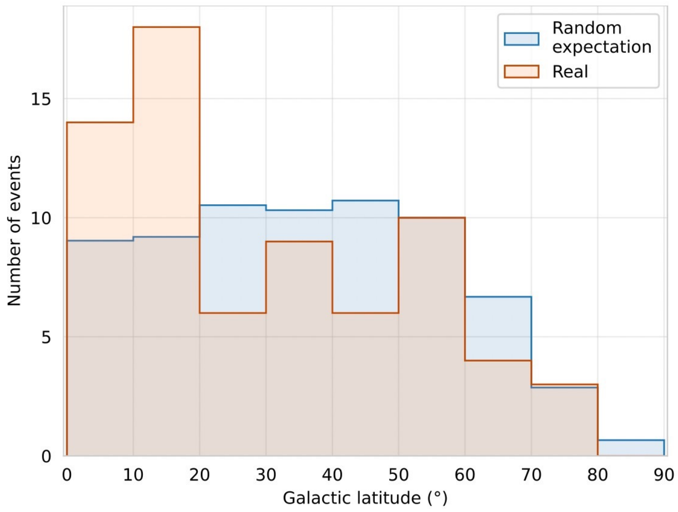


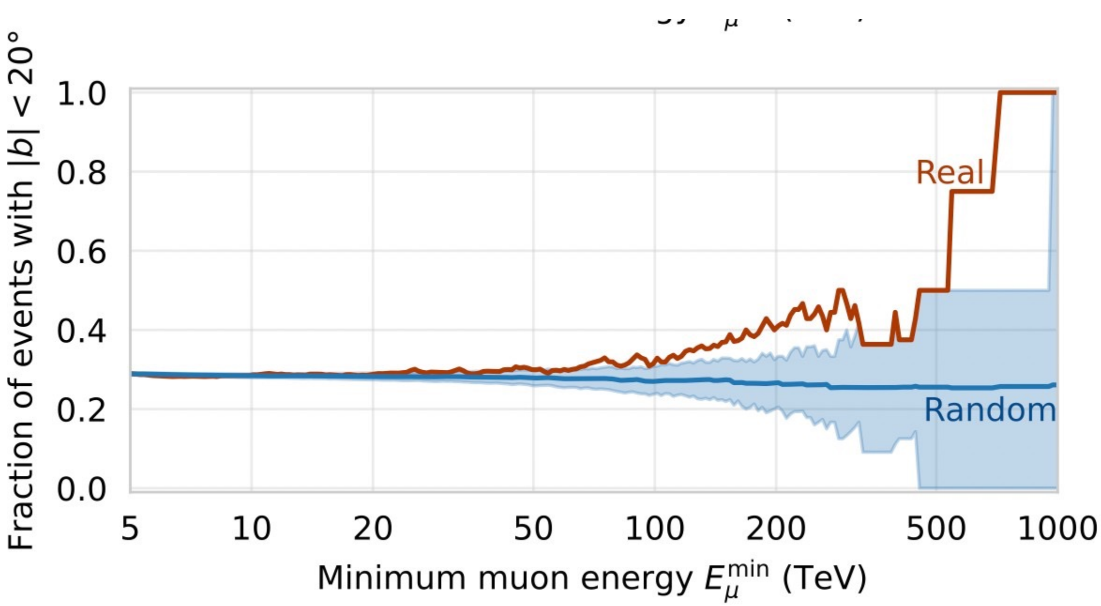
In ANTARES no statistically significant observation of the cosmic diffuse flux.

Where is the galactic diffuse component ?

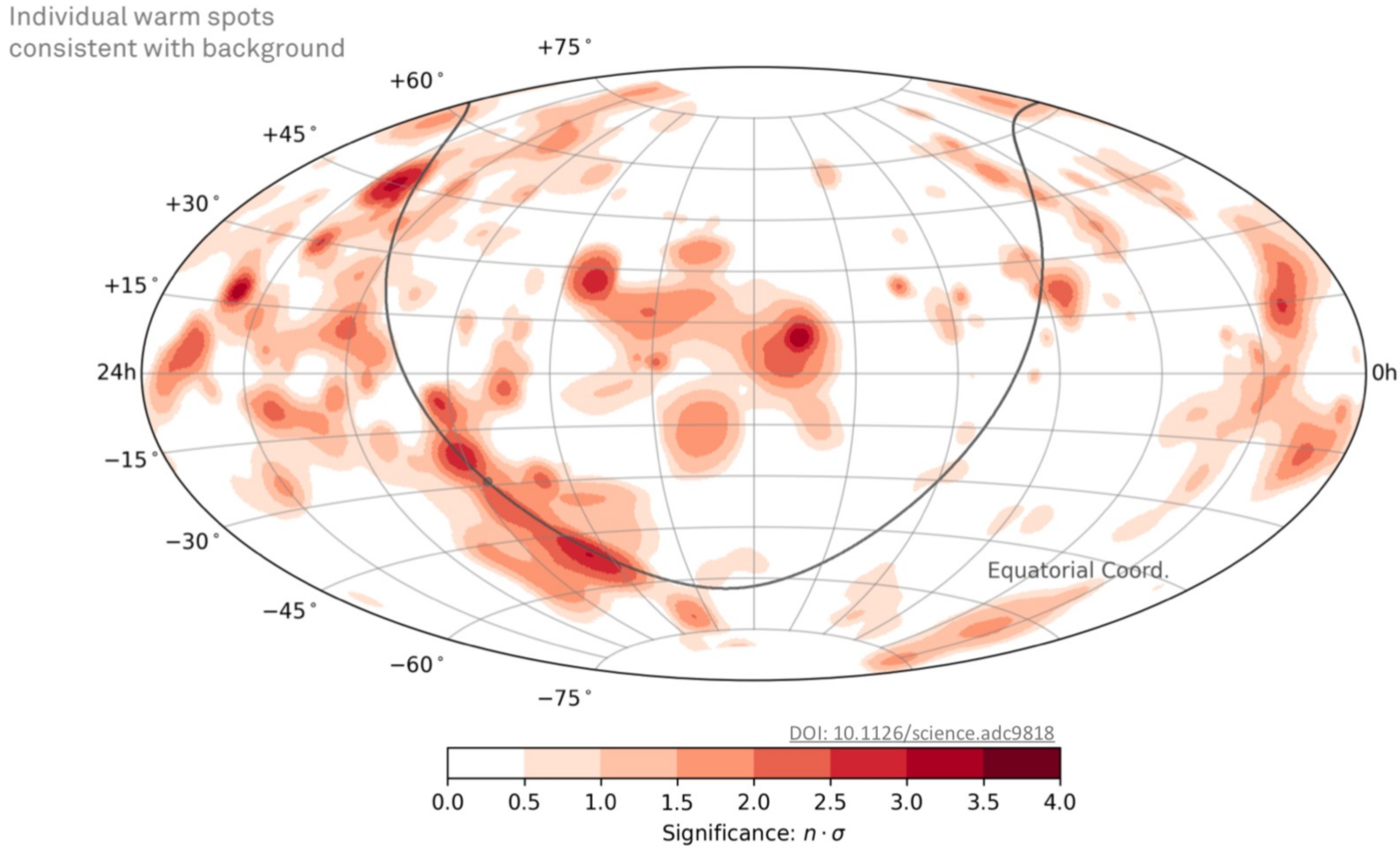


Very interesting correlation between the Galactic plane and IceCube public events above 200 TeV (4.1 **σ**) and the normalisation of the flux consistent with the prediction of the gamma-ray flux detected by Tibet above 100 TeV





