X.
High Energy neutrino Astrophysics

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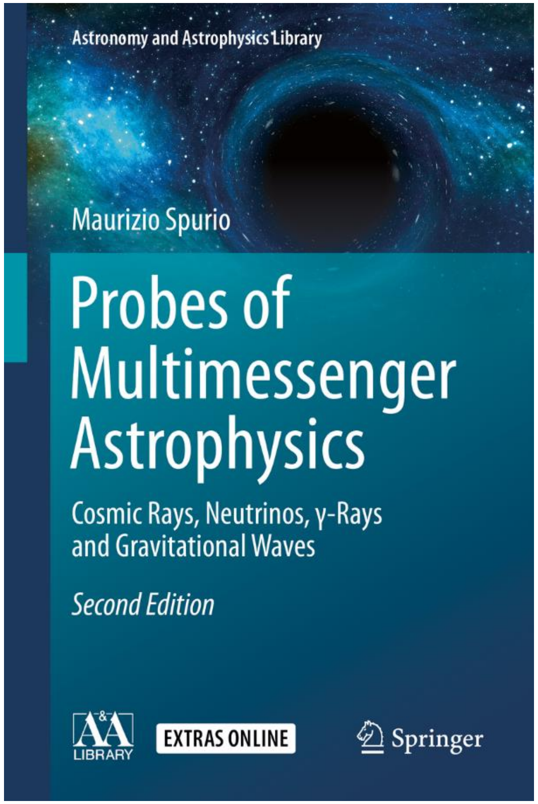
Content



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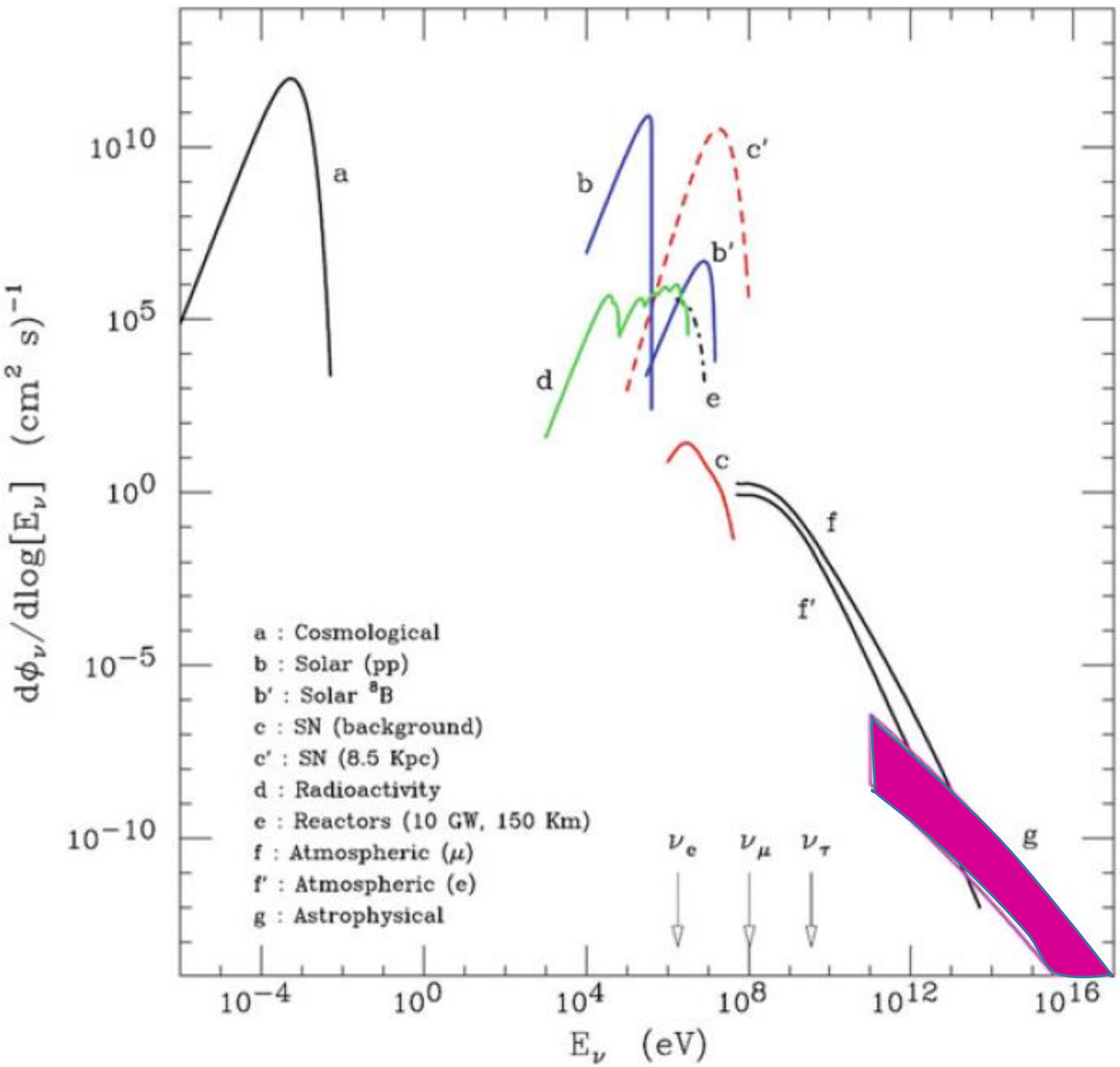
Neutrinos from the Cosmos



Flux of neutrinos at the surface of the Earth.

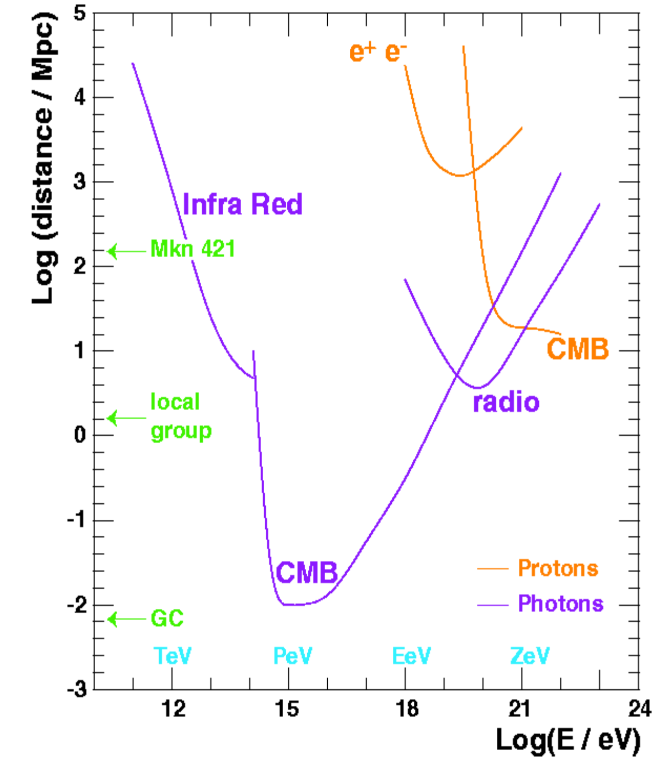
Arrow indicate the energy threshold for CC production of the charged lepton

- Big Bang neutrinos
- Neutrinos from the Sun
- Neutrinos from SNe
- Atmospheric neutrinos
- High-energy cosmic neutrinos

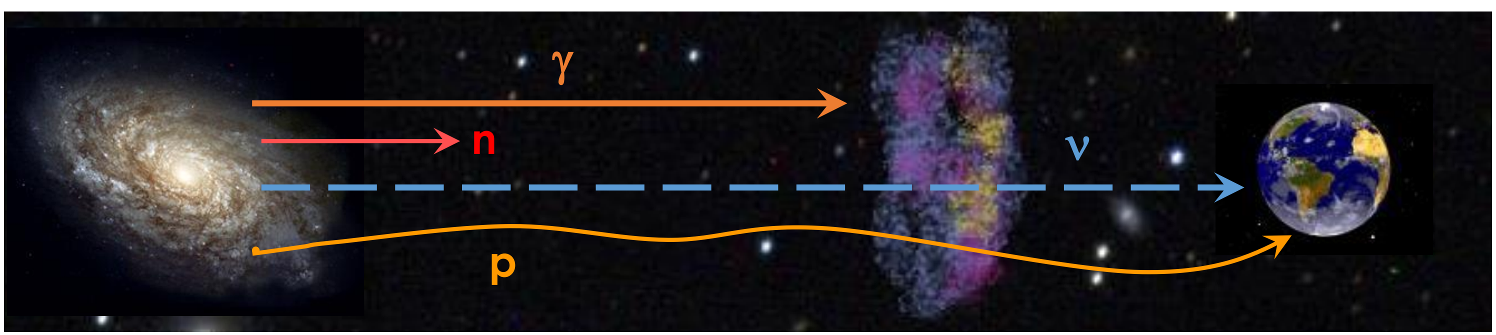
Why HE neutrino astronomy?

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

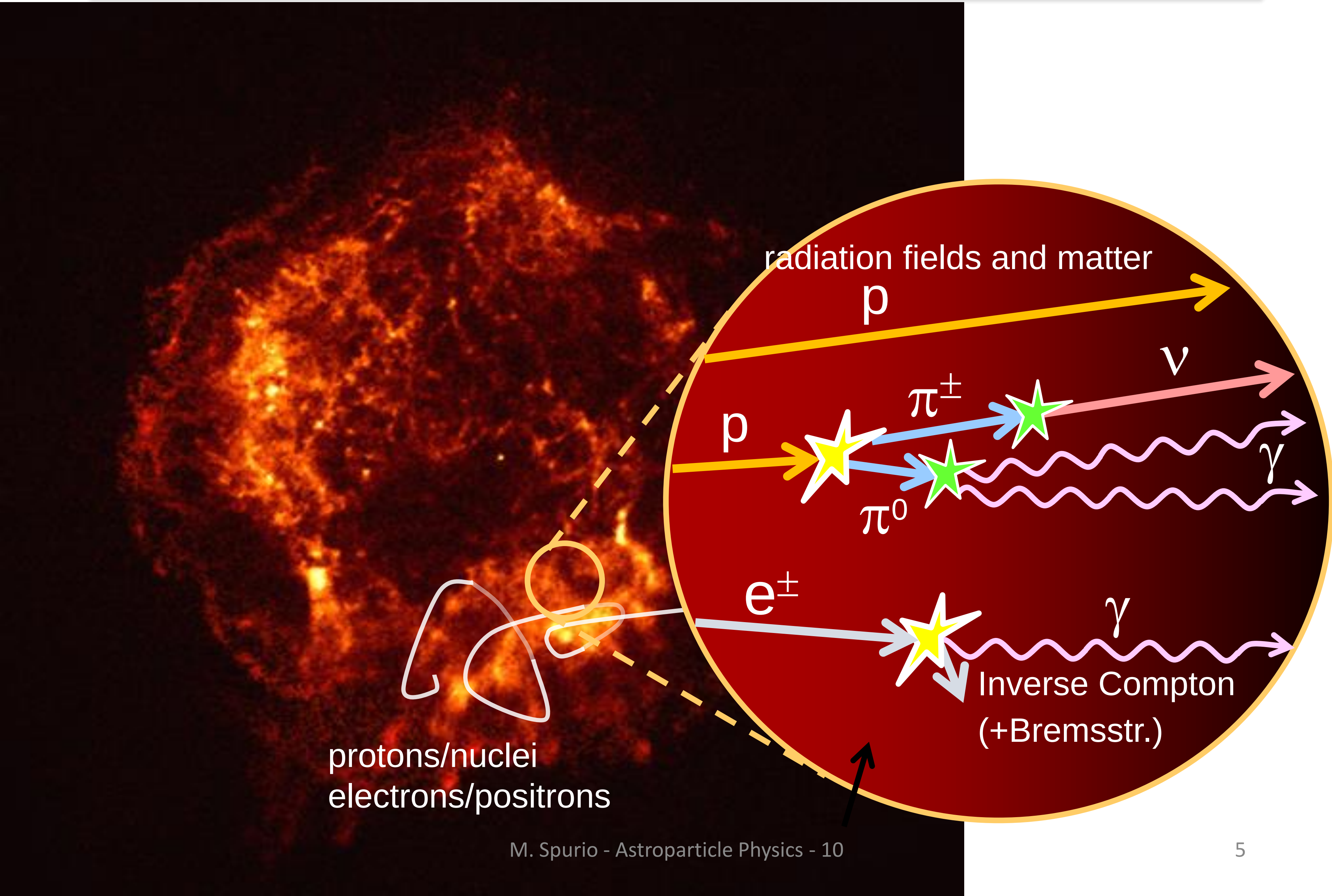
Photon and proton mean free range path



- Advantages:
  - **γ-rays**: interact with CMB and matter (r~10 kpc @100 TeV)
  - **Protons**: interact with CMB (r~10 Mpc@10^{11} GeV) and are deflected by magnetic fields ($\Delta\theta > 3^o$, E<$5\cdot 10^{10}$ GeV)
  - **Neutrons**: are not stable (r~10 kpc @10^9 GeV)
- Drawback: large detectors (~GTon) are needed.

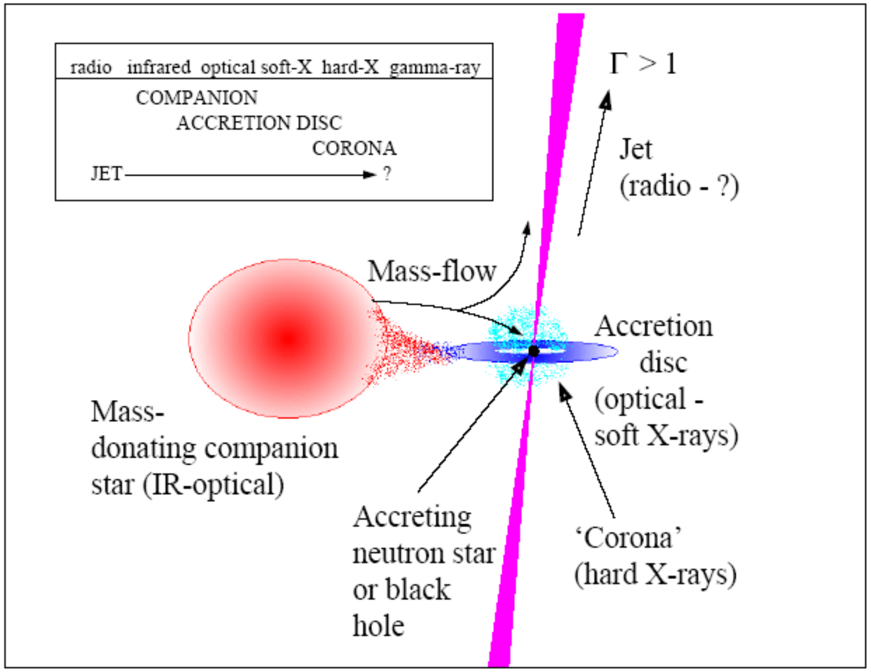


CRs and Secondary neutral particles@sources (Chap. 9)



Candidate 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.

Candidate Astrophysical Sources

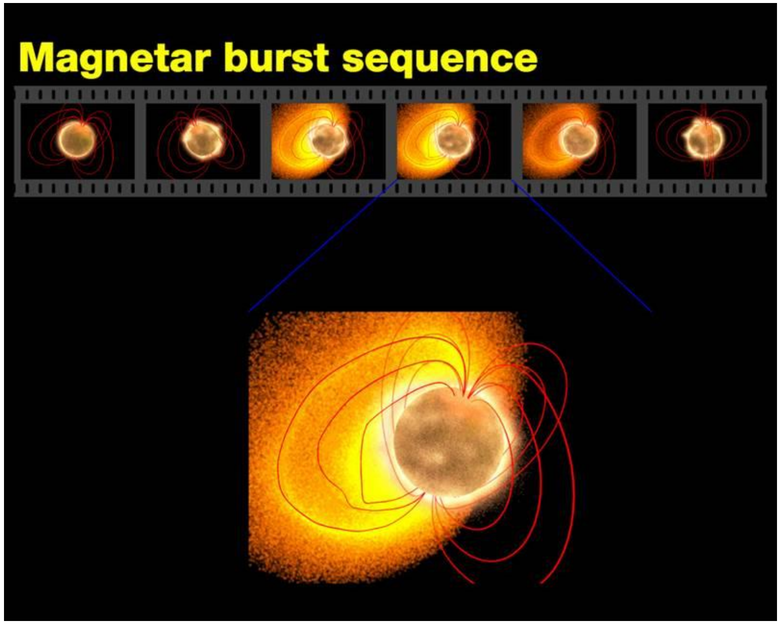
- **<u>Galactic sources</u>**: these are near objects (few kpc) so the luminosity requirements are much lower.
  - Micro-quasars
  - Supernova remnants

Several different objects (with different neutrino production scenarios):

- Plerions (center-filled SNRs)
- Shell-type SNRs:
- SNRs with energetic pulsars

Candidate Astrophysical Sources

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

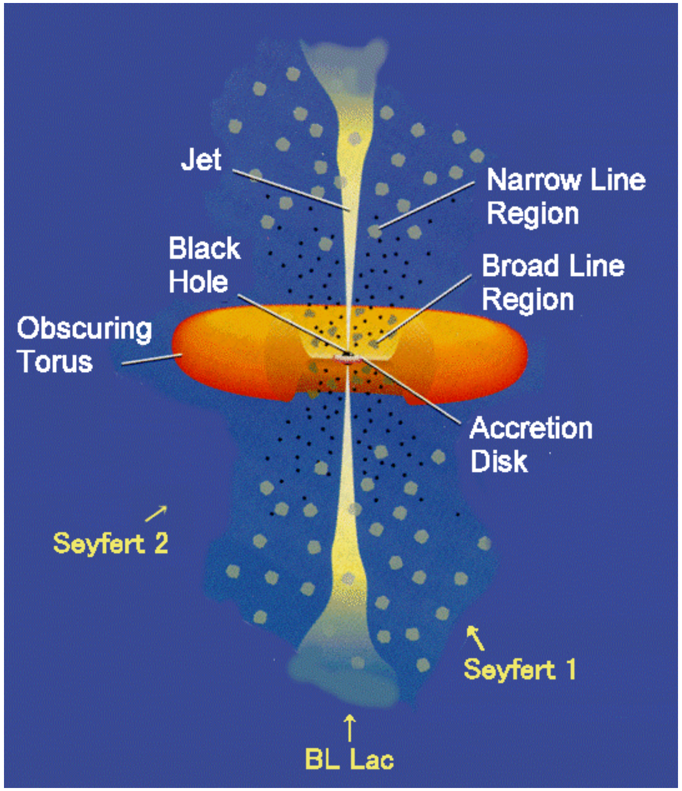


- Isolated neutron stars with surface dipole magnetic fields ~10^{15} G, much larger than ordinary pulsars.
- Seismic activity in the surface could induce particle acceleration in the magnetosphere.

Candidate Astrophysical Sources

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

- **<u>Extra-galactic sources</u>**: most powerful accelerators in the Universe
  - AGNs

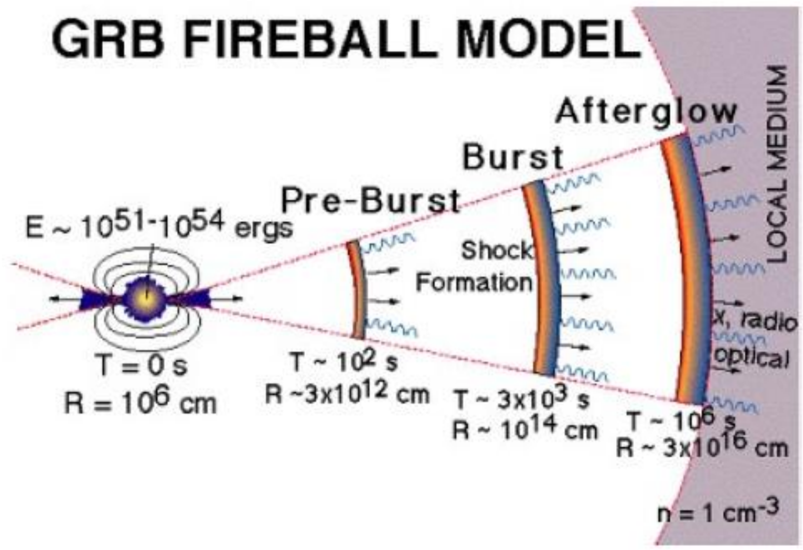


- Active Galactic Nuclei includes Seyferts, quasars, radio galaxies and blazars.
- Standard model: a super-massive (10^6-10^8 M_o) black hole towards which large amounts of matter are accreted.

Candidate Astrophysical Sources

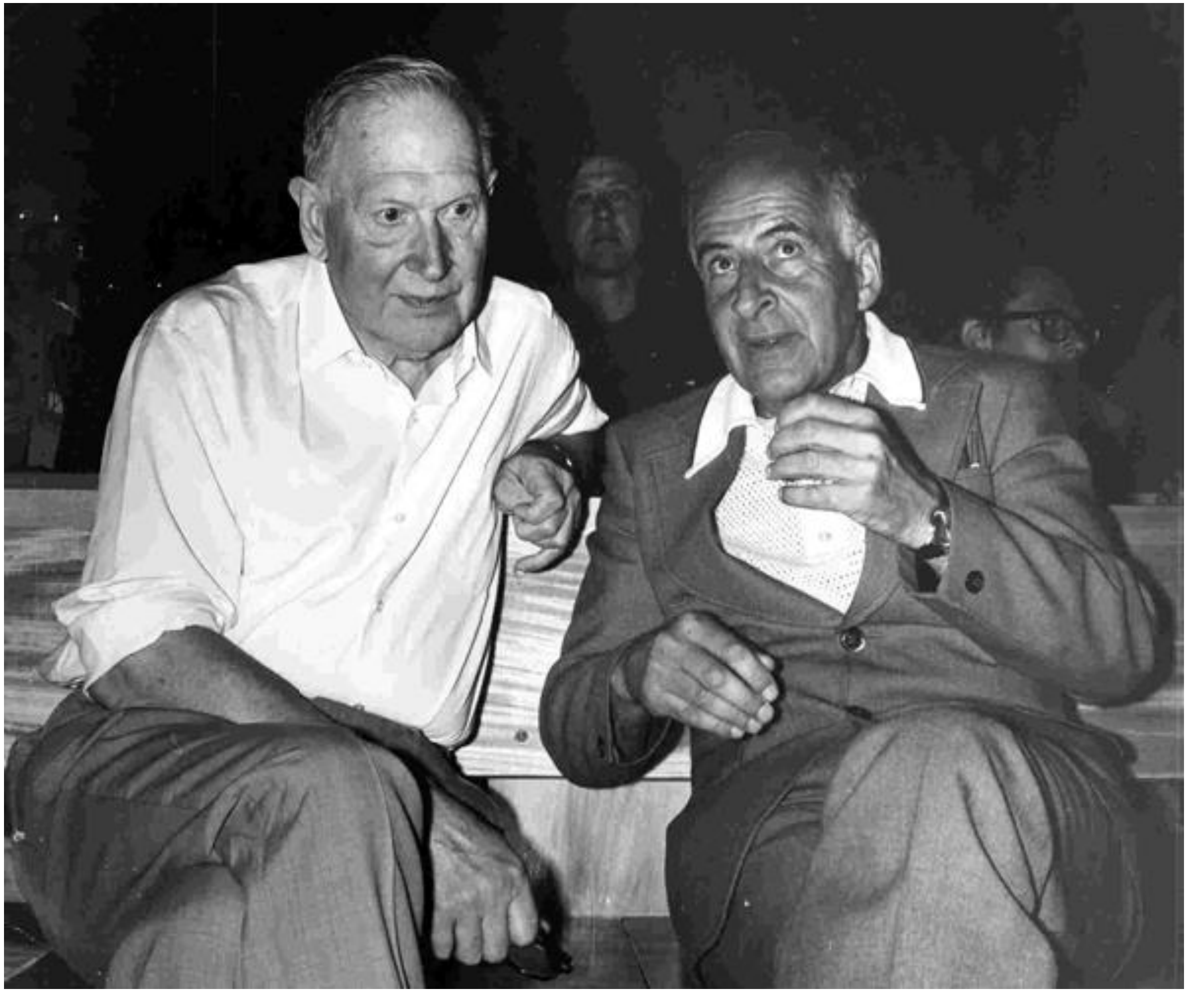
- **<u>Galactic sources</u>**: these are near objects (few kpc) so the luminosity requirements are much lower.
  - Micro-quasars
  - Supernova remnants
  - Magnetars
  - …

- **<u>Extra-galactic sources</u>**: 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.
- <u>Time correlation</u> enhances the neutrino detection efficiency.

