SFB 1258 Neutrinos Dark Matter Messengers

Observing cosmic neutrinos in water

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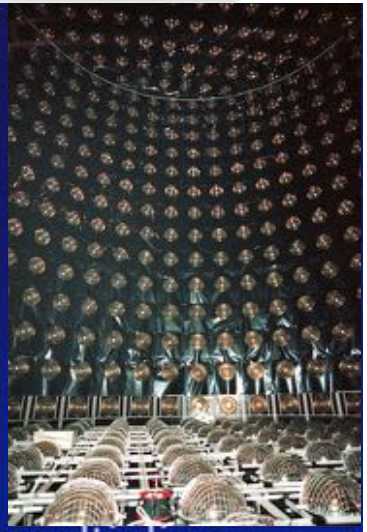
Birth of multimessenger astrophysics (1987)

The SN1987A

- Water Cherenkov detectors
  - Kamiokande (Japan)
  - IMB (Ohio)
- Liquid scintillation telescopes
  - Baksan – USSR Academy of Sciences, in North Caucasus Mountains, Russia
  - Mont Blanc – Italian Soviet collaboration, in Mont Blanc Laboratory, France

Kamiokande II



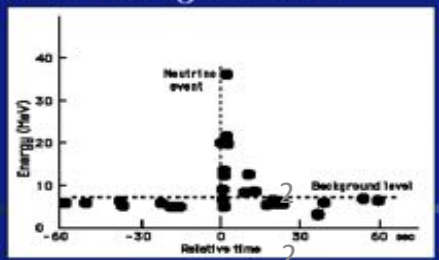
- Located in the Kamioka mine in Japan
- 1000m underground
- Cylindrical tank
  - d = 15.6m, h = 16m
- Large (D = 20 inches) photomultipliers
- Volume of water weighs 3000 metric tons

IMB

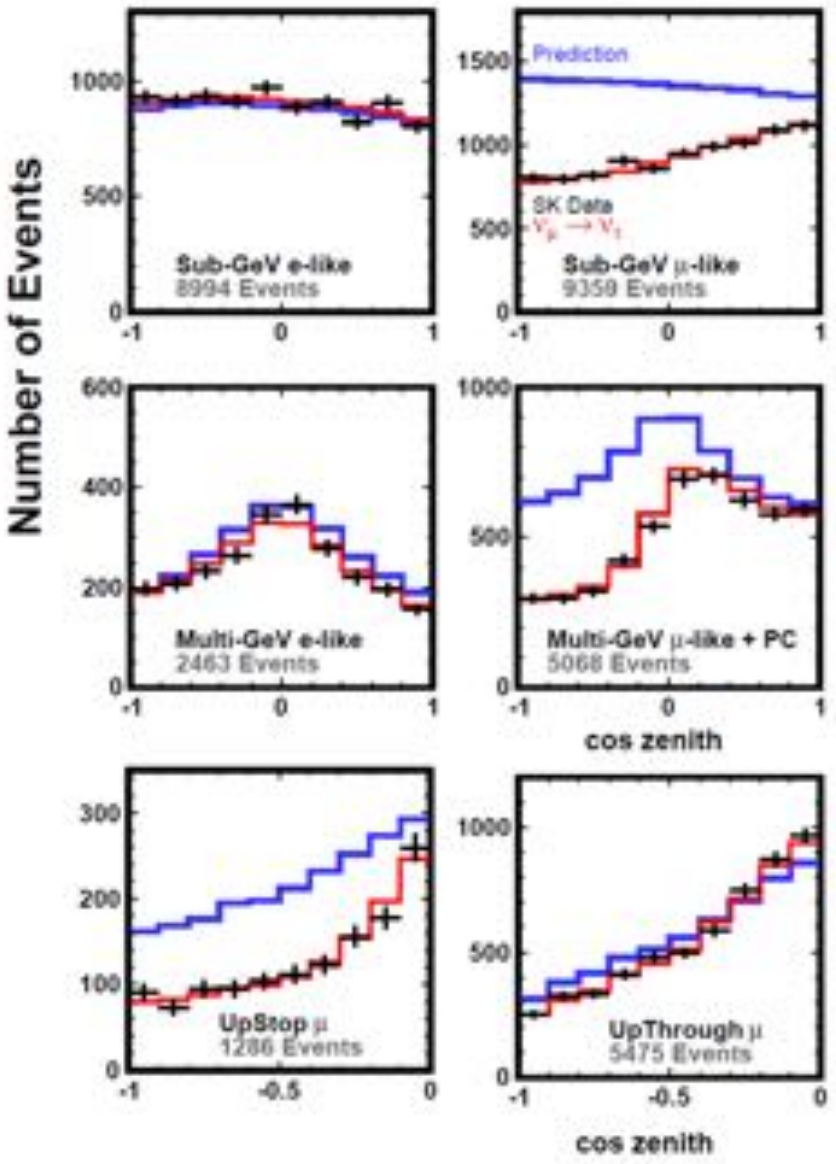
- Located in the Morton Thiokol mine in Ohio
- 580m underground
- Rectangular tank
  - 18 by 17 by 23 m
- 2048 8" photomultipliers
- 2.5 million gallons of water
- Compared to Kamiokande II: Larger volume, but not as deep

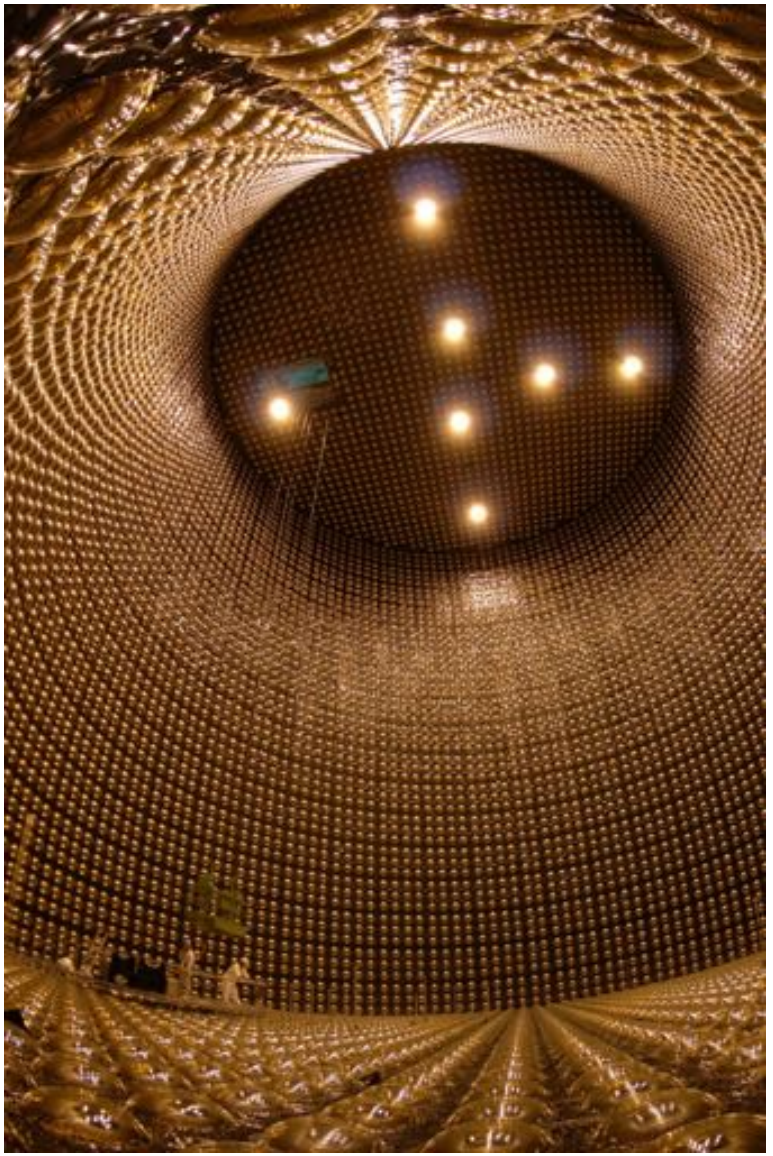
Results

- Feb 23, 7:36 UT:
  - K II records 9 neutrinos within 2 sec, 3 more neutrinos 9-13 seconds later
  - IMB records 8 neutrinos within 6 seconds
  - Baksan records 5 neutrinos within 5 seconds
- 25 neutrinos detected!

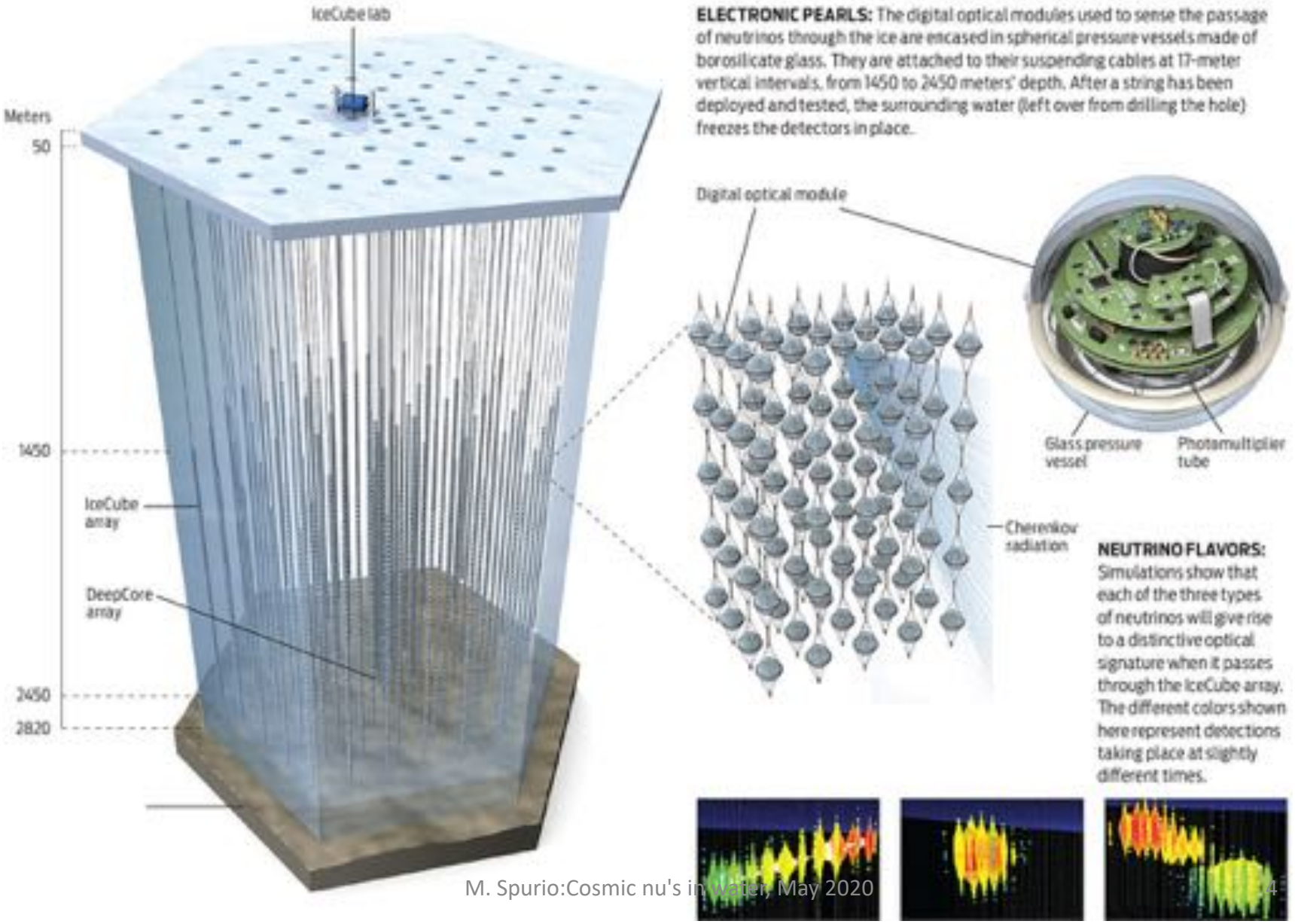


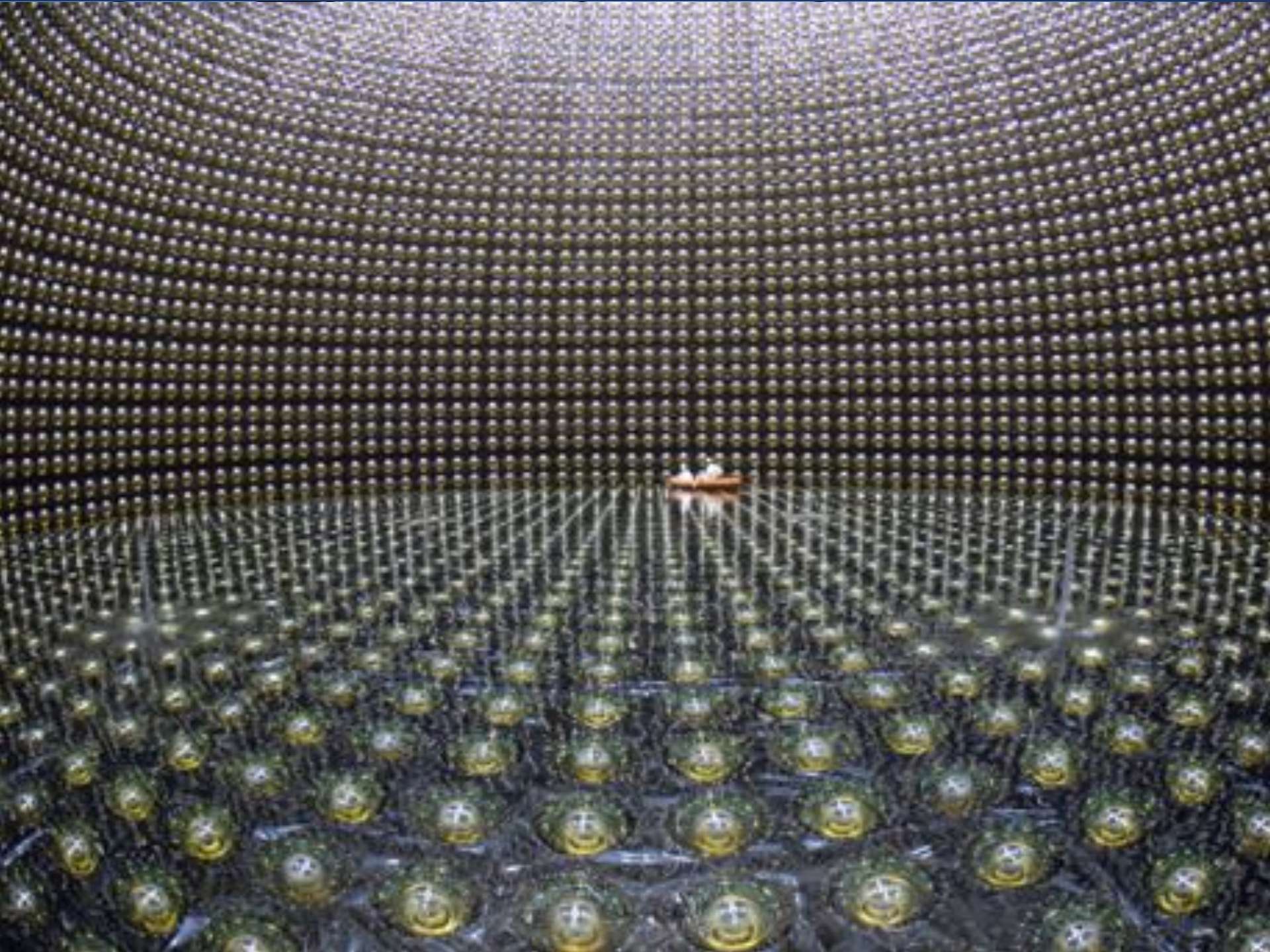
Neutrino masses through oscillations (1998)



