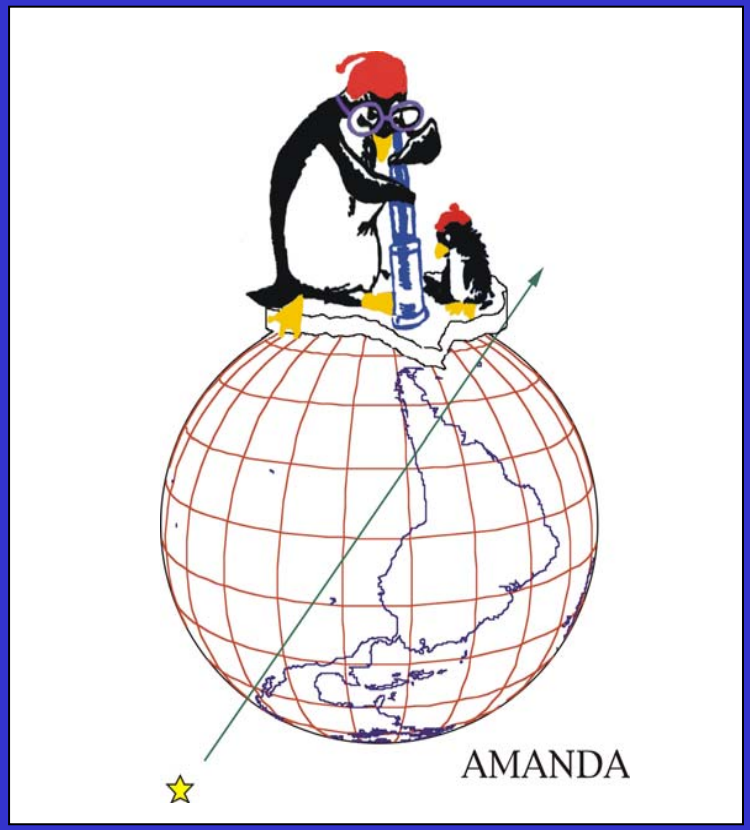
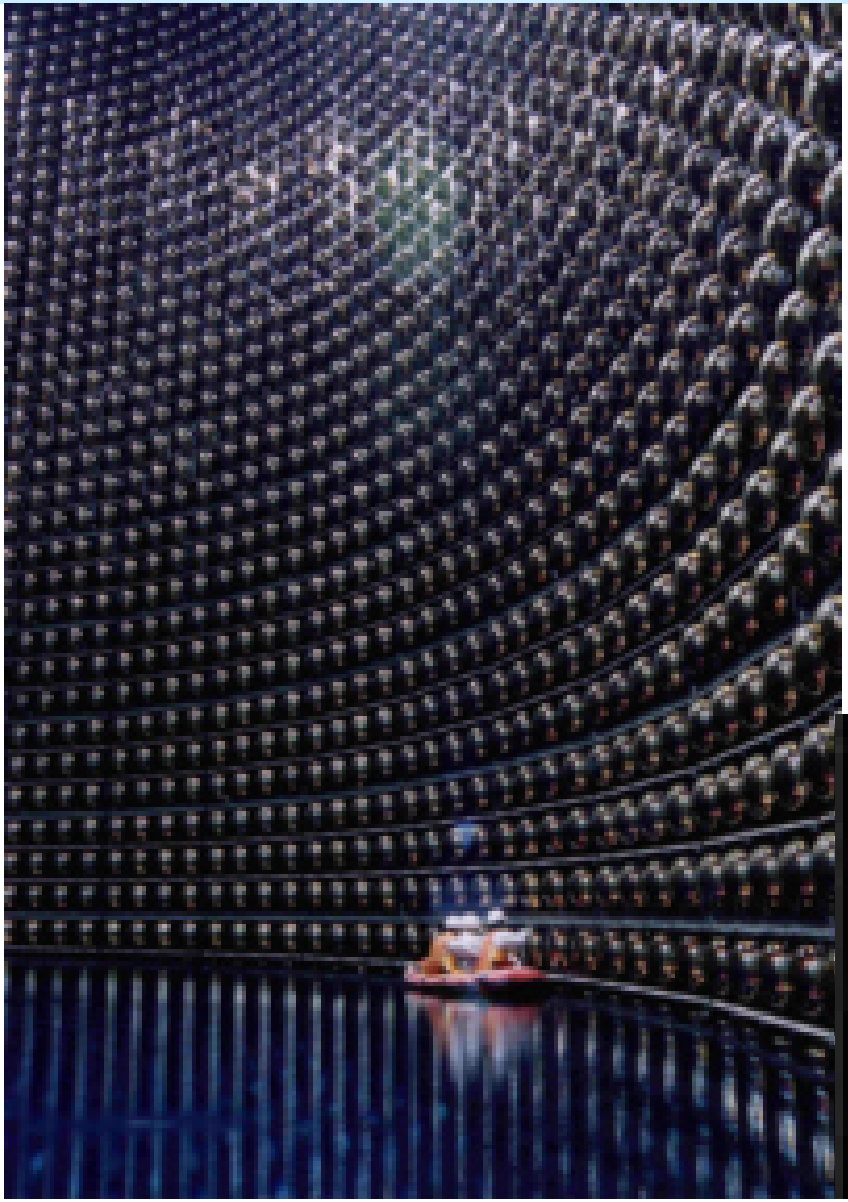
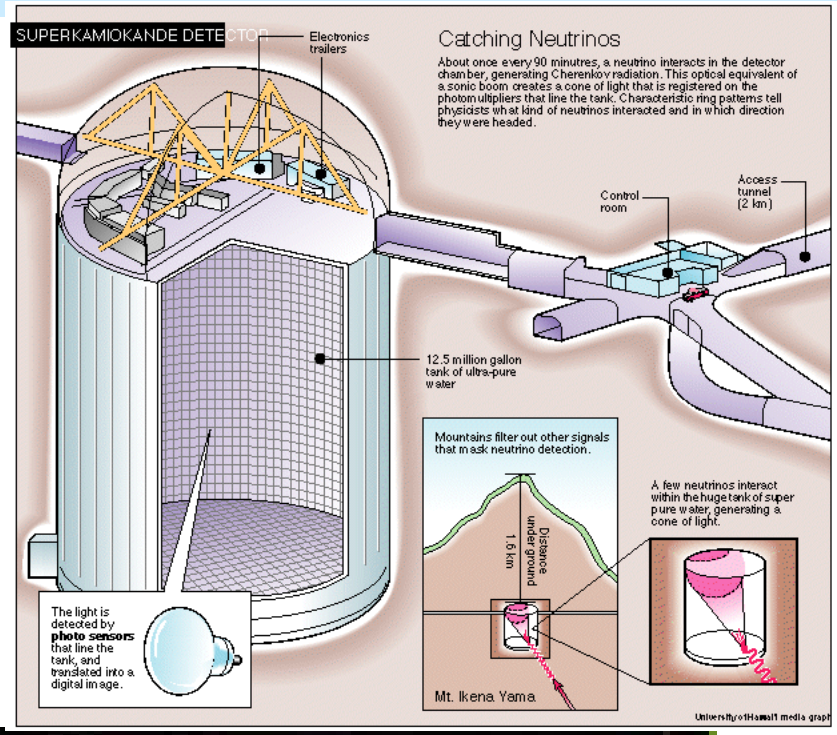
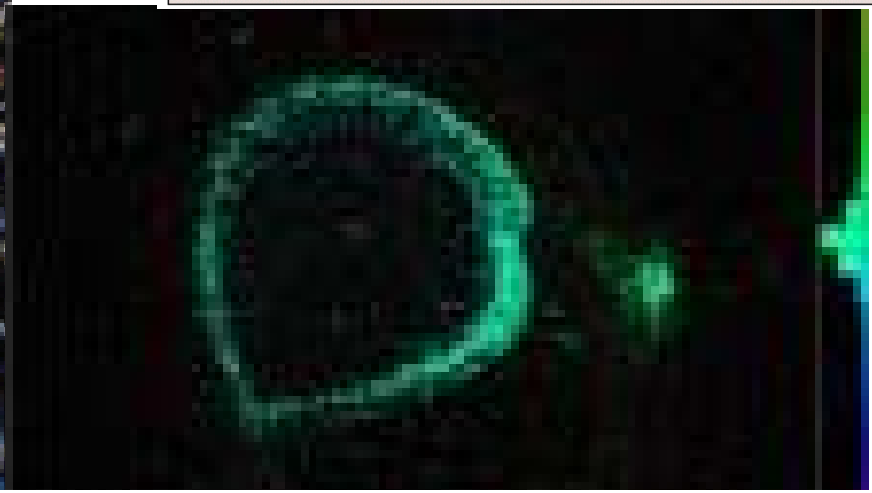
Neutrino Astrophysics



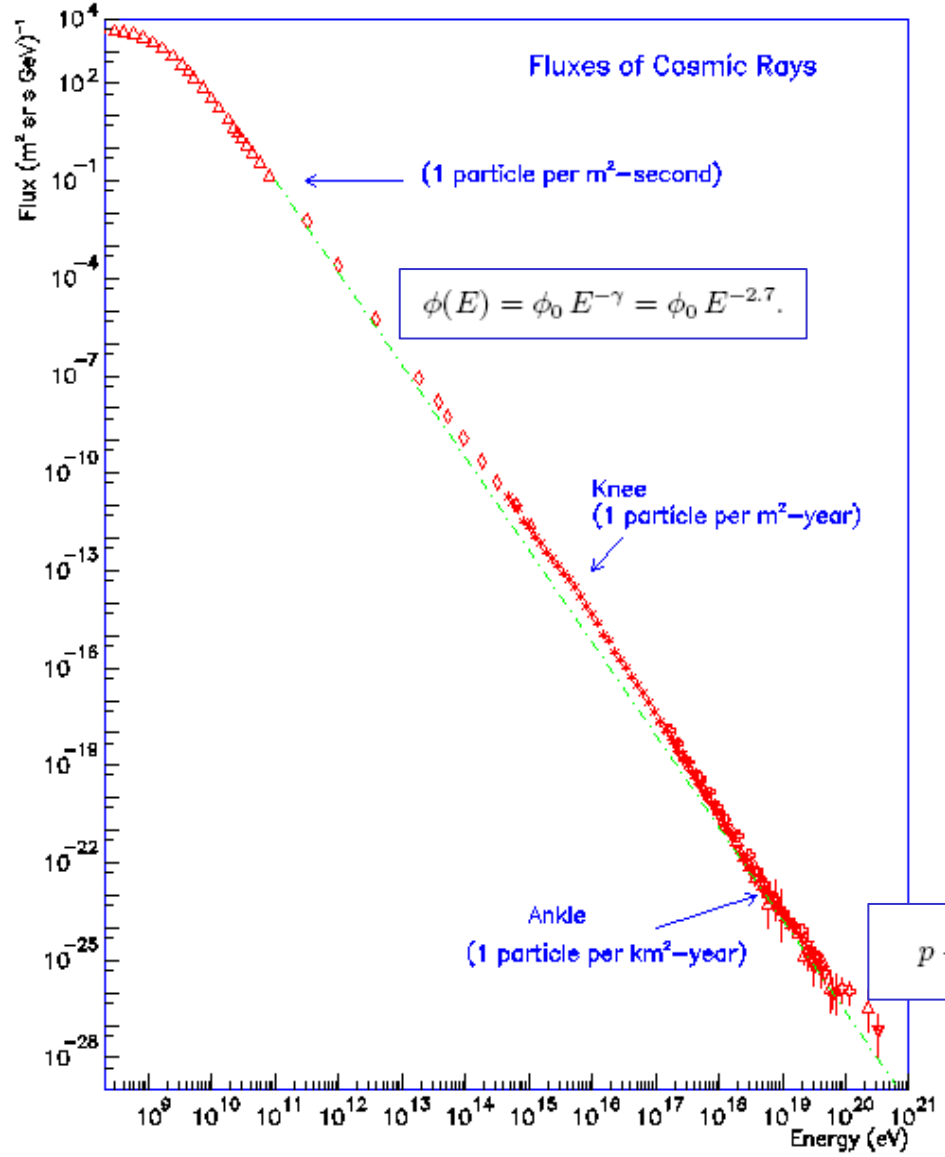
Ring Imaging in Water Tanks

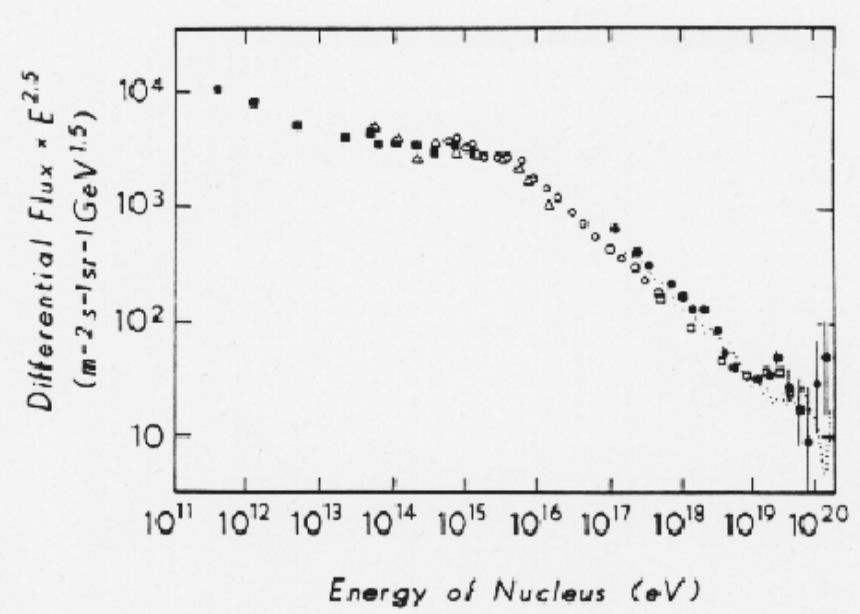






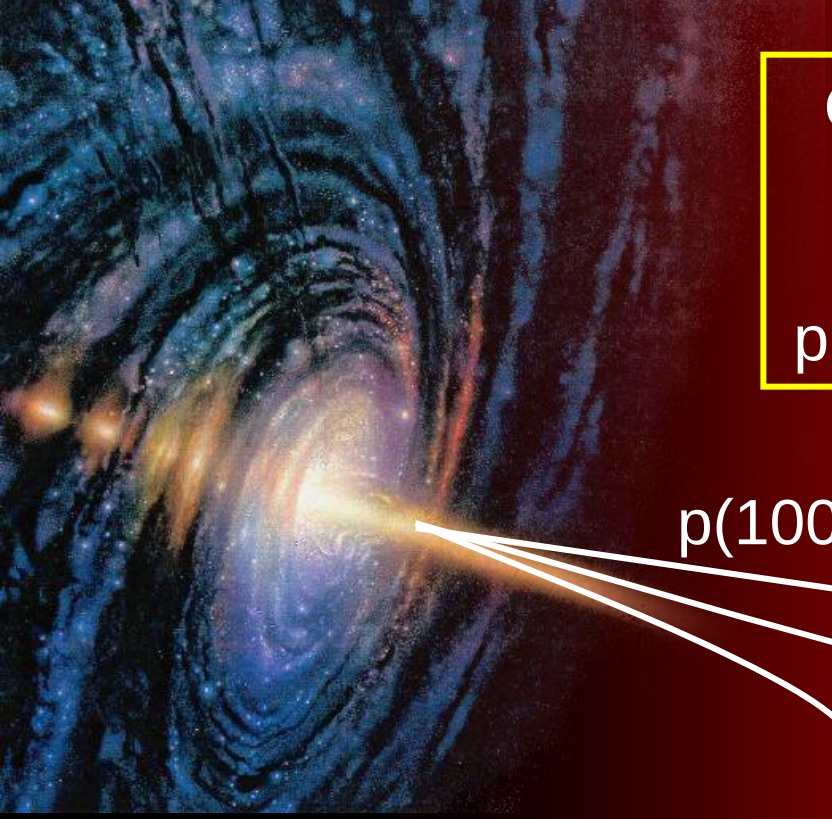
Energiespektrum





$$I_N(E) \approx 1.8\, E^{-\alpha} \frac{\text{nucleons}}{\text{cm}^2\ \text{s}\ \text{sr}\ \text{GeV}}$$

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



Greisen-Zatsepin-Kuzmin Cut-Off:
Energy loss in cosmic microwave background (CMB)
$p(100\ EeV) + \gamma(CMB) \rightarrow p + \pi,\ n + \pi$

p(100 EeV)

