高エネルギーニュートリノ

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宇宙線将来計画シンポジウム(Dec.5/6,2005@ICRR)

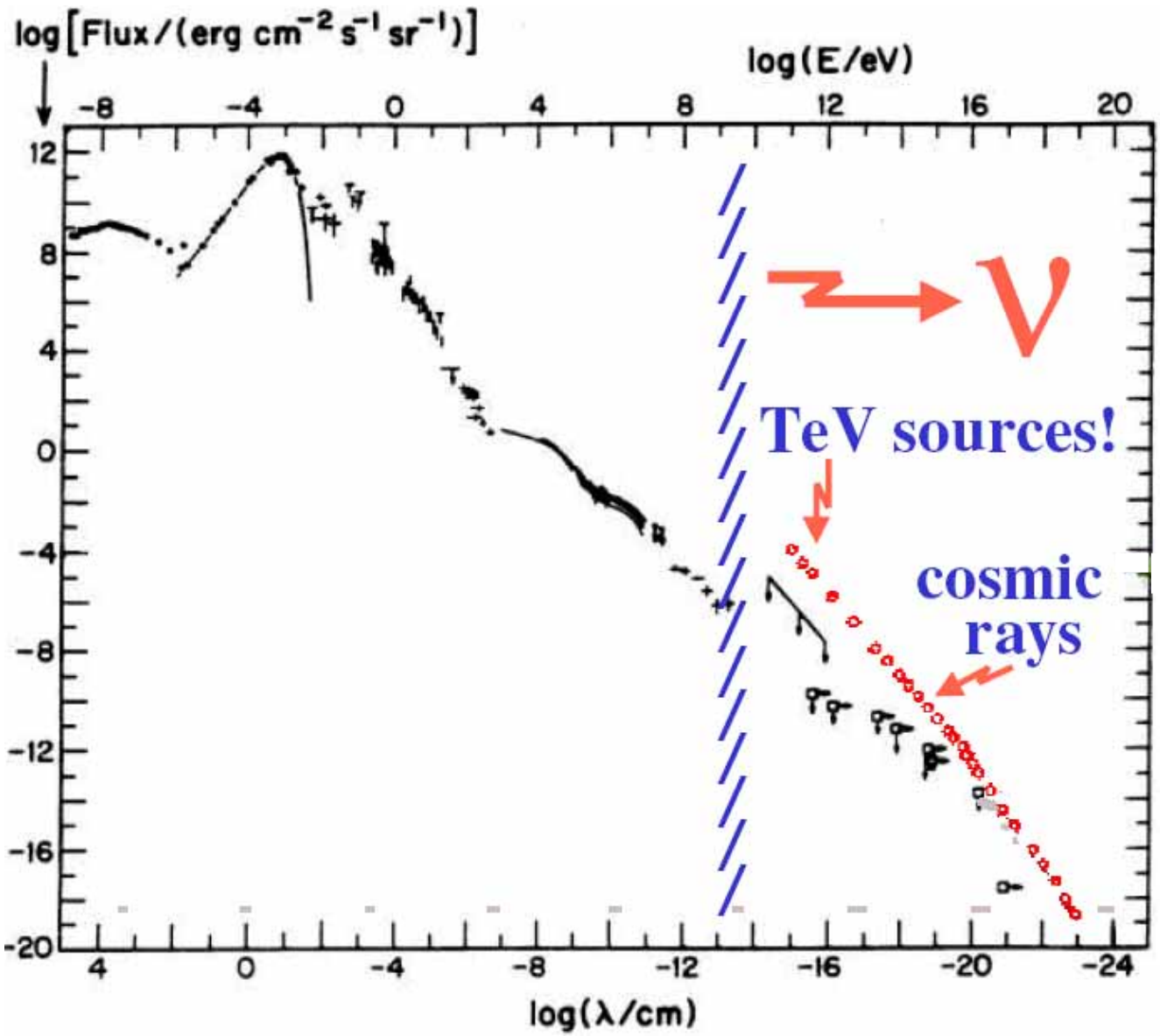
Outline

- Why HE neutrinos ?
- Summary of current projects
- Brief review of Ashra
- Brief review of IceCube
- Summary and comments

Why High Energy Neutrinos ?

- Open the new window of astronomy
- Settle the origin of high energy cosmic rays
- Search for EHE neutrinos
  - GZK neutrinos, Z-burst, TD, decay of super-heavy particles ……
- Search for neutrinos from the annihilation of WIMPs, magnetic monopoles, ……
- Neutrino properties, ……

New Windows

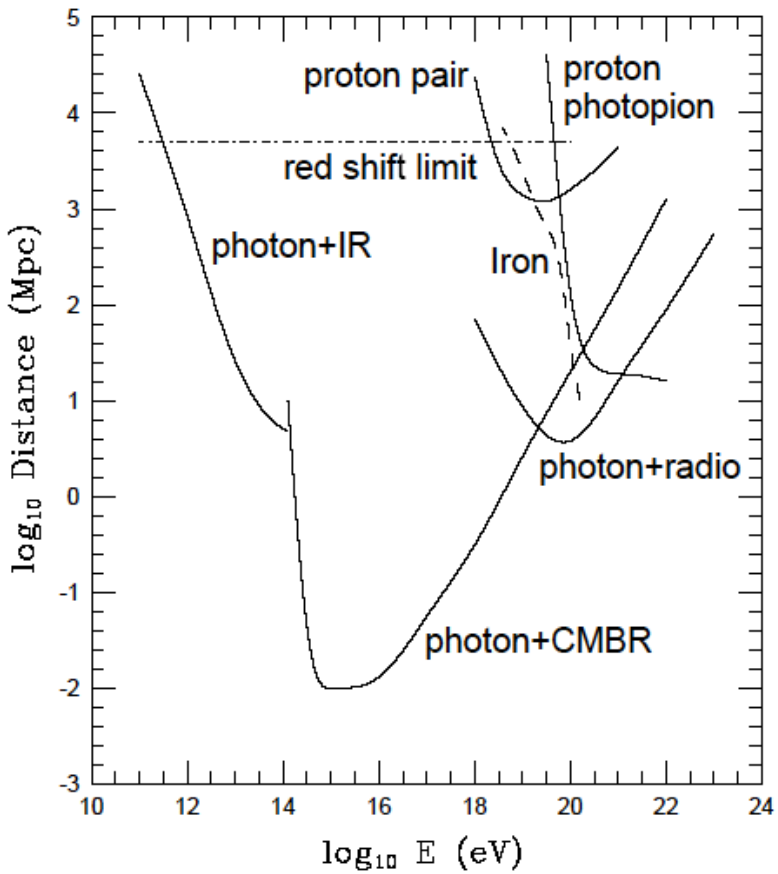

log[Flux/(erg cm^{-2} s^{-1} sr^{-1})]
log(E/eV)
-8
-4
0
4
8
12
16
20
12
8
4
0
-4
-8
-12
-16
-20
4
0
-4
-8
-12
-16
-20
-24
log(λ/cm)
ν
TeV sources!
cosmic rays

What are Advantages of Neutrinos?

- Gamma-rays

$$\gamma + \gamma_{\text{bkgnd}} \rightarrow e^{+} + e^{-}$$

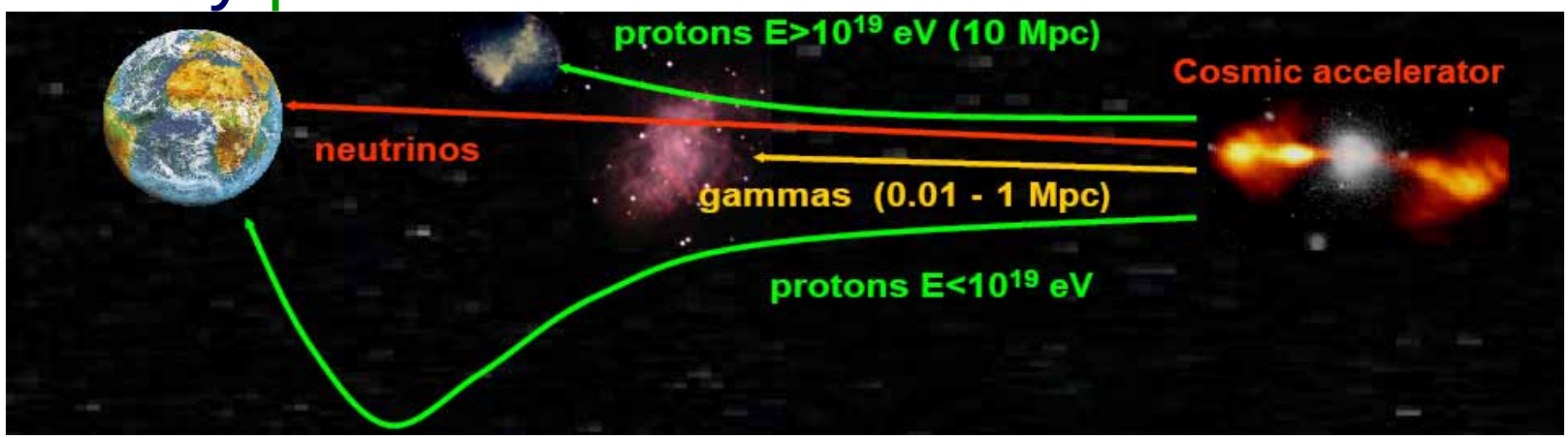
  - absorbed on dust and radiation
    - TeVγ+ IR photons (~100 Mpc)
    - PeVγ+ CMB (~ 10 kpc)
  - The Universe is not transparent to photons of TeV energy and above.



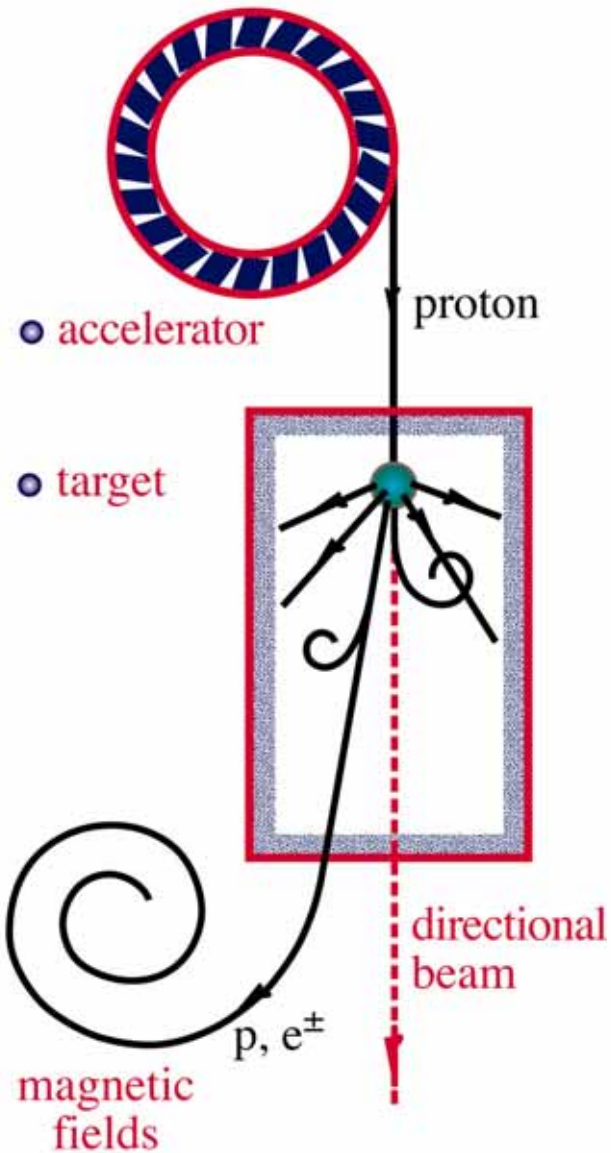
- Protons/Nuclei
  - deviated by magnetic field
  - reactions with radiation(CMB)

