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lecture cource on

Astroparticle physics

15.09.2009 – 15.12.2009

B. Lecture Contents

Astroparticle physics: topics and tentative schedule

- high-energy cosmic rays (15.09. and 22.09.) ☞
- past, current and future experiments (06.10.)
- Sun (stars) and solar neutrinos (13.10.)
- supernovae, supernova and relic supernova neutrinos (27.10.)

- atmospheric and geoneutrinos (03.11.)
- double beta-decay (10.11.)
- dark matter (17.11.)
- proton decay (24.11.)
- background in underground measurements (01.12.)
- cosmic microwave background, Big Bang nucleosynthesis, gravitational waves (15.12.)

5 Atmospheric and geoneutrinos

5.1 Geoneutrinos

Anti-neutrinos from the Earth – A new probe to study the interior of the Earth

- What is the amount of uranium (U), thorium (Th) and kalium (^{40}K) in the Earth?
- Test a fundamental geochemical paradigm: the Bulk Silicate Earth
- Determine the radiogenic contribution to terrestial heat flow
- A georeactor at the core of the Earth?

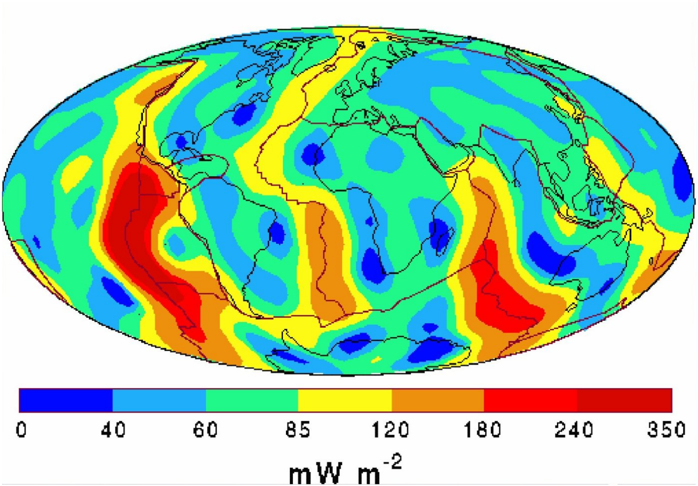
5.1 Geoneutrinos

Heat production in the Earth

- The total heat flow emitted by the Earth is approximately 45 TW
  - equivalent to the heat production of 15000 power plants of 1000 MW_{el}
- The heat flow has been measured at approximatey 25000 locations at the surface of the Earth
  - the map shows large variations (factor of 20) between the locations
- The heat is generated, for example, by the natural radioacivity inside the Earth
  - Uranium (U), Thorium (Th), and Potassium (K)
- The same radioactive decays are believed to be the source of geoneutrinos

5.1 Geoneutrinos

Anti-neutrinos from the Earth – The Earth heat flow



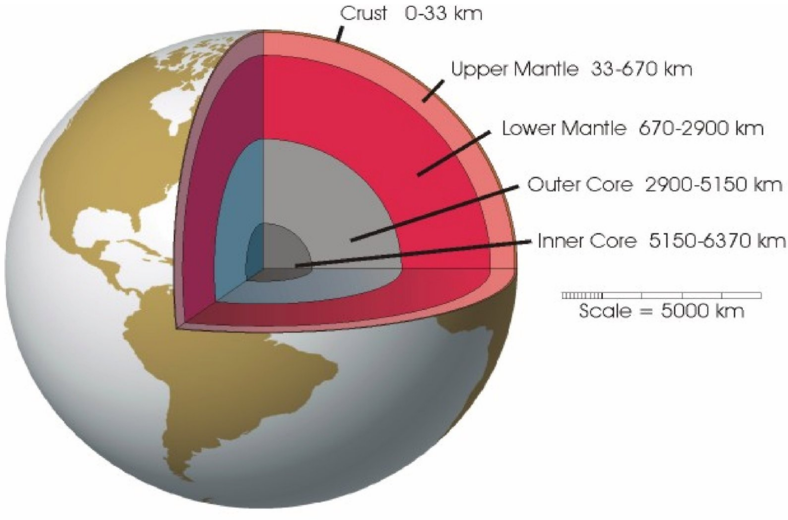
5.1 Geoneutrinos

Models for the Earth

- The deepest drill hole approximately 12 km
  - at Kola Peninsula, Russia
  - initial aim 15 km, 12.261 km reached at 1989 ($T = 180\ ^\circ$C)
  - difficult to drill much deeper due to high temperature and pressure (15 km : $T = 300\ ^\circ$C)
  - approximately one-third on the Baltic continental crust
- Information on the deeper parts obtained/derived from
  - the speed, reflection and refraction of seismic waves
  - the moment of inertia and precession motion of planets
  - physical, chemical and minerological data obtained from meteorites
- The most accepted model of the Earth composition is the Bulk Silicate Earth model (BSE)
  - direct and indirect information combined
  - estimated radiogenic heat production of U, Th, and K in the crust and mantle (r$<$3000 km) not explained correcly