Recipes for a Neutrino Telescope (NT)

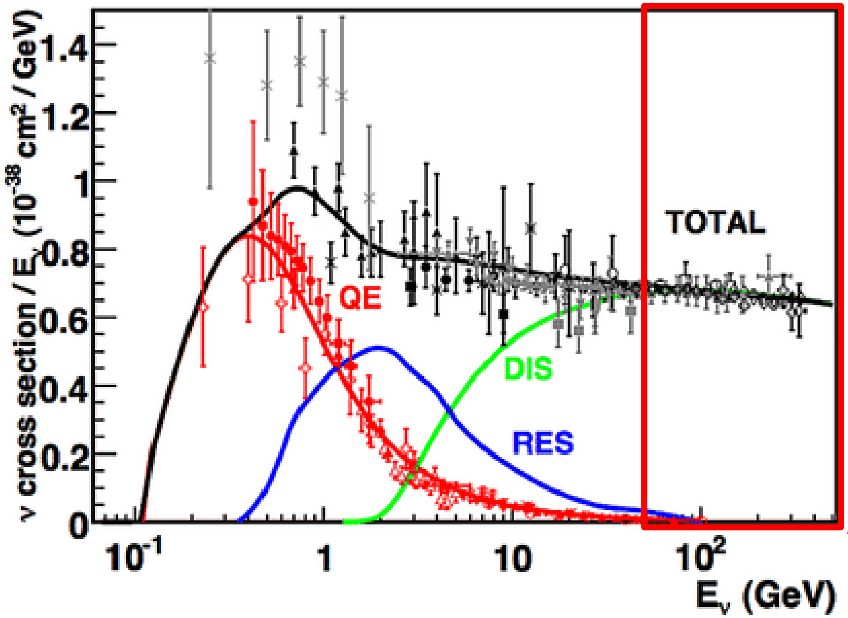


M.A. Markov and B.M. Pontecorvoat the International conference on neutrino physics and astrophysics. Baksancanyon, Cheget, the Caucasus, 1977

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

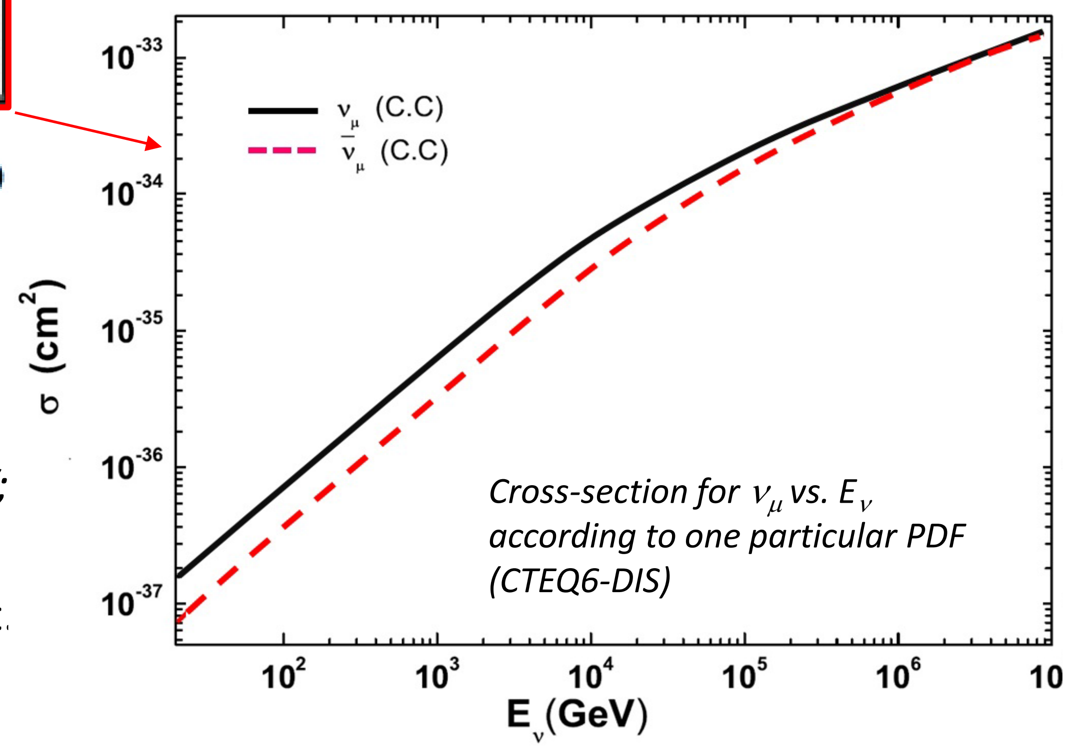
Neutrino cross section



- Below few GeV, the neutrino interaction cross section is dominated by processes in which conservation rules play an important effect: we will discuss this in Chap. 12 for solar neutrinos and neutrinos from SN explosion.

- *Top: Different processes for the neutrino interaction on nucleons*

- *Right: the DIS The cross-section increases linearly $\sigma \sim E_\nu$ up to 10^4 GeV;*
- At higher energies, the linear rise of the cross section starts flattening out.



Cross-section for ν_μ vs. E_ν according to one particular PDF (CTEQ6-DIS)

Neutrino interaction: Deep inelastic Scattering

- At energies above some GeV, neutrino interactions occur via the so-called "**deep inelastic scattering (DIS)**"

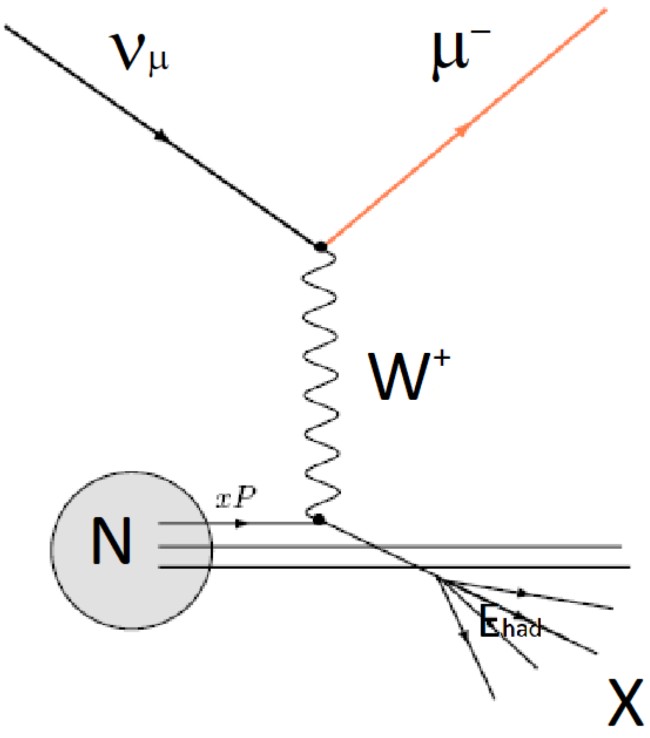
- High energy neutrinos interact with *partons* of the nucleons, via either charged current (CC) weak interactions (l = e; μ; τ)

$$\nu_l + N \rightarrow l + X$$

- or neutral current (NC)

$$\nu_l + N \rightarrow \nu_l + X$$

- The hadronic system X carries part of the incoming neutrino energy.
- **Question**: why we do not mention the neutrino cross-section on electrons?
- Which is the expected behavior for ν+e?



ν absorption in the Earth

- The interction length (Chapter 3) is:

$$\lambda = \frac{1}{n\sigma}\ [cm]$$

- n=number density (nucleons) that depends on the mass M, density of the material

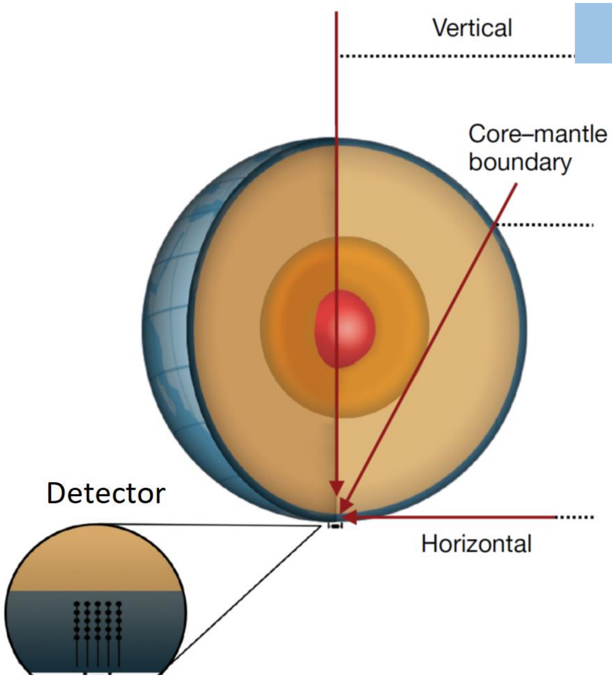
$$n = \frac{N_A}{M}\rho\ \ [cm^{-3}]$$

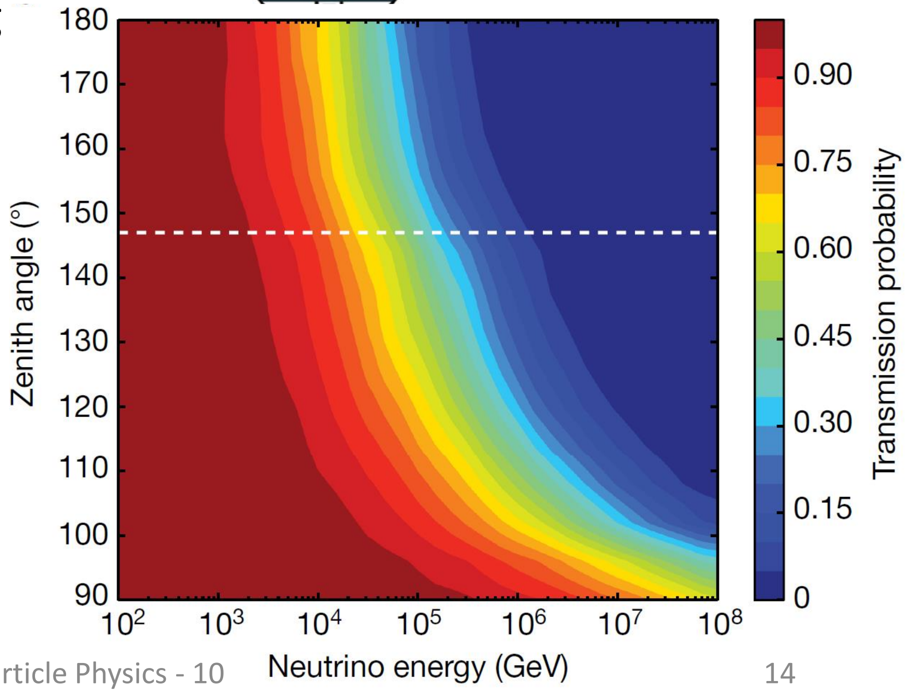
- Due to the interaction length, the surviving fraction of particles is:

$$N(x) = N_o e^{-x/\lambda}$$

  - A γ-ray of 1 TeV has an interaction length (in water) λ = 42 cm;
  - a ν of 1 TeV has λ~ $2\text{x}10^9$ m.

- The increase of the σ_ν with energy is such that the Earth absorption becomes not negligible at E_ν > 100 TeV.





Deep in a transparent medium

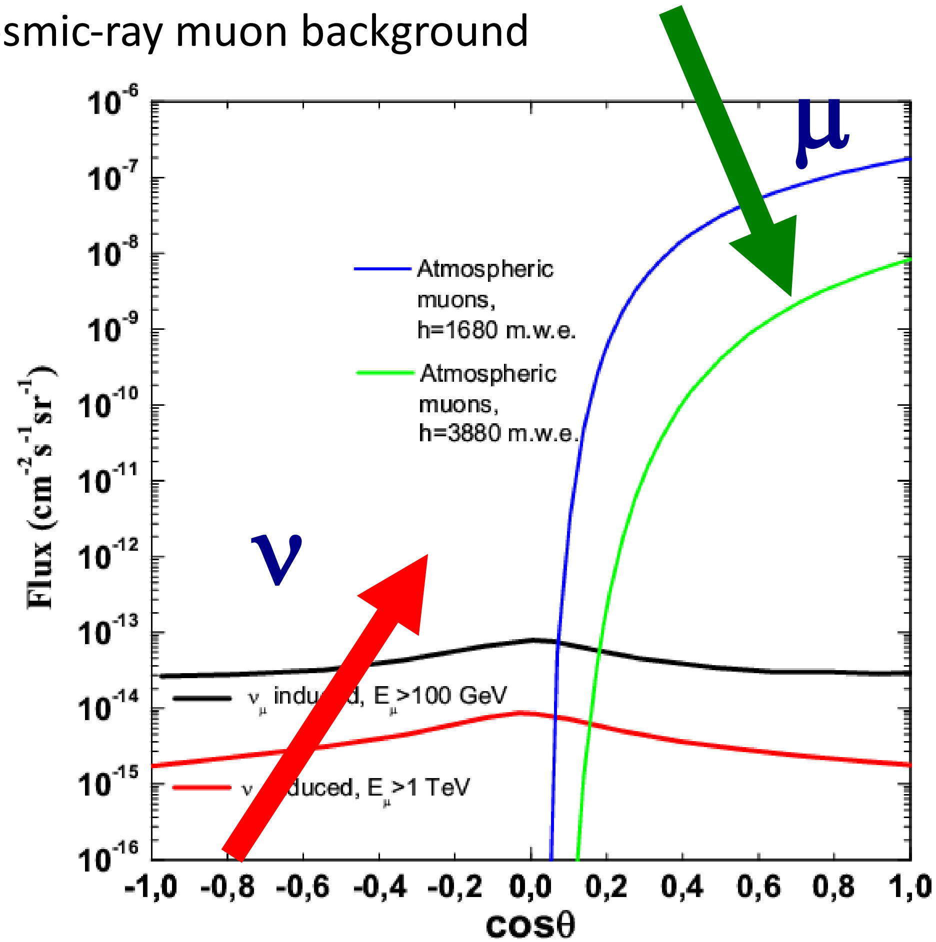
Water and Ice:

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

Figure: *Flux as a function of the cosine of the zenith angle of:*

i. atmospheric muons for two different depths;

ii. Neutrino-induced muons (CC interactions of atm. ν_μ) for two different muon energy thresholds, E_μ . Up- (down-) going events have $\cos\theta < 0$ (>0)

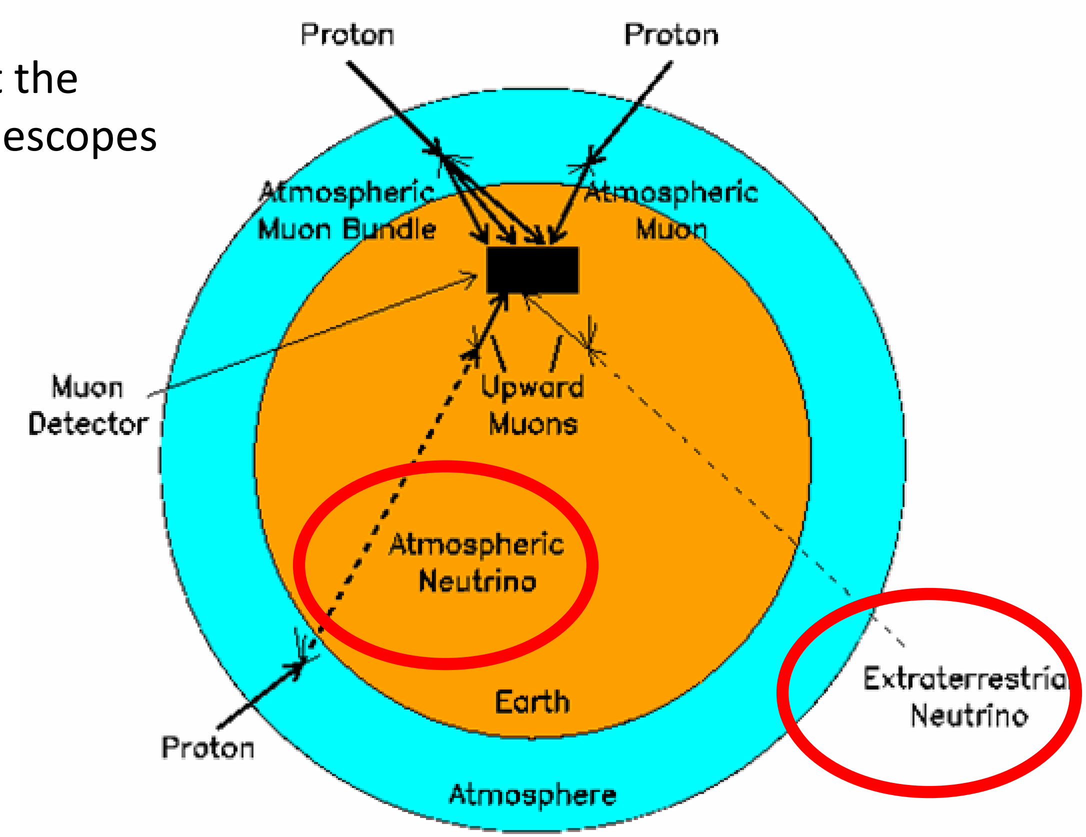


The background in neutrino telescopes

- **Down- and up-going hemisphere**: atmospheric neutrinos
- **Downgoing hemisphere**: atmospheric μ's dominate by many order of magnitude the muons induced by neutrinos
- Only upward-going particles are candidate for extraterrestrial ν .

- Atmospheric neutrinos represent the irreducible background for nu-telescopes

Upward-going muons (or horizontal muons) if correctly reconstructed ARE neutrino-induced!

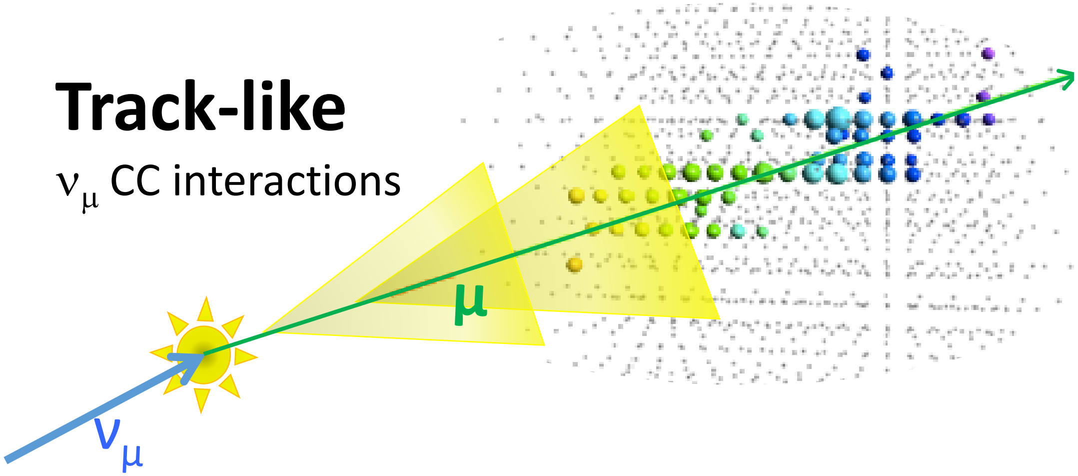


Shower- and track-like events

- **ν_e,ν_τ, neutral currents: <u>showers</u> in the detector**
  - Better energy measurement (energy dissipated in the detector)
- **ν_μ <u>tracks</u> in the detector**
  - Better direction estimate (the muon collinear with the neutrino)