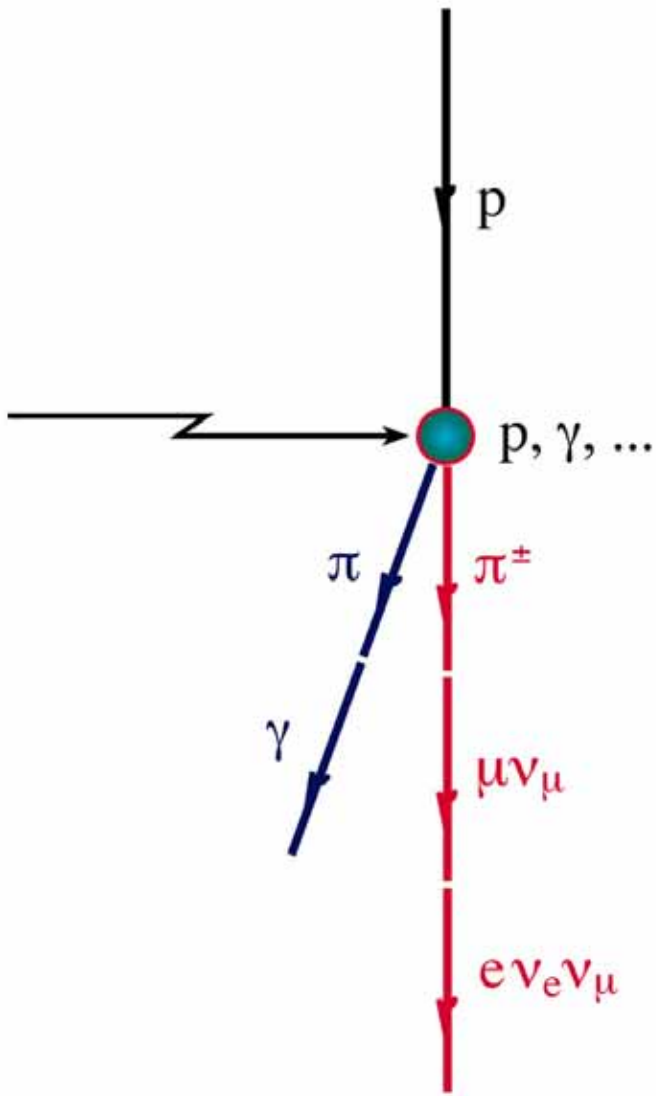
What are Advantages of Neutrinos?

- Neutrinos traverse space without deflection or attenuation.
  - Far distant high energy universe may be investigated only with neutrinos.
  - They allow for a view into dense environment, obscured sources and hidden sources.
  - They point back to their sources

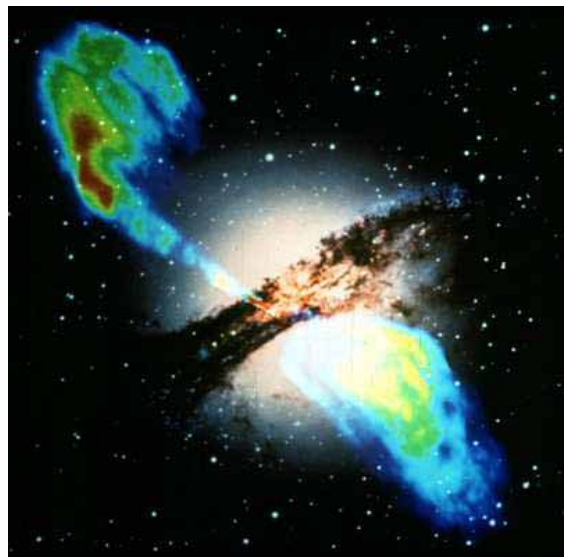


Generation of Neutrinos





Black hole



Radiation enveloping black hole

Origin of Cosmic Rays

- Settle the origin of high energy cosmic rays
  - Galatic: Supernovae, SNRs, Microquasars, Pulsar/Plerion, ……
  - Extragalactic: AGN, GRB, ……
- Neutrinos are produced in high energy hadronic processes. → Unlike gammas, neutrinos provide unambiguous evidence for cosmic ray acceleration!

$$p + p(\gamma) \rightarrow p(n) + \pi \rightarrow \gamma$$
$$\rightarrow \mu + \nu$$

Galactic Sources

Table 4 Brief summary of the models described in this review paper. The source type and distance are indicated, the process that produces neutrinos, the duration of the neutrino emission (D) or/and the source age (A), the relevant energy region for producing the given event rates in a km^2 detector per year and the neutrino flux spectrum.

Source type	distance (kpc)	process	duration of emission (D) or source age (A)	E_ν (GeV)	dN/dE_ν (GeV^{-1} m^{-2} s^{-1})	N_{ν_μ} ($km^{-2}yr^{-1}$)	Ref.
supernovae	10						
shocks		pp	~ 1 hr (D) ~ 10 hrs (A)	$\lesssim 10^3$	$\propto E^{-2}$	~ 100	Waxman & Loeb (2001)
pulsars		$Fe-\gamma \to n$	~ 0.1 yrs (D)	$\sim (10^2 - 10^6)$	$(10^{-5} - 10^{-4})E^{-(1.7 \div 1.8)}(< 10^4 GeV)$	$50 - 10^3$	Protheroe et al.
		np			$(10^3 - 10^6)\ E^{-(3.6 \div 3.7)}(> 10^4 GeV)$		(1998)
					(for P = 5-10 ms)		
		$N-\gamma$+Fe-N	$10^4 - 10^7$ s (D)	$\sim 10^5 - 10^8$	$\propto E^{-1}$	$\sim 10 - 10^3$	Beall & Bednarek (2002)
		pp	$\lesssim 100$ yrs (D)	$\sim 10 - 10^8$		$\lesssim 10^3$	Nagataki (2004)
Plerions	0.5-4.4	pp	$\lesssim 3 \cdot 10^4$ yrs (A)	$< 10^3 - 10^5$	$(0.15 - 1.85) \cdot 10^{-10} E^{-(2.4 \div 2.6)}$	$\sim 1 - 12$	Guetta & Amato (2003, private communication)
		$Fe-p$		$\sim 10^3 - 5 \cdot 10^5$		$\lesssim 1$	Bednarek (2003a)
Crab	2	$Fe-\gamma \to n$	$\sim 10^3$ yrs (A)	$\sim 10^3 - 5 \cdot 10^5$	$1.7 \cdot 10^{-6}\ E^{-1.6}(< 10^4 GeV)$	few	Bednarek & Protheroe
		np			$1.5 \cdot 10^2\ E^{-3.6}(> 10^4 GeV)$		(1997)
		$Fe-p$		$\sim 10^3 - 5 \cdot 10^5$	$4 \cdot 10^{-8}\ E^{-1.44}(< 6 \cdot 10^4 GeV)$	~ 1	Bednarek (2003a)
					$3.1 \cdot 10^{14}\ E^{-6.11}(> 6 \cdot 10^4 GeV)$	~ 1	Bednarek (2003a)
		pp		$10 - 10^6$	$\propto E^{-2.25}$	$\sim 4 - 14$	Amato et al. (2003)
shell SNRs							
SNR RX J1713.7-3946	6	pp	$\sim 10^3$ yrs (A)	$\lesssim 10^4$	$4.1 \cdot 10^{-4}\ E^{-2}$	~ 40	Alvarez-Muniz & Halzen
Sgr A East	8		$\sim 10^4$ yrs (A)	$\lesssim 10^5$		~ 140	(2002)
Pulsars + clouds							
Galactic Centre	8	$Fe-p$	$\sim 10^4$ yrs (A)	$10^4 - 10^7$	$0.166 \cdot E^{-2.64}$	$\sim 2 - 30$	Bednarek (2002)
Cygnus OB2	1.7	pp	$\sim 10^6$ yrs (A)	$> 10^3$	$\propto E^{-2}$	few	Torres et al. 2004
		$Fe-p$	$\sim 10^4$ yrs (A)	$10^4 - 10^7$		~ 0.5	Bednarek (2003b)
		$Fe-\gamma \to n$	$\sim 10^6$ yrs (A)	$\lesssim 10^6$	$\propto E^{-3.1}$	~ 4	Anchordoqui et al. (2003a)
binary systems							
A0535+26	2.6	pp	$\sim 10^6$ yrs (A)	$3 \cdot 10^2 - 10^3$	$4.2 \cdot 10^{-3} E^{-2.35}$	few	Anchordoqui et al. (2003b)
Microquasars	1-10	pp	days/yrs (D)	$10^3 - 10^5$	$\propto E^{-2}$	1-300	Distefano et al. (2002)
magnetars	3-16	$p\gamma$	$< 10^4$ yrs (A)	$\lesssim 100$ TeV	$\propto E^{-2}$	$1.7\times\ (0.1/\Delta\Omega)(5/d)^2$	Zhang et al. (2003)

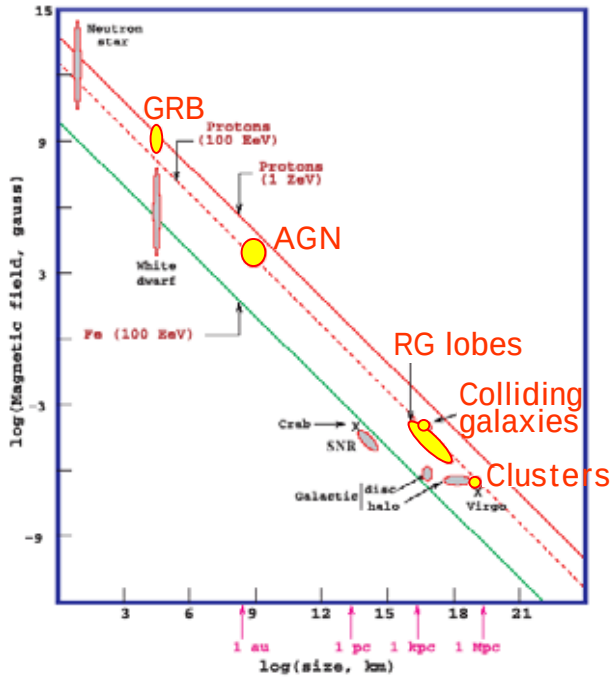
W.Bednarek, G.F.Burgio, and T. Montaruli, New Astron.Rev. 49 (2005) 1

Extragalactic Sources

- Cosmic accelerator $\Rightarrow$ $E = \Gamma c B R$
- Luminosity constraint for UHECR sources from potential drop generated by an outflow of magnetized plasma

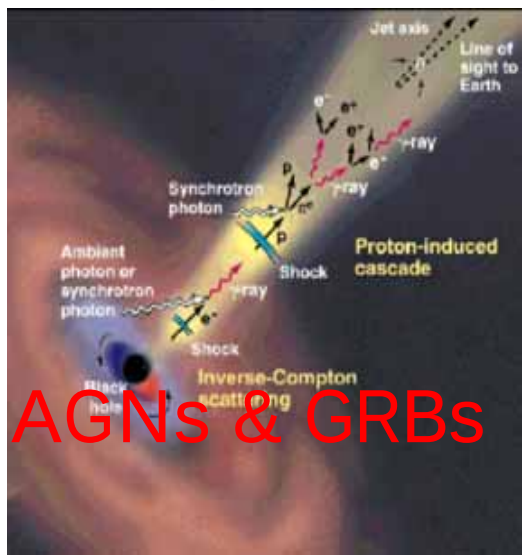
$$L > 10^{45.5} \frac{\Gamma^2}{\beta} \left(\frac{E_p}{10^{20}\,\mathrm{eV}} \right)^2 \mathrm{erg/s}$$