5.1 Geoneutrinos

Models for the Earth



5.1 Geoneutrinos

Anti-neutrinos from the Earth

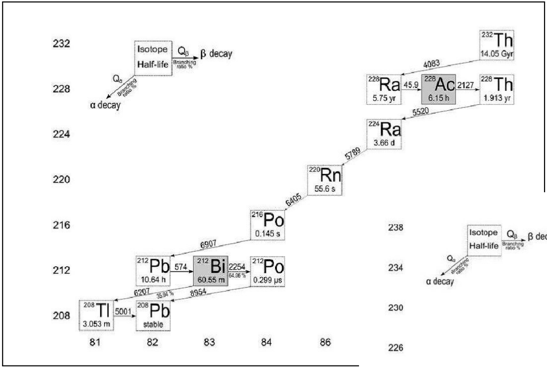
Uranium, thorium and potassium in the Earth release heat together with anti-neutrinos

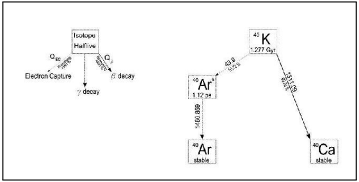
- $^{238}\text{U} \longrightarrow {}^{206}\text{Pb} + 8\cdot\, {}^{4}\text{He} + 6e^{-} + 6\bar{\nu}$
- $^{232}\text{Th} \longrightarrow {}^{208}\text{Pb} + 6\cdot\, {}^{4}\text{He} + 4e^{-} + 4\bar{\nu}$
- $^{40}\text{K} \longrightarrow {}^{40}\text{Ca} + e^{-} + \bar{\nu}$ (K1, 88.8 %)
  $^{40}\text{K} + e^{-} \longrightarrow {}^{40}\text{Ar} + \nu$ (K2, 11.2 %)

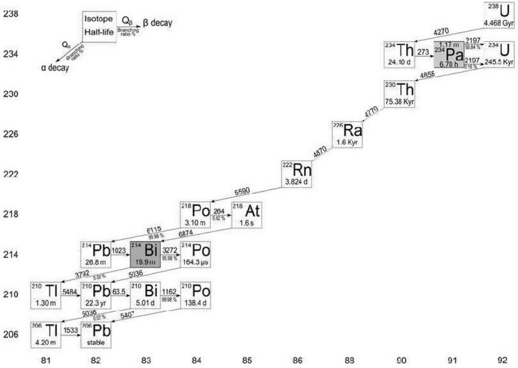
Decay chain	Q [MeV]	$t_{1/2}$ [10^9 yr]	E_{max} [MeV]	ϵ_{H} [W/kg]	$\epsilon_{\bar{\nu}}$ [$\text{kg}^{-1}\cdot\text{s}^{-1}$]
U	51.7	4.47	3.26	0.95×10^{-4}	7.41×10^{7}
Th	42.8	14.0	2.25	0.27×10^{-4}	1.63×10^{7}
K1	1.32	1.28	1.31	0.36×10^{-8}	2.69×10^{4}

5.1 Geoneutrinos

Anti-neutrinos from the Earth – decay chains







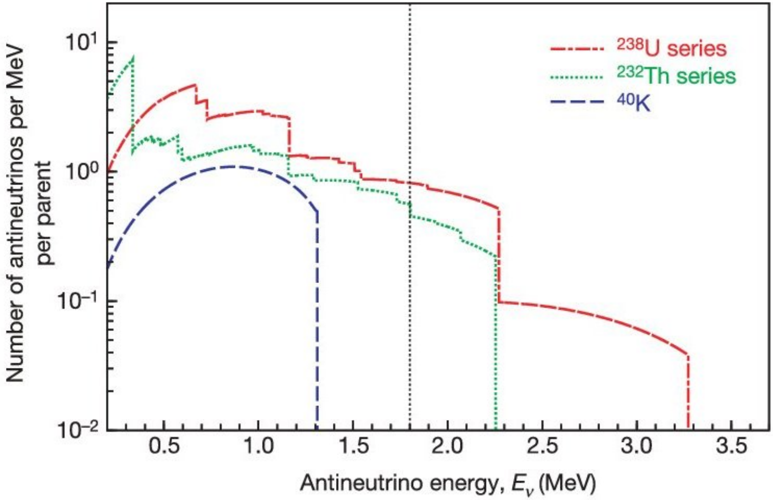
5.1 Geoneutrinos

Anti-neutrinos from the Earth

- High-energy part of neutrinos from U and Th are above the 1.8-MeV threshold for inverse beta decay: $\bar{\nu} + p \longrightarrow n + e^+$
  - can be detected, for example, by liquid scintillation detector
- Different components may be distinguished due to different energy spectra: $\bar{\nu}$ with highest energy comes from uranium
- Main source of background: neutrinos from nuclear reactors
  - energy spectra not complete overlapping:
    nuclear reactor neutrinos originate from fission fragments (geoneutrinos from the chains)
  - neutrino oscillations (depends on energy and distance)

