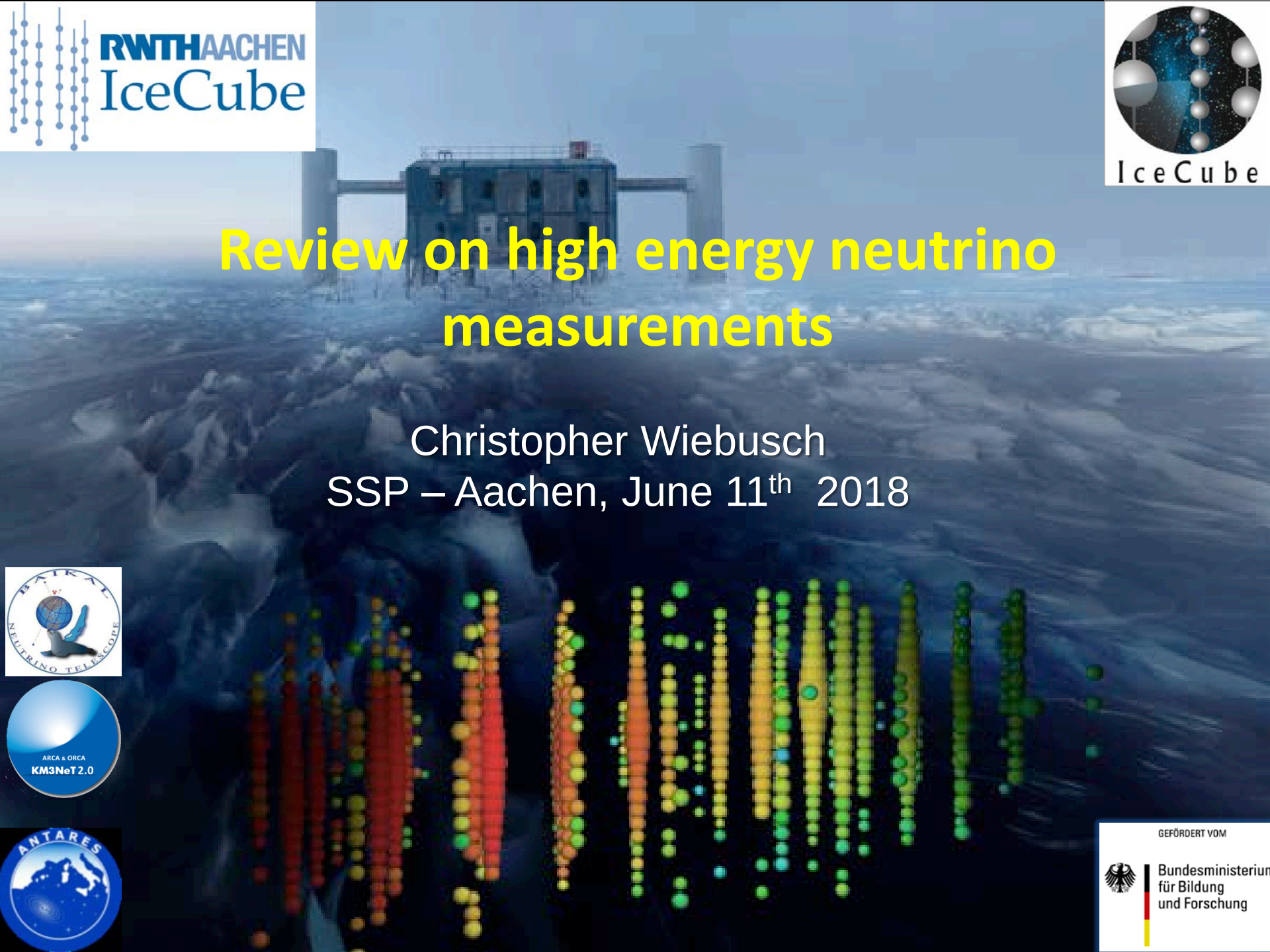


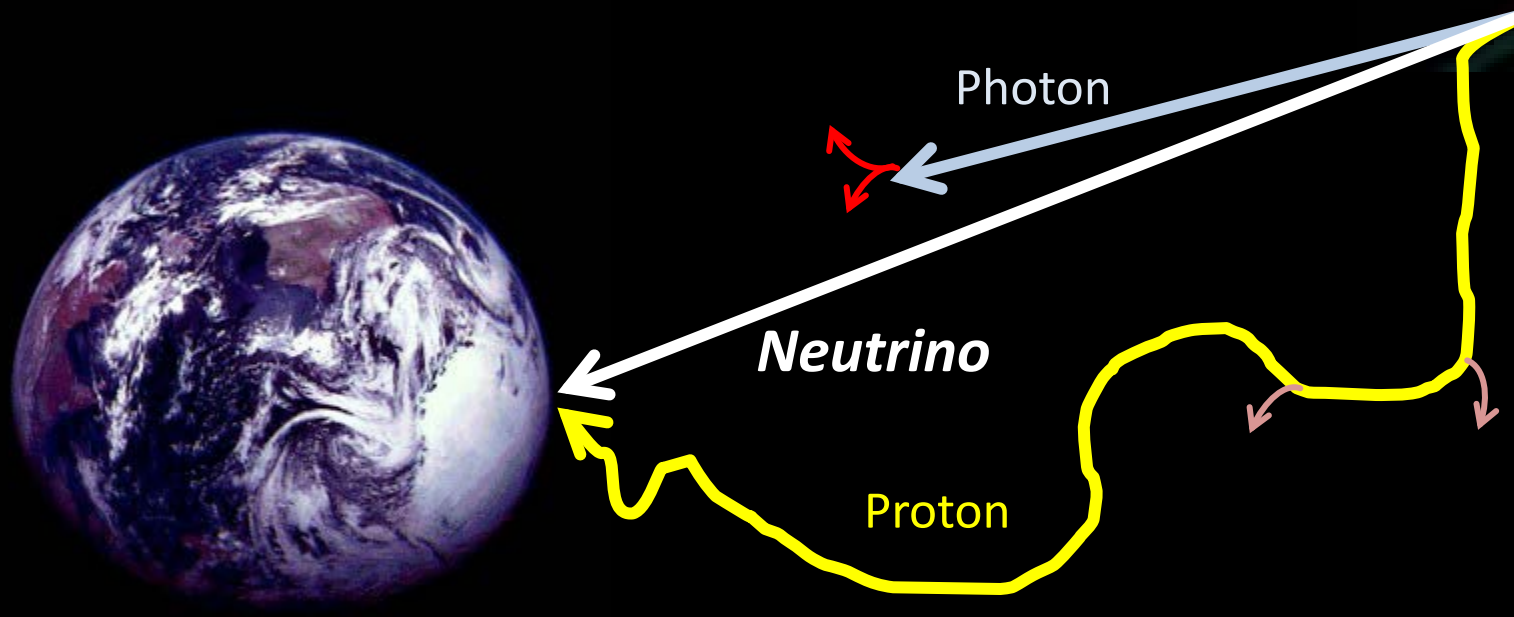
Review on high energy neutrino measurements

Christopher Wiebusch

SSP – Aachen, June 11th 2018

GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

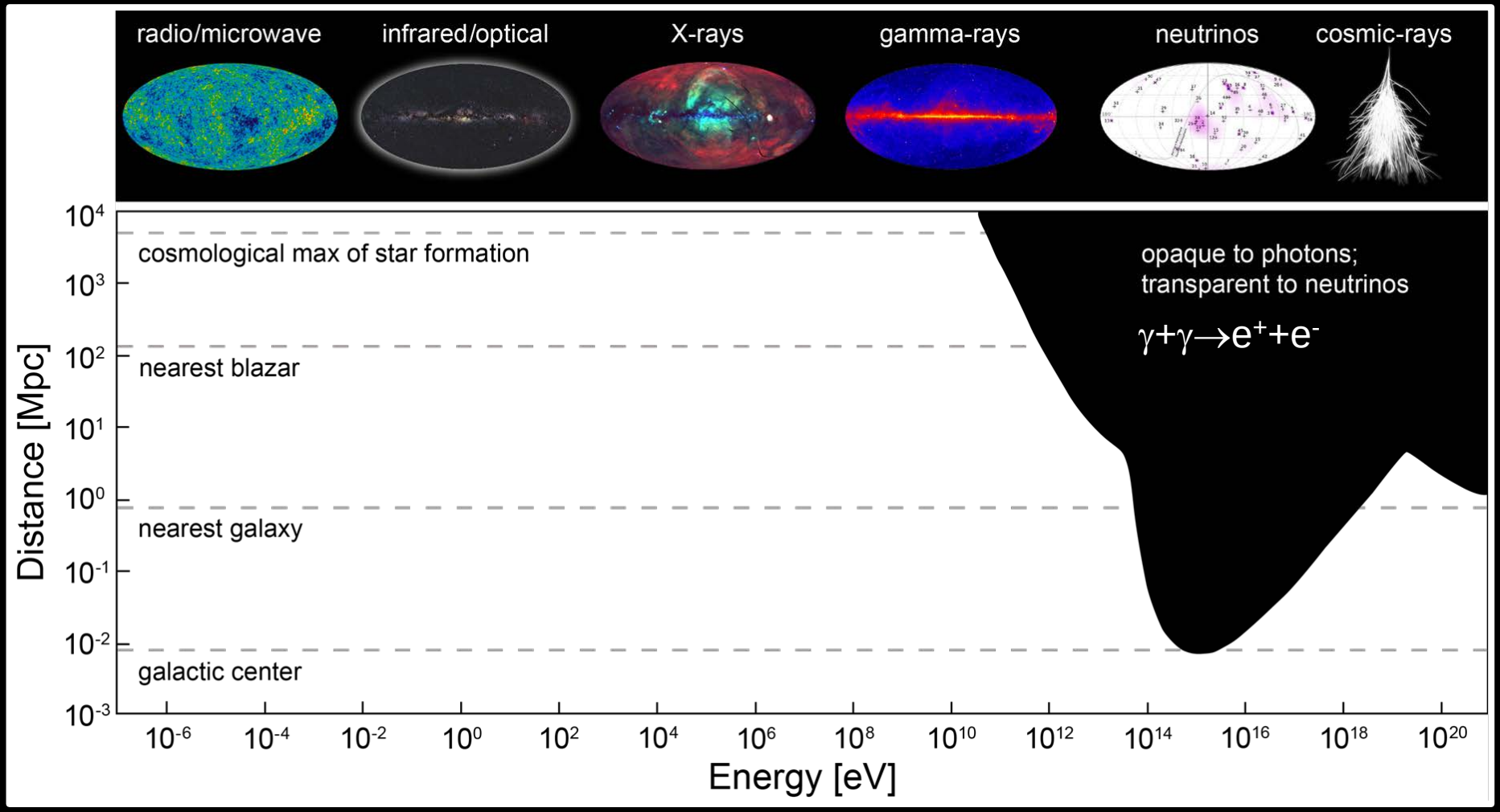
Messengers from the high-energy Universe



Neutrinos are ideal messenger particles: neutral stable unabsorbed
Measurement: Direction, Energy, Time

- Unambiguous tracers of hadronic sources
- Need large detectors on the km^3 scale

The multi-wavelength Universe



Outline

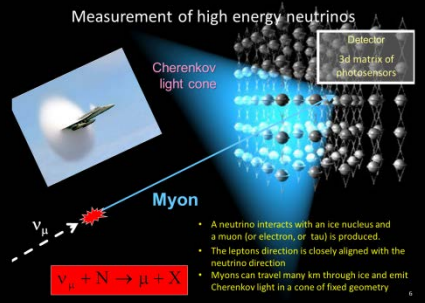
A. Cosmic neutrinos – Detection principles and Neutrino observatories

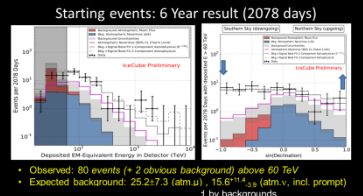
B. Discovery of high energy cosmic neutrinos

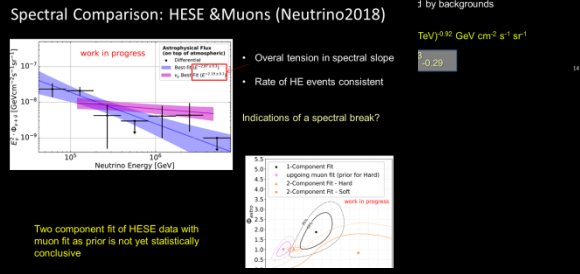
C. Characterisation of the cosmic neutrino flux

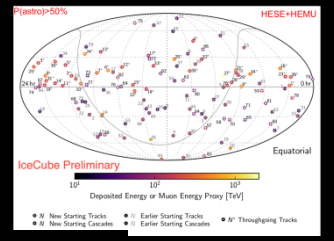
D. Selected results on the search for the origin of the cosmic neutrinos

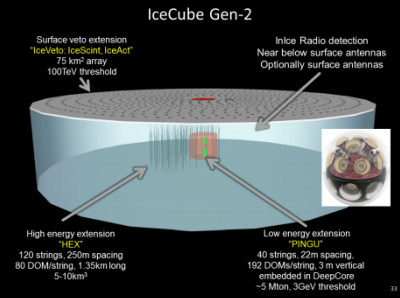
E. Outlook, Next-generation instruments











Measurement of high energy neutrinos

Cherenkov light cone

Detector

3d matrix of photosensors

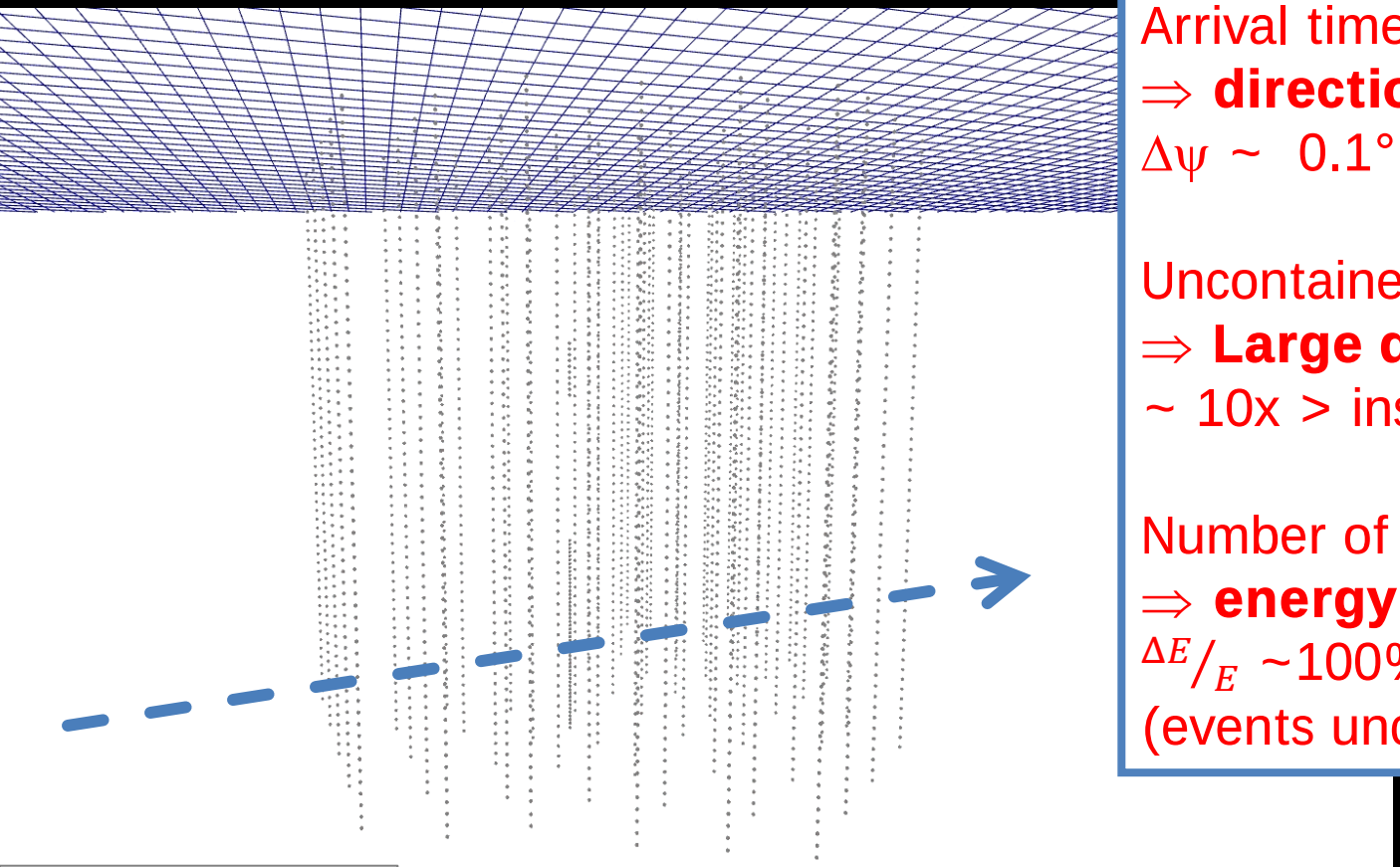
Myon

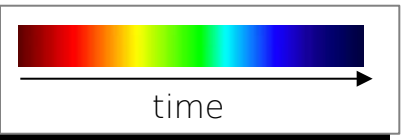
ν_μ

$$\nu_\mu + N \rightarrow \mu + X$$

- A neutrino interacts with an ice nucleus and a muon (or electron, or tau) is produced.
- The leptons direction is closely aligned with the neutrino direction
- Myons can travel many km through ice and emit Cherenkov light in a cone of fixed geometry