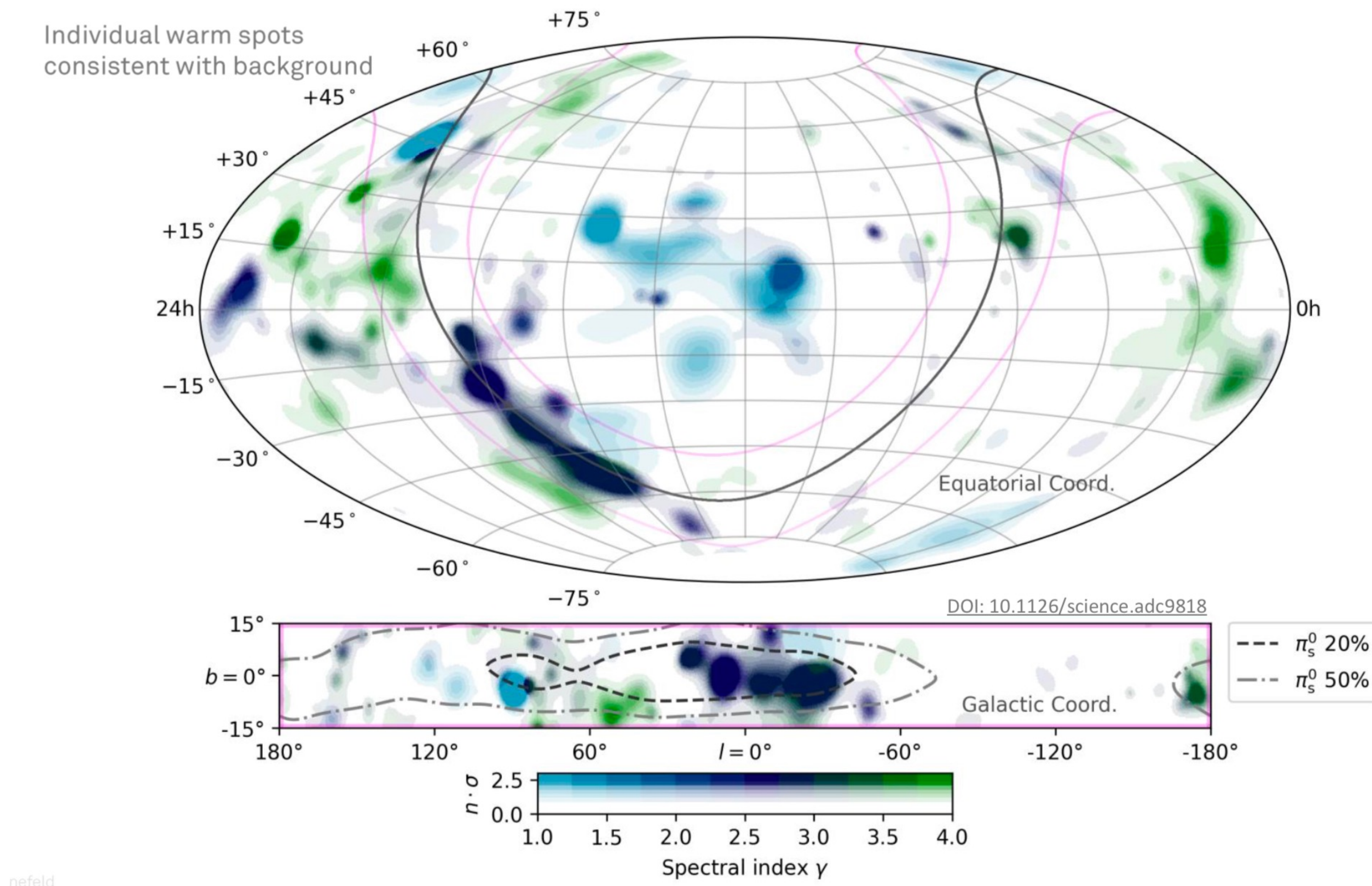
The galactic diffuse component



DOI: 10.1126/science.adc9818

the flux is ~ 10% of the extragalactic flux at 30 TeV

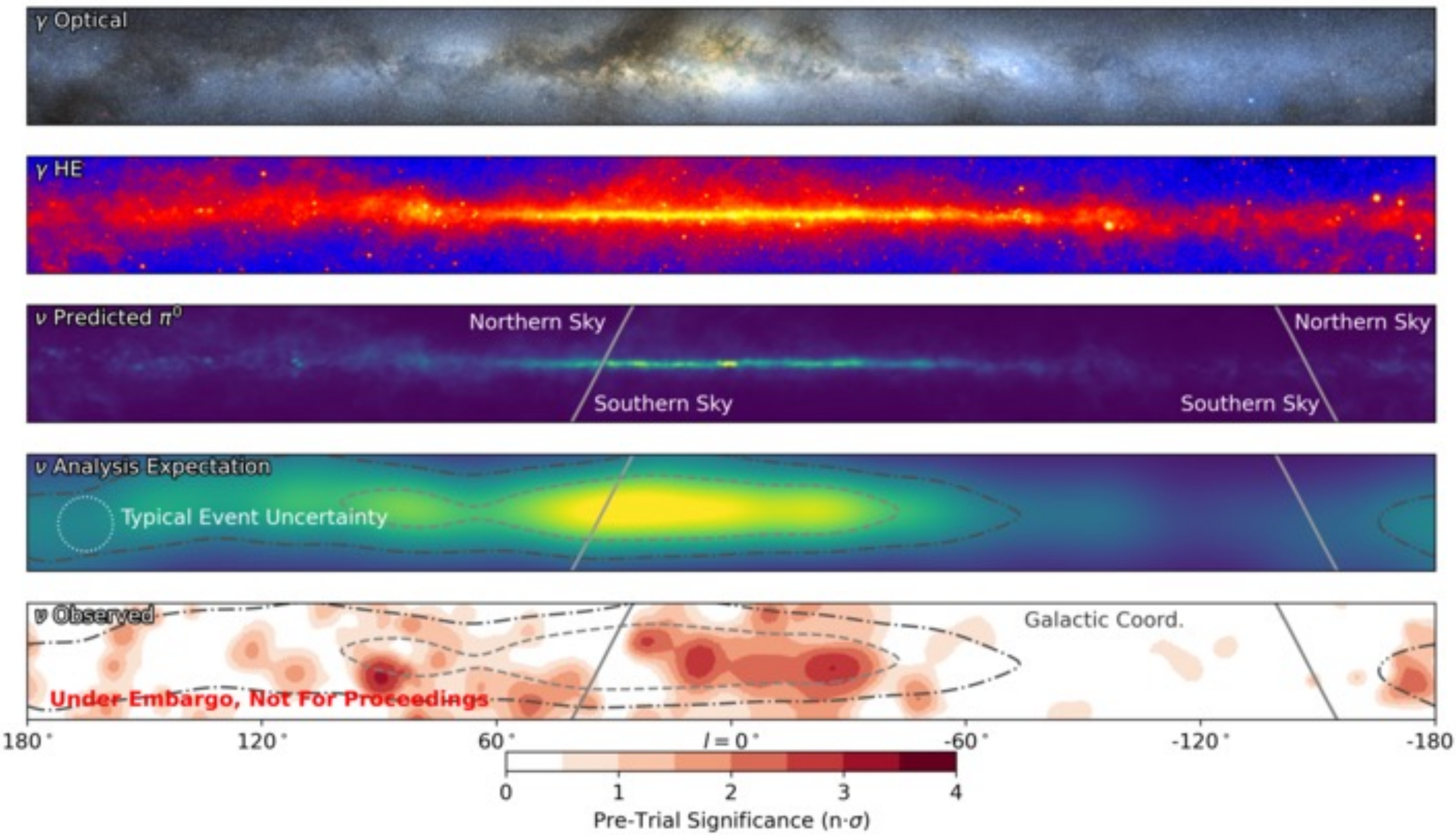
The galactic diffuse component



DOI: 10.1126/science.adc9818

Other hot spots consistent with background

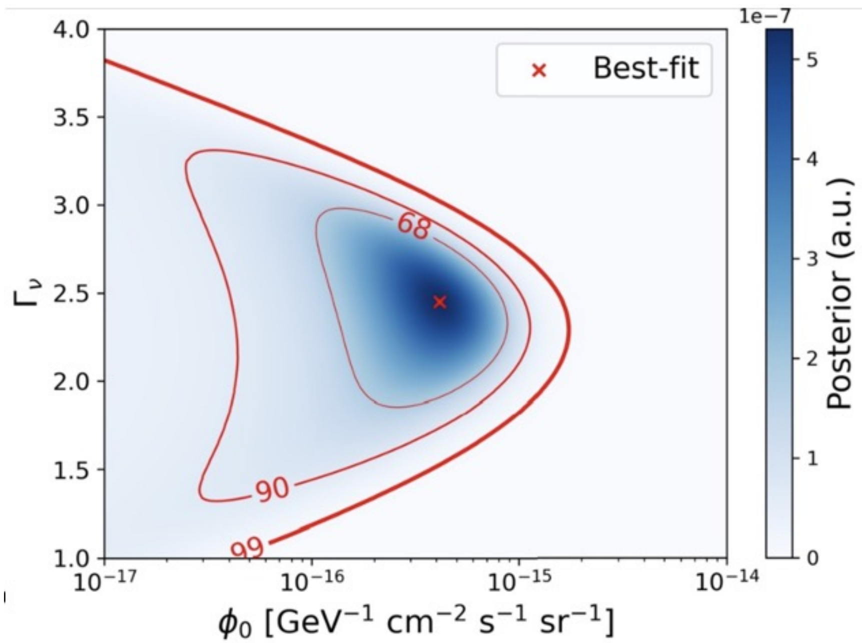
The galactic plane

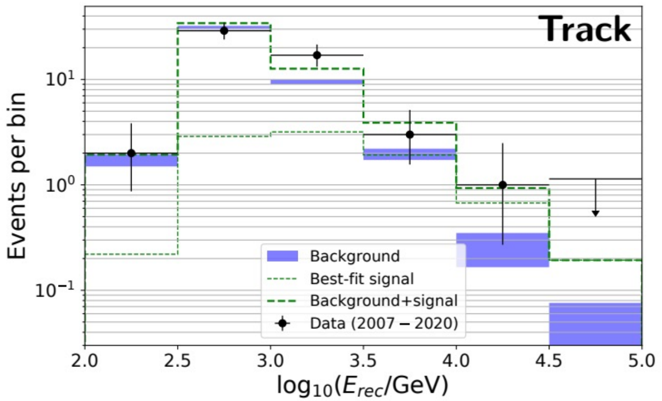


4.5σ significance

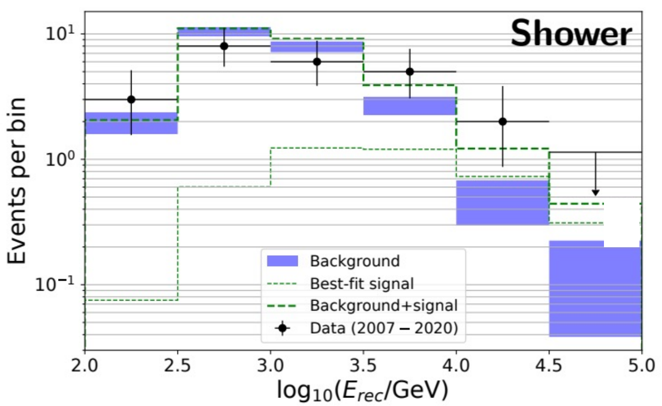
Galactic plane with ANTARES

- ANTARES 2007-2020 data → 2σ excess in tracks and showers → hint for Galactic signal





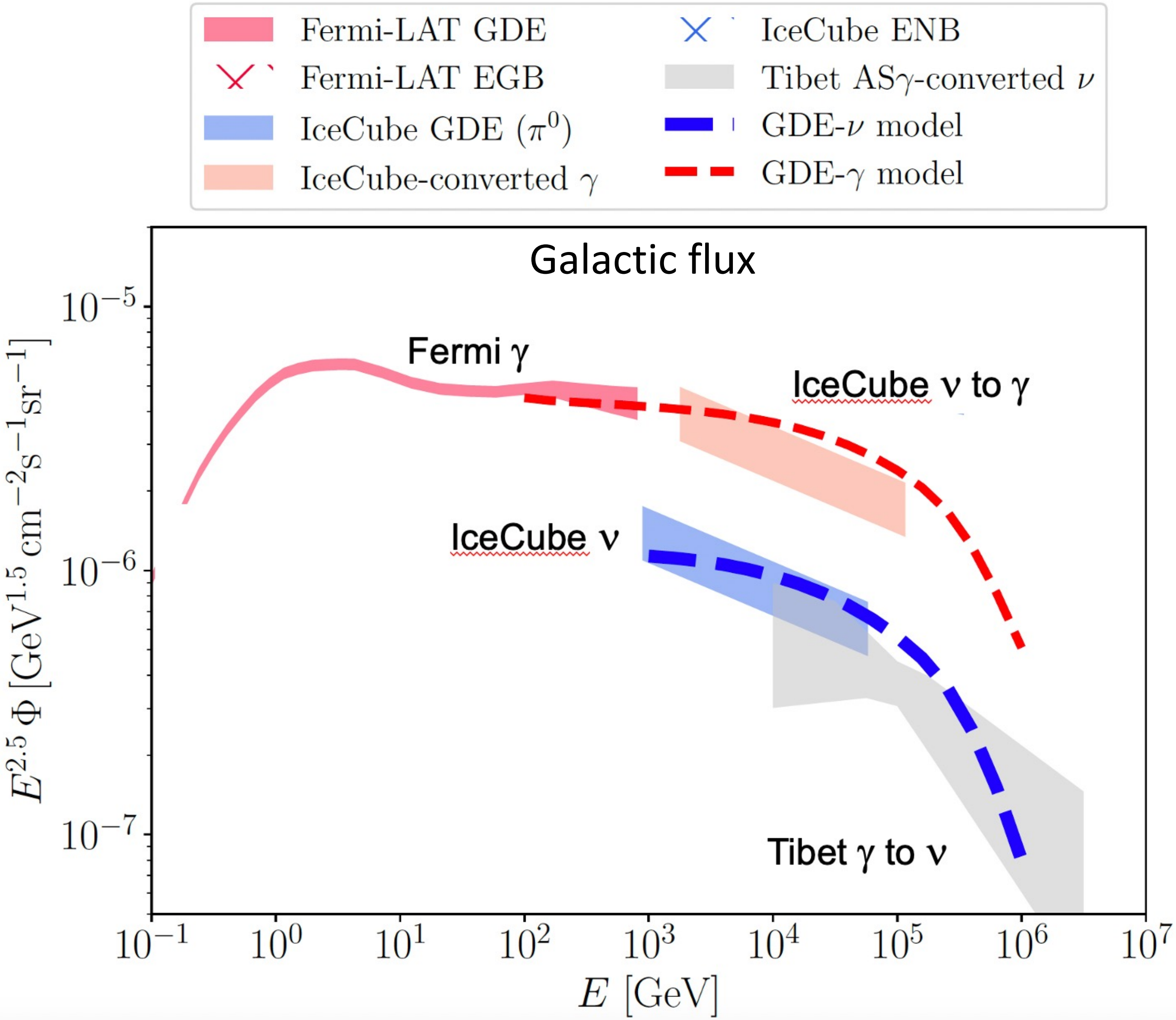
(a) Track-like events



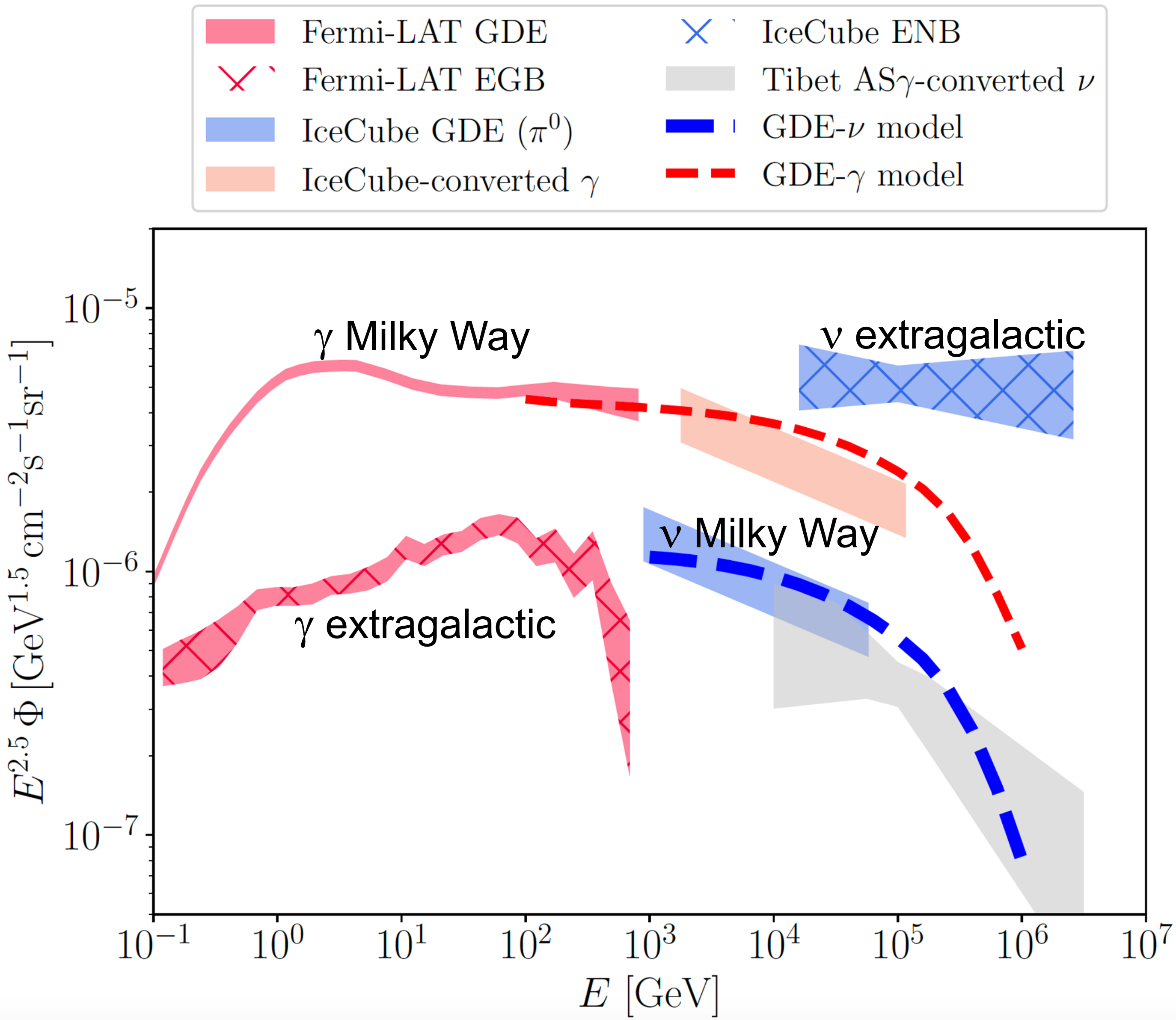
(b) Showering-like events

For Ev>1 TeV
21 track events observed -> 11.7±0.6 back. expected
13 shower events observed -> 11.2±0.9 back. expected