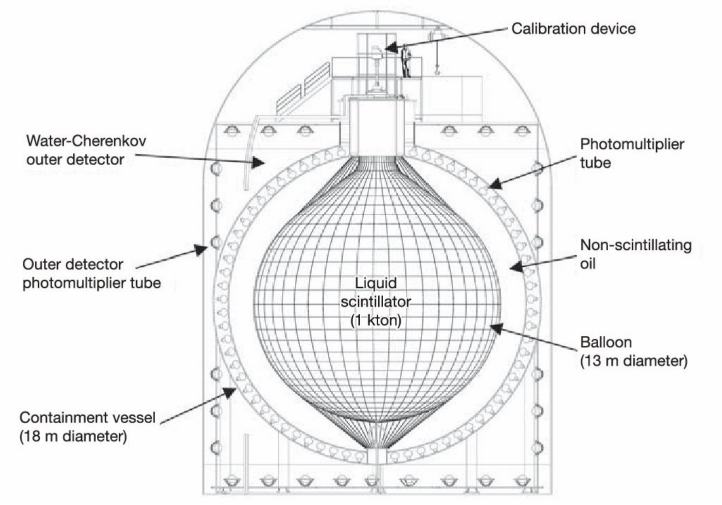
5.1 Geoneutrinos

Anti-neutrinos from the Earth – the energy spectrum



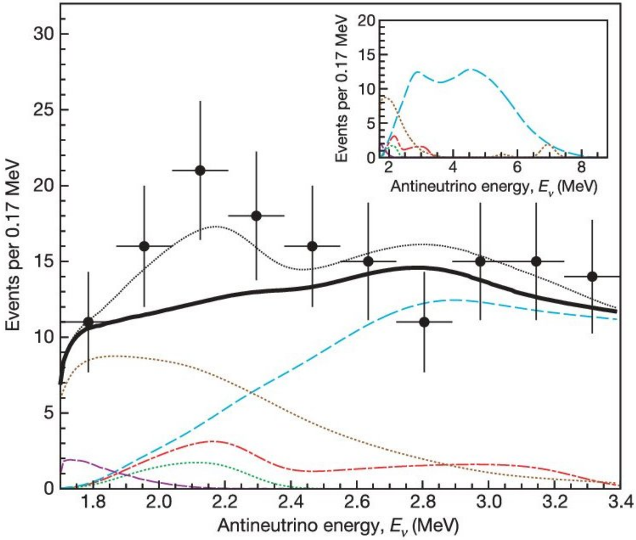
5.2 KamLAND measurement on geoneutrinos

KamLAND – Kamioka Liquid scintillator Antineutrino Detector – 1 kton, depth 1 km



5.2 KamLAND measurement on geoneutrinos

KamLAND – measured energy spectrum



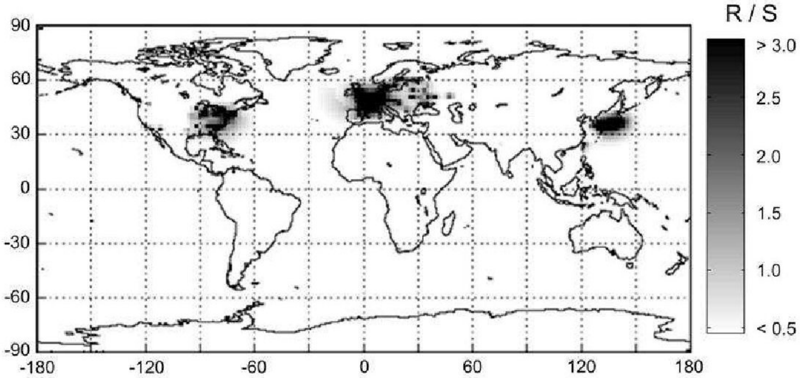
5.2 KamLAND measurement on geoneutrinos

Results & Outlook

- The total number of observed $\bar{\nu}_e$ was 152 in the energy window relevant for geo-ν's
- Background events: 127±13
  - reactor neutrinos: 80.4±7.2
  - radioimpurities of ^{210}Pb: 42±11
    (α-decay of ^{210}Po: $\alpha + {}^{13}\text{C} \longrightarrow {}^{16}\text{O} + \text{n}$)
    can be purified; result of Borexino $\Longrightarrow$ factor ~150 lower
- Measuring time 749 days (~2 years)
- Number of target protons 3.5×10^{31}
- Estimated that geo-ν's arrived in the distance of 200 km
- In Japan, large reactor neutrino background ☞