Track-like

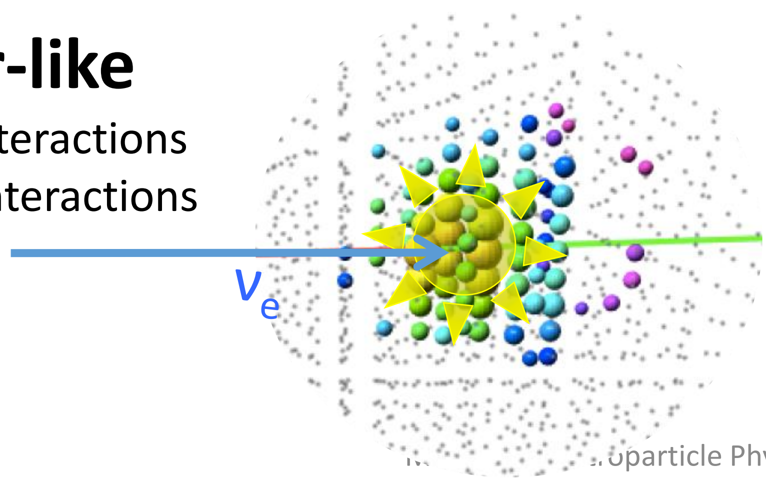
ν_μ CC interactions



Shower-like

ν_e , ν_τ CC interactions

ν_X NC interactions



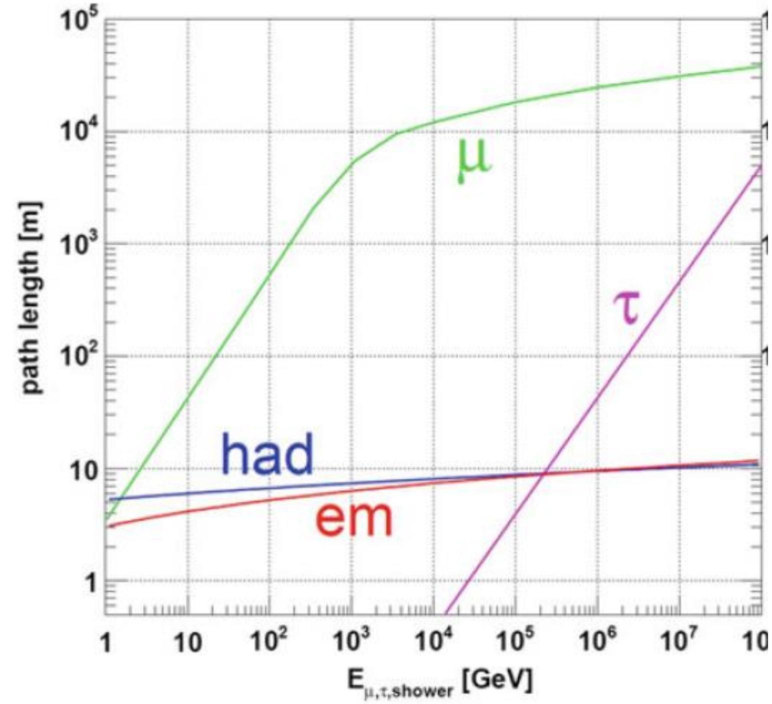
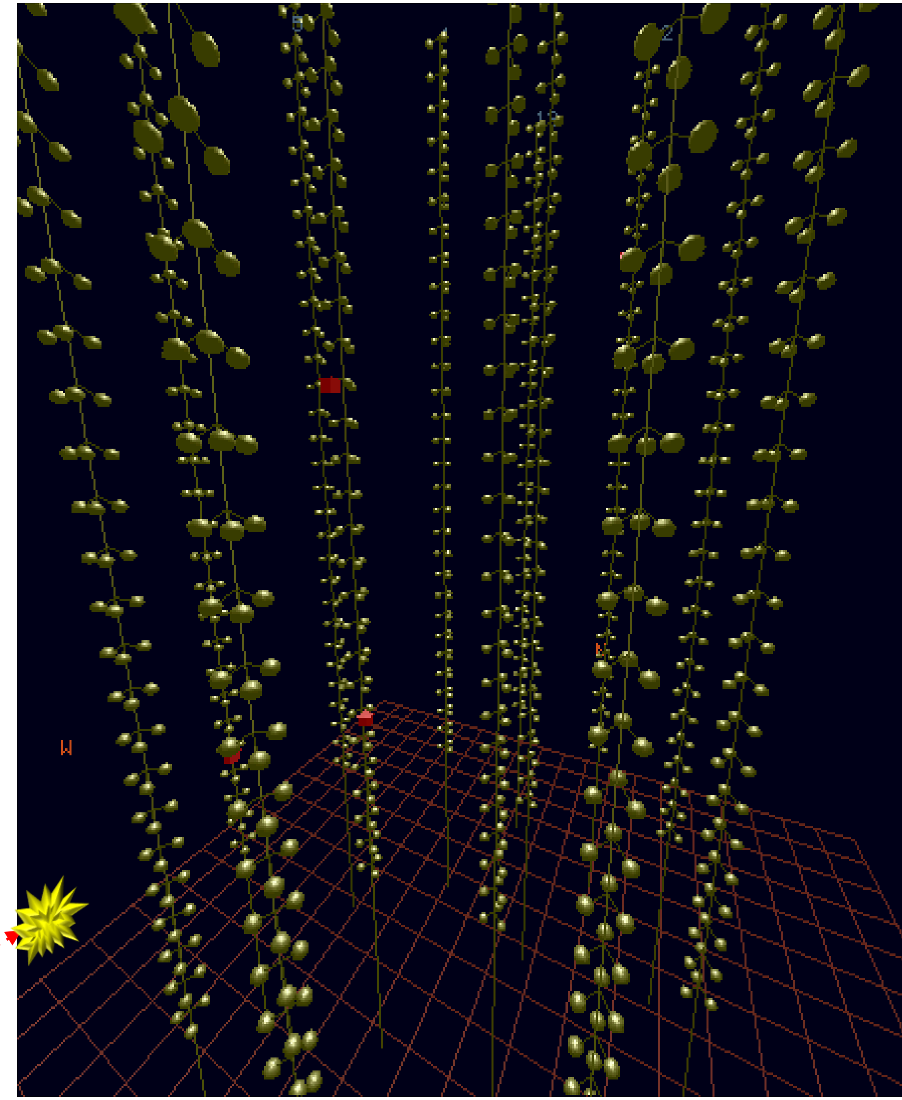


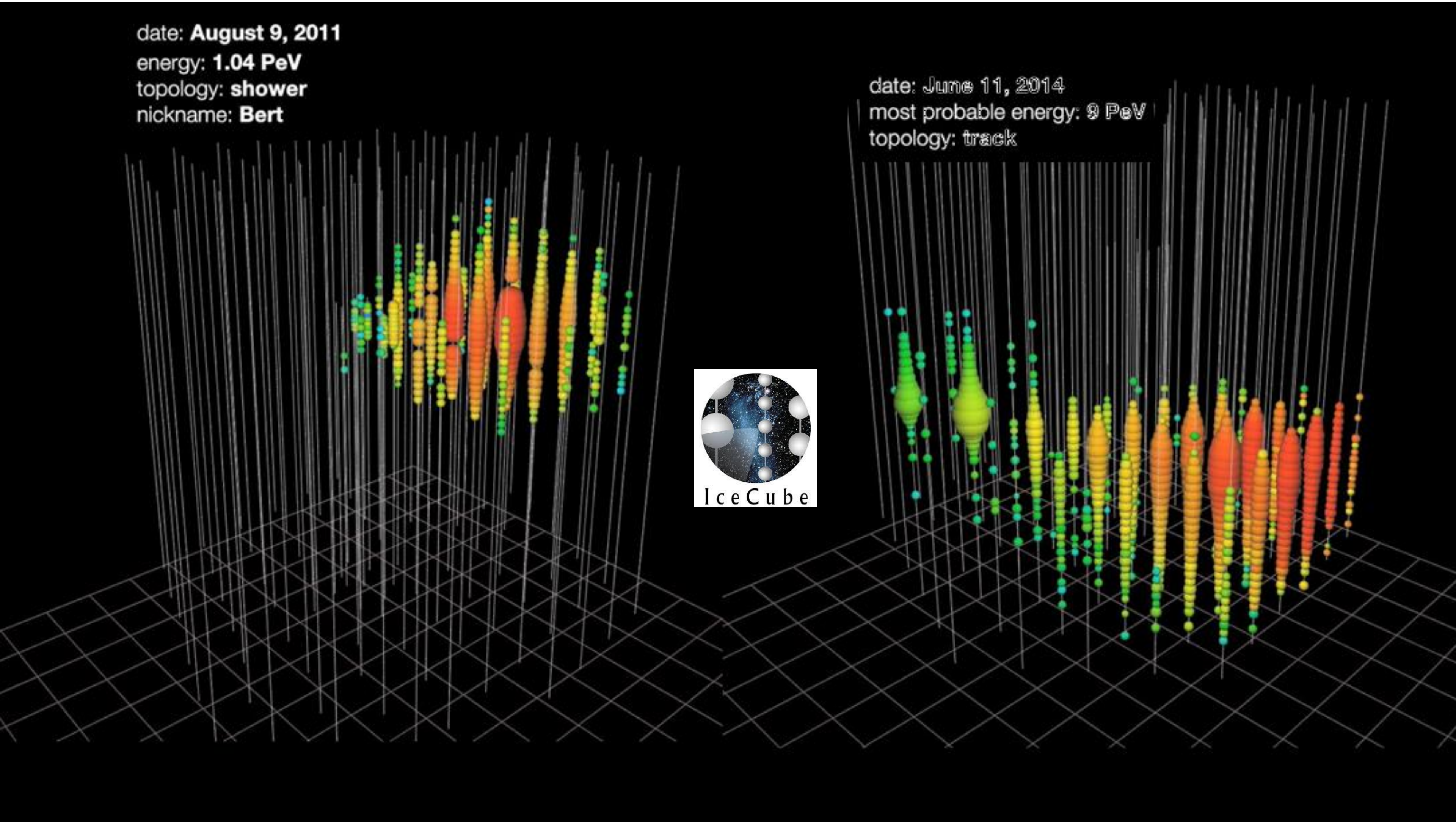
Figure: *Path length (m) of particles produced by different neutrino flavors and interactions in water versus their respective energy.*

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 in the detector
- **Cascades (CC ν_e+ NC):** Short pattern (point like)
- **Neutrino Direction** reconstructed from time-space correlation between ***hits*** produced by Cherenkov photons
- **Neutrino Energy** reconstructed from signal amplitudes of the detected hits



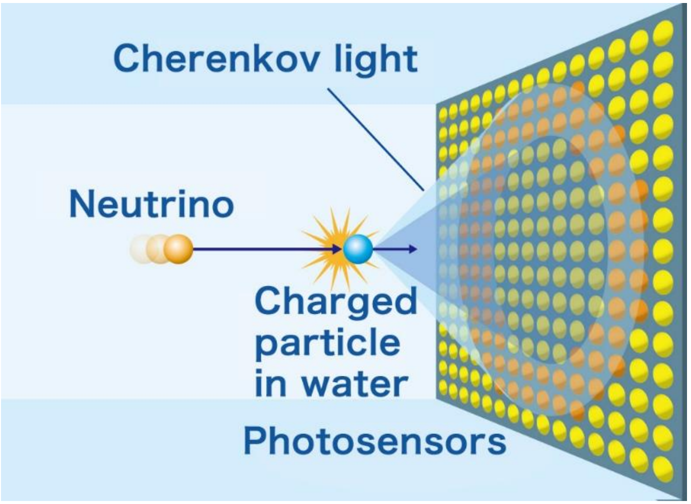
Two real events in IceCube



Cherenkov light emission

- The detection principle of operating NT is based on the collection of the optical photons produced by the Cherenkov effect of relativistic particles.
- The light is measured by a three-dimensional array of photomultiplier tubes **(PMTs)**. The information provided by the **number of photons** detected and their **arrival times** are used to infer the neutrino flavor, direction and energy.
- Cherenkov radiation is emitted by charged particles crossing an insulator medium with speed exceeding that of light in the medium. The coherent radiation is emitted along a cone with a characteristic angle θ_C such that $\theta_C = \frac{1}{\beta \cdot n}$, where n is the refracting index of the medium and β is the particle speed in units of c.
- For relativistic particles ($\beta \sim 1$) in seawater (n=1.364), the Cherenkov angle is $\theta_C = 43^o$
- The number of Cherenkov photons, per unit wavelength interval, $d\lambda$, and unit distance travelled, dx, by a charged particle of charge e is given by the Frank-Tamm formula:

$$\frac{d^2 N_C}{dx d\lambda} = \frac{2\pi}{137\lambda^2}\left(1 - \frac{1}{n^2\beta^2}\right)$$

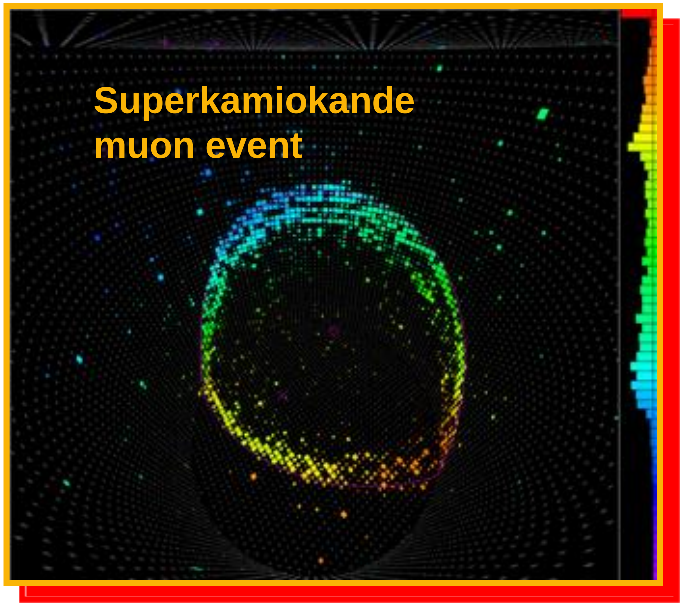


Cherenkov light emission (exercise)

- The number of Cherenkov photons, per unit wavelength interval, dλ, and unit distance travelled, dx, by a charged particle of charge e is given by the Frank-Tamm formula:

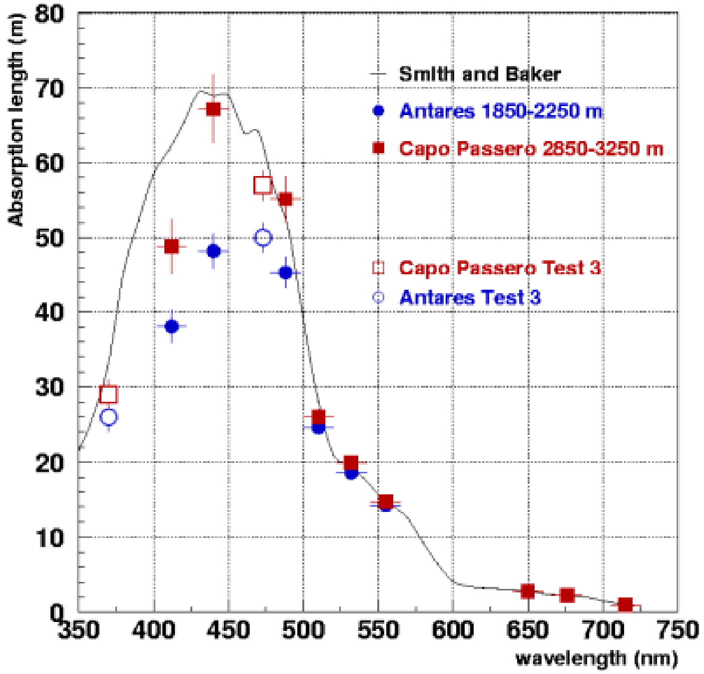
$$\frac{d^2 N_C}{dx d\lambda} = \frac{2\pi}{137\lambda^2}\left(1 - \frac{1}{n^2\beta^2}\right)$$

- **Determine** that for a relativistic particle (β=1) in seawater (n=1.364), in the range of optical wavelength between 300 and 600 nm the emitted number of photons for Z=1 charged particles is about **300/cm**



Water/Ice properties

- The effects of the medium (water or ice) on light propagation are **absorption** and **scattering** of photons. These affect the reconstruction capabilities of the telescope.
- Water/ice are transparent only for wavelengths 300 nm<λ< 600 nm.
- The **absorption** length is ~100 m for deep polar ice in the blue-UV region; it is ~ 70m for see water (see fig. on the right).
- **Scattering** changes the direction of the Cherenkov photons, and consequently delays their arrival time on the PMTs; this degrades the measurement of the direction of the incoming neutrino.

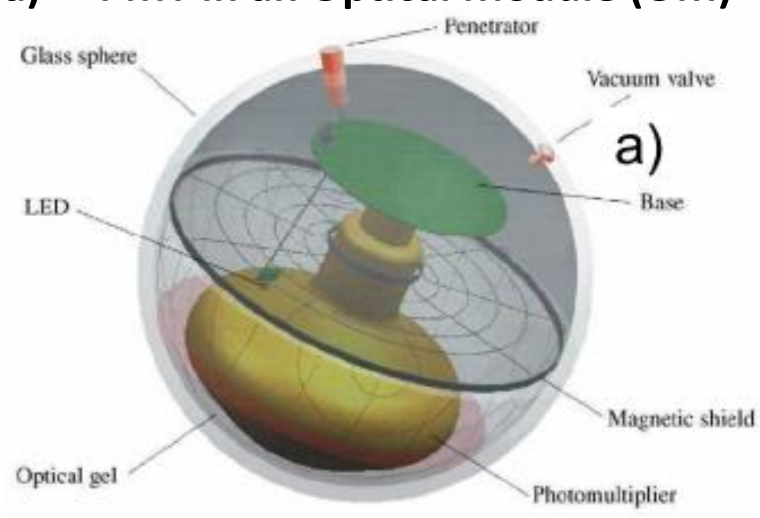


- Seawater has a smaller value of the absorption length w.r.t. ice, which is more transparent. The same instrumented volume of ice corresponds to a larger effective volume with respect to seawater.
- The effective scattering length for ice is smaller than water. This is a cause of a larger degradation of the angular resolution of detected events in ice w.r.t. water.

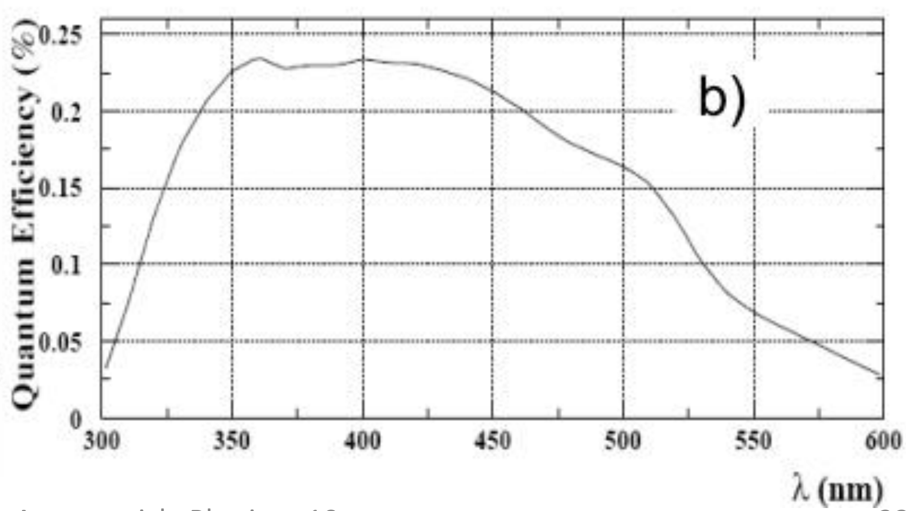
Optical modules

- The **optical background** in seawater has two main natural contributions: the decay of radioactive elements dissolved in water, and the bio-luminescence
- The ^{40}K is by far the dominant of all radioactive isotopes present in seawater, and its β-decay is above the threshold for Cherenkov light production.
- The deep polar ice is almost free from radioactive elements (no optical background)
- Figure shows one typical optical module configuration used in NT.
- The PMT quantum efficiency (right side) is large within the wavelength range 300–600 nm, matching well the region in which ice and water are transparent to light.

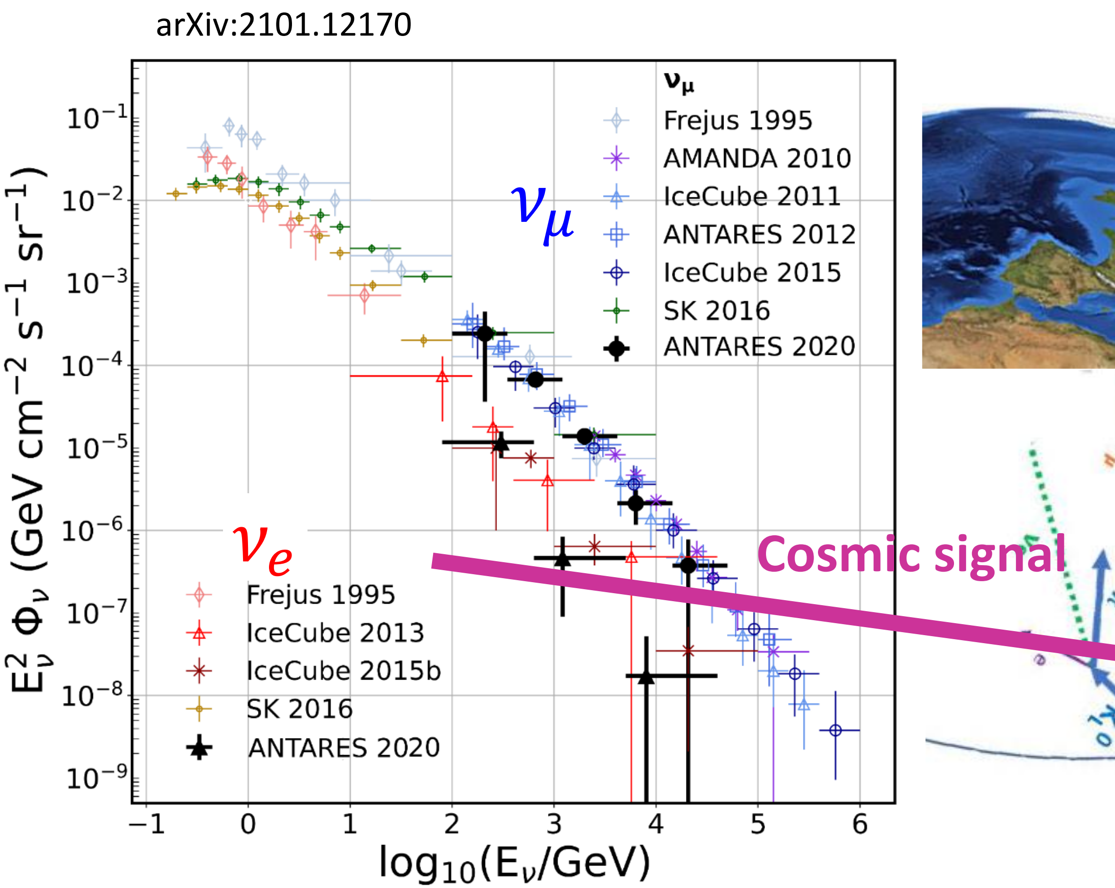
a) PMT in an Optical Module (OM)

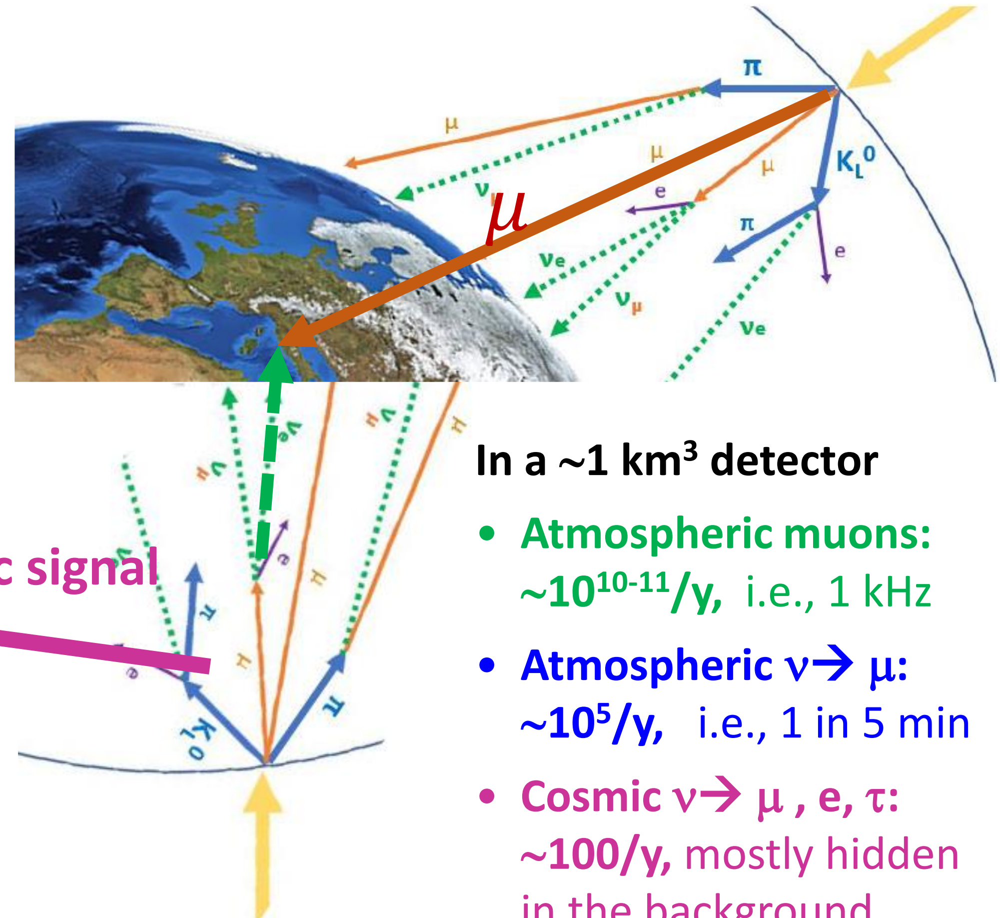


b) OM quantum efficiency



Background: atmospheric muons and neutrinos



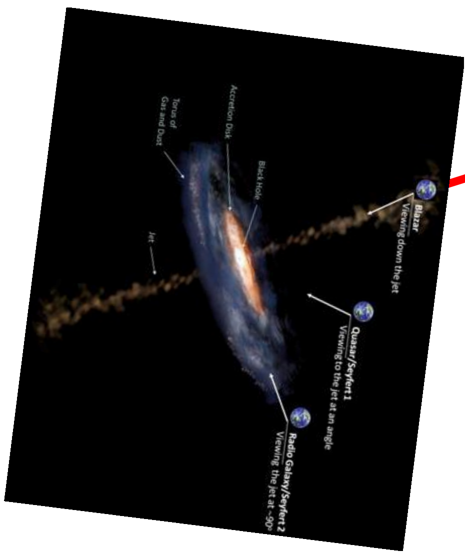


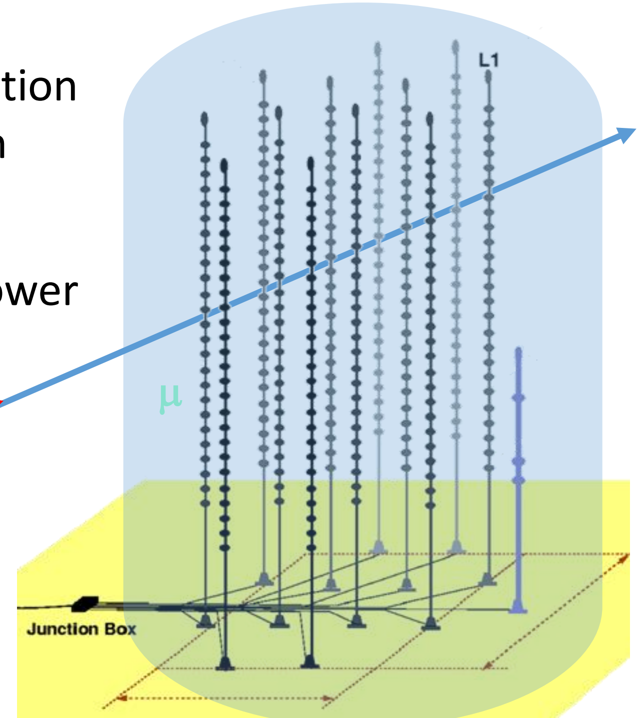
In a ~1 km^3 detector

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

Detecting cosmic ν

- **Event rate (s^{-1}) in the detector in a time T**: neutrino detection through CC interaction with production of a charged lepton
- **Neutrino spectrum from the source (ν/cm^2 s GeV)**
- **Neutrino- effective area (cm^2).** Different for track and shower events





