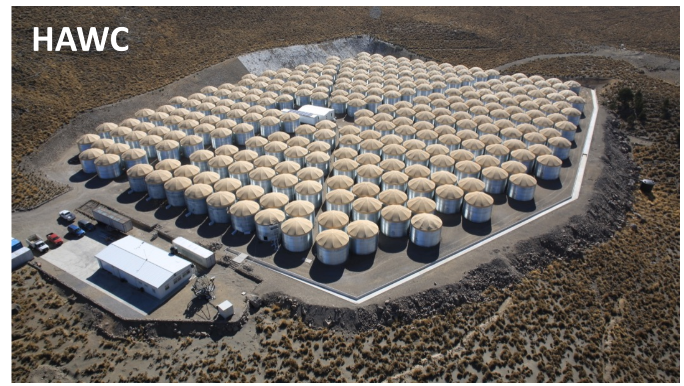
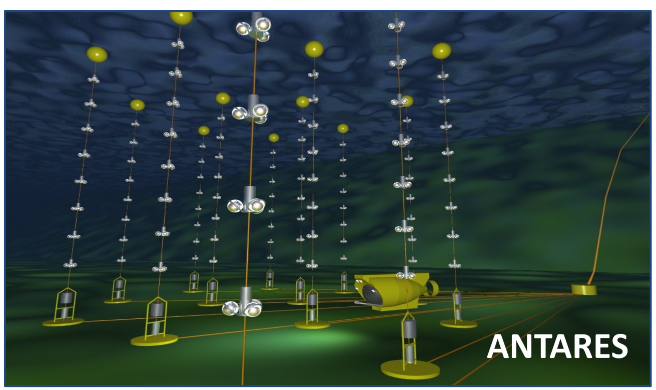
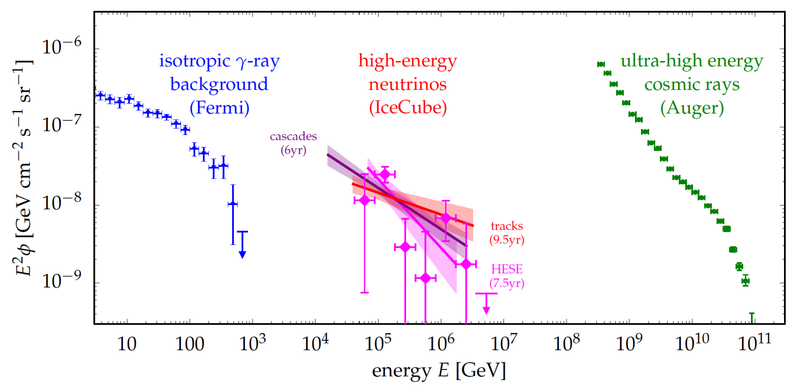
EPFL Physics and Applied Physics master programs - A.Y. 2024-2025

Introduction to astroparticle physics

Part 2 – Lesson 6 – May 30, 2025







Prof. **Chiara Perrina**

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Learning outcomes and goals

Describe the cosmic ray (CR) energy spectrum and composition.
Discuss CR origin, acceleration and propagation.

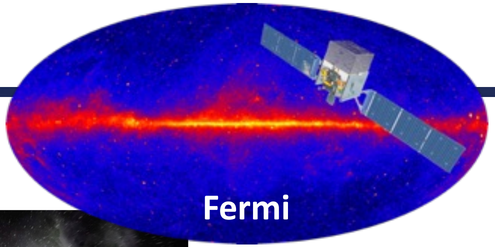
Explain the relationship between charged CRs, gamma rays and neutrinos.

Discuss the detection principles and measured quantities (mass, charge, momentum, energy, rigidity, direction, …) of astroparticle physics experiments.

Interpret the main results of selected experiments

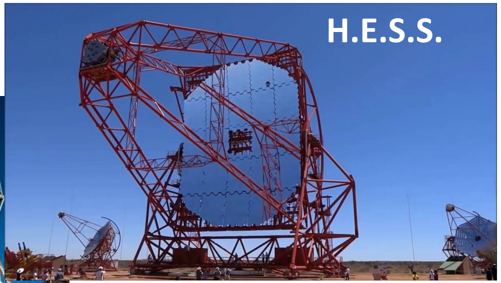
Assess / Evaluate the state of the art of astroparticle physics

Gamma-ray experiments (now)

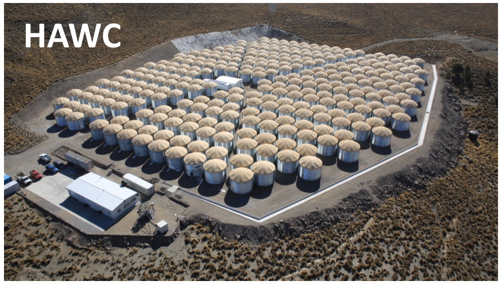


Satellites (E < 100 GeV)

Imaging Atmospheric Cherenkov Telescopes “IACTs” (E > 100 GeV)



Extensive Air Shower Detectors (E < 100 TeV)

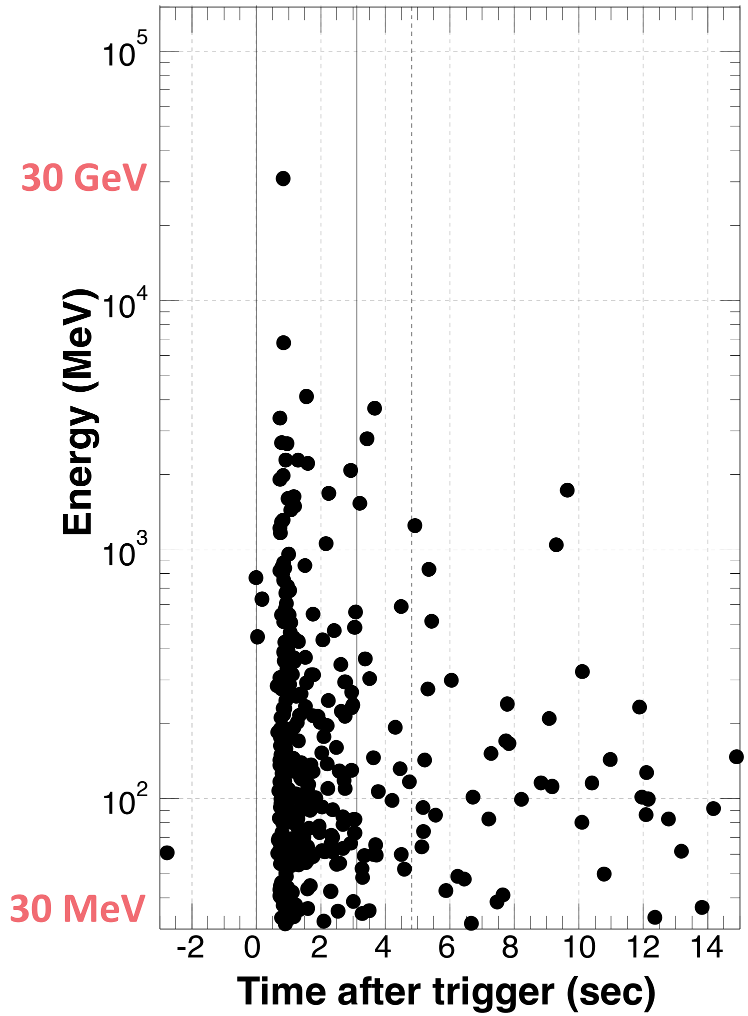


Detection of GRB 090510 – Lorentz Invariance validation

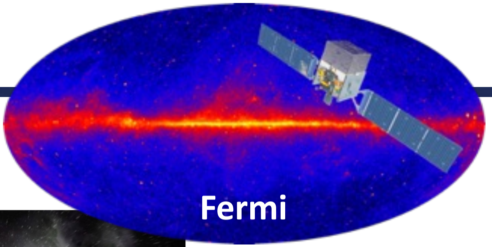
C. Couturier et al., https://arxiv.org/pdf/1308.6403.pdf

The Lorentz Invariance prediction of Einstein's Special Theory of Relativity hold that all observers measure the same speed of light in vacuum i.e., the speed of light in vacuum does not depend on the energy of photons.

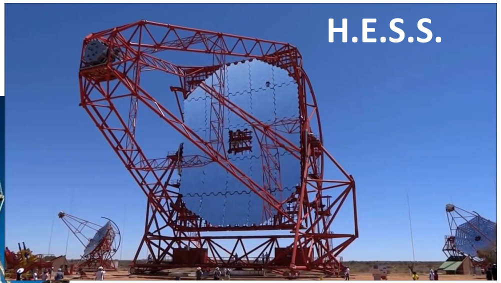
In May 2009, both low energy (30 MeV) and high energy (30 GeV) photons from a GRB were detected by Fermi at the same time.



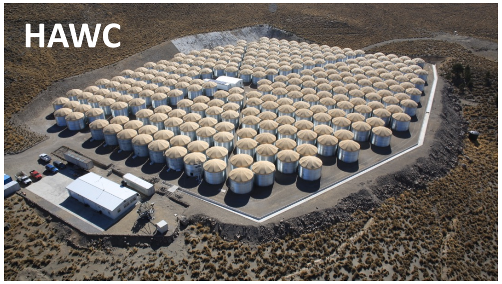
Gamma-ray experiments



Satellites (E < 100 GeV)
+ China Space Station (HERD)

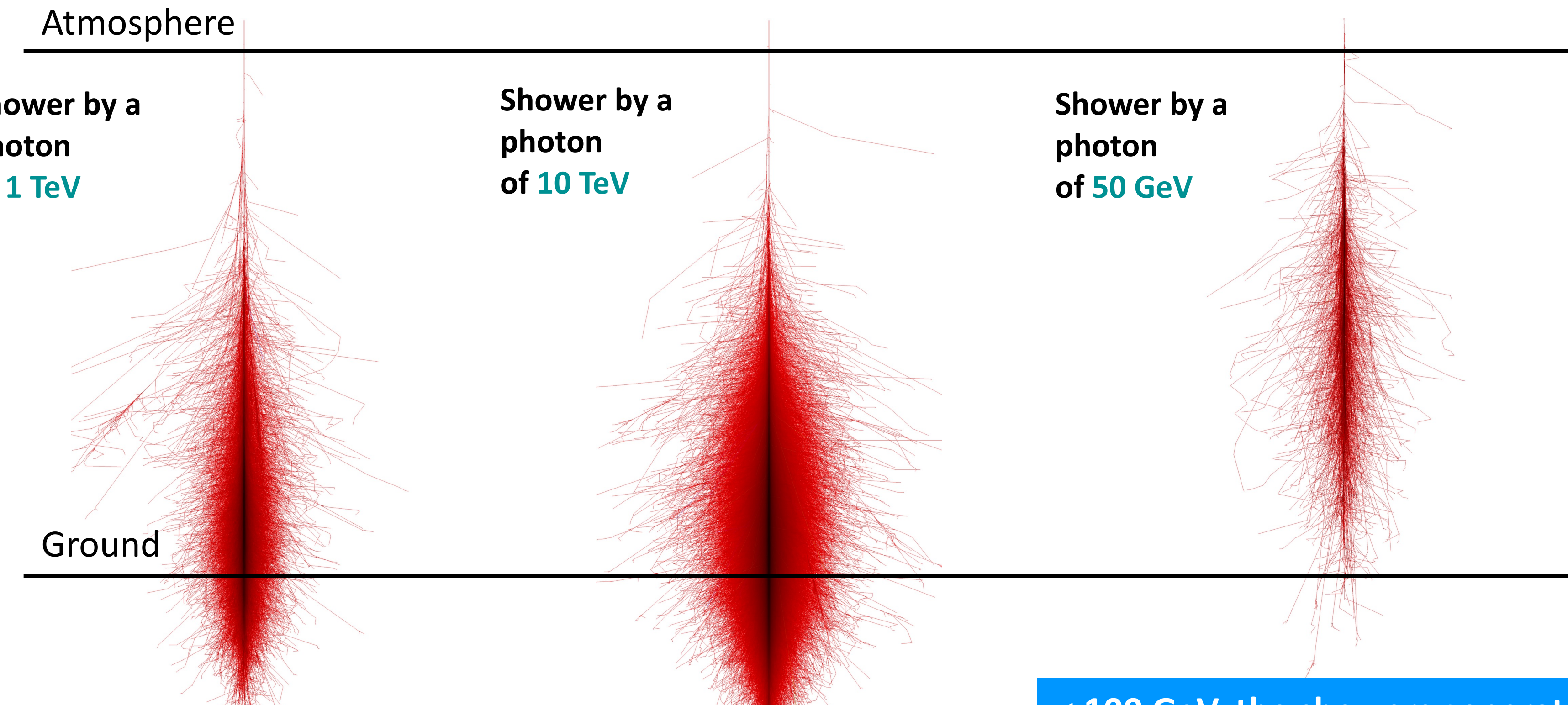


Imaging Atmospheric Cherenkov Telescopes “IACTs”
(E > 100 GeV)



Space-borne exps and ground-based exps are complementary

- At **TeV energies the flux is too low** to be detected with space-borne detectors. They have areas of the order of 1 m^2 at most, due to their cost, and to the cost of the launch, and at TeV energies even the most luminous gamma-ray source has a flux smaller than 1 photon/m^2 every ten hours.



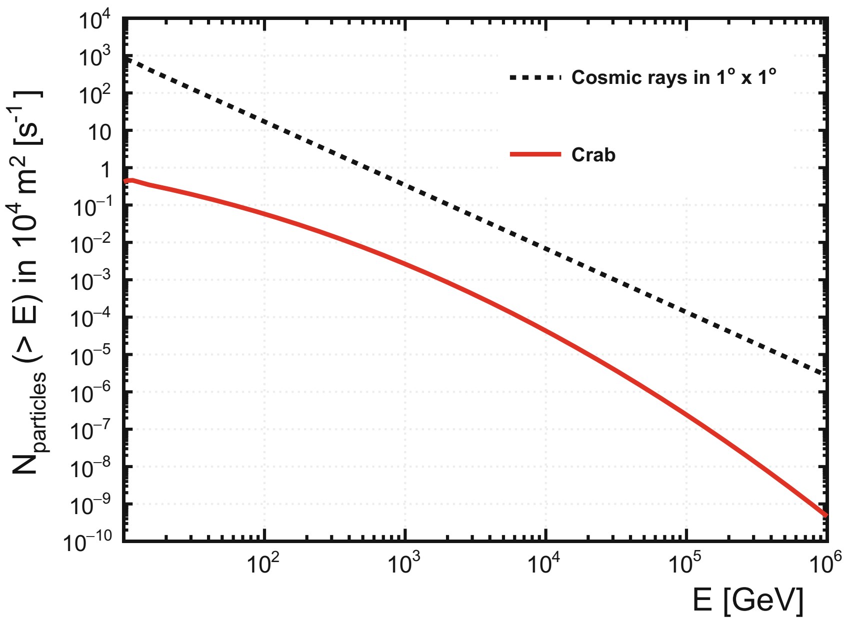
Ground-based detectors have larger **effective area**, **low costs,** but they detect a **huge amount of background** events.

< 100 GeV, the showers generated by photons do not have the time to develop properly, and thus the only way to detect such photons is with satellites.

Background for ground-based experiments

The main problem of ground-based detection is the rejection of the background from **showers generated by protons**.

Crab Nebula, a nearby (~2 kpc away) pulsar wind nebula (PWN), is the first source detected in high-energy gamma rays and the brightest gamma-ray source, it is called "**standard reference**" in high-energy gamma-ray astronomy.



An <u>angular resolution</u> of 1° or better is needed, and possibly a way to distinguish the e.m. showers induced by gamma rays from the mixed (e.m. + hadronic + muonic) showers induced by protons (e.g., by the shower <u>topology</u> or by the presence of <u>muons</u>).

Imaging Atmospheric Cherenkov Telescopes “IACTs”

VERITAS: Very Energetic Radiation Imaging Telescope Array System (Southern Arizona, USA, **altitude: 1’268 m**).
- From 2007: 4 telescopes with a diameter of 12 m

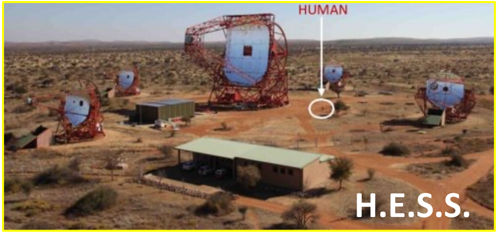
https://veritas.sao.arizona.edu

MAGIC: Major Atmospheric Gamma Imaging Cherenkov Telescopes (La Palma, Canary Islands, **altitude: 2’200 m**).
- From 2004+2009: 1+1 telescopes with a diameter of 17 m

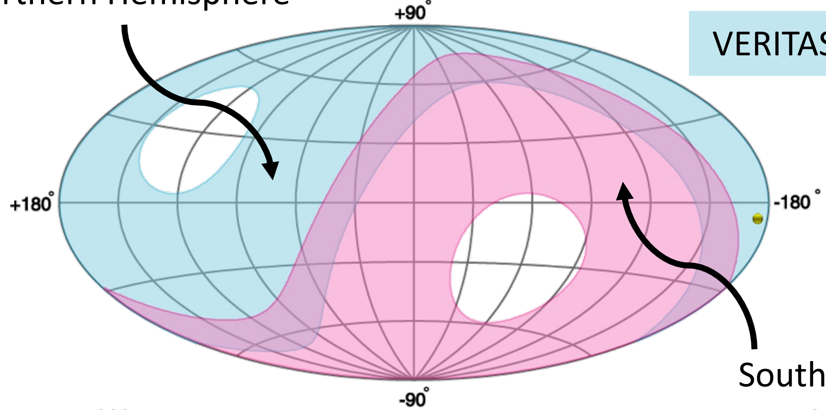
https://magic.mpp.mpg.de

H.E.S.S.: High Energy Stereoscopic System (Namibia, **altitude: 1’800 m**)
- From 2003: 4 telescopes with a diameter of 12 m
- From 2012: 1 telescope with a diameter of 28 m

https://www.mpi-hd.mpg.de/hfm/HESS/



Northern Hemisphere



H.E.S.S. visibility

VERITAS/MAGIC visibility

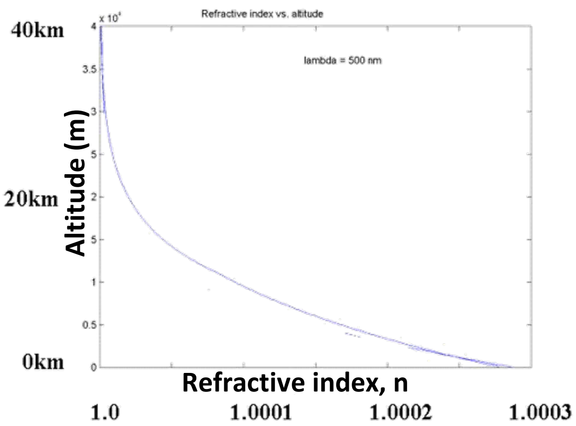
Southern Hemisphere

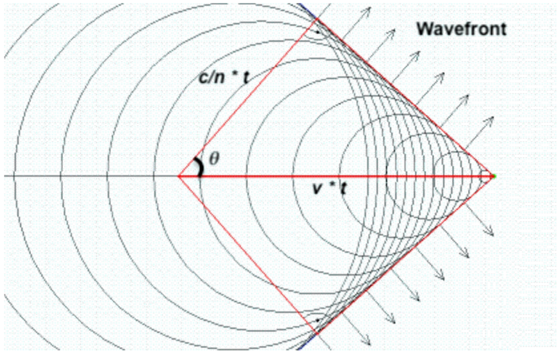
+ TAIGA, MACE, CTA

IACT detection principle

Cherenkov-light pool

Refractive Index vs. Altitude (500nm wavelength)





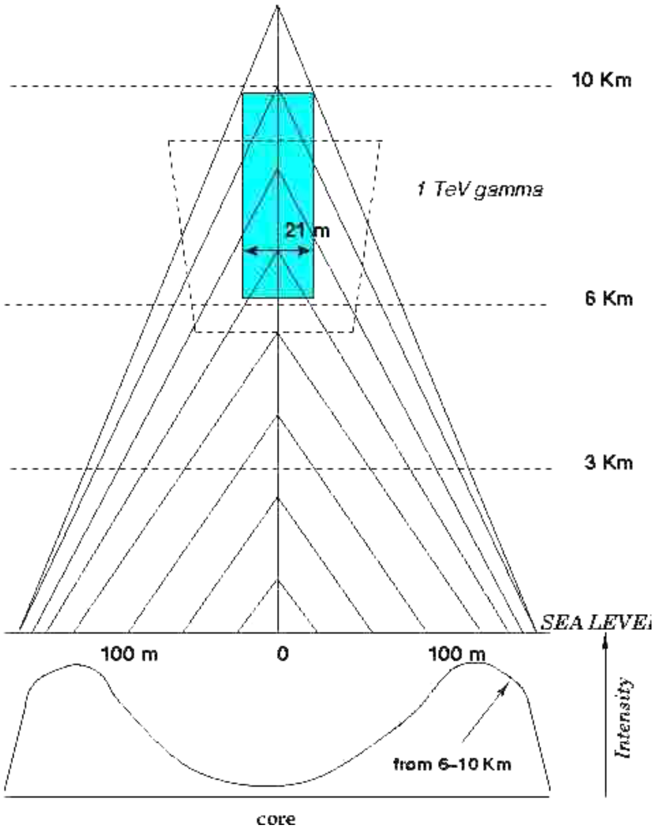
$$\boxed{\cos\theta = \frac{1}{\beta n} < 1}$$

- With decreasing altitude (*h*), the refractive index of the air increases.