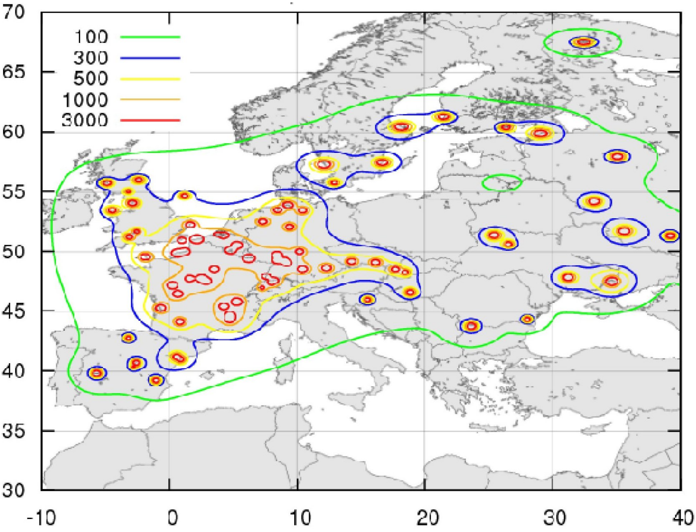
5.2 KamLAND measurement on geoneutrinos

Reactor-ν vs geo-ν events – worldwide



5.3 LENA at Pyhäsalmi

Reactor neutrino events per kiloton



5.3 LENA at Pyhäsalmi

LENA – liquid scintillation detector – 50 kton, depth 1.4 km

Liquid Scintillator
ca. 50kt PXE/LAB

Inner Nylon Vessel
radius: 13m

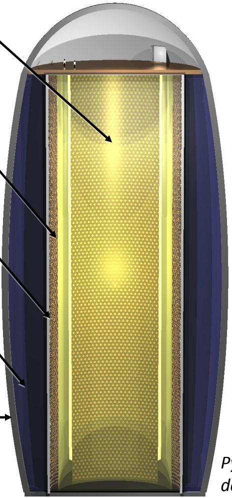
Buffer Region
inactive, Δr = 2m

Steel Tank, 13500 PMs
r = 15m, h = 100m,
optical coverage: .3

Water Cherenkov Veto
1500 PMTs, Δr > 2m
fast neutron shield

Egg-Shaped Cavern
about 10^8 m^3

Overburden: 4000 mwe



Pyhäsalmi design

LENA

Low-Energy
Neutrino
Astrophysics

organic liquid:
in total 70kt

diameter
governed by
scintillator
transparency

PM config
optimization
PMm^2

5.3 LENA at Pyhäsalmi

For geo-ν detection

- Three advantages over KamLAND
  - nuclear reactor background lower (factor of $\sim$10)
  - larger detector volume
    (number of target protons 2.5×10^{33})
  - better purification to clean ^{210}Pb (obtained in Borexino)
    $\Longrightarrow$ nearly negligible contribution
- Geo-ν events in Pyhäsalmi $\sim$1300 per year
  - nuclear reactor ν events $\sim$300
  - ^{210}Pb events $\sim$10
- Accurate determination of nuclear reactor background under investigation, including the newest and closest reactors
- 2 TW hypothetical georeactor at the core of the Earth could be identified after one year measurement

5.4 Atmospheric neutrinos

General

- Atmospheric neutrinos are produced in the decays of pions, kaons and muons
  - π, K and μ created by cosmic-ray secondary particles
  - $\pi^+ \longrightarrow \mu^+ + \nu_\mu$, $\qquad \pi^- \longrightarrow \mu^- + \bar{\nu}_\mu$
  - $\mu^+ \longrightarrow e^+ + \nu_e + \bar{\nu}_\mu$, $\qquad \mu^- \longrightarrow e^- + \bar{\nu}_e + \nu_\mu$
  - $K^+ \longrightarrow \mu^+ + \nu_\mu$, $\qquad K^- \longrightarrow \mu^- + \bar{\nu}_\mu$

    $K_L \longrightarrow \pi^\pm + e^\pm + \nu_\mu(\bar{\nu}_\mu)$
- Energy classification
  - below the knee energies $\Longrightarrow$ high energies
  - above the knee $\Longrightarrow$ ultra-high energies (☞ 5.6)
- Energy of high-energy atmospheric neutrinos is at the GeV range
  - the spectrum of secondary particles peaks at about 1 GeV, tail goes to higher energies
  - at above few GeV the contribution of muons is getting smaller and contribution of kaons is becoming more important
  - flux of cosmic rays is known pretty well, solar effects