γ

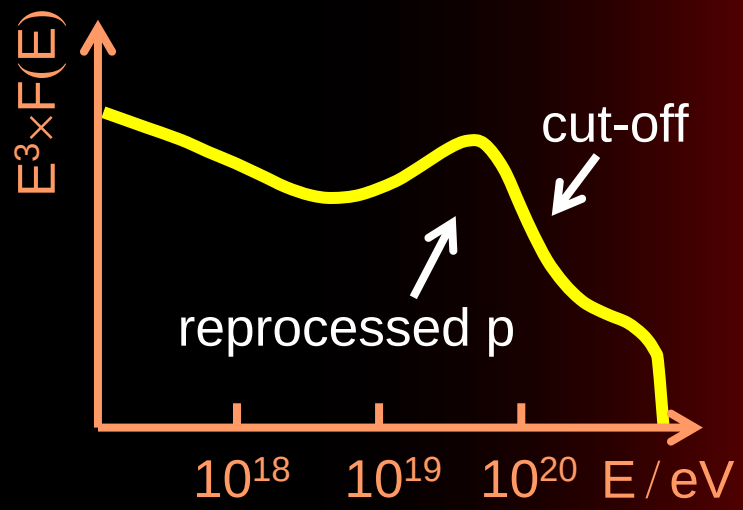
p

π

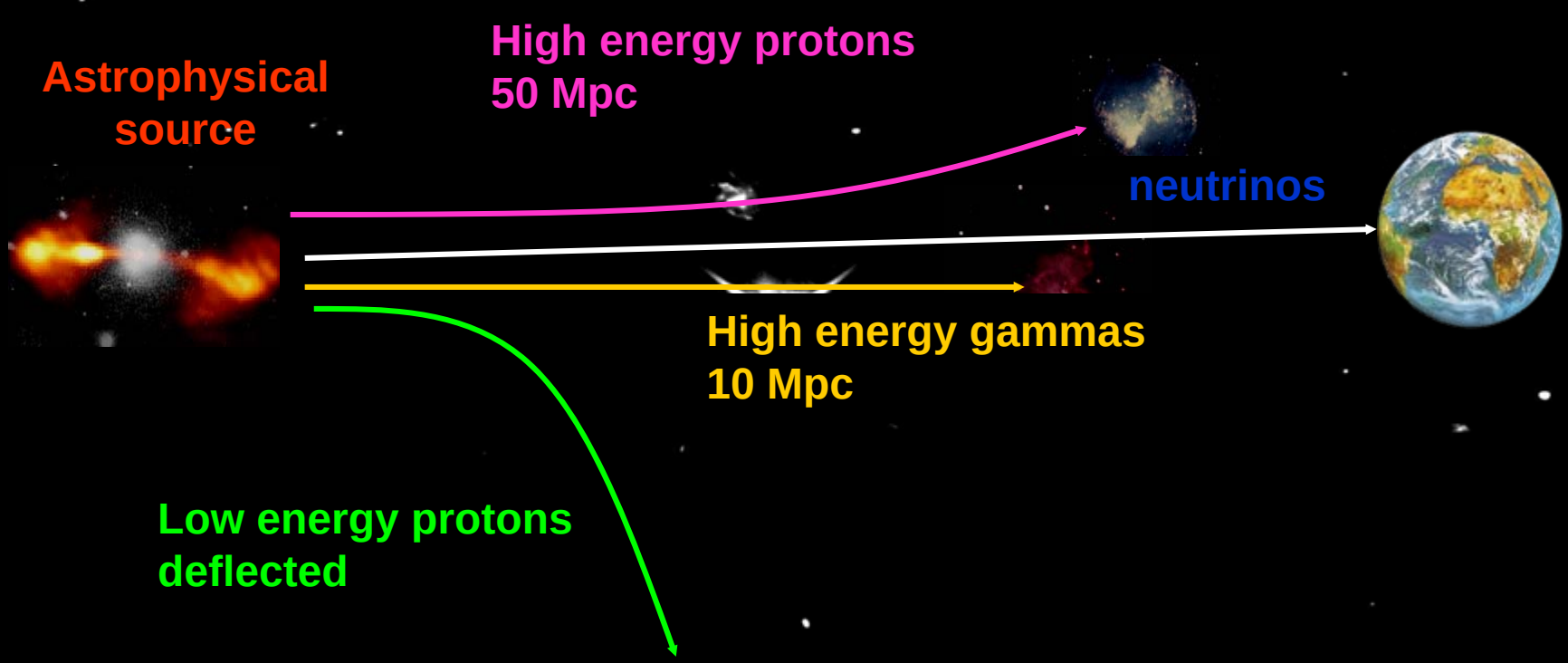
p beyond ankle

p below ankle

$\rightarrow$ isotropized in B-fields



Neutrino vs. HE gamma and proton astronomy



Neutrino-Production

by proton interaction with matter or with a photon field

$$p + p \rightarrow \pi + ...$$

$$\hookrightarrow \mu + \nu_\mu$$

$$\hookrightarrow e + \nu_e + \nu_\mu$$

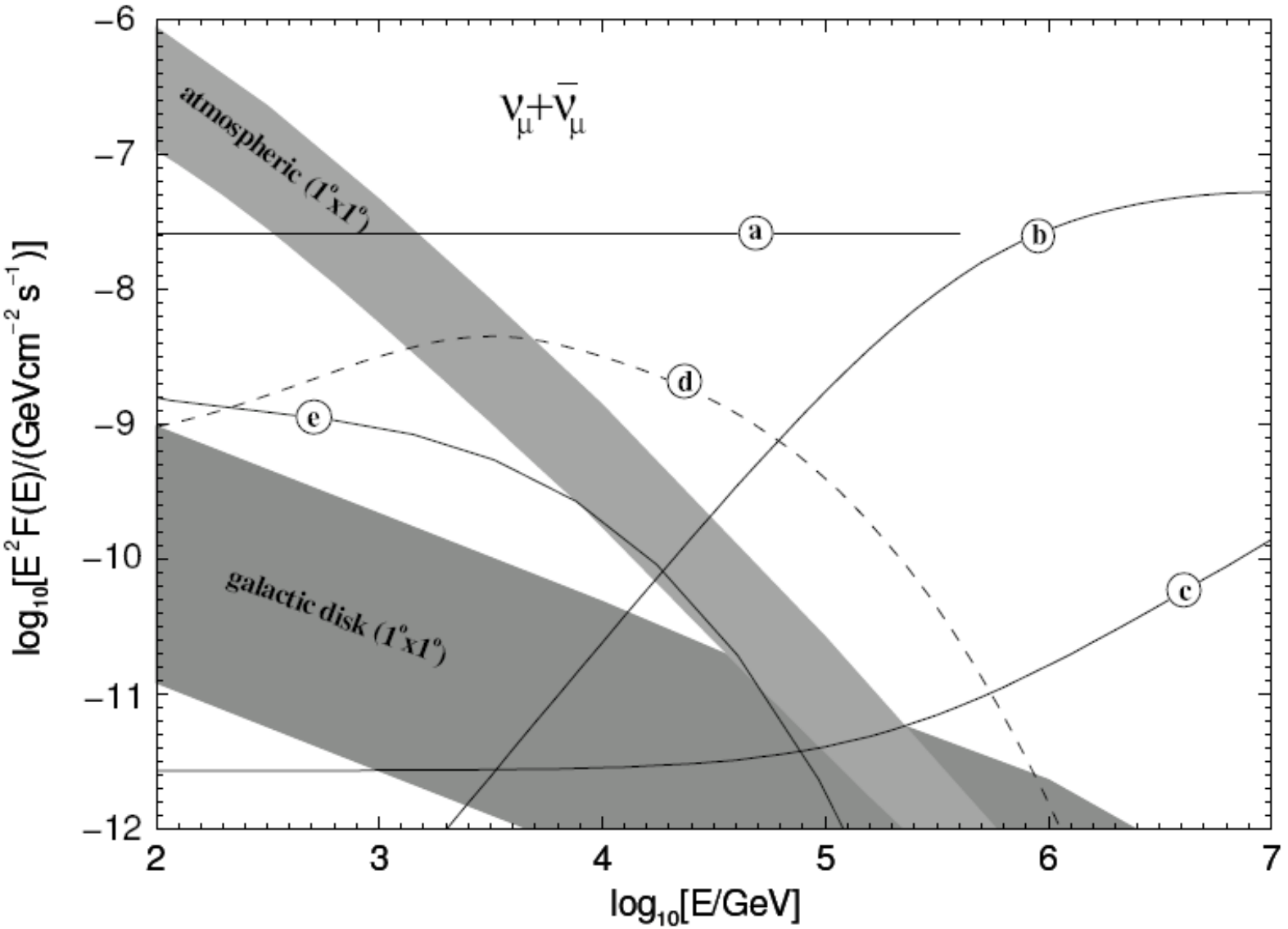
$$p + \gamma \rightarrow n + \pi^+ \qquad \rightarrow p + \pi^0$$

or

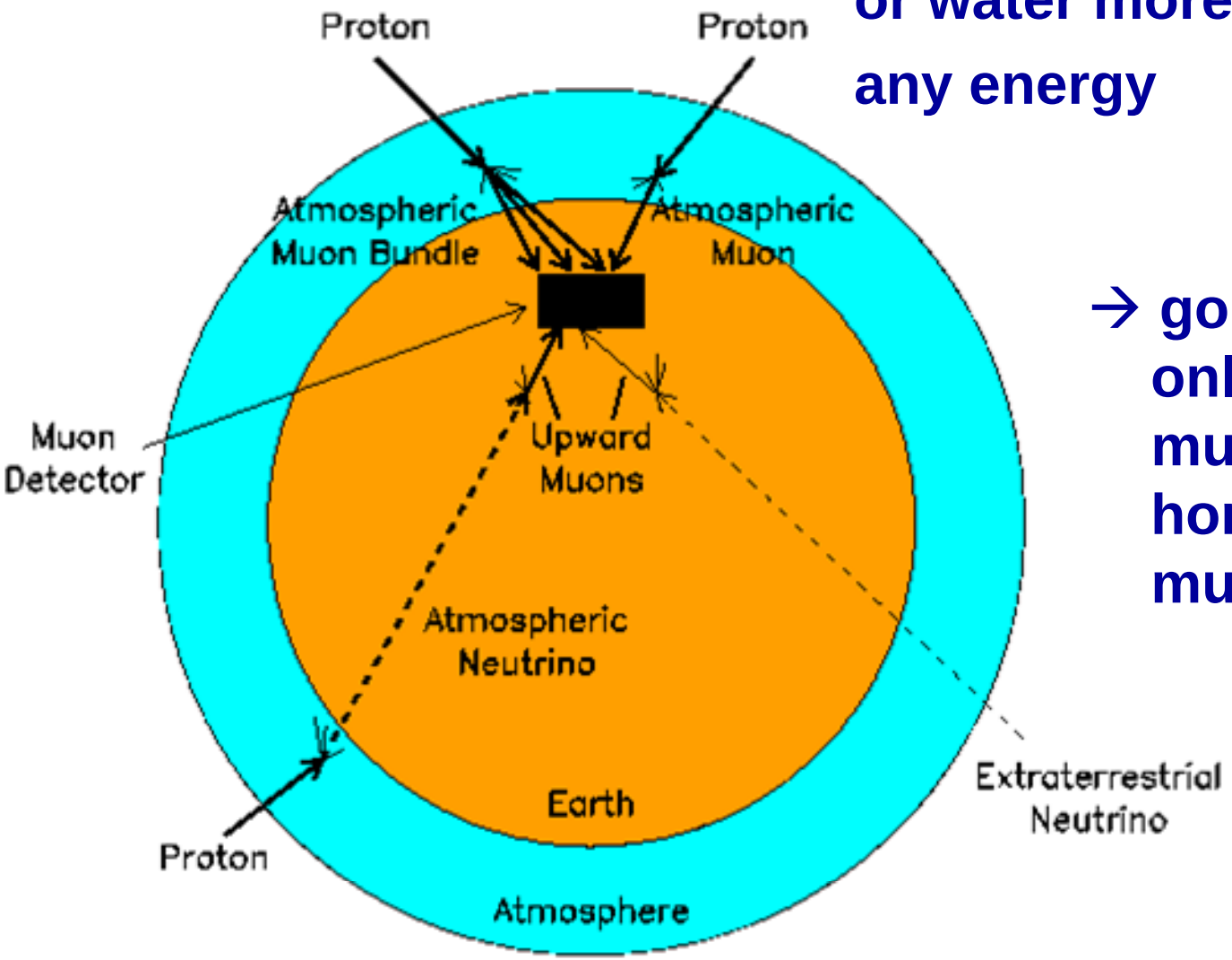
$$\hookrightarrow \mu + \nu \qquad \hookrightarrow \gamma + \gamma$$

i.e. $\nu_e : \nu_\mu : \nu_\tau \sim 1:2:0$

Vorhersagen für ν-Spektren



Muons cannot travel in rock or water more than ≈ 50 km at any energy



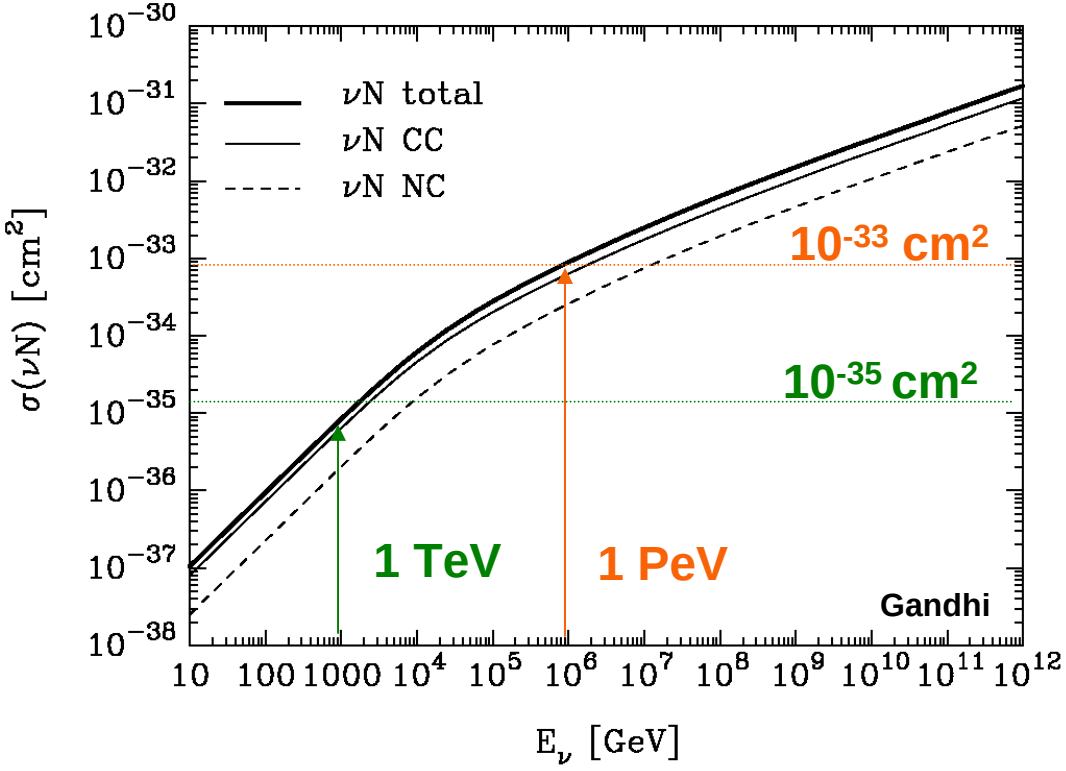
→ **go deep, look only to upward muons or horizontal muons.**

νN-Wirkungsquerschnitte

Neutrinos are detected indirectly, following an interaction on a target nucleus N:

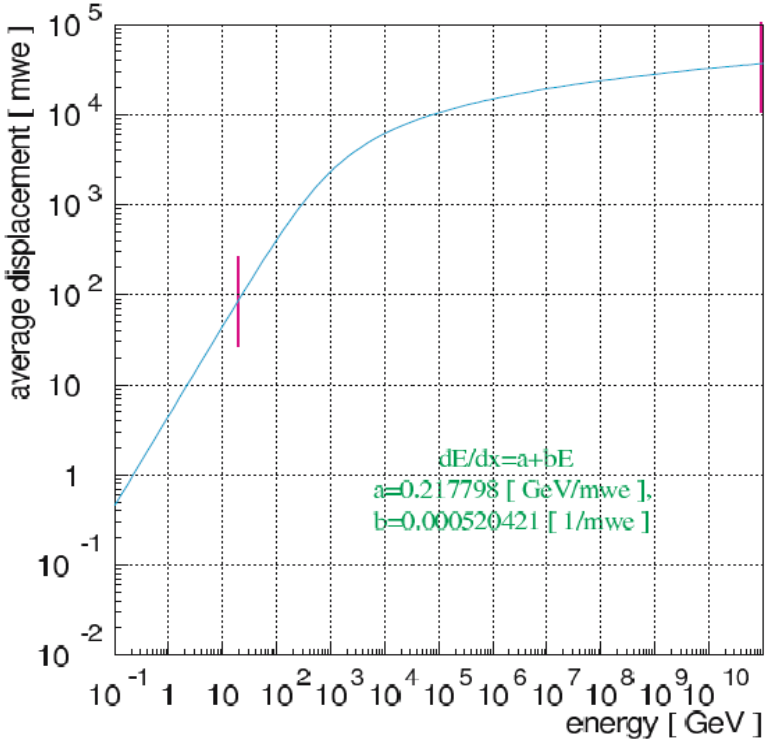
$$\nu_\ell + N \rightarrow \ell^- + X$$

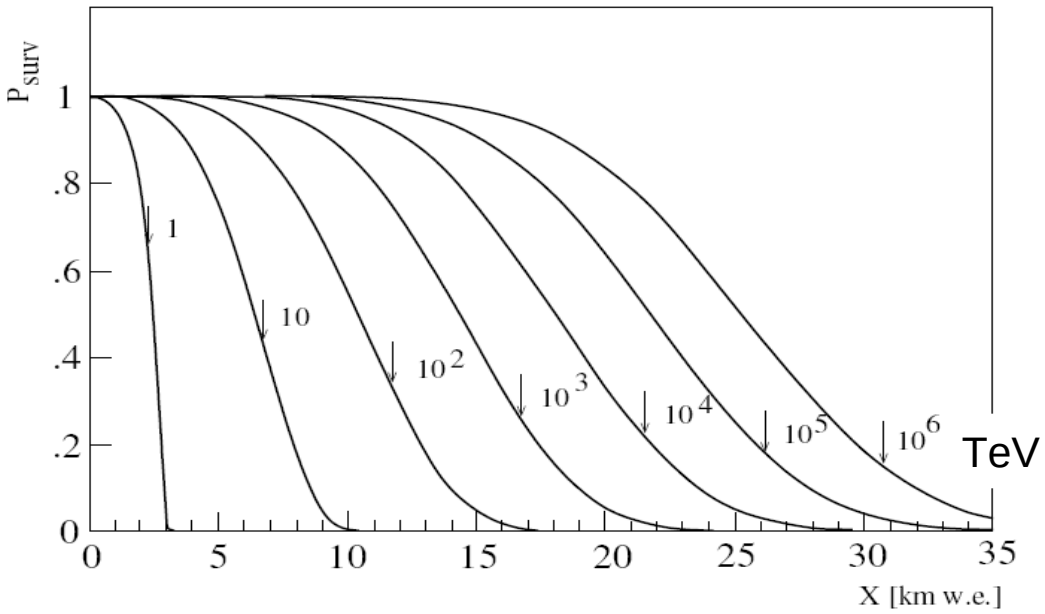
$$\sigma_{\nu N} \begin{cases} \propto E_\nu & E_\nu \leq 5\,\text{TeV} \\ \propto E_\nu^{0.4} & E_\nu > 5\,\text{TeV} \end{cases}$$



E_ν [GeV]	10^3	10^6	10^9
$\sigma_{\rm tot}(\nu N)$ [cm^2]	$8.4 \cdot 10^{-36}$	$8.9 \cdot 10^{-34}$	$1.5 \cdot 10^{-32}$
$\rho\Lambda$ [km w.e.]	$2.0 \cdot 10^6$	$1.9 \cdot 10^4$	$1.1 \cdot 10^3$

Myon-Reichweite





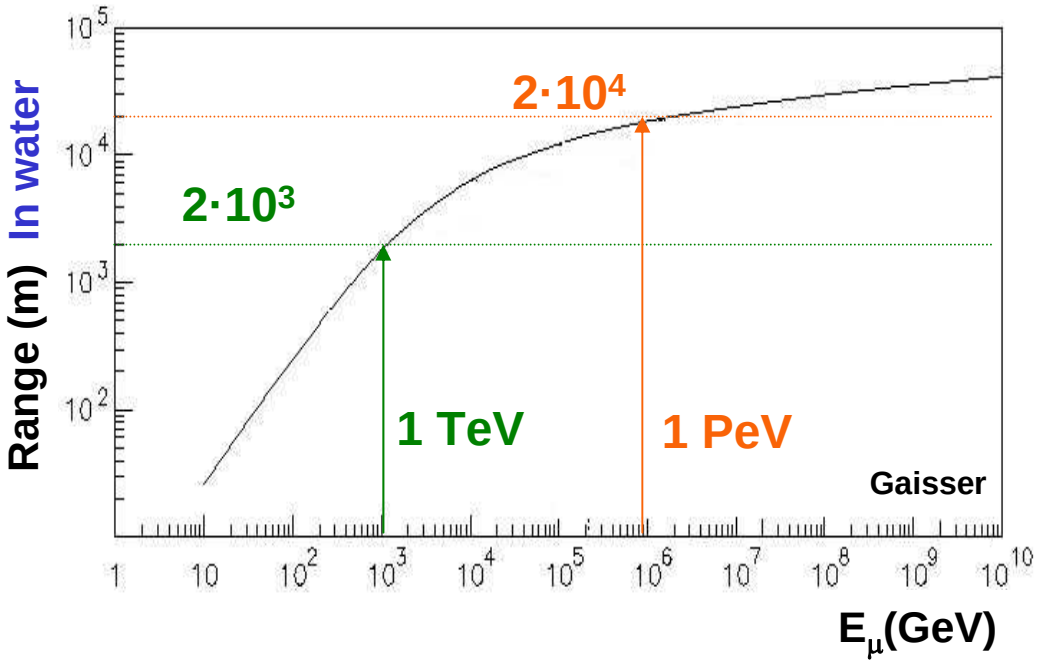
Muon Range

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

$$a = 0.2\left[\frac{GeV cm^2}{g}\right]$$

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

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

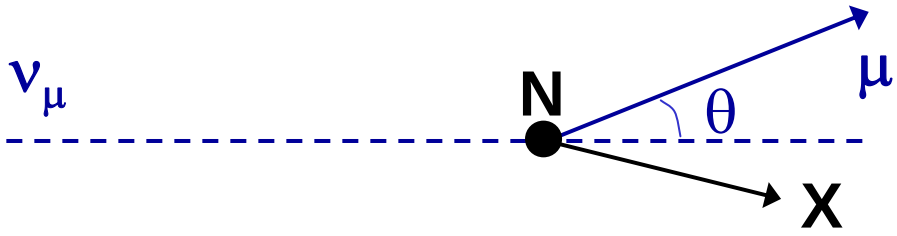


Muons have long tracks in water $R_\mu\left(E_\mu = 300GeV\right) \approx 1\ km$

Due to the long muon range the target volume is much bigger than the detector instrumented volume

