OBSERVATION OF HIGH ENERGY NEUTRINOS

G. Marsella

SEXTEN CENTER FOR ASTROPHYSICS RICCARDO GIACCONI

UNIVERSITÀ DEGLI STUDI DI PALERMO

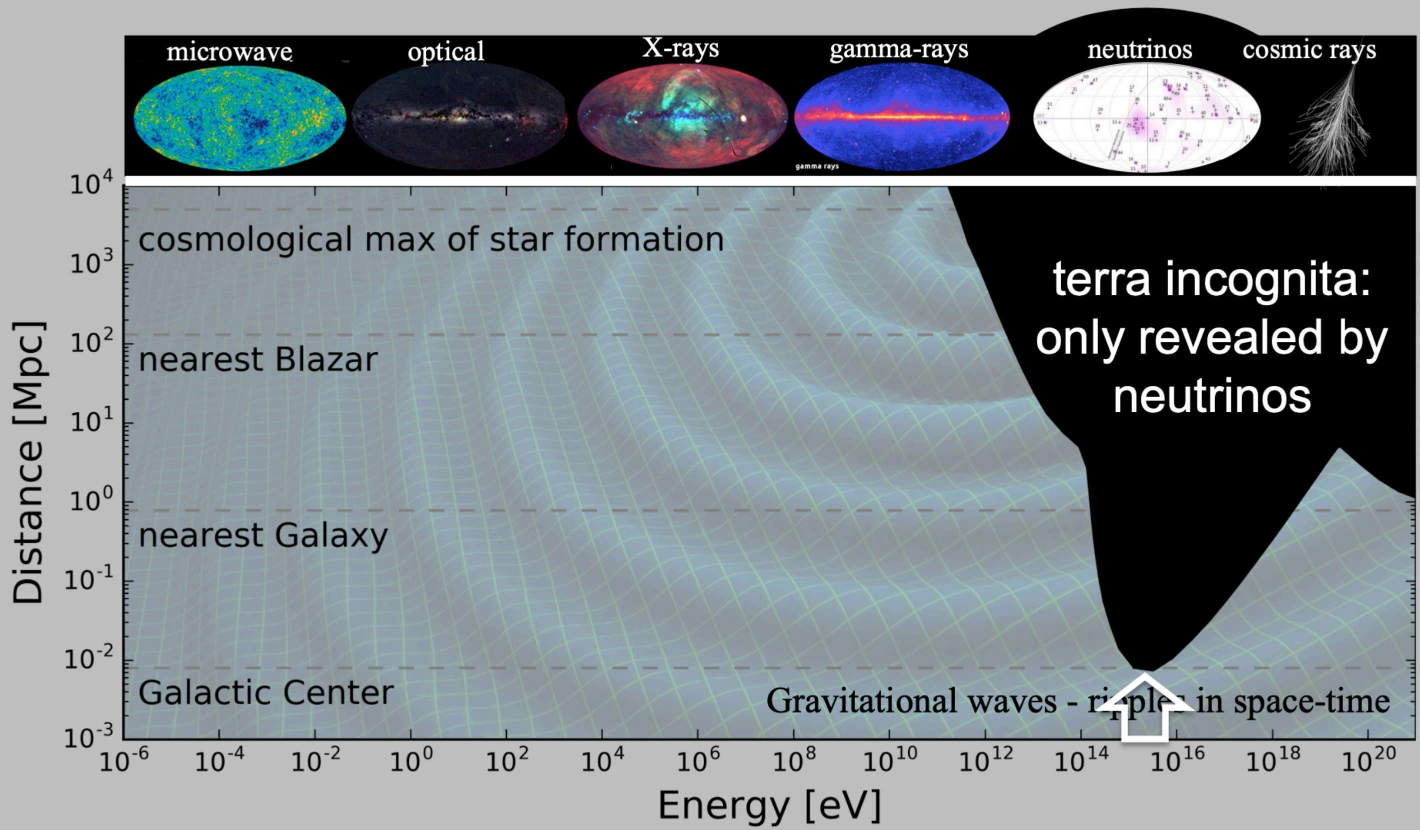
DiFC Dipartimento di Fisica e Chimica - Emilio Segrè

INFN

Outline

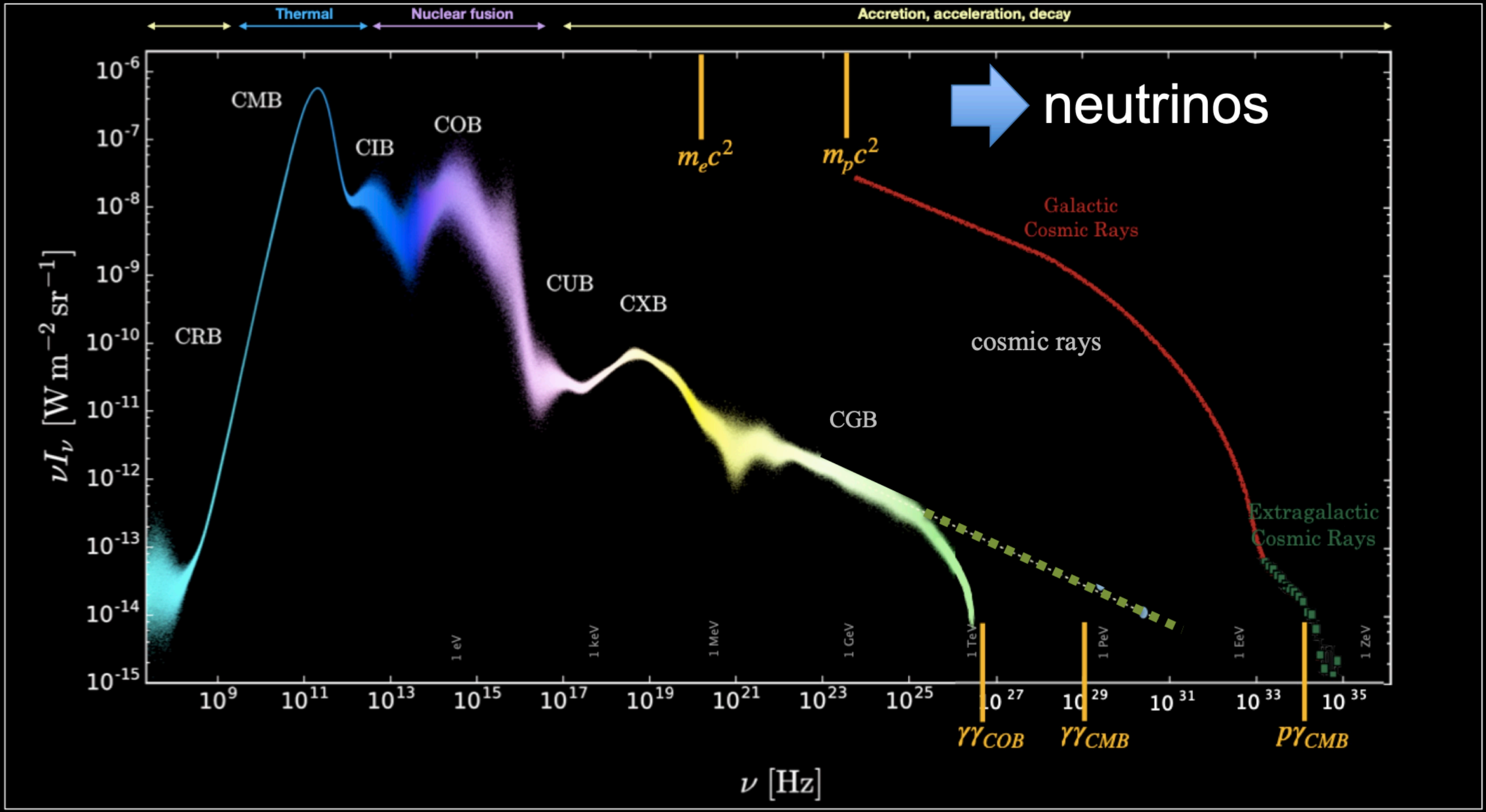
- Introduction on high energy neutrino detection
- IceCube
- KM3NET
- AUGER

- Introduction on high energy neutrino detection highest energy “radiation” from the Universe: cosmic rays, mostly protons



Credits:
F. Halzen

the Extreme Universe is opaque to gamma rays beyond our Galaxy energy in the Universe as a function of the color of light



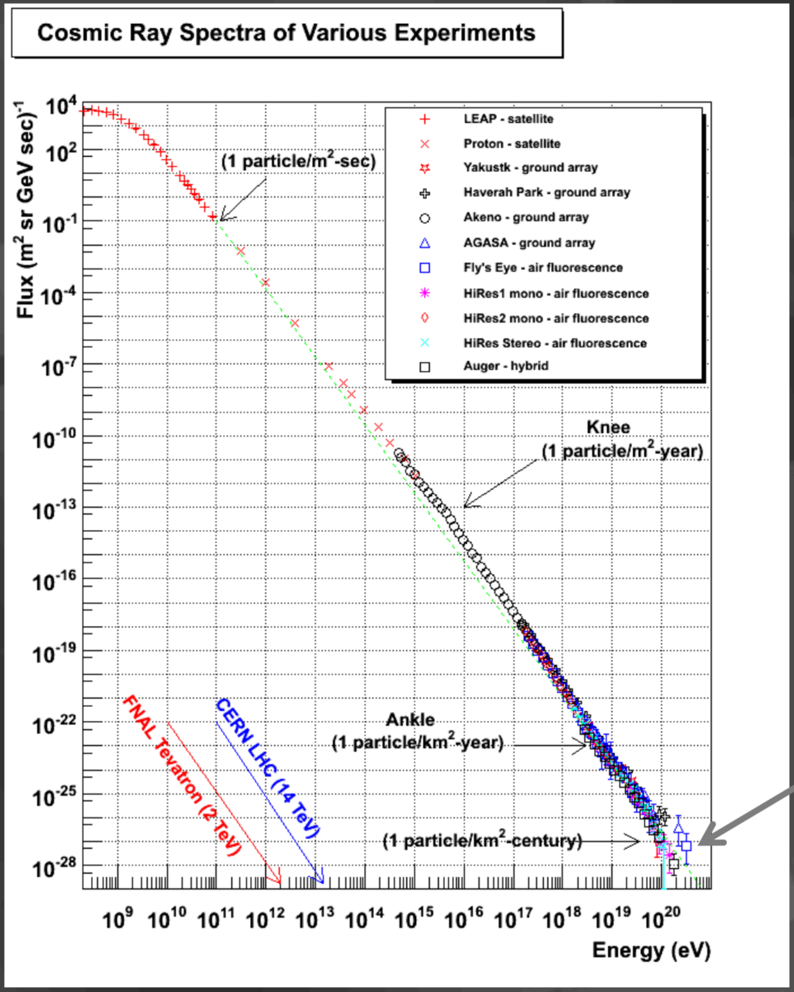
in the extreme universe neutrinos are unique astronomical messengers

neutrinos: perfect messengers

- electrically neutral
- massless (in this talk)
- like a photon but weakly interacting
- track cosmic ray sources

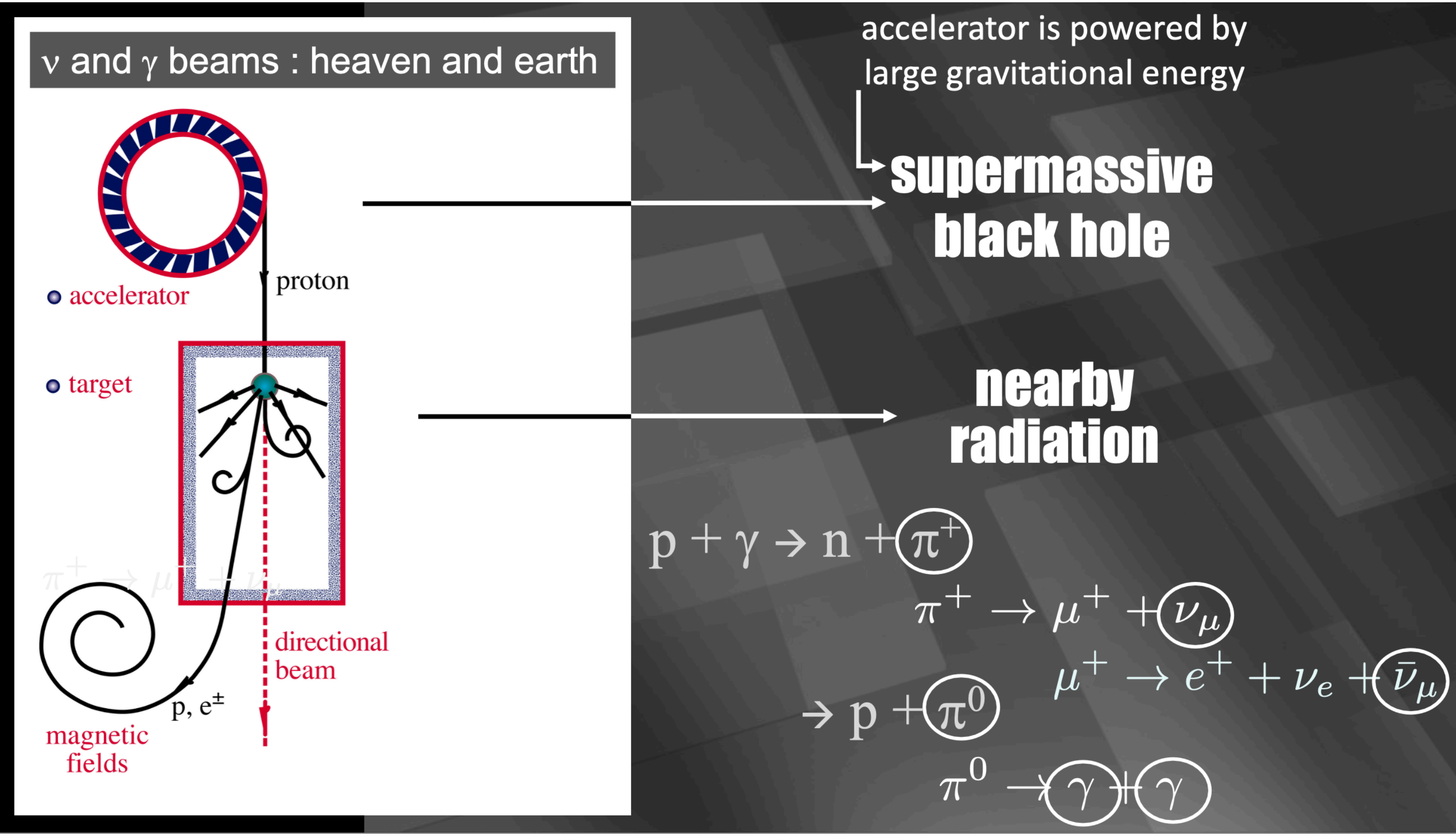
- … but difficult to detect

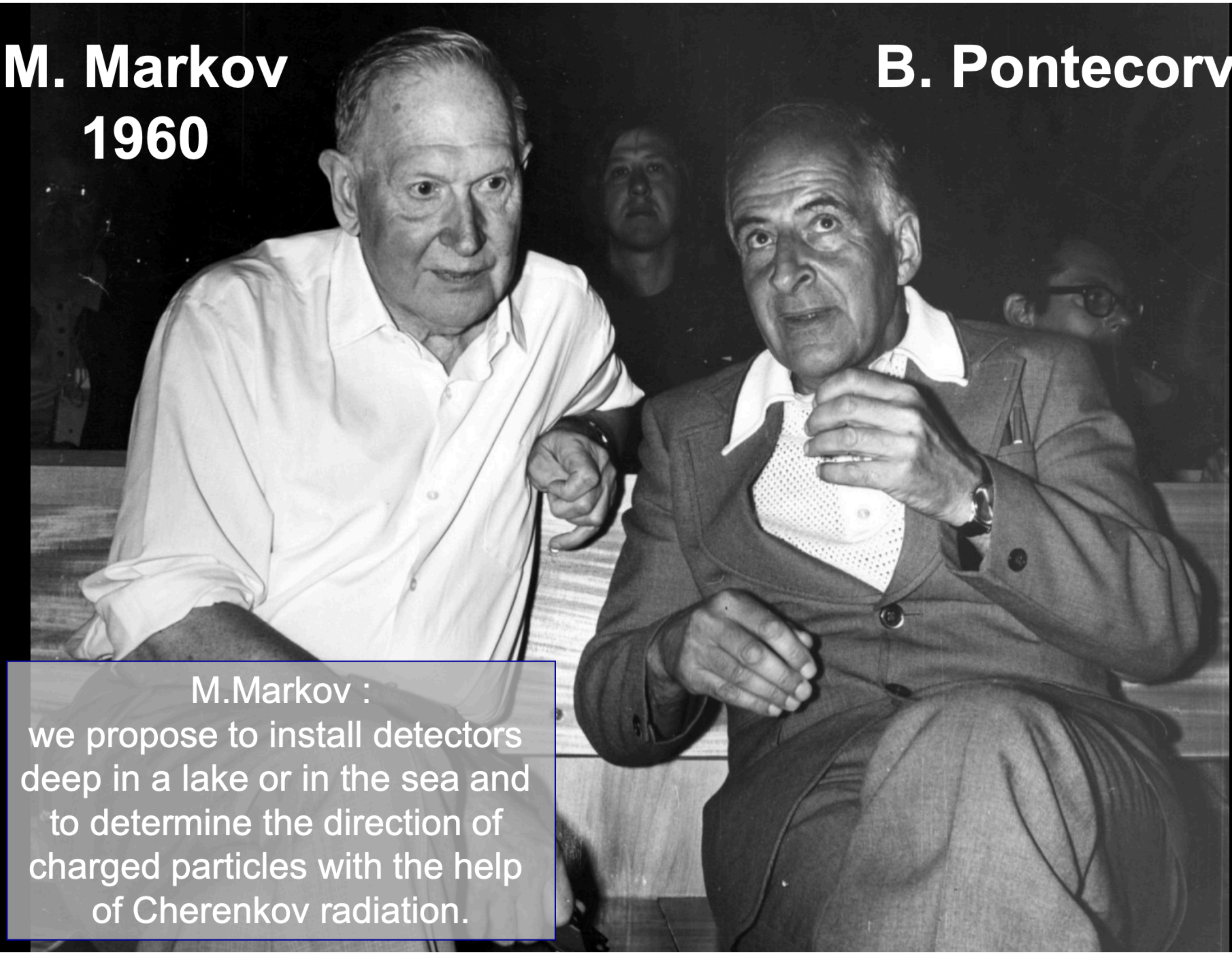
origin of cosmic rays: oldest problem in astronomy



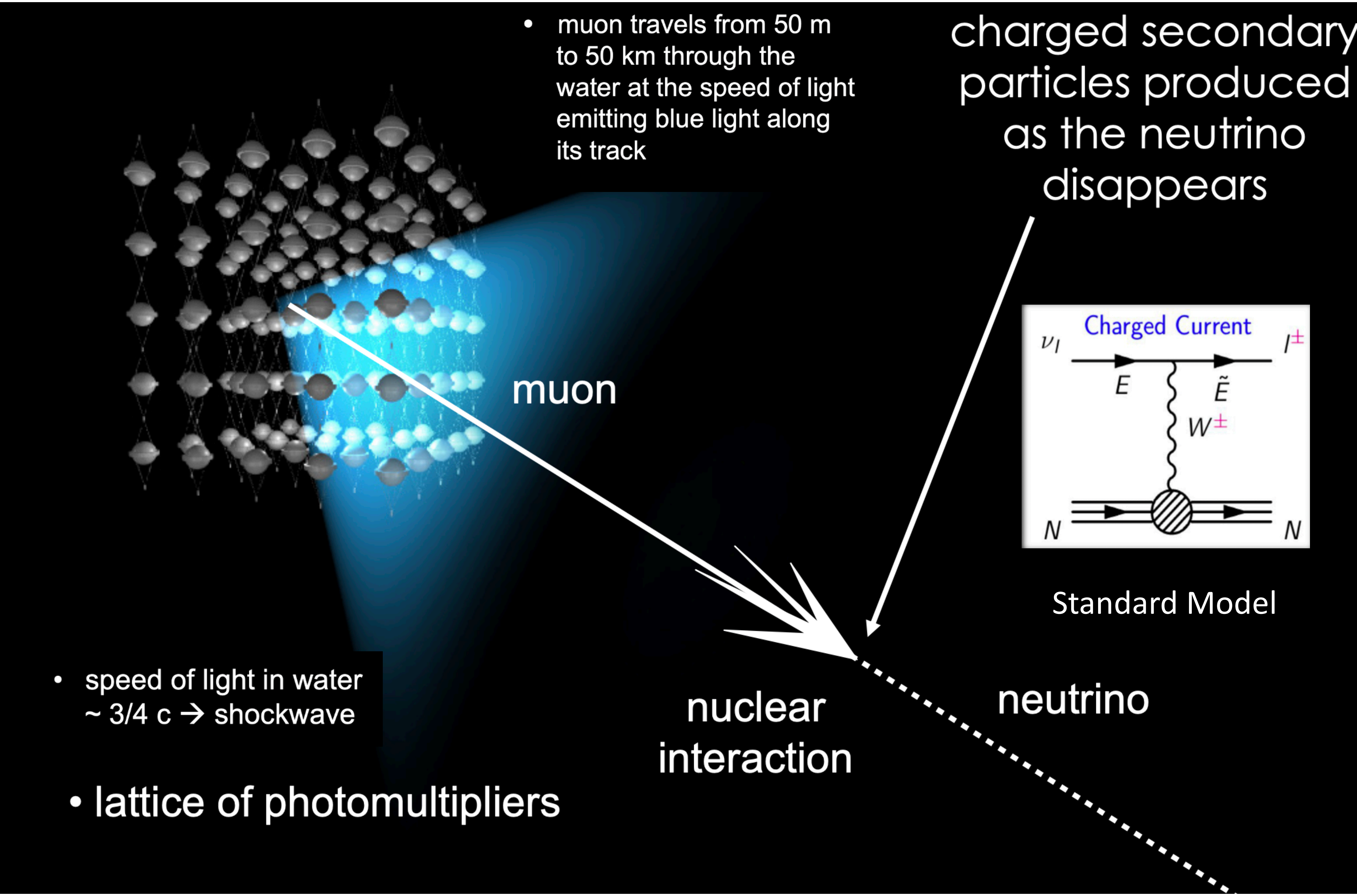
cosmic ray challenge

- both the energy of the particles and the total *luminosity* of the accelerators are large
- gravitational energy from matter accreting on black holes is converted into particle acceleration?
- gamma ray bursts, active galaxies, galaxy clusters, or…?