5.4 Atmospheric neutrinos

General – high energies

- Atmospheric neutrinos are used for studying neutrino oscillation
  - oscillation phenomenom is a function of L/E
- Atmospheric neutrinos provide a long range for the baseline: $L \sim 10^0$ km – 10^4 km
  - up- and down-going neutrinos (muons)
- First hints for neutrino oscillation at the end of 1980's from Kamiokande, IMB and others
  - were too small for definitive conclusions
- Super-K made the definitive measurement (1489 days):

$$\frac{(N_\mu/N_e)_{\text{data}}}{(N_\mu/N_e)_{\text{MC}}} = 0.688 \pm 0.016 \pm 0.050$$

  - sub-GeV region
  - relative quantities are used as absolute fluxes involve large uncertainties

5.5 Accelerator neutrinos

Long-baseline experiments: KEK to Kamioka, K2K

- First accelerator-based long-baseline neutrino experiment
- Neutrinos are produced by 12 GeV protons hitting on Al target of 65 cm long and 2 cm diameter
  - average energy of ν_μ is 1.4 GeV
  - contamination of muon decay and kaons $\sim$1 %
- Baseline 250 km
  - near detector 300 m away from the production target (1 kt WC)
- First year of data taking: 2.3×10^{29} pot (protons on target)
- Super-K observed 56 μ_μ-events, but expected 80$\pm$6 (from the near detectors hits)
  - this is clear deficit
  - in good agreement with results obtained from atmospheric data
  - if the deficit stays with more statistics, it would be significant result
- KEK upgrade to 50 GeV protons
  - allows to search for ν_τ appearence

5.5 Accelerator neutrinos

Long-baseline experiments: Fermilab to Soudan, MINOS

- Fermilab to Soudan baseline 730 km
- Average neutrino energy is 3 GeV
- MINOS experiment at Soudan mine (far detector)
  - calorimeter of 486 magnitized iron plates of 2.54 cm thick
  - interrupted by 4.1 cm thick plastic scintillation detectors
  - average toroidal magnetic field of 1.3 T
  - total mass 5.4 kt
- Near detector: 980 tons 900 metres away from the production target
- Data taking started 2005
  - aim: pure ν_μ-disappearance search
  - An exposure of 10 kt $\times$ year ($\sim$two years) needed

5.5 Accelerator neutrinos

Long-baseline experiments: CERN to Gran Sasso, CNGS

- CERN to Gran Sasso baseline 732 km
- Idea is to search directly for ν_τ-appearance
- Two detectors at Gran Sasso
  - ICARUS: liquid argon TPC detector of $\sim$3 ktons
  - OPERA: lead-emulsion detector of $\sim$2 ktons
- In five years of data taking 2.25×10^{20} pot and a total of 18 events expected (OPERA)
  - used event-by-event analysis $\longrightarrow$ considered background free
- Running a couple of years

5.5 Accelerator neutrinos

Long-baseline experiments: CERN to LAGUNA baselines

5.6 Ultra-high energy neutrinos

General

- Idea: existence and observation of cosmic rays at high energies (up to $\sim 6\times 10^{19}$ eV)
  $\Longrightarrow$ possibilities to observe neutrinos at up to the same energy
- Originate from decay of secondaries like pion and kaon
- Like photon, neutrino is not affected by a magnetic field
- Are not absorbed by the interstellar medium or radiation
  - above 1 TeV the view of the universe in photons is limited: TeV photons are damped due to reactions with the IR background and PeV photons by the CMB

  $\Longrightarrow$ search for hidden sources
- Neutrinos are thus excellent candidates for finding point sources
  - might help to identify the sources of cosmic rays
- Upward-going muons
- NESTOR and ANTARES, and AMANDA and ICECUBE, and KM3NeT

5.6 Ultra-high energy neutrinos

Science case

- Astroparticle physics with neutrinos
  - HE neutrinos « astronomy »
  - Diffuse flux and link with CR
- Dark matter and exotic particles
  - Dark matter (WIMP) annihilation in the center of the Sun or in the GC
  - Magnetic monopoles…
- Neutrino and particle physics (~10^5 ν_{atm}/year)
  - UHE cross section
  - Neutrinos oscillation
  - Lorentz invariance test…
- Earth and marine sciences
  - Long-term, continuous measurements in deep-sea
  - Marine biology, oceanography, geology/geophysics, …

