High Energy Neutrino Astronomy

VII International Pontecorvo School
Prague, August 2017

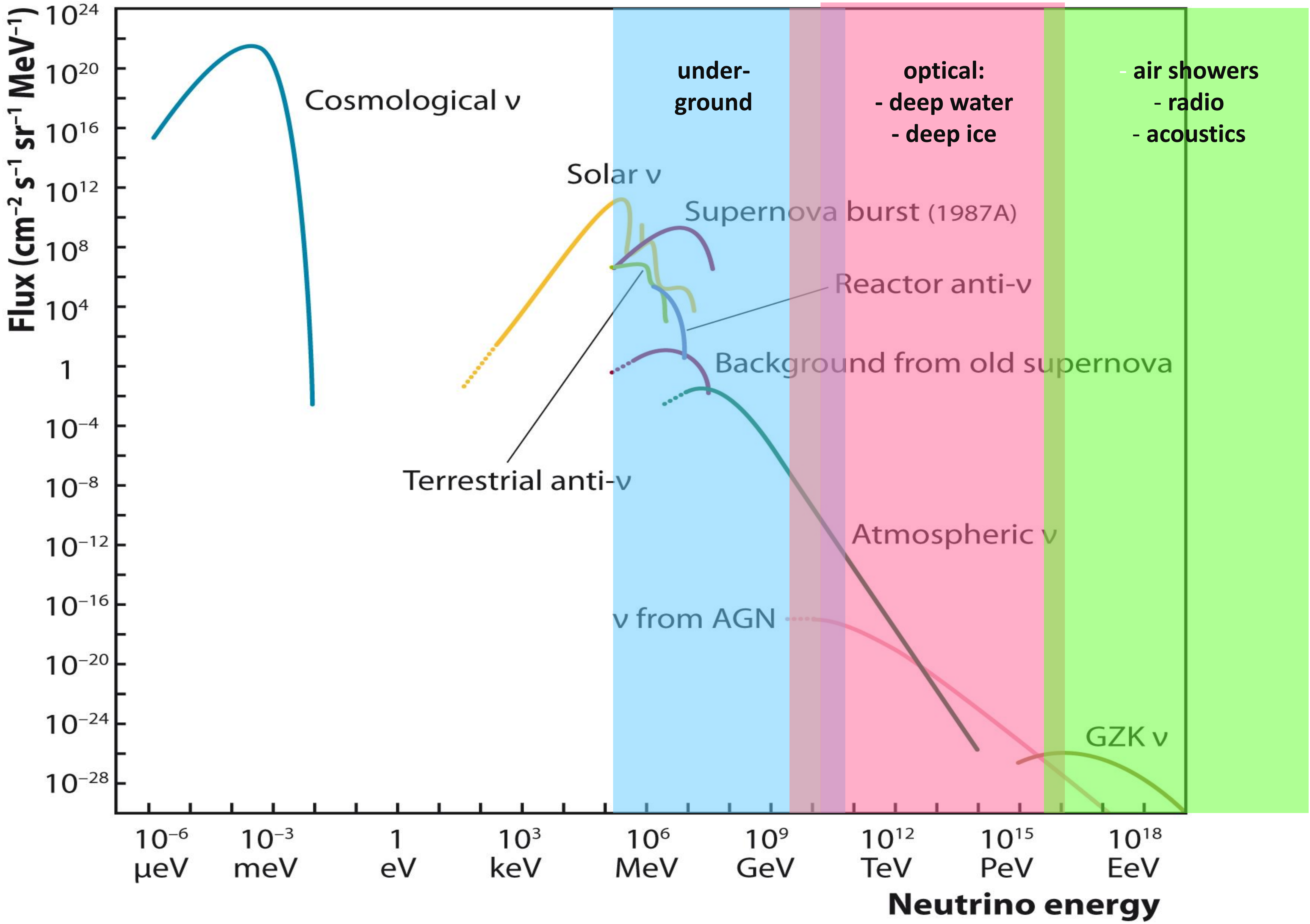
Christian Spiering, DESY Zeuthen

Content

- **Lecture 1**
  - Scientific context
  - Operation principles
  - The detectors
  - Atmospheric neutrinos
- **Lecture 2**
  - Search for steady point sources
  - Search for transient sources and the multi-messenger concept
  - The diffuse flux of cosmic neutrinos
  - Search for Dark Matter (indirect) and magnetic monopoles
  - A look to the future

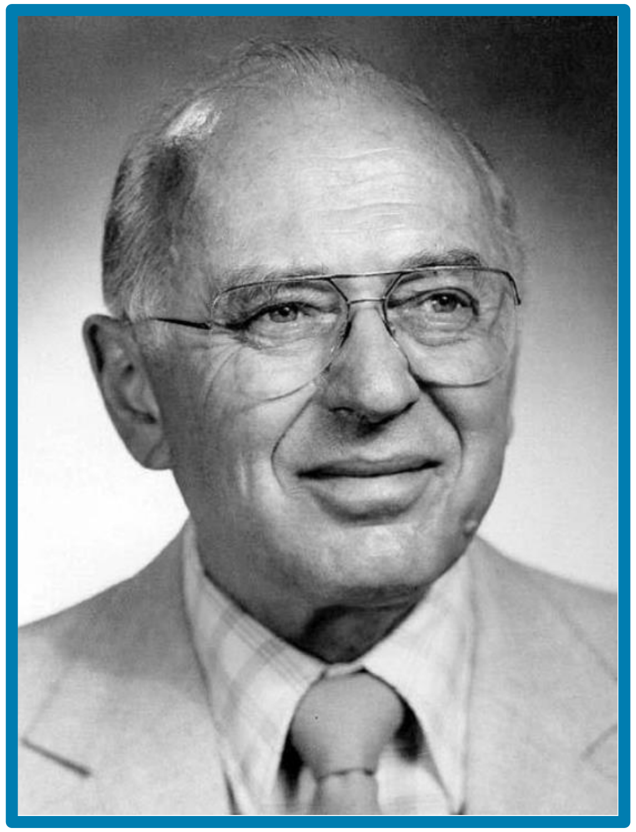
SCIENTIFIC CONTEXT

Neutrinos: a synoptic spectrum

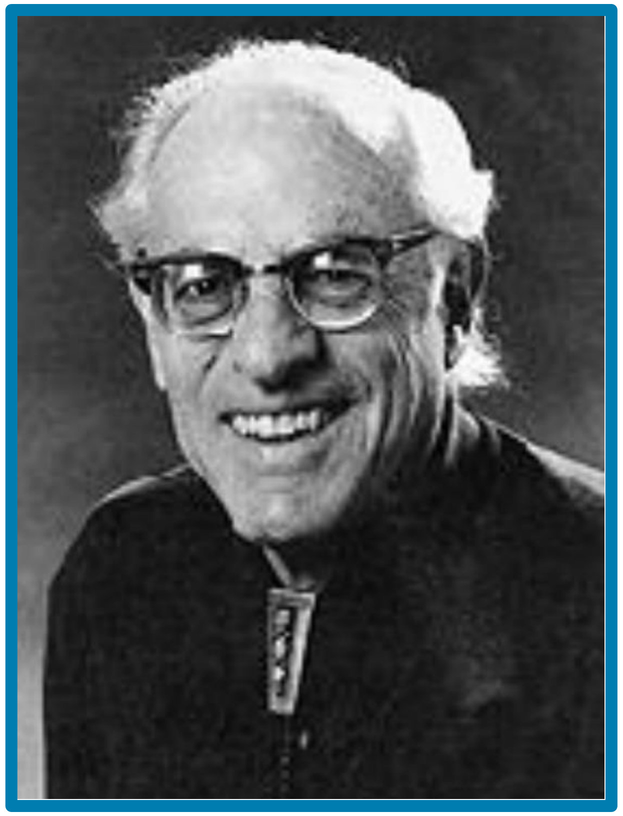


First ideas

1960



K. Greisen



F. Reines

M. Markov
(with I. Zheleznykh)

… discuss ways to detect cosmic high-energy neutrinos deep underground or underwater.

Moisej Markov   Bruno Pontecorvo

M.Markov, **1960**:

„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“ Proc. 1960 ICHEP, Rochester, p. 578.

Physics with neutrino telescopes

- **Search for the sources of high-energy cosmic rays with neutrinos**
- **Dark Matter and Exotic Physics**
  - WIMPs
  - Magnetic Monopoles and other superheavies
  - Violation of Lorentz invariance
- **Neutrino and Particle Physics**
  - Neutrino oscillation studies
  - Charm physics, cross sections at highest energies, …
- **Supernova Collapse Physics**
  - MeV neutrinos in bursts → early SN phase, neutrino hierarchy, …
- **Cosmic Ray Physics**
  - Spectrum, composition and anisotropies

Physics with neutrino telescopes

- **Search for the sources of high-energy cosmic rays with neutrinos**
- Dark Matter and Exotic Physics
  - WIMPs
  - Magnetic Monopoles and other superheavies
  - Violation of Lorentz invariance
- Neutrino and Particle Physics
  - Neutrino oscillation studies
  - Charm physics, cross sections at highest energies ...
- Supernova Collapse Physics
  - MeV neutrinos in bursts → early SN phase, neutrino hierarchy, ...
- Cosmic Ray Physics
  - Spectrum, composition and anisotropies

$$p + \text{target} \rightarrow \pi^+ + \ldots..$$

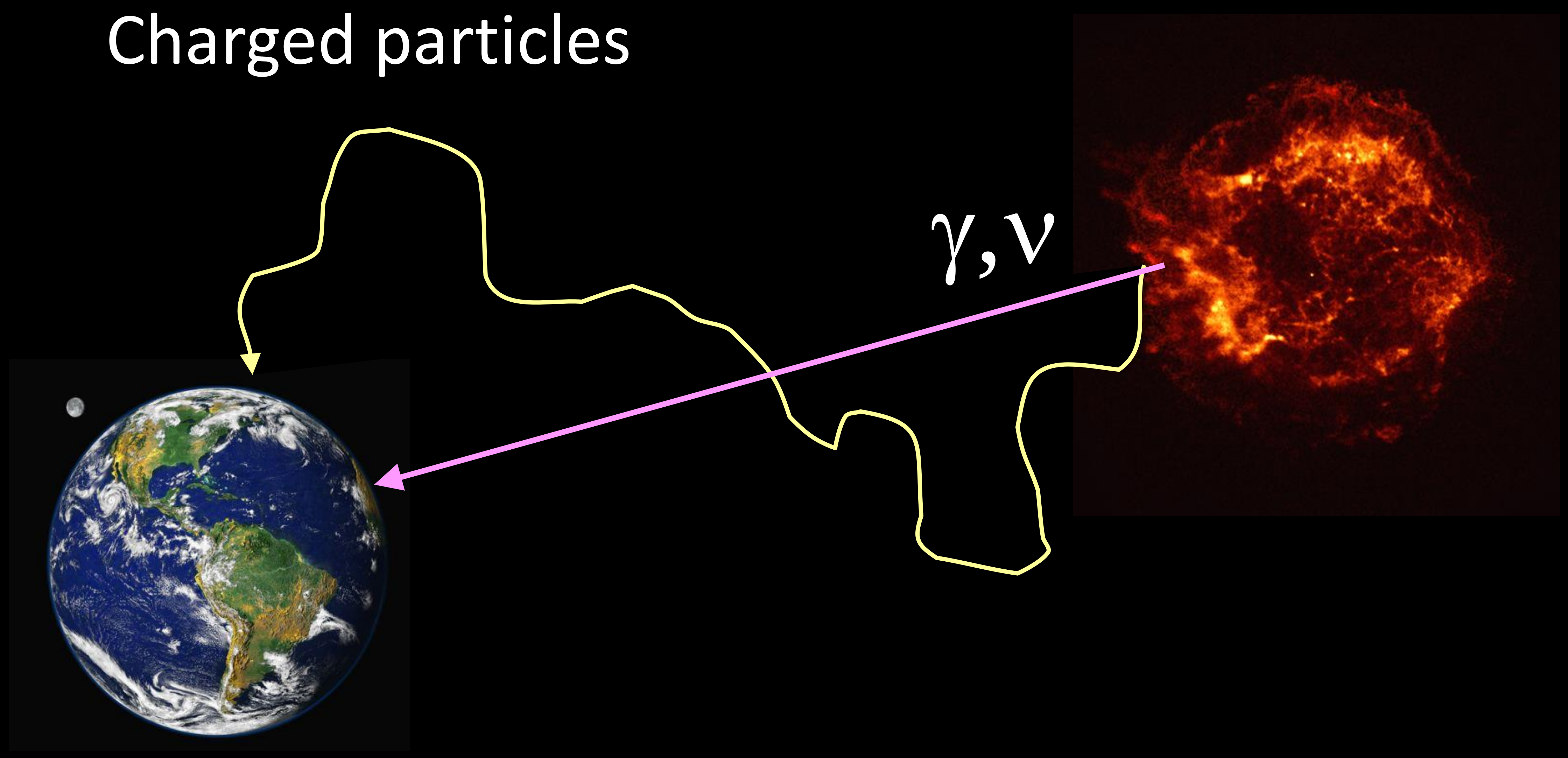
$$\rightarrow \mu^+ + \nu_\mu$$

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

at source: $\nu_e : \nu_\mu : \nu_\tau = 1:2:0$

at Earth: $\nu_e : \nu_\mu : \nu_\tau = 1:1:1$

Charged cosmic rays vs. gamma rays vs. neutrinos



Gamma Rays: hadronic or electromagnetic origin?

Hadronic:

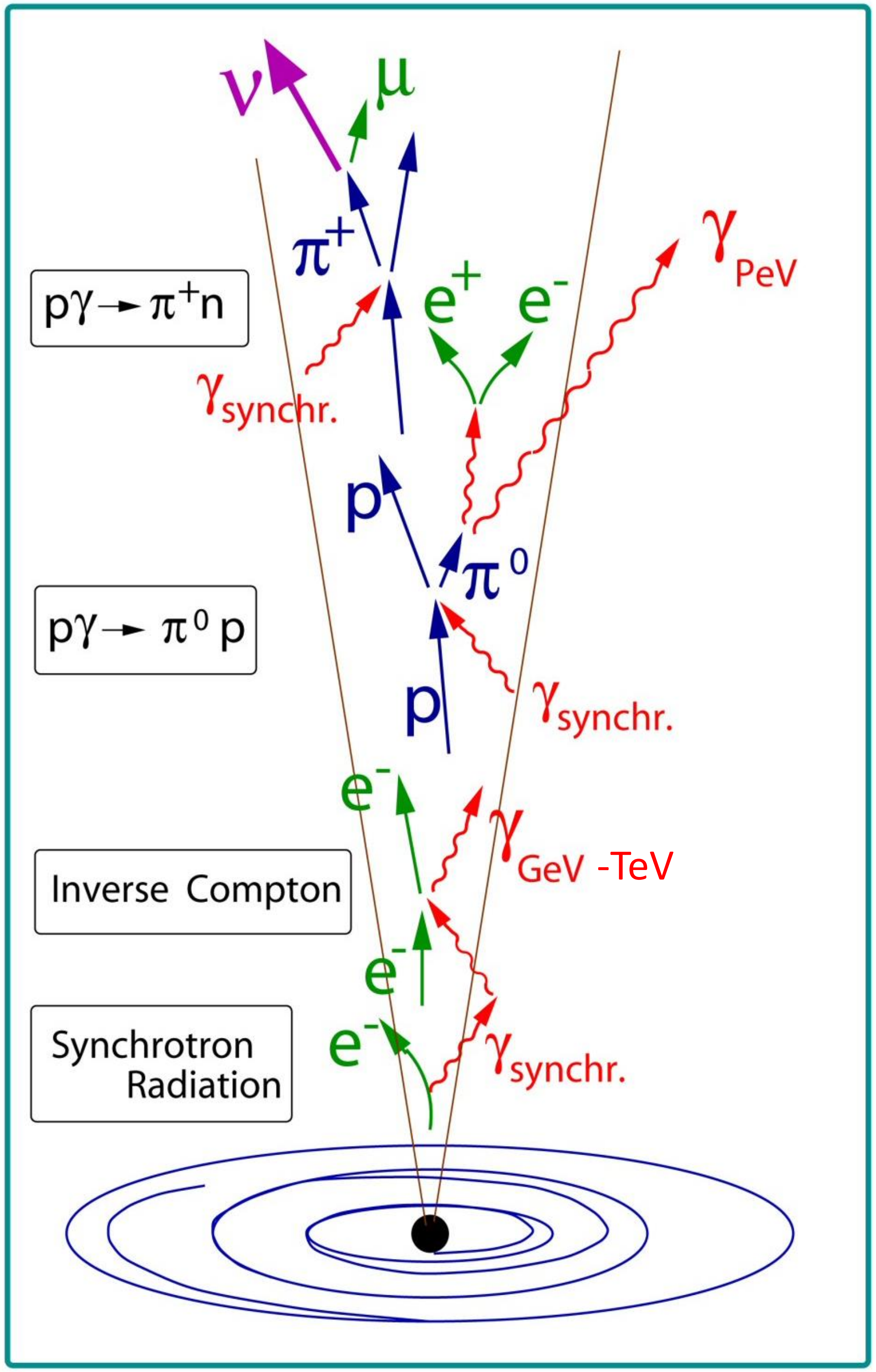
$$p + \gamma \rightarrow \Delta^{+} \rightarrow \begin{cases} \pi^{0} + p \\ \pi^{+} + n \end{cases}$$

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

Electromagnetic (Inverse Compton Scattering):

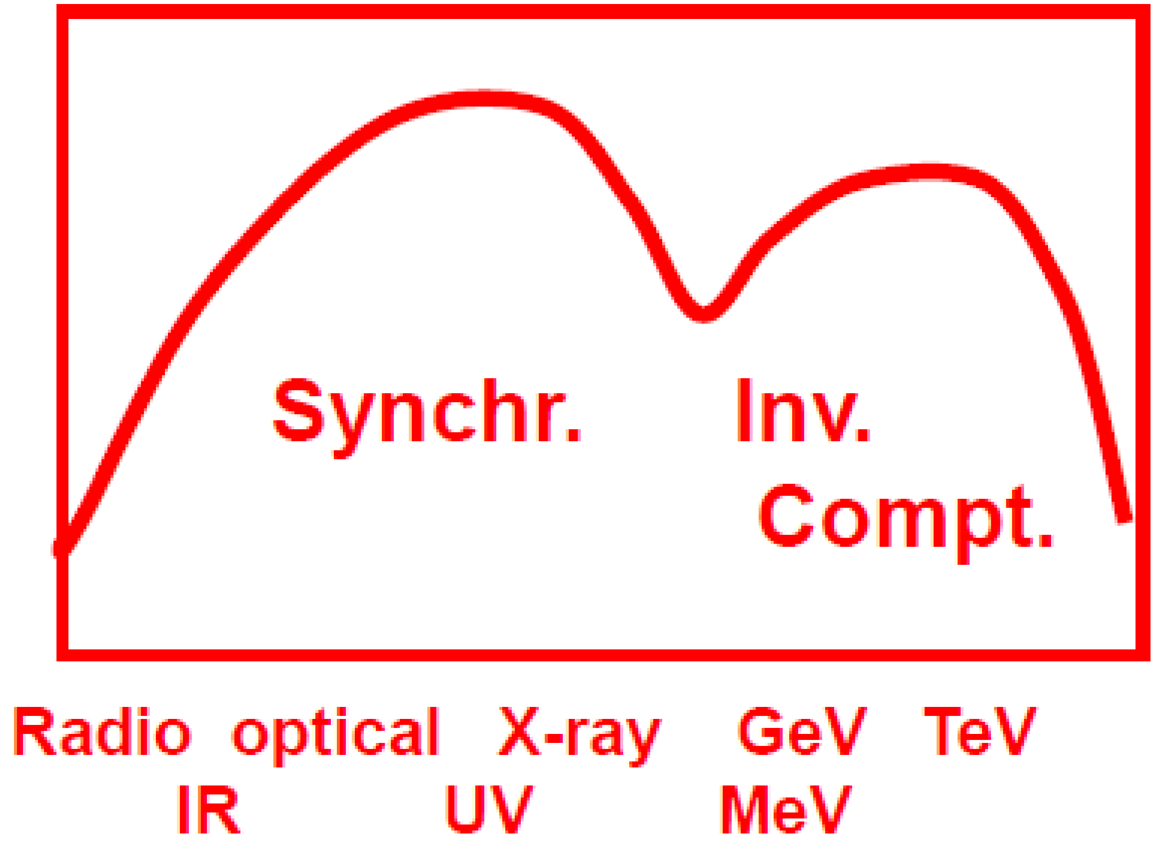
$$e^{-} + \gamma_{\text{low energy}} \rightarrow e^{-} + \gamma_{\text{high energy}}$$

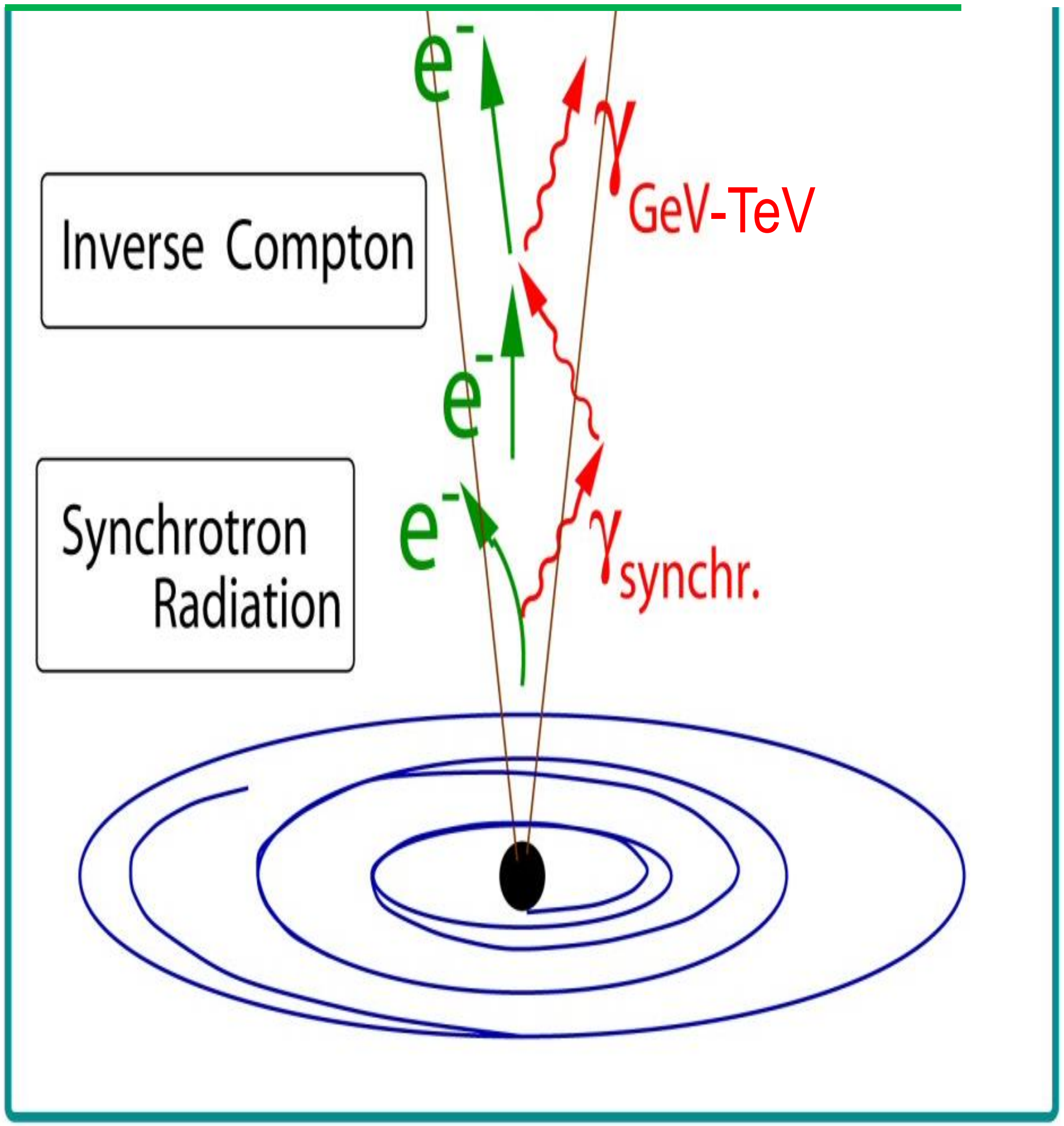
An electron-hadron accelerator



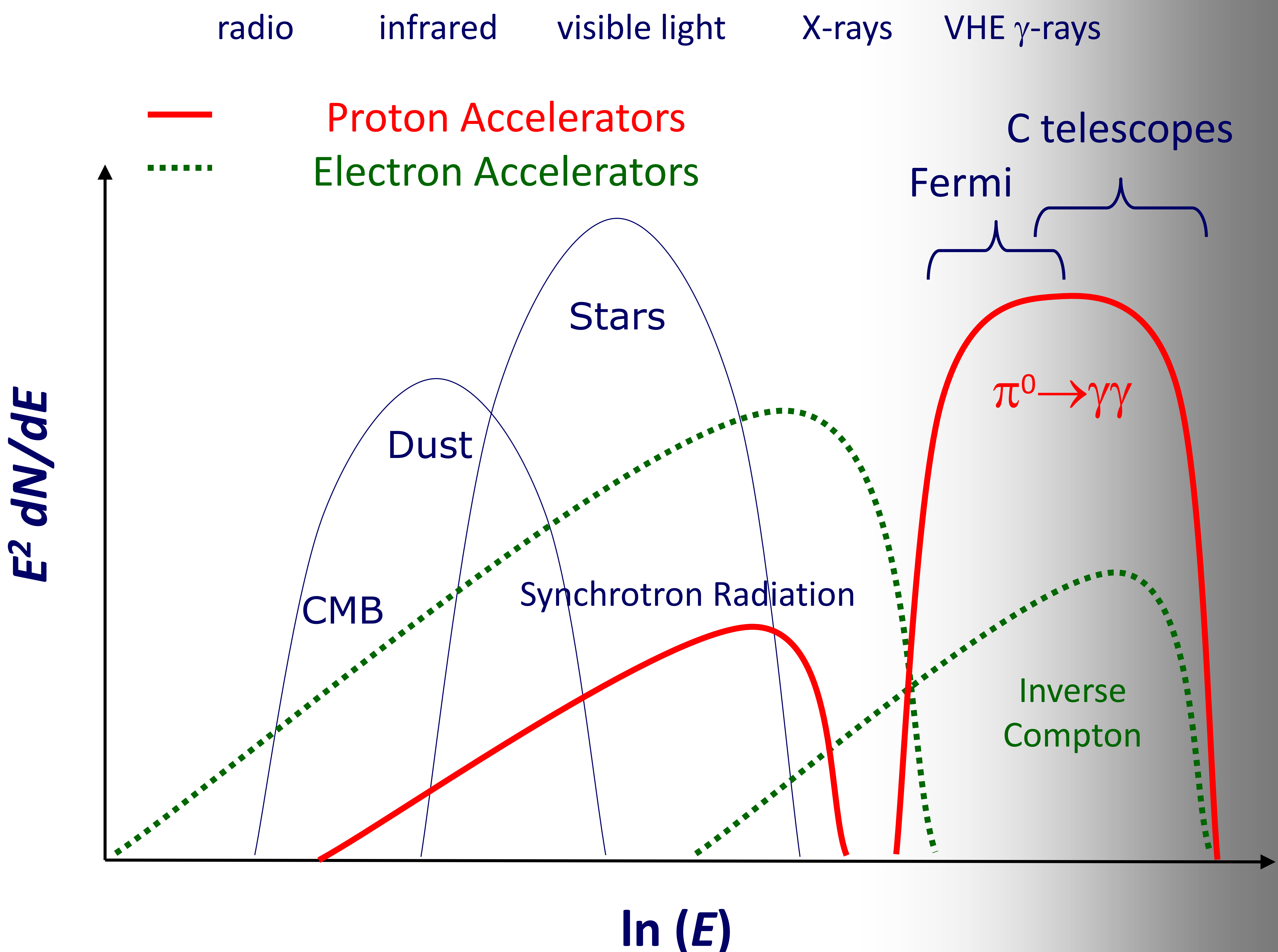
C.Spiering

An electron accelerator



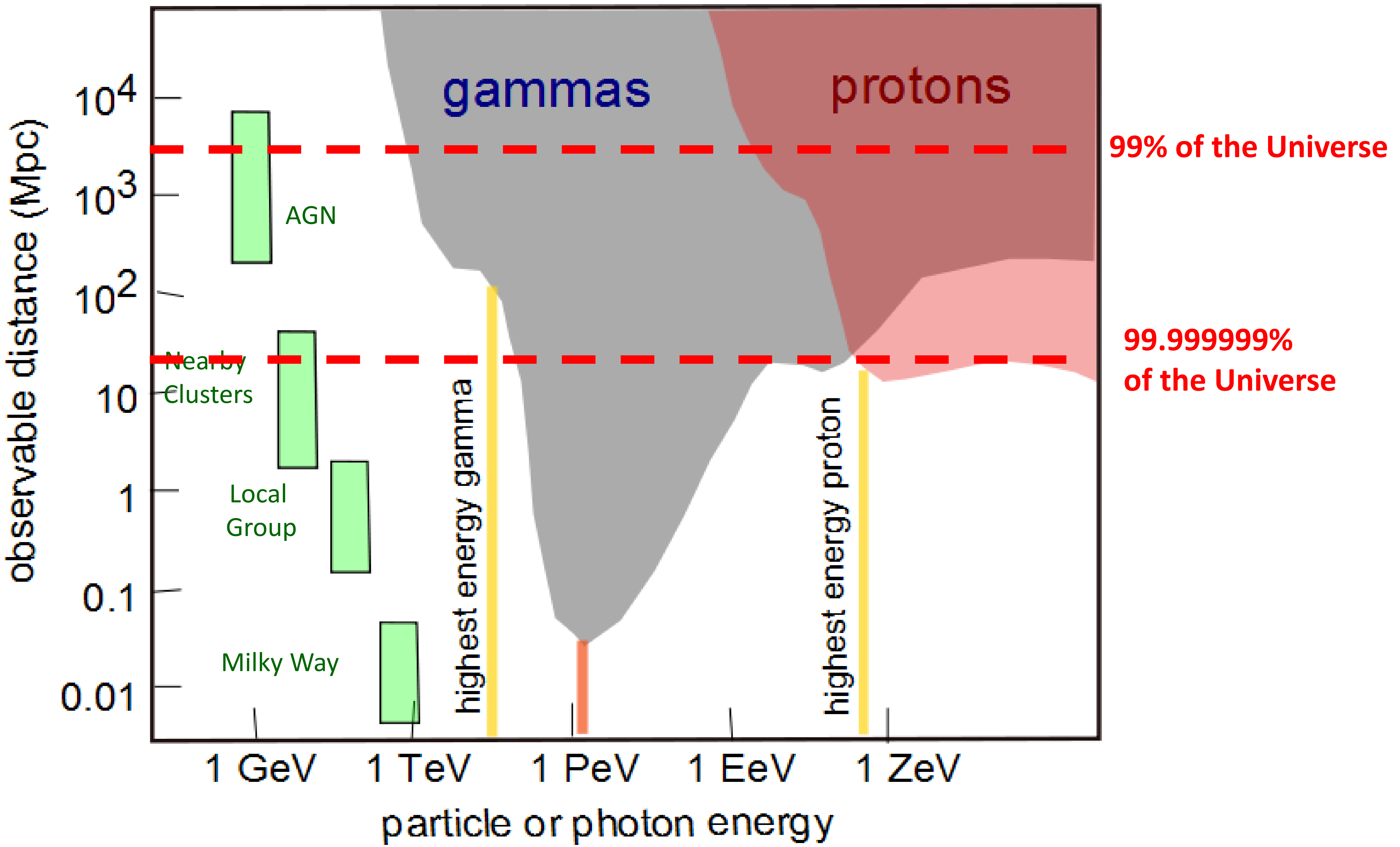


C.Spiering



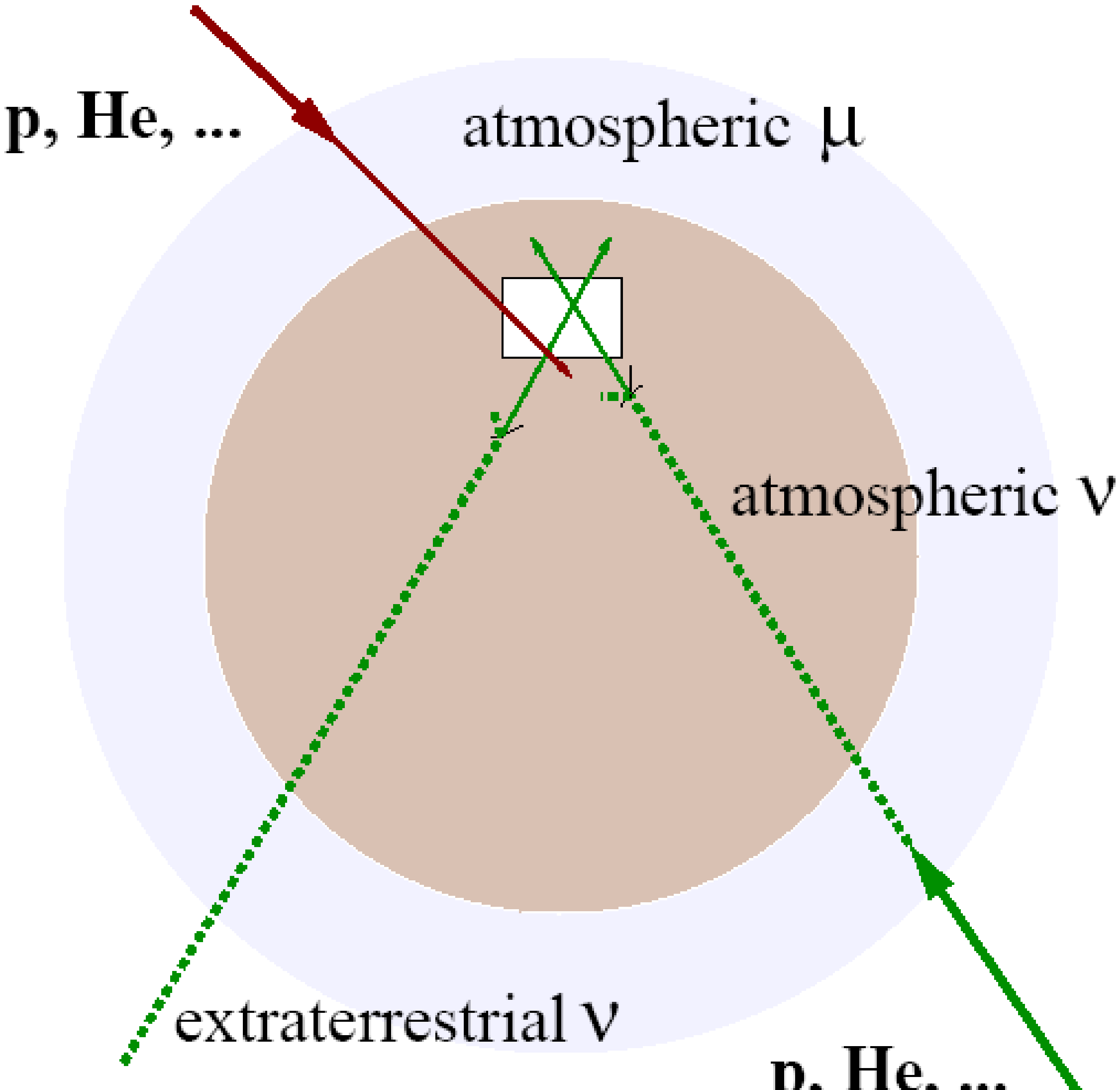
radio
infrared
visible light
X-rays
VHE γ-rays
Proton Accelerators
Electron Accelerators
C telescopes
Fermi
Stars
Dust
CMB
Synchrotron Radiation
π⁰→γγ
Inverse Compton
E² dN/dE
ln (E)