Instrumented detector $D<R_\mu$

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

Example: neutrinos from a Galactic source

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

  $p + \gamma \rightarrow \Delta^+ \rightarrow \pi^o + p$ $\qquad$ $p + \gamma \rightarrow \Delta^+ \rightarrow \pi^+ + n$

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

  $p + p \rightarrow$ many hadrons (mostly π^+, π^-, π^o)

- Then, neutral mesons decay in **photons**: $\quad \pi^o \rightarrow \gamma\gamma$
- While charged mesons decay in **neutrinos**:

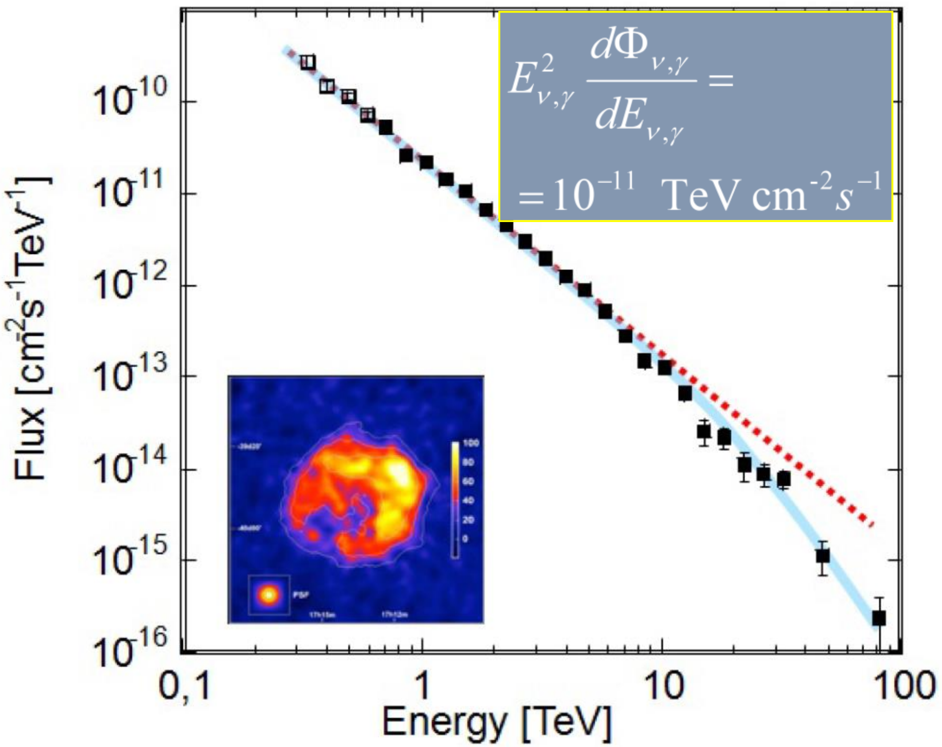
$\pi^+ \rightarrow \nu_\mu + \mu^+$ $\qquad$ $\mu^+ \rightarrow \nu_\mu + \nu_e + e^+$

$\pi^- \rightarrow \nu_\mu + \mu^-$ $\qquad$ $\mu^- \rightarrow \nu_\mu + \nu_e + e^-$

- In all cases, at first order:

$$\frac{d\Phi_\nu}{dE} \cong \frac{d\Phi_\gamma}{dE} = 10^{-11} E^{-2} \text{ TeV cm}^{-2}\text{s}^{-1}$$

*Figure: **RX J1713.7-3946** as seen by HESS (γ–rays)*



Detector effective area

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

$$A_\nu^{eff}(E) = A \cdot P_{\nu\rightarrow\mu}(E, E_\mu) \cdot \epsilon_{det} \cdot e^{-\sigma(E)\cdot\rho\cdot N_A\cdot Z(\theta)}$$

- The effective area, $A_\nu^{eff}(E)$ of a NT corresponds to the quantity that, convoluted with the neutrino flux, gives the event rate.
- The A_{eff} depends on the **neutrino flavor and interaction type** (if the interaction yields a track- or shower-like, the latter either through a CC or NC interaction); on the neutrino **energy** and incoming **direction**; on the **status** of the detector; and on the **cuts** that each particular analysis uses for the suppression of the background.
- A is the geometrical area of the detector (the surface of the instrumented volume)
- $P_{\nu\rightarrow\mu}$ represents the probability that a neutrino with energy E produces a muon arriving with a residual threshold energy E_μ at the detector.
- ϵ_{det} is the detector efficiency (only determined through Monte Carlo)
- The $e^{-\sigma(E)\cdot\rho\cdot N_A\cdot Z(\theta)}$ term takes in the account the Earth absorption;
- In the following, we describe the ingredients necessary to construct, in a simplified analytic method A_{eff} for the ν_μ CC channel, assuming only dependence on energy E_ν .
- Only detailed and dedicated Monte Carlo simulations can determine A_{eff}

The $P_{\nu\to\mu}$ term in the detector effective area

- $P_{\nu\to\mu}(E, E_\mu)$ = Probability that a ν induces a muon reaching the detector:

$$P_{\nu\to\mu}(E, E_\mu) = \sigma_{\nu\mu} \times n\,(cm^{-3}) \times R\,(cm)$$

- The neutrino CC cross-section can be parameterized as

$$\sigma_{\nu\mu} \cong 10^{-35}\left(\frac{E}{TeV}\right)(cm^2)$$

- Roughly, half of the neutrino energy is transferred
- The target number density is $n \cong 10^{23}\ cm^{-3}$;
- The muon range R depends on the muon energy,
- ***Exercise***: a better analytical solution for the range of a muon of energy E is determined by the muon energy-loss formula: $-\frac{dE}{dx} = (a + bE)$, with a=2 MeV g^{-1} cm^{-2} and b=4x10^{-6} g^{-1} cm^{-2}. Determine the muon range at high energy (E>0.5 TeV).
- In the high energy limit the muon range $R = \int (\frac{dE}{dx})^{-1} dx \cong 10^6$ cm;
- Thus, and estimate of the probability is:

$$P_{\nu\to\mu}(E, E_\mu) = 10^{-35}\left(\frac{E}{TeV}\right) \times 10^{23}(cm^{-3}) \times 10^6(cm) = 10^{-6}\left(\frac{E}{TeV}\right)$$

Detector effective area

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

$$A_\nu^{eff}(E) = A \cdot P_{\nu\to\mu}(E, E_\mu) \cdot \epsilon_{det} \cdot e^{-\sigma(E)\cdot\rho\cdot N_A\cdot Z(\theta)}$$

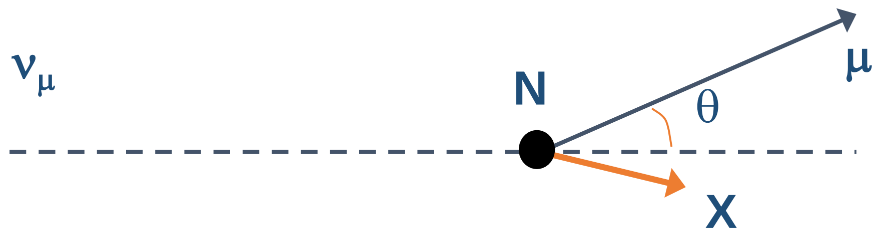
- The effective area, $A_\nu^{eff}(E)$ of a NT corresponds to the quantity that, convoluted with the neutrino flux, gives the event rate.
- In a detector with projected surface: A =1 km^2=10^{10} cm^2:
- Under very simple assumption for $\nu \to \mu$: $P_{\nu\to\mu} \cong 10^{-6}\left(\frac{E}{TeV}\right)$;
- For a perfect detector: $\epsilon_{det} = 1$
- Neglecting the Earth absorption: $e^{-\sigma(E)\cdot\rho\cdot N_A\cdot Z(\theta)} = 1$

$$A_\nu^{eff} = A \cdot P_{\nu\to\mu} \cdot \epsilon \cong 10^4 \left(\frac{E}{\rm TeV}\right) [\rm cm^2] = 1\left(\frac{E}{\rm TeV}\right)[\rm m^2]$$

- **Under our simple estimates, the effective area of a neutrino telescope of 1 km^2 area for neutrinos of 1 TeV is ~1 m^2. It increases with increasing energy**
- **Exercize**: Compare the neutrino effective area with the effective area of the Fermi-LAT satellite γ-ray experiment

Example in the following: the ν_μ channel

- The μ reconstruction allows the measurement of the ν direction
- For E_ν >TeV, μ and ν are almost collinear.
- For shower-like events, the angular resolution is worse (3°-15°, depending on the neutrino energy)



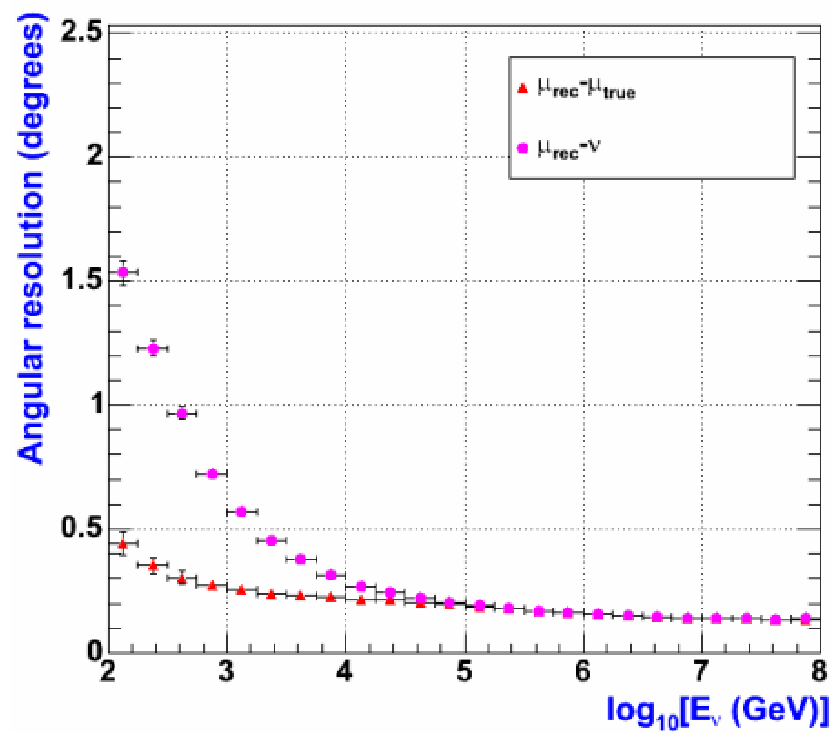
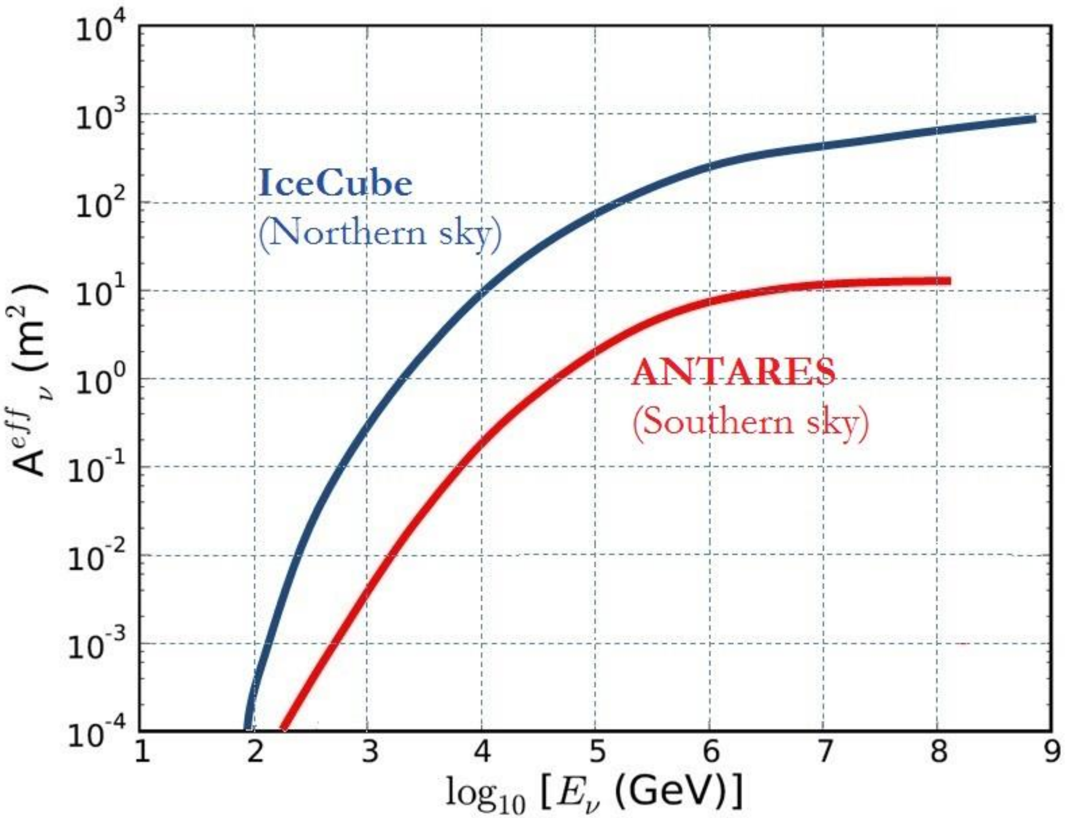


***Figure**: Average differences between the true and reconstructed muon directions (red Δ) and the difference with respect to the neutrino direction (pink o), evaluated with a Monte Carlo vs. event energy in the ANTARES detector. This value represents the **angular resolution** of the detector at a given energy*

«Real» effective areas

- Neutrino effective area as a function of the true simulated neutrino energy obtained for the events selected by the IceCube and ANTARES detectors.
- A full Monte Carlo simulation is necessary to describe the triggering, tracking and selection efficiencies of the two detectors (term $\boldsymbol{\epsilon_{det}}$ in the effective area)
- The plots refer to the ν_μ channel for upgoing particles, selected in order to have angular resolution <1° and small contamination of atmospheric muons



Number of expected events in a Neutrino Tel

$$\frac{N_\nu}{T} = \int dE \cdot \frac{\boldsymbol{d\Phi_\nu}}{\boldsymbol{dE}} \cdot \boldsymbol{A_\nu^{eff}(E)}$$

- Let us merge all the above information to have the event rate N_ν/T;
- The cosmic signal is provided by the neutrino flux from the galactic source is

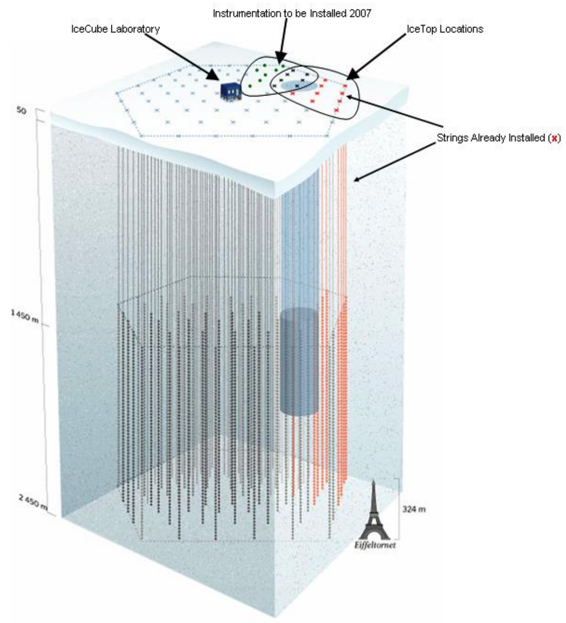
$$\frac{d\Phi}{dE} = 10^{-11}\ /E^2 \quad [\mathrm{TeV^{-1}cm^{-2}s^{-1}}]$$

- The effective area is of the order of **~1 m²** at 1 TeV and increases with energy

- Integrating the event rate formula between 1 TeV and 100 TeV, we obtain

$$N_\nu = T\int_1^{100} \frac{10^{-11}}{E^2} \cdot 10^4\ E\ \cdot dE = T \cdot 10^{-7} \ln(100)$$

- For T=1y=3 10^7 s, this corresponds **to**
  $\boldsymbol{N_\nu =}$ **some event/y**
- (depends on the value of detector efficiency $\boldsymbol{\epsilon_{det}}$).



How many light sensors → € ?

Exercize: Assume a muon track of L_μ=1 km. How many PMTs **(N_{PMT})** are needed in 1 km^3 detector volume in order to detect ~100 p.e. (N_{pe}) ?
Note that O(100 p.e.) in O(10) PMTs are necessary for track reconstruction

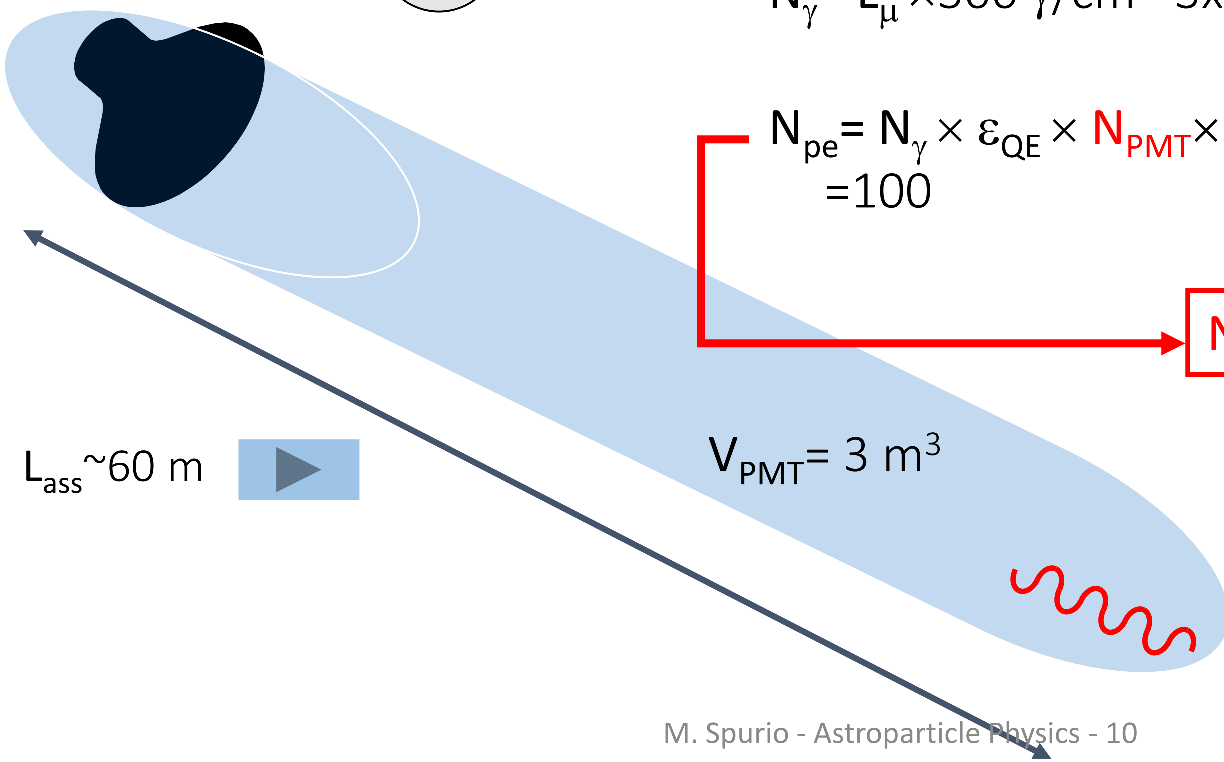
10" PMT =0.05 m^2

$\varepsilon_{QE}=0.25$

$N_\gamma = L_\mu \times 300\ \gamma/\text{cm} = 3\times10^7\ \gamma$

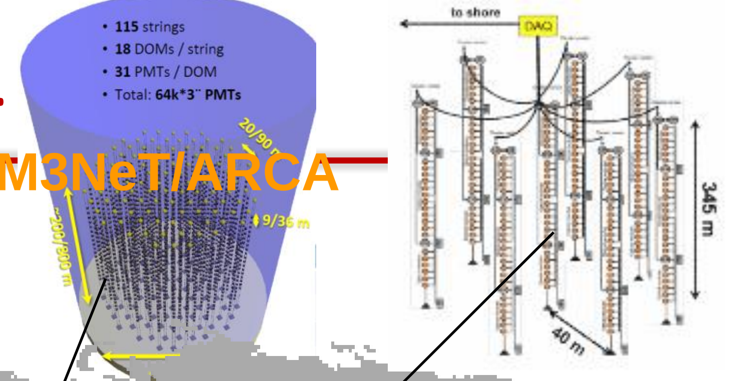
$N_{pe} = N_\gamma \times \varepsilon_{QE} \times N_{PMT} \times (V_{PMT}/1\ \text{km}^3) = 100$