Muon tracks: a measured high-energy ν_μ in IceCube





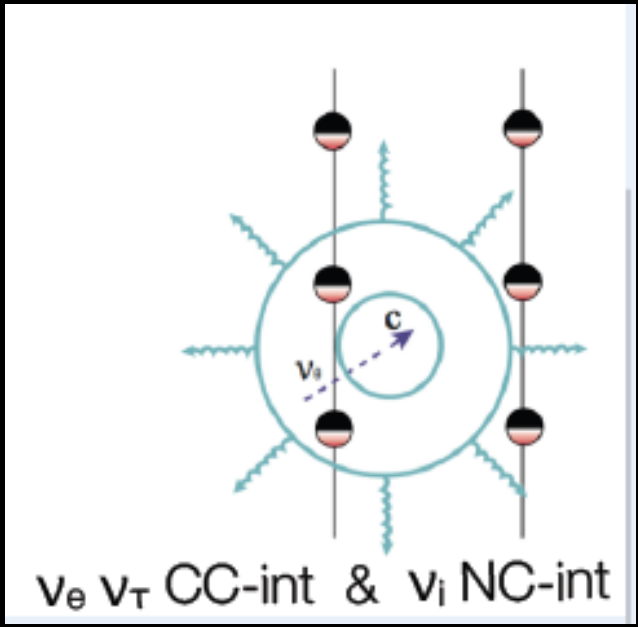
Apollon: Highest energy muon in 2009 ν_μ Analysis
91.2°, E_μ~400TeV, E_ν~0.5-1 PeV

Arrival time of photons
⇒ **direction & geometry**
$\Delta\psi$ ~ 0.1° - 2°

Uncontained events
⇒ **Large detection volume**
~ 10x > instrumented volume

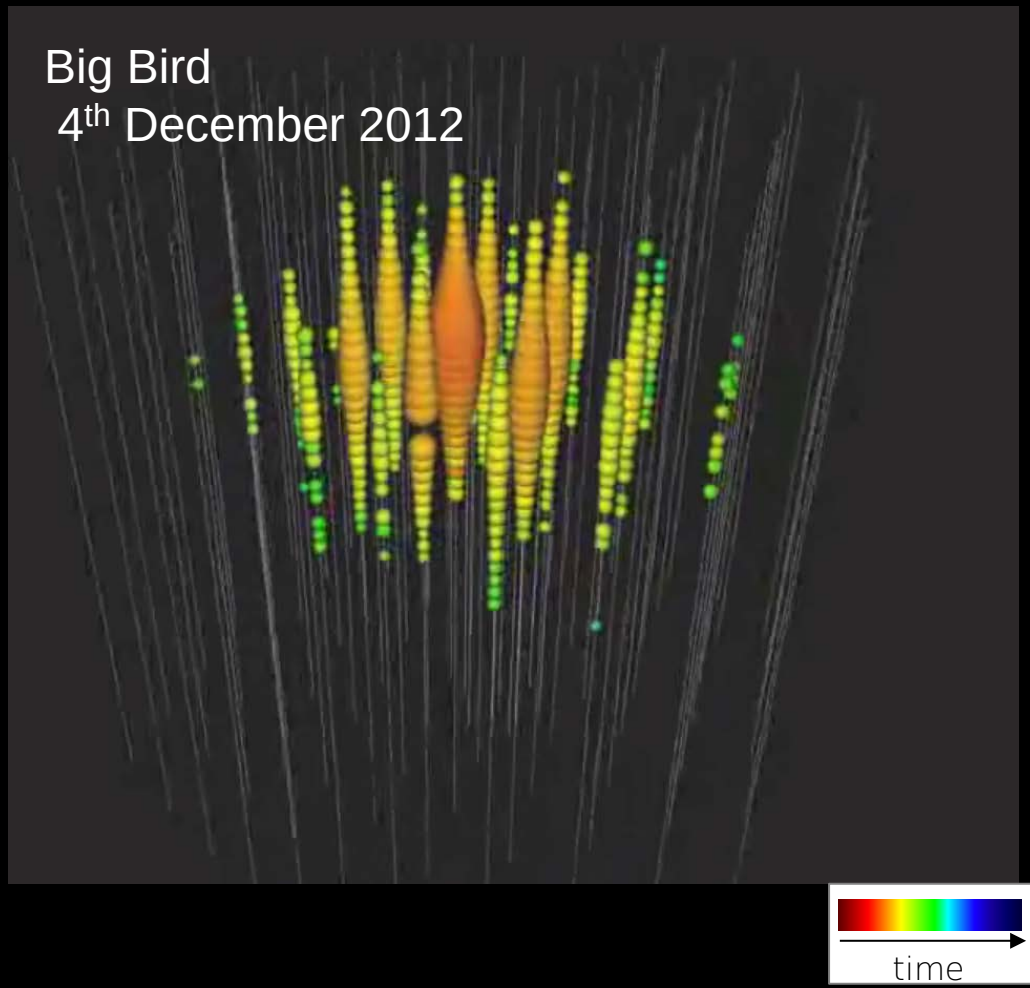
Number of registered photons
⇒ **energy-loss**
$^{\Delta E}/_{E}$ ~100%
(events uncontained)

Extensions to other Neutrino flavors: Cascade events



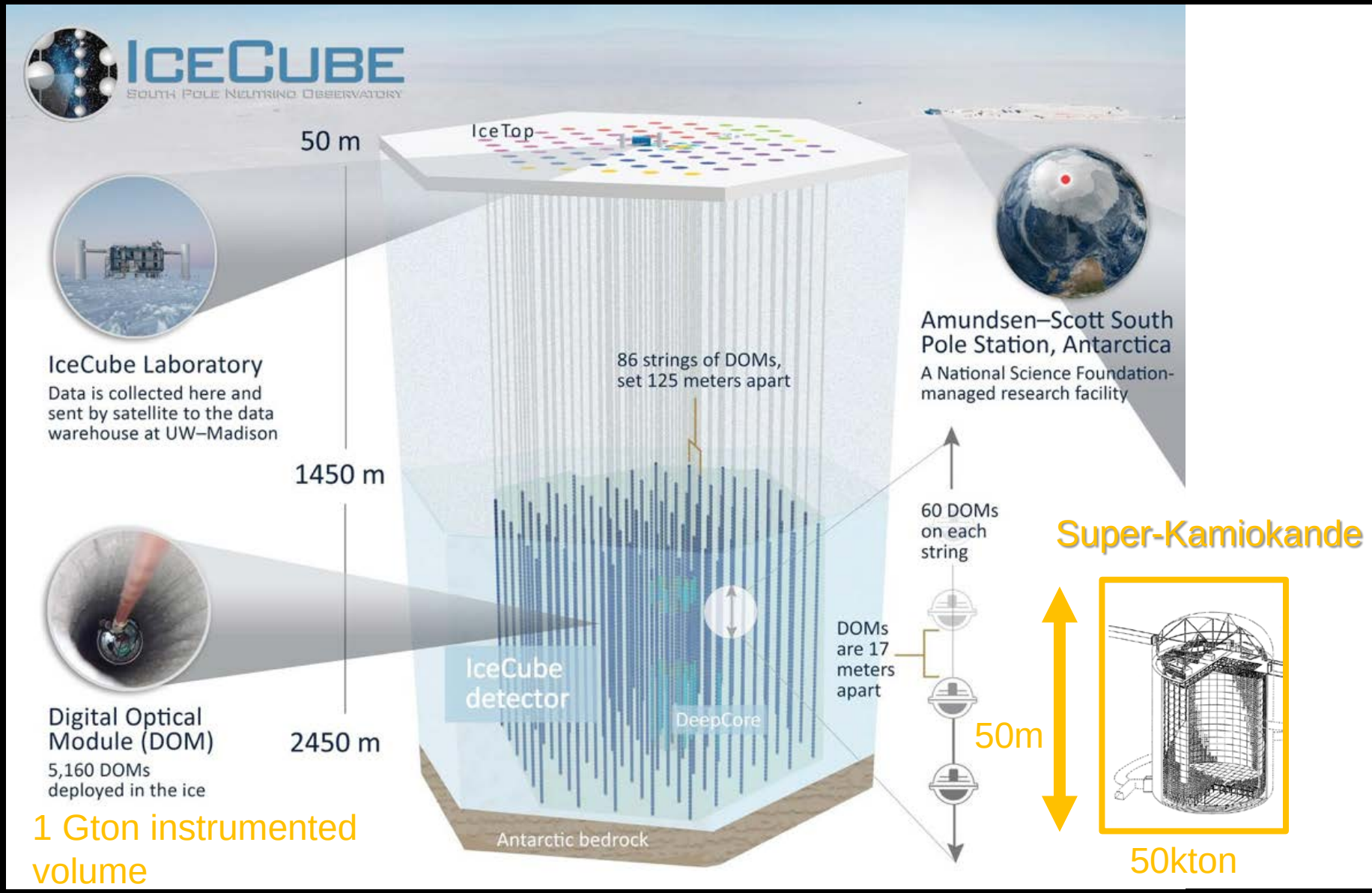
Comparison to tracks:

- Smaller volume
- poorer angular resolution
  $\Delta\psi \sim 5° - 10°$
- Excellent energy reconstruction
  $\Delta E/E \sim 5\%$
- Smaller atmospheric background



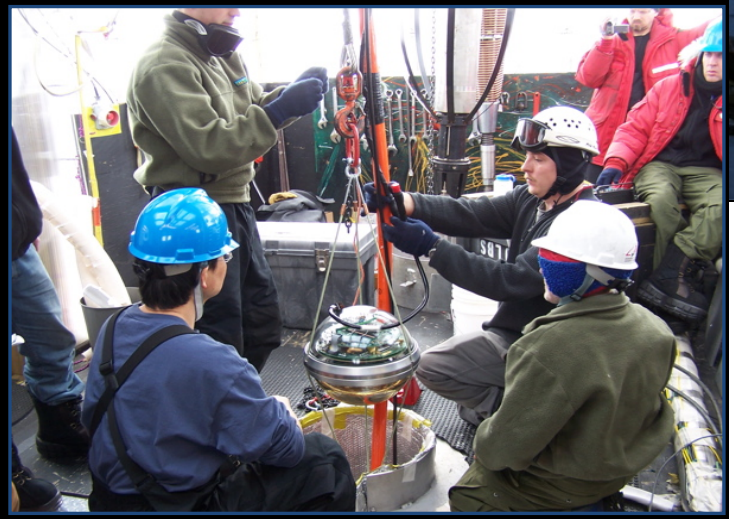
About 2 PeV deposited energy (e.m.eq.)

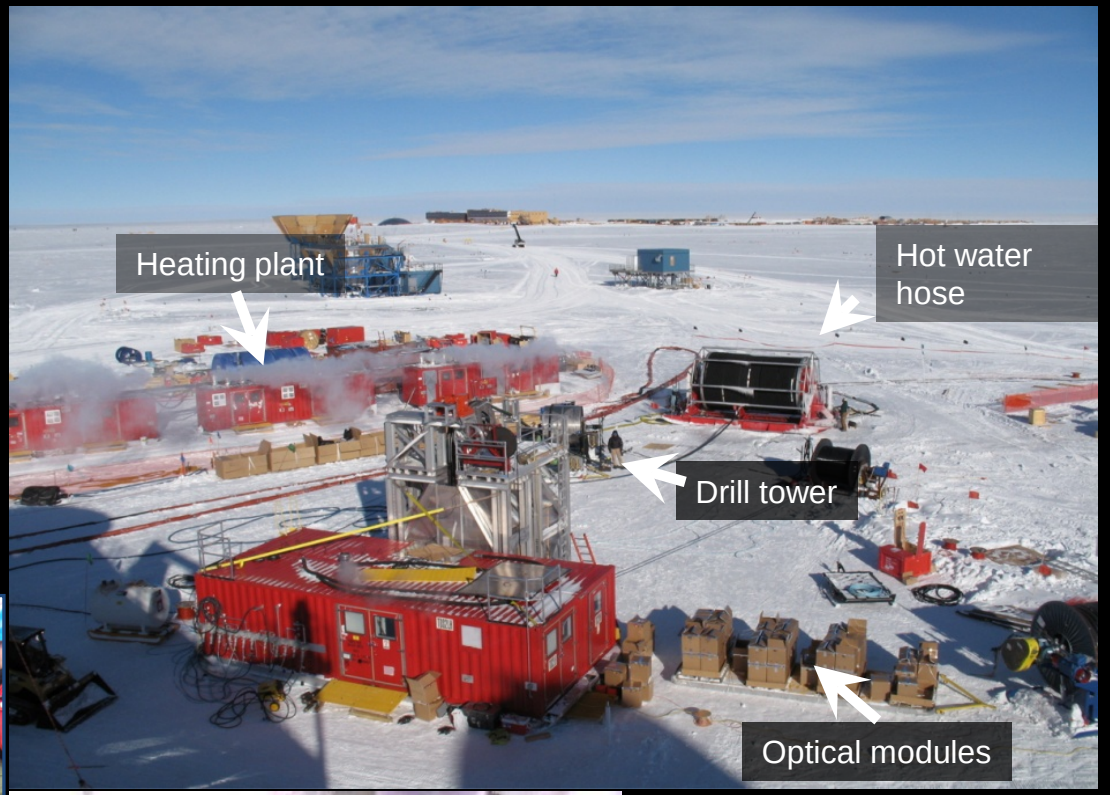
The IceCube Neutrino Observatory at the South Pole



The IceCube Neutrino Observatory: Instrumentation and Online Systems JINST 12 (2017) no.03, P03012, arXiv:1612.05093

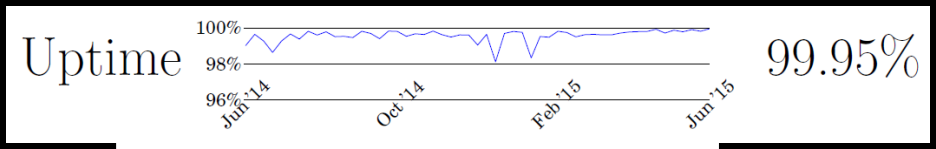
Installation of the IceCube Neutrino Observatory