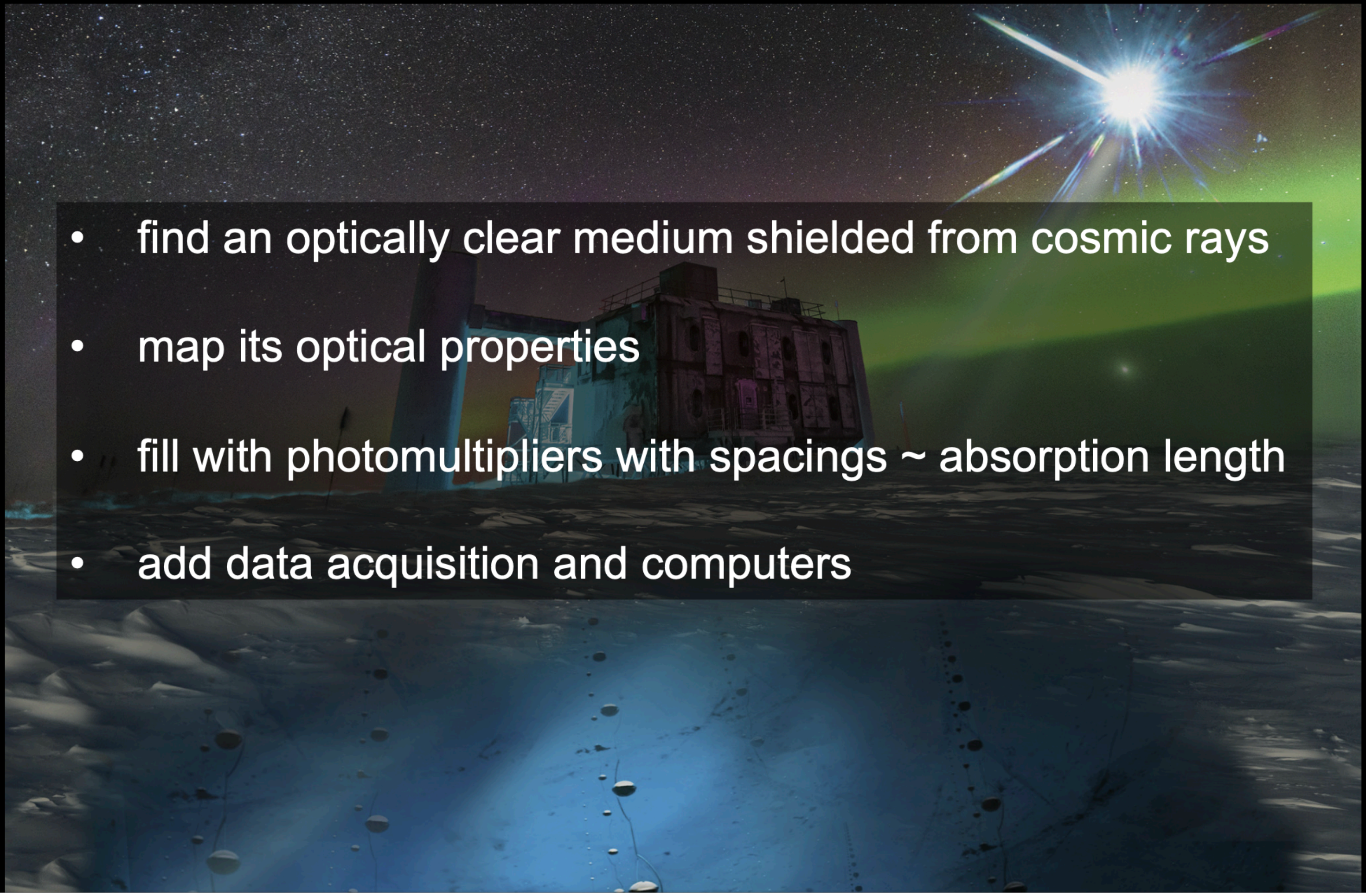

ν and γ beams : heaven and earth
accelerator
target
proton
directional beam
p, e±
magnetic fields
accelerator is powered by large gravitational energy
supermassive black hole
nearby radiation
p + γ → n + π+
π+ → μ+ + ν_μ
μ+ → e+ + ν_e + ν̄_μ
→ p + π0
π0 → γ + γ


M. Markov
1960
B. Pontecorvo
M.Markov :
we propose to install detectors deep in a lake or in the sea and to determine the direction of charged particles with the help of Cherenkov radiation.

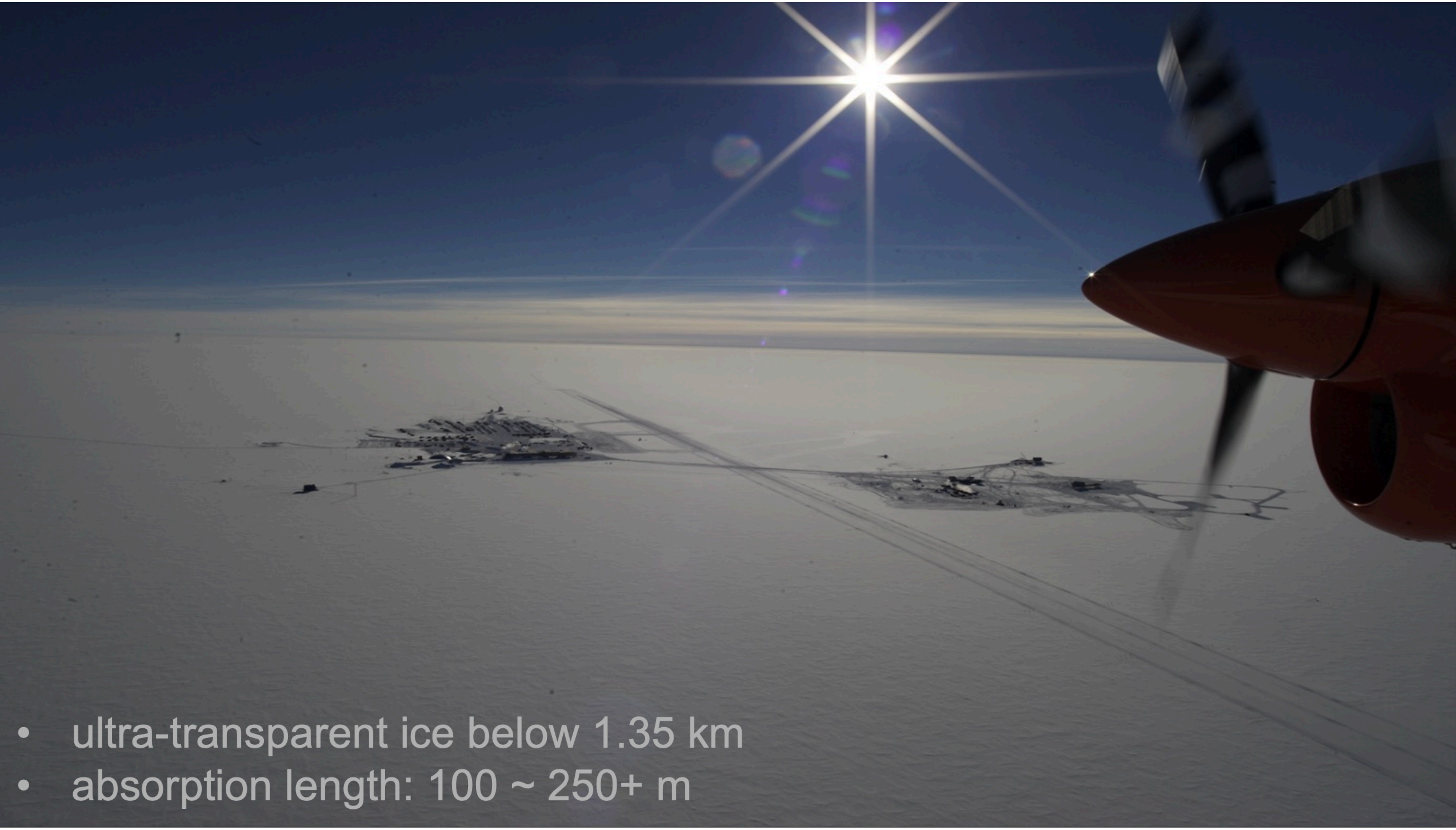
- IceCube


• muon travels from 50 m to 50 km through the water at the speed of light emitting blue light along its track
charged secondary particles produced as the neutrino disappears
Charged Current
ν_l
$l^\pm$
E
$\tilde{E}$
$W^\pm$
N
N
Standard Model
muon
• speed of light in water ~ 3/4 c → shockwave
nuclear interaction
neutrino
• lattice of photomultipliers

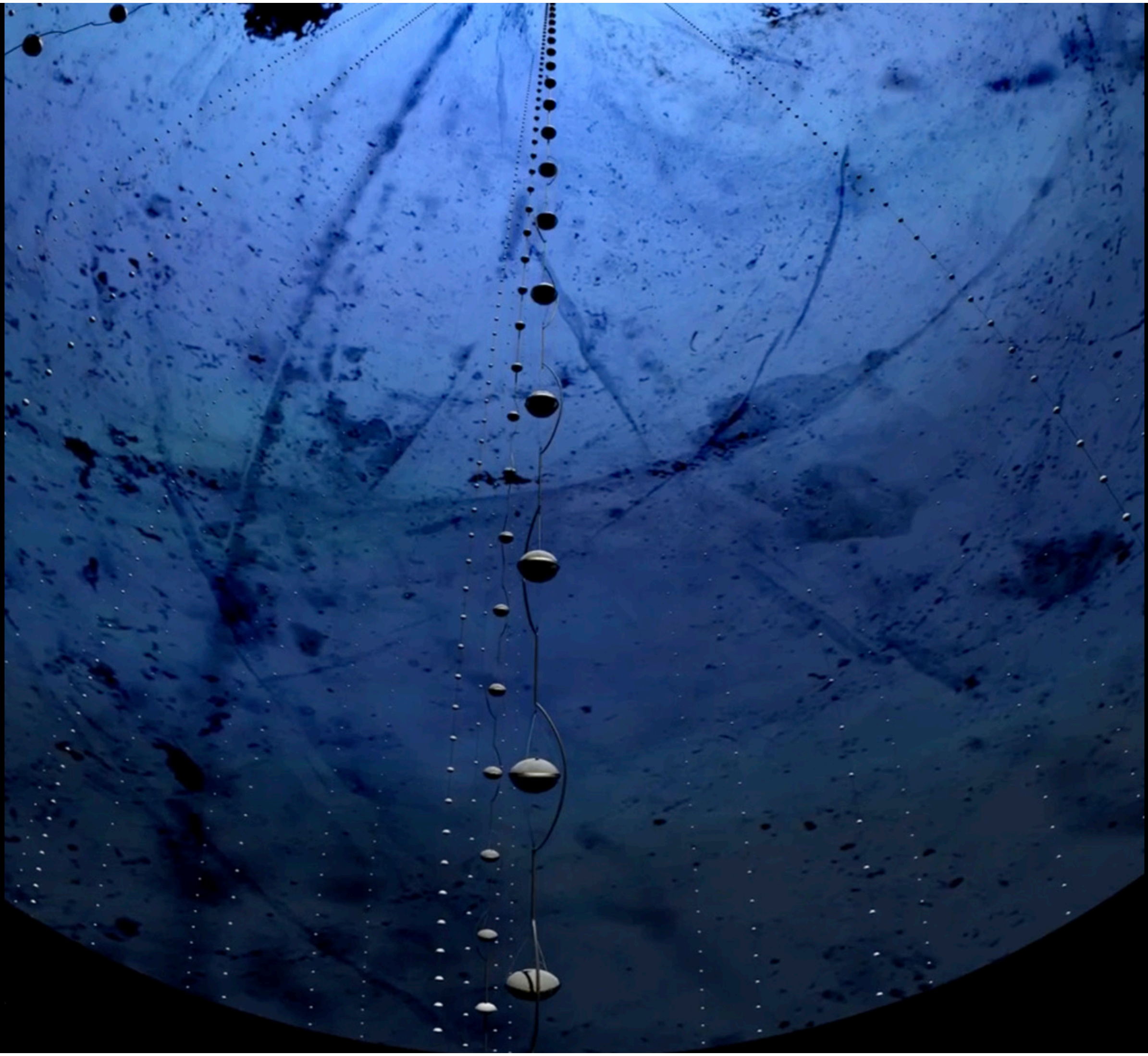
ice 1.4 kilometers below geographic South Pole



- find an optically clear medium shielded from cosmic rays
- map its optical properties
- fill with photomultipliers with spacings ~ absorption length
- add data acquisition and computers

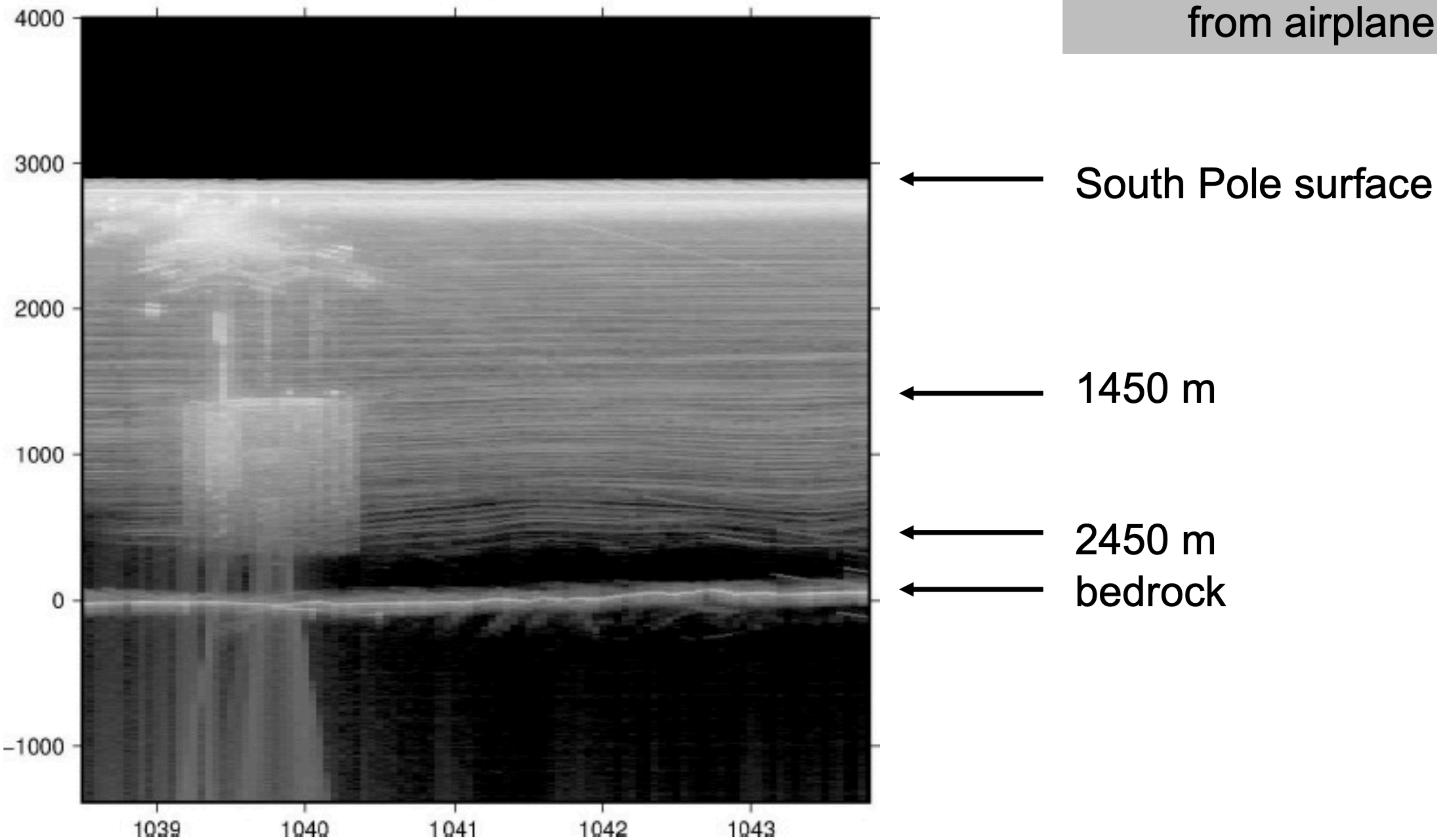

• ultra-transparent ice below 1.35 km
• absorption length: 100 ~ 250+ m

IceCube:
5160 photomultipliers
instrument one km^3 of
Antarctic ice between
1.4 and 2.4 km depth
as a Cherenkov detector



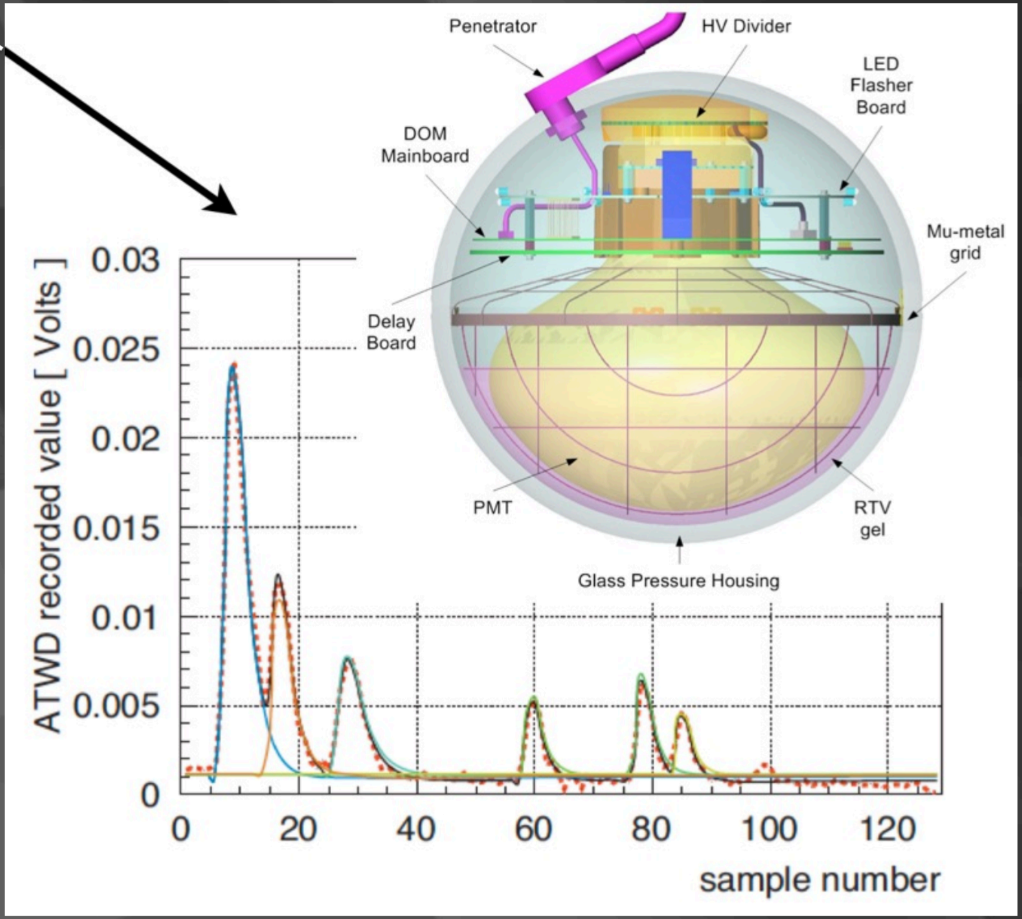
ground-penetrating radar
from airplane

IceCube Array at 60 MHz

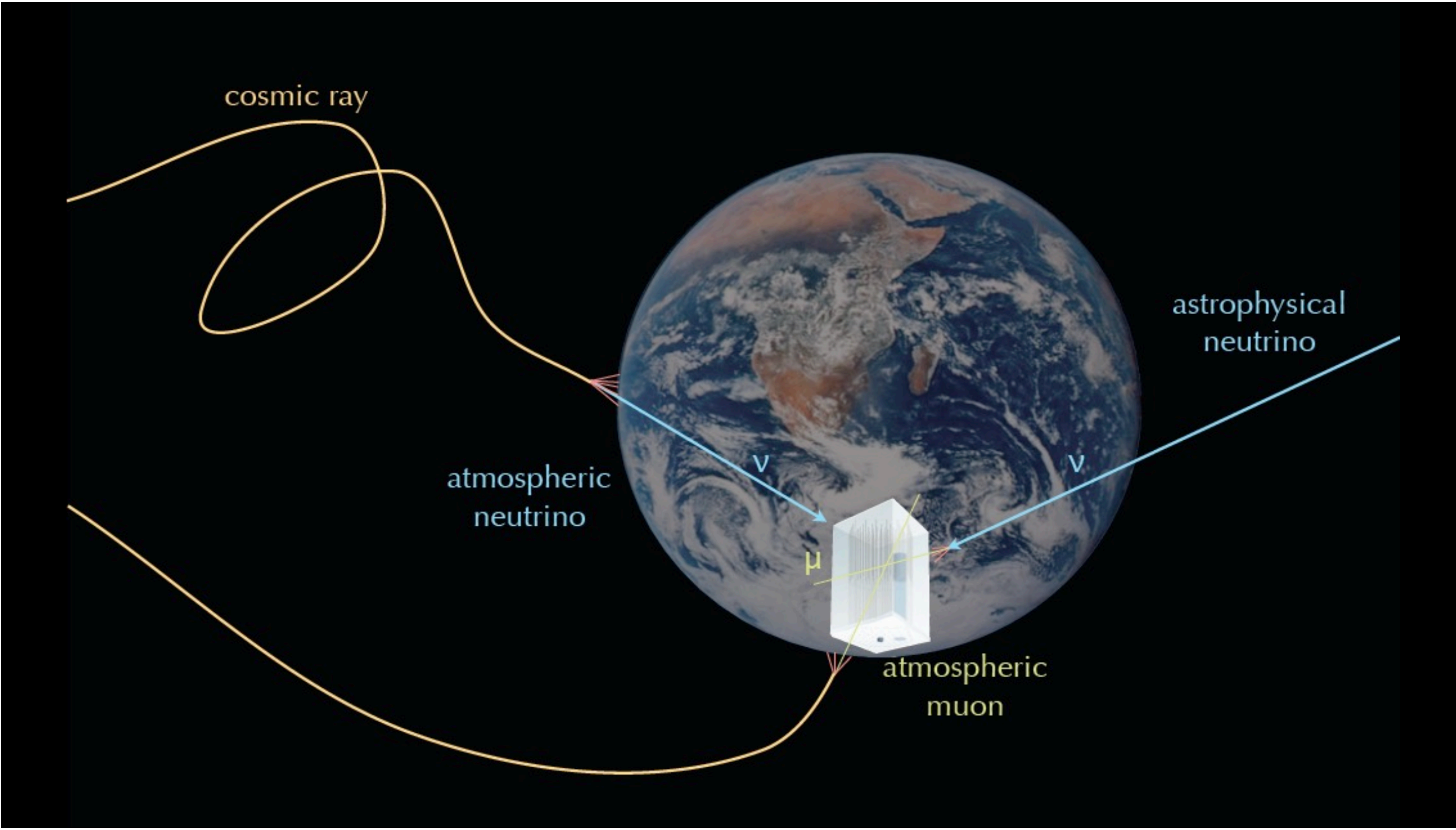


digitized light signals (waveforms)

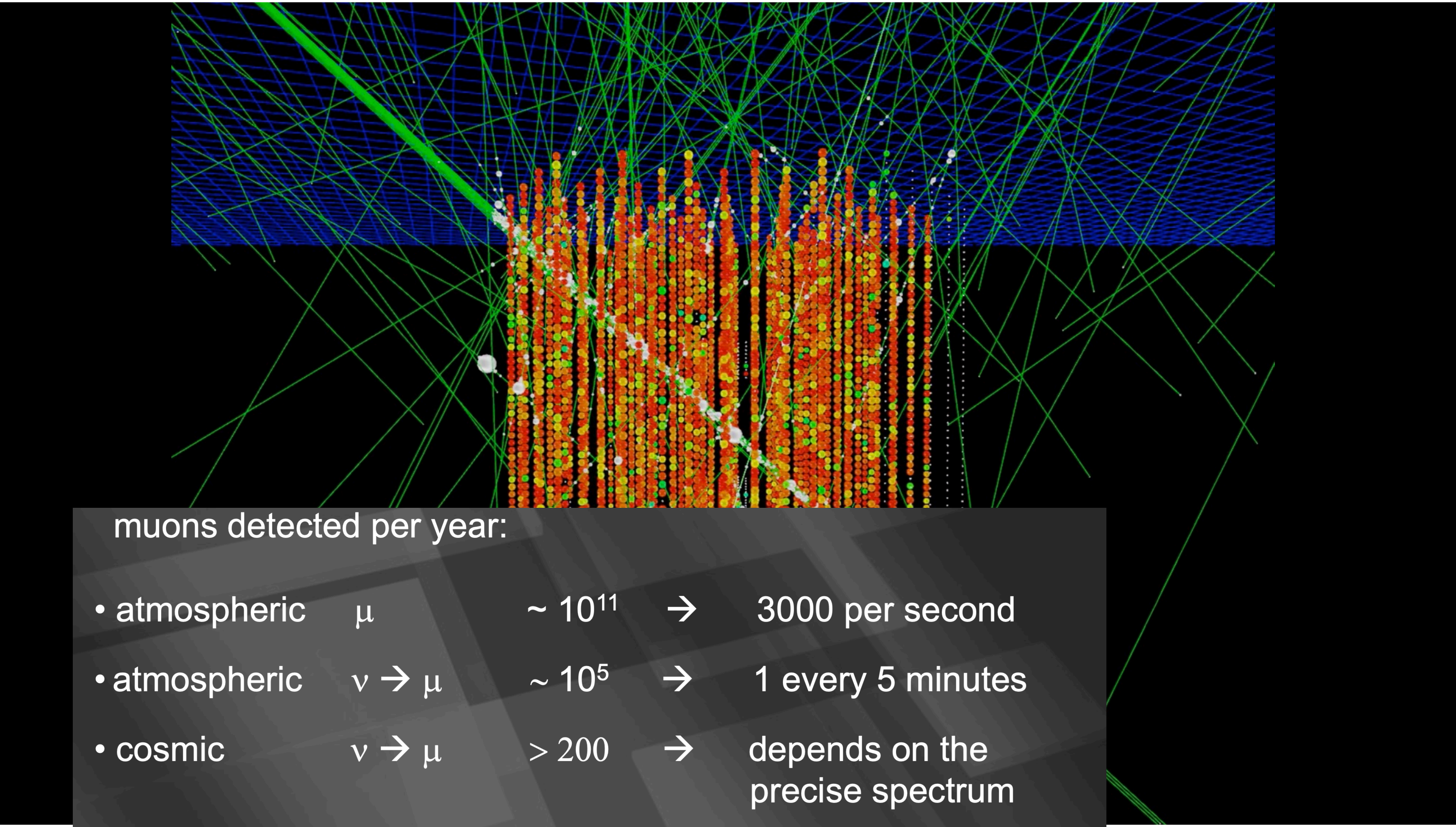
- each Digital Optical Module independently collects light signals like this, digitizes them and
- time stamps them with 2 nanoseconds precision, and sends them to a computer that sorts them in events…



WHAT DOES ICE-CUBE REVEAL?