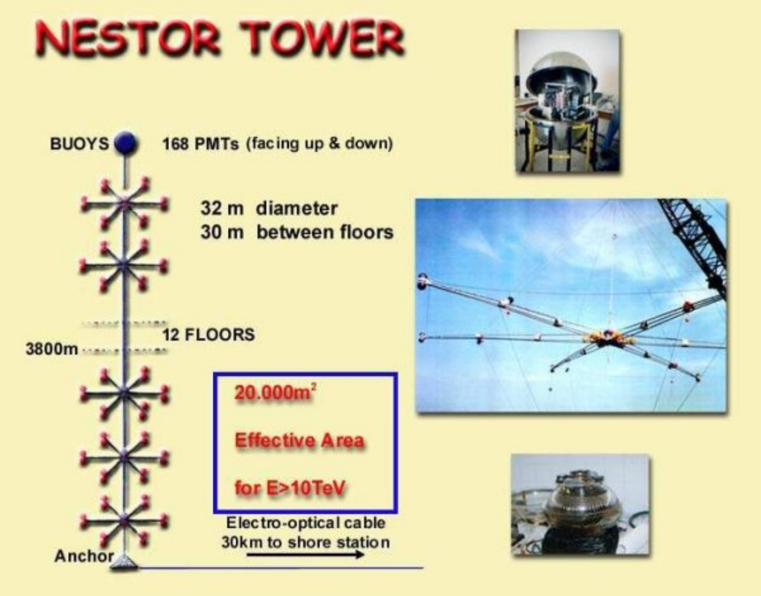
5.6 Ultra-high energy neutrinos

Experiments – NESTOR and ANTARES – at Mediterranean Sea

- NESTOR – Neutrino Extended Submarine Telescope with Oceanographic Research
  - at Mediterranean Sea, 14 km off the shore in Pylos, Greece, at the depth of 3800 m
  - water Cherenkov detector with 169 PMT's ☞
  - aim seven towers, installation started in March 2003
- ANTARES – Astronomy with a Neutrino Telescope and Abyyss environmental RESearch
  - was completed in May 2008
  - at Mediterranean Sea, 40 km off the shore near Toulon, France, at the depth of 2400 m
  - water Cherenkov detector, design: ∼900 PMT's in 10 lines, lines separated by 60 m ☞
  - energy threshold of 10 GeV