Detector completed 2010 after 6 years construction

IceCube data taking



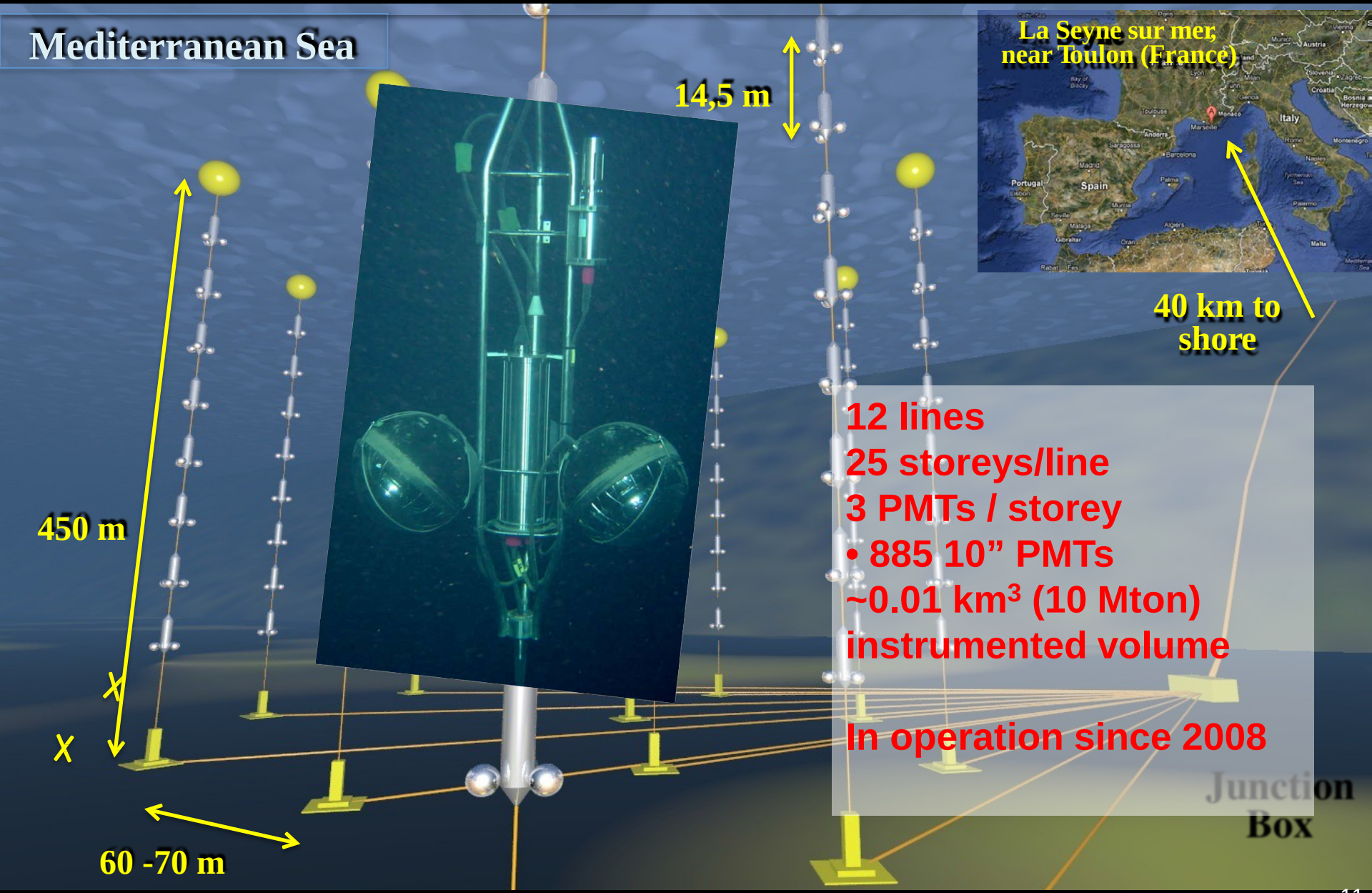
Operation-time > 99.9 %
Physics data > 98.9%

Digital data acquisition at the surface
Automated detector calibration
Automated data processing and transmission by satellite north
Special real-time systems for Alerts (2 minutes latency)

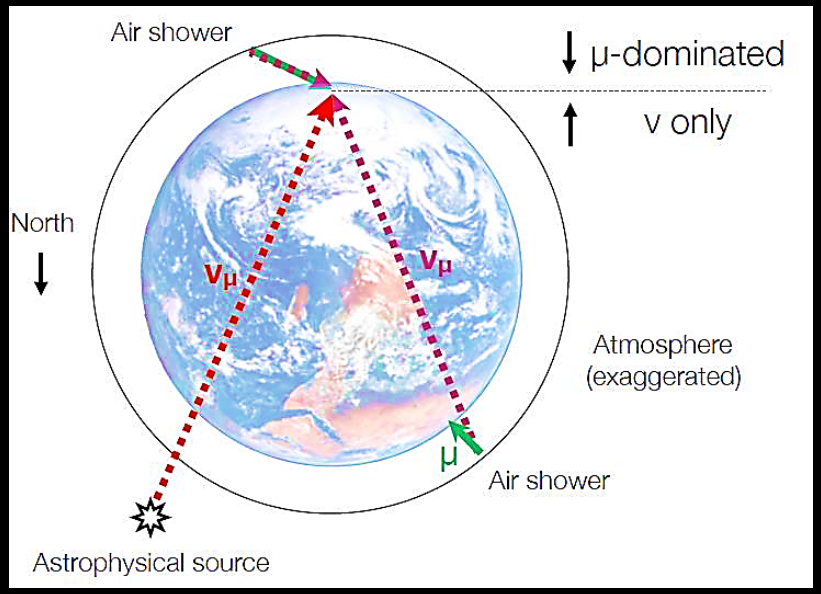
Strings	Year	μ rate	ν_μ rate
IC22	2007	500 Hz	18 / day
IC40	2008	1100 Hz	40 / day
IC59	2009	1700 Hz	130 / day
IC79	2010	2000 Hz	*~170 / day*
IC86	2011	2100 Hz	*~200 / day*

⇒ 1 neutrino (>TeV) every 7 minutes

The ANTARES neutrino telescope



Astrophysical signal and atmopheric foregrounds

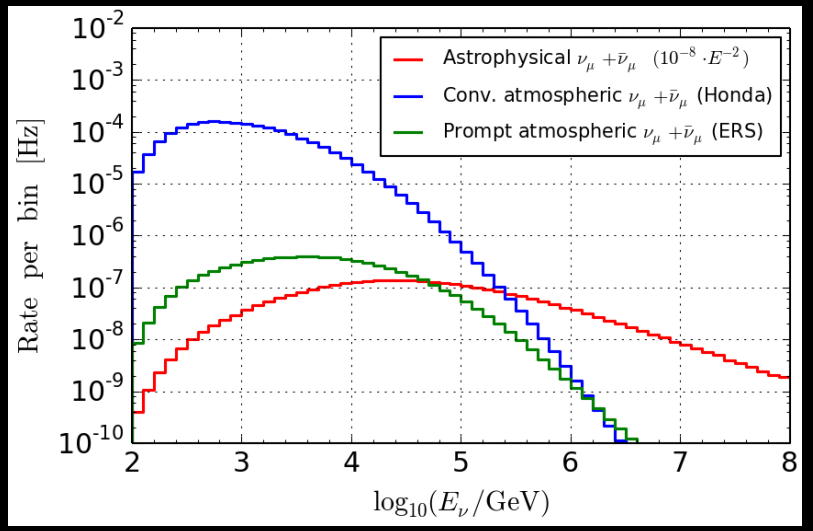


Atmospheric Foreground:

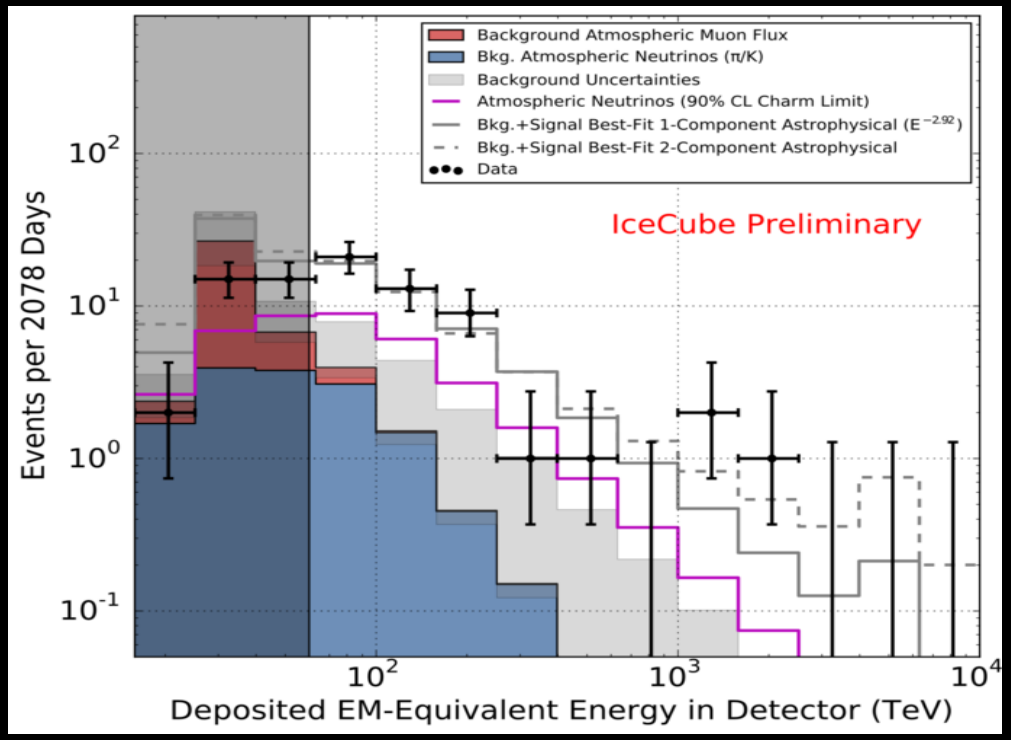
- Atmospheric muons
  - down-going, steep spectrum
  - 2000 / second
- Conventional atmospheric neutrinos
  - All directions, soft spectrum, $E^{-3.7}$
  - 100 k / year
- Prompt from heavy quarks
  - harder spectrum $E^{-3.0}$
    small flux < 20 events/year

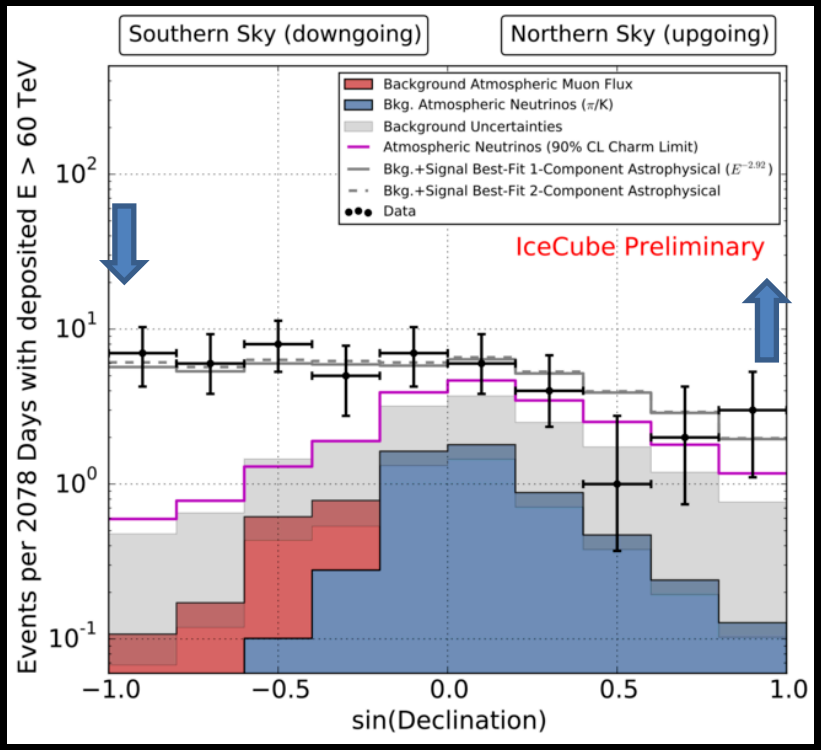
Two independent discovery channels for astrophysical neutrinos

1. HE Starting Events inside detector
   - Mostly down-going (atmospheric self-veto !)
   - All flavor (cascade dominated)
   - 1 astrophysical event / month
2. Uncontained HE up-going muons
   - Largest effective area
   - Largest signal at and below horizon
   - 100 astrophysical events / year



Starting events: 6 Year result (2078 days)





- Observed: 80 *events (+ 2 obvious background)*
- Expected background: 25.2±7.3 (atm.μ) , $15.6^{+11.4}_{-3.9}$ (atm.ν, incl. prompt)
- Angular distribution cannot be described by backgrounds
- Spectrum relatively soft

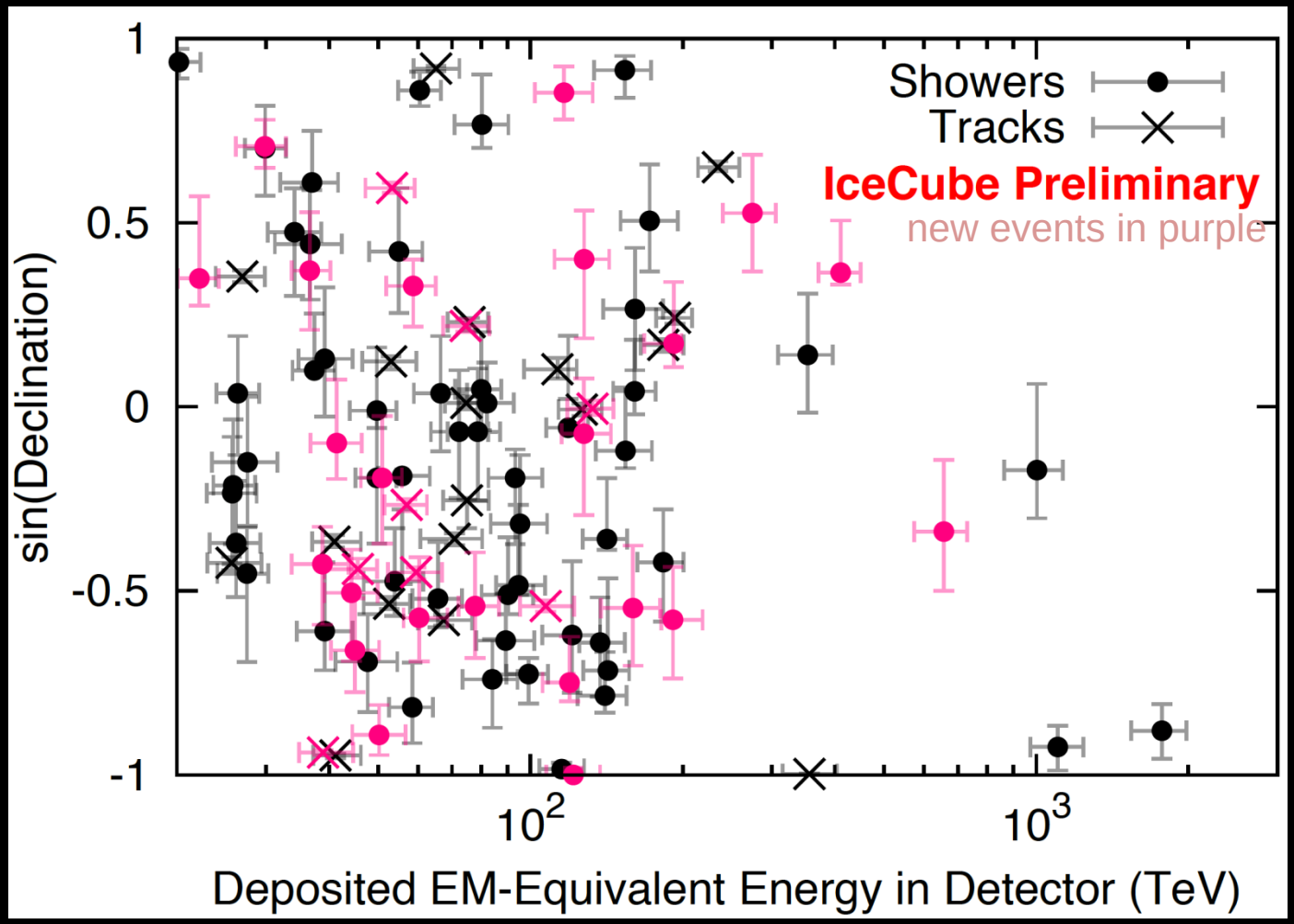
All flavor flux:

$$E^{-2}\phi = 2.46 \pm 0.8 \times 10^{-8} \times (E / 100\text{TeV})^{-0.92}\ \text{GeV cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$$

$$\gamma = 2.92^{+0.33}_{-0.29}$$

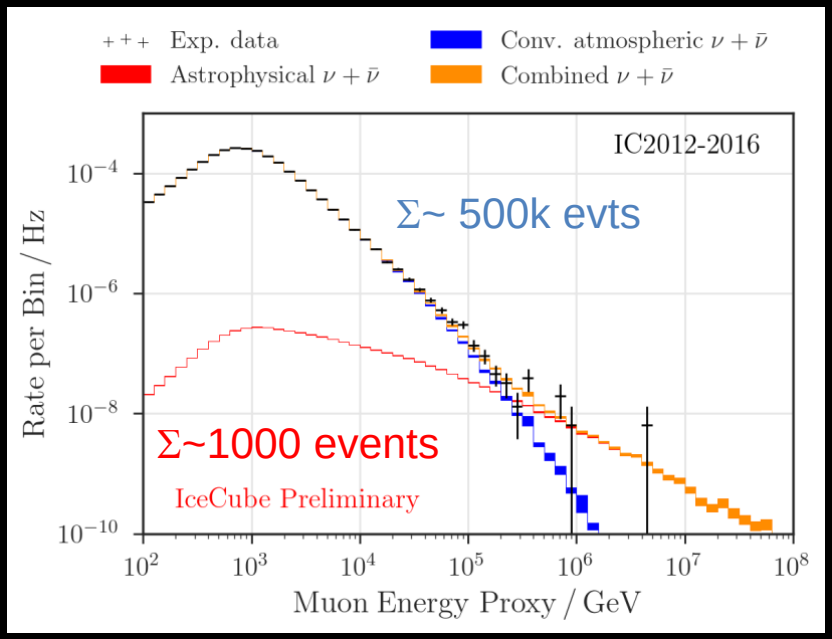
A PeV events ("Ernie", 1.1 PeV) in Aachen-scale