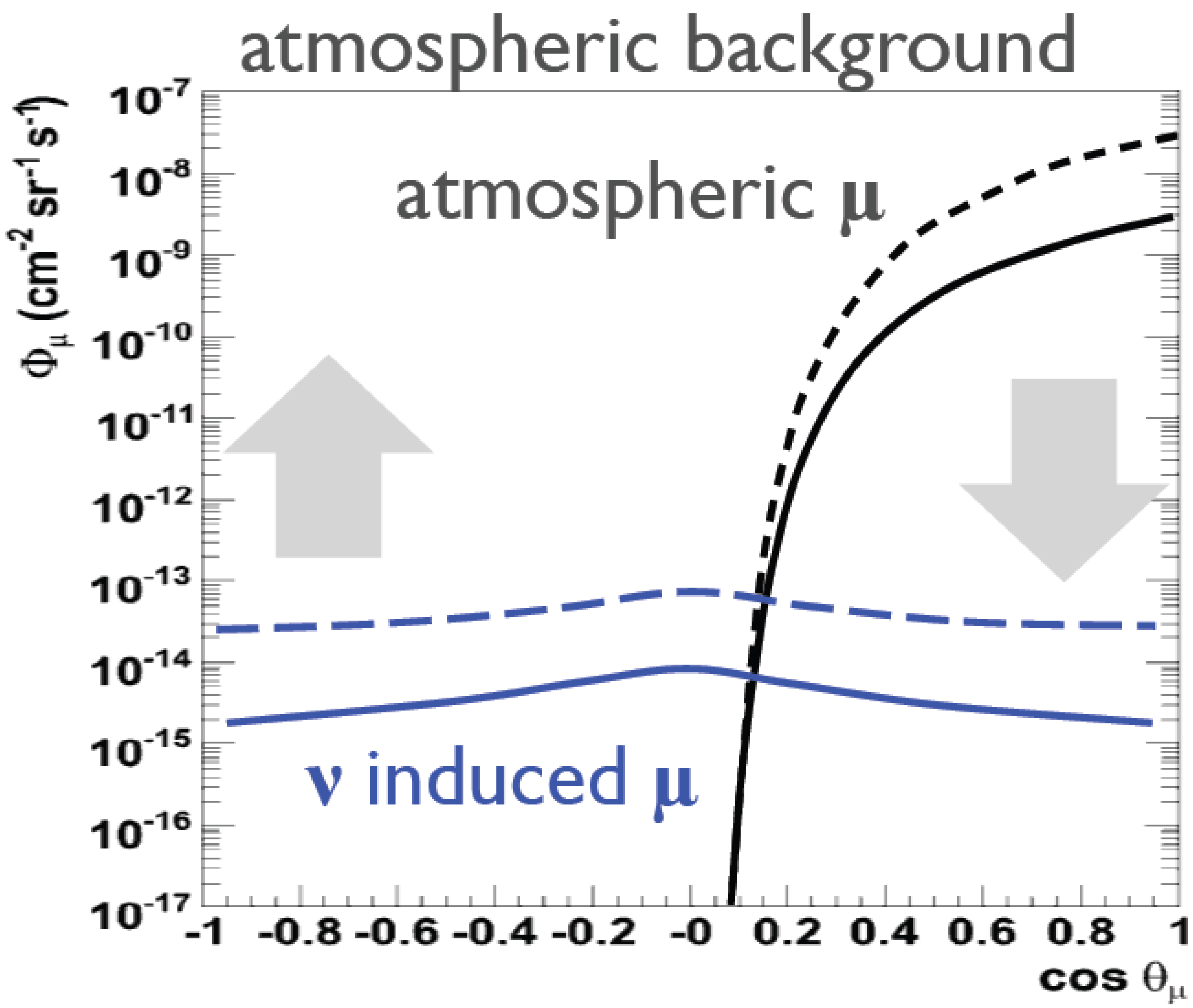
The viewing range



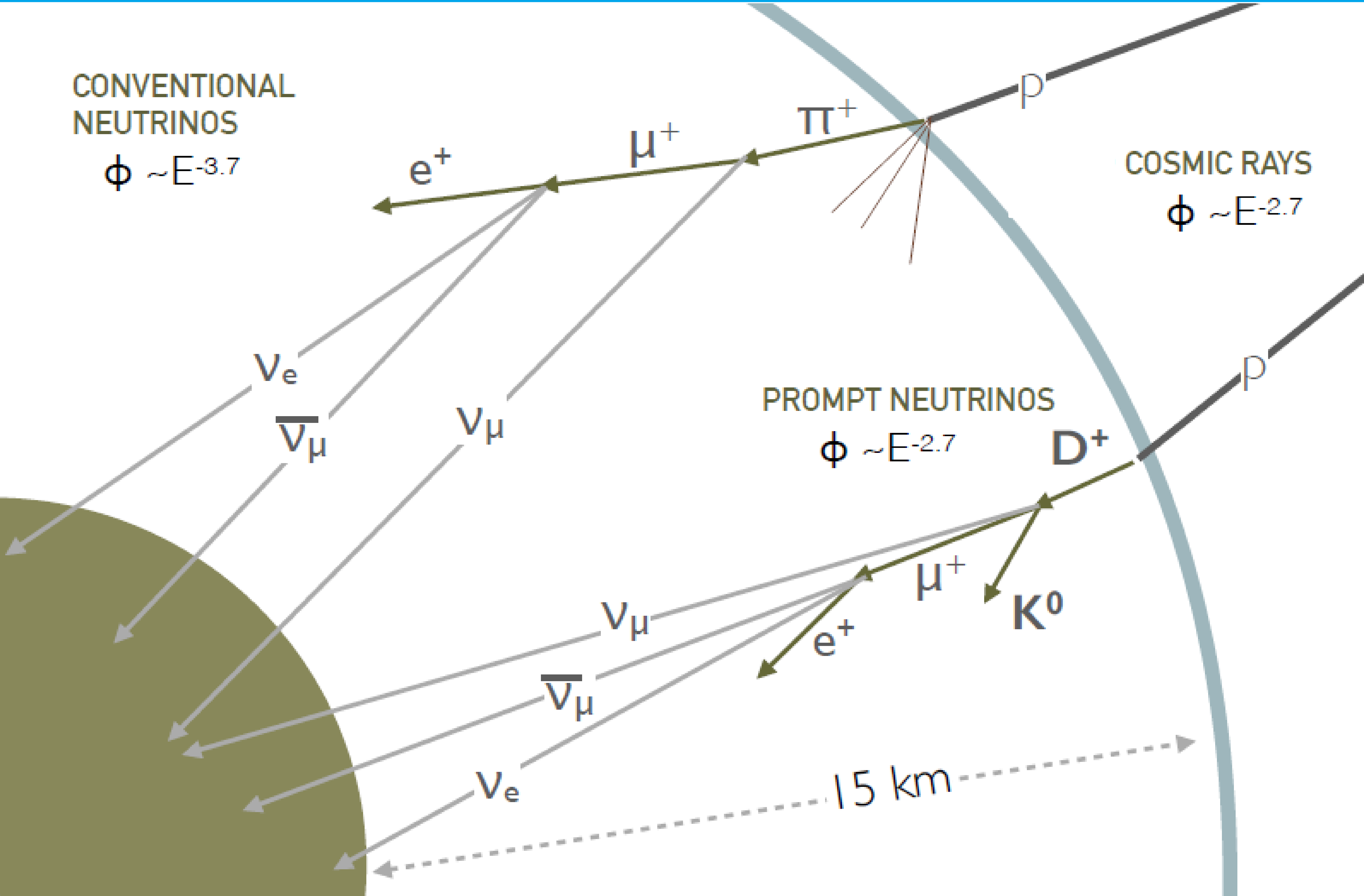
DETECTION PRINCIPLE

Detection deep under-ground/-water/-ice





Atmospheric neutrinos

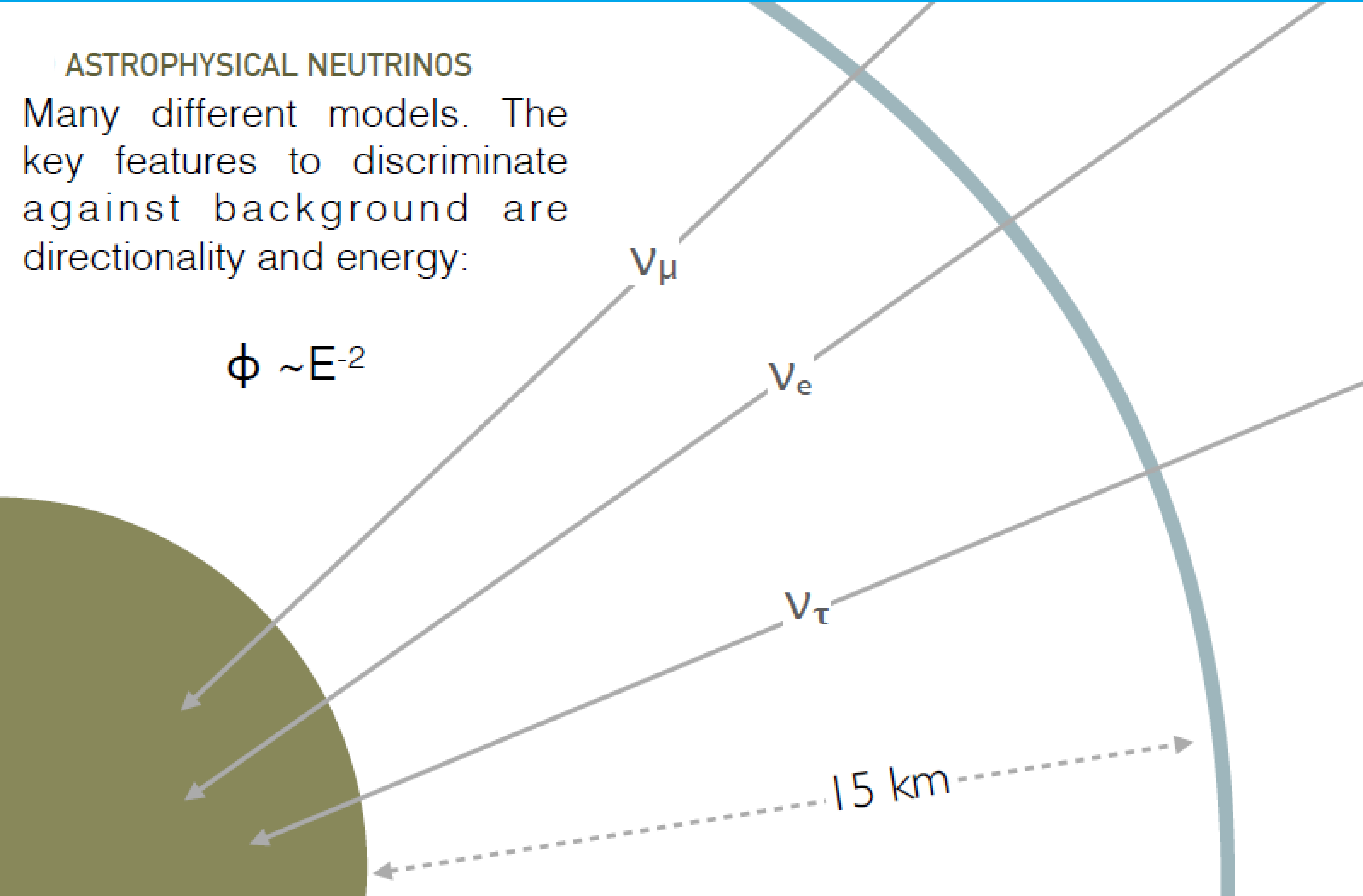


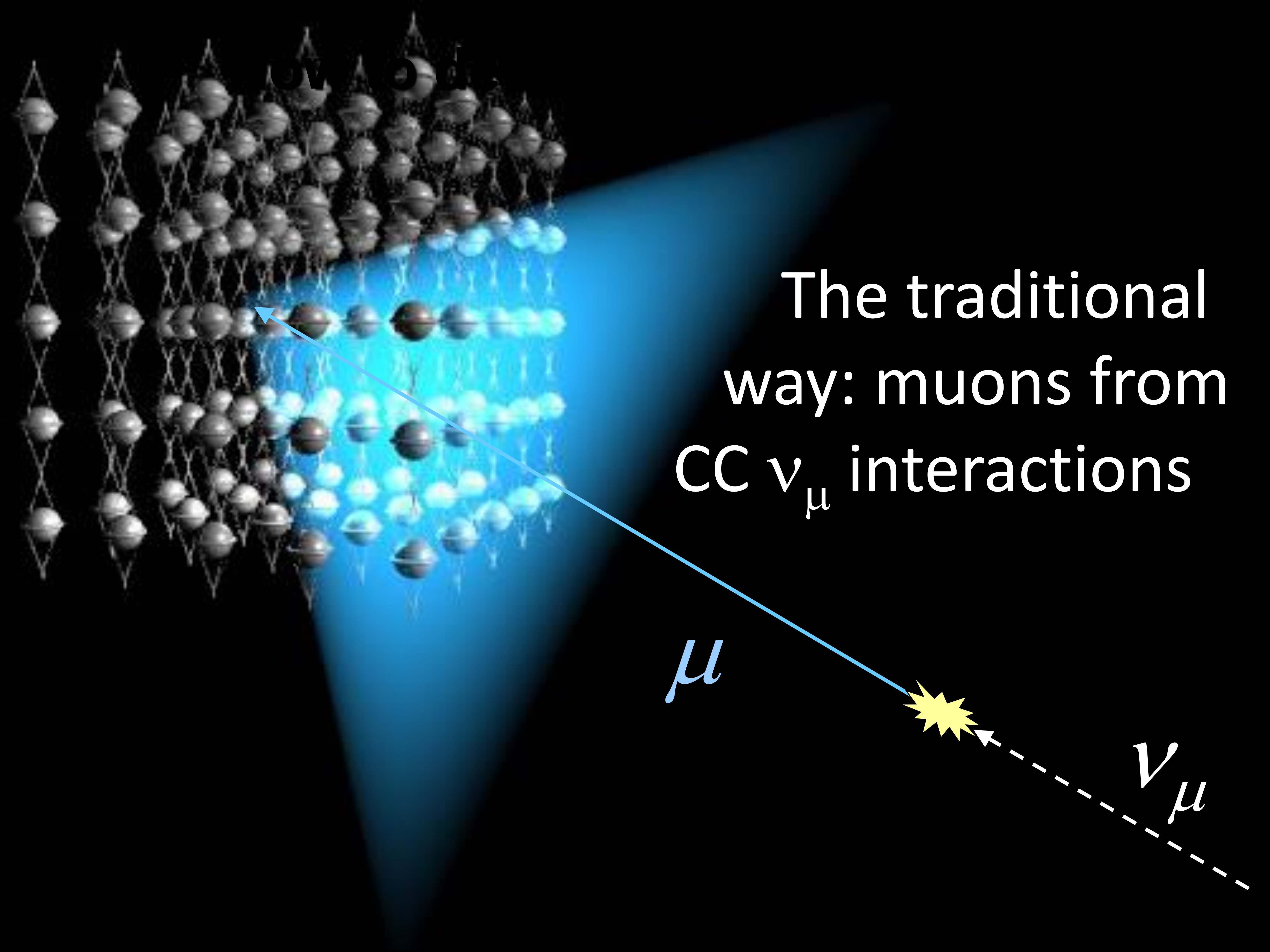
Astrophysical („cosmic“) neutrinos

ASTROPHYSICAL NEUTRINOS

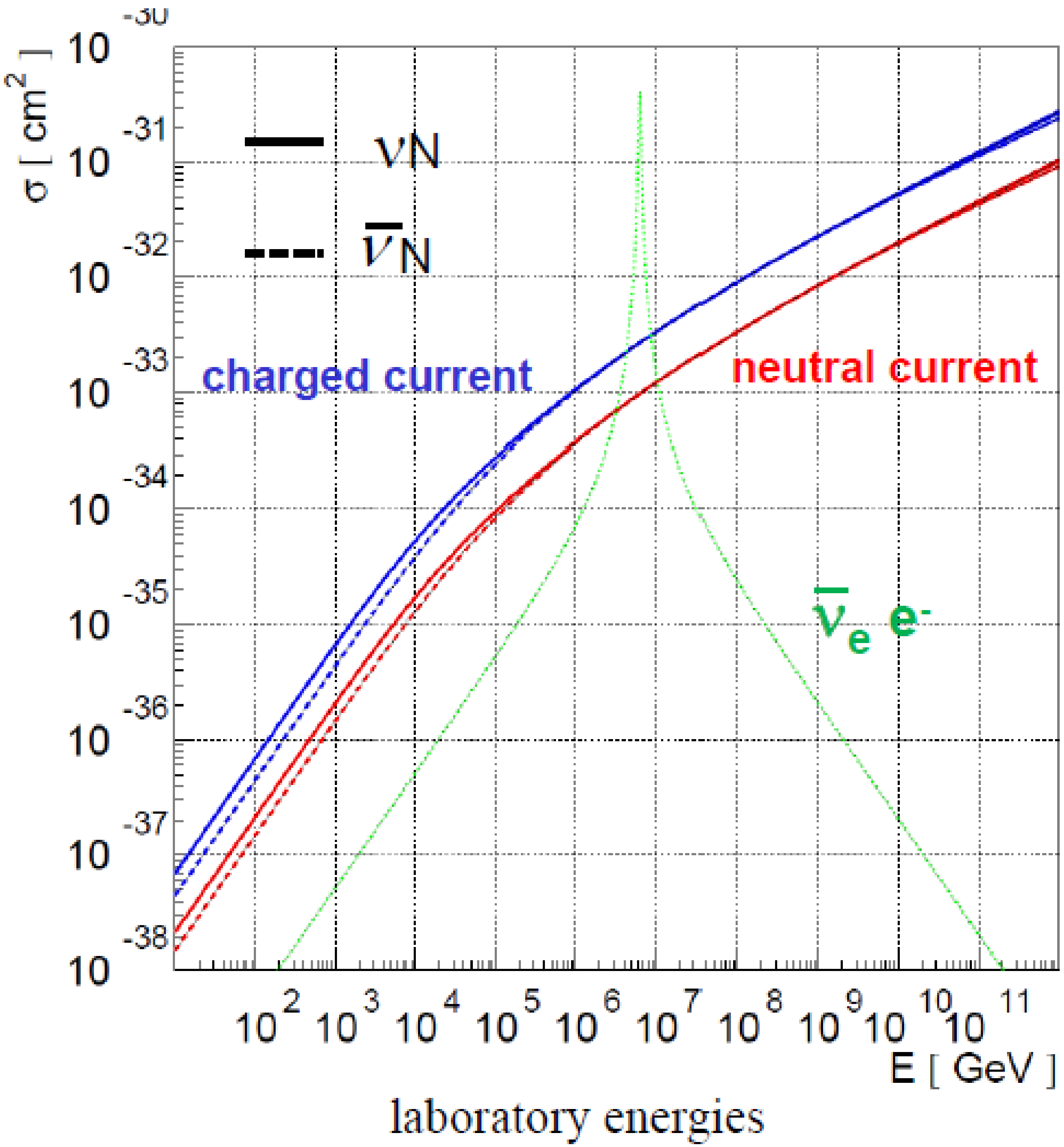
Many different models. The key features to discriminate against background are directionality and energy:

$\phi \sim E^{-2}$

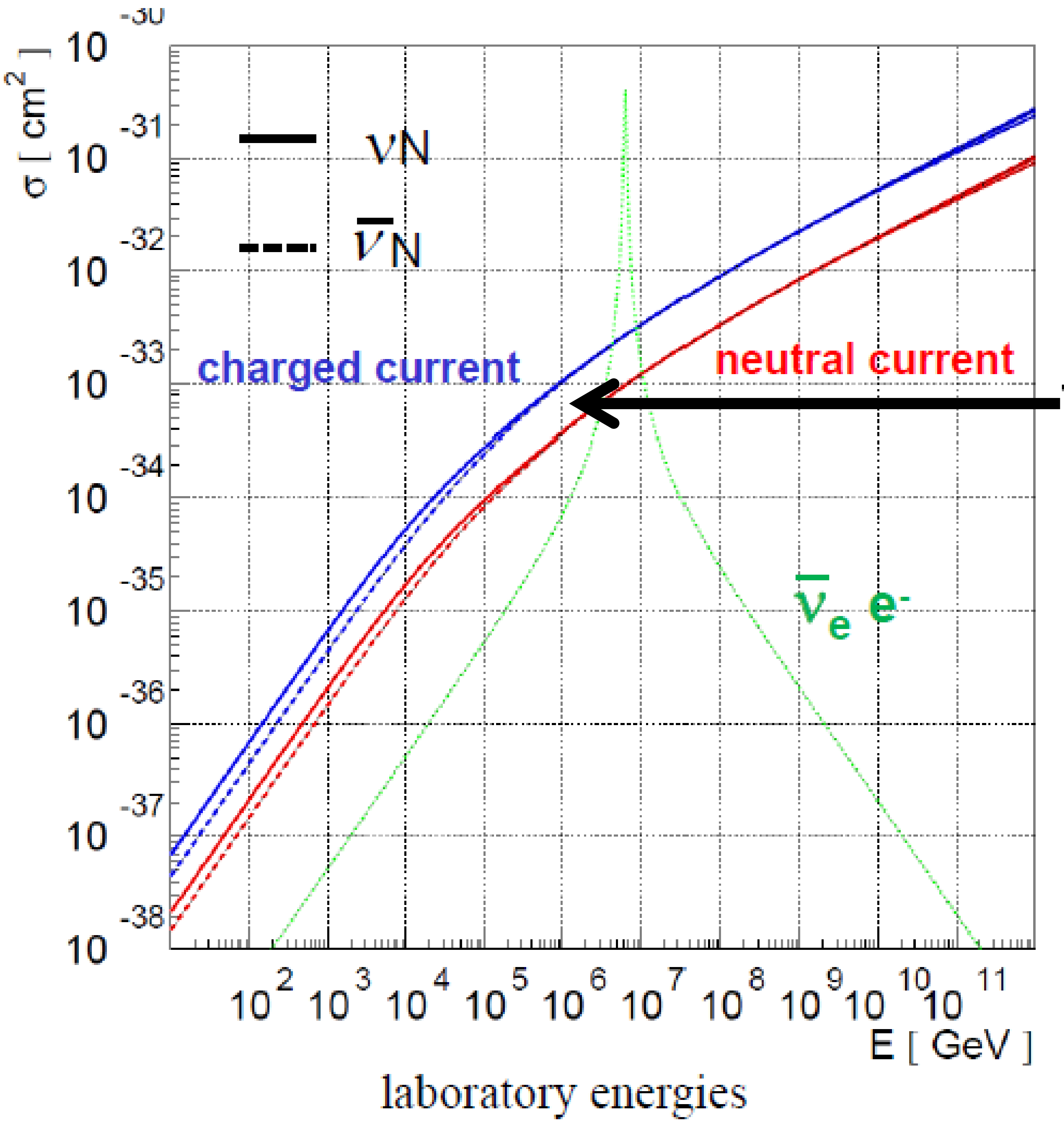



The traditional way: muons from CC ν_μ interactions
μ
ν_μ

Neutrino cross sections



Neutrino cross sections



The propagator effect:

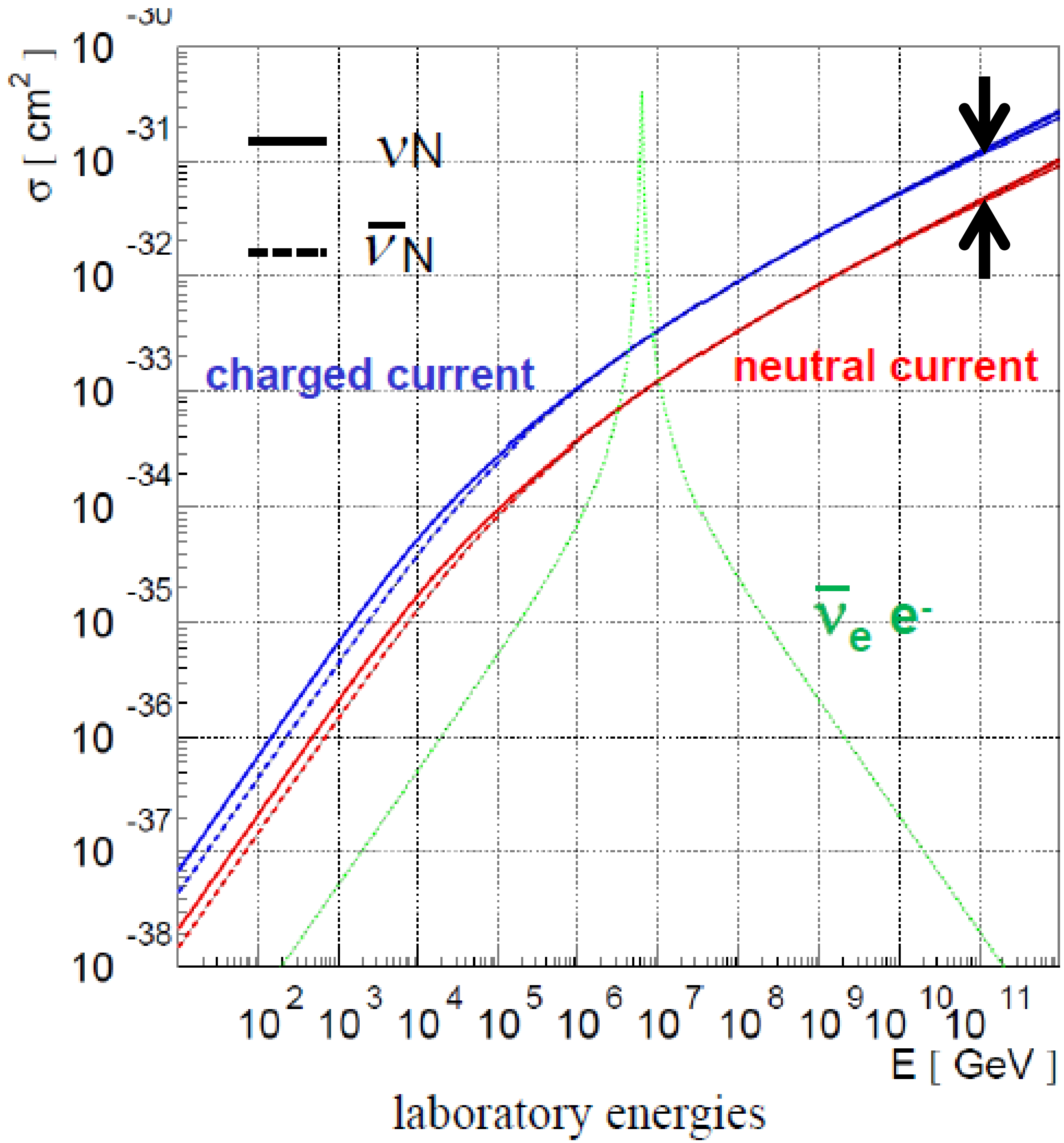
kink at the point were the maximum Q^2 (which grows with E_ν) comes close to the W mass squared.

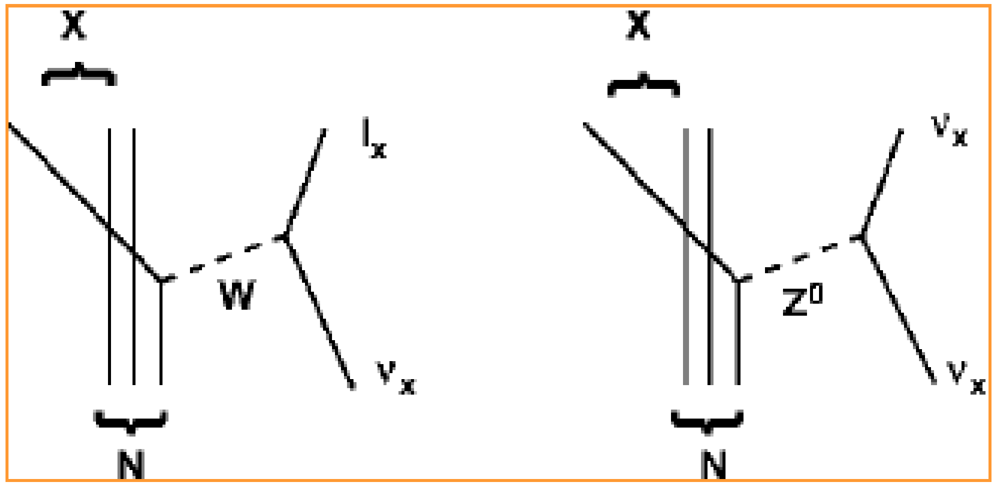
$$\frac{d\sigma^2}{dxdy} = \frac{2\ G_F{}^2 E_\nu}{\pi} \cdot \left(\frac{M_W{}^2}{Q^2+M_W{}^2}\right) \cdot$$

$$\cdot \left(xq(x,Q^2) + x\bar{q}\,(x,Q^2)(1-y)^2\right)$$

$$\sigma_{\nu N} \begin{cases} \propto E_\nu & E_\nu \leq 5\mathrm{TeV} \\ \propto E_\nu^{0.4} & E_\nu > 5\mathrm{TeV} \end{cases}$$

Neutrino cross sections

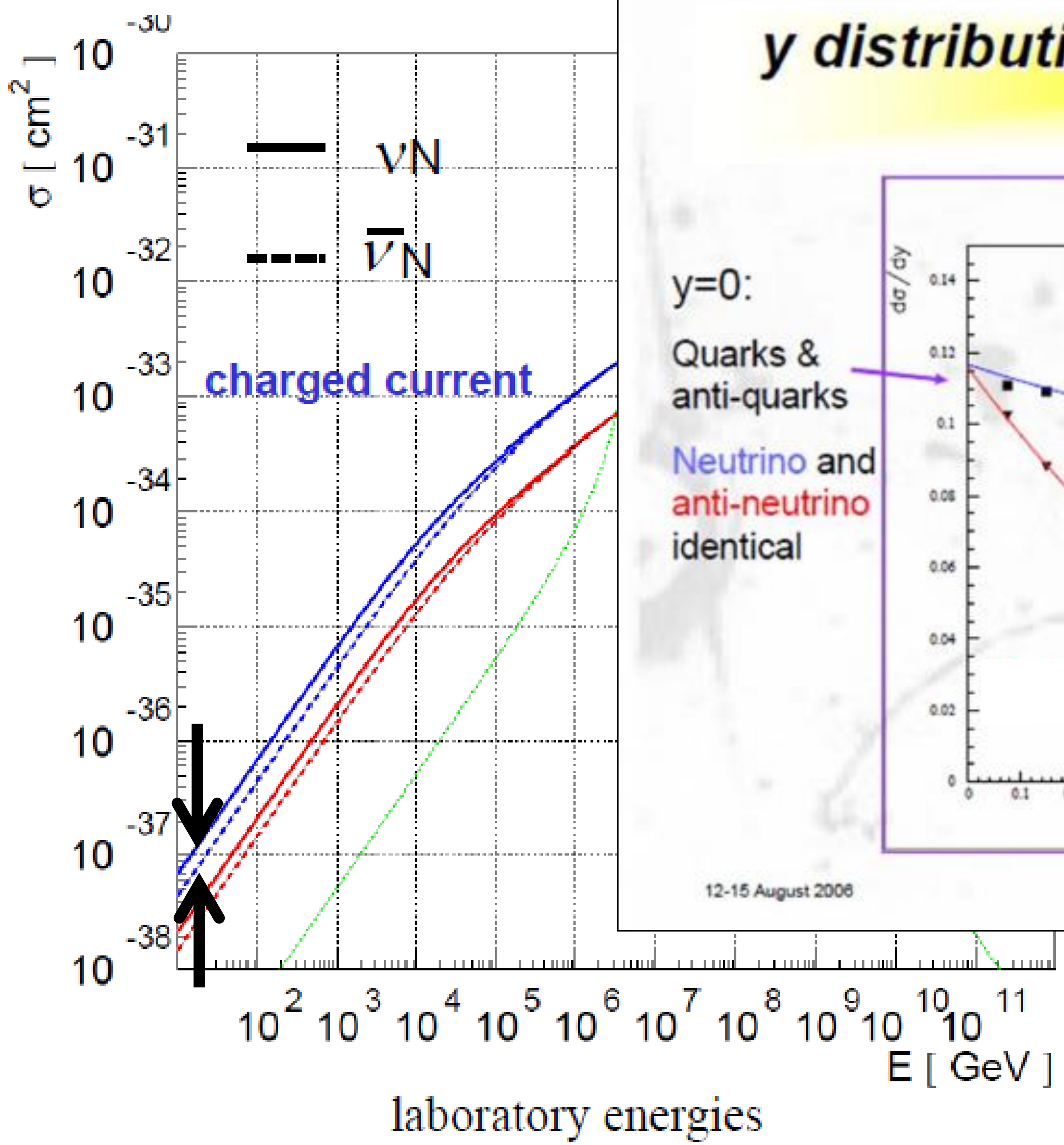


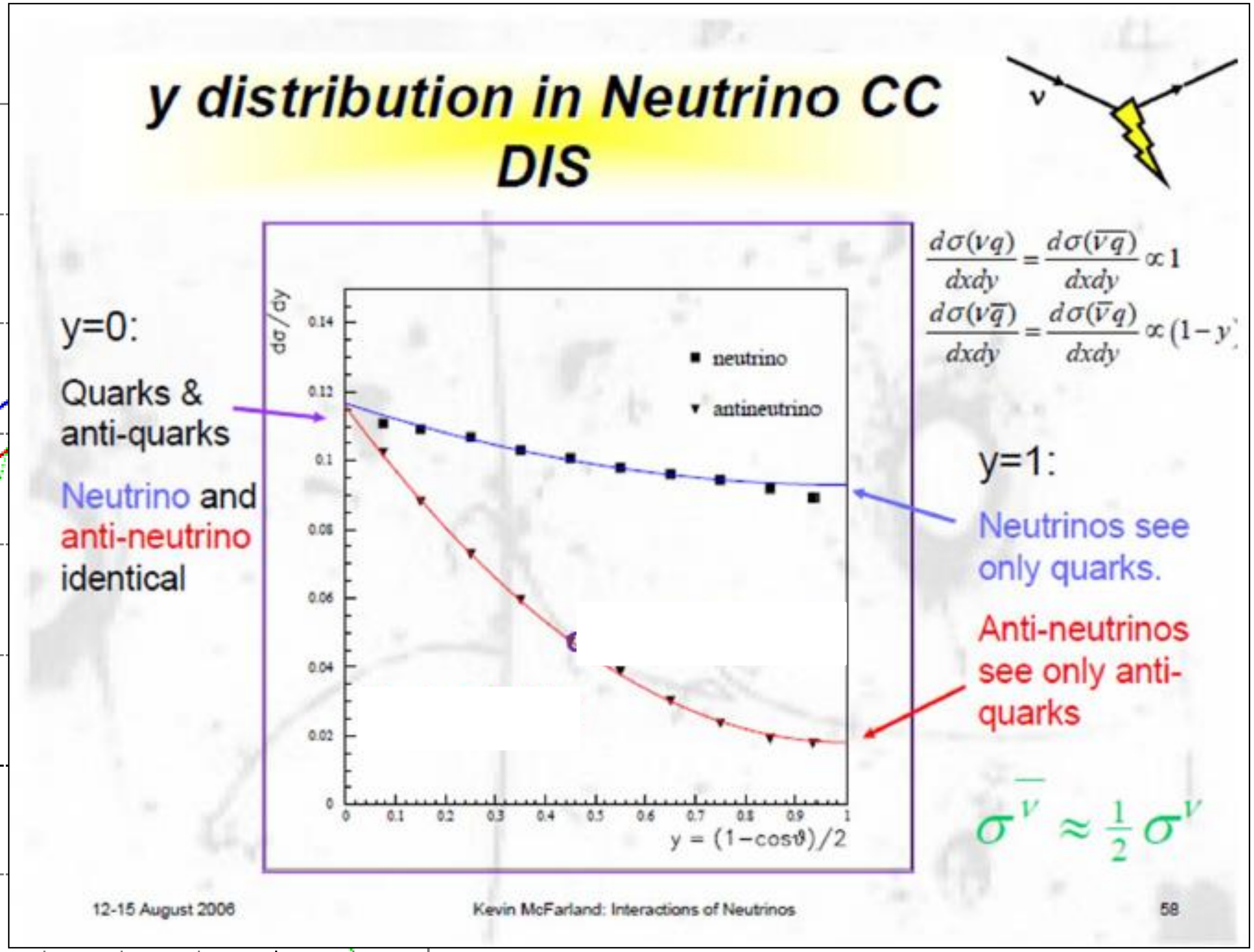


- W-exchange is pure V-A current (only left handed coupling)
- Z has also right handed coupling
- Z slightly heavier than W