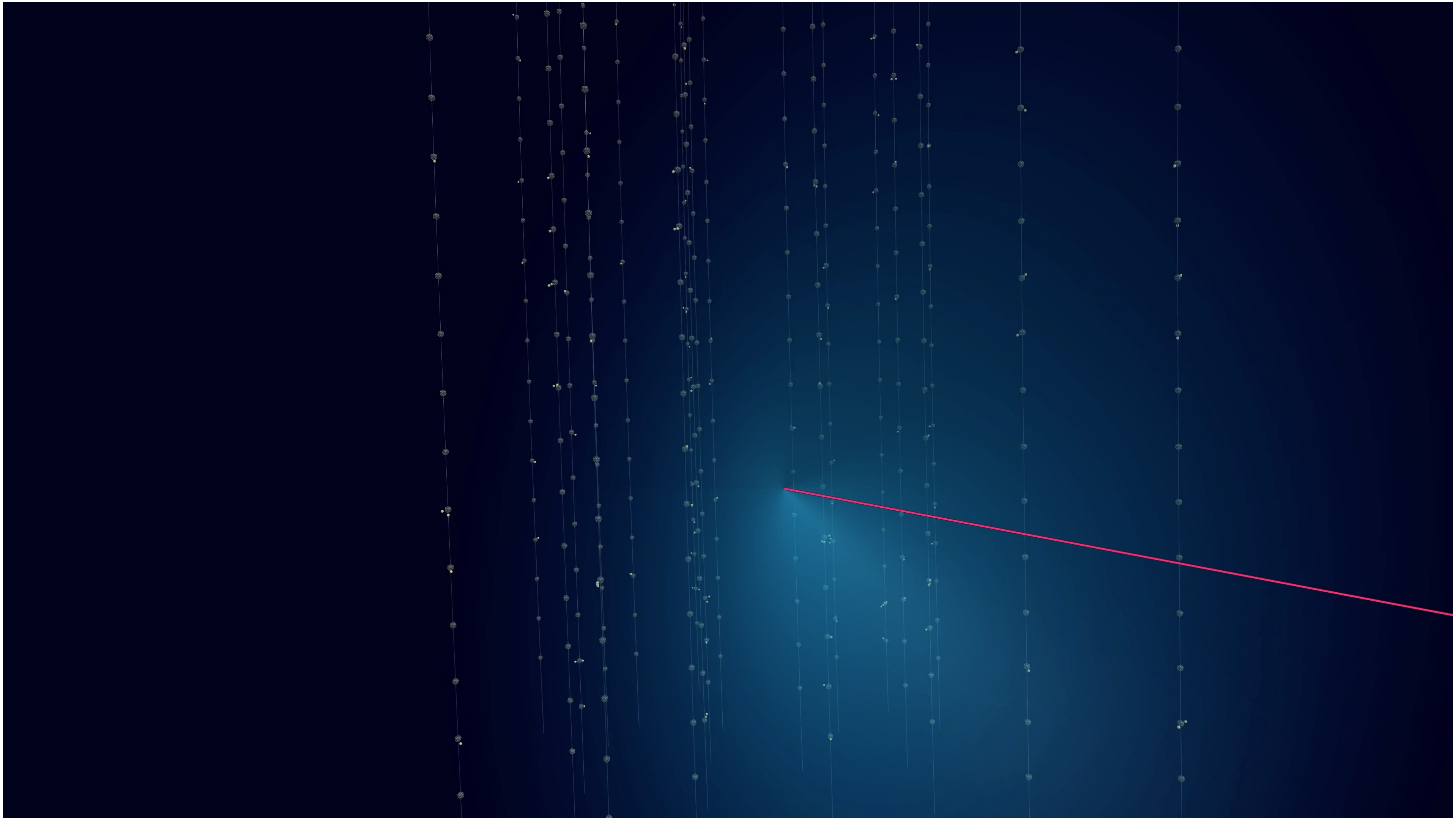
Comparison with gamma galactic plane



Comparison with gamma galactic plane

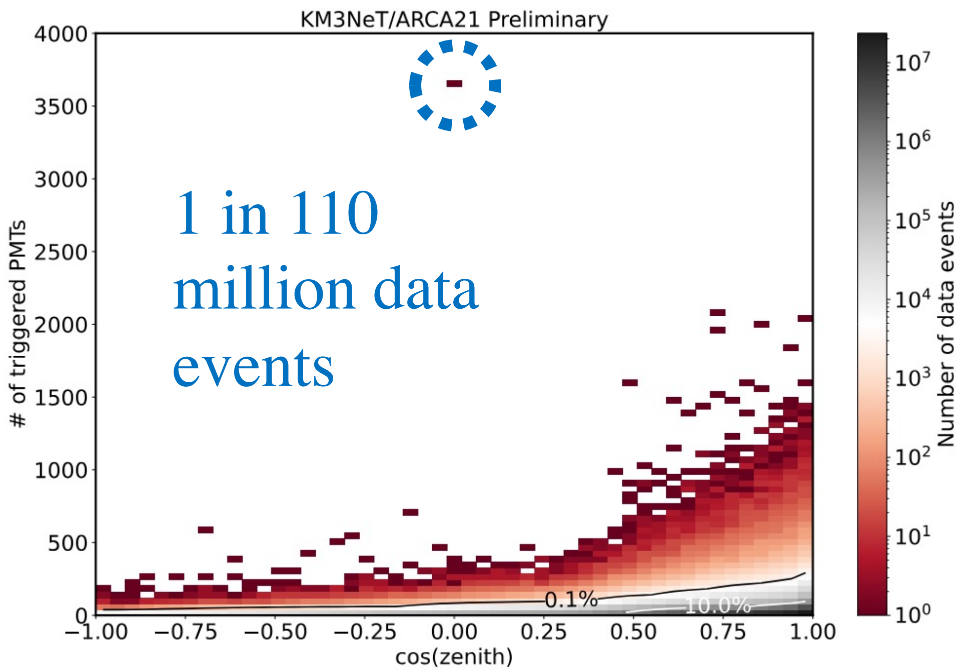


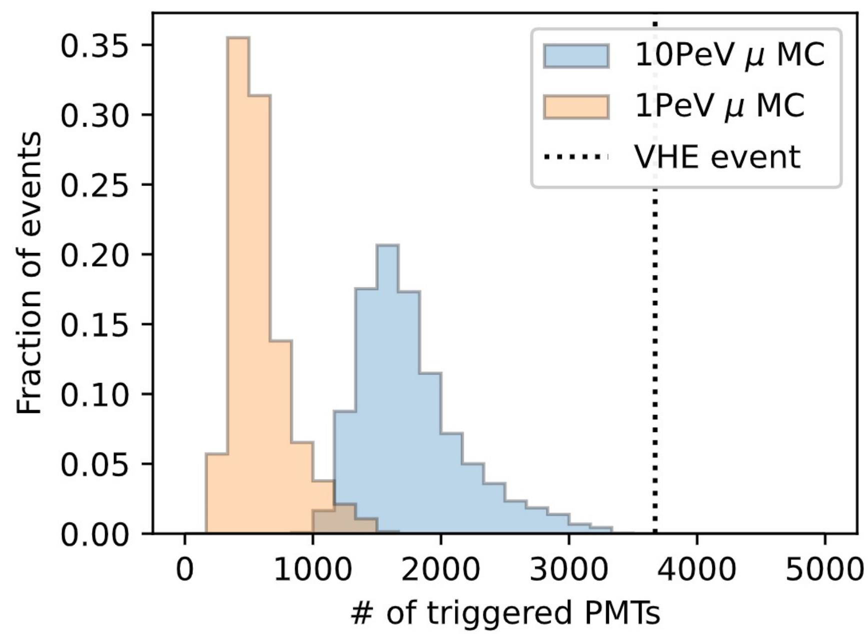
The KM3NeT high energy event



The KM3NeT high energy event

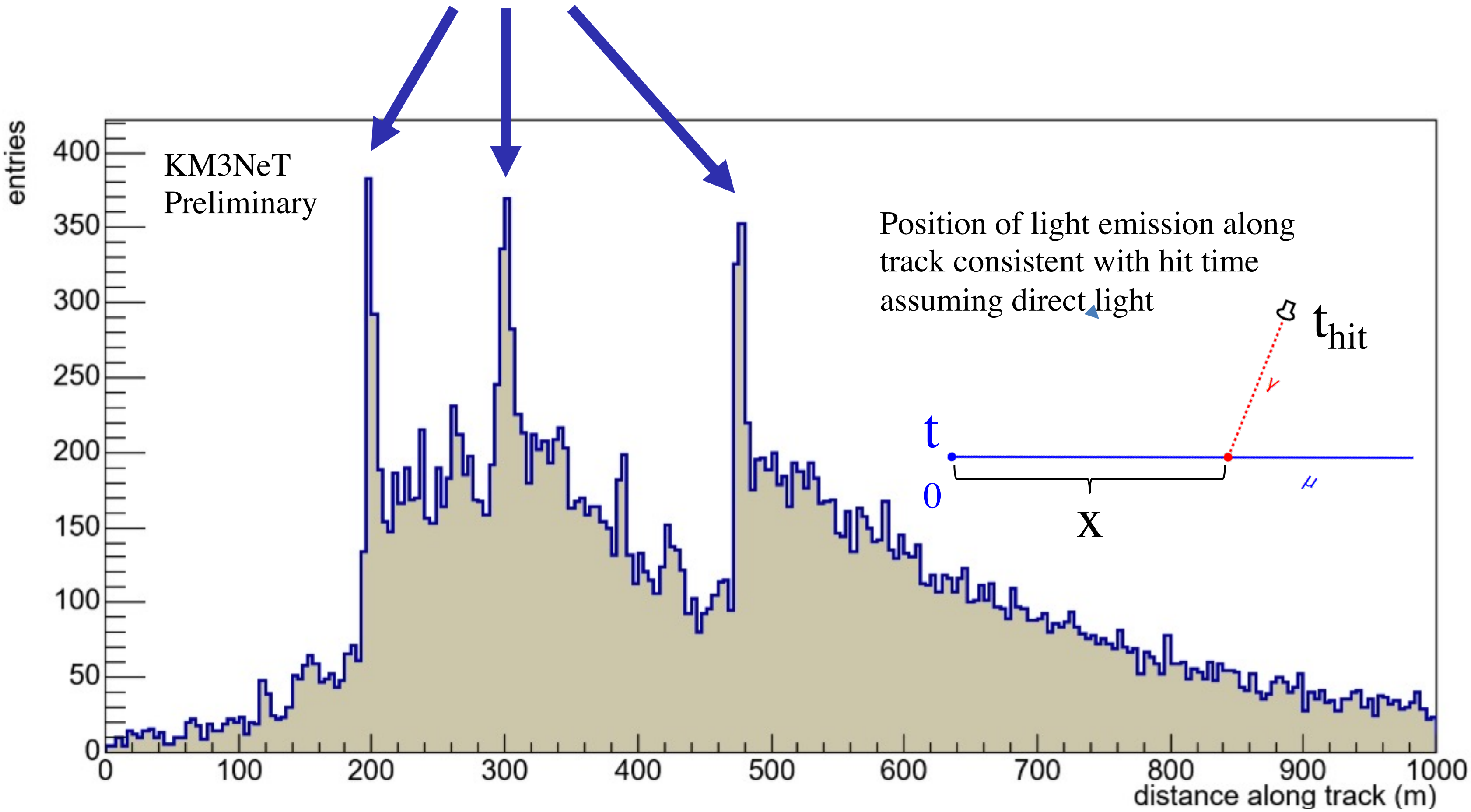
- Significant event observed with huge amount of light
- Horizontal event (1° above horizon) as expected since earth opaque to neutrinos at PeV scale
- 3672 PMTs (35%) were triggered in the detector
- Muons simulated at 10 PeV almost never generate this much light





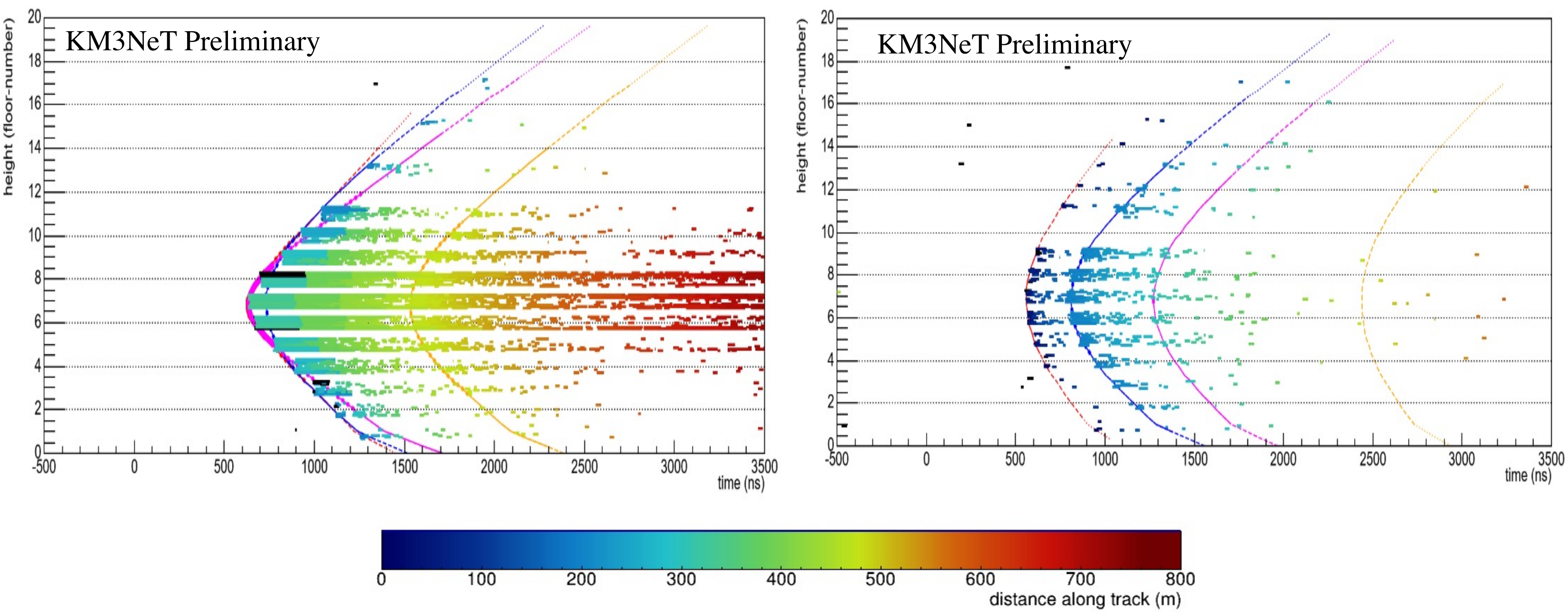
The KM3NeT high energy event

- Light profile consistent with at least 3 large energy depositions along the muon track
- Characteristic of stochastic losses from very high energy muons