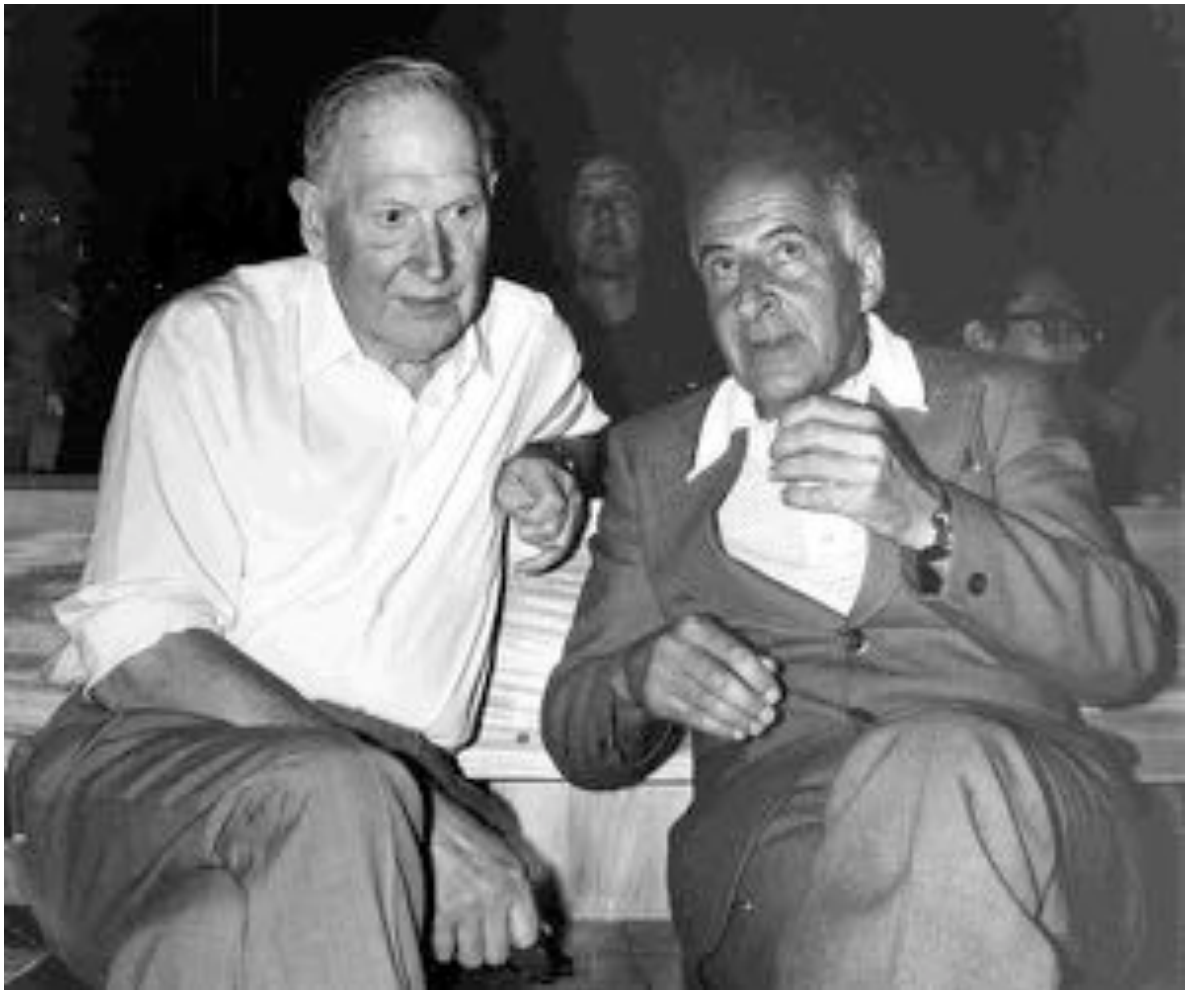


Observation of cosmic HE neutrinos (2013)





Recipes for a Neutrino Telescope (NT)



M.A. Markov and B.M. Pontecorvo at the International conference on neutrino physics and astrophysics. Baksancanyon, Cheget, the Caucasus, 1977

M. 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

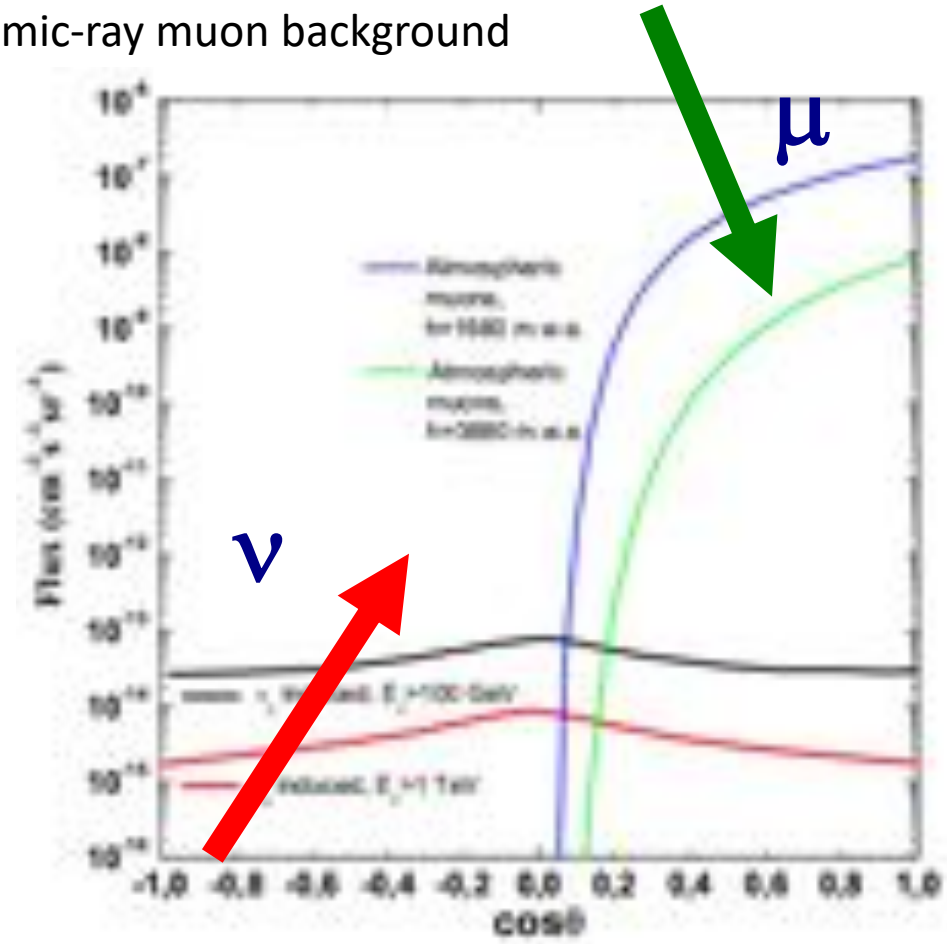
Deep in a transparent medium

Water and frozen water (deep ice):

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

In a ~1 km-scale detector there are:

- **Atmospheric muons:** **~$10^{10\text{-}11}$/y,** i.e., 1 kHz
- **Atmospheric ν→ μ :** **~10^5/y,** i.e., 1 in 5 minutes
- **Cosmic ν→ μ :** **~100/y,** i.e., 2/weeks, mostly hidden in the atmosph. bck



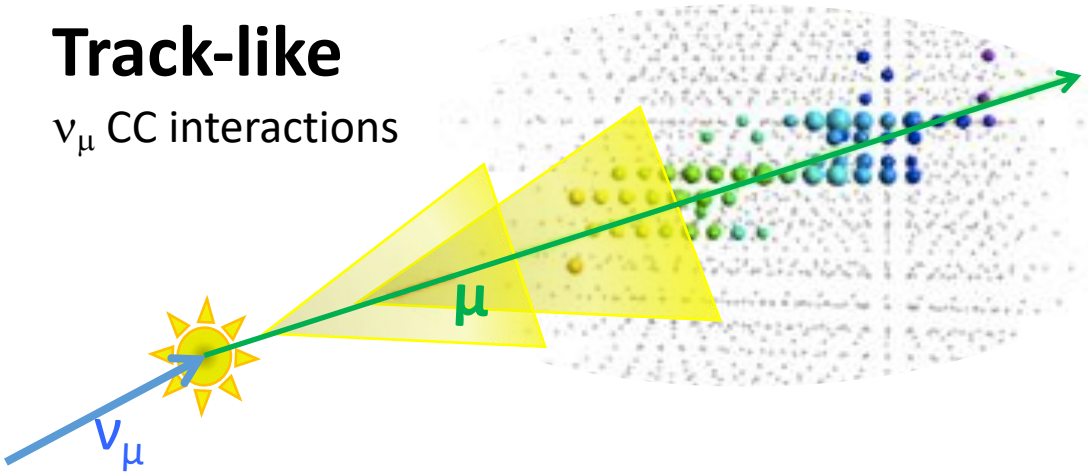
Two topology (track/showers) of events

Detection principle: Optical Cherenkov radiation

- 6 order of magnitude in energy (GeV-PeV)
- All flavour detection

Track-like

ν_μ CC interactions

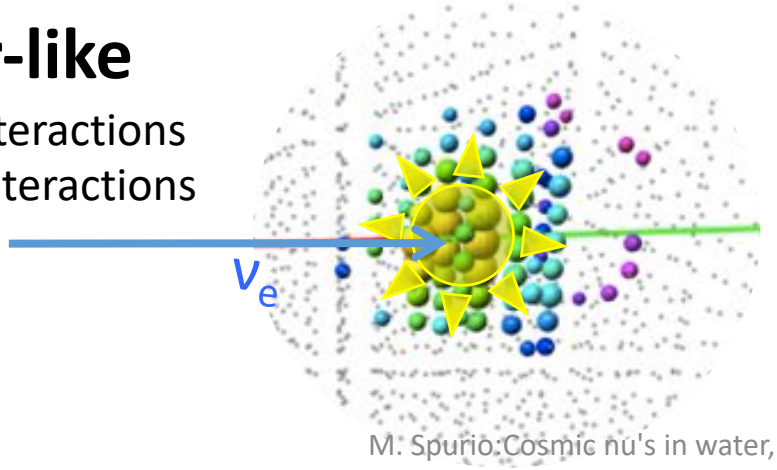


Angular resolution:
~0.1° (full, E>10 TeV)

Energy resolution:
<0.5 (log E_μ)

Shower-like

ν_e , ν_τ CC interactions
ν_x NC interactions

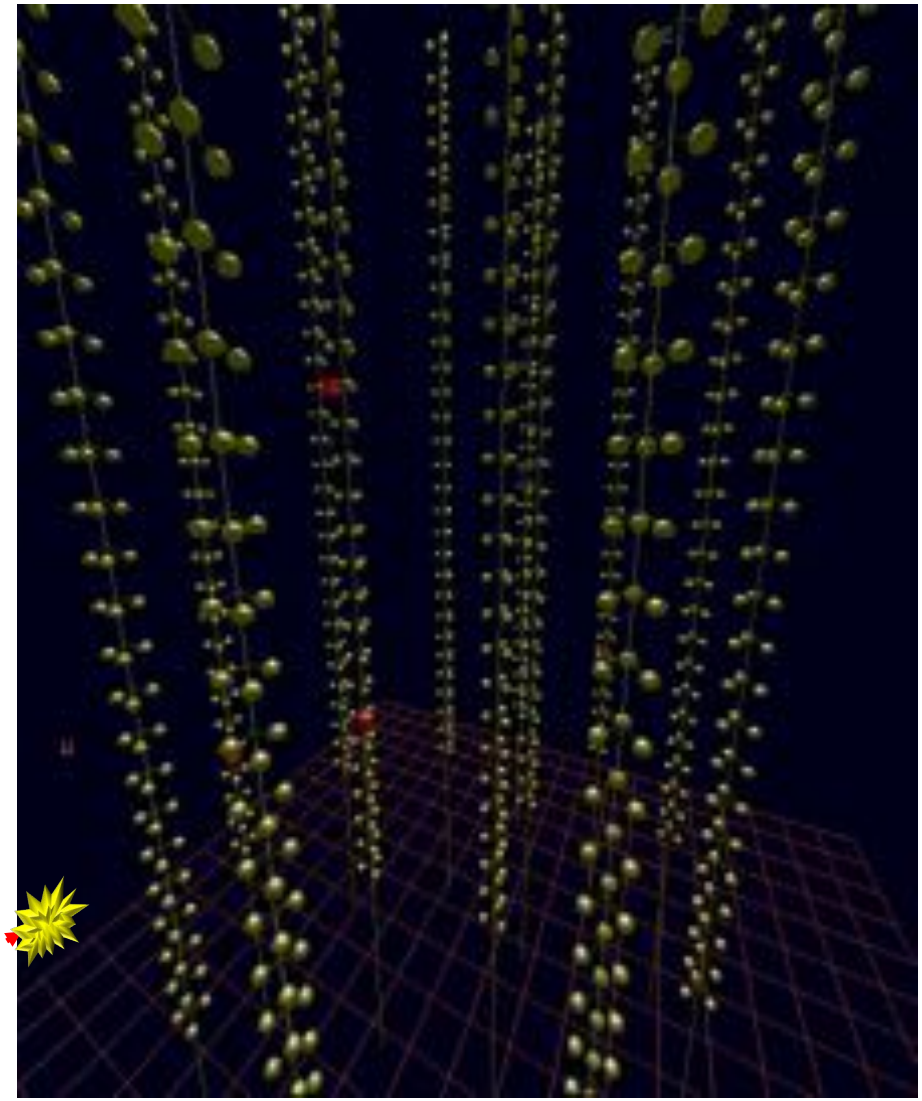


Angular resolution:
~3° (full, E>10 TeV)

Energy resolution:
(E_ν) ~25%

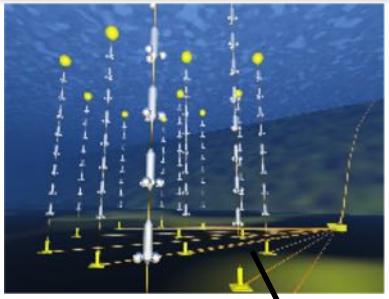
Shower- and track-like events

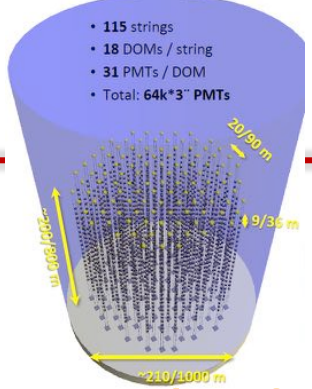
- Cherenkov photons emitted by charged particles are correlated (space/time)
- **Event Reconstruction** based on time-space correlations of fired PMTs (hits) in the PMTs
- **Tracks** (**CC** ν_μ): Long pattern
- **Cascades (CC** ν_e**+ NC):** Short pattern
- **Neutrino Direction** reconstructed from time-space correlation between ***hits*** produced by Cherenkov photons
- **Neutrino Energy** reconstructed from signal amplitudes of the detected hits