  → The Cherenkov angle is increasing downwards

1. First Cherenkov photons are emitted close to the axis, subsequent photons lie further and further from the axis.

2. On ground a circular or elliptic "pool" of light is formed.

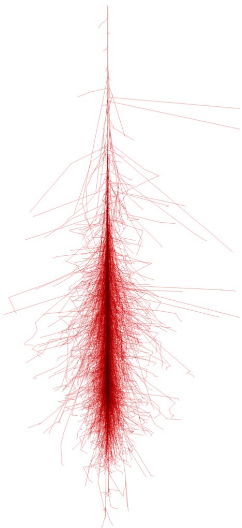


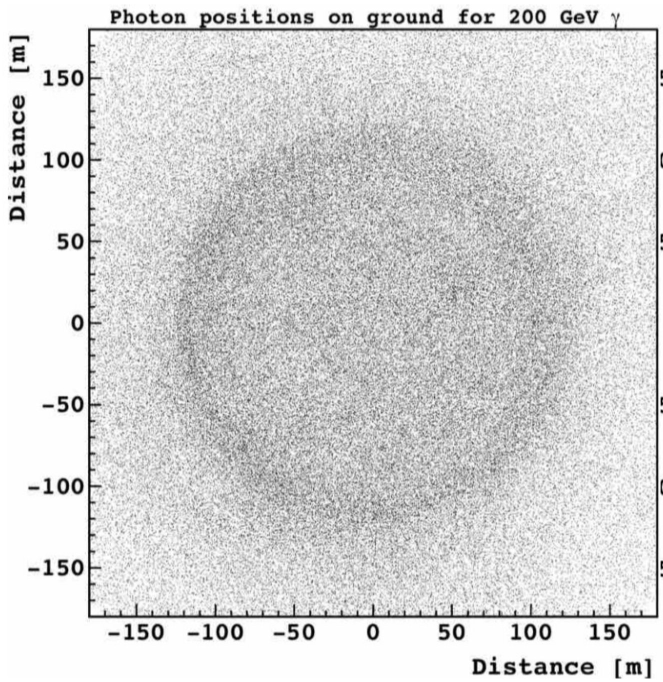
Distribution of Cherenkov light on the ground

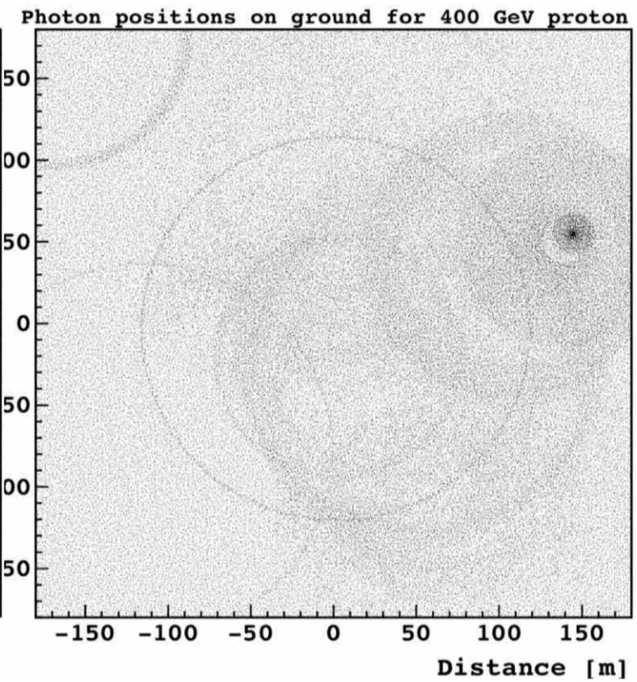
Shower induced by a
200 GeV gamma ray

Shower induced by a
400 GeV proton

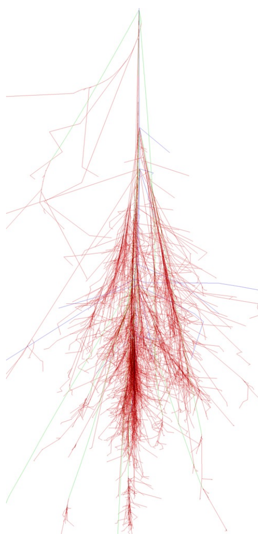
100 GeV γ



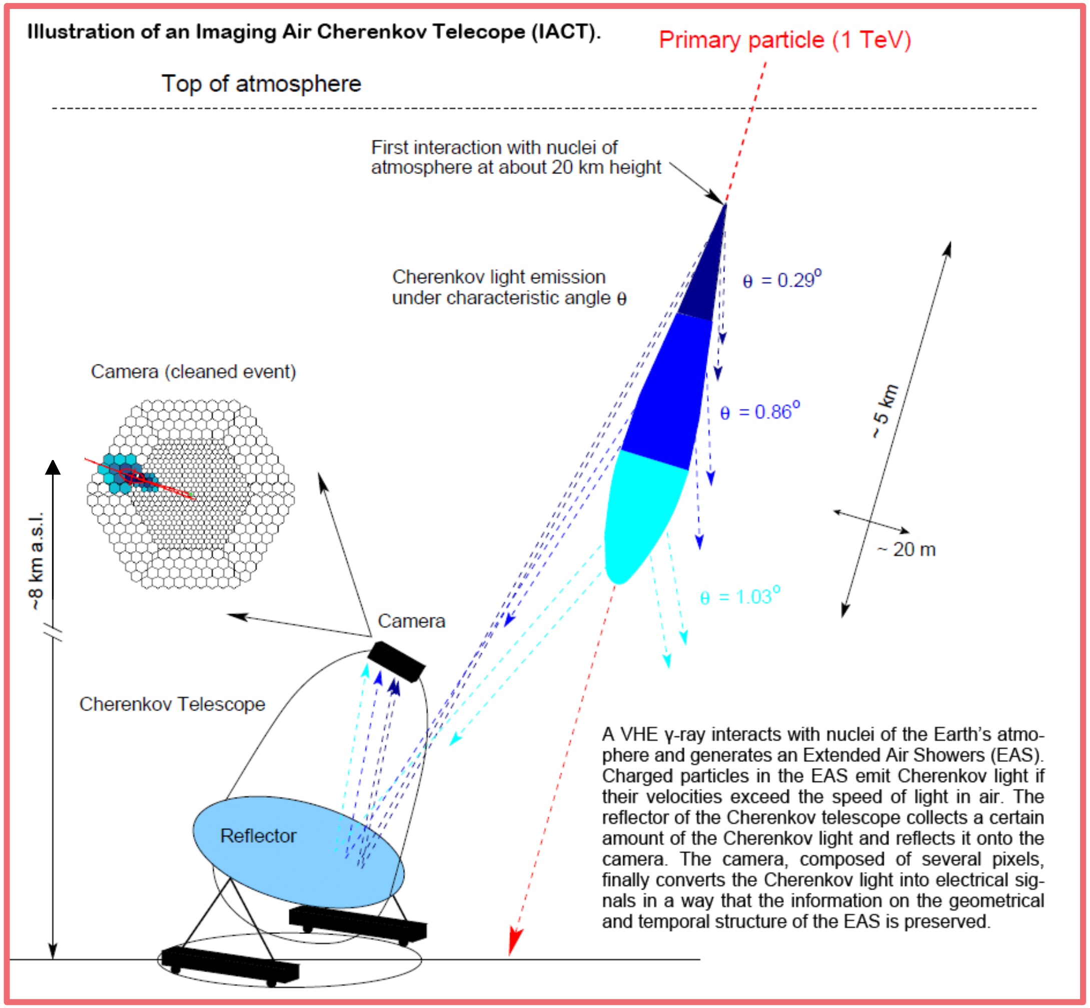


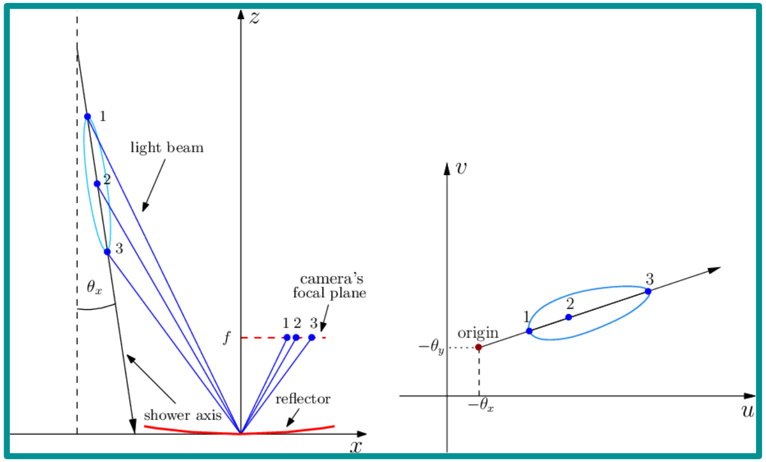


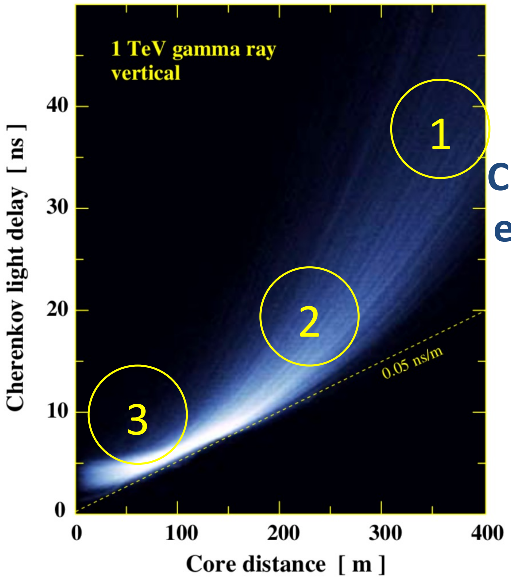
100 GeV p



IACT detection method



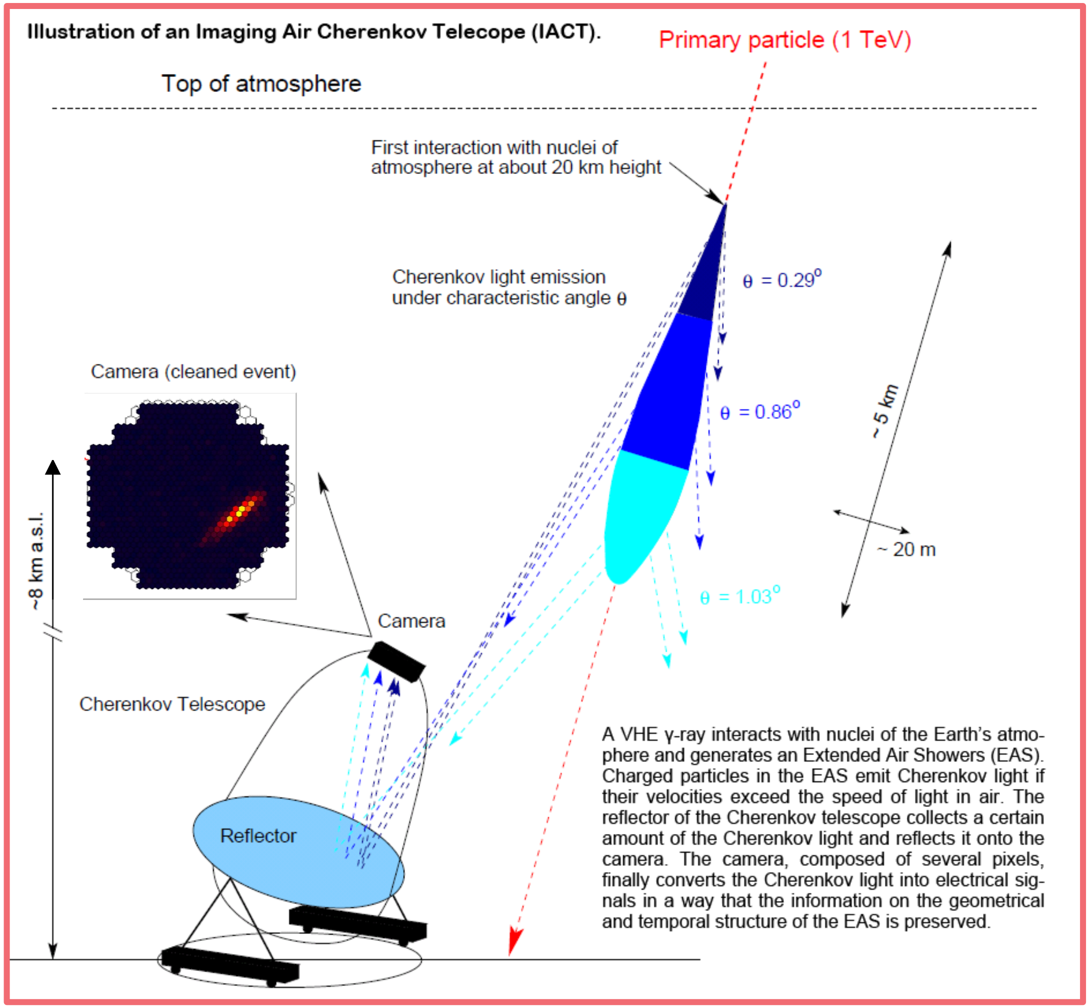




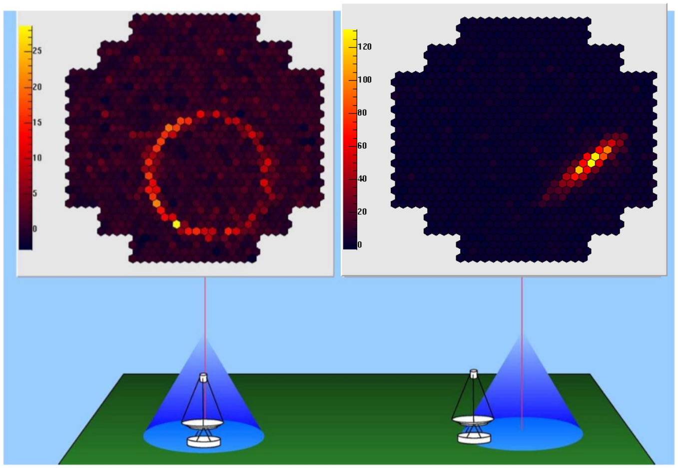
Cherenkov light emitted earlier arrives later

IACT detection method

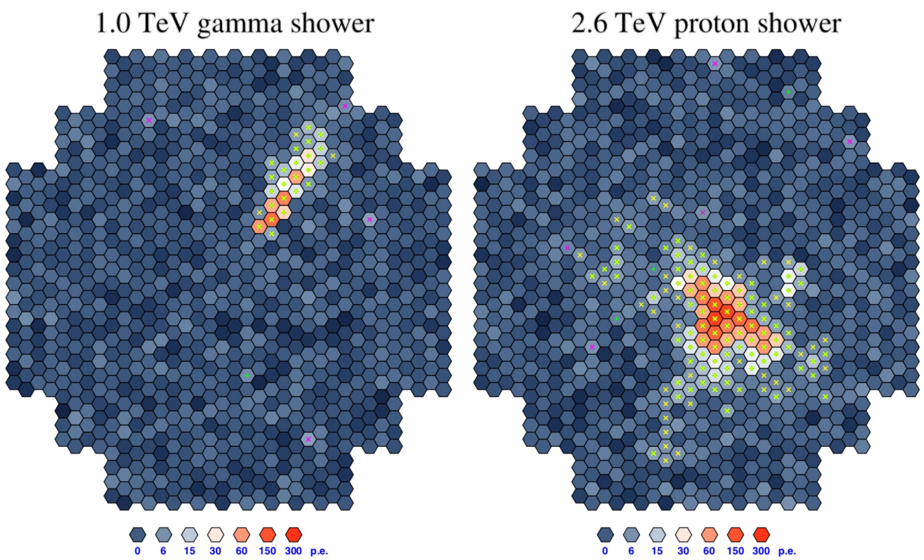
https://www.mpi-hd.mpg.de/hfm/HESS/pages/about/telescopes/



The movie shows Cherenkov images recorded with the first H.E.S.S. telescope in 2002. We can see the typical **elongated shower images (arcs)** and the **muon "rings"** generated when an air-shower charged particle hits the mirror.

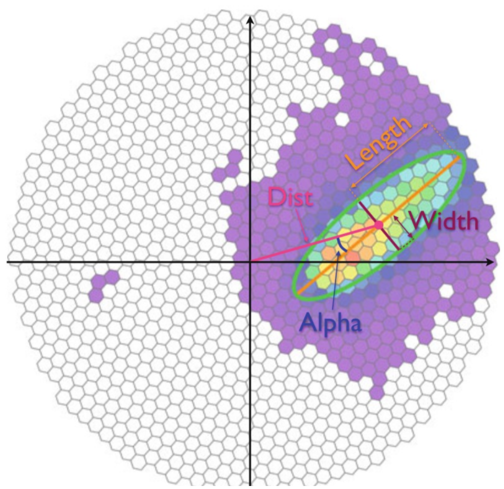


Gamma-ray shower vs. proton shower

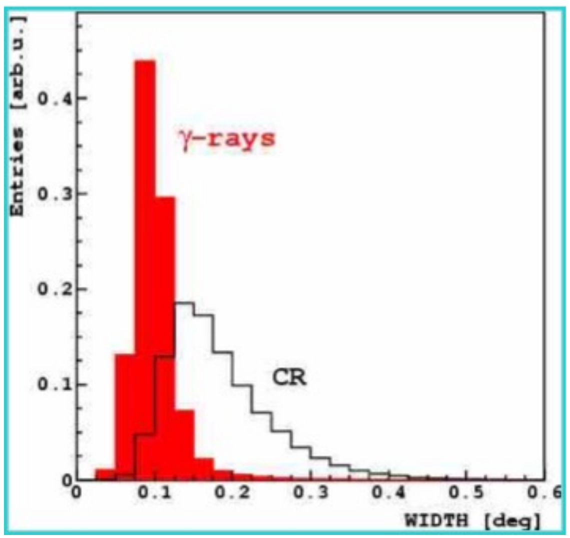


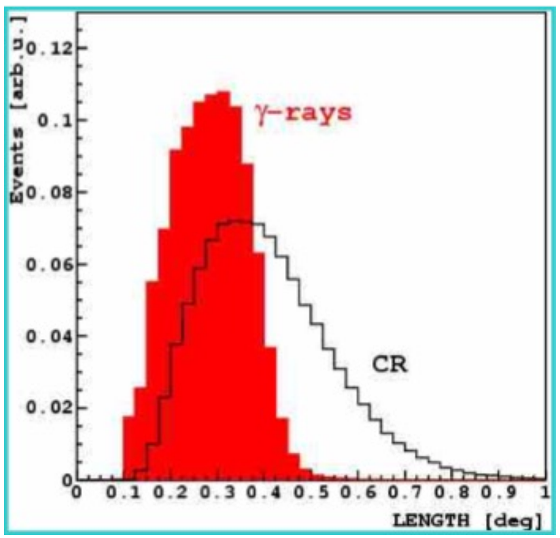
A **gamma ray** produces a **narrow** island.

A **proton/hadron** produces a wide island.



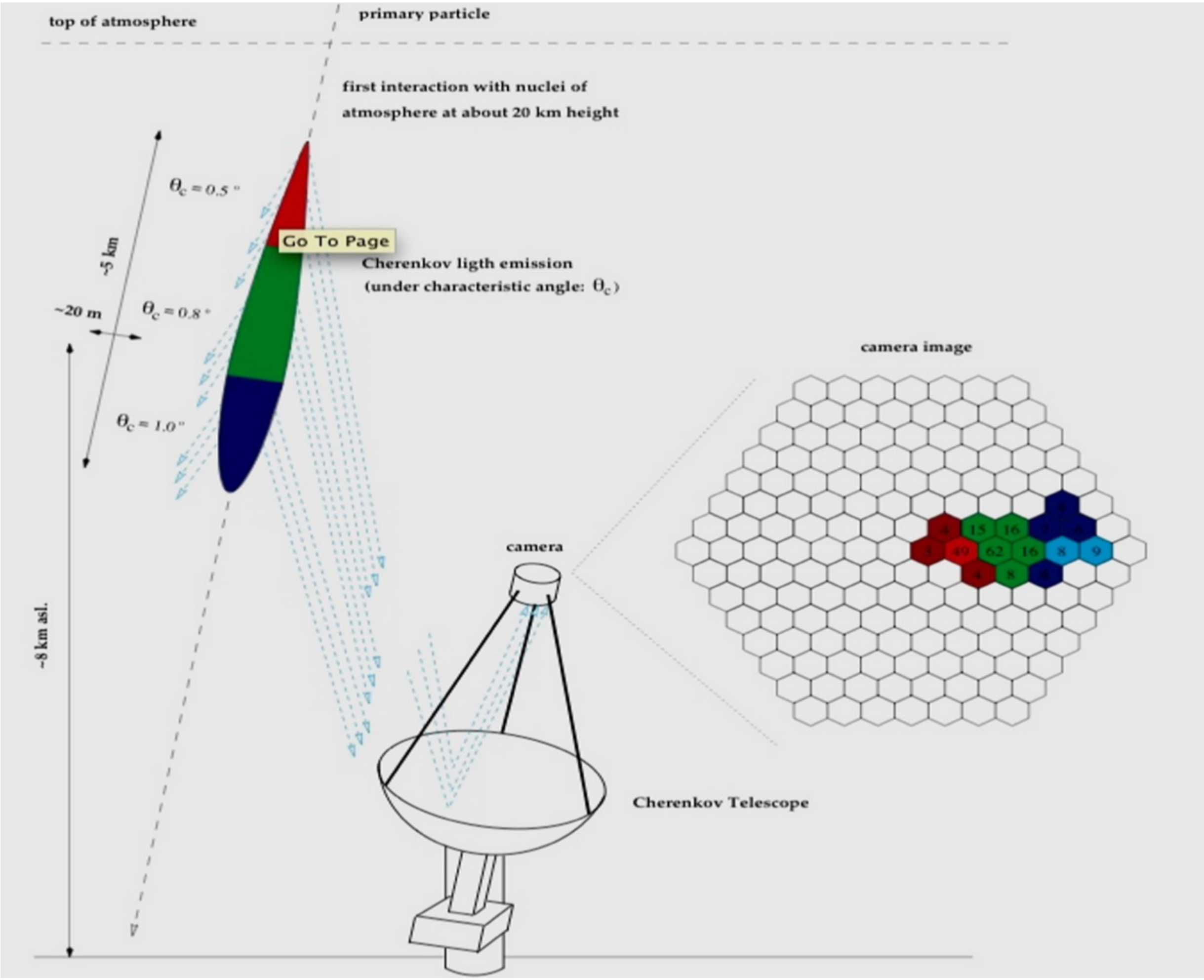
Hillas parameters





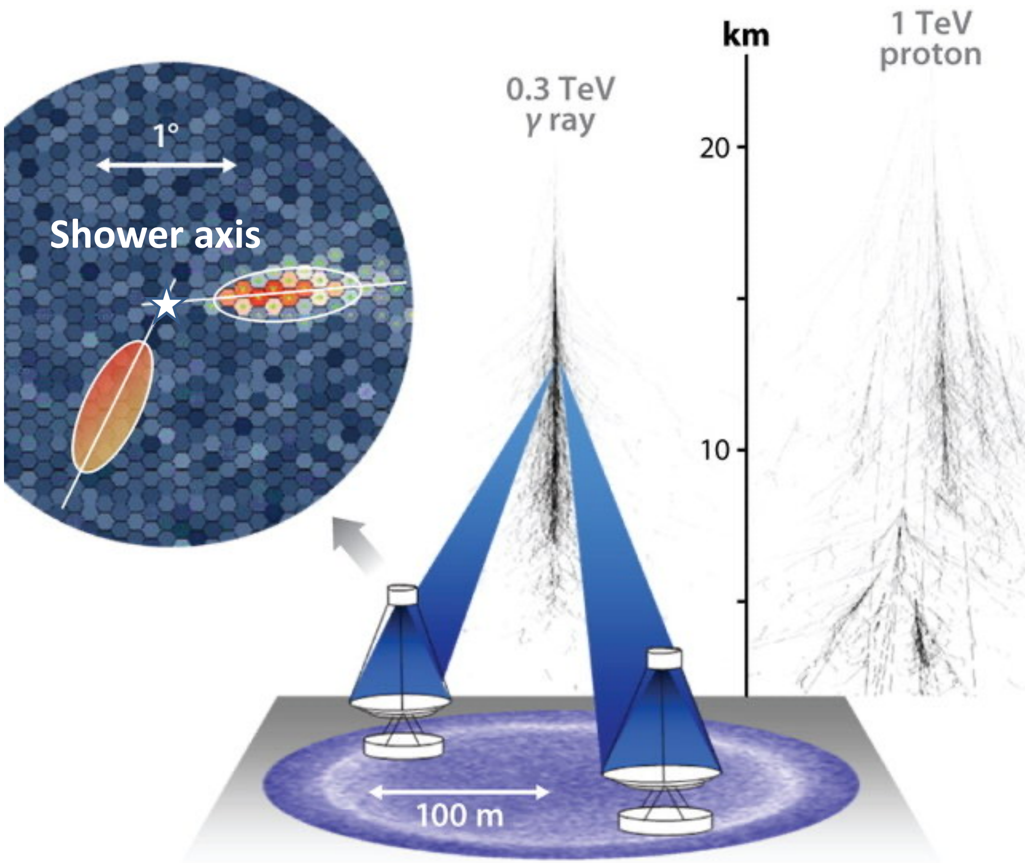
Shape of the image
↳**Gamma/hadron separation**

Measurement of the primary photon energy



Intensity of the image
↳ Photon **energy**

Reconstruction of the primary photon direction: the stereoscopic image



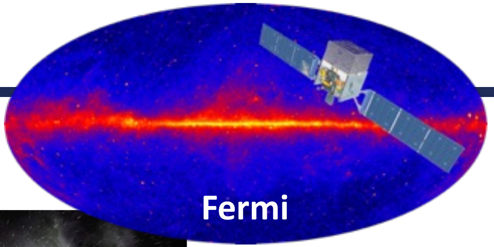
Hinton JA, Hofmann W. 2009.
Annu. Rev. Astron. Astrophys. 47:523–65

Geometry of the image
↳ Photon **direction**

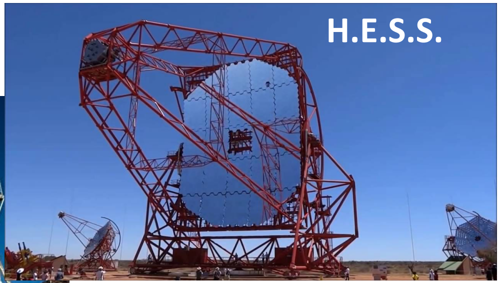
- ✓ Better **background** rejection
- ✓ Better **energy** resolution
- ✓ Better **angular** resolution

Gamma-ray experiments

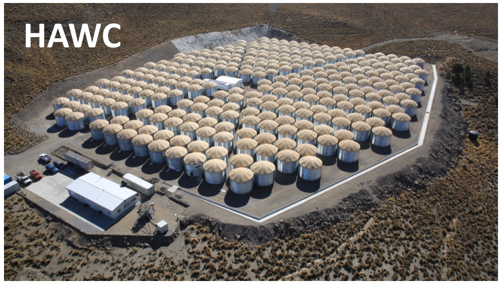
Satellites (E < 100 GeV)
+ China Space Station (HERD)



Imaging Atmospheric Cherenkov Telescopes “IACTs”
(E > 100 GeV)



Extensive Air Shower Detectors (E < 1 PeV)

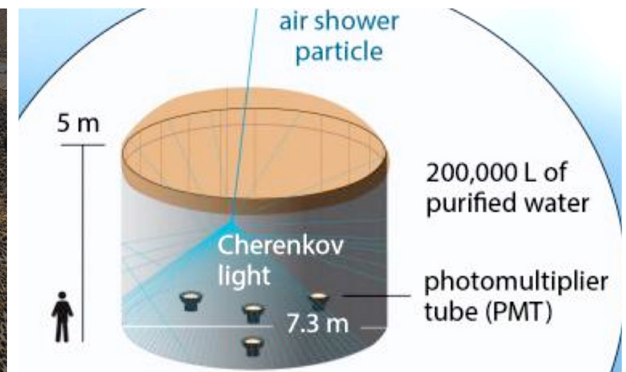


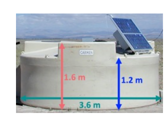
Extensive Air Shower Experiments (EAS exps)

The EAS technique, originally developed for the detection of EAS induced by charged CRs at PeV and EeV energies, can also be adopted for gamma-ray astronomy. The mandatory requirement is that the **energy threshold must be lowered by two or three orders of magnitude**, which requires a **dense matrix** of detectors located at **very high altitudes**. The feasibility of ground-based detection of showers initiated by gamma rays has been successfully demonstrated by the Milagro and ARGO collaborations.

