Neutrinotelescopes and Neutrinoastronomy

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

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KSETA Workshop, Durbach

14.2. 2017

Content

- Motivation for neutrino astronomy
- Working principle of a neutrino telescope
- Results from running neutrino telescopes
- Next generation of neutrino telescopes

Astronomical Observations

B General Method: Source → Light → Earth

?

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Cosmic Messengers

- photons

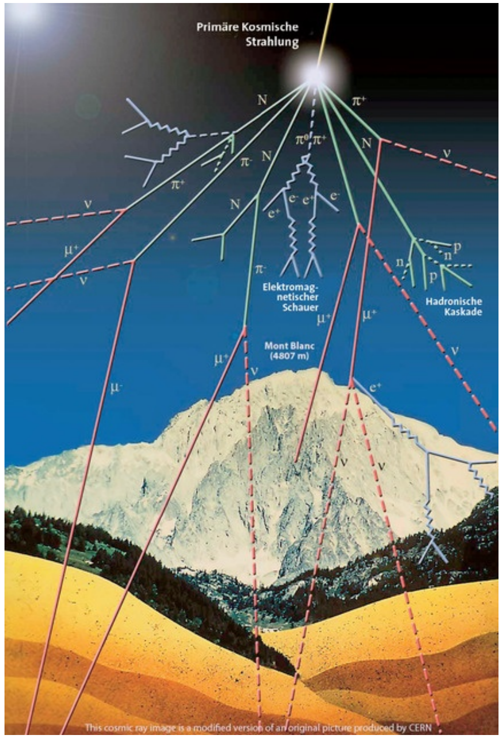
  radio – infrared – visibile – X-ray – gamma-rays

- charged particles

  electrons, protons, nuclei

- neutrinos

- gravitational waves



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Cosmic Messengers

- photons

  radio – infrared – visibile – X-ray – gamma-rays

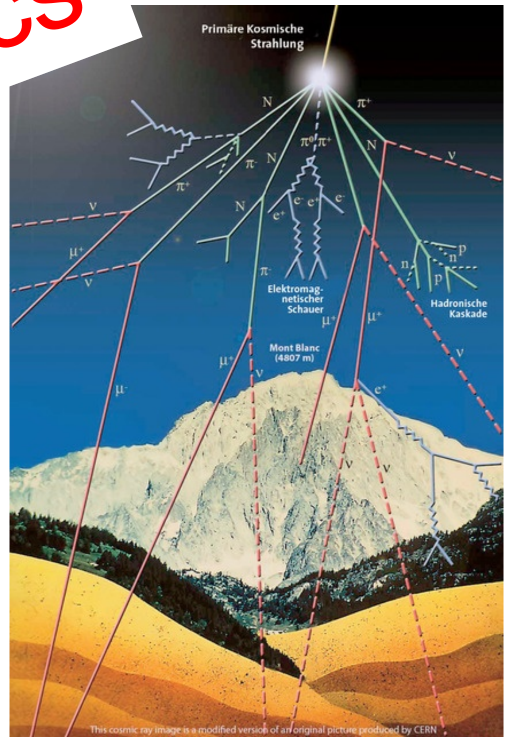
- charged particles

  elec… nuclei

- neutrinos

- gravitational waves

Astroparticle physics



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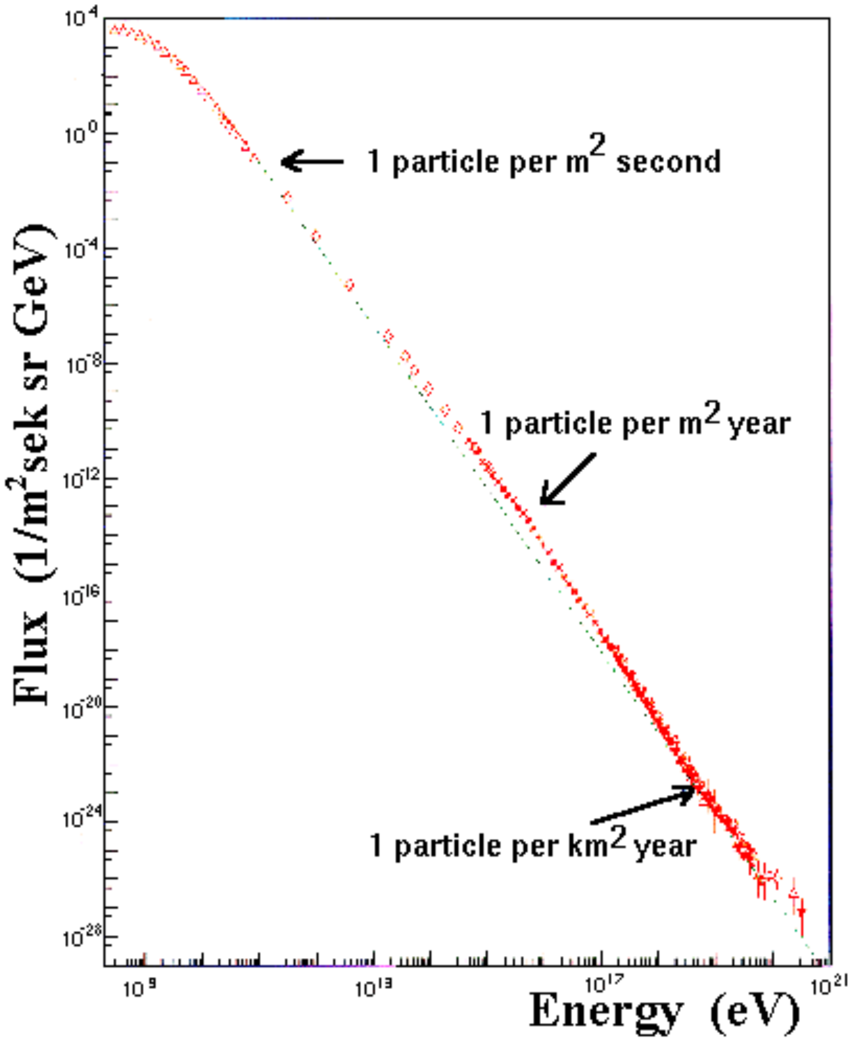
Cosmic Messengers – cosmic rays



Kinetic energy of a single cosmic ray proton

=

Kinetic energy of a tennis ball

=

10^{26} times kinetic energy of a single proton in the tennis ball

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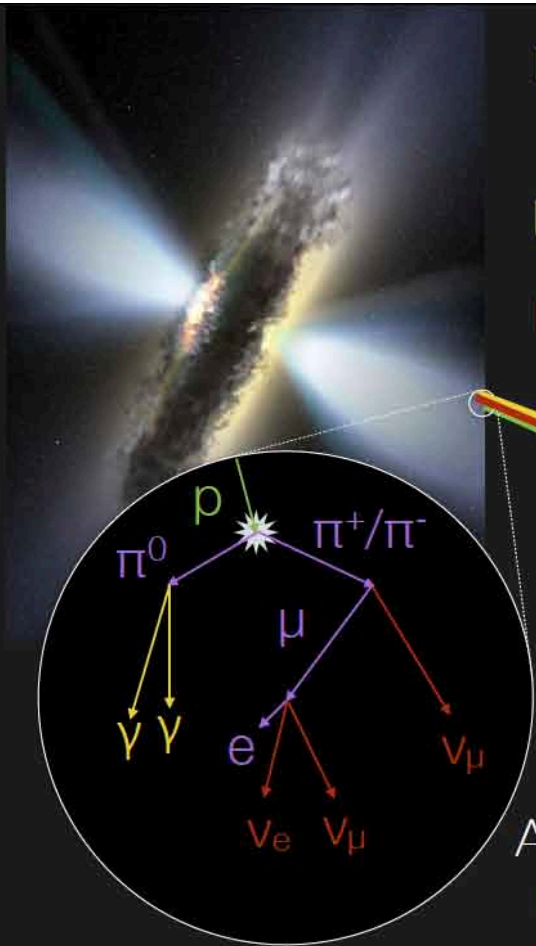
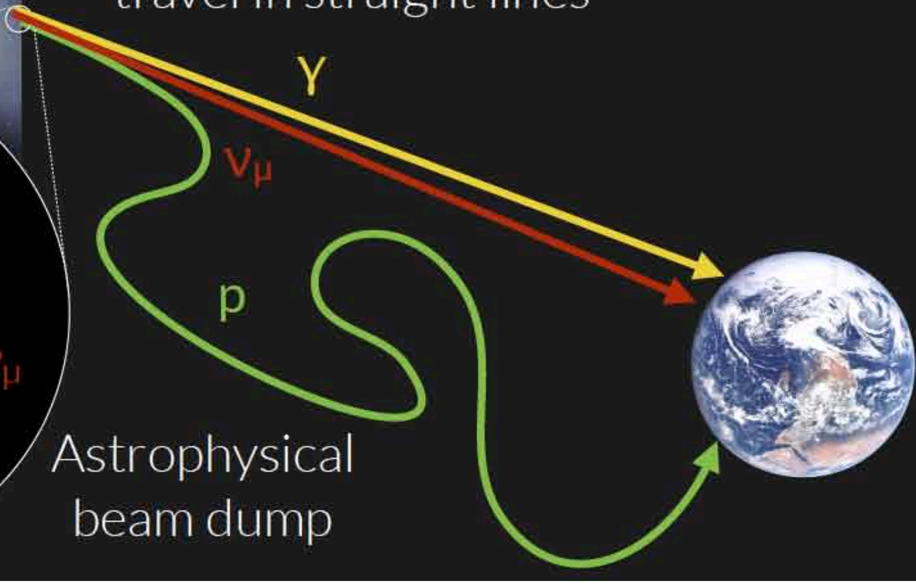
Cosmic messengers

- **Nuclei** can be deflected by magnetic fields
- **Gamma rays** can be absorbed
- **Neutrinos** are difficult to stop and travel in straight lines





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Research with high energy neutrinos

- cosmic accelerators
- dark matter annihilation
- atmospheric neutrinos and oscillations

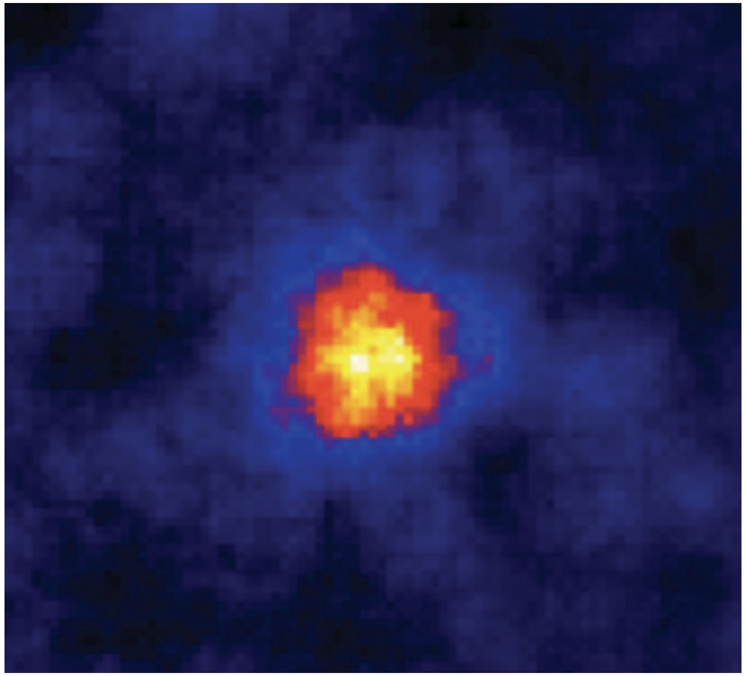
Possible Sources of high energy cosmic rays

Vb1 dk1ENb y c g

auG1Nk N3C.

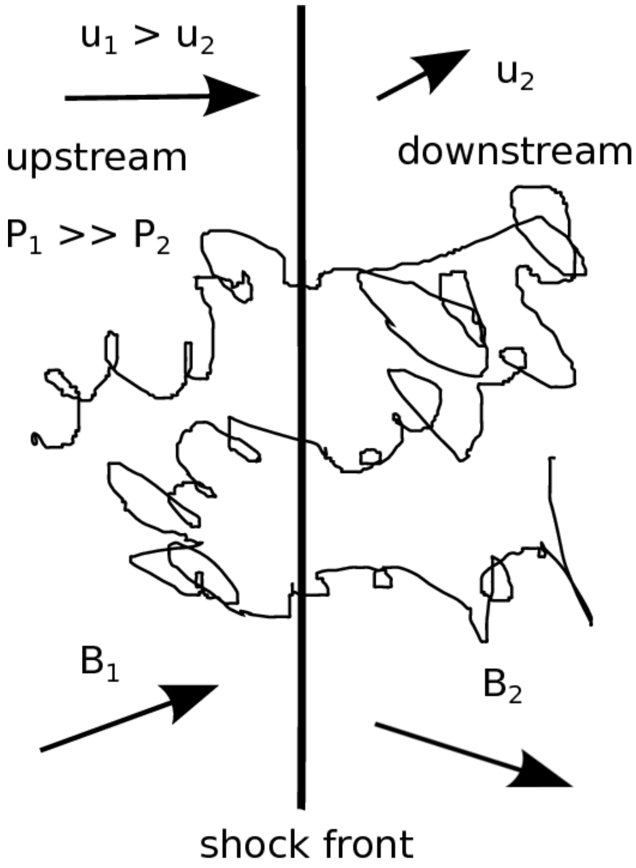
• bRRb Vb- G

0Vk6u 2 E11Nk y Tb0k okNG0HTk



0Vk6u 2 y y 0HNb1HVb.uHd

Shock acceleration

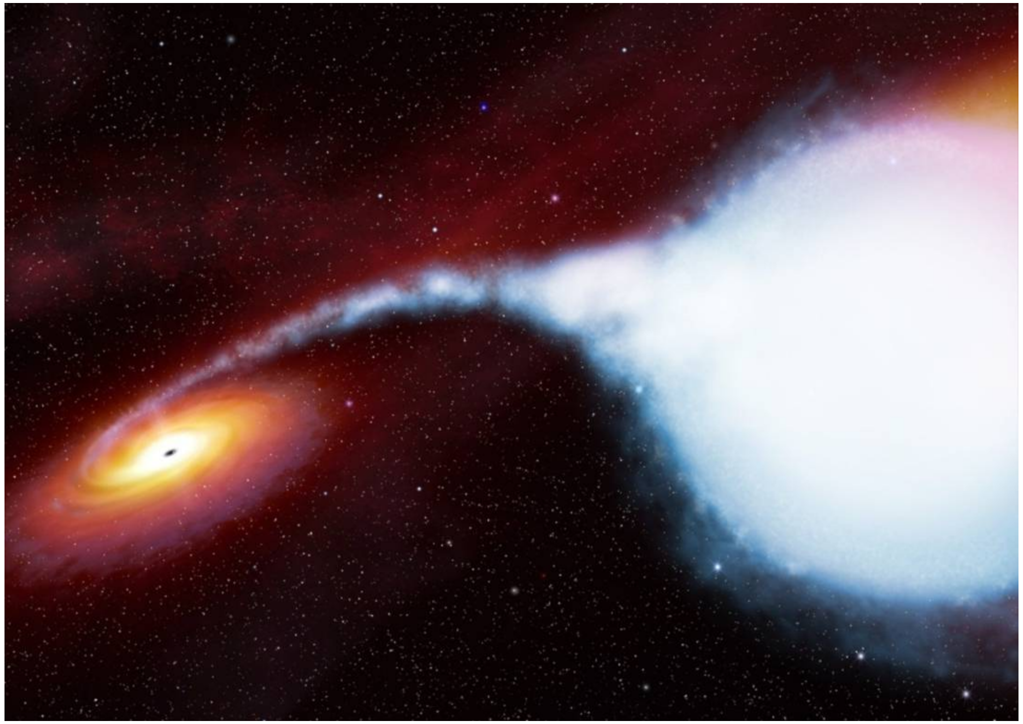


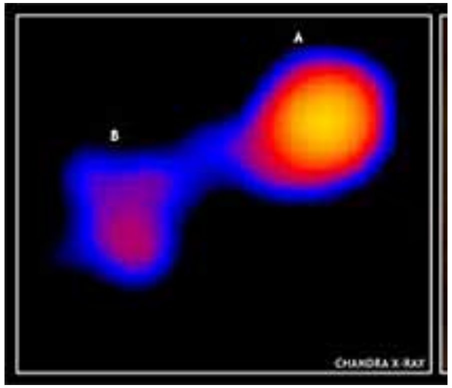
Collisionless shock:
Particles do not scatter
→ No energy loss

Charged particle deflected by magnetic fields
→ energy gain due to reflection from moving mirrors

Possible Sources of high energy cosmic rays

Cosmic particle accelerators ? Binary system





X-ray image of
Mira B (white dwarf)
and A (red giant)
credit: Chandra

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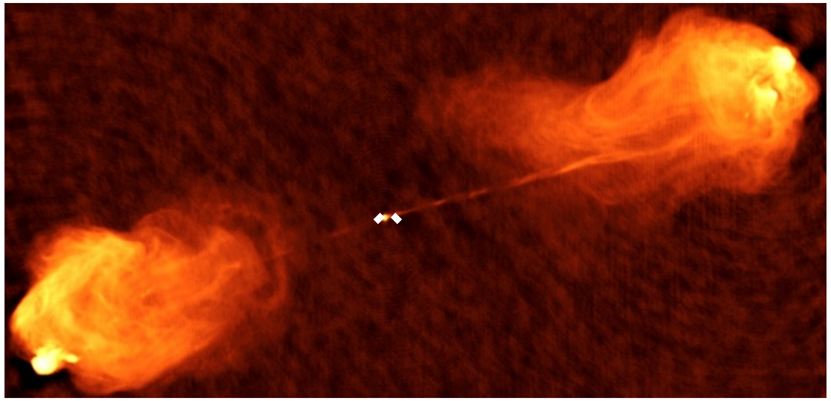
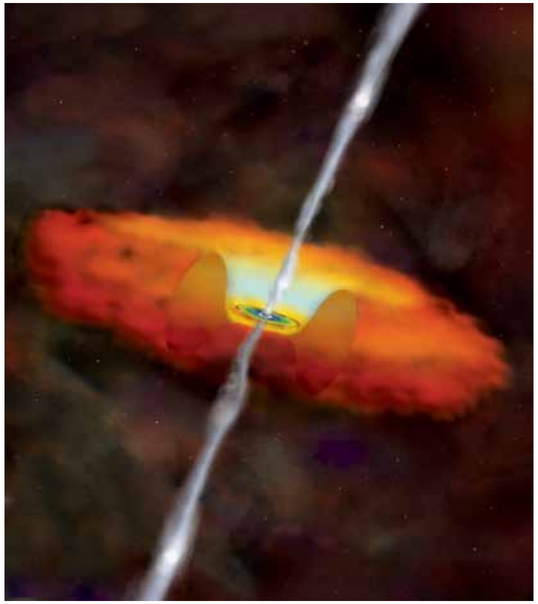
Possible Sources of high energy cosmic rays

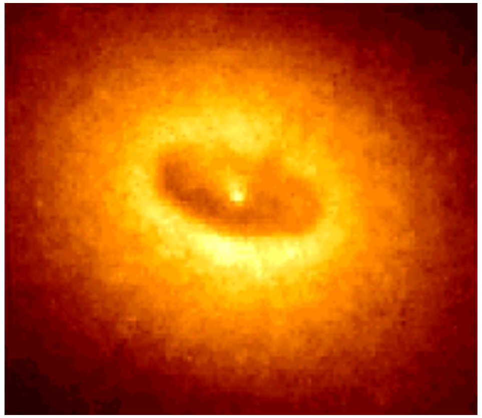
supermassive black hole

with accretion disc (AGN)

→ highly relativistic outflow







Artists view; NASA

Cygnus A radio galaxy NRAO/AUI/VLA

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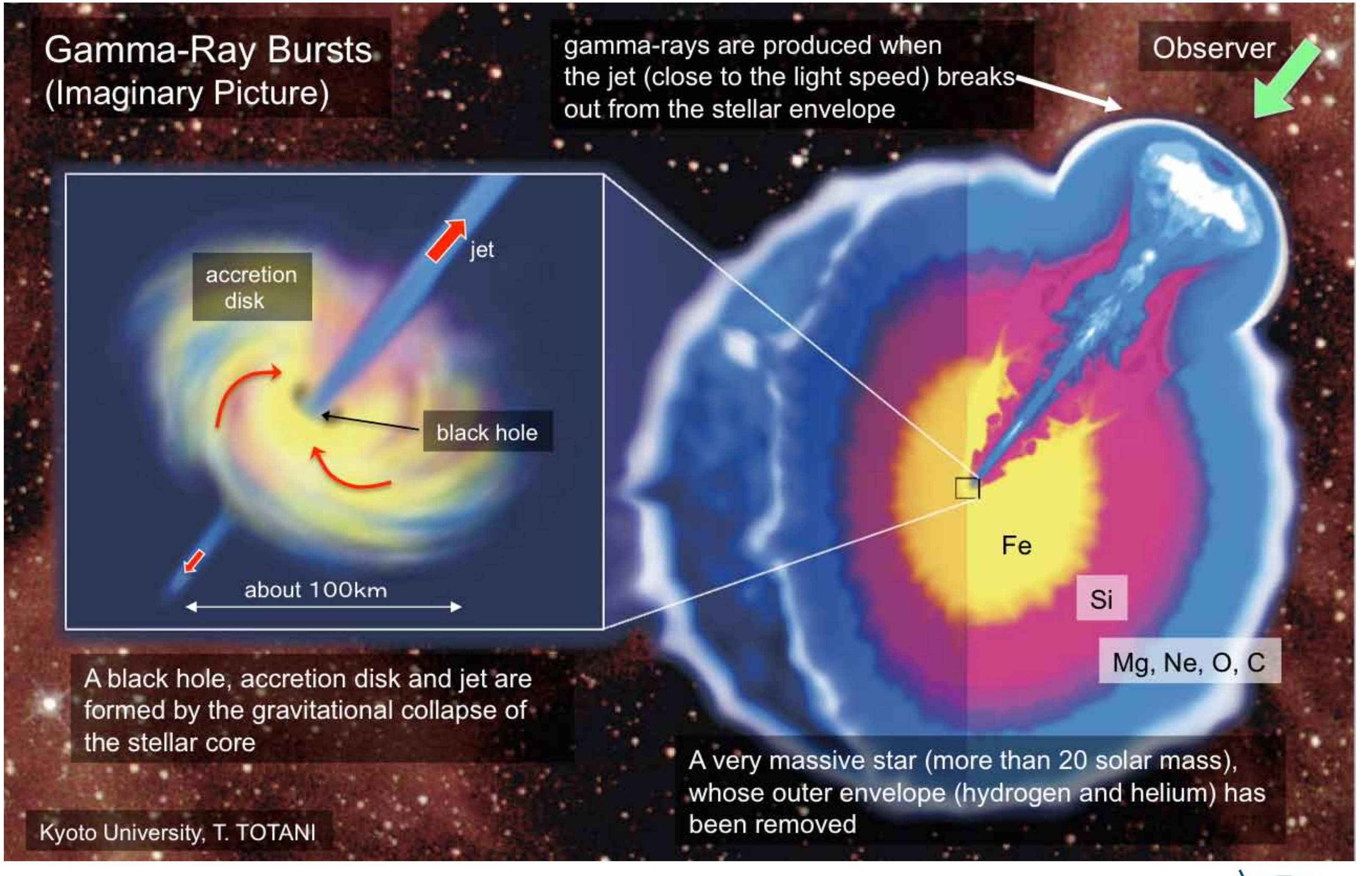
Gamma Ray Burst



Possible Sources of high energy cosmic neutrinos

$$p + \gamma \rightarrow \pi^0 + p$$

or p, ...

$$\hookrightarrow \gamma + \gamma + p$$

$$\rightarrow \pi^+ + n$$

$$\hookrightarrow \mu^+ + \nu_\mu + n$$

$$\hookrightarrow e^+ + \nu_{\bar{\mu}} + \nu_e + \nu_\mu + n$$

TeV gamma rays

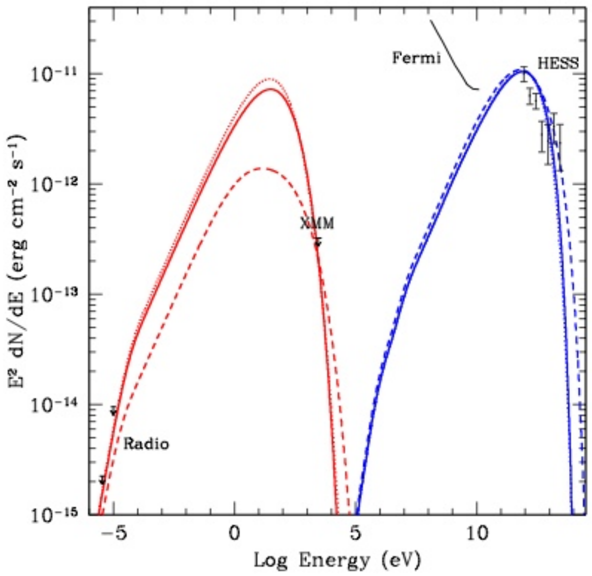
(can also be from leptonic processes...)