- NC/CC ~ 0.31 (0.38) for ν (anti-ν)

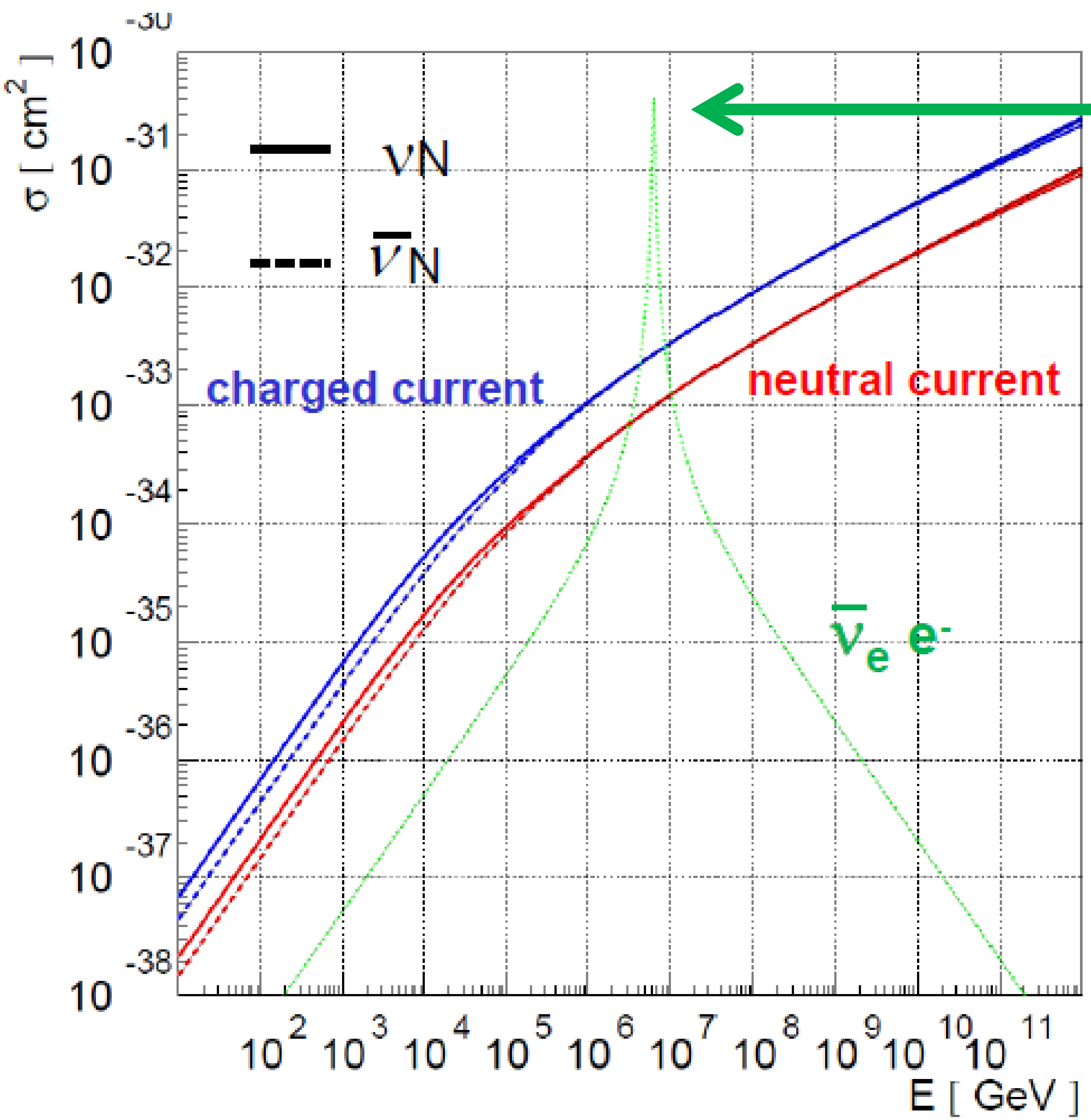
Neutrino cross sections





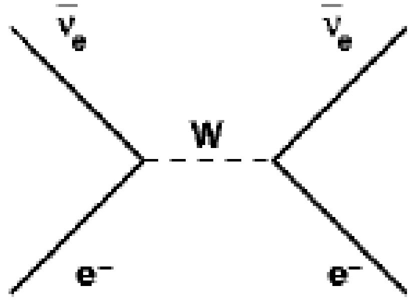
slide R. Nahnhauer

Neutrino cross sections



laboratory energies

resonant production of real W$^-$ from hitting ambient electrons:



neutrino laboratory energy: 6.3 PeV = 6.3 x 10^{15} eV
resonance width: ±130 TeV
peak cross section: 5 x 10^{-31} cm^2

„Glashow resonance"

Only way to distinguish ν and anti-ν !

Muon energy loss

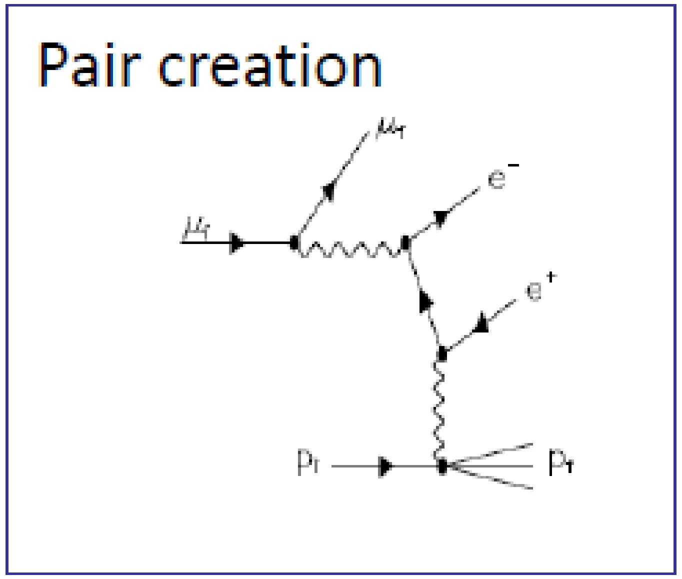
$$-\frac{dE}{dx} \propto a + b \cdot E$$

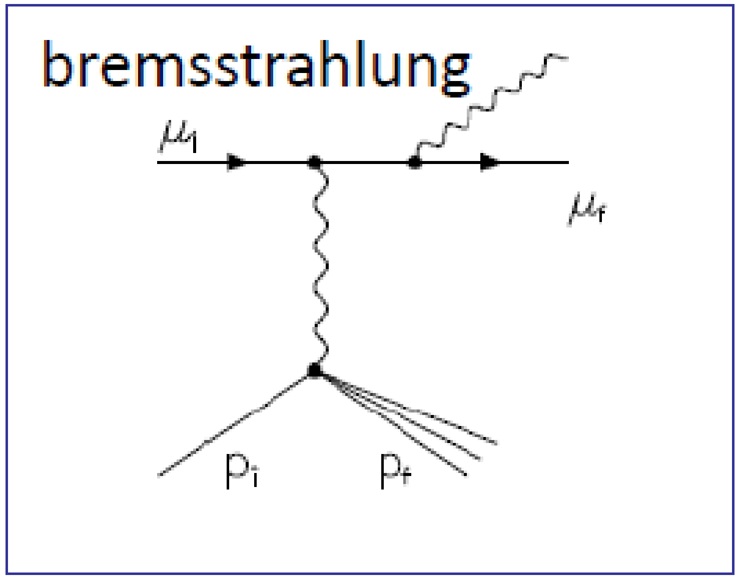
$$a = 0.2 \left[\frac{\text{GeVcm}^2}{\text{g}}\right]$$ → ionization

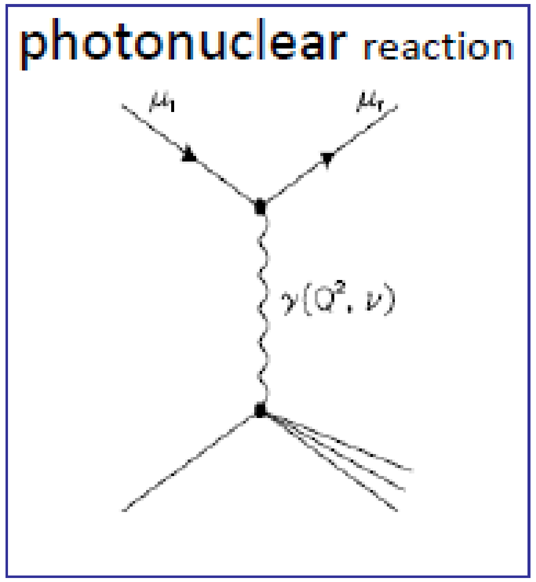
$$b = 4 \cdot 10^{-4} \left[\frac{\text{cm}^2}{\text{g}}\right]$$

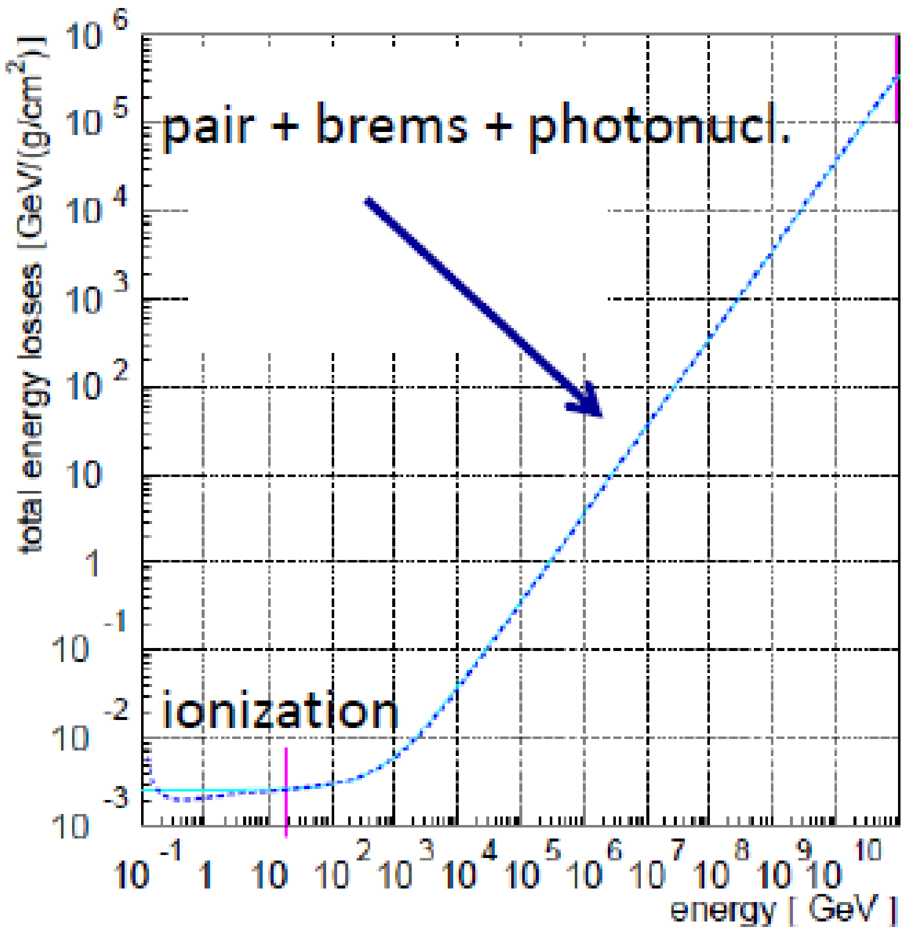
$$R_\mu = \frac{1}{b} \ln\left[a + bE_\mu\right]$$

0.002



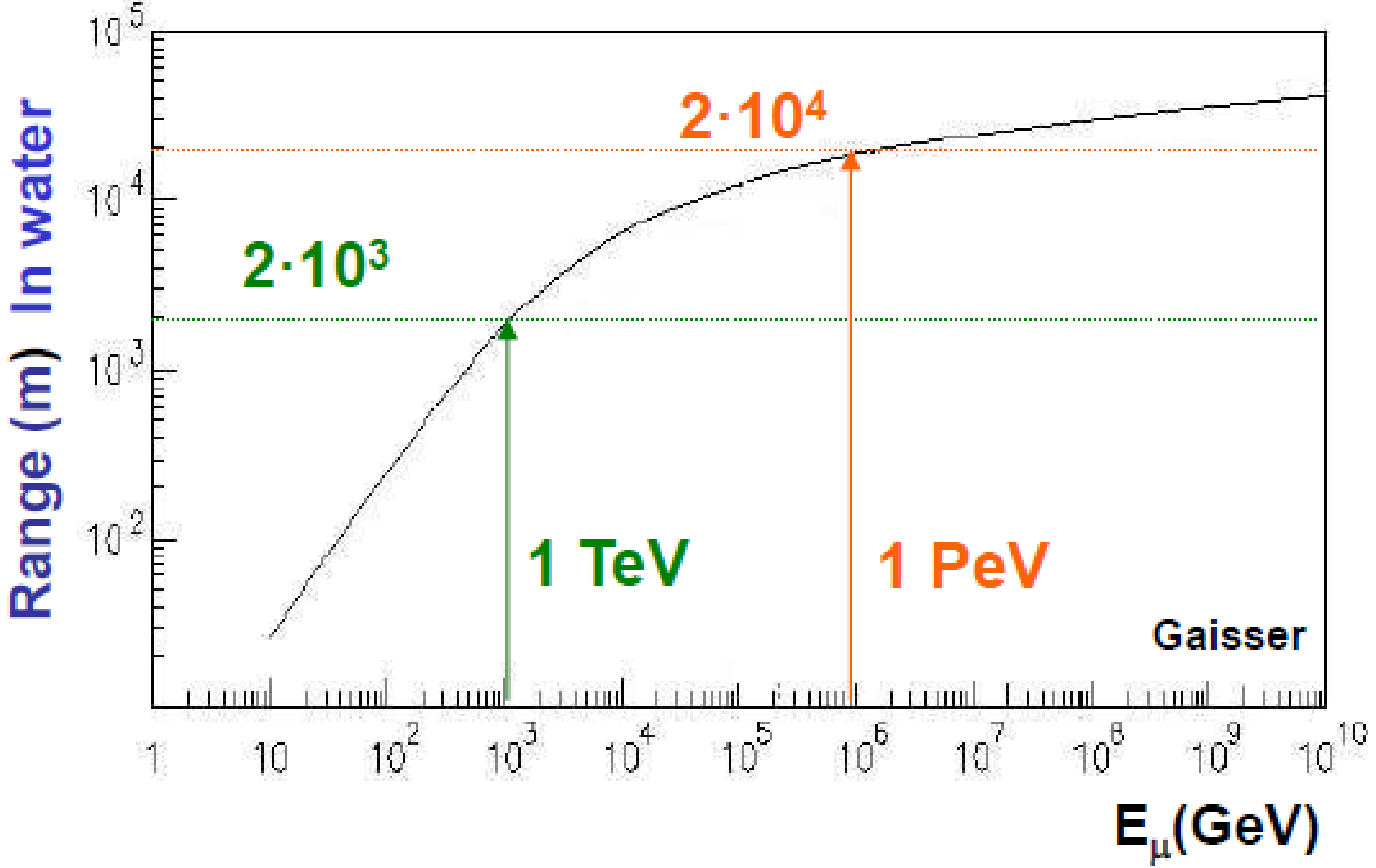






Pair creation: often, with small dE
Bremsstrahlung: rare, with larger dE
Photonuclear: very rare, very large dE

Muon energy loss and range in water



Number of muon events per detection area A_μ and observation time T

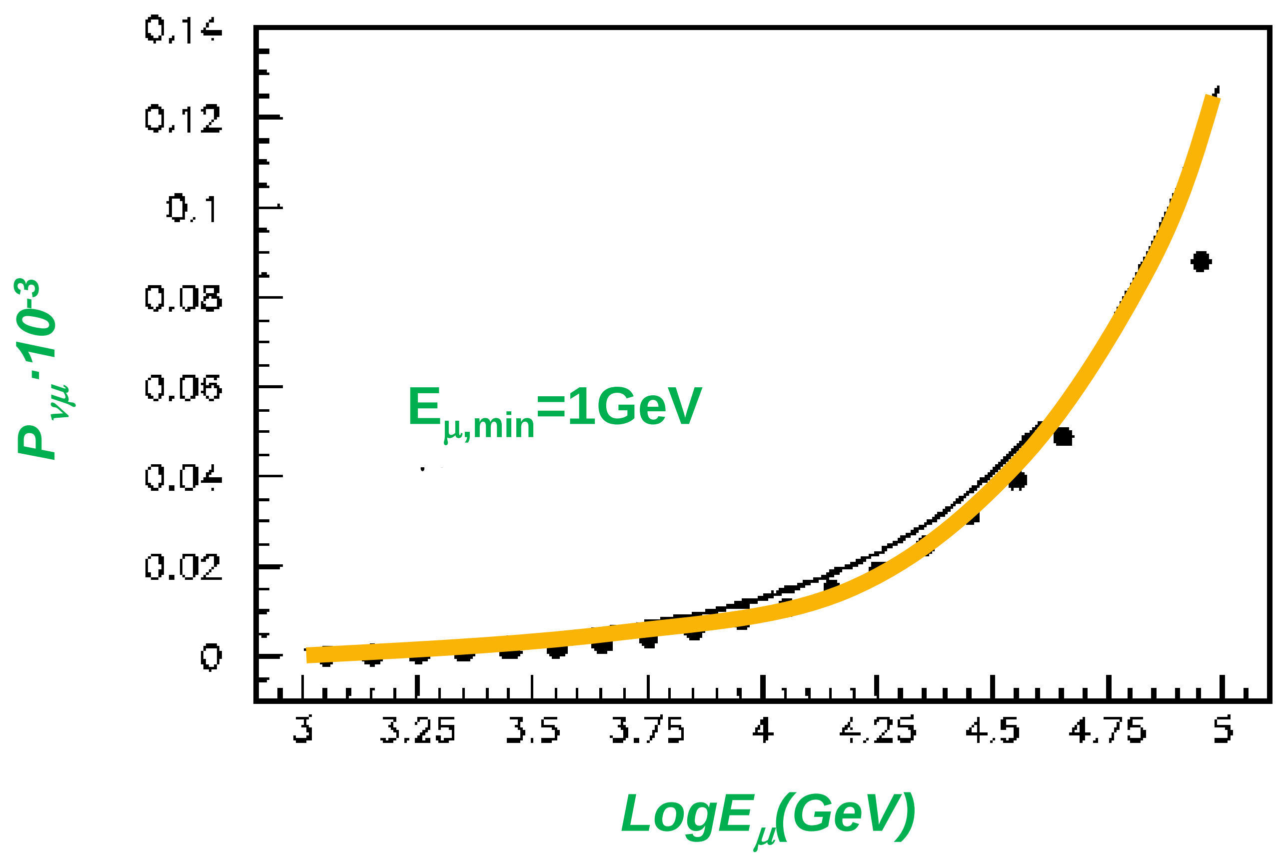
$$\frac{N_\mu\left(E_{\mu,min},\vartheta\right)}{AT}=\int_{E_{\mu,min}}^{E_\nu} dE_\nu \Phi_\nu\left(E_\nu,\vartheta\right)\cdot P_{\nu\mu}\left(E_\nu,E_{\mu,min}\right)\cdot e^{-\sigma_{tot}\left(E_\nu\right)N_A Z(\vartheta)}$$

- **Neutrino flux spectrum**

Number of muon events per detection area A_μ and observation time T

$$\frac{N_\mu\left(E_{\mu,min},\vartheta\right)}{AT}=\int_{E_{\mu,min}}^{E_\nu} dE_\nu \Phi_\nu\left(E_\nu,\vartheta\right)\cdot P_{\nu\mu}\left(E_\nu,E_{\mu,min}\right)\cdot e^{-\sigma_{tot}(E_\nu)N_A Z(\vartheta)}$$

- **Neutrino flux spectrum**
- **Probability to produce a detectable (E_μ>E_{min}) muon**

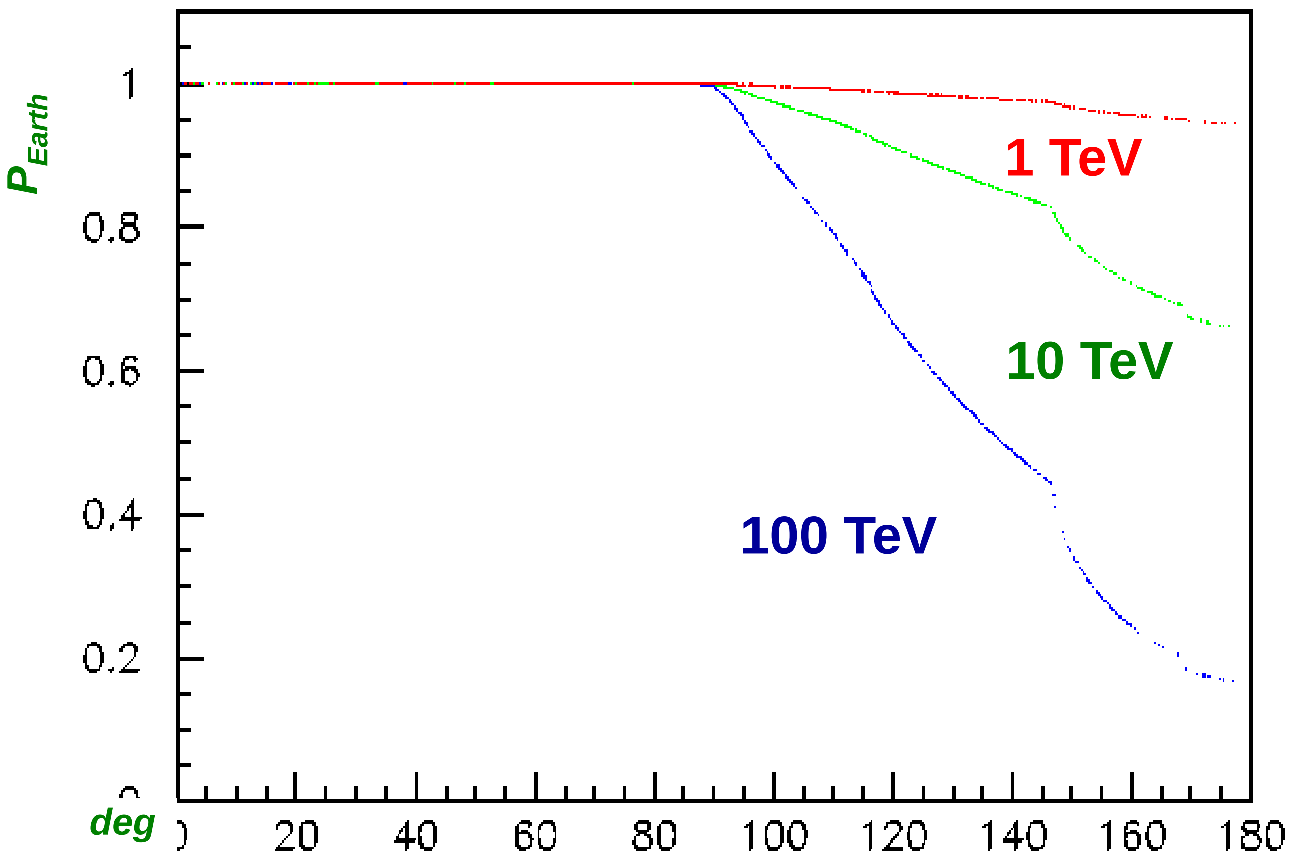


10^{-6} @ 1 TeV

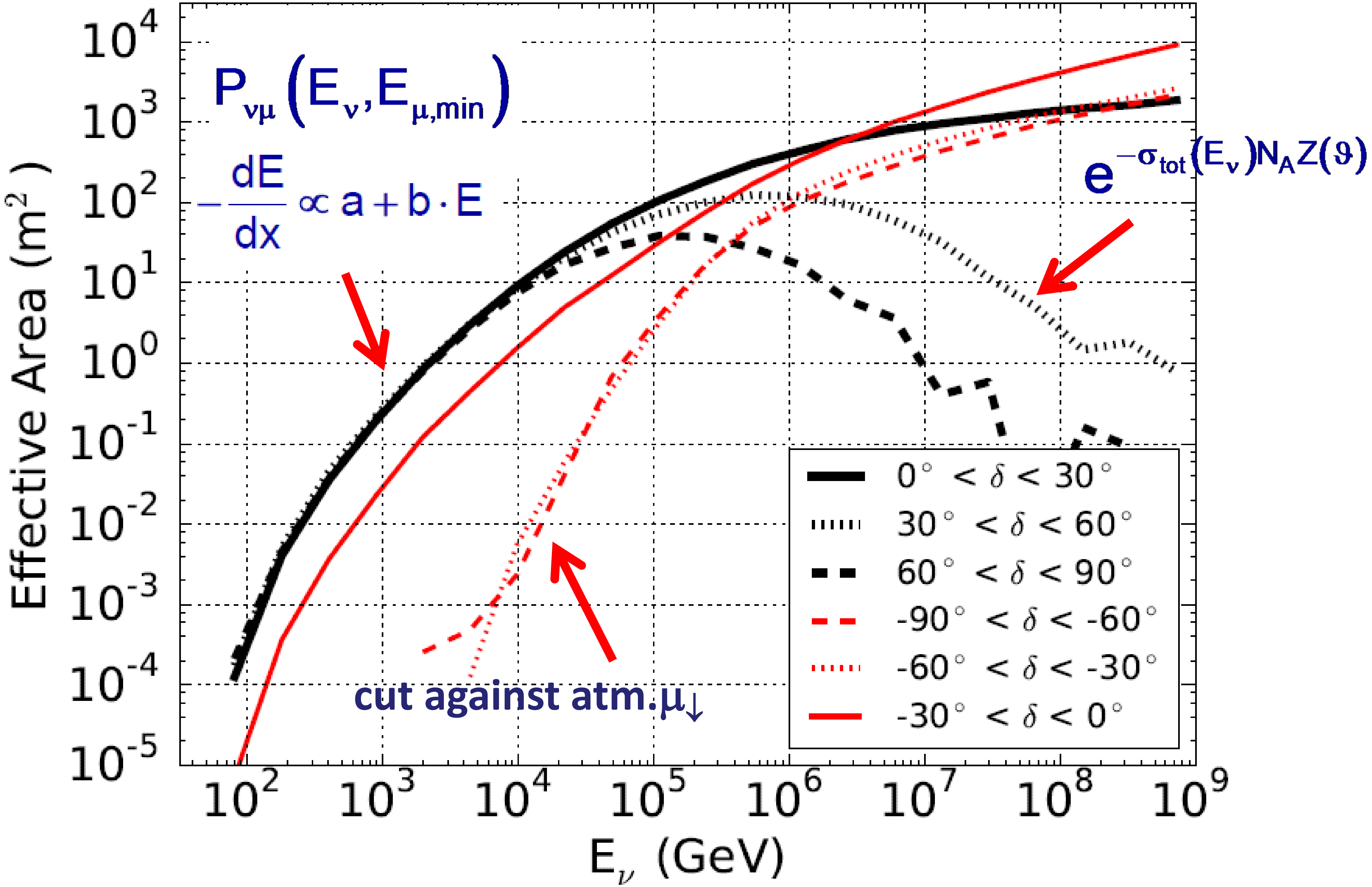
Number of muon events per detection area A_μ and observation time T

$$\frac{N_\mu\left(E_{\mu,min},\vartheta\right)}{AT} = \int_{E_{\mu,min}}^{E_\nu} dE_\nu \Phi_\nu\left(E_\nu,\vartheta\right) \cdot P_{\nu\mu}\left(E_\nu,E_{\mu,min}\right) \cdot e^{-\sigma_{tot}(E_\nu) N_A Z(\vartheta)}$$

- **Neutrino flux spectrum**
- **Probability to produce a detectable ($E_\mu > E_{min}$) muon**
- **Earth transparency to HE neutrinos**