Past	Now
MILAGRO Tibet-AS ARGO-YBJ	HAWC LHAASO

- High Altitude Water Cherenkov Experiment
- Volcano Sierra Negra, Puebla, Mexico
    - **Altitude: 4’100 m**
- 300 densely packed WCDs on 0.022 km^2 (**14k/km^2**) [Auger: alt: 1’500 m, 1’600 WCDs on 3’000 km^2: 0.53/km^2

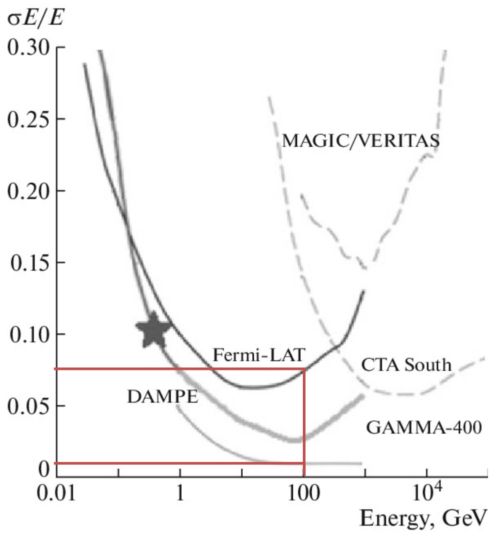


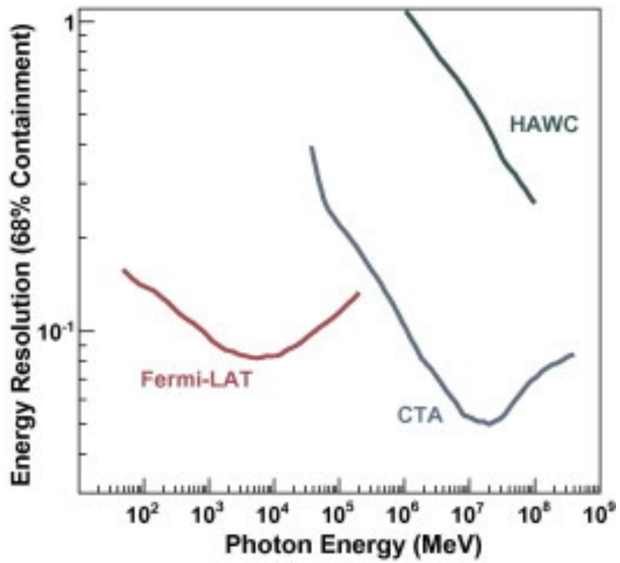


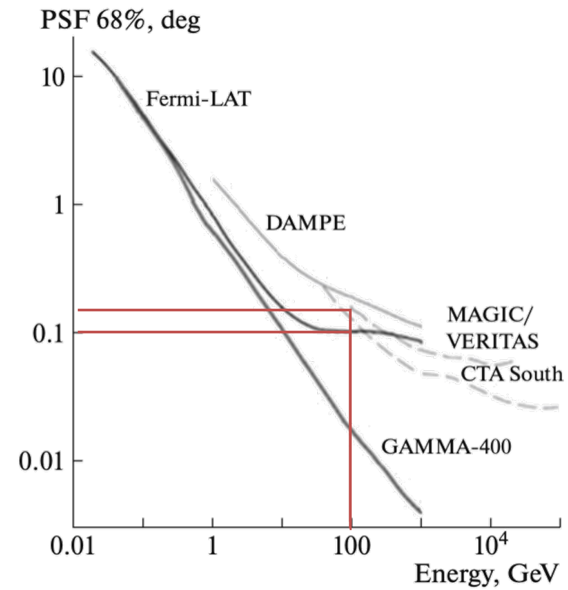
https://www.hawc-observatory.org

https://en.wikipedia.org/wiki/High_Altitude_Water_Cherenkov_Experiment

Energy and angular resolutions



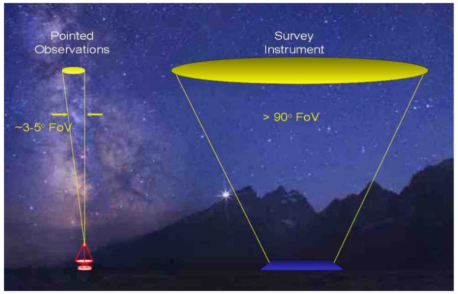




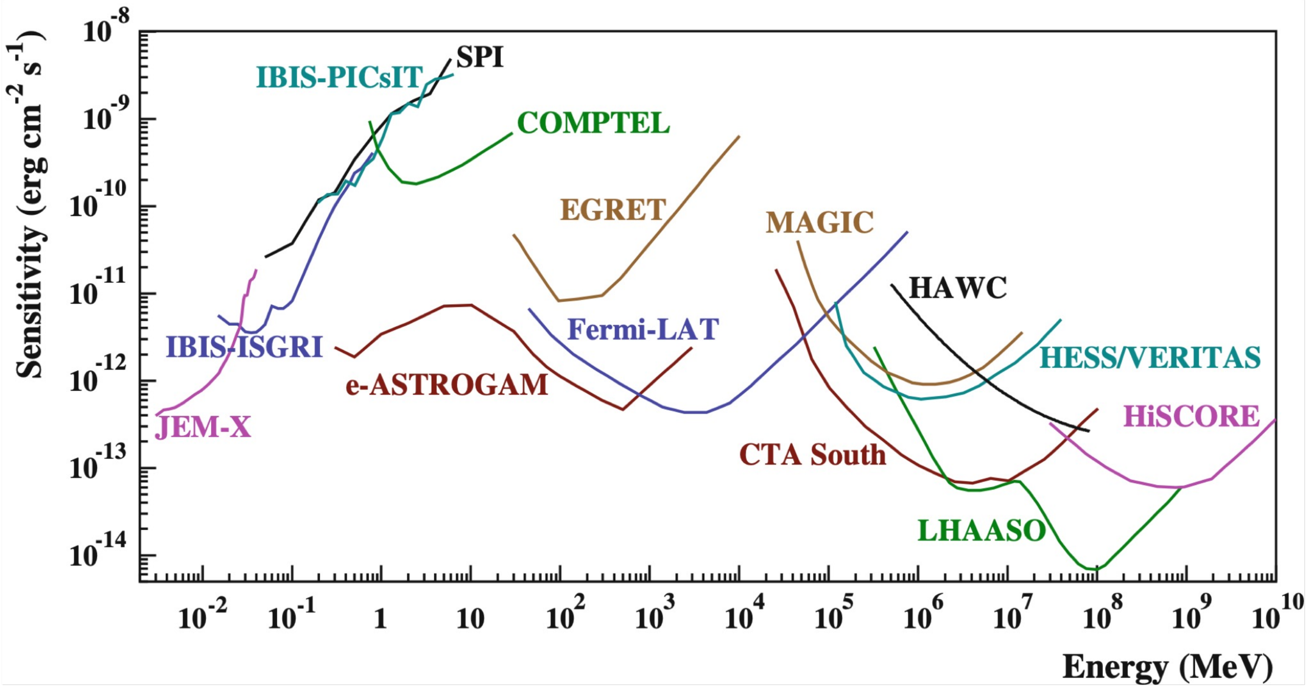
https://doi.org/10.1134/S106377882113038X

Quantity	*Fermi*	IACTs	EAS
Energy range	20 MeV–200 GeV	100 GeV–50 TeV	400 GeV–100 TeV
Energy res.	5–10%	15–20%	$\sim$50%
Duty cycle	80%	15%	$>$90%
FoV	$4\pi/5$	$5° \times 5°$	$4\pi/6$
PSF (deg)	0.1	0.07	0.5
Sensitivity	1% Crab (1 GeV)	1% Crab (0.5 TeV)	0.5 Crab (5 TeV)

Sensitivity: 1 year | 50 hours | 1 year



Detector sensitivity



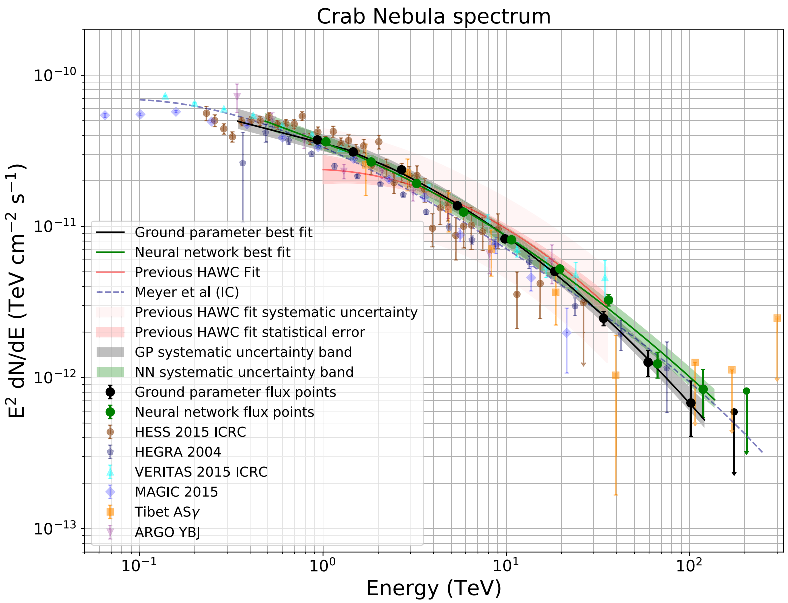
Experiment	Observation time (τ)
COMPTEL and EGRET	9 years
Fermi/LAT	10 years
MAGIC, H.E.S.S., VERITAS, and CTA	50 h
HAWC	5 years
LHAASO	1 year
HiSCORE	40 days
e-ASTROGAM	1 year

Results (Light curves and SEDs)

https://fermi.gsfc.nasa.gov/ssc/data/access/lat/LightCurveRepository/

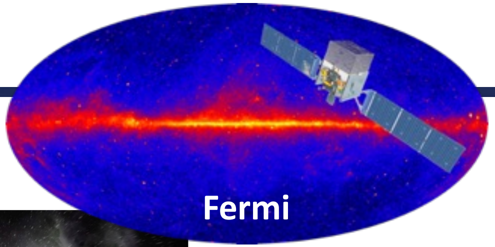
http://tevcat.uchicago.edu
An online catalogue built to keep track of all the ground-based detections.
Its content is continuously updated.

An example:



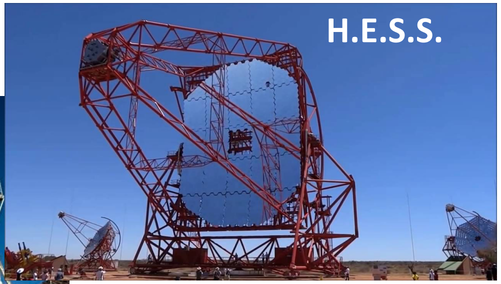
HAWC Collaboration., The Astrophysical Journal, 881:134 (13pp), 2019 August 20

Gamma-ray exps (summary)



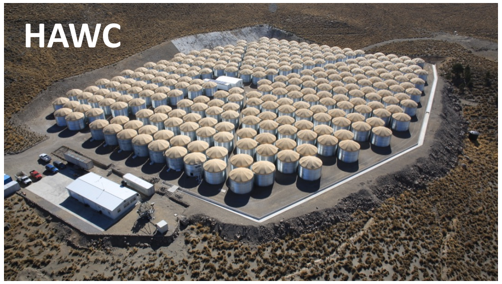
Space-borne exps (E < 100 GeV):

- Small area (1 m^2). Background free. Large duty cycle.
- Extragalactic sources, diffuse emission at 100 GeV, dark matter, …



Imaging Atmospheric Cherenkov Telescopes "IACTs" (E > 100 GeV):

- Excellent pointing.
- Very good background rejection.
- Low duty cycle and low field of view.
- Source morphology at TeV. High resolution spectra, study of known sources.



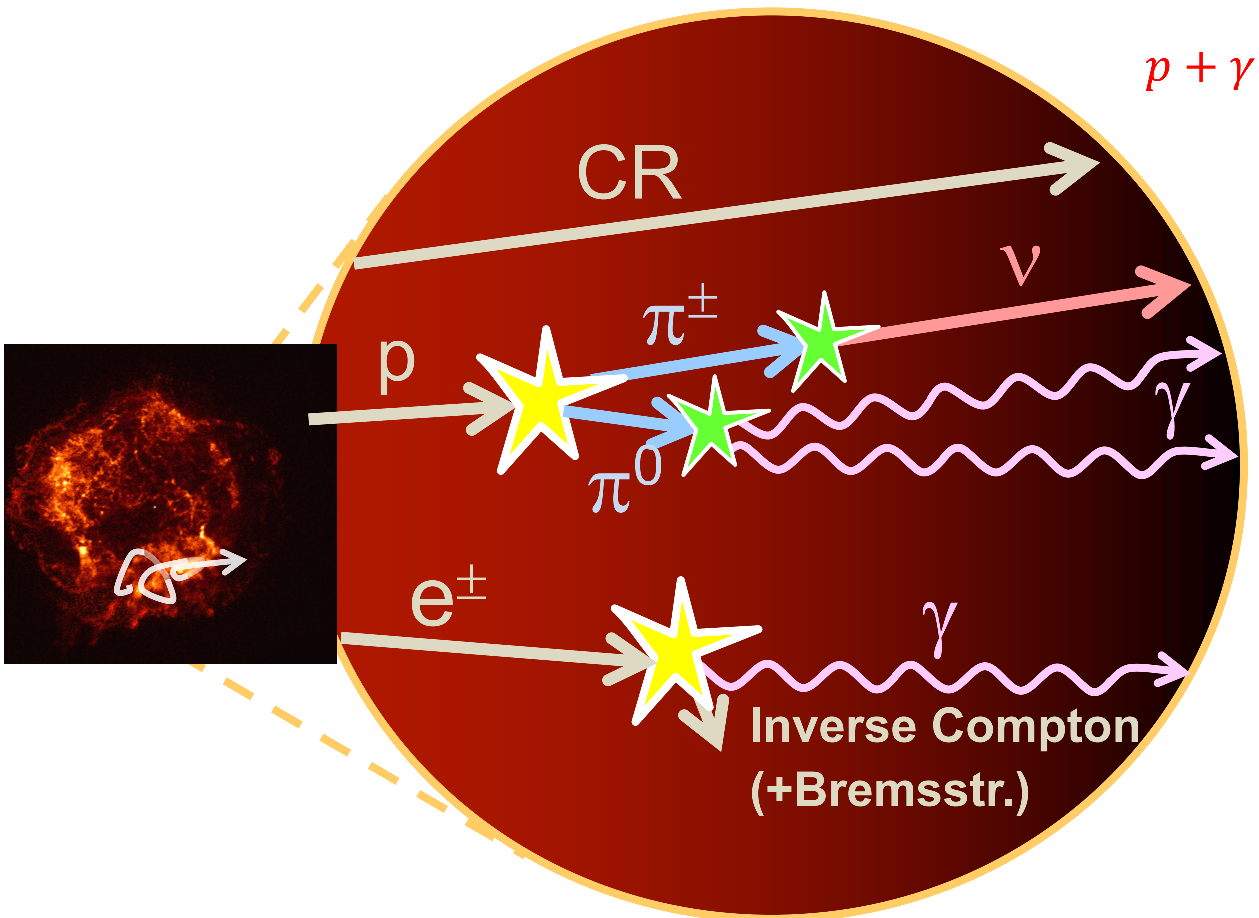
Extensive Air Shower Detectors (E < 1 PeV):

- Good background rejection.
- Larger energy threshold.
- Large duty cycle (~ 100%) and large field of view.
- Sky surveys, Extended sources, …

Neutral cosmic rays: cosmic neutrinos

Ultra-high energy neutrinos (UHEνs)

The UHECR models predict neutrino fluxes from the decay of charged pions produced in the interactions of cosmic rays with radiation or matter fields inside or close to their sources.

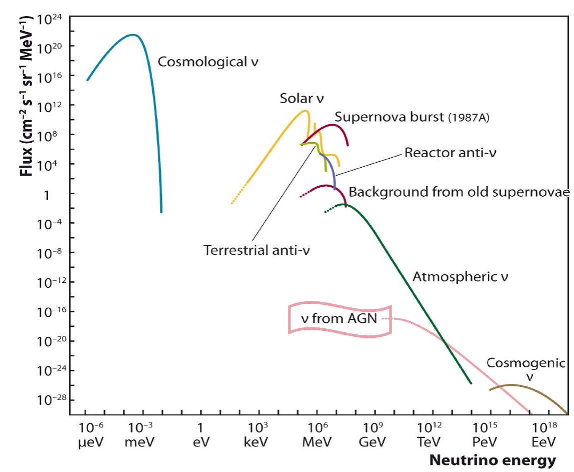


$$p + \gamma \text{ or } p + p \rightarrow N_1\pi^{\pm} + N_2\pi^{0} + X$$

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

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

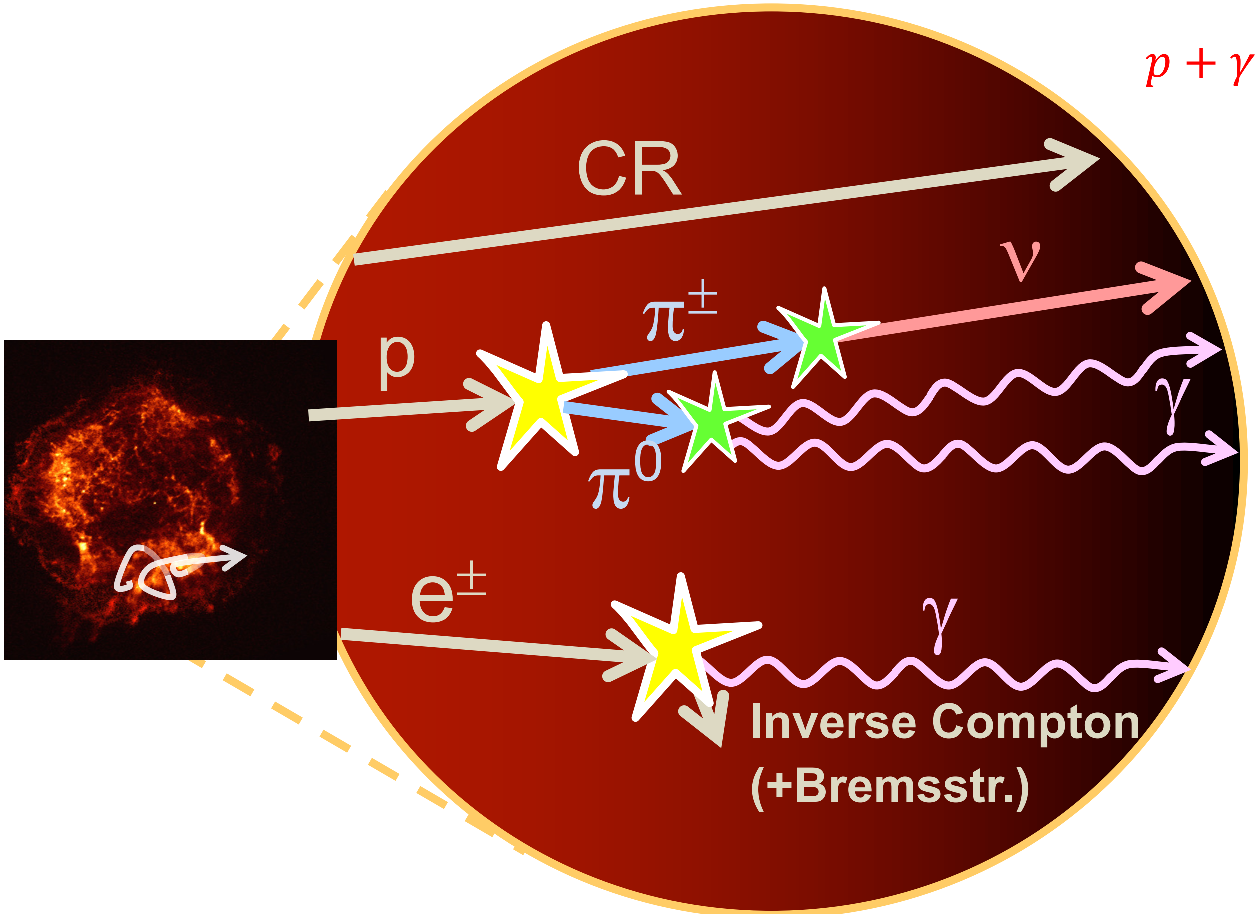
$$\pi^{0} \rightarrow \gamma\gamma$$



Ultra-high energy neutrinos (UHEνs)

The UHECR models predict neutrino fluxes from the decay of charged pions produced in the interactions of cosmic rays with radiation or matter fields inside or close to their sources.