Update: 7.5 Years result (last week Neutrino-2018)

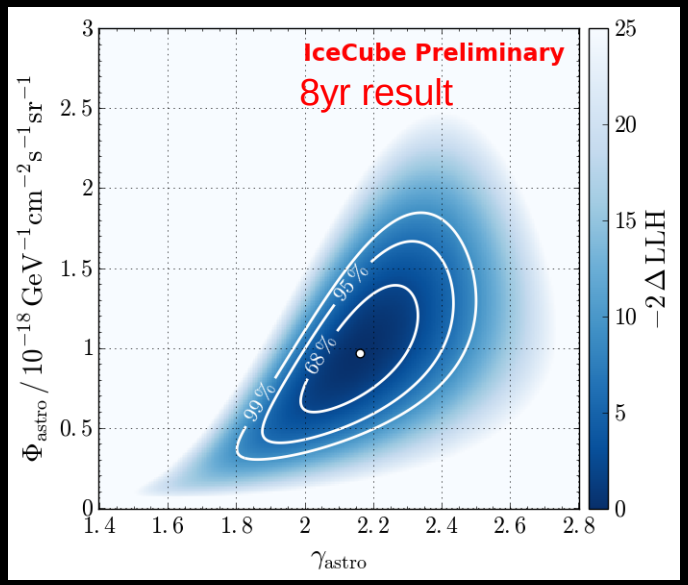


- 103 events total, 60 events with Edep > 60 TeV (>75% astroph. purity)
- Improved calibration and reconstruction
- Spectral fit largely unchainged $\gamma = 2.87 \pm 0.3$
- Work ongoing

Up-going Muons: 8 yr data (2017)

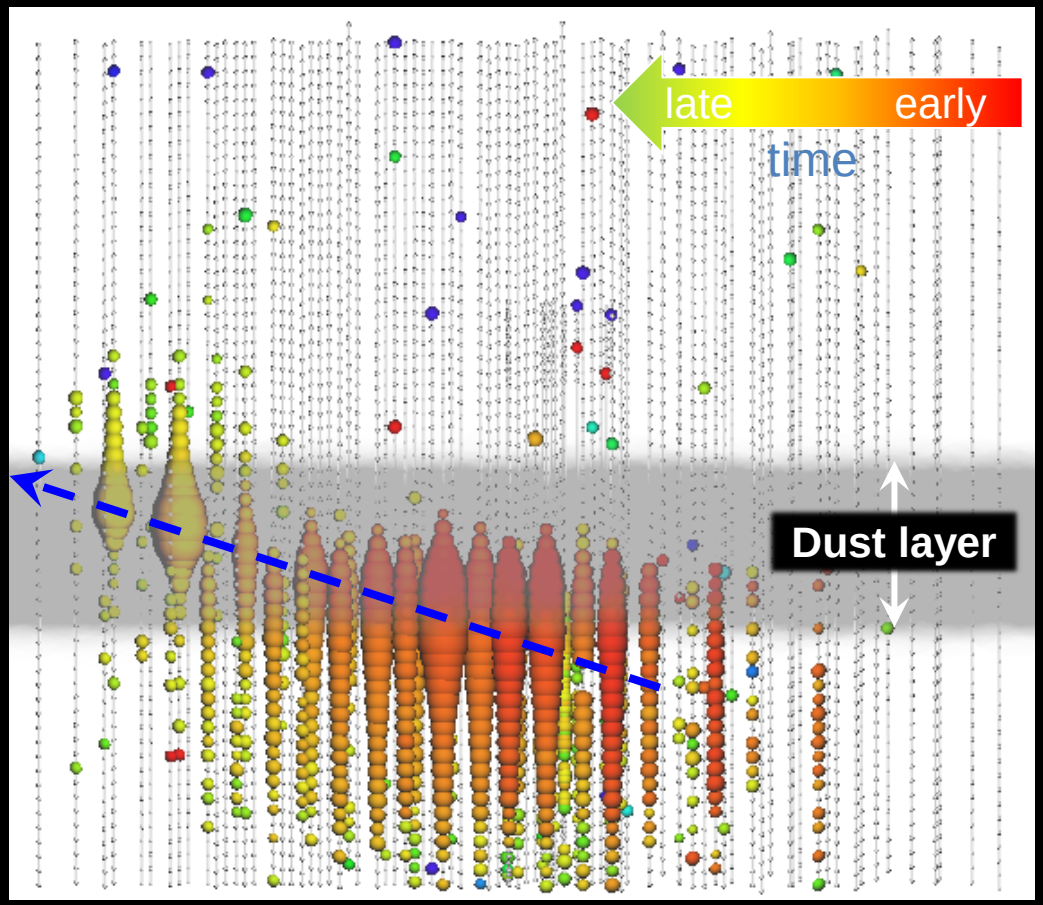


- High statistics
  ~500 000 neutrino events,
  purity > 99.7%
- Global fit of all data set including systematic uncertainties
  ⇒ Excellent agreement with simulation
  Exclusion of atmospheric origin @ 6.7 σ
- Clear high energy excess above about 200TeV

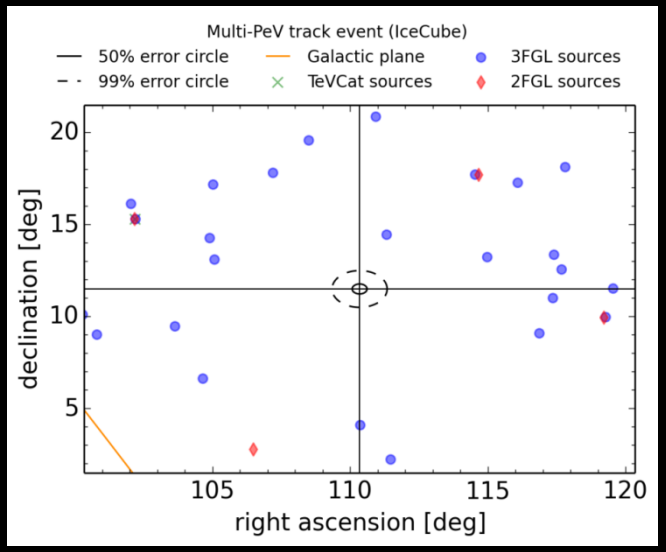


- Astro Flux $\nu_\mu + \bar{\nu}_\mu$ @ 100TeV:
  $(1.01^{+0.26}_{-0.23}) \times 10^{-18}\ \mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$
- Hard Spectral index:
  $\gamma_{\mathrm{astro}} = 2.19 \pm 0.10$
- No indication of prompt
- 36 events E_μ> 200TeV (p_{astro} >50%)
- Total ~1000 astrophysical neutrinos with good pointing

Multi-PeV track event, June 11th 2014



Declination 11.48 deg, Right Ascension 110.34 deg



- $E_{deposit}$ = 2.6 ± 0.3 PeV
- Muon energy **4.5 PeV** (median)
- **Neutrino energy 8.7 PeV** (median)
- Directional error (stat.+sys.):~0.27°
- p-value < 0.01% to be of atmospheric origin (4σ)

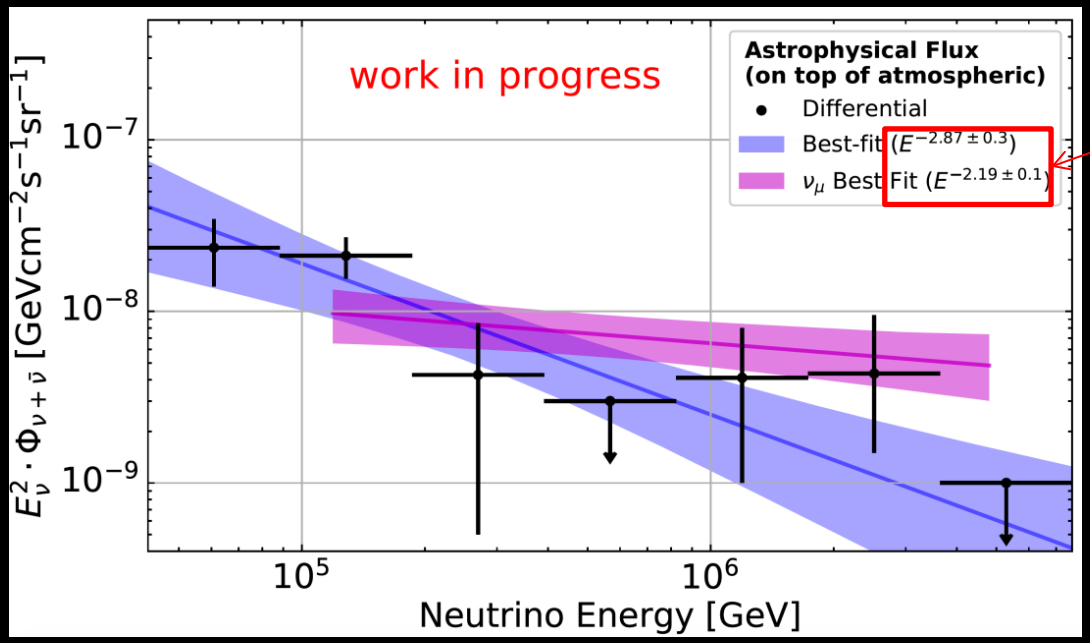
⇒ evident cosmic ν by itself
⇒ No known gamma sourse nearby

Astronomer's Telegram (ATEL): #7856, arXiv:1607.08006 [astro-ph.HE]

C. Characterisation of the cosmic neutrino flux

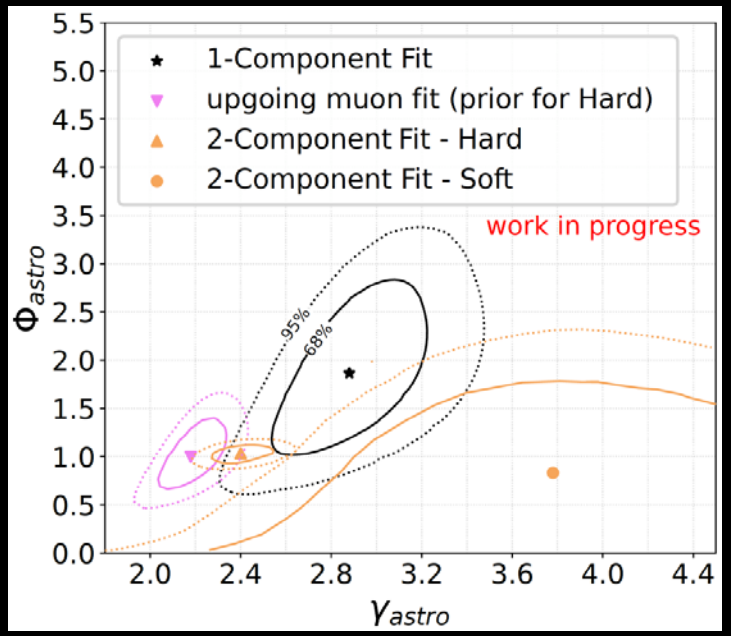
- Is there a spectral break/tension ?
- Is there a spectral cut off ?
- Are there Glashow-resonance events at 6.5 PeV ?
- What is the flavor composition ?
- Are there ν_τ ?
- Are there indications of prompt atmospheric neutrinos from charmed meson decays

Spectral Comparison: HESE &Muons (Neutrino2018)



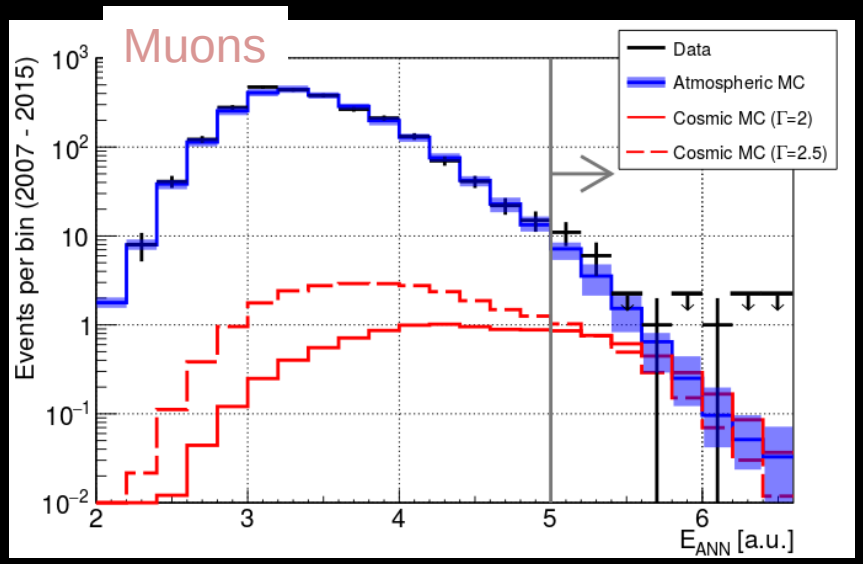
- Overal tension in spectral slope
- Rate of HE events consistent

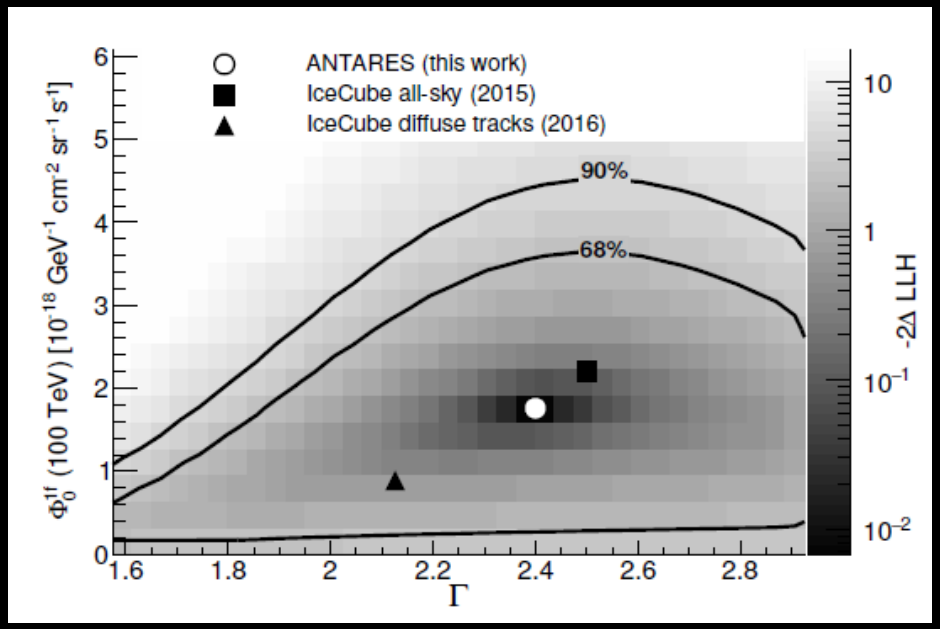
Indications of a spectral break?