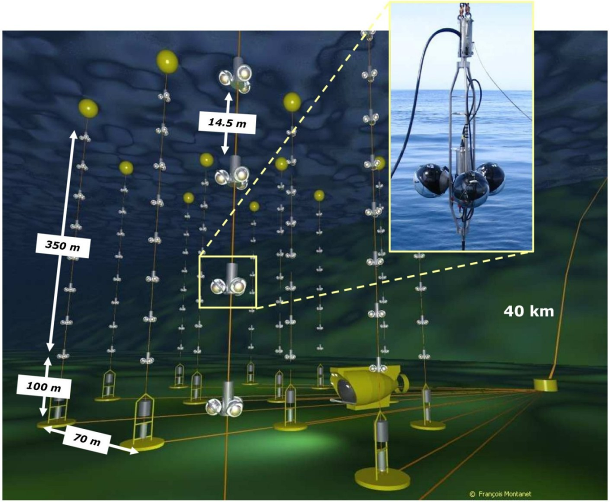
5.6 Ultra-high energy neutrinos

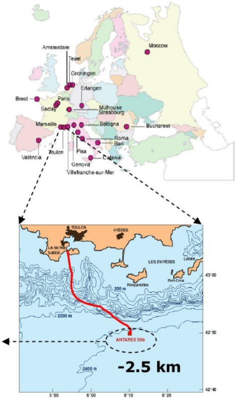
Experiments – NESTOR – at Mediterranean



5.6 Ultra-high energy neutrinos

Experiments – ANTARES – at Mediterranean

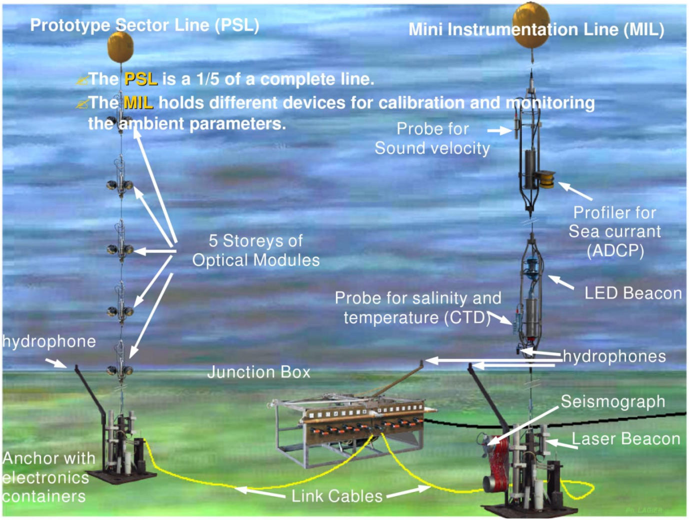




12 lines
25 storeys/line
3 PMTs/storey
900 PMTs

5.6 Ultra-high energy neutrinos

Experiments – ANTARES – at Mediterranean



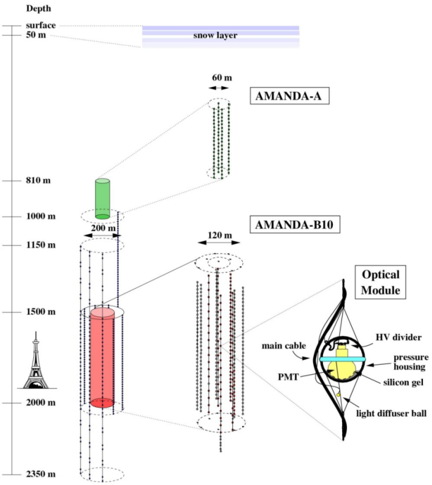
5.6 Ultra-high energy neutrinos

Experiments – AMANDA and ICECUBE – South Pole

- Ice Cherenkov detectors in the Antarctica
- AMANDA – Antarctic Muon And Neutrino Detector Array
  - AMANDA-A – exploratory phase, at a depth of 800–1000 m
  - AMANDA B-10 – installed between 1995 and 1997 at a depth of 1500–2000 m, consists of 302 PMT's, outer diameter 120 m
  - AMANDA-II – completed January 2000, 677 PMT's
- AMANDA-II – four years of data ☞
- ICECUBE
  - with the surface detector ICETOP
  - goal 1 km^3 detector, under construction

5.6 Ultra-high energy neutrinos

Experiments – AMANDA



AMANDA as of 2000
Eiffel Tower as comparison
(true scaling)

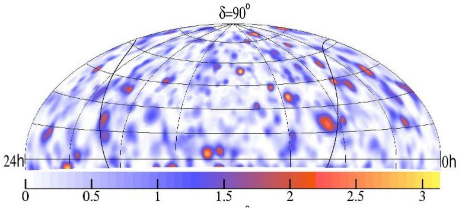
zoomed in on
AMANDA-A (top)
AMANDA-B10 (bottom)

zoomed in on one
optical module (OM)

5.6 Ultra-high energy neutrinos

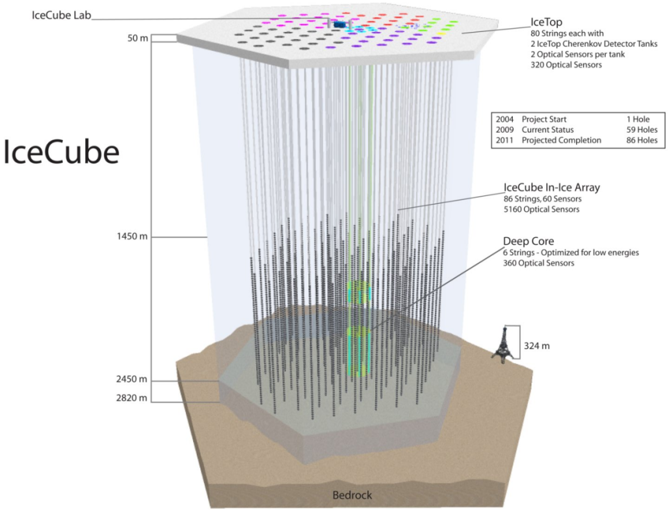
Experiments – AMANDA – results from 1387 days and 6595 events

Candidate	$\delta(°)$	$\alpha(h)$	Φ_{90}	p	$\Psi(°)$	N
3C 273	2.05	12.49	8.71	0.086	2.1	3
SS 433	4.98	19.19	3.21	0.64	2.2	1
GRS 1915+105	10.95	19.25	7.76	0.11	2.3	8
M87	12.39	12.51	4.49	0.43	2.3	3
PKS 0528+134	13.53	5.52	3.26	0.64	2.3	0
3C 454.3	16.15	22.90	2.58	0.73	2.3	5
Geminga	17.77	6.57	12.77	0.0086	2.3	2
Crab Nebula	22.01	5.58	9.27	0.10	2.3	7
GRO J0422+32	32.91	4.36	2.75	0.76	2.2	3
Cyg X-1	35.20	19.97	4.00	0.57	2.1	3
MGRO J2019+37	36.83	20.32	9.67	0.077	2.1	7
4C 38.41	38.14	16.59	2.20	0.85	2.1	4
Mrk 421	38.21	11.07	2.54	0.82	2.1	3
Mrk 501	39.76	16.90	7.28	0.22	2.0	6
Cyg A	40.73	19.99	9.24	0.095	2.0	3
Cyg X-3	40.96	20.54	6.59	0.29	2.0	8
Cyg OB2	41.32	20.55	6.39	0.30	2.0	8
NGC 1275	41.51	3.33	4.50	0.47	2.0	4
BL Lac	42.28	22.05	5.13	0.38	2.0	2
H 1426+428	42.68	14.48	5.68	0.36	2.0	3
3C66A	43.04	2.38	8.06	0.18	2.0	6
XTE J1118+480	48.04	11.30	5.17	0.50	1.8	3
1ES 2344+514	51.71	23.78	5.74	0.44	1.7	2
Cas A	58.82	23.39	3.83	0.67	1.6	2
LS I +61 303	61.23	2.68	14.74	0.034	1.5	5
1ES 1959+650	65.15	20.00	6.76	0.44	1.5	5