$\Rightarrow$ AGNs & GRBs



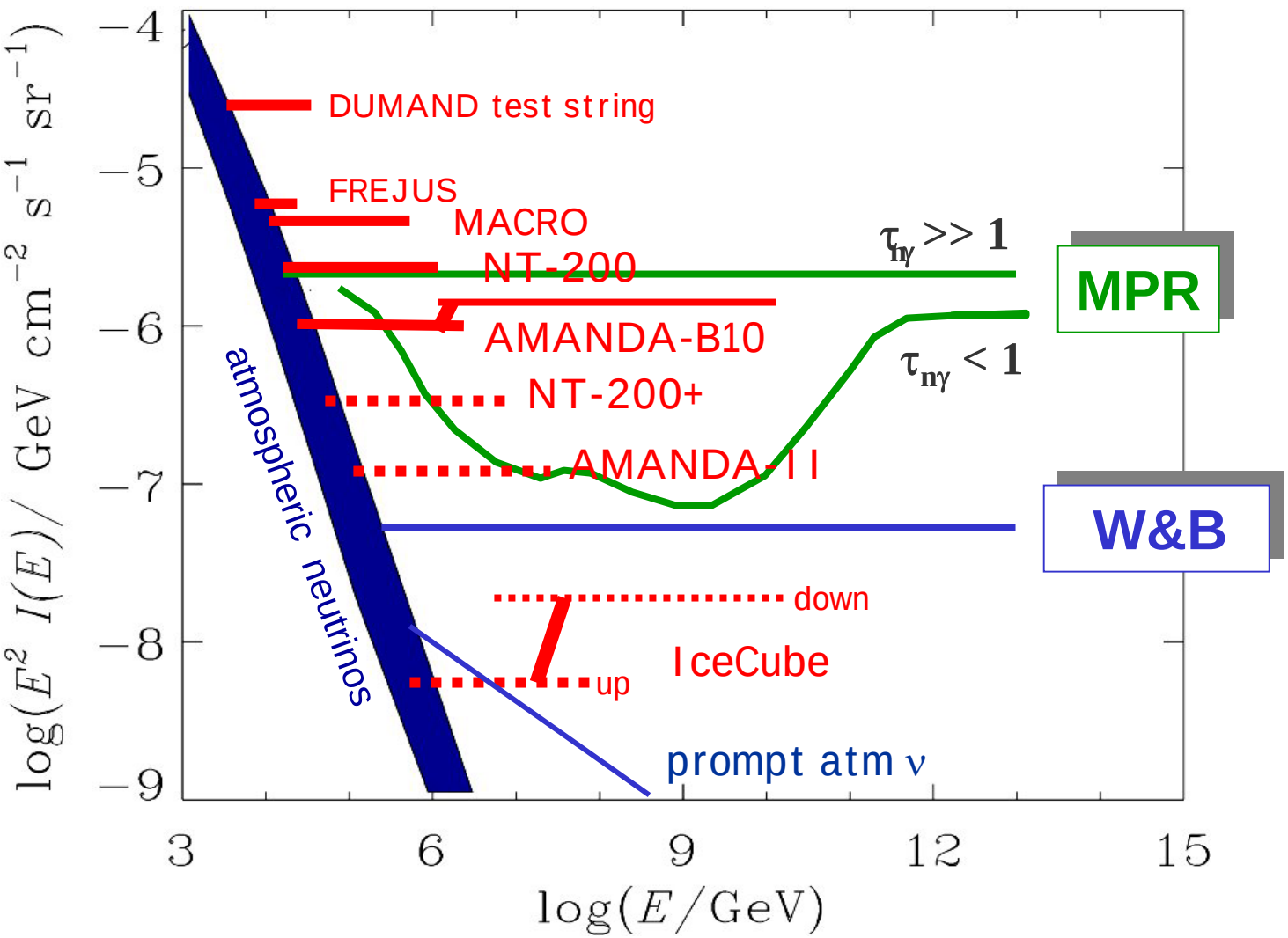
- Neutrino flux required for the detection $\rightarrow$ Luminosity

$$L_\nu \approx 10^{46} N d_{L,28}^2 \left(\frac{E_\nu}{100\mathrm{TeV}} \right)^{1-\alpha} \left(\frac{\mathrm{AT}}{\mathrm{km}^2\mathrm{yr}} \right)^{-1} \mathrm{erg/s} \Rightarrow$$



AGNs & GRBs

Diffuse Fluxes: Theoretical Bound and Experimental Limits



EHE Neutrino Sources

- GZK neutrinos

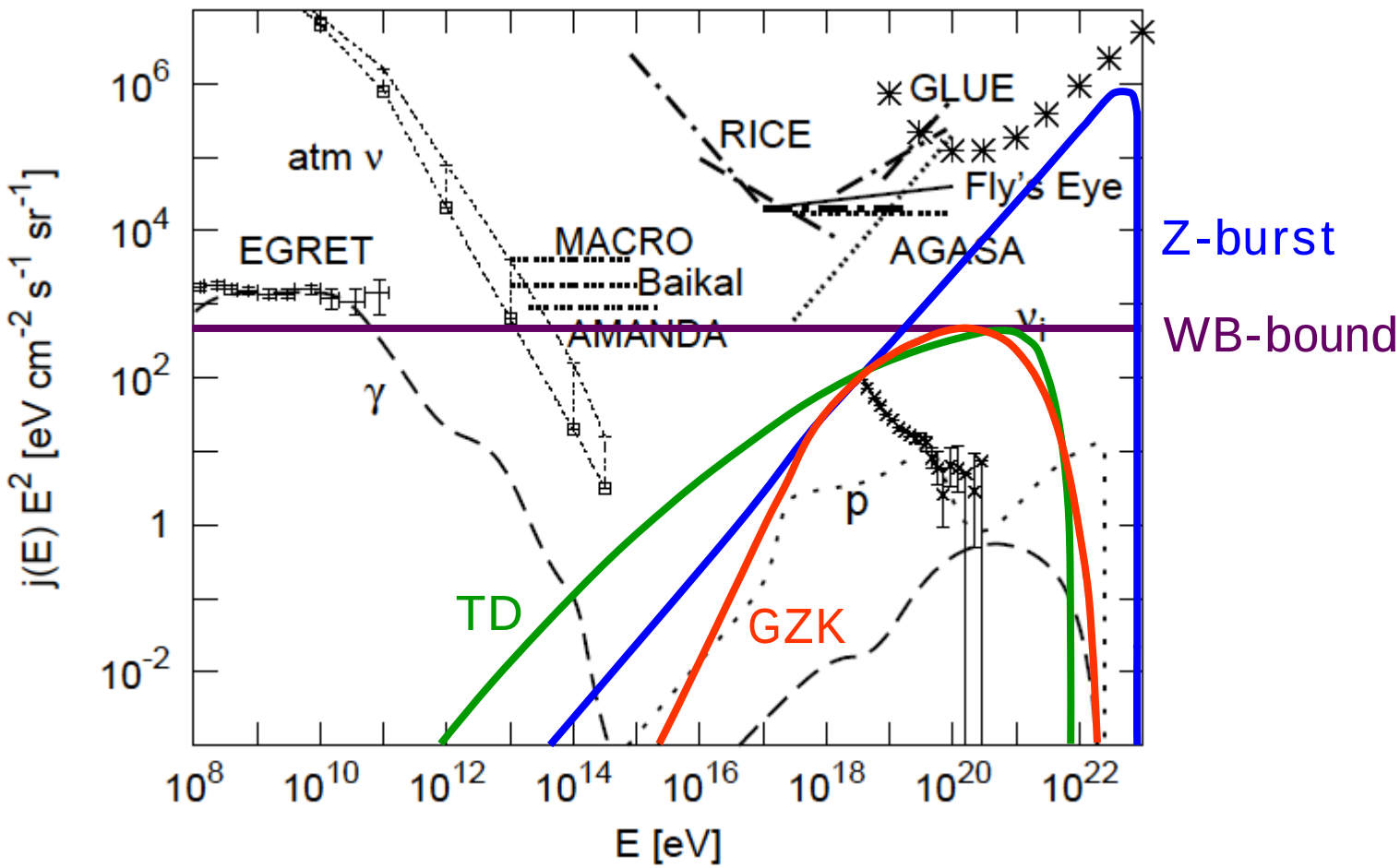
$$p(>5\times10^{19}\text{eV}) + \gamma \rightarrow \Delta \rightarrow \pi^0(\pi^+) + p(n)$$

- *Z*-burst

$$\nu + \nu_b \rightarrow Z$$

- Top-down neutrinos
  - Topological defects
  - Neutrinos from the annihilation of WIMPs
  - Decay of super-heavy particles with the masses up to $M_{\text{GUT}} \sim 10^{16}$ GeV
  - magnetic monopoles
  - Vibrating cosmic strings
  - Hawking radiation from primordial black holes
  - etc. ……

Predicted Neutrino Fluxes

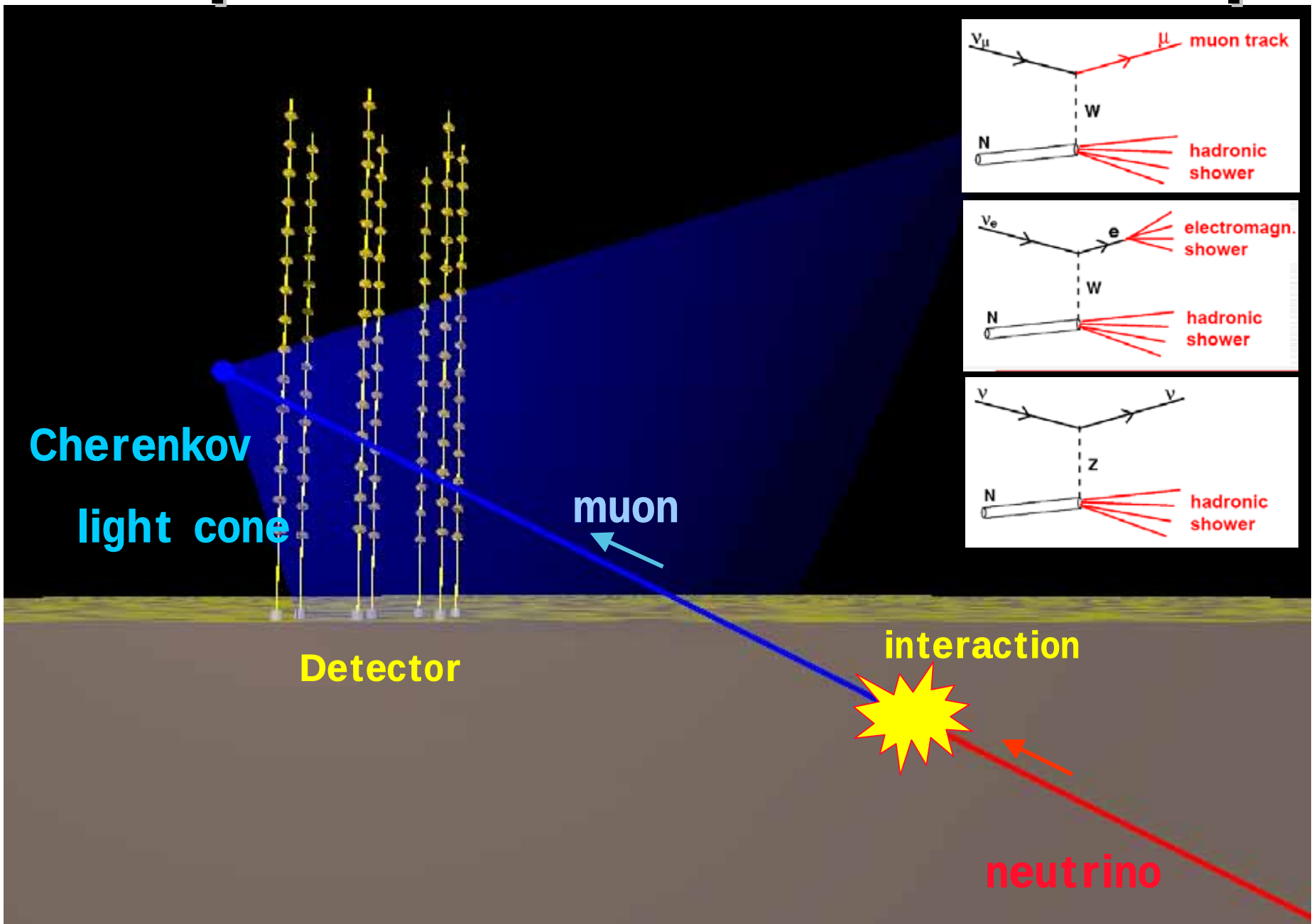


O.E.Kalashev et al., PRD66,063004(2003)

Neutrino Telescope

- **Cherenkov** telescope under water and ice
  - BIKAL
  - AMANDA
  - ICECUBE
  - ANTARES
  - NESTOR
  - NEMO
- **Acoustic** detection
  - AUTEC
- **Radio** detection
  - RICE
  - GLUE
  - ANITA
  - SALSA
- **Air showers**
  - AGASA
  - HiRes
  - AUGER
  - TA
  - EUSO
  - Ashra, … …