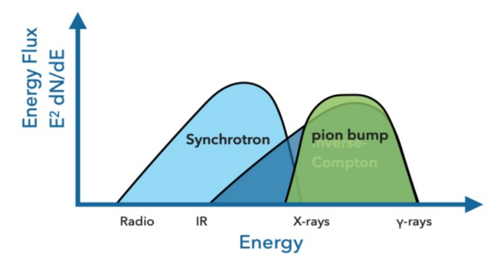
$$p + \gamma \text{ or } p + p \rightarrow N_1\pi^{\pm} + N_2\pi^{0} + X$$



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

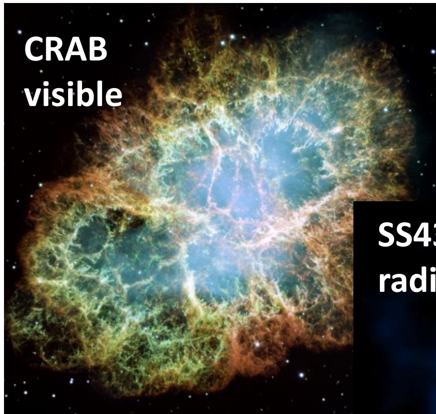
$$\pi^{-} \rightarrow \mu^{-} + \bar{\nu}_{\mu}$$
$$\hookrightarrow e^{-} + \bar{\nu}_e + \nu_{\mu}$$

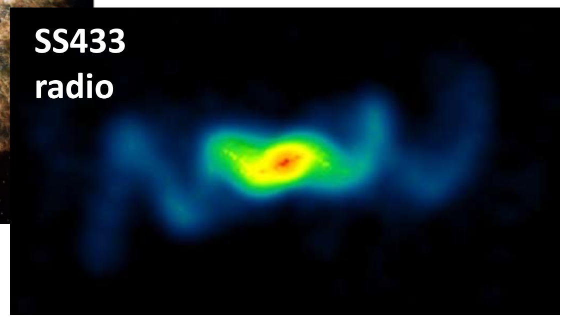
$$\pi^{0} \rightarrow \gamma\gamma$$



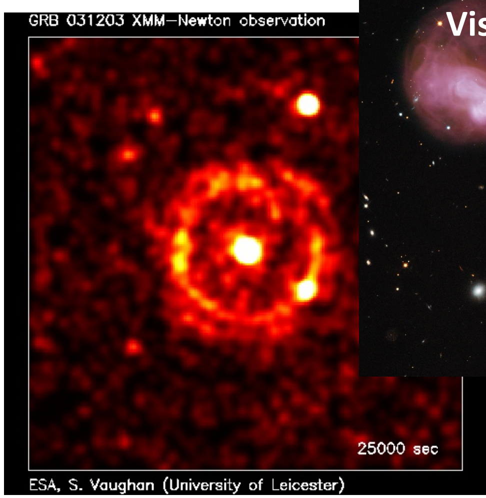
Neutrinos are the smoking gun signature of hadronic processes in the high-energy Universe

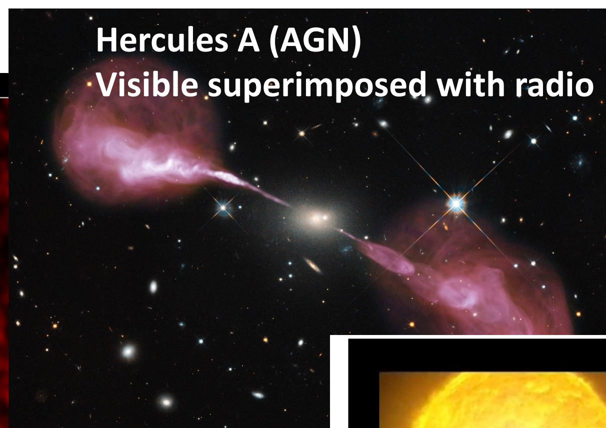
Possible sources



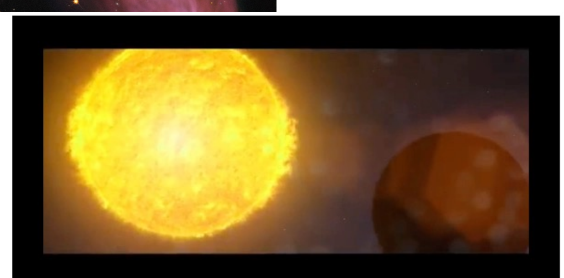


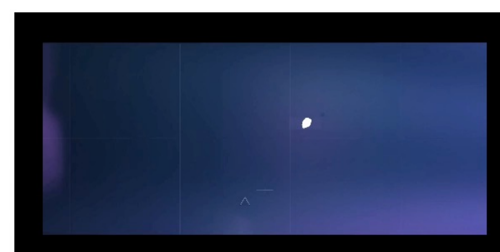
Galactic sources:
supernova remnants (SNRs), pulsars, microquasars, nebulae, binary sistems, ...





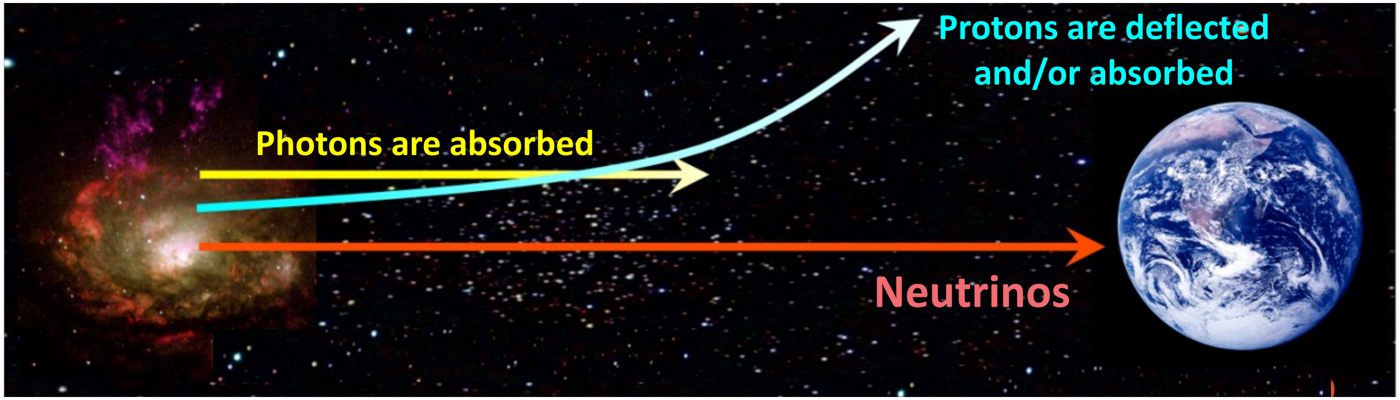
Extra-galactic sources:
active galactic nuclei (AGNs),
gamma-ray bursts (GRBs),
tidal disruption events (TDEs), [...]





https://www.star.le.ac.uk/~sav2/grb031203/

Neutrino astronomy



☹ **Photons** abundant and easy to detect but:

- hot and dense regions opaque to photons;
- High-energy gamma rays interact with the CMB radiation producing e^+e^- pairs.

☹ **Protons:**

- at high energy (> 10^{19} eV) interact with the CMB;
- at lower energy are deviated by galactic magnetic fields.

☺ **Neutrinos: the optimal choice**

- **electrically neutral** (not deflected by magnetic fields like protons → point back to their source);
- **weakly interacting** (propagate through regions opaque to photons);
- **stable** (can travel along big distances).

Neutrinos are the smoking gun signature of hadronic processes in the high-energy Universe

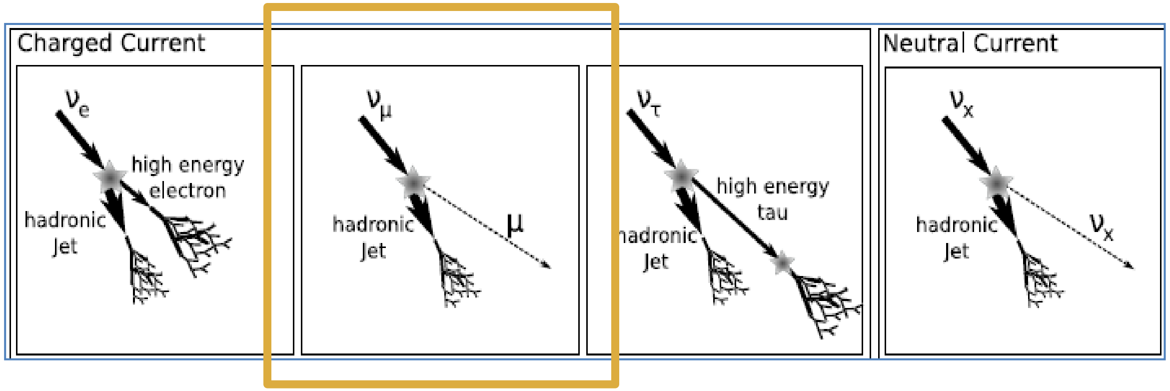
How can we detect neutrinos?

To be detected neutrinos have to interact with matter in the proximity of the detector or inside its volume via charged-current (CC) interactions

$$\nu_\ell(\bar{\nu}_\ell) + N \rightarrow l^-(l^+) + X$$

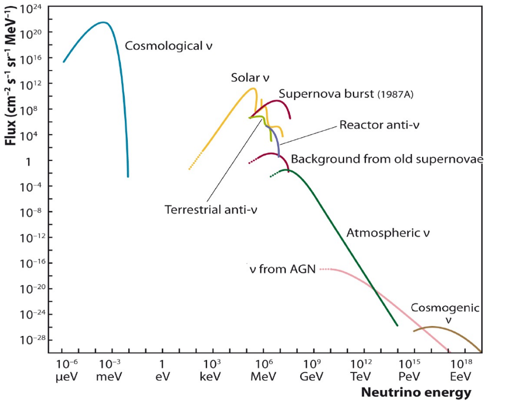
or neutral-current (NC) interactions

$$\nu_\ell(\bar{\nu}_\ell) + N \rightarrow \nu_\ell(\bar{\nu}_\ell) + X$$



A neutrino detector has to be:

- **Huge** to intercept the faint flux of neutrino events at high energies;
- **Massive**, since a large amount of target nucleons are necessary to produce a neutrino interaction, because of the small neutrino-nucleon cross section.



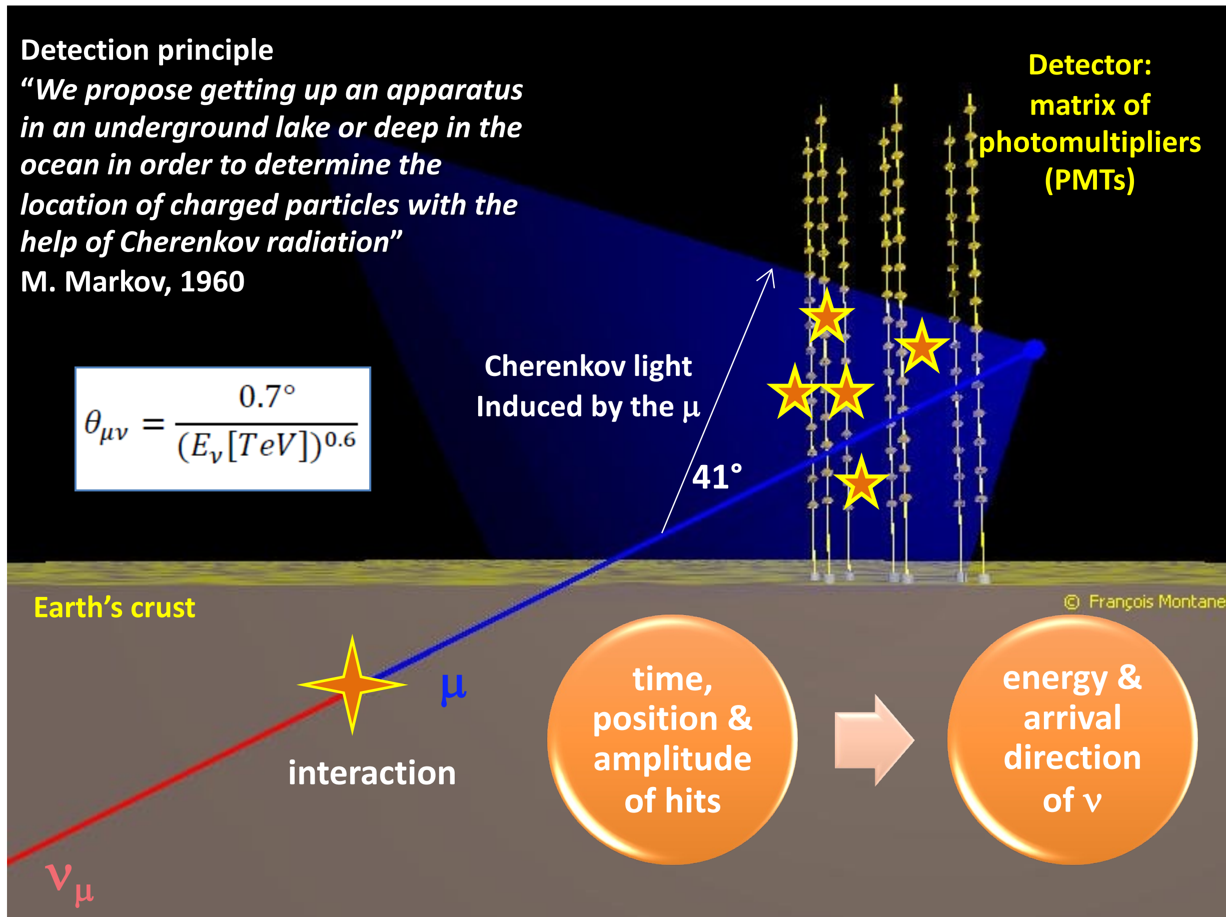
Neutrino Astronomy: how?

- These two requirements drive to the employ of a natural target, as **oceanic water** or **Antarctic ice**, since no human-made laboratory could be large enough to host such an apparatus **(~ km^3)**.

- Neutrinos can be detected collecting the visible **Cherenkov radiation** induced by the **charged particles** produced in the neutrino interactions while they propagate through a transparent dielectric medium with superluminal velocity.

Main detection channel:
Track-like events:
ν_μ CC-interaction giving a relativistic μ

Other detection channels:
Shower-like events:
ν_e & ν_τ CC-interaction and
ν_μ, ν_e, ν_τ NC-interaction

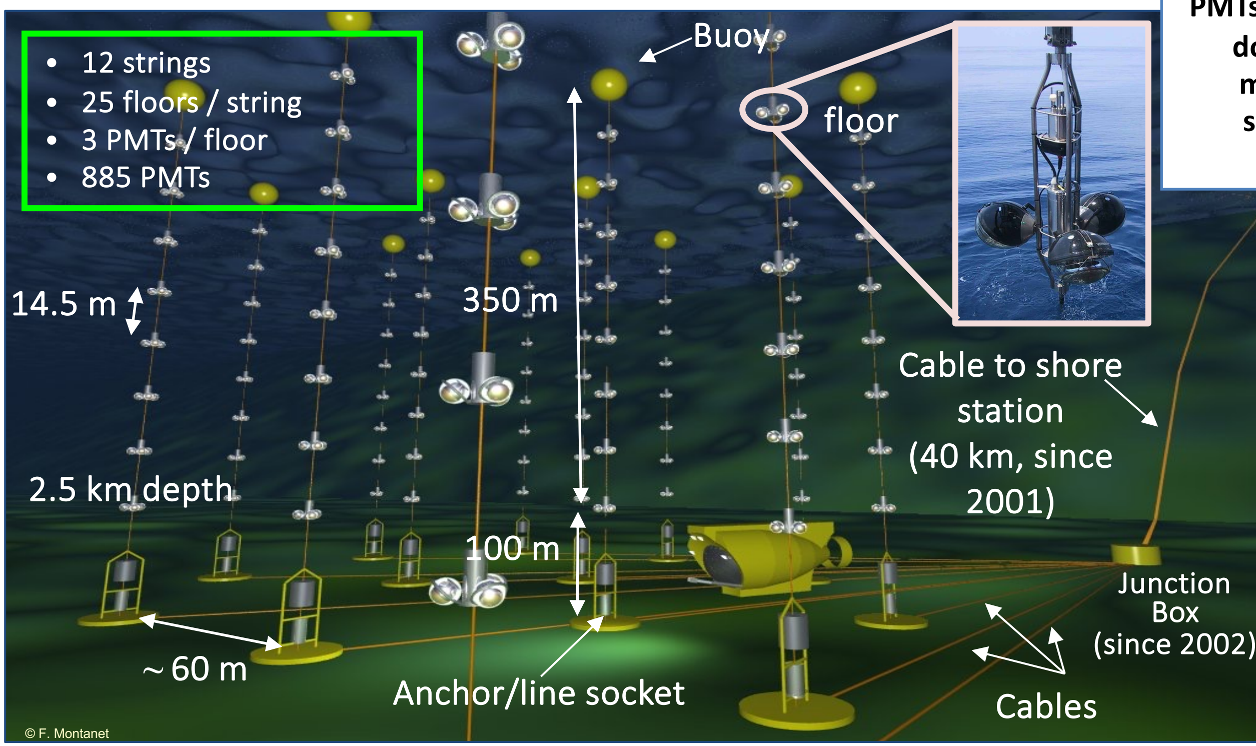


ANTARES (2008 – Feb. 2022)

https://antares.in2p3.fr/
A. Kouchner @Les Rencontres de Blois (May 2022)

- **A**stronomy with a **N**eutrino **T**elescope and **A**byss environmental **RES**earch.
- Located at a depth of ~ 2.5 km in the Mediterranean Sea, ~ 40 km South-East off the coast from Toulon, France.
- The 1st undersea ν telescope, completed in May 2008.
- Instrumented volume **~ 0.02 km^3**.

ANTARES Collaboration, NIM A 656 (2011) 11-38



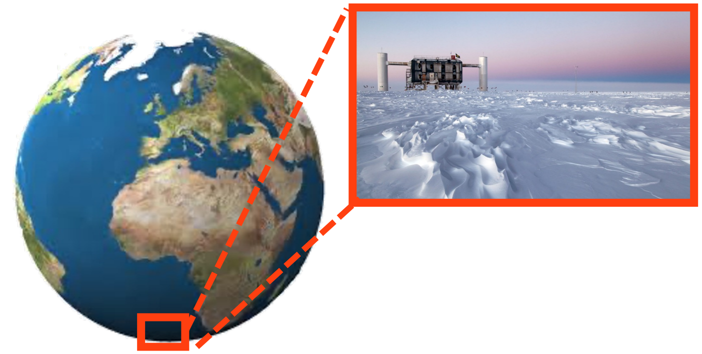
PMTs oriented at 45° downwards to maximize the sensitivity to up-going μ

IceCube (2010 – now)

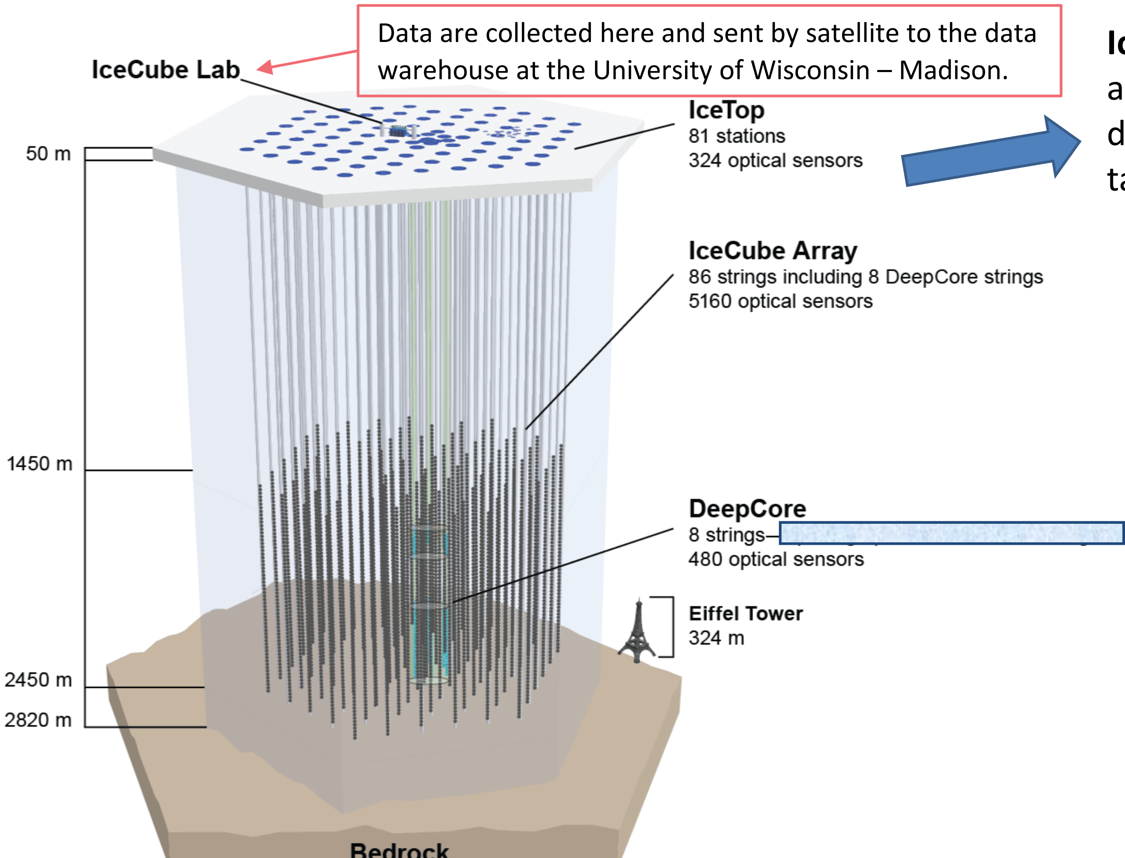
https://icecube.wisc.edu

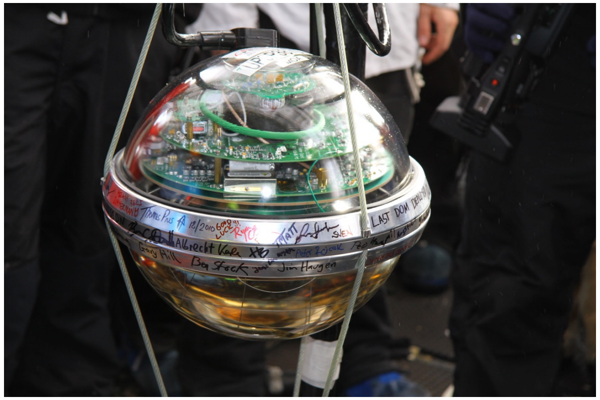
IceTop: NIM A 700 (2013) 188–220

- IceCube, the South Pole neutrino observatory, is a cubic-kilometer particle detector located near the Amundsen-Scott South Pole Station.
- Located at a depth of ~ 2.5 km.
- Completed in 2010.
- Instrumented volume **~ 1 km³**.



IceTop is the veto array for IceCube @2.8 km altitude and is used for cosmic ray shower detection. It consists of 162 ice Cherenkov tanks (2 above each IceCube string).