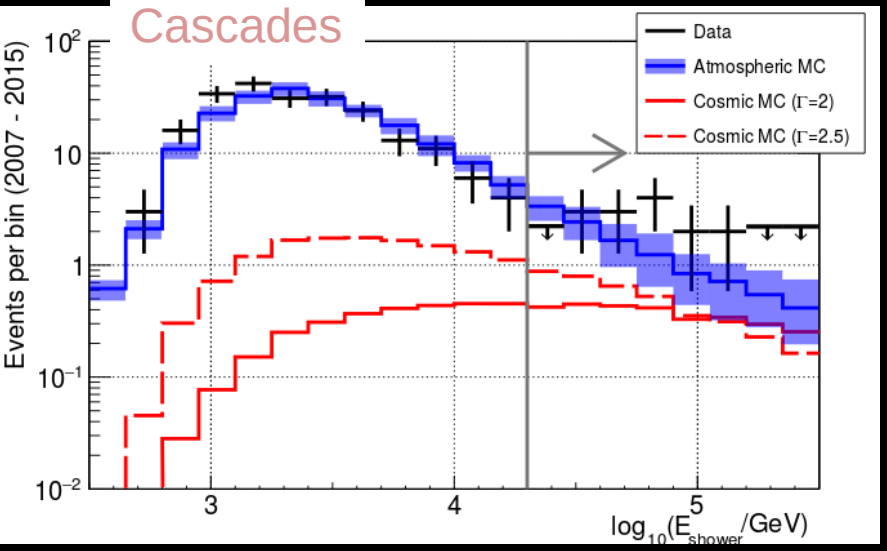


Two component fit of HESE data with muon fit as prior is not yet statistically conclusive

Multi-flavor Searches by ANTARES



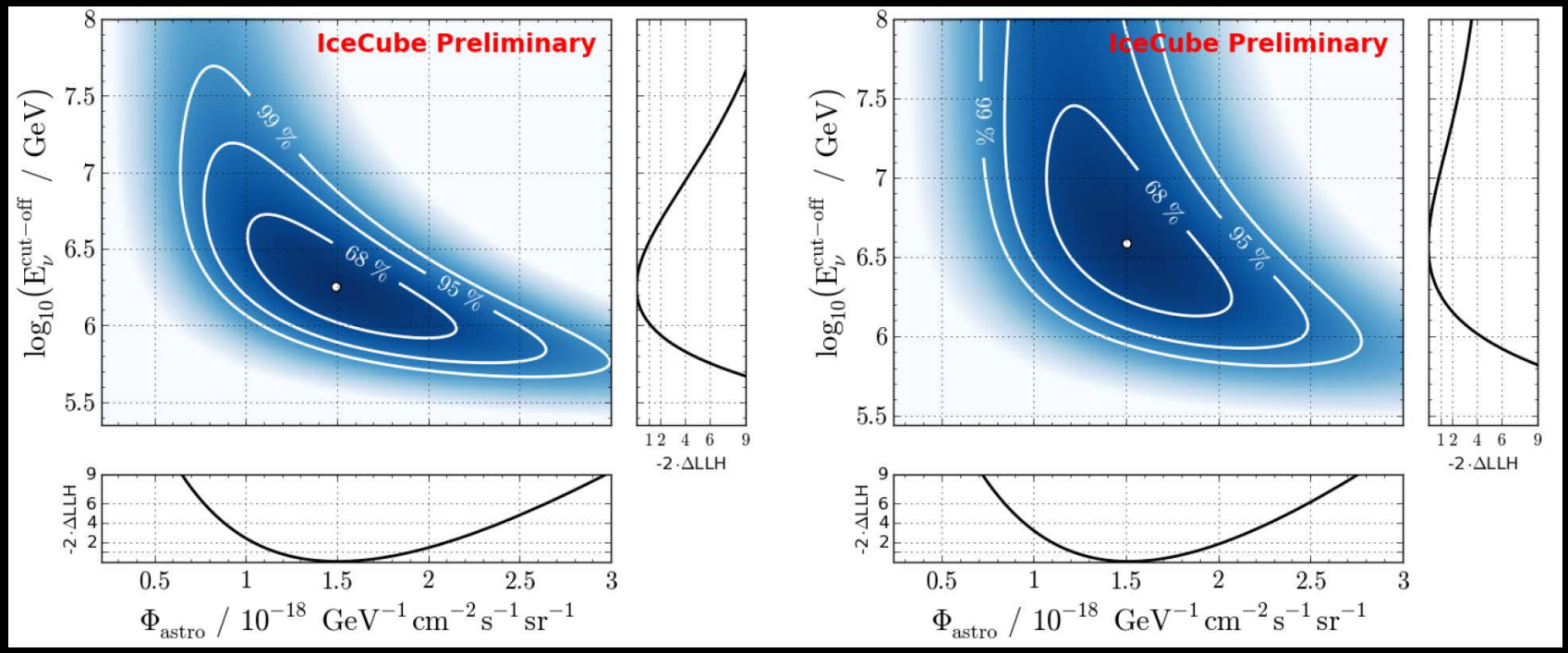




- 9 year observational data of high-energy tracks and cascades
- 1.6 σ excess, consistent with IceCube observation

arXiv:1711.07212v1

8 years up-going muons
Testing astrophysical flux for a cut-off



- Model:

$$\frac{d\phi}{dE} = N_a \cdot E^{-2} \cdot \exp\left(\frac{E}{E_{\text{cut-off}}}\right)$$

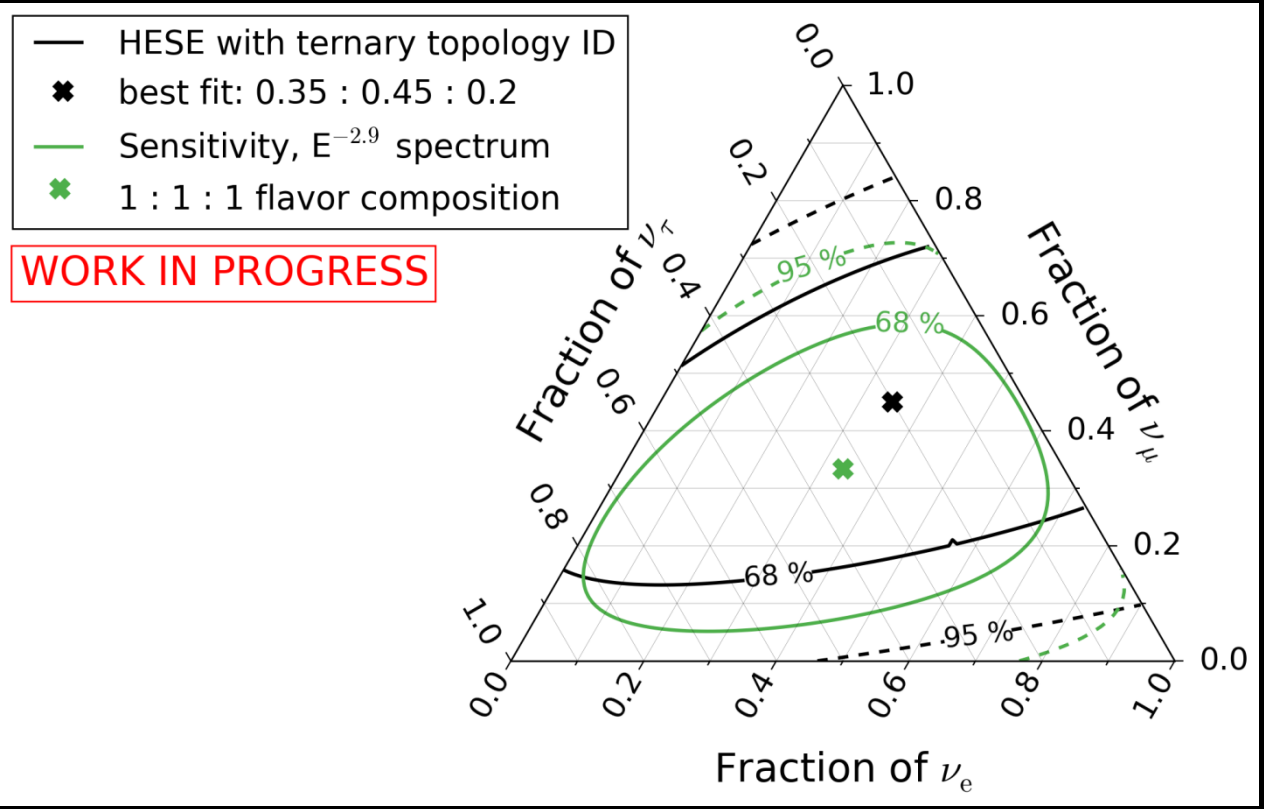
- Model:

$$\frac{d\phi}{dE} = N_a \cdot E^{-2.19} \cdot \exp\left(\frac{E}{E_{\text{cut-off}}}\right)$$

- For a hard γ=2.0 spectrum a cut-off at 2 PeV is preferred at the 4 σ level.
- For the best-fit spectrum hard γ=2.19 a cutoff is not significant (<2σ)

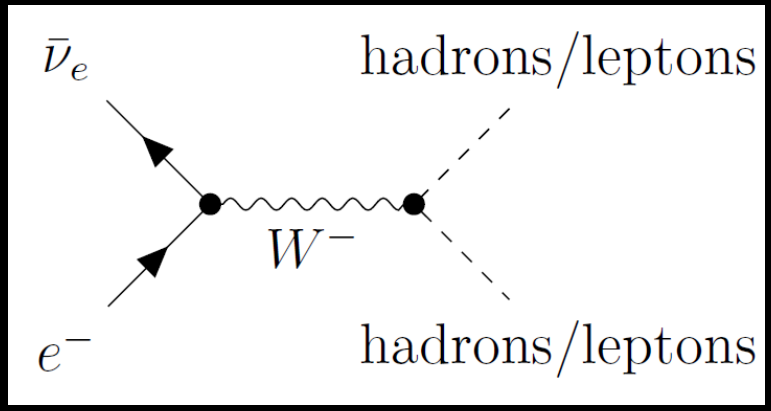
Low energy resolution: muons cannot distinguish a soft spectral index from a cut-off

Flavor analysis of HESE data (Neutrino2018)

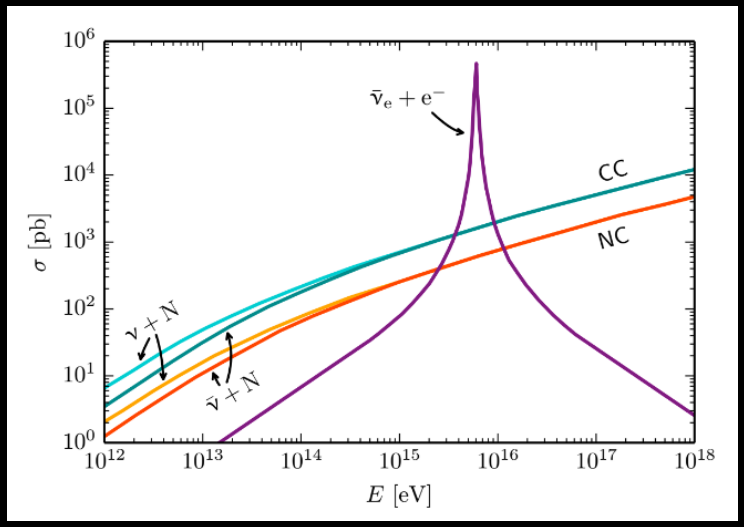


- Result consistent with full 1:1:1 mixing
- Neutrino oscillations over >Mpc baselines
- Single flavor fluxes excluded
- Neutron decay scenario disfavored

Glashow resonance for $\bar{\nu}_e$ at 6.3PeV



S. L. Glashow, Phys. Rev. 118 (1960) 316-317.



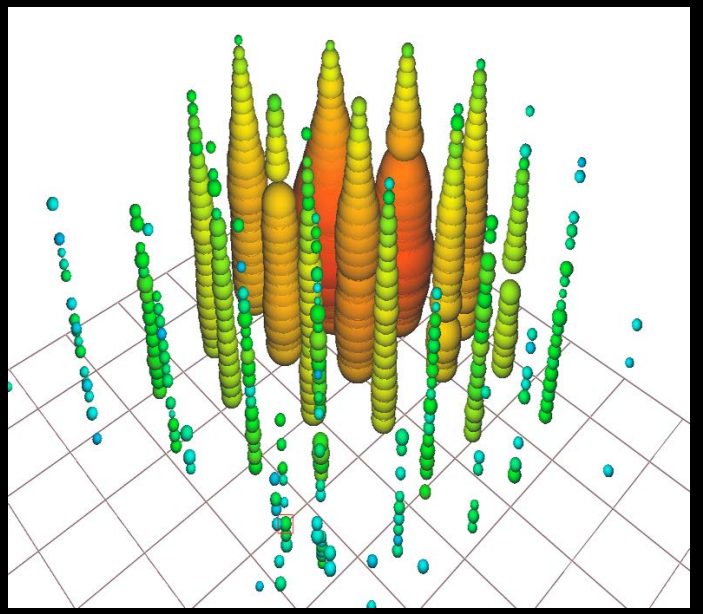
Resonance: Ev = 6.3 PeV
Typical hadronic visible energy is 93%

Observed partially-contained event
Evis = 5.9±0.18 PeV (stat)
Indications of hadronic origin

Very difficult analysis in terms of background and systematics

Implications:

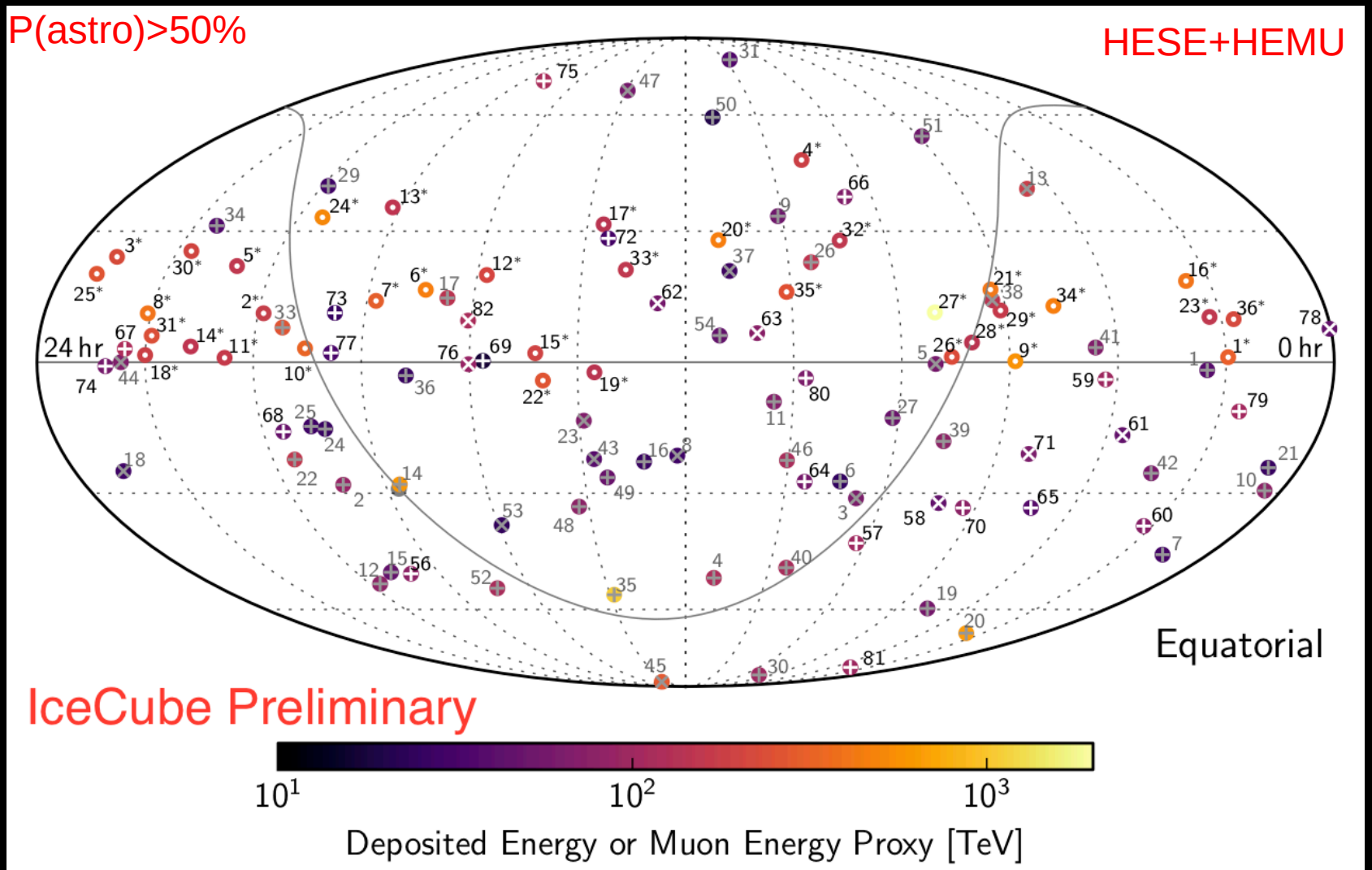
- Non-Existence of a cut-off
- Evidence for $\bar{\nu}$
- Measure $\bar{\nu}$ /ν flux ratio



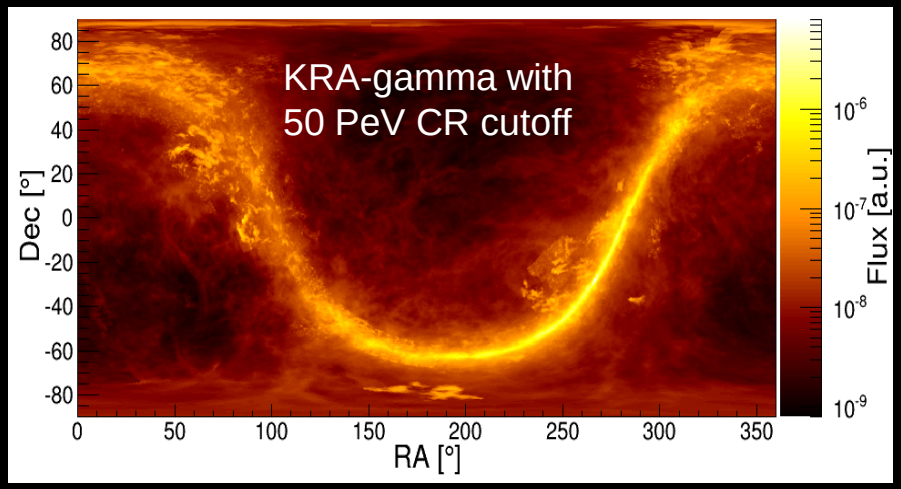
D. Search for the origin of the cosmic neutrinos

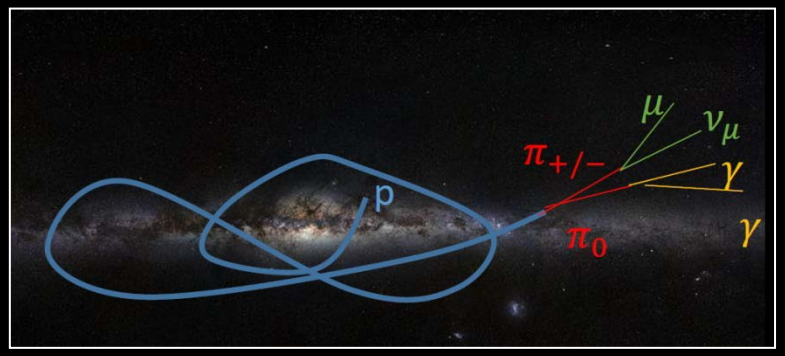
- Where do the highest energy events come from?
- Search for a galactic component ?
- Search for point sources ?
- Gamma follow-up for Neutrino alerts ?
- Are there indications of weak clustering?
- Alternative scenarios: decaying heavy dark matter ?

The high-energy neutrino sky (2017)



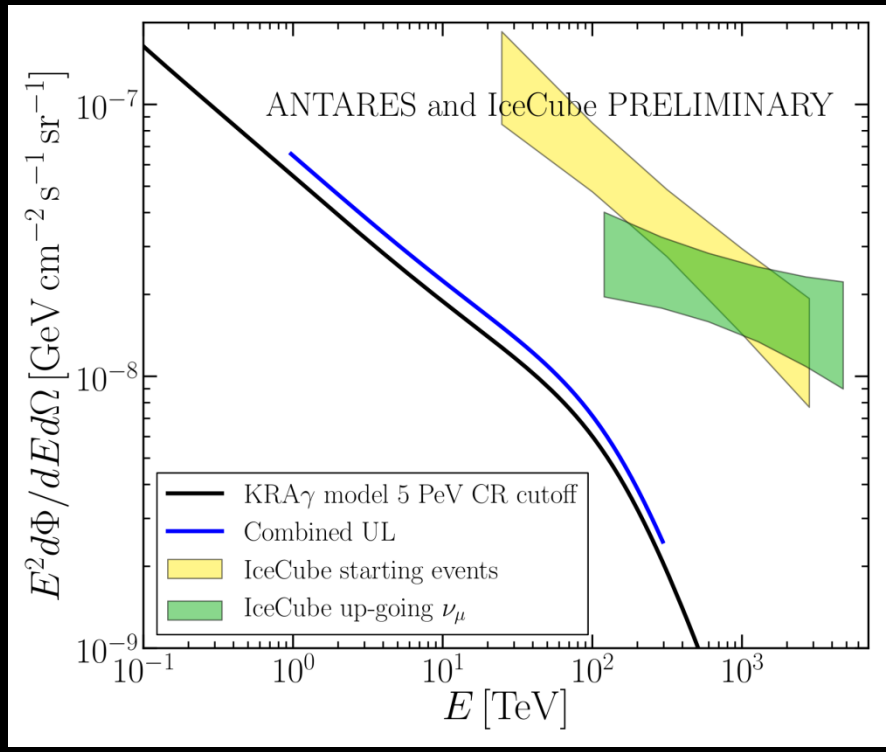
Galactic plane: Combined IceCube Antares Result





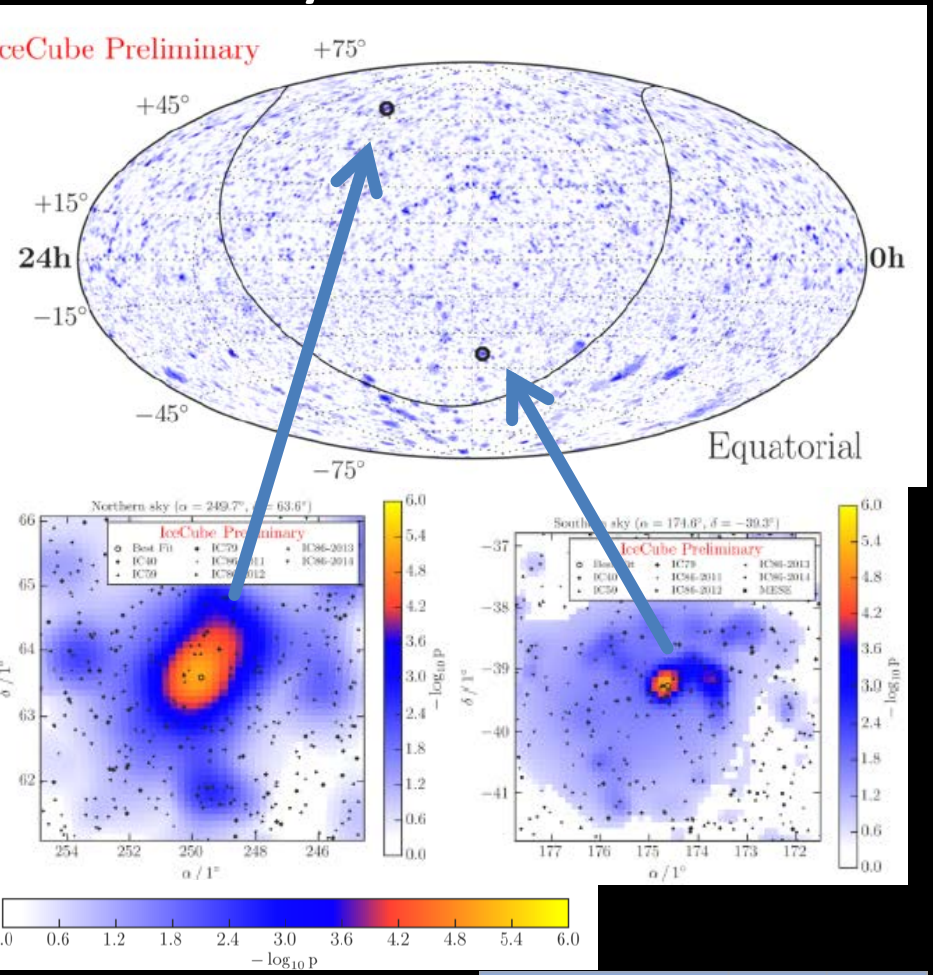
Guaranteed (but weak) flux from galactic plane due to CR interactions with the ISM

- Expect ~40 ν/a
- Measurement observes slight overfluctuation
- Upper limit very close to realistic estimate



(ANTARES) Phys. Rev. D96 (2017) 062001
(IceCube) ApJ 849 (2017) 67
Combined result in preparation

All-sky Point source searches 7 years (2008-2014)



Total events: 424,000 (upgoing)
+ 289,000 (downgoing)
+ 1700 starting
Livetime: 7 year data , 2431days

- *No significant excess*
- *No significant time variability*
- *No spot of increasing significance with time*
- *No significant correlation with known TeV gamma sources*
- *No significant extended sources*
- *No significant signal from galactic plane*
- *No signal from GRB*

Hemisphere	North	South
N_Sources	27.22	15.54
Gamma	1.95	2.84
Test statistic	18.99	20.26
-log10(Pre-Trial P)	5.24	5.33
Post Trial P	44%	39%

New analysis with diffuse sample and constraints is underway

arXiv:1609.04981

Test of prominent astrophysical objects (8a ICRC 2017)

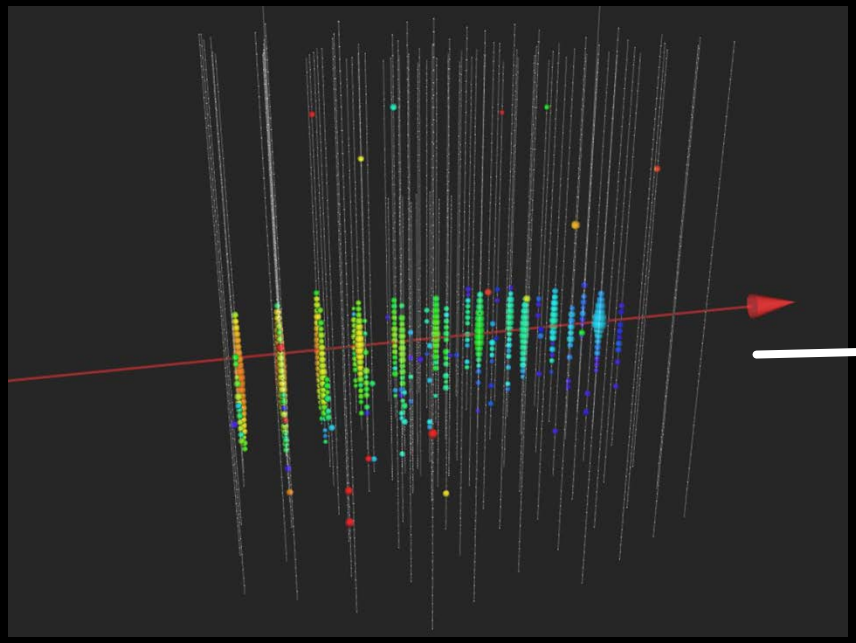
4 sources in the source list result in a pre-trial p-value < 1%

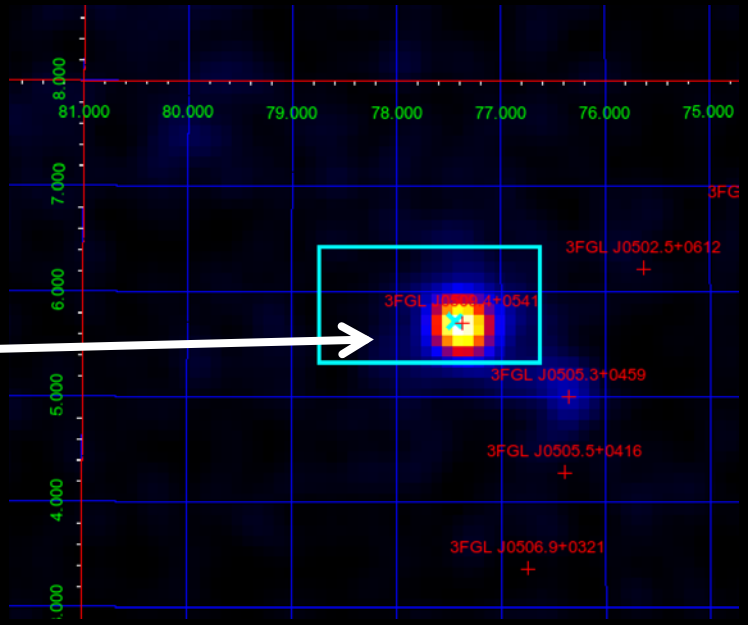
- 1 galactic: MGRO J1908
- 2 FSRQ: 4C38.41, 3C454.3
- 1 FR-II radio galaxy: Cyg-A
- Hottest source: pre-trial 0.3% post-trial 10.2%