Principle of Cherenkov Telescope



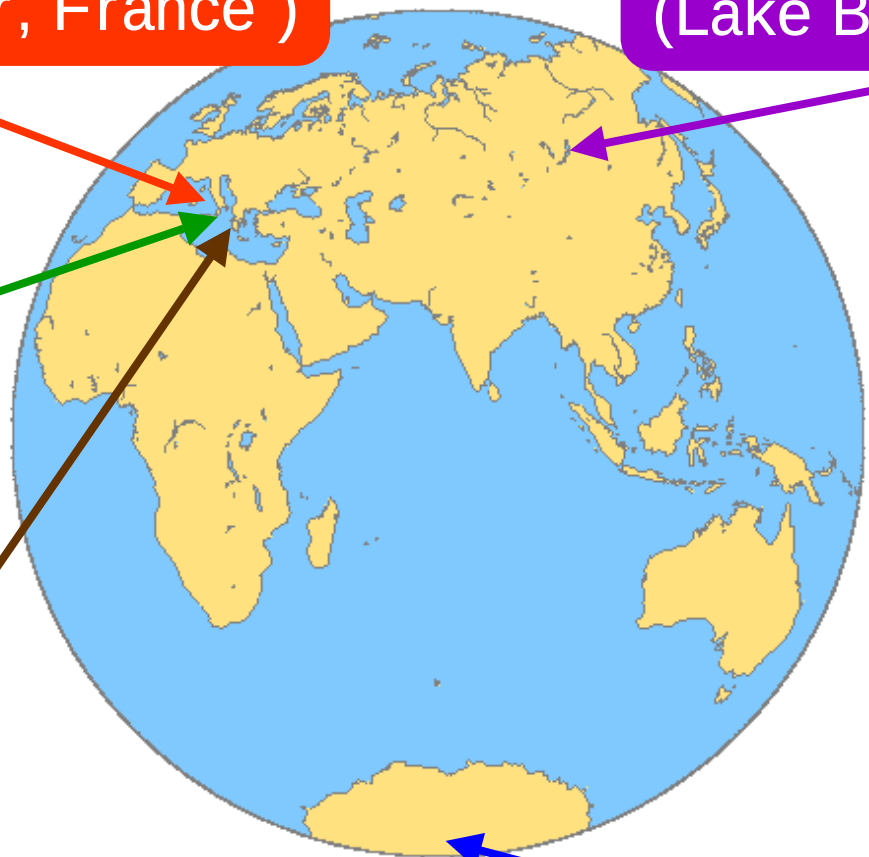
Optical Cherenkov Telescope Map

ANTARES (2007~)
(La-Seyne-sur-Mer, France)

Baikal(1998~)
(Lake Baikal, Russia)

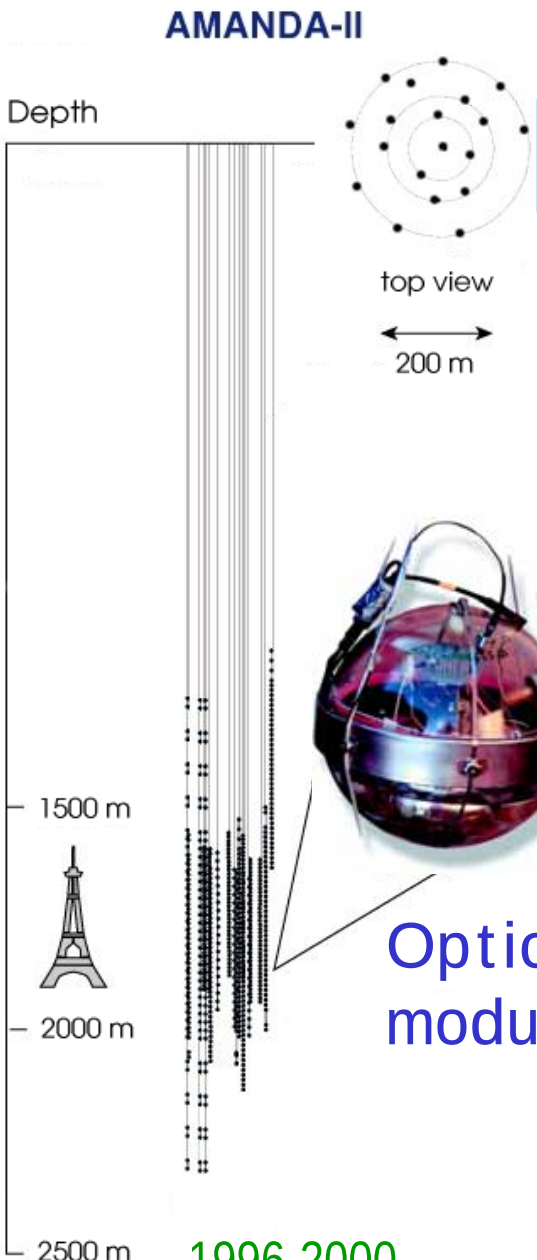
NEMO
(Catania, Italy)

NESTOR
(Pylos, Greece)



AMANDA(1996~) & ICECUBE (2009~)
(Geophysical south pole, Antarctica)