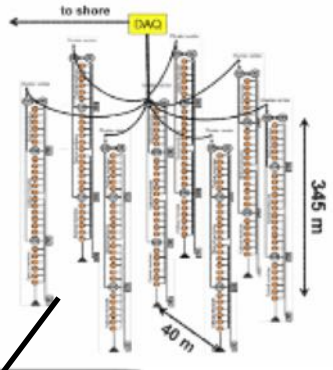
Neutrino telescopes. Where …

ANTARES
KM3NeT/ORCA

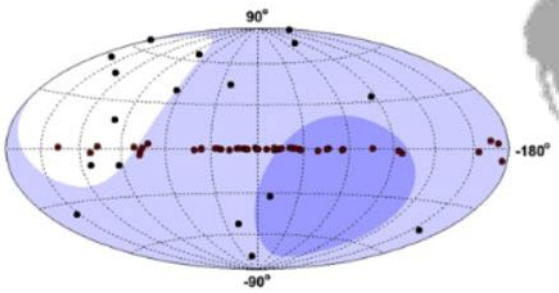




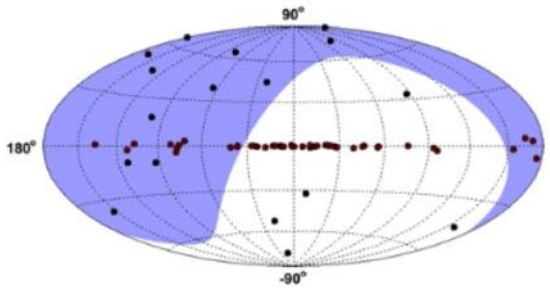
KM3NeT/ARCA

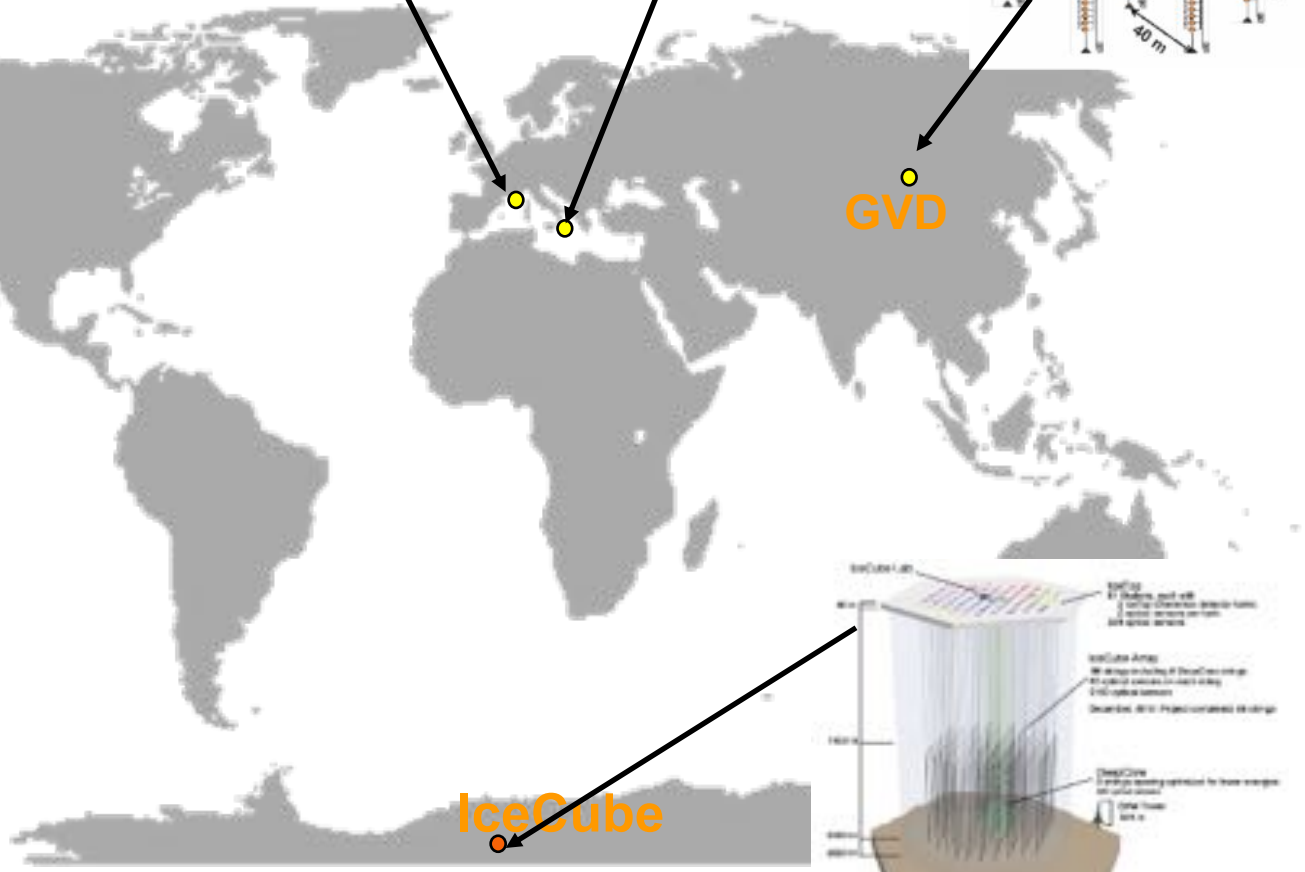


Visibility ANTARES (Mediterranean)
- 75%
- 5% – 75%
- 25%



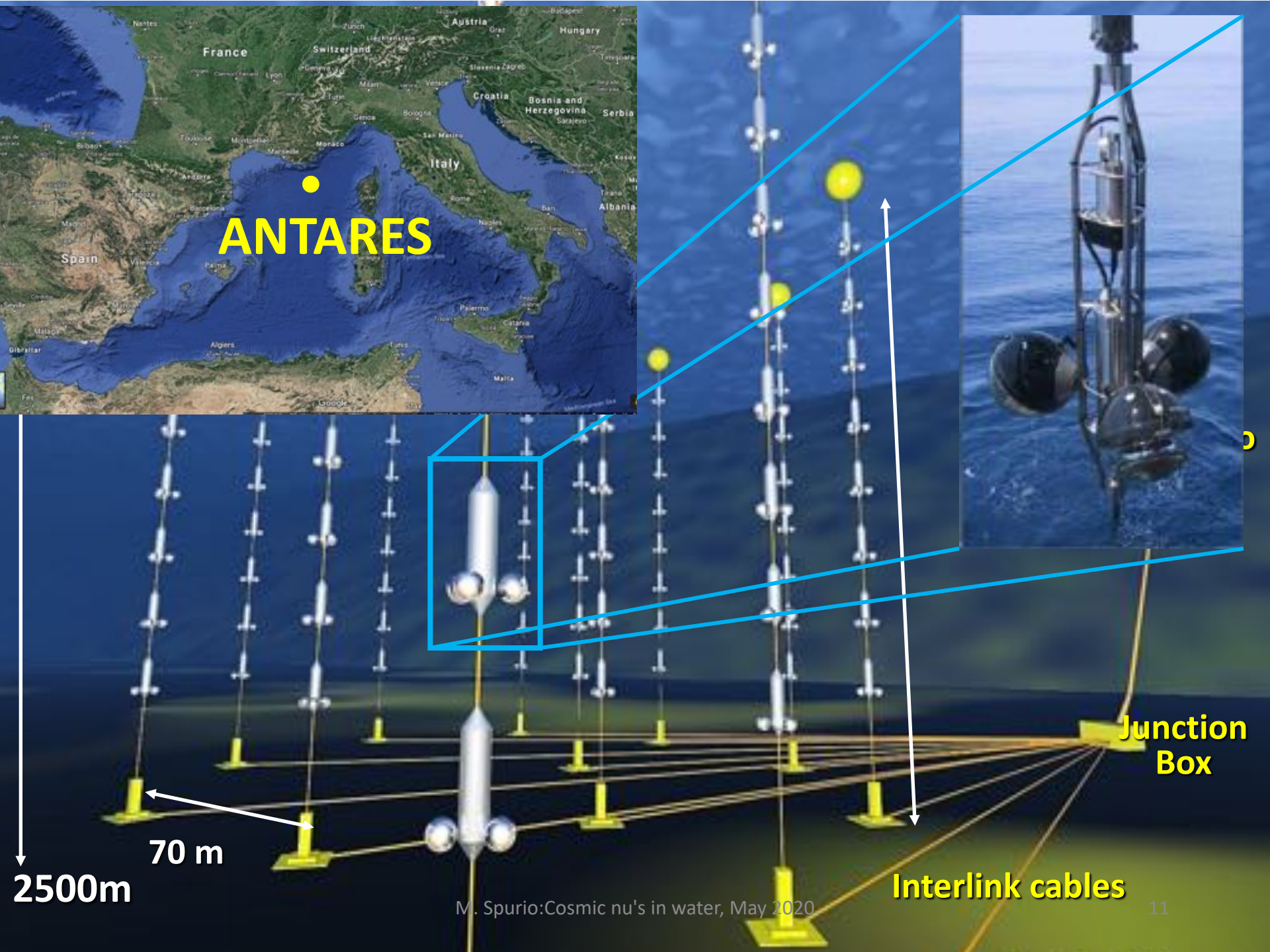
Visibility IceCube (South Pole)
- 100%
- 0%





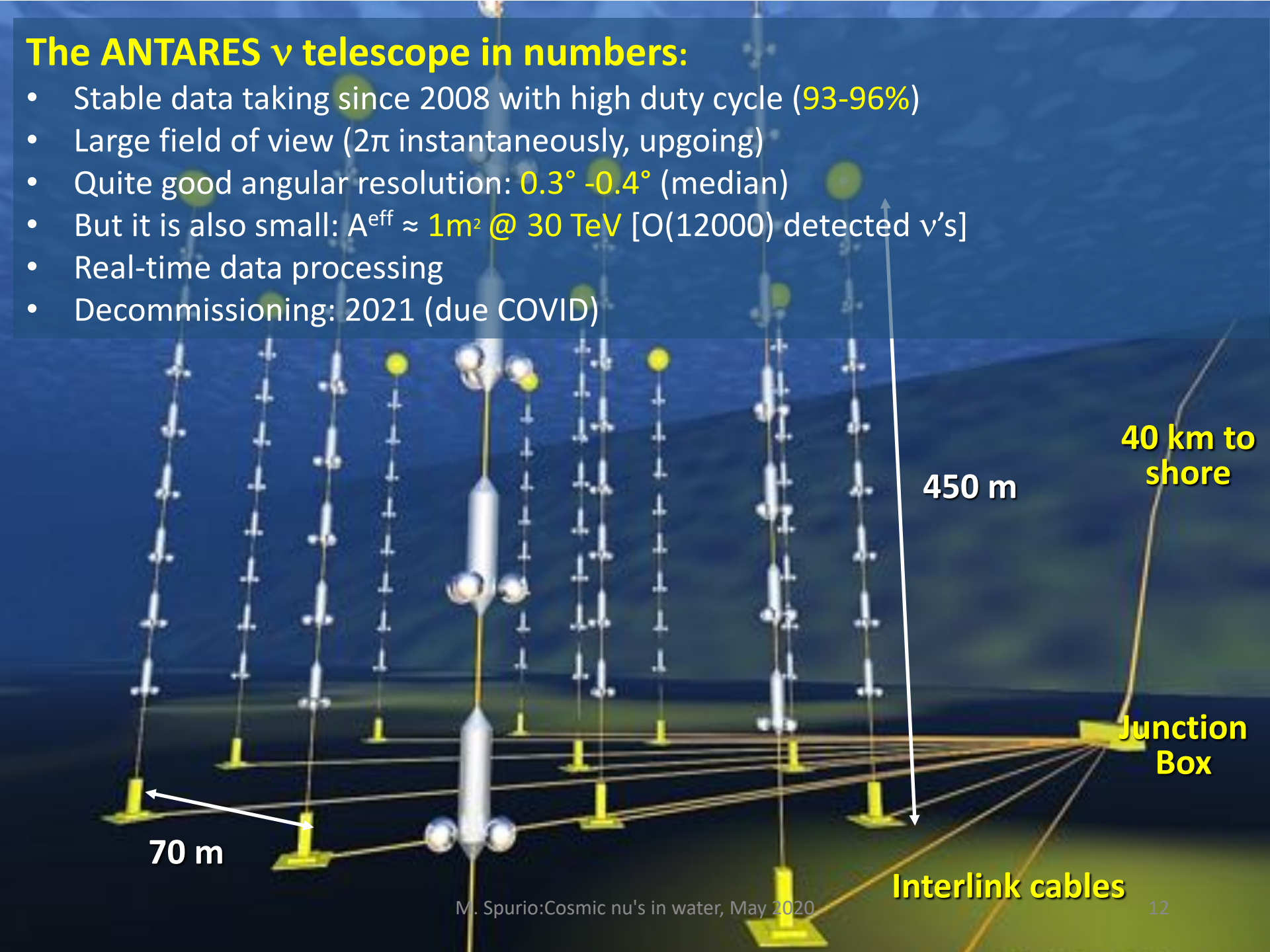
GVD

IceCube

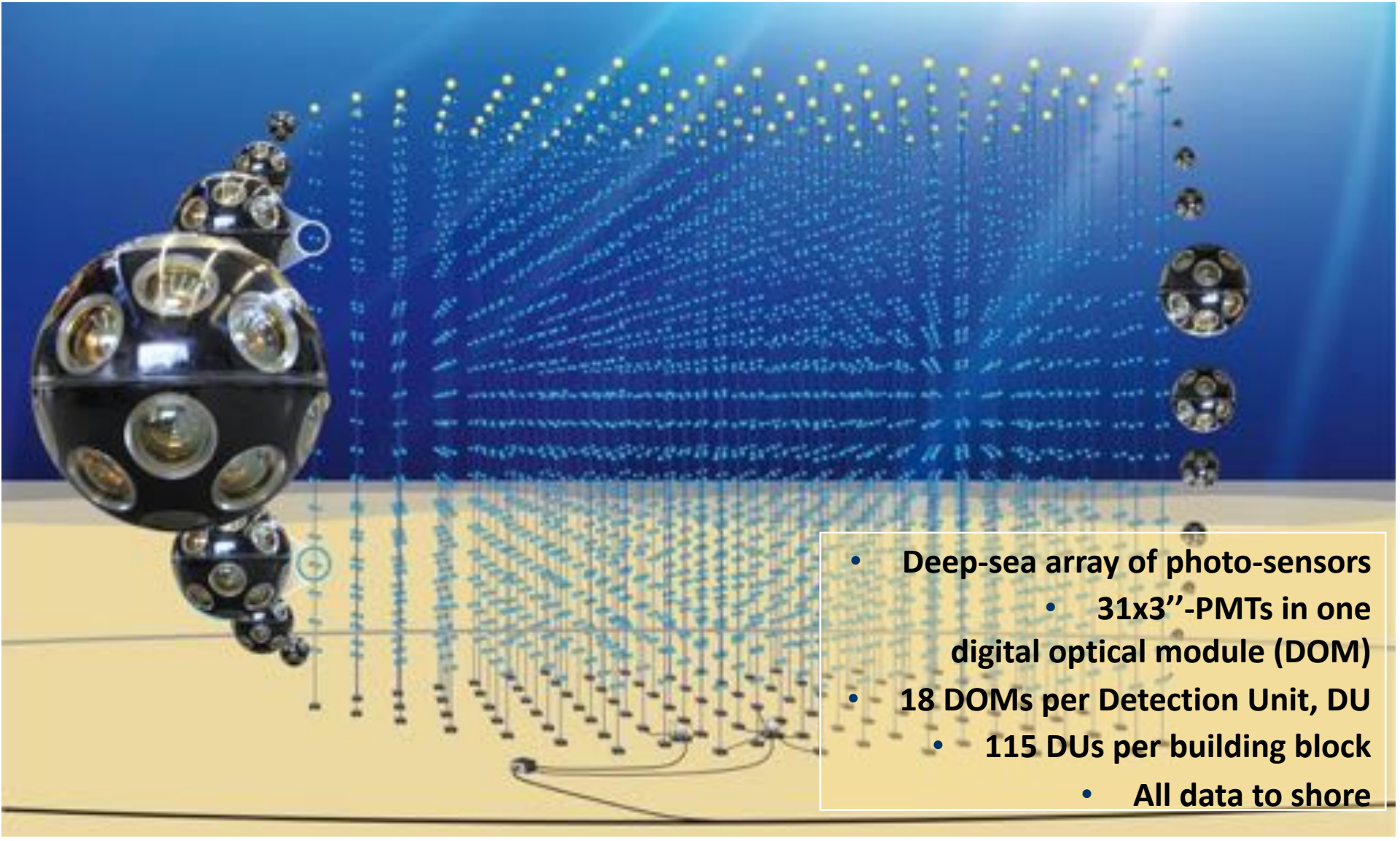

France
Switzerland
Austria
Hungary
Croatia
Bosnia and Herzegovina
Serbia
Italy
Spain
ANTARES
2500m
70 m
Junction Box
Interlink cables

The ANTARES ν telescope in numbers:

- Stable data taking since 2008 with high duty cycle (93-96%)
- Large field of view (2π instantaneously, upgoing)
- Quite good angular resolution: 0.3° -0.4° (median)
- But it is also small: $A^{eff} \approx 1m^2$ @ 30 TeV [O(12000) detected ν's]
- Real-time data processing
- Decommissioning: 2021 (due COVID)



The future: KM3NeT



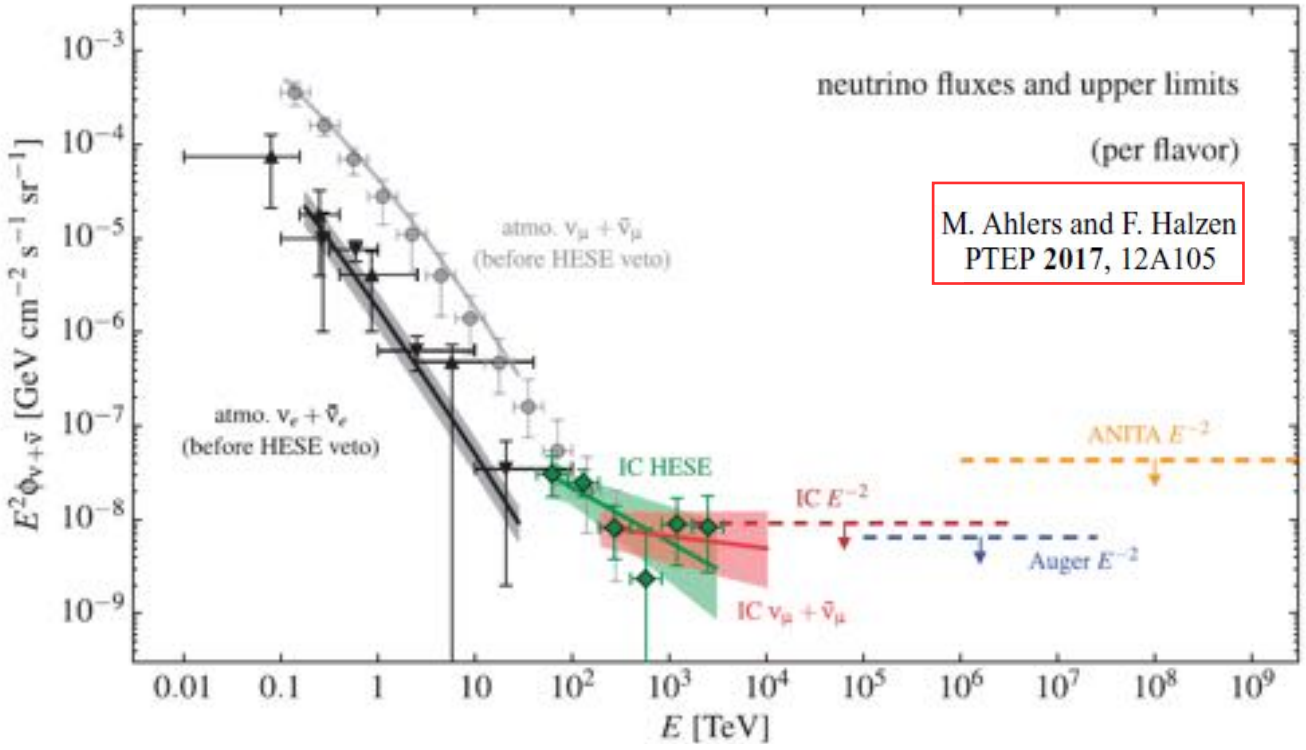
- Deep-sea array of photo-sensors
- 31x3’’-PMTs in one digital optical module (DOM)
- 18 DOMs per Detection Unit, DU
- 115 DUs per building block
- All data to shore

Detecting cosmic neutrinos

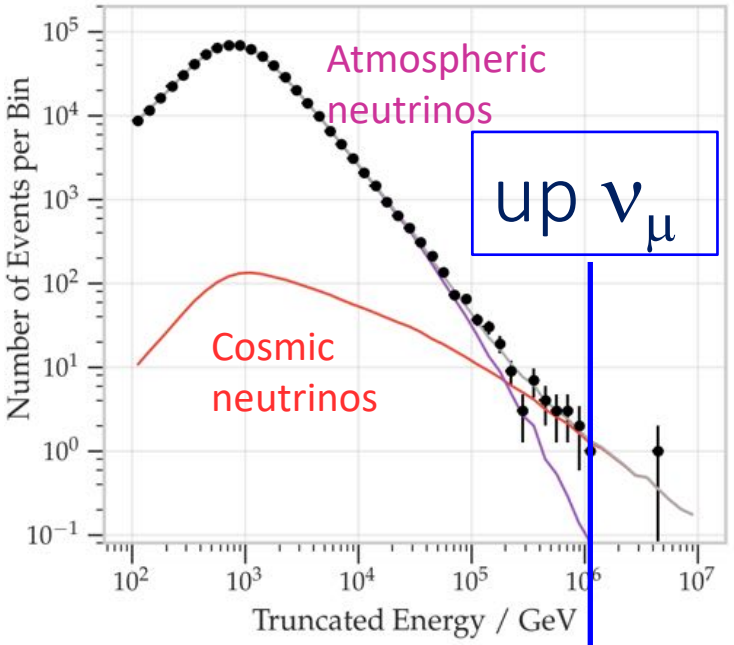
I. Excess in the sky map **(point sources)**. Rely on the detector angular resolution and the measurement of the **ν direction**