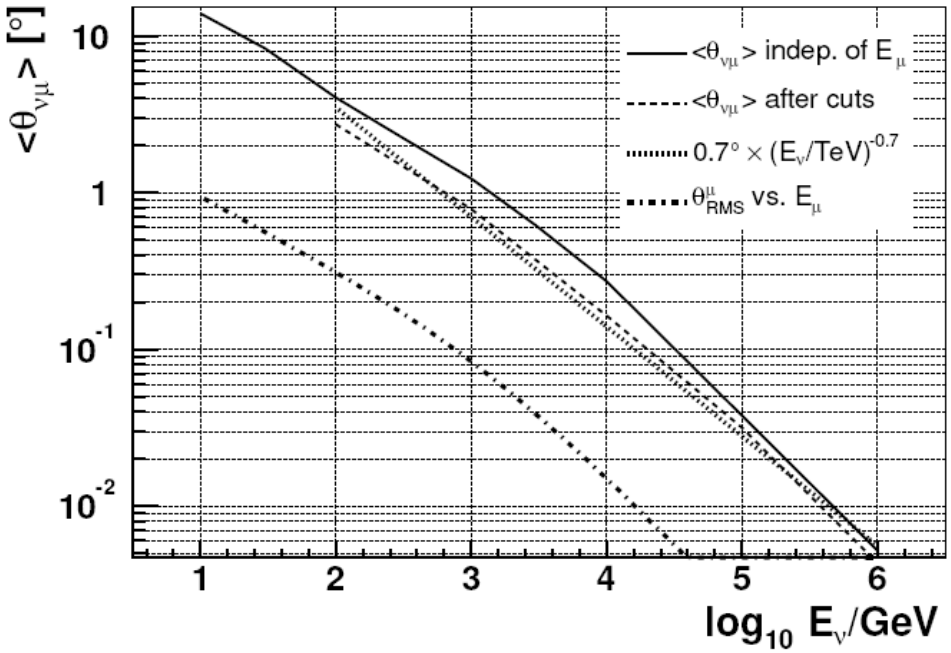
νμ-Winkel

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

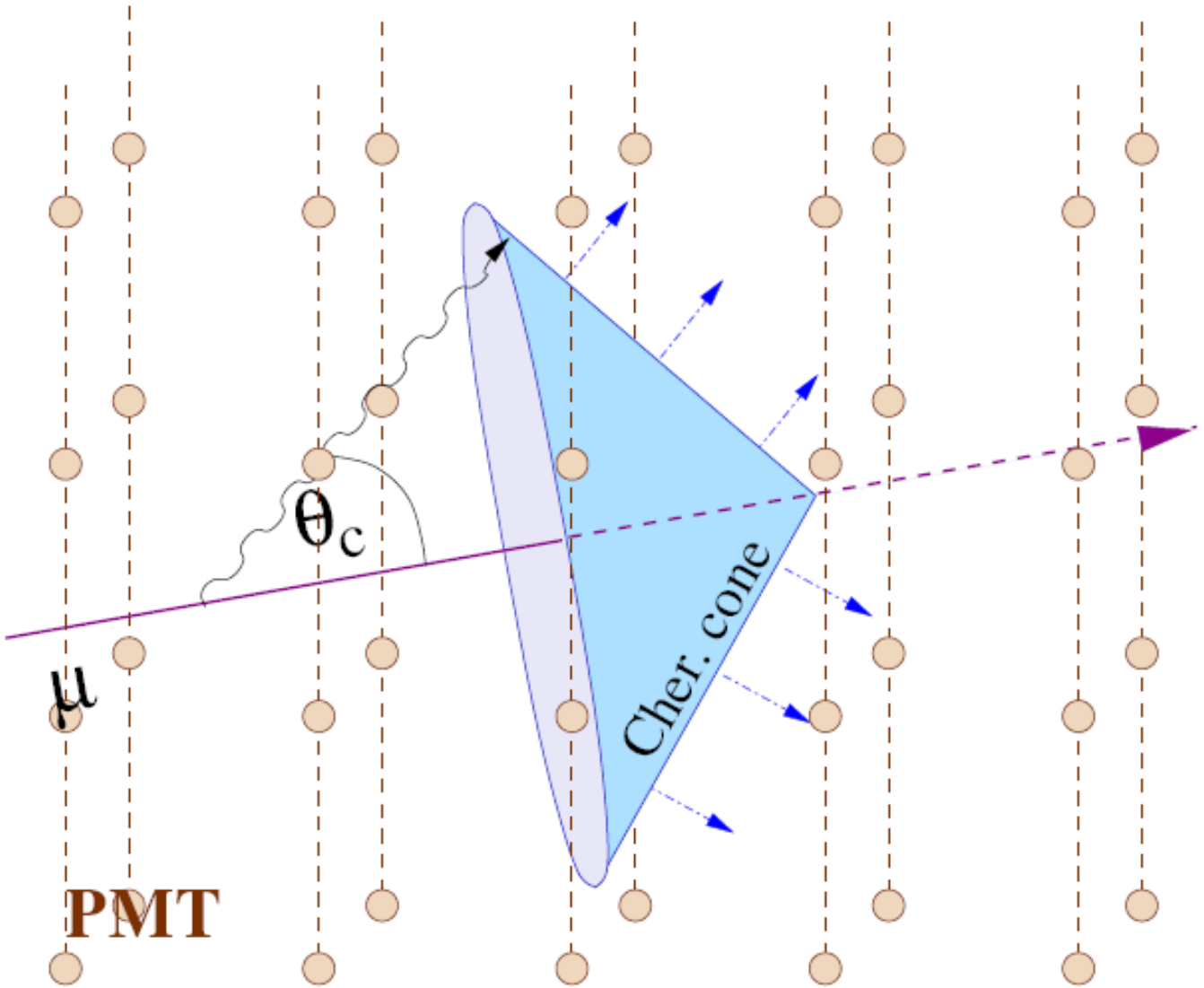


$$\langle\theta\rangle \approx \frac{1.5°}{\sqrt{E_\nu\,[\mathrm{TeV}]}}$$

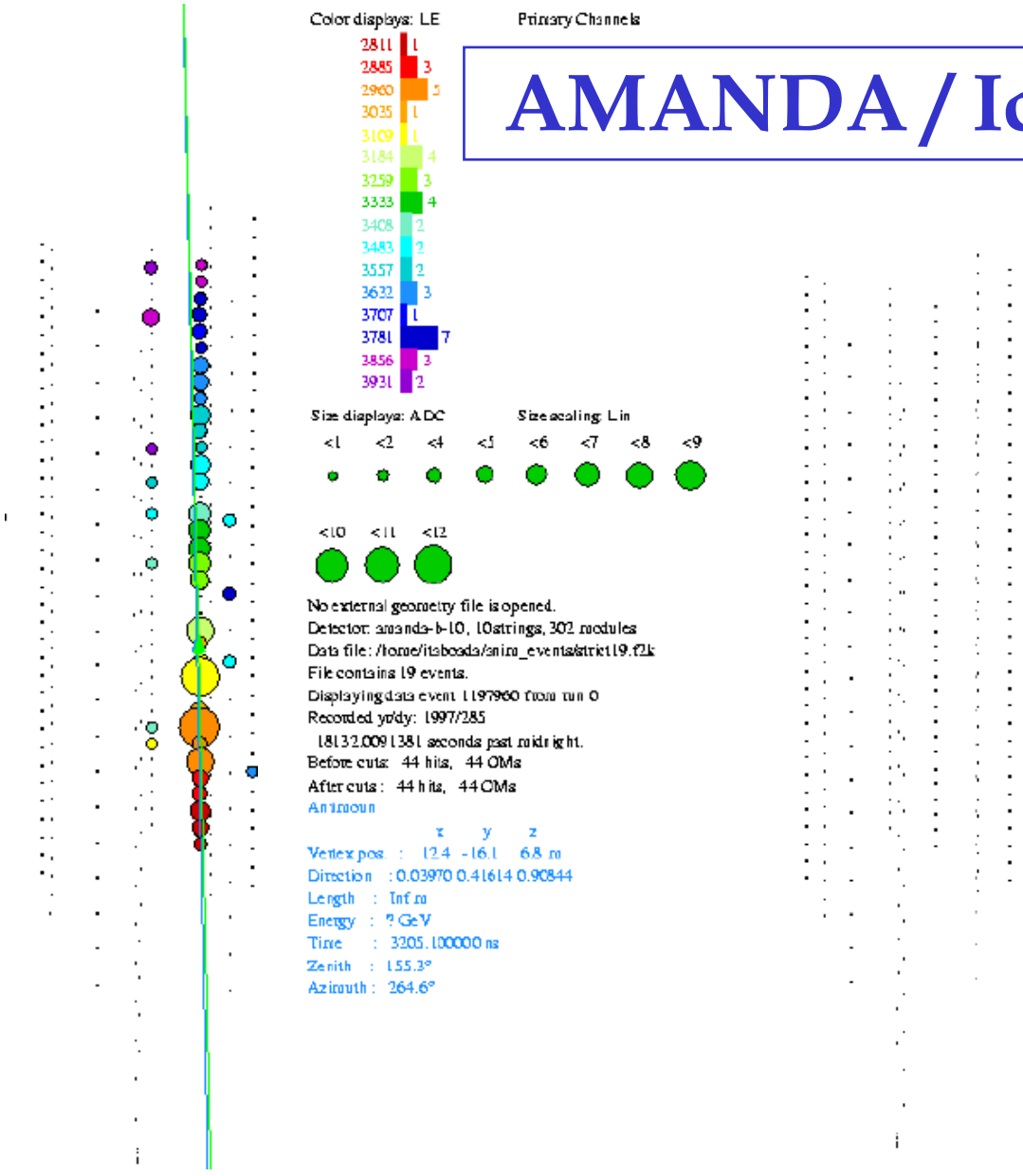
Reconstruction of the μ trajectory allows the identification of the ν direction



Myonspur im Eis/Wasser

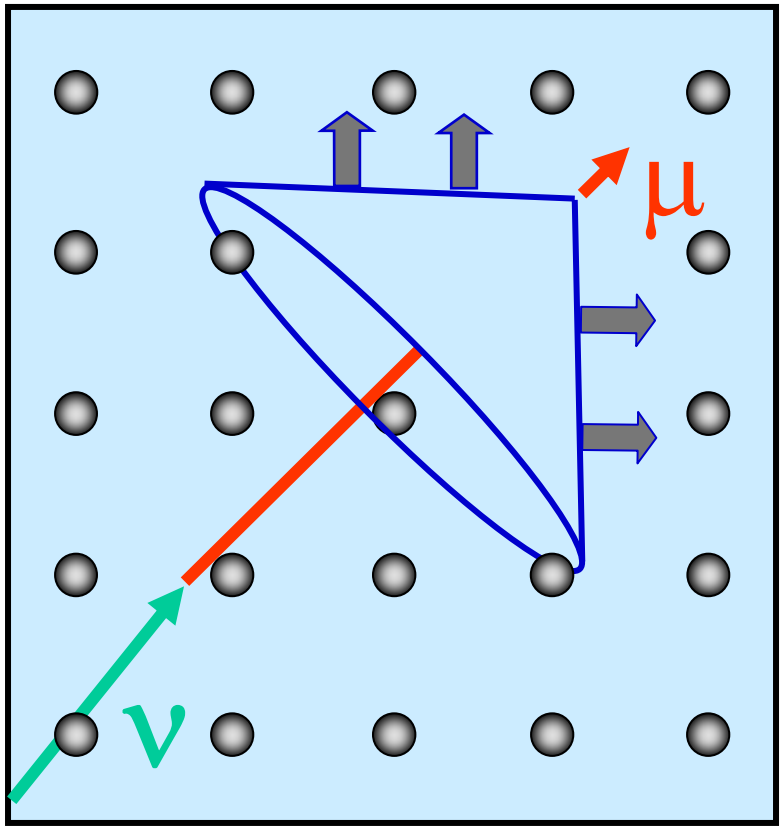


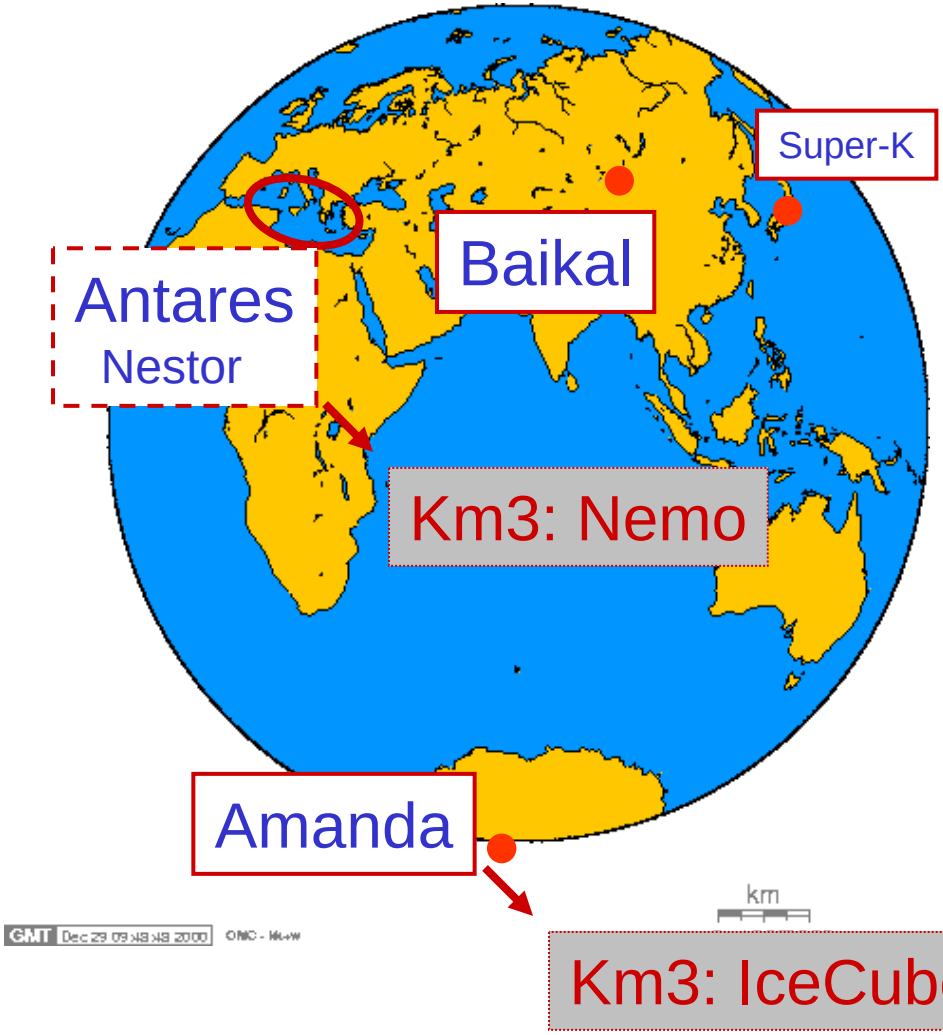
AMANDA / IceCube

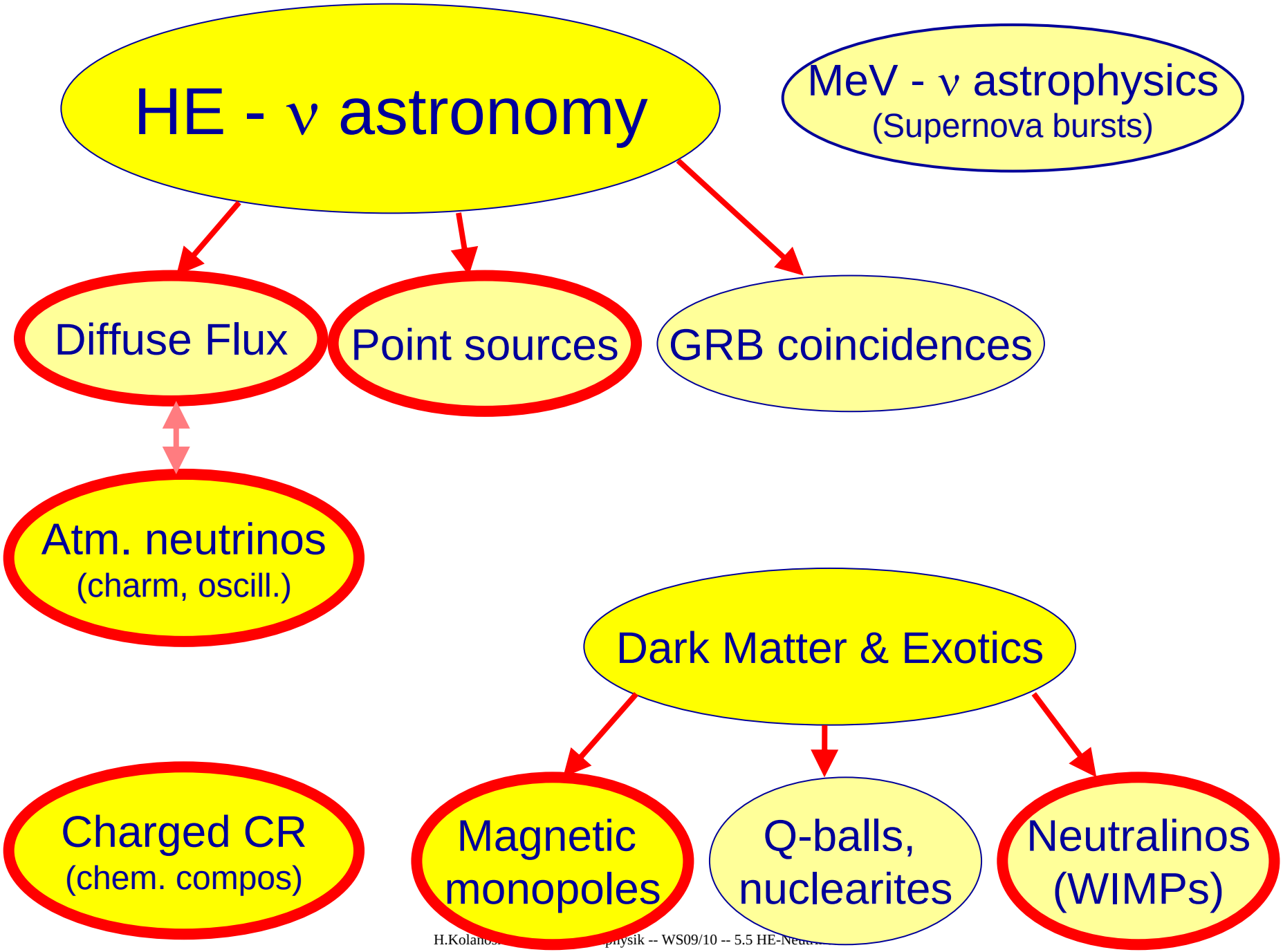


$\nu_\mu + N \rightarrow \mu + X \Rightarrow$ high energy μ above C-threshold in ice

Neutrino Telescopes in Water and Ice






HE - ν astronomy
MeV - ν astrophysics
(Supernova bursts)
Diffuse Flux
Point sources
GRB coincidences
Atm. neutrinos
(charm, oscill.)
Dark Matter & Exotics
Charged CR
(chem. compos)
Magnetic
monopoles
Q-balls,
nuclearites
Neutralinos
(WIMPs)