AMANDA

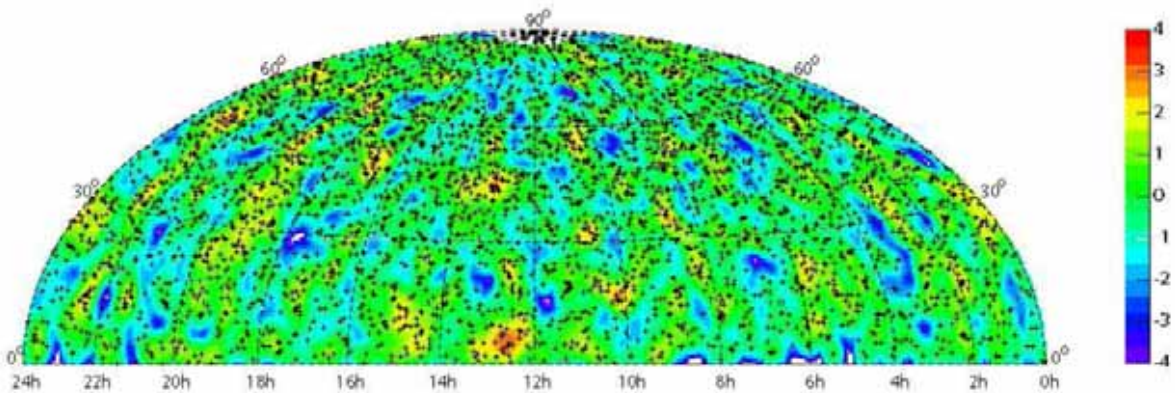


19 strings with 677 PMTs

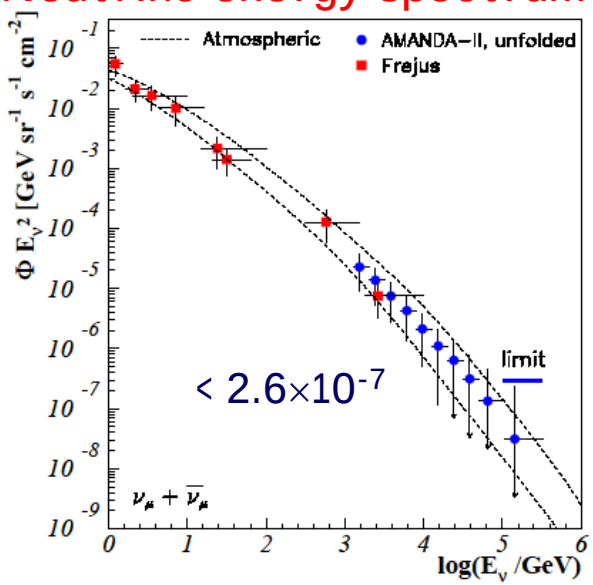
Optical module

1996-2000

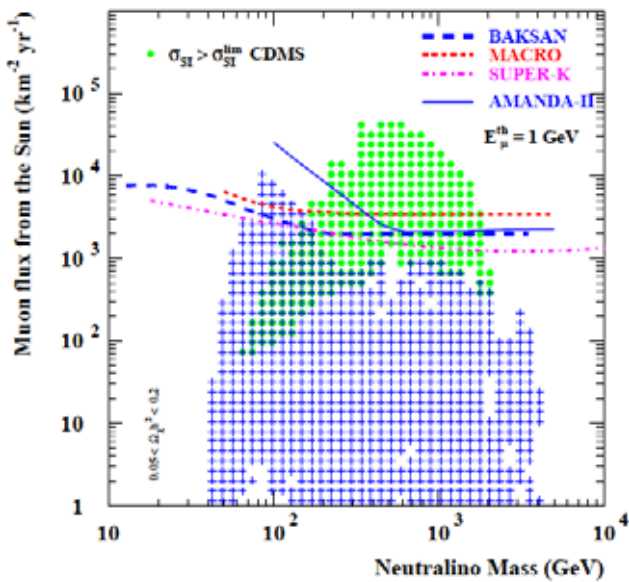
Point Sources



Neutrino energy spectrum

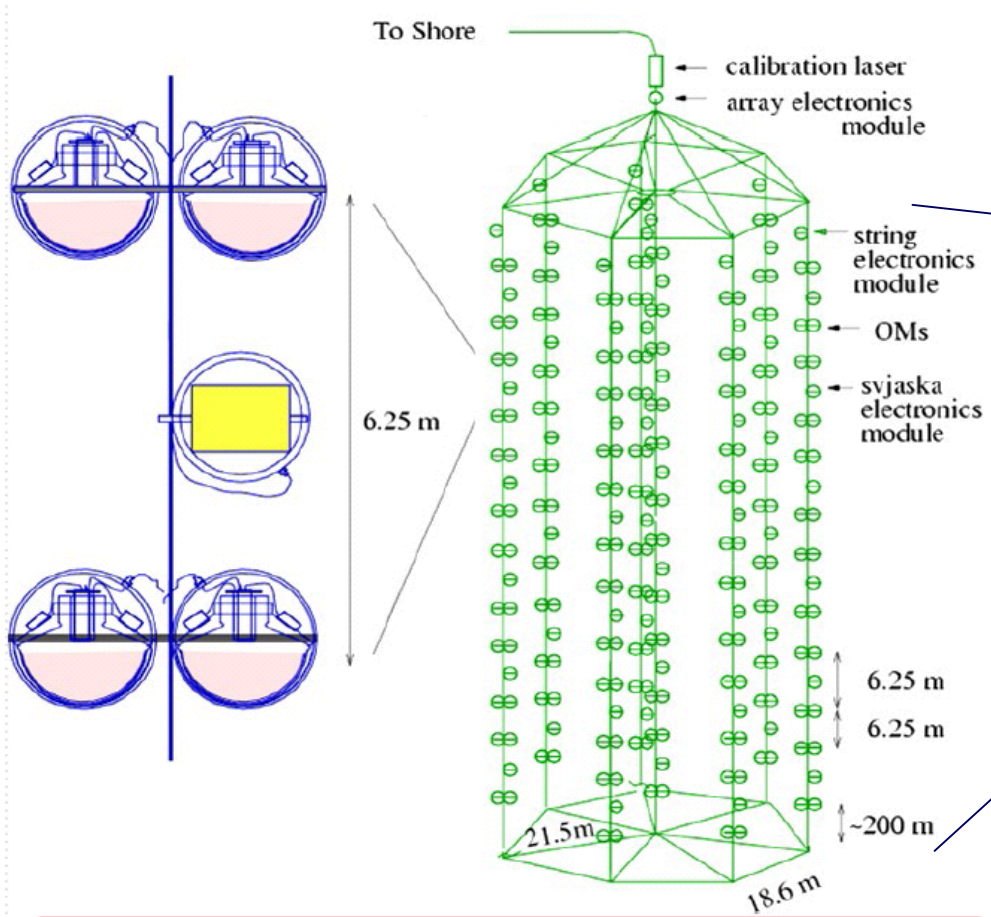


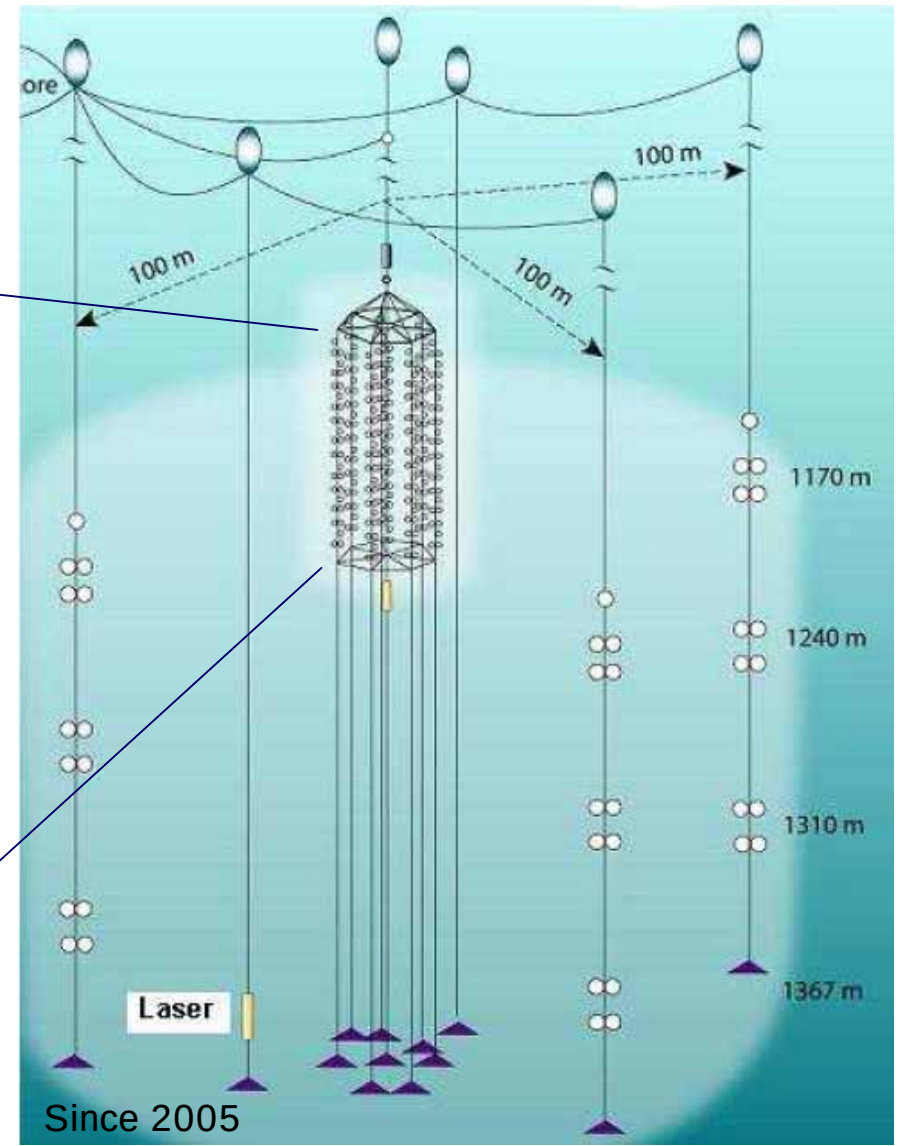
Muon flux from WIMPs



BAIKAL

- Pioneers in under-water neutrino telescope

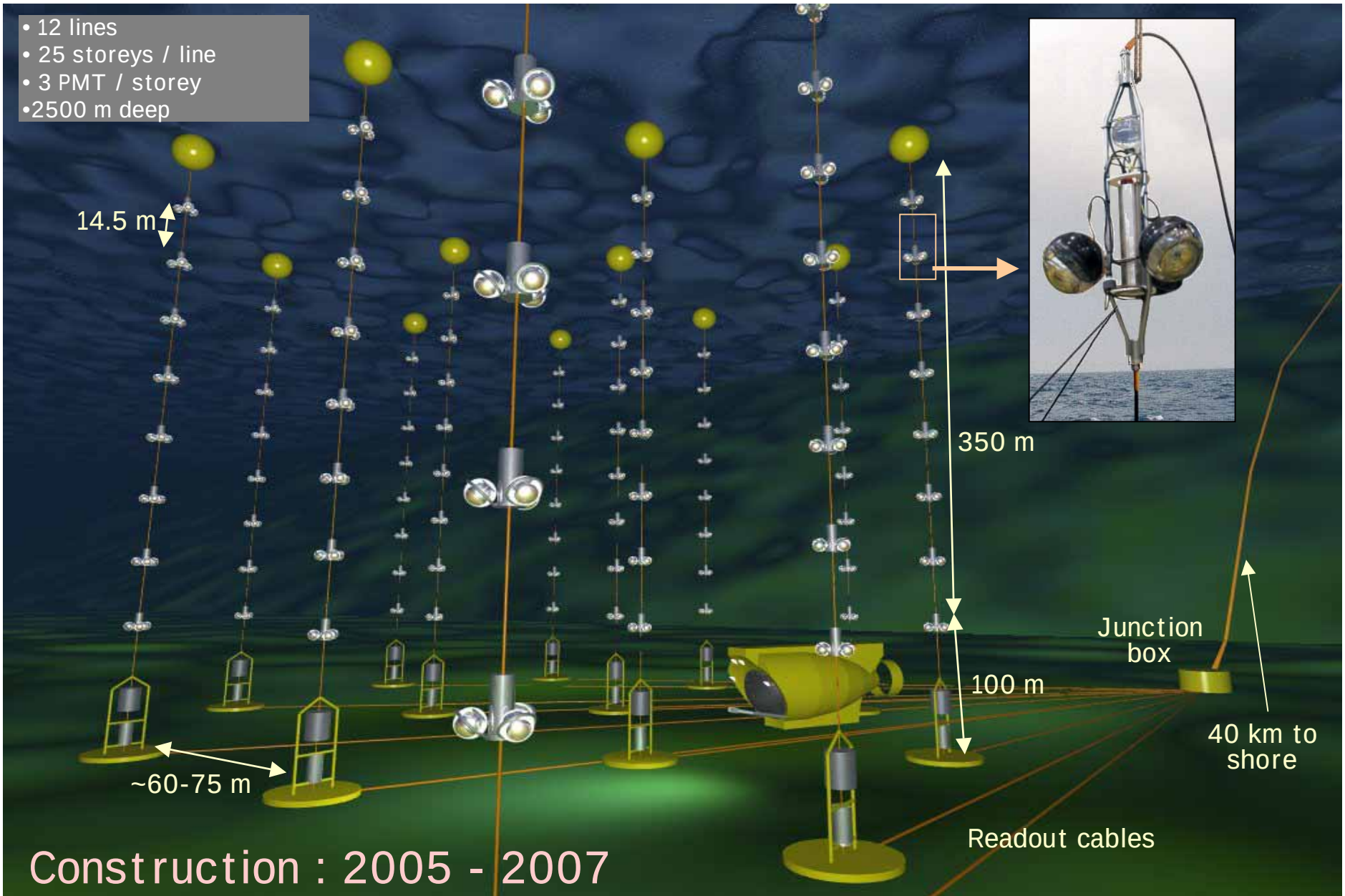




8 strings (72 m long) with 192 15” PMTs
+ 3 strings (140 m long) with 36 15” PMTs

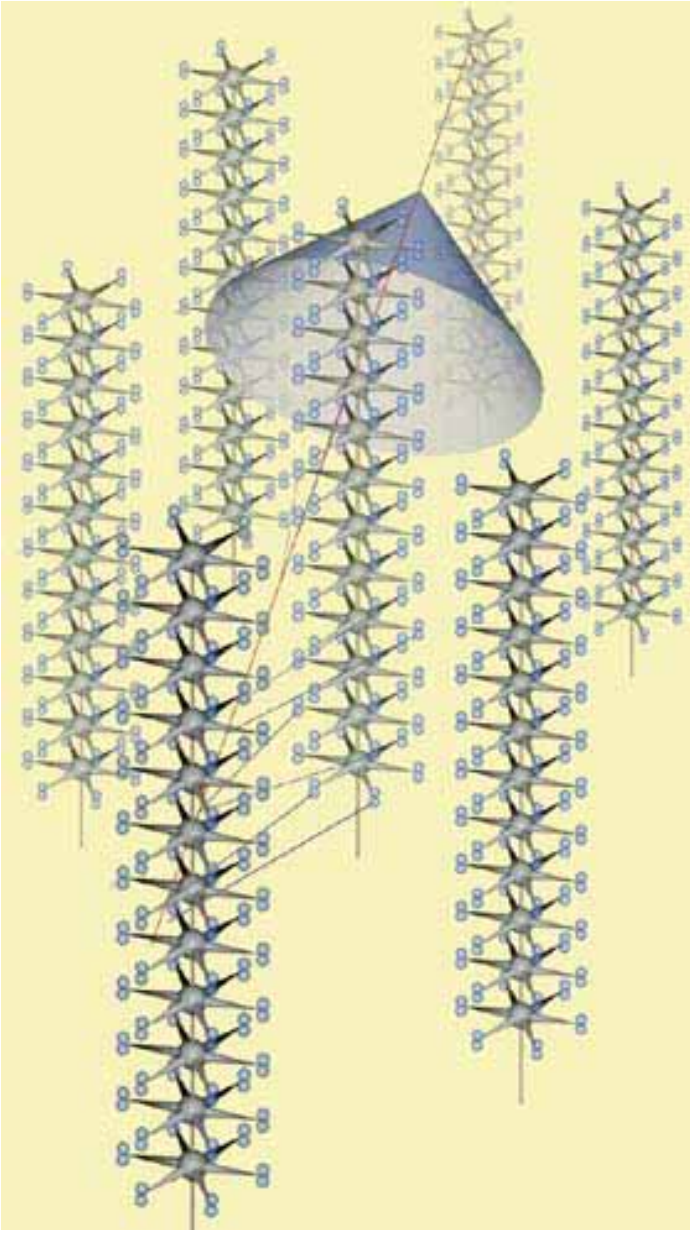
Since 2005

ANTARES



Construction : 2005 - 2007

NESTOR



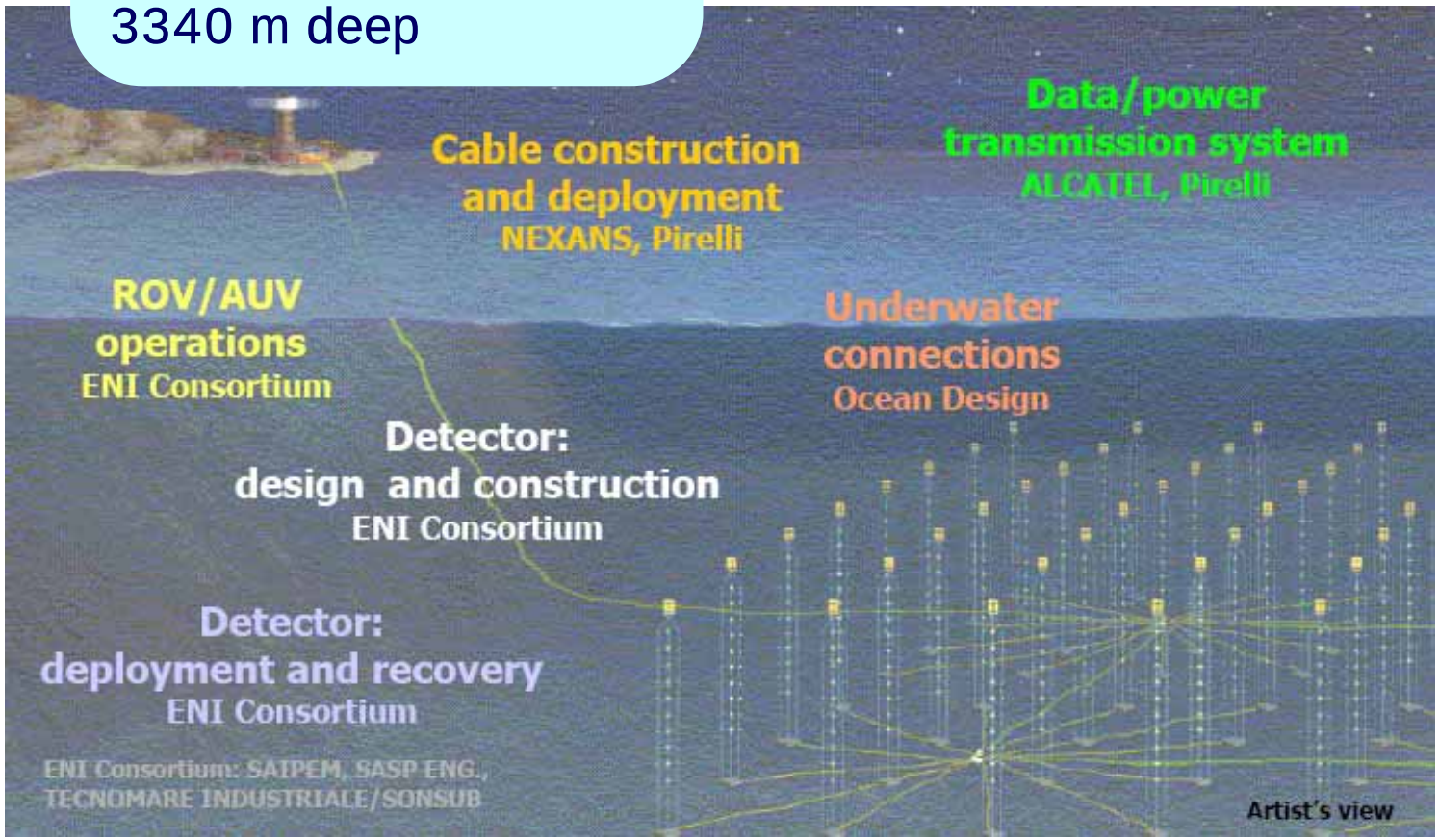
Tower based
Dry connections
3800 m deep
First floor(reduced size)
deployed and operated in 2003