Cosmic rays?

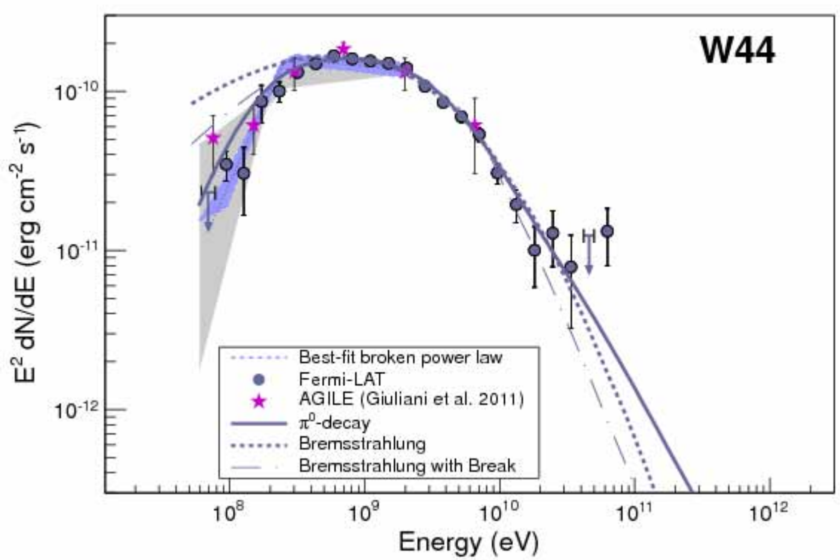
TeV neutrinos

Photon distribution from electron sources

leptonic scenario with synchrotron (red) and inverse Compton emission (blue)



Model spectrum for HESS J1708-406
Credit: H.E.S.S.



Pionic contribution in W44
Credit: H.E.S.S.

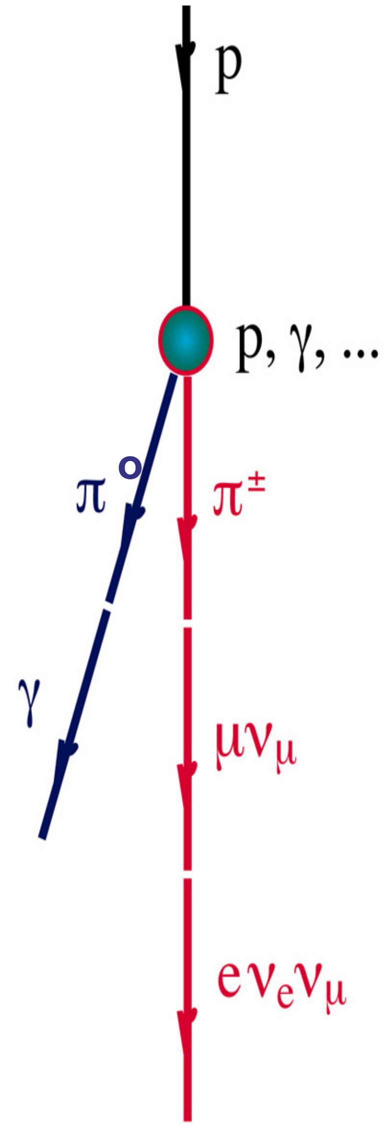
Protons, Photons and Neutrinos

- High energetic protons and nuclei interact with protons, nuclei, photons
  → production of pions π^0, π^+ , π^-

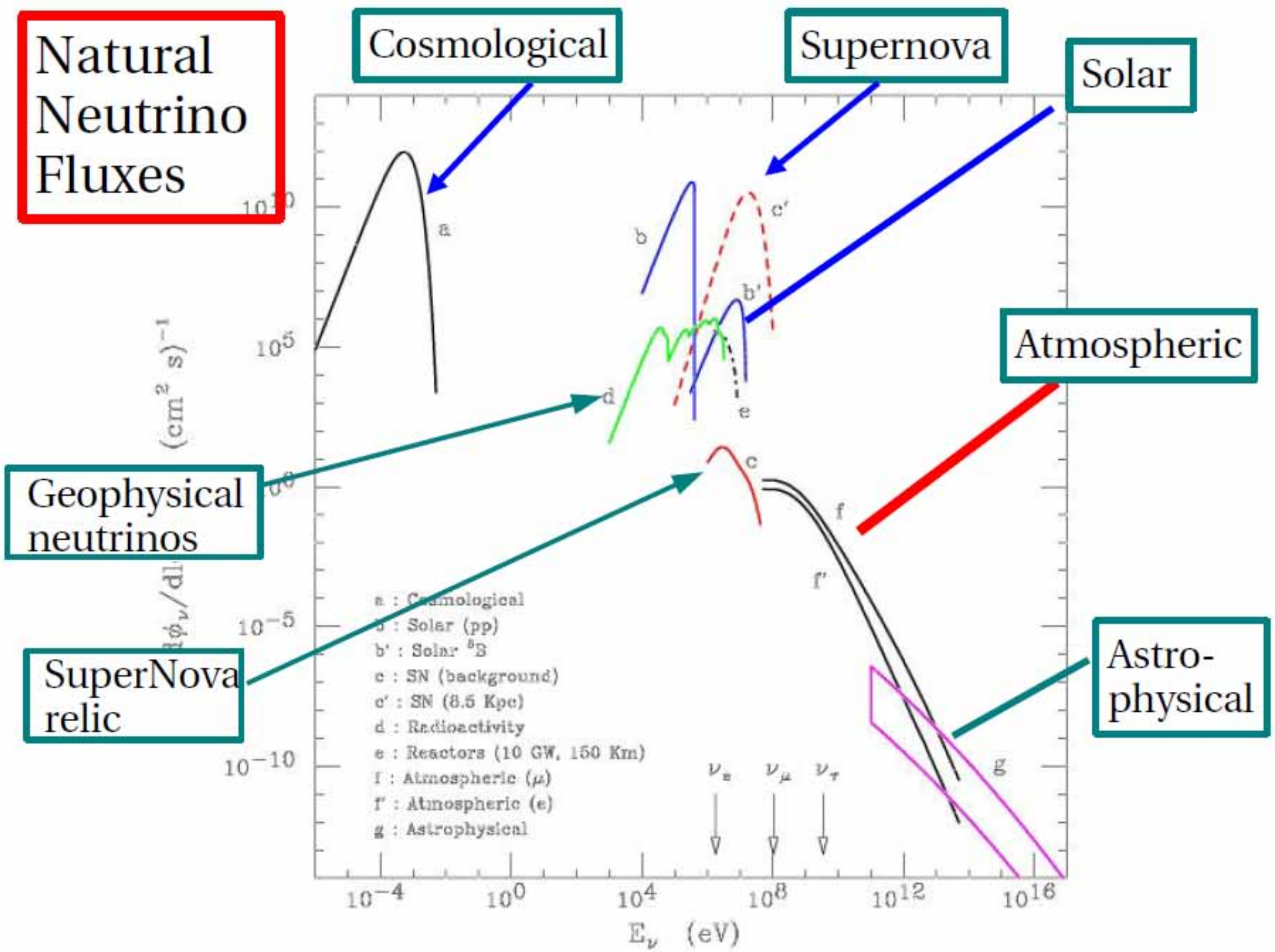
- π^0 → photons
  $\pi^\pm$ → neutrinos

- Photons can be produced as well by electrons (Compton), not so neutrinos!

- **Neutrinos are the smoking gun signature for hadron acceleration!**



Cosmic Neutrinos



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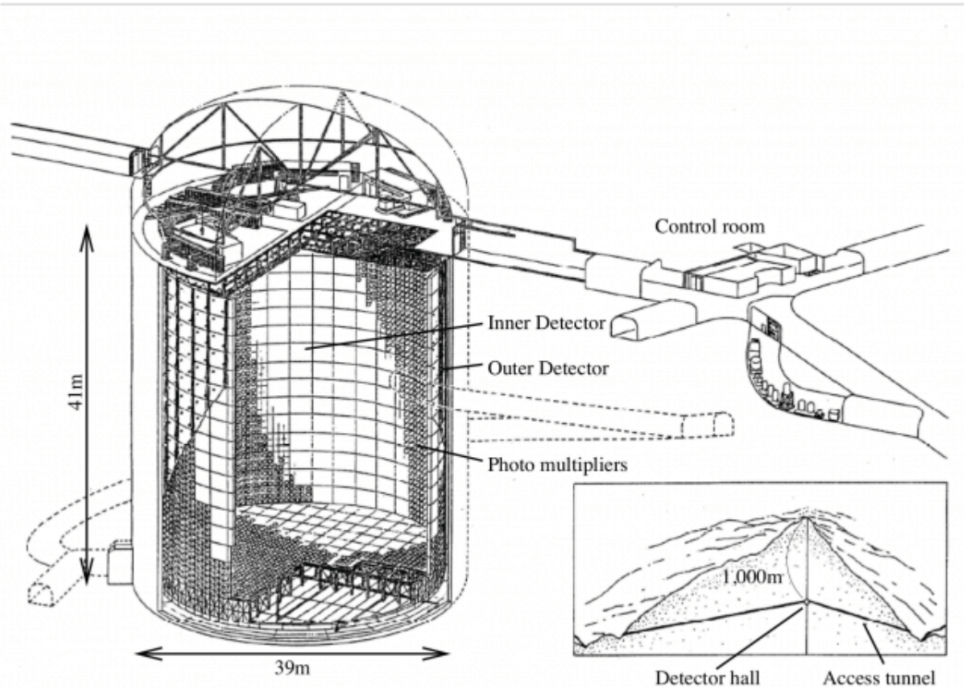
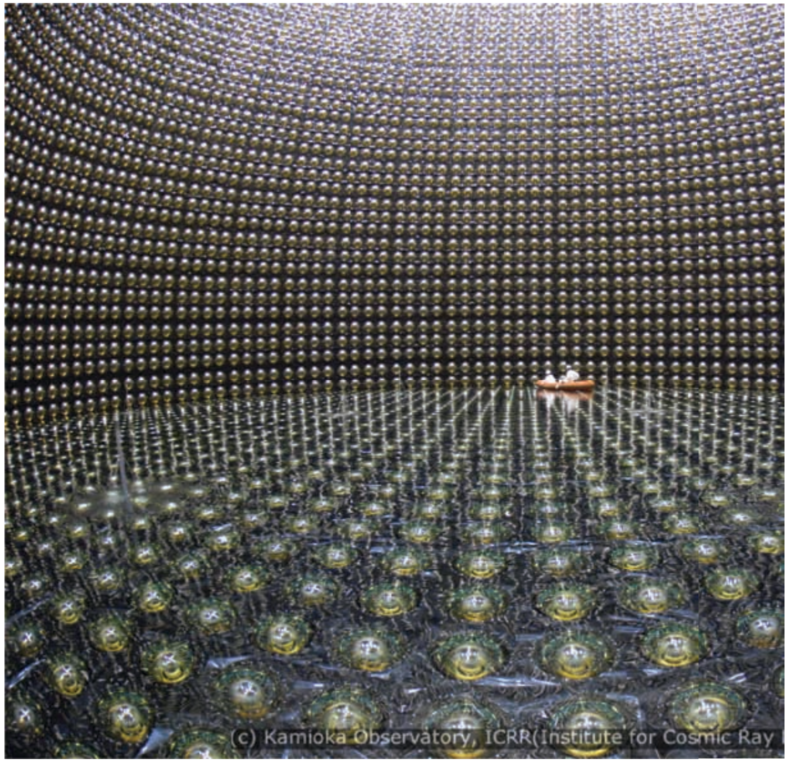
Working principle of a neutrino telescope

Superkamiokande – a water Cherenkov telescope





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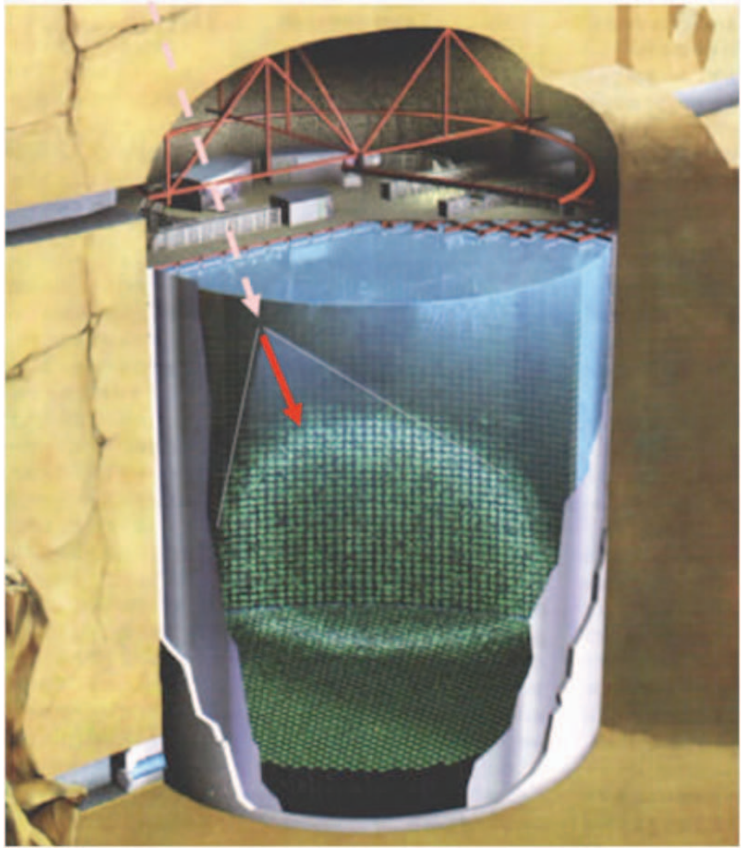
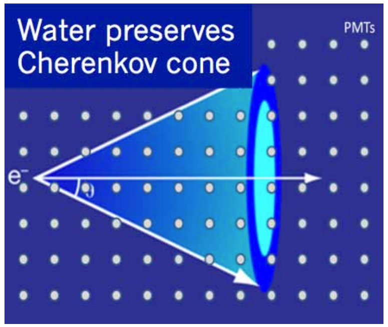
Superkamiokande – a water Cherenkov telescope



Vk6u y ETk VSbR uHSbd6k

0Cb V8k6 TbV.u0Nk v uC) P 0
kR uG Ck VkdSHP TCH.HdGv uC
kR uGGuHd bd8Nk x

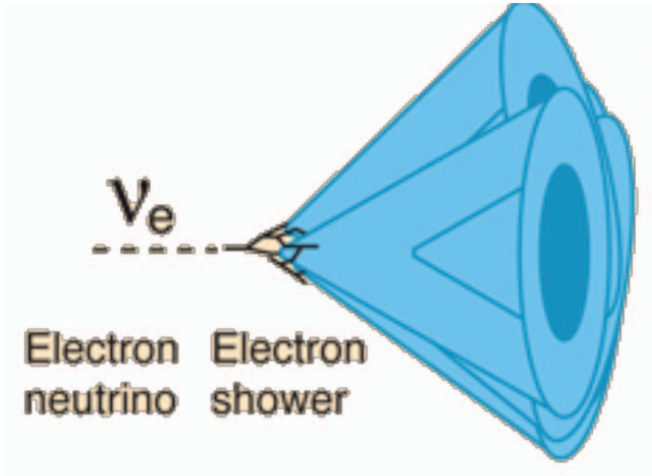
0HGx) d



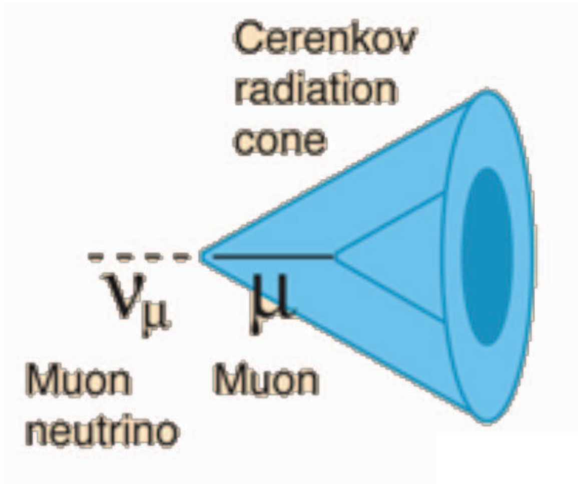
Vk6u y ETk VSbR uHSbd6k

Superkamiokande – a water Cherenkov telescope

kNk0.VHd □hVHR ν_k ud.kVb0.uHd □

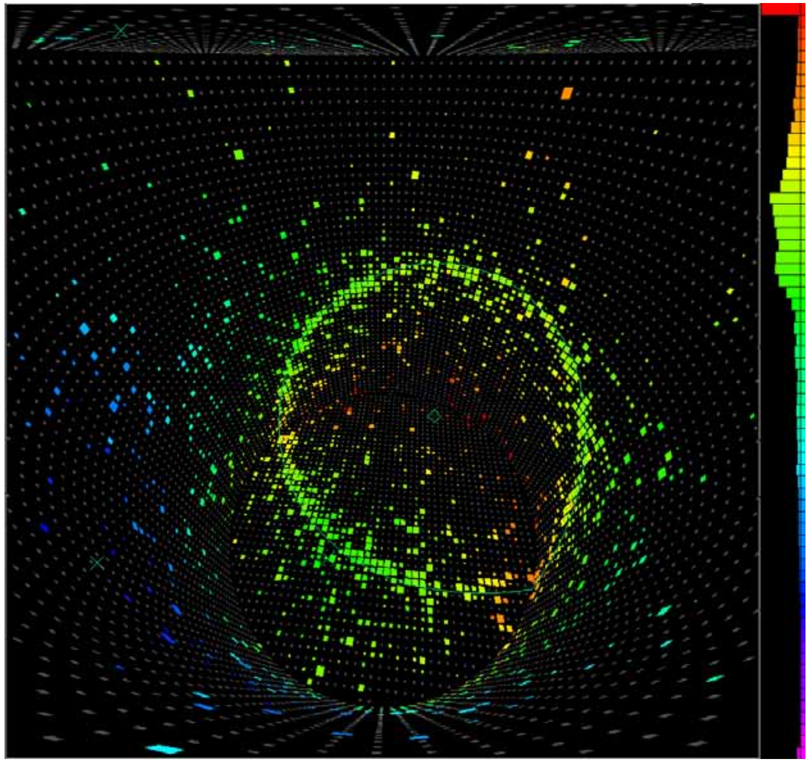


REHd □hVHR ν_μ ud.kVb0.uHd □

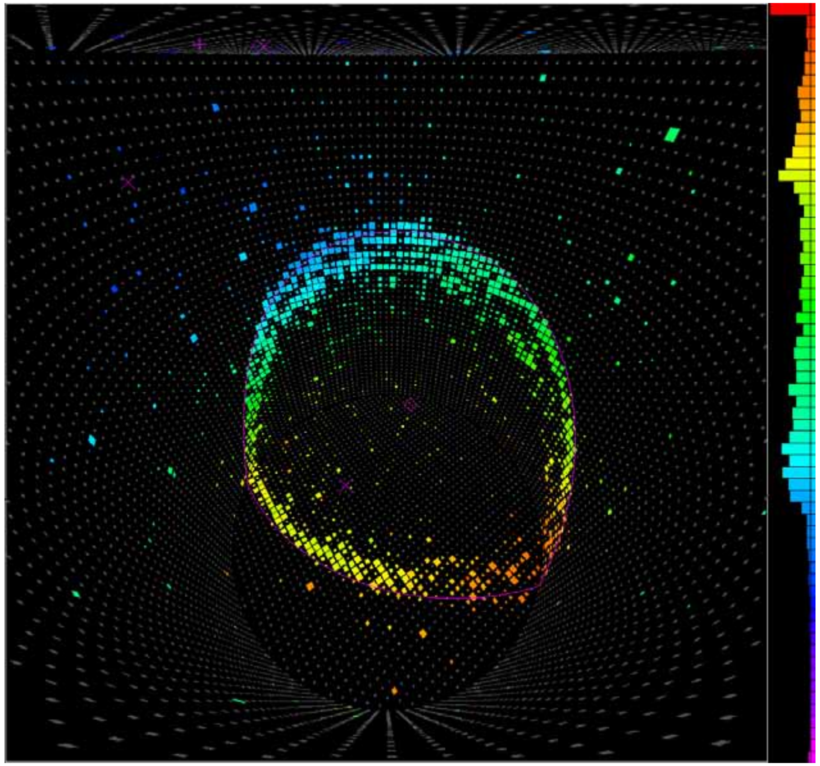


Superkamiokande – a water Cherenkov telescope

electron (from ν_e interaction)
energy: 500 MeV



muon (from ν_μ interaction)
energy: 600 MeV



Diamond: track crosses wall; crosses: projection of reconstructed vertex on the walls;
credit: Superkamiokande