✓ II. Excess of HE neutrinos over the background of atmospheric events **(diffuse flux)** +"self veto" for down events. Based on the estimation of the **ν energy.**

✓ III. Coincident event in a restricted time/direction windows with EM/γ/GW. Relaxed ν energy/direction measurement + **transient/ multimessenger** information



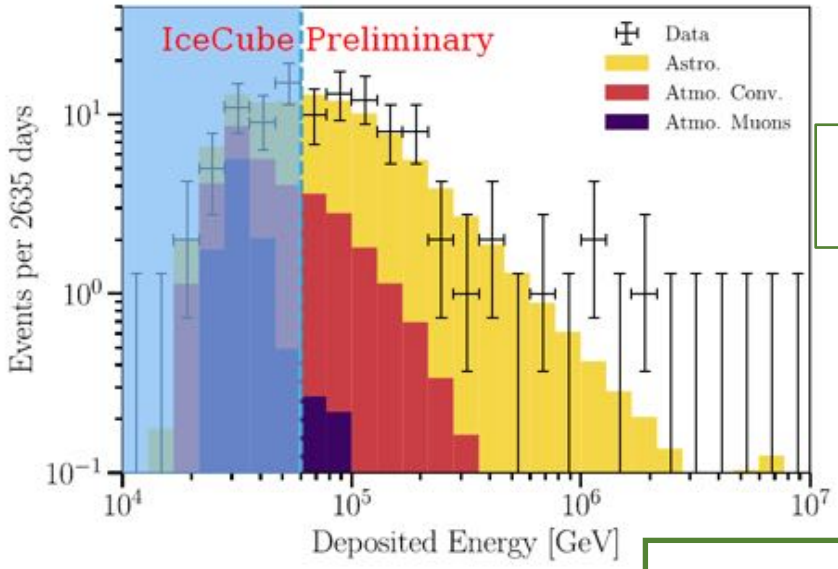
II. Excess of cosmic neutrinos in IceCube (2013→)



up ν_μ

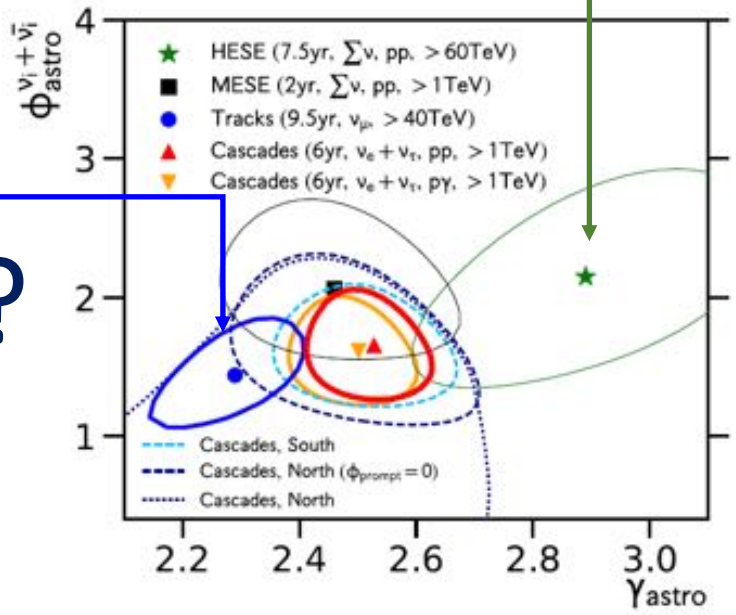
Cosmic flux

$$\frac{dN}{dE} = \Phi \cdot E^{-\gamma}$$



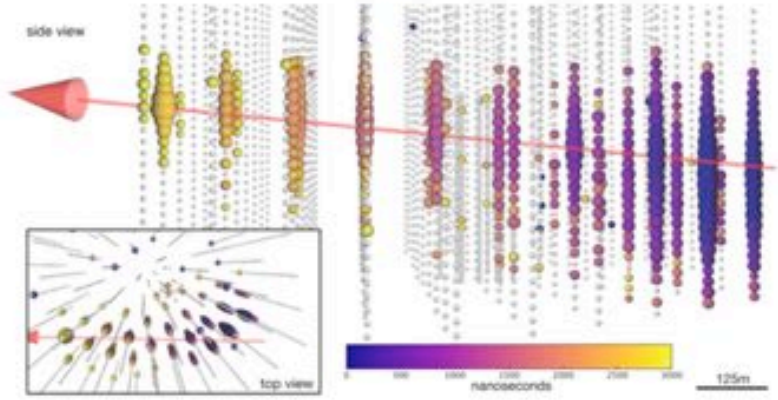
HESE

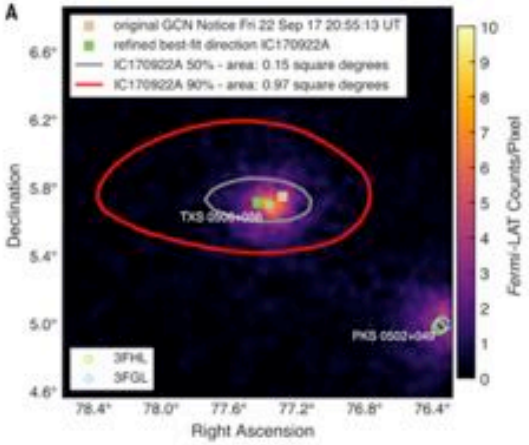
Discrepancy ?



III. Neutrinos from the blazar TXS 0506+056 (2018)

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





Observed by Fermi-*LAT* and MAGIC

Significance for correlation: 3σ

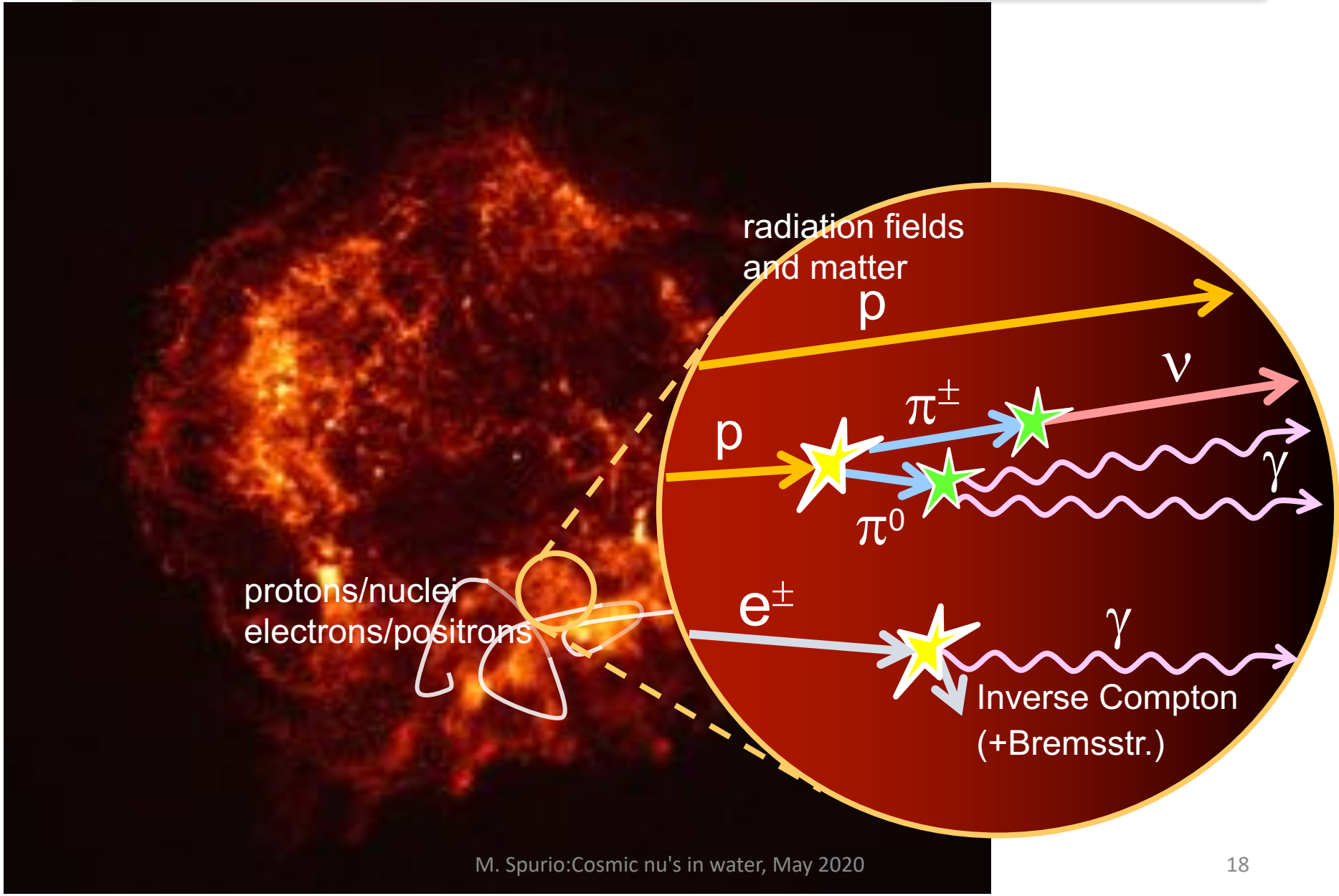
Science 361 (2018) no. 6398, eaat1378

- An **electromagnetic follow-up** campaign of the event IceCube-170922A* indicated that this event came from the direction of a known AGN blazar named TXS 0506+056.
- TXS 0506+056 is a BL Lac object, found at redshift z=0.3365±0.0010
- It was at that time flaring at multiple wavelengths.
- In particular, TXS 0506+056 was monitored by FERMI-LAT and observed by MAGIC after the IC trigger

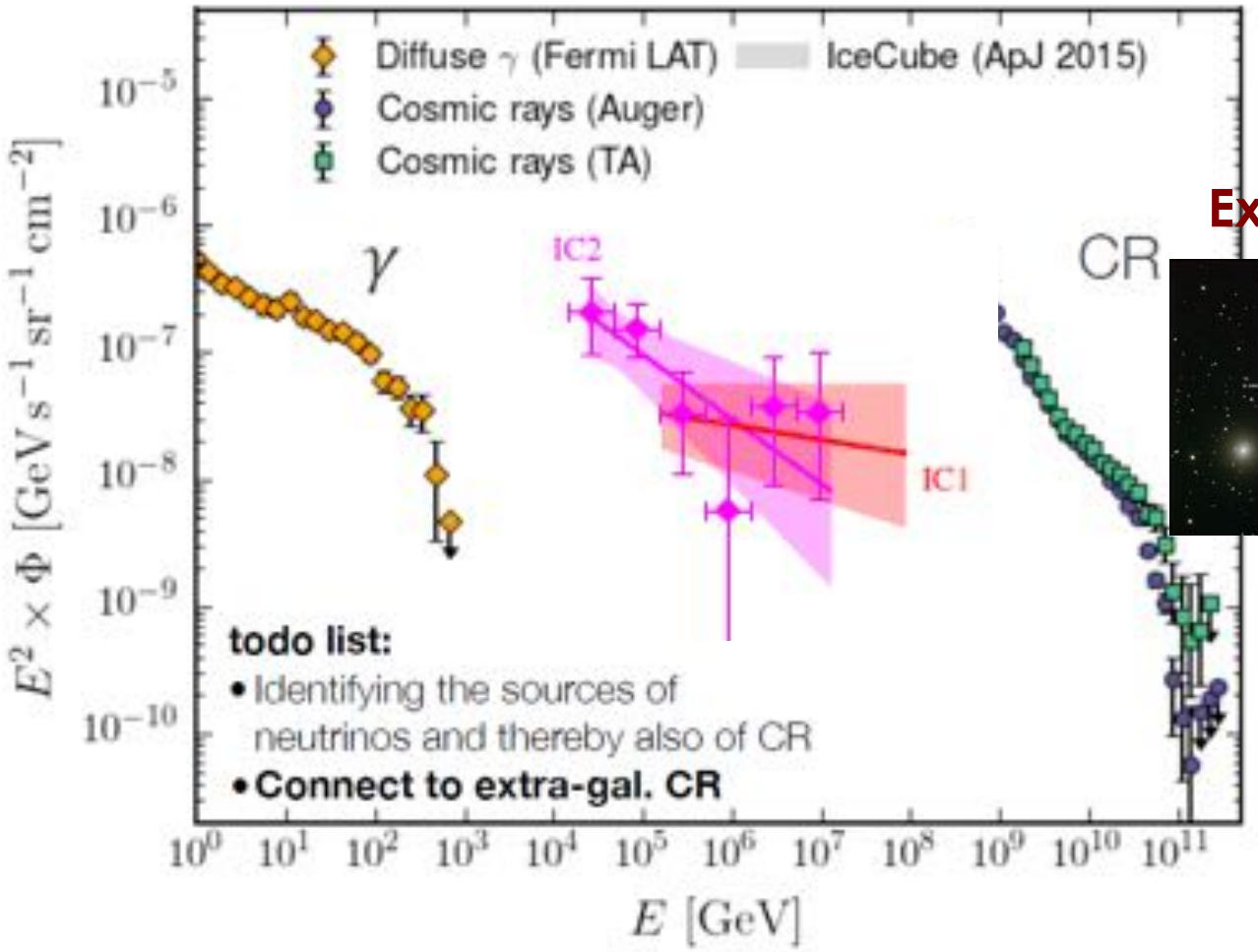
** muon neutrino, angular resolution < 1°*

I. Why we do not have a “neutrino map”?

CRs, γ-rays and neutrinos



The CR, gamma and neutrino connection



ExtraGalactic

CR

Galactic

ExtraGalactic

- **Galactic "TeV-PeVatrons": requires a 1 km3 ν telescope in the Northern hemisphere**

Example: neutrinos from a Galactic source

- TeV γ-rays and ν's can be produced from **photoproduction** **hadronic processes**:

  $p + \gamma \rightarrow \Delta^{+} \rightarrow \pi^{o} + p$

  $p + \gamma \rightarrow \Delta^{+} \rightarrow \pi^{+} + n$

- The same occurs in **beam-dump collisions** of CRs with matter

  $p + p \rightarrow$ many hadrons (mostly $\pi^{+}, \pi^{-}, \pi^{o}$)

- Neutral mesons: $\pi^{o} \rightarrow \gamma\gamma$
- Charged mesons:

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

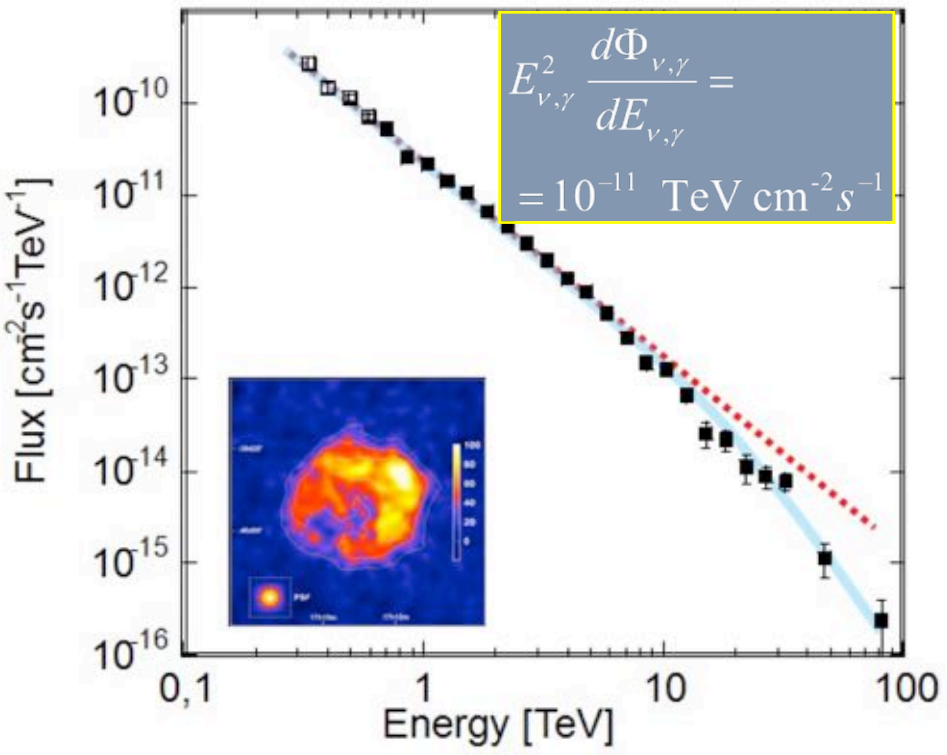
$\pi^{-} \rightarrow \nu_{\mu} + \mu^{-}$ $\quad\quad$ $\mu^{-} \rightarrow \nu_{\mu} + \nu_{e} + e^{-}$