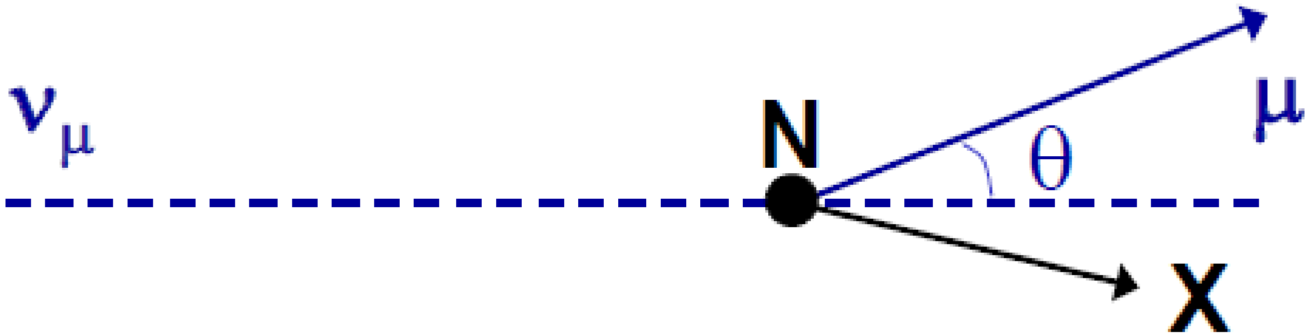


Neutrino effective area for IceCube



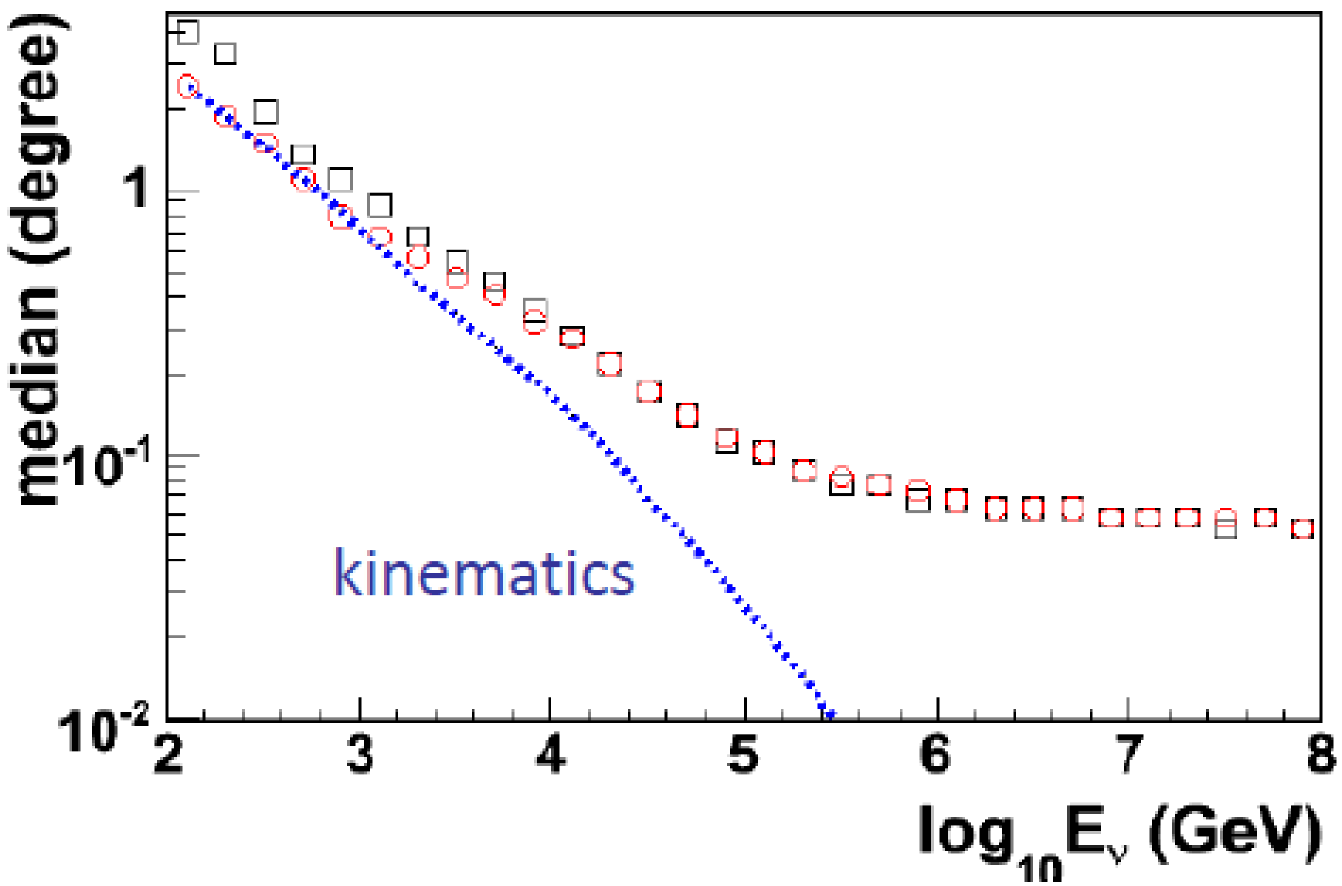
Pointing accuracy

At >TeV energies the muon and the neutrino are co-linear



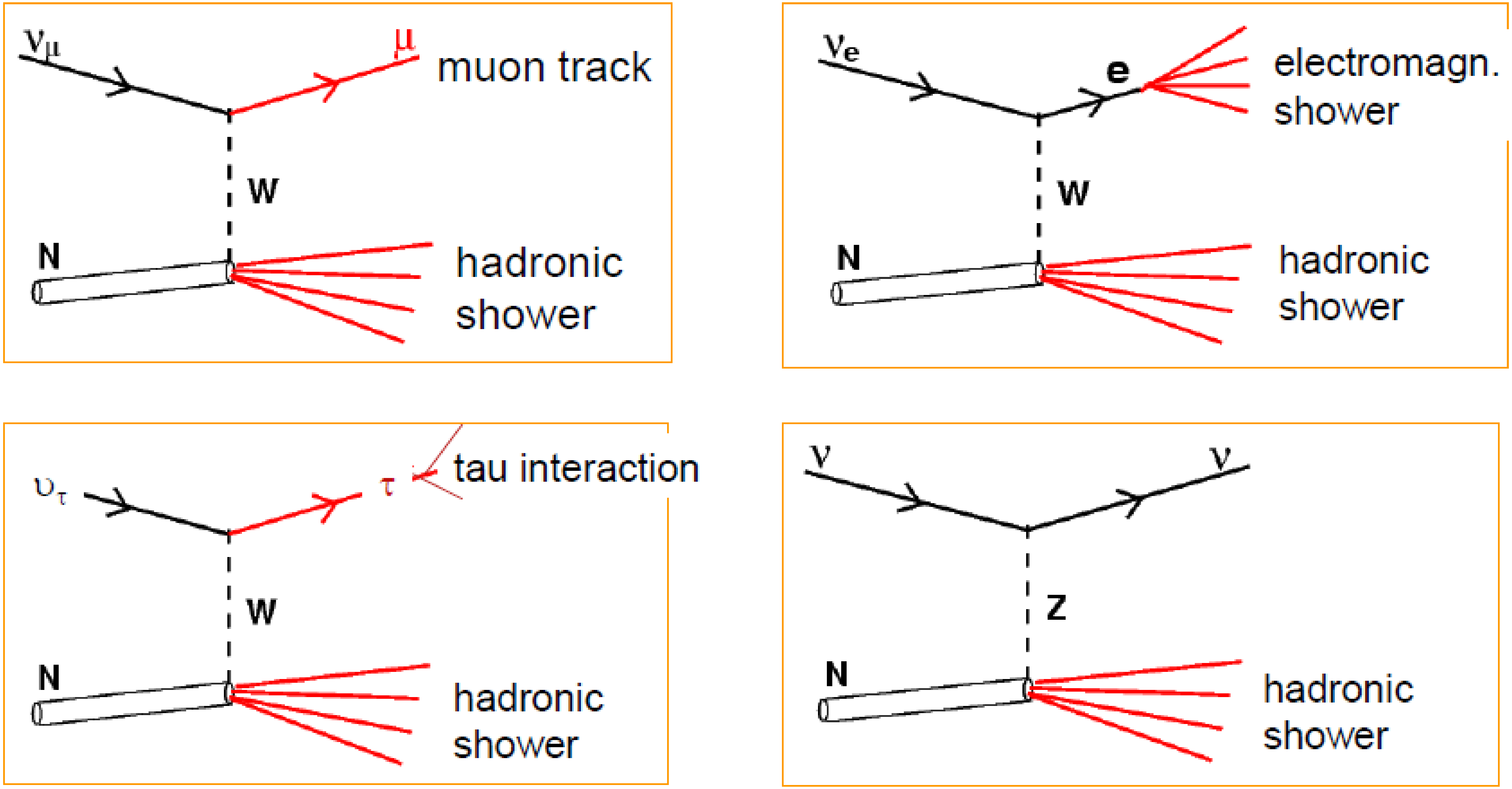
$$\langle\theta\rangle \approx \frac{1.5^\circ}{\sqrt{E_\nu\,[\mathrm{TeV}]}}$$

Reconstruction of the μ trajectory allows the identification of the ν direction

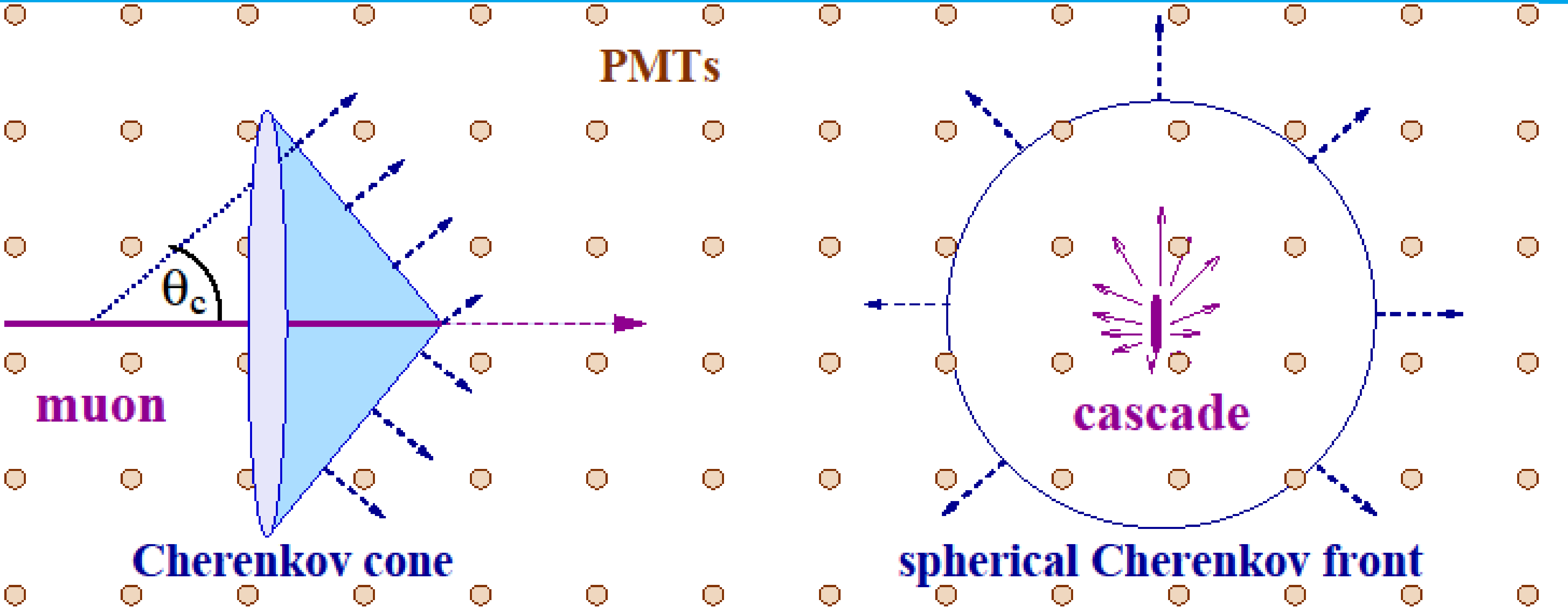


Calculated median of the angular error in KM3NeT

Tracks, showers, double bang events

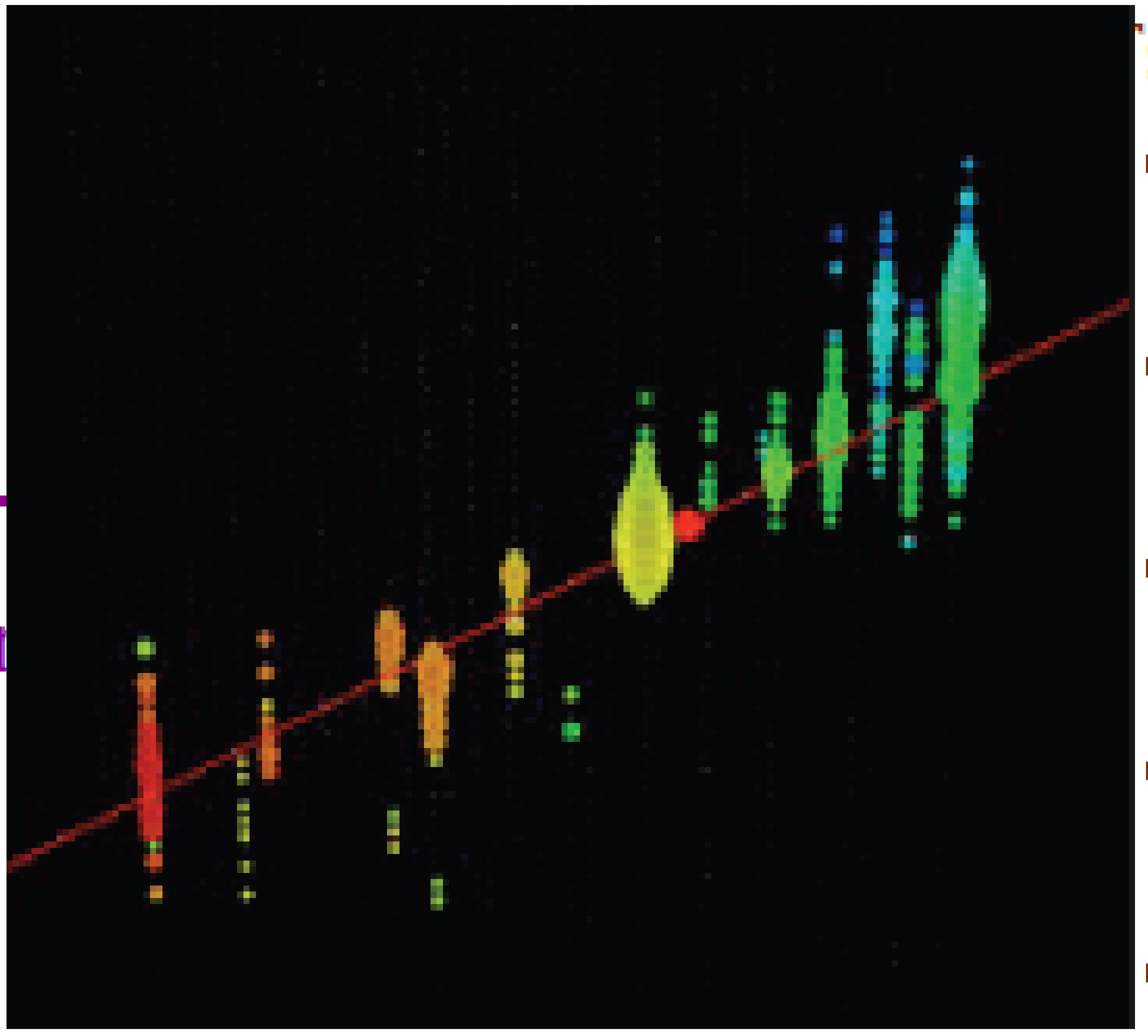


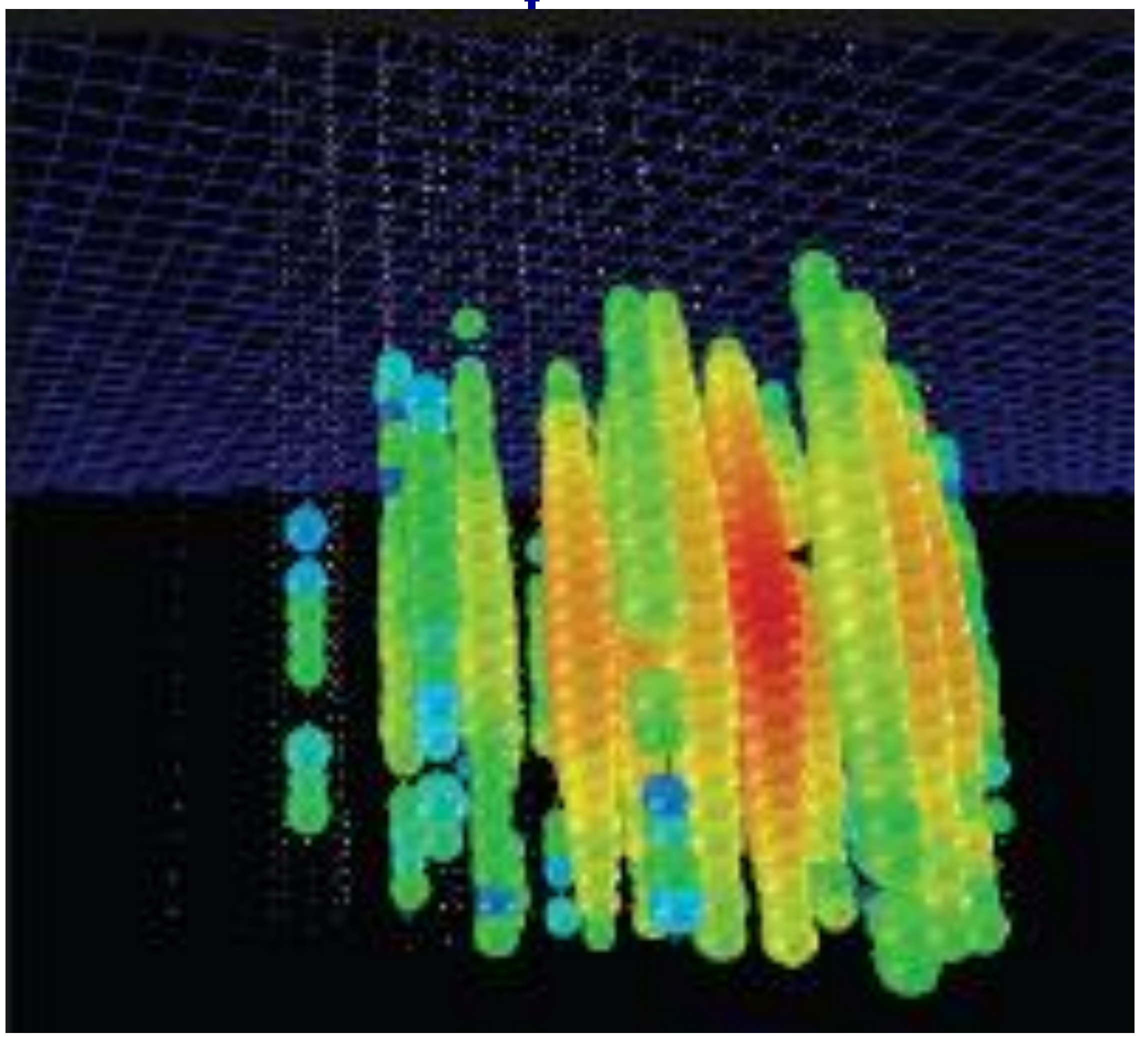
Two Detection Modes: tracks and cascades



- $\nu_\mu + A \rightarrow \mu + \ldots$
  - Angular resolution < 1°
  - dE/dx gives E_μ within factor 2-3
- $\nu_{e,\tau} \rightarrow e, \tau + \ldots$
- $\nu_X \rightarrow \nu_X + \ldots$
  - Angular resolution 2-15° @ 100 TeV
  - Energy resolution ~ 15%

Two Detection Modes





- $\nu_\mu + A \rightarrow \mu + \ldots$
  - Angular resolution < 1°
  - dE/dx gives E_μ within factor 2-3
- $\nu_{e,\tau} \rightarrow e, \tau + \ldots$
- $\nu_X \rightarrow \nu_X + \ldots$
  - Angular resolution 2-15° @ 100 TeV
  - Energy resolution ~ 15%

THE DETECTORS

The (first) pioneer

DUMAND

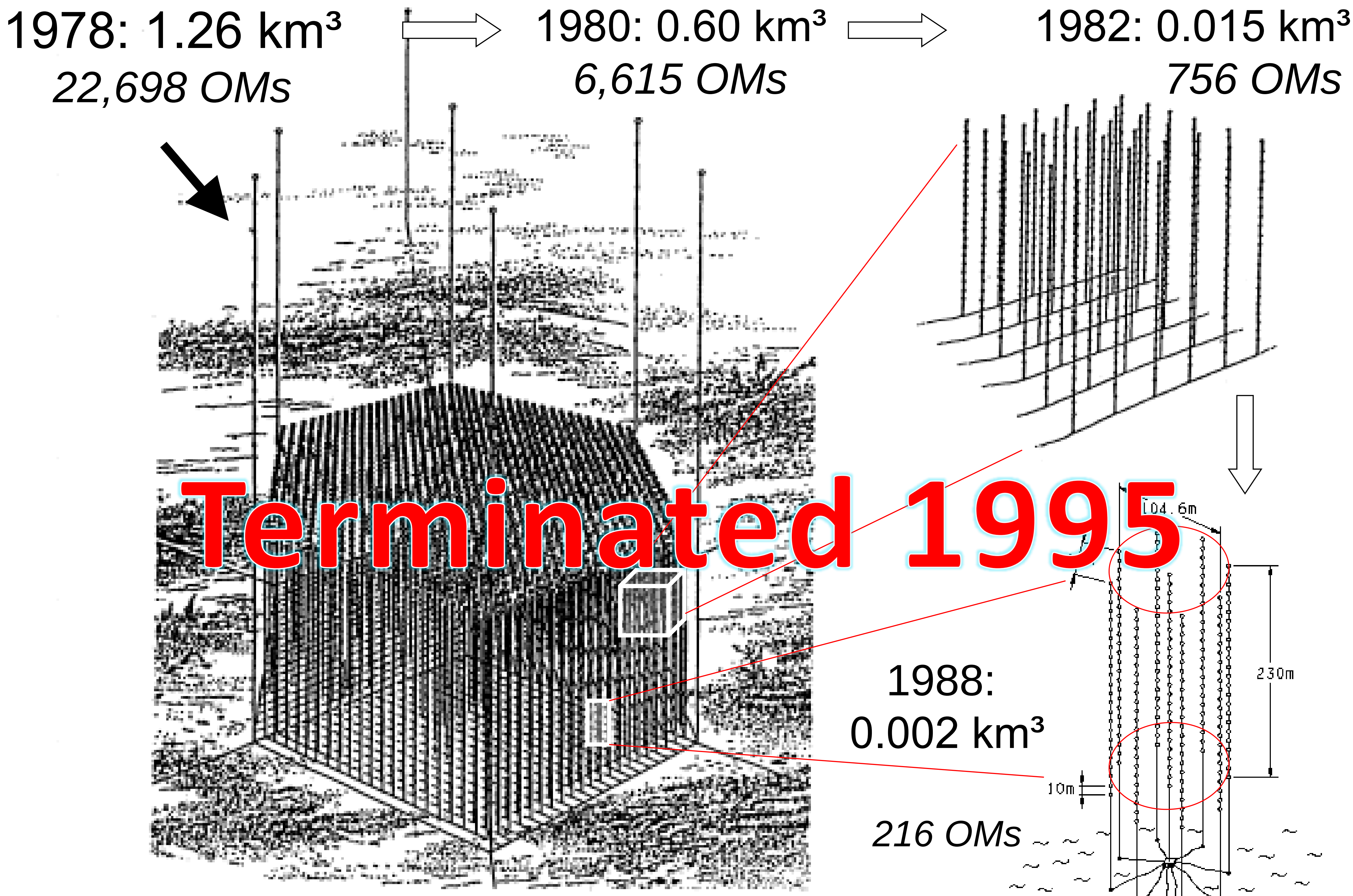
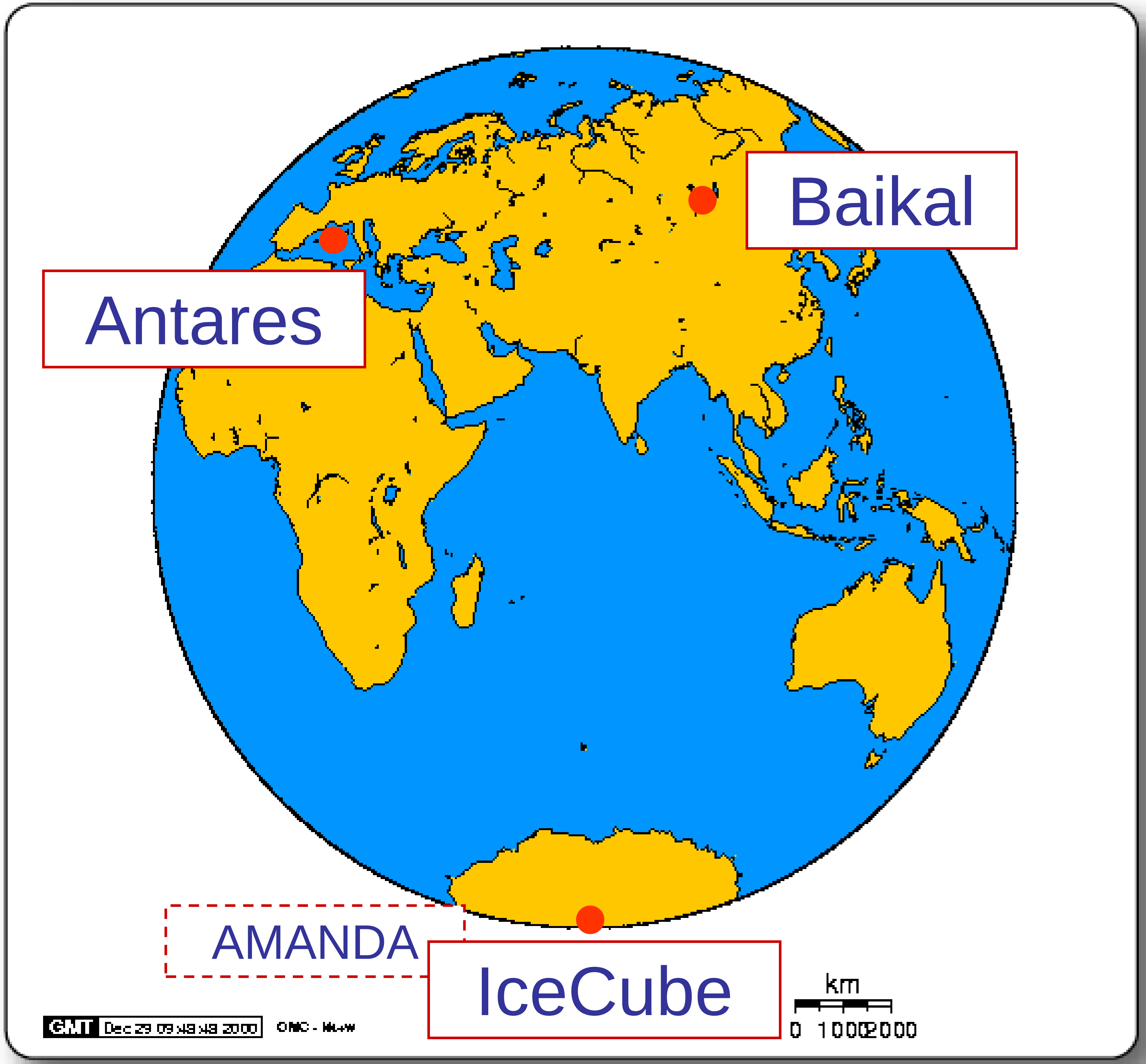
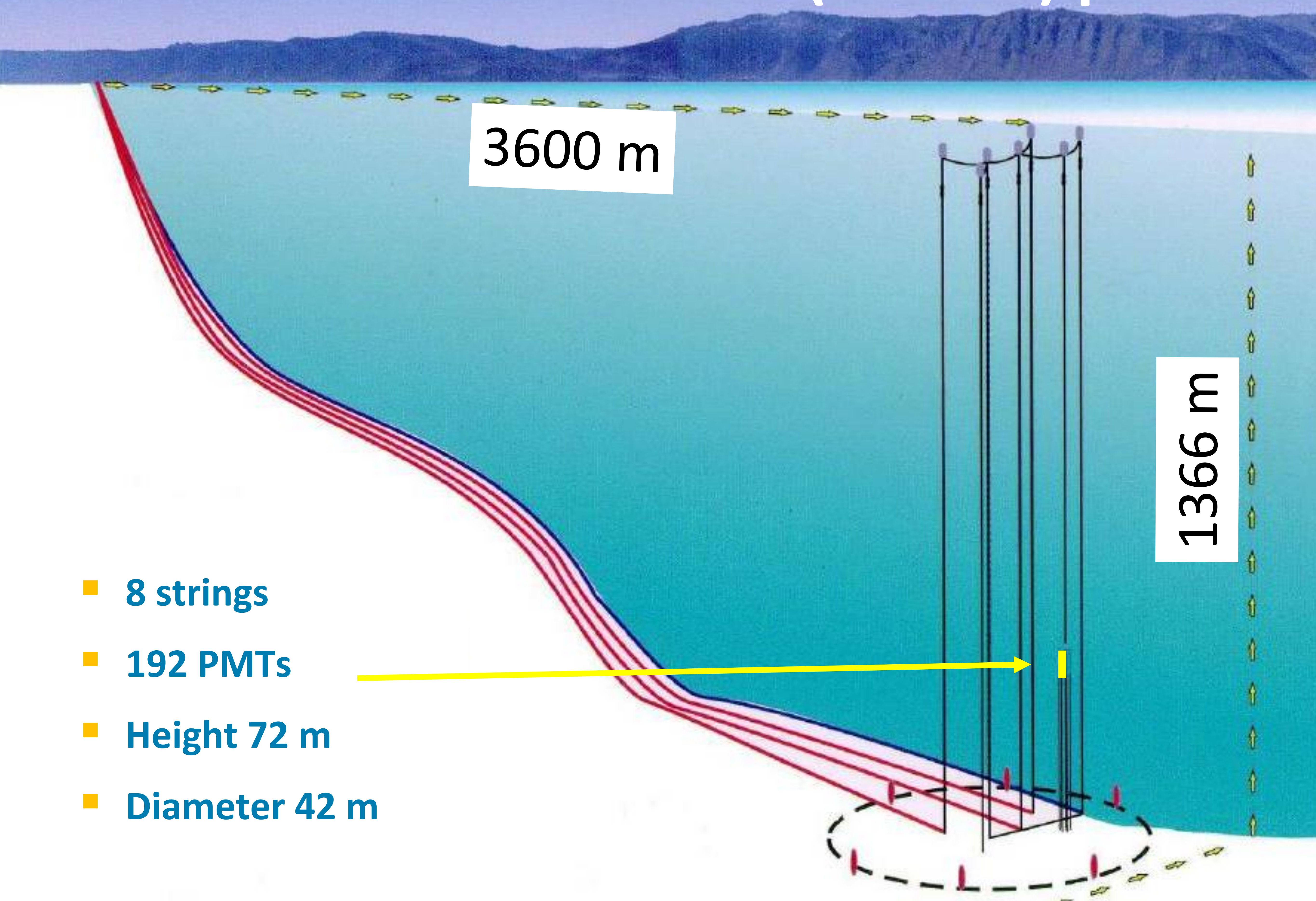


FIG. 9. The first DUMAND array: DUMAND G, the 1978 model. See text for details (Roberts and Wilkins, 1978).

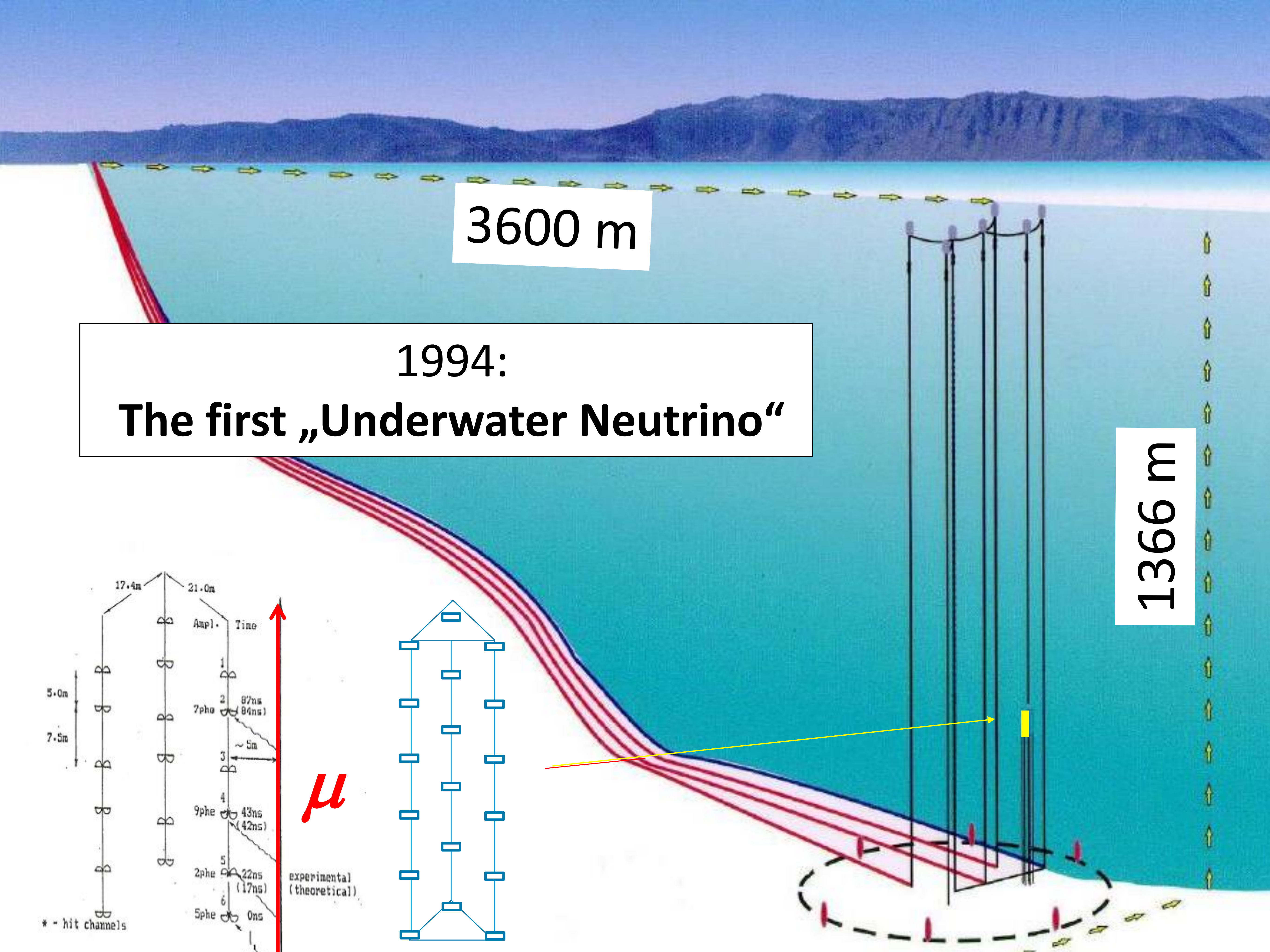
Operating neutrino telescopes




NT200 in Lake Baikal: the (second) pioneer

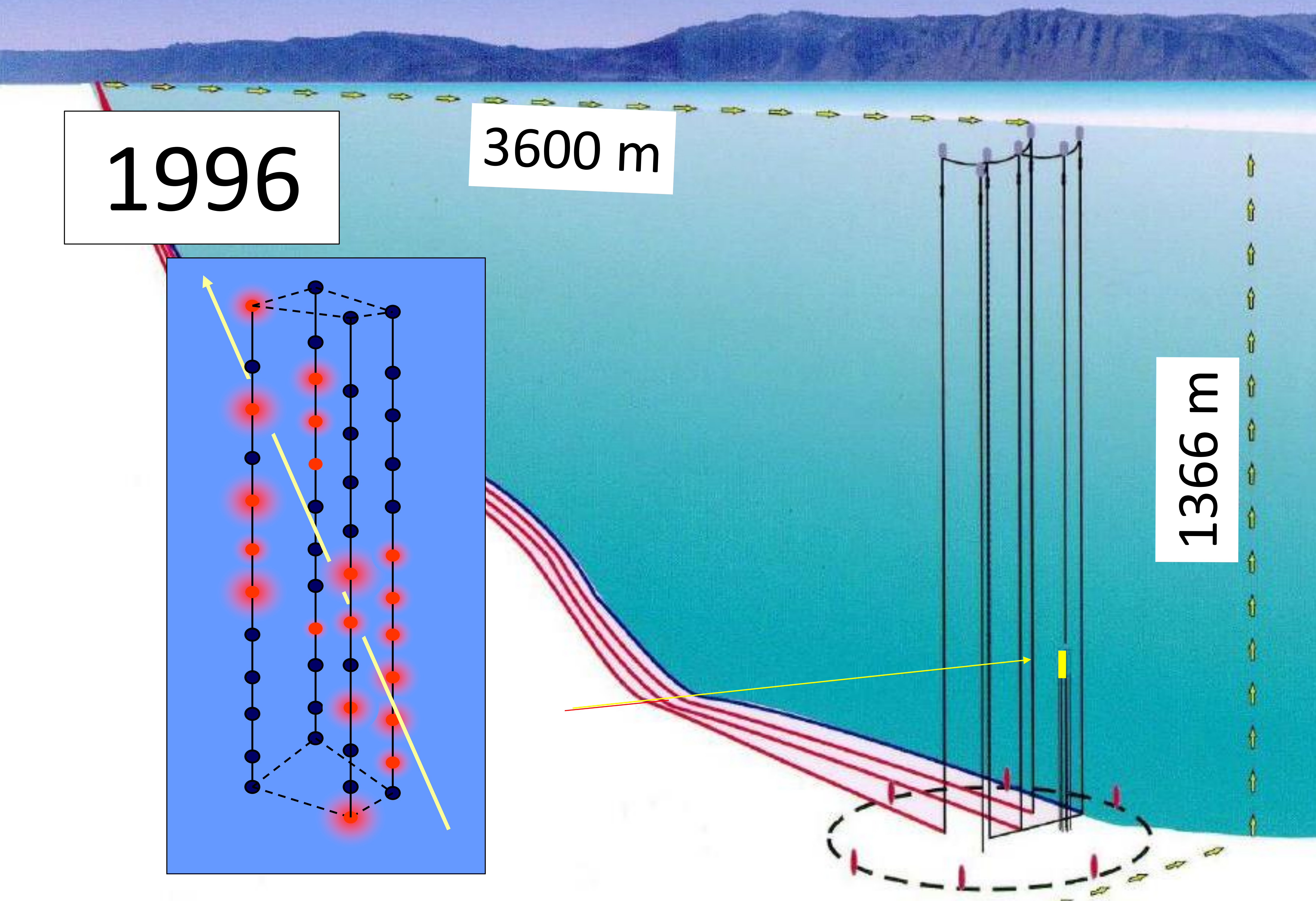


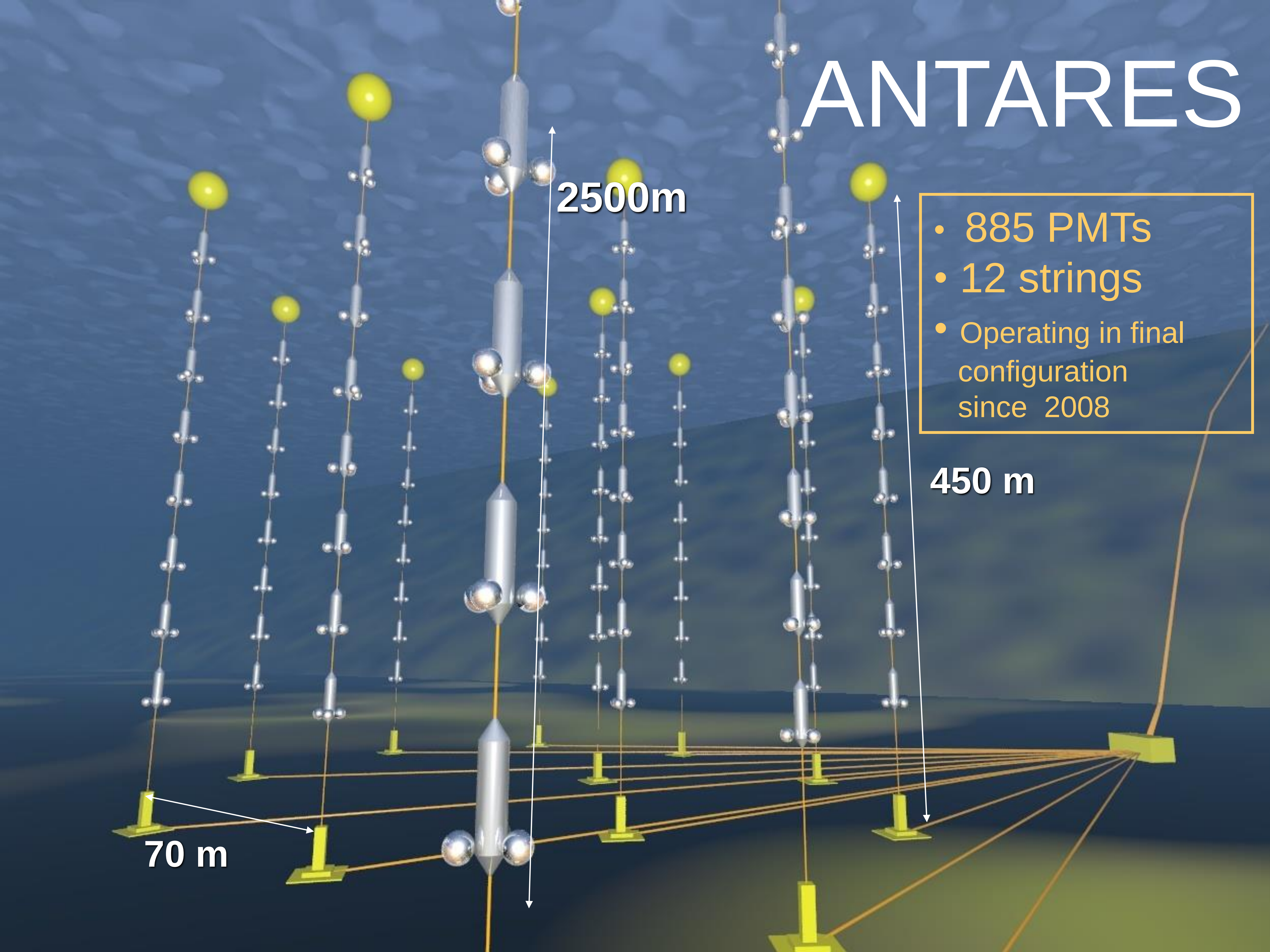
- **8 strings**
- **192 PMTs**
- **Height 72 m**
- **Diameter 42 m**