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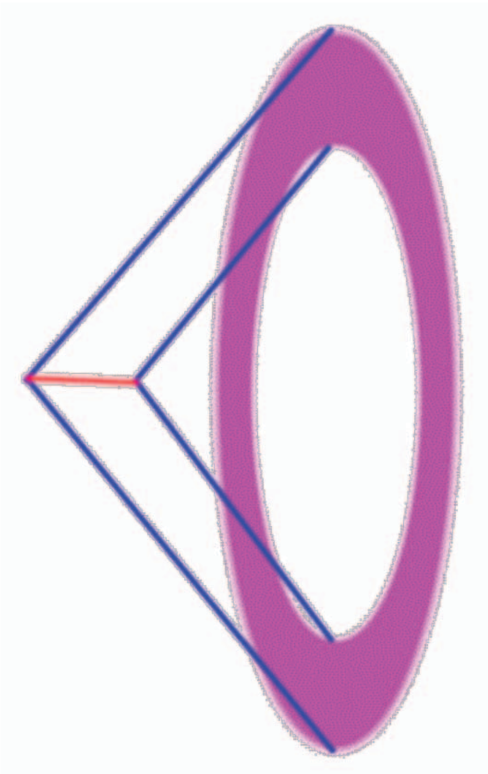
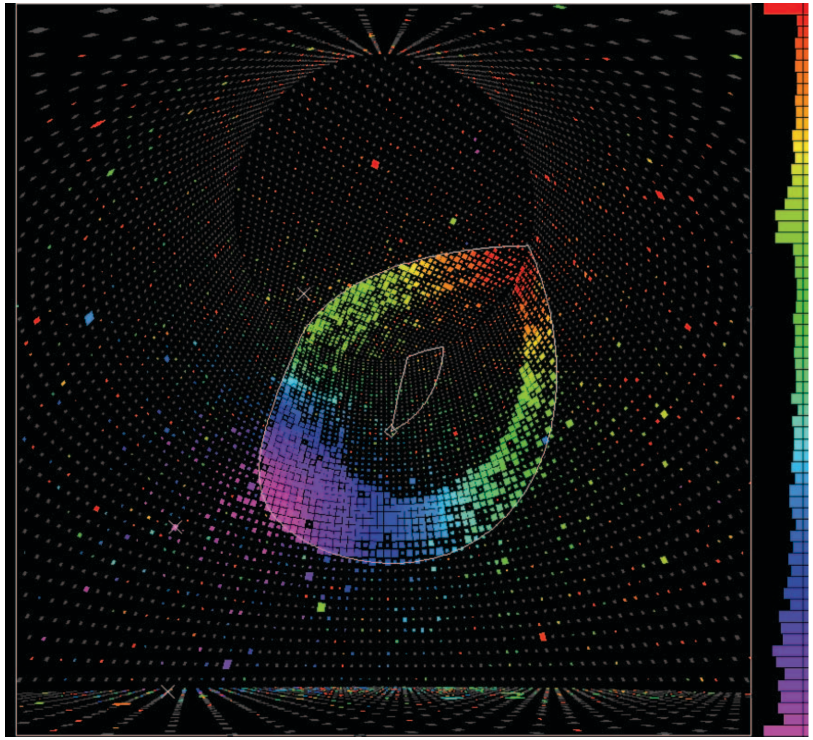
Superkamiokande – a water Cherenkov telescope

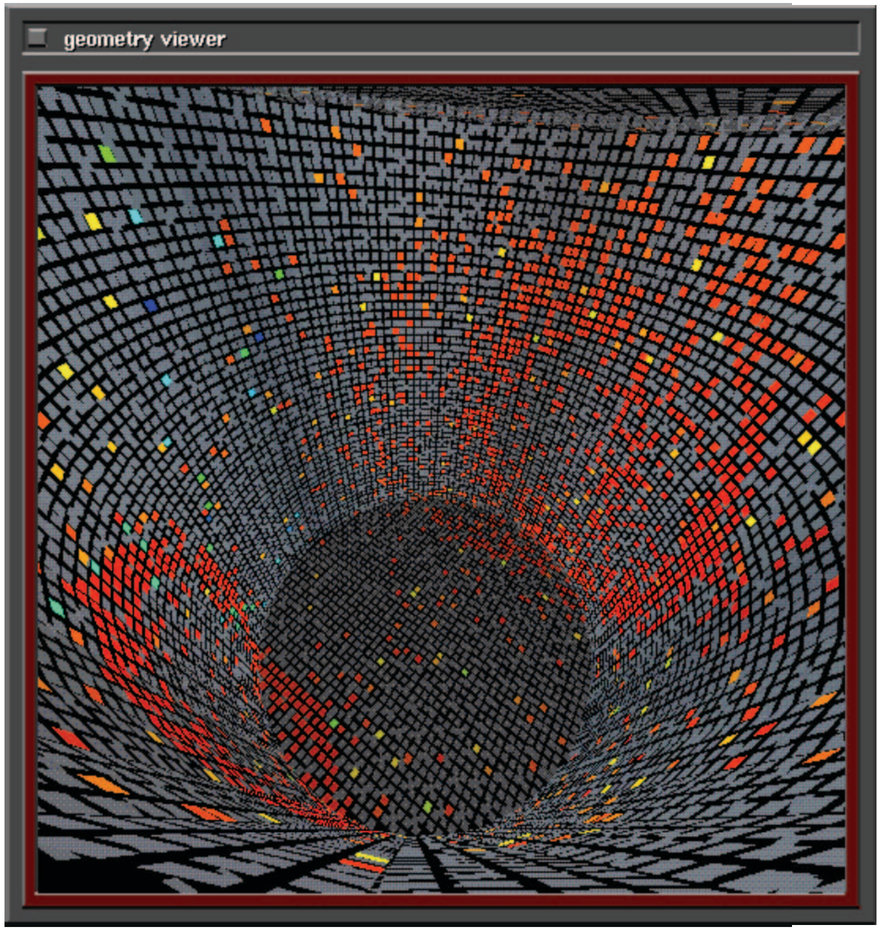


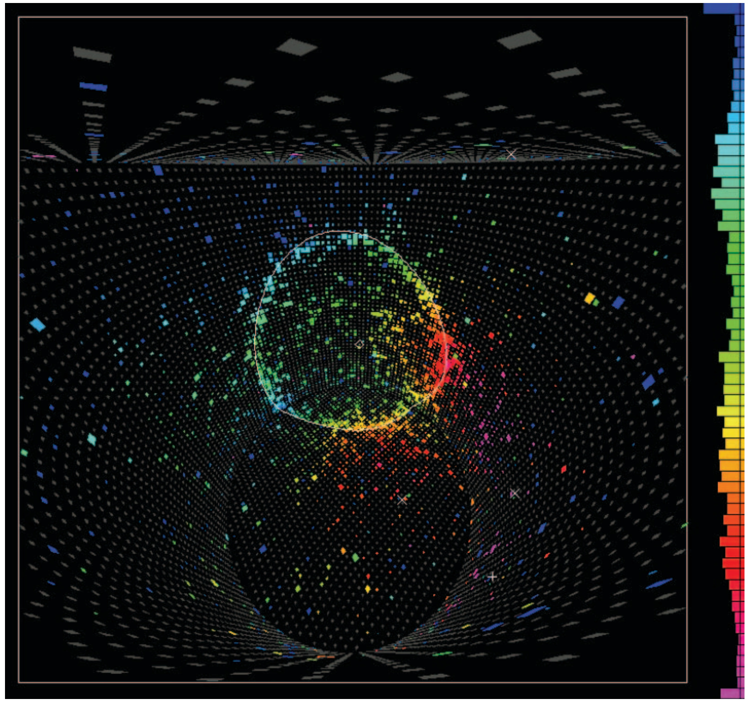
REHd□□□• ka
.Vb0SNkd8.C□R



□Vk6u□y ETkVSbR uHSbd6k

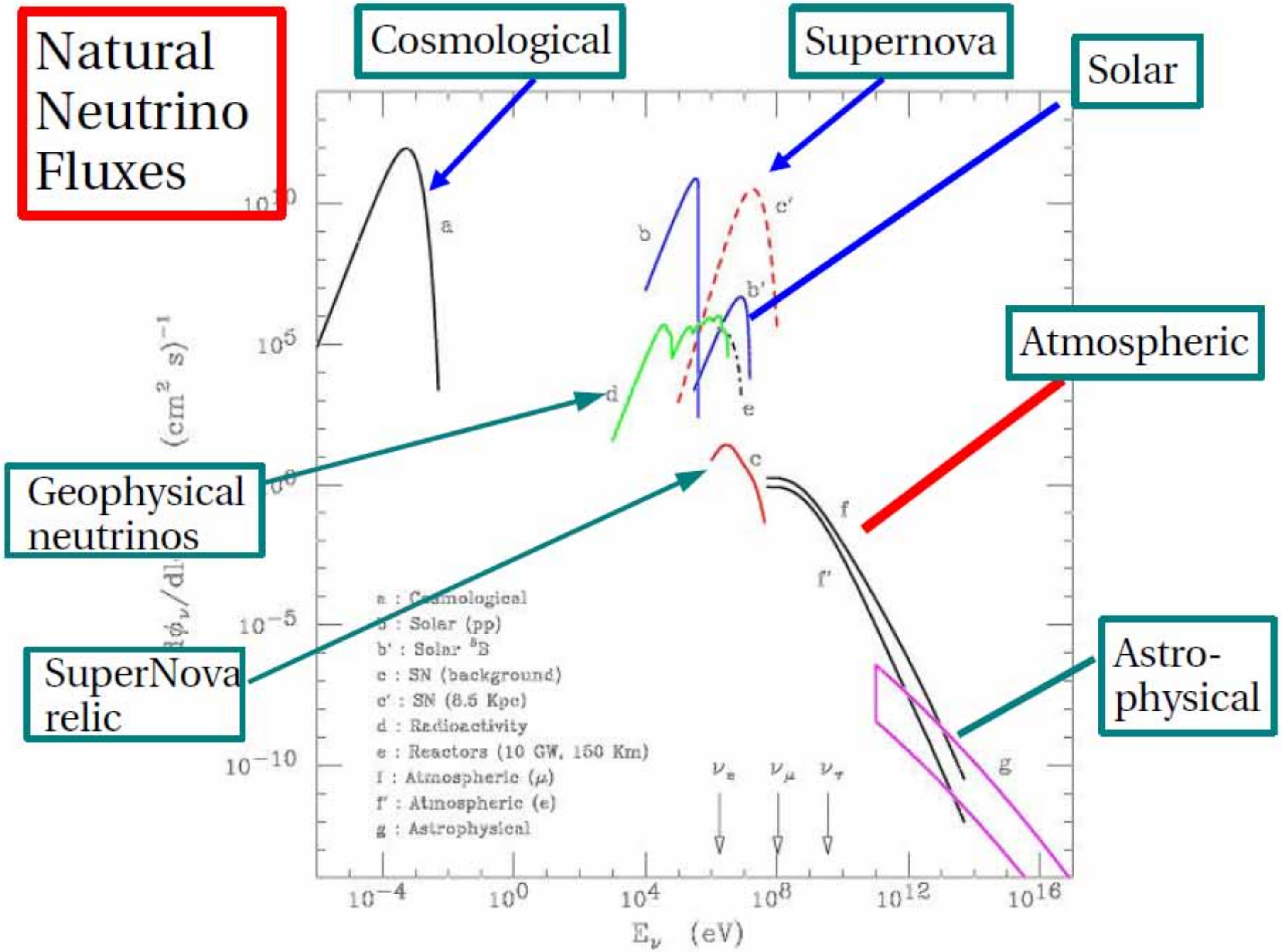
Superkamiokande – a water Cherenkov telescope





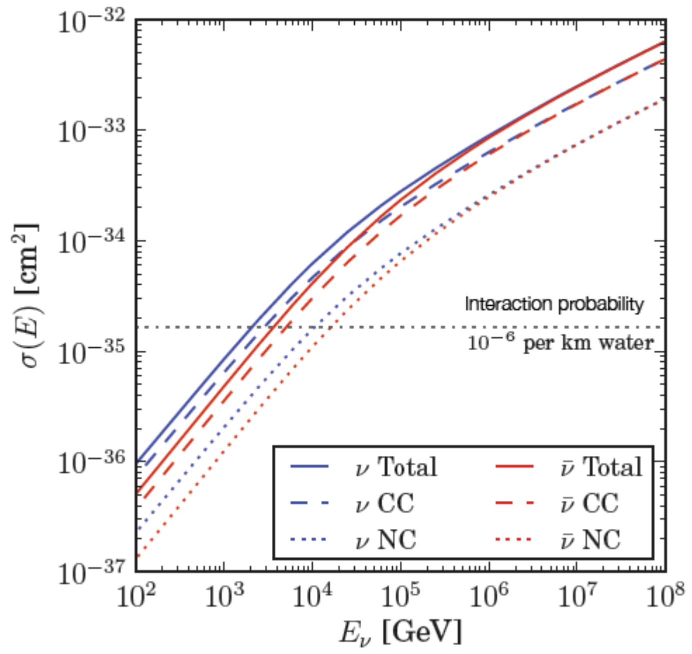
Vk6u y ETk VSbR uHSbd6k

Cosmic Neutinos



Neutrino telescope concept

- Telescope for higher energies
  - cross section increases: $\sigma \approx E$
  - flux decreases: $\Phi \approx E^{-3\pm1}$
  - event size increases



- Large detector volume
  - ice or water as detector medium
  - natural abundance
  - overburden for shielding

- IceCube and ANTARES/KM3NeT and Baikal

Neutrino telescope specification

- Flux sensitivity → large volume

  we need n $\geq$ 1 events (!!!)
- Event quality:

  direction resolution

  energy resolution

  neutrino flavor identification

  background suppression
- Optimisation (statistical and systematical):

  current telescopes: statistics dominating (very few events)

  future telescopes: systematics dominating

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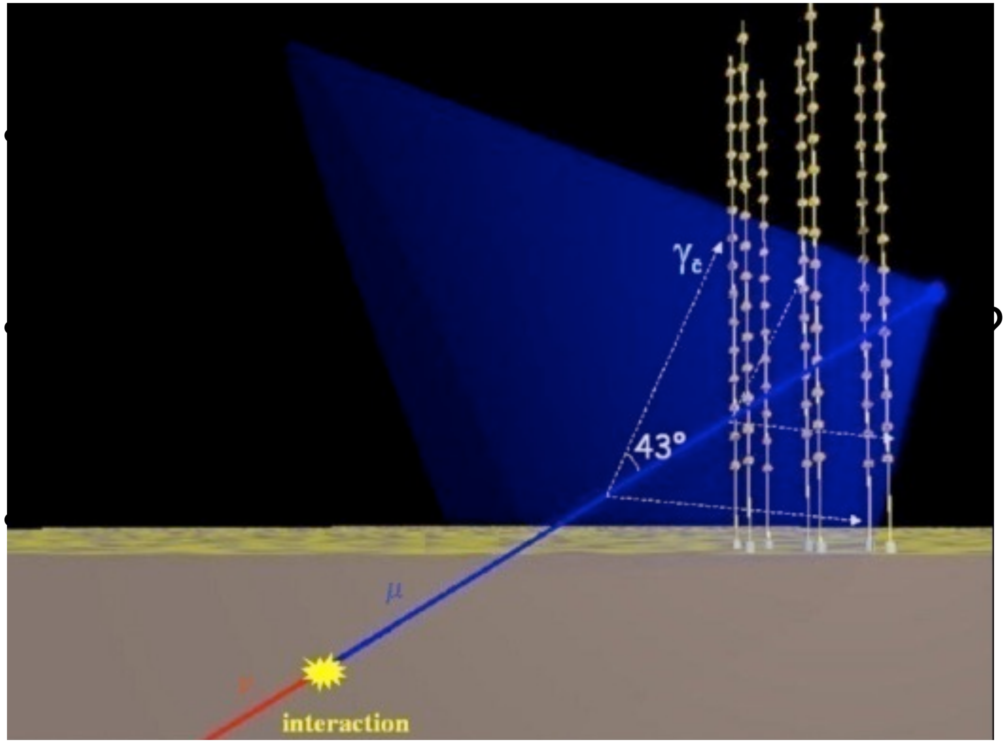
Detection of neutrinos in ice or water



Credit: ANTARES

Example:

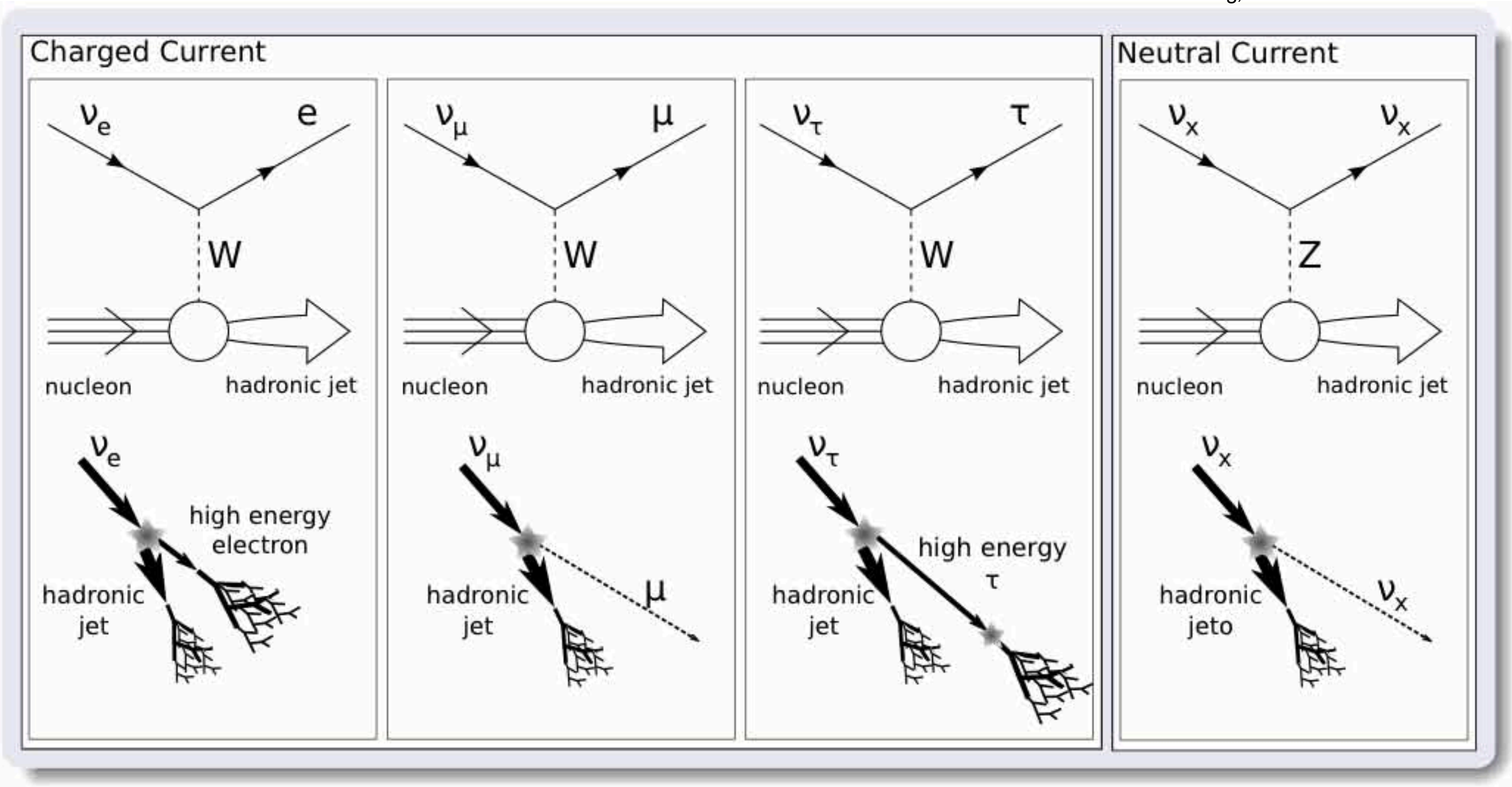
$\nu_\mu + A \rightarrow \mu + X$

μ-track reconstruction from time and position of detected Cherenkov light
→ neutrino direction