Source	Type	α [deg]	δ [deg]	p-value	TS	n_s	Φ_0 [TeV cm^{-2} s^{-1}]
MGRO J1908+06	NI	286.99	6.27	0.0032	6.284	3.28	$1.13 \cdot 10^{-12}$
Cyg A	SRG	299.87	40.73	0.0049	6.335	4.30	$1.78 \cdot 10^{-12}$
4C 38.41	FSRQ	248.81	38.13	0.0055	5.686	6.62	$1.72 \cdot 10^{-12}$
3C454.3	FSRQ	343.50	16.15	0.0072	5.503	5.98	$1.26 \cdot 10^{-12}$
Crab Nebula	PWN	83.63	22.01	0.1188	0.709	4.32	$8.65 \cdot 10^{-13}$
Cas A	SNR	350.85	58.81	0.2069	0.033	0.88	$1.05 \cdot 10^{-12}$
1ES 1959+650	BL Lac	300.00	65.15	0.2069	0.124	1.69	$1.17 \cdot 10^{-12}$
PKS 1502+106	FSRQ	226.10	10.52	0.2322	-0.000	0.00	$5.98 \cdot 10^{-13}$
Mrk 421	BL Lac	166.11	38.21	0.2433	0.029	0.48	$8.68 \cdot 10^{-13}$
NGC 1275	SRG	49.95	41.51	0.2582	0.007	0.25	$8.31 \cdot 10^{-13}$
LSI 303	XB/mqso	40.13	61.23	0.2843	0.001	0.17	$1.01 \cdot 10^{-12}$
PKS 0528+134	FSRQ	82.73	13.53	0.2870	-0.002	0.00	$5.74 \cdot 10^{-13}$
Cyg OB2	SFR	308.09	41.23	0.3174	-0.002	0.00	$7.53 \cdot 10^{-13}$
Cyg X-3	XB/mqso	308.11	40.96	0.3230	-0.003	0.00	$7.28 \cdot 10^{-13}$
3C66A	BL Lac	35.67	43.04	0.3306	-0.001	0.00	$7.50 \cdot 10^{-13}$
3C 273	FSRQ	187.28	2.05	0.3807	-0.014	0.00	$4.42 \cdot 10^{-13}$
W Comae	BL Lac	185.38	28.23	0.4420	-0.055	0.00	$5.37 \cdot 10^{-13}$
TYCHO	SNR	6.36	64.18	0.4471	-0.019	0.00	$8.14 \cdot 10^{-13}$
1ES 0229+200	BL Lac	38.20	20.29	0.4762	-0.059	0.00	$4.47 \cdot 10^{-13}$
BL Lac	BL Lac	330.68	42.28	0.5104	-0.028	0.00	$5.58 \cdot 10^{-13}$
Cyg X-1	XB/mqso	299.59	35.20	0.5422	-0.106	0.00	$4.93 \cdot 10^{-13}$
M87	SRG	187.71	12.39	0.6711	-0.256	0.00	$2.85 \cdot 10^{-13}$
Mrk 501	BL Lac	253.47	39.76	0.6847	-0.172	0.00	$3.51 \cdot 10^{-13}$
S5 0716+71	BL Lac	110.47	71.34	0.7230	-0.380	0.00	$3.84 \cdot 10^{-13}$
PKS 0235+164	BL Lac	39.66	16.62	0.7355	-0.400	0.00	$2.04 \cdot 10^{-13}$
H 1426+428	BL Lac	217.14	42.67	0.7890	-0.243	0.00	$1.96 \cdot 10^{-13}$
IC443	SNR	94.18	22.53	0.8153	-0.457	0.00	$1.22 \cdot 10^{-13}$
HESS J0632+057	XB/mqso	98.24	5.81	0.8359	-0.917	0.00	$1.01 \cdot 10^{-13}$
SS433	XB/mqso	287.96	4.98	0.8738	-1.085	0.00	$1.01 \cdot 10^{-13}$
M82	SRG	148.97	69.68	0.8887	-0.888	0.00	$1.83 \cdot 10^{-13}$
3C 123.0	SRG	69.27	29.67	0.9055	-0.747	0.00	$1.30 \cdot 10^{-13}$
1ES 2344+514	BL Lac	356.77	51.70	0.9264	-0.808	0.00	$1.58 \cdot 10^{-13}$
Geminga	PWN	98.48	17.77	0.9754	-2.424	0.00	$1.16 \cdot 10^{-13}$
MGRO J2019+37	PWN	305.22	36.83	0.9884	-3.191	0.00	$1.39 \cdot 10^{-13}$
Hottest spot of the unbiased scan on the Northern hemisphere							
				$10^{-5.14}$	17.271	10.28	—

MGRO J1908 is a known γ-source observed by HAWC >50TeV

The alert IceCube-20170922A and TXS 0506+056

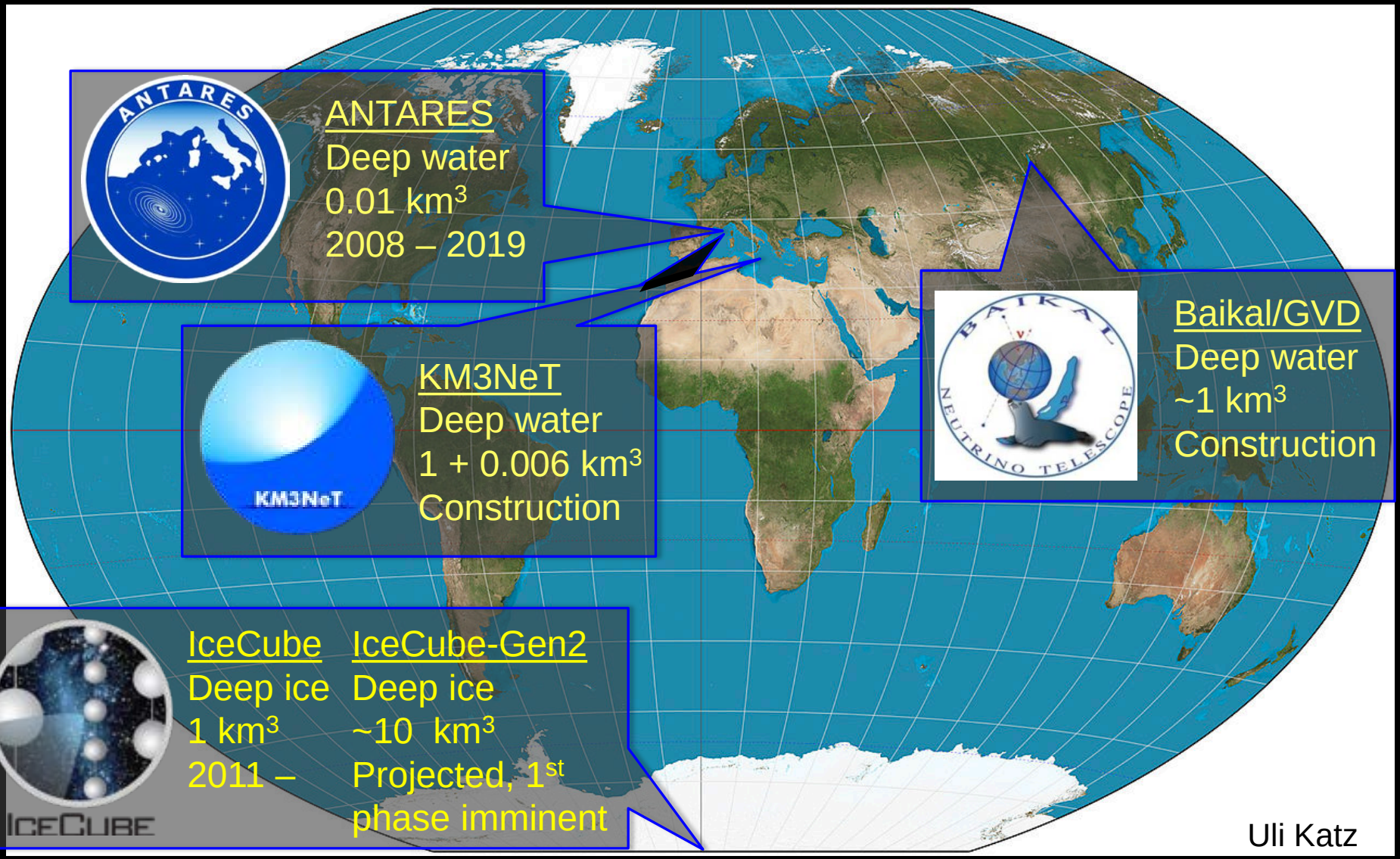




- **22.9 2017 :** Observation of a high-energy neutrino (p(astro)>50%) with good direction
- Alert triggers follow-up observations by 16 astronomical telescopes from radio to HE-γ
- Known Blazar TXS-0506+056 agrees within 0.1°with the neutrino direction
- FERMI: TXS-0506+056 is in strongly flaring state
- MAGIC: detects source at high energy: first discovered HE Blazar based on neutrino alert

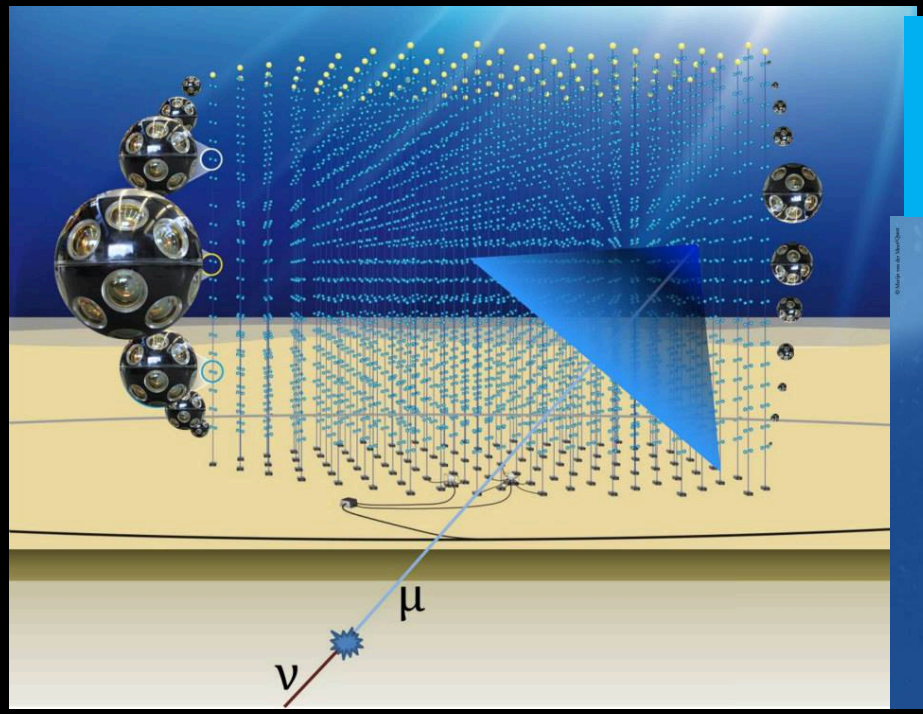
Full information to be released on July 12th 18:00 CET in press conference by NSF

E.Next-generation instruments

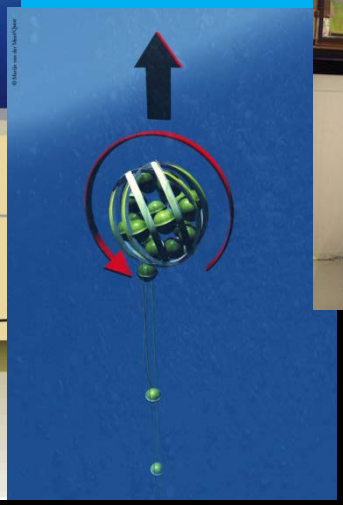


Future in the Mediterranean: ARCA and ORCA

Two sites: Toulon (ORCA), Catania (ARCA)



115 string/block
18 Detection Units/string
31 PMT per DU



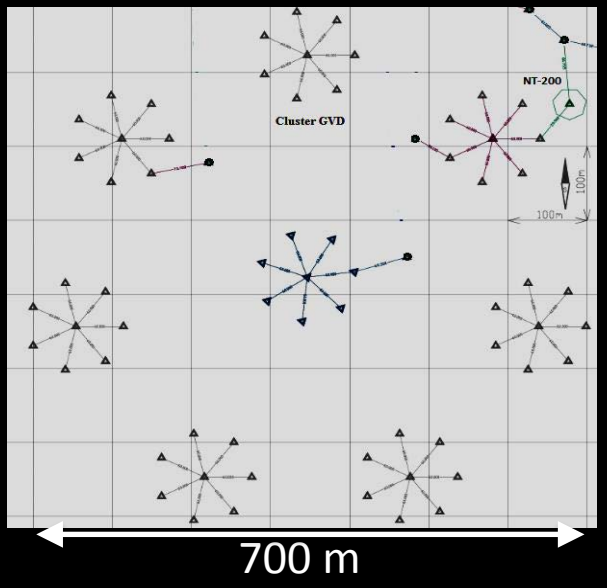
Phase	ORCA (Low energy) 9m DU spacing 20m string spacing	ARCA (High energy) 36m DU spacing 90m string spacing
I: 2019-20	6 strings	24 strings
II: 2020-22	1 block of 115 strings	2 blocks of 115 strings
III: >2023	1 block of 115 strings	6 blocks of 115 strings

- 3 ARCA strings deployed, 2015-17
- 1 ORCA string deployed 2017
- Operation until technical problems (power, cables) stopped operations
- First atmospheric neutrinos observed

Baikal-GVD: Gigaton detector in Lake Baikal

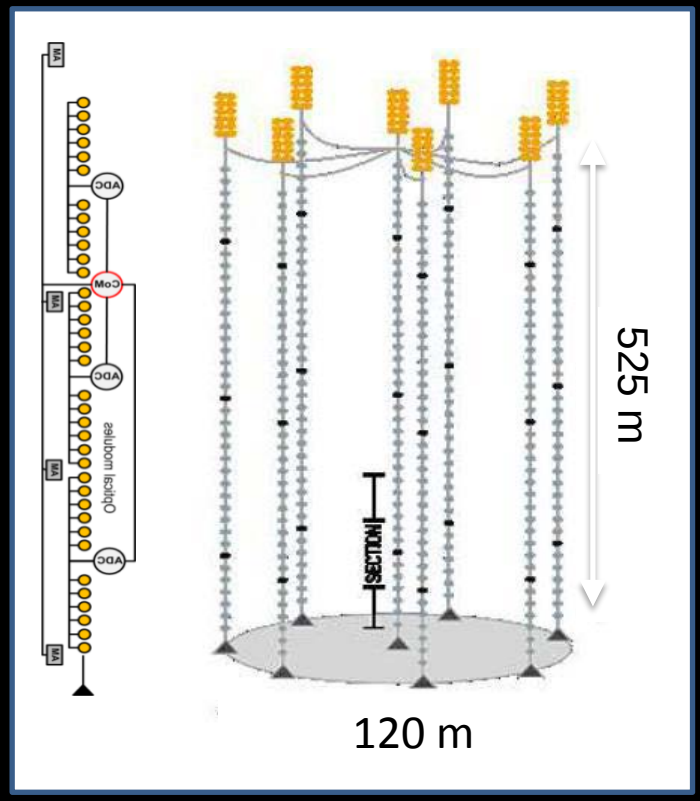
Phase 1 (GVD-1):

- 8 clusters, 0.4 km^3
- 3 Clusters installed, operating
- Completion by 2020
- First atm. Neutrinos detected
- Observed 1 event ~157 TeV



Final goal: 27 clusters, 1.5 km^3

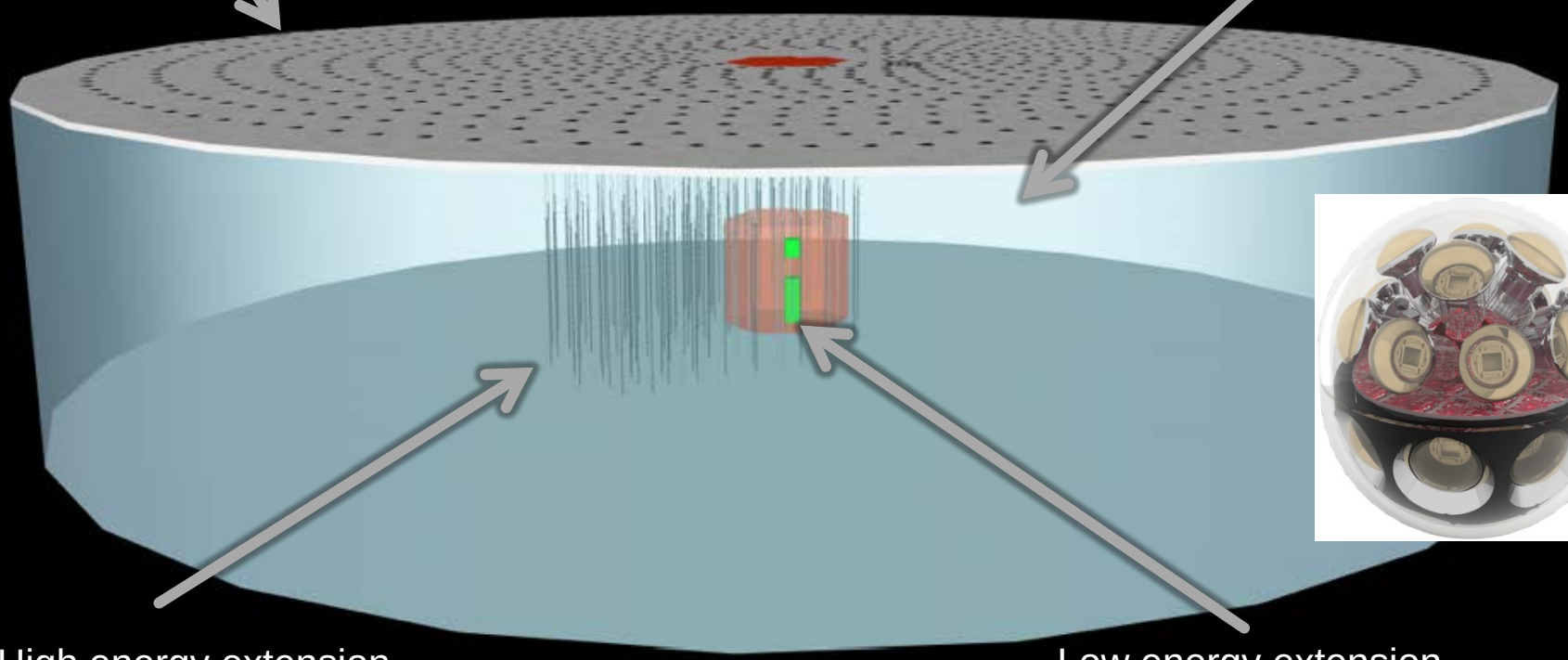
Currently largest neutrino detector in the Northern hemisphere