- At first order:

$$\frac{d\Phi_{\gamma}}{dE} \cong \frac{d\Phi_{\nu}}{dE}$$

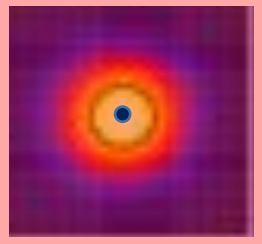
- Refer to: F.L. Villante , F. Vissani , **Phys. Rev. D 78 (2008) 103007**

RX J1713.7-3946 *as seen by H.E.S.S.)*



Signal and background for a Point Source

Signal: $\Phi_s, \frac{\nu_s}{cm^2 \cdot s \cdot GeV}$



Detector PSF, $\Delta\theta$

Background: $\mathrm{B}, \frac{\nu_b}{cm^2 \cdot s \cdot sr \cdot GeV}$

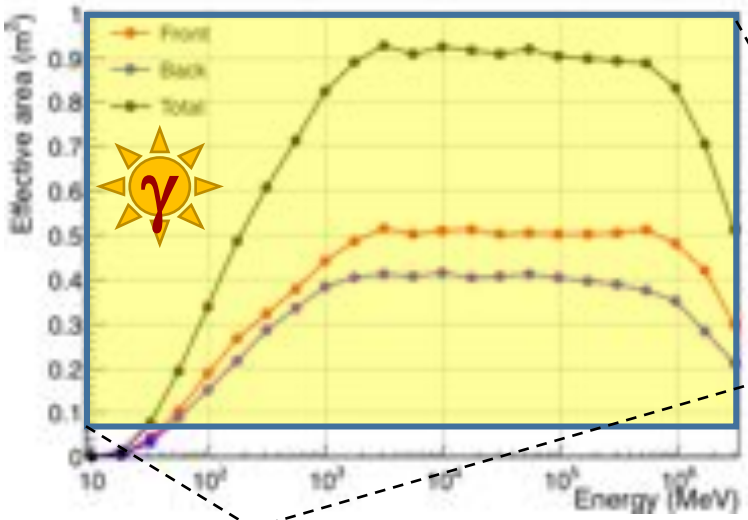
$$N_B = T \int dE \cdot A_{eff} \cdot \mathrm{B} \cdot (\Delta\theta)^2$$

$$N_s = T \int dE \cdot A_{eff} \cdot \Phi_s$$

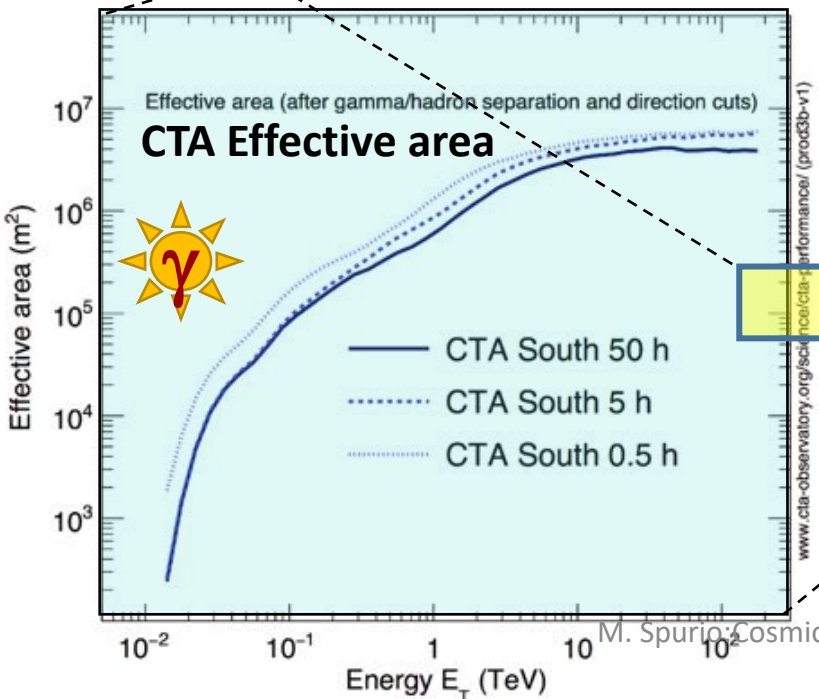
The signal/noise ratio, N_s/N_B increases with a better depends on key experimental quantities:

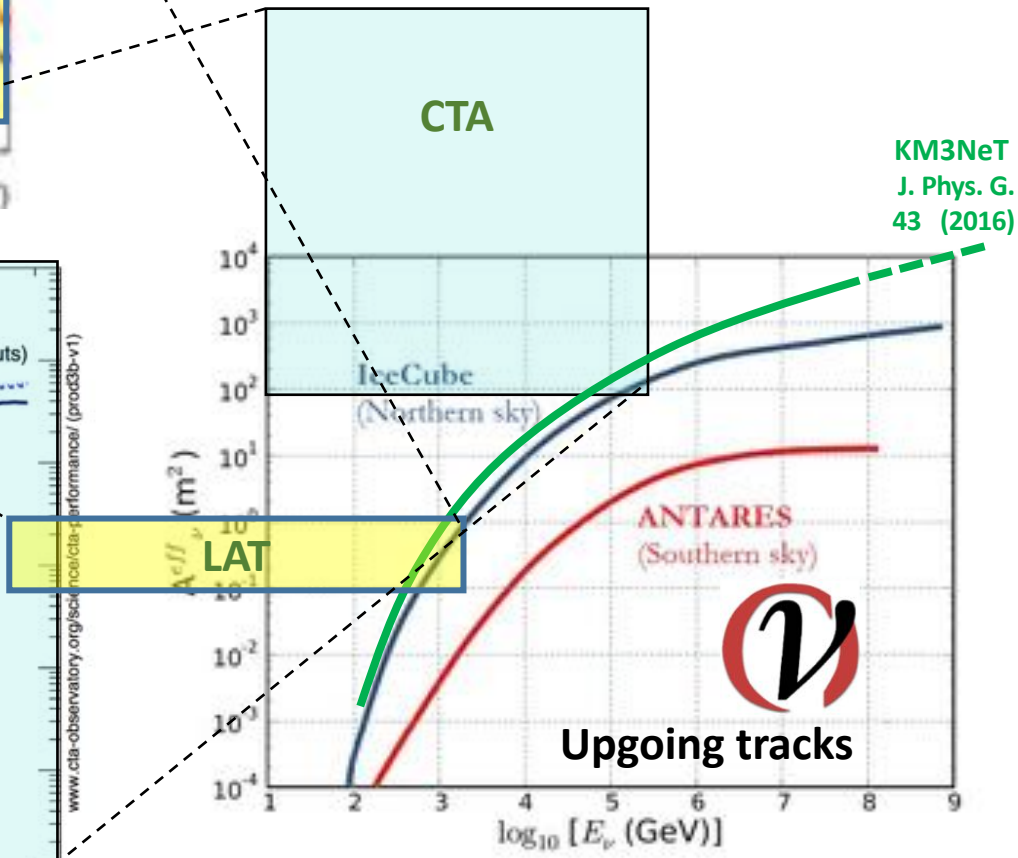
- **Effective area**
- **Angular resolution**

Detecting ν: effective area A_{eff}

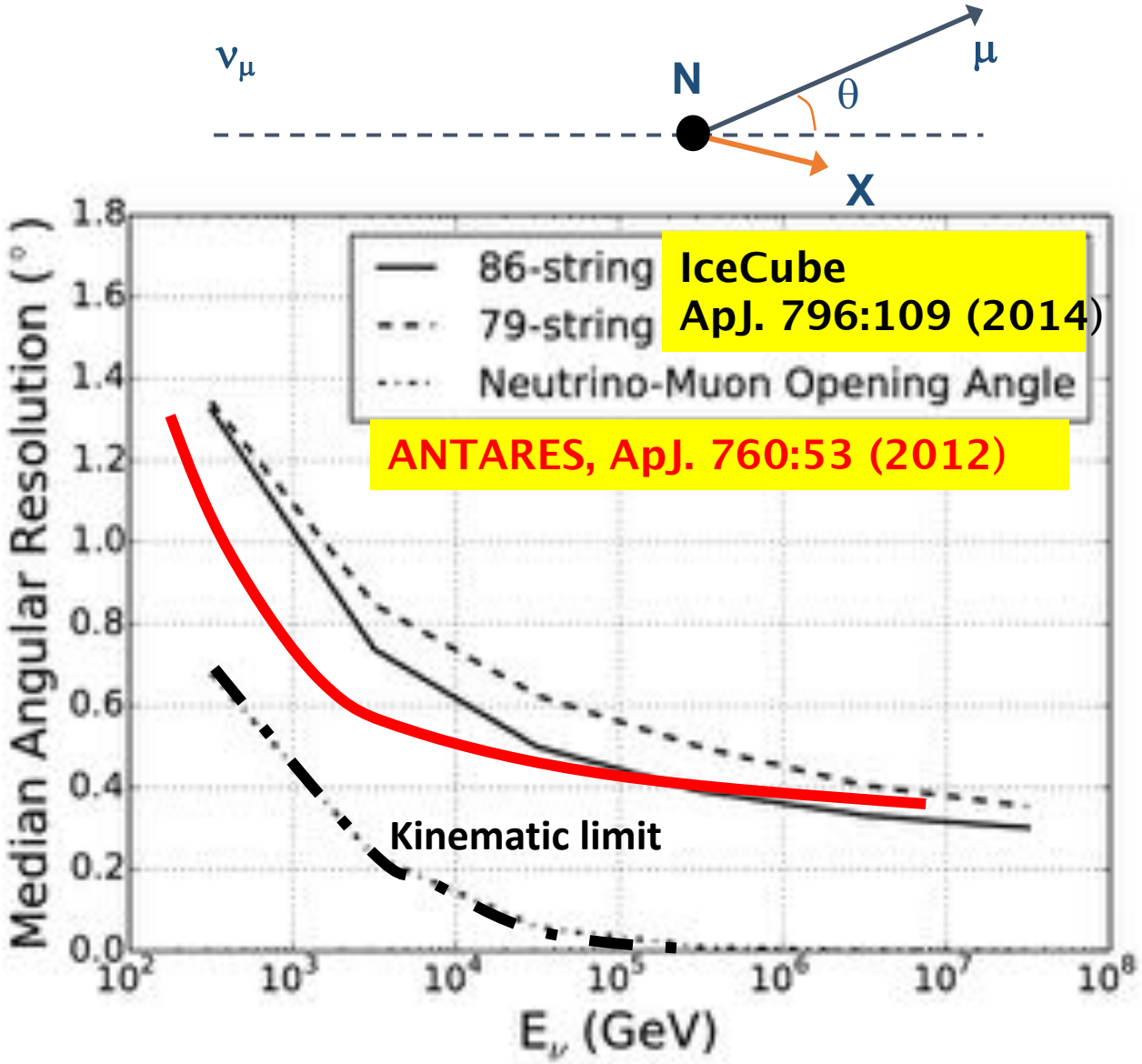


Fermi-LAT *effective area vs. E*

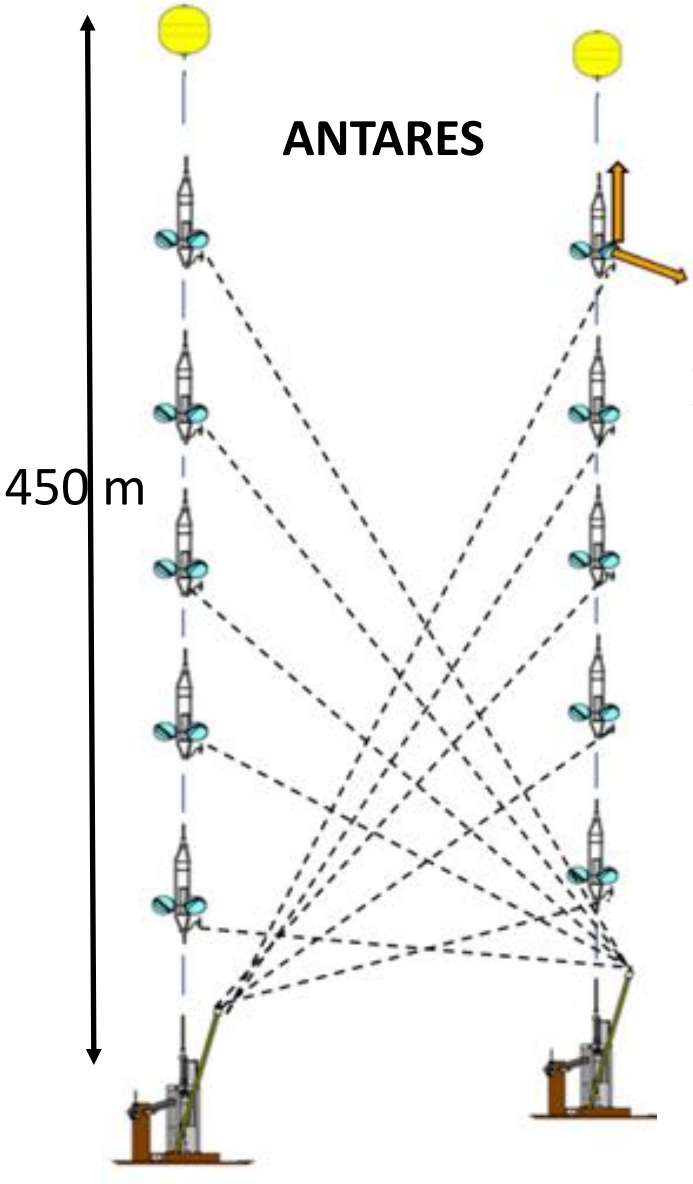




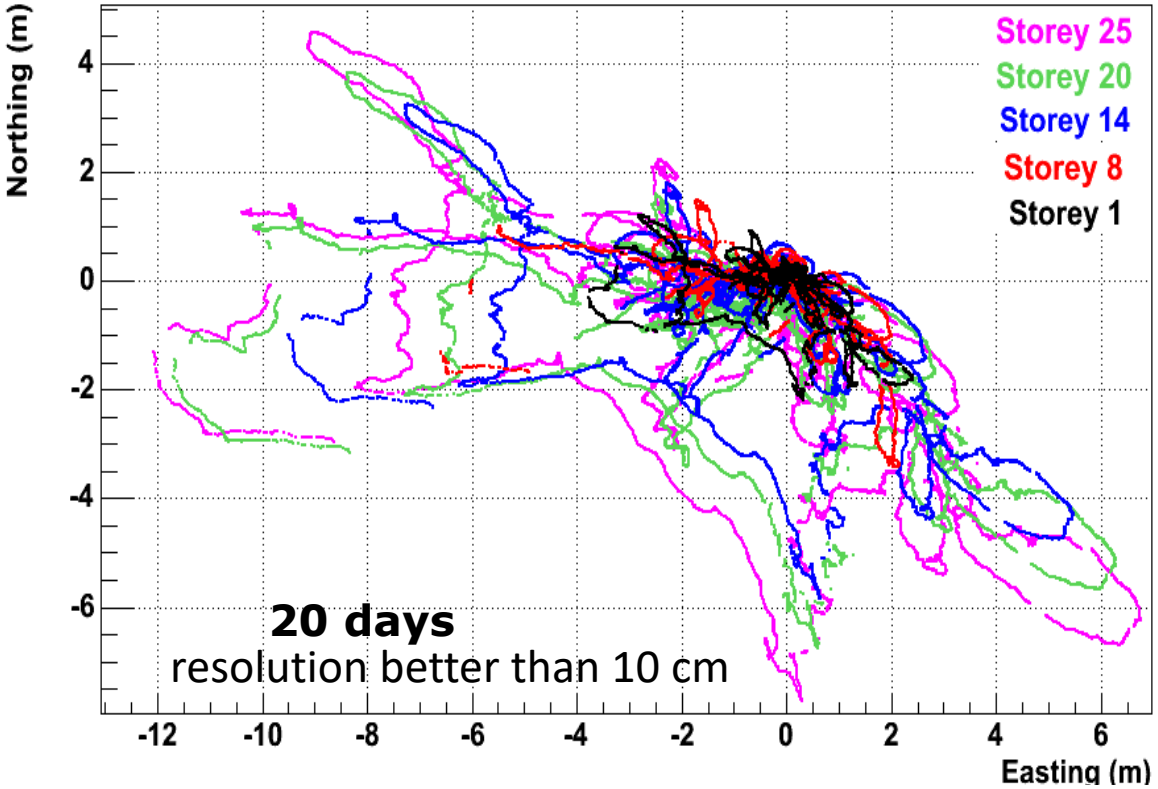
(Median) Angular resolution- present detectors