observed light and light densitiy
→ neutrino energy

Event classes in the detector

credit: J. Tiffenberg, NUSKY11



shower-like | track-like | shower-like (17% track-like, τ → μ) | shower-like

ν_e^{CC} | ν_μ^{CC} | ν_τ^{CC} | $\nu_{e,\mu,\tau}^{NC}$

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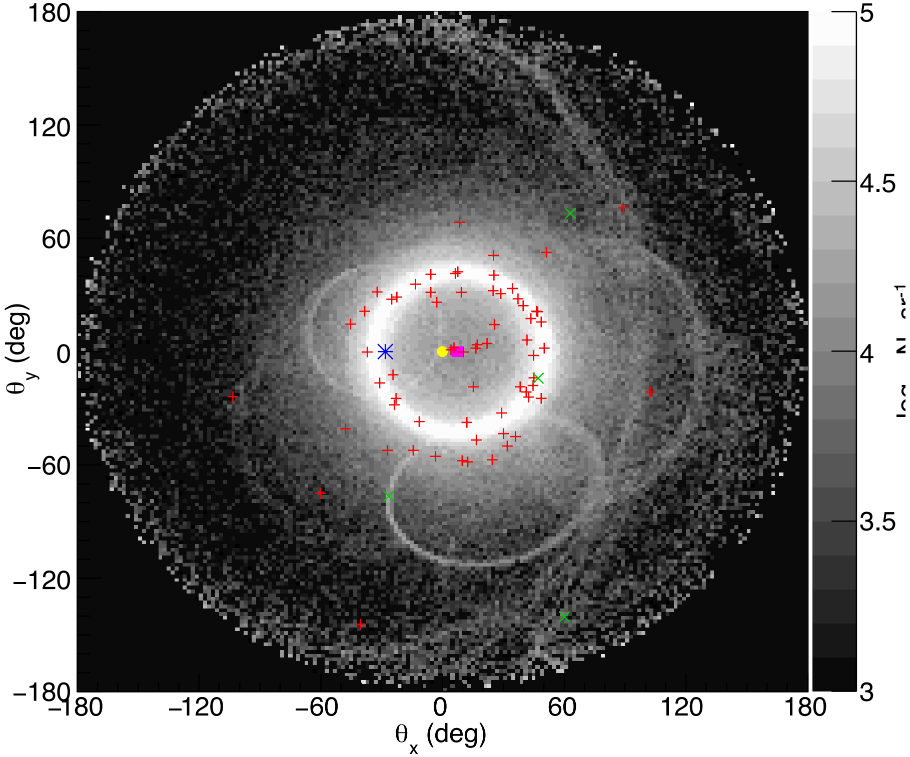
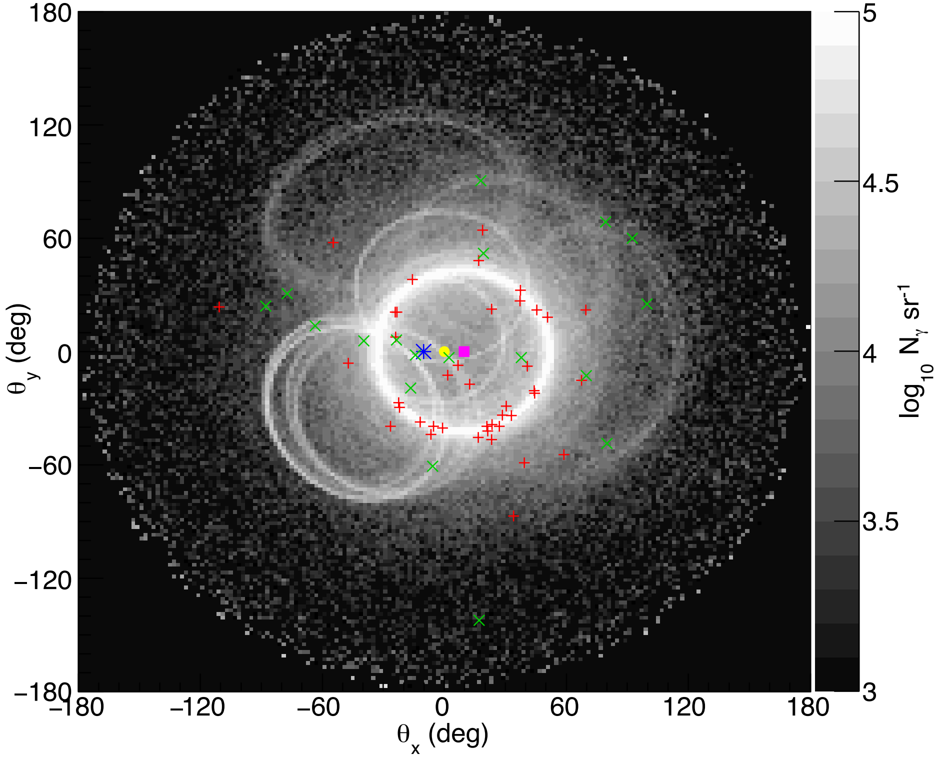
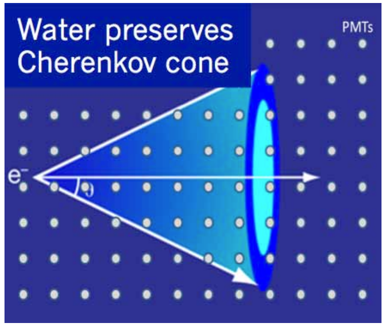
Simulated Cerenkov Photons from electrons/hadrons in water





Credit: KM3NeT

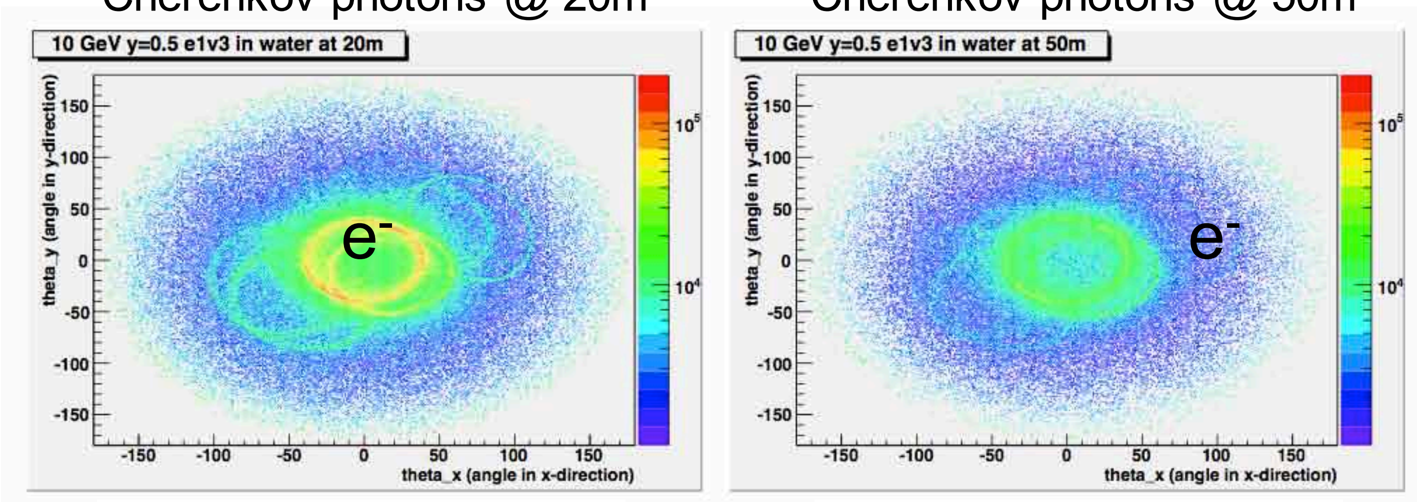


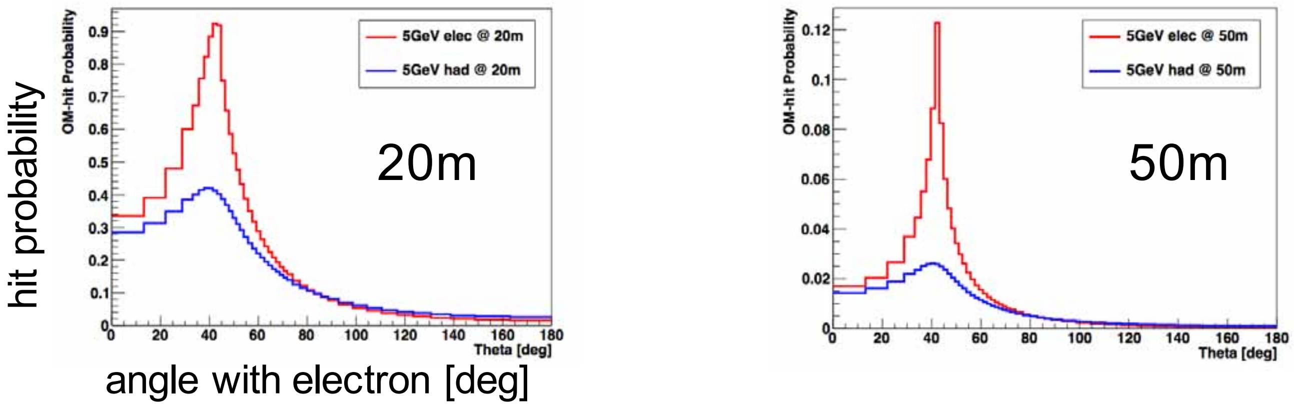
Electron neutrino charged-current event

Simulated ν_e^{CC} event with E_ν = 10 GeV and y=0.5

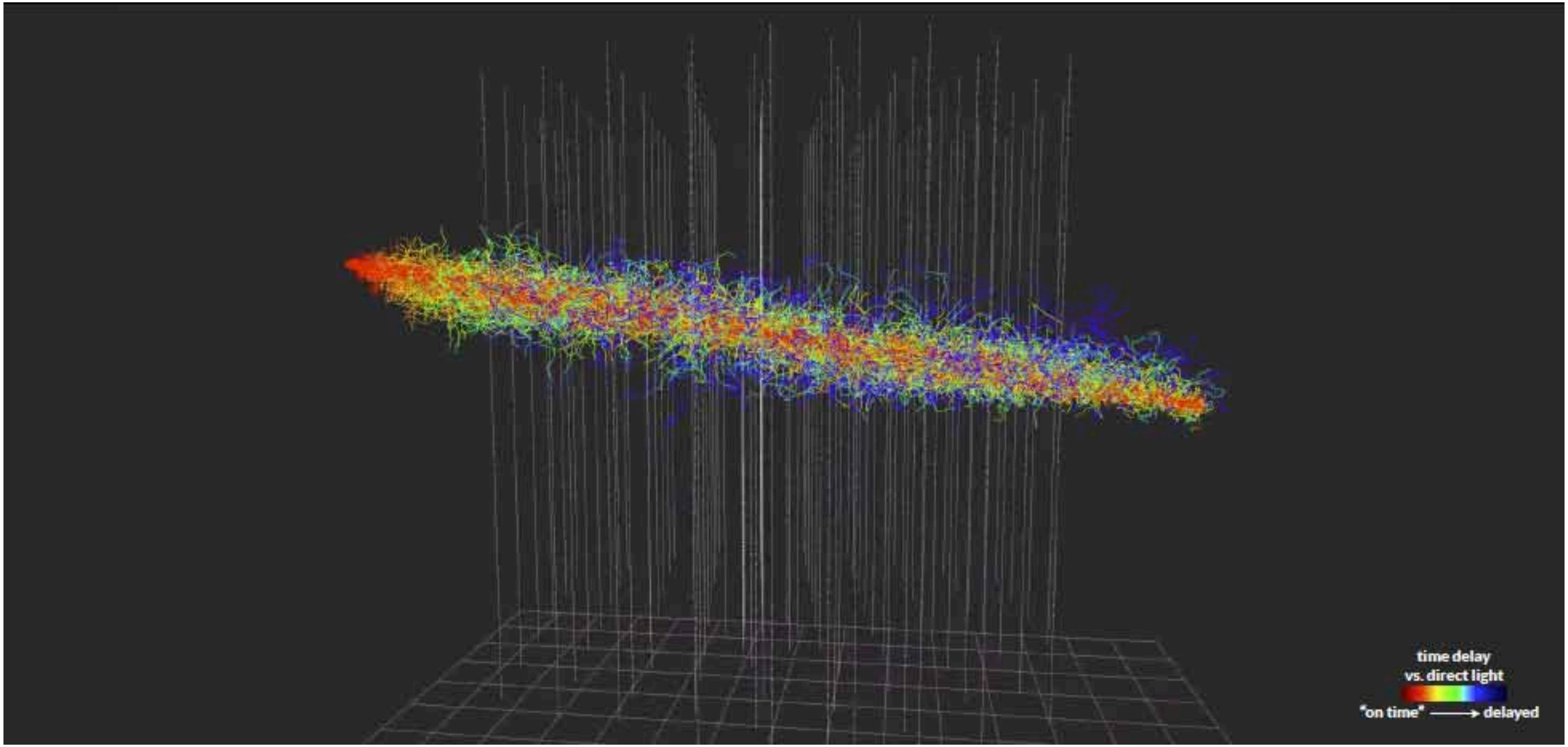
Cherenkov photons @ 20m

Cherenkov photons @ 50m



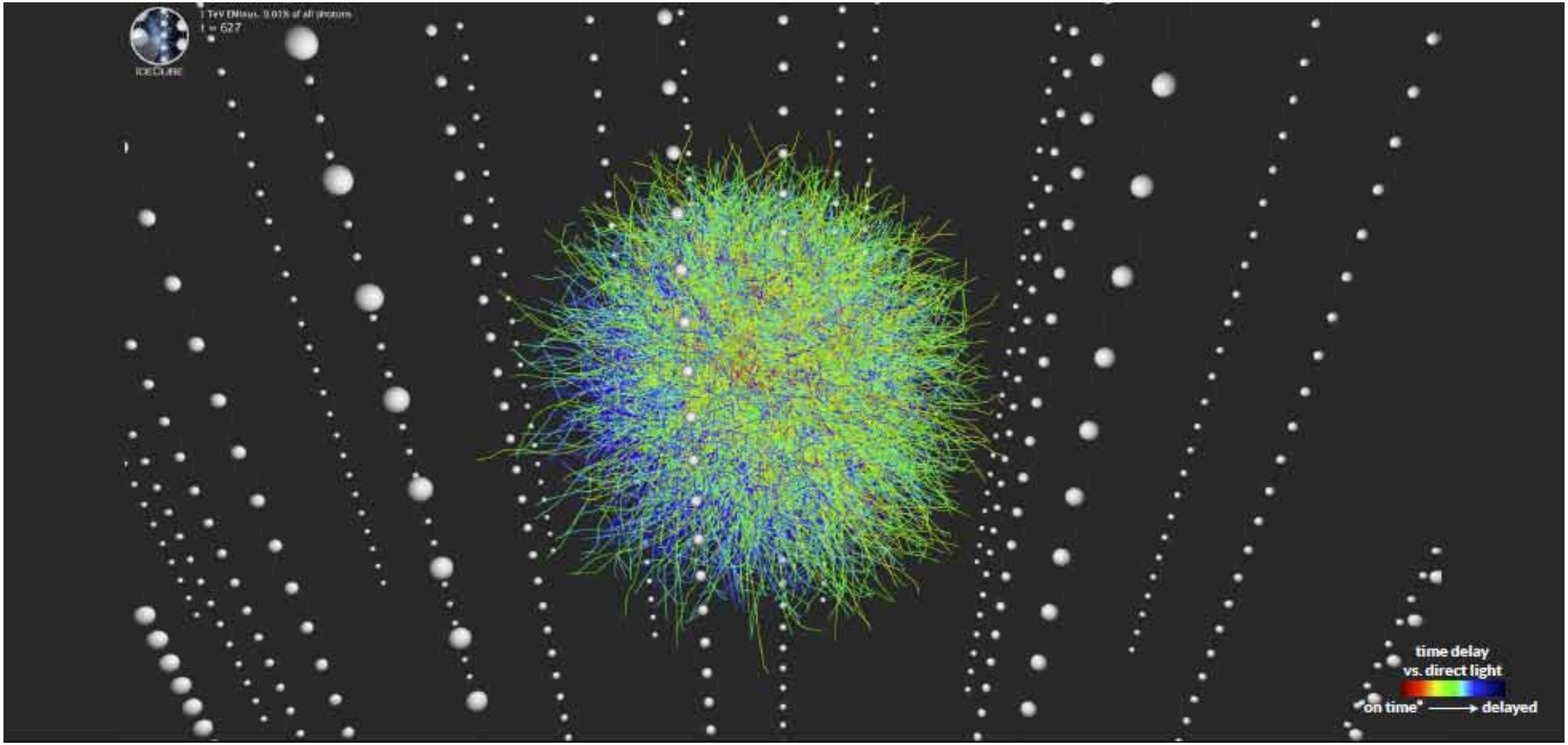


Simulated Cherenkov Photons from muon track in ice



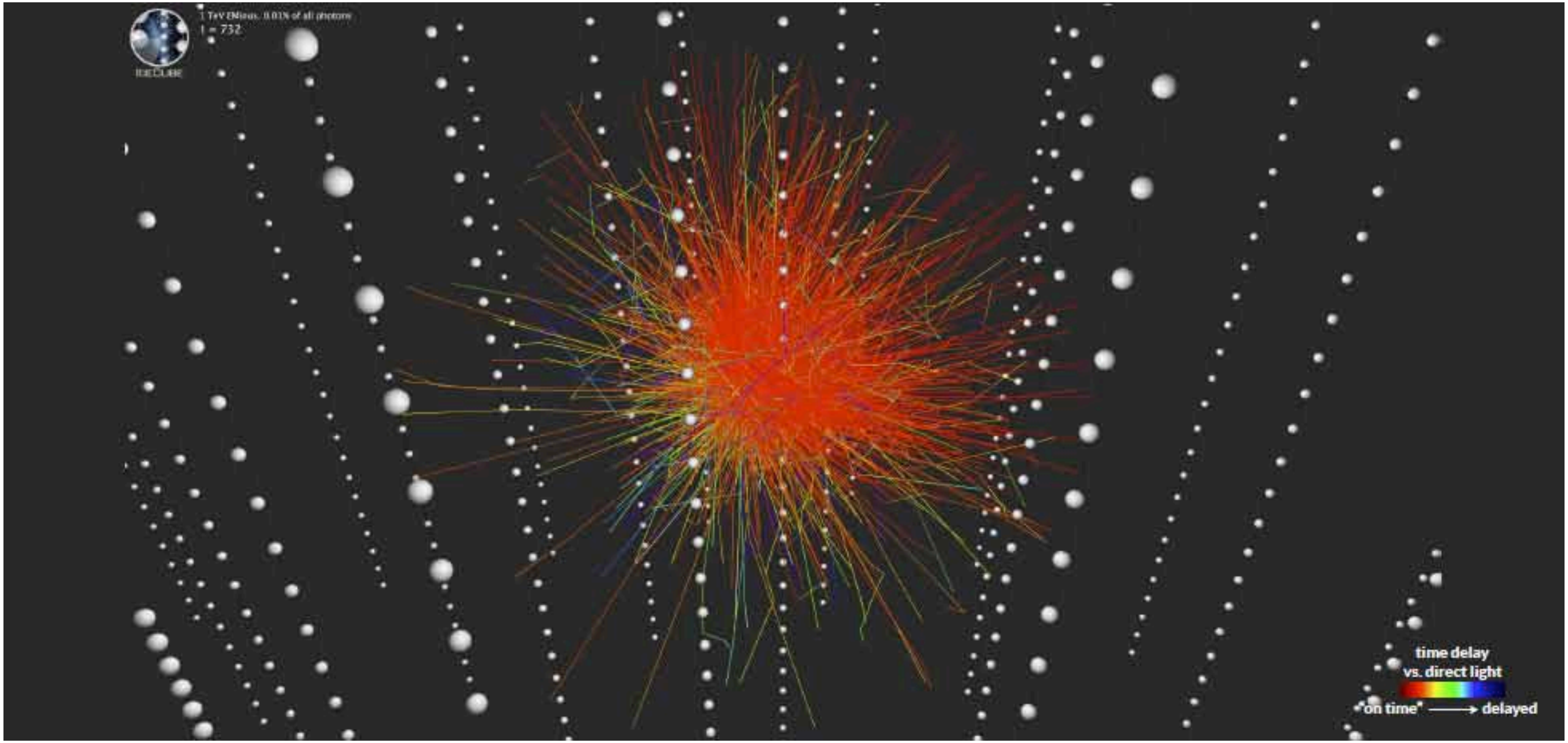
$\nu_\mu + A \rightarrow \mu + X \quad \rightarrow \quad$ muon track

Simulated Cherenkov Photons from a shower in ice



$\nu_e + A \rightarrow e + X \quad \rightarrow \quad$ electromagnetic shower

The same shower event in water



$\nu_e + A \rightarrow e + X \quad \rightarrow$ electromagnetic shower

Properties of ice and water

- Absorption length

  should be as long as possible

  determines distance between optical sensors

- Scattering length

  should be as long as possible

  → direction resolution

  → energy resolution

  → neutrino flavor identification

  → background suppression

Properties of ice and water

- Absorption length

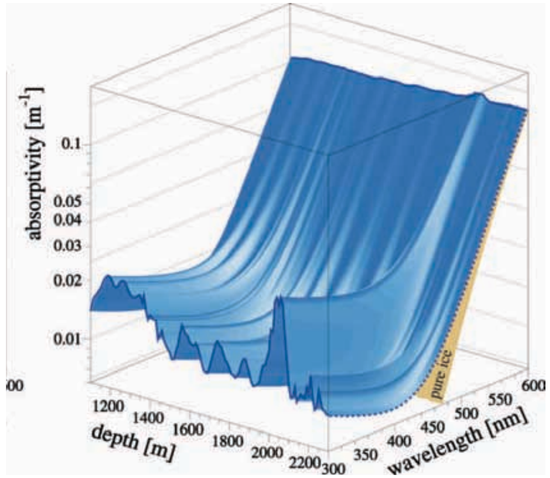
  ice: 110 m

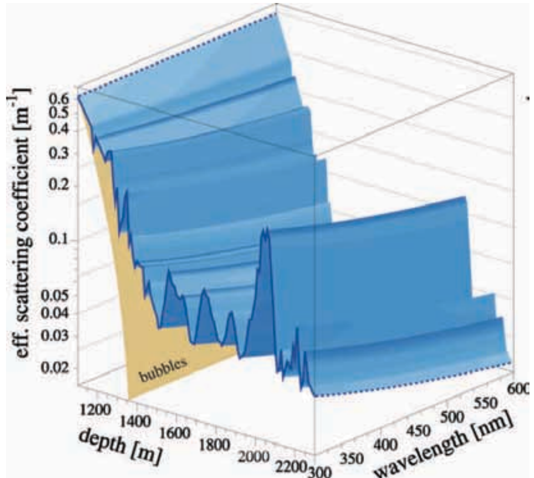
  water: 63 m

- Scattering length

  ice: 30 m

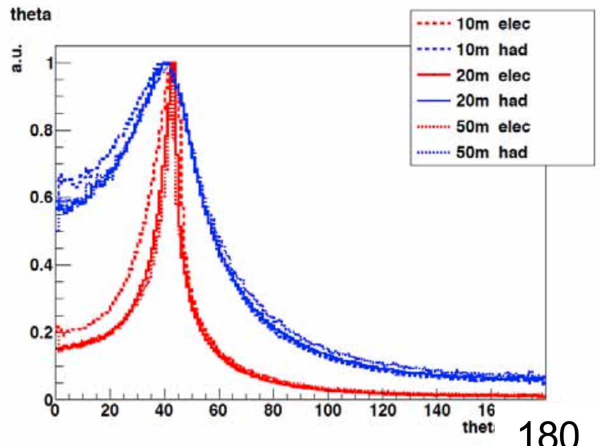
  water: 250 m





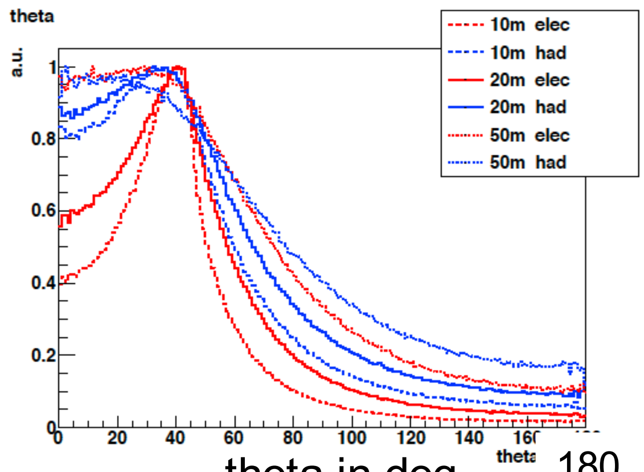
Photon propagation parameters: water versus ice

water

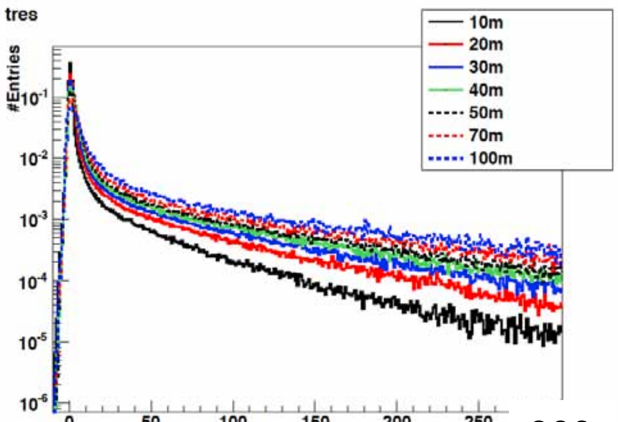


theta in deg 180

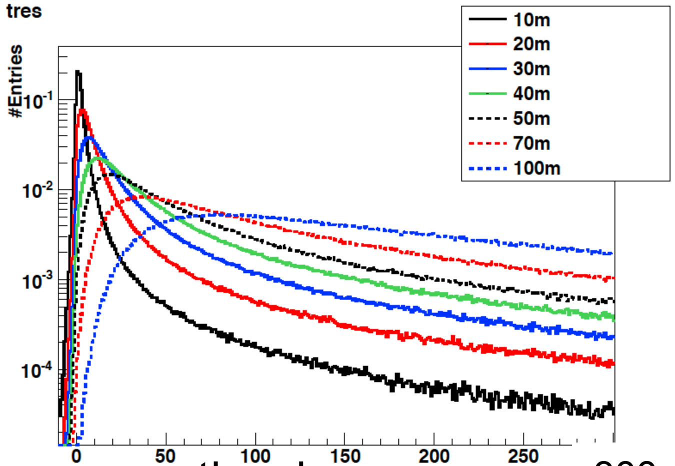
ice



theta in deg 180



time in ns 300



time in ns 300

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Properties of ice and water – optical background