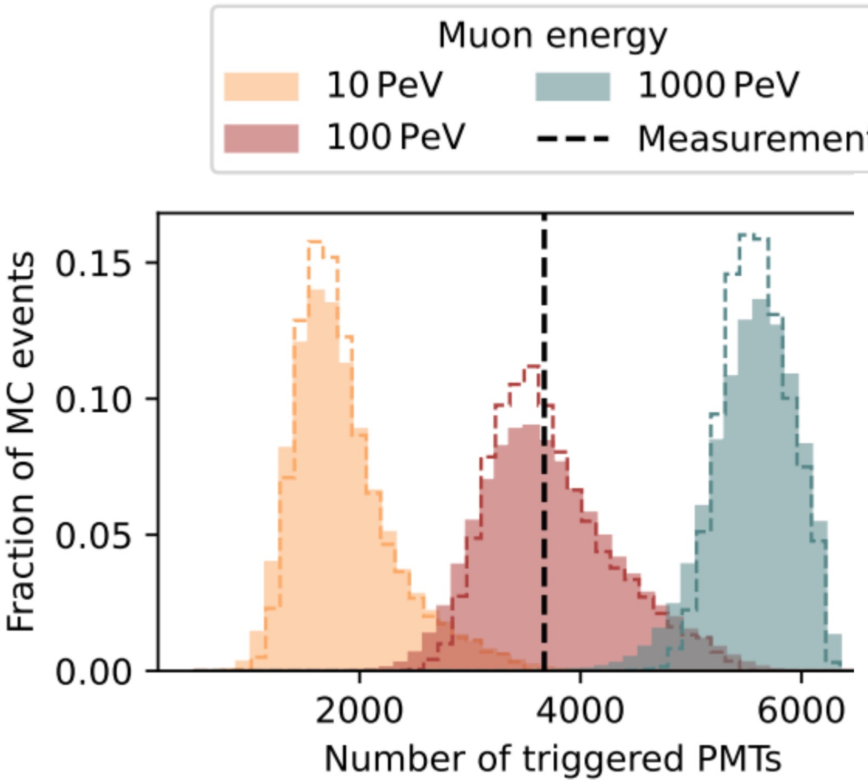


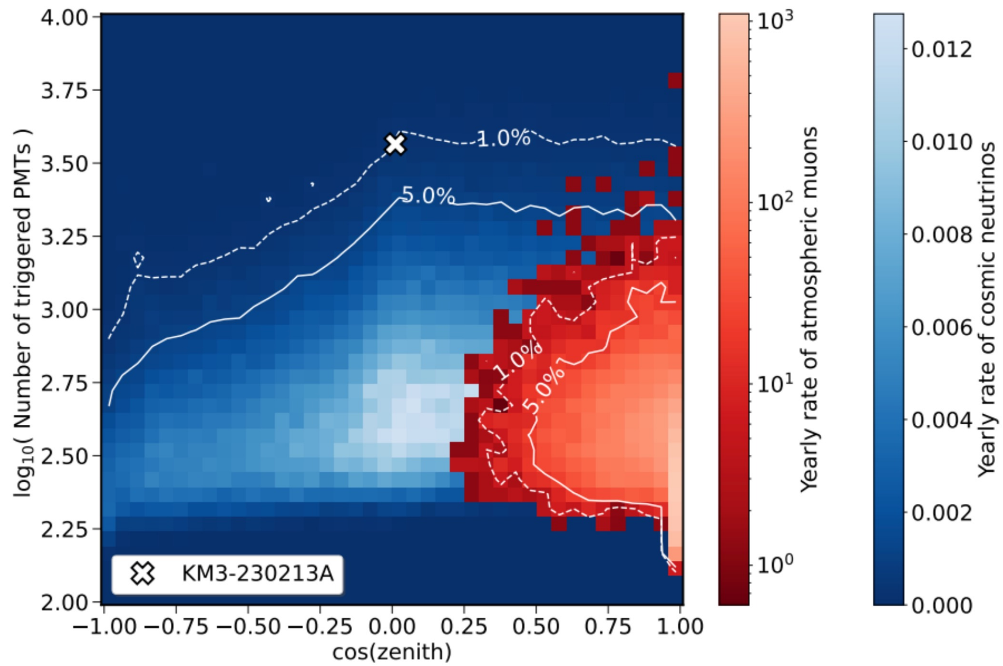
The KM3NeT high energy event

- Light profile consistent with at least 3 large energy depositions along the muon track
- Characteristic of stochastic losses from very high energy muons
- Space-time distribution of light consistent with shower hypothesis associated with these energy depositions
- Low scattering is key to observing this richness of detail



The KM3NeT high energy event





Estimated energy: 120^{+110}_{-60} PeV

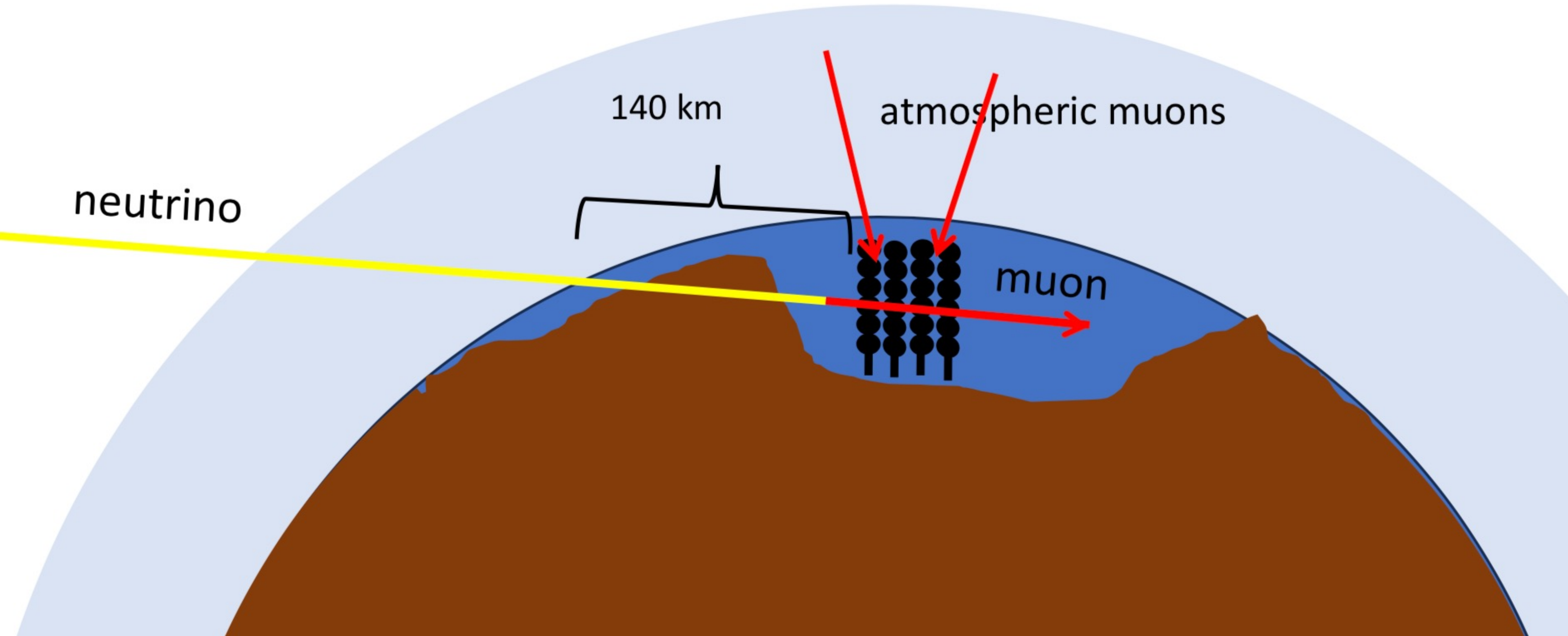
An isotropic flux of neutrinos in this energy range would give rise to events detected near the horizon.

For downgoing neutrinos, the acceptance is limited due to the reduced column density available for the neutrino interaction, while the upgoing neutrino flux is severely suppressed as the neutrinos would interact in the Earth. The direction of the observed event thus matches this scenario.

The KM3NeT high energy event

- Could this event be a muon?

A muon can not cross 140 km of Earth's crust

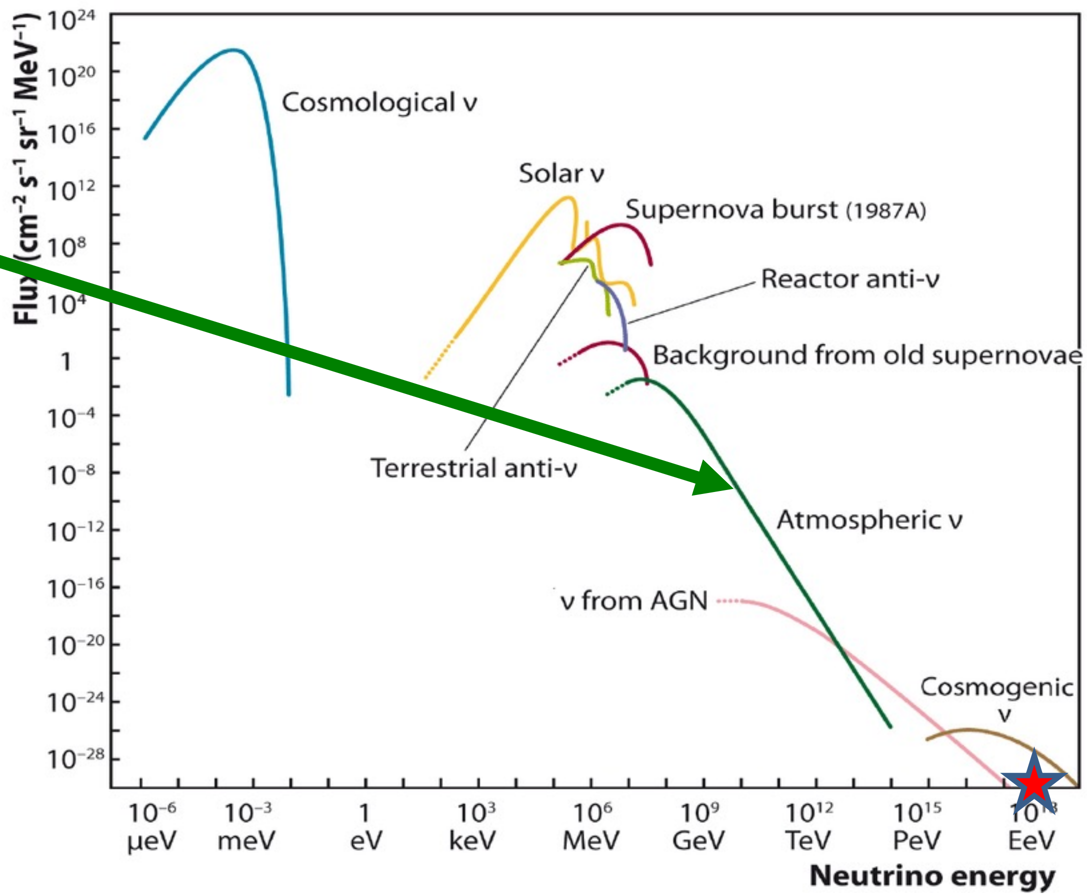


The KM3NeT high energy event

- Could this event be an atmospheric neutrino?

The numer of expected neutrinos at energies above 100 PeV is 1-5 events in 100000 years

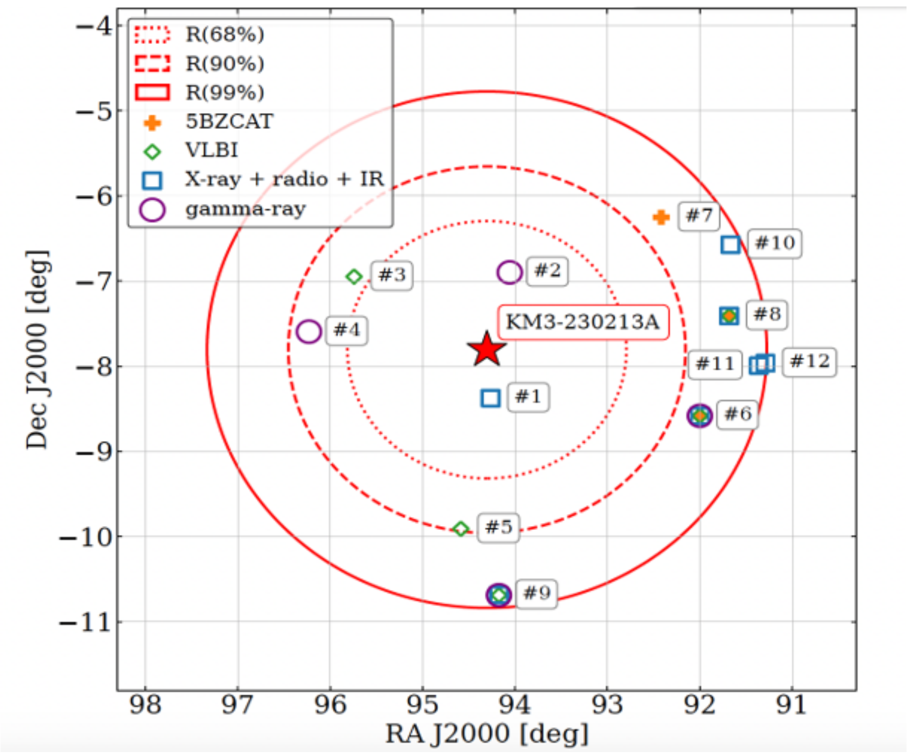
Cosmic origin is much more likely



The KM3NeT high energy event

No significative association with:

- Galactic sources
- gamma ray bursts/supernovae
- tidal disruption events
- blazars



The KM3NeT high energy event

Search for signal excess at the coordinate of the exceptional event in ANTARES, KM3NeT-ORCA e IceCube data.