DOM (digital optical module)
PMT diameter: 10 inches

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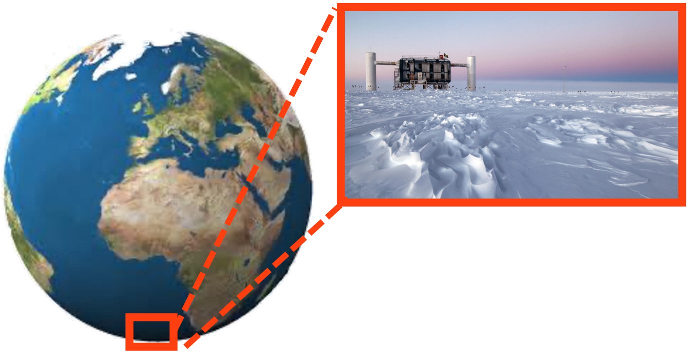
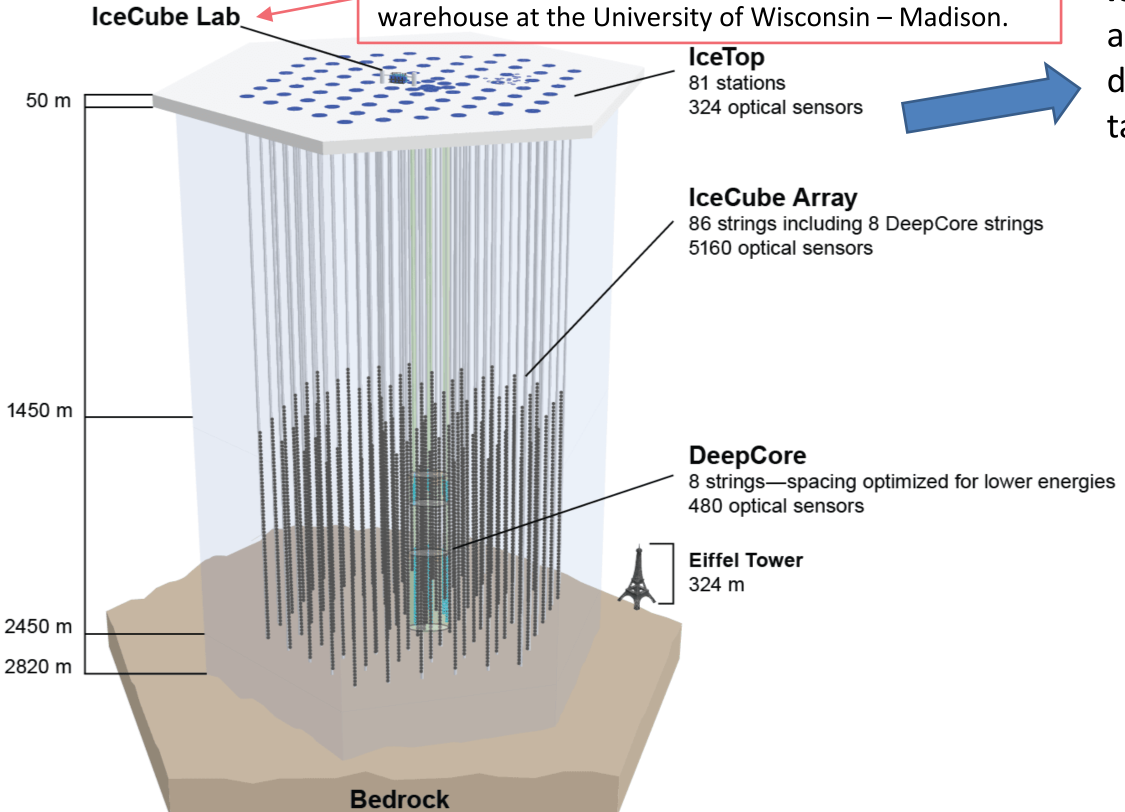


Data are collected here and sent by satellite to the data warehouse at the University of Wisconsin – Madison.



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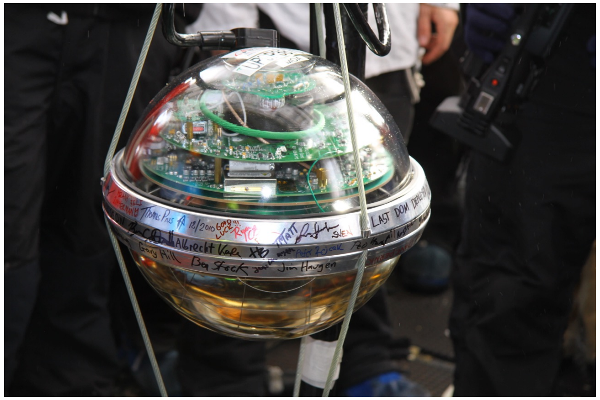


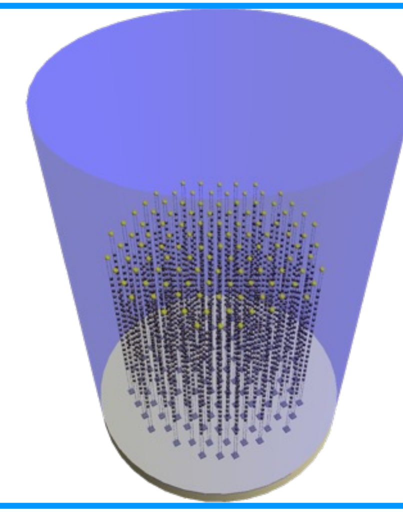
DOM (digital optical module)
PMT diameter: 10 inches

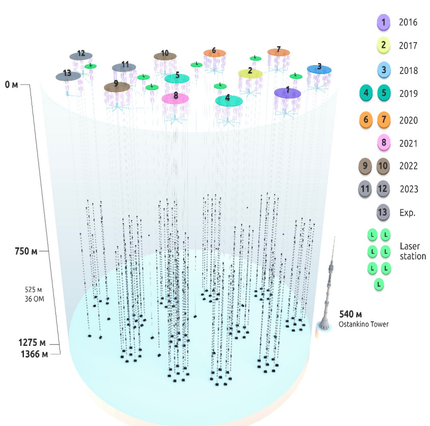
Current H20 (liquid + solid) neutrino telescopes

Cosmic neutrino detectors are usually called «**telescopes**» since we use them to observe the Sky and study physical phenomena occurring in the Universe.

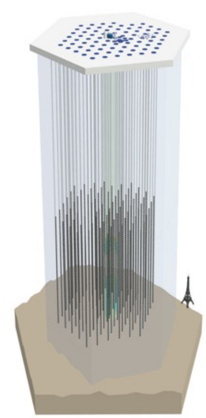
ANTARES (2008-2022)
Med. Sea (-2.5 km)
12 strings
885 PMTs (10“)
~1/100 km^3

KM3NeT
Med. Sea (-2.5 km/-3.4 km)
115/230 strings
18 DOMs/string
31 PMTs (3“)/DOM
~192‘500 PMTs (3“)
(equiv. ~18‘600 10“- PMTs)
1 km^3



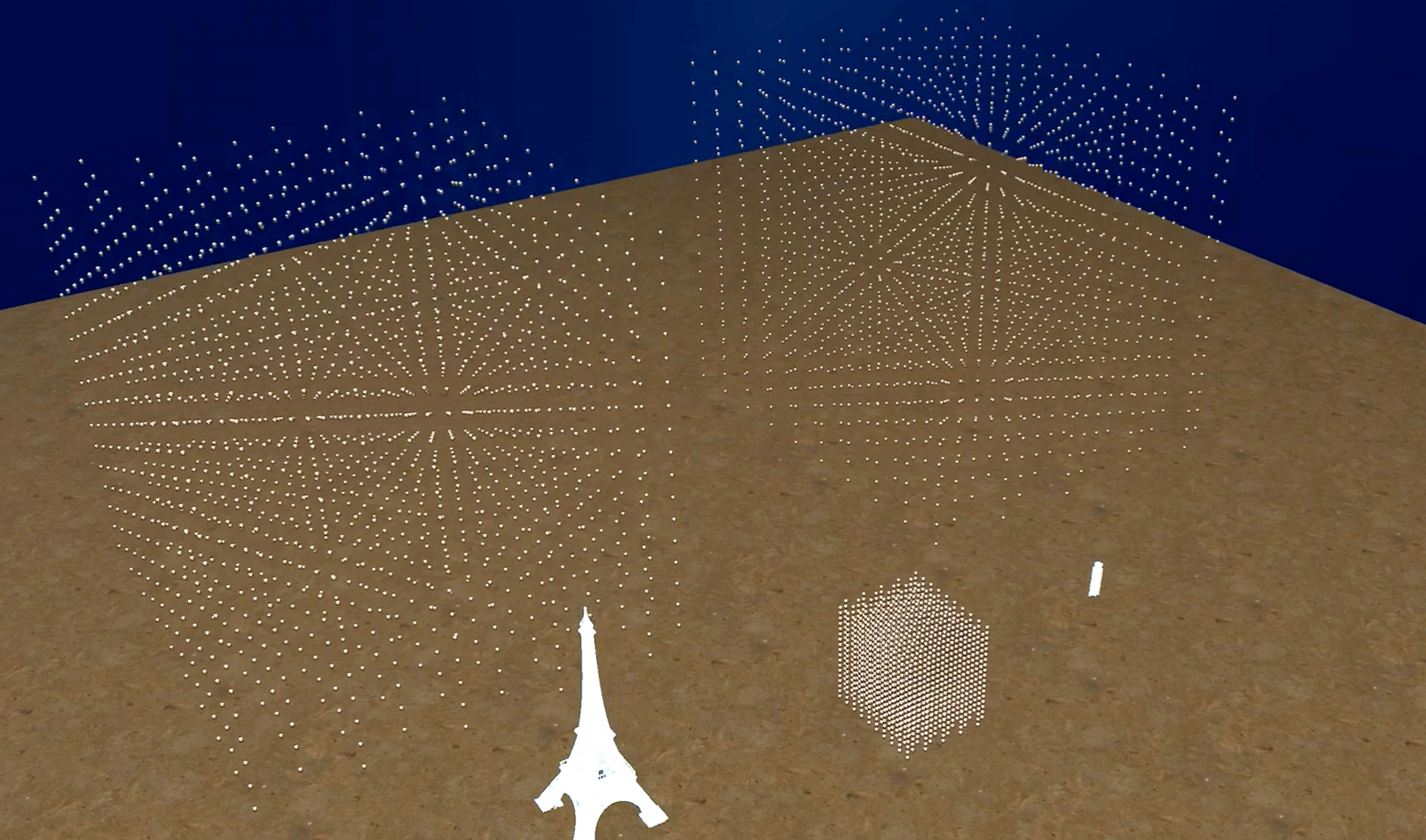


Baikal-GVD
Lake Baikal (-1.3 km)
18 clusters of 8 strings
36 PMTs/string
5‘184 PMTs (10“)
1 km^3



IceCube
South Pole (-2.5 km)
86 strings
5’160 PMTs (10”)
1 km^3

KM3NeT detectors: ARCA and ORCA

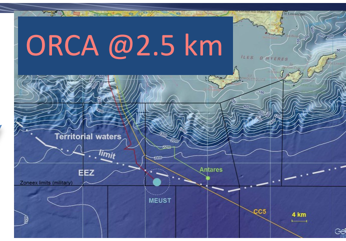


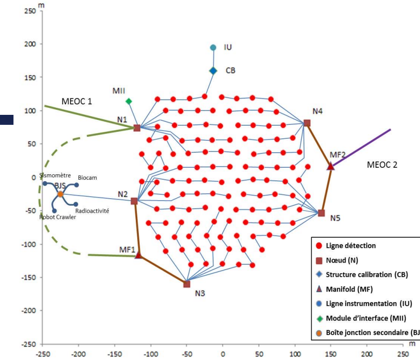
Courtesy Paschal Coyle

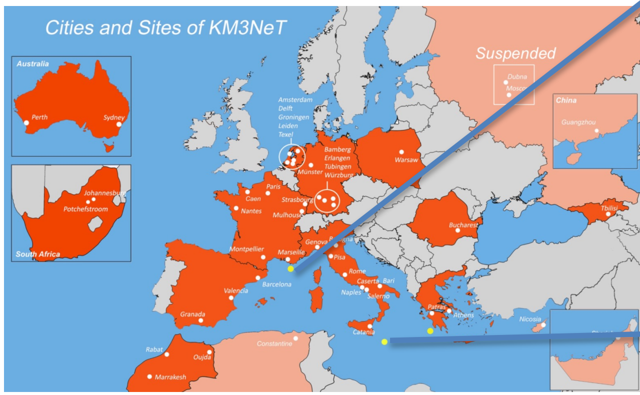
KM3NeT

[KM3NeT 2.0: Letter of Intent]

- Multi-site, deep-sea neutrino telescope
- Single collaboration and single technology

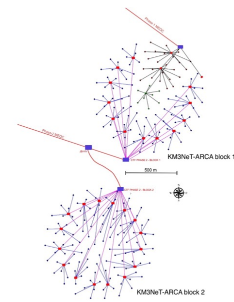






Oscillation **R**esearch with **C**osmics in the **A**byss:

- 1 building block of 115 DUs (DU interspacing: 20 m, DOM interspacing: 9 m).
- Now **28 strings**.



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

- 2 building blocks of 115 DUs each (DU interspacing: 90 m, DOM interspacing: 36 m).
- Now **33 strings**

https://www.km3net.org

~ 700 or 200 m

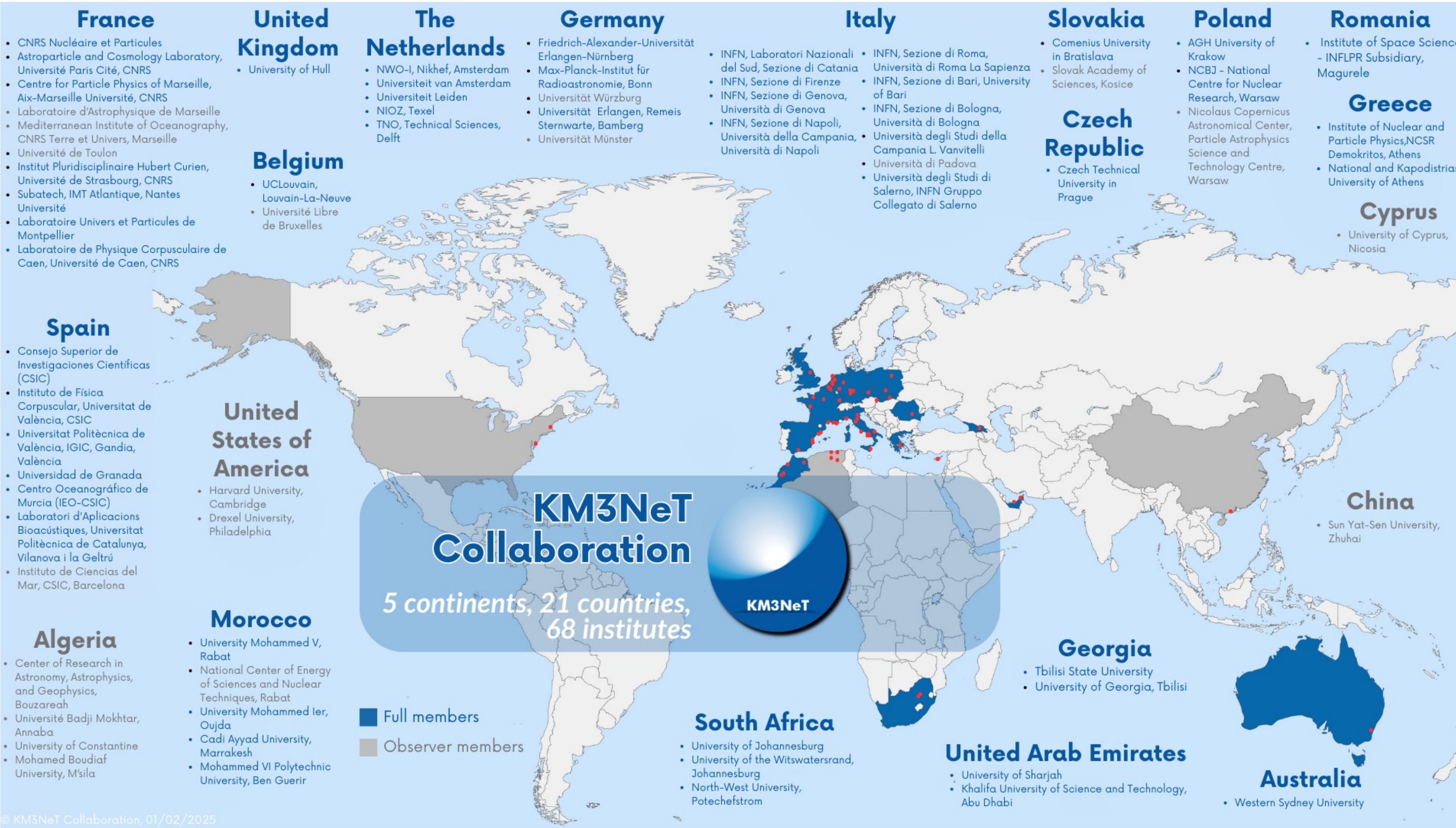
Detection Unit (DU)

- 18 DOMs.

Digital Optical Module (DOM)

- Multi-PMT: 31 x 3” PMTs.
- ns timing

The KM3NeT Collaboration

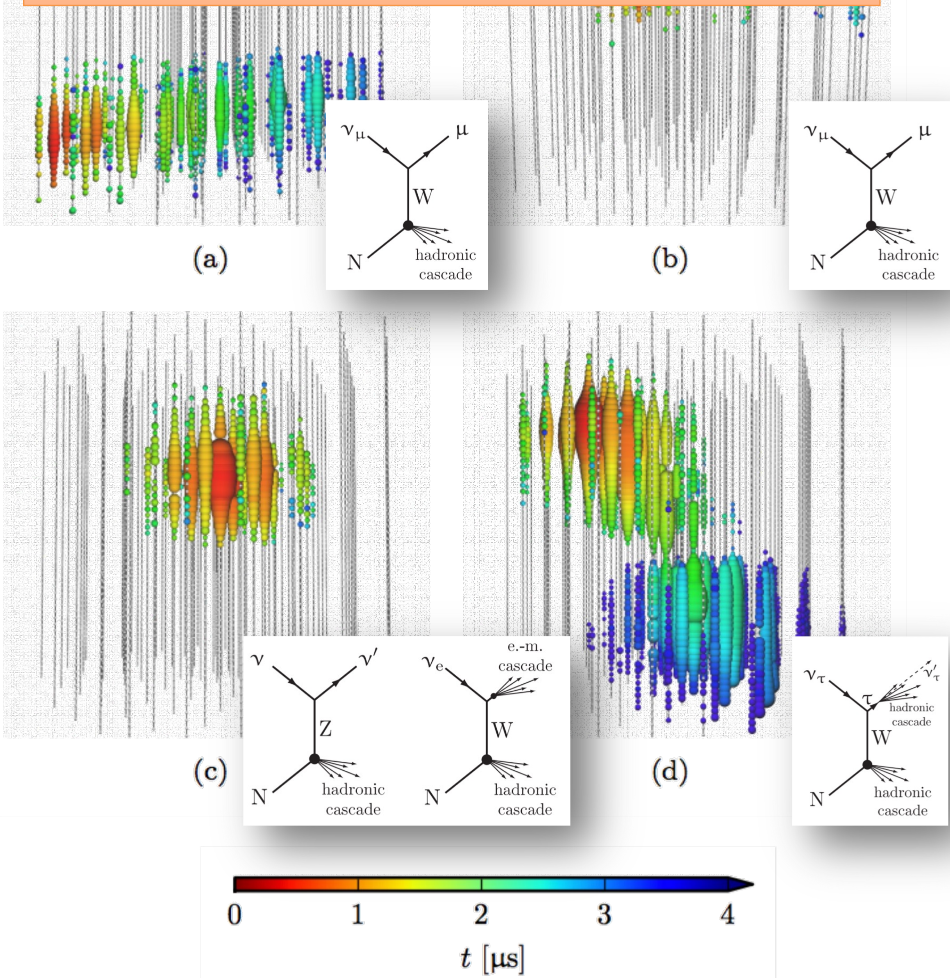


IceCube Collaboration (12 countries, 53 institutions)

Neutrino-event topologies

IceCube Collaboration, 2014 JINST 9 P03009.
http://dx.doi.org/10.1088/1748-0221/9/03/P03009

White spheres: PMTs.
Coloured spheres: PMTs that have detected light.
Spheres size scales with the amount of detected light.
Colours indicate arrival time of Cherenkov photons (time resolution: 2 ns).



Track-like event signatures
(CC interactions of ν_μ)

(a) through-going muon track ~140 TeV
(b) Starting muon track ~70 TeV (HESE: high energy starting event)

- μ travels up to several km
- Angular resolution < 0.4°
- Energy resolution (30% at 100 TeV)

Shower-like event signatures
(CC interactions of ν_e & ν_τ, NC interactions)

(c) Shower event ~1PeV
(d) "double bang" event ~200 PeV (simulated)

- Only interactions **inside/close** to the instrumented volume
- (Worse) angular resolution (15° at 100 TeV IceCube, < 4° ANTARES)
- (Better) energy resolution: (15% at 100 TeV)

Neutrino-event topologies

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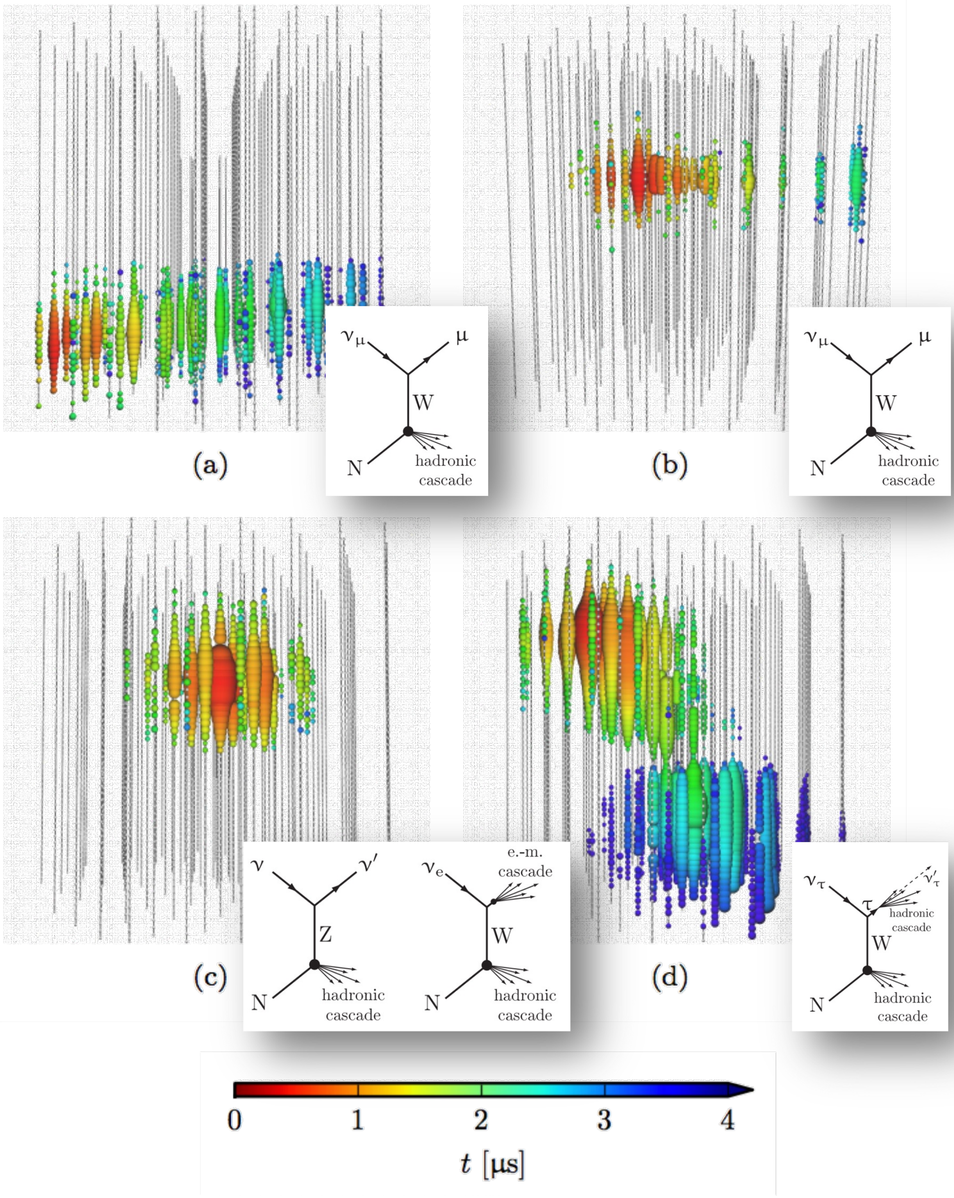