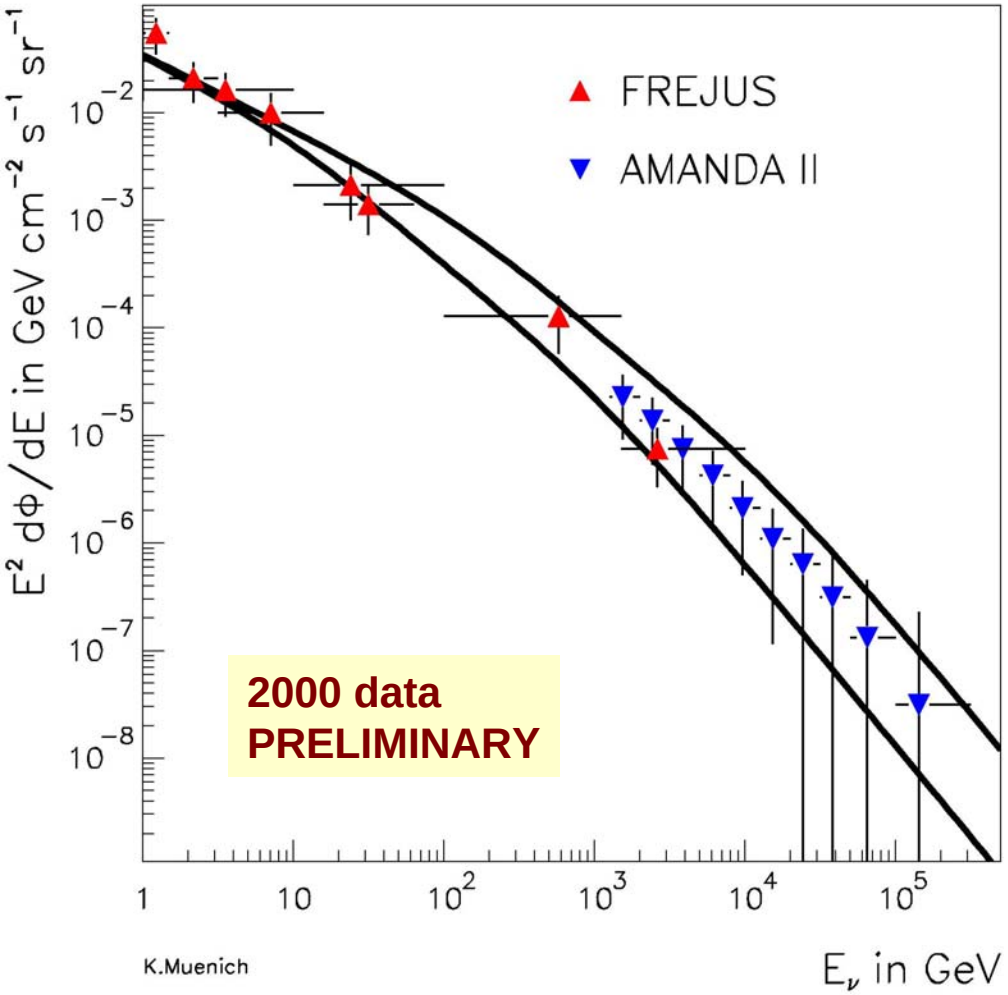
AMANDA-II

2000 data

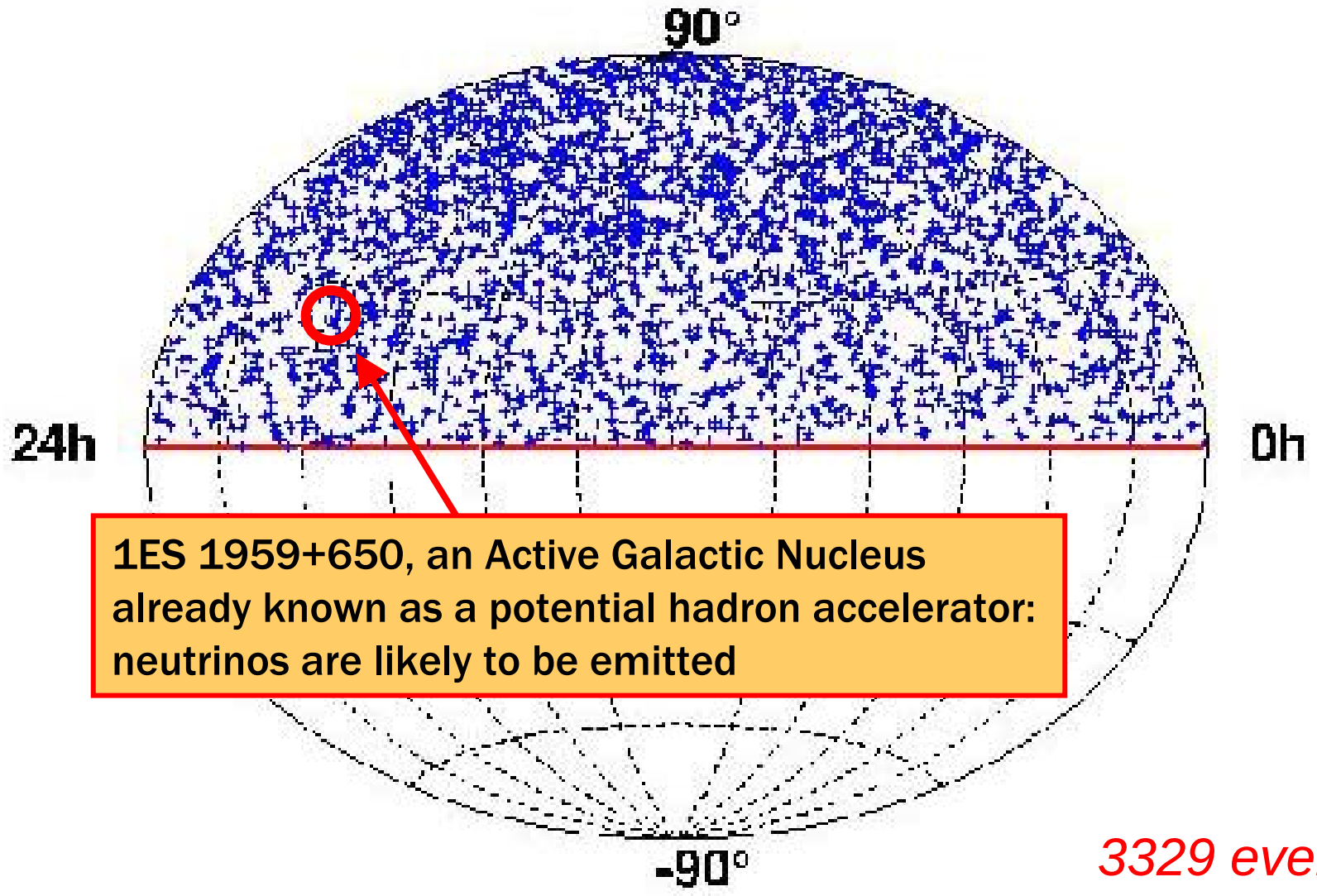
First spectrum > 3 TeV:

- up to 100 TeV

- matches lower-energy Frejus data



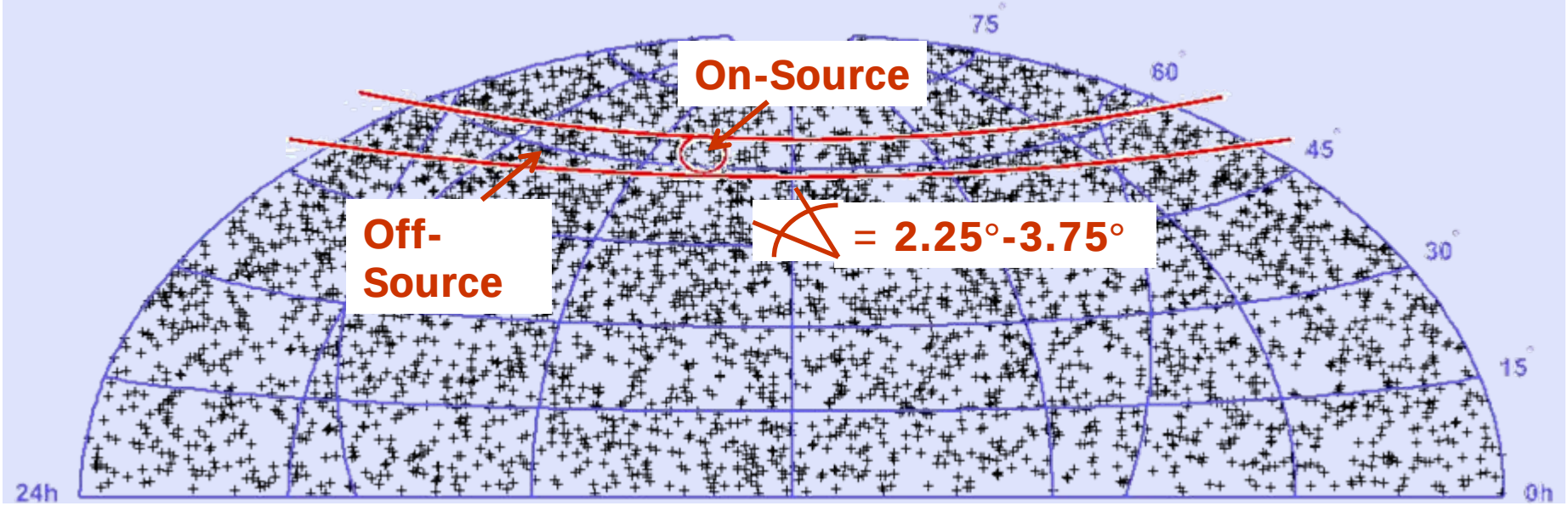
AMANDA skyplot 2000-2003



1ES 1959+650, an Active Galactic Nucleus already known as a potential hadron accelerator: neutrinos are likely to be emitted

3329 events

preliminary



2000-2004:

4282 events

1001 days live-time

- Search for an excess of events
  - **from candidate sources**
  - **anywhere on the northern sky**
- Atm-ν Background from 'off-source' data
- No detection yet, flux upper limits set

Candidate sources

Source	Events observed/ background (5 years)	Events observed/ background (4 years)	Flux upper limit Sys. unc. 15% sig, 8% bg $\Phi_{90\%}(E_\nu>10\ \mathrm{GeV})$ [$10^{-8}\mathrm{cm}^{-2}\mathrm{s}^{-1}$] (5 years)
Markarian 421	6 / 7.37	6 / 5.58	0.43
Markarian 501	8 / 6.39	5 / 4.96	0.85
1ES1959+650	5 / 4.77	5 / 3.71	0.78
M87	6 / 6.08	4 / 4.90	0.50
3C273	8 / 4.72		0.99
SS433	4 / 6.14	2 / 4.50	0.27
CI Cam	9 / 6.72	5 / 5.11	1.04
Cygnus X-1	8 / 7.01	4 / 5.21	0.76
Cygnus X-3	7 / 6.48	6 / 5.04	0.67
Crab Nebula	10 / 6.74	10 / 5.36	1.01

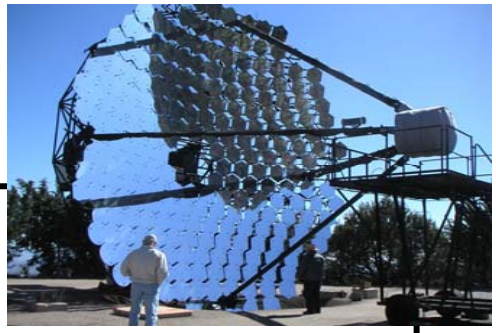
No significant excess, no indication for a neutrino source

No new events seen from the direction of Crab Nebula

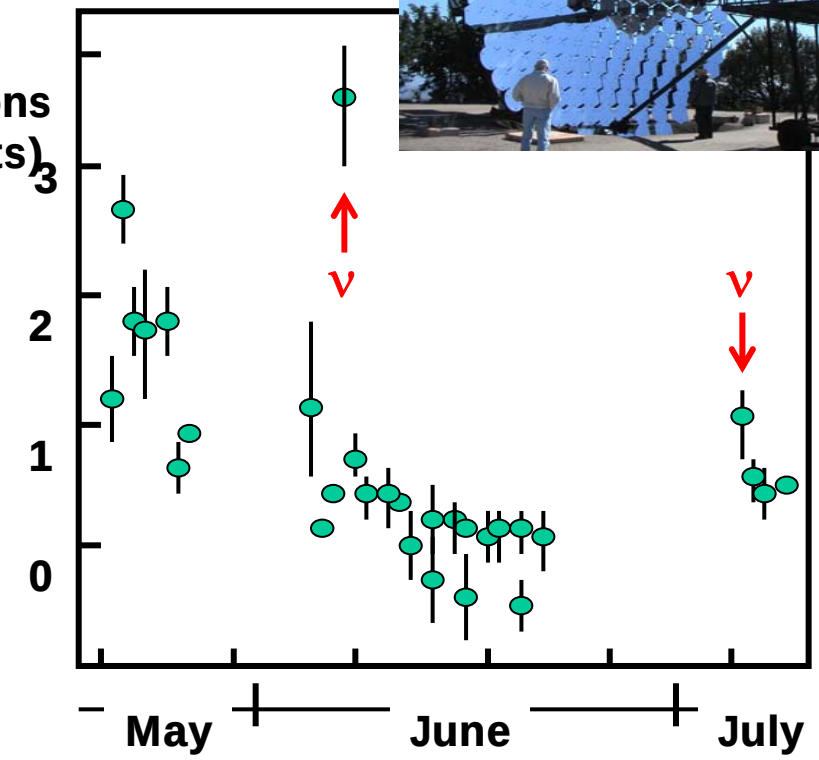
Flux upper limits improved

preliminary

Did we see already the first signal ?

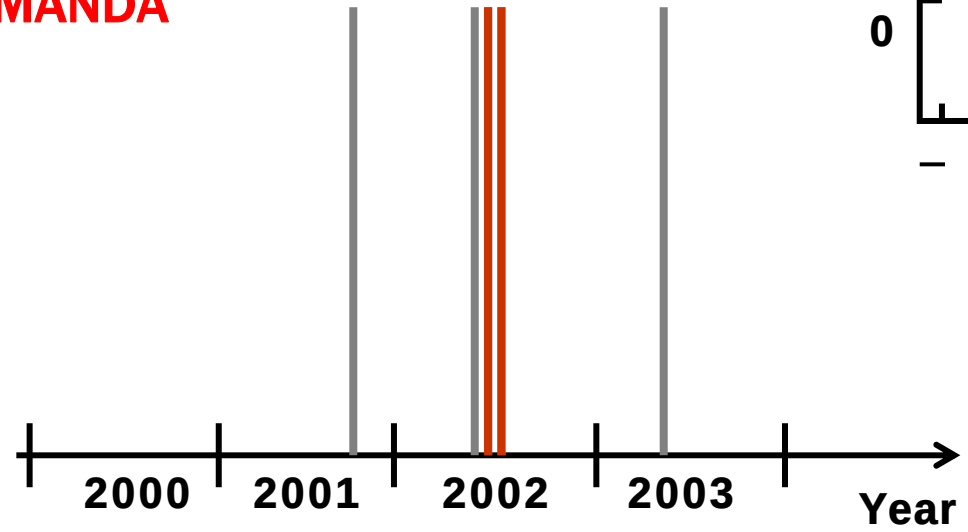


Flux of TeV photons (arb. units)

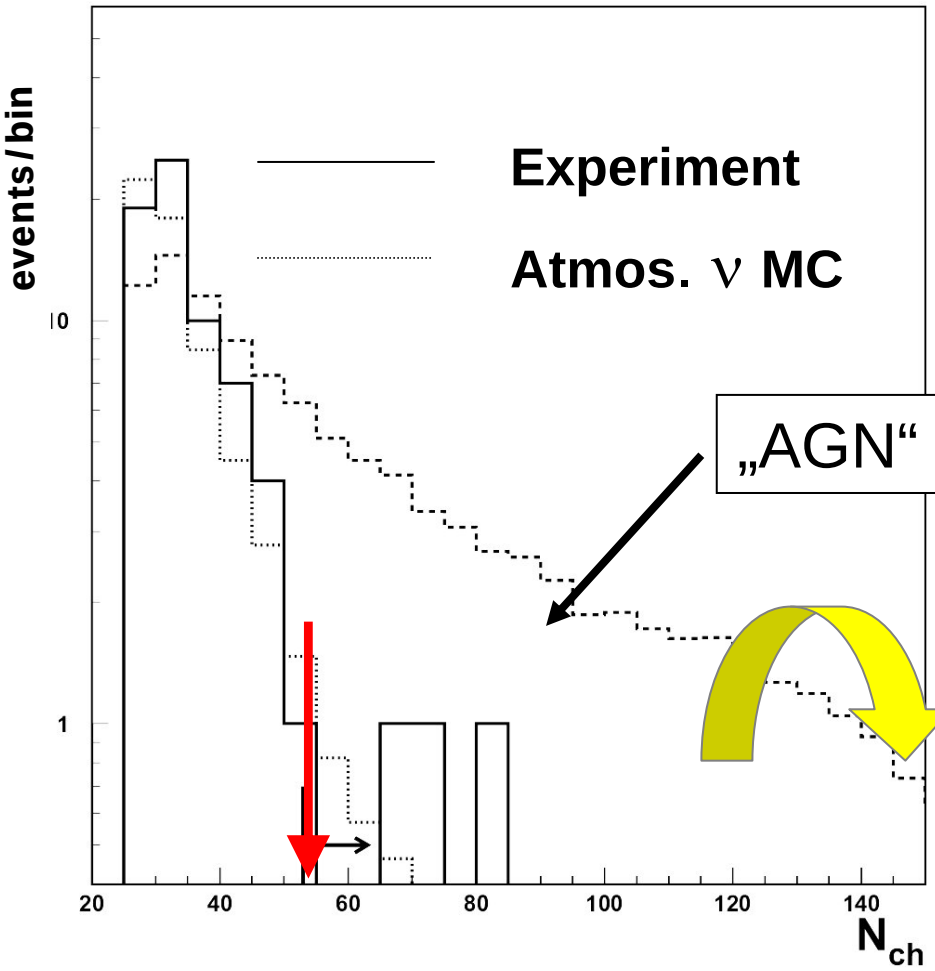


Gamma-rays detected by a TeV gamma telescope

Arrival time of the neutrinos from the direction of ES1959+650 detected by AMANDA



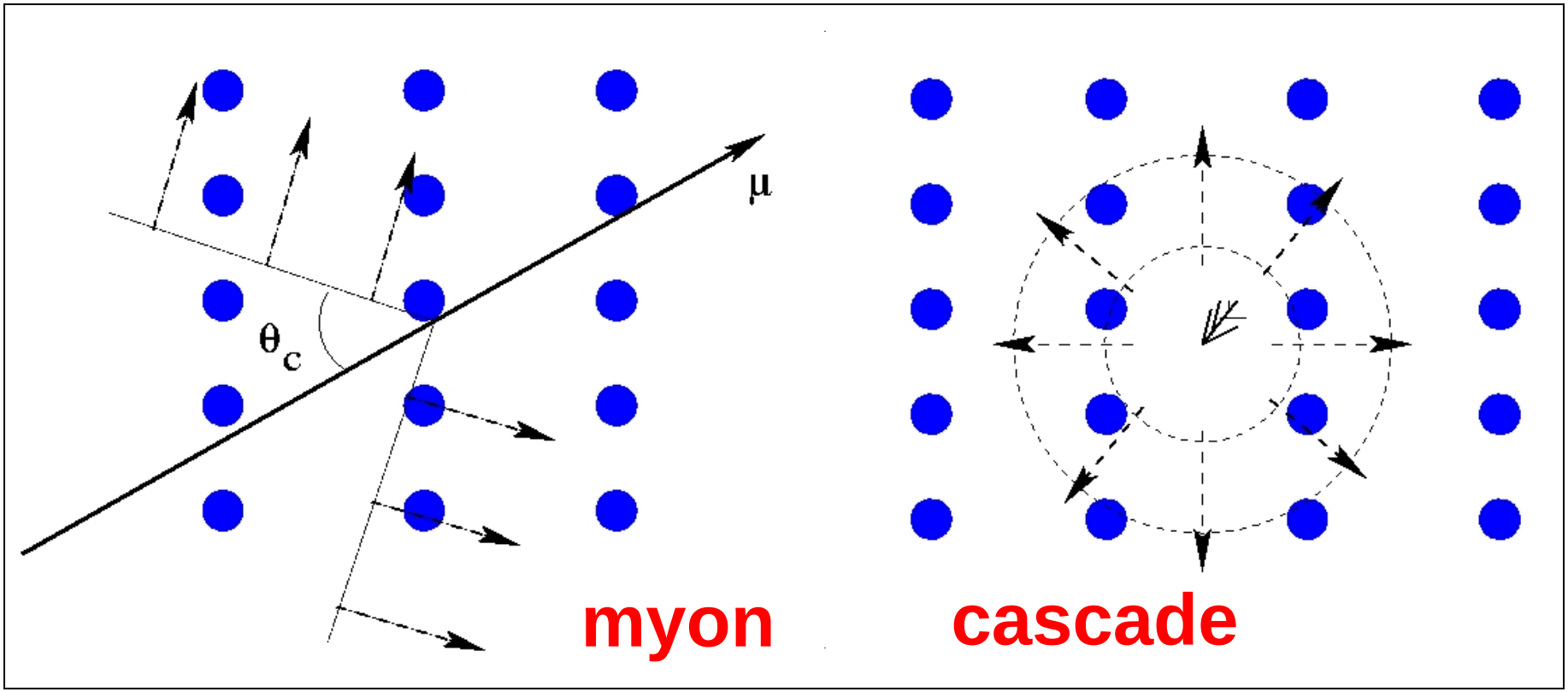
1. Diffuse flux of muon neutrinos (energy < 1 PeV)