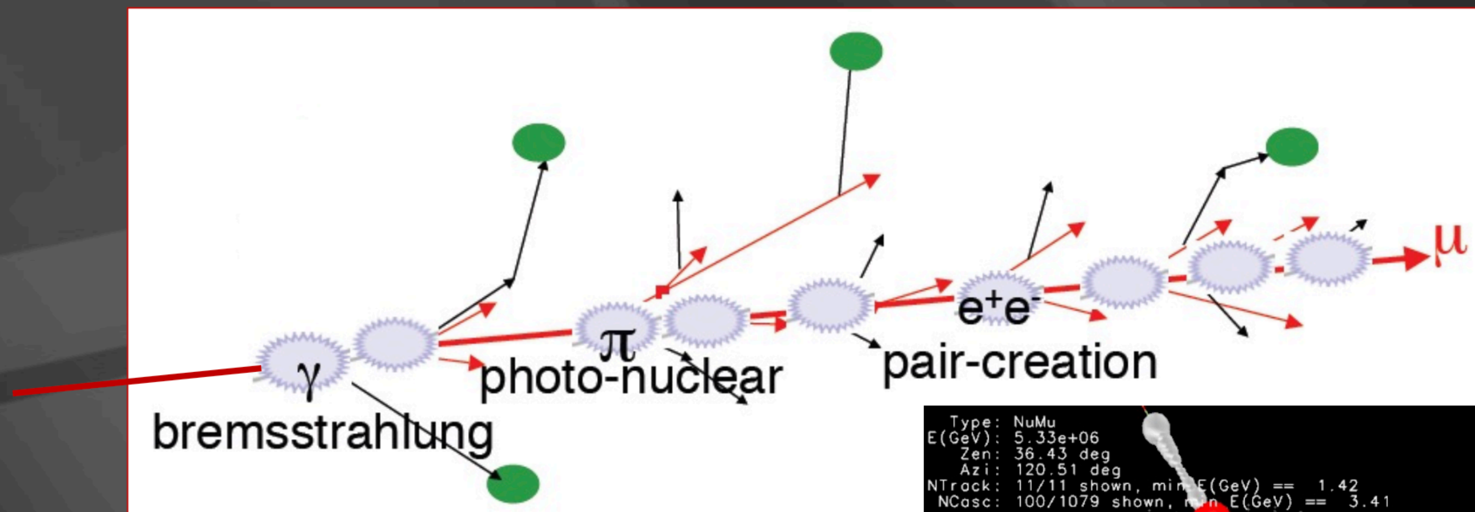
WHAT DOES ICE-CUBE REVEAL?

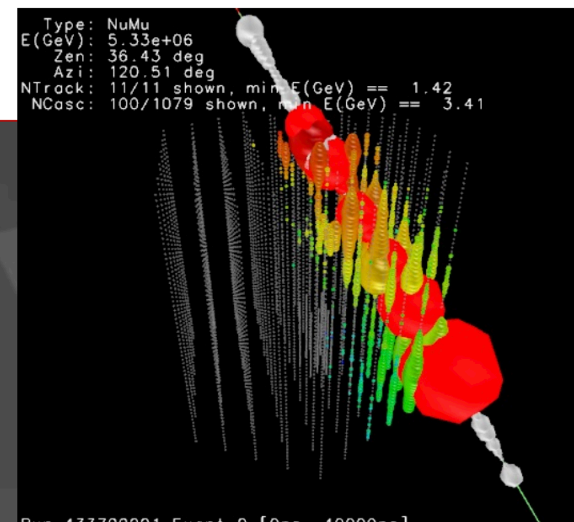


muons detected per year:

• atmospheric	μ	$\sim 10^{11}$	→	3000 per second
• atmospheric	$\nu \rightarrow \mu$	$\sim 10^{5}$	→	1 every 5 minutes
• cosmic	$\nu \rightarrow \mu$	> 200	→	depends on the precise spectrum

energy measurement

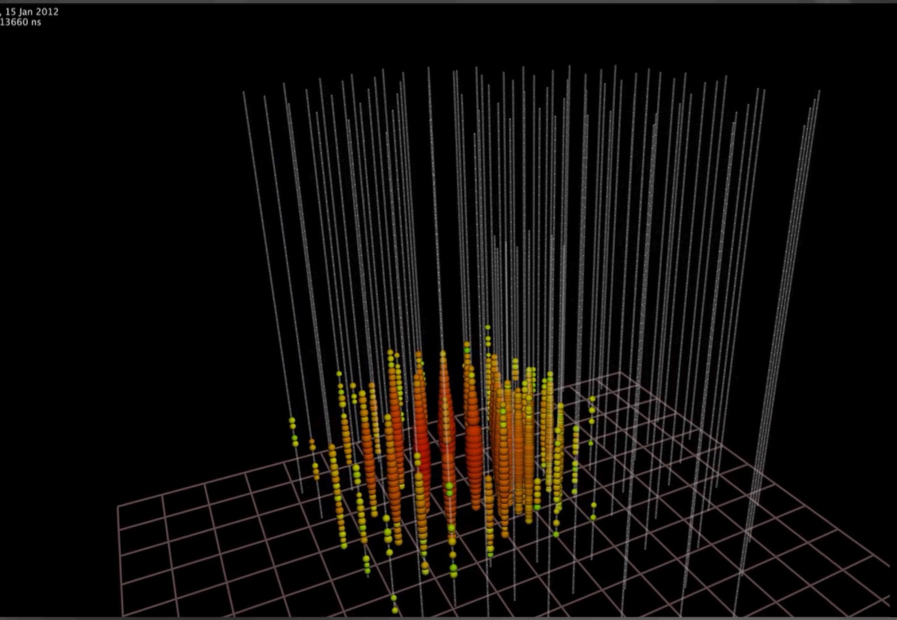


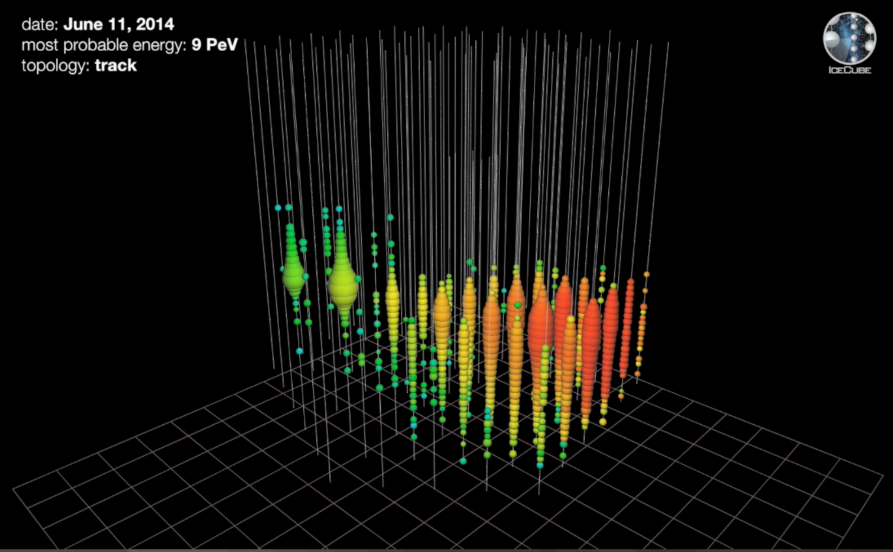


convert the amount of Cherenkov light emitted and its stochasticity to a measurement of the energy muon track

neutrinos interacting
inside the detector

muon neutrinos
filtered by the Earth

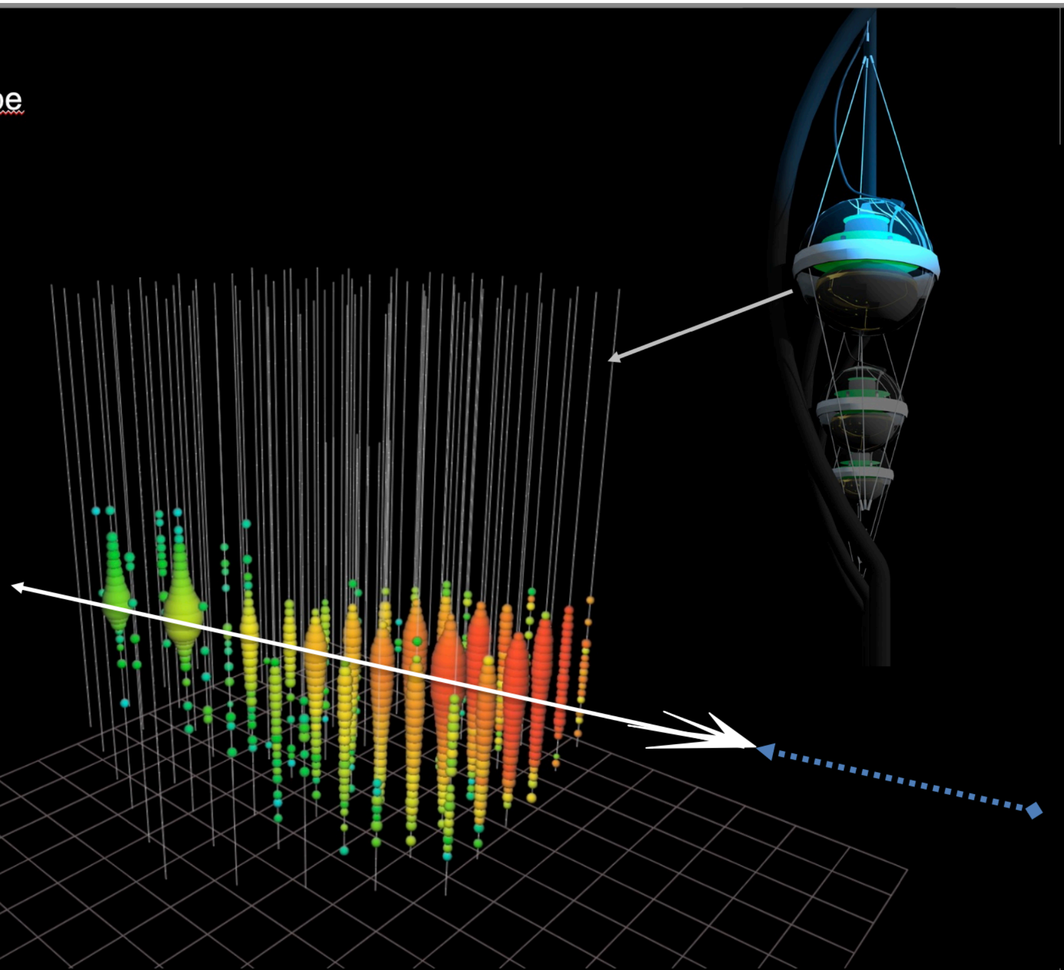




superior total energy
measurement
to 10%, all flavors, all sky

superior angular resolution 0.3°
including systematics

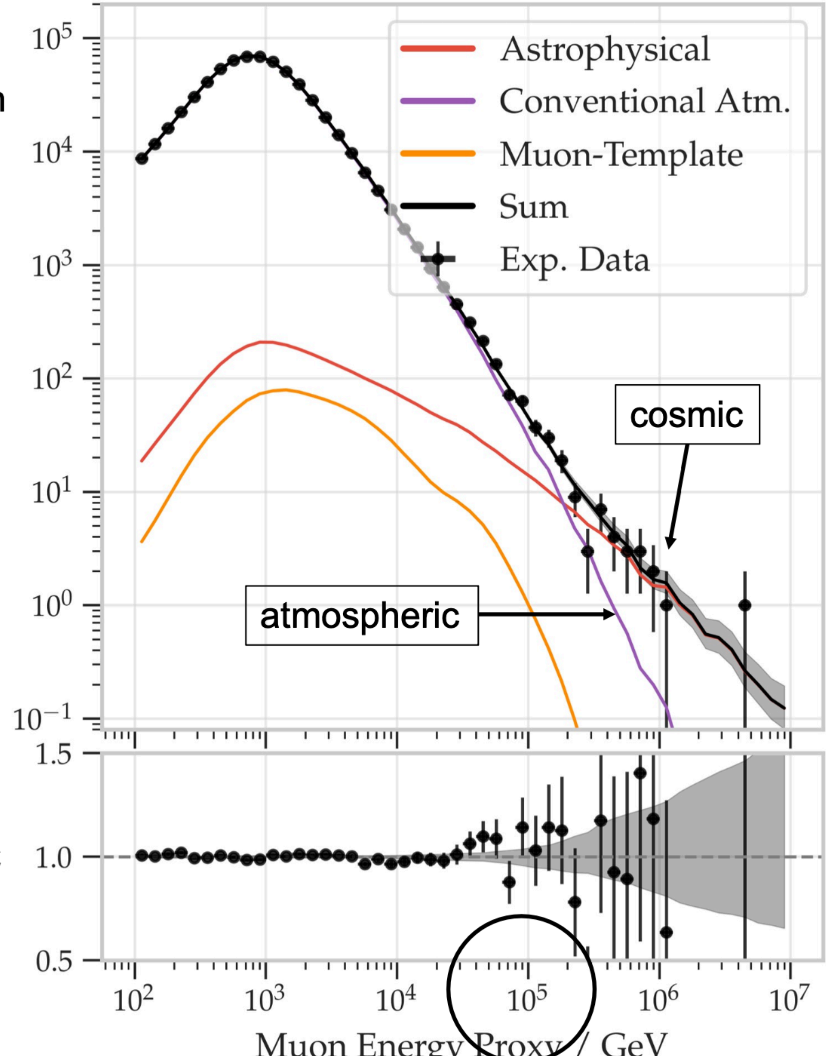
- muon produced by neutrino near IceCube
- comes through the Earth
- 2,600 TeV inside detector
- not atmospheric

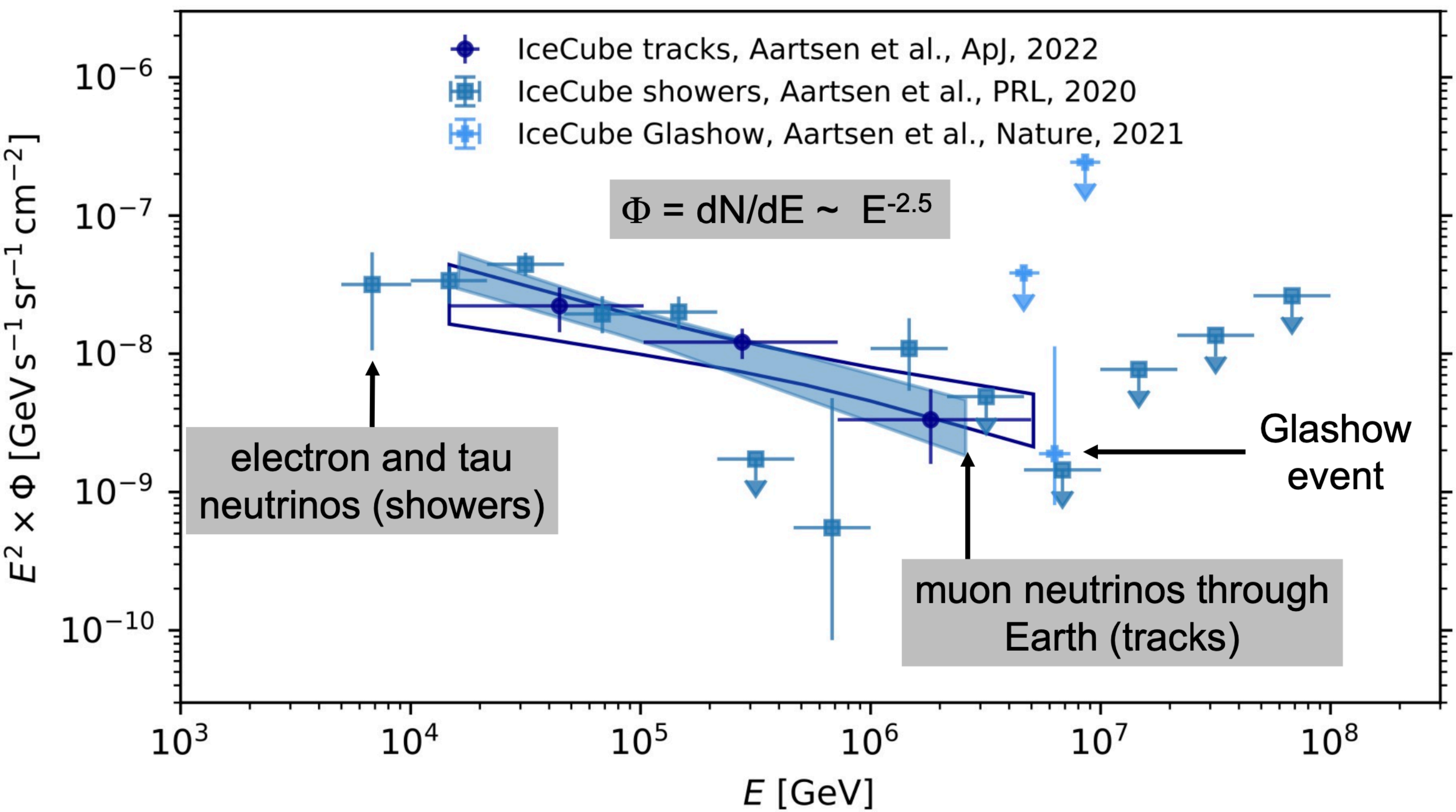


Number of Events per Bin

muon neutrino flux filtered by the Earth: atmospheric vs cosmic

Data/MC



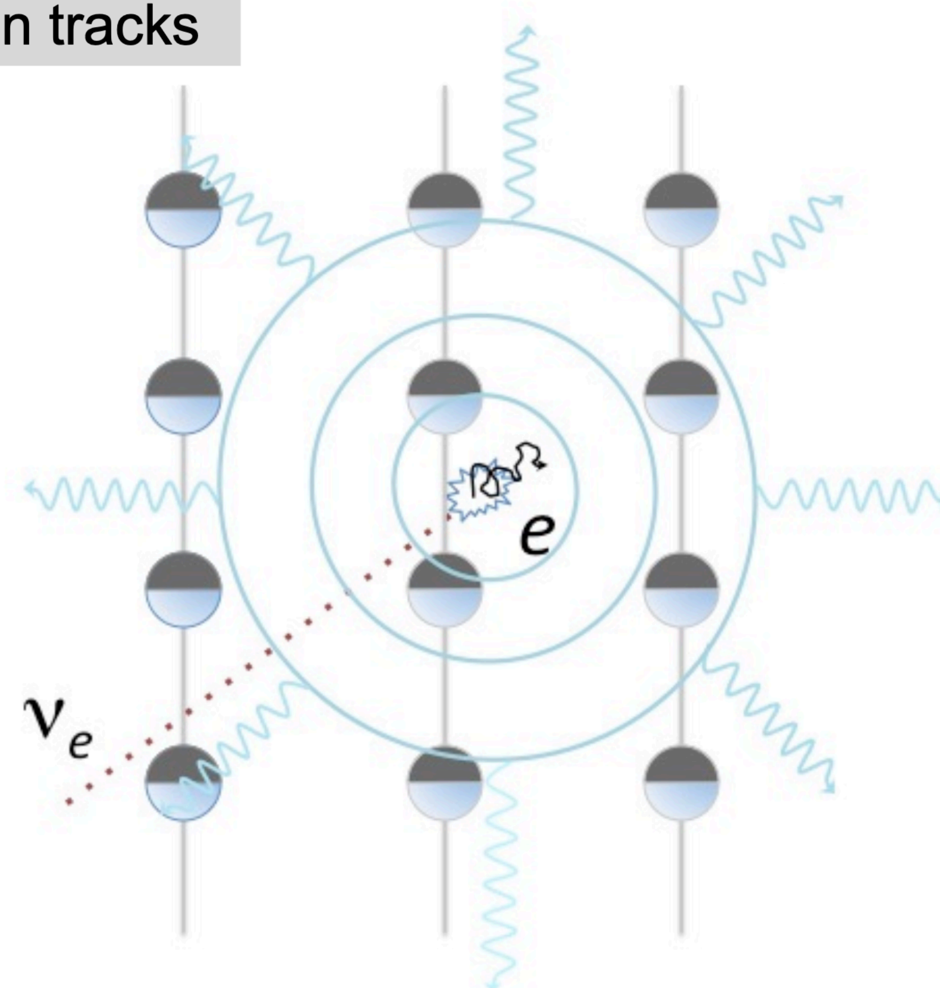


IceCube tracks, Aartsen et al., ApJ, 2022
IceCube showers, Aartsen et al., PRL, 2020
IceCube Glashow, Aartsen et al., Nature, 2021
$\Phi = dN/dE \sim E^{-2.5}$
electron and tau neutrinos (showers)
muon neutrinos through Earth (tracks)
Glashow event
$E^2 \times \Phi$ [GeV s^{-1} sr^{-1} cm^{-2}]
E [GeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^3
10^4
10^5
10^6
10^7
10^8