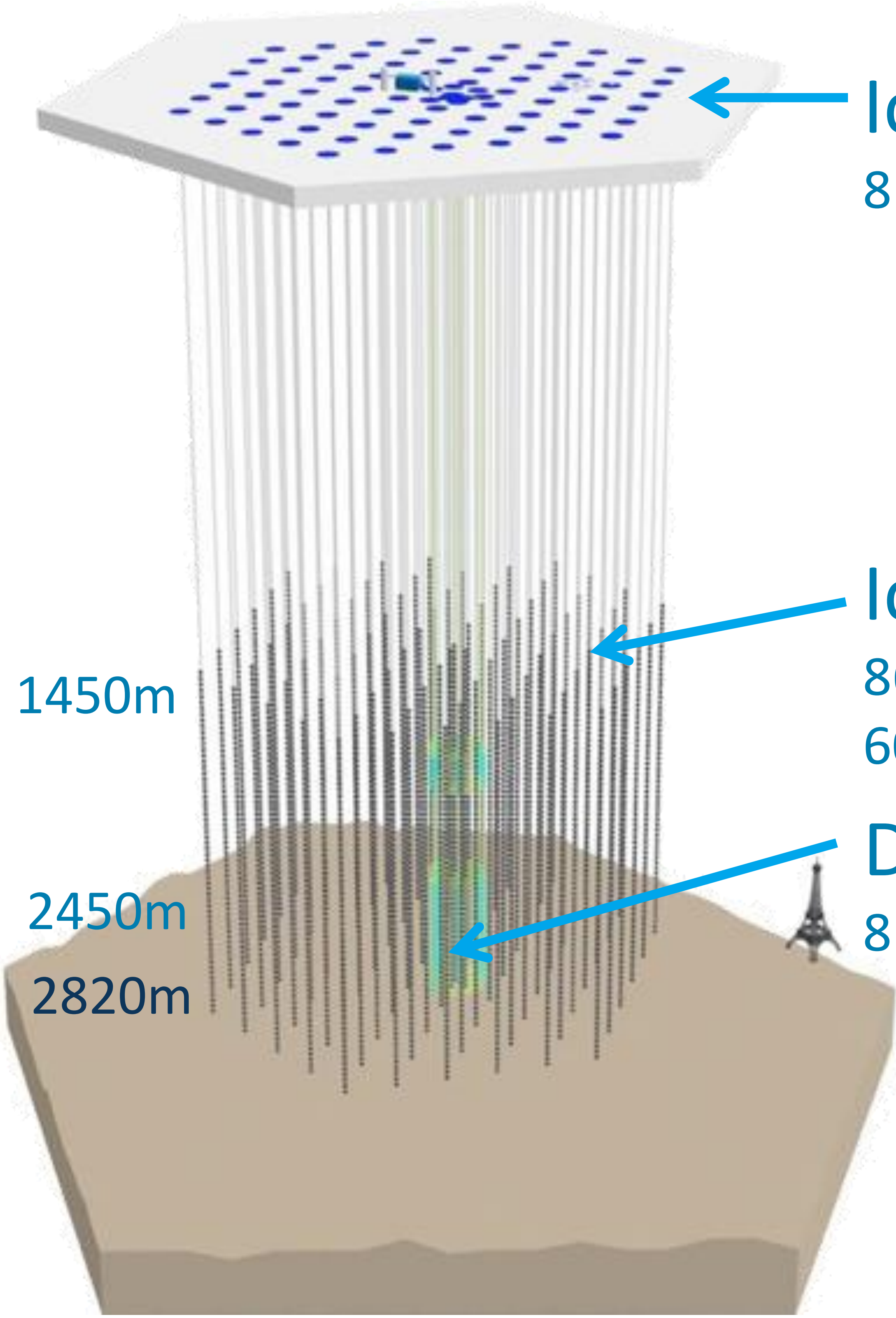
3600 m
1994:
The first „Underwater Neutrino“
1366 m
17.4m
21.0m
Ampl.
Time
5.0m
7.5m
1
2
7phe
87ns
(84ns)
~ 5m
3
4
9phe
43ns
(42ns)
5
2phe
22ns
(17ns)
6
5phe
0ns
* - hit channels
experimental
(theoretical)
μ

A textbook underwater neutrino event




ANTARES
• 885 PMTs
• 12 strings
• Operating in final configuration since 2008
2500m
450 m
70 m

IceCube Neutrino Observatory



IceTop air shower detector

81 pairs of water Cherenkov tanks

IceCube

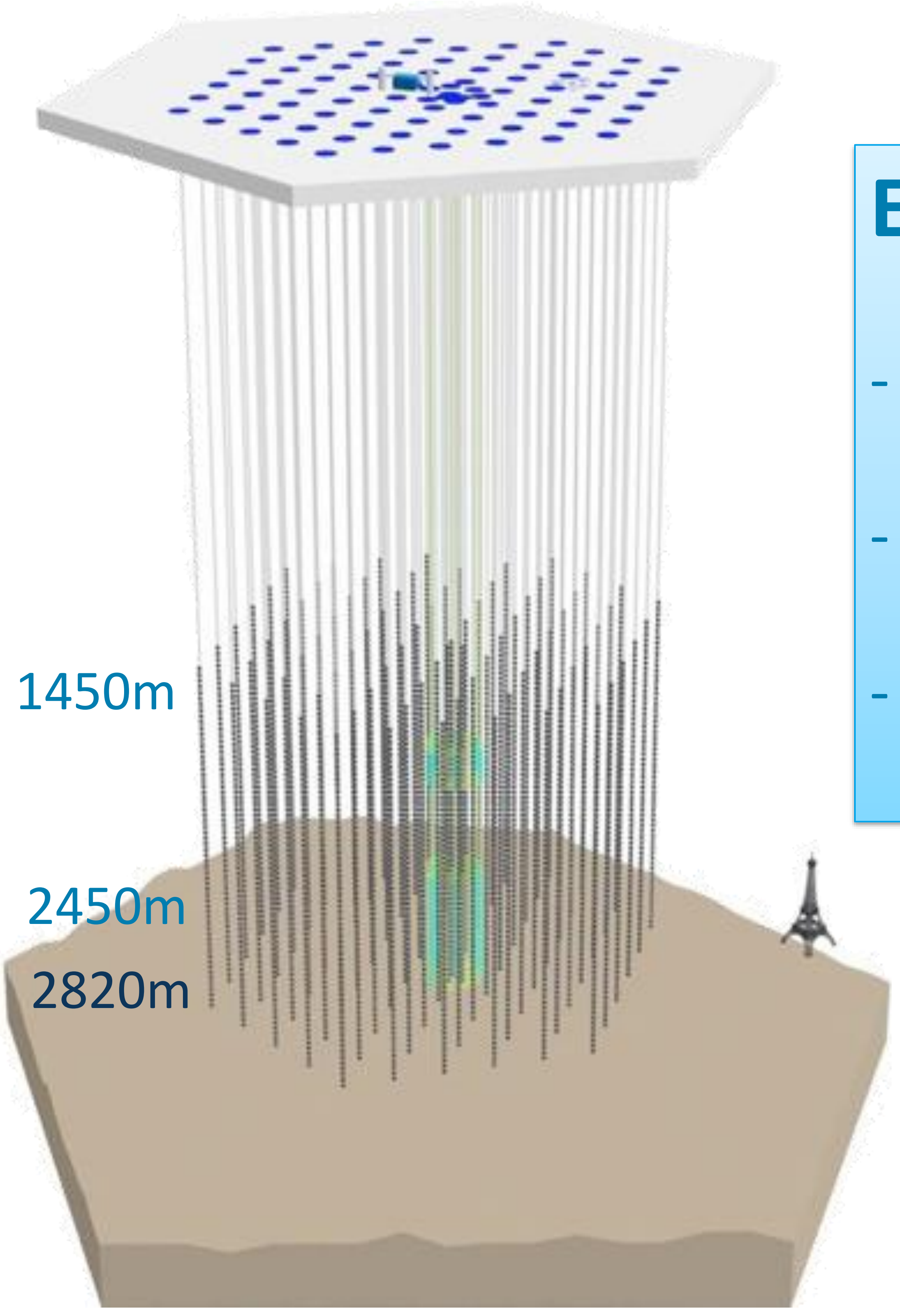
86 strings including 8 Deep Core strings
60 PMT per string

DeepCore

8 closely spaced strings

Threshold:	**IceCube**	**~ 100 GeV**
	DeepCore	**~10 GeV**

IceCube Neutrino Observatory

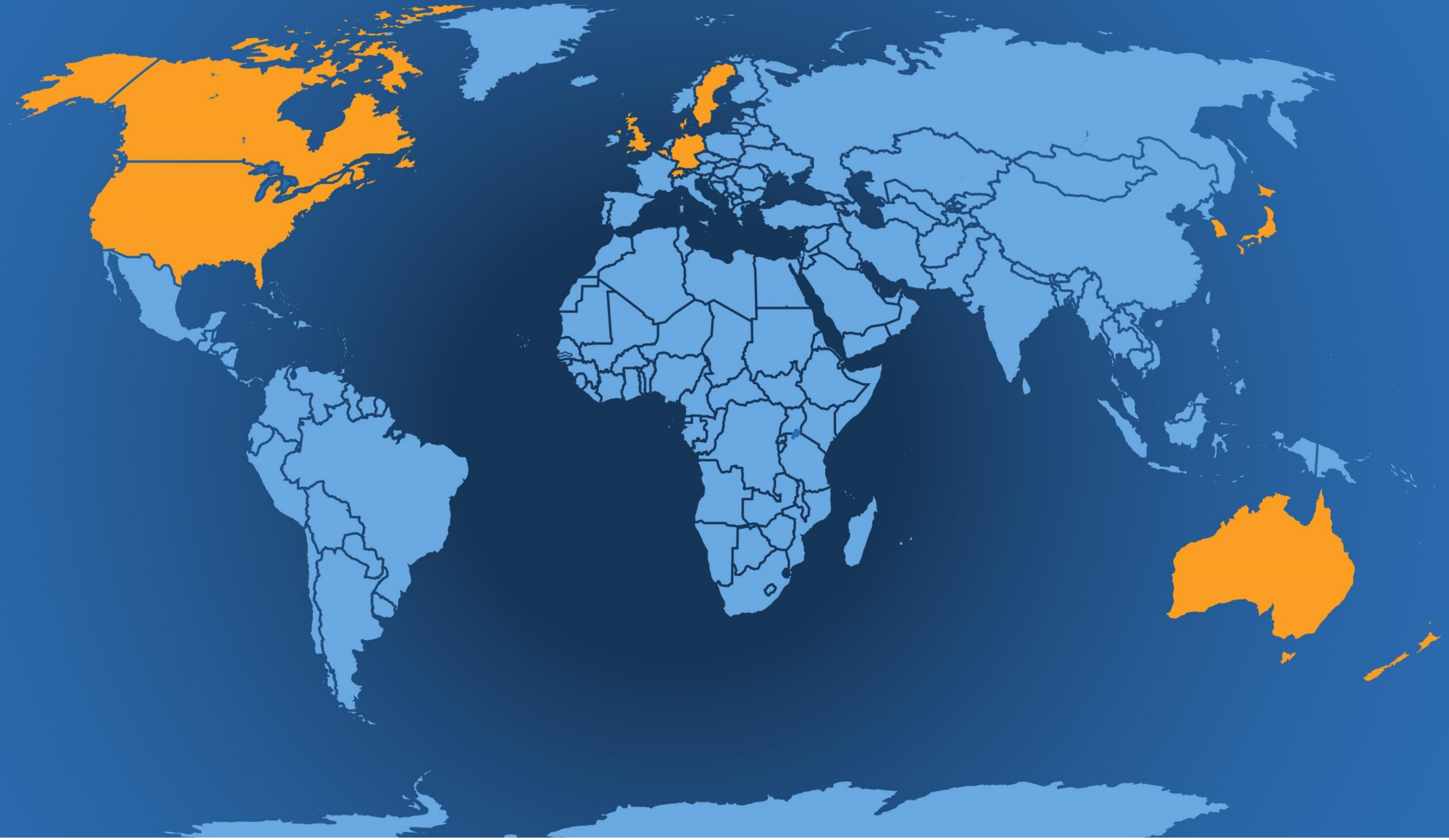


Events per year:

- Downgoing muons ~ 2×10^{11}
- Atmospheric neutrinos ~ 100,000
- Cosmic neutrinos ~ 100

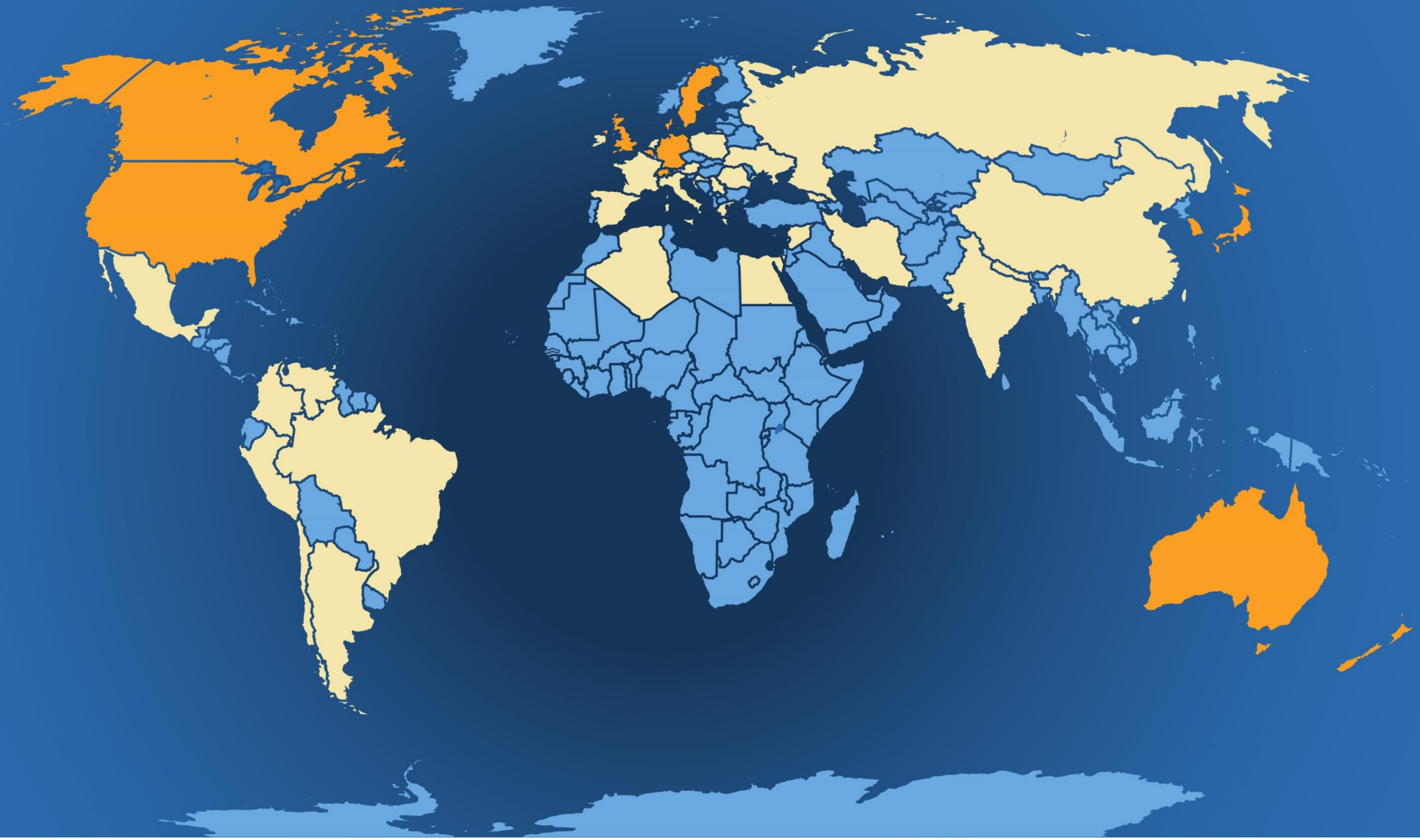
Threshold: IceCube ~ 100 GeV
DeepCore ~10 GeV

The IceCube Collaboration



46 institutions from 12 countries

...and this is where we come from.



Algeria
Argentina
Australia
Austria
Belgium
Brazil
Canada
Chile
China
Colombia
Croatia
Denmark
Egypt
France
Germany
Georgia
Greece
India
Iran
Ireland
Israel
Italy
Japan
Lebanon
Mexico
Nepal
New Zealand
Peru
Poland
Romania
Russia
Serbia
South Korea
Spain
Sweden
Switzerland
Syria
Taiwan
The Netherlands
The UK
Trinidad and Tobago
Ukraine
USA
Venezuela

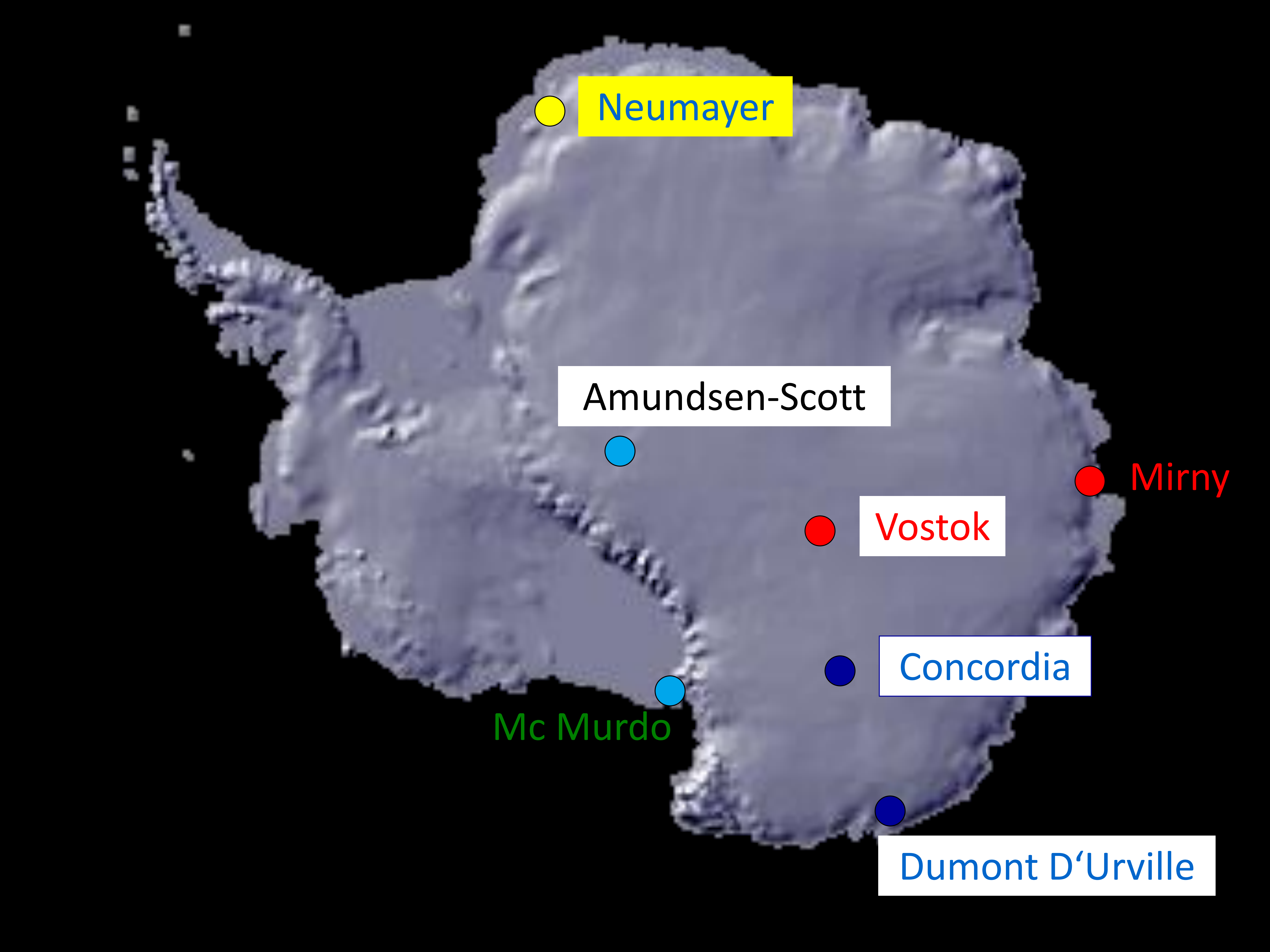
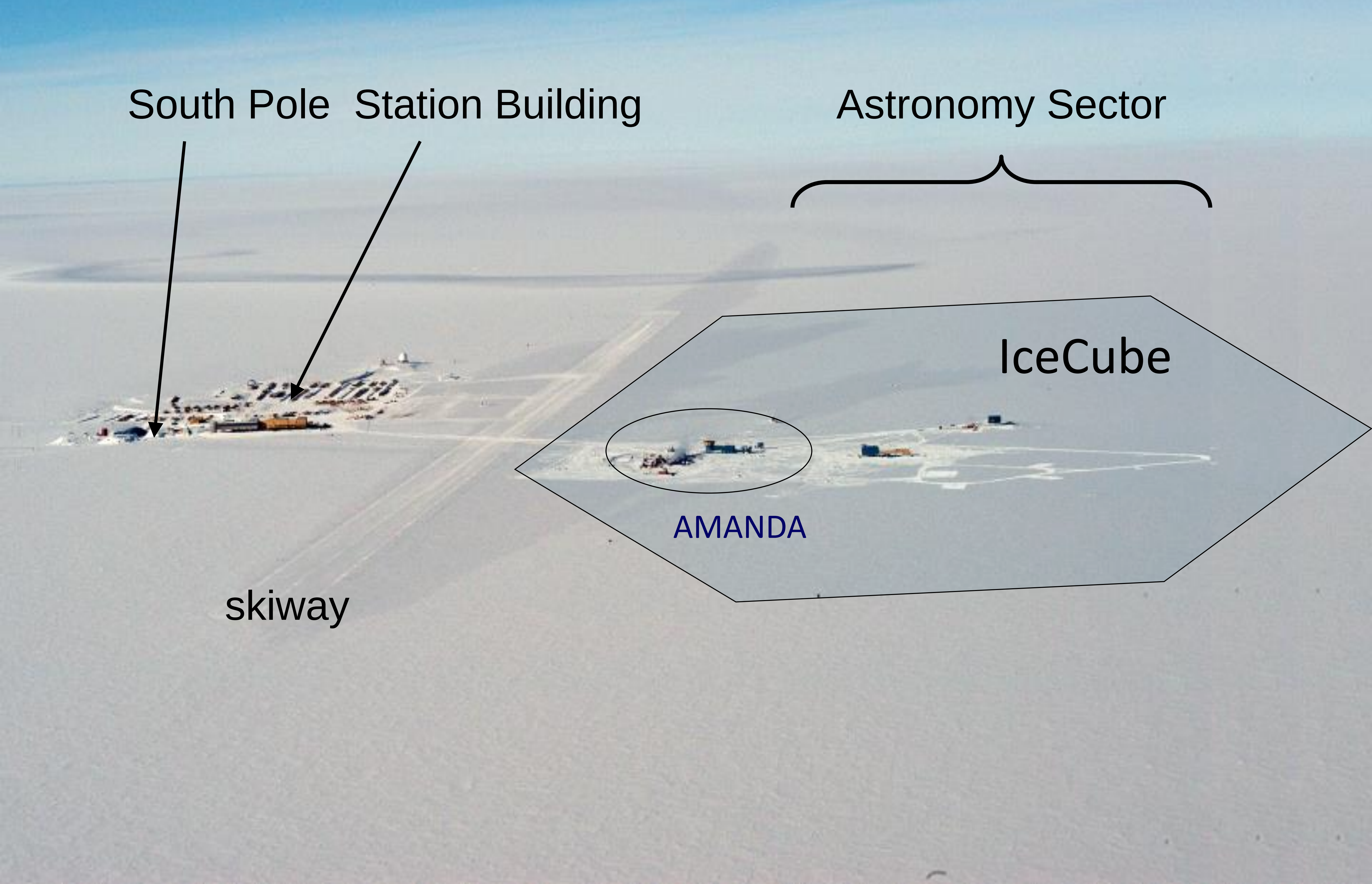