AMANDA B10,1997 data

„AGN“ with $10^{-5}\ E^{-2}\ GeV^{-1}\ cm^{-2}\ s^{-1}\ sr^{-1}$

$E^2\ \Phi$
$< 0.8 \cdot 10^{-6}\ GeV^{-1}\ cm^{-2}\ s^{-1}\ sr^{-1}$

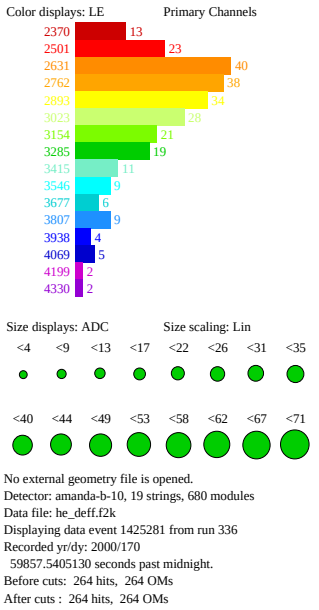

μ
θc
myon
cascade

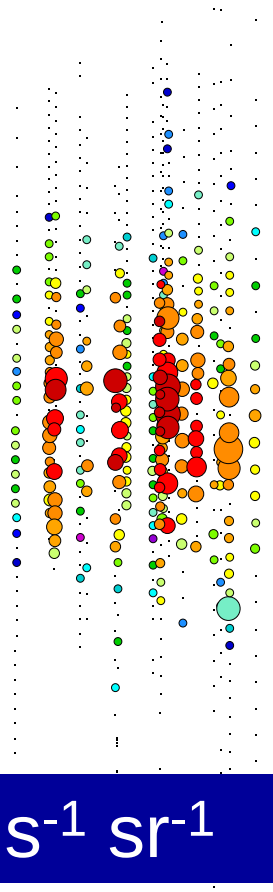
Cascades inside detector

Sensitive to all 3 flavors

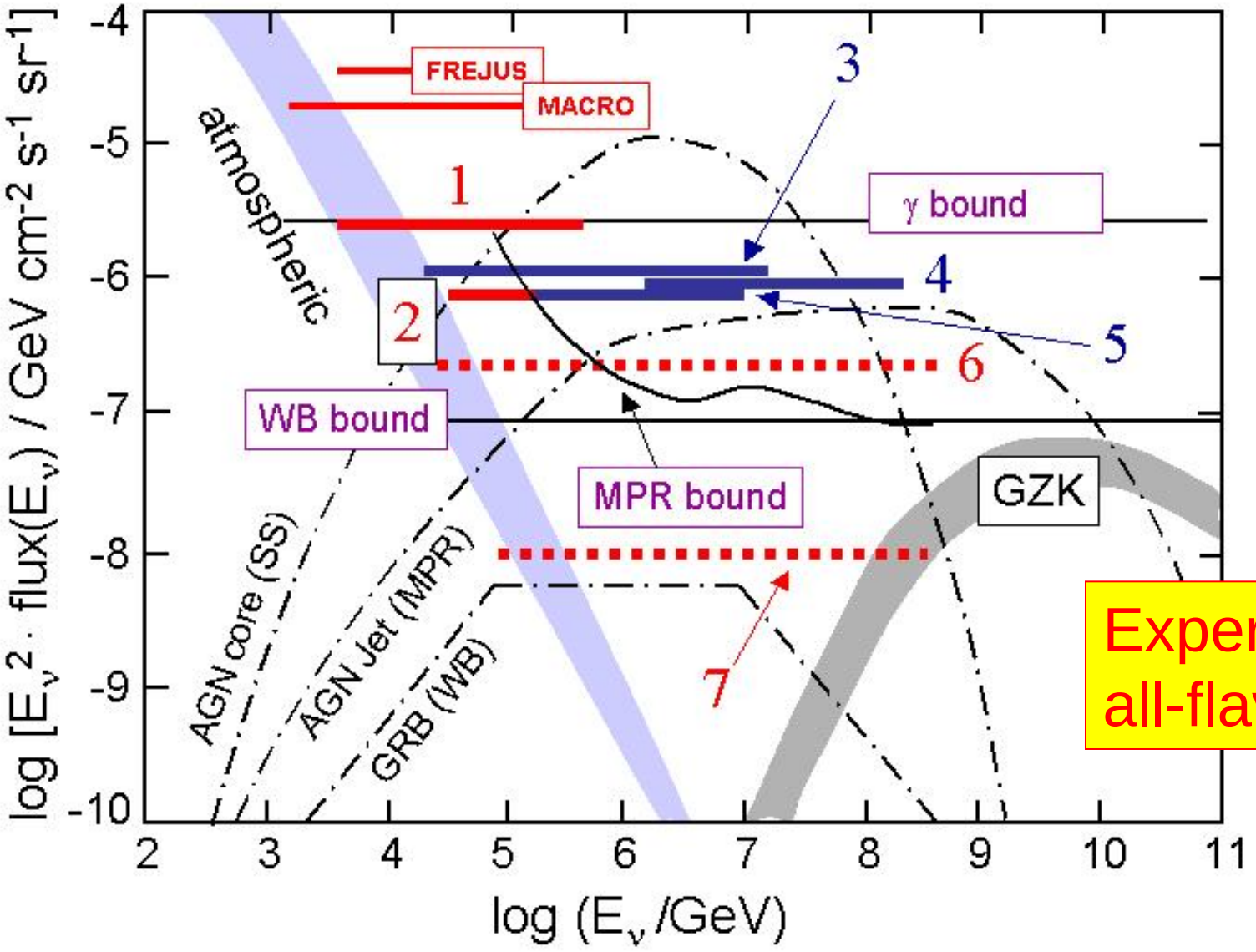
- CC electron and tau neutrino interaction:
- $\nu_{(e,\tau,)} + N \rightarrow$ **(e, τ) + X**
- NC neutrino interaction:

$\nu_x + N \rightarrow \nu_x +$ **X**





$E^2 \Phi_{all-\nu} < 0.6 \cdot 10^{-6}\ GeV^{-1}\ cm^{-2}\ s^{-1}\ sr^{-1}$

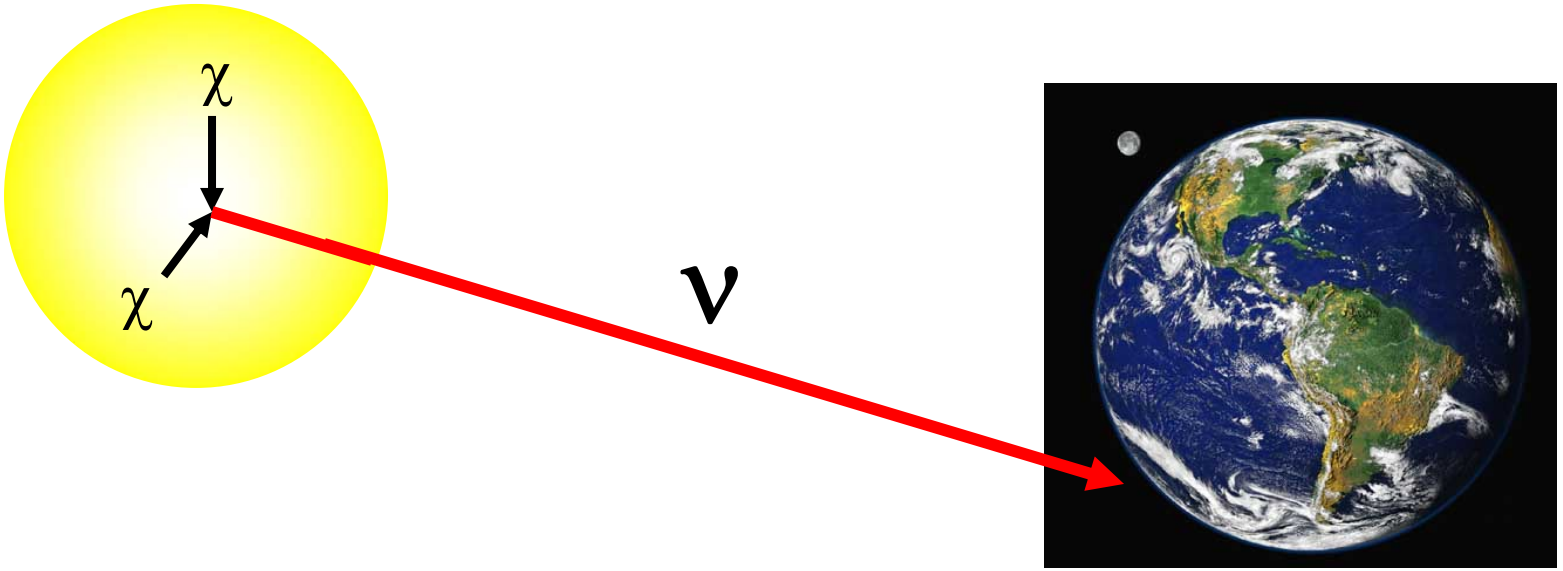


Experimental all-flavor limits

1: Amanda-B10, muons
2: Amanda-II, muons
3: Baikal all flavor
4: Amanda all flavor UHE
5: Amanda cascades

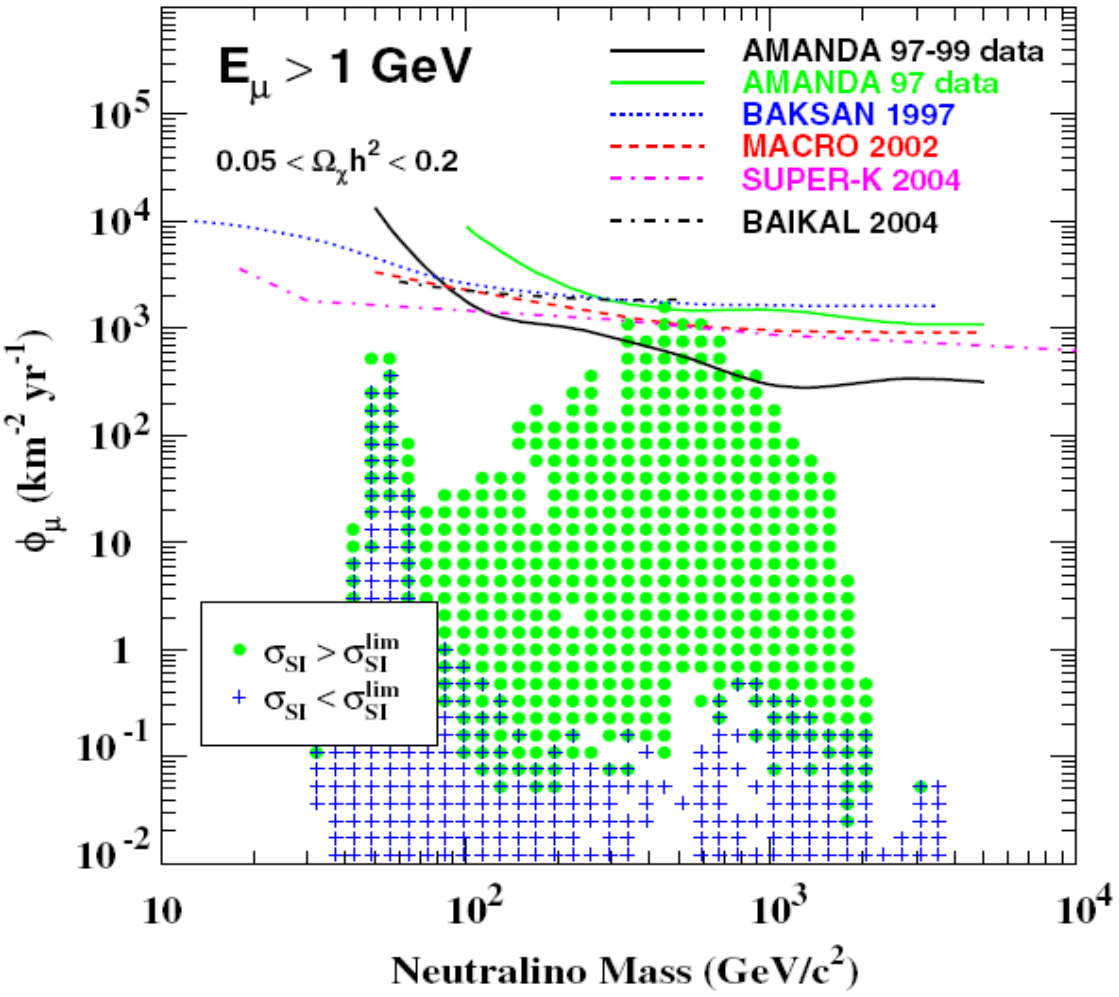
Expected:
6: Amanda-II, 4 years
7: IceCube 3 years

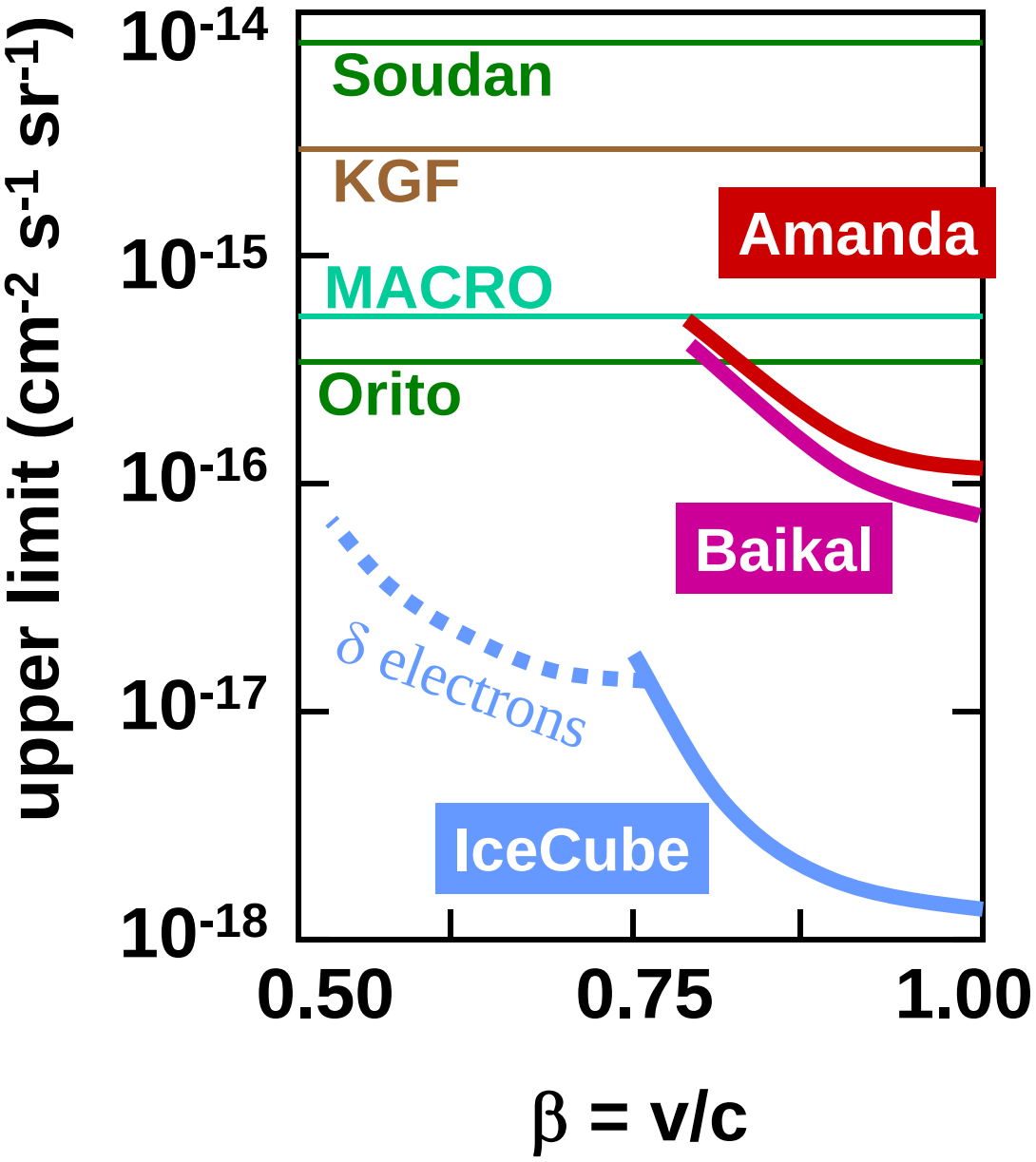
Indirect Search for WIMPs



At South Pole the Sun sinks maximally 23° below horizon. Therefore only Amanda-II with its dramatically improved reconstruction capabilities for horizontial tracks (compared to Amanda-B10) can be used for solar WIMP search.