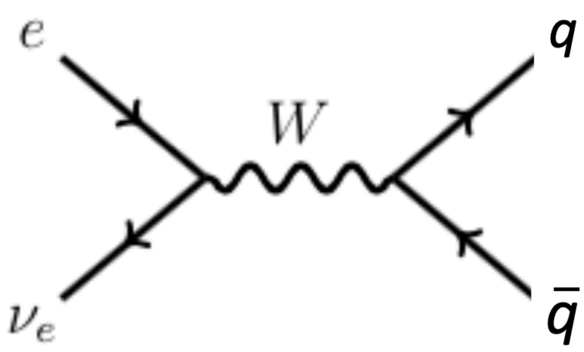
electron showers versus muon tracks

PeV ν_e and ν_τ showers:

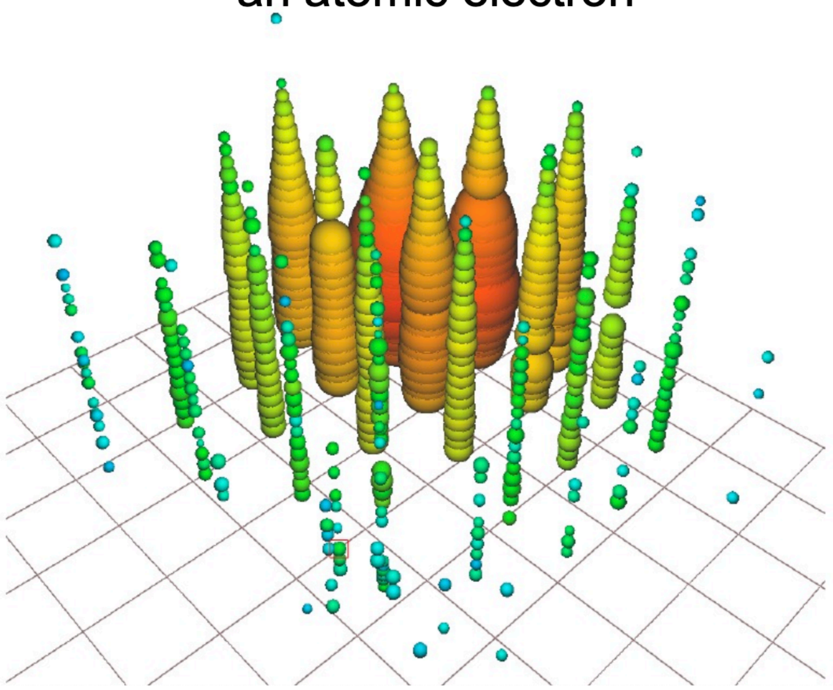
- 10 m long
- volume ~ 5 m^3
- isotropic after 25~50 m



Glashow resonance event with energy 6.3 PeV

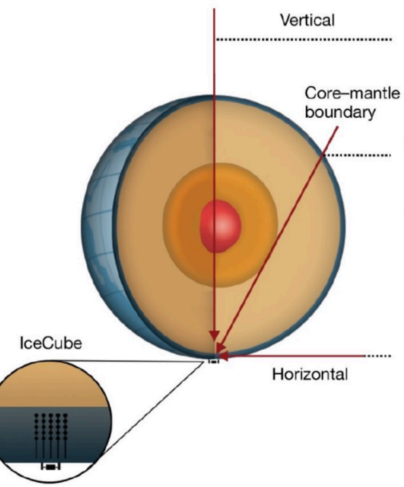


resonant production of a weak intermediate boson by an anti-electron neutrino interacting with an atomic electron

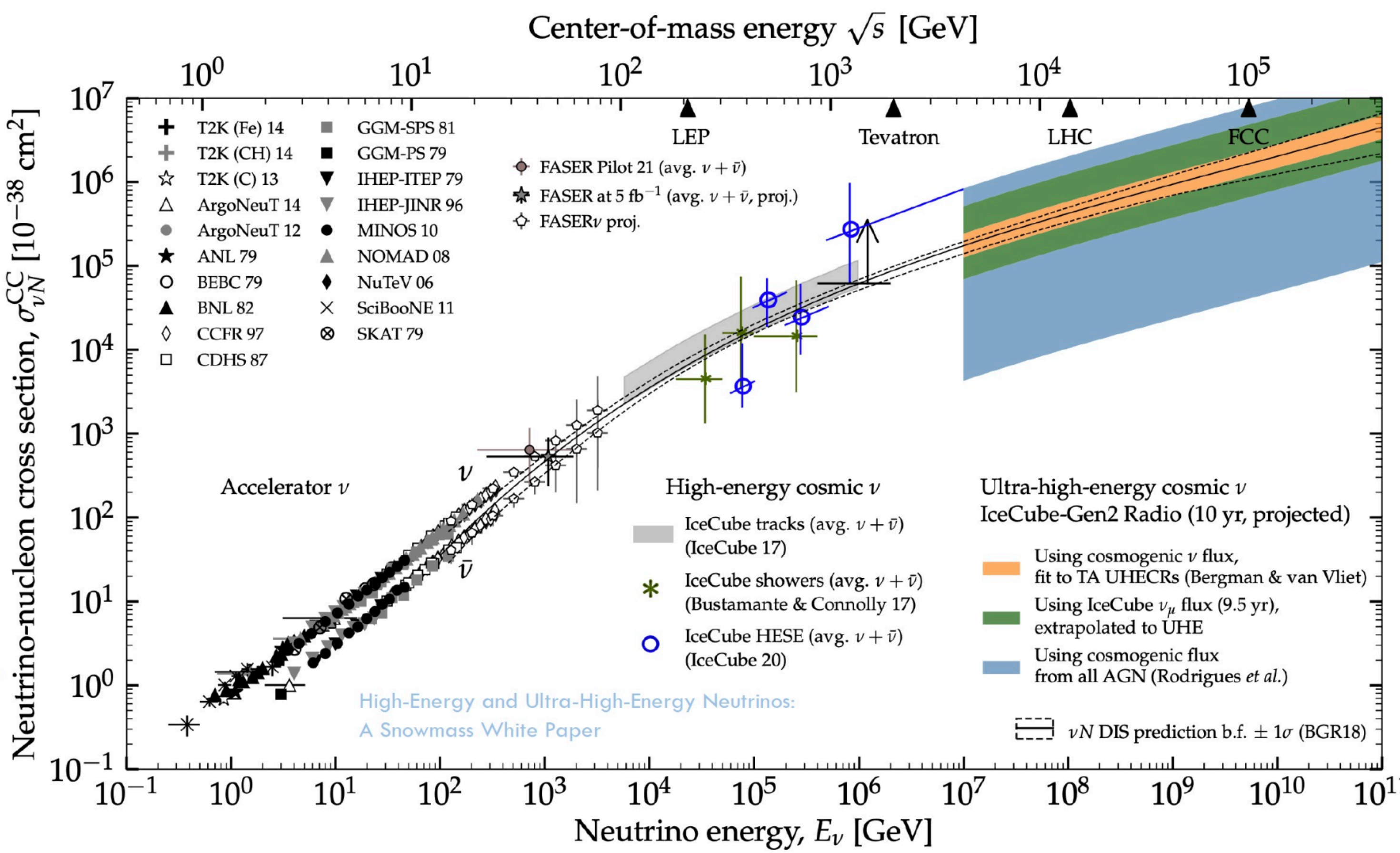


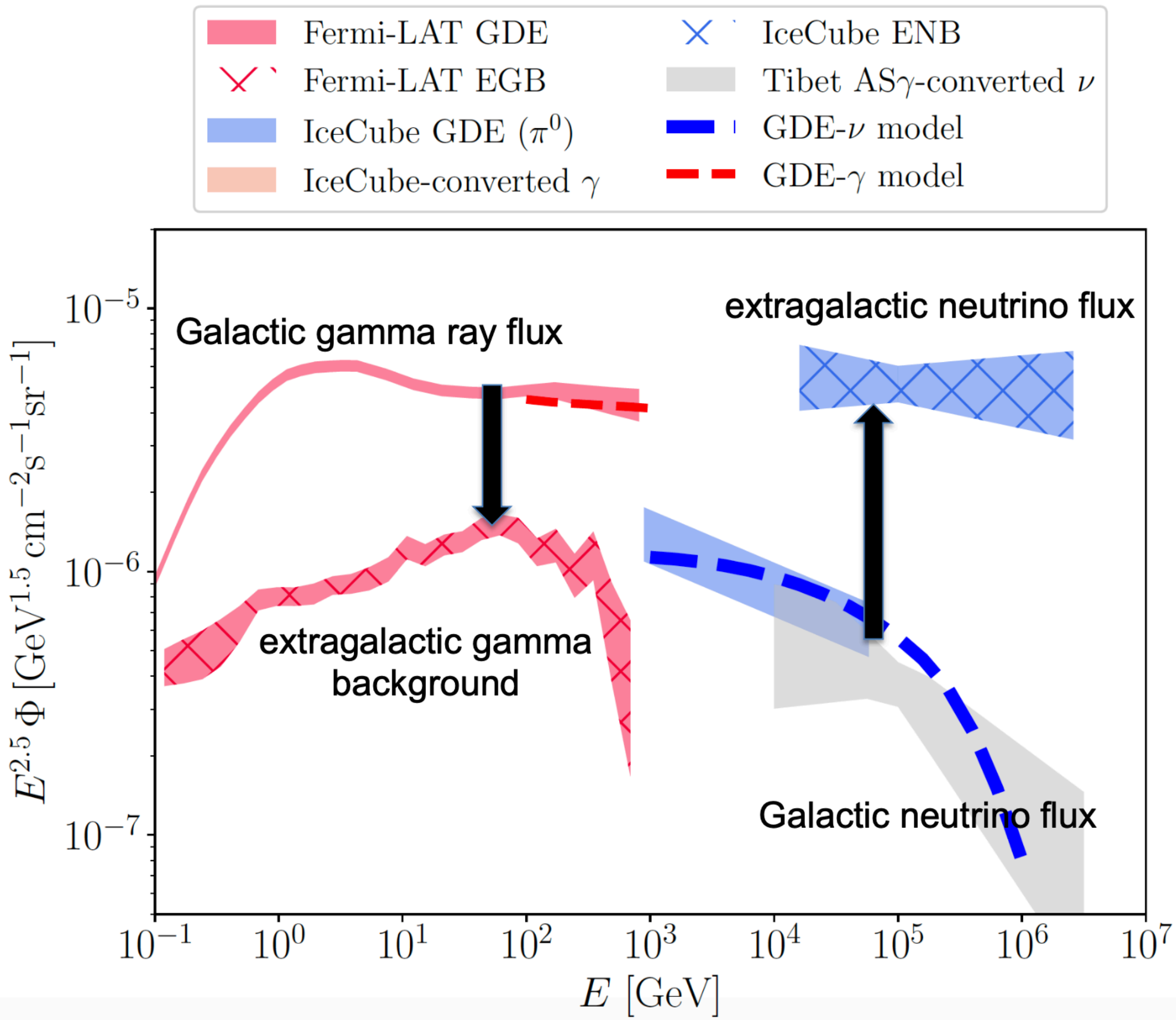
$$E_R = M_W^2/[2m_e] = 6.32\,\mathrm{PeV}$$

CROSS SECTION WITH EARTH AS THE TARGET



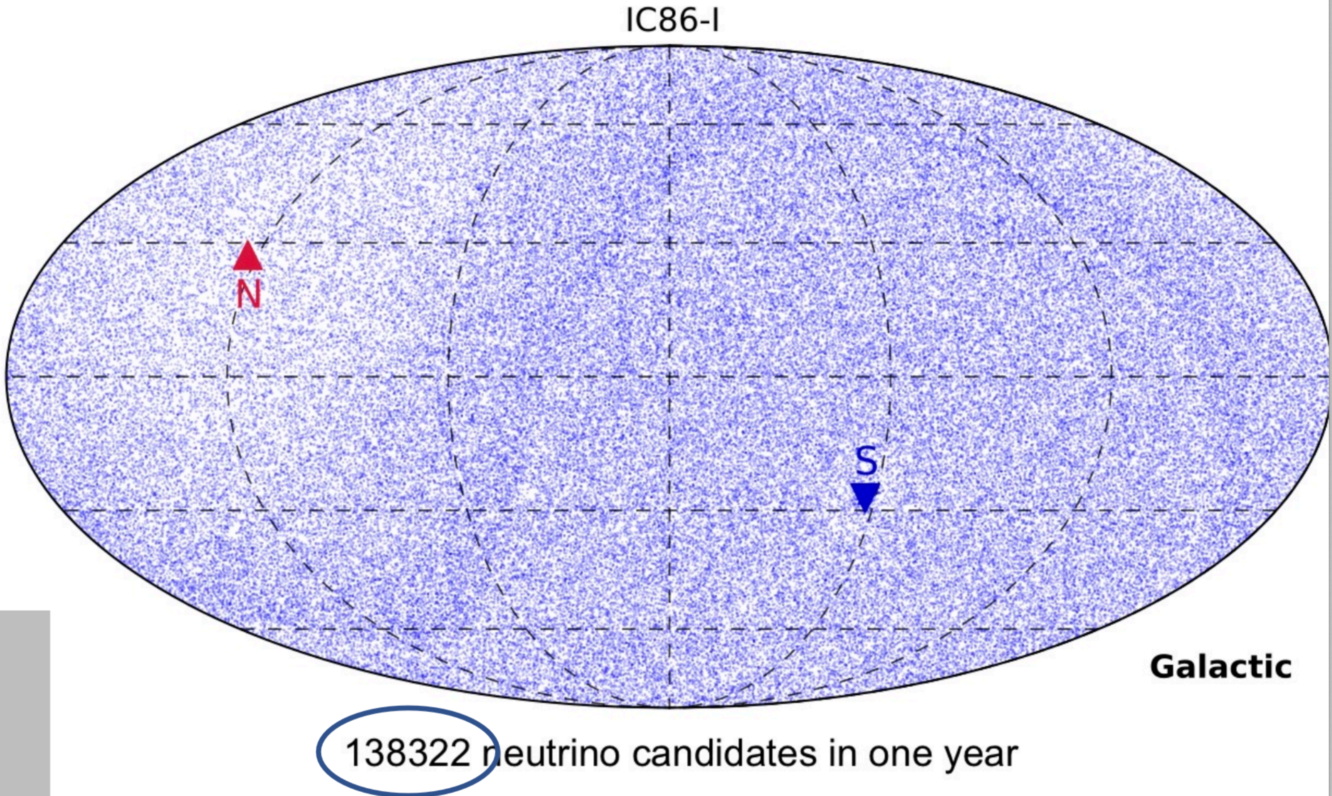
Extending x-section measurements to energies beyond Earth-based accelerators




Fermi-LAT GDE
Fermi-LAT EGB
IceCube GDE (π^0)
IceCube-converted γ
IceCube ENB
Tibet ASγ-converted ν
GDE-ν model
GDE-γ model
Galactic gamma ray flux
extragalactic neutrino flux
extragalactic gamma background
Galactic neutrino flux
$E^{2.5}\,\Phi$ [GeV$^{1.5}$ cm^{-2}s^{-1}sr^{-1}]
10^{-5}
10^{-6}
10^{-7}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
E [GeV]

one year of IceCube neutrinos >100 GeV

(reaches neutrino purity of 97% but overwhelmingly atmospheric)



~ 200 cosmic neutrinos
~12 separated from atmospheric background with E>60 TeV

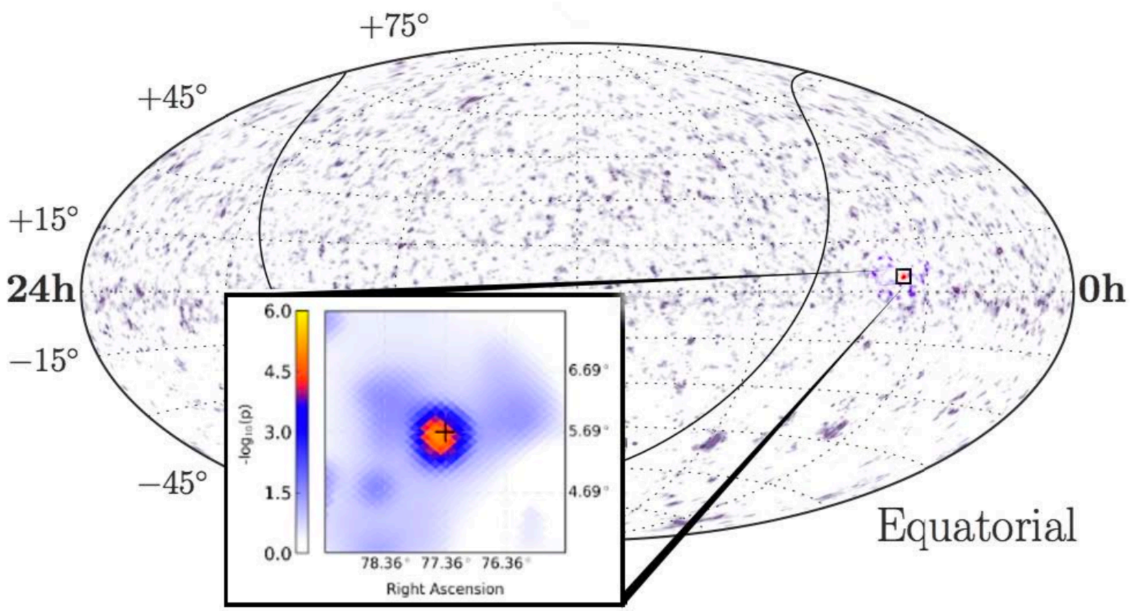
search in the directions of 110 preselected source candidates

Phys.Rev.Lett. 124 (2020)

Source List Results

Name	Class	α [deg]	δ [deg]	$\hat{n}_s$	$\hat{\gamma}$	$-\log_{10}(p_{local})$	$\phi_{90\%}$
PKS 2320-035	FSRQ	350.88	-3.29	4.8	3.6	0.45	3.3
3C 454.3	FSRQ	343.50	16.15	5.4	2.2	0.62	5.1
TX[illegible]	FSRQ	[illegible]	[illegible]	[illegible]	3.8	0.42	5.6
RGB J2243+203	BLL	340.99	20.36	0.0	3.0	0.33	3.1
CTA 102	FSRQ	338.15	11.73	0.0	[illegible]	[illegible]	2.8
BL Lac	BLL	330.69	42.28	0.0	[illegible]	[illegible]	[illegible]
OX 169	FSRQ	325.89	17.73	2.0	1.7	0.69	5.1
B2 2114+33	BLL	319.06	33.66	0.0	3.0	0.30	3.9
PKS 2032+107	FSRQ	308.85	10.94	0.0	2.4	0.33	3.2
2HWC J2031+415	GAL	307.93	41.51	13.4	3.8	0.97	9.2
Gamma Cygni	GAL	305.56	40.26	7.4	3.7	0.59	6.9
MGRO J2019+37	GAL	304.85	36.80	0.0	3.1	0.33	4.0
MG2 J201534+3710	FSRQ	303.92	37.19	4.4	4.0	0.40	5.6
MG4 J200112+4352	BLL	300.30	43.89	6.1	2.3	0.67	7.8
1ES 1959+650	BLL	300.01	65.15	12.6	3.3	0.77	12.3
1RXS J194246.3+1	BLL	295.70	10.56	0.0	2.7	0.33	2.6
RX J1931.1+0937	BLL	292.78	9.63	0.0	2.9	0.29	2.8
NVSS J190836-012	UNIDB	287.20	-1.53	0.0	2.9	0.22	2.3
MGRO J1908+06	GAL	287.17	6.18	4.2	2.0	1.42	5.7
TXS 1902+556	BLL	285.80	55.68	11.7	4.0	0.85	9.9
HESS J1857+026	GAL	284.30	2.67	7.4	3.1	0.53	3.5
GRS 1285.0	UNIDB	283.15	0.69	1.7	3.8	0.27	2.3
HESS J1852-000	GAL	283.00	0.00	3.3	3.7	0.38	2.6
HESS J1849-000	GAL	282.26	-0.02	0.0	3.0	0.28	2.2
HESS J1843-033	GAL	280.75	-3.30	0.0	2.8	0.31	2.5
OT 081	BLL	267.87	9.65	12.2	3.2	0.73	4.8
S4 1749+70	BLL	267.15	70.10	0.0	2.5	0.37	8.0
1H 1720+117	BLL	261.27	11.88	0.0	2.7	0.30	3.2
PKS 1717+177	BLL	259.81	17.75	19.8	3.6	1.32	7.3
Mkn 501	BLL	253.47	39.76	10.3	4.0	0.61	7.3
4C +38.41	FSRQ	248.82	38.14	4.2	2.3	0.66	7.0
PG 1553+113	BLL	238.93	11.19	0.0	2.8	0.32	3.2
GB6 J1542+6129	**BLL**	**235.75**	**61.50**	**29.7**	**3.0**	**2.74**	**22.0**
B2 1520+31	FSRQ	230.55	31.74	7.1	2.4	0.83	7.3
PKS 1502+036	AGN	226.26	3.44	0.0	2.7	0.28	2.9
PKS 1502+106	FSRQ	226.10	10.50	0.0	3.0	0.33	2.6
PKS 1441+25	FSRQ	220.99	25.03	7.5	2.4	0.94	7.3
PKS 1424+240	**BLL**	**216.76**	**23.80**	**41.5**	**3.9**	**2.80**	**12.3**
NVSS J141826-023	BLL	214.61	-2.56	0.0	3.0	0.25	2.0
B3 1343+451	FSRQ	206.40	44.88	0.0	2.8	0.32	5.0
S4 1250+53	BLL	193.31	53.02	2.2	2.5	0.39	5.9
PG 1246+586	BLL	192.08	58.34	0.0	2.8	0.35	6.4
MG1 J123931+0443	FSRQ	189.89	4.73	0.0	2.6	0.28	2.4
M 87	AGN	187.71	12.39	0.0	2.8	0.29	3.1
ON 246	BLL	187.56	25.30	0.9	1.7	0.37	4.2
3C 273	FSRQ	187.27	2.04	0.0	3.0	0.28	1.9
4C +21.35	FSRQ	186.23	21.38	0.0	2.6	0.32	3.5
W Comae	BLL	185.38	28.24	0.0	3.0	0.32	3.7
PG 1218+304	BLL	185.34	30.17	11.1	3.9	0.70	6.7
PKS 1216-010	BLL	184.64	-1.33	6.9	4.0	0.45	3.1
B2 1215+30	BLL	184.48	30.12	18.6	3.4	1.09	8.5
PKS B1130+008	BLL	173.20	0.58	15.8	4.0	0.96	4.4
Mkn 421	BLL	166.12	38.21	2.1	1.9	0.38	5.3
4C +01.28	BLL	164.61	1.56	0.0	2.9	0.26	2.4
1H 1013+498	BLL	153.77	49.43	0.0	[illegible]	0.29	4.5
[illegible]	FSRQ	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	10.6
M 82	SBG	148.95	69.67	0.0	2.6	0.36	8.8
PMN J0948+0022	AGN	147.24	0.37	9.3	4.0	0.76	3.9
OJ 287	BLL	133.71	20.12	0.0	2.6	0.32	3.5
PKS 0829+046	BLL	127.97	4.49	0.0	2.9	0.28	2.1
S4 0814+42	BLL	124.56	42.38	0.0	2.3	0.30	4.9
OJ 014	BLL	122.87	1.78	16.1	4.0	0.99	4.4
1ES 0806+524	BLL	122.46	52.31	0.0	2.8	0.31	4.7
PKS 0736+01	FSRQ	114.82	1.62	0.0	2.8	0.26	2.4
PKS 0735+17	BLL	114.54	17.71	0.0	2.8	0.30	3.5
4C +14.23	FSRQ	111.33	14.42	8.5	2.9	0.60	4.8
S5 0716+71	BLL	110.49	71.34	0.0	2.5	0.38	7.4
PSR B0656+14	GAL	104.95	14.24	8.4	4.0	0.51	4.4
1ES 0647+250	BLL	102.70	25.06	0.0	2.9	0.27	3.0
B3 0609+413	BLL	93.22	41.37	1.8	1.7	0.42	5.3
Crab nebula	GAL	83.63	22.01	1.1	2.2	0.31	3.7
OG +050	FSRQ	83.18	7.55	0.0	3.2	0.28	2.9
TXS 0518+211	BLL	80.44	21.21	15.7	3.8	0.92	6.6
TXS 0506+056	**BLL**	**77.35**	**5.70**	**12.3**	**2.1**	**3.72**	**10.1**
PKS 0502+049	FSRQ	76.34	5.00	11.2	3.0	0.66	4.1
S3 0458-02	FSRQ	75.30	-1.97	5.5	4.0	0.33	2.7
PKS 0440-00	FSRQ	70.66	-0.29	7.6	3.9	0.46	3.1
MG2 J043337+2905	BLL	68.41	29.10	0.0	2.7	0.28	4.5
PKS 0422+00	BLL	66.19	0.60	0.0	2.9	0.27	2.3
PKS 0420-01	FSRQ	65.83	-1.33	9.3	4.0	0.52	3.4
PKS 0336-01	FSRQ	54.88	-1.77	15.5	4.0	0.99	4.4
NGC 1275	AGN	49.96	41.51	3.6	3.1	0.41	5.5
NGC 1068	**SBG**	**40.67**	**-0.01**	**50.4**	**3.2**	**4.74**	**10.5**
PKS 0235+164	BLL	39.67	16.62	0.0	3.0	0.28	3.1
4C +28.07	FSRQ	39.48	28.80	0.0	2.8	0.30	3.6
3C 66A	BLL	35.67	43.04	0.0	2.8	0.30	3.9
B2 0218+357	FSRQ	35.28	35.94	0.0	3.1	0.33	4.3
PKS 0215+015	FSRQ	34.46	1.74	0.0	3.2	0.27	2.3
MG1 J021114+1051	BLL	32.81	10.86	1.6	1.7	0.43	3.5
TXS 0141+268	BLL	26.15	27.09	0.0	2.5	0.31	3.5
B3 0133+388	BLL	24.14	39.10	0.0	2.6	0.28	4.1
NGC 598	SBG	23.52	30.62	11.4	4.0	0.63	6.3
S2 0109+22	BLL	18.03	22.75	2.0	3.1	0.30	3.7
4C +01.02	FSRQ	17.16	1.59	0.0	3.0	0.26	2.4
M 31	SBG	10.82	41.24	11.0	4.0	1.09	9.6
PKS 0019+058	BLL	5.64	6.14	0.0	2.9	0.29	2.4
PKS 2233-148	BLL	339.14	-14.56	5.3	2.8	1.26	21.4
HESS J1841-055	GAL	280.23	-5.55	3.6	4.0	0.55	4.8
HESS J1837-069	GAL	279.43	-6.93	0.0	2.8	0.30	4.0
PKS 1510-089	FSRQ	228.21	-9.10	0.1	1.7	0.41	7.1
PKS 1329-049	FSRQ	203.02	-5.16	6.1	2.7	0.77	5.1
NGC 4945	SBG	196.36	-49.47	0.3	2.6	0.31	50.2
3C 279	FSRQ	194.04	-5.79	0.3	2.4	0.20	2.7
PKS 0805-07	FSRQ	122.07	-7.86	0.0	2.7	0.31	4.7
PKS 0727-11	FSRQ	112.58	-11.69	1.9	3.5	0.59	11.4
LMC	SBG	80.00	-68.75	0.0	3.1	0.36	41.1
SMC	SBG	14.50	-72.75	0.0	2.4	0.37	44.1
PKS 0048-09	BLL	12.68	-9.49	3.9	3.3	0.87	10.0