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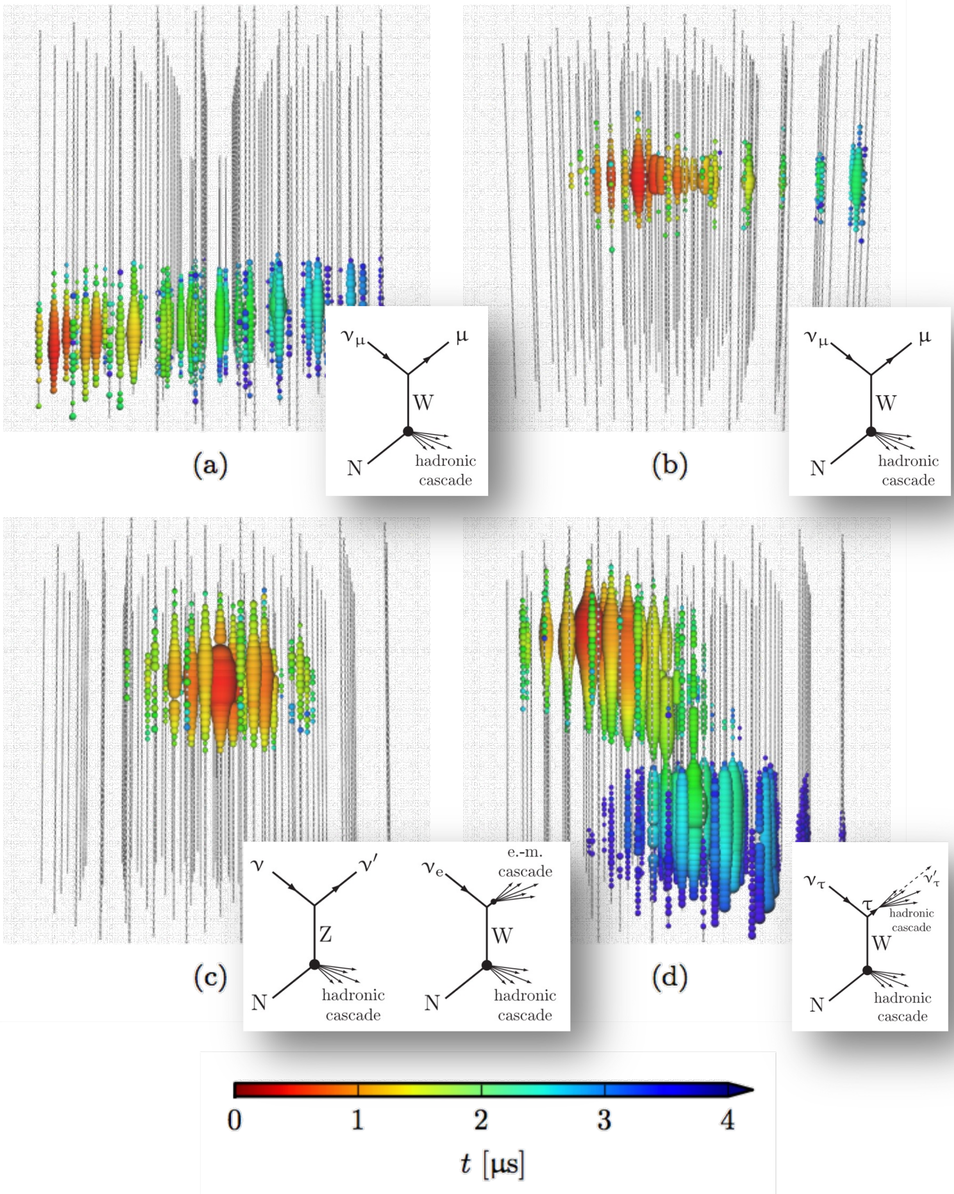
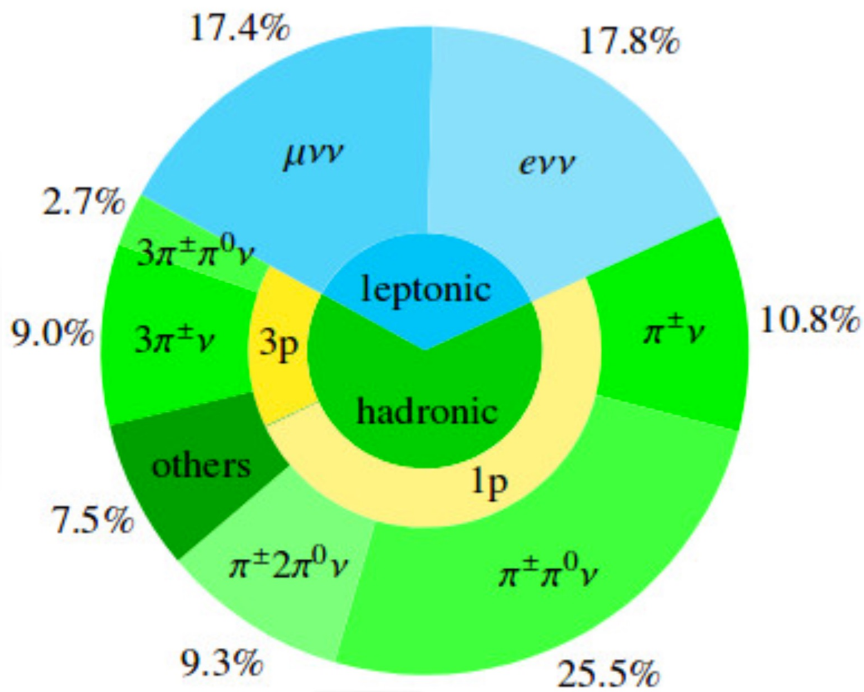
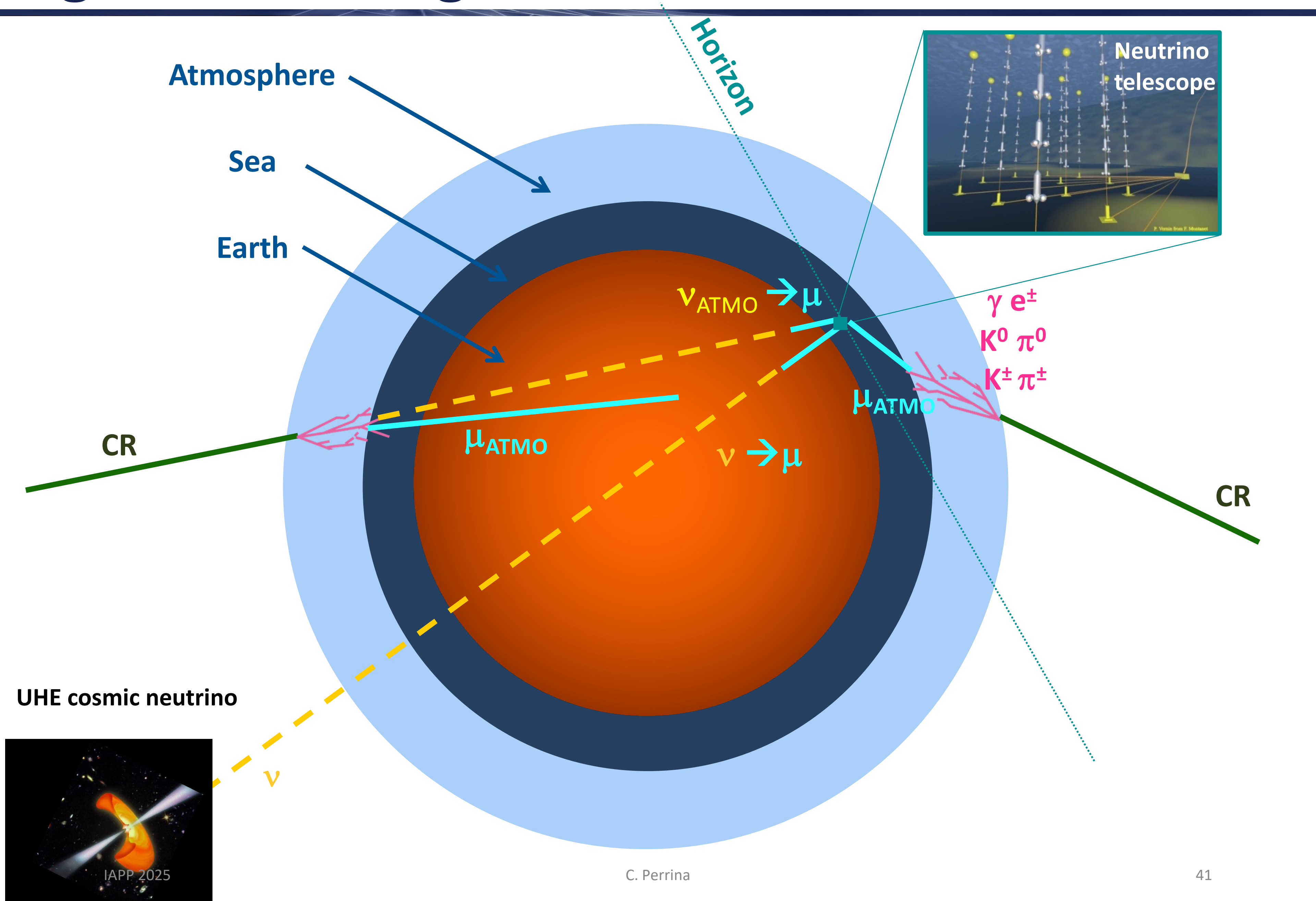




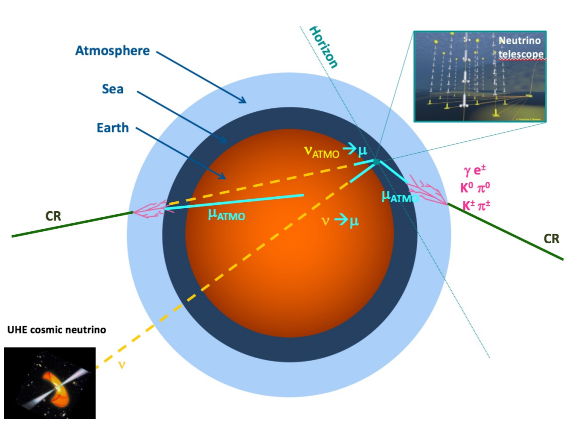
Dominating tau-lepton decay modes.

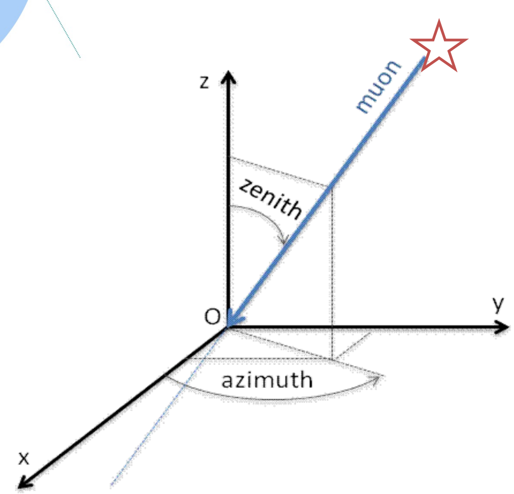
From Tasneem Saleem «Development of pixel detector for ATLAS Inner Tracker(ITK) upgrade at HL-LHC and Searching for the Standard Model Higgs boson decay into b-quark pair with ATLAS experiment».

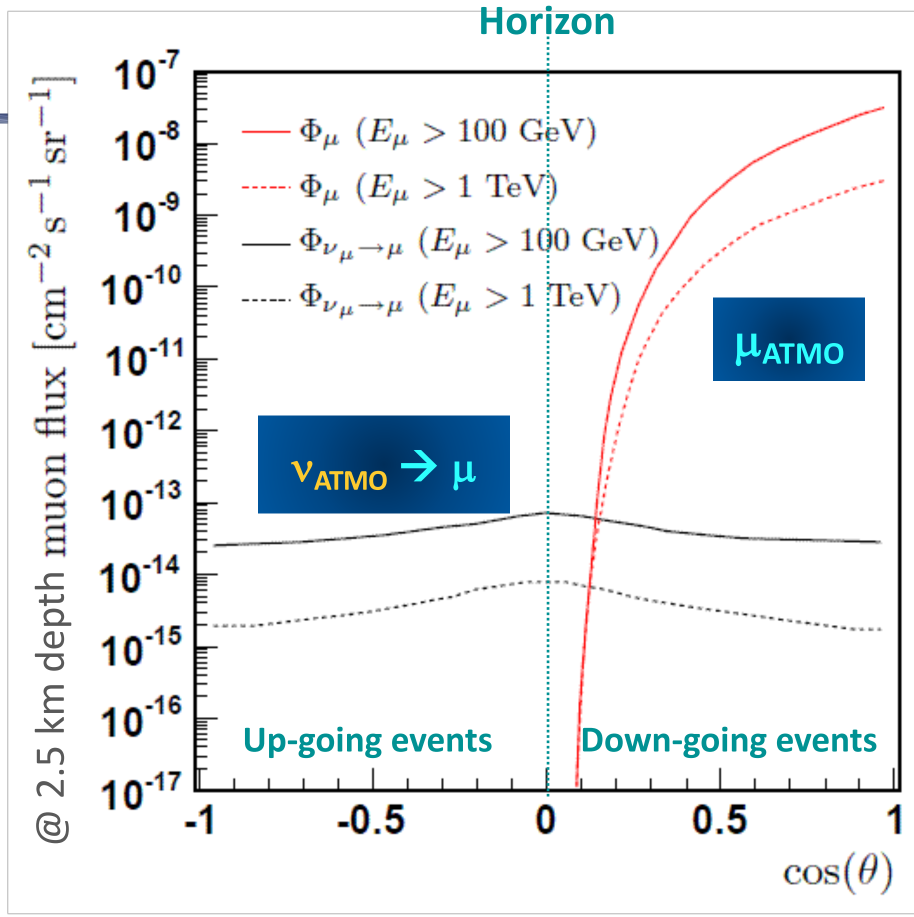
Signal and background



Background







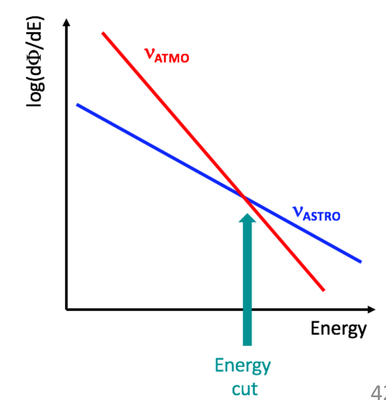
- To reject atmospheric μ, only **up-going** events are usually considered.
- To discriminate atmospheric neutrinos (irreducible background):

  → energy:

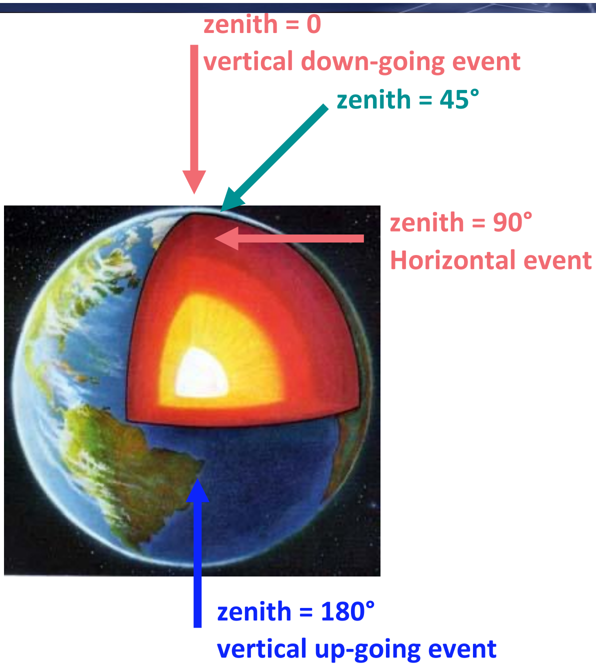
  - Atmospheric neutrino flux ~ $E_\nu^{-3.5}$

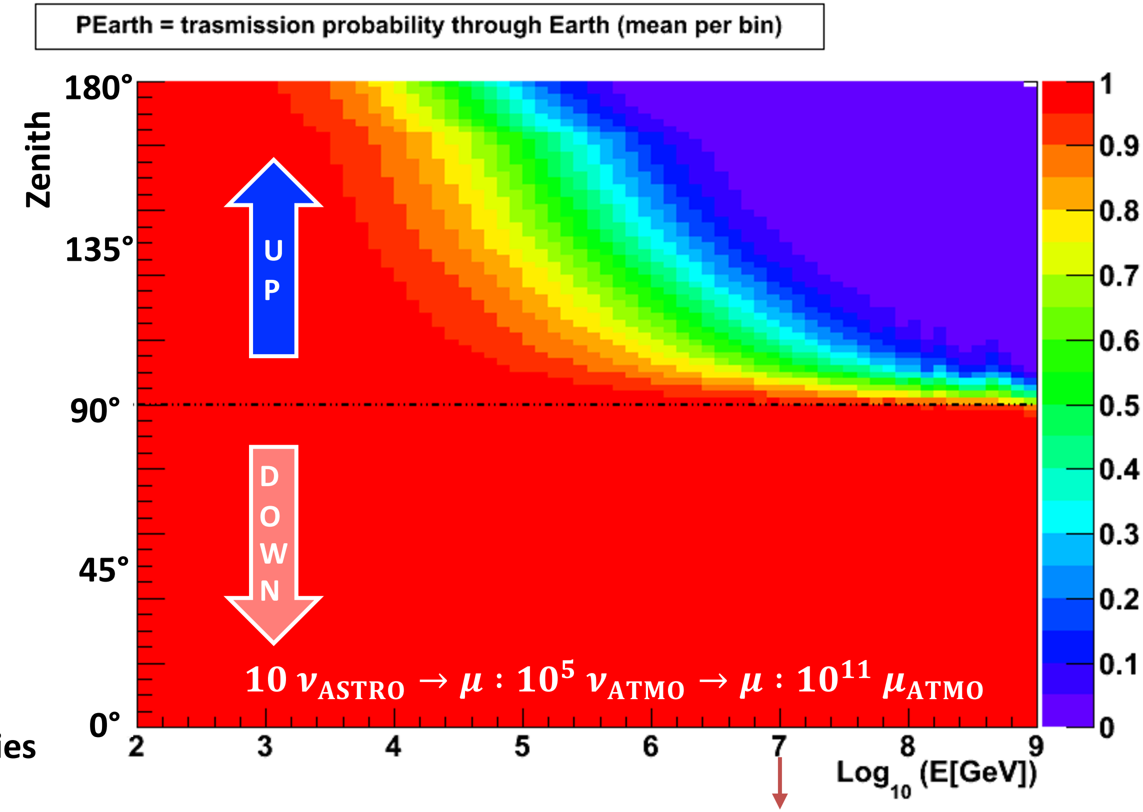
  - Astrophysical neutrino flux ~ E_ν^{-2}

  → angular distribution: **isotropic for background** vs. **directional for signal from point-like sources** (event clustering, statistical basis).

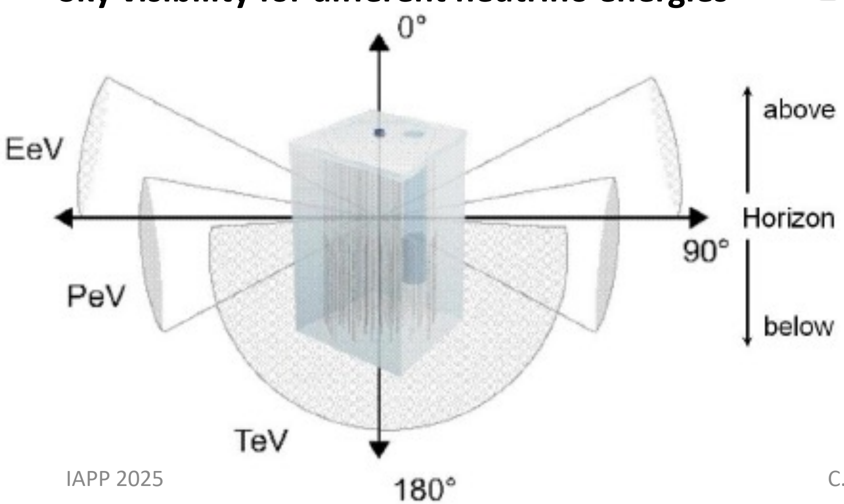


The most energetic events





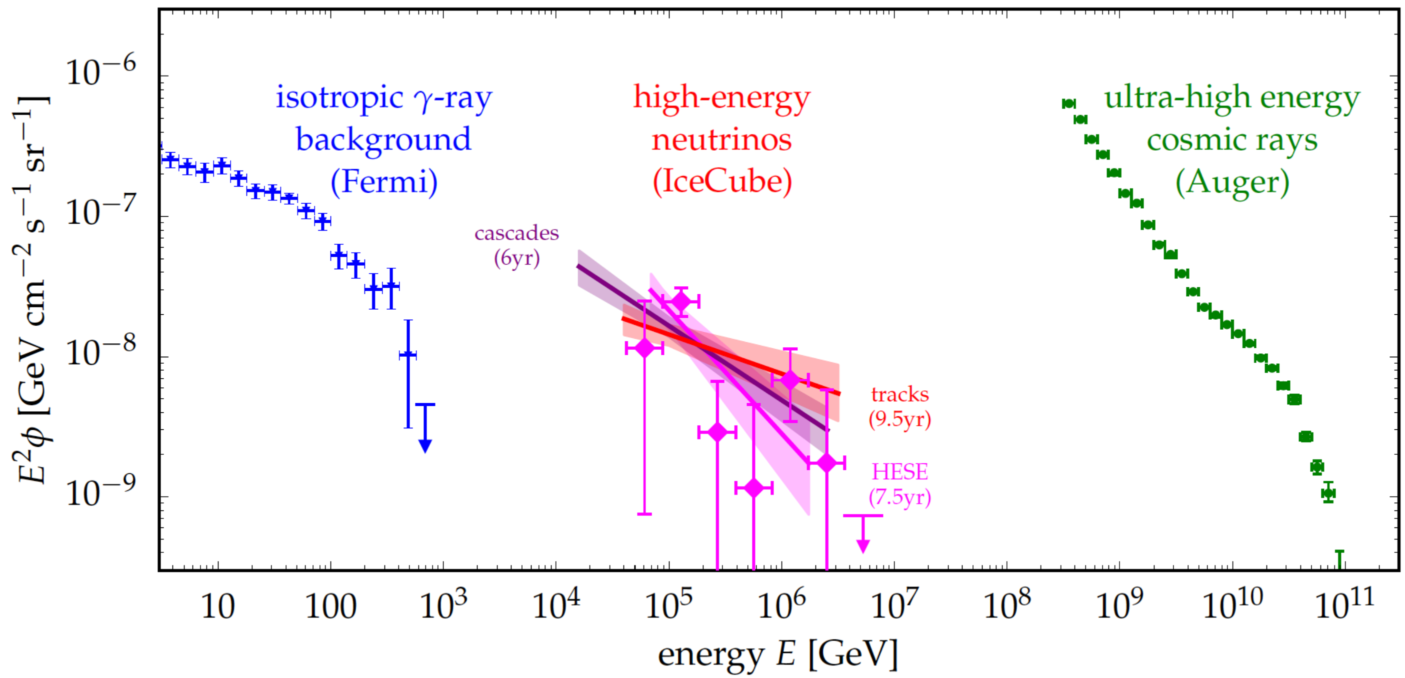
Sky visibility for different neutrino energies



Neutrinos with energy > 10 PeV cannot cross the Earth. Therefore, the neutrinos of energy from PeV to EeV arrive from directions near or above the horizon.