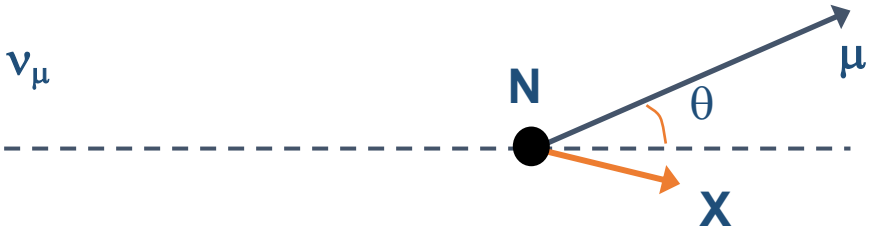
Positioning of the detector in seawater

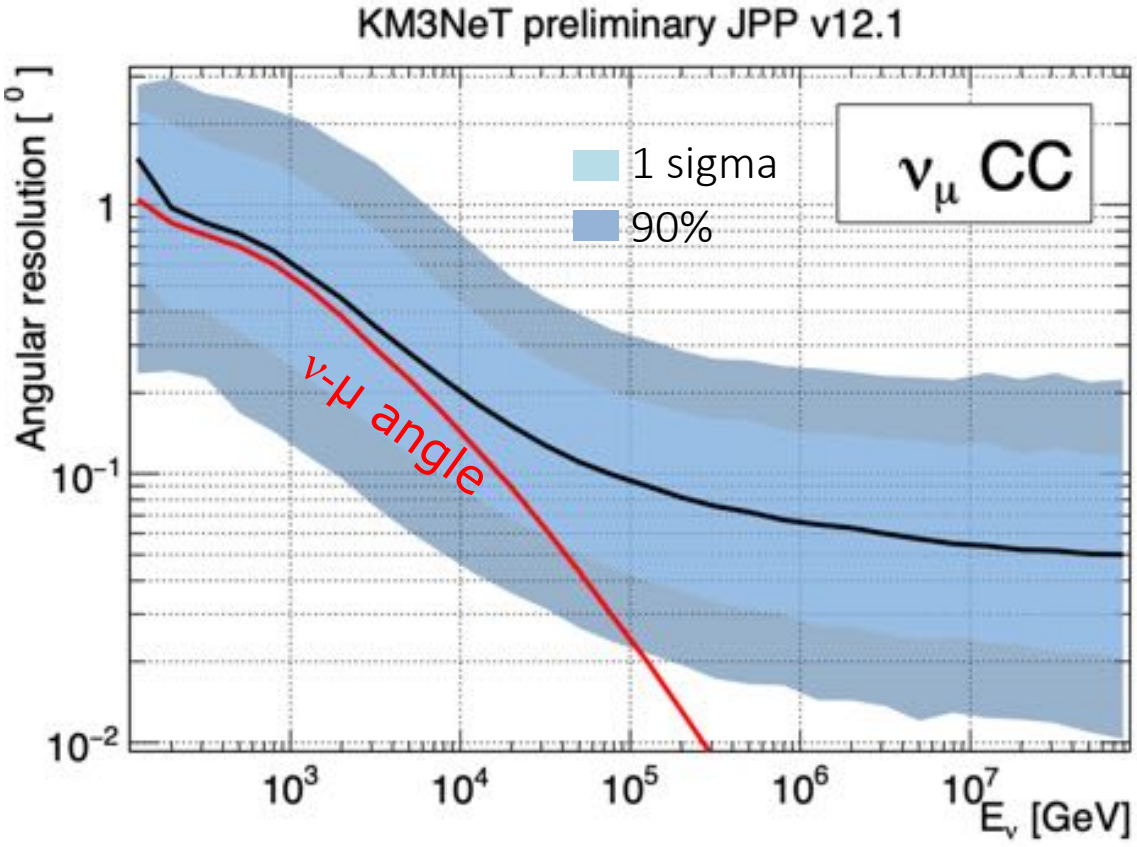


- Transceivers on the bottom of each line
- Hydrophones at specific heights on each line
- Autonomous transponders around the apparatus
- Sound velocimeters installed at various depths
- Tiltmeter and compass at each storey
- Measurements performed every 2 minutes

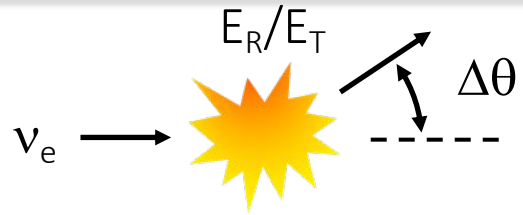


KM3NeT: Track angular Resolutions

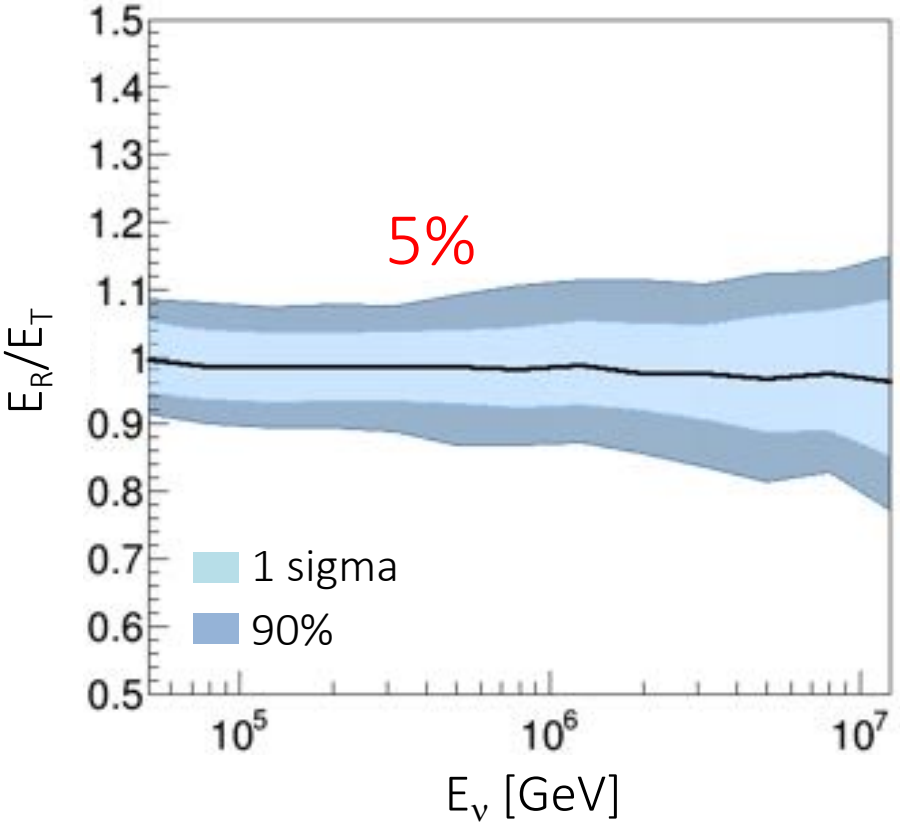




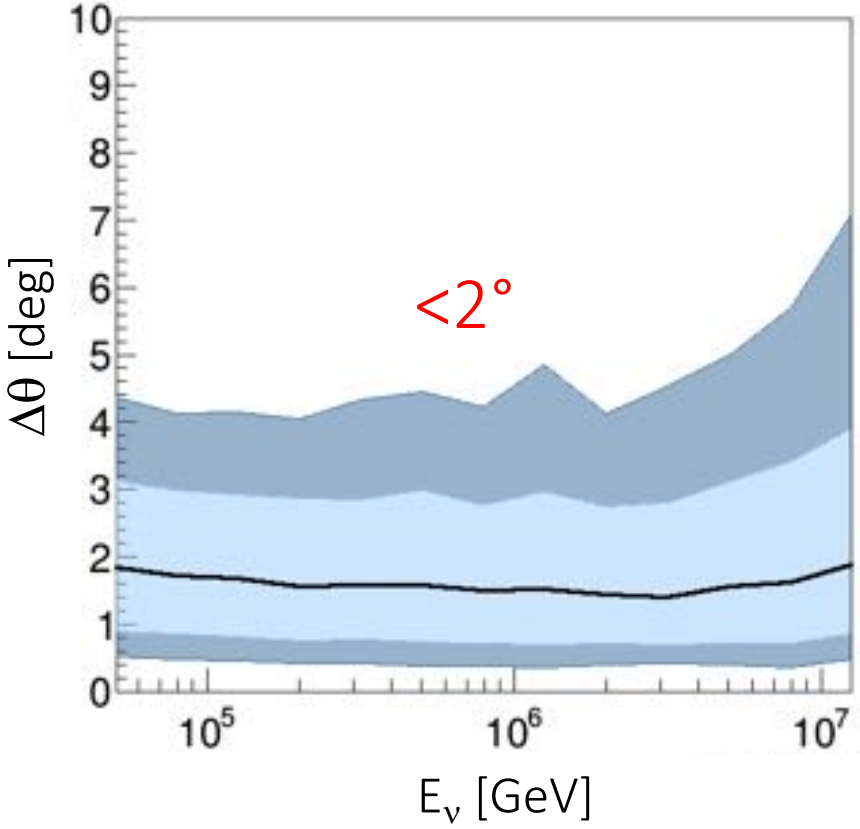
KM3NeT/ARCA: Cascade Resolutions



Energy

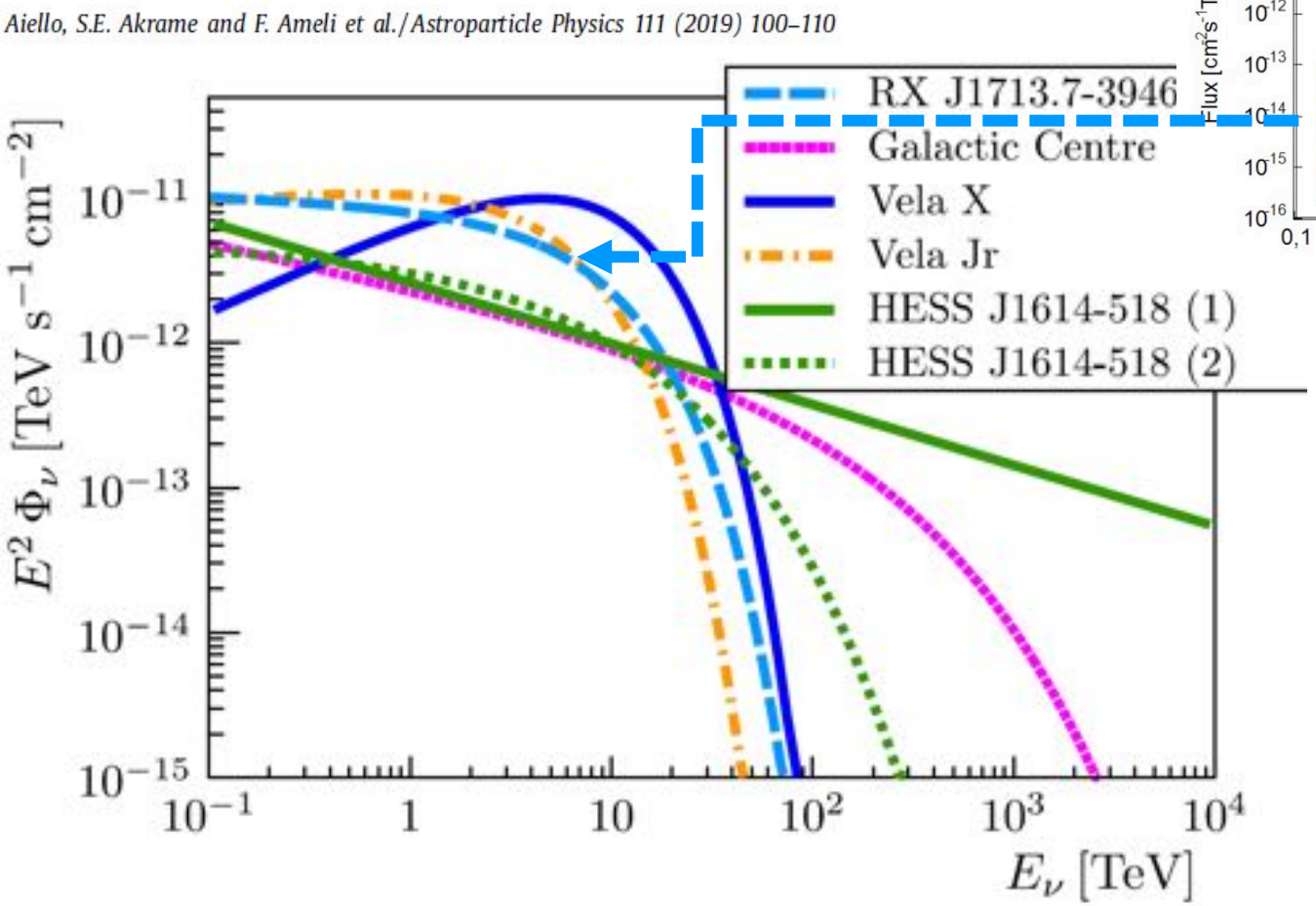


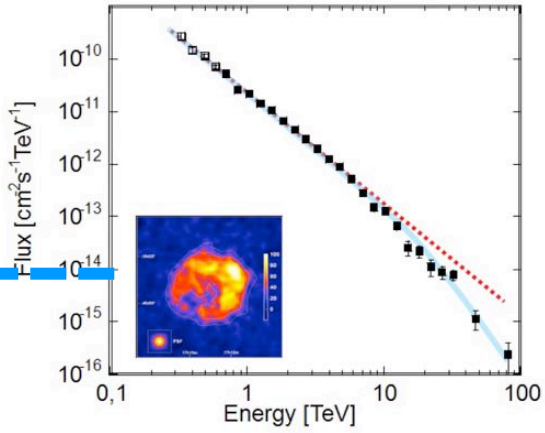
Direction



Are they enough?

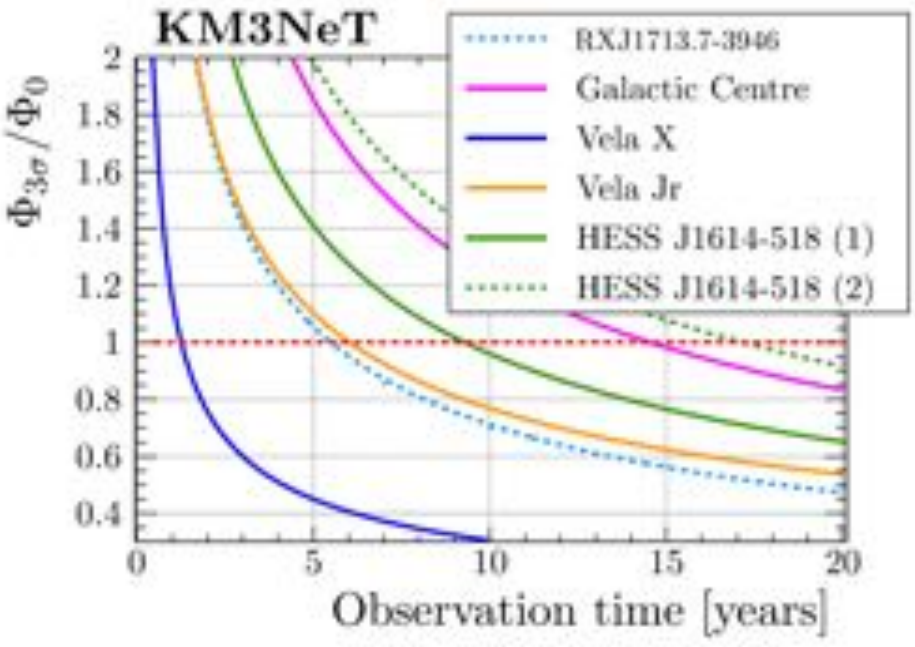
Galactic fluxes

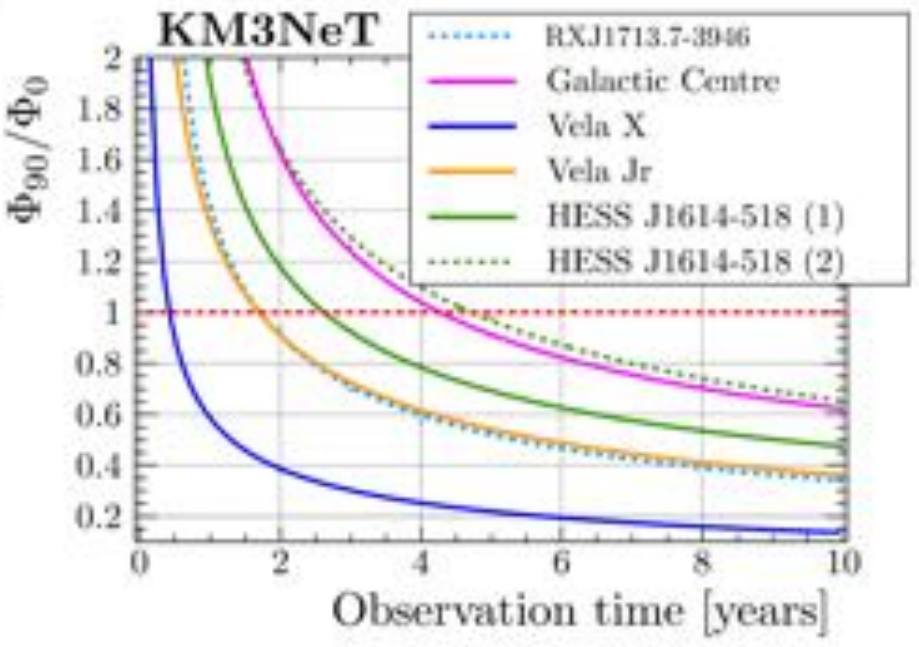




$$\Phi_\nu(E) = k_0 \left(\frac{E}{1\,\mathrm{TeV}}\right)^{-\Gamma} \exp\left[-\left(\frac{E}{E_{\mathrm{cut}}}\right)^{\beta}\right],$$