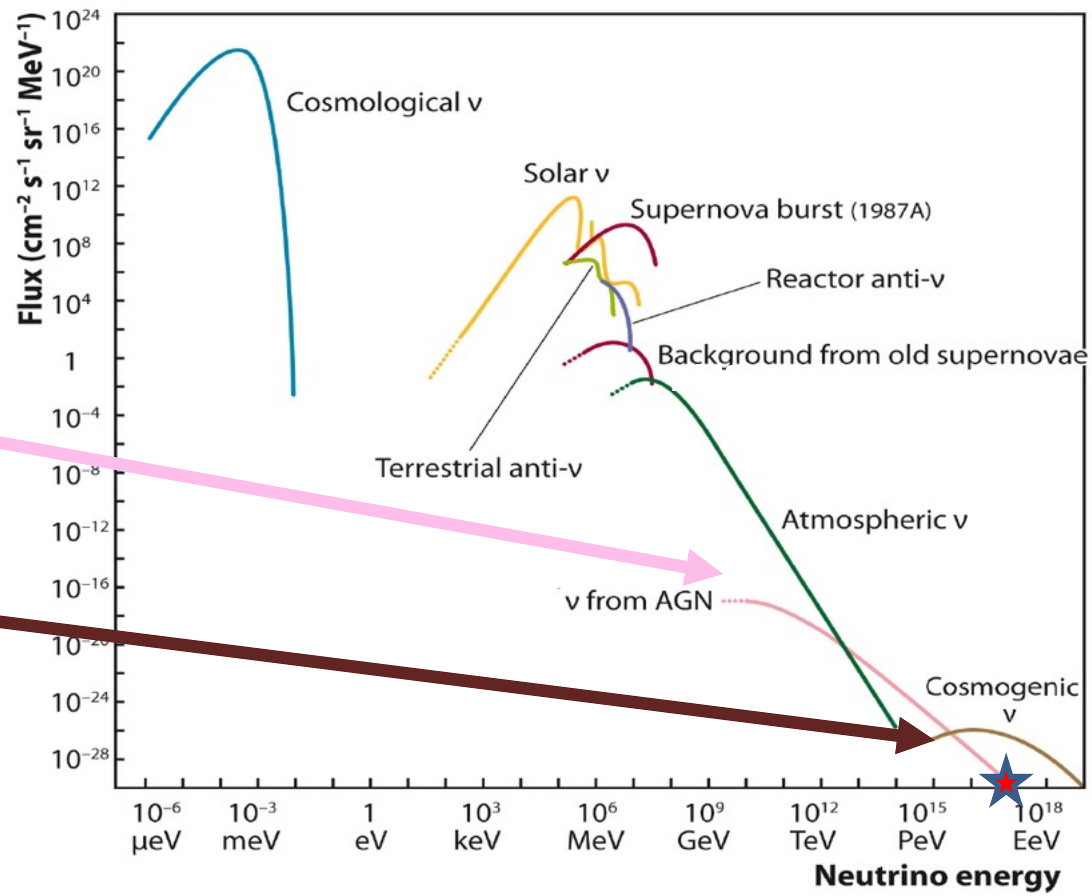
Only 1 events has been found in the IceCube sample at 2.4 deg from the exceptional event, coincidence signifcance too low to claim correlation.

The KM3NeT high energy event

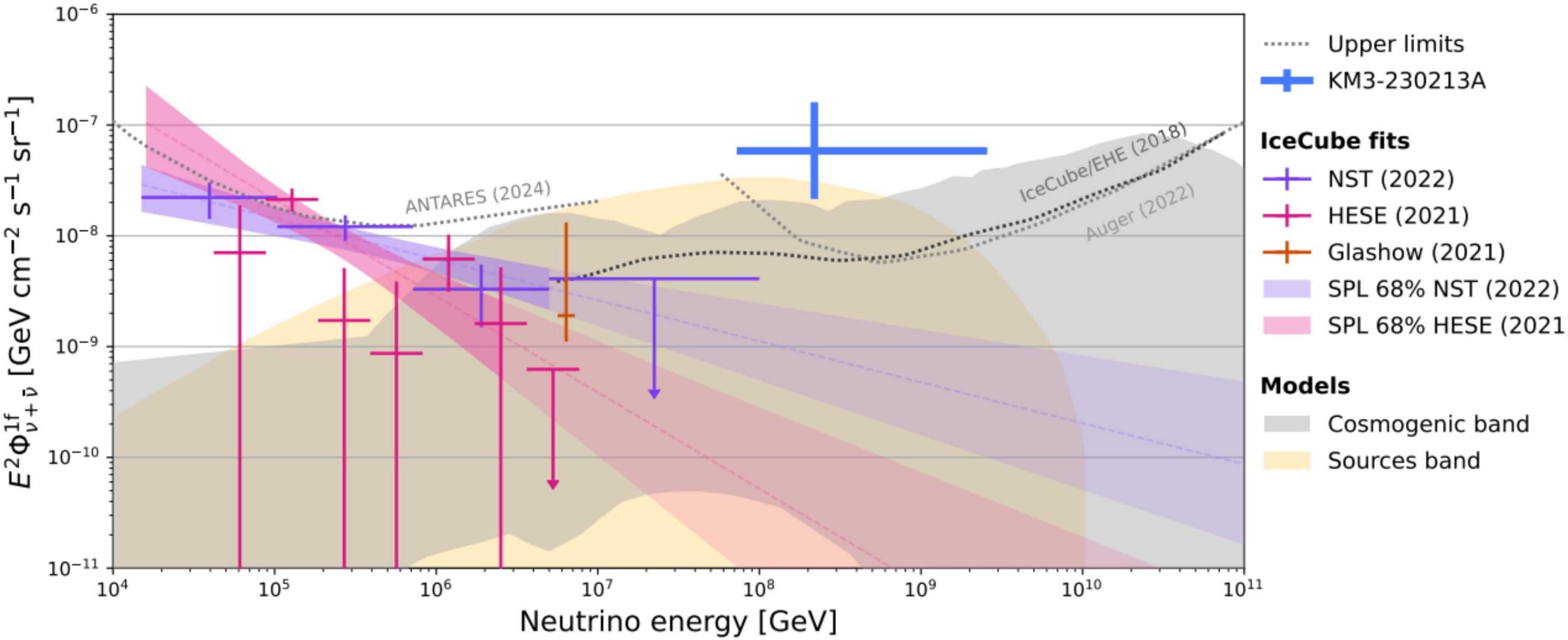
Cosmogenic neutrino= neutrino produced by the interaction of cosmic rays with CMB or background extragalactic light

0,12 neutrino expected from cosmic neutrino in the KM3NeT sample

Cosmogenic neutrino is an intriguing alternative hypothesis



The KM3NeT high energy event

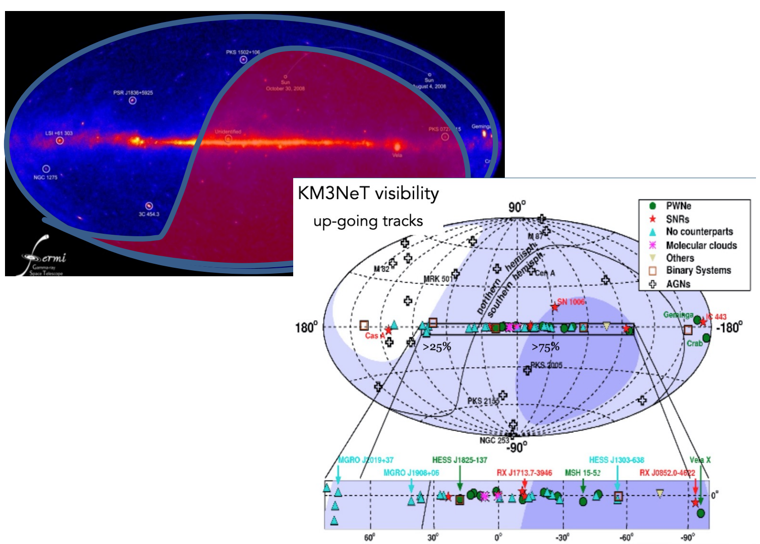


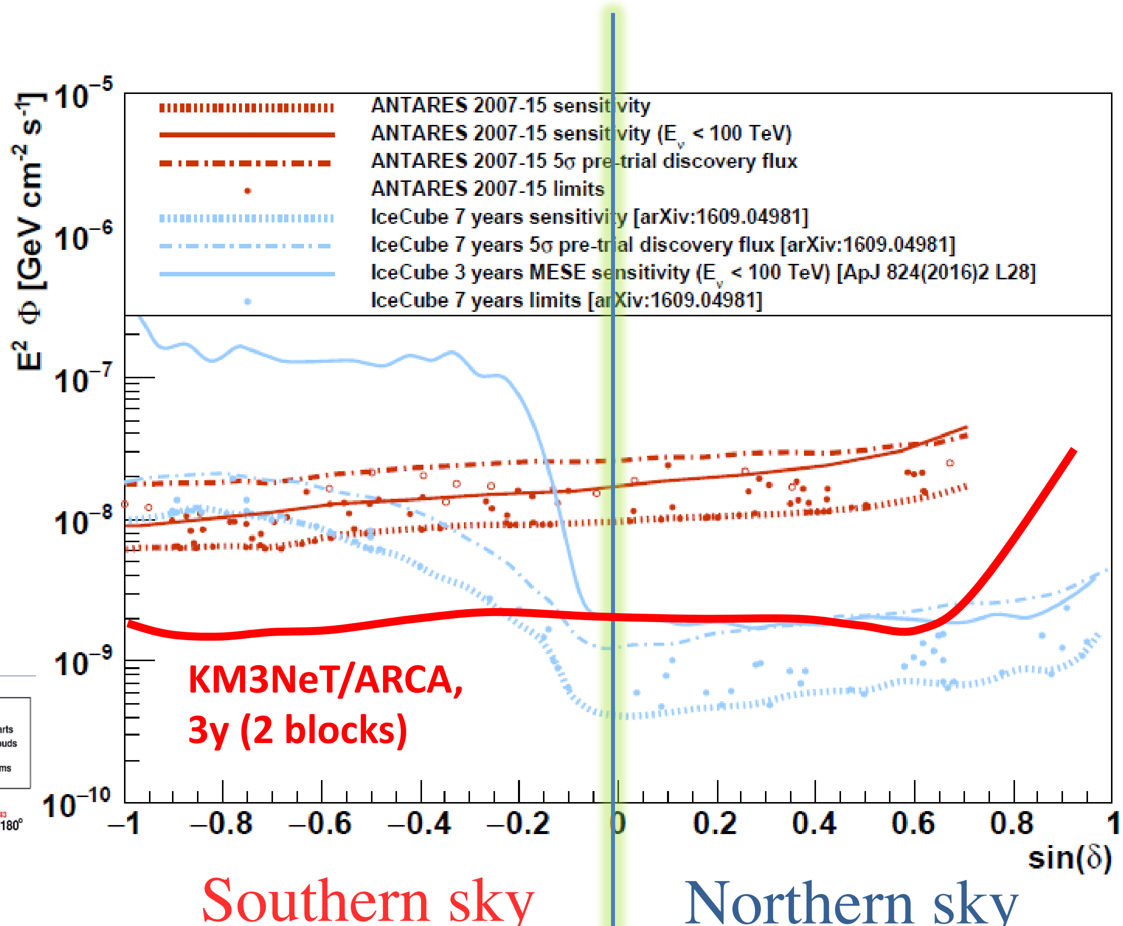
First detection of a cosmogenic neutrino?

Search for ν point-sources

- Excess of events from a given direction
- Only with the ν_μ channel (tracks with $\Delta\theta < 1^o$)

- COMPLEMENTARITY IceCube dominates in the Northern sky
- ANTARES dominated in the Southern,in particular for E_ν<100 TeV
- KM3NeT: galactic sources?





So far no evidence for a galactic neutrino source*

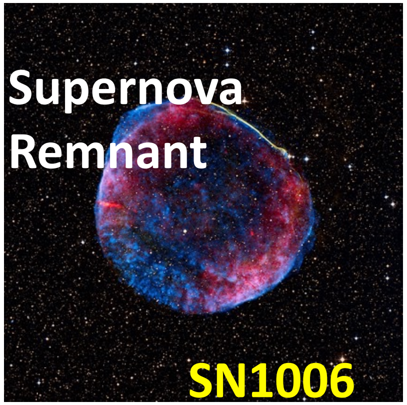
*excluding galactic plane

VHE γ-ray observations as a potential guide

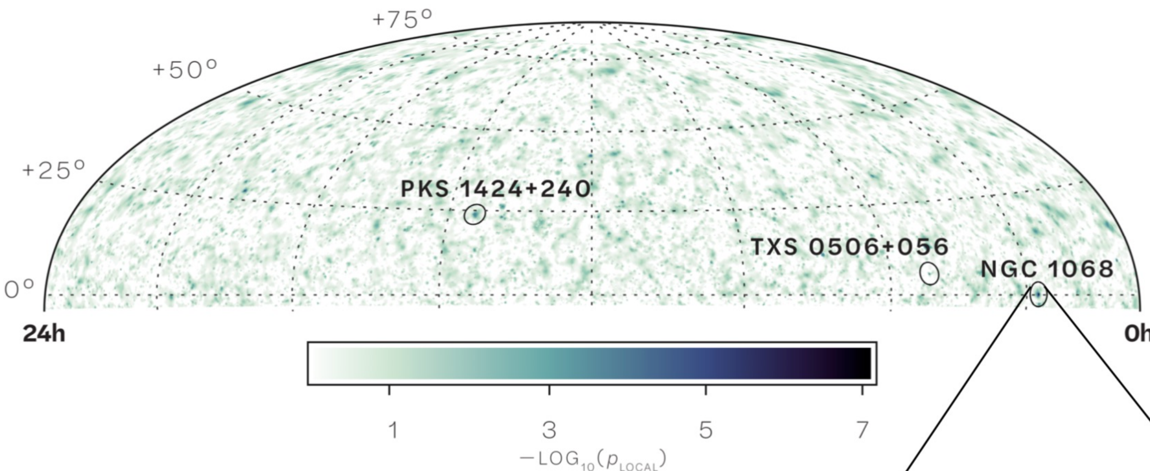
- Supernova Remnants, Pulsar Wind Nebulae, Binaries, Nova, ...
- IACTs and ground arrays have reported more than hundreds of Galactic
- sources LHAASO report gamma rays with up to PeV range

⟹ Emission measured from many **γ**-ray sources is leptonic-dominated but there are hadronic components

⟹ Need to wait for 1st neutrino measurement. KM3NeT/GVD are well located to do so.