IceCube Gen-2

Surface veto extension
"IceVeto: IceScint, IceAct"
75 km^2 array
100TeV threshold

InIce Radio detection
Near below surface antennas
Optionally surface antennas



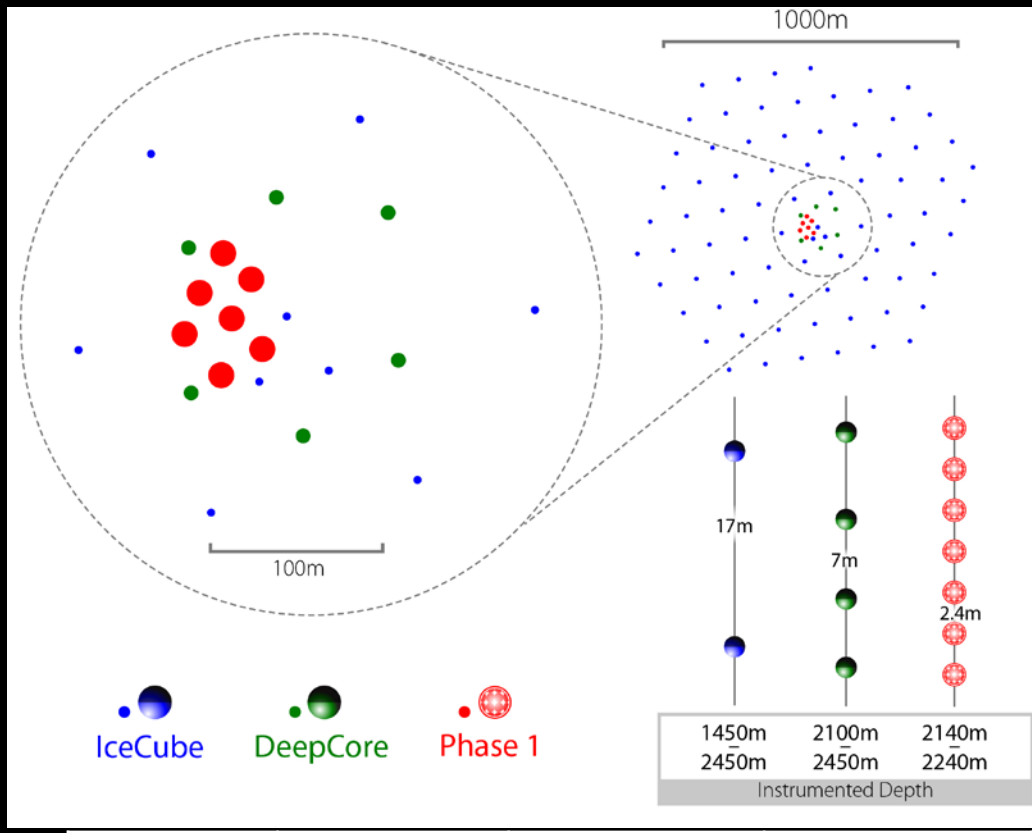
High energy extension
"HEX"
120 strings, 250m spacing
80 DOM/string, 1.35km long
5-10km^3

Low energy extension
"PINGU"
40 strings, 22m spacing,
192 DOMs/string, 3 m vertical
embedded in DeepCore
~5 Mton, 3GeV threshold

IceCube Upgrade (Gen2-Phase1)

IceCube-Upgrade

- 7+x additional strings in Deep Core domain, densely instrumented
- Objectives:
  - GeV neutrinos: τ appearance, PNMS Matrix unitarity,…
  - Improved calibration of ice properties → reduced systematic uncertainties
  - R&D for Gen2 (drill)
- Funding commitment expected very soon



Array	String Spacing	Module Spacing	Modules / String
IceCube	125 m	17 m	60
DeepCore	75 m	7 m	60
Upgrade	20 m	2 m	125

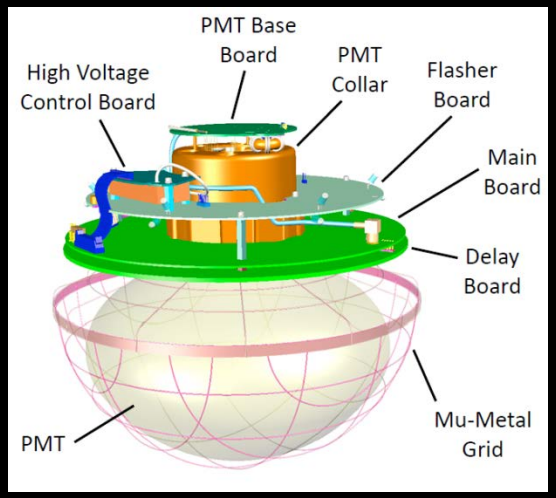
Summary

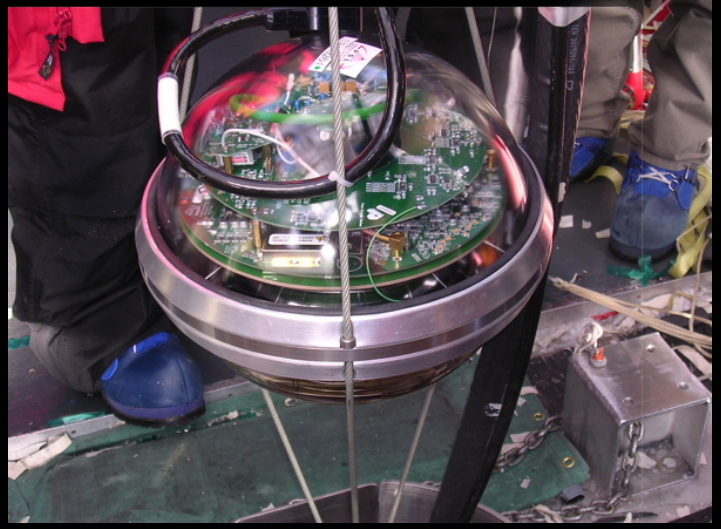
- Neutrino telescopes open a new window to the Universe from TeV to EeV
- High energy cosmic Neutrino flux has been discovered by IceCube in 2 (+1) independent detection channels with high significance
- Sources are unknown to date
- Soft spectrum at low energy and hard at higher energy
  - Spectral break at 100-200 TeV
  - North-South difference of the diffuse flux
  - ?????
- No conclusion on a cut-off at PeV energy
  - Softer spectra do not require cut-off
  - Candidate of a Glashow event
- No evident tau detection, but data consistent with 1:1:1 scenario
- No positive identification of galactic plane (yet)
- Observation of a neutrino in coincidence with the flaring Blazar TXS

- New results coming soon
  - Press conference July, 12th 2018
- New instruments:
  - KM3NeT: ARCA & ORCA by 2020 (?)
  - IceCuube Upgrade by 2022/23, IceCube Gen2 in preparatio in parallel
  - Baikal GVD

Backup

Digital Optical Modules (DOM)





- 99.1% (5435) DOMs have survived installation
- Failure rate: ~1-2/year ⇒ MTBF: 850 years
- After >15 years operation (2025) we expect 97.2 %±0.4% of the detector remains operational

Low noise 10” PMT Hamamatsu R-7081

Time resolution 2ns , Deadtime < 1%

Dynamic range: 500pe/15 ns, $25 \cdot 10^3$ pe/6.4 μs

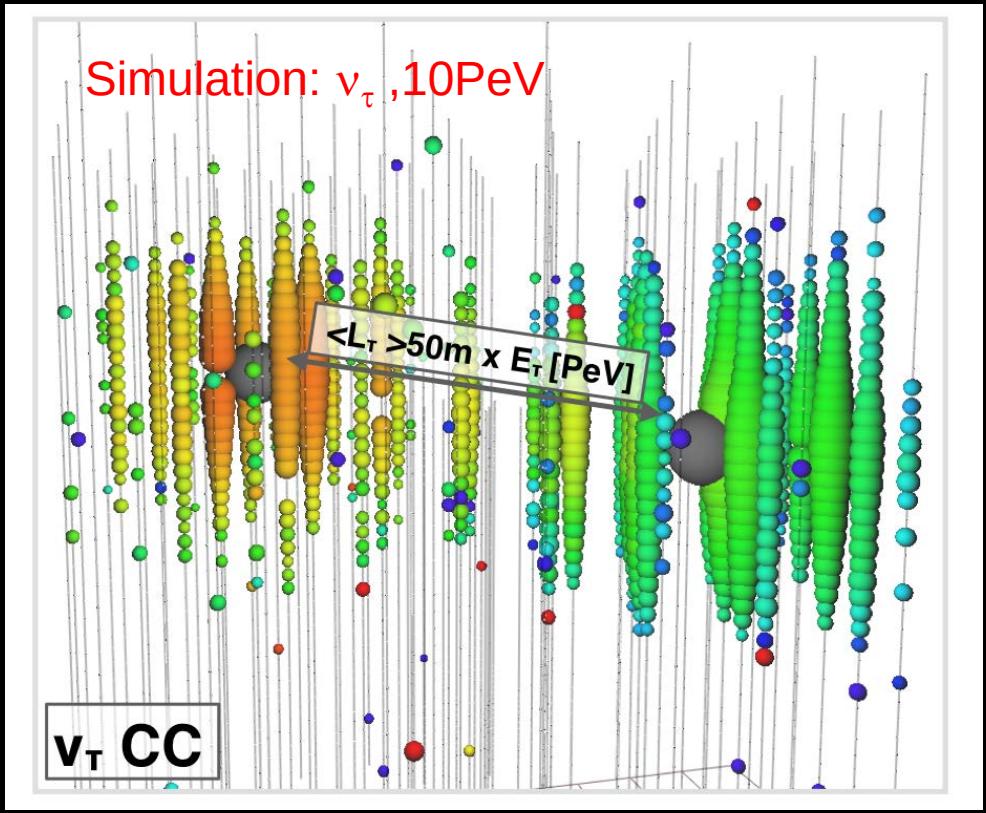
12 controllable LEDs at 0^o or 45^o

Fully digital surface DAQ,

Fully automized calibration and synchronization with the surface (< 2ns precision)

Each DOM is an autonomous detector unit

A smoking gun: Double-Bang of high energy ν_τ

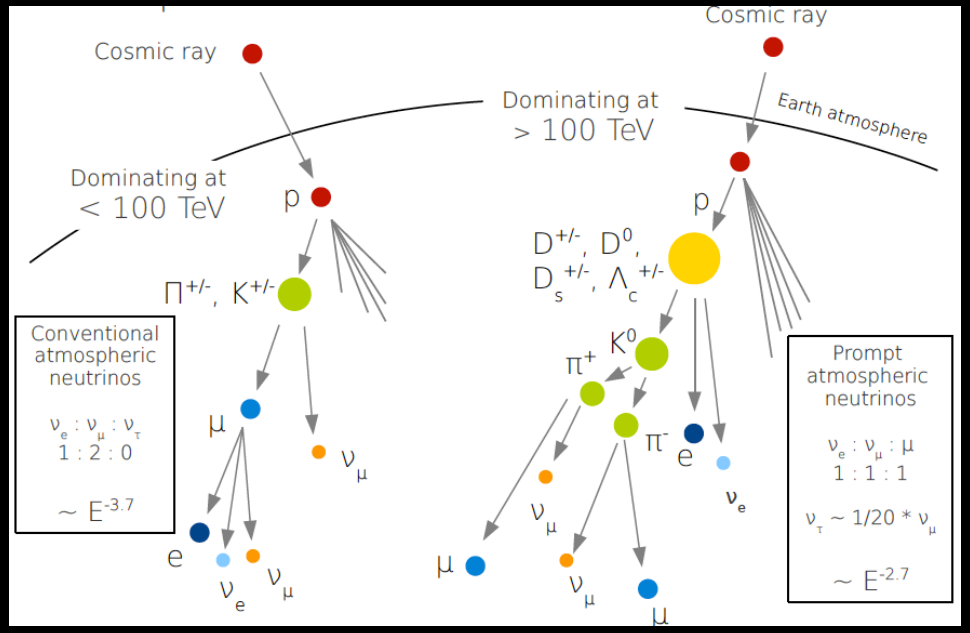


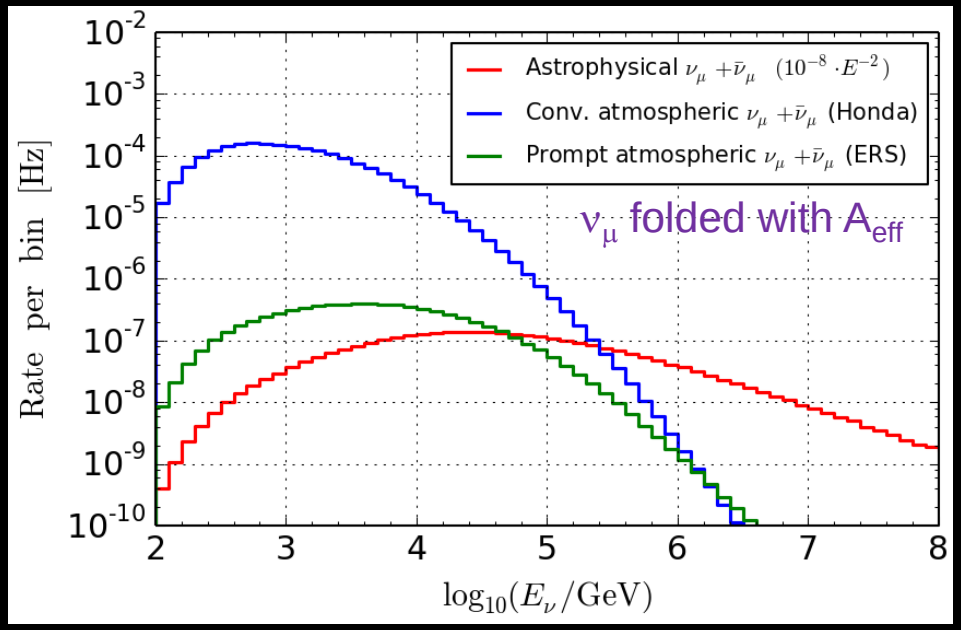
No atmopheric background
Good energy resolution
Good directional resolution

For E≤PeV misidentification
- Fluctuations in hadronic cascades
- Anisotropy of photon propagation in ice

Learned and Pakvasa, Astropart. Phys. 3, 1995

Atmospheric neutrino foreground





Conventional atmospheric neutrinos

- From pion and kaon decays produced by cosmic ray interactions with the atmosphere
- Energy spectrum: $\frac{d\phi}{dE} \propto E^{-3.7}$

Prompt atmospheric neutrinos

- From heavy meson decays produced by cosmic ray interactions with the atmosphere (not measured yet)
- Energy spectrum: $\frac{d\phi}{dE} \propto E^{-2.7}$

Astrophysical neutrino signal

- Energy spectrum: $\frac{d\phi}{dE} \propto E^{-2}$