$N_{PMT}=5000$

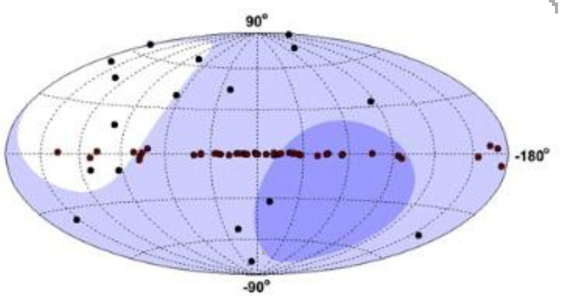


L_{ass}~60 m

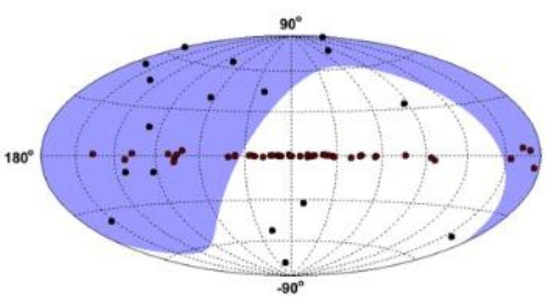
Neutrino telescopes. Where …



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

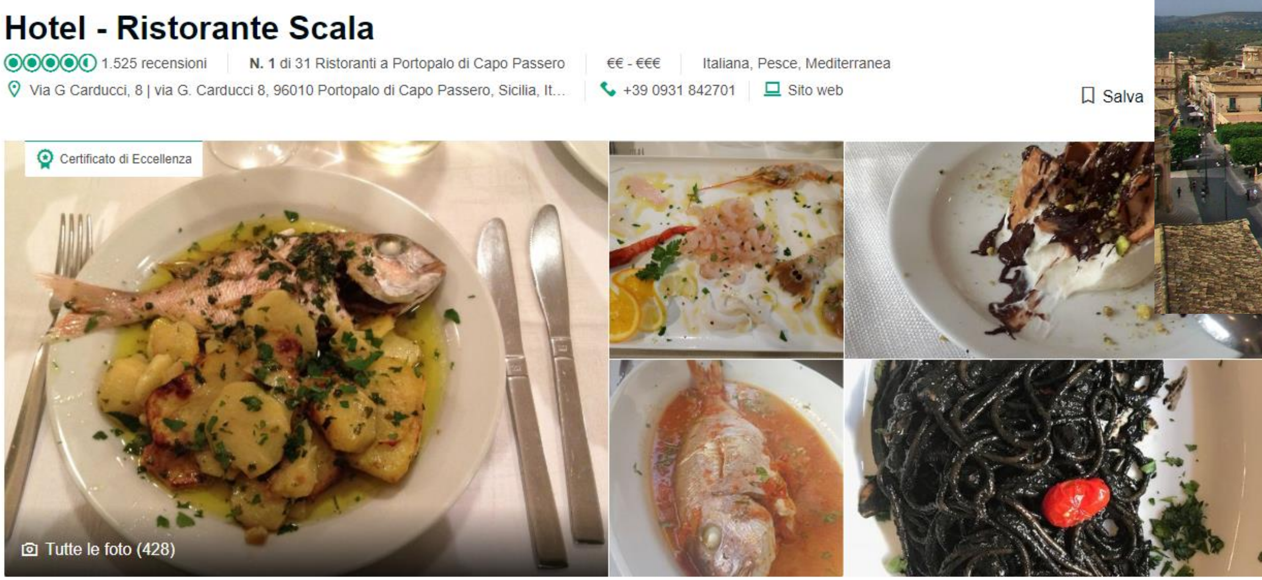


Visibility IceCube (South Pole)
- 100%
- 0%

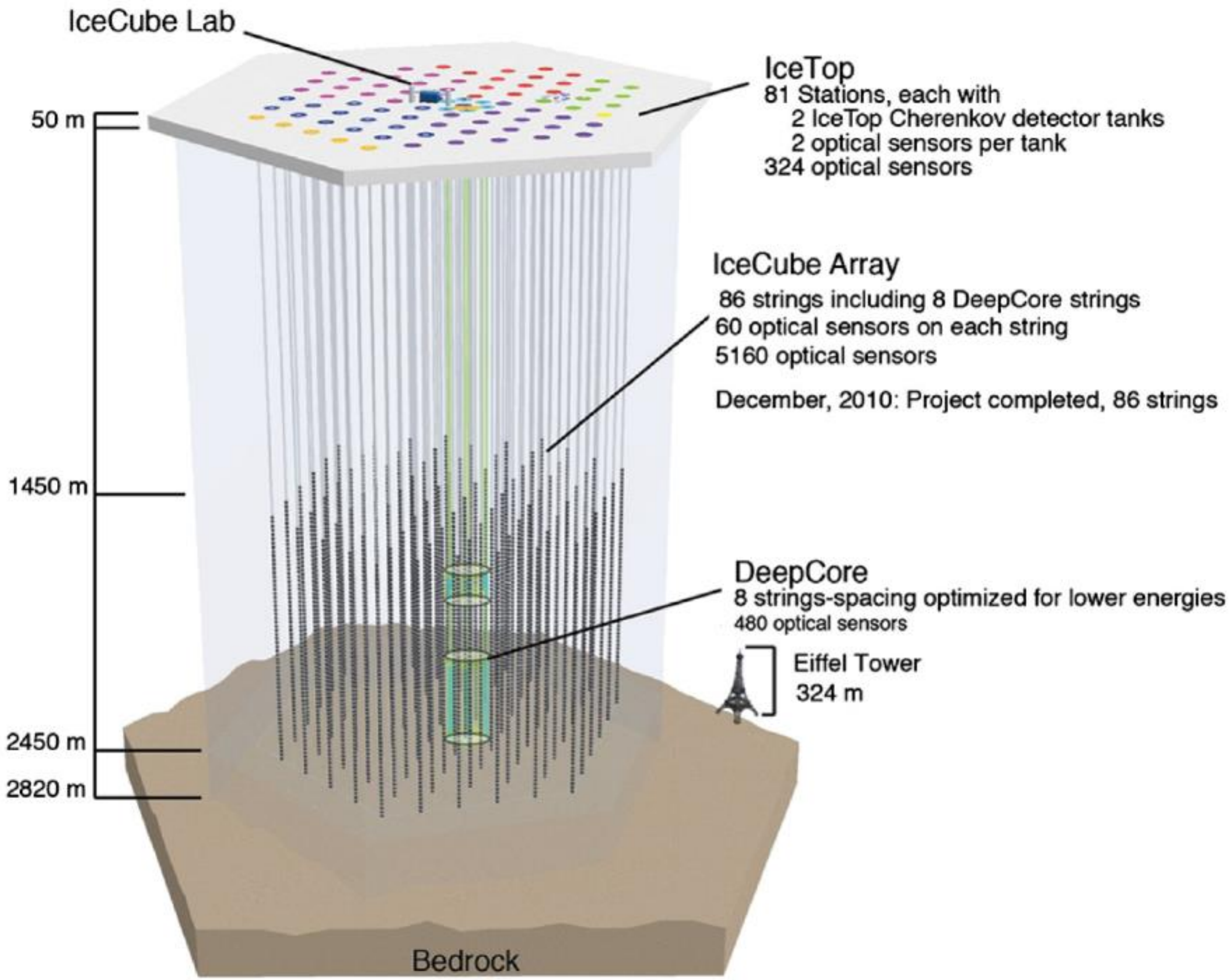


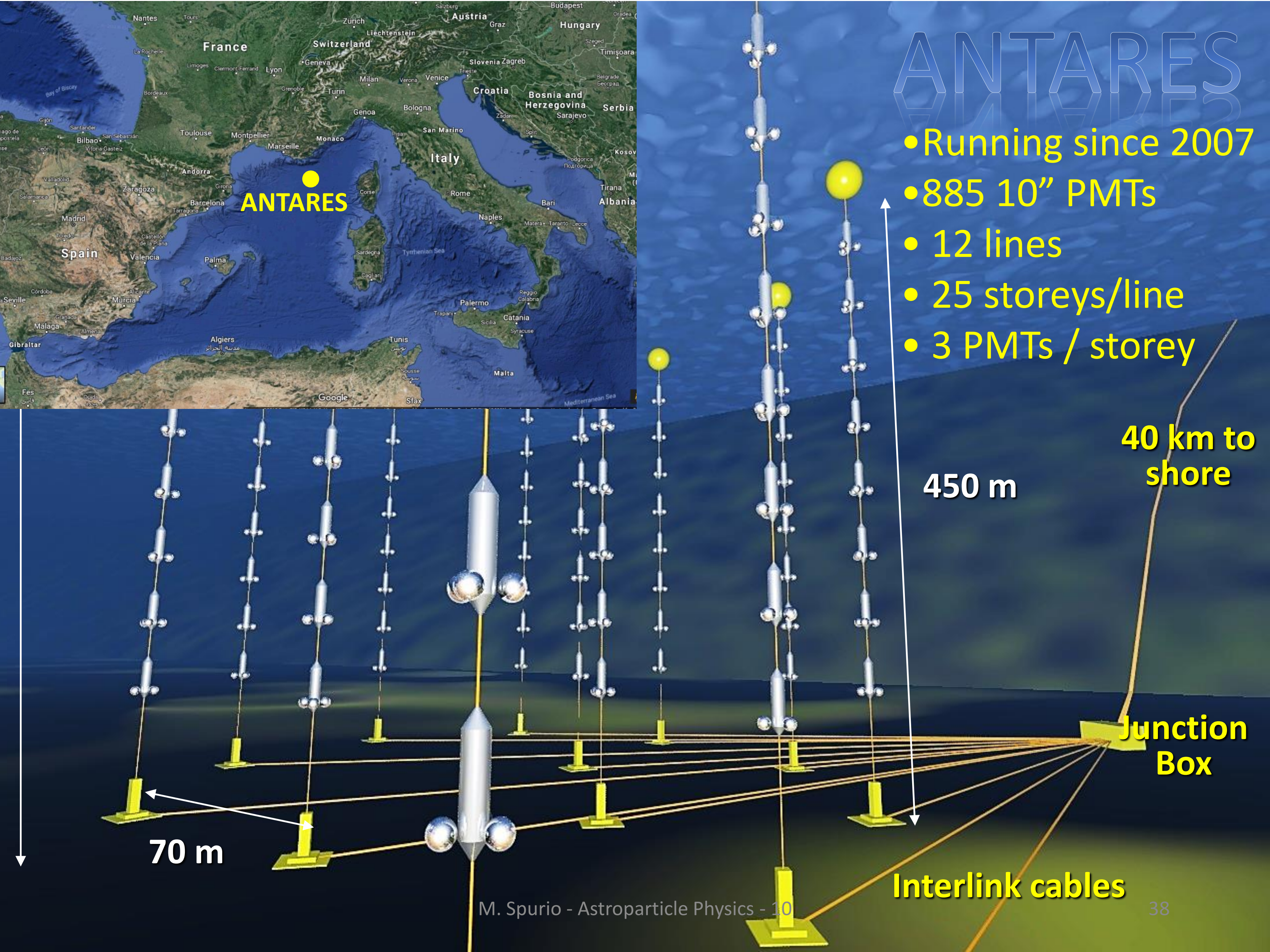
Difference between ice…

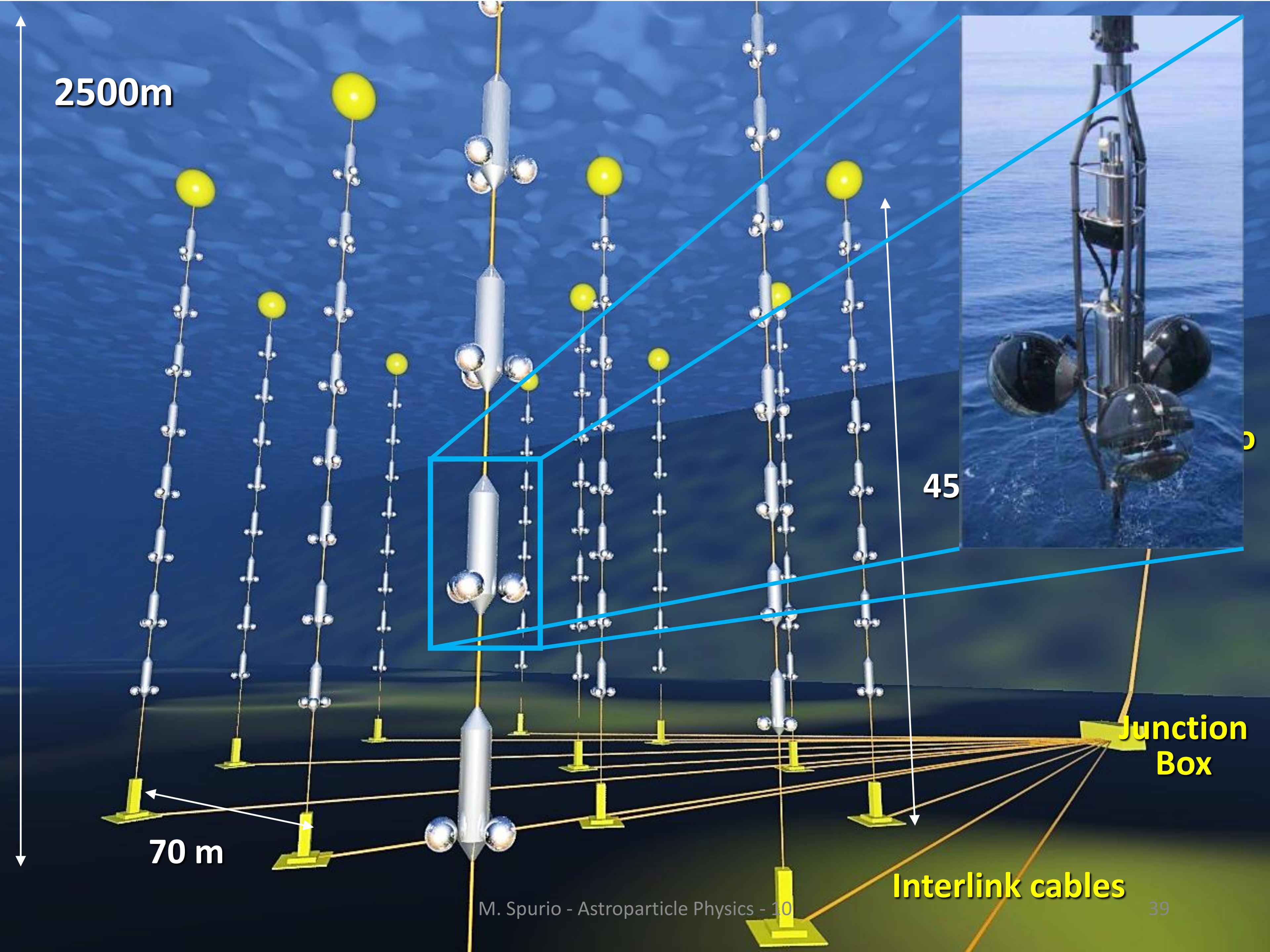
… and Mediterranean water



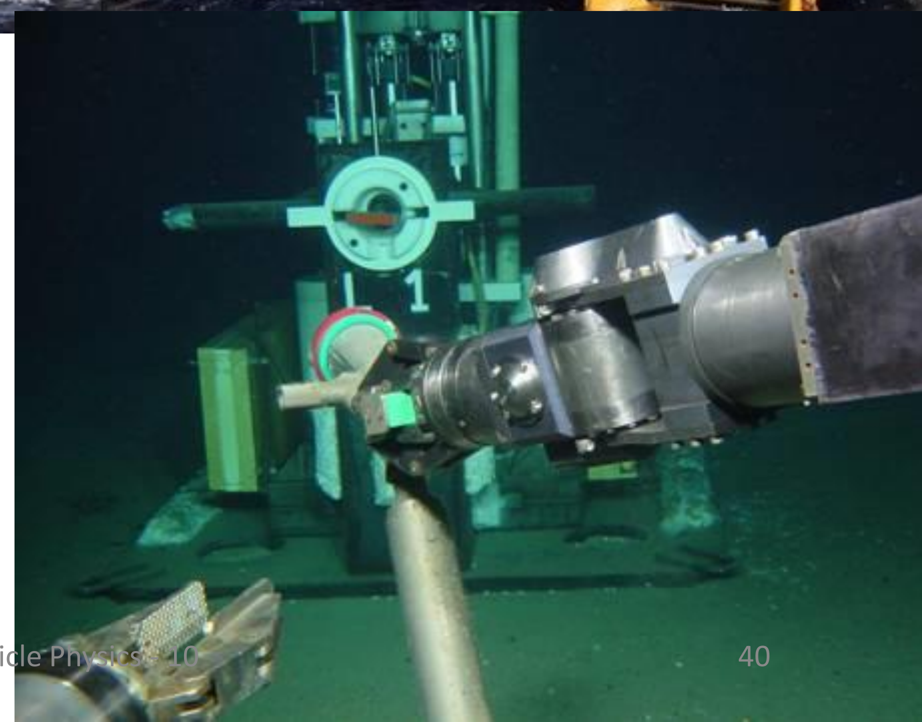
IceCube @South Pole



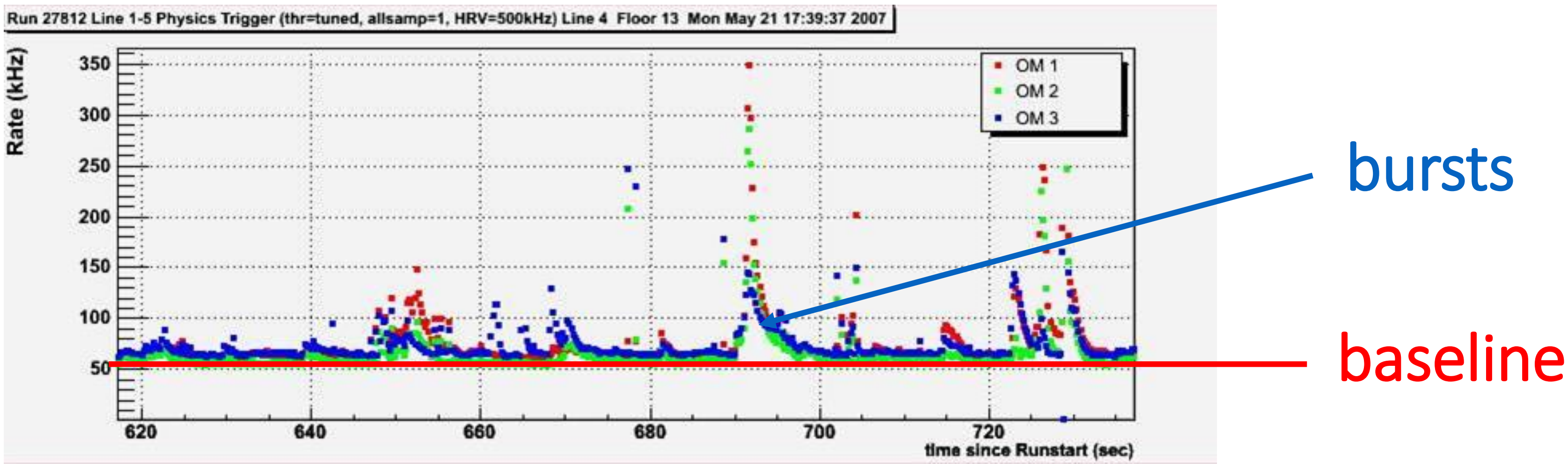

ANTARES
•Running since 2007
•885 10” PMTs
• 12 lines
• 25 storeys/line
• 3 PMTs / storey
450 m
40 km to shore
Junction Box
70 m
Interlink cables
ANTARES
France
Switzerland
Austria
Hungary
Italy
Croatia
Bosnia and Herzegovina
Serbia
Spain
Albania
Marseille
Monaco
Toulouse
Montpellier
Barcelona
Madrid
Valencia
Palma
Rome
Naples
Palermo
Algiers
Tunis
Malta
Gibraltar
Google


2500m
45
Junction Box
70 m
Interlink cables


LOXAM



1

Optical background

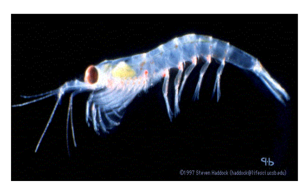


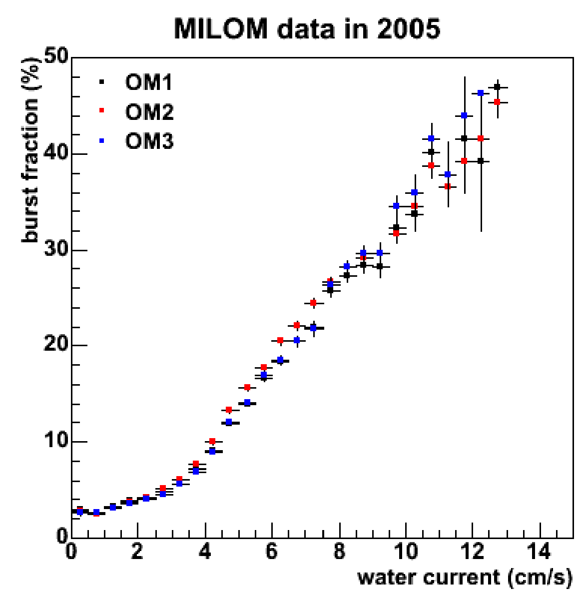
Baseline:

^{40}K decays + bacteria luminescence

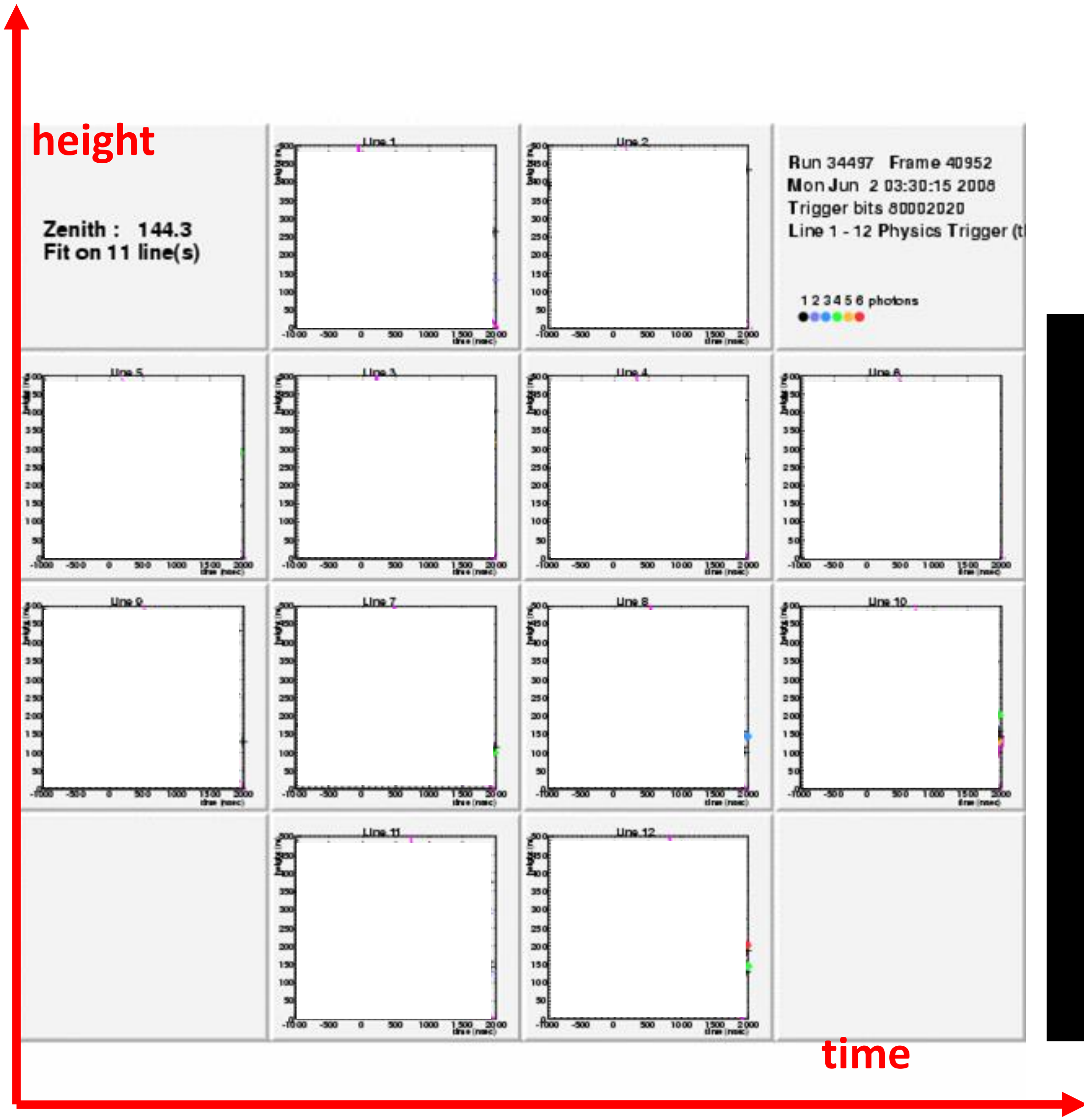
Bioluminescence bursts:

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

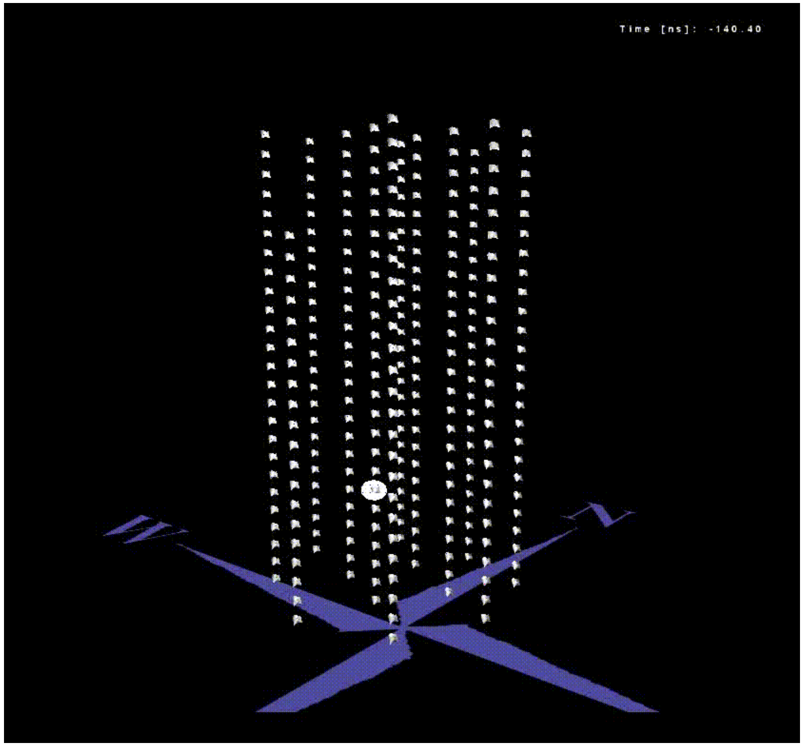




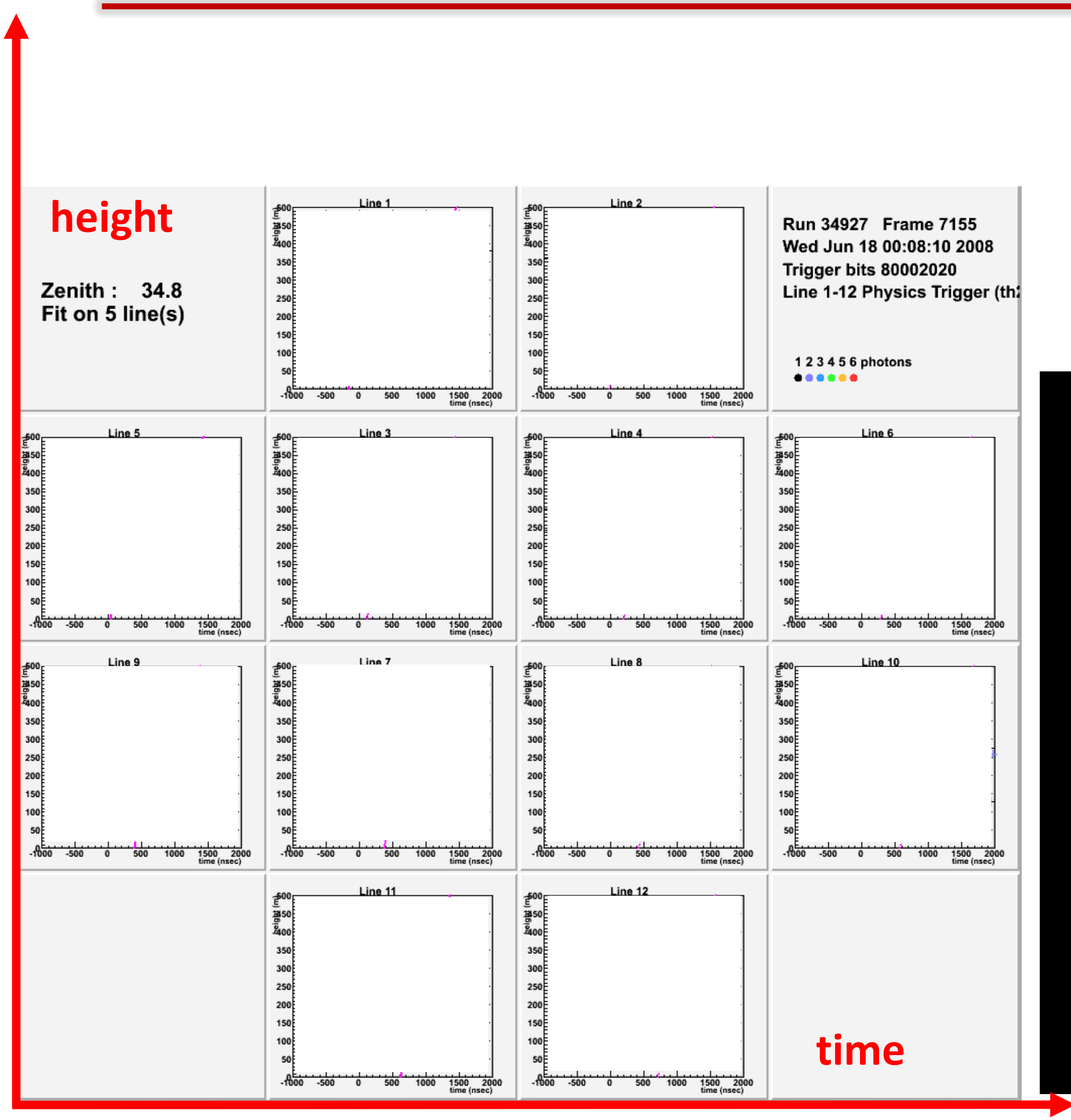
ANTARES: atmospheric muons



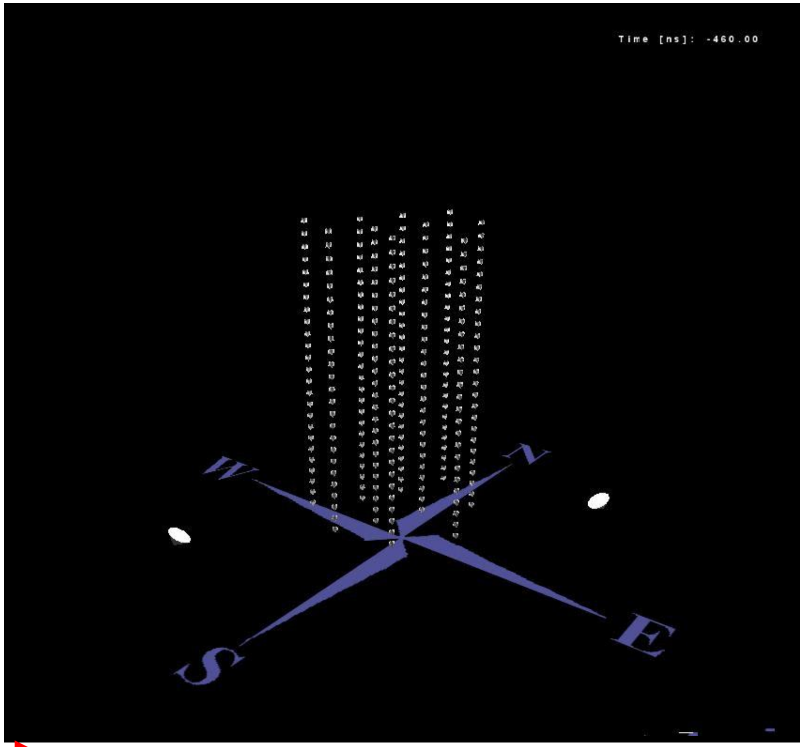
Example of a reconstructed down-going muon in ANTARES detected in all 12 detector lines:



ANTARES: ν-induced muon



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

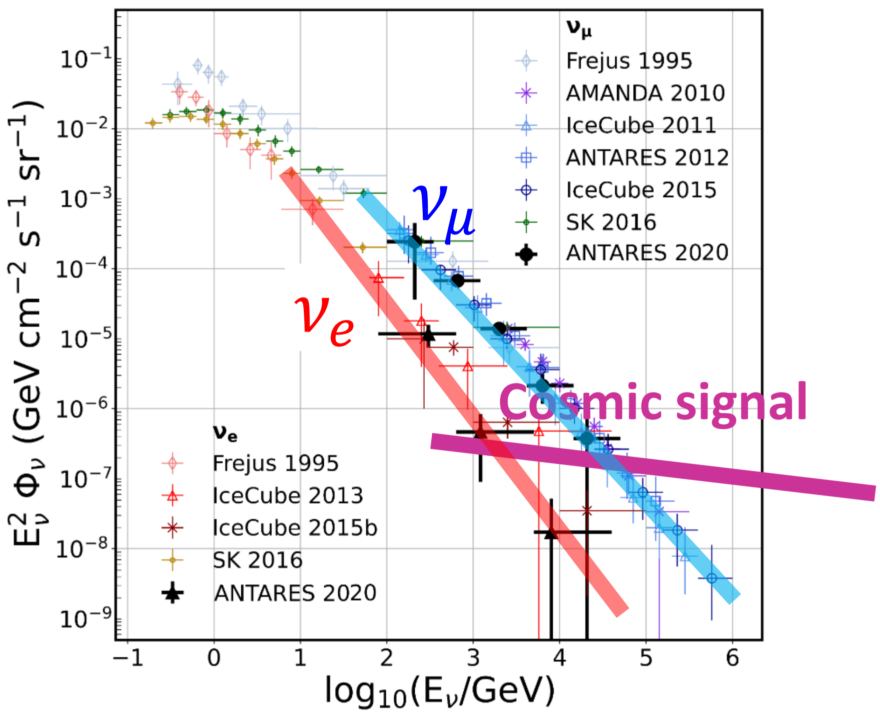


Detecting cosmic neutrinos: status in 2021

I. Point-like neutrino sources: search for significant excess of events in the sky map. Based on measurement of the **ν direction**

II. Excess of high-energy neutrinos over the background of atmospheric events. Based on the estimation of the **ν energy**

III. Coincident event in a restricted time/direction windows with EM/γ/GW counterparts: **transient/ multimessenger** information



- **Atmospheric neutrino flux (background):**

$$\frac{dN}{dE} = k_b E^{-3.6}$$

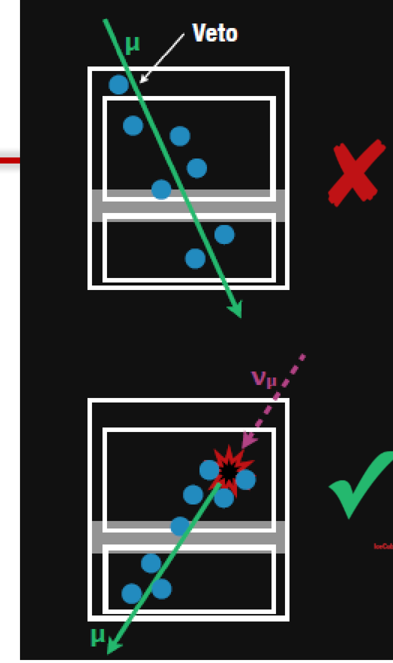
- Dominant < 50 TeV
- **Cosmic flux**

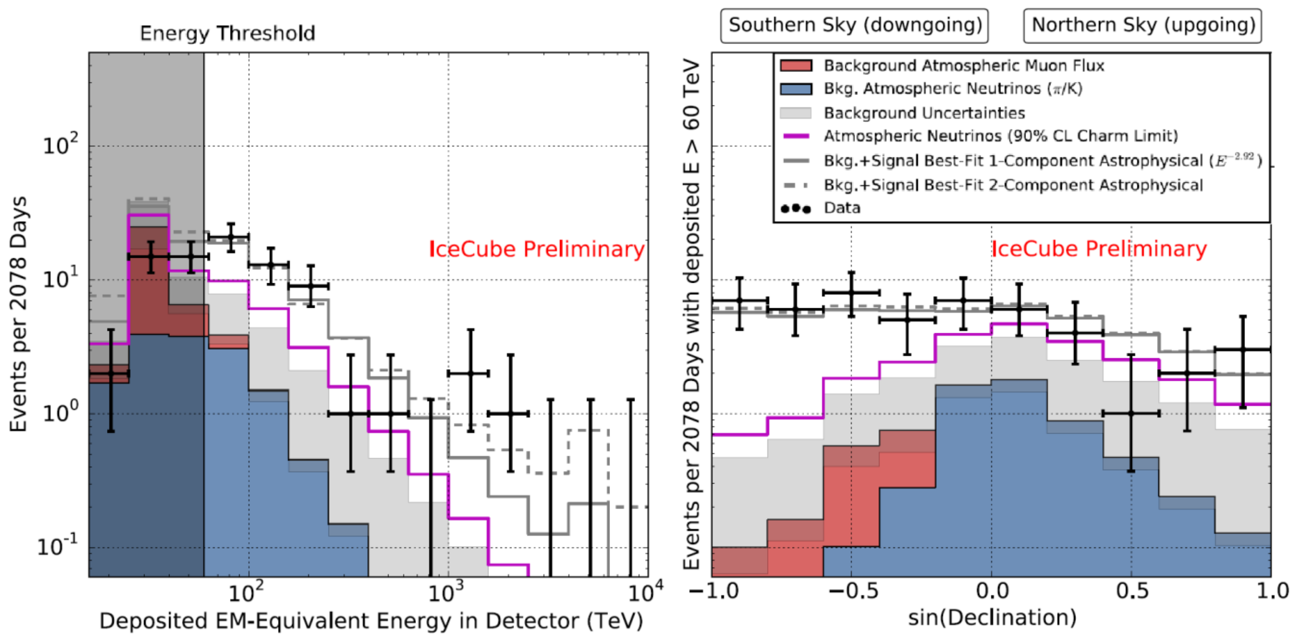
$$\frac{dN}{dE} = k_s E^{-2}$$

First HE detection from IceCube… 2013

Excess of HESEvents over background

- **High Energy Starting Events** (**HESE**) in IceCube
- Events selected in a restricted fiducial volume (SK-like)
- Mostly showers with poor angular determination (>10°)
- Excess fitted with a power-law: $\Phi_\nu = \Phi_0 E^{-\Gamma}$

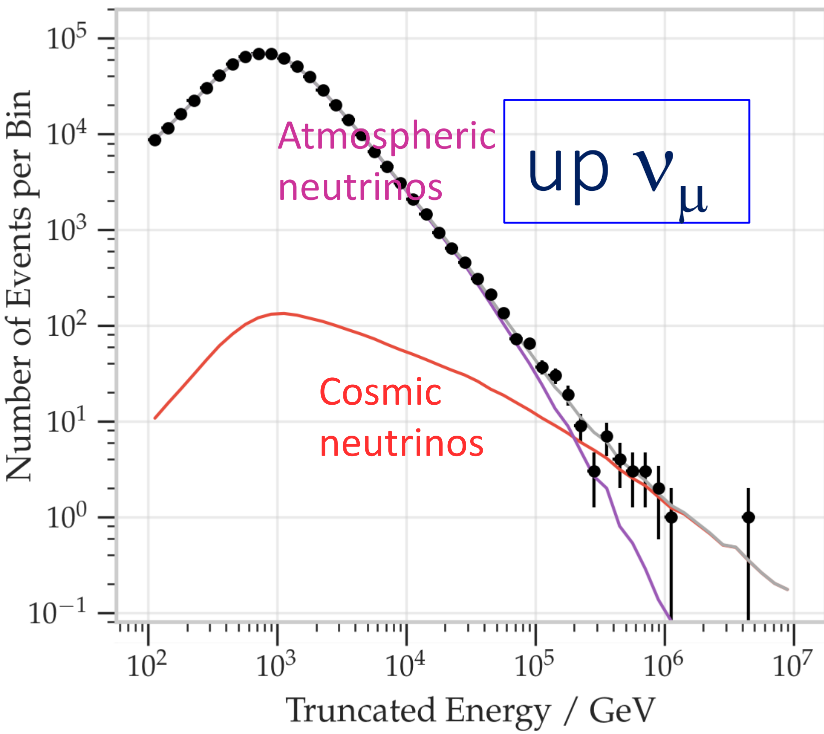


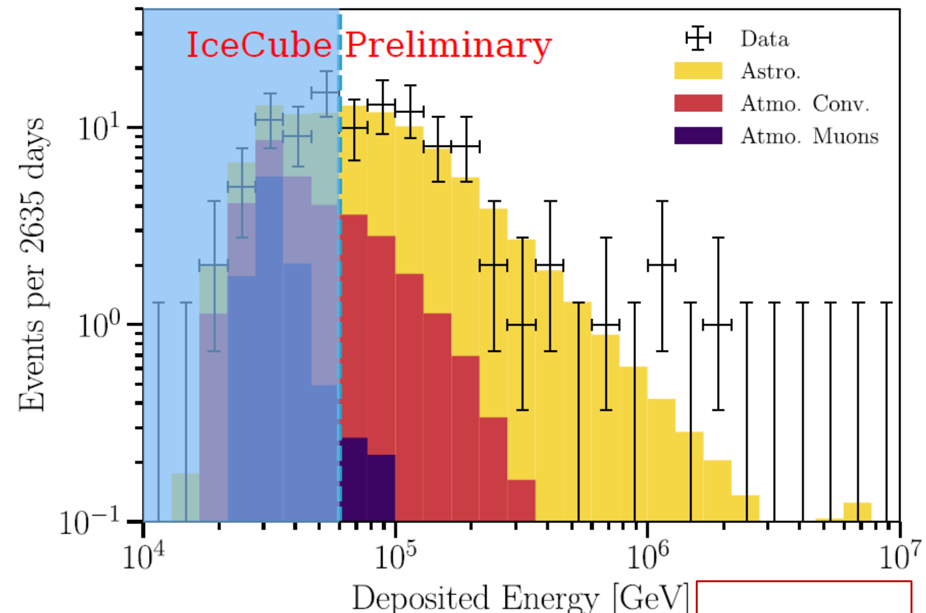


- Atmospheric muons
- Atmospheric neutrinos
- **Signal= excess of HE events**

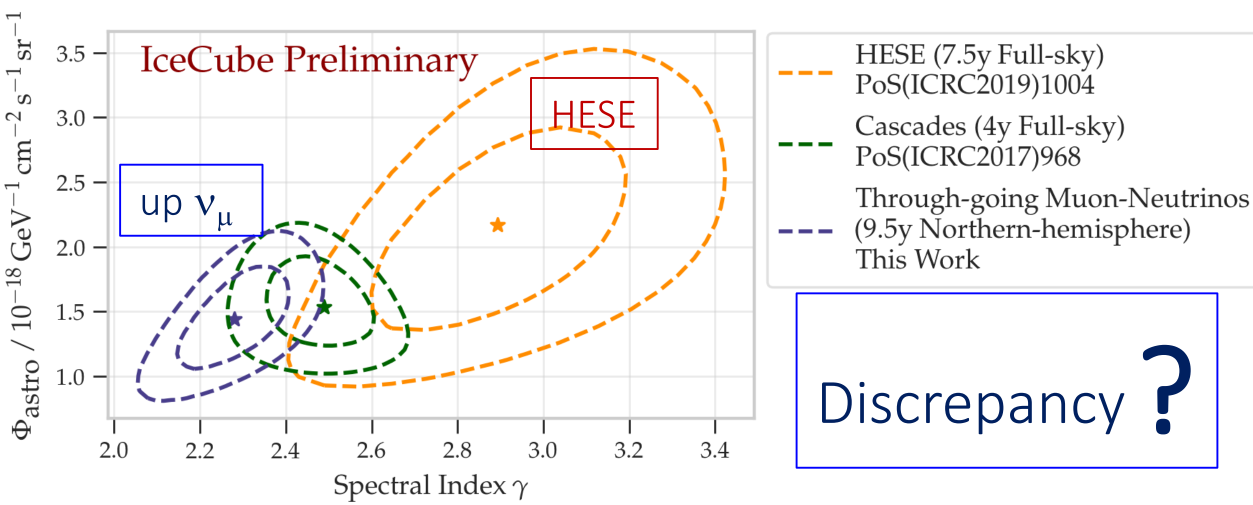
*Deposited energies E_{dep} **(left)** and arrival directions **(right)** of IceCube events (crosses), 6 years. The hashed region shows uncertainties on the sum of all backgrounds, due to atmospheric muons and atmospheric neutrinos. The contribution of an astrophysical (ν + ν) flux for E_{dep} > 60 TeV is signal-background.*