Neumayer
Amundsen-Scott
Mirny
Vostok
Concordia
Mc Murdo
Dumont D‘Urville


PHOTO BY CHARLIE KAMINSKI
SOUTH POLE DEC 2, 2000

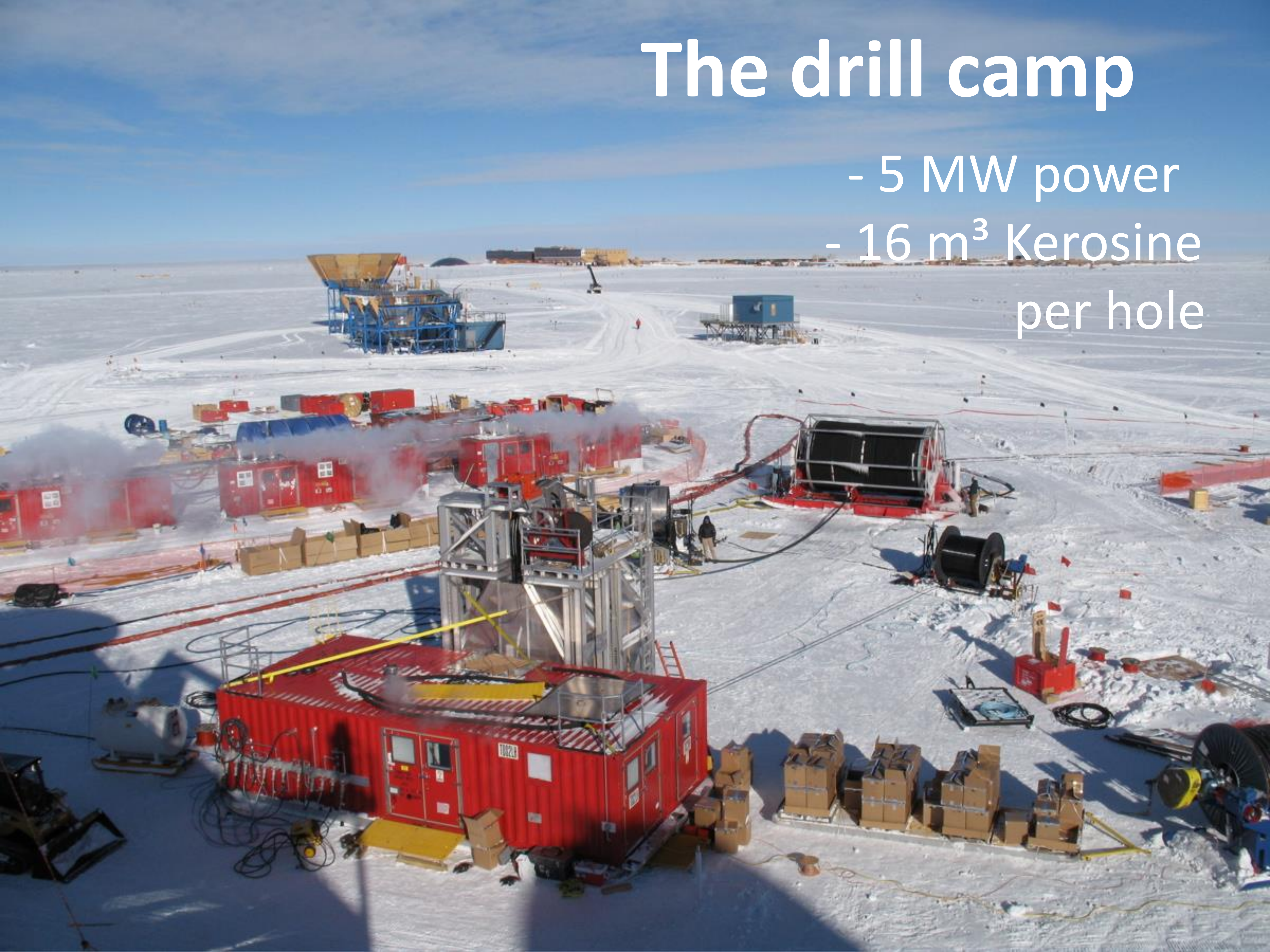
The Amundsen-Scott Station

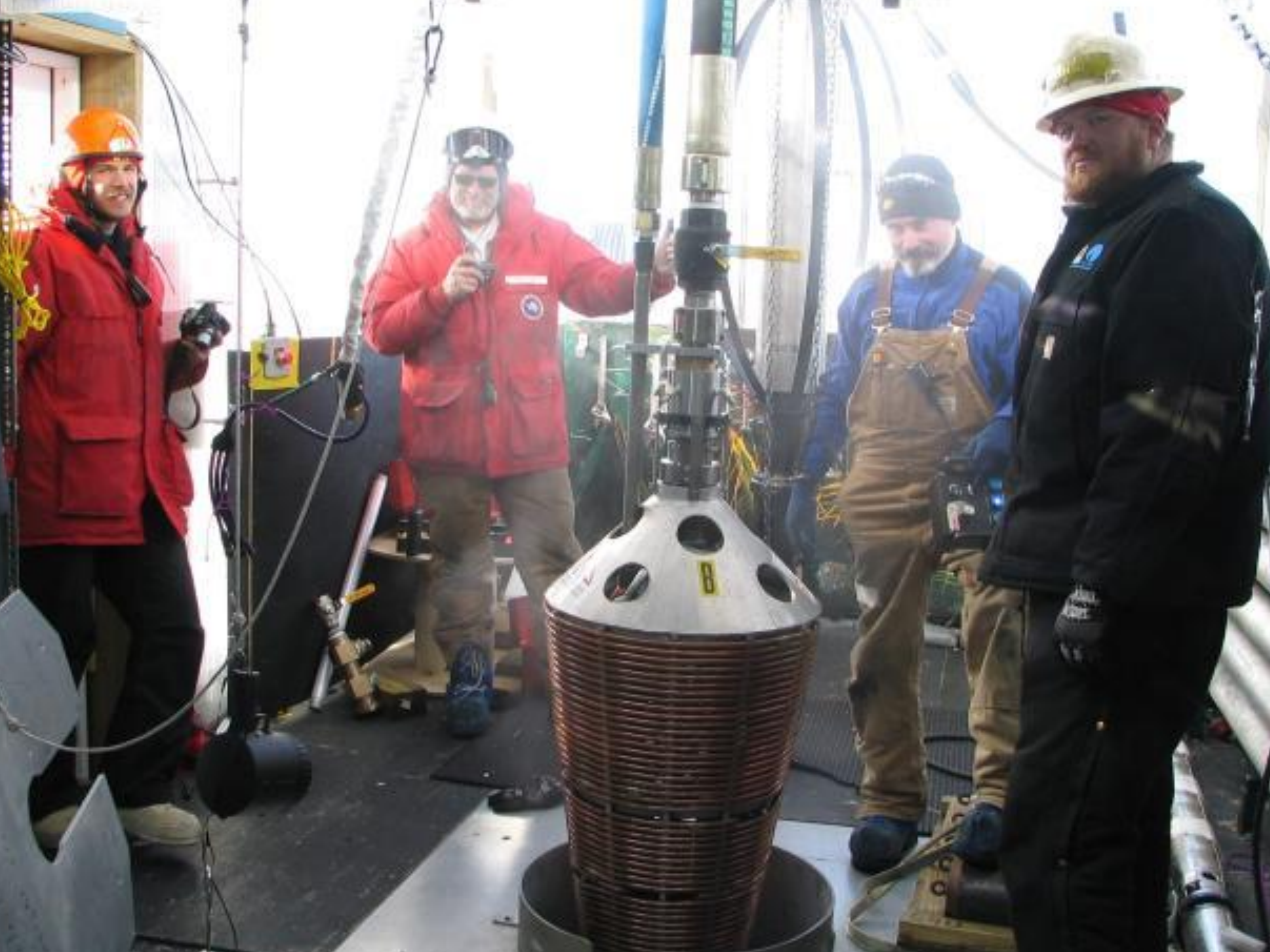


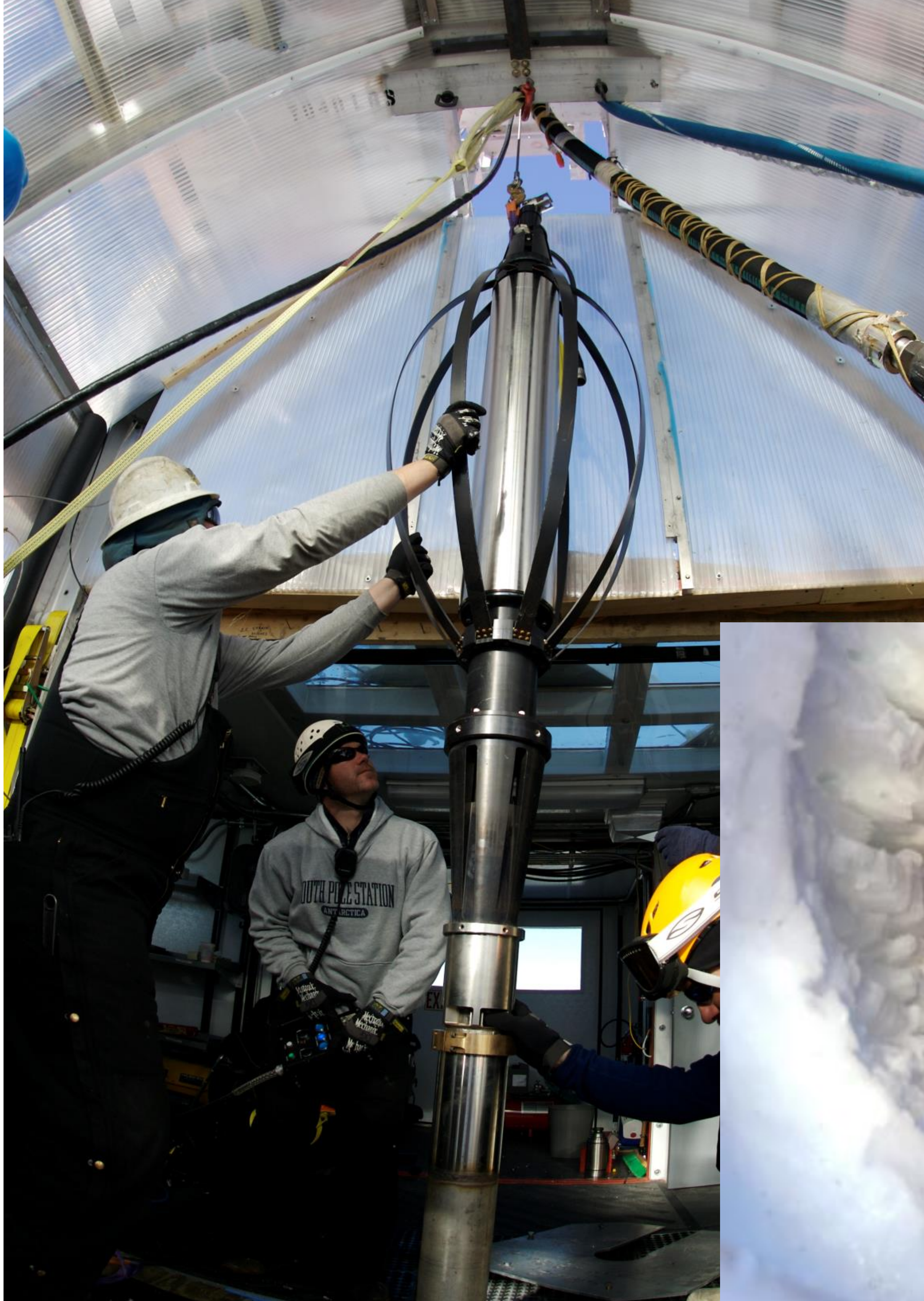

Infrastructure and support:
NSF / Raytheon Polar Services
NSF/ Lockheed Martin (ASC)

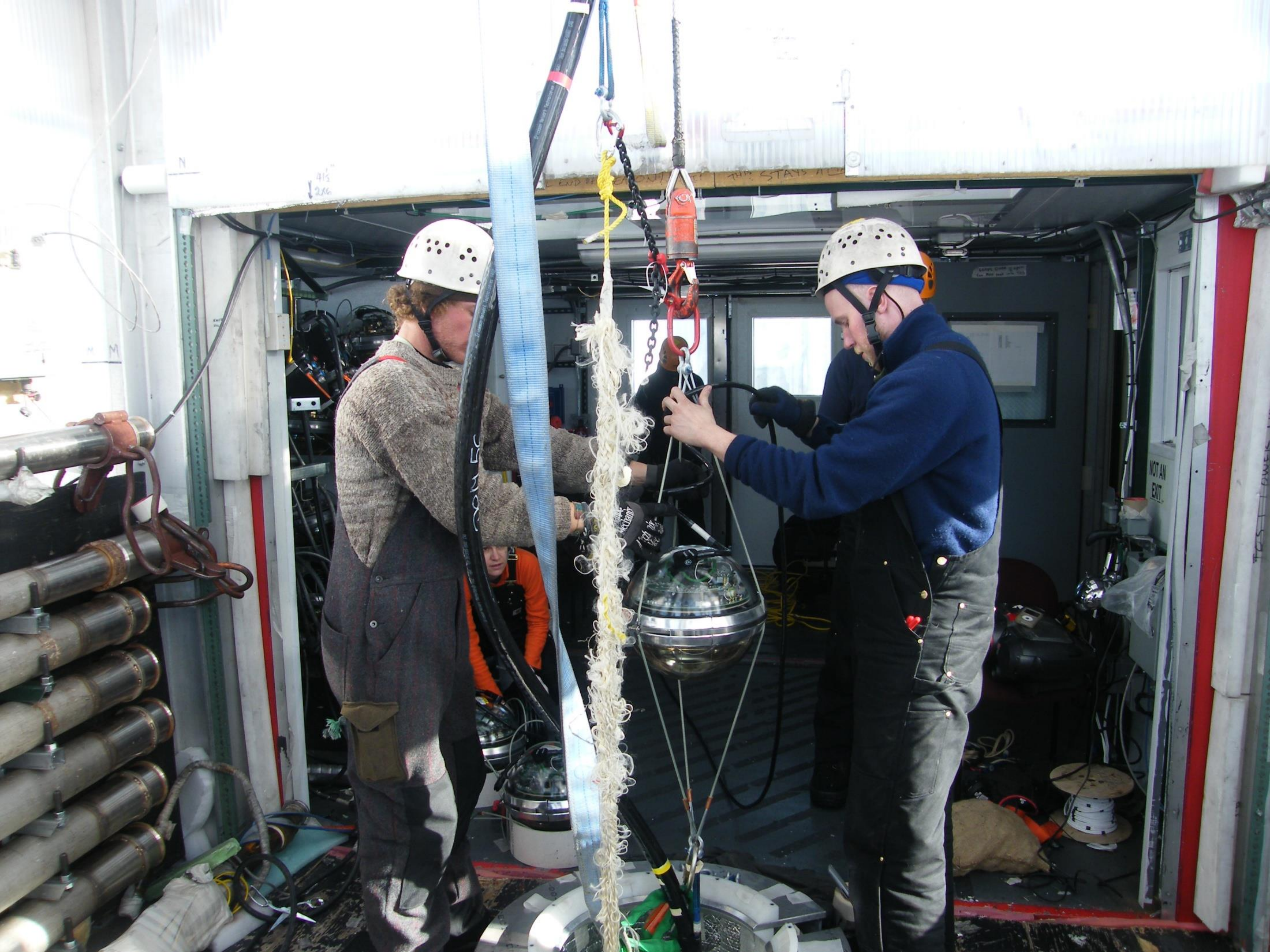
The drill camp

- 5 MW power
- 16 m³ Kerosine per hole

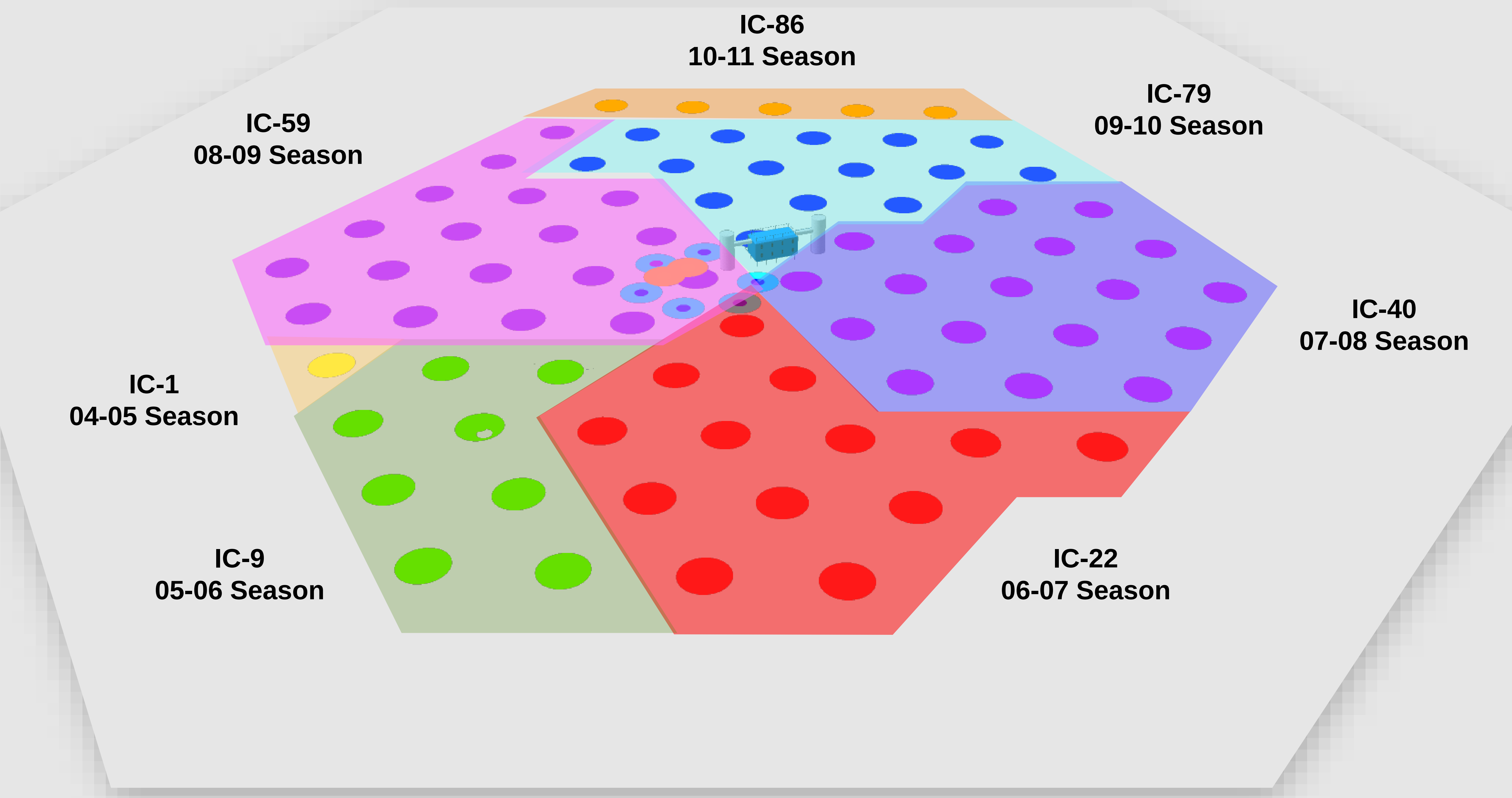



8



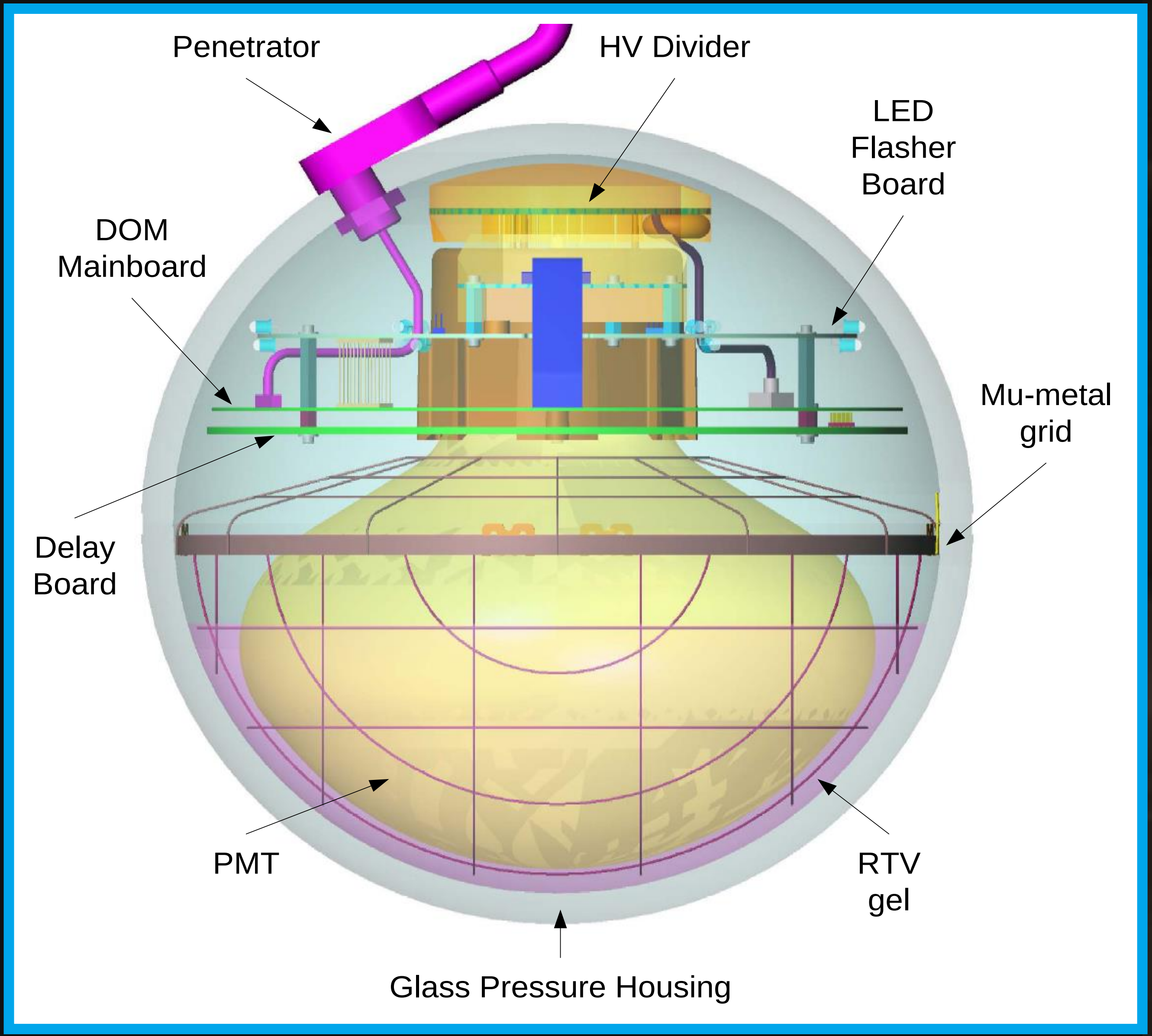

NOT AN EXIT

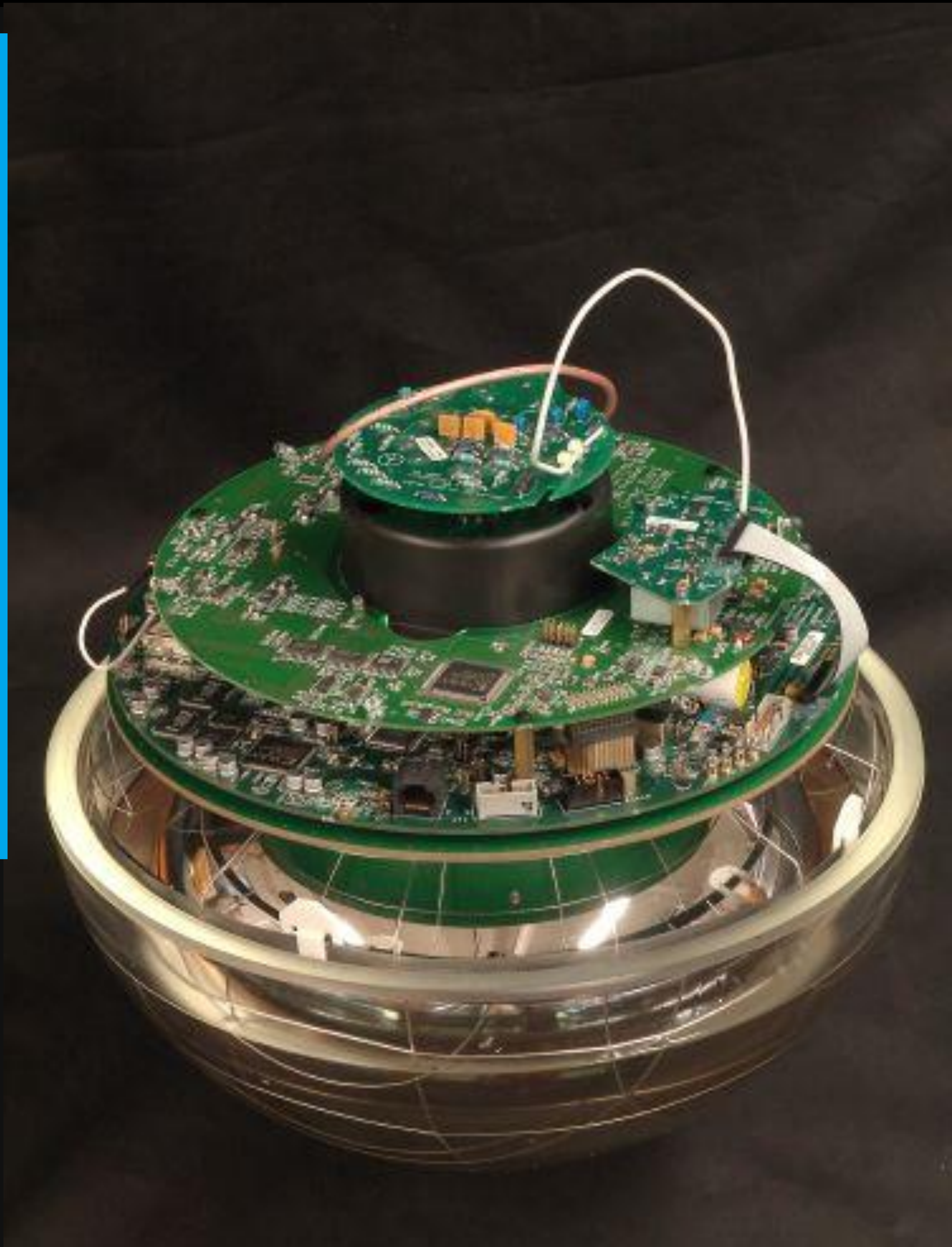
Construction 2004 - 2010




NOT AN EXIT
B.
18.Dec. 2010: the last string

The Digital Optical Module (DOM)

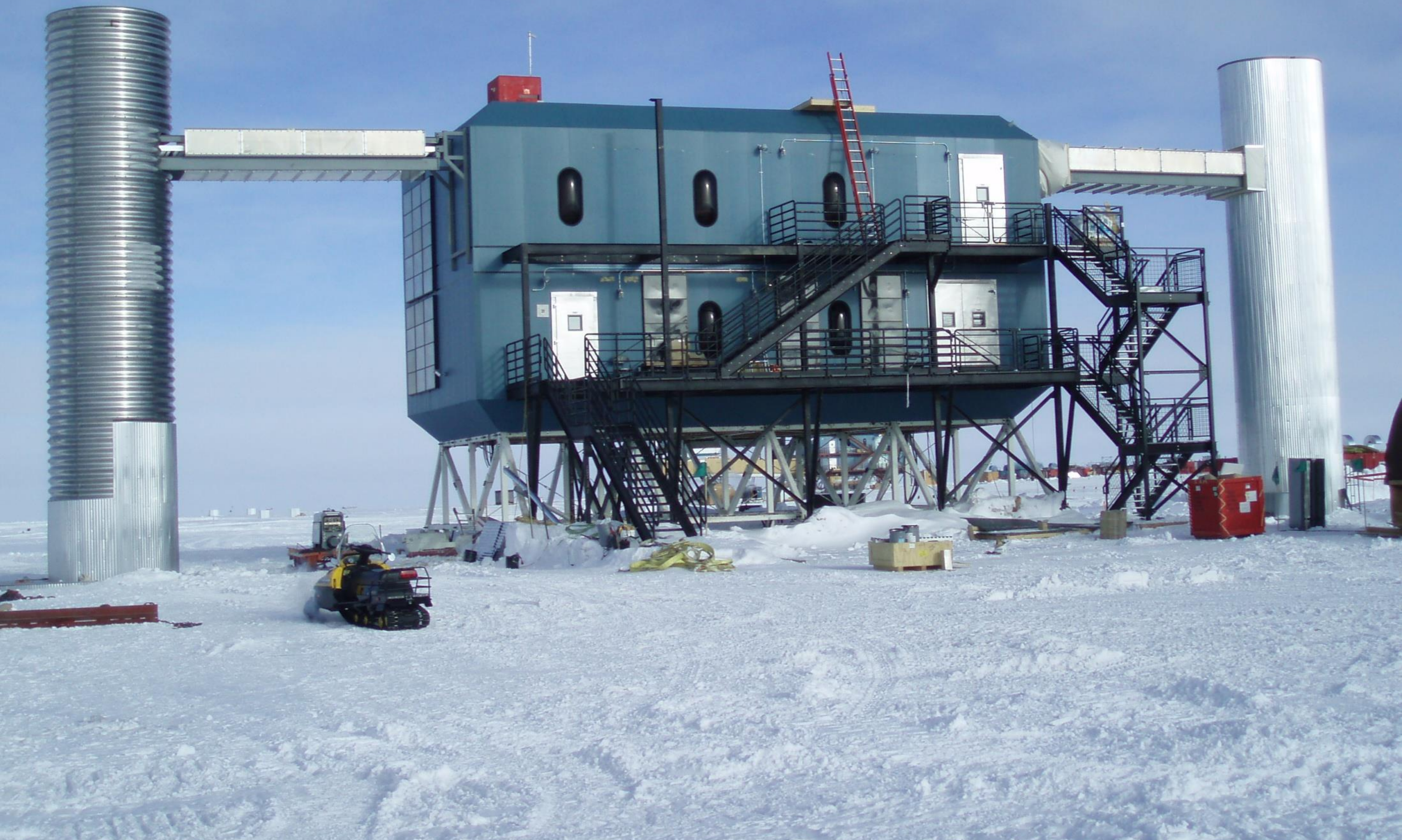




Failure rate < 2 DOM/year

(out of > 5000!)

IceCube Laboratory and Data Center



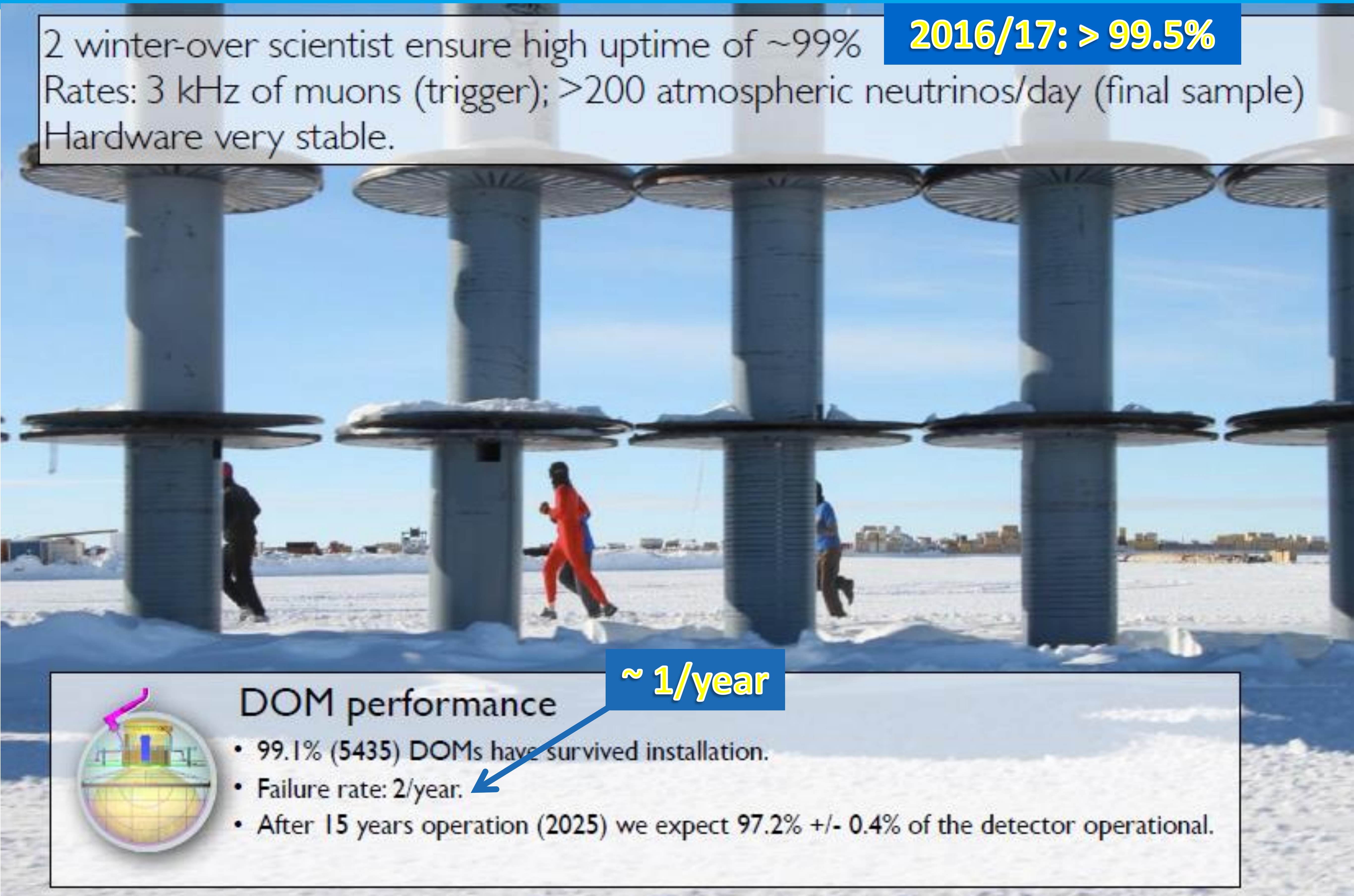
Performance

2 winter-over scientist ensure high uptime of ~99%

2016/17: > 99.5%

Rates: 3 kHz of muons (trigger); >200 atmospheric neutrinos/day (final sample)

Hardware very stable.

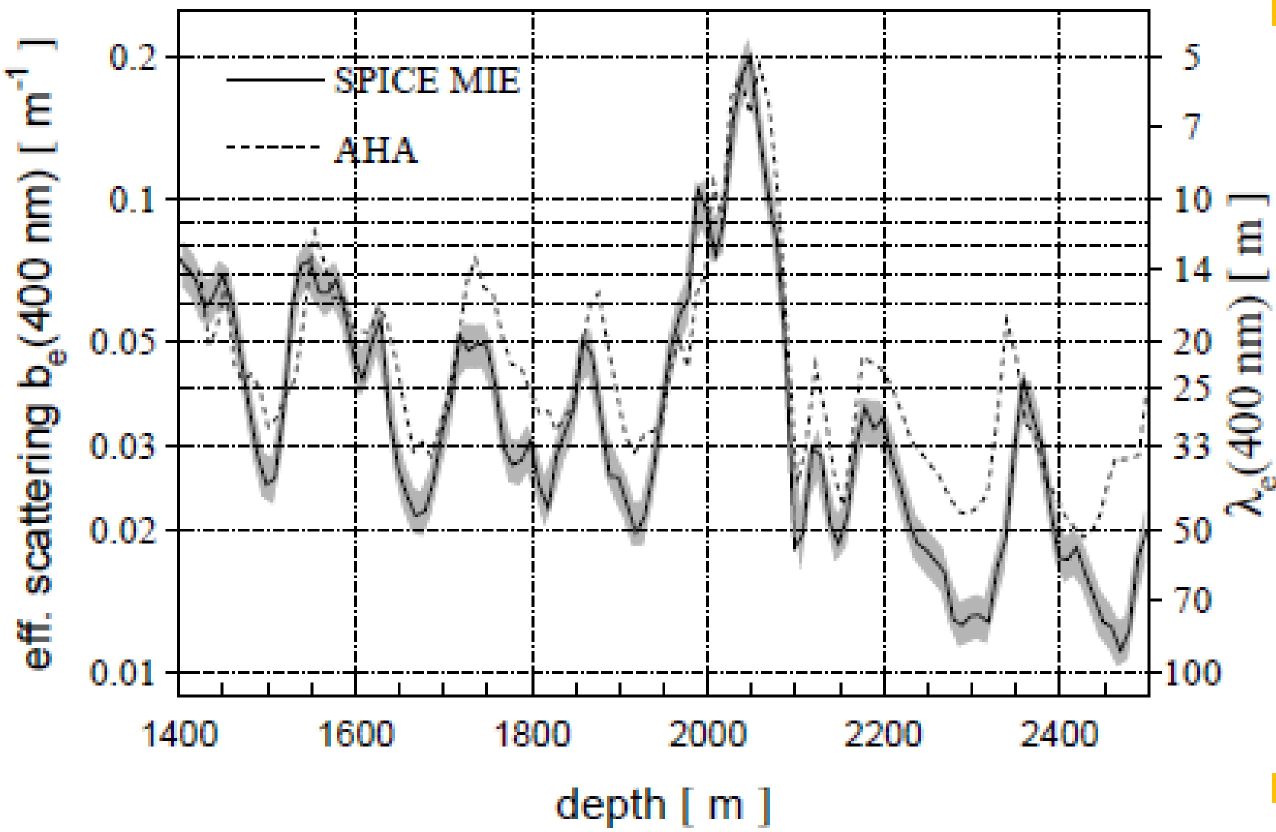


DOM performance

~ 1/year

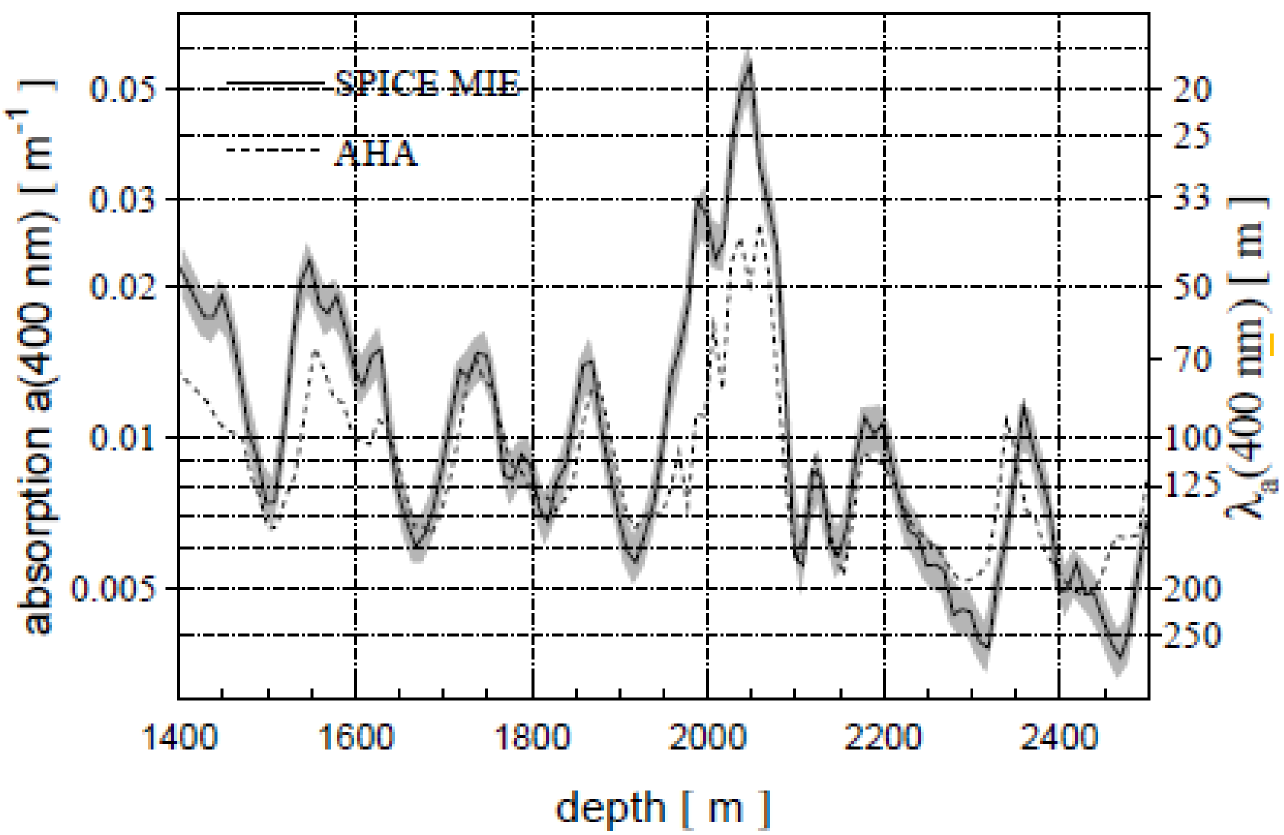
- 99.1% (5435) DOMs have survived installation.
- Failure rate: 2/year.
- After 15 years operation (2025) we expect 97.2% +/- 0.4% of the detector operational.