IceCube Collaboration, Nature 551, 596–600 (2017). https://doi.org/10.1038/nature24459

Diffuse ν_{ASTRO} flux (IceCube 2013)



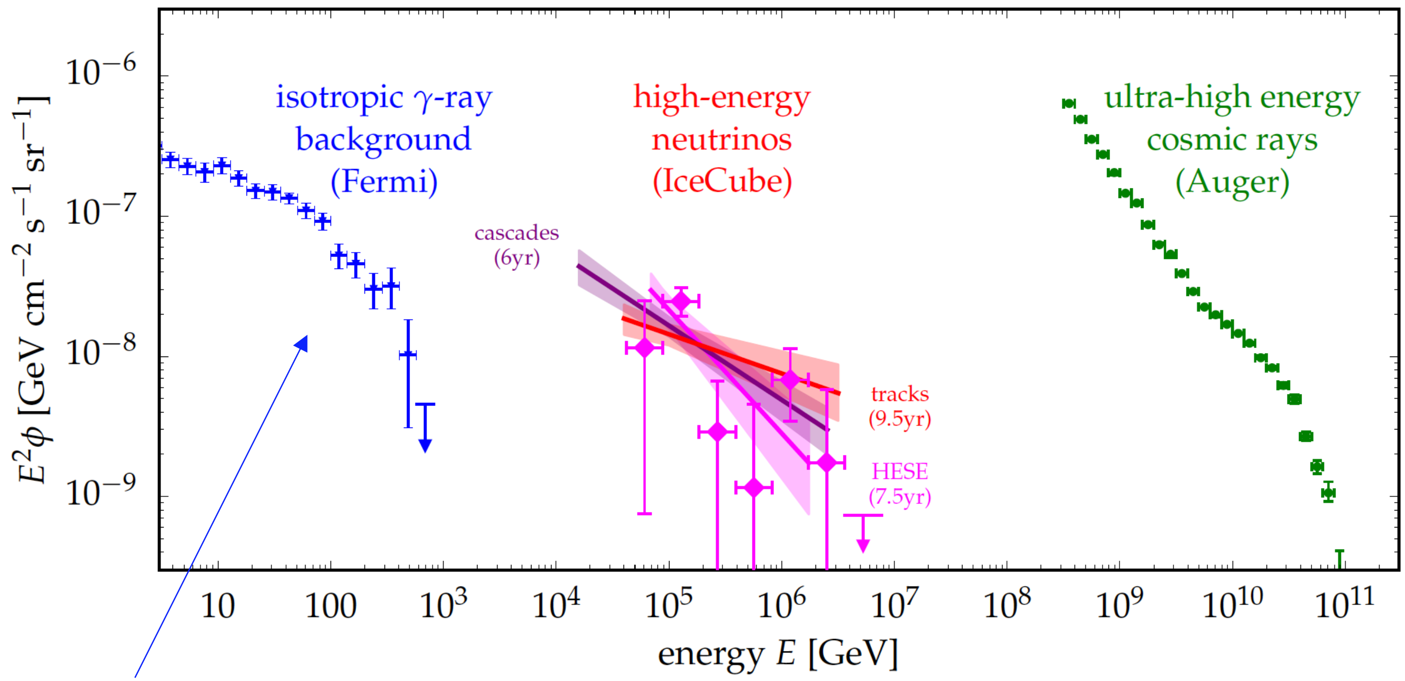
Do the 3 messengers (gamma rays, neutrinos and cosmic rays) have the same origin?

Shower events
$\propto E_\nu^{-2.53}$ consistent with a single power-law model as expected from Fermi acceleration.

Track events
$\propto E_\nu^{-2.28}$

High-Energy Starting Events
$\propto E_\nu^{-2.87}$

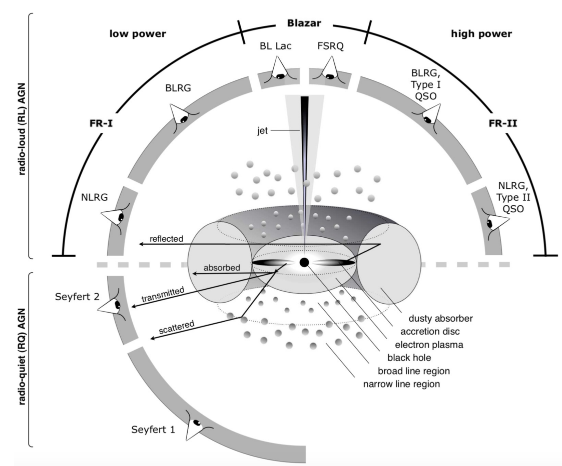
Diffuse ν_{ASTRO} flux (IceCube 2013)



Do the 3 messengers (gamma rays, neutrinos and cosmic rays) have the same origin?

At an energy of 100 GeV, roughly half of the total extragalactic gamma-ray background (EGB) intensity has been resolved into individual sources by Fermi-LAT, predominantly blazars of the BL Lacertae type.

Fermi-LAT Collaboration: https://doi.org/10.1088/0004-637X/799/1/86



Where do the neutrinos come from?

Search for point-like sources

The aim of this search is to detect significant excesses of events from particular regions of the sky (over the isotropic background).

The search can be performed

1. over the full sky
2. in the direction of *a priori* selected candidate-source locations that correspond e.g. to known γ-ray emitters.

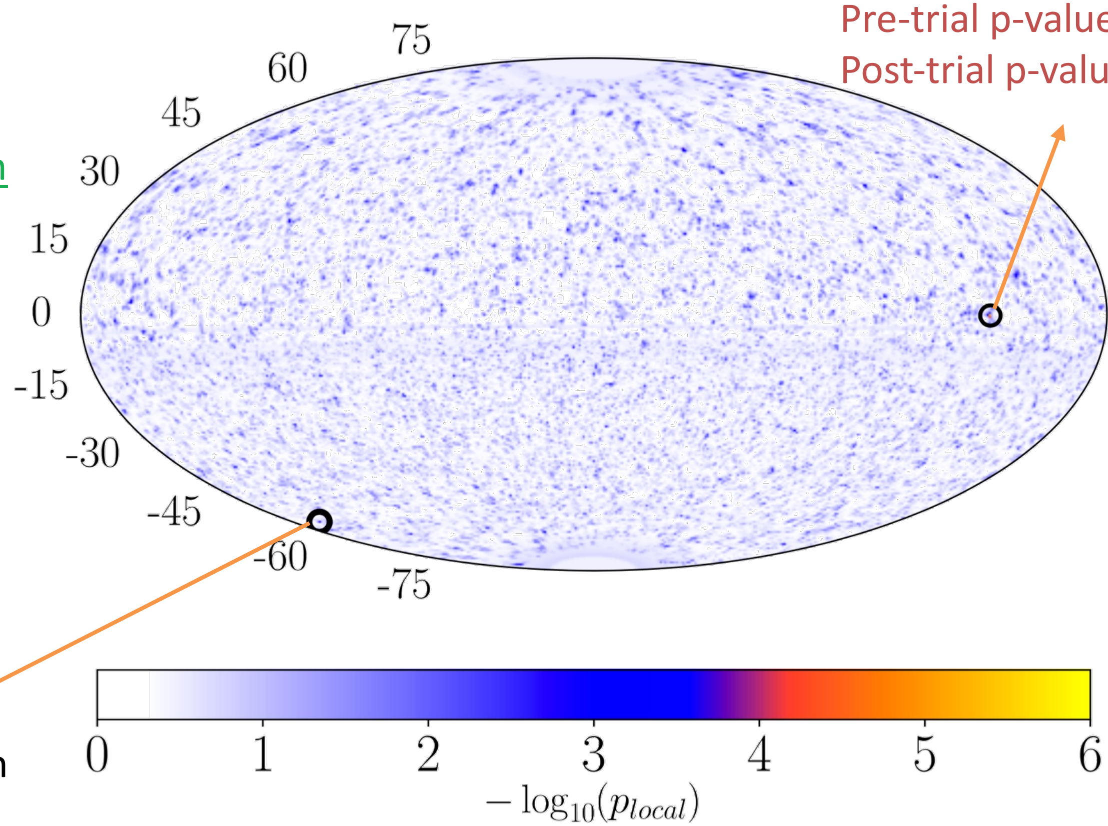
All-Sky search

[IceCube Collaboration, PHYSICAL REVIEW LETTERS 124, 051103 (2020)]

Most significant hotspot in the Northern hemisphere

Pre-trial p-value = 3.5e-7
Post-trial p-value = 0.099

The p-value (probability value) tells us how likely a cluster we see in the sky is due to a random background fluctuation or it is due to a source of high-energy neutrinos. P-value <= significant level → we reject the null hypothesis → cluster is due to a source



Most significant hotspot in the Southern hemisphere

Pre-trial p-value = 4.3e-6
Post-trial p-value = 0.75

P-value equatorial map

IceCube, data set: 2008 - 2018.

Both hotspots are consistent with the background-only hypothesis.

https://en.wikipedia.org/wiki/Look-elsewhere_effect

Candidate-source list

If you know where to look, you can reduce significantly the number of trials.

Look at 110 predefined sources chosen based on the gamma-ray flux

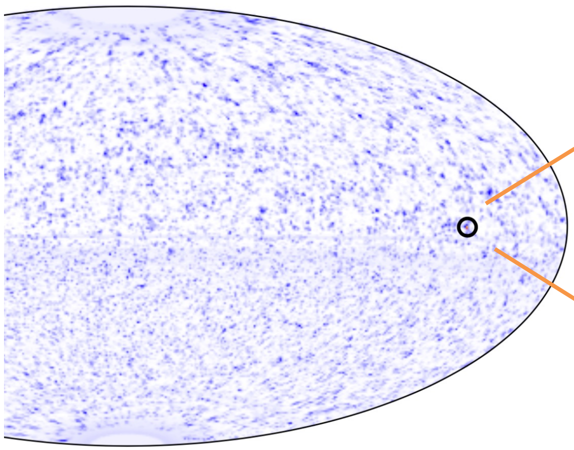
Source List Results

Name	Class	α [deg]	δ [deg]	$\hat{n}_s$	$\hat{\gamma}$	$-\log_{10}(p_{local})$	σ_{local}	$\phi_{90\%}$
PKS 2320-035	FSRQ	350.88	-3.29	4.8	3.6	0.45	0.4	3.3
3C 454.3	FSRQ	343.50	16.15	5.4	2.2	0.62	0.7	5.1
TXS 2241+406	FSRQ	341.06	40.96	3.8	3.8	0.42	0.3	5.6
RGB J2243+203	BLL	340.99	20.36	0.0	3.0	0.33	0.1	3.1
CTA 102	FSRQ	338.15	11.73	0.0	2.7	0.30	-0.0	2.8
BL Lac	BLL	330.69	42.28	0.0	2.7	0.31	0.0	4.9
⋮		⋮						
NGC 1275	AGN	49.96	41.51	3.6	3.1	0.41	0.3	5.5
NGC 1068	**SBG**	**40.67**	**-0.01**	**50.4**	**3.2**	**4.74**	**4.1**	**10.5**
PKS 0235+164	BLL	39.67	16.62	0.0	3.0	0.28	-0.0	3.1
4C +28.07	FSRQ	39.48	28.80	0.0	2.8	0.30	-0.0	3.6

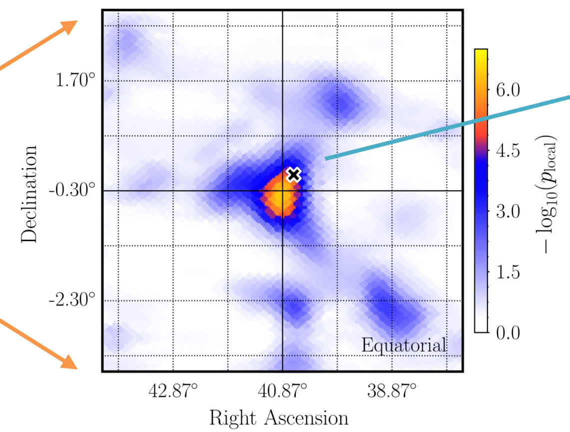
The **most significant source** in this list of 110 sources is **NGC 1068** (NGC = New General Catalogue of Nebulae and Clusters of Stars, SBG = starburst galaxy). – log10 (local p-value) = 4.74 → local p-value = 1.8e-5 = 4.1 σ

NGC 1068 (M77)

Equatorial coordinates



Most significant hotspot in the Northern hemisphere

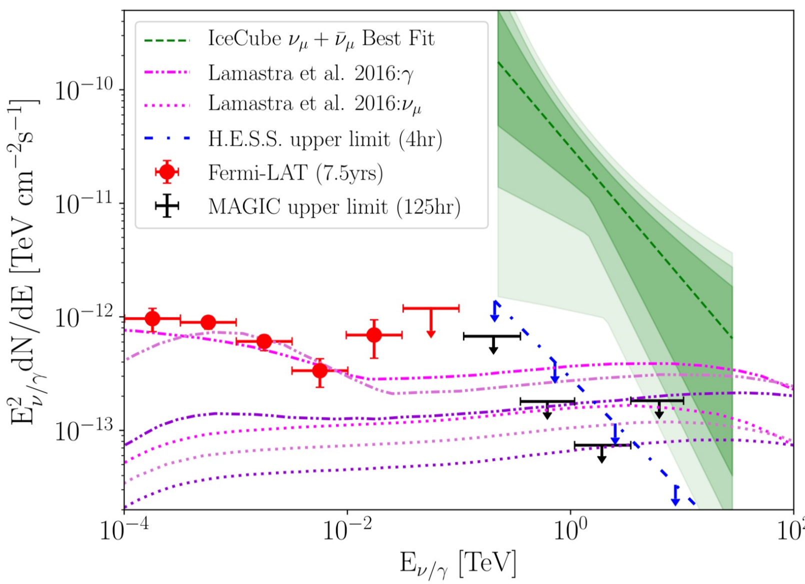


NGC 1068:

- Nearby (14 Mpc) type 2 Seyfert galaxy
- AGN and star forming activity

NGC 1068 is located close to the hottest spot found in the Northen hemisphere.

Post-trial p-value: 2e-3 (2.9 σ).



Gamma rays are absorbed

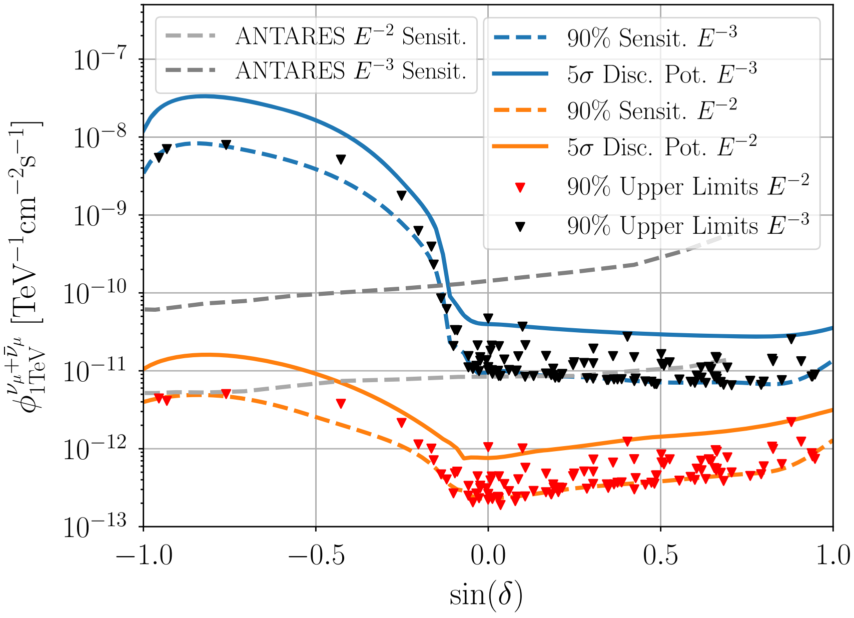
Upper limits

[IceCube Collaboration, PHYSICAL REVIEW LETTERS 124, 051103 (2020)]

IceCube, data set: 2008 - 2018.

- **No significant** (5σ) cluster in the **all-sky search**.
- **No significant** (5σ) cluster in the **candidate-source list search**.

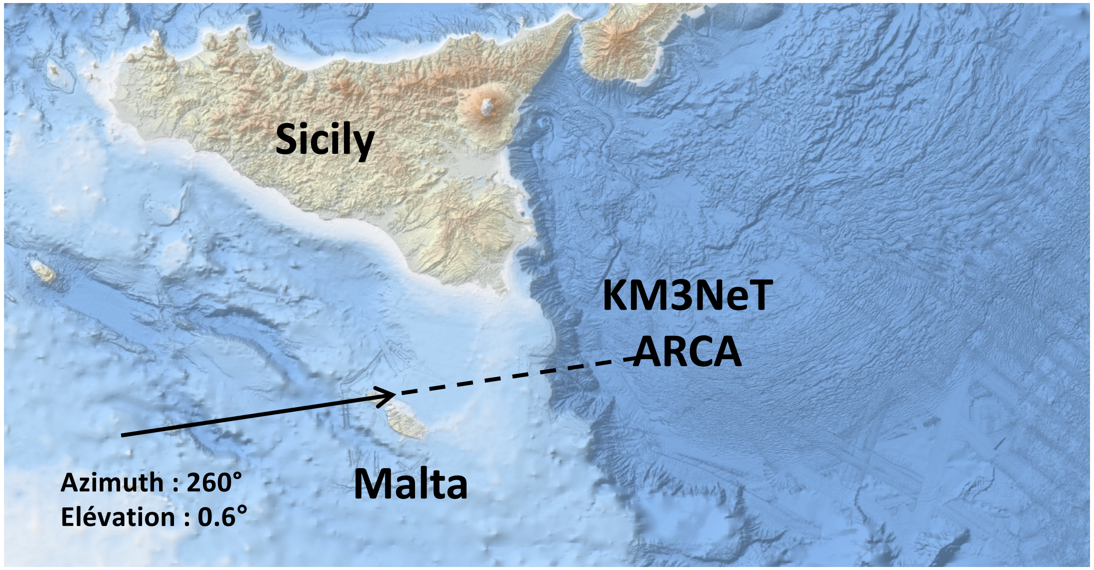
→ Upper limits are set:



Southern hemisphere | Northern hemisphere

Event KM3-230213A

KM3NeT Coll., Nature 638 (2025) 8050



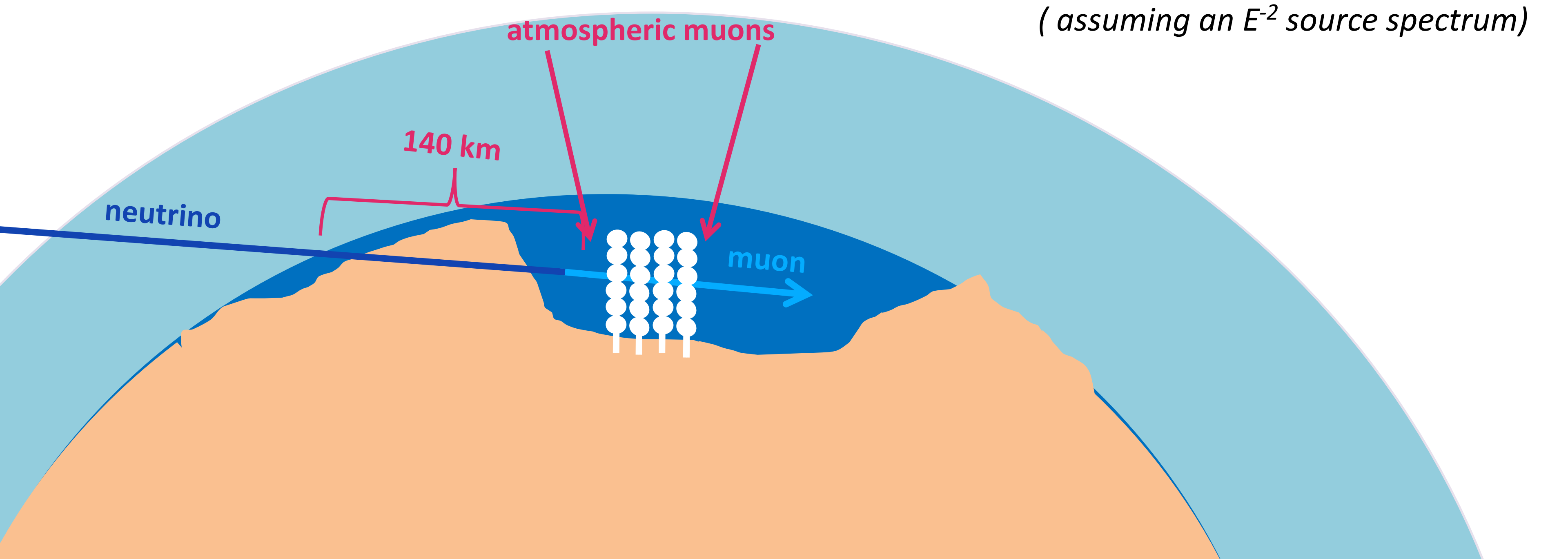
- **Energy is measured from the amount of light:**

$$E_\mu = 120^{+110}_{-60}\ \mathrm{PeV}$$

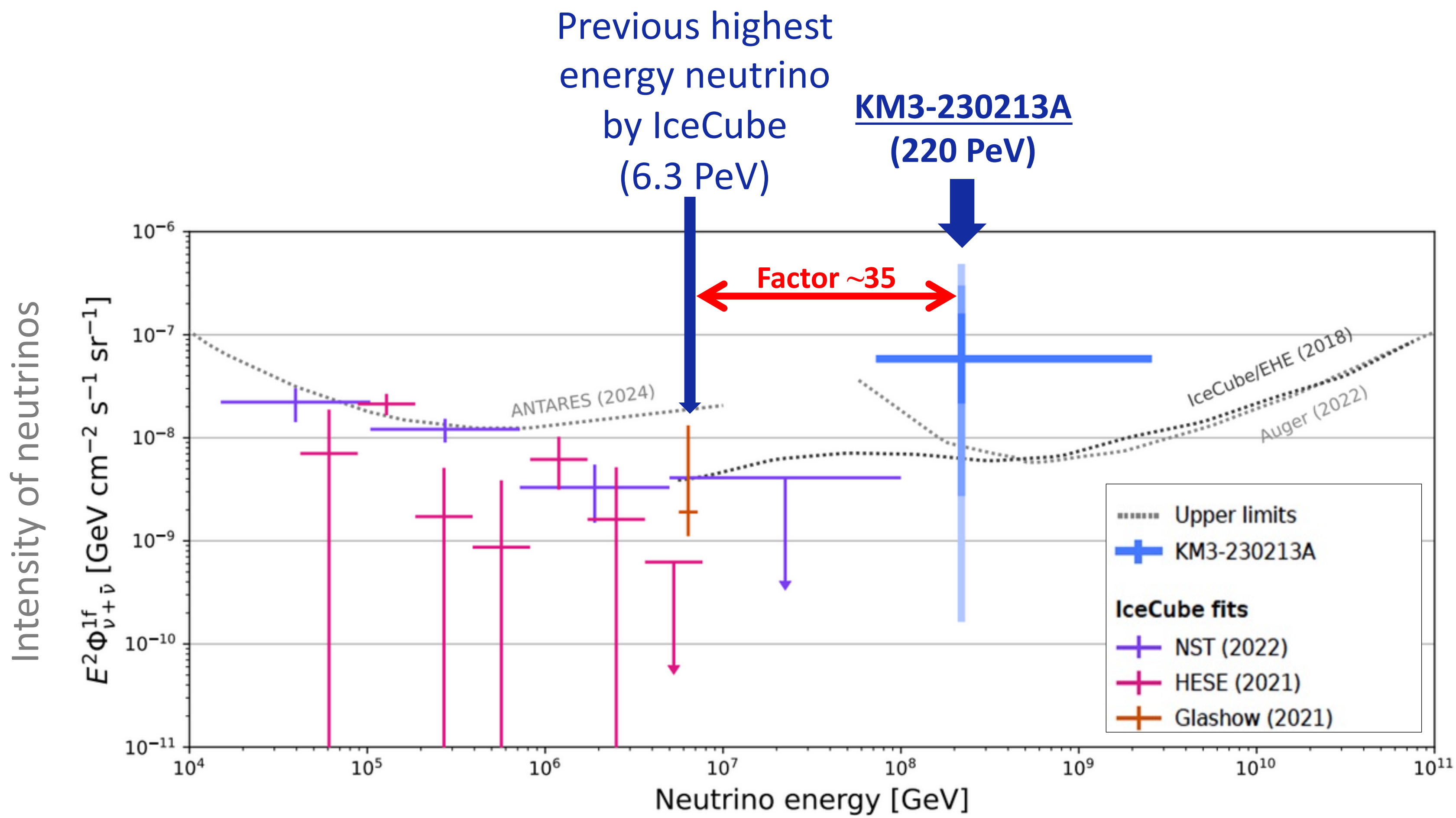
- **The neutrino Energy is higher:**

$$E_\nu = 220^{+570}_{-100}\ \mathrm{PeV}$$

(assuming an E^{-2} source spectrum)