Limits on the muon flux from neutralino annihilations at the center of the Earth with AMANDA





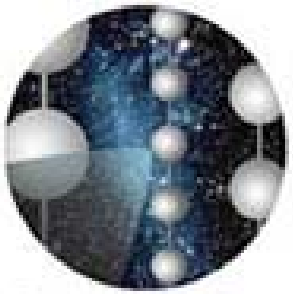
Relativistic Magnetic Monopoles

Cherenkov-Light $\propto$ $n^2 \cdot (g/e)^2$

$n = 1.33$

$(g/e) = {}^{137}/_{2}$

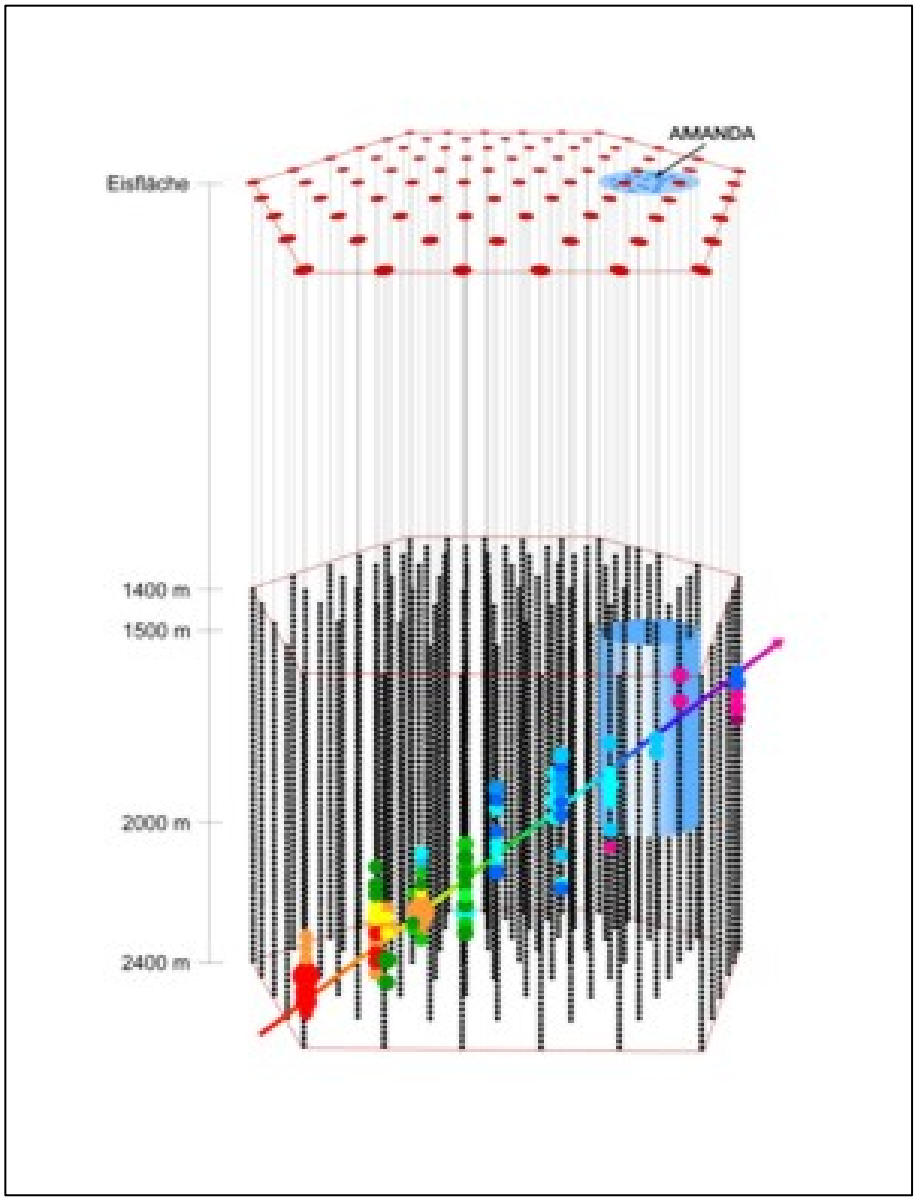
≈ 8300

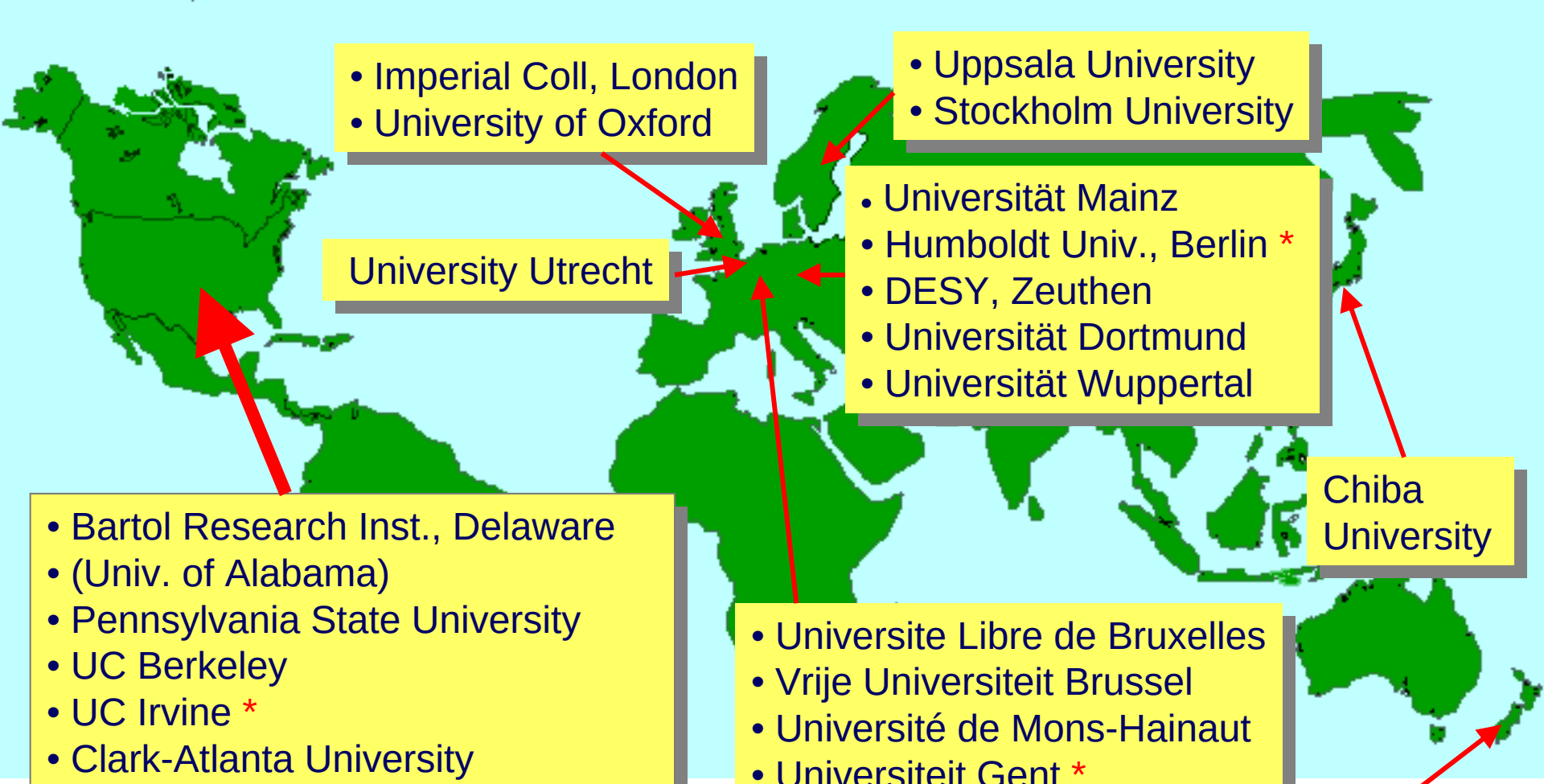


- 80 Strings
- 4800 PMTs

Instrumented Volume: 1 km^3

Installation: 2005-2010





- Imperial Coll, London
- University of Oxford

- Uppsala University
- Stockholm University

- Universität Mainz
- Humboldt Univ., Berlin *
- DESY, Zeuthen
- Universität Dortmund
- Universität Wuppertal

University Utrecht

Chiba University

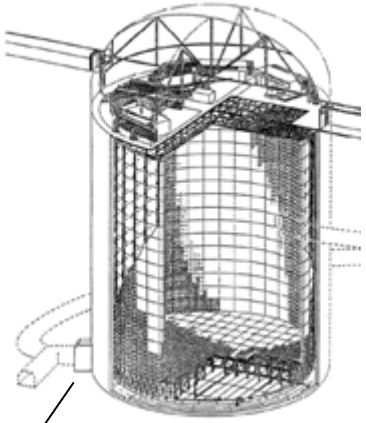
- Bartol Research Inst., Delaware
- (Univ. of Alabama)
- Pennsylvania State University
- UC Berkeley
- UC Irvine *
- Clark-Atlanta University
- Univ. of Maryland
- IAS, Princeton
- University of Wisconsin-Madison
- University of Wisconsin-RiverFalls
- LBNL, Berkeley
- University of Kansas
- Southern Univ., Baton Rouge

- Universite Libre de Bruxelles
- Vrije Universiteit Brussel
- Université de Mons-Hainaut
- Universiteit Gent *

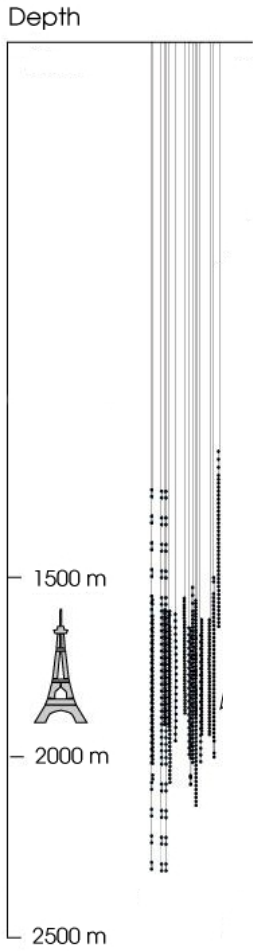
Univ. of Canterbury, Christchurch

The IceCube Collaboration

6 Amanda modules

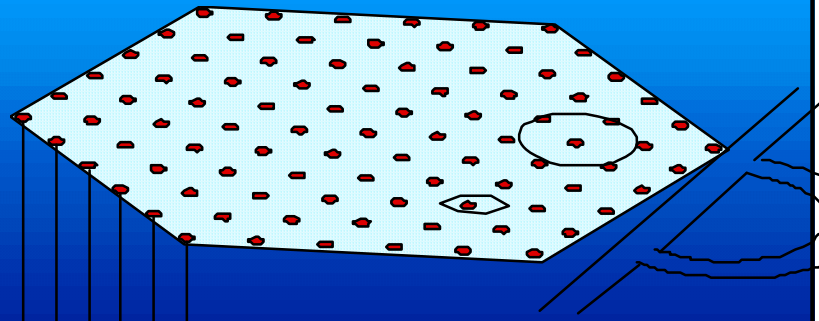


AMANDA-II

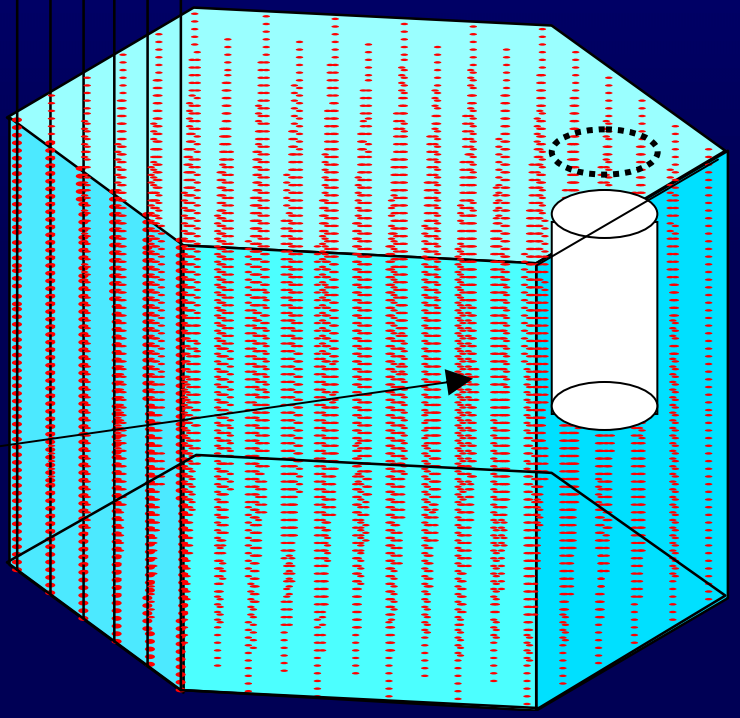


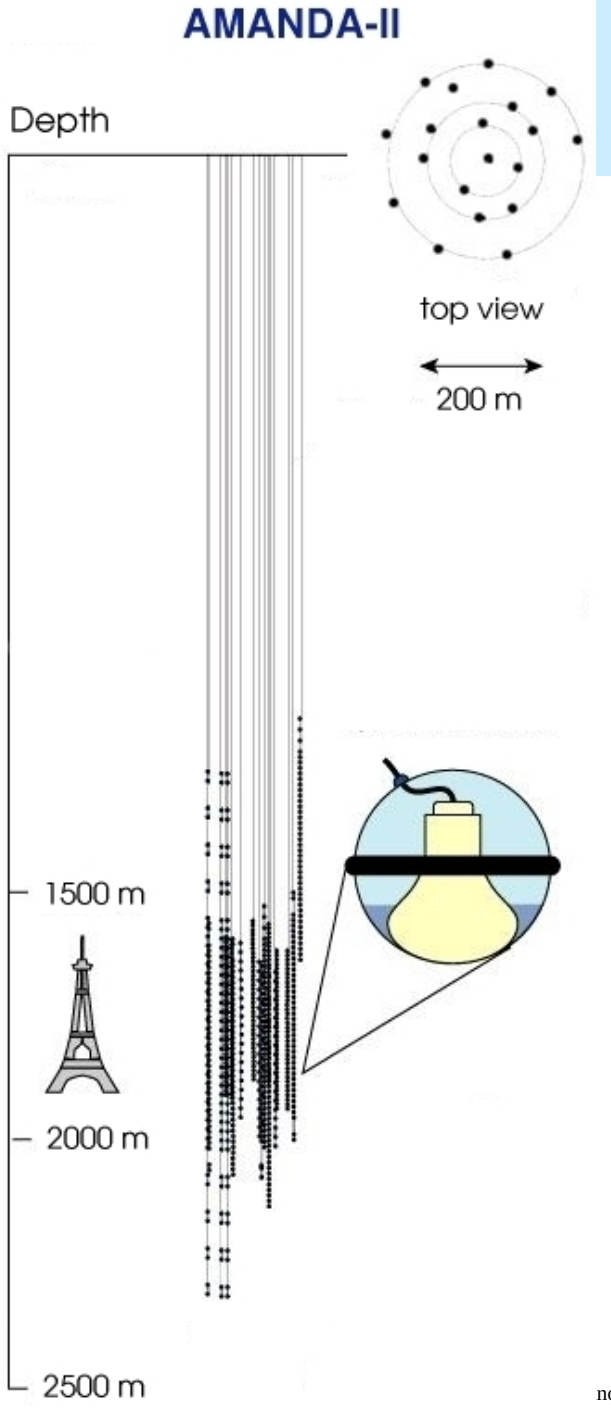
Super-Kamiokande (Japan)