Ice properties



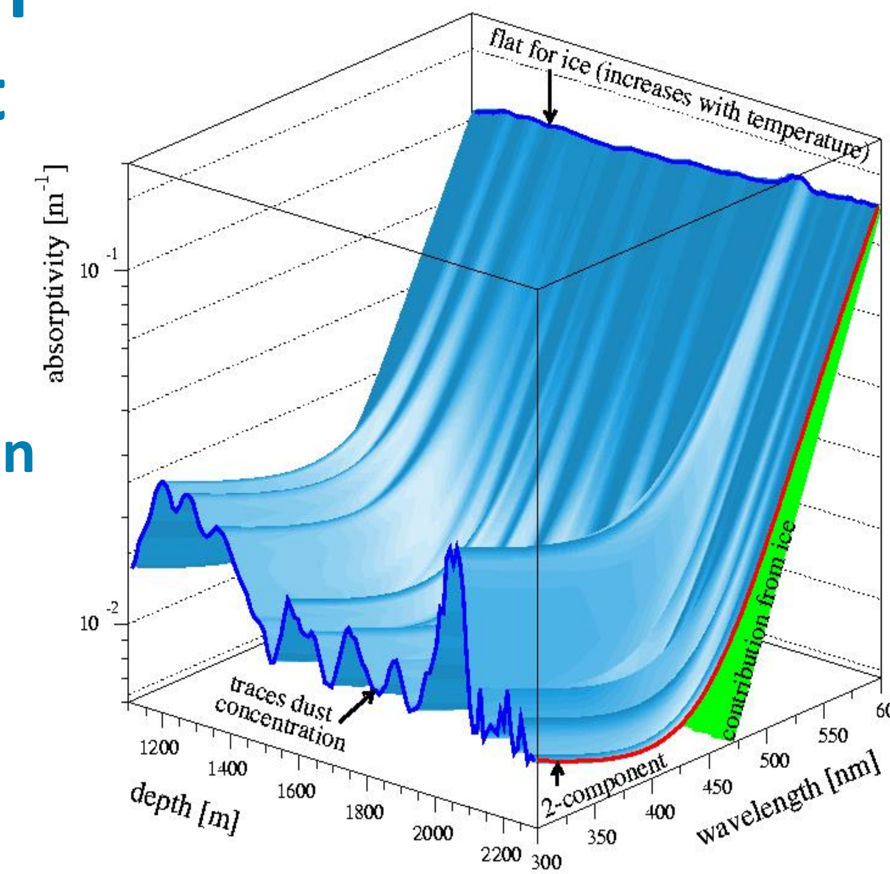
- **Scattering coefficient**

  Much stronger scattering than in water !

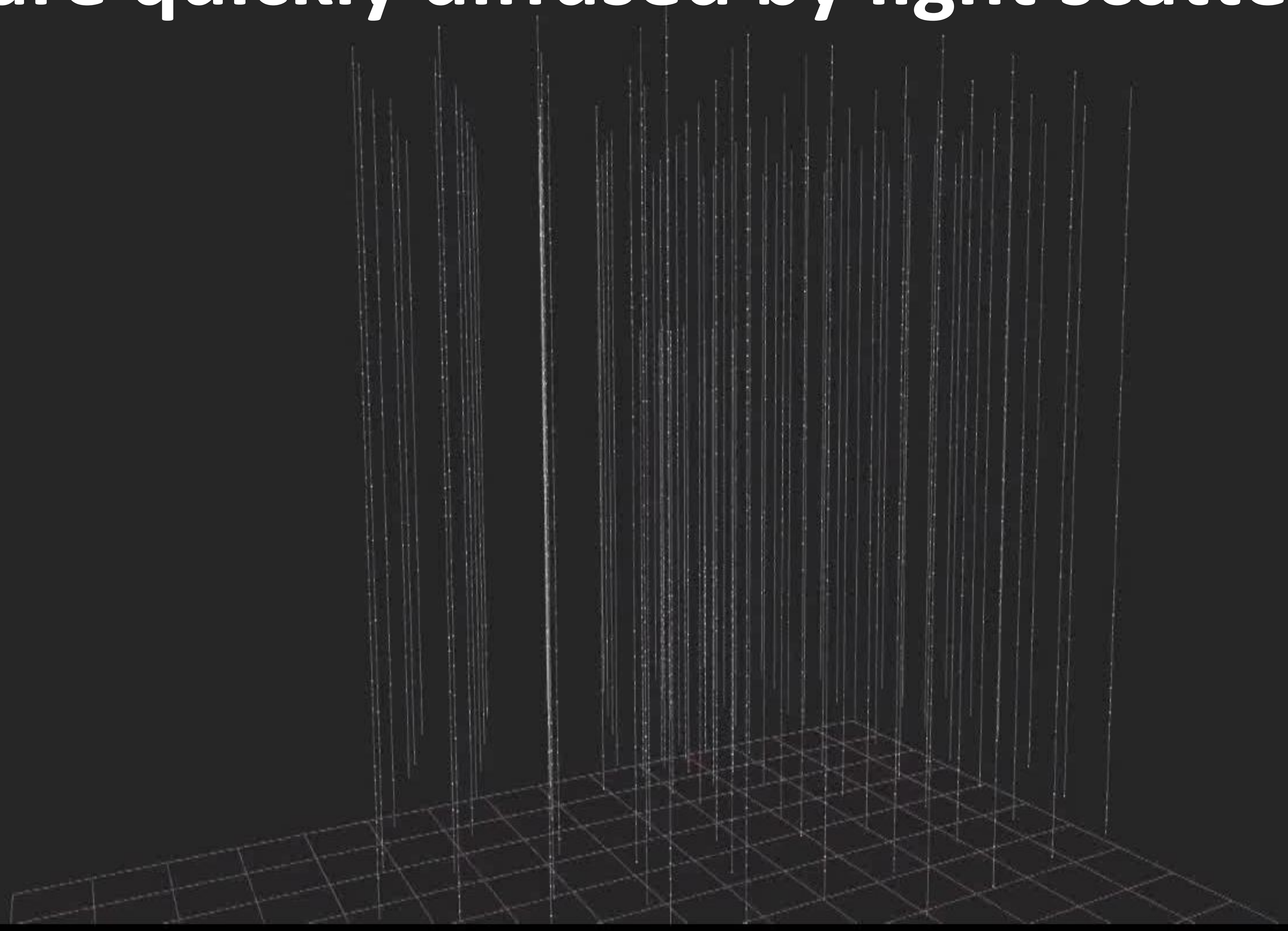


- **Absorption coefficient**

  Up to 2 times less absorption than in water

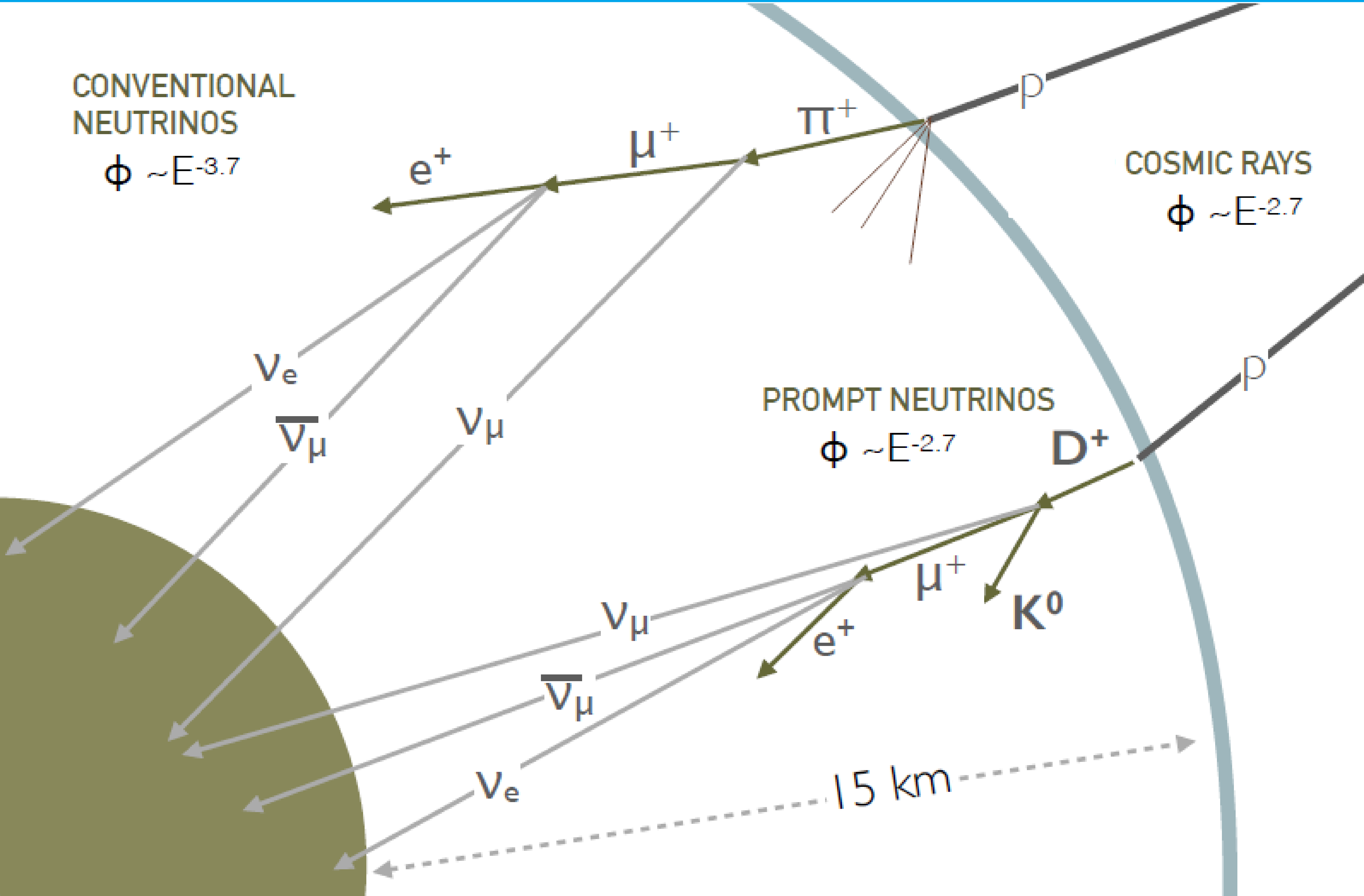


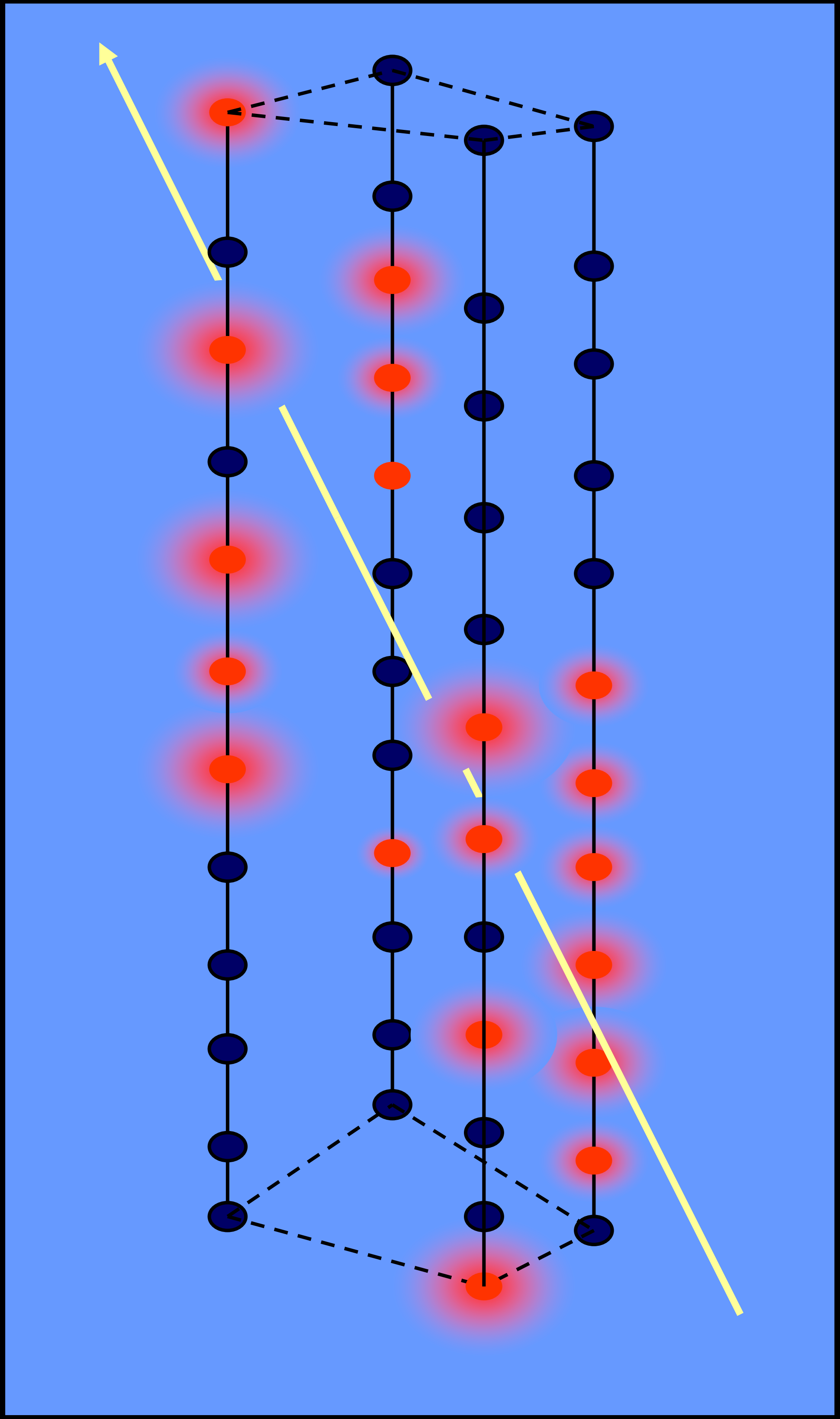
CHERENKOV PHOTONS
are quickly diffused by light scattering

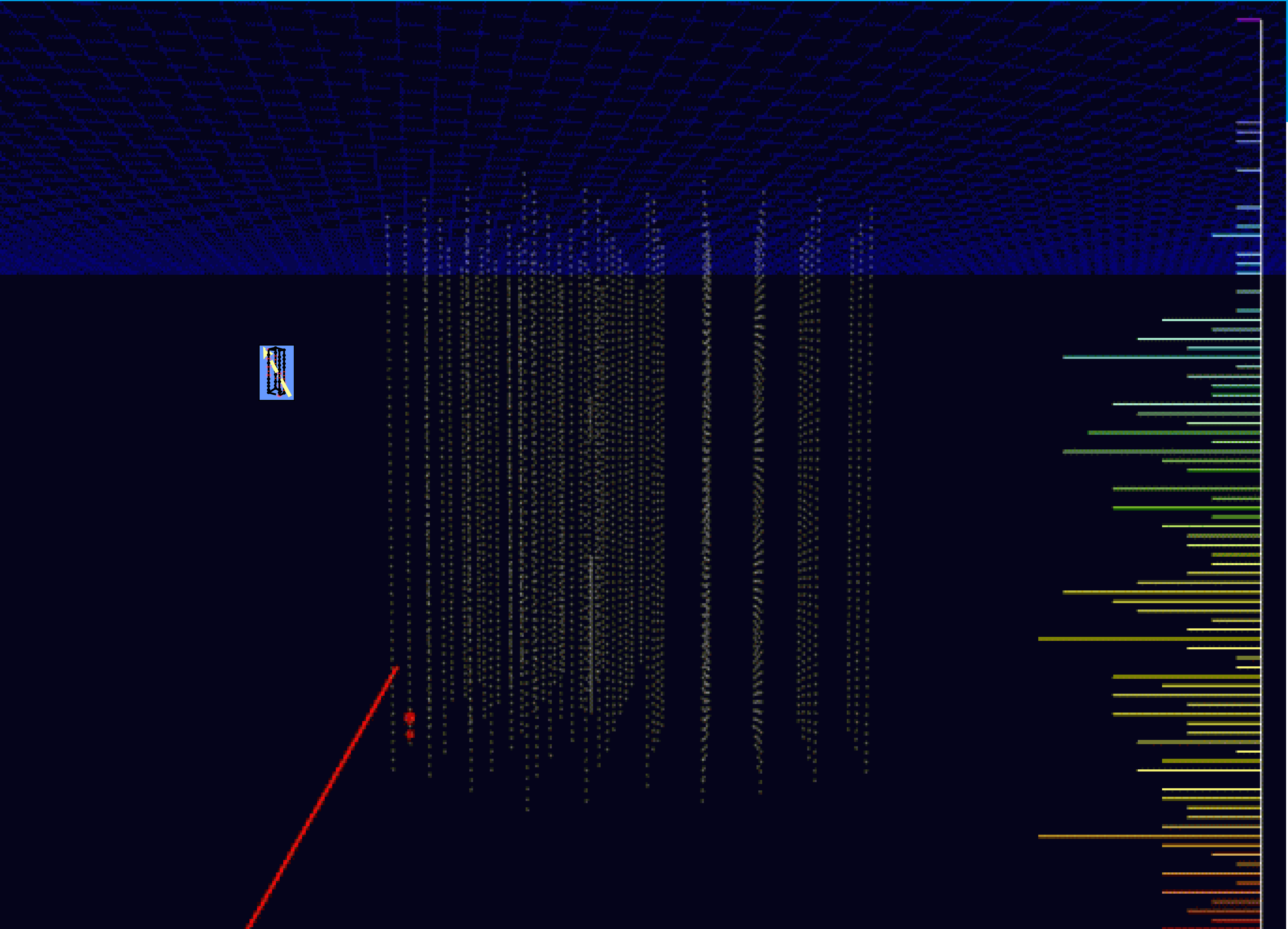


ATMOSPHERIC NEUTRINOS

Atmospheric neutrinos





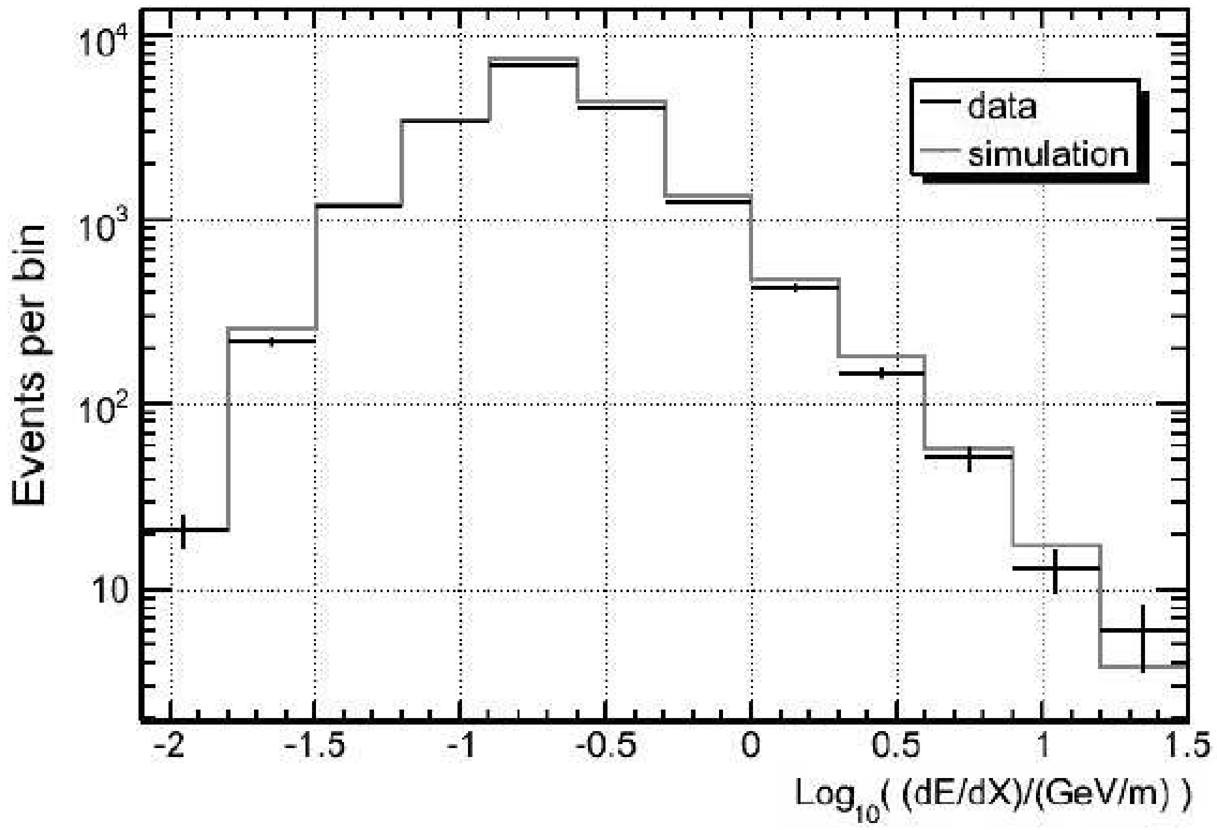


Run 113641   Event 33553254   [6000ns, 9952ns]

SPECTRUM AT

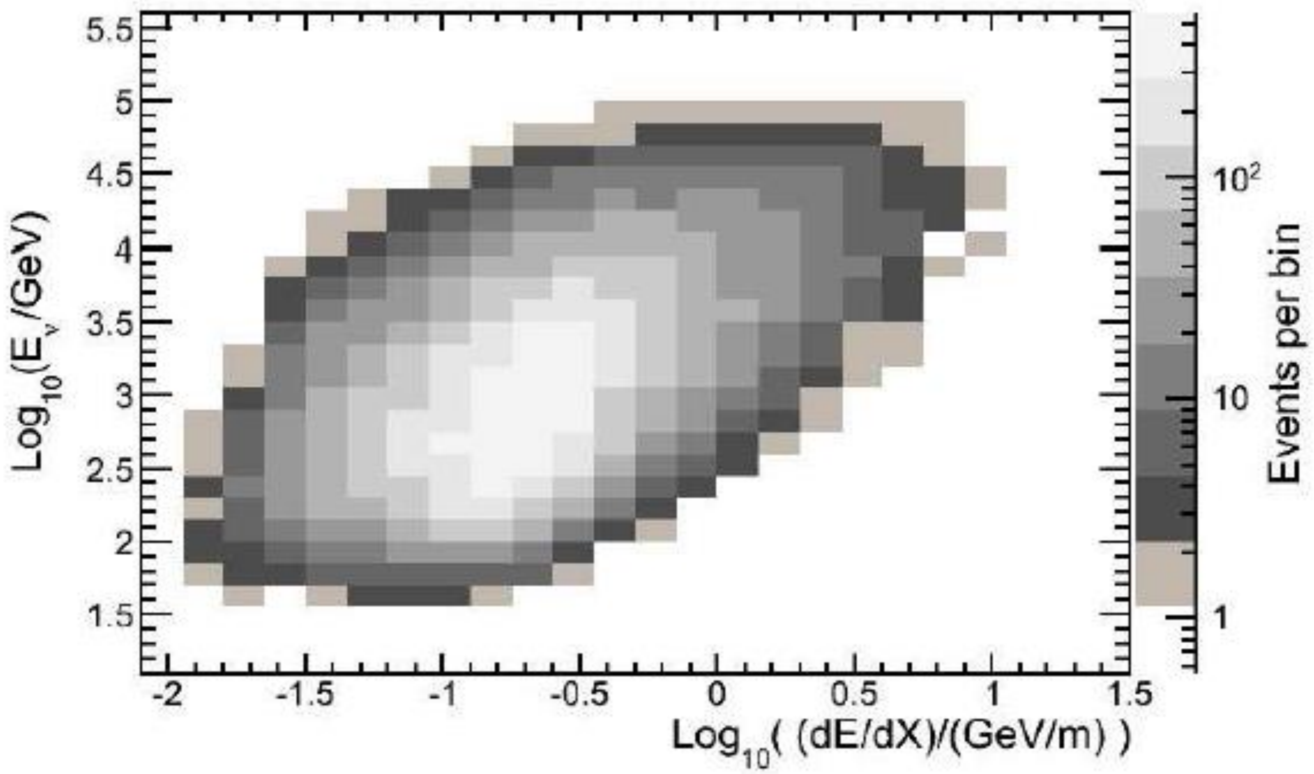
HIGH ENERGIES (> 100 GEV)

Atmospheric muon neutrinos in IceCube



- $dE_\mu/dx \rightarrow E_\mu \rightarrow E_\mu(0) \rightarrow E_\nu$

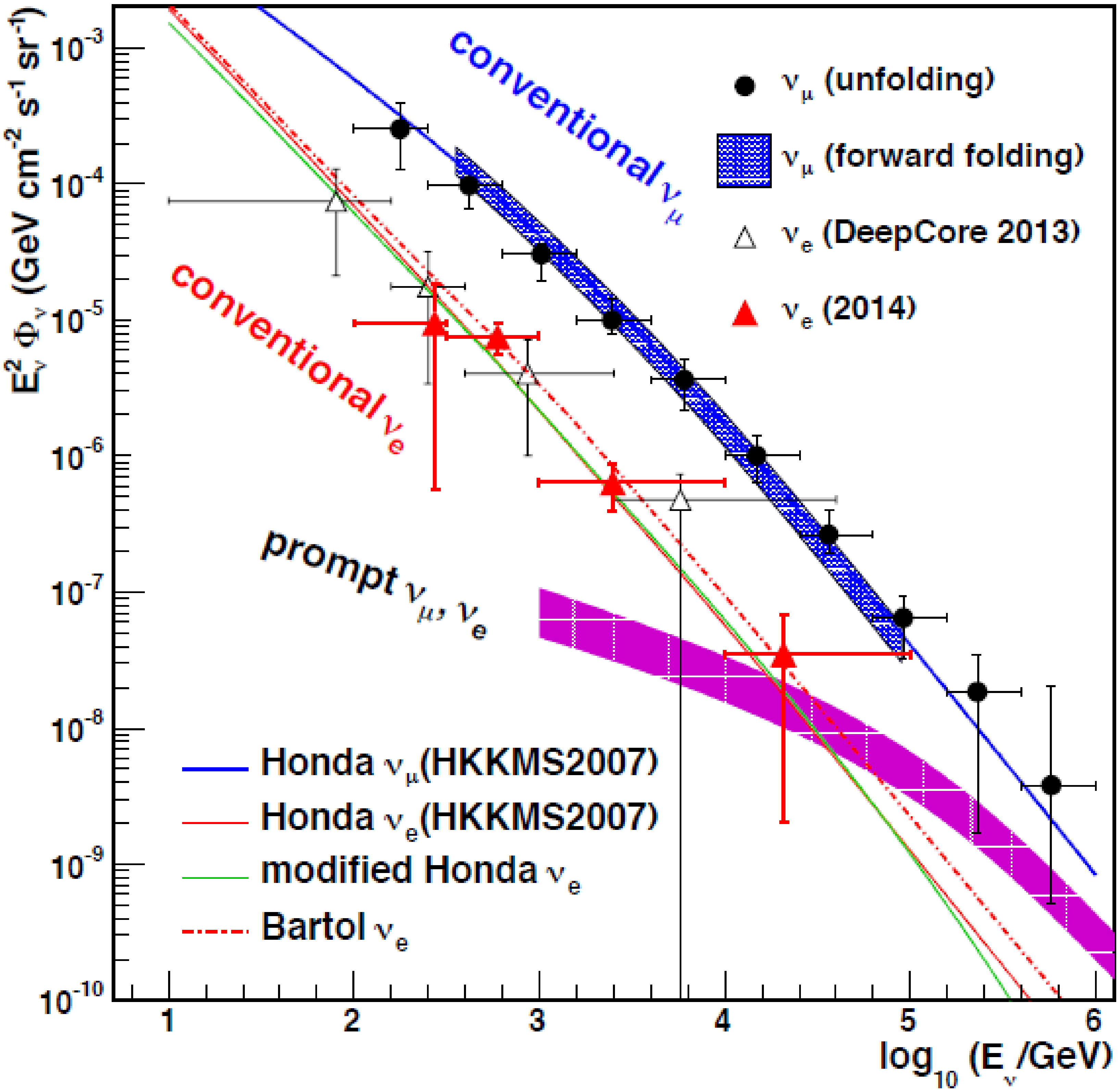
- **Measured dE/dx**

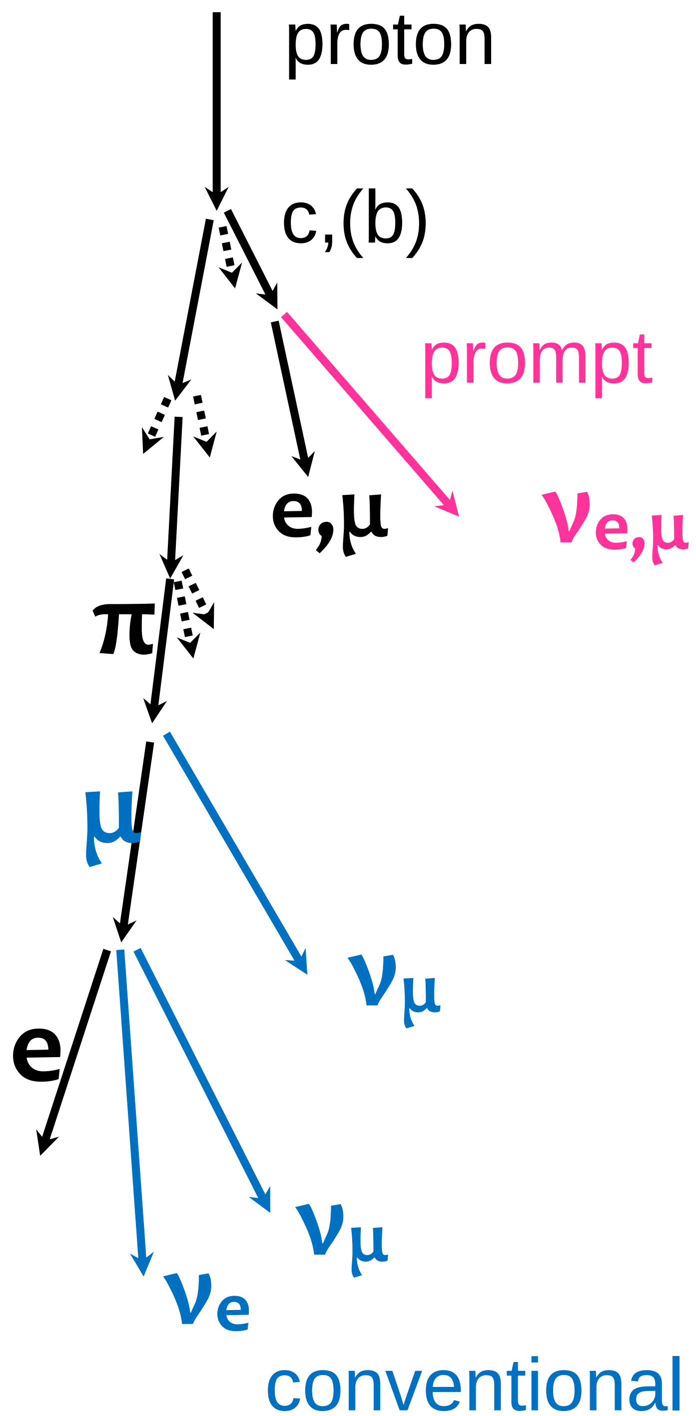


- **Monte Carlo:**
  Correlation between dE/dx and E_ν

Phys.Rev.D83:012001,2011 and arXiv:1010:3980

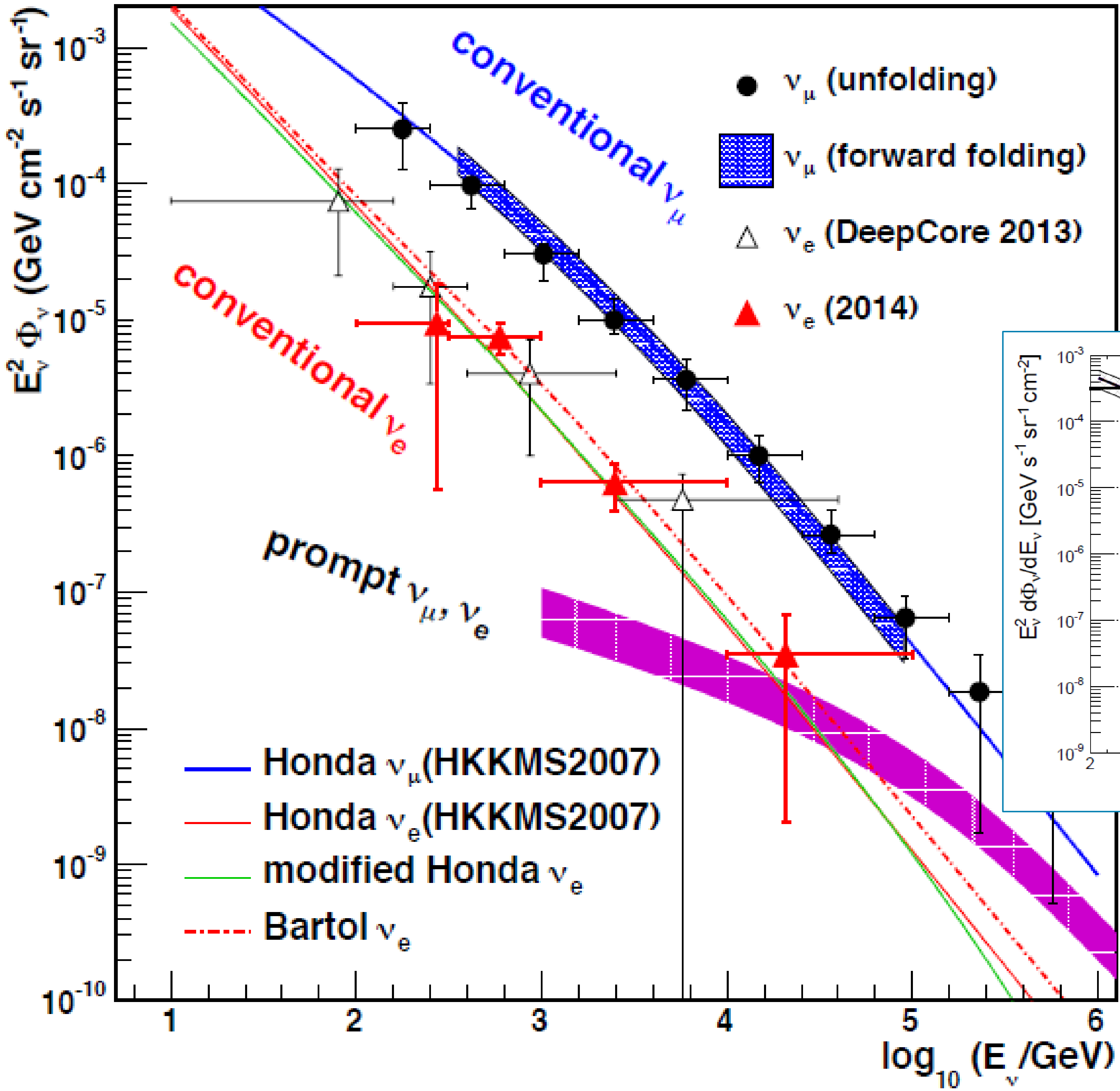
IceCube: Spectrum of atmospheric neutrinos