Excess of HE neutrinos in IceCube: diffuse cosmic





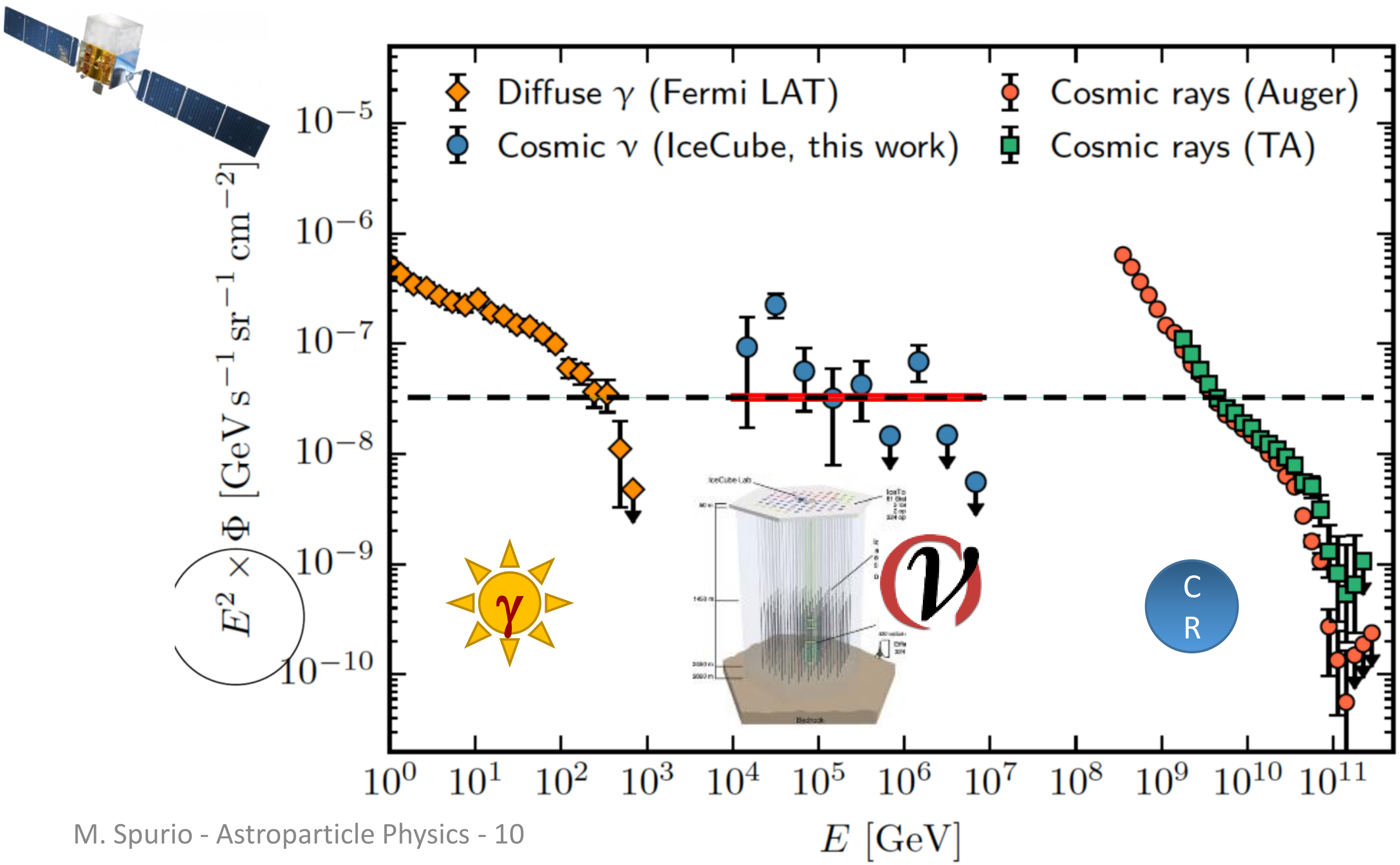
HESE



$$\frac{d\Phi_\nu}{dE} = \Phi_{astro} \cdot E^{-\gamma}$$

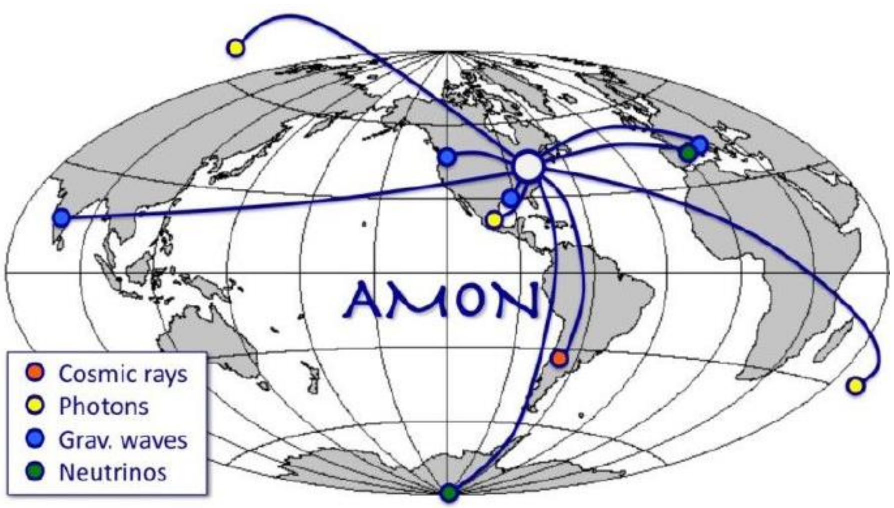
Discrepancy ?

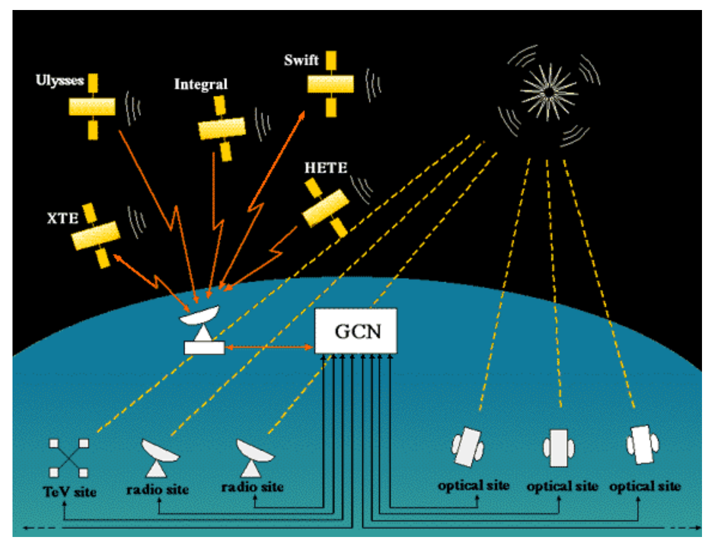
Diffuse flux of cosmic neutrinos vs CRs and γ-rays



Multimessenger: the GCN/AMON networks

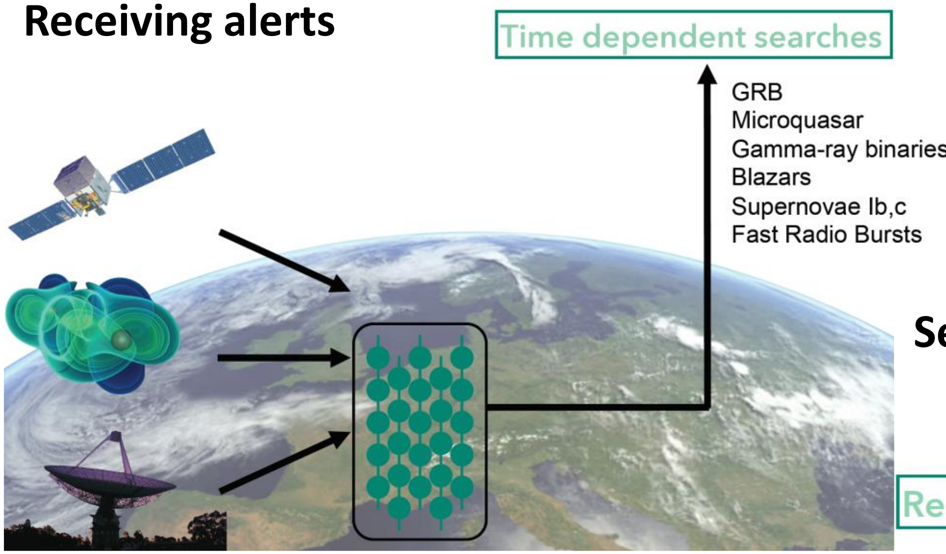
- The **GCN** is a system that distributes information (*notices)* about GRBs and other transients detected by various ground and space experiments and receives and distributes messages (*circulars*) about follow-up observations to interested individuals and institutions.
- **AMON** searches for multimessenger transients using the messenger particles of all four fundamental interactions. **Follow-up Observatories** receive and respond to AMON alerts
  - **Triggering**: IceCube, ANTARES, Pierre Auger, HAWC, VERITAS, FACT, Swift BAT, Fermi LAT & GBM, LIGO-Virgo*
  - **Follow-up**: Swift XRT & UVOT, VERITAS, FACT, HESS, MAGIC, MASTER, LCOGT



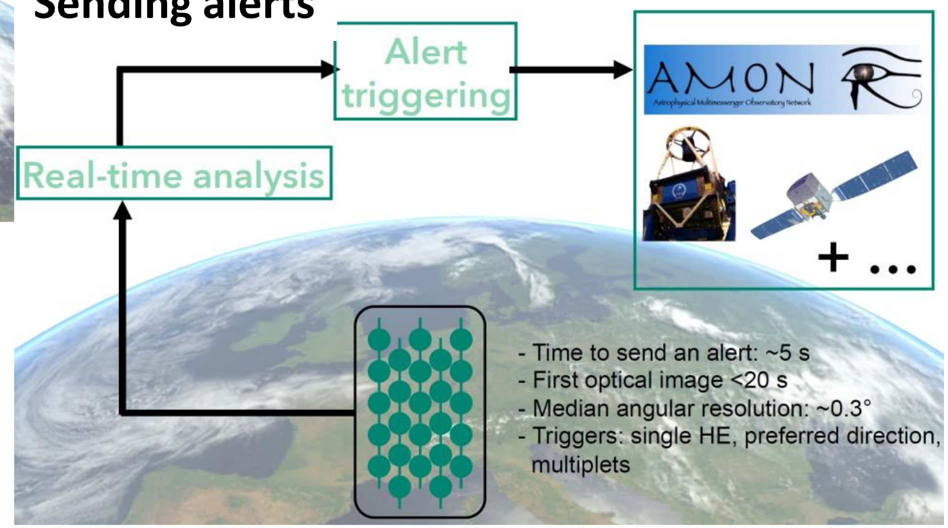


Multi-messenger approaches

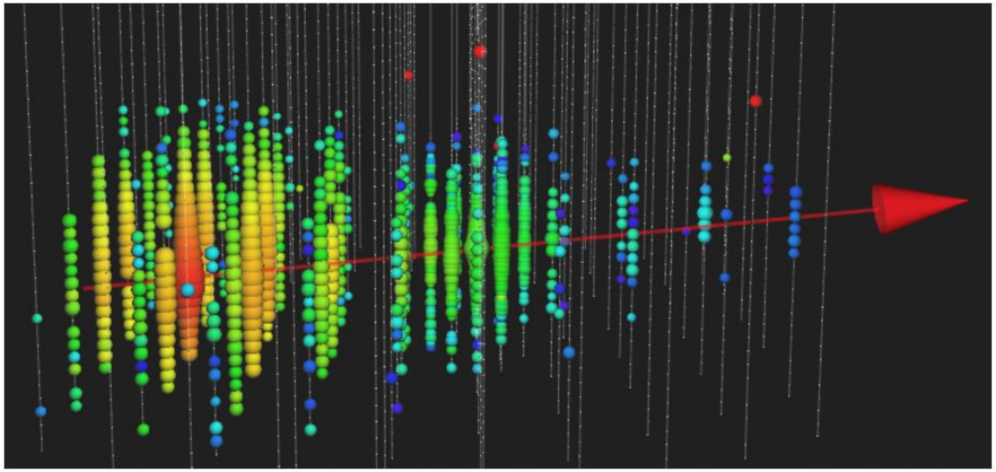
Receiving alerts



Sending alerts

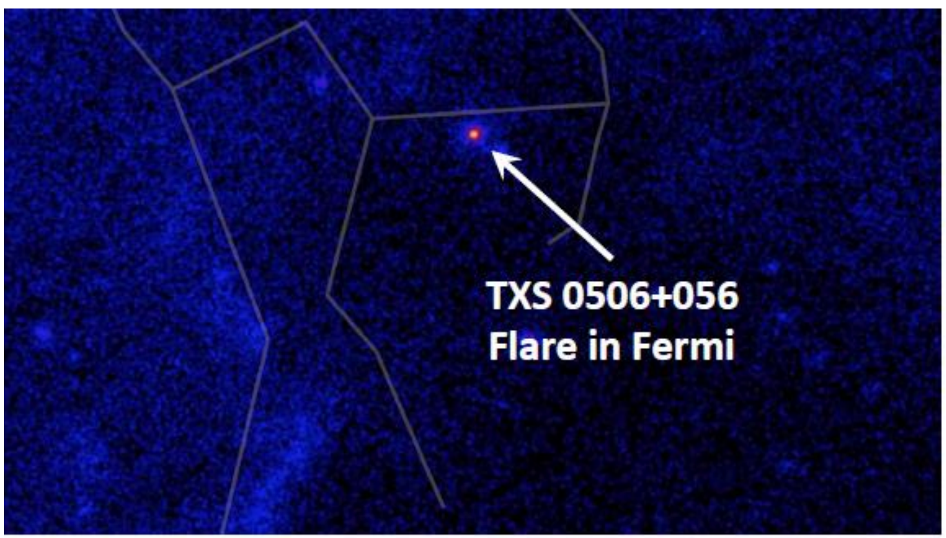


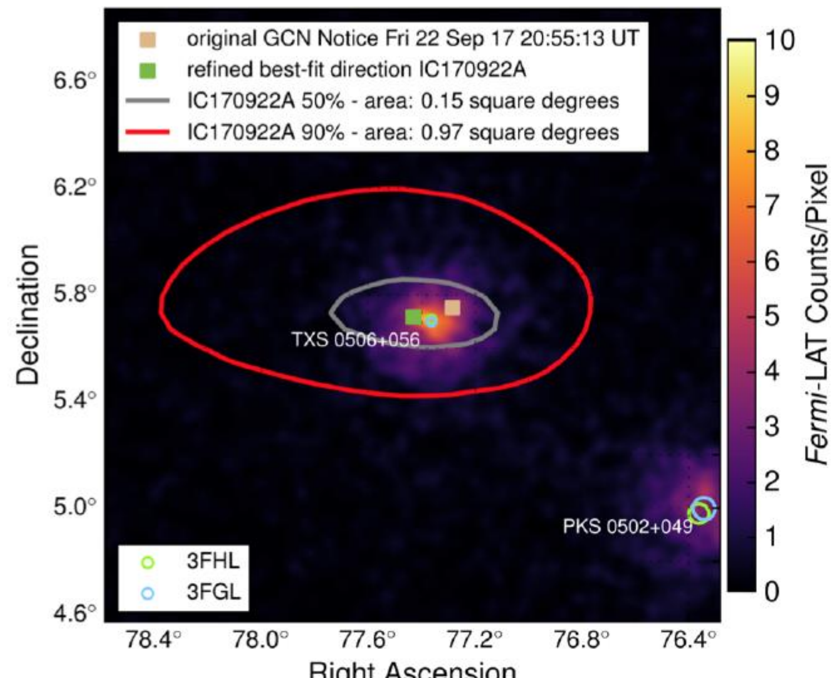
The first evidence for a ν source (2018)



First public ν Alert: IceCube-160427

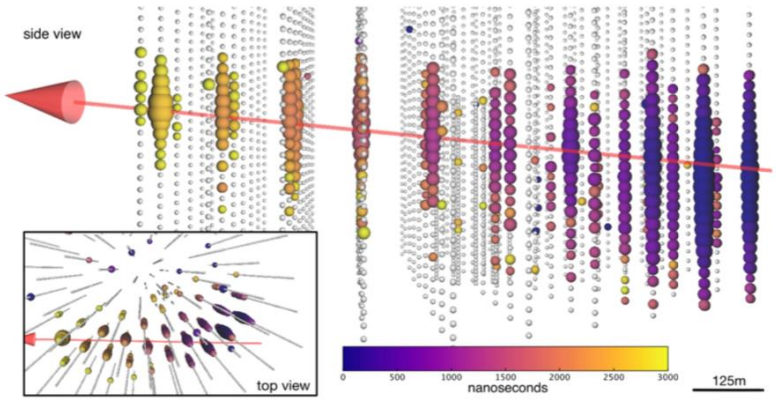
- **IceCube-170922:** a neutrino alert issued by IceCube
- **Fermi** and **MAGIC** identify a spatially coincident flaring blazar (TXS 0506+056)
- A ν-flare was found in archival IceCube data

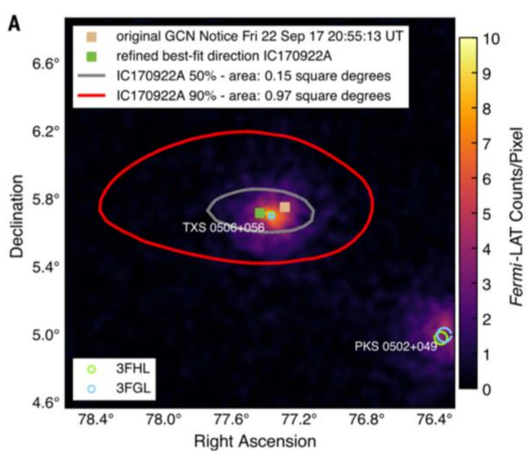




Neutrinos from the blazar TXS 0506+056 (I)

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

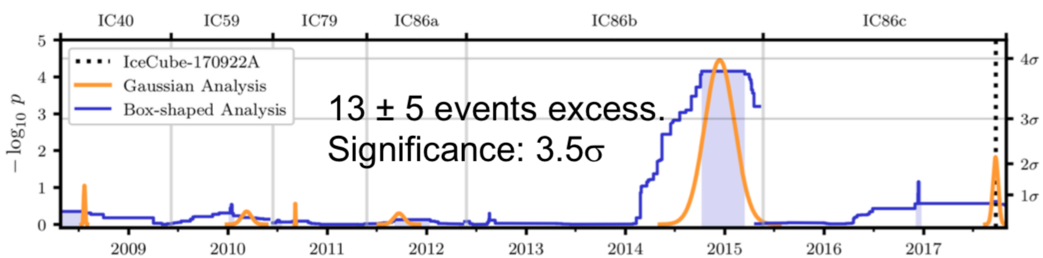
- An **electromagnetic follow-up** campaign of the event IceCube-170922A* indicated that this event came from the direction of a known AGN blazar named TXS 0506+056.
- TXS 0506+056 is a BL Lac object, found at redshift z=0.3365±0.0010
- It was at that time flaring at multiple wavelengths.
- In particular,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

** muon neutrino, angular resolution < 1^o*

Neutrinos from the blazar TXS 0506+056 (II)