AMANDA-II

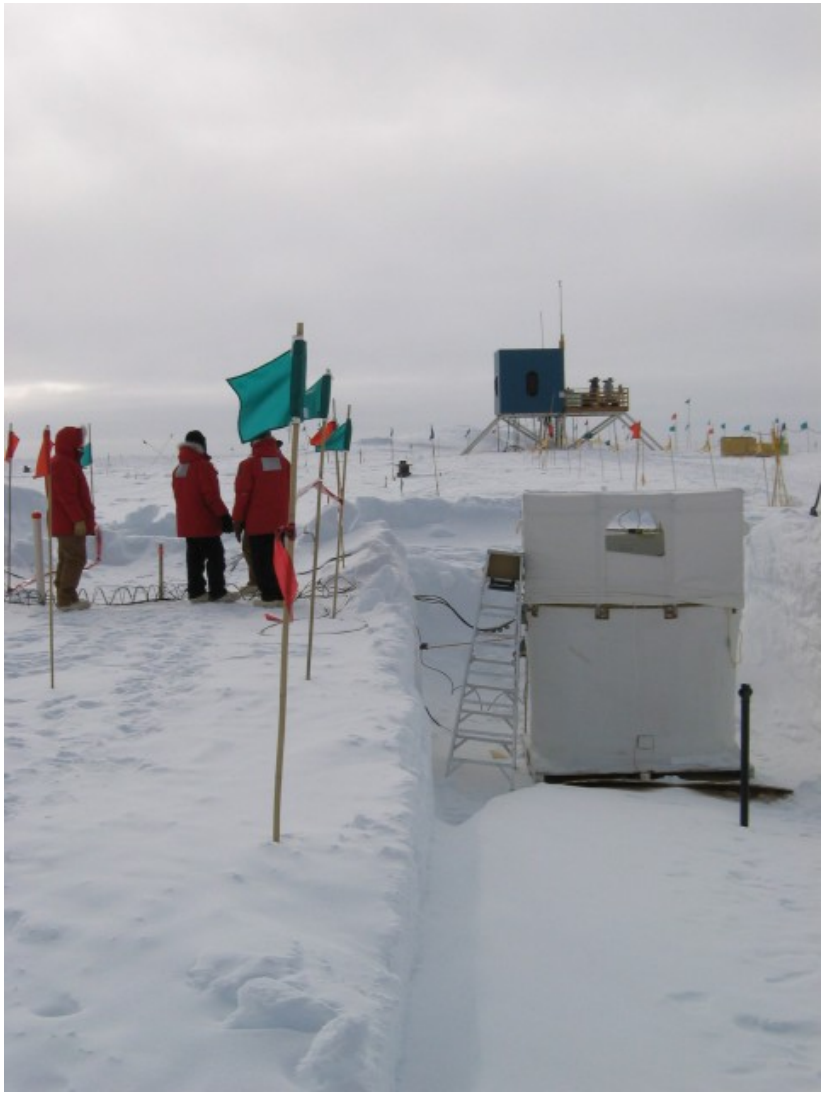


IceCube




AMANDA-II
Depth
top view
200 m
1500 m
2000 m
2500 m

Cherenkov tank arrays: IceTop



Southpole, Antarctica

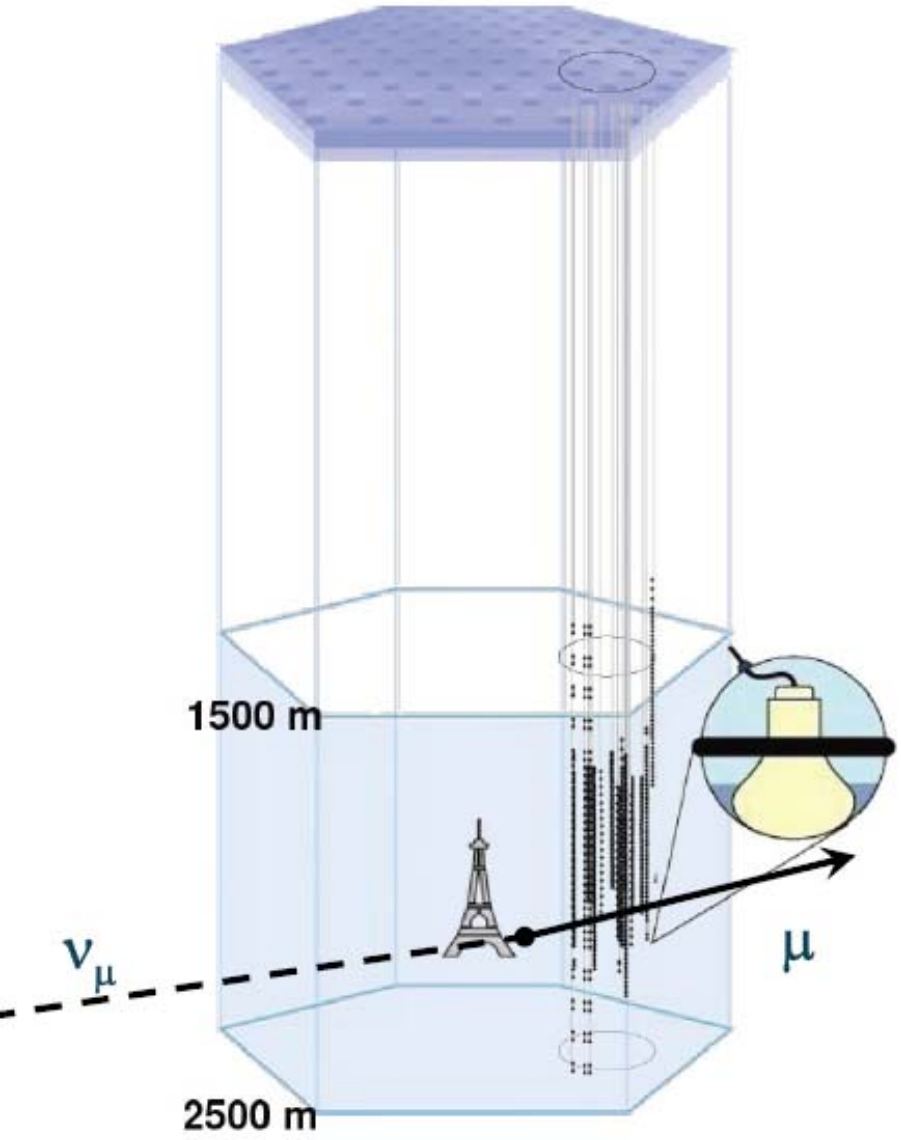
1 km²

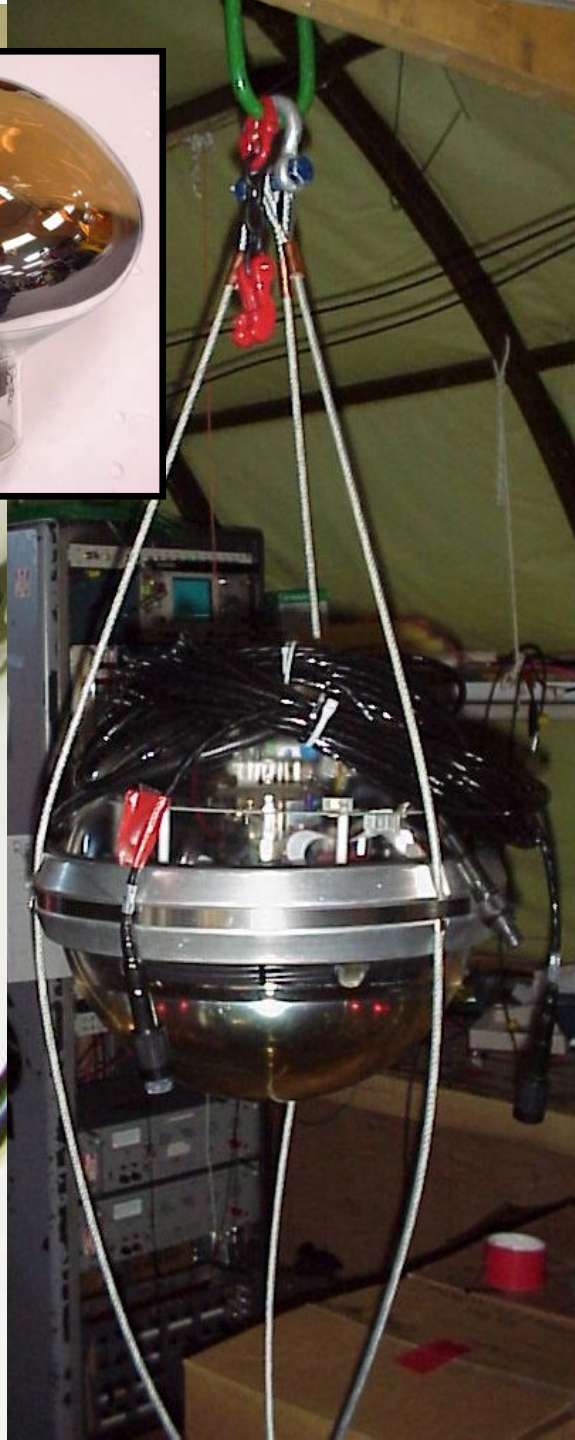
80 Stations x 2 x 3.14 m²
= 503 m²

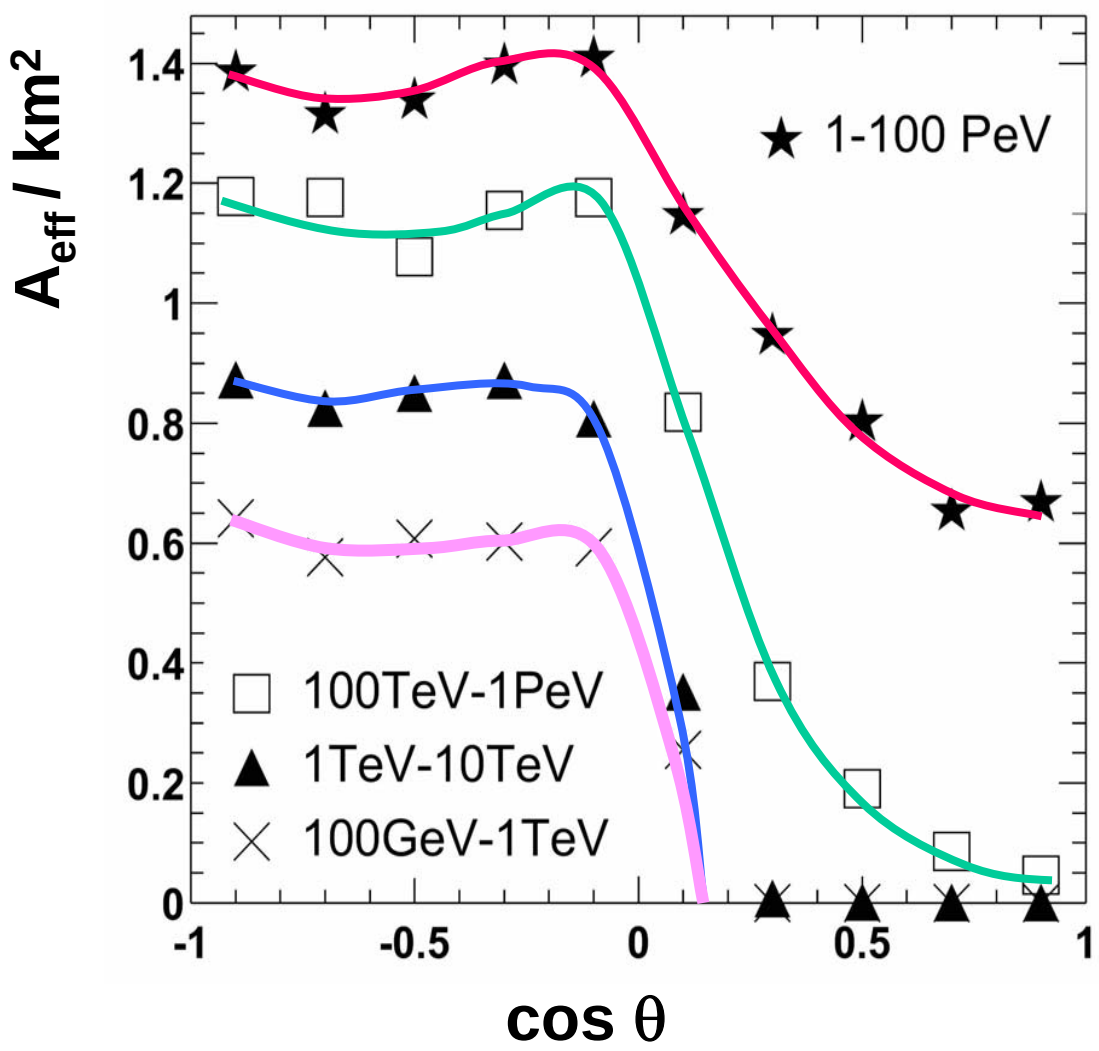
E > 0.3 PeV

slightly larger than K-GRANDE

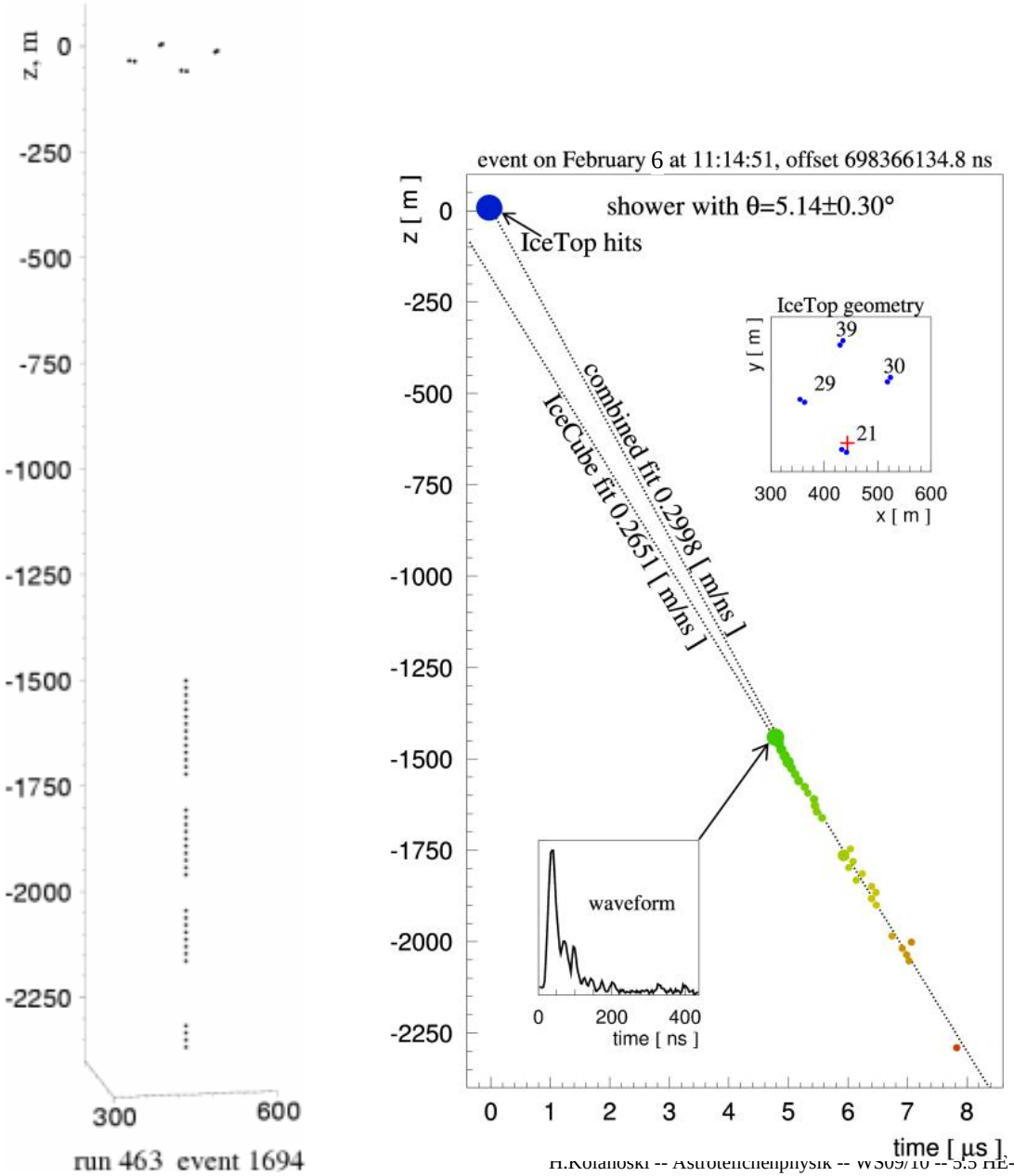
IceCube: DOM






A_{eff} / km^2
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-1
-0.5
0
0.5
1
cos θ
1-100 PeV
100TeV-1PeV
1TeV-10TeV
100GeV-1TeV

The first muon – IceTop shower coincident event



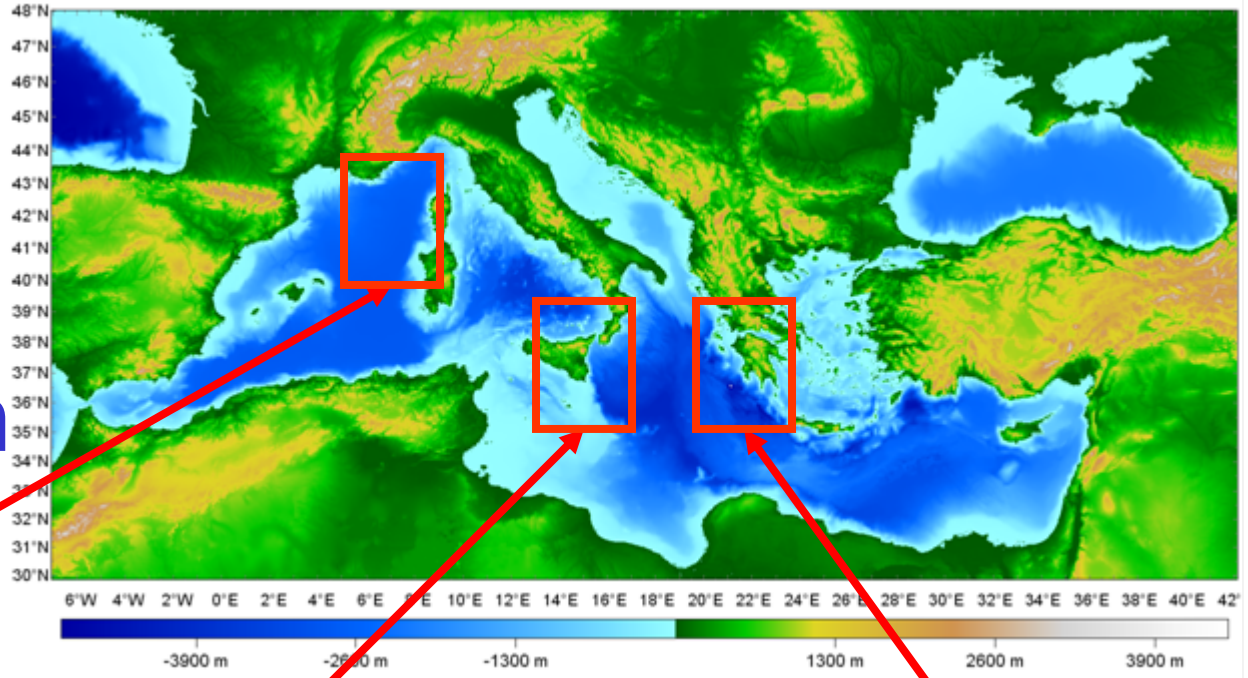
January 23
First runs with the four IceTop stations (8 tanks) taken

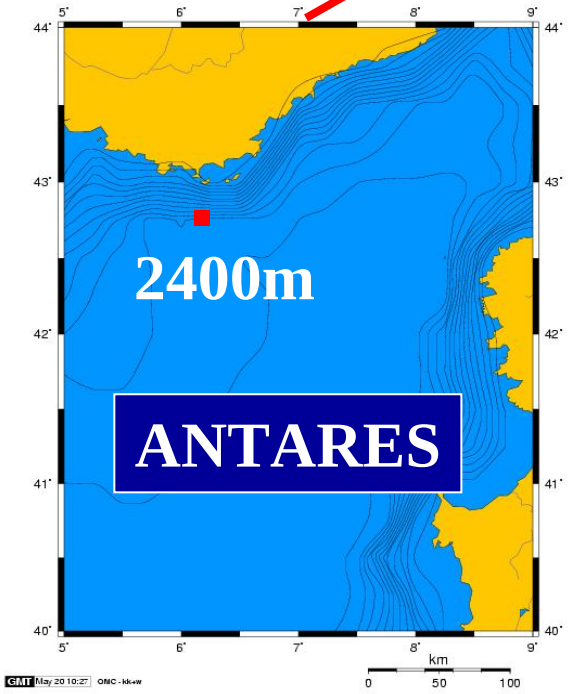
January 29 1:31
First IceCube string deployed

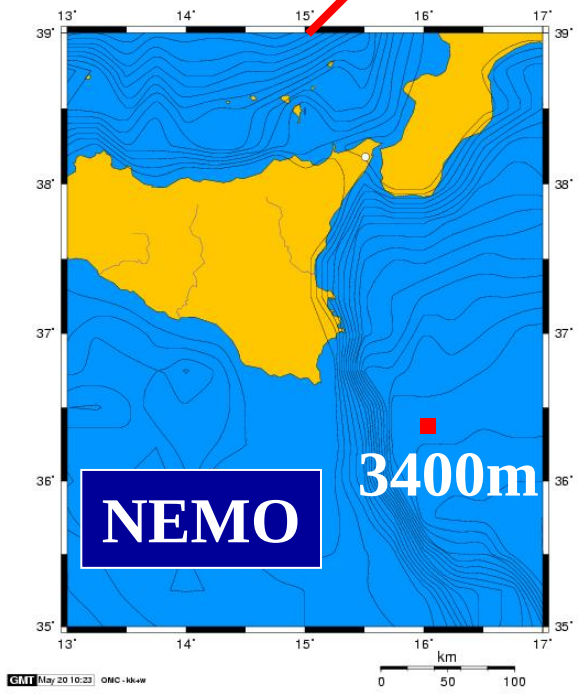
February 9
First shower/muon coincidence events found

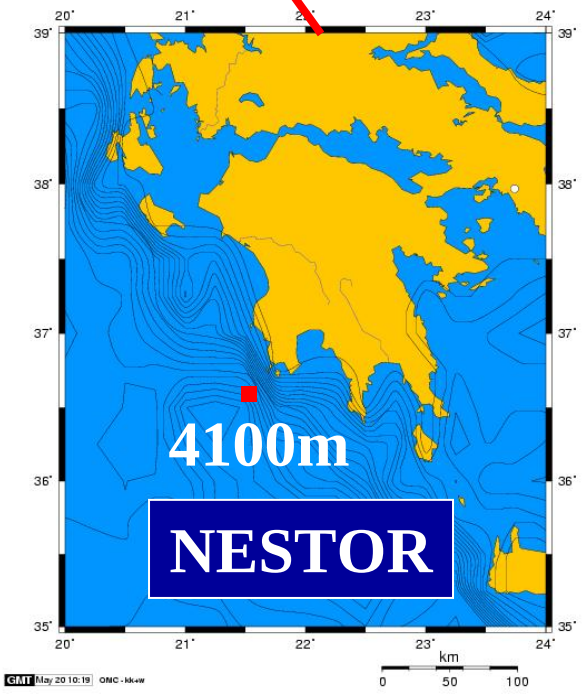
Under construction:

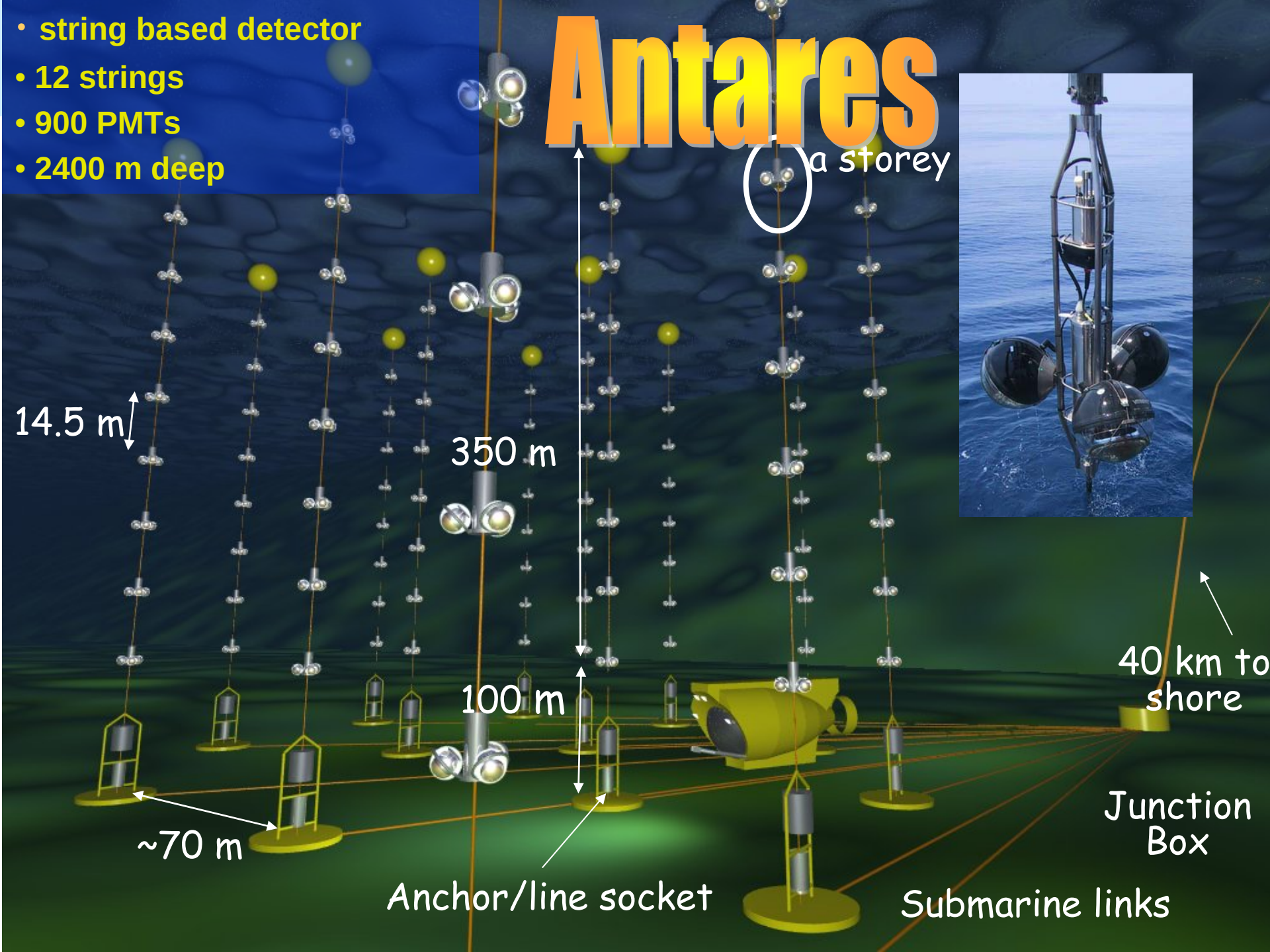
Telescopes in Mediterranean



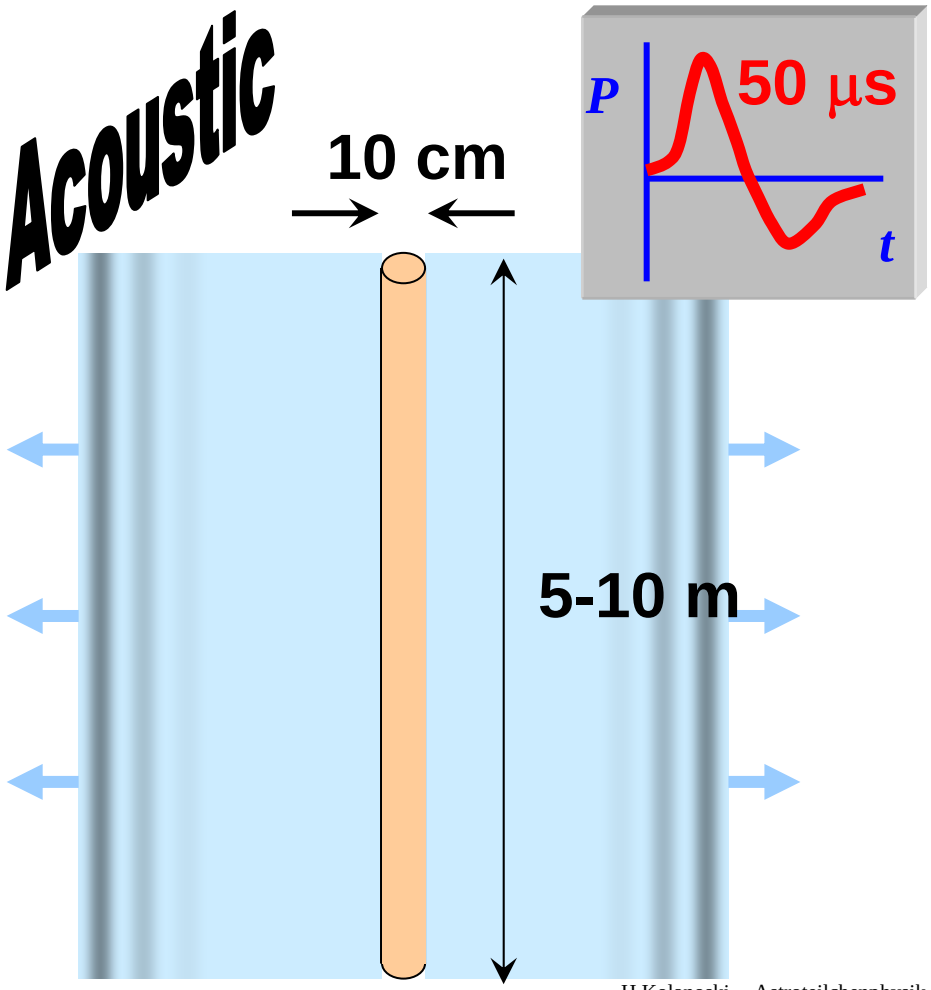




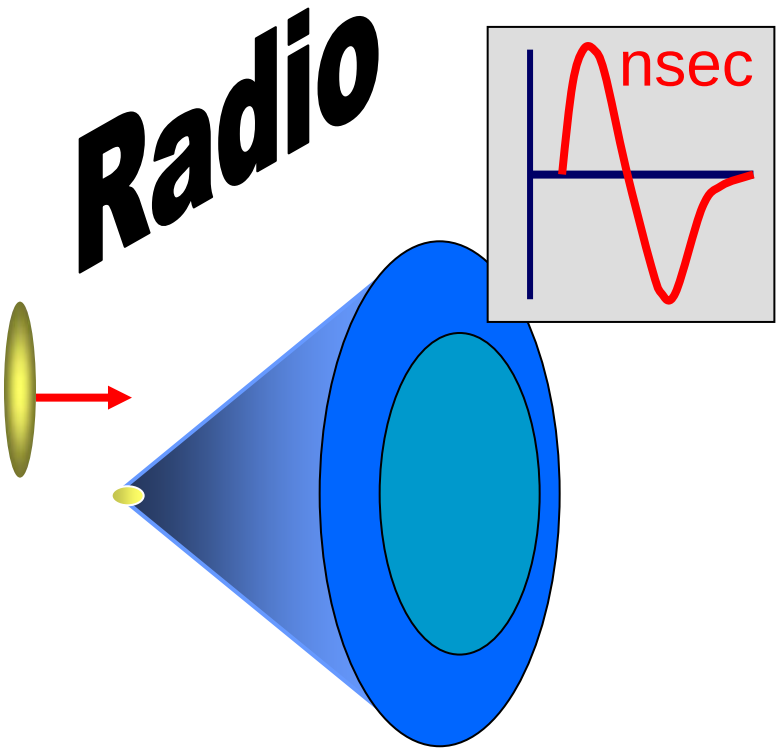



• string based detector
• 12 strings
• 900 PMTs
• 2400 m deep
Antares
a storey
14.5 m
350 m
100 m
~70 m
Anchor/line socket
Submarine links
Junction Box
40 km to shore

Above 10-100 PeV:
Detection by Acoustic and Radio Waves



attenuation length in ice 1-4 km !!



Sehen und Hören: Nutze alle Sinne

Teilchen hören ?!!

Akustische Sensoren für den IceCube Detektor

Thermoakustisches Modell:

⇨ Ultrahochenergetische Kaskade

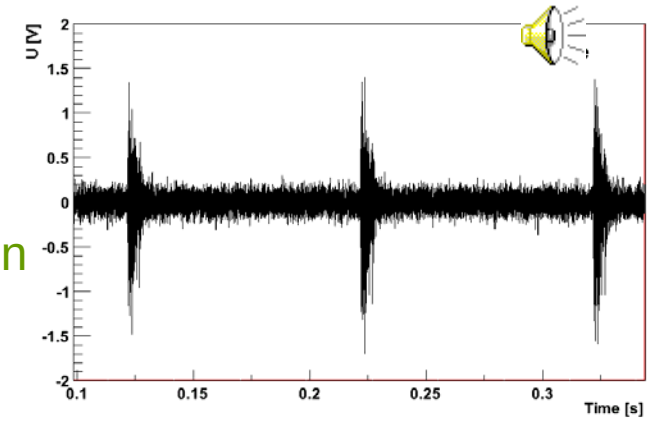
⇨ Lokale Erwärmung

⇨ Expansion

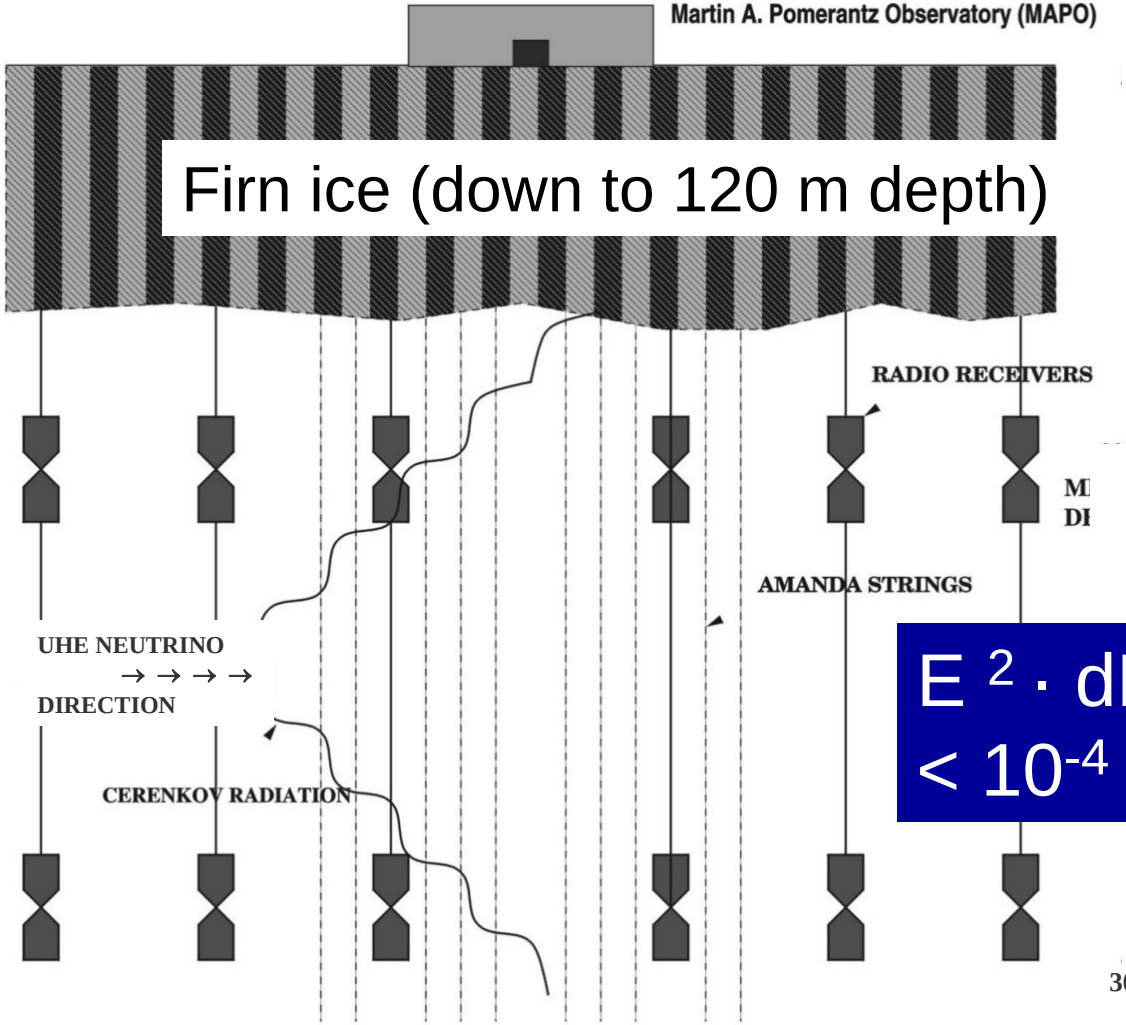
⇨ Schallwelle

Akkustische Sensoren

180 MeV Protonen
TSL, Uppsala



RICE **R**adio **I**ce **C**herenkov **E**xperiment



South Pole

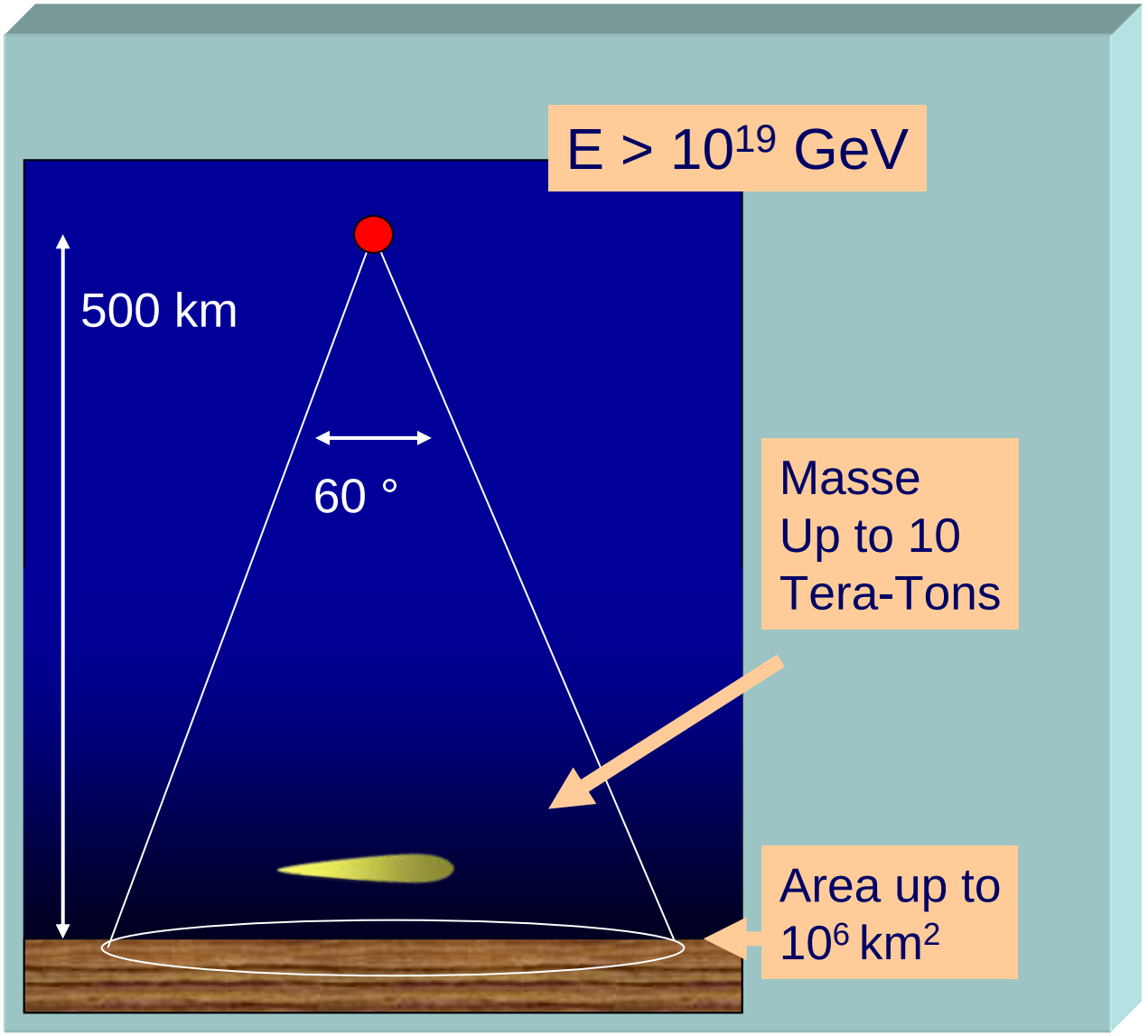
20 transmitter + receiver

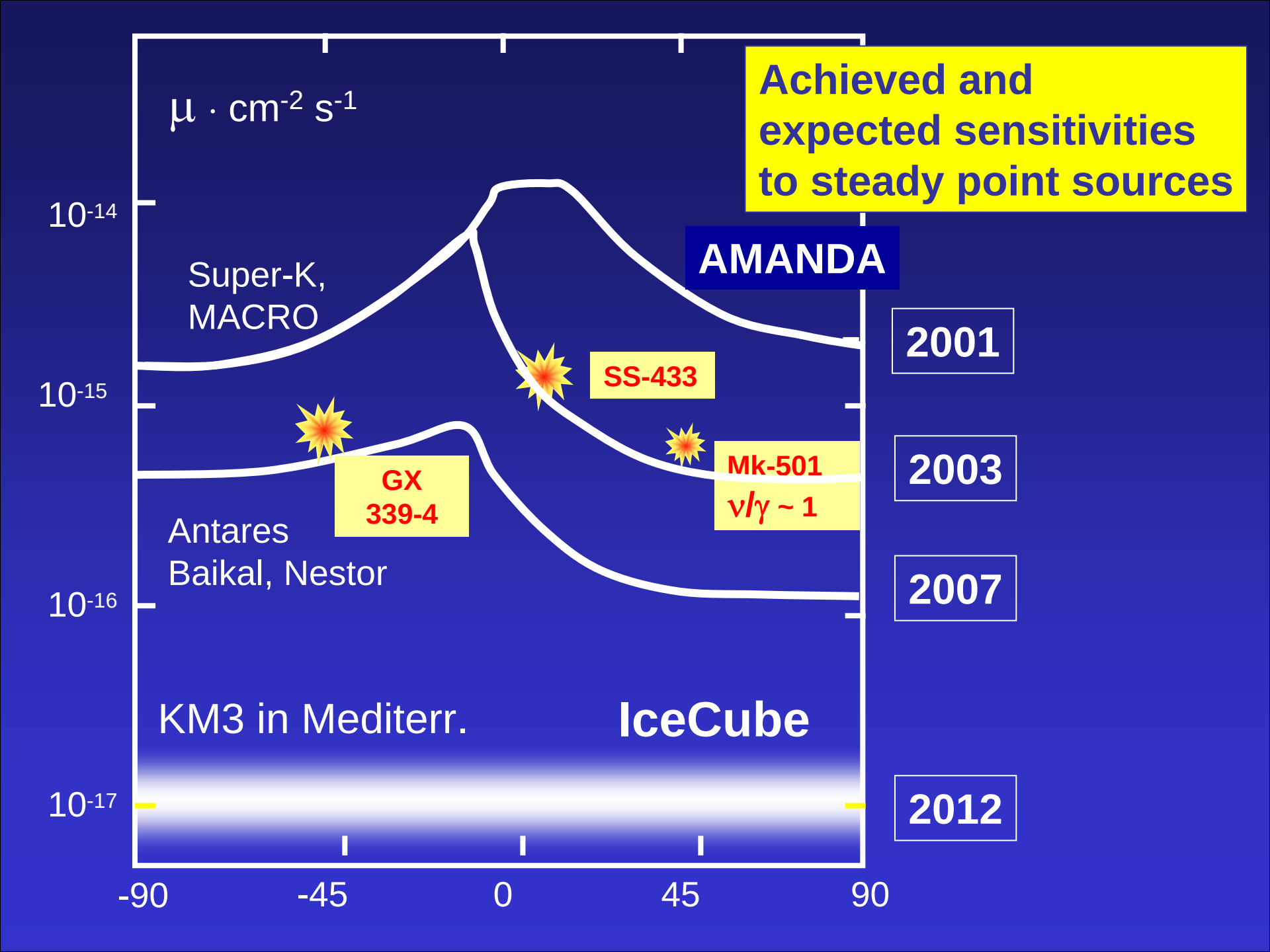
$E^2 \cdot dN/dE$

$< 10^{-4}$ GeV · cm^{-2} · s^{-1} · sr^{-1}

at 100 PeV

Measurement of horizontal air showers from Satellites




Achieved and expected sensitivities to steady point sources
μ · cm-2 s-1
10-14
10-15
10-16
10-17
Super-K, MACRO
AMANDA
2001
SS-433
Mk-501
ν/γ ~ 1
2003
GX 339-4
Antares
Baikal, Nestor
2007
KM3 in Mediterr.
IceCube
2012
-90
-45
0
45
90

AMANDA skyplot 2000-2003