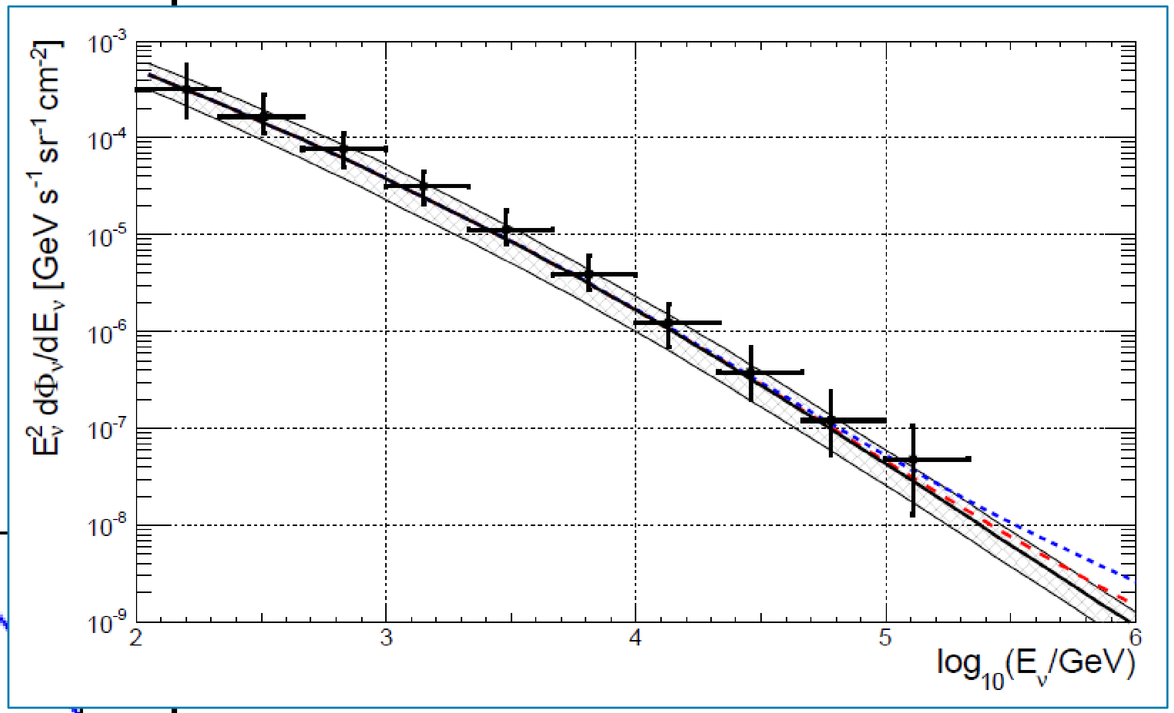


Phys.Rev. D91 (2015) 122004)

IceCube: Spectrum of atmospheric neutrinos



.. and ANTARES



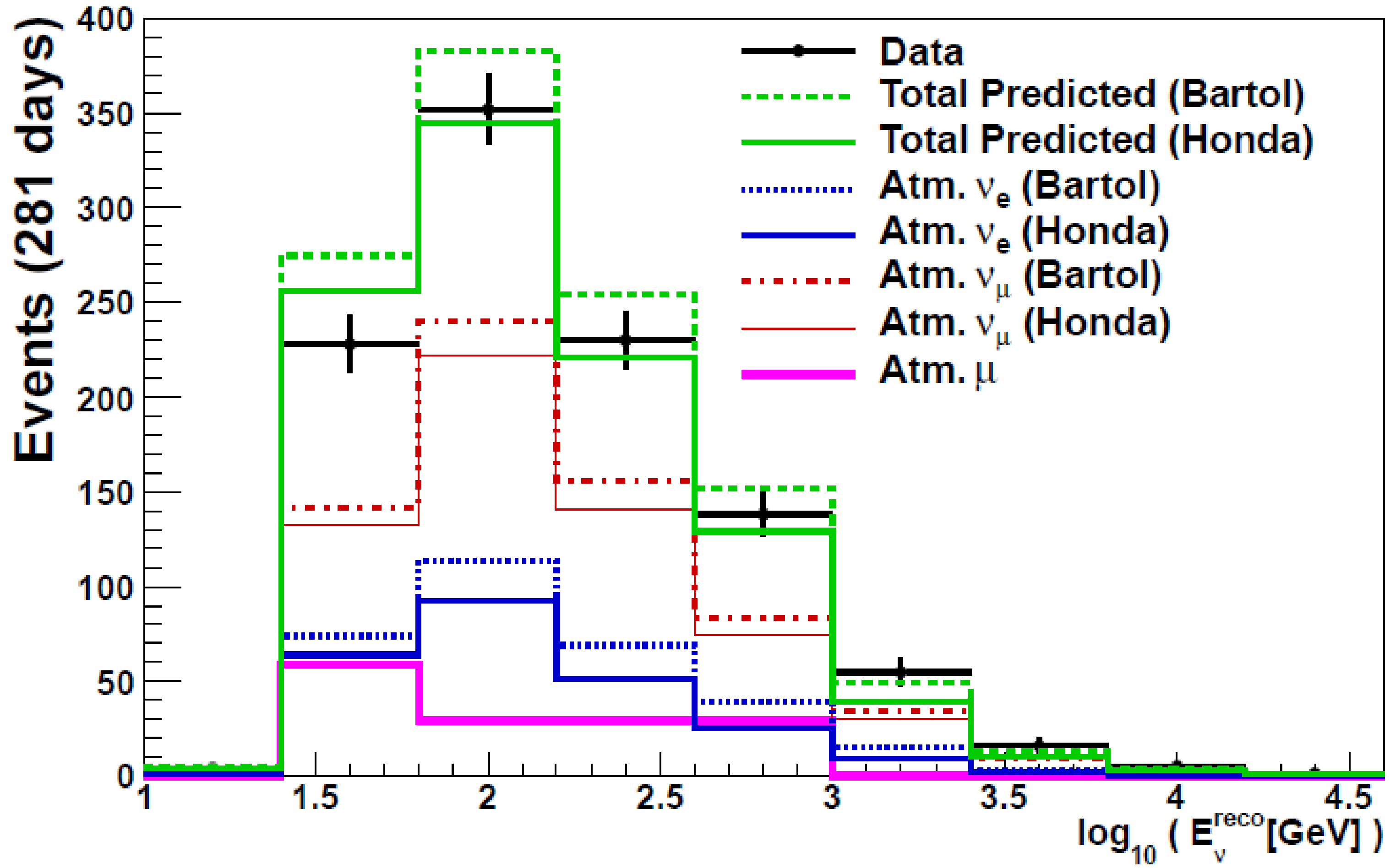
arXiv:1308.1599

Phys.Rev. D91 (2015) 122004)

Measurement of atmospheric ν_e

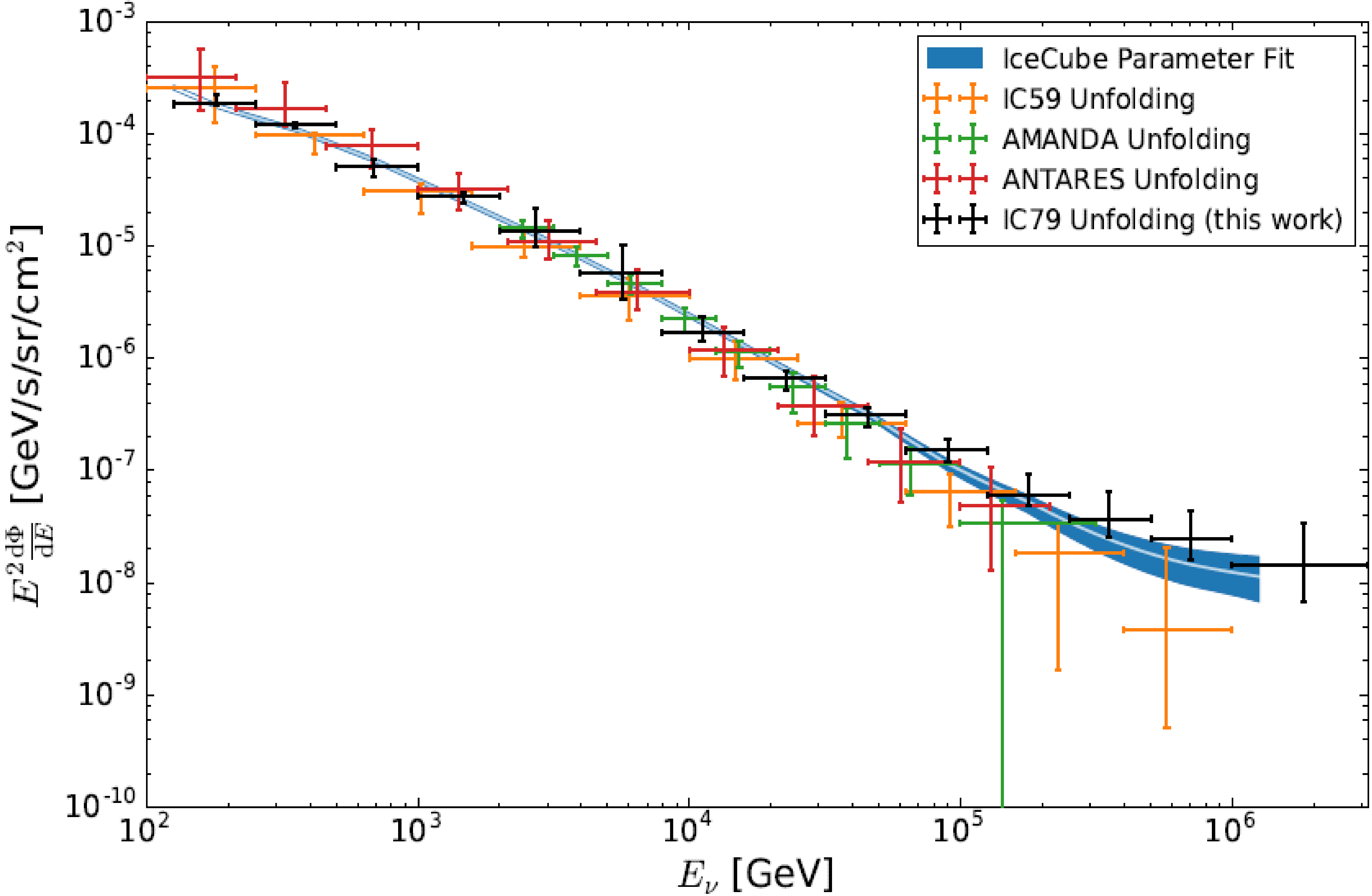
- **Signature: cascade events**
- **Subtract NC events and background**

Type	Signal			Background		MC	N^{obs}
	ν_eNC	ν_eCC	ν_μNC	ν_μCC	atm. μ	Sum	
Bartol	26	290	267	403	147	1134	-
Honda	19	227	245	368	147	1007	-
Average	23	259	256	385	147	1070	-
Data	-	-	-	-	-	-	1029

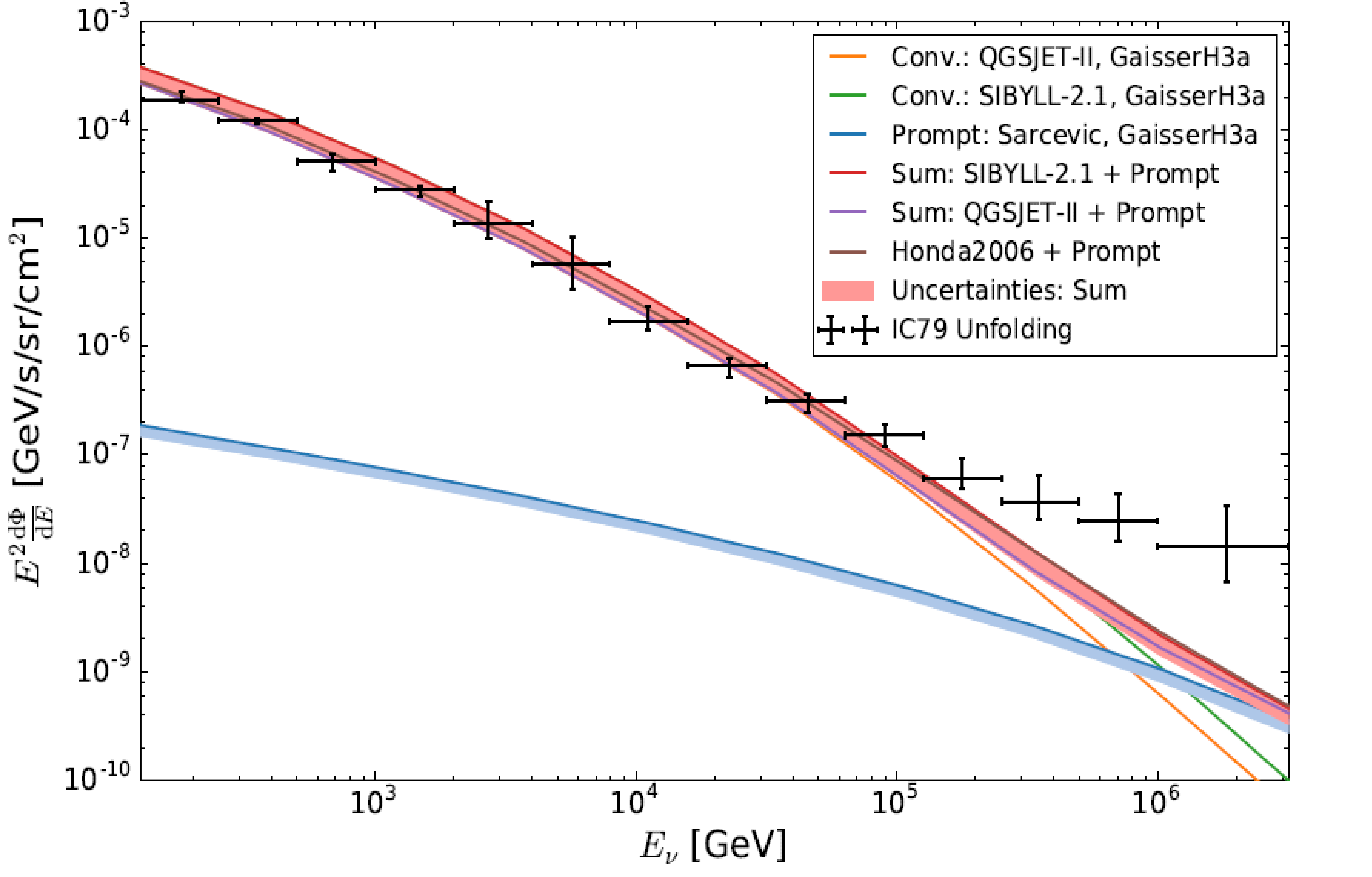


- **Phys. Rev. Lett. 110 (2013) 151105 and arXiv:1212.4760**

Impact of non-atmospheric (i.e. cosmic) neutrinos at > 100 TeV



Impact of non-atmospheric (i.e. cosmic) neutrinos at > 100 TeV

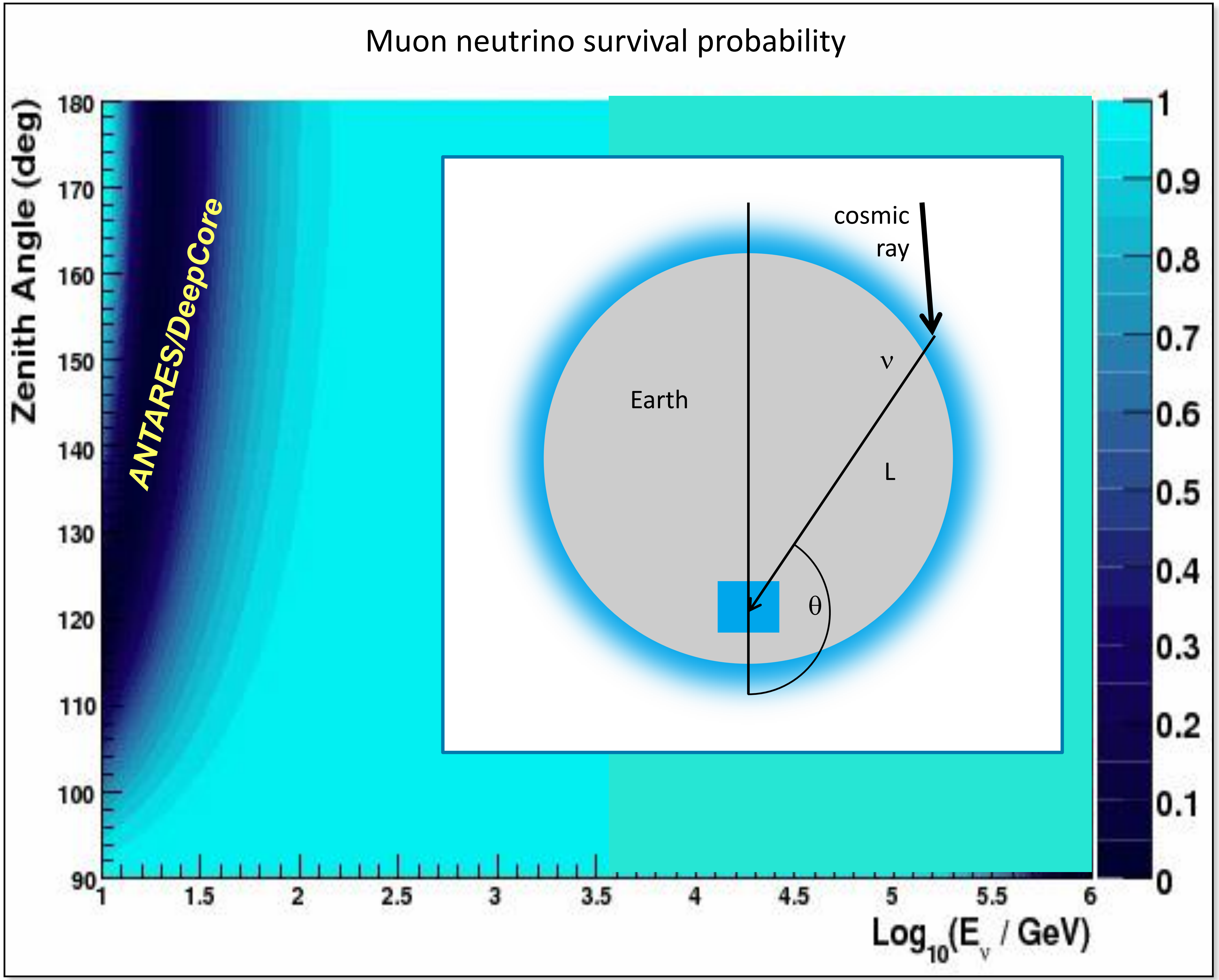


OSCILLATION PHYSICS

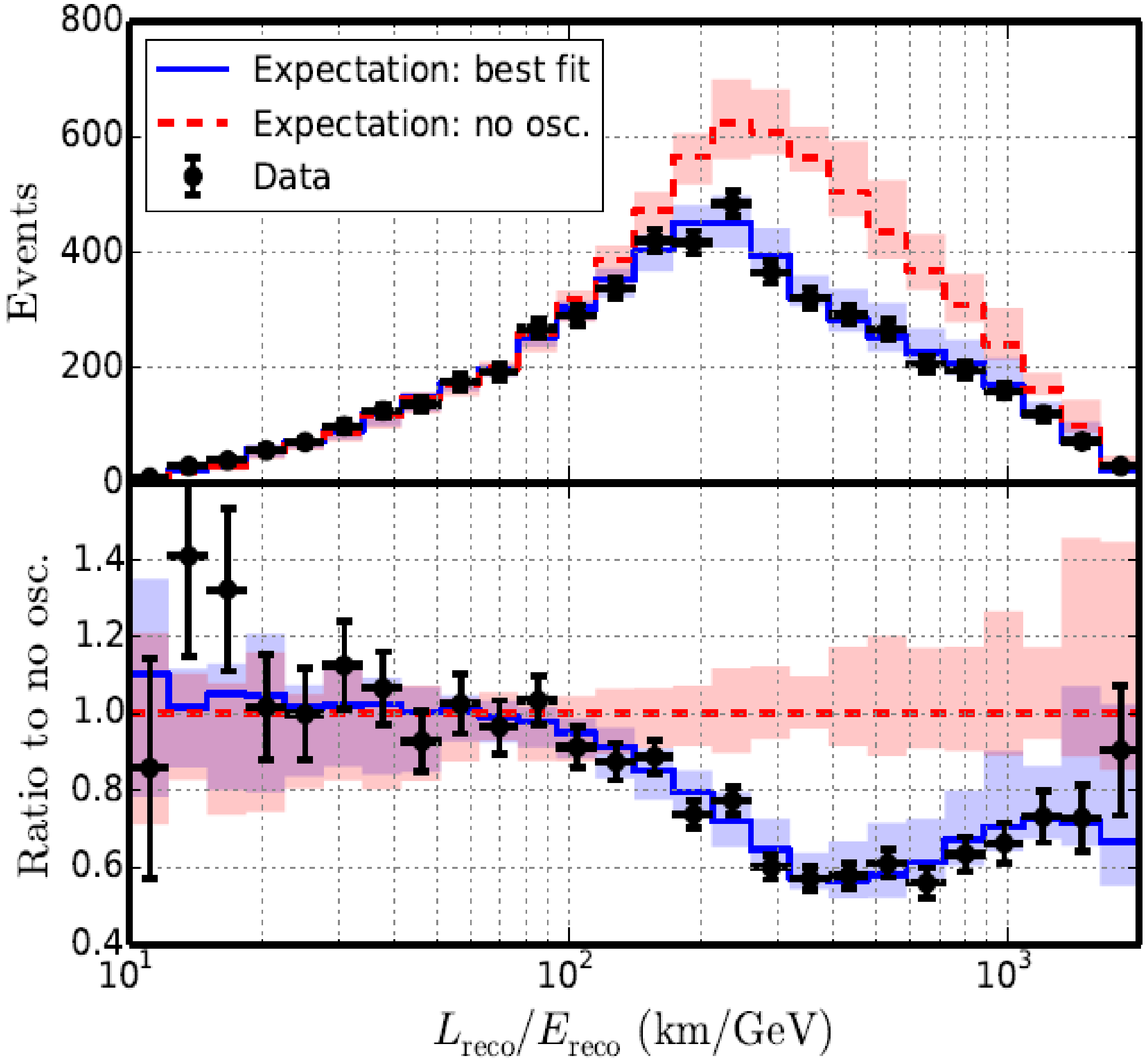
Oscillations of atmospheric neutrinos

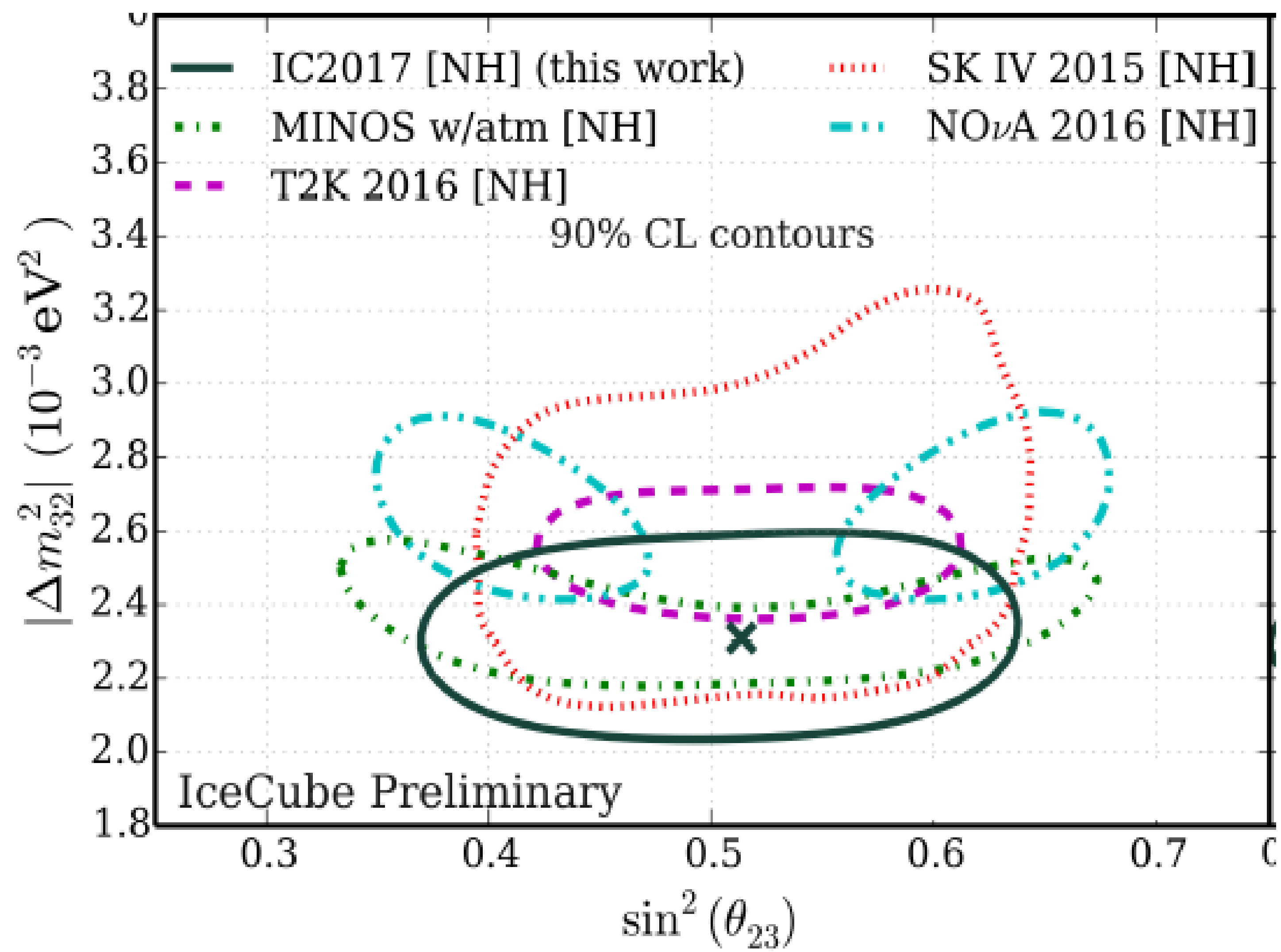
Vertically upward

Horizontal



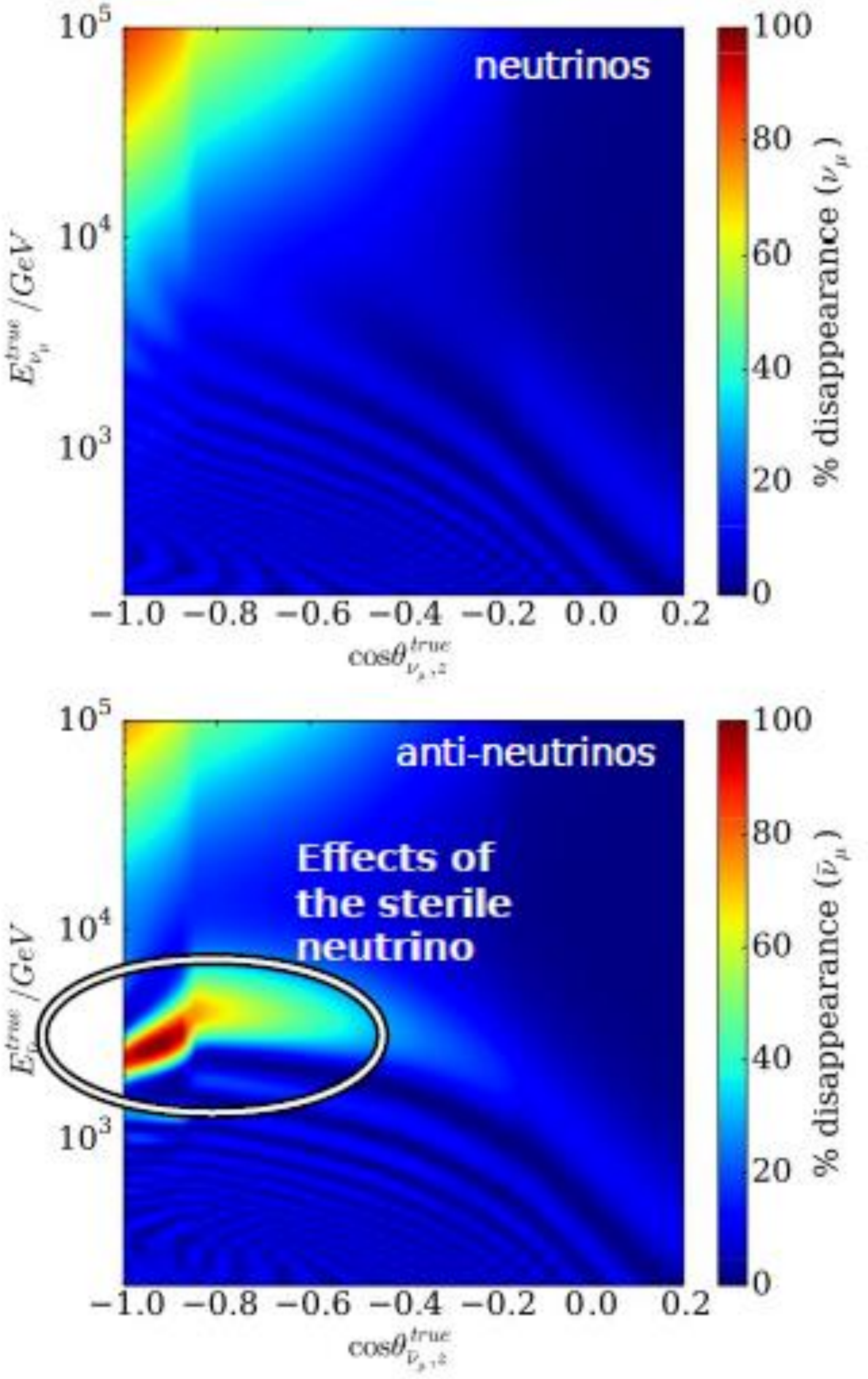
DeepCore: Oscillations for atmospheric neutrinos (E < 30-40 GeV)



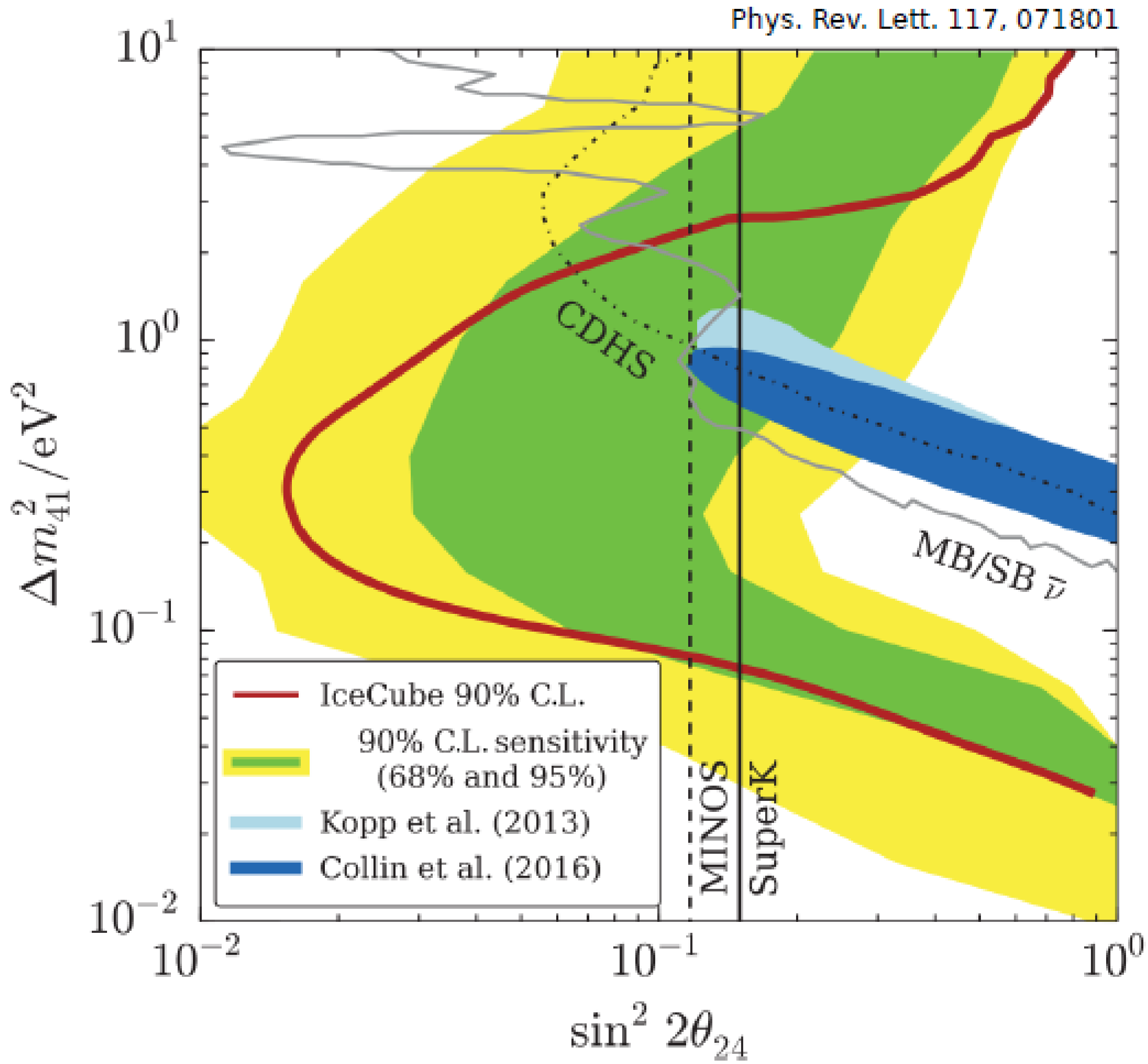


- Consistent and competitive with accelerator-based measurement
- Different energy range and baseline than for accelerator studies!

IceCube: search for sterile neutrinos (E > 1 TeV)



- **MSW resonance-like transition of atm. ν_μ to ν_s at high energies**
- **Sensitive to mixing angle θ_{24}**



END OF LECTURE 1