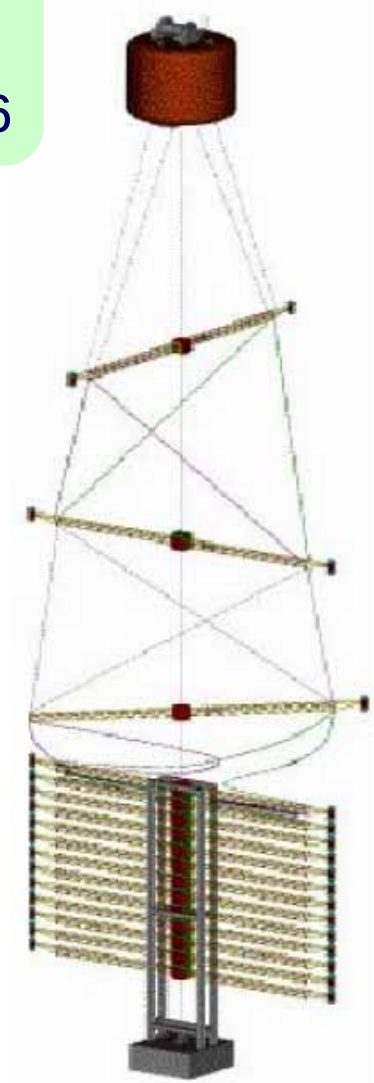
Plan : Tower(s) with 12 floors
32 m diameter
30 m between floors
144 PMs per tower

NEMO

16 arms per tower
20 m arm length
Arm 40 m apart
64 PMs per tower
Underwater connection
3340 m deep

Phase-I
2000 m deep
Completion expected by 2006





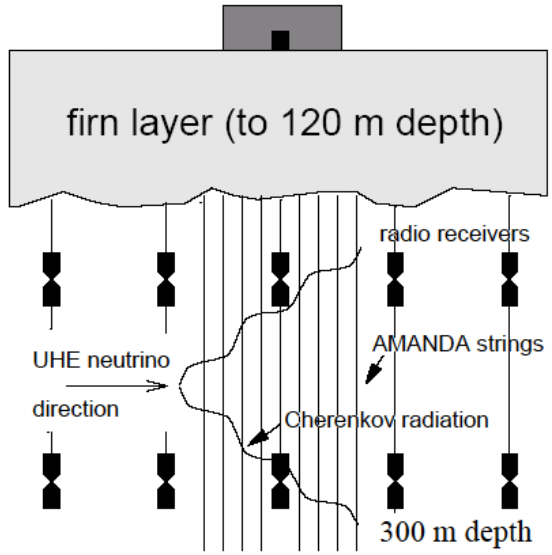
KM3NeT

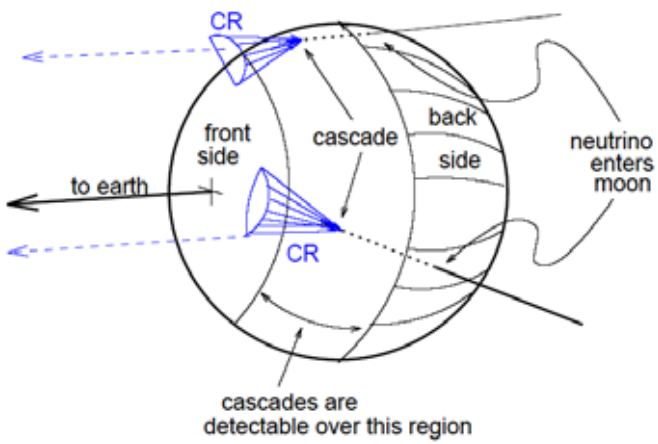
- Design study for a deep-sea facility in the Mediterranean for neutrino astronomy and associated science
- Participants : Cyprus, France, Germany, Greece, Italy, Netherlands, Spain, UK
  - Detection principle: water Čerenkov.
  - Location in Europe: in the Mediterranean Sea.
  - Detection view:
    maximal angular acceptance for all possible detectable neutrino signals including down-going neutrinos at VHE.
  - Detection volume: 1 km³, expandable.
  - Angular resolution: close to the intrinsic resolution
    ($< 0.1°$ for muons with $E_\mu > 10$ TeV).
  - Lower energy threshold:
    a few 100 GeV for upward going neutrinos with the possibility to go lower for ν from known point sources.
  - Energy reconstruction: within a factor of 2 for muon events.
  - Reaction types: all neutrino flavors.
  - Duty cycle: close to 100%.
  - Operational lifetime: ≥ 10 years.
  - Cost-effectiveness: < 200 M€ per km³.

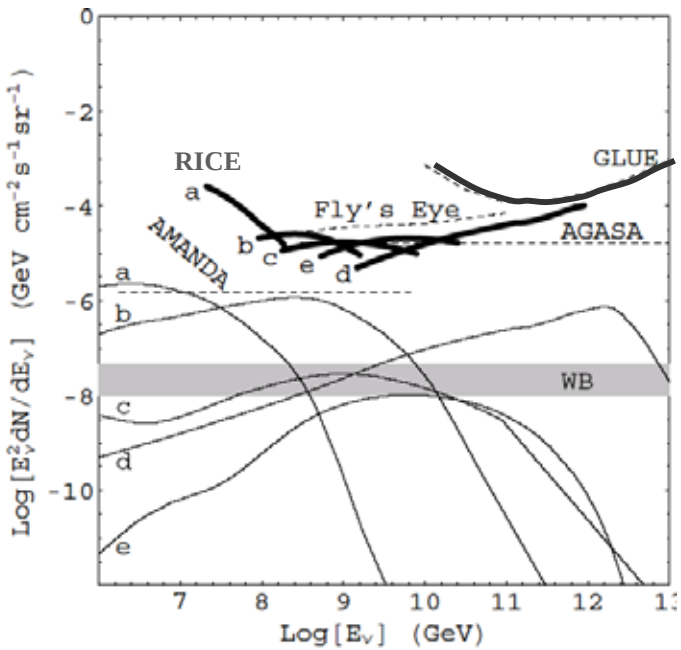
2006 : Start of design study
2009–2013 : Construction
2010-20XX : Operation

Radio Detection

- Electromagnetic shower → coherent Cherenkov radiation
  - Bipolar radio pulse with a width of 1-2 nsec ($\propto E^2$)
- **RICE**(geographical South Pole)
- **GLUE**(the Goldstone Lunar Ultra-high Energy Neutrino Experiment)
  - Moon surface skimming

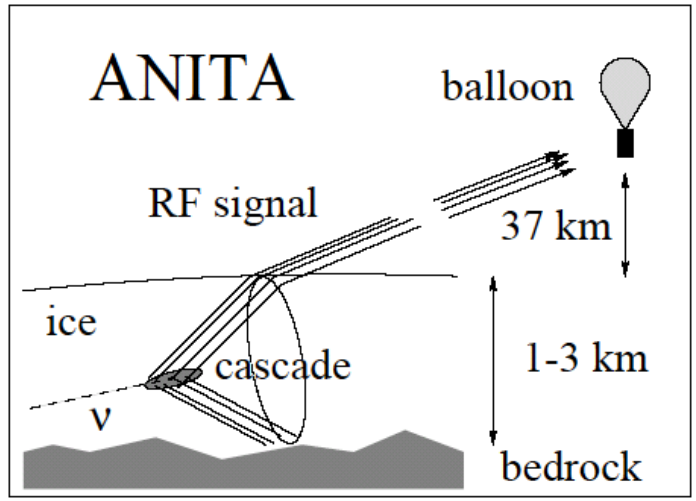






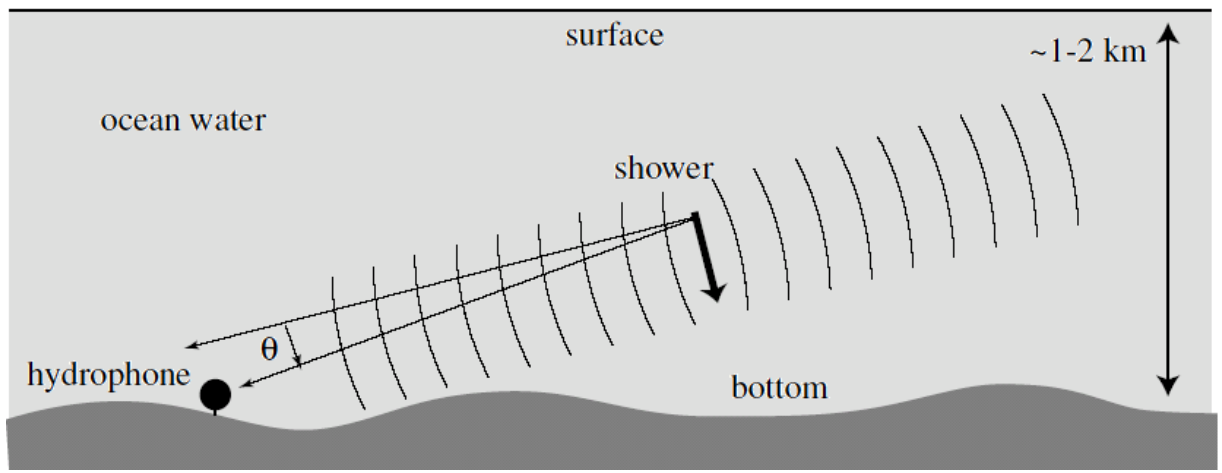
Radio Detection

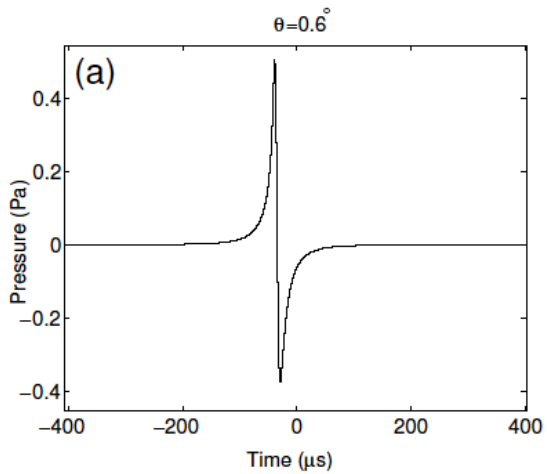
- **ANITA**(Antarctic Impulsive Transient Array)
  - Array of radio antennas planned to be flown at a balloon
  - 36 dual-polarized antennas covering 0.2 – 1.2 GHz
  - Effective area : 10x6 km^2
  - Sensitivity : 10^{-7} E_ν^{-2} GeV^{-1} cm^{-2} s^{-1} sr^{-1} at 10 EeV (30 day flight)
  - Flight schedule : Dec.2006/Jan.2007(15 days), two additional flights
- **SALSA**
  - Natural salt dome
  - Expected 3 orders better