pre-trial p-value for clustering of high energy neutrinos

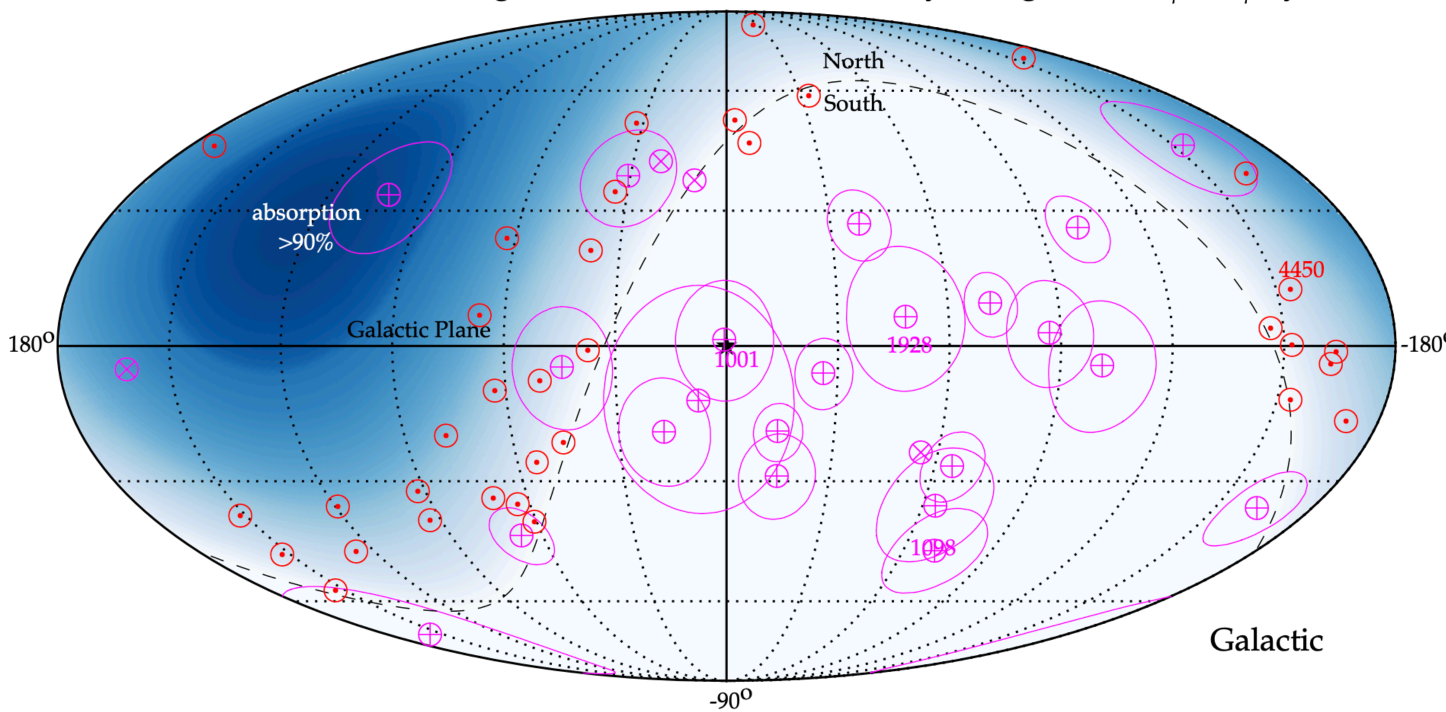


- hottest spot coincident with NGC 1068
- also hottest spot in the sources list (2.9σ)

statistical fluctuations or neutrino sources?

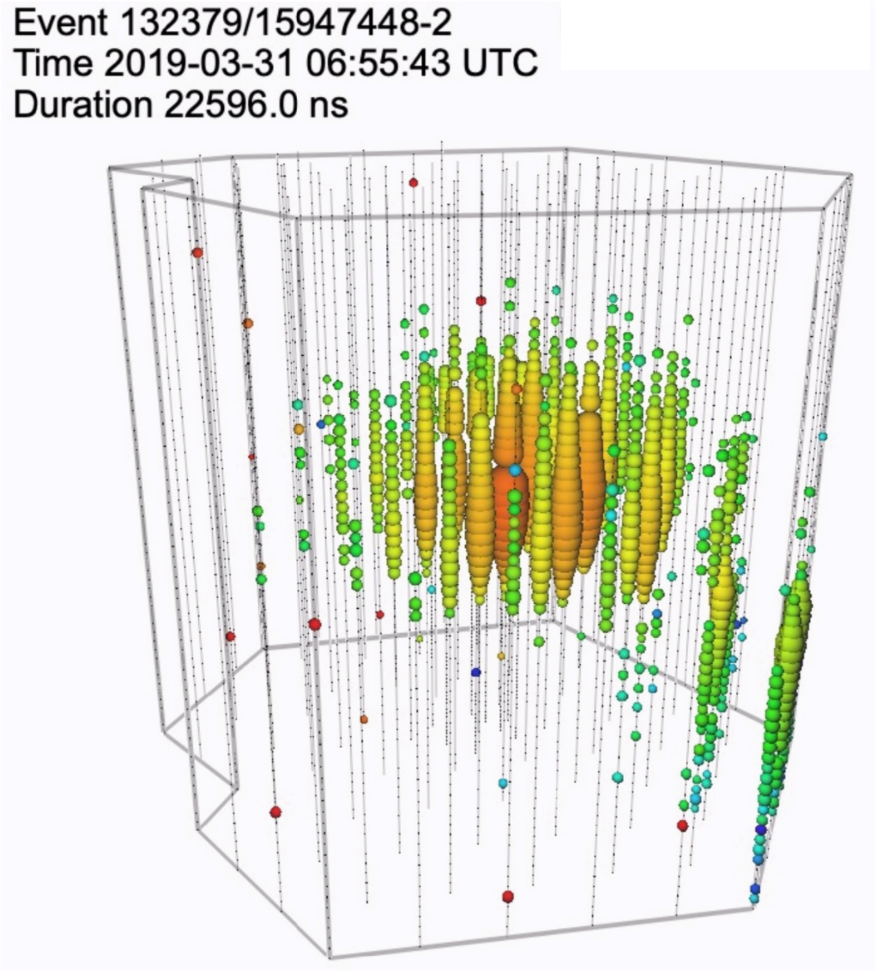
neutrinos with probable cosmic origin:
are they correlated to astronomical sources?

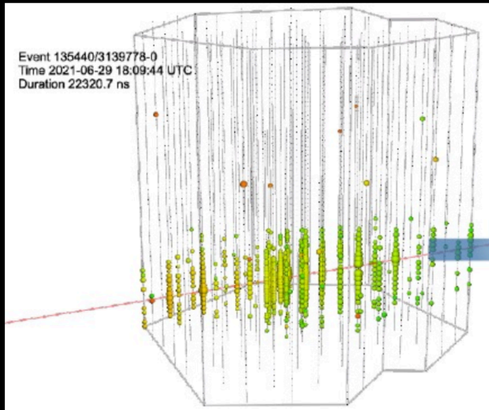
Arrival directions of most energetic neutrino events (HESE 6yr (magenta) & $\nu_\mu + \overline{\nu}_\mu$ 8yr (red))



THE HIGHEST ENERGY NEUTRINO

- Muon neutrino with contained vertex position
- Deposited energy 4.8 PeV
- dE/dx ~ 1.125 TeV/m over last 400m
- Resimulation: **neutrino energy 11.4 +-2.5 PeV**





HIGH-ENERGY EVENTS NOW PUBLIC ALERTS!

We send our high-energy events in real-time as public GCN alerts now!

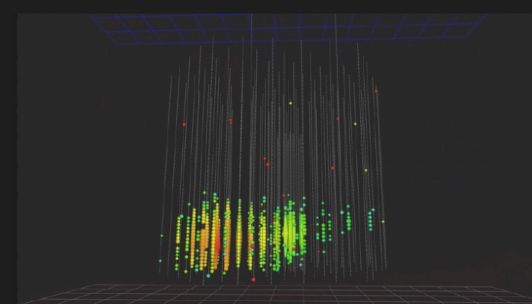
47

from light in the ice to astronomer in less than one minute

TITLE:	GCN/AMON NOTICE
NOTICE_DATE:	Wed 27 Apr 16 23:24:24 UT
NOTICE_TYPE:	AMON ICECUBE HESE
RUN_NUM:	127853
EVENT_NUM:	67093193
SRC_RA:	240.5683d {+16h 02m 16s} (J2000), 240.7644d {+16h 03m 03s} (current), 239.9678d {+15h 59m 52s} (1950)
SRC_DEC:	+9.3417d {+09d 20' 30"} (J2000), +9.2972d {+09d 17' 50"} (current), +9.4798d {+09d 28' 47"} (1950)
SRC_ERROR:	35.99 [arcmin radius, stat+sys, 90% containment]
SRC_ERROR50:	0.00 [arcmin radius, stat+sys, 50% containment]
DISCOVERY_DATE:	17505 TJD; 118 DOY; 16/04/27 (yy/mm/dd)
DISCOVERY_TIME:	21152 SOD {05:52:32.00} UT
REVISION:	2
N_EVENTS:	1 [number of neutrinos]
STREAM:	1
DELTA_T:	0.0000 [sec]
SIGMA_T:	0.0000 [sec]
FALSE_POS:	0.0000e+00 [s^-1 sr^-1]
PVALUE:	0.0000e+00 [dn]
CHARGE:	18883.62 [pe]
SIGNAL_TRACKNESS:	0.92 [dn]
SUN_POSTN:	35.75d {+02h 23m 00s} +14.21d {+14d 12' 45"}

GCN notice for starting track sent Apr 27

We send **rough reconstructions first** and then **update them**.



- KM3NET

Credits:
R. Coniglione

KM3NeT is a Mediterranean research infrastructure hosting two neutrino detectors and instrumentations for earth and sea sciences

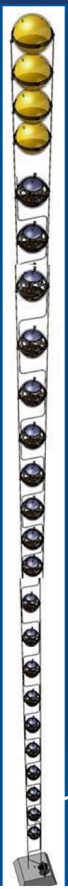
- KM3NeT/ARCA (Astroparticle Research with Cosmics in the Abyss)
  - observation of high energy (GeV ÷ PeV) neutrino sources 👉 a telescope offshore Capo Passero (Sicily-Italy) is in construction at a depth of 3500m
- KM3NeT/ORCA (Oscillation Research with Cosmics in the Abyss)
  - determination of the neutrino mass hierarchy 👉 a detector offshore Toulon (France) able to detect neutrinos of tens of GeV is in construction at a depth of 2500m

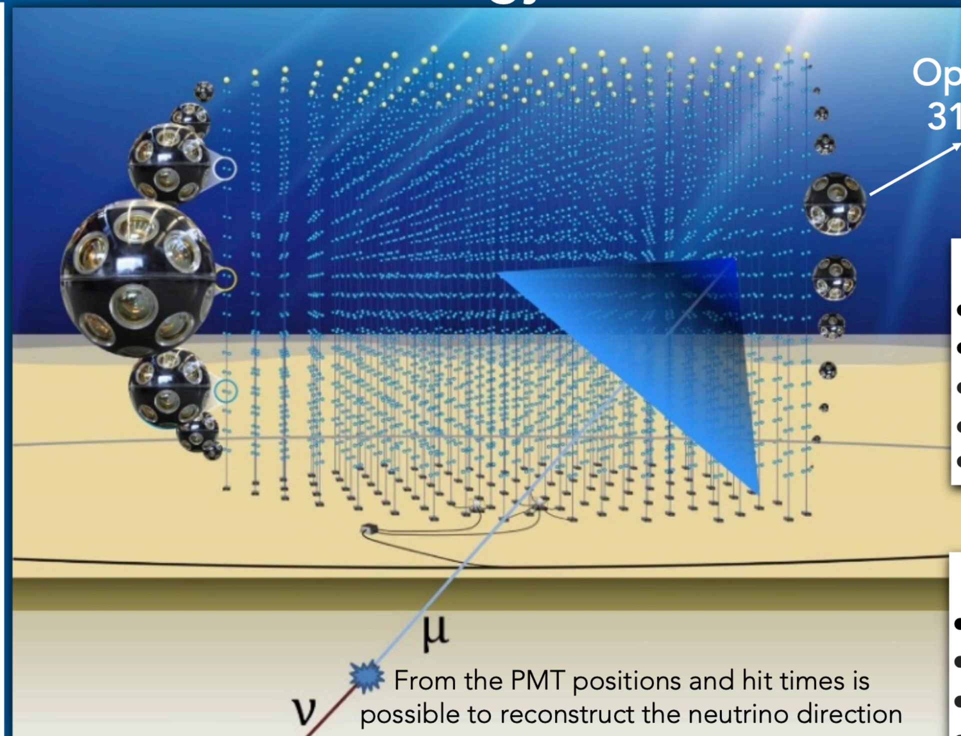
1 collaboration 1 technology 👉 2 detectors

THE KM3NET DETECTORS

3

Same technology for the two detectors



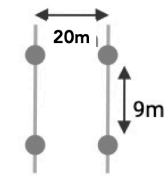


Optical sensor (DOM)
31 PMTs of 3 inches

Detection Unit (DU)

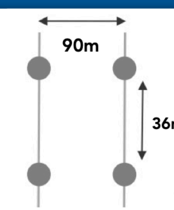
ORCA

- Depth ~2500 m
- One block of 115 Detection Units
- Distance between Detection Units ~20 m
- Vertical distance between DOMs ~9 m
- **≈8 Mton**



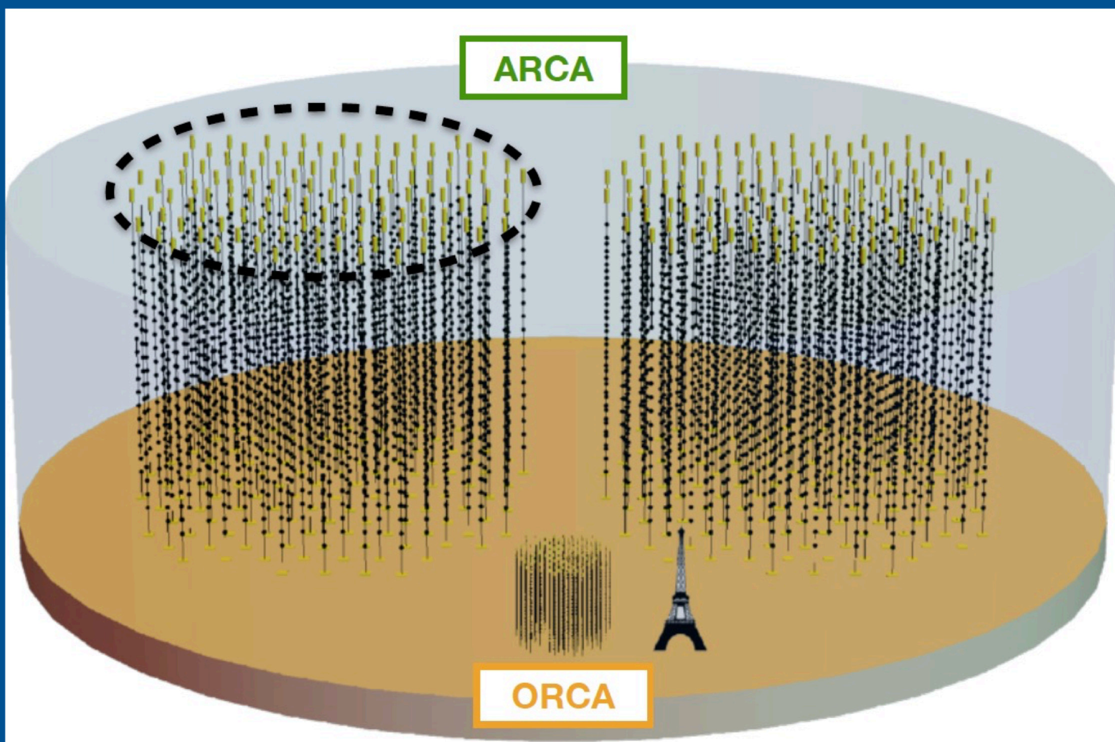
ARCA

- Depth ~3500 m
- Two blocks of 115 Detection Units each
- Distance between Detection Units ~90 m
- Vertical distance between DOMs ~36 m
- **Volume (0.5 × 2) km3**



Detectors in construction and taking data

THE KM3NET DETECTORS

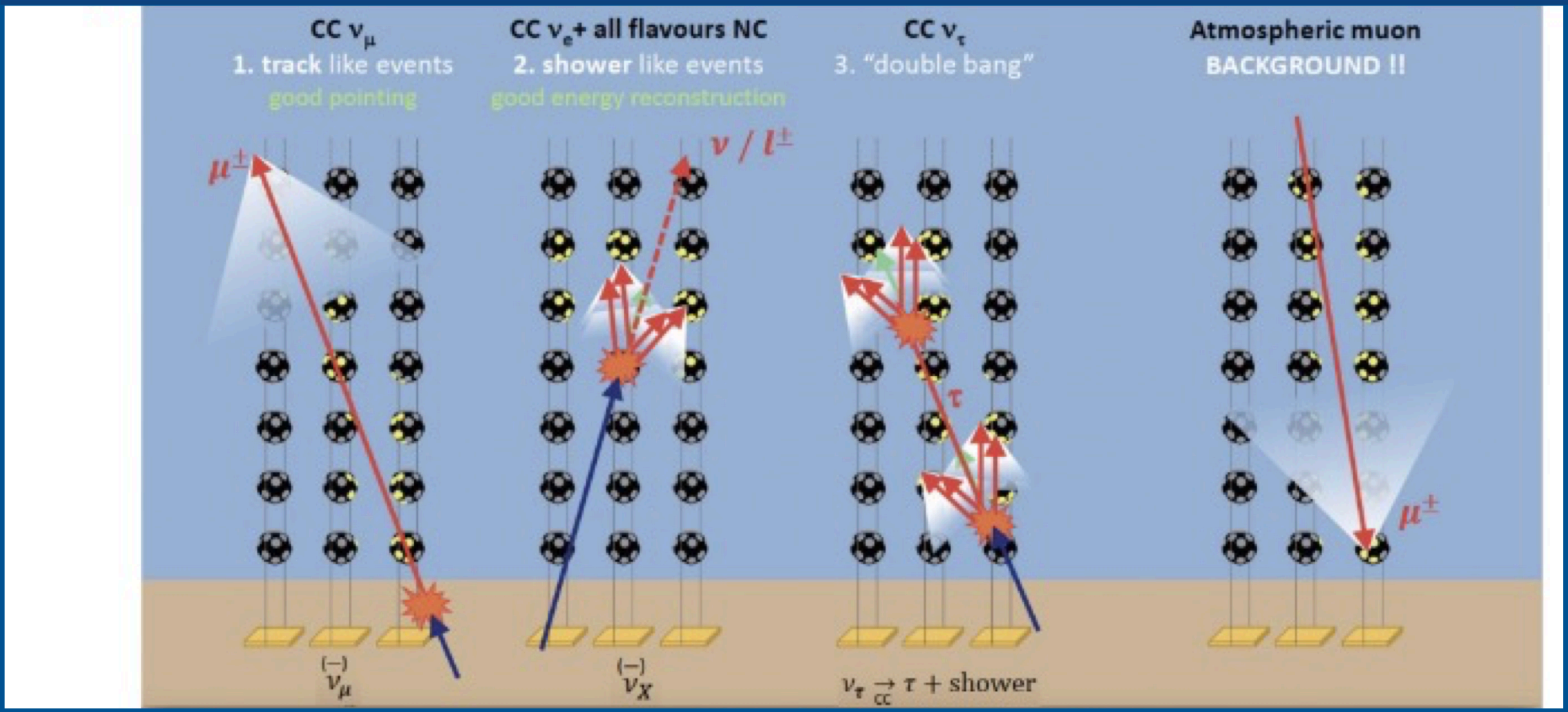


1 Building Block (BB) 👉115 Detection Units
ARCA 2 BB (230 DUs)
ORCA 1BB (115DUs)

Difference in the spatial distance of optical sensors

DETECTION PRINCIPLE

5



Tracks 👉 @E_ν>100 TeV Ang. res. below 0.1° - Energy res. ~ factor 2

Shower 👉 @E_ν>100 TeV Ang. res. below 2° - Energy res. ~6%

THE TECHNOLOGY

6

The basic elements:

- Optical sensors 👉 DOMs (Digital Optical Module)
- Strings 👉 DU (Detection Unit)
- Seafloor network 👉 Electro-optical cables and JBs (Junction Boxes)

The Digital Optical Module

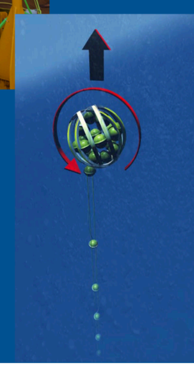
DOM

It is a 17” glass sphere containing:

- 31 3” PMTs (photocathode aerea ≃ 3 × 10” PMTs)
- LED and Piezo
- Front-end electronics -> FPGA

Video of the DOM integration

The Detection Unit



18 DOMs in a DU

Video of a DU integration

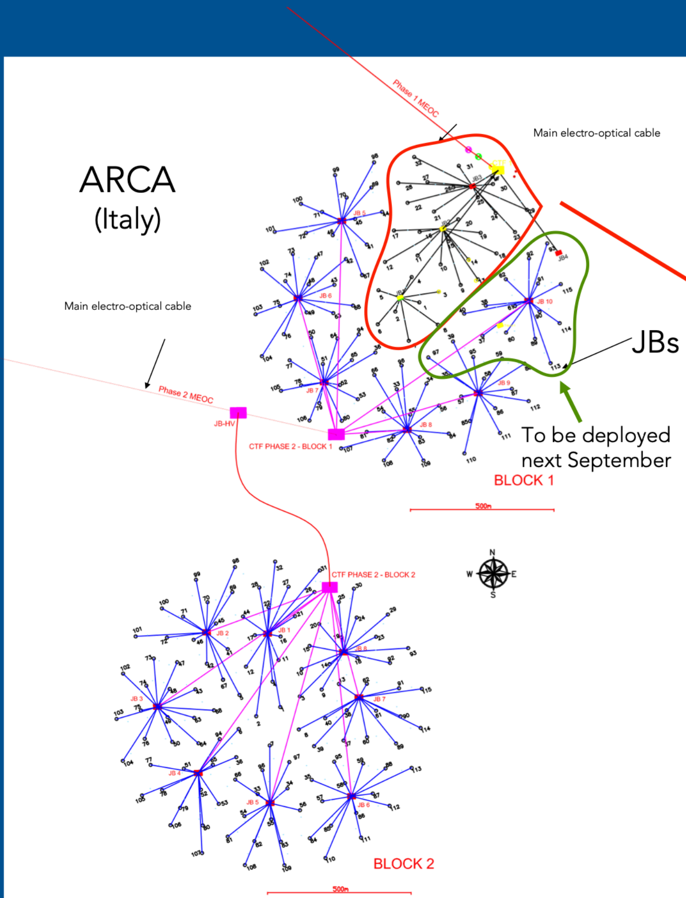
The Sea floor network:

- Electro-optical cables from shore to the deep sea
- Junction boxes/nodes to distribute power and optical fibers
- In ARCA Cable Termination Frames (2 already installed)
- Interlink cables for connection of DU to JB and JB to the main cable

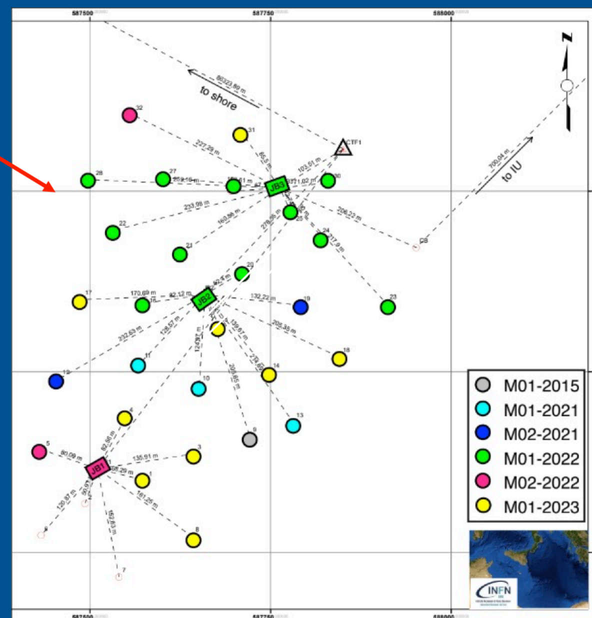
ARCA JB

THE KM3NET/ARCA STATUS

7



Current status 28 DUs deployed
+ 3 JB



1 sea campaigns per year

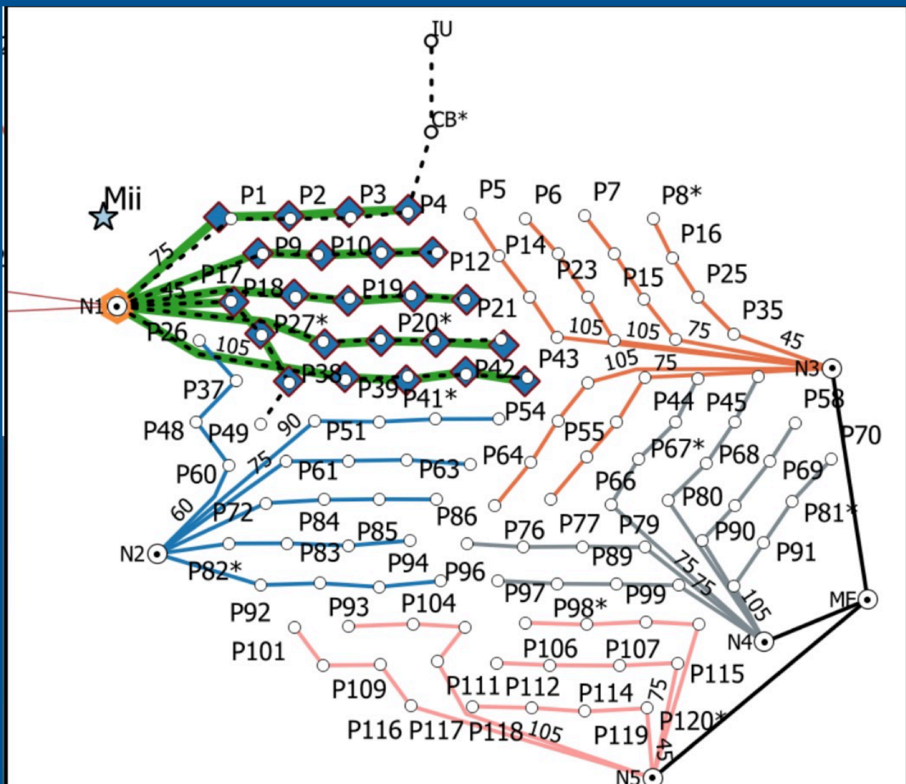
The next one in September 2024
To be deployed:
2 JB + ~19DUs + Instrumentation Unit (IU)

~47 DUs at the end of this year
(~40% of the first block)

THE KM3NET/ORCA STATUS

8

Current status 23 DUs deployed

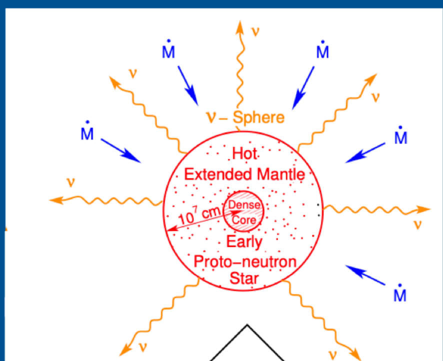


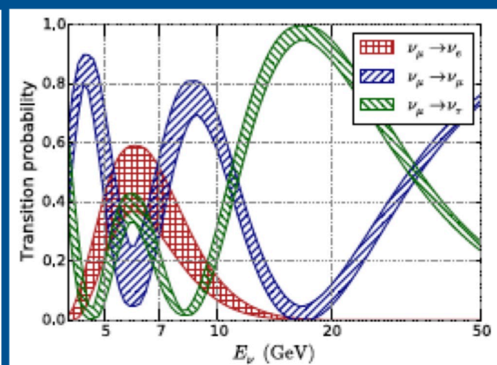
Many sea campaigns/year

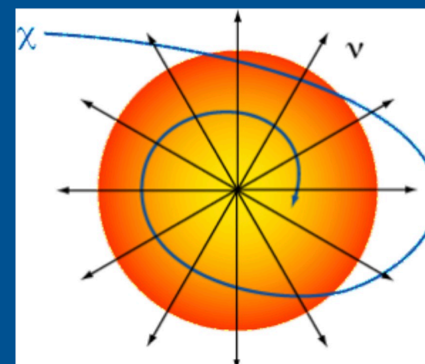
Next one foreseen before the end of the year 👉 complete the DUs of node1 and deploy the node2 & 4-5 DUs

Almost completed the first node
👇
20% of the full detector in water

THE PHYSICS







Supernova explosions
Single DOMs as detectors
ARCA&ORCA

Neutrino oscillation
Main topic of ORCA

Dark Matter
ORCA & ARCA

HE neutrinos
Multi-messenger program
Main topic of ARCA

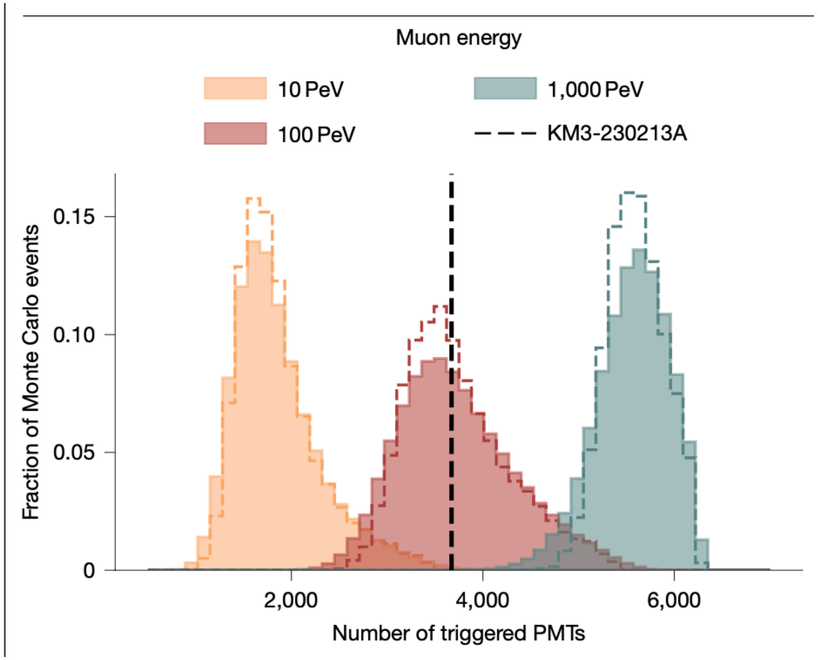
From MeV … …. to PeV

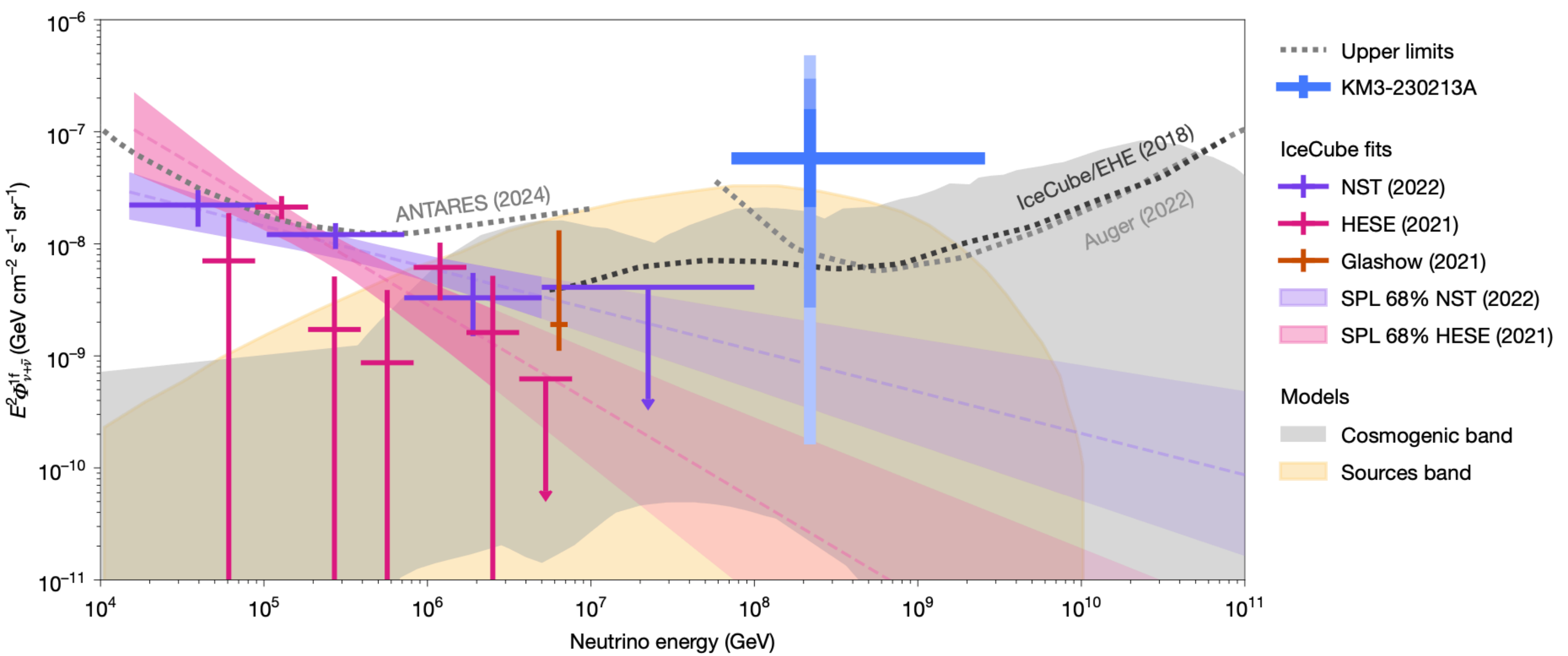
KM3-230213°

The most Energetic neutrino ever detected

The KM3NeT Collaboration. Observation of an ultra-high-energy cosmic neutrino with KM3NeT. *Nature* **638**, 376–382 (2025). https://doi.org/10.1038/s41586-024-08543-1

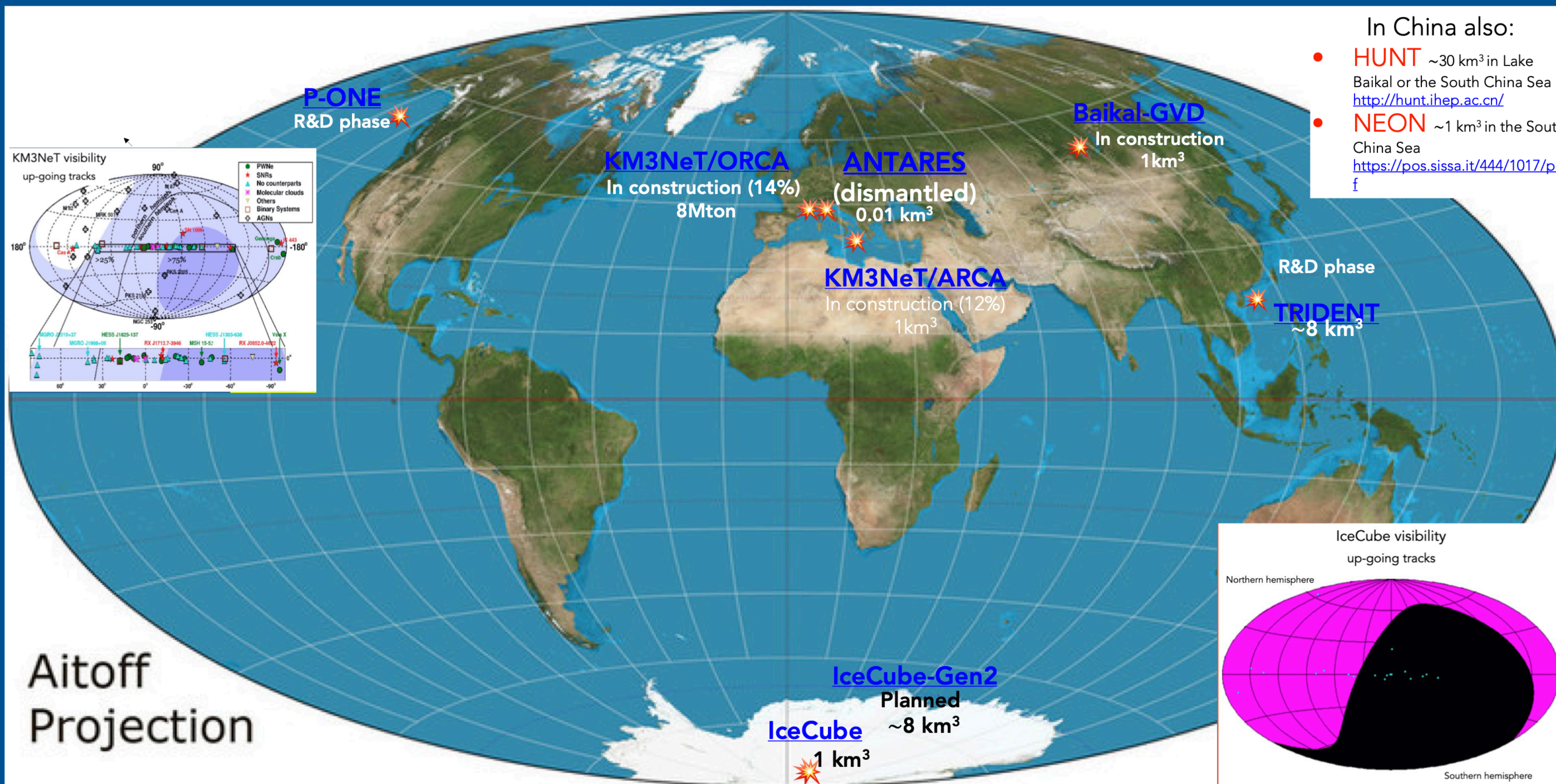
$\mathbf{E_\mu = 120\ PeV \rightarrow E_\nu = 220\ PeV}$



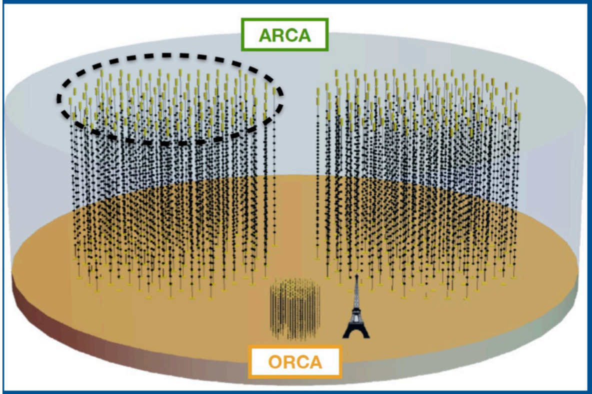


THE HIGH ENERGY NEUTRINO DETECTORS

28



A dedicated software is installed at the shore stations for Real-Time Analysis (RTA)



Sending alerts

Send neutrino alert to external communities

Receiving alerts

Receive alert from external communities - on-line analysis and follows ups

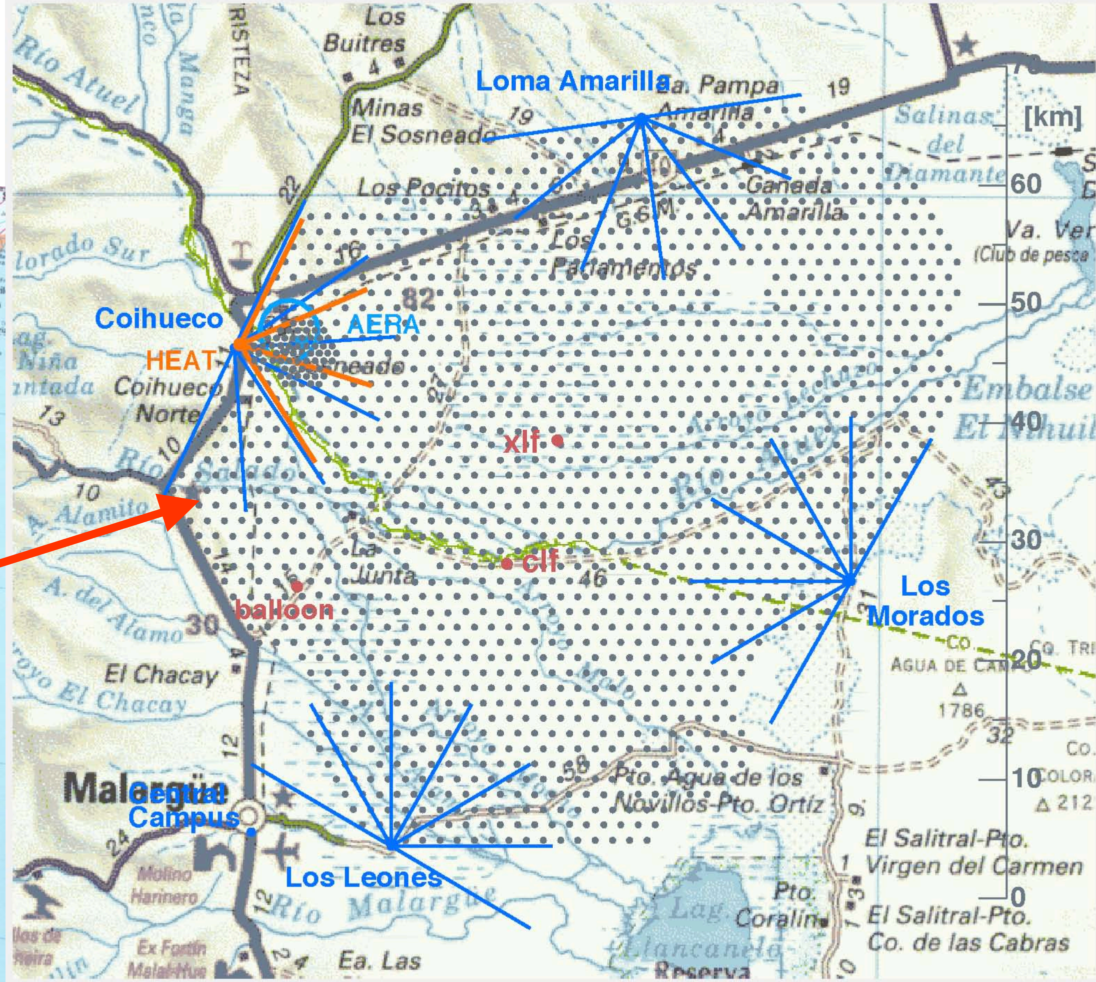
Receiving alert system operative 👉 RTA platform already active from November 2022 in ARCA and in ORCA detectors

Sending alert system on going 👉 High-energy neutrino alerts will be sent in real-time by end of 2024.