- Optical background in South Pole ice

  about 700 Hz per PMT

- Optical background in Mediterranean water

  K-40 in water:

  40 kHz per PMT

  bioluminescence:

  up to MHz per PMT bursts

  seasonal variation

optical background almost negligible due to short event time

Event quality in ice and water

- Tracks

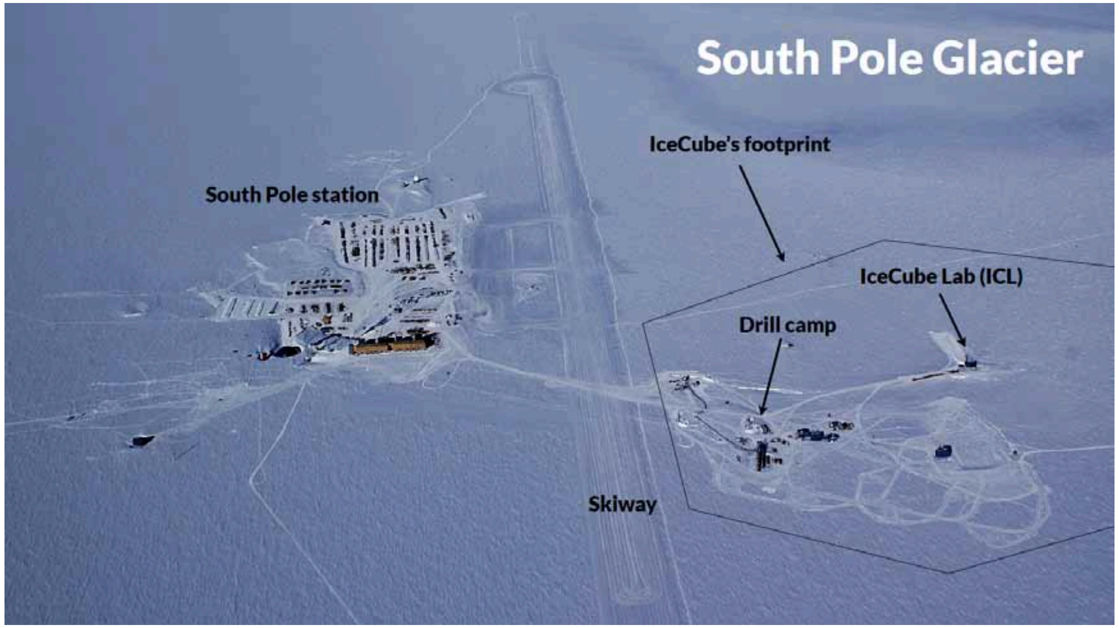
Tracks		ice	water
angular resolution	1 TeV	1.0°	0.7°
	100 TeV	0.5°	0.1°
energy resolution	dE/E	1	1

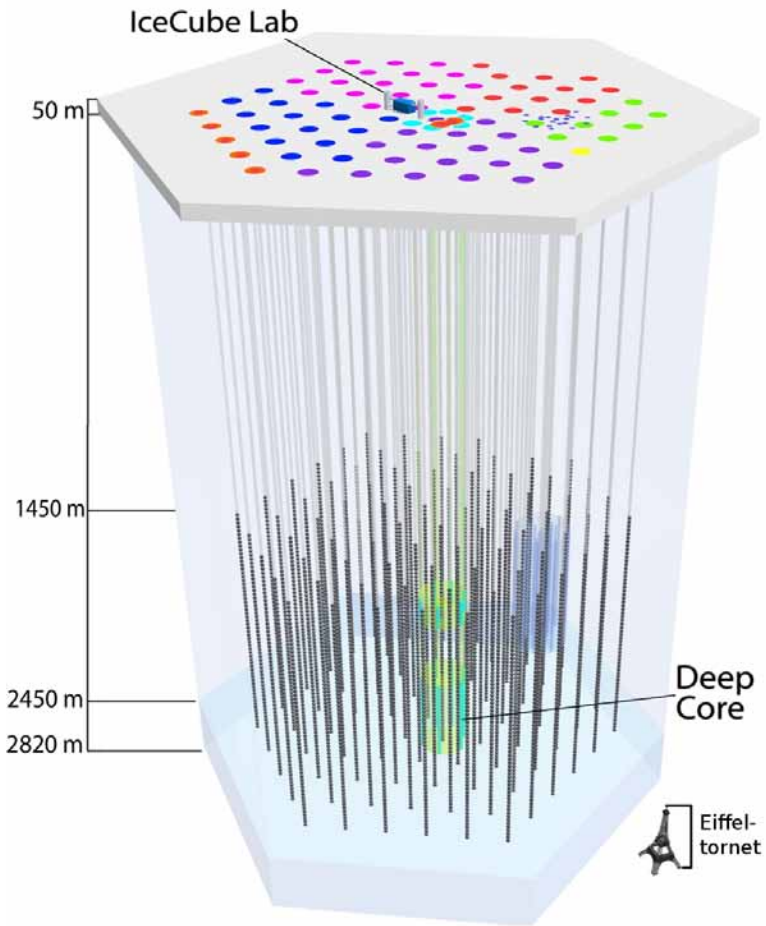
- Showers

Showers		ice	water
angular resolution	1 TeV	15°	4°
	100 TeV	10°	2°
energy resolution	dE/E	0.5	0.5

IceCube

- 86Lines; 5160 PMTs
- Completion 2010
- Instrumented volume: 1 km^3

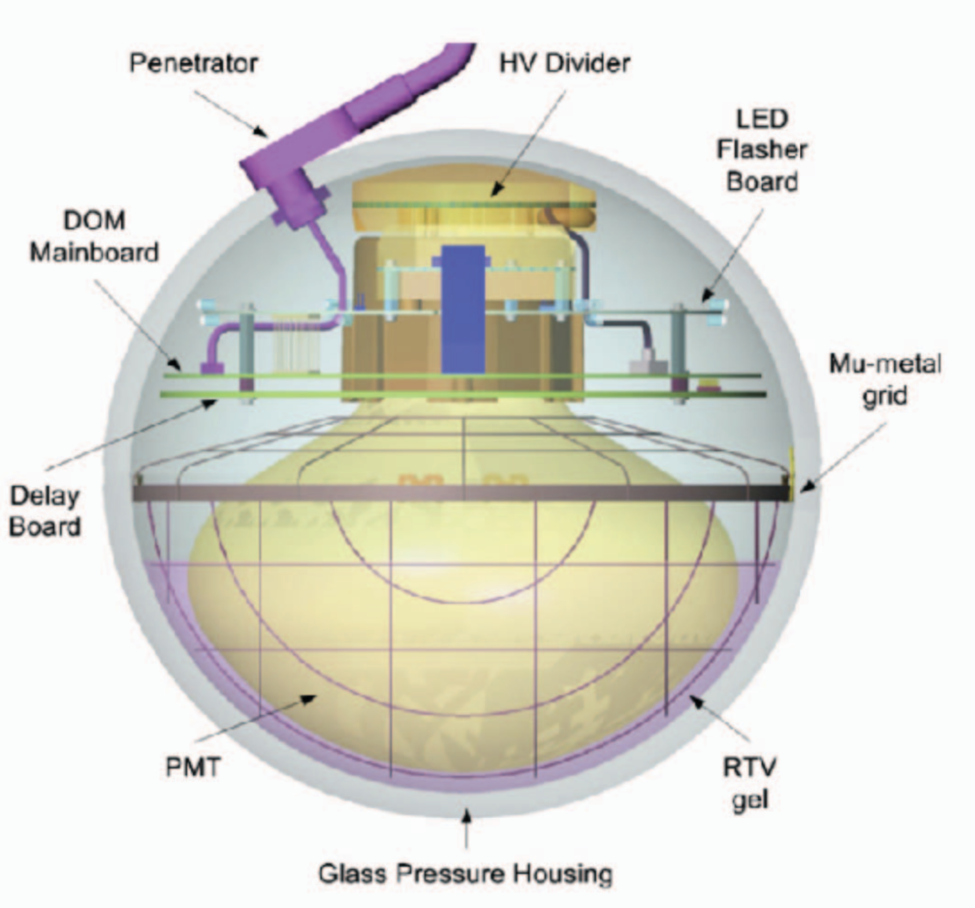


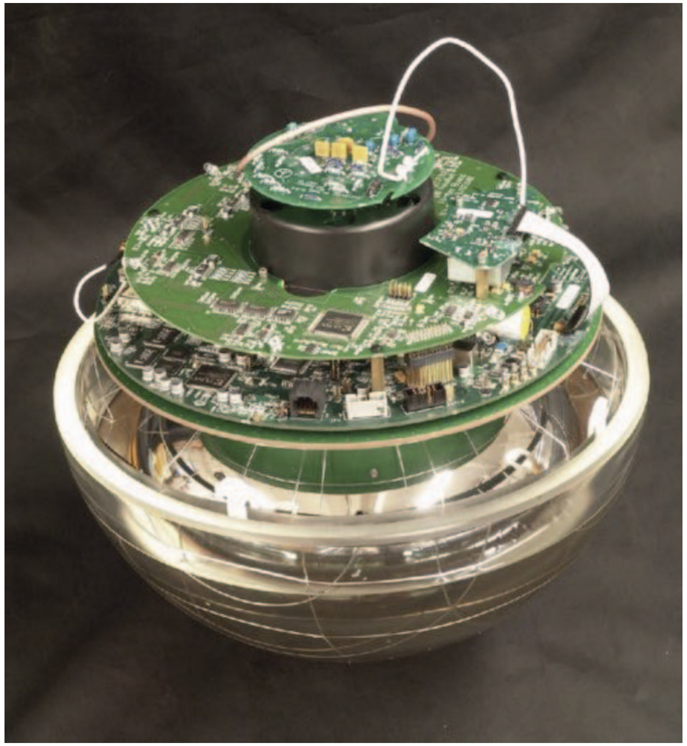


Credit: IceCube

South Pole

The IceCube Optical Module





IceCube

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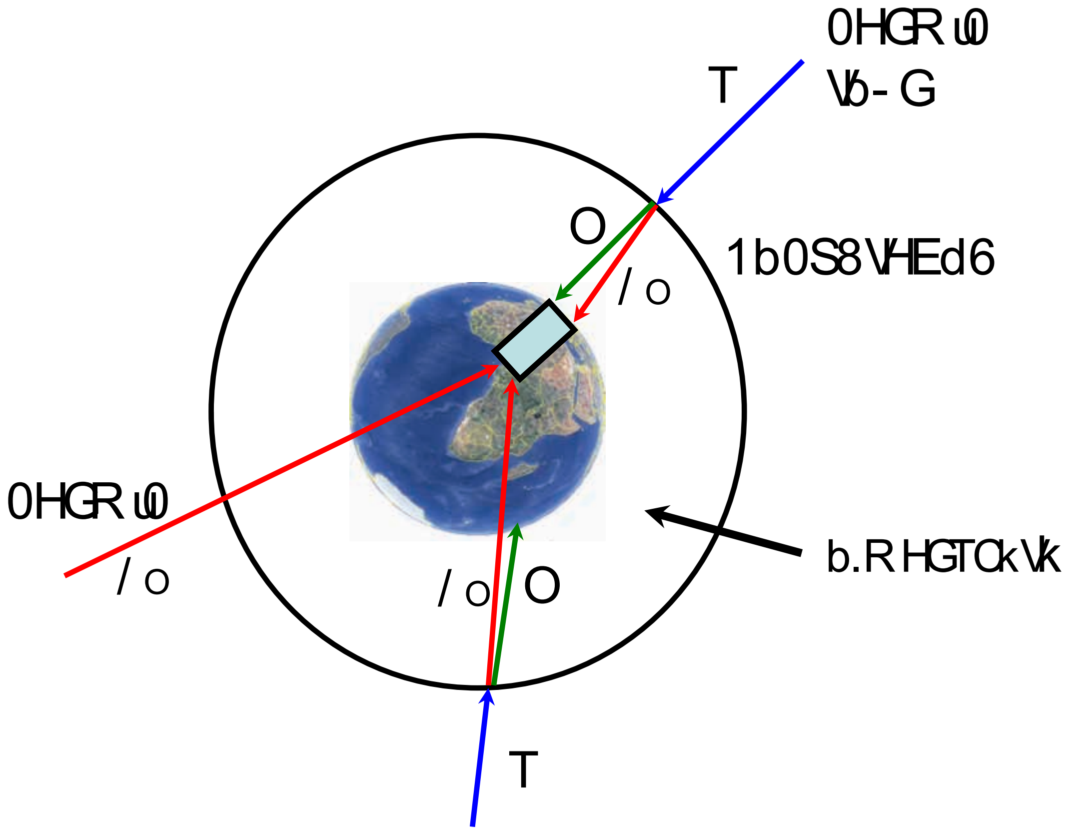
Credit: IceCube

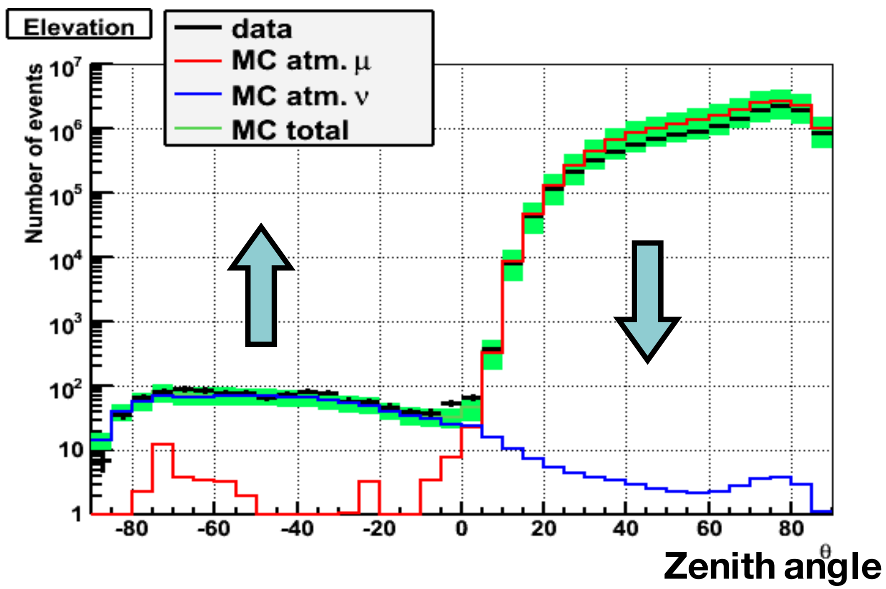
Particle background: atm. muons and neutrinos

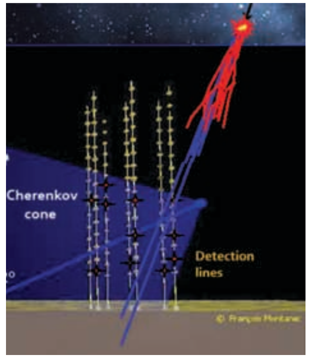


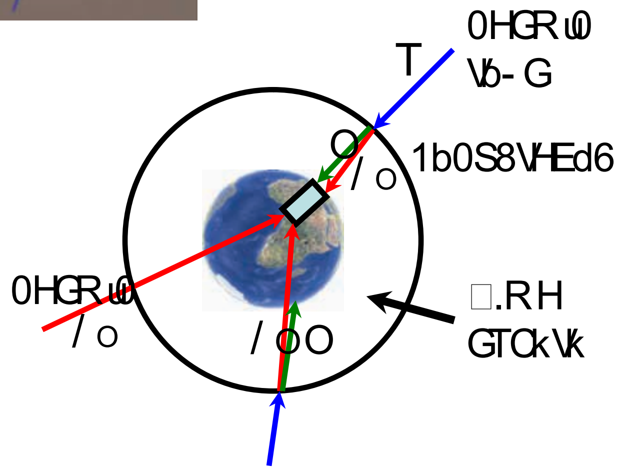
B □NEX□hVHR □b1HPk□6HR udb.k6 □1-□b.R HGTCkV0 □R EHdG