Acoustic detection

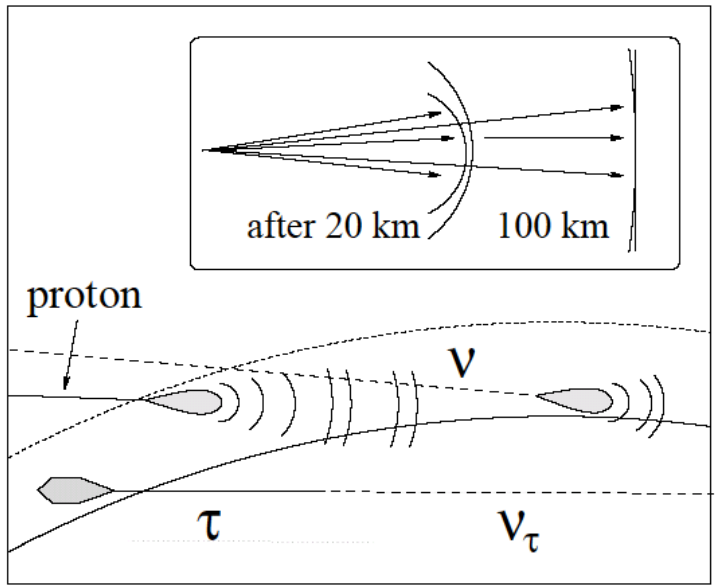
- Cascade → Ionization loss → Heat → a fast expansion → Bipolar acoustic pulse with a width of a few ten msec in water and ice.
  - Peak at 20 kHz -> attn. Length~a few km
  - Combination : NESTOR, ANTARES, ICECUBE
- **AUTEC**
  - 52 hydrophones spans as area of 250 km^2, 1-50kHz sensitive, >100EeV with tolerable false alarm rates

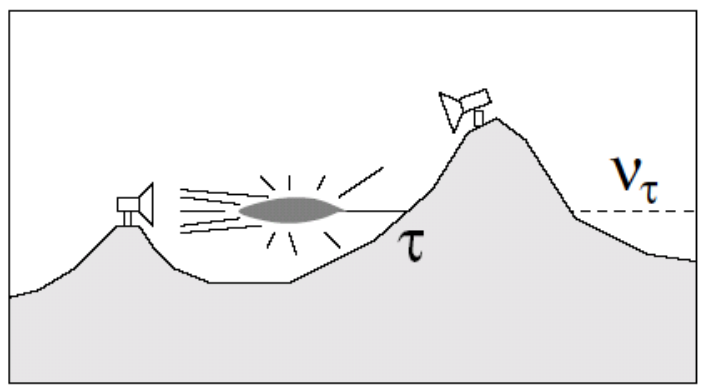




Air Showers

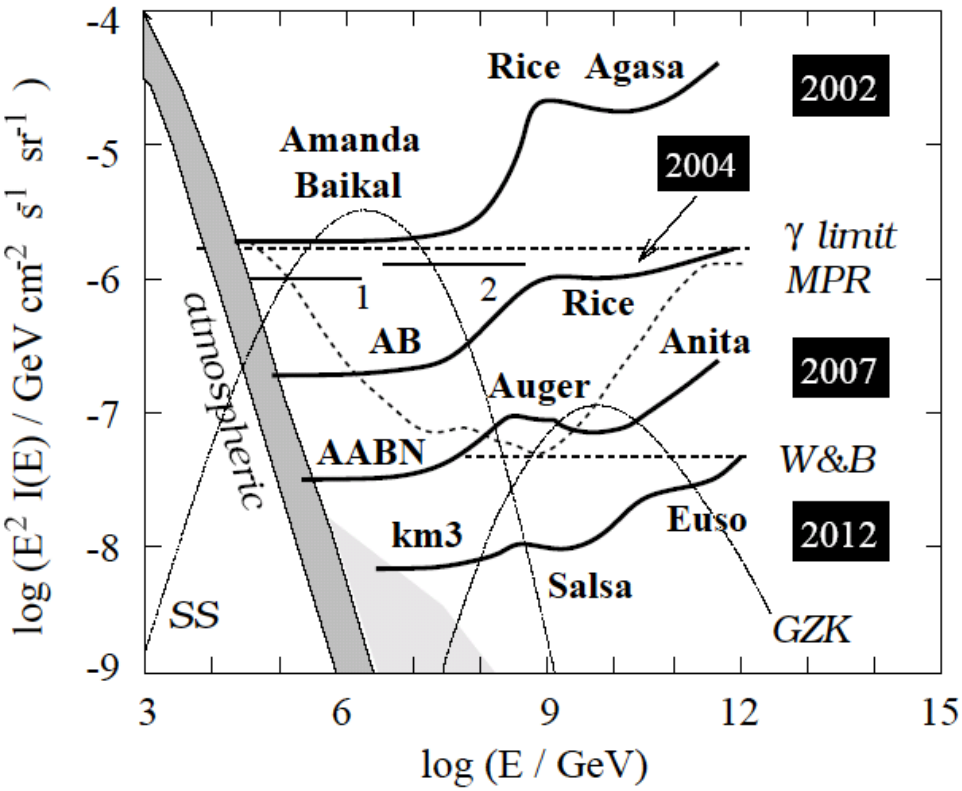
- **AUGER**
  - >3000 km^2 water tank array + atmospheric fluorescence
  - Effective detector mass:1-20 Gton
  - Sensitivity for horizontal air showers: 10^{-8} E_ν^{-2} GeV^{-1} cm^{-2} s^{-1} sr^{-1} at 1-100 EeV
  - Sensitivity for τ: 10^{-8} E_ν^{-2} GeV^{-1} cm^{-2} s^{-1} sr^{-1} at 1 EeV
- **Fly's Eye**
- **AGASA**
- **TA**
- **EUSO**
  - 500 km height
  - Monitored mass : 10 Ttons >10 EeV
- **Ashra**





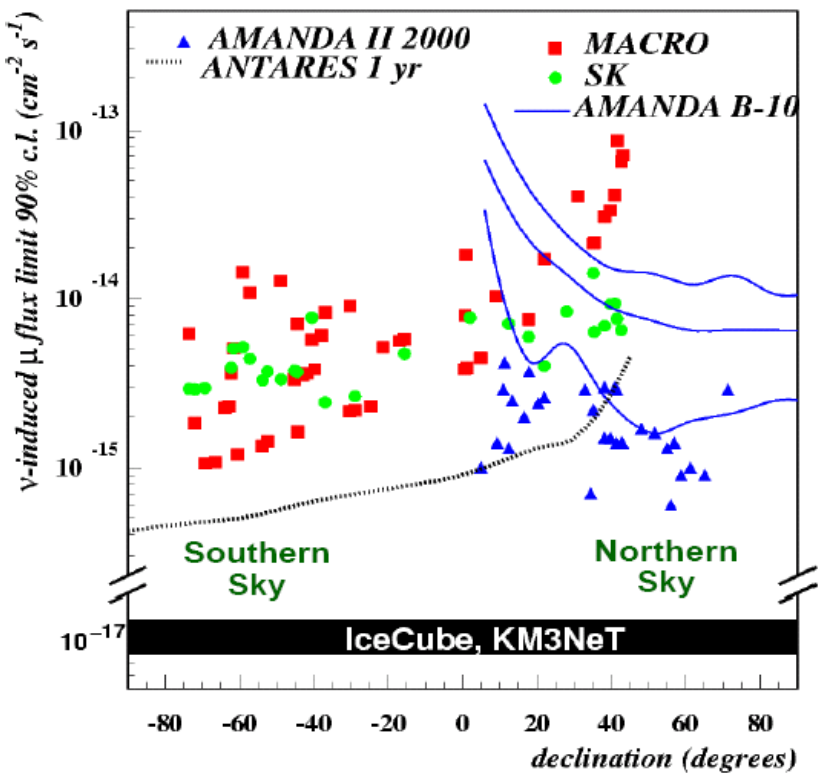
Scenario for the Improvement of experimental sensitivities

Diffuse



A.B.McDonald *et al.*,
Rev.Sci.Instrum. 75 (2004) 293-316

Point



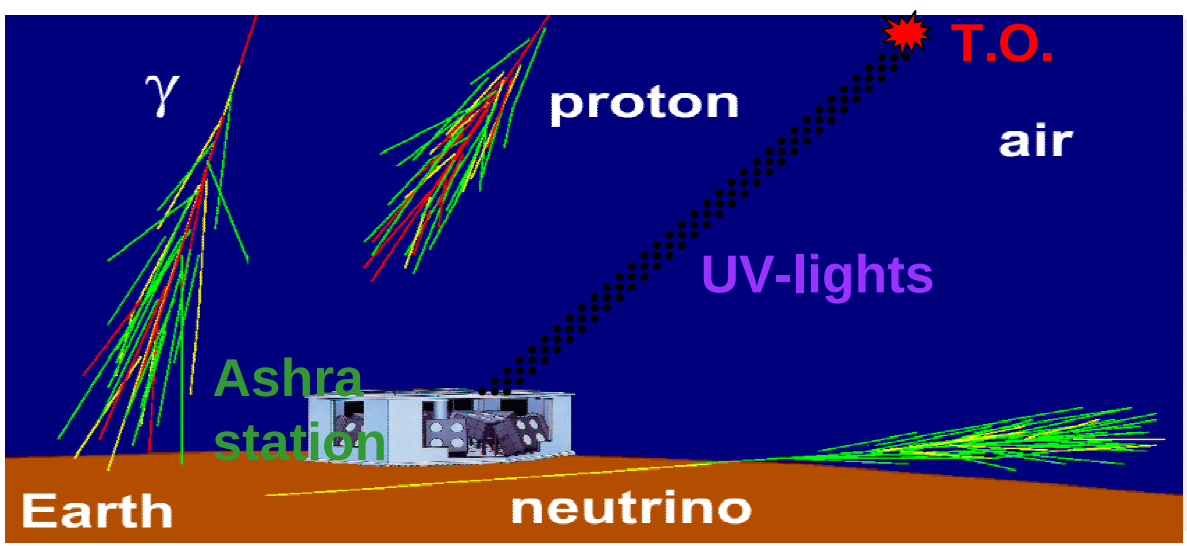
T.Montaruli (2003) modified by U. Katz. (2005)

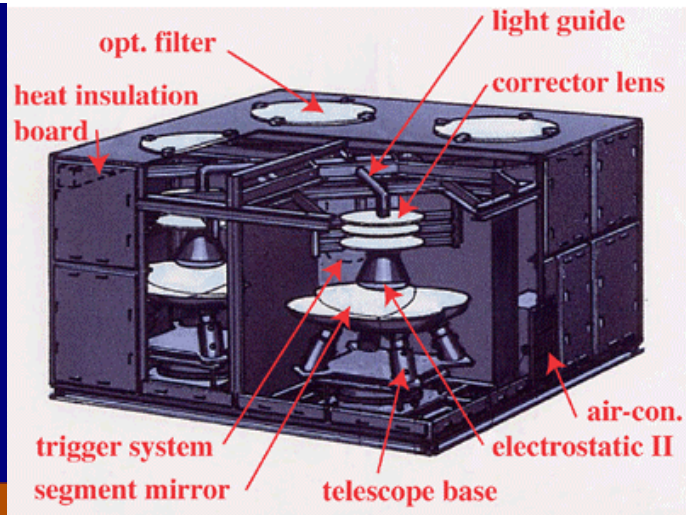
Ashra

All-sky Survey High Resolution Air-shower telescope

- Wide field of view & high angular resolution
  → Transient objects
- U.V. and Blue light
- TeV gamma-rays
- PeV neutrinos
- EeV energy CRs

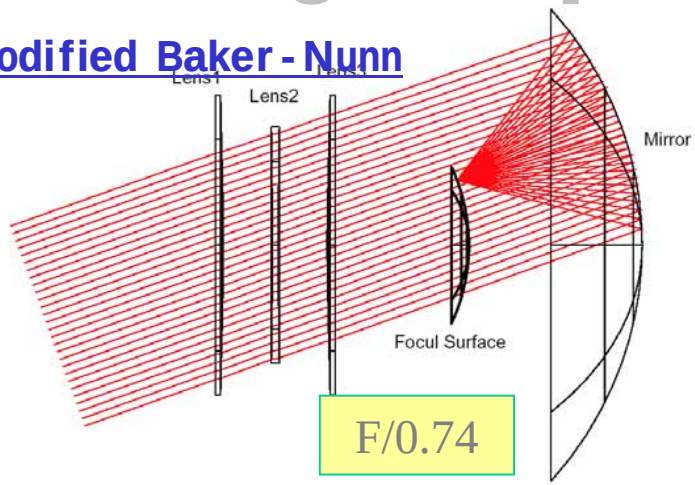
3 stations (30-40 km apart)
12 detector units per station