KM3-230213A: Unexplored energy regime

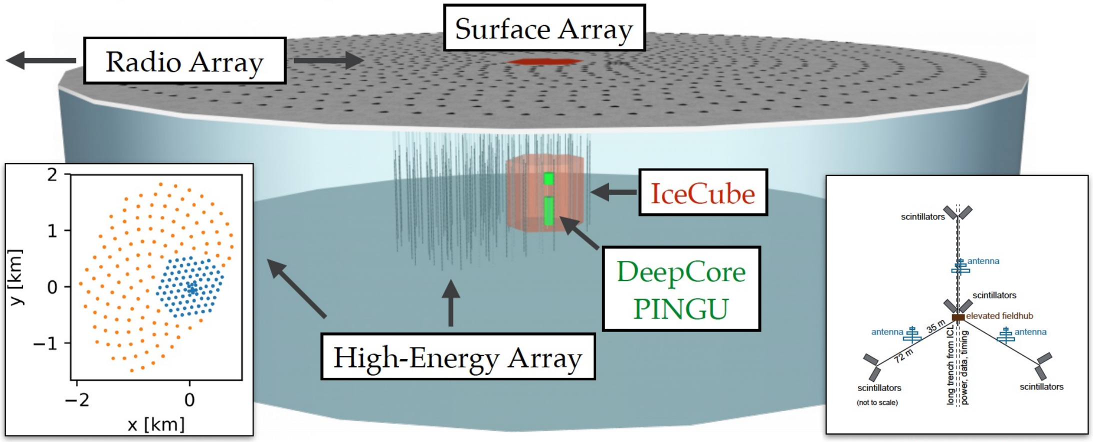


Announcement of the KM3-230213A event discovery: https://www.youtube.com/watch?v=2jgyZlBpkl8

IceCube Gen-2

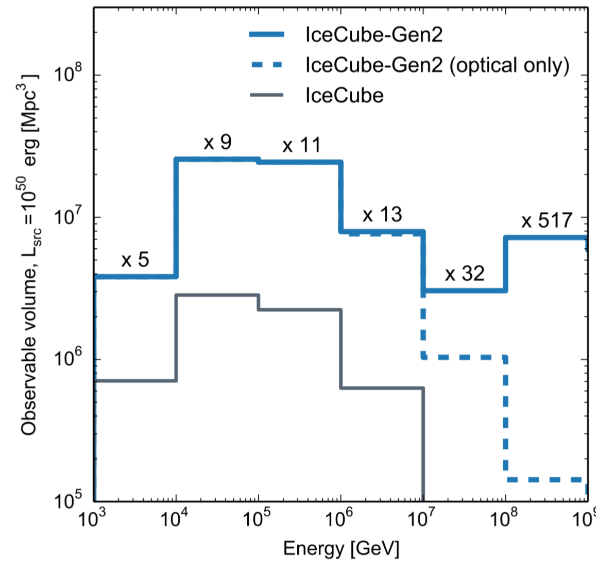
IceCube-Gen2, White Paper (2020). https://arxiv.org/pdf/2008.04323.pdf

- **Multi-component facility** (low- and high-energy & multi-messenger)
- **In-ice optical Cherenkov array** with 120 strings and 240m spacing
- **Surface array** (scintillators & radio antennas) for PeV-EeV CRs & veto
- **Askaryan radio array** for >10PeV neutrino detection



string layout

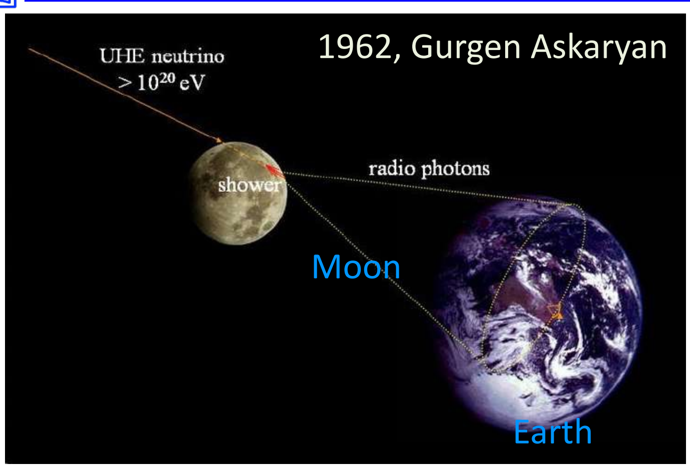
surface station



https://doi.org/10.1142/9789814759410_0015

Radio detection principle: the Askaryan effect

If a charged particle moves at a speed greater than the speed of light in the medium, a cone of coherent **radio or microwave radiation** is emitted (result of the Cherenkov radiation from individual particles in the shower).



Lesson 6 -- Bibliography

- **Probes of Multimessenger Astrophysics**

  Maurizio Spurio

  Springer (Second Edition)

  Chapter 9 (gamma rays), 12 (neutrinos)

  https://link.springer.com/book/10.1007%2F978-3-319-96854-4

- **Introduction to Particle and Astroparticle Physics**

  Alessandro De Angelis and Mário Pimenta

  Springer (Second Edition, 2018)

  Chapter 10.2.6: Sources of Neutrinos

  Chapter 10.3.3: First multimessenger Neutrino & Gamma-ray detection

  Chapter 10.5: Future experiments and open questions

  https://link.springer.com/book/10.1007%2F978-3-319-78181-5

- **Particles and Nuclei**

  Bogdan Povh, Klaus Rith, Christoph Scholz, Frank Zetsche, Martin Lavelle

  Springer, Berlin, Heidelberg

  Chapter 4.2: Cross sections

  https://link.springer.com/content/pdf/10.1007%2F978-3-540-79368-7.pdf

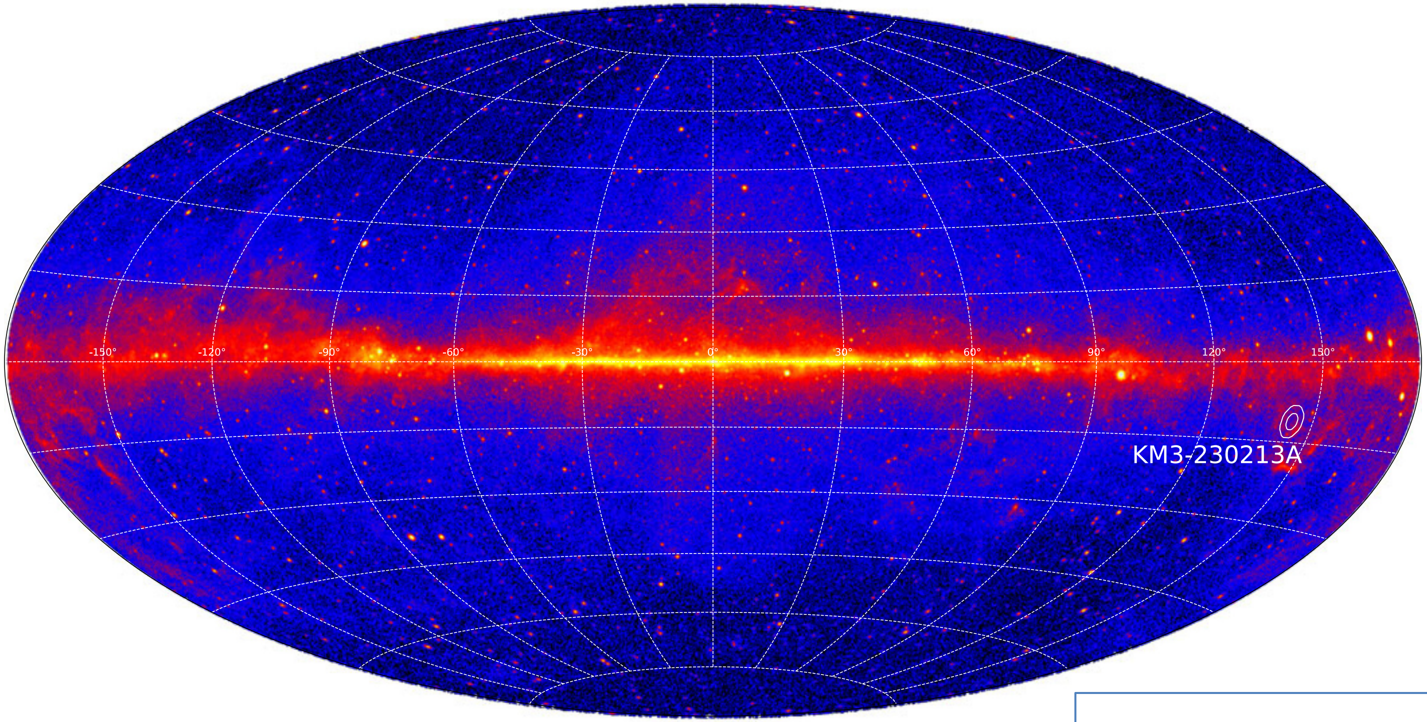
Extra slides

CERN Colloquium

Physics in the abyss with KM3NeT: from cosmic rays to neutrino oscillations

March 27, 2025

https://cds.cern.ch/record/2929477?ln=en

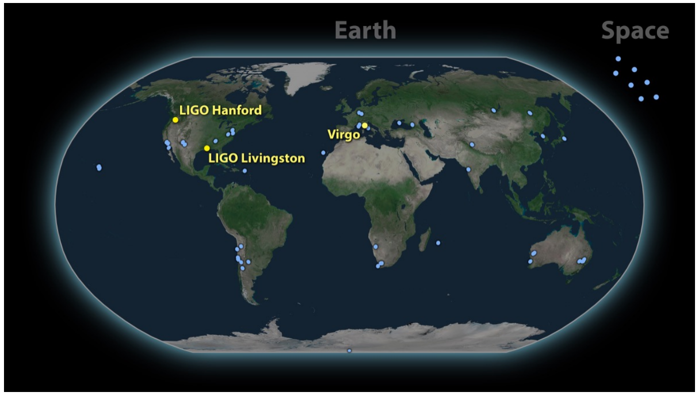


No compelling source
→ unlikely galactic

GW170817: The birth of multi-messenger astronomy - 1st multimessenger gravitational wave – e.m event

- At 8:41 a.m. EST on August 17, 2017, **LIGO,** the twin **L**aser **I**nterferometer **G**ravitational Wave **O**bservatories in Hanford (WA, USA) and Livingston (LA, USA) detected a gravitational wave signal.

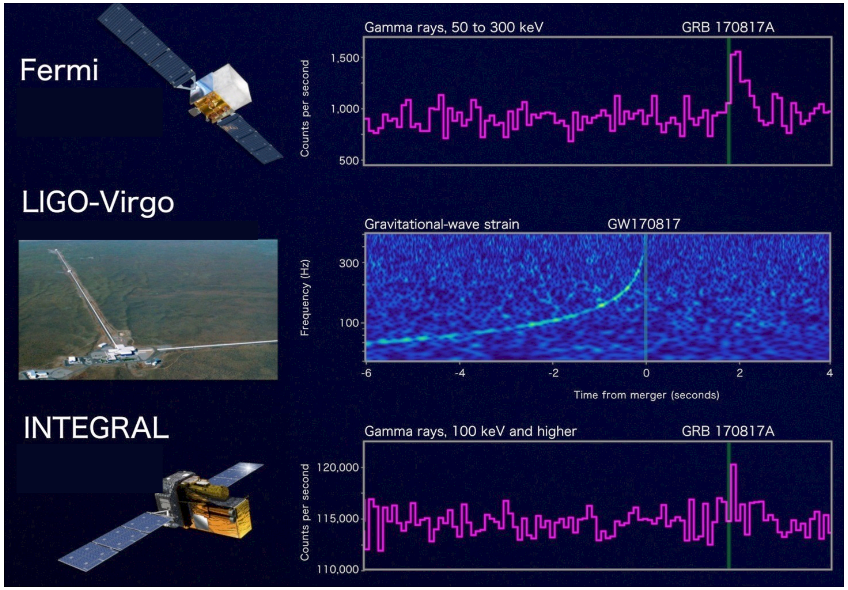
- The VIRGO interferometer near Pisa (Italy) detected the same signal.



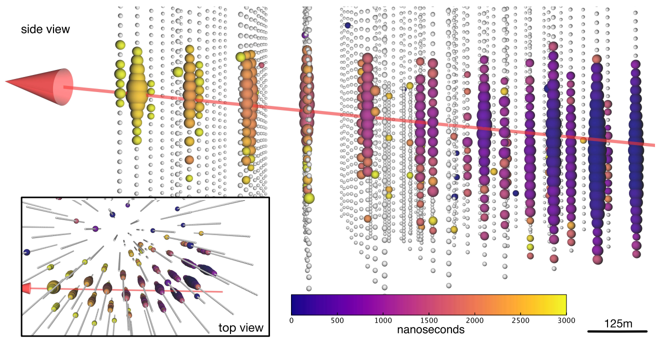
This Gravitational wave signal had the theoretical predicted characteristic of a binary neutron star merger from the galaxy NGC 4993 (0.13 Gly) that should produce a **very short high-energy gamma-ray burst**.

- 2 s later, the Fermi GBM detected a very short, high energy GRB in the galaxy NGC 4993, located 130 million light years from the Earth in the constellation Hydra.

- LIGO/VIRGO and Fermi sent worldwide a notification that triggered more than 70 follow-up detections and confirmations of this **multimessenger** event.



IceCube-170922A: 1st multimessenger neutrino – e.m event: a 290 TeV Neutrino

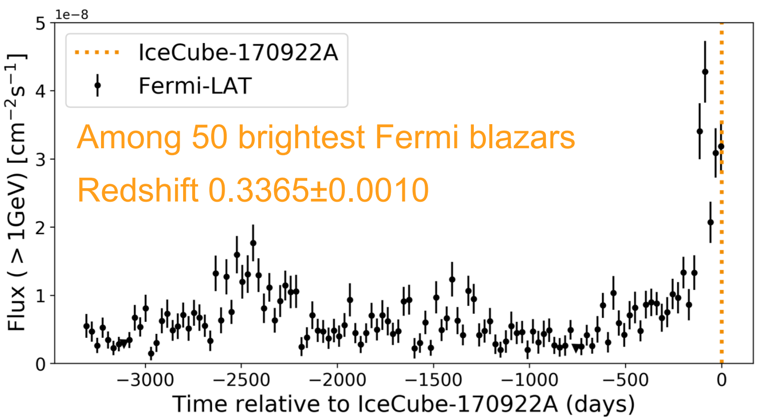


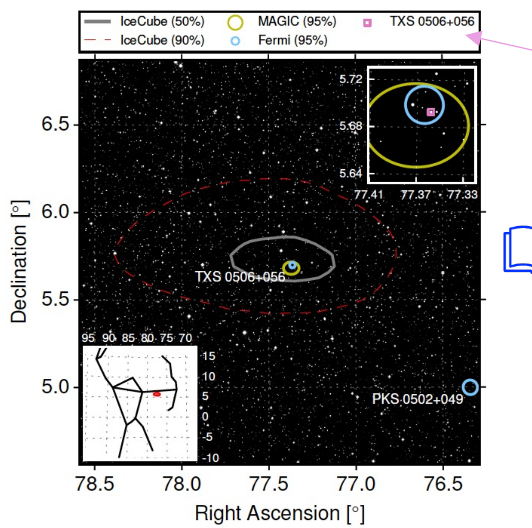
→ Alert sent worldwide within 1 min of detection

✓ **Fermi: neutrino direction consistent with the location of a known gamma-ray blazar: TXS 0506+056 (4 Gly)**

✓ **MAGIC: emission of gamma rays > 100 GeV**

✓ Measurements of the source have also been completed at x-ray, optical, and radio wavelengths.





Pink square:
TXS 0506+056 optical position

IceCube Collaboration, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S., INTEGRAL, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, Swift/NuSTAR, VERITAS, and VLA/17B-403 Collaboration, Science 361, 146 (2018). http://dx.doi.org/10.1126/science.aat1378

- Correlation significant at the level of 3.0 σ
- The energies of the gamma rays and the neutrino indicate that blazar jets may accelerate charged cosmic rays up to at least tens PeV.

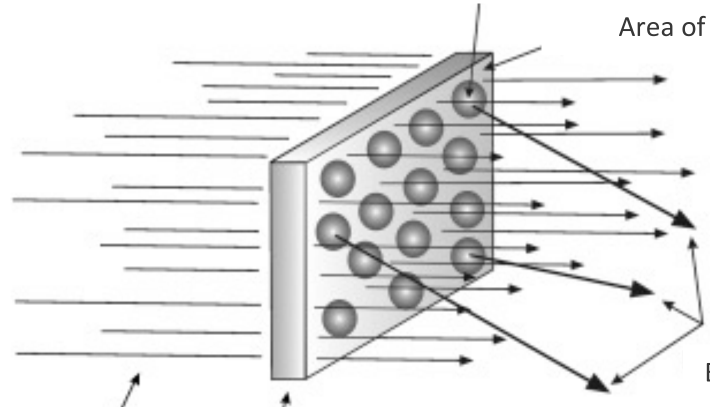
Exercise 6.2

Cross section

We consider the reaction

$$\mathbf{a} + \mathbf{b} \rightarrow c + d$$

a : projectile particle
b : target scattering center
c and d: products of the reaction



In an idealized experiment, we expose to a beam of particles **a** a target of thickness *x* and area *S* in which the scattering centers are **b**.

- N_b is the number of scattering centers
- n_b is the number density of scattering centers
- σ_b is the cross-sectional area of each scattering center.
- The reaction rate is $R \equiv \dfrac{dN_r}{dt} = \phi_a\, \sigma_b\, n_b\, S\, x$

Particles and Nuclei, https://link.springer.com/content/pdf/10.1007%2F978-3-540-79368-7.pdf

Number density of scattering centers (n_b)

Molar mass (m_{mol})

$$m_{mol} = m_{atom} \times N_A$$

Molar mass = mass of 1 mol of atoms

Mass of 1 atom

Avogadro number:
$N_A = 6.022 \times 10^{23}\ \mathrm{mol}^{-1}$
Number of atoms in 1 mol

Density of the target: ρ

$$\rho = \frac{M}{V} = \frac{m_{atom} \times N_{atoms}}{V} = \frac{m_{mol} \times N_{atoms}}{N_A \times V}$$

If the scattering center is the atom:

$$n_b = \frac{N_{atoms}}{V} = \frac{\rho \times N_A}{m_{mol}}$$

If the scattering center is the nucleon of the atom (mass number of the atom: A):

$$n_b = \frac{N_{nucleons}}{V} = \frac{A \times N_{atoms}}{V} = \frac{A \times \rho \times N_A}{m_{mol}} \Longrightarrow \boxed{\frac{n_b}{\mathrm{cm}^{-3}} = \frac{\rho}{\mathrm{g/cm}^3} \times \frac{N_A}{\mathrm{mol}^{-1}}}$$

The mass number is approximately equal to the numerical value of the molar mass: $A = \frac{m_{mol}}{\mathrm{g/mol}}$.

For the atmosphere A = 28.96 and m_{mol} = 28.96 g/mol.

6.2) Crypton flux

$$\boldsymbol{dN_r} = 11$$
$$\boldsymbol{dt} = 14 \text{ years} = 4.41 \times 10^8 \text{ s}$$
$$\boldsymbol{S} = 100 \text{ km}^2 = 10^{12} \text{ cm}^2$$
$$\boldsymbol{\sigma_b} = 10^{-8} \text{ pb} = 10^{-44} \text{ cm}^2$$
$$\boldsymbol{h} = 900 \text{ m} = 0.9 \text{ km}$$

$$\frac{dN_r}{dt} = \phi_a \, \sigma_b \, n_b \, S \, x = \phi_a \, \sigma_b \, S \, n_b \, X$$

Unknown

Thickness of the target = atmospheric depth X

(See exercise 4.2)

$$X(h) = X(h=0)\, e^{-\frac{h/\text{km}}{8}} = 1033 \frac{\text{g}}{\text{cm}^2} e^{-\frac{0.9}{8}} = 923.09 \frac{\text{g}}{\text{cm}^2}$$

$$\frac{X}{\text{cm}} = \frac{X}{\text{g/cm}^2} \times \frac{1}{\frac{\rho}{\text{g/cm}^3}}$$

$$\frac{n_b}{\text{cm}^{-3}} = \frac{\rho}{\text{g/cm}^3} \times \frac{N_A}{\text{mol}^{-1}}$$

$$\frac{n_b}{\text{cm}^{-3}} \frac{X}{\text{cm}} = \cancel{\frac{\rho}{\text{g/cm}^3}} \times \frac{N_A}{\text{mol}^{-1}} \times \frac{X}{\text{g/cm}^2} \times \cancel{\frac{1}{\frac{\rho}{\text{g/cm}^3}}} = \frac{N_A}{\text{mol}^{-1}} \times \frac{X}{\text{g/cm}^2} = 6.022 \times 10^{23} \times 923.09 = 5.56 \times 10^{26}$$

$$\phi_a = \frac{dN_r}{dt} \times \frac{1}{\sigma_b \, S \, n_b \, X} = \frac{11}{4.41 \times 10^8 \text{ s}} \times \frac{1}{10^{-44} \text{ cm}^2 \times 10^{12} \text{ cm}^2 \times 5.56 \times 10^{26} \text{ cm}^{-2}} = 4.5 \times 10^{-3} \text{ s}^{-1}\text{cm}^{-2}$$

AGASA is a ground-based experiment sensitive to the the down-going extensive air showers (half the total solid angle)

$$\phi_a = \frac{4.5 \times 10^{-3} \text{ s}^{-1}\text{cm}^{-2}}{2\pi \text{ sr}} = \boxed{7.1 \times 10^{-4} \text{ s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1}}.$$

6.3)

Article

Detection of a particle shower at the Glashow resonance with IceCube

https://doi.org/10.1038/s41586-021-03256-1

Received: 28 July 2020

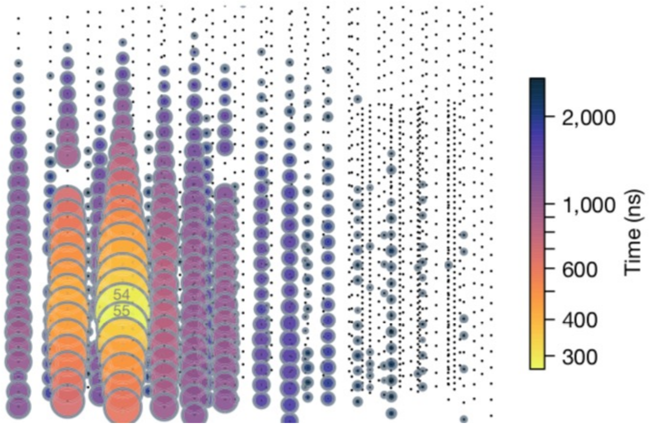
Accepted: 18 January 2021

Published online: 10 March 2021

Check for updates

The IceCube Collaboration*

The Glashow resonance describes the resonant formation of a W^- boson during the interaction of a high-energy electron antineutrino with an electron[1], peaking at an antineutrino energy of 6.3 petaelectronvolts (PeV) in the rest frame of the electron. Whereas this energy scale is out of reach for currently operating and future planned particle accelerators, natural astrophysical phenomena are expected to produce antineutrinos with energies beyond the PeV scale. Here we report the detection by the IceCube neutrino observatory of a cascade of high-energy particles (a particle shower) consistent with being created at the Glashow resonance. A shower with an energy of 6.05 ± 0.72 PeV (determined from Cherenkov radiation in the Antarctic Ice Sheet) was measured. Features consistent with the production of secondary muons in the particle shower indicate the hadronic decay of a resonant W^- boson, confirm that the source is astrophysical and provide improved directional localization. The evidence of the Glashow resonance suggests the presence of electron antineutrinos in the astrophysical flux, while also providing further validation of the standard model of particle physics. Its unique signature indicates a method of distinguishing neutrinos from antineutrinos, thus providing a way to identify astronomical accelerators that produce neutrinos via hadronuclear or photohadronic interactions, with or without strong magnetic fields. As such, knowledge of both the flavour (that is,



IceCube Collaboration, Nature | Vol591 | 11March2021 https://doi.org/10.1038/s41586-021-03256-1