Expectations for KM3NeT

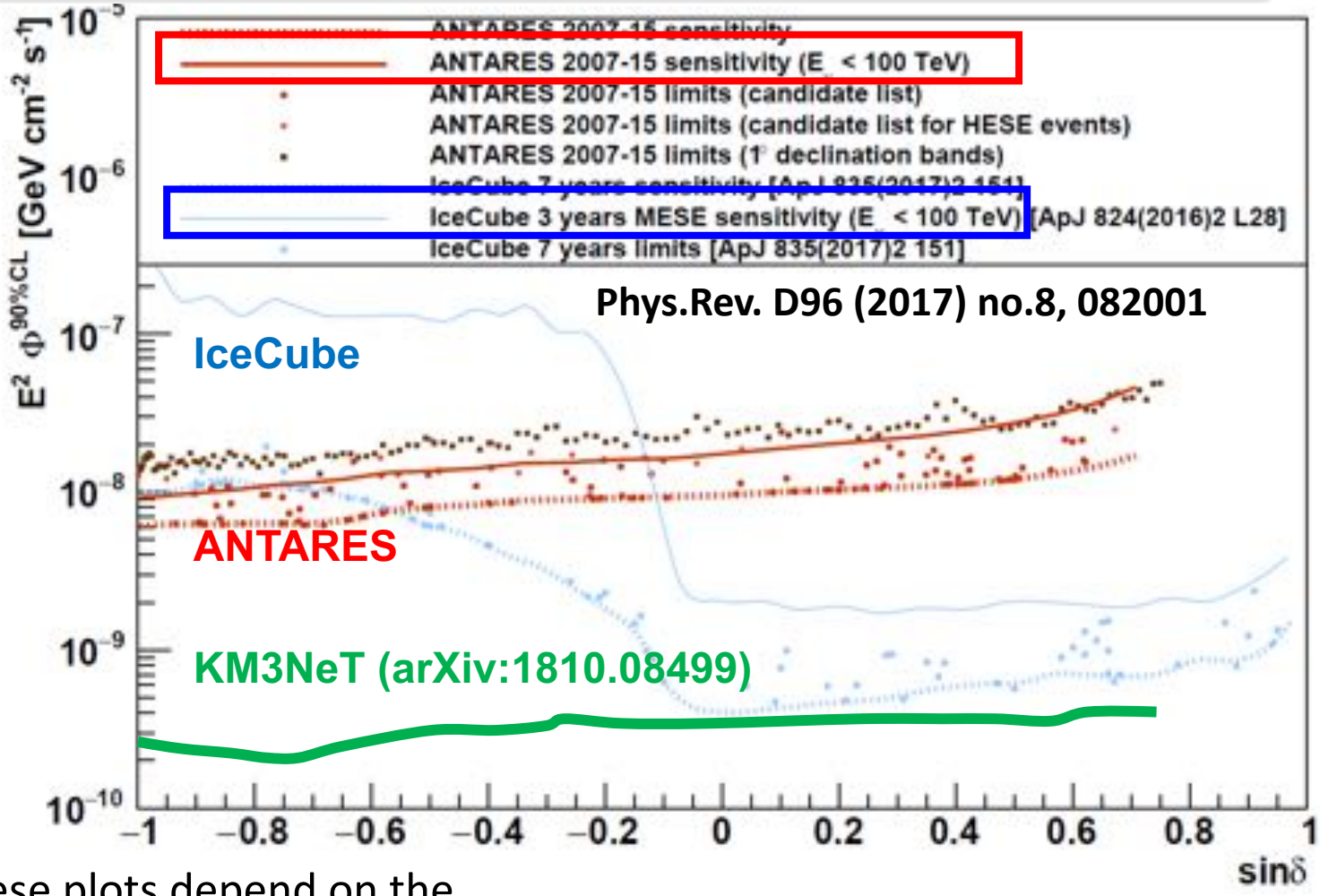




Ratio of the **discovery potential $\boldsymbol{\Phi_{3\sigma}}$** (left) and **sensitivity $\boldsymbol{\Phi_{90}}$** (right) to the expectation flux Φ_0 as a function of the observation time for the three fluxes assumed.

Question for further discussion: do you know a definition of *sensitivity* of an experiment and its *discovery potential* (at a given C.L.) ?

U.L. and Sensitivities (also E_ν<100 TeV)



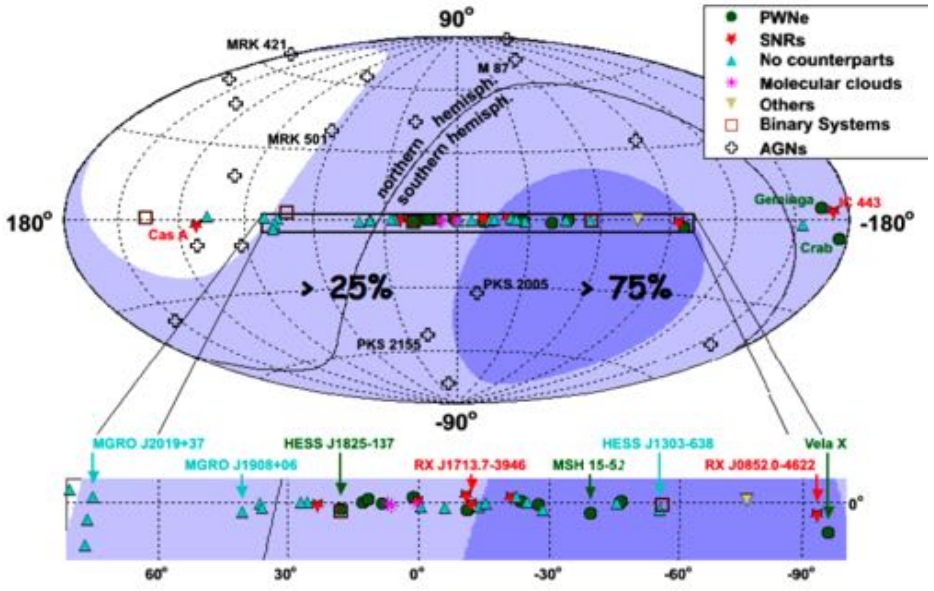
Note: these plots depend on the

- assumed **spectral index** of the source
- differential **energy sensibility** of the detector

Neutrino telescopes in the Mediterranean sea

- **Upgoing events**: O(0.1°) **angular resolution** for tracks; O(3°) for showers
- **Complementary f.o.v.** for Mediterranean and South Pole detectors. Most of the Galactic plane seen as "upgoing events"
- **Online analysis**, fast response (few seconds), immediate alert
- Water is an homogeneous medium, but detectors need **for positioning calibrations** due to sea currents

- Very high **duty cycle** (~100%)
- Large observation **solid angle** (2π upgoing events, 4π in fiducial volume)
- Telescopes in water optimized for E_ν<100 TeV
- ν's not significantly absorbed by the Earth for E_ν<100 TeV



The near future: KM3NeT

- **KM3NeT** is the neutrino research infrastructure in the deep Mediterranean Sea
  - Study of high neutrino sources in the Universe

  ARCA (off shore Capo Passero, It @ 3500 m depth)
  - Determine neutrino mass hierarchy

  ORCA (off shore Toulon, Fr @2500 m depth)
- Same collaboration, same technology, two installation sites
  - 15 Countries
  - 55 Institutes
  - >240 Scientists
  - Number of Institutes and

  Scientists constantly increasing
- Here, ARCA (Astrophysics) features presented

KM3NeT: A Phased Approach

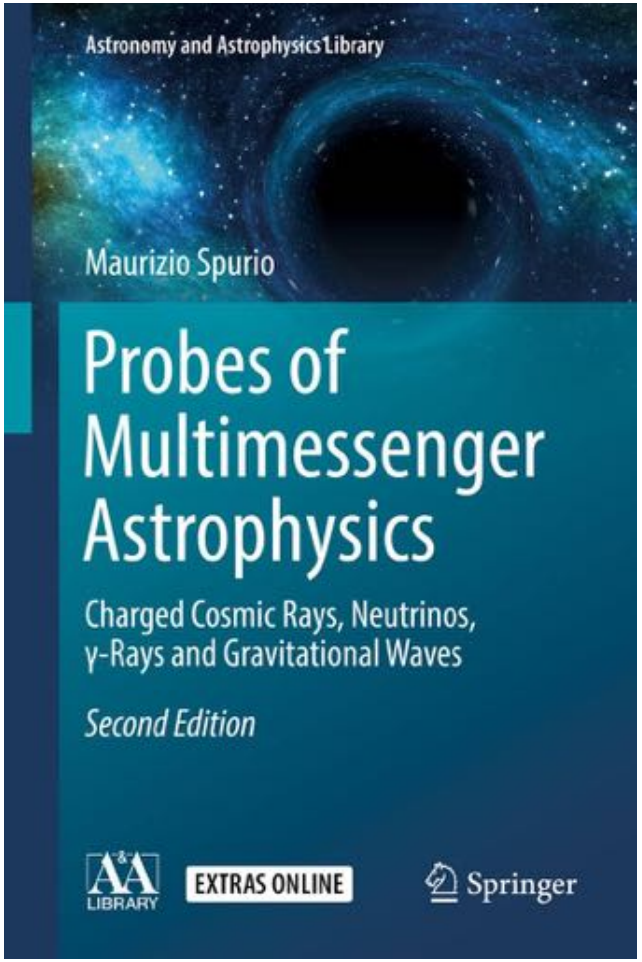
PHASE	BLOCKS	PRIMARY DELIVERABLES	FUNDS
1	0.2	Proof of feasibility and first science results **24 ARCA strings** + 6 ORCA	Fully funded
2	2+1	All flavor neutrino physics and astronomy **2 x 115 ARCA strings** 1 x 115 ORCA strings	Funding in progress
3	6	Neutrino astronomy including Galactic sources	Not yet

- **KM3NeT** LoI: *J. Phys. G*, **43** (2016) 084001
- H2020: funds to prepare the ERIC
- Since 2016 (2018) **KM3NeT** is back in the ESFRI (APPEC) roadmap
- The process to build the **KM3NeT** ERIC is in progress

More information available

My "preprint" version of the book freely available:
https://www.dropbox.com/s/31mhpdxrgc2qse0/astroparticle-IIedc.pdf?dl=0

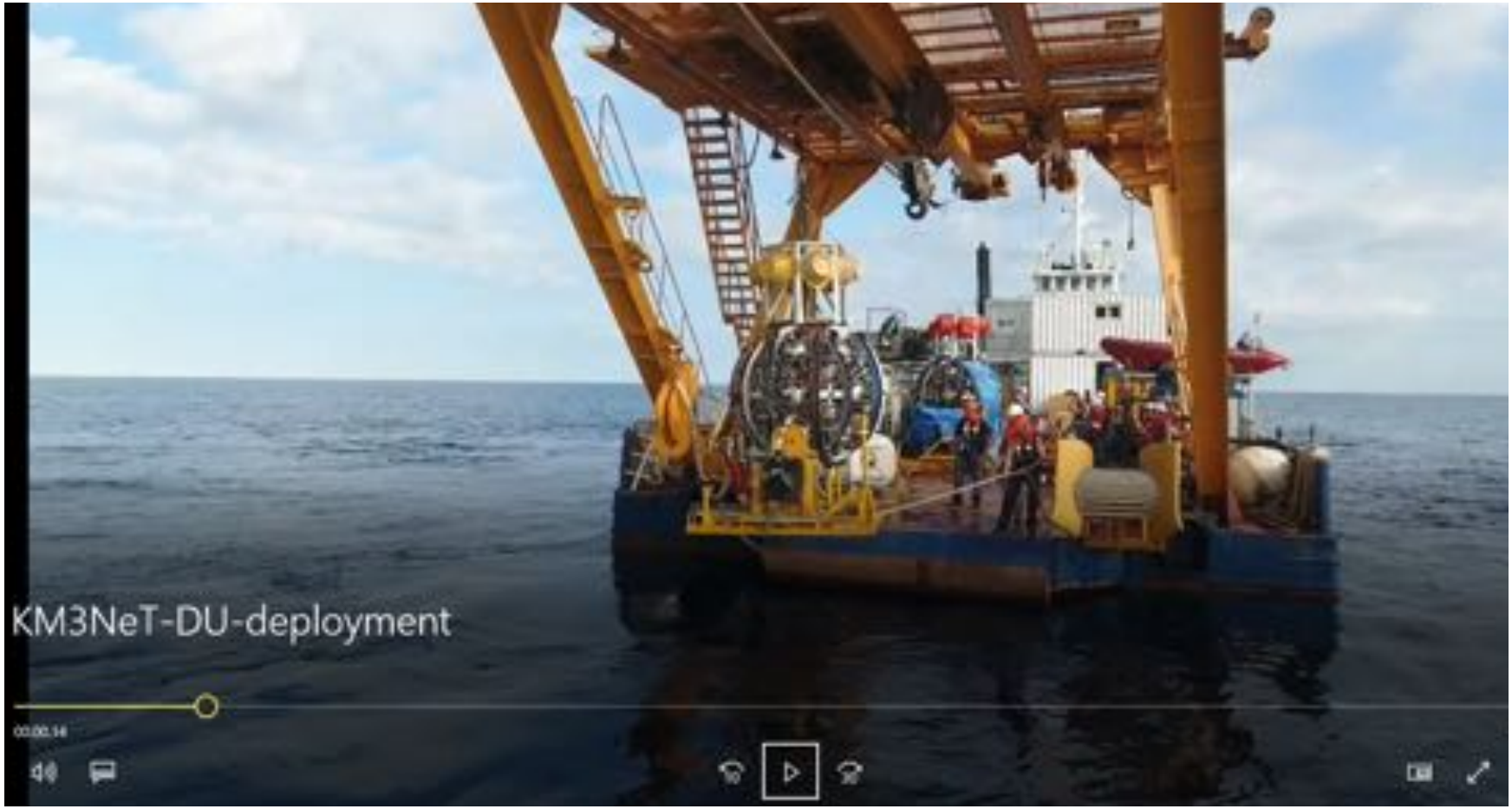
1. An Overview of Multimessenger Astrophysics
2. Charged Cosmic Rays in Our Galaxy
3. Direct Cosmic Ray Detection
4. Indirect Cosmic Ray Detection
5. Diffusion of Cosmic Rays in the Galaxy
6. Galactic Accelerators and Acceleration Mechanisms
7. The Extragalactic Sources and UHECRs
8. The Sky Seen in γ-rays
9. The TeV Sky and Multiwavelength Astrophysics
10. **High-Energy Neutrino Astrophysics**
11. **Atmospheric Muons and Neutrinos**
12. **Low-Energy Neutrino Physics and Astrophysics**
13. Basics on the Observations of GravitationalWaves
14. Microcosm and Macrocosm



Summary and Perspectives

- ν fundamental probe to identify the production sites of high energy cosmic particles and test the neutrino sector of the SM and BSM
- ν are key ingredient of multi-messenger astronomy
- A ν telescope in the Mediterranean Sea is fundamental to understand the origin of IceCube HE astrophysical neutrinos
- ν telescopes: opportunities for precision measurements in ν physics
- ANTARES: more than 10 years of continuous data taking! Data taking up to the end of GW O3 (COVID-19 postponed the May 2020 start of decommissioning)
- ANTARES results from various searches of astrophysical ν emission.
  - (point-like, diffuse, extended regions, dark matter, …)
- ANTARES/KM3NeT active multi-messenger program
- Best practice and multi-messenger collaborations ported to KM3NeT!
- Galactic “TeV-PeVatrons”: necessary a ν telescope in the Northern hemisphere