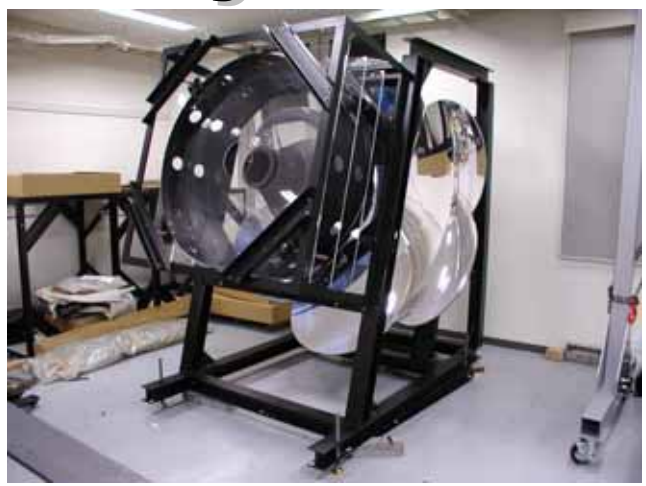


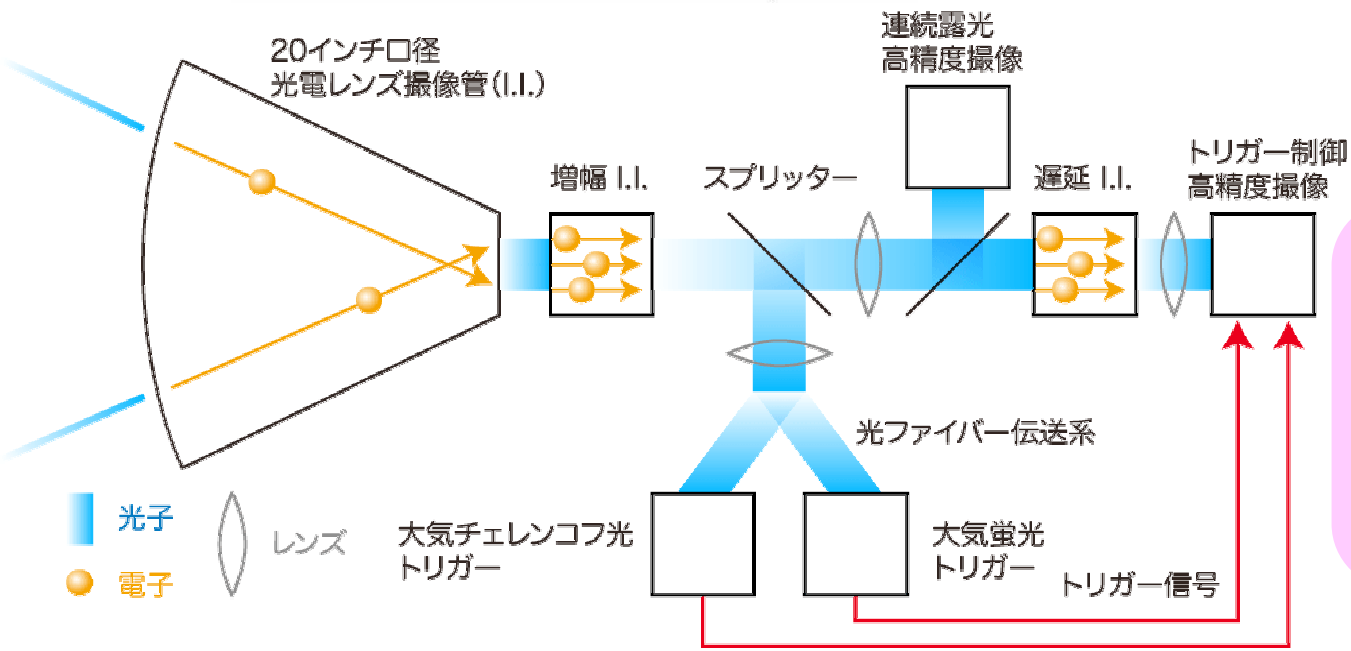


Ashra Optical and Photoelectric Image Pipeline Systems

Modified Baker - Nunn







II + CMOS

Image delay

+

a moving electronic shutter

Ashra Collaboration

- **JAPAN**
  - ICRR, Univ. of Tokyo, Chiba Univ., Ibaraki Univ., NAO, KEK, Toho Univ., TIT
- **Taiwan**
  - Natinal Taiwan Univ., National United Univ.
- **USA**
  - Univ. of Hawaii at Manoa, Univ. of Hawaii at Hilo

Sensitivity

- Effective target mass :
  70 Gton (1 EeV)
- Energy Resolition :
  6 % @ 1 EeV
  10 % @ 100 EeV
- Angular resolution :
  0.01 – 0.03º (> 1EeV)

Expected number of neutrino events per year with mono-station assuming 10% of duty factor

	$CC\nu_e$	$CC\nu_\mu$	$CC\nu_\tau$	NC	$ES\nu_\tau$	Total
Greisen	0.26	0.13	0.18	0.16	1.16	1.90
AGN-jet	3.5	1.3	2.1	1.6	17.4	25.9
AGN-core	2.2	0.2	0.9	0.5	1.7	5.4
GRB	0.26	0.10	0.15	0.12	1.00	1.64
TD	0.06	0.04	0.04	0.04	0.11	0.28
Z-Bursts	0.32	0.21	0.20	0.22	0.32	1.27

Expected number of neutrino events per year with multi-station assuming 10% of duty factor

	$CC\nu_e$	$CC\nu_\mu$	$CC\nu_\tau$	NC	$ES\nu_\tau$	Total
Greisen	0.11	0.03	0.06	0.05	0.16	0.42
AGN-jet	0.9	0.2	0.4	0.3	1.2	3.0
AGN-core	0.0	0.0	0.0	0.0	0.0	0.1
GRB	0.07	0.02	0.03	0.03	0.09	0.25
TD	0.04	0.02	0.02	0.02	0.03	0.13
Z-Bursts	0.22	0.13	0.12	0.14	0.14	0.74

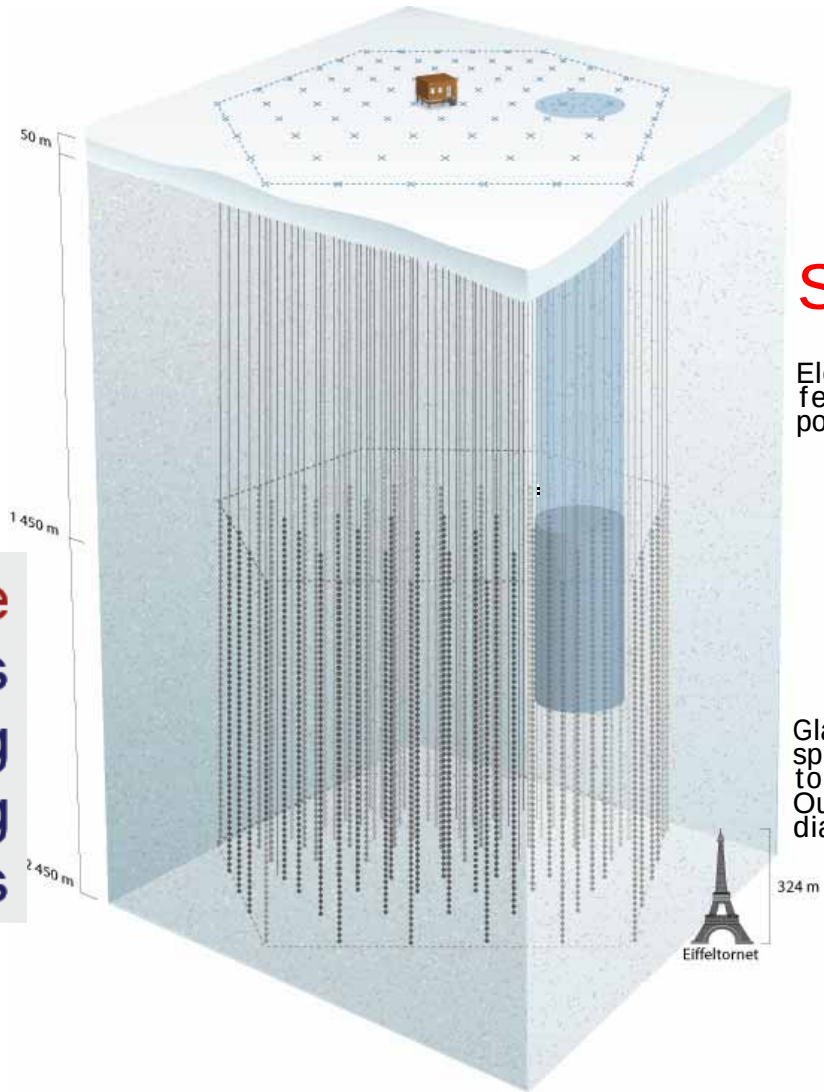
Schedule & Cost

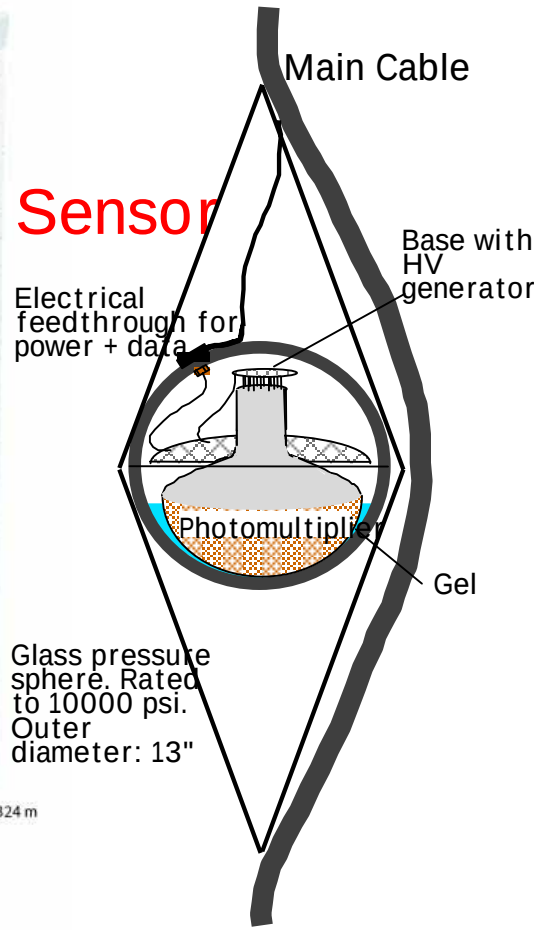
- Phase I (observation start in 2006)
  - 1 main station at Mauna Loa
  - 1 sub-station for Cherenkov (z<42degree, at a distance of 100 m)
  - 1 sub-station for fluorescence (z>42, at a distance of 32 km, Camp Kilohana)
  - Cost : ~¥1.2B(construction only)
- Phase II (?)
  - 3 main stations
  - 3 sub-stations for Cherenkov
  - Cost : ~¥1.2B(construction only)

IceCube

IceTop
160 tanks
frozen-water tanks
2 OMs / tank

IceCube
80 strings
60 OMs/string
17 m vertical spacing
125 m between strings





South Pole

IceCube Collaboration

USA (12)

- Bartol Research Institute, Delaware,
- Univ. of Alabama, USA
- Pennsylvania State University, USA
- UC Berkeley, USA
- Clark-Atlanta University, USA
- Univ. of Maryland, USA
- IAS, Princeton, USA
- University of Wisconsin-Madison, USA
- University of Wisconsin-River Falls, USA
- LBNL, Berkeley, USA
- University of Kansas, USA
- Southern University and A&M College, Baton Rouge, USA

Venezuela

- Universidad Simon Bolivar, Caracas, Venezuela

Europe (12)

- Universite Libre de Bruxelles, Belgium
- Vrije Universiteit Brussel, Belgium
- Université de Mons-Hainaut, Belgium
- Universität Mainz, Germany
- DESY-Zeuthen, Germany
- Universität Dortmund, Germany
- Universität Wuppertal, Germany
- Uppsala university, Sweden
- Stockholm university, Sweden
- Imperial College, London, UK
- Oxford university, UK
- Utrecht,university, Netherlands