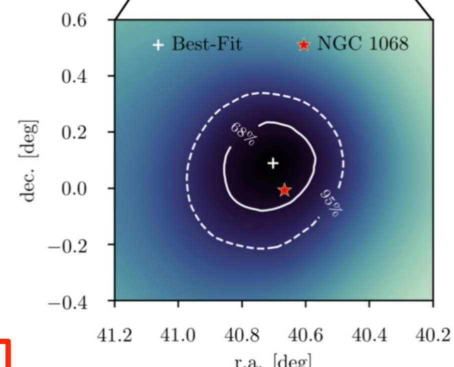


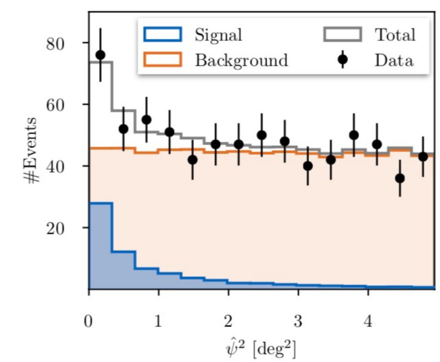
NGC 1068



- Most significant point in sky **0.11 degrees from NGC 1068**
- **81 events** give 5.2σ pretrial significance **→4.2σ after trials**
- TXS 0506 and PKS 1424 also have pre-trial significances > 3.5σ

Seyfert galaxy: the nuclear source emits at visible wavelengths an amount of radiation comparable to that of the whole galaxy's constituent stars
Quasar: the nuclear source is brighter than the constituent stars by at least a factor of 100.





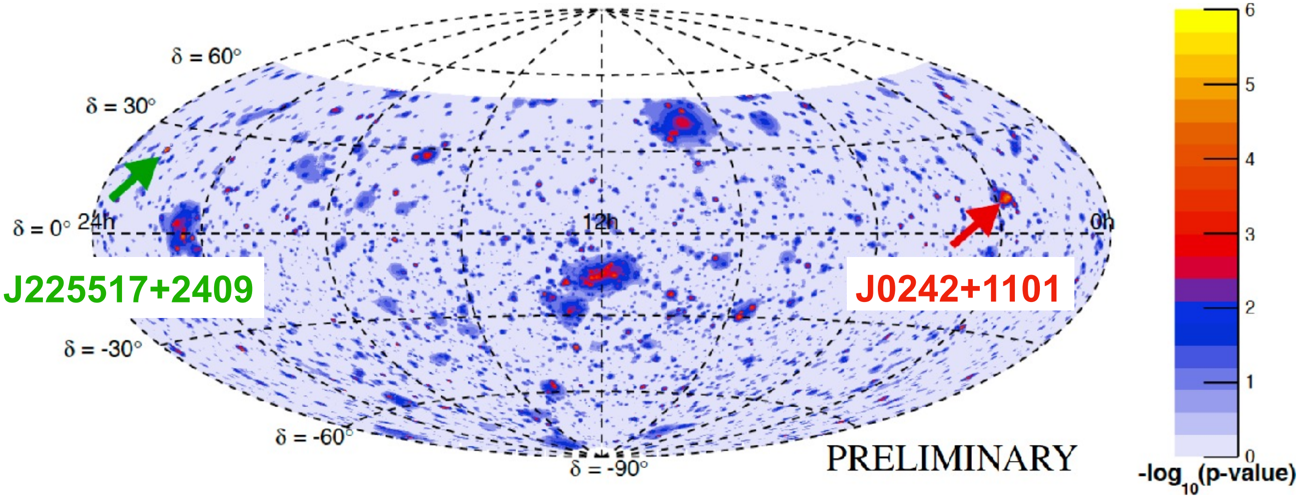
Seyfert 2 galaxy (NFC 1069 a.k.a. M77) at 14 Mpc (star forming region)

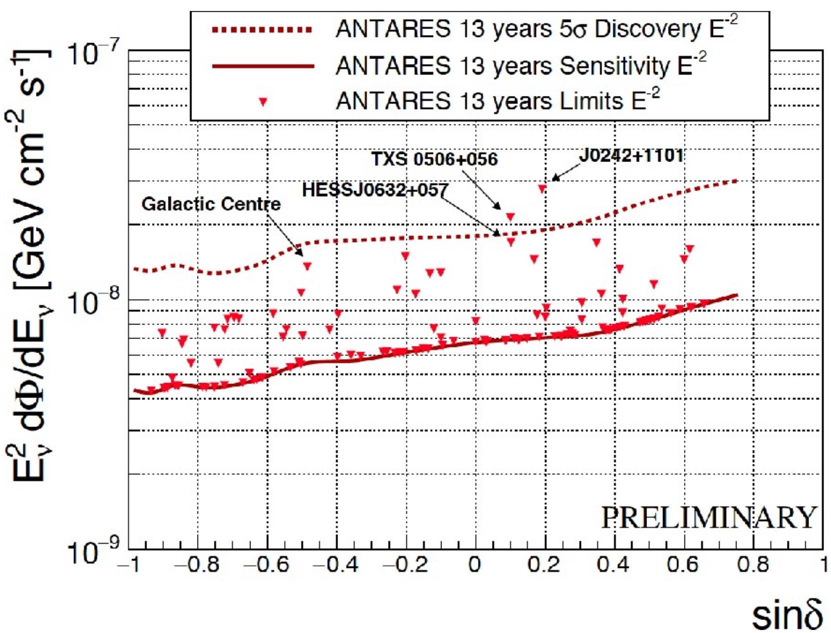
Neutrino production only at the vicinity of the SMBH (intense X-ray target): reported neutrino flux is higher than the GeV gamma-ray flux

⟹ significant γ-rays absorption

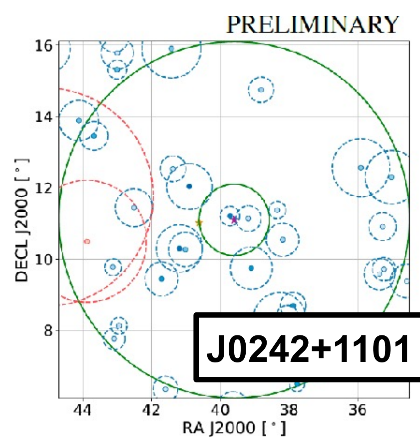
NGC 1068 is one of the intrinsically brightest
X-ray Seyfert galaxy, i.e. after correcting the attenuation effects due to the molecular torus located in the line-of-sight.
=> Coherent with the assumption that the neutrino production is proportional to the accretion disc luminosity.
Next potential discovery: Centaurus A and Circinus galaxy with KM3NeT (but extended)

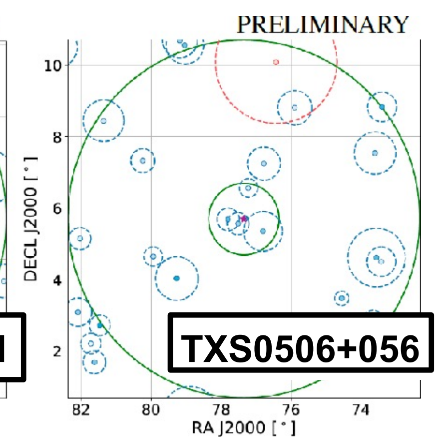
Last ANTARES PS results 2007-2020





Radio-bright blazars





3.8σ pre-trial

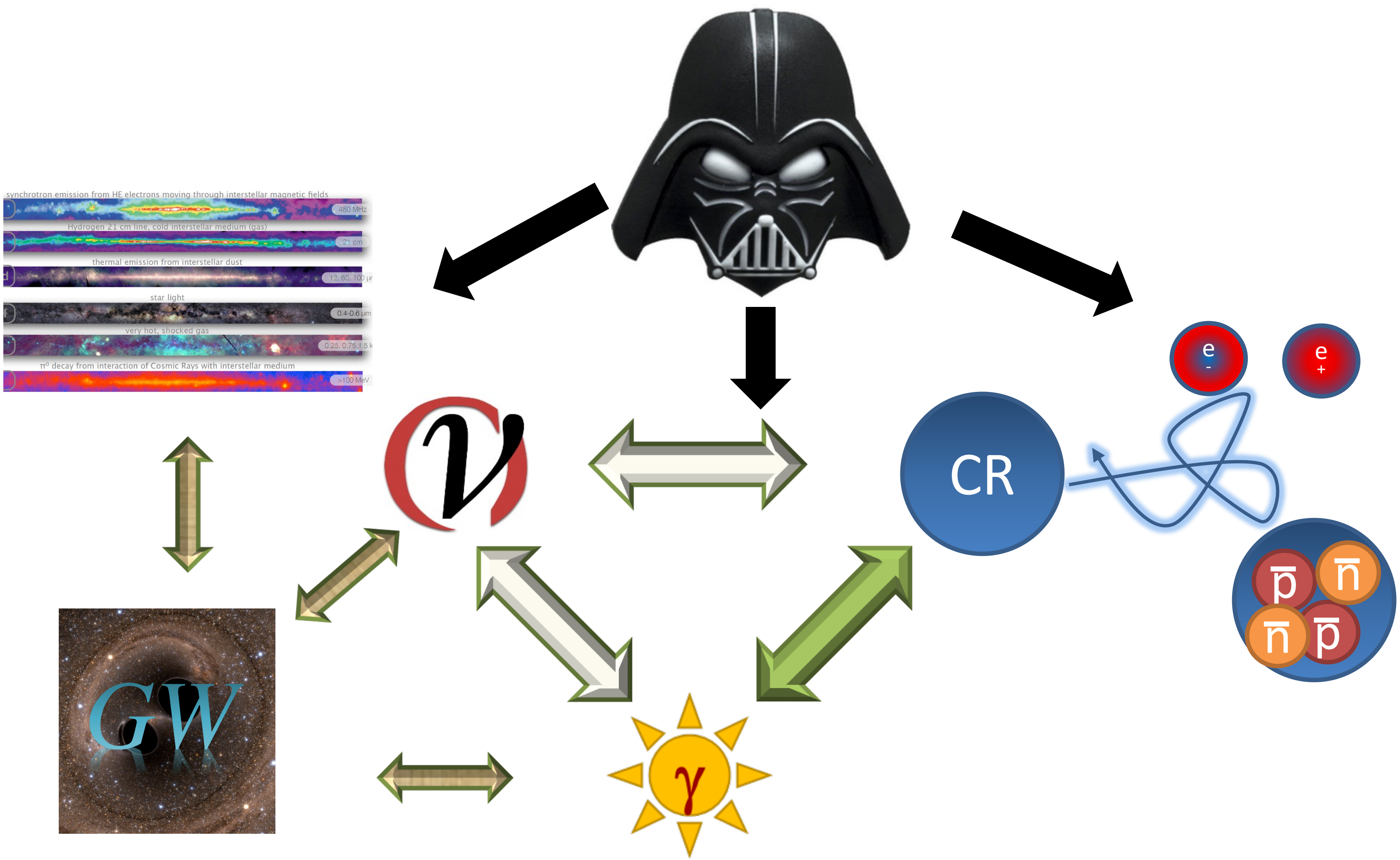
2.4σ post-trial

2.8σ pre-trial

(increasing significance compare to the last search)