- AUGER

Pierre Auger Observatory (PAO)

- low population density (< 0.1 / km^2)
- special climate
(dry atmosphere, clear sky, low light pollution)
- flatness of the landscape



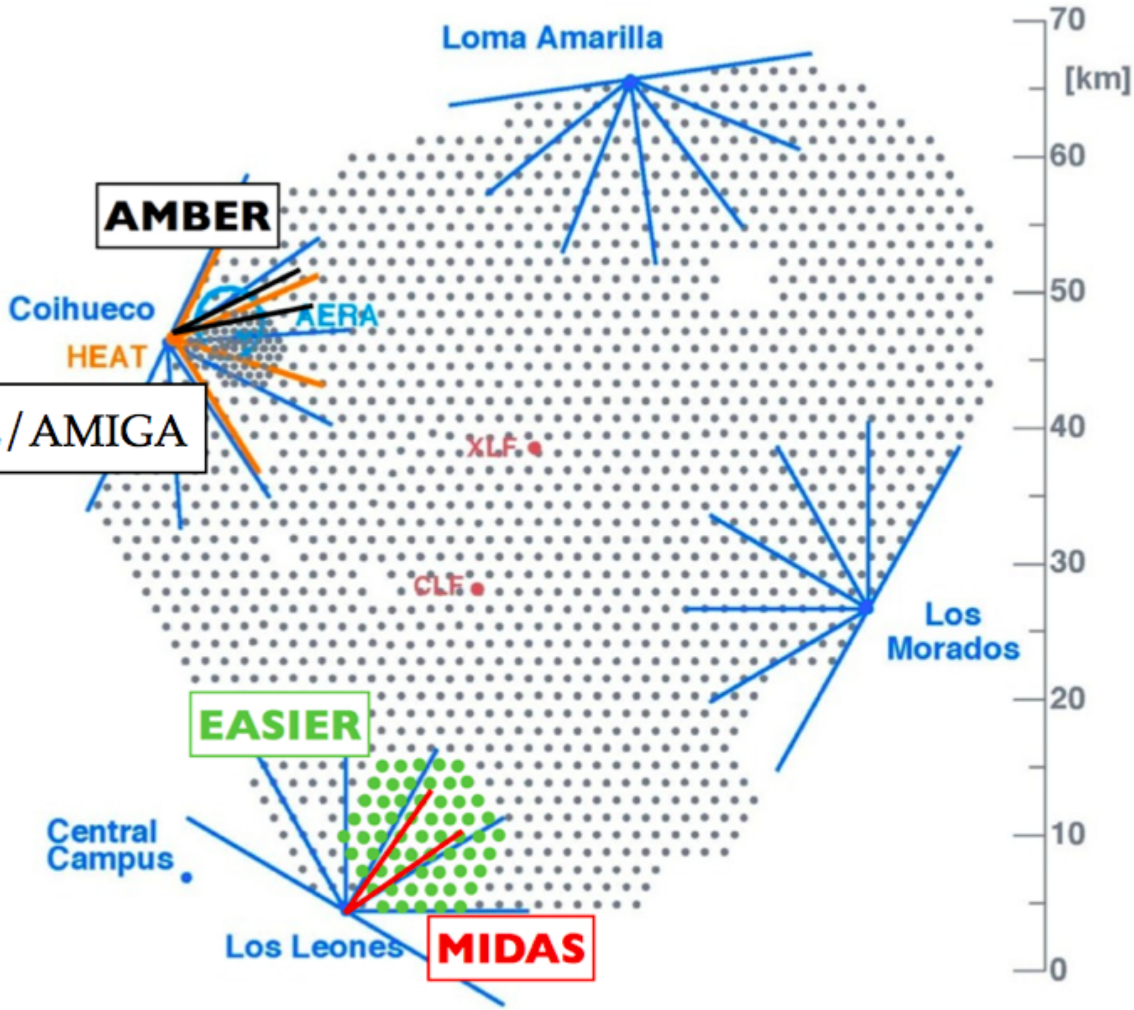
35.2° S latitude
69.5° W longitude
~1400 m a.s.l.
<X> = 880 g/cm^2

Area ≃ 3000 km^2

- 24 fluorescence telescopes (FD)
- 1600 water Cherenkov stations (SD), spacing= 1.5 km

Pierre Auger Observatory

the world's largest cosmic ray observatory in operation since 2004



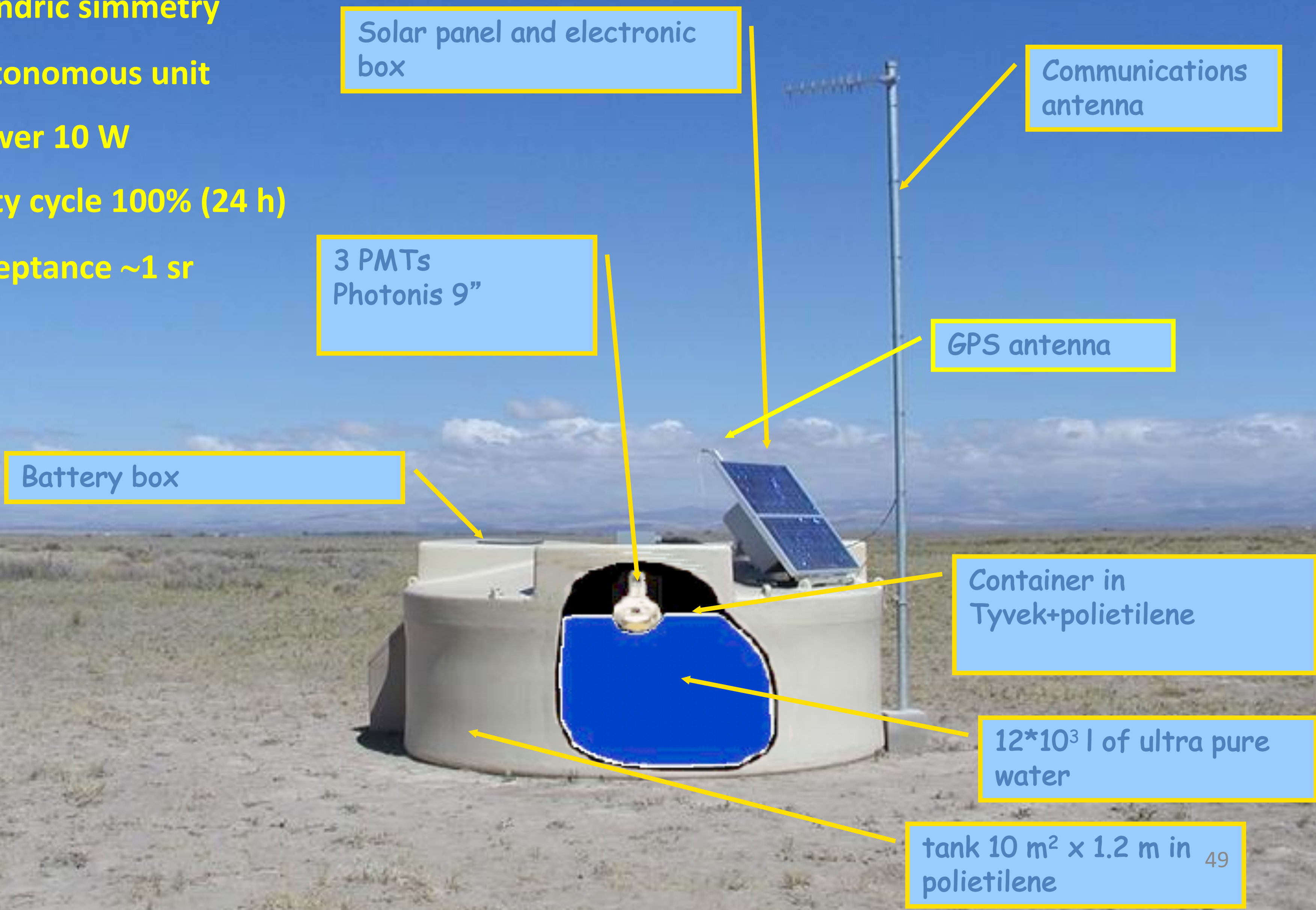
- **SD:** 1600 water Cherenkov det. regular grid of 1.5 km, 3000 km²
- **Infill:** 71 water Cherenkov det. 750 m spacing over 30 km² ;
- **AMIGA:** extension in progress (7 muon counters in place);
- **FD**: 4 sites (Eyes) with 6 fluor. telescopes (180° x30°) f.o.v.;
- **HEAT:** 3 fluorescence telescop. @ Coihueco, 30° -60° in elevatio

- **AERA:** 124 radio sensors in MHz range over 6 km² ;
- **EASIER:** 61 radio sensors in GHz range, 100 km² ;
- **AMBER:** 1 imaging radio telescope in GHz range, (14° x14°) f.o.v.;
- **MIDAS:** 1 imaging radio telescope in GHz range, (10° x20°) f.o.v.

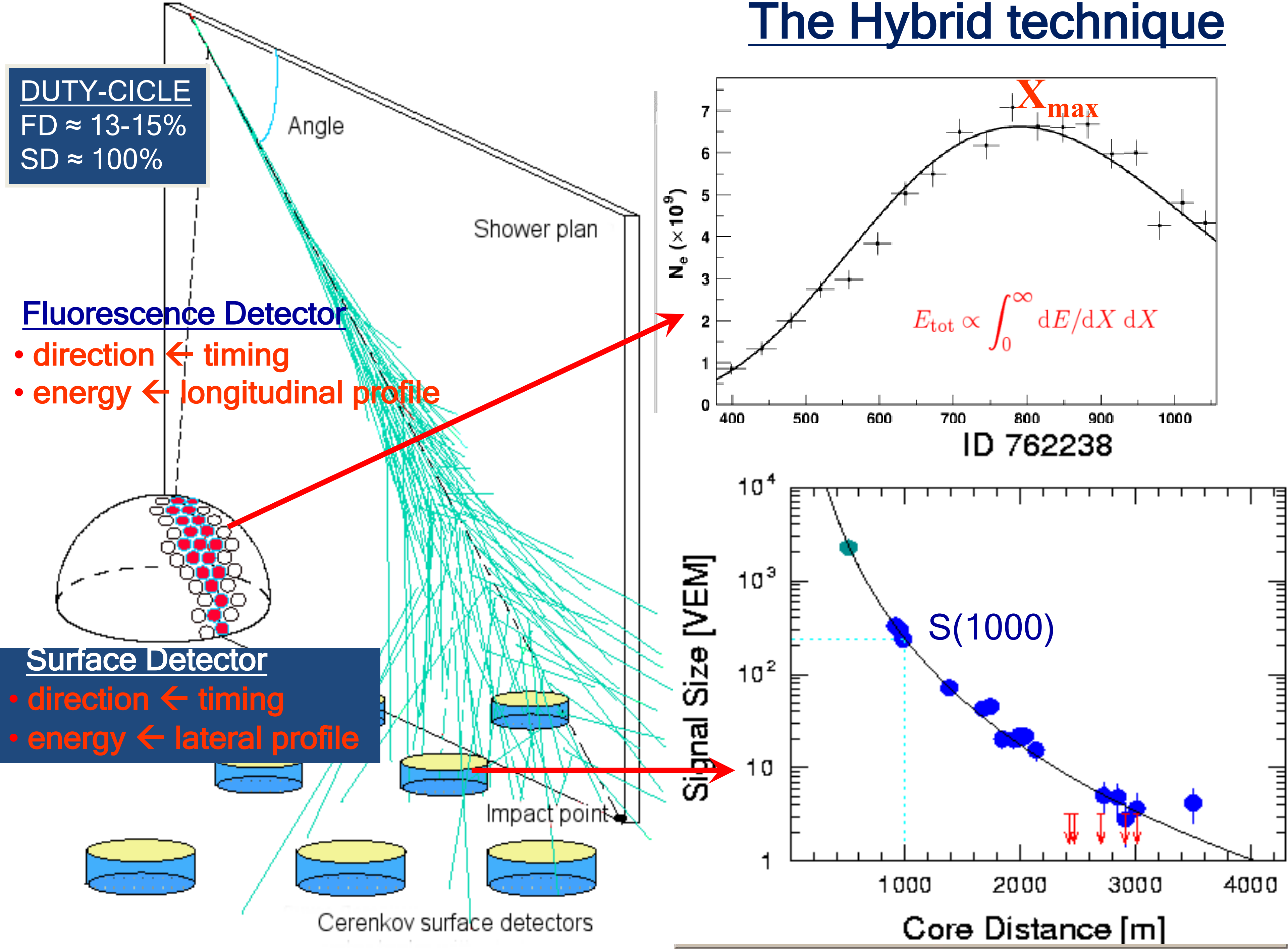
R&D

The Surface Detector

- ✓ **Cerenkov Water Tank**
- ✓ **Cilindric simmetry**
- ✓ **Autonomous unit**
- ✓ **Power 10 W**
- ✓ **Duty cycle 100% (24 h)**
- ✓ **Acceptance ~1 sr**



The Hybrid technique



PIERRE AUGER OBSERVATORY

QUESTION:
Are there UHE neutrinos?

Or search for the UHE neutrinos and the evaluation of their flux upper limit

ANSWER: no neutrinos! (??)

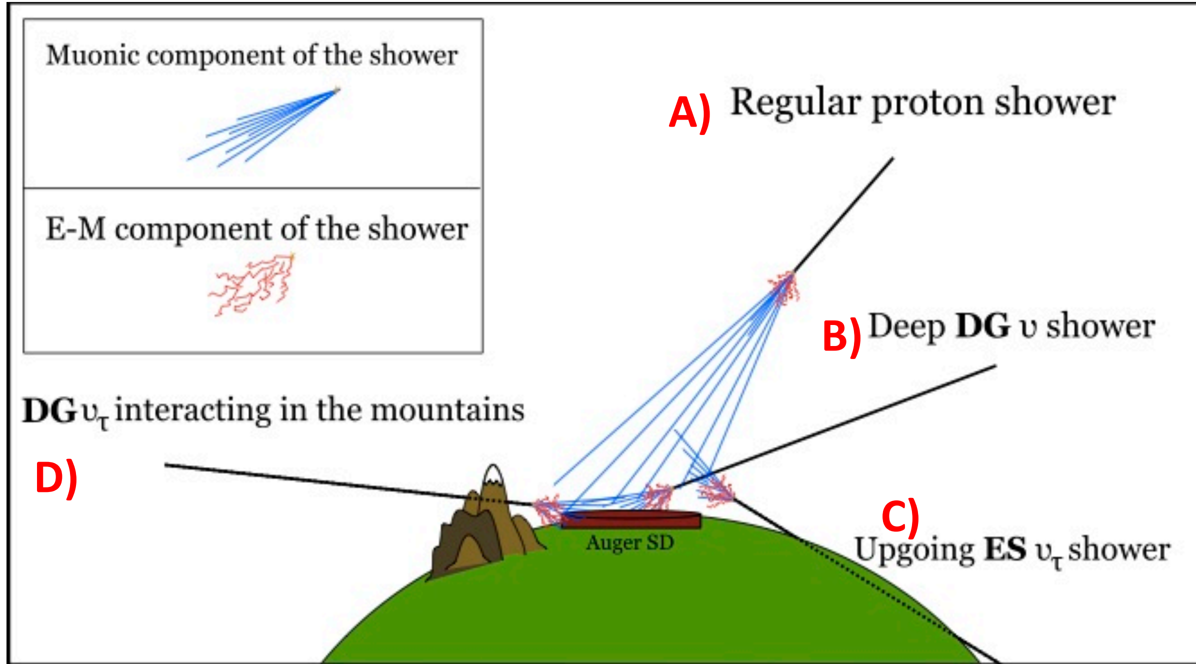
- first upper limit (95% C.L.) of the
- upper limit (90% C.L) of diffuse neutrino flux
- upper limit on flux of UHE neutrinos from point sources
- results constrain astrophysical source models

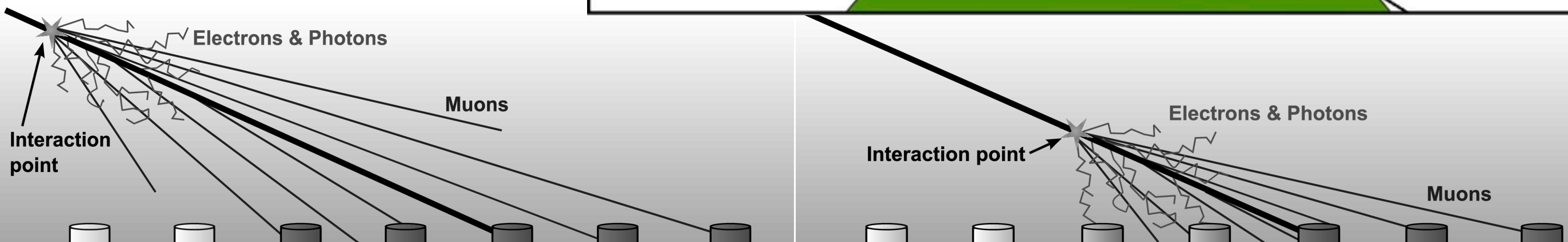
P.Auger Collaboration Advances in HEP, 2013 (2013) 708680
P.Auger Collaboration Astrophysical Journal Lett., 755 (2012) L4
P.Auger Collaboration Phys.Rev.D 84,122005(2011)
P.Auger Collaboration Phys.Rev.D 79,102001(2009)
P.Auger Collaboration Phys.Rev.Lett. 100,211101(2008)

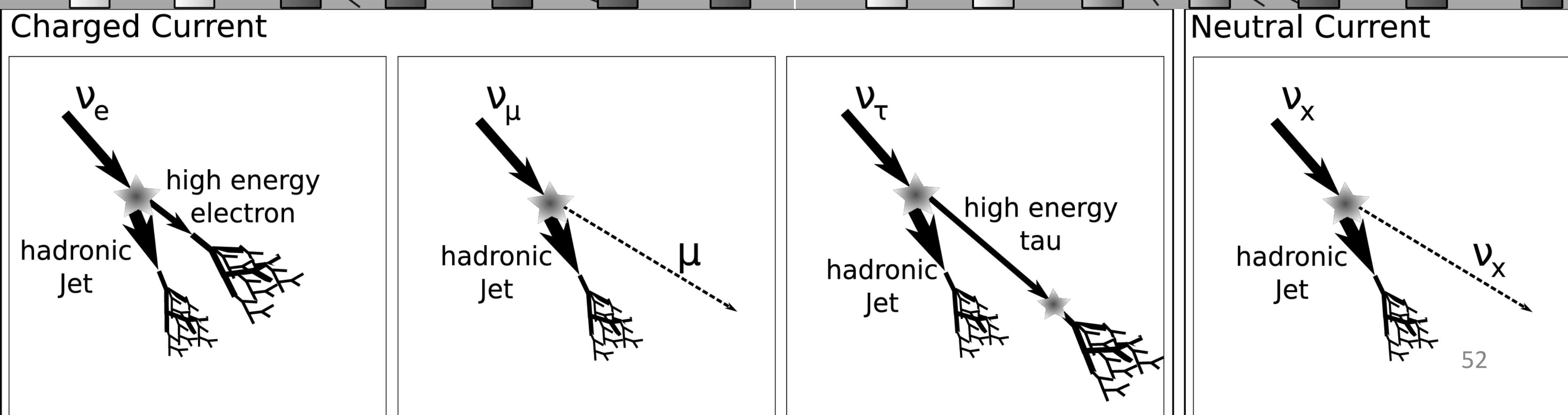
Identification of neutrinos

SELECTION CRITERIA:

B) Down-going (DG) low angle: 60°-75°
B), D)
DG high angle: 75°-90°
C) Earth-skimming (ES): 90°-95°

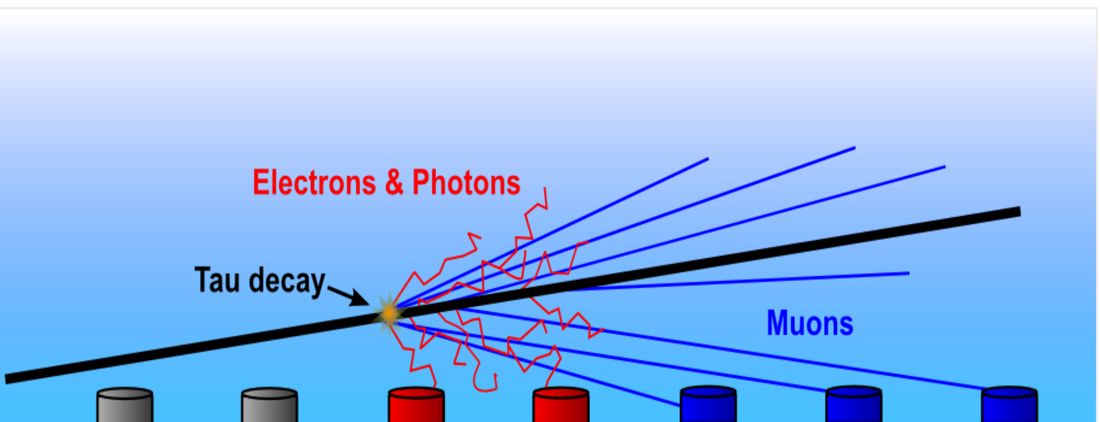


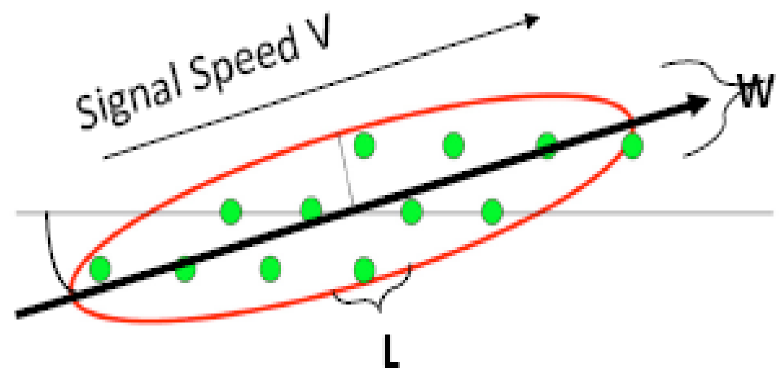


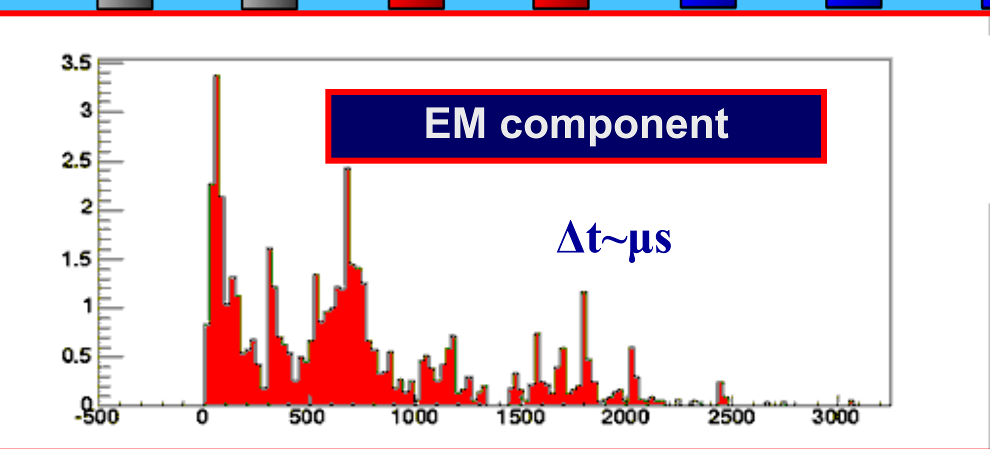


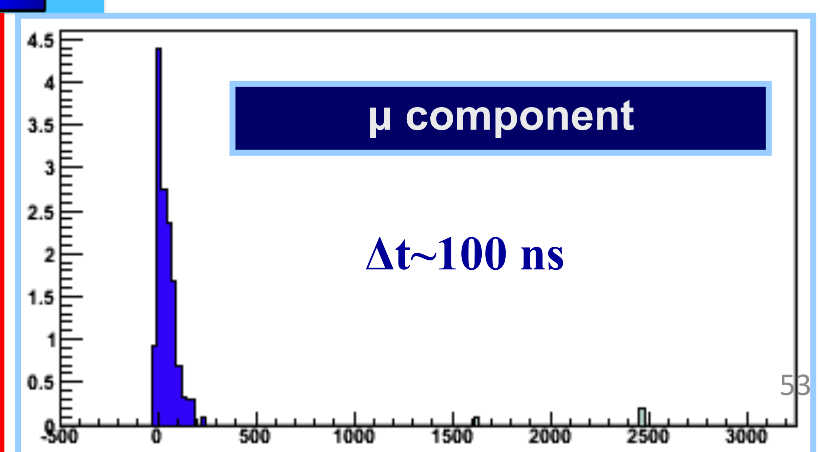
Features of UHE ν_τ-induced showers:

- at source, very few ν_τ $\nu_e:\nu_\mu:\nu_\tau \simeq 1:2:0$;
  at Earth expected oscillations with max. mixings $\nu_e:\nu_\mu:\nu_\tau \simeq 1:1:1$;
- very inclined ($80^\circ < \theta < 95^\circ$) and young showers (in early stage of development) close to the detector;
- Signatures:
  - slow and broad signal in time producing a (ToT) local trigger
  - speed of propagation of signal along the footprint $V_{ij} = D_{ij}/\Delta T \approx c$

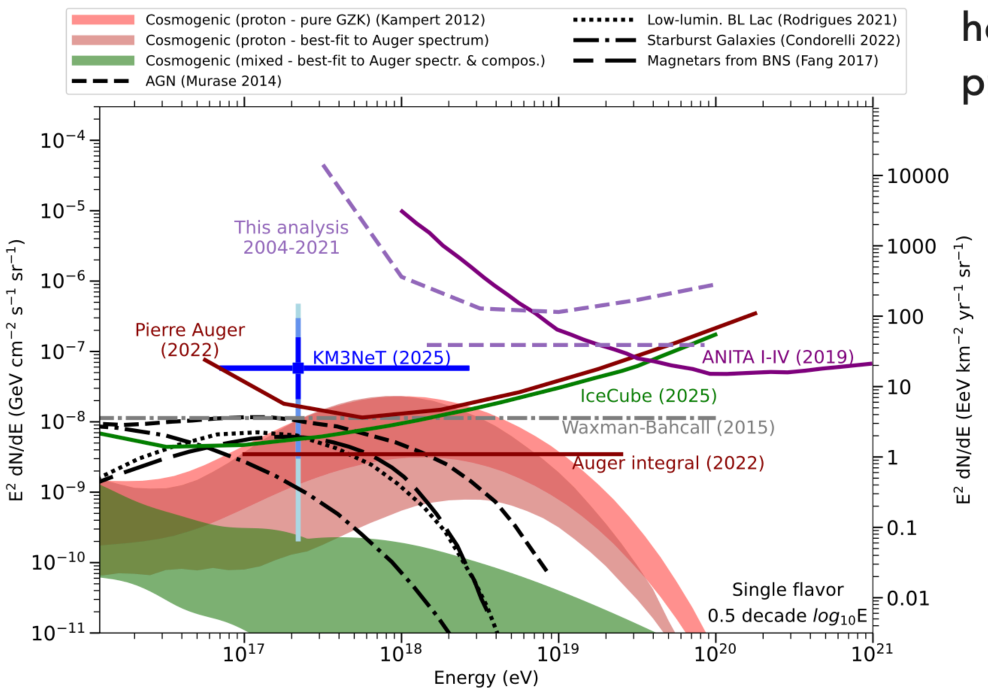








CURRENT NEUTRINO SEARCH STATUS IN THE UHE REGIME



- Ultra High Energy (UHE, E $\geq 10^{17}$eV) neutrinos help identify how and where cosmic rays are produced
  - Point right back to the sources (astrophysical)
  - Can also be produced during propagation (cosmogenic)

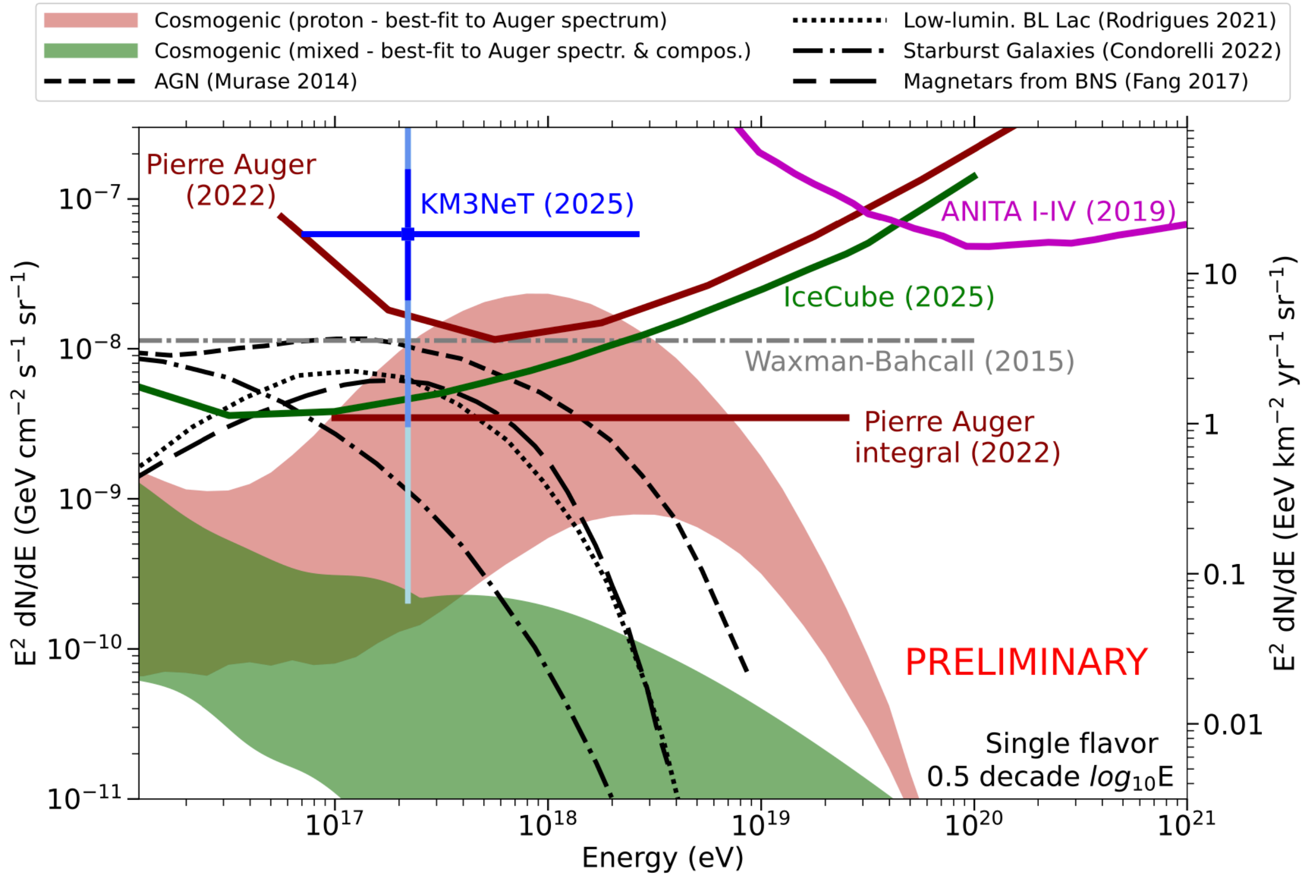
CURRENT STATUS

- Pierre Auger and IceCube Observatory have performed searches
- Both have complementary limits to UHEνs above 10^{18}eV
- Searches have helped constrain the composition of UHE cosmic rays

KM3NeT event

Assuming the estimated neutrino flux central value ~ 29 events should have been detected with Auger SD1500...

(~ 1.5 events assuming central value minus 2 sigma)



PIERRE AUGER OBSERVATORY

AugerPRIME

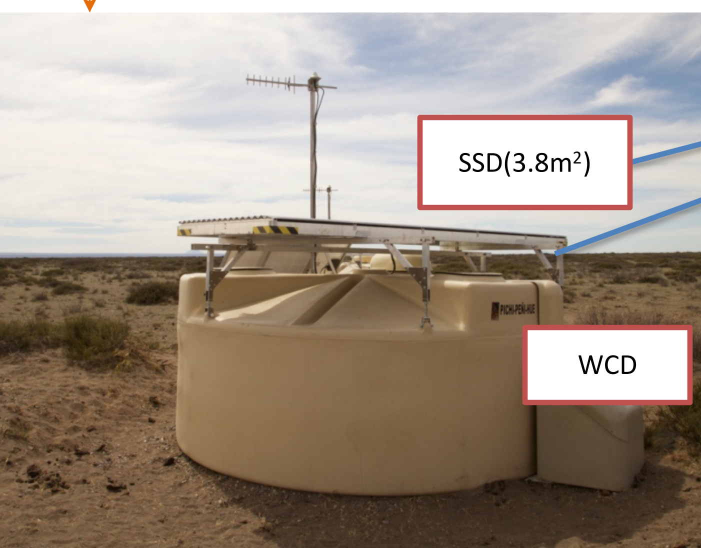
Extension of operation of the Pierre Auger Observatory.

(MOUs have been signed in Nov 2015)

Main improvements:

1. A new detector above each of the existing water-Cherenkov detectors (WCD)
2. A new electronics for the SD and the extension of the dynamic range (smallPMT)
3. Extended FD operation
4. Underground Muon Detector with AMIGA to have a direct muon measurement
5. Radio antenna on every SD station.

100% duty cycle



Complementarity of particle response used to discriminate electromagnetic and muonic components of air showers

The New electronic has improved the resolution (x4)

The sample frequency 40 MHz -> 120 MHz

Better time resolution

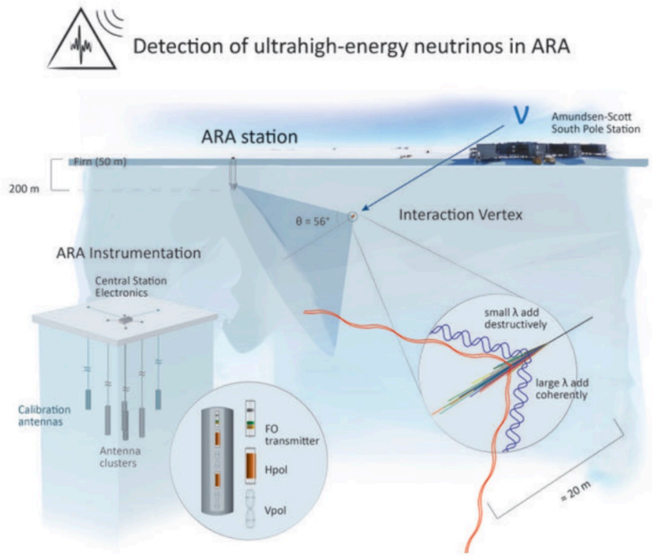
FPGA based -> possibility to implement new Triggers

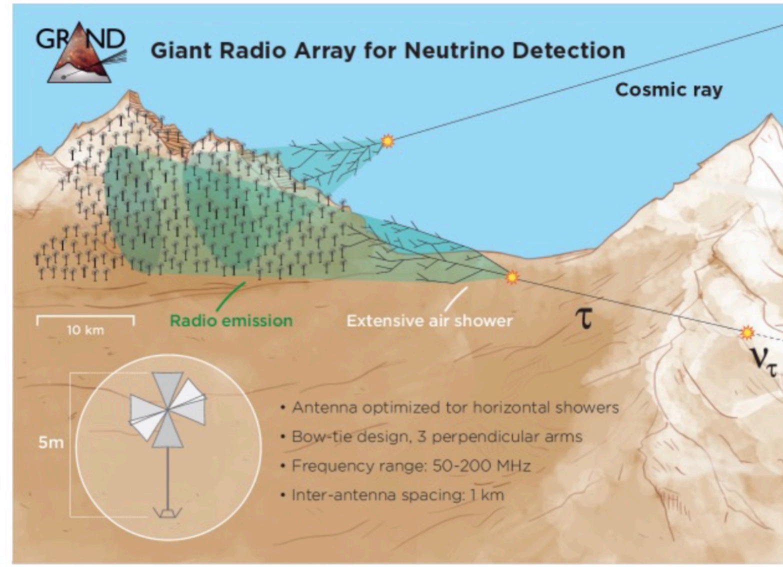
New Triggers would allow a better efficiency
To neutrino showers.

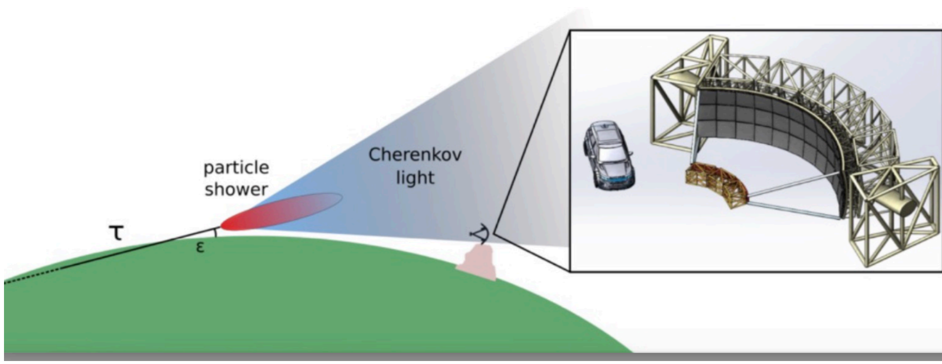
Future

It's an exciting period for neutrino Astrophysics

Ultra-high energy neutrinos





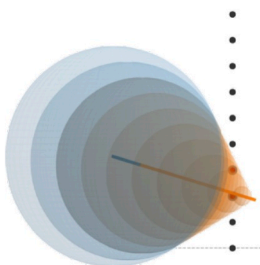


Thanks for the attention!

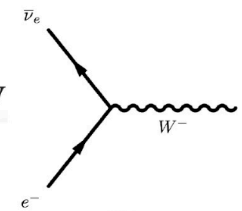
- BACKUP SLIDES

First hint of W boson resonance in data (Glashow resonance)

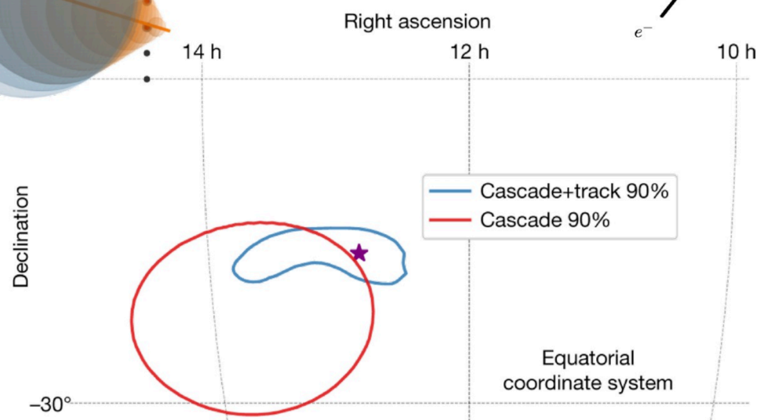
Nature **591,** 220–224 (2021)

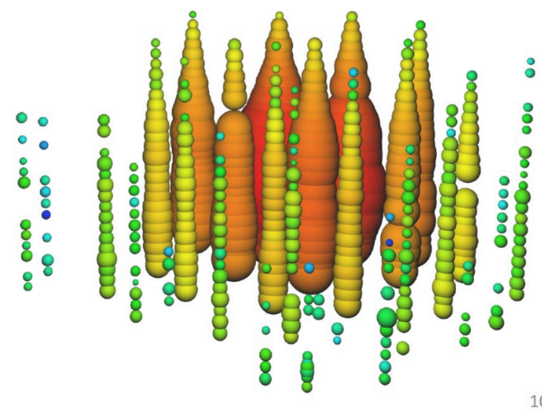


$$E_R = M_W^2/(2m_e) = 6.32\text{PeV}$$



By measuring nu/nubar -> probe source environment directly (magnetic field, pp/pgamma)

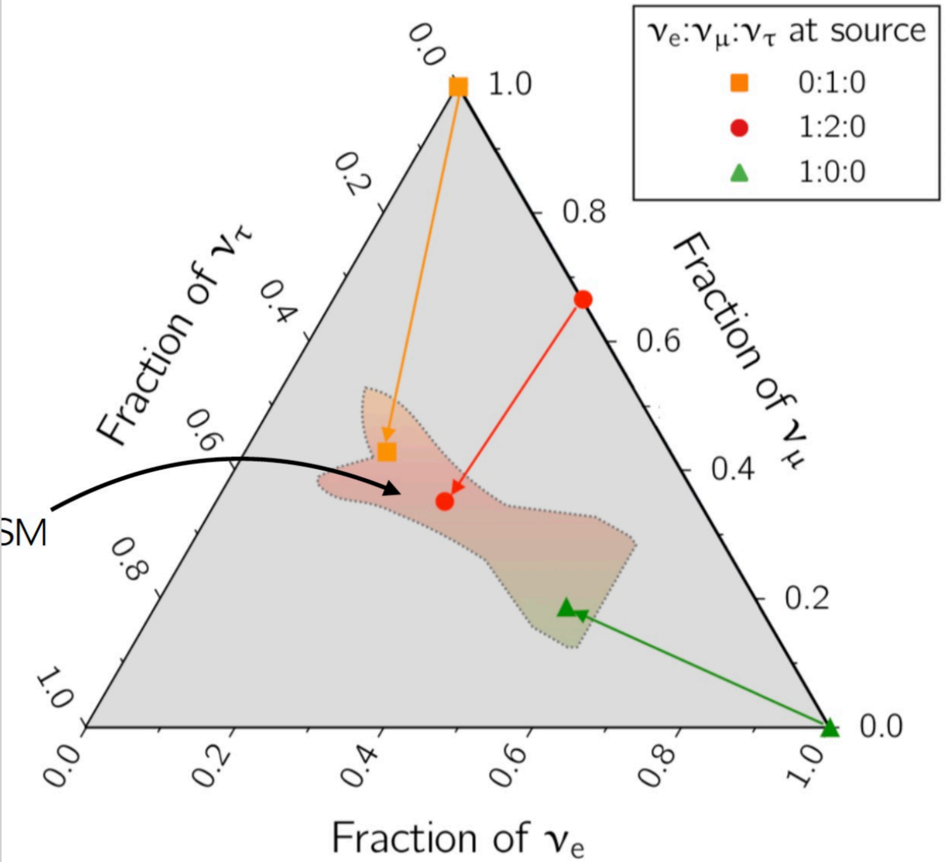


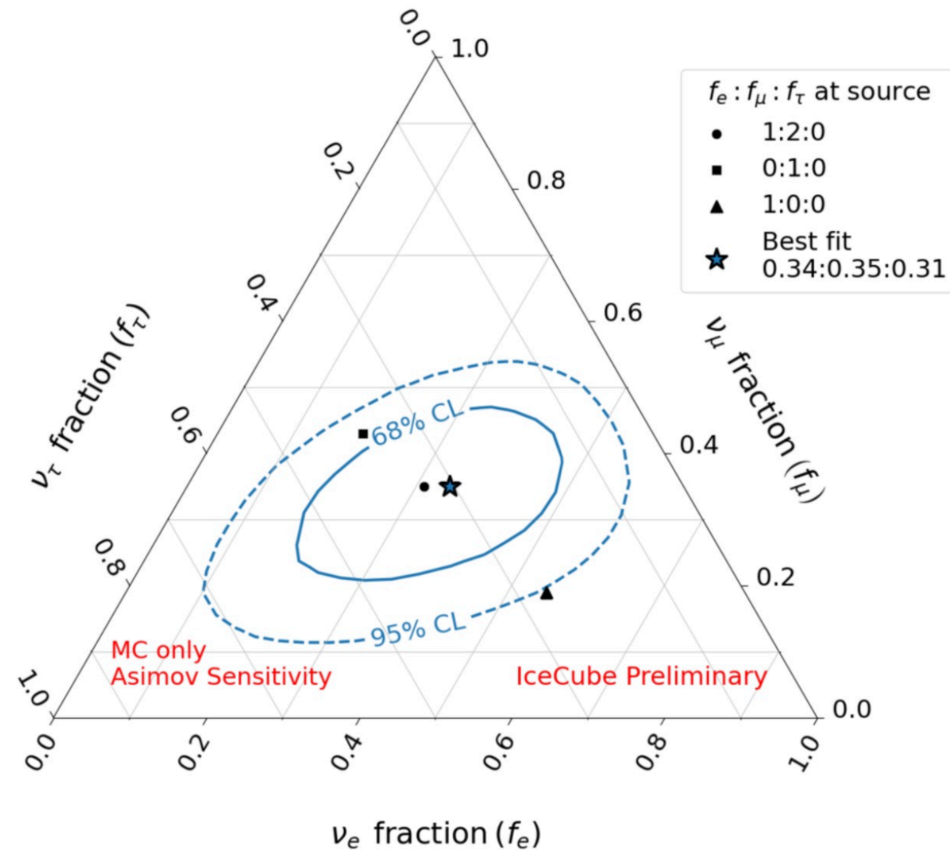


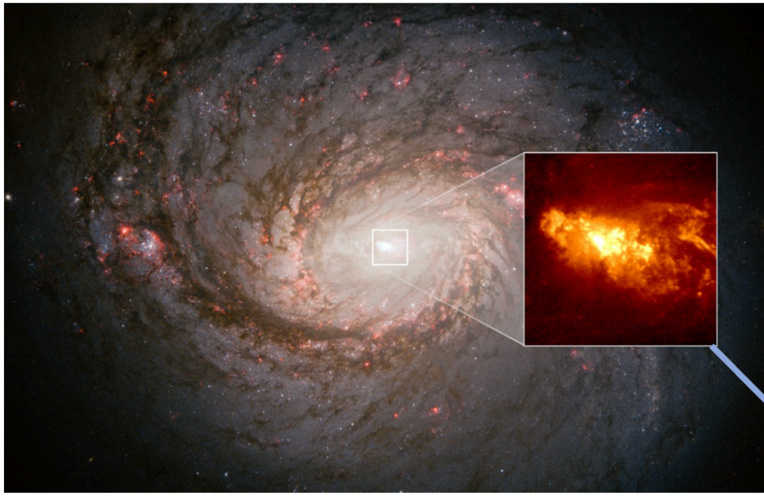
Identified muonic component from the hadronic shower

angular uncertainty contour shrinks by a factor of 5 with hybrid reco

oscillations of PeV neutrinos over cosmic distances to 1:1:1







80 high-energy neutrinos from the direction of the active galaxy NGC 1068