Work in progress…

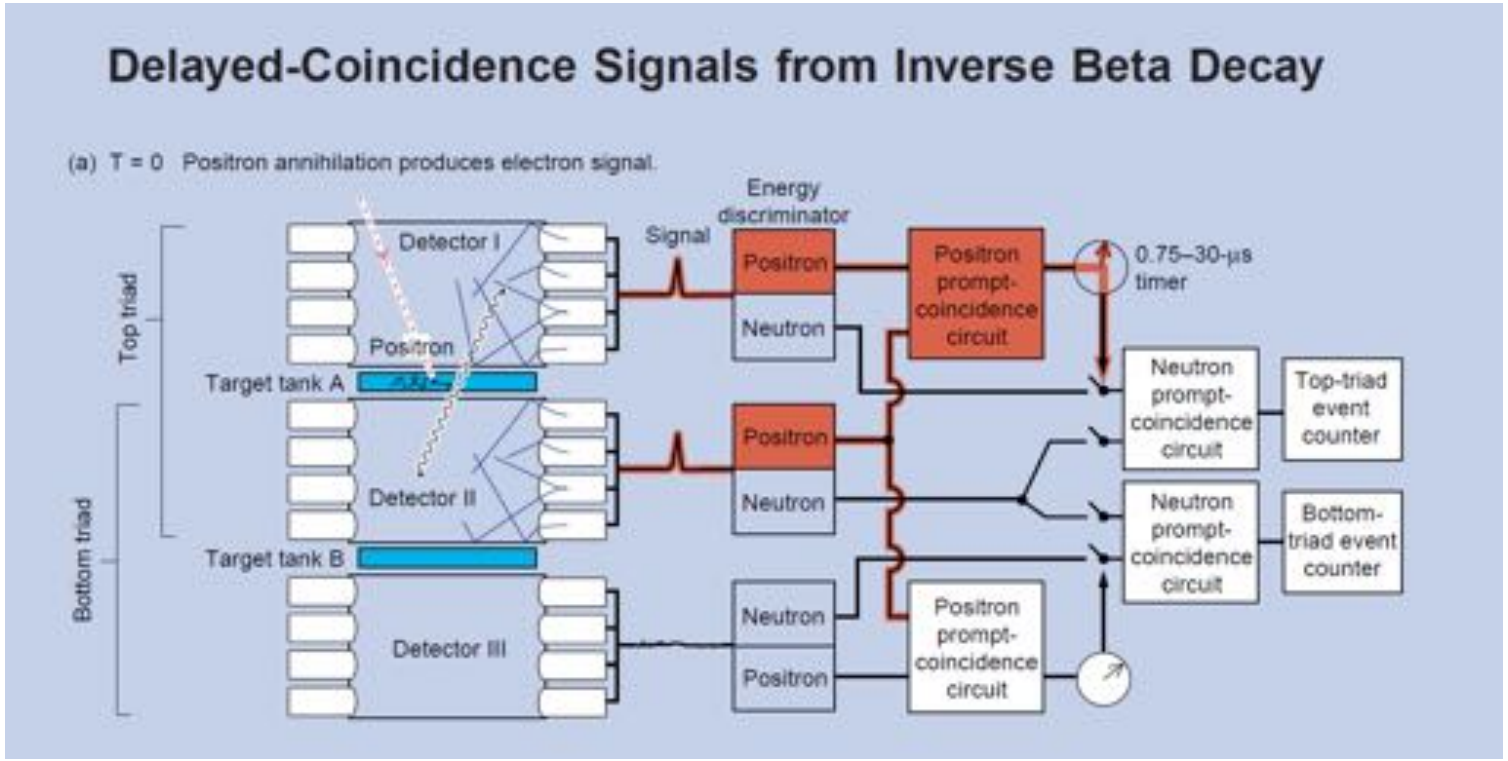


Spares

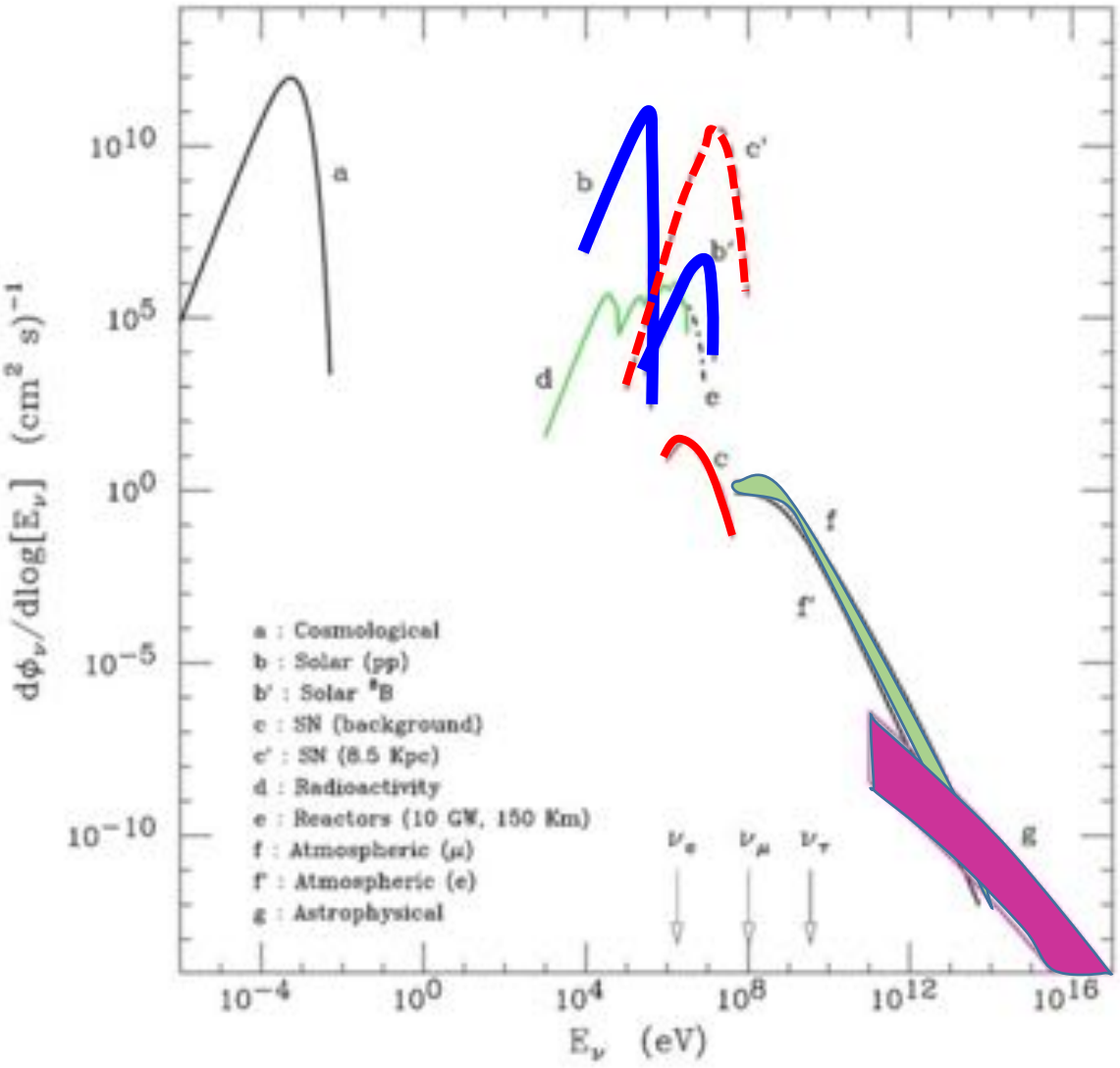
Neutrino have been discovered in water (1955)

- Neutrinos ($\bar{\nu}_e$) have discovered in water by the Cowan & Reines experiment (1955) , see:

https://permalink.lanl.gov/object/tr?what=info:lanl-repo/lareport/LA-UR-97-2534-02



Neutrinos from the Cosmos

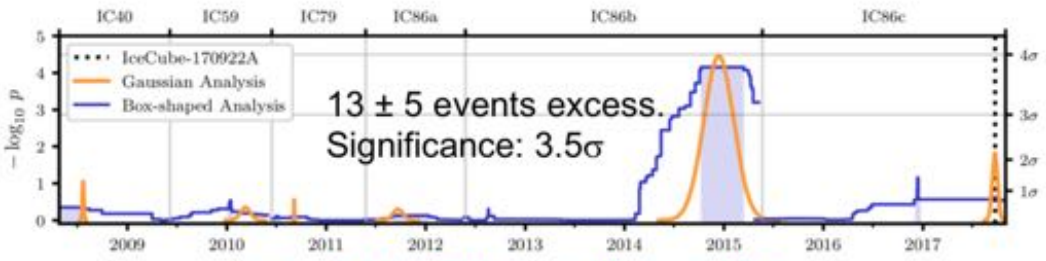


Flux of neutrinos at the surface of the Earth.

- Atmospheric neutrinos
- Solar neutrinos
- ν's from stellar gravitational collapse
- HE cosmic neutrinos

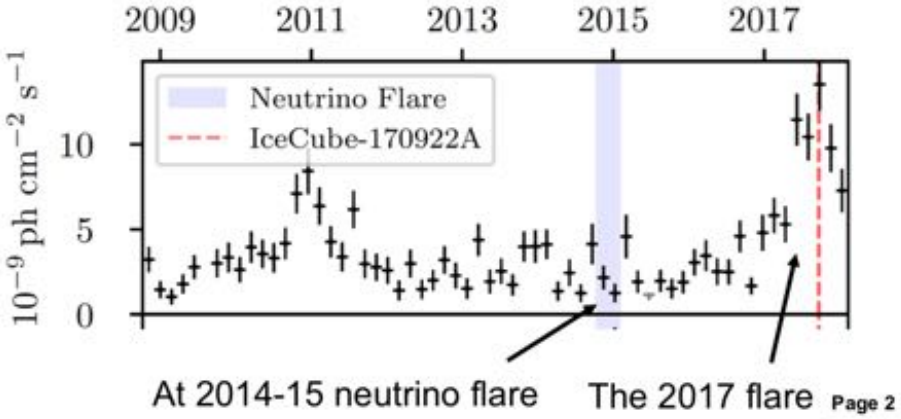
Neutrinos from the blazar TXS 0506+056 (II)

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

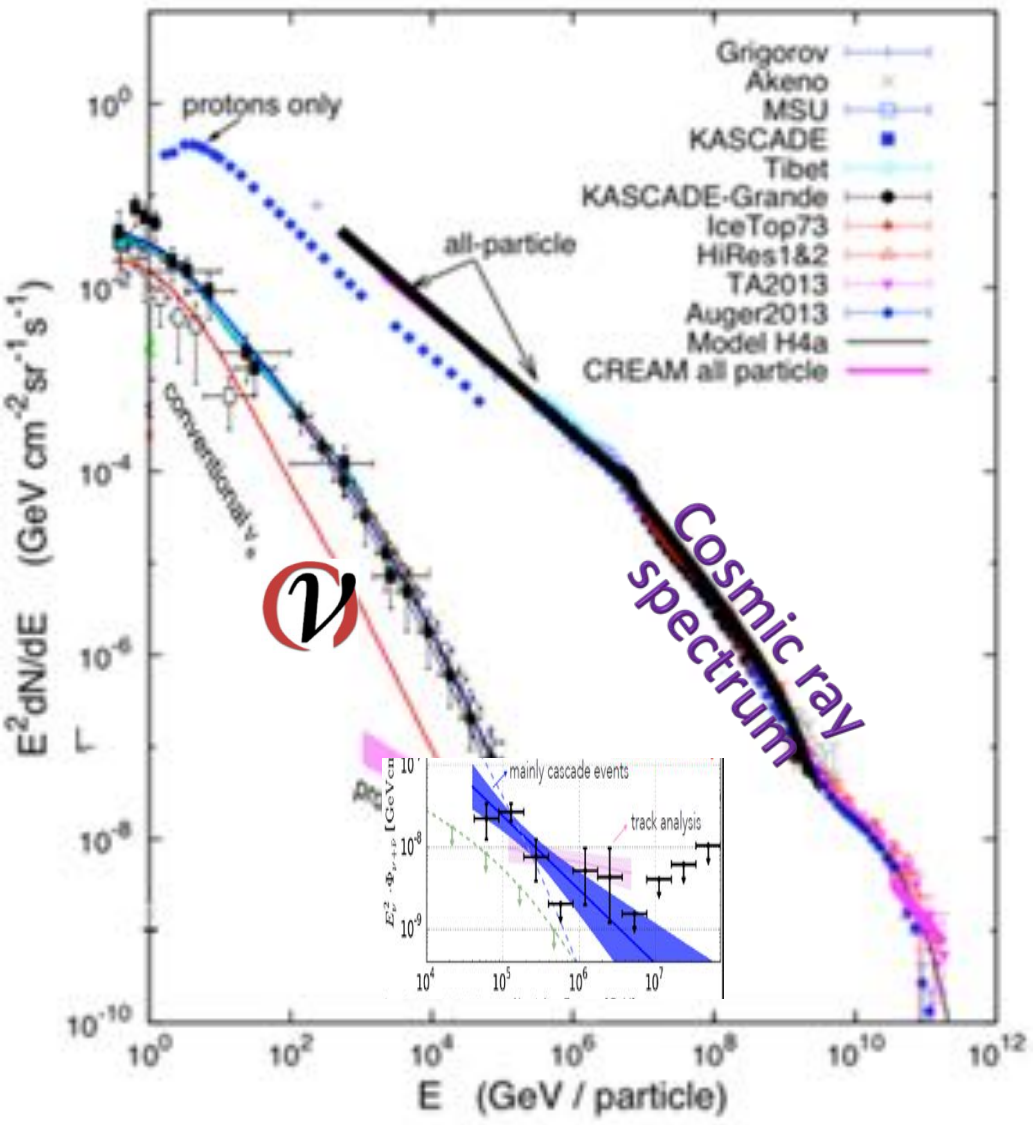


PoS(ICRC2019)1032

- A further analysis of **archival IceCube data** revealed that this blazar was emitting neutrinos before;
- Within Oct. 2014-March 2015 an excess of 13±5 events over background was found.
- During this period, there was no significant EM flaring activity
- Not simple theoretical interpretation

IceCube conclusion: **Compelling evidence** of a HE ν from a blazar

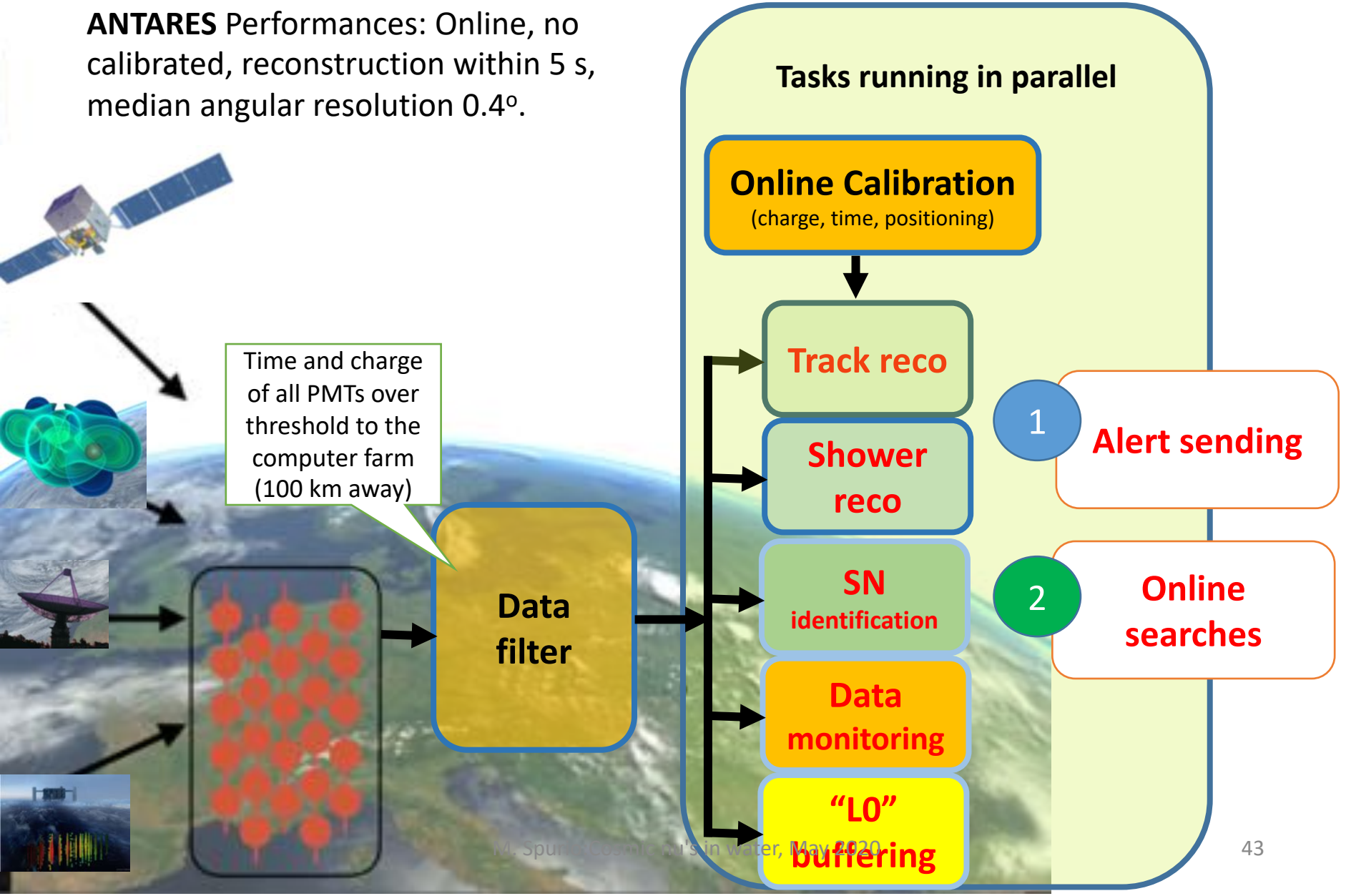
Open questions for neutrino astrophysics



- Neutrino: fundamental probe to identify galactic and extragalactic **Cosmic Ray (CR) sources**
- **Origin** of IceCube HE astrophysical neutrinos
- **Production sites** of high energy cosmic particles
- Study of galactic and extra galactic **propagation of CR** with neutrinos as tracers
- Test the neutrino sector of the SM and BSM physics
- **Galactic "TeV-PeVatrons": necessary a ν telescope in the Northern hemisphere**

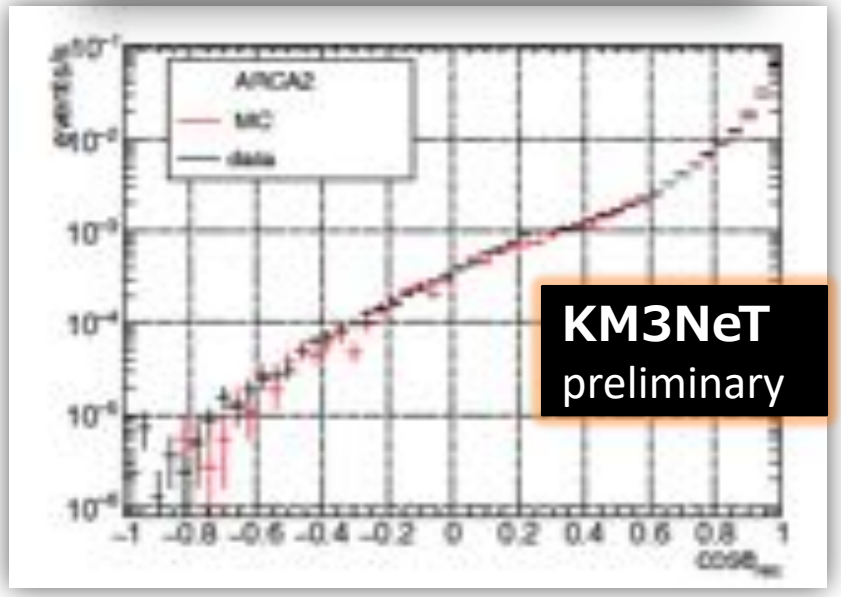
KM3NeT online alert system

ANTARES Performances: Online, no calibrated, reconstruction within 5 s, median angular resolution 0.4°.



The Detection Units (DUs)

DOM



- **18 DOM** in one DU string
- Strings arranged on the LOM, ready for deployment