PoS(ICRC2021)1161

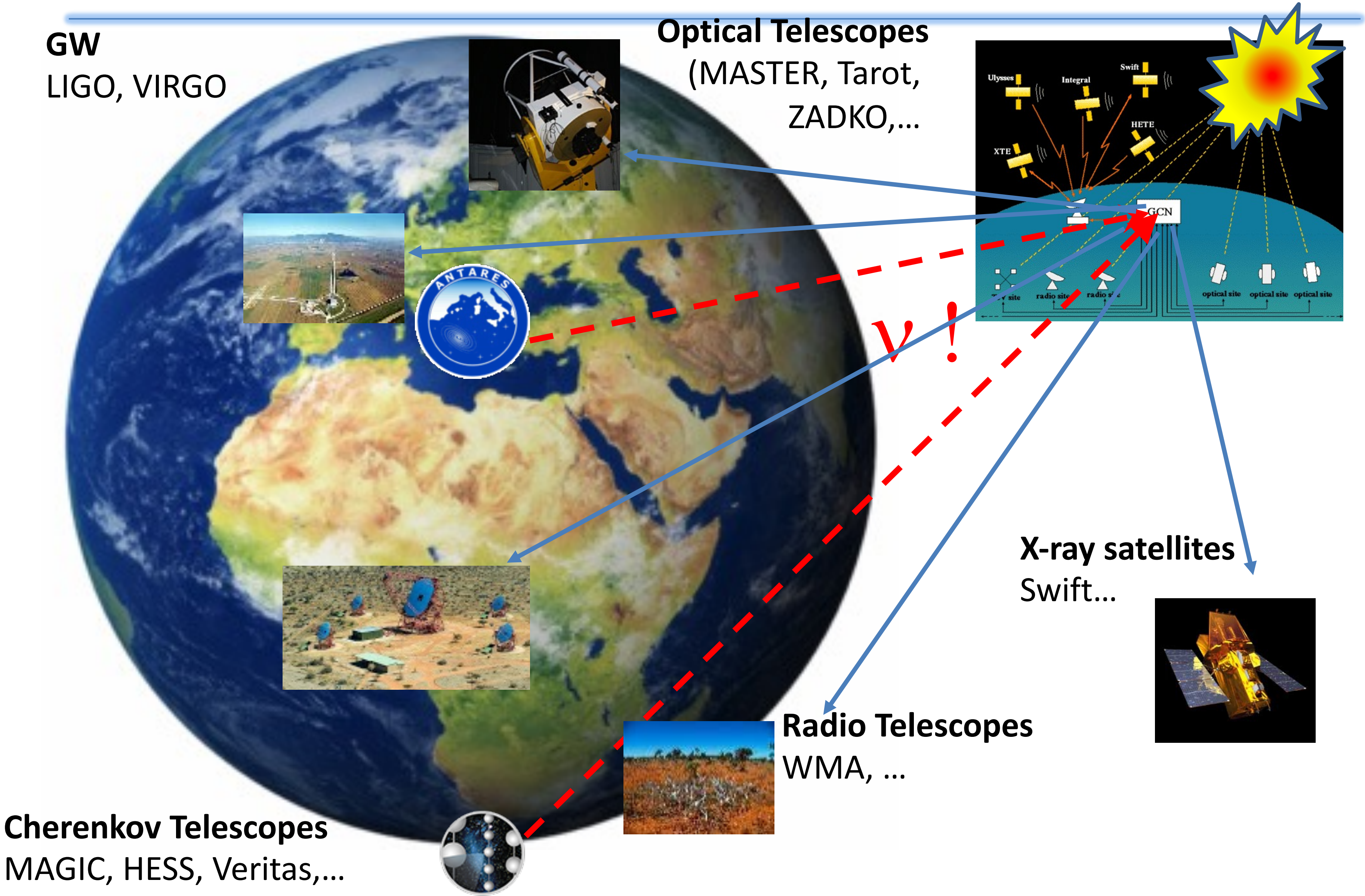
The multimessenger programs



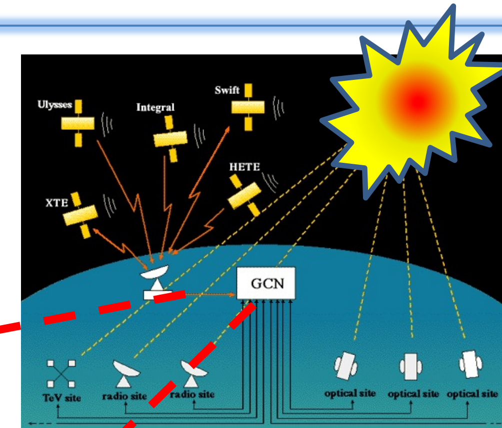
The multimessenger programs

friends 80+

Multimessenger: Info dissemination from NT



Multimessenger: external alert to NT

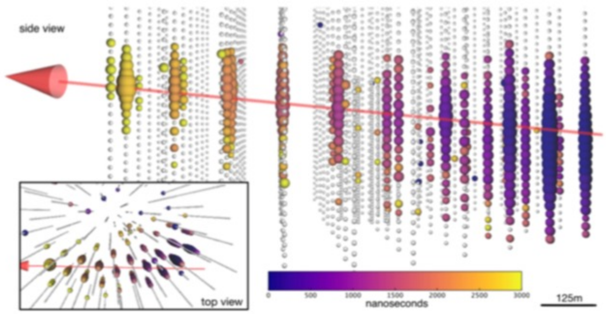


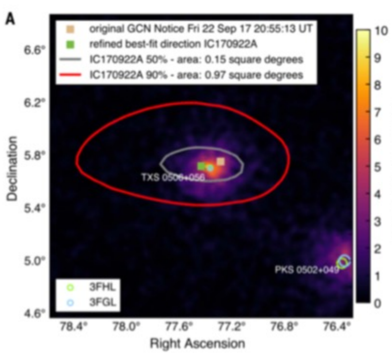
- GRB
- GW
- Supernova
- FRB

Search for ν point-source

Neutrinos from the AGN blazar TXS 0506+056

Sept. 22, 2017:
A neutrino in coincidence with a blazar flare



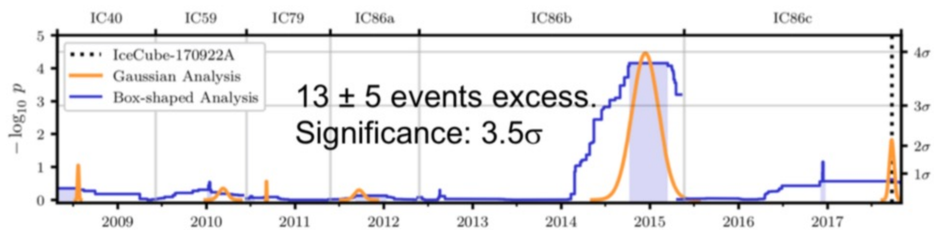


Observed by Fermi-*LAT* and MAGIC

Significance for correlation: 3σ

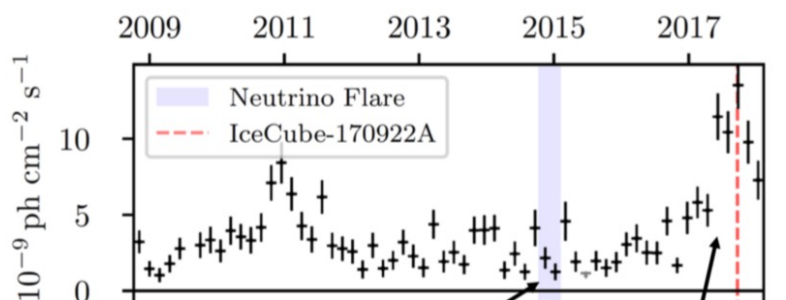
Science 361 (2018) no. 6398, eaat1378

2014-2015: A (orphan) neutrino flare found from the same object in historical data



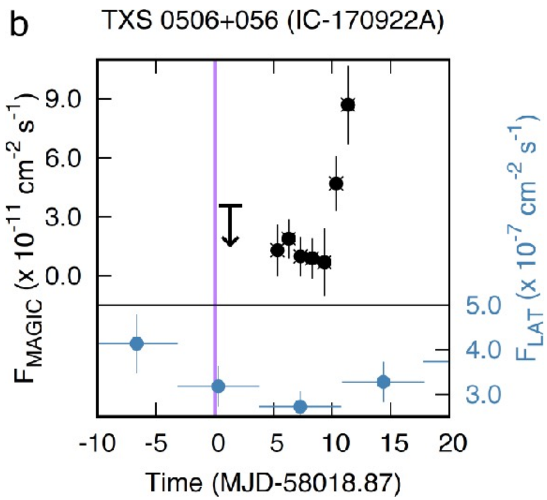
Science 361 (2018) no. 6398, eaat2890

Fermi-*LAT* data; Padovani et al, MNRAS 480 (2018) 192

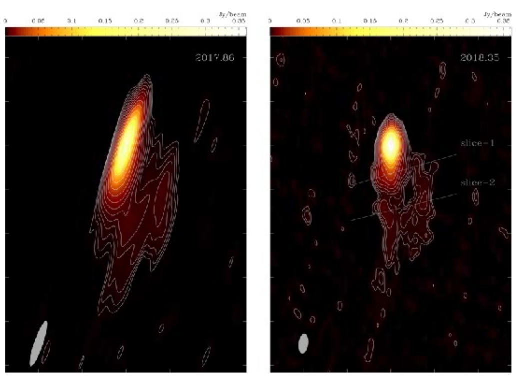


Neutrino luminosity is ~4 times higher than gamma-ray luminosity
⟹ challenge for models

Refined multi-wavelength follow-up



- MAGIC, HESS and VERITAS: no TeV gamma rays at the time the neutrino was produced
- MAGIC: onset of the TeV flux 5 days after IC170922
- MASTER: the blazar switches from the "off" to "on" state 2 hours after the neutrino

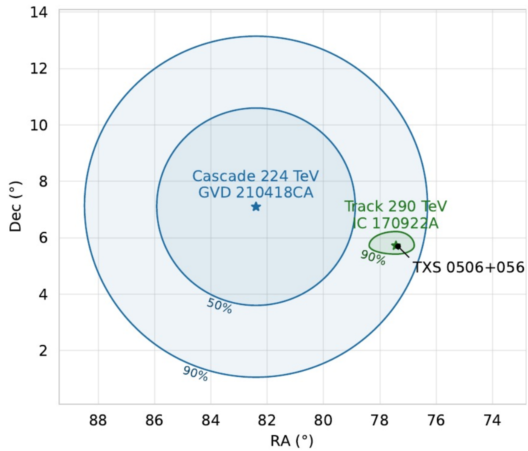


- Radio interferometry images show that the jet interacts with a target close to the base of the jet
- γ-rays accompanying the neutrinos lose their energy in the target that produces them

TXS is not a blazar at times that neutrinos are produced.

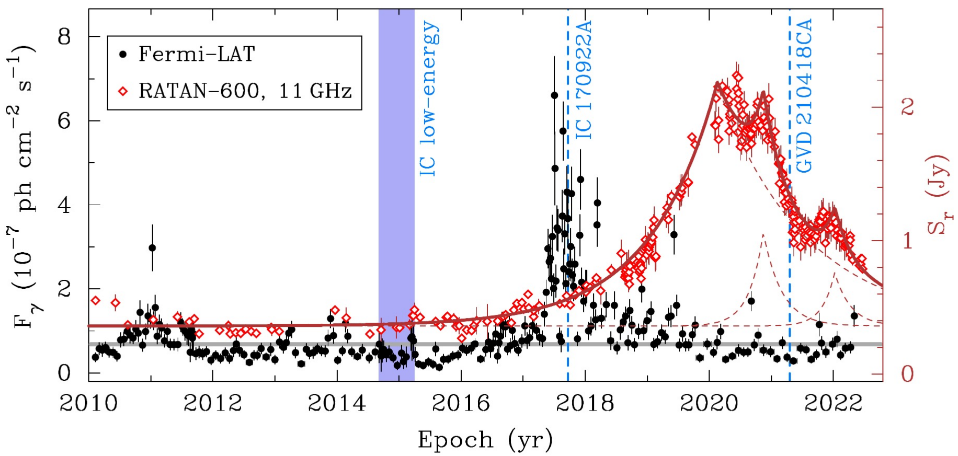
When a source is transparent to HE γ-rays there is an insufficient photon or matter target density to produce neutrinos.

Baikal GVD follow-up of TXS



Upgoing cascade analysis, highest energy event (18.04.2021):

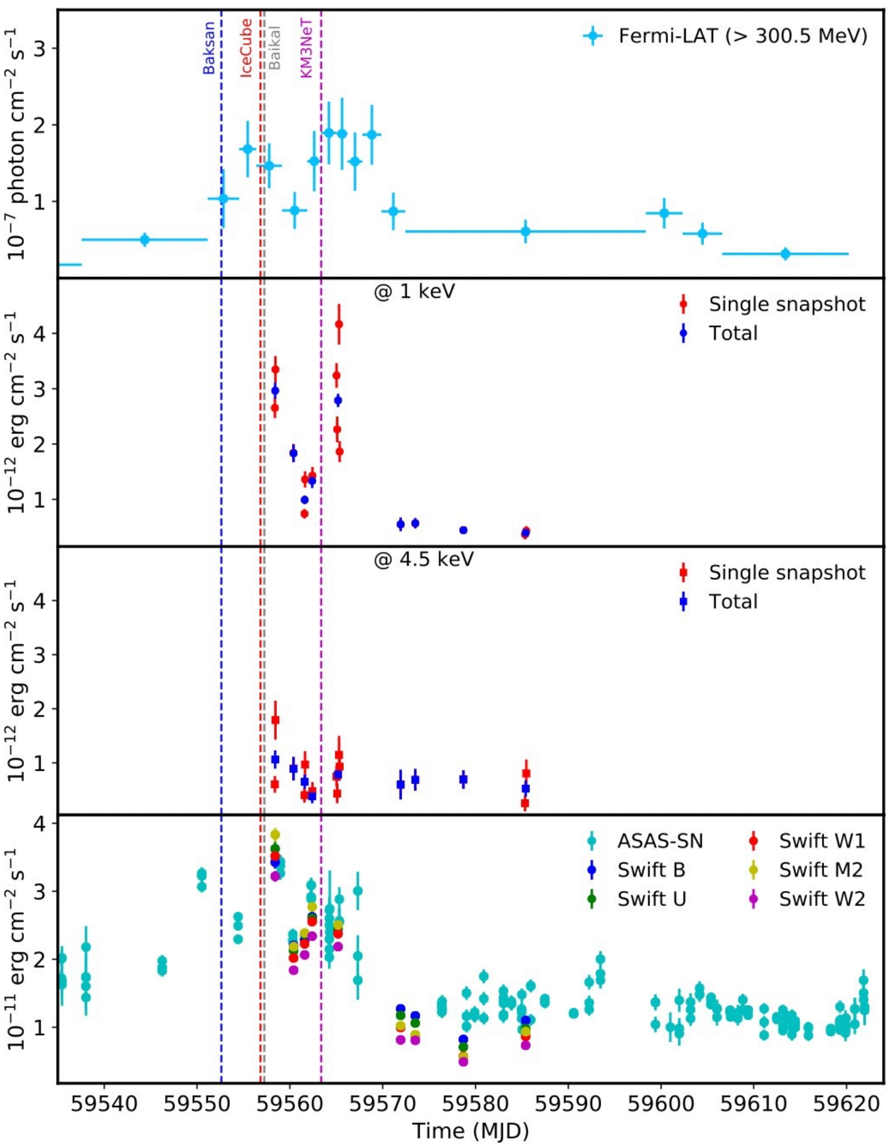
- 224 TeV, 24 hits
- Neutrino source candidate TXS 0506+056 is within 90% containment circle
- Signalness: 97.1% (probability of astro origin)
- Chance coincidence probability (E>200 TeV): 0.0074



Analysis of RATAN-600 radiotelescope data (11GHz) showed increased activity

- IC event registered during γ flare
- Baikal event during radio flare
- Consistency with IC observations: 8% or 13% depending on ν spectrum assumption

Intriguing association with PKS0735+178



IceCube: 1 bronze alert (~172 TeV) [GCN #31191]

ANTARES: no coincidence [ATel #15106]

GVD-Baikal: 1 cascade event (~43 TeV), ~4h after the IC neutrino, ~5deg from the blazar direction (2.85 **σ**) [ATel #15112]

KM3NeT: 1 track neutrino candidate (~18 TeV) in ARCA, 1.8 deg from the blazar (p=0.14). No coincidence in ORCA [ATel #15290]

Baksan: 1 track neutrino (1 GeV), 2.2 deg from the blazar (~3 **σ**) [ATel #15143]

The blazar was found to experience a strong flare in gamma rays (ATel #15099, ATel #15129), X-rays (ATel #15102, ATel #15108, ATel #15109, ATel #15113, ATel #15130), optical (ATel #15098, ATel #15100, ATel #15132, ATel #15136, ATel #15148) and radio (ATel #15105) bands.