Bc kE.VdH□.kNkG0HTkGHT.uR uGk6 □.H□1k □□GkdGuPk□.H□dkE.VdHG□VHR □1kNHv

Particle background: atm. muons and neutrinos

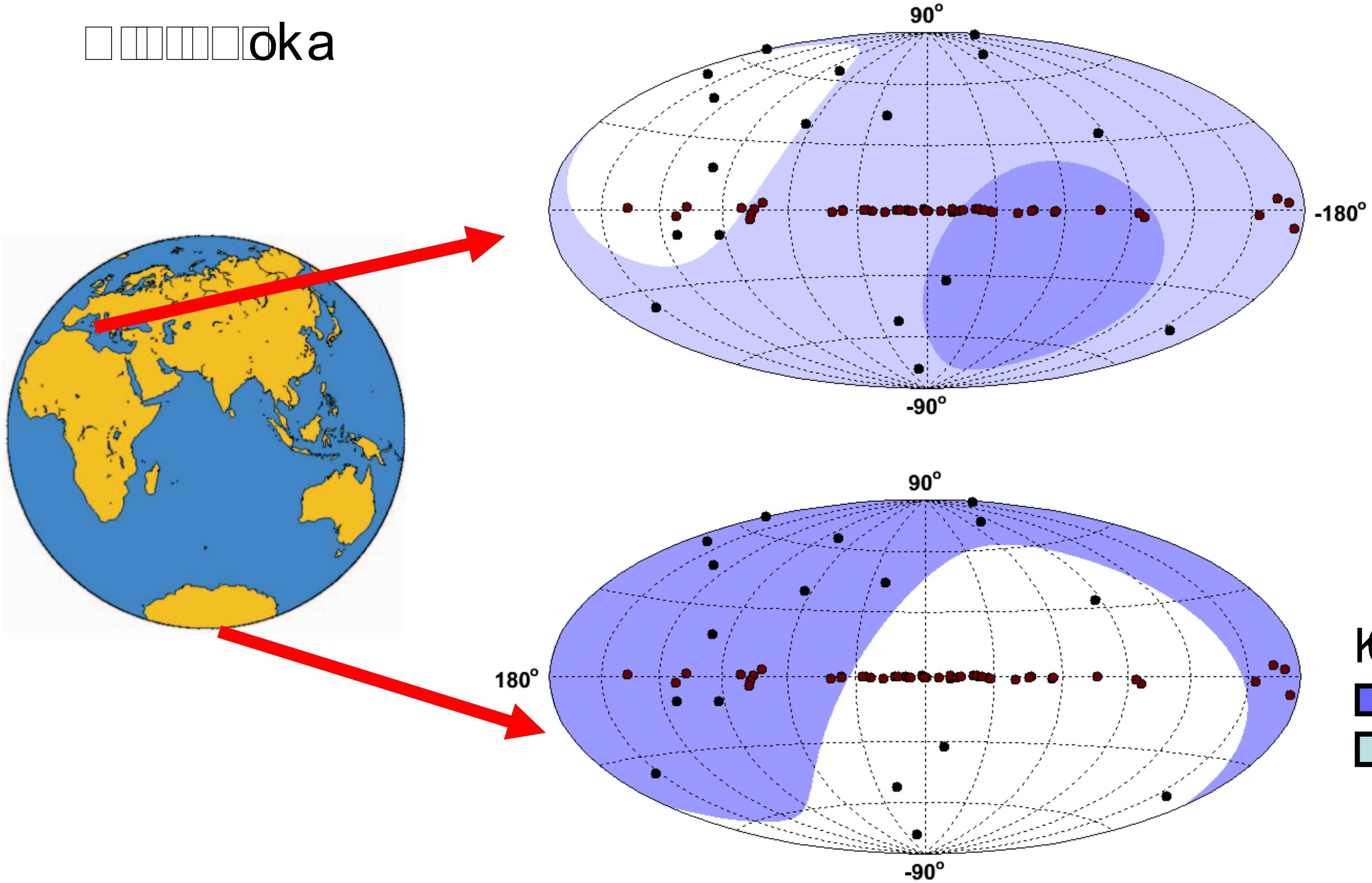






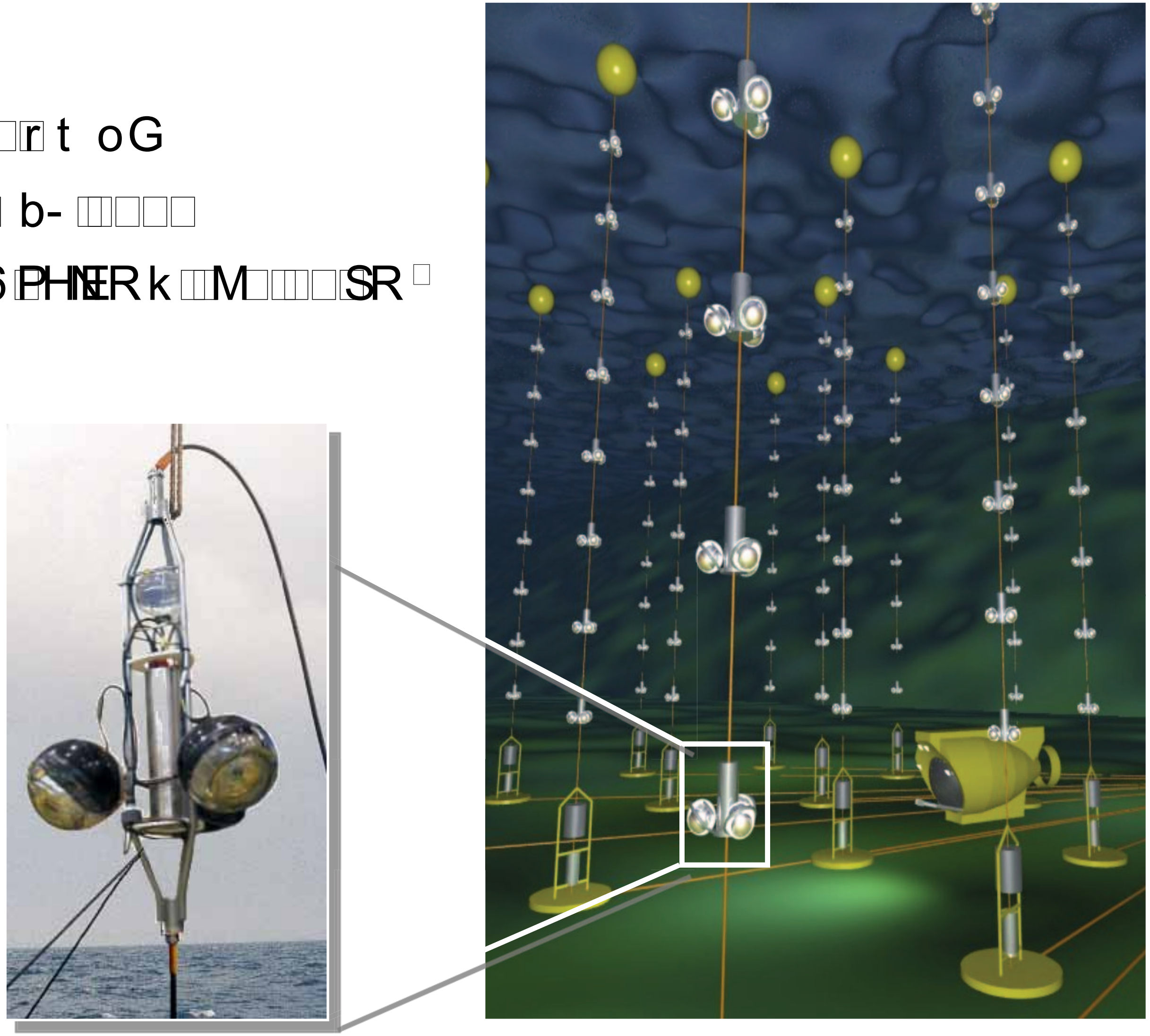
- B □NEX□hVHR □b1HPk□6HRudb.k6□1-□b.RHGTCkV0□REHdG
- Bc kE.VdH□.kNG0HTkGHT.uRuGk6□H□1k□GkdGuPk□H□dkE.VdHGhVHR□1kNHv

Sky coverage of neutrino telecopes



Antares

- □□□eudkG□□□□□r t oG
- □HRTNk.uHdt□ b- □□□□□
- KdGVERkd.k6□PHNERk □□M□□□□□SR□

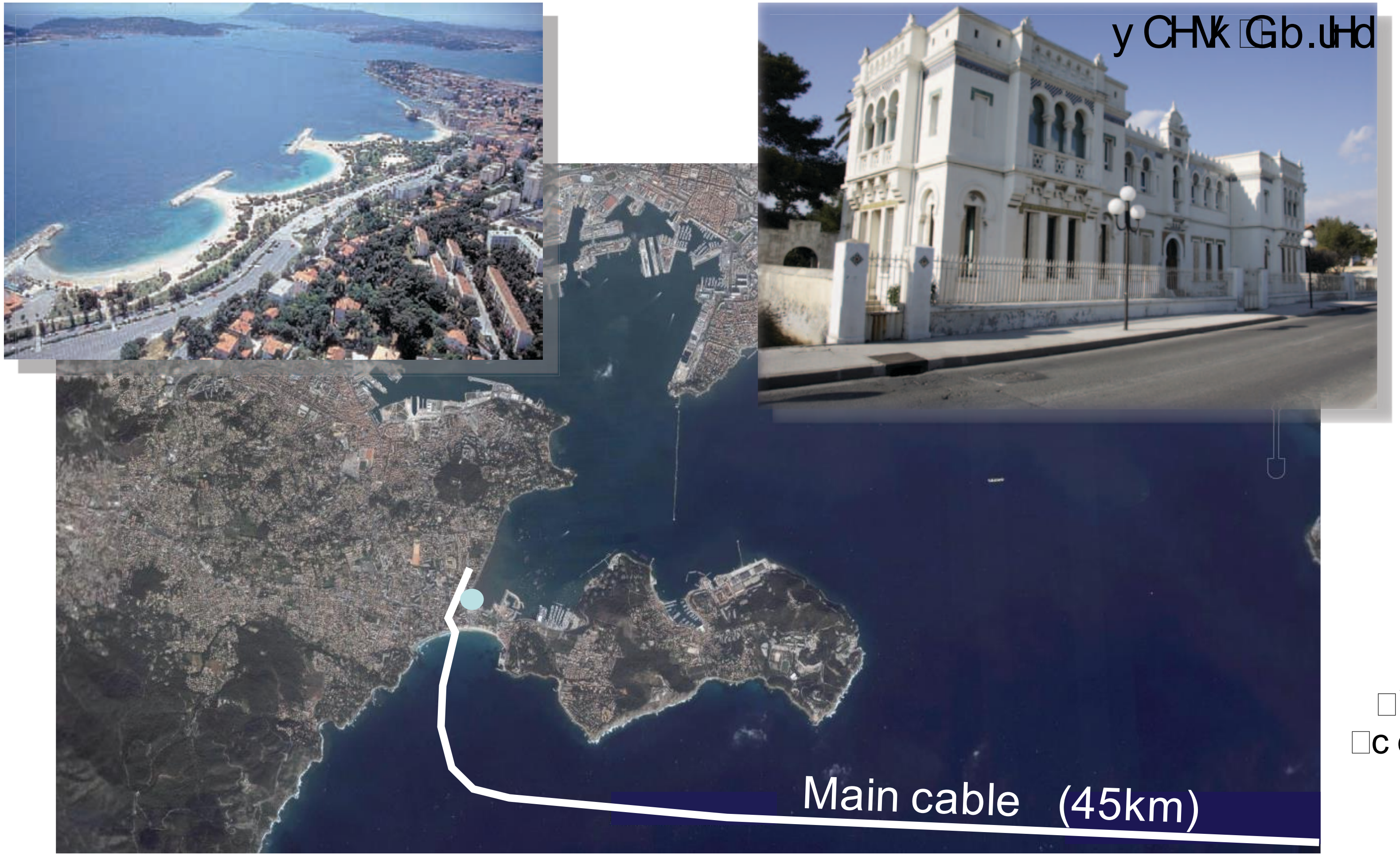


□□□□□R

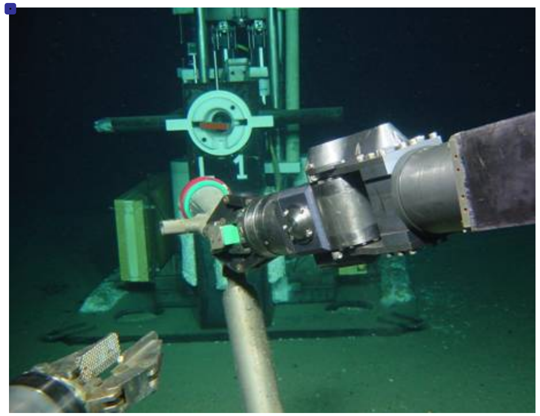
□□□□□R

□Vk6u□□c o□g □y

ANTARES in the Mediterranean Sea



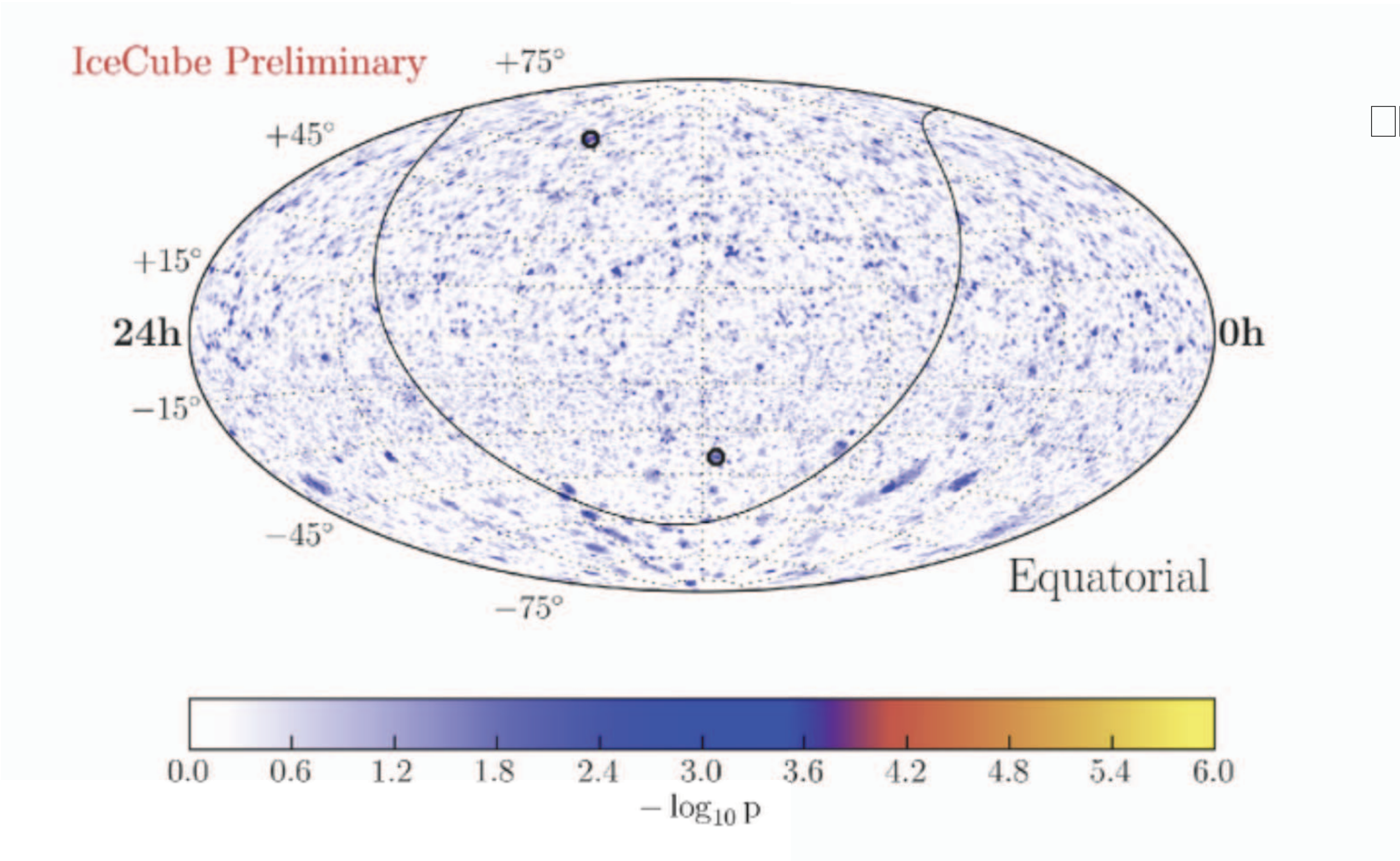
ANTARES deployment



Credit: ANTARES

Results from running neutrino telescopes

IceCube Neutrino Skymap: ν_μ Neutrinos



kPkd.G

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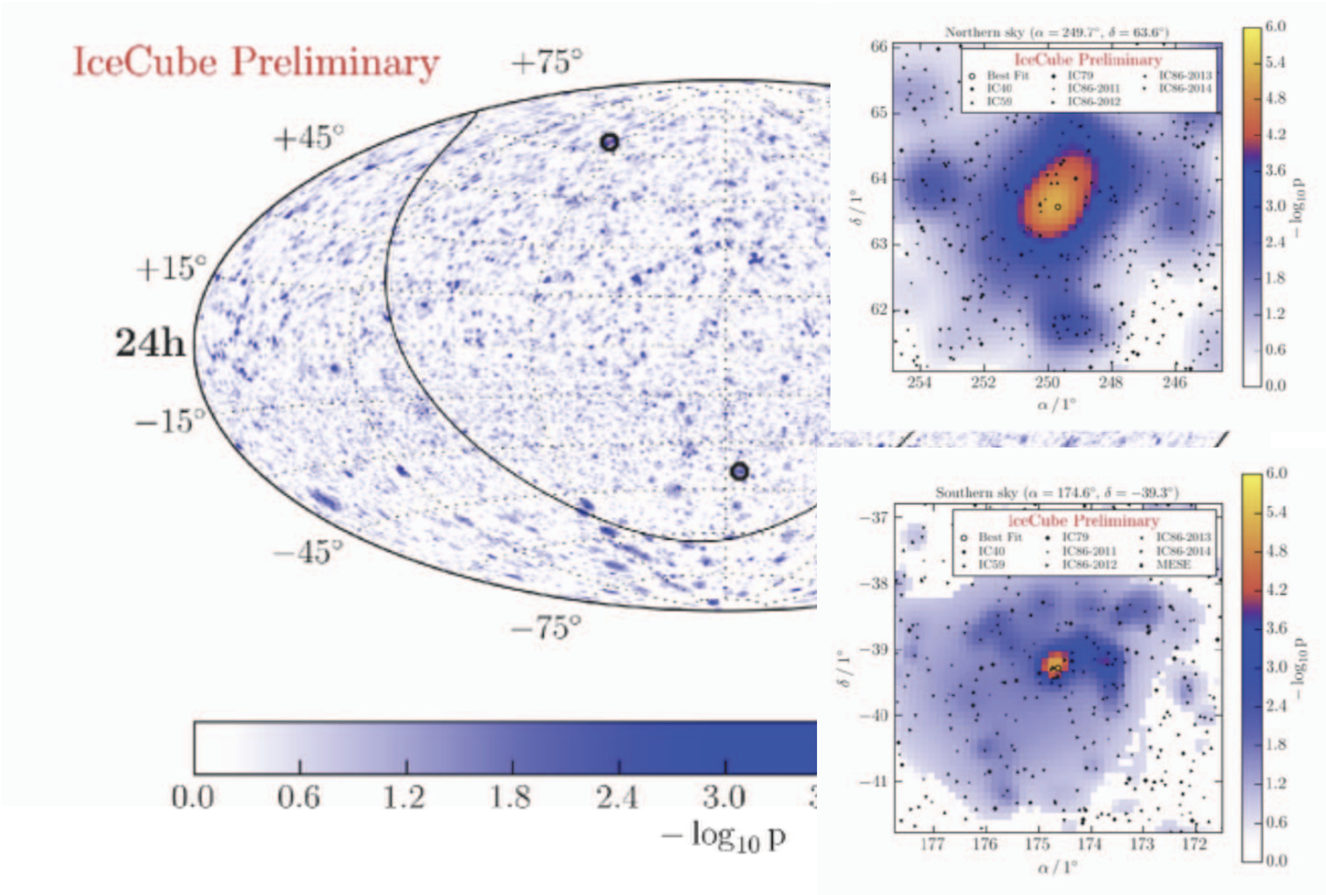
IceCube Neutrino Skymap: ν_μ Neutrinos



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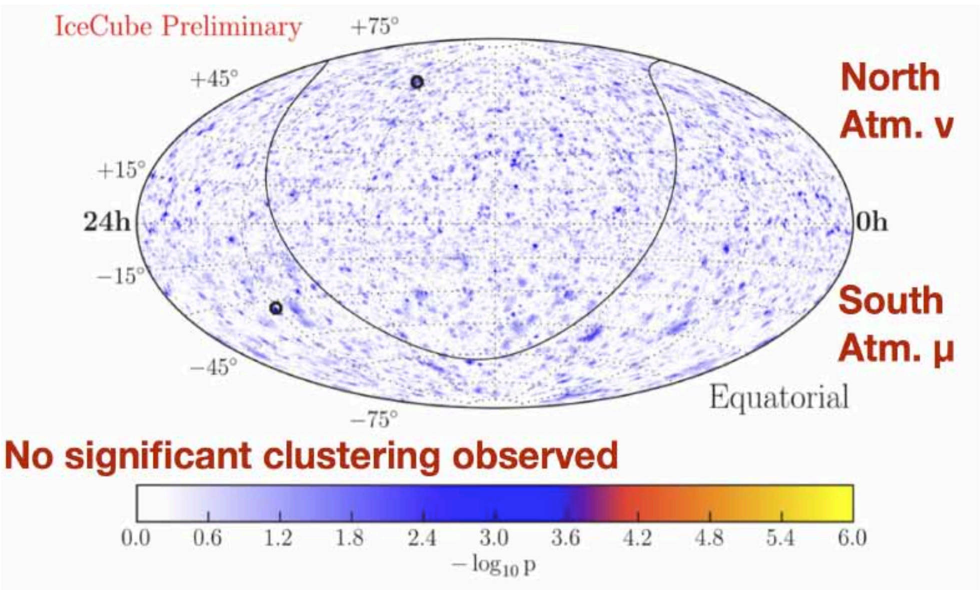
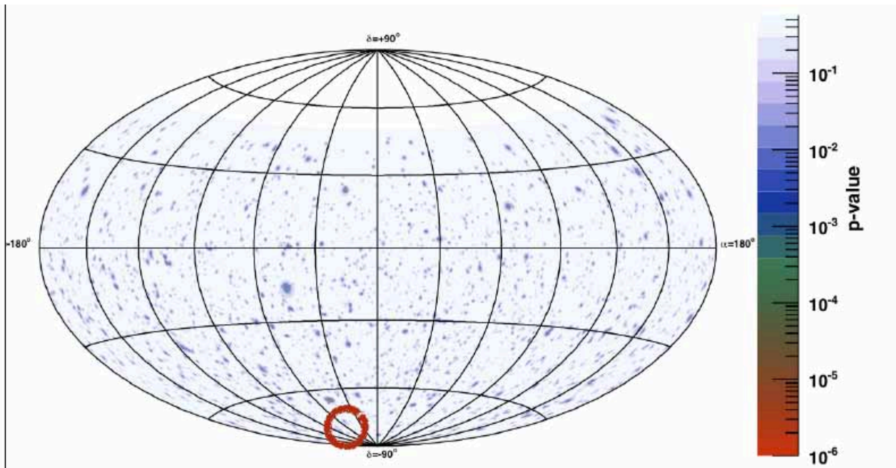
Search for neutrino point sources

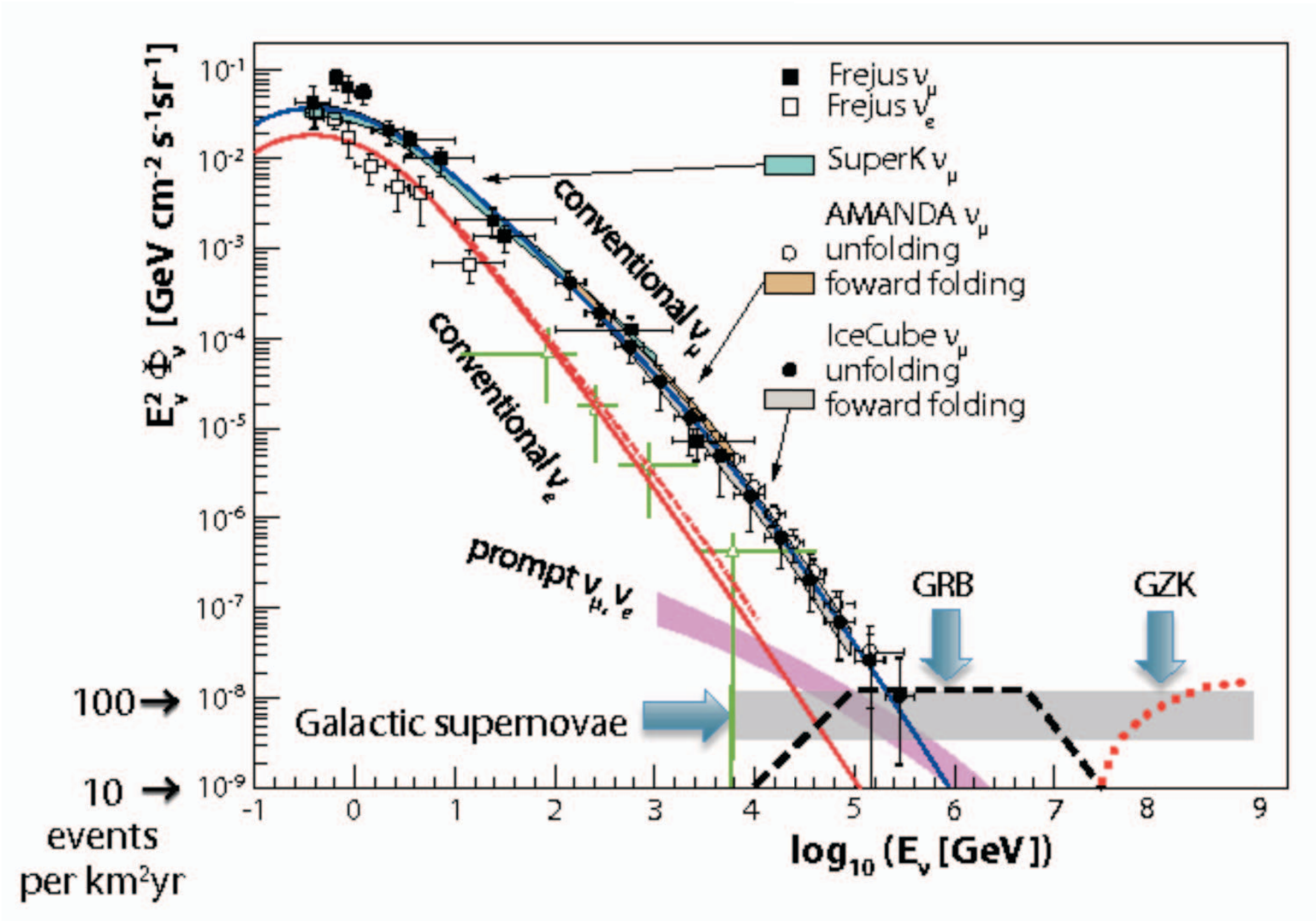
IceCube 6 years,
Northern sky: p-value: 35%
PeV-southern sky: 87%