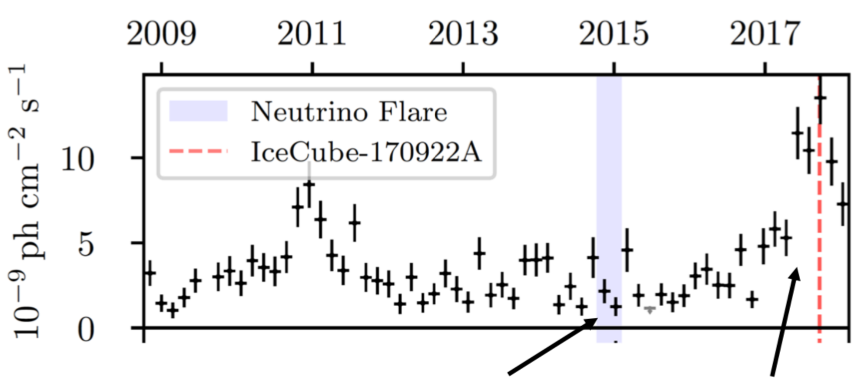
PoS(ICRC2019)1032

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



At 2014-15 neutrino flare

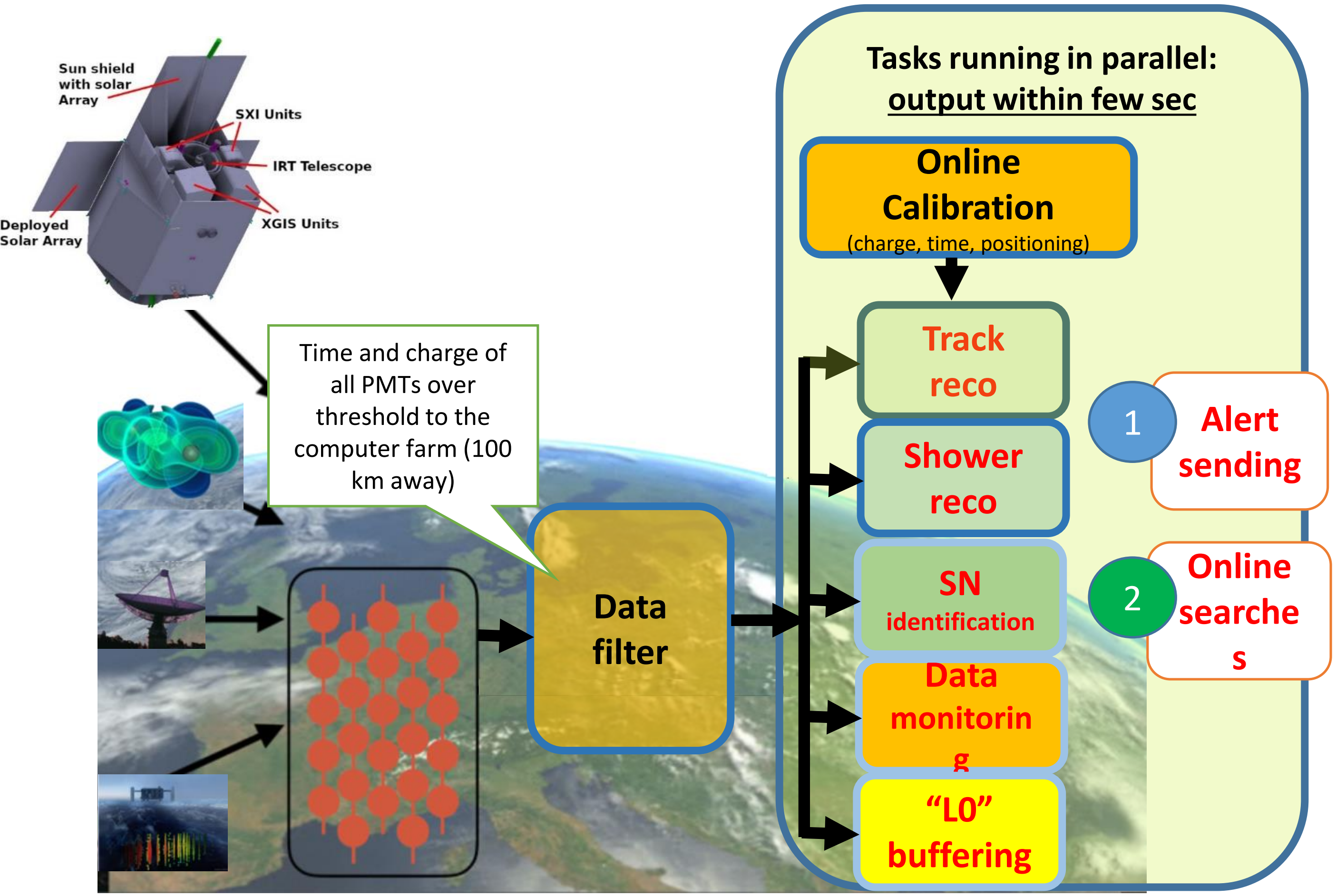
The 2017 flare

Page 2

- 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

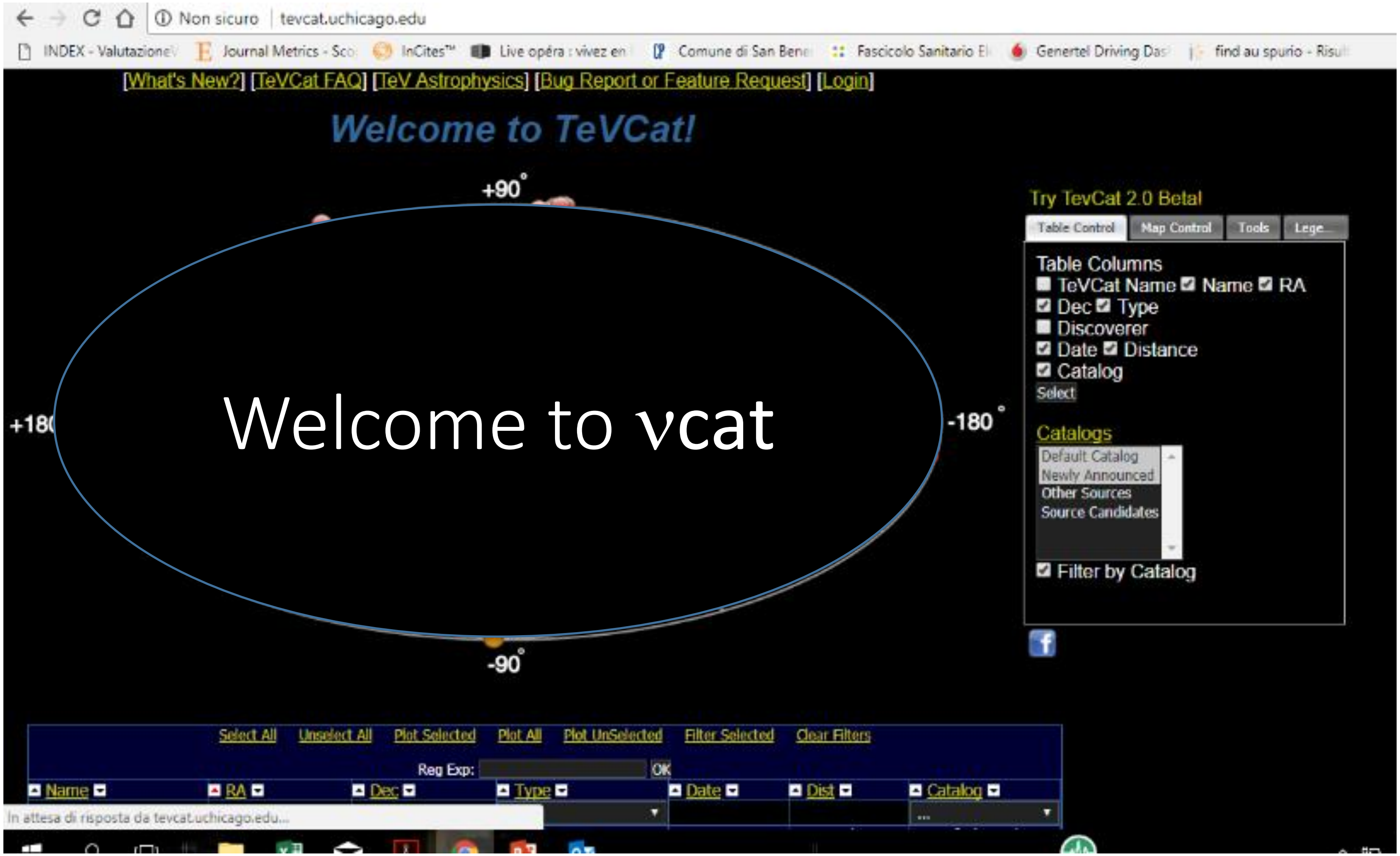
KM3NeT online alert system



ANTARES/IceCube

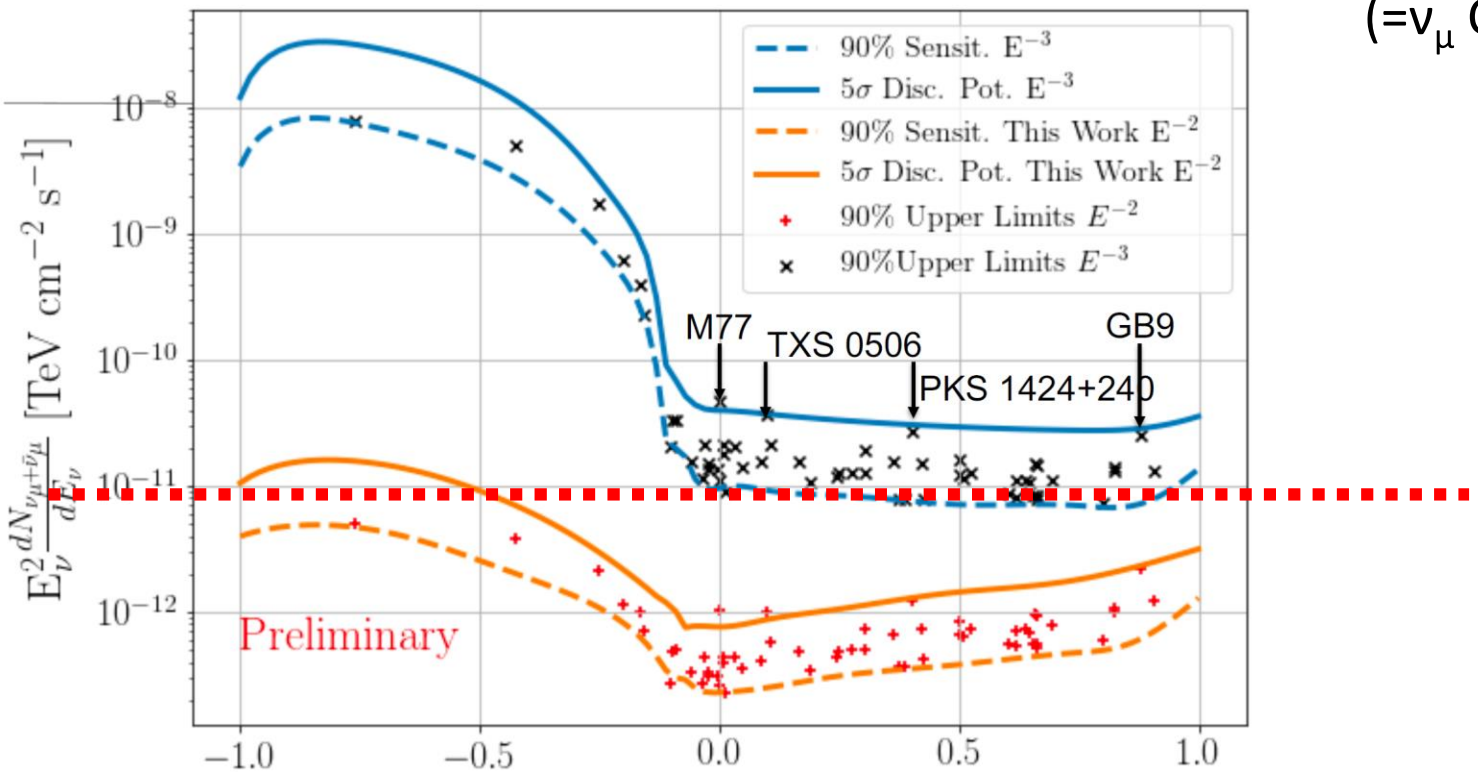
- Sending alert within 15s-60s from the event
- Angular resolution, depending on event type (track ~ 1^o, showers 10^o)
- “signalness”

Still, we do not have a “neutrino map”



Neutrino sky map

https://arxiv.org/abs/2101.09836



Southern sky
Mediterranean sea

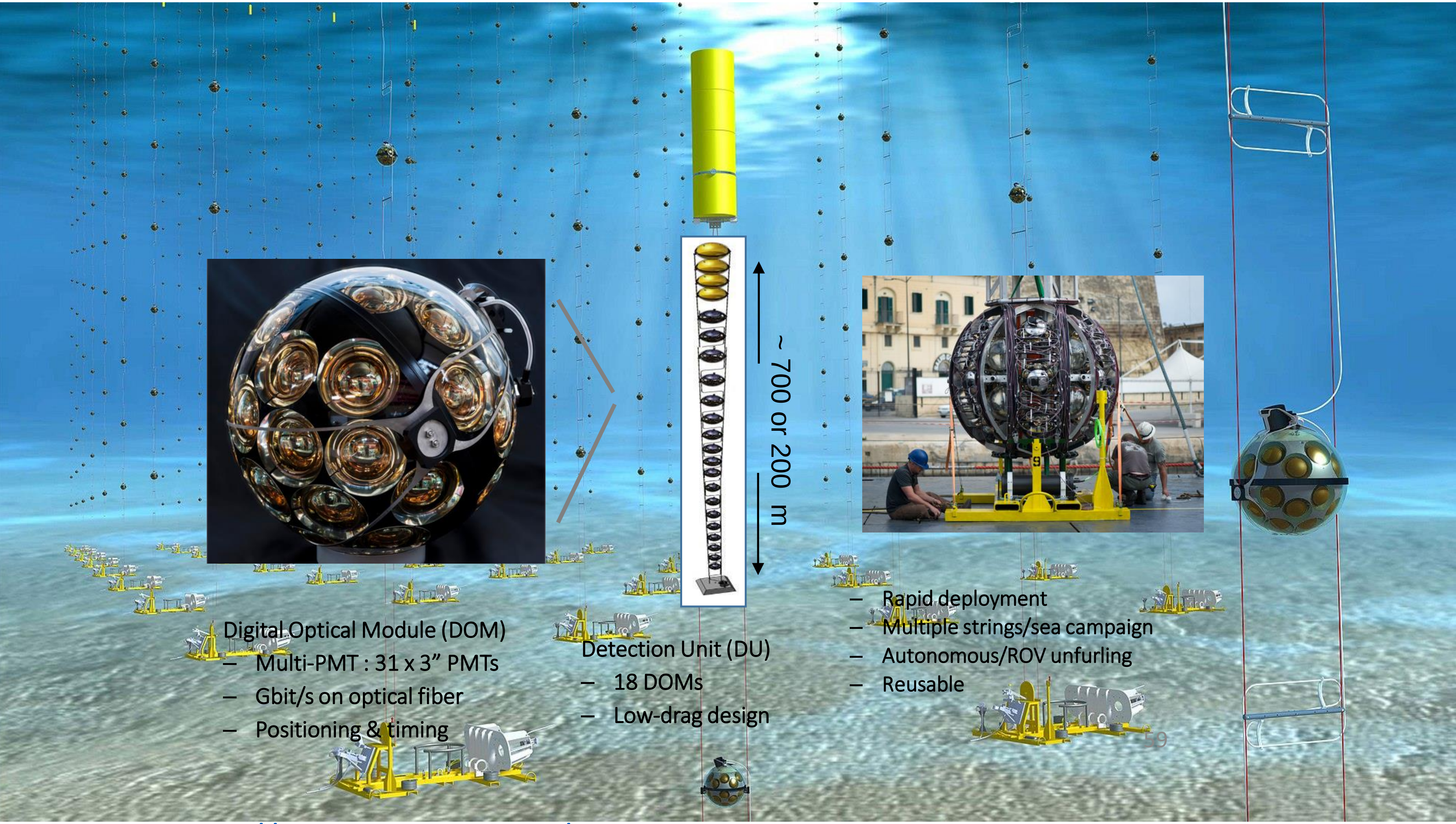
sin(declination)

Northern sky
South Pole ice

- Use "track" channel ($=\nu_\mu$ CC interactions)

Do you remember?

New telescopes in water: KM3NeT



Digital Optical Module (DOM)
- Multi-PMT : 31 x 3" PMTs
- Gbit/s on optical fiber
- Positioning & timing

Detection Unit (DU)
- 18 DOMs
- Low-drag design

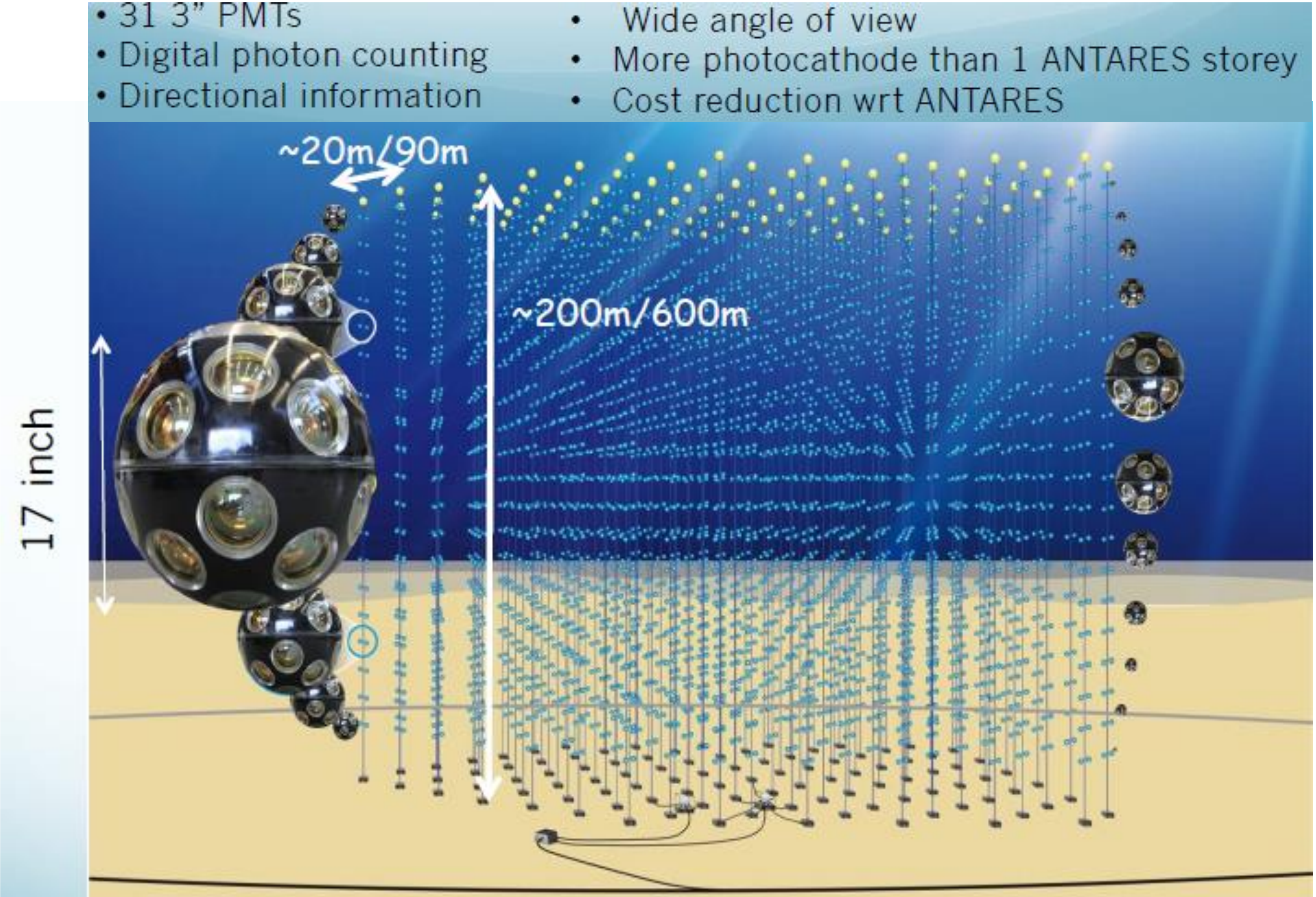
- Rapid deployment
- Multiple strings/sea campaign
- Autonomous/ROV unfurling
- Reusable

https://www.youtube.com/watch?v=tzxHlLgAahE

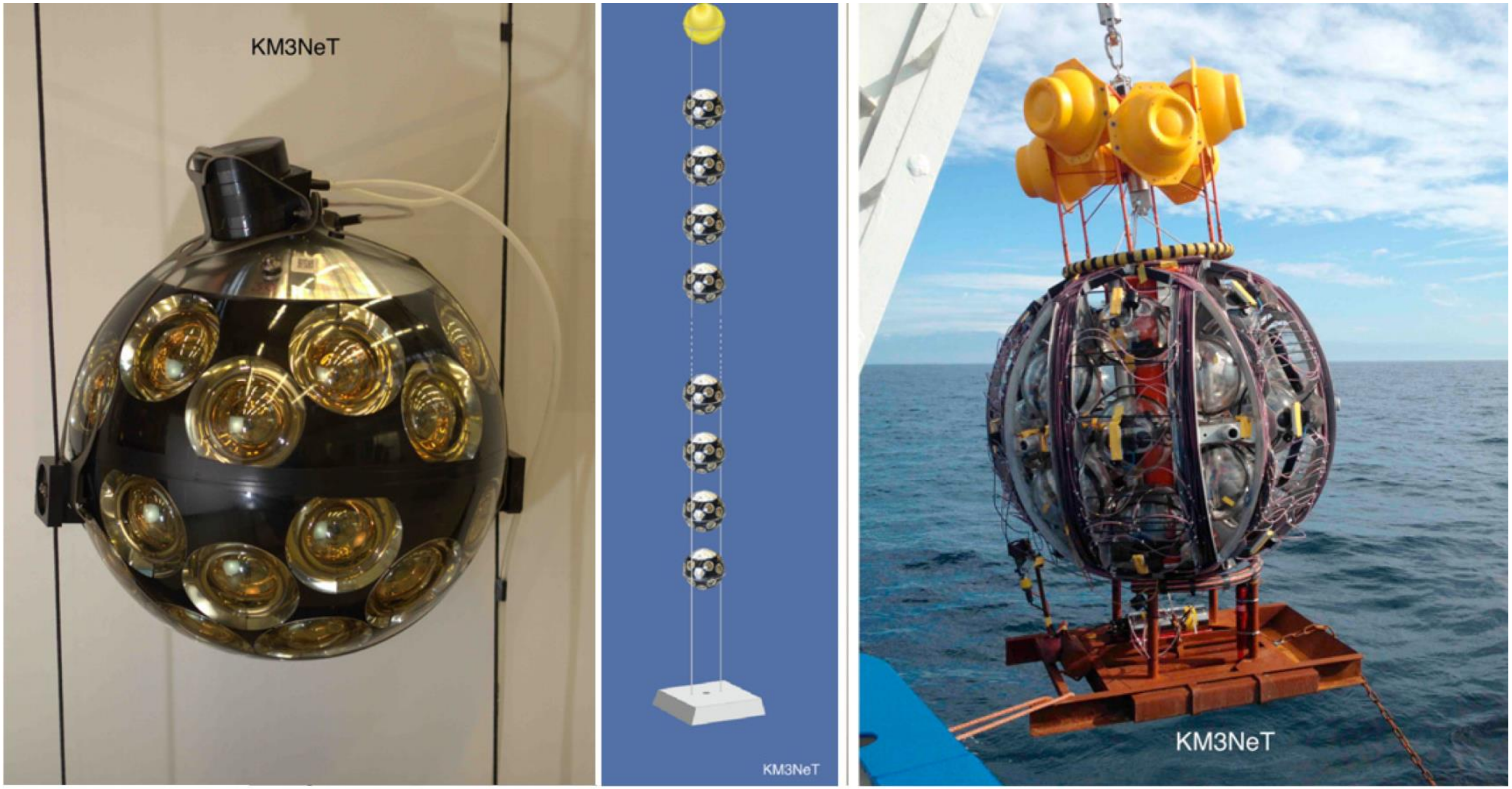
https://www.youtube.com/watch?v=omlFkdCkbYk&t=3s

KM3Net: the future

KM3NeT Detector technology



KM3NeT Detector technology

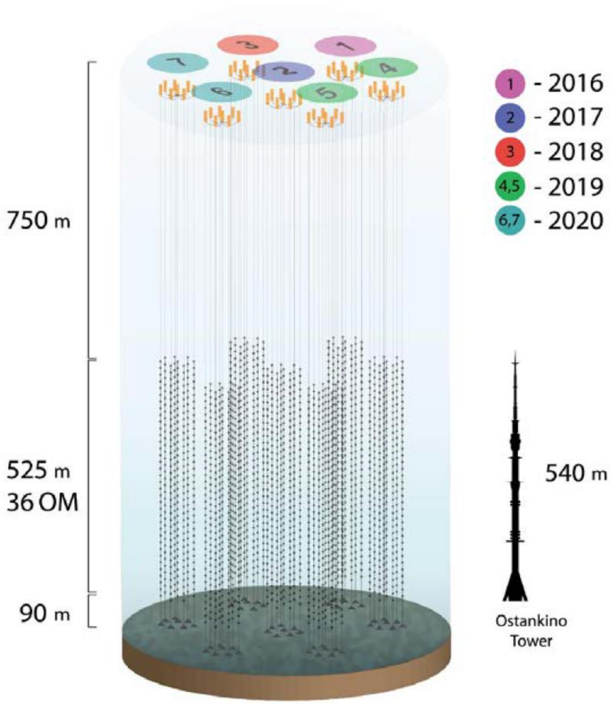


The KM3NeT Digital Optical Modules (DOMs) and Detector Units (DUs).
***Left**: a DOM consisting of a 17” pressure-resistant glass sphere with 31 small (3”) PMTs.*
***Middle**: a DU string with the breakout box and the fixation of the DOMs on the two parallel ropes.*
***Right**: Photo of a launch vehicle deployment containing a DU with 18 OMs.*
Credit: KM3NeT Collaboration Adrián-Martínez et al. (2016)

ANTARES and KM3NeT collaborations

New telescopes in water: GVD (Baikal)

Baikal-GVD construction status and schedule



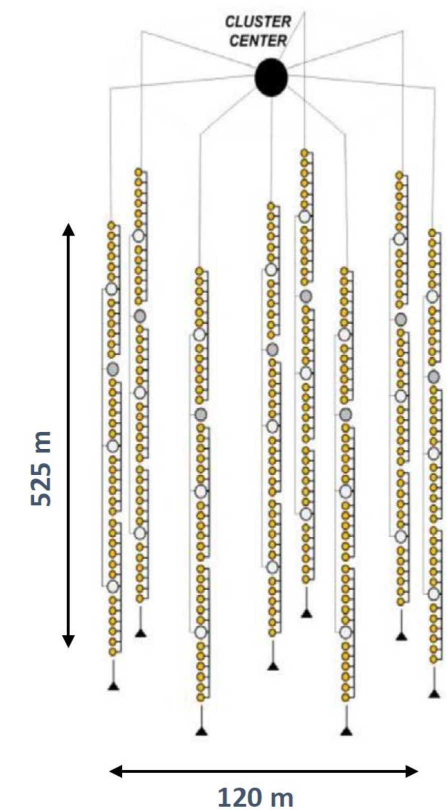
300 m step between clusters

Deployment schedule

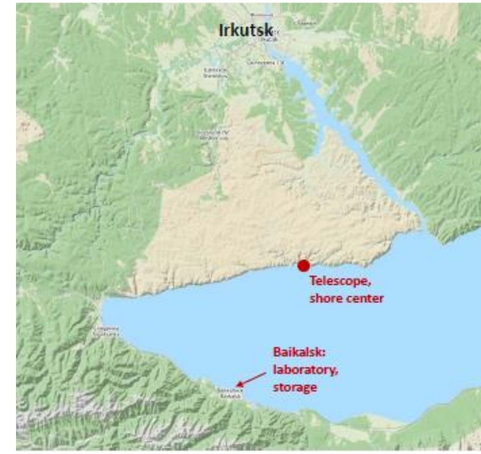
Year	Total number of clusters	Total number of strings	Number of OMs
2016	1	8	288
2017	2	16	576
2018	3	24	864
2019	5	40	1440
2020	**7**	**56**	**2016**
2021	8	64	2304
2022	10	80	2880
2023	12	96	3456
2024	14	112	4032

Effective volume 2020: 0.35 km^3

CLUSTER:
8 strings



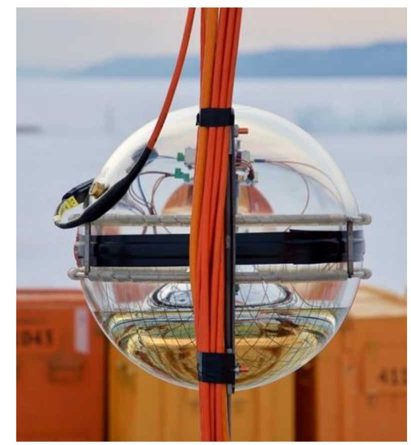
New telescopes in water: GVD (Baikal)



Winter expedition 2020

Despite harsh ice conditions
this winter

two new clusters were
deployed (576 OMs)



Thanks to: Zh.-A. Dzhilkibaev, INR (Moscow),
for the Baikal Collaboration (Neutrino Tescopes 2021, Venice)