Sahakyan et al (arXiv:2204.05060)

19. Conclusions (I)

- Astrophysics with neutrino telescope is a young, growing discipline in its discovery phases
- **Large area detectors** mandatory (multi km^2) to reach the needed sensitivity for the detection of point-like sources
- Almost 20 year of R&D to arrive at IceCube, Baikal and ANTARES/KM3NeT
- **Robust, cheap and reliable** technology needed (the sea and ice are hostile environments). Experimental requirements similar to space experiments
  - Ice: operations at the South Pole (not simple logistic)
  - Sea: see operations rely on expertise of commercial companies serving oil exploration/services and telecommunications (boats, ROV,…)
- Photosensors: so far, the only reliable technology also for medium term experiments
- Order of 10^4 optical sensors/km^3 needed with present technology (10” PMT). Connected with:
  - medium transparency
  - Cherenkov light yield
  - PMT quantum efficiency

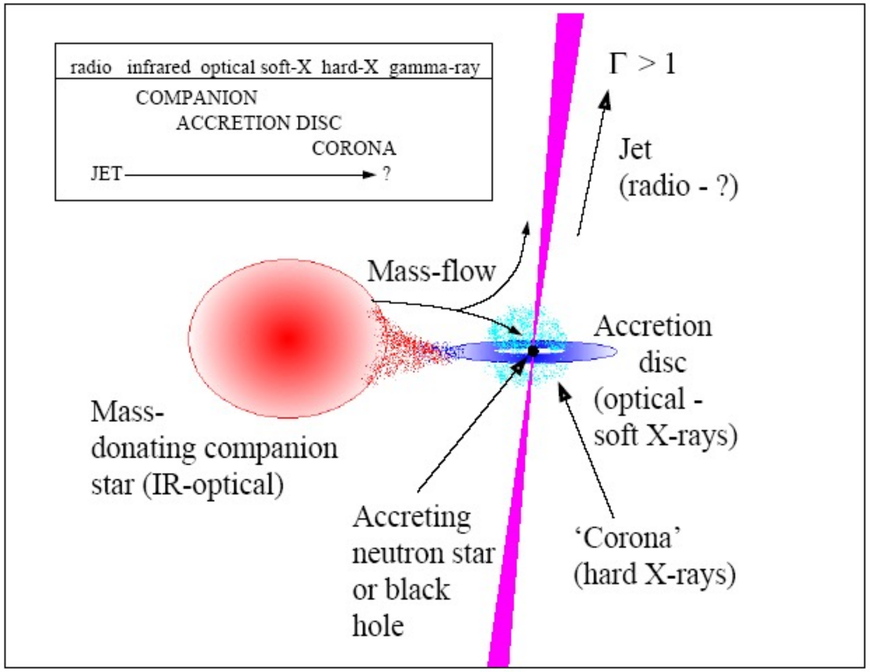
19. Conclusions (II)

- (Sub)Detector for neutrino mass hierarchy:
  - Sensible to neutrinos above few GeV
  - Identification of neutrino flavour (track=muon, shower=e+NC)
  - different volume of the instrumented medium (Gton→ Mton)
  - same technology
- Astrophysics: (multi)TeV-PeV cosmic neutrinos **are** there!
- But many neutrino sources (and CR sources) still unknown!

BACKUP

Astrophysical Sources

- **<u>Galactic sources</u>**: these are near objects (few kpc) so the luminosity requirements are much lower.
  - Micro-quasars



- Micro-quasars: a compact object (BH or NS) towards which a companion star is accreting matter.
- Neutrino beams could be produced in the Micro-quasar jets.

Astrophysical Sources

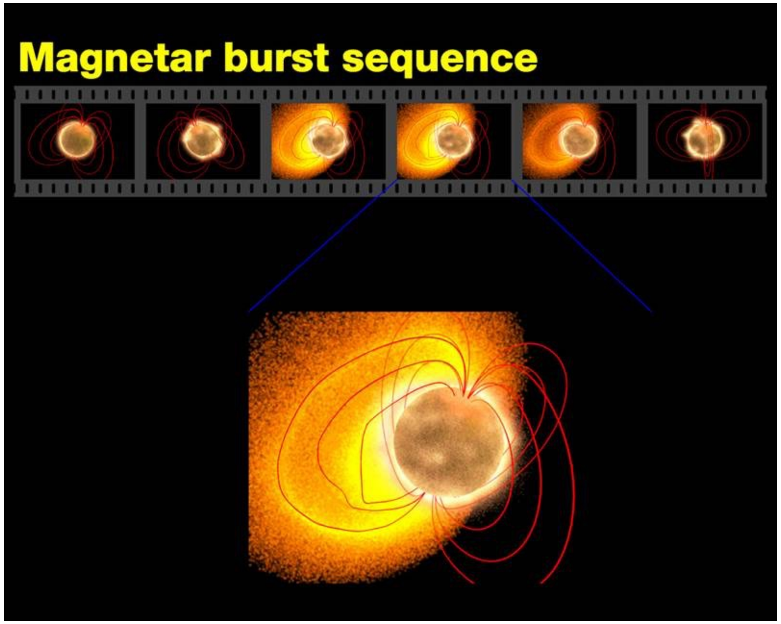
- **<u>Galactic sources</u>**: these are near objects (few kpc) so the luminosity requirements are much lower.
  - Micro-quasars
  - Supernova remnants

Several different objects (with different neutrino production scenarios):

- Plerions-PWN (center-filled SNRs)
- Shell-type SNRs

Astrophysical Sources

- **<u>Galactic sources</u>**: these are near objects (few kpc) so the luminosity requirements are much lower.
  - Micro-quasars
  - Supernova remnants
  - 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.

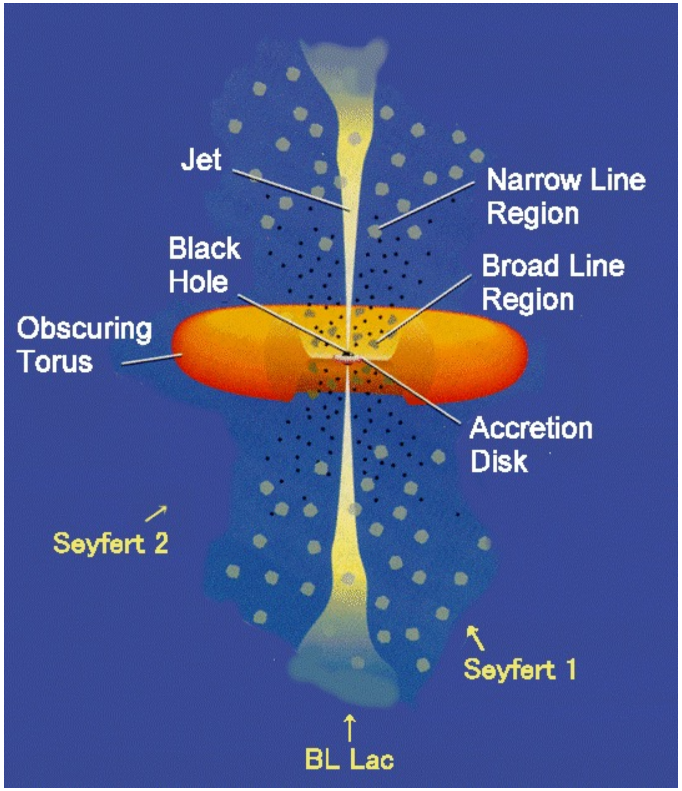
Astrophysical Sources

- **<u>Galactic sources</u>**: these are near objects (few kpc) so the luminosity requirements are much lower.
  - Micro-quasars
  - Supernova remnants
  - Magnetars
  - Galactic ridge

Astrophysical Sources

- **Galactic sources**: these are near objects (few kpc) so the luminosity requirements are much lower.
  - Micro-quasars
  - Supernova remnants
  - Magnetars
  - Galactic ridge

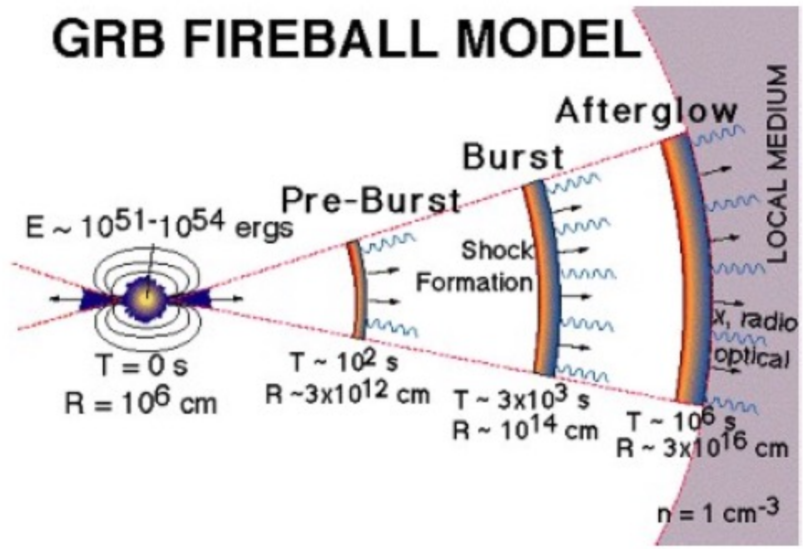
- **Extra-galactic sources**: most powerful accelerators in the Universe
  - AGNs



- Active Galactic Nuclei includes quasars, radio galaxies and blazars.
- Standard model: a super-massive (10^6-10^8 M_s) black hole towards which large amounts of matter are accreted.

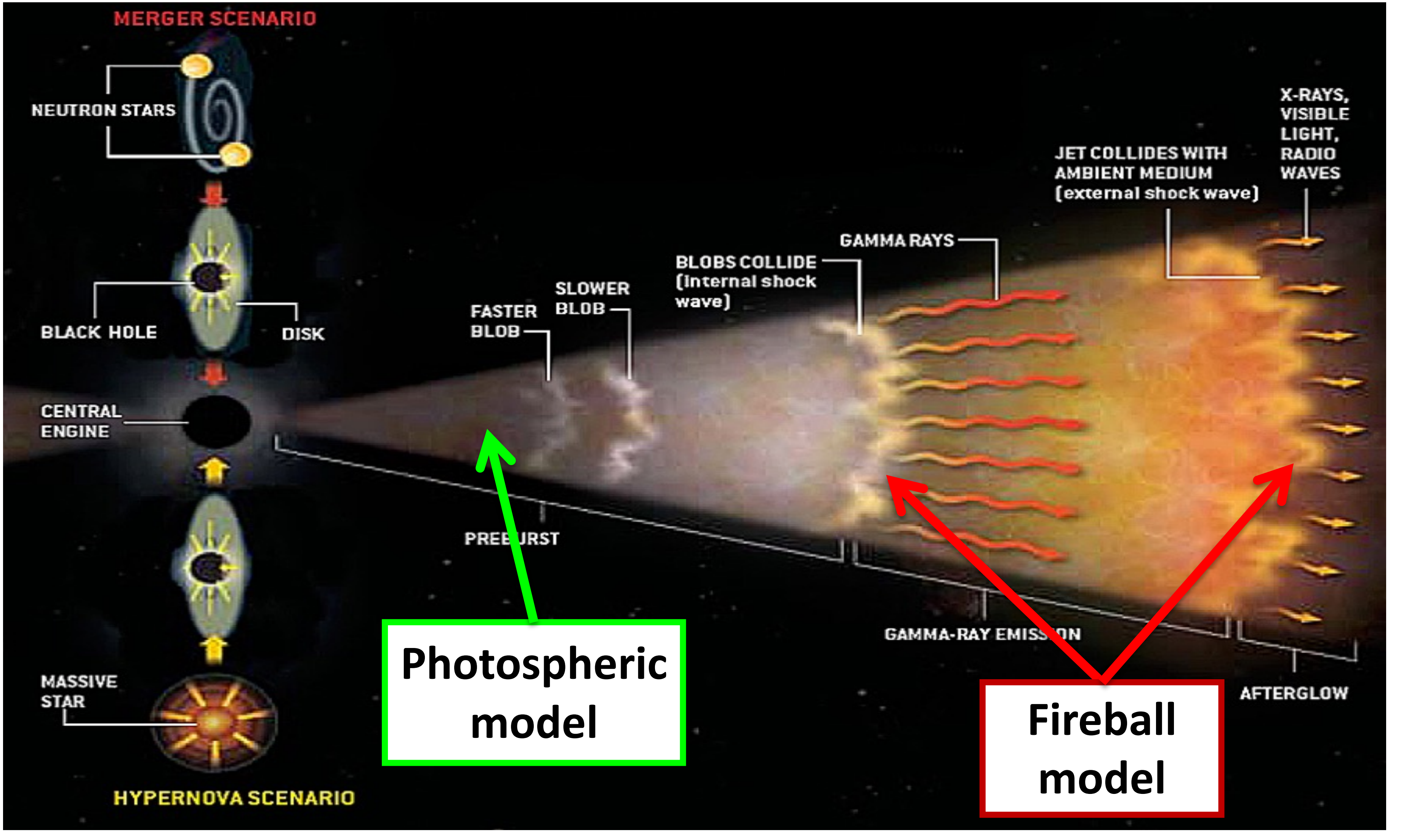
Astrophysical Sources

- **Galactic sources**: these are near objects (few kpc) so the luminosity requirements are much lower.
  - Micro-quasars
  - Supernova remnants
  - Magnetars
  - …
- **Extra-galactic sources**: most powerful accelerators in the Universe
  - AGNs
  - GRBs



- GRBs are brief explosions of γ 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.
- Time correlation enhances the neutrino detection efficiency.

Gamma ray bursts



Gamma ray bursts

- Photospheric and fireball model can both reproduce the gamma ray burst spectrum

- The photospheric model can also reproduce some particular features of the emission:

  – the “Amati correlation” (correlation between isotropic energy and peak energy)

  – the correlation between the luminosity and the Lorentz factor of the burst

- These particular features can be reproduced by the fireball model only with a fine tuning