ANTARES 4 years
best p-value 2,6%





Background: atmospheric neutrino flux



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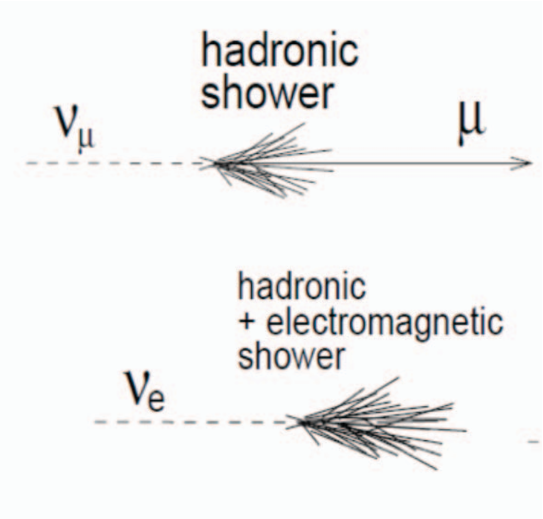
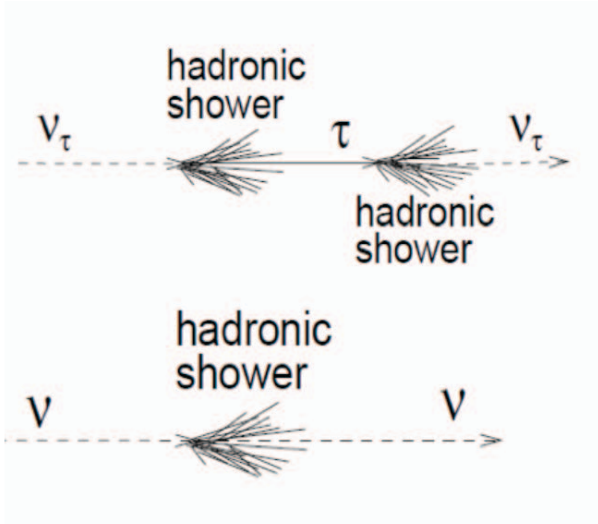
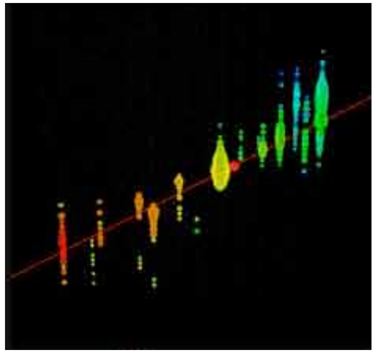
More selective neutrino searches....

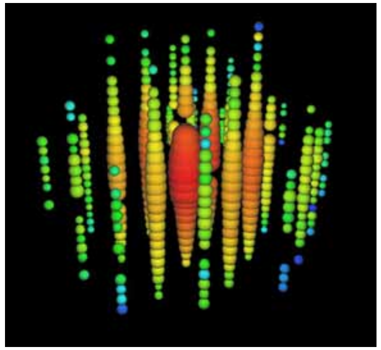
IceCube highest energy events







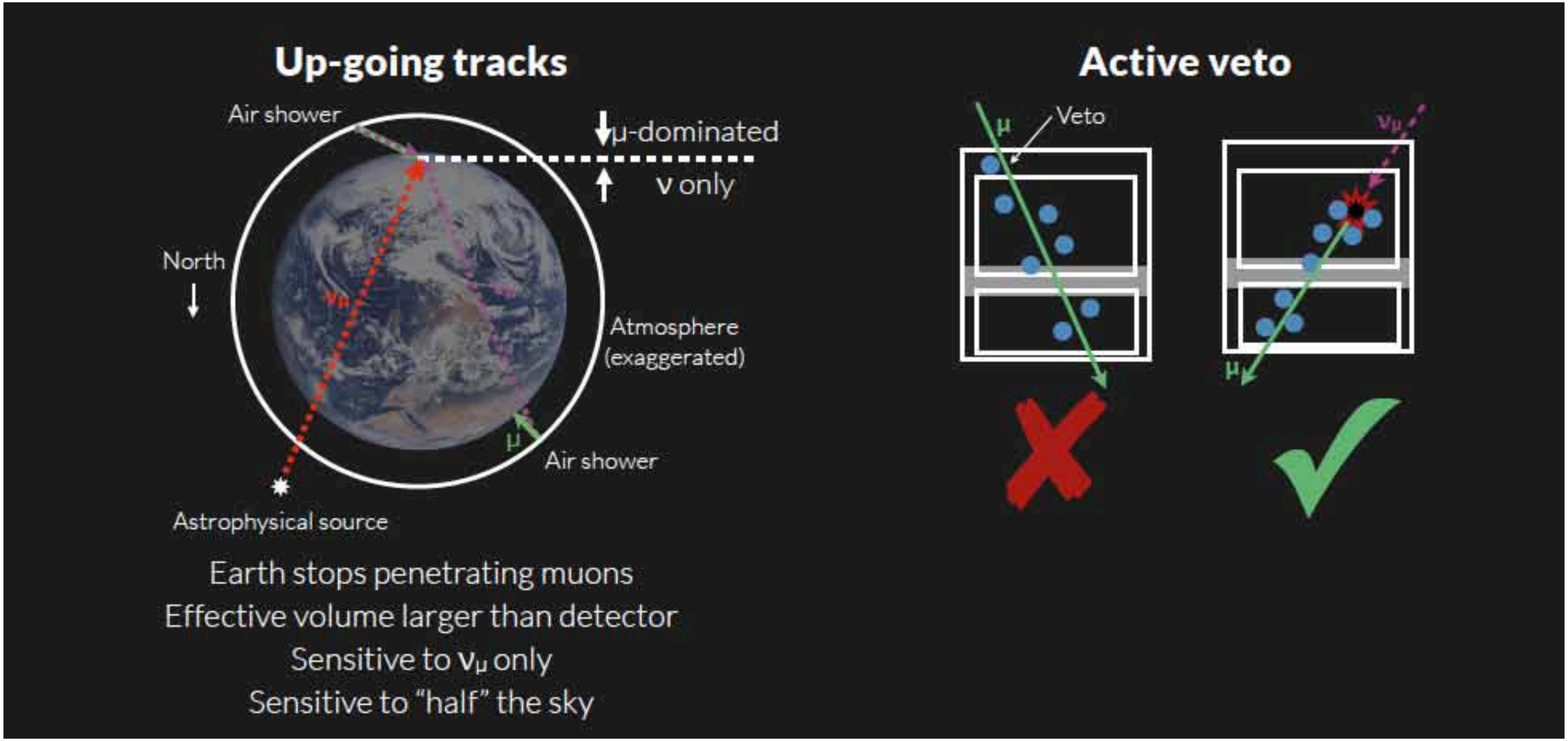
.Vb0S
kPkd.



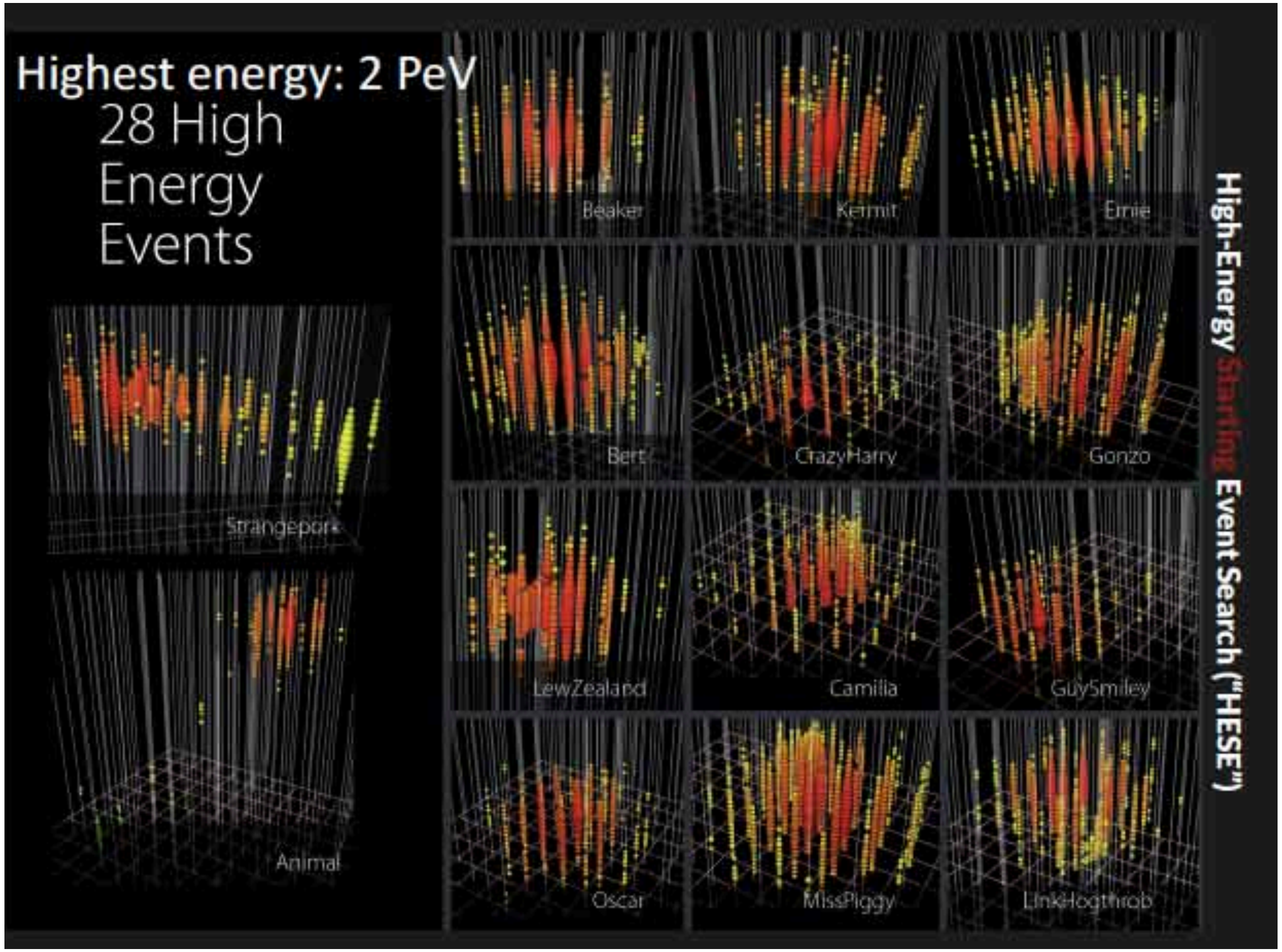
GCHv kV
kPkd.

r ka

Vetoing downgoing muons

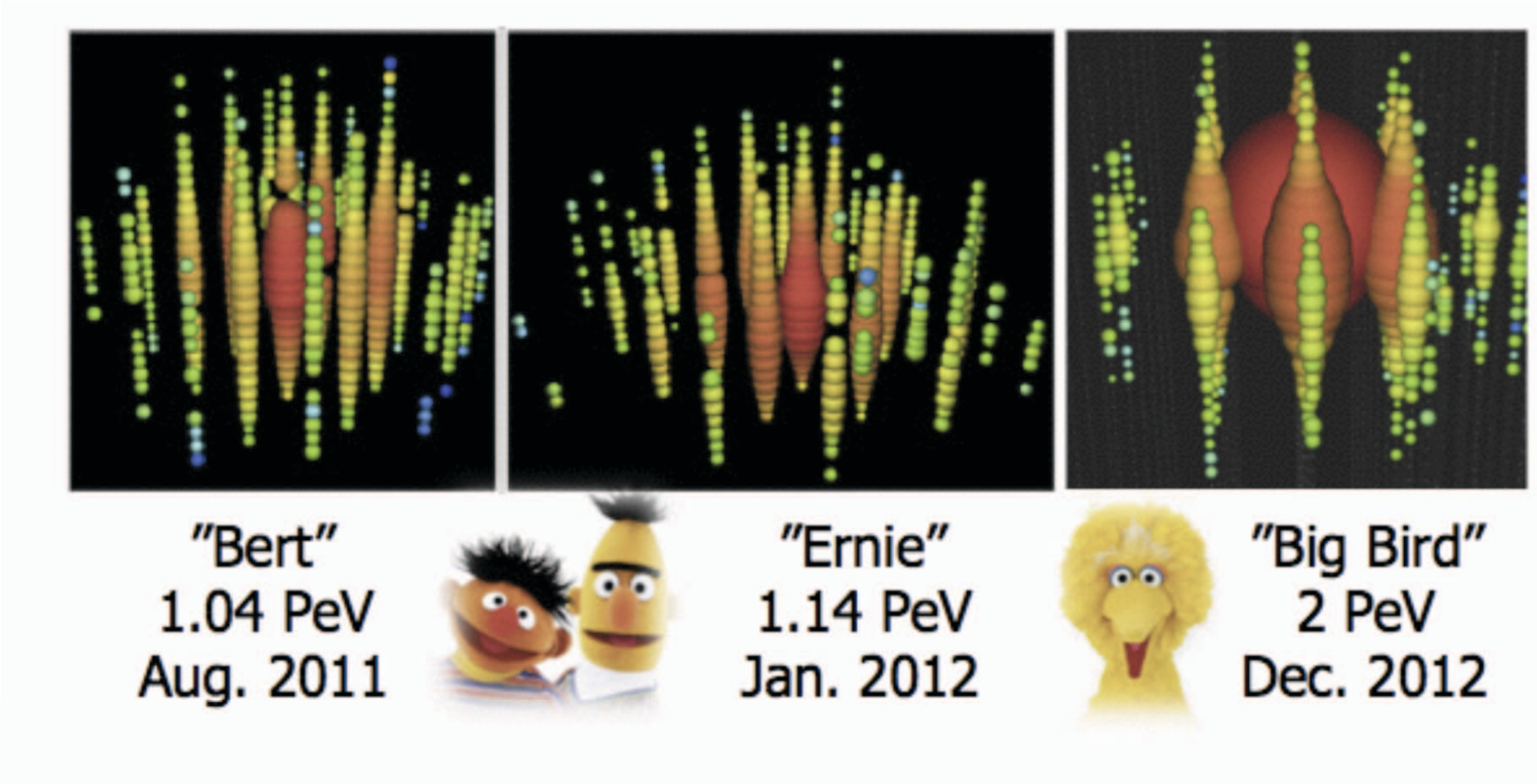


High energy starting events

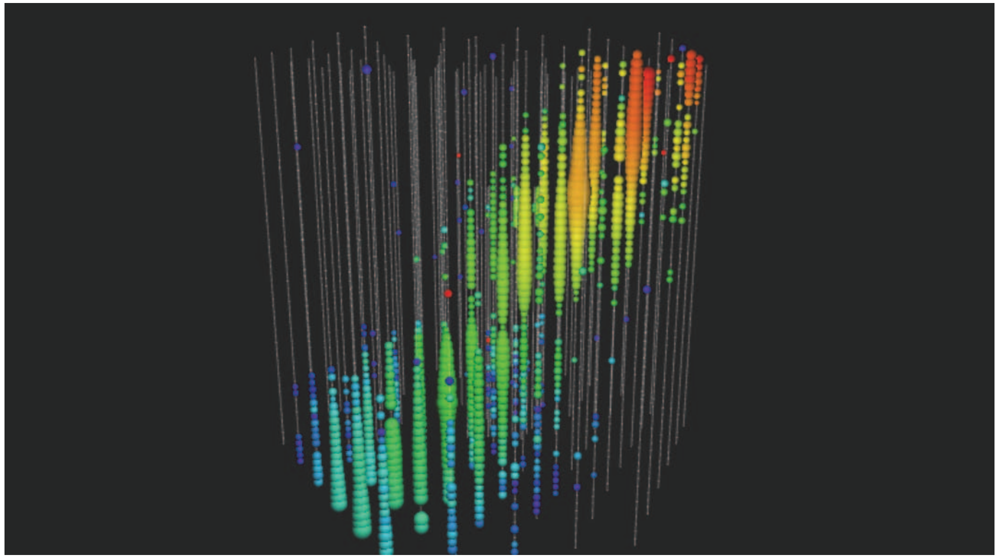


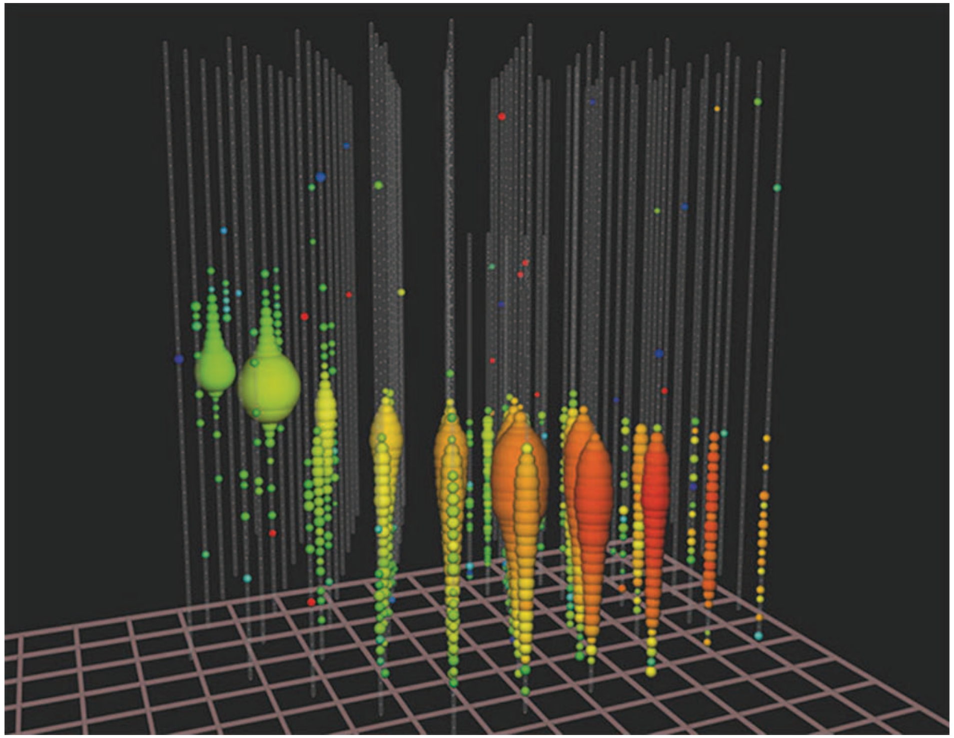
Most starting events are showers; Energy around a PeV