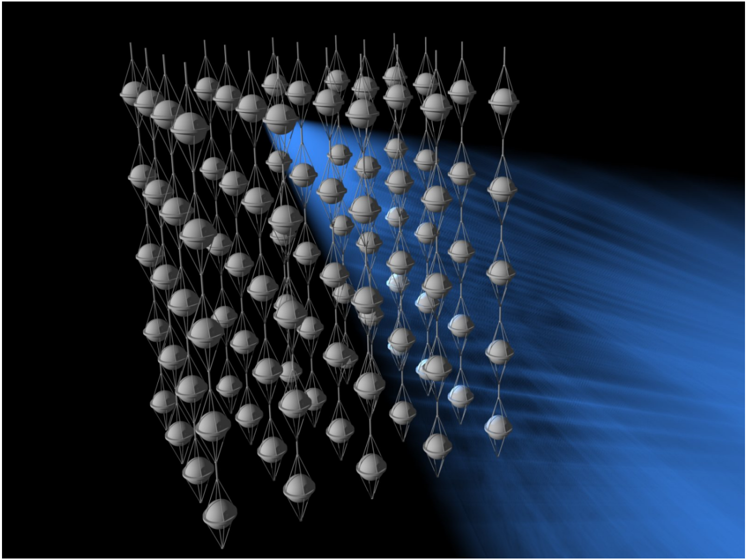
5.6 Ultra-high energy neutrinos

Experiments – ICECUBE – South Pole



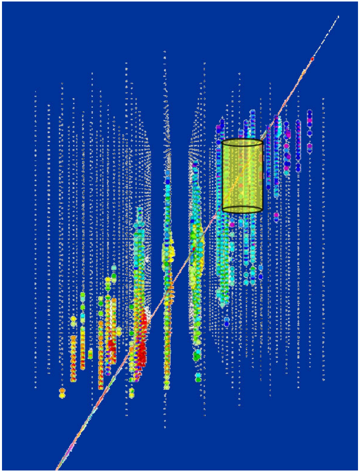
5.6 Ultra-high energy neutrinos

Experiments – ICECUBE – South Pole



5.6 Ultra-high energy neutrinos

Experiments – ICECUBE – South Pole



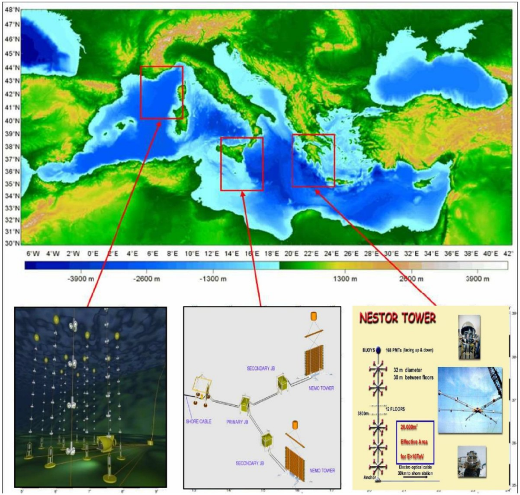
5.6 Ultra-high energy neutrinos

Future experiments – KM3NeT – Mediterranean Sea

- Cubic kilometre size (**KM3**) **Ne**utrino **T**elescope
- Neutrino telescope at the Mediterranean Sea
  - volume at least one cubic kilometre
- Experience from ANTARES, NESTOR and NEMO experiments
- In preparatory phase, design study completed soon
- Construction should start around March 2011
- Data taking should start around September 2011 (with partial setup)

5.6 Ultra-high energy neutrinos

Future experiments – KM3NeT – Mediterranean Sea



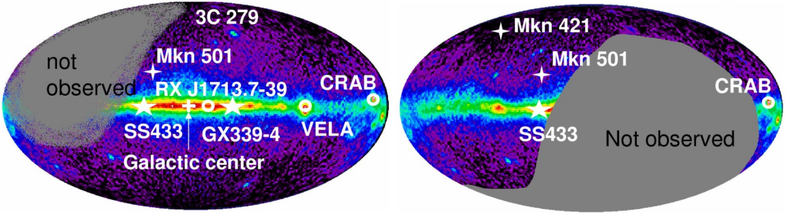
- Locations of the three pilot projects:
  - ANTARES: Toulon
  - NEMO: Capo Passero
  - NESTOR: Pylos
- All appear to be suitable
- Long-term site characterisation measurements performed and ongoing
- Decisions: KM3NeT-PP

5.6 Ultra-high energy neutrinos

Complementarity of the experiments

Instantaneous common view: 0.5 π sr
Averaged common view : 1.5 π sr

KM3NeT (43° North) | ICECUBE (South Pole)



Galactic center: visibility 0.66

Angular resolution:
E>10 TeV: ~0.1 deg

GC not seen

Angular resolution
E>10 TeV: ~0.7 deg