Shower events



High energy track events





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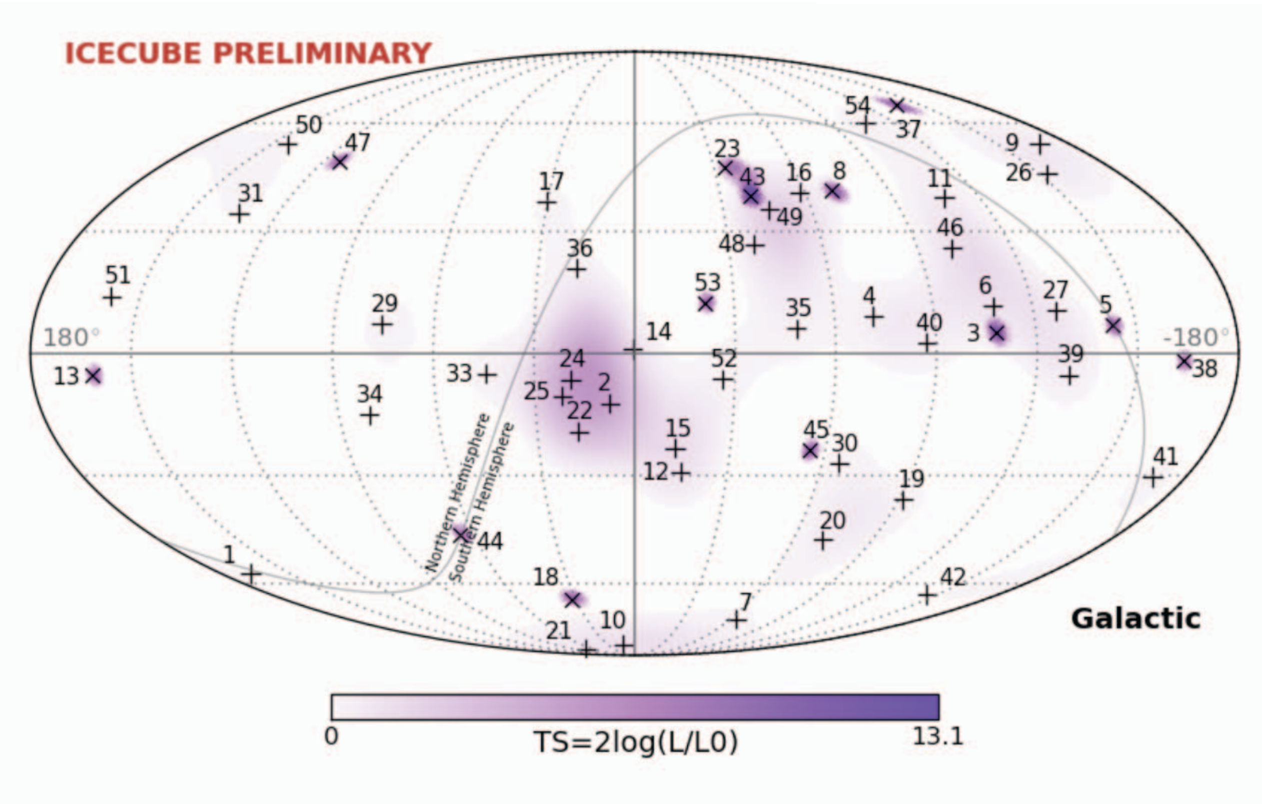
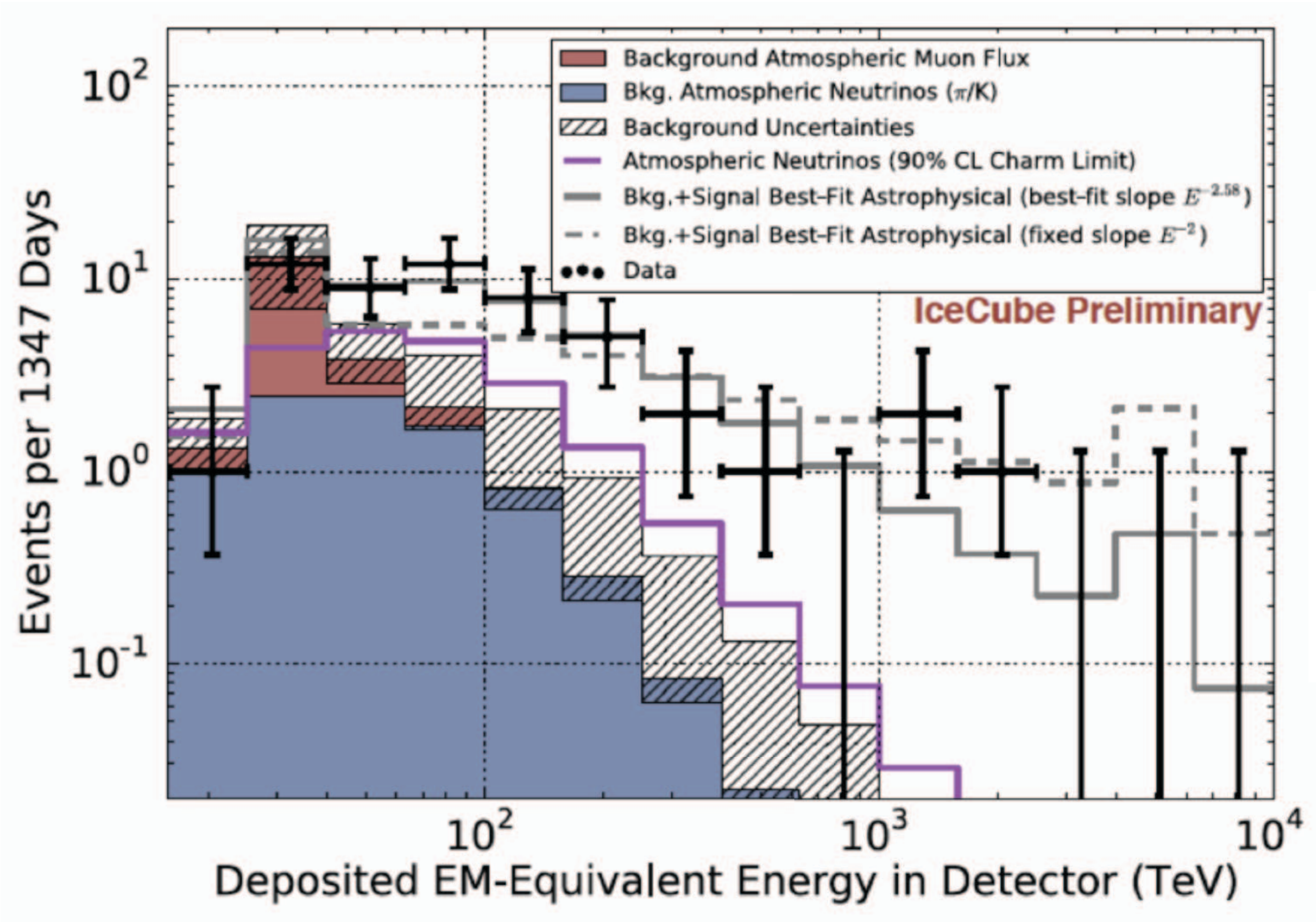
IceCube Neutrino Skymap: Neutrinos E>100 TeV



T
dHG8dul0bd.
0NEGkV

K0kE1k r g e

Detection of diffuse cosmic neutrino flux



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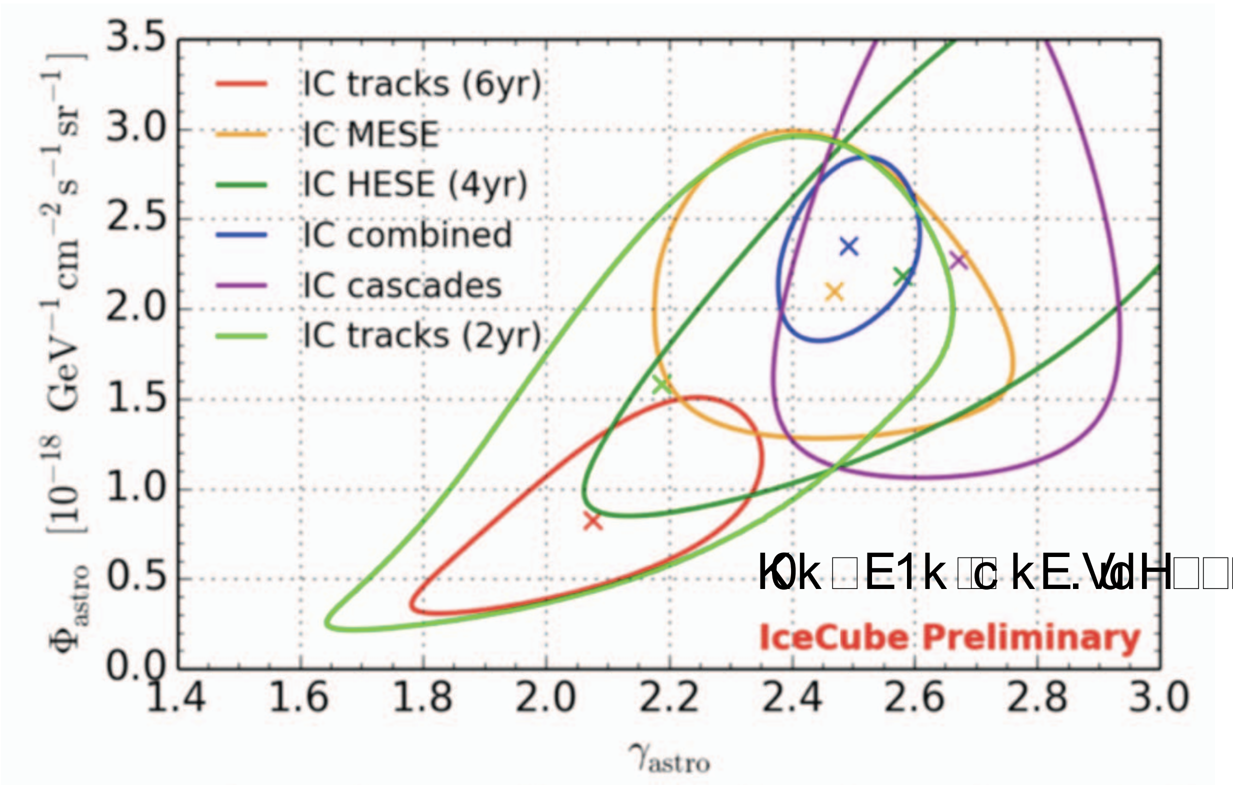
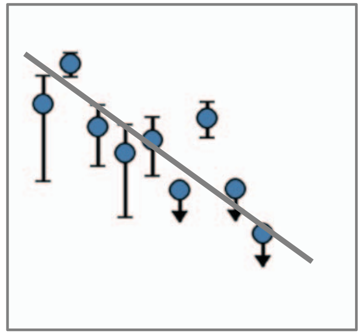
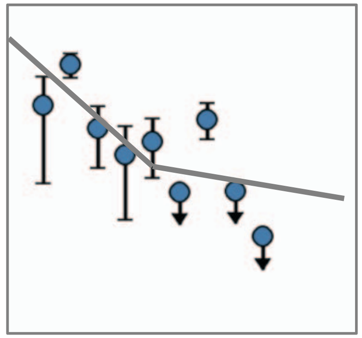
Astrophys. neutino spectrum E>100 TeV

GGER T.uHd Gud8Nk THv kVNbv Φ_H $^{\gamma}$



K0k E1k c kE.VdH





HR 1udk6 GTk0.VbNd6kX A

2 u8Ck dk V8- .Vb0SG A

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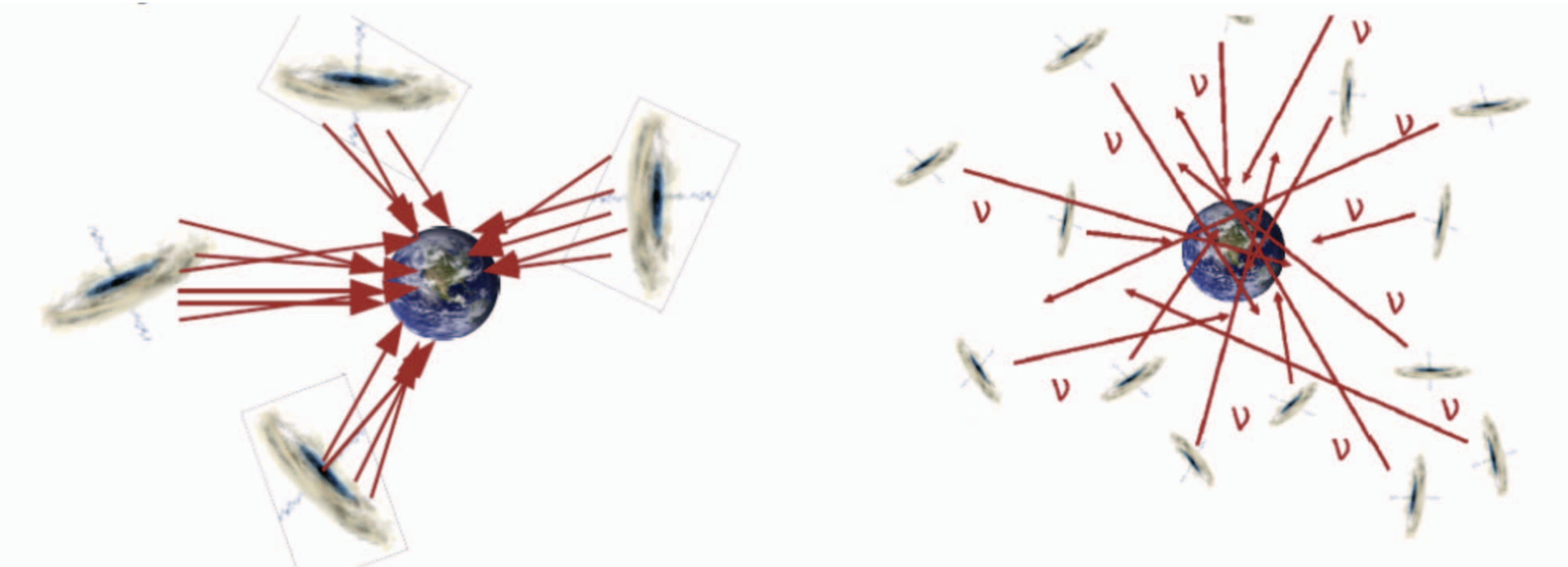
Astrophysical Neutrinos



Point Sources: Find > 1 neutrinos from the same direction (source).

Diffuse Flux: Superposition of many weak sources; Identification via neutrino energy

Search for correlated neutrino emission

- Steady sources:
  Source stacking (SNR, AGN, Black holes...)

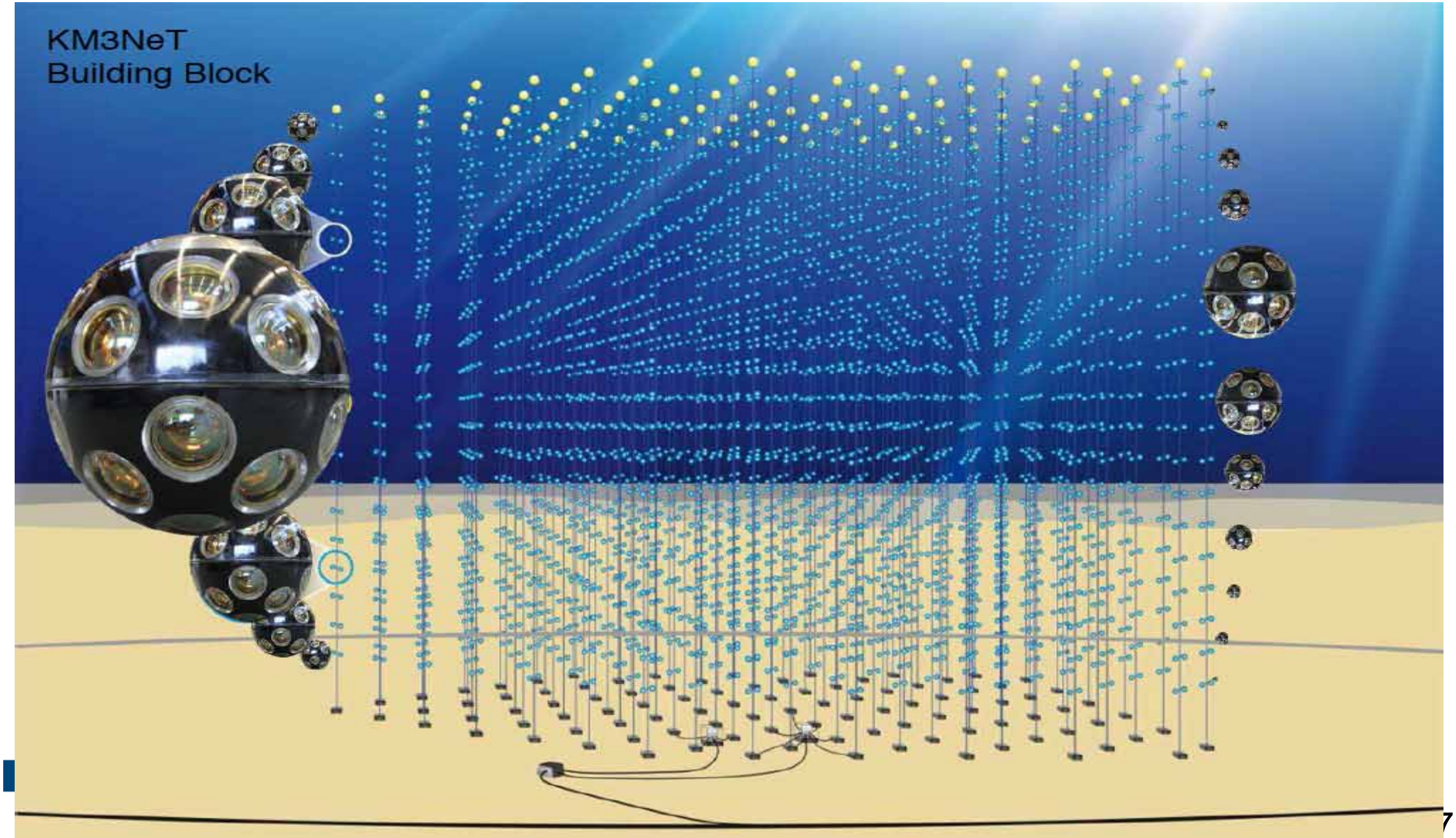
- Time coincident searches:
  GRBs, AGN flares

- Sending alerts:
  highest energy ν_μ

No significant signal yet ($p<5\sigma$)

Next generation of neutrino telescopes

KM3NeT



KM3NeT line production

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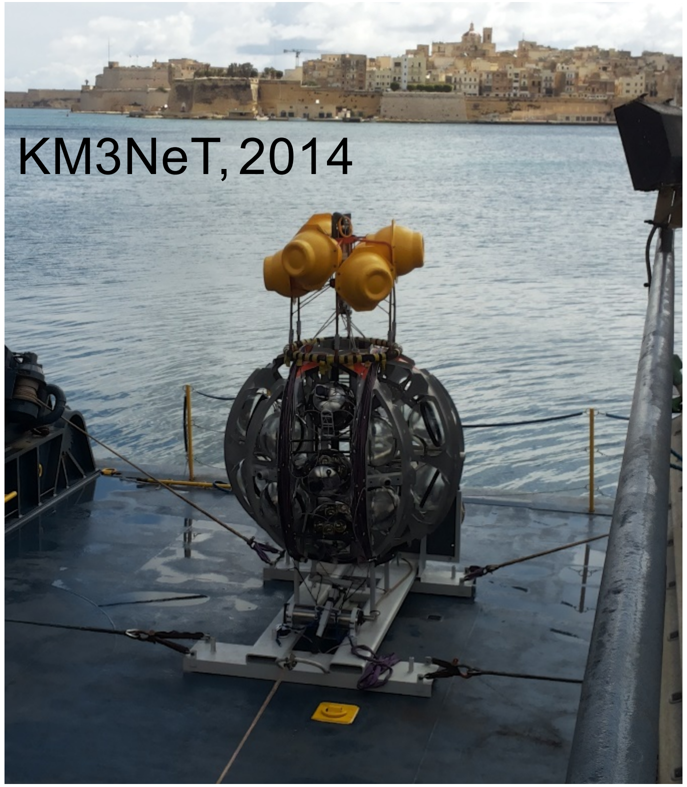
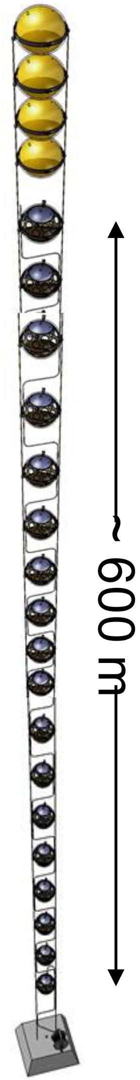
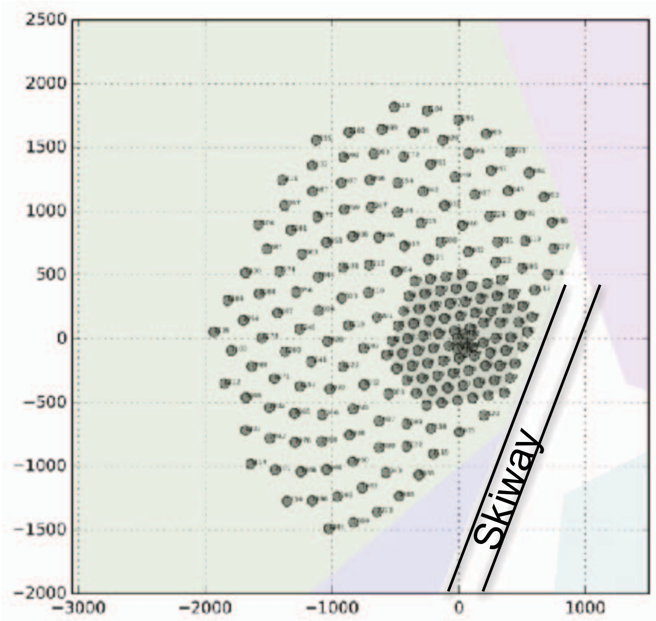
KM3NeT launching vehicle

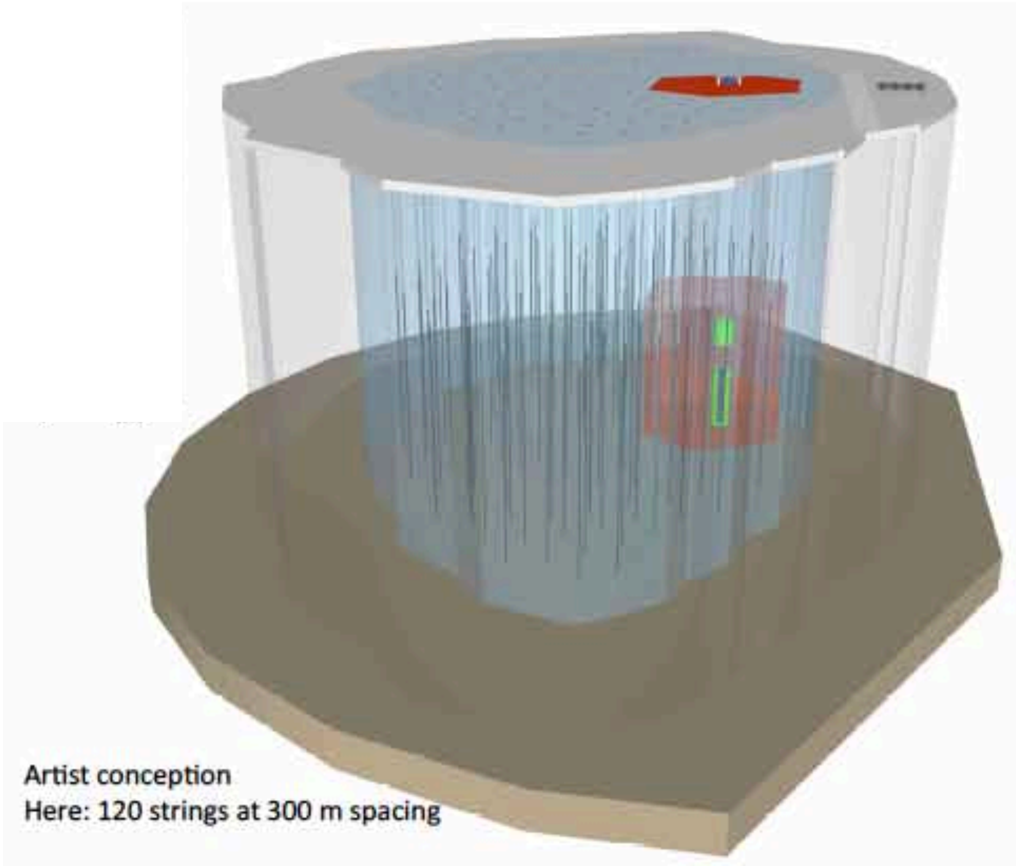
- rapid deployment
- autonomous unfurling
- recoverable





IceCube next Generation





Summary and Conclusion

- Very high energy hadronic particles are produced in the universe
- Charged particles at Earth do not point back to their sources
- Neutral particles point back to sources:

  Photons: „easy“ to detect, but can be produced by electrons

  Neutrinos: very hard to detect, but clear hadronic origin

- Neutrino telescopes:

  IceCube detects cosmic high energy neutrinos since 2013

  Future telescopes: KM3NeT / IceCube Gen2

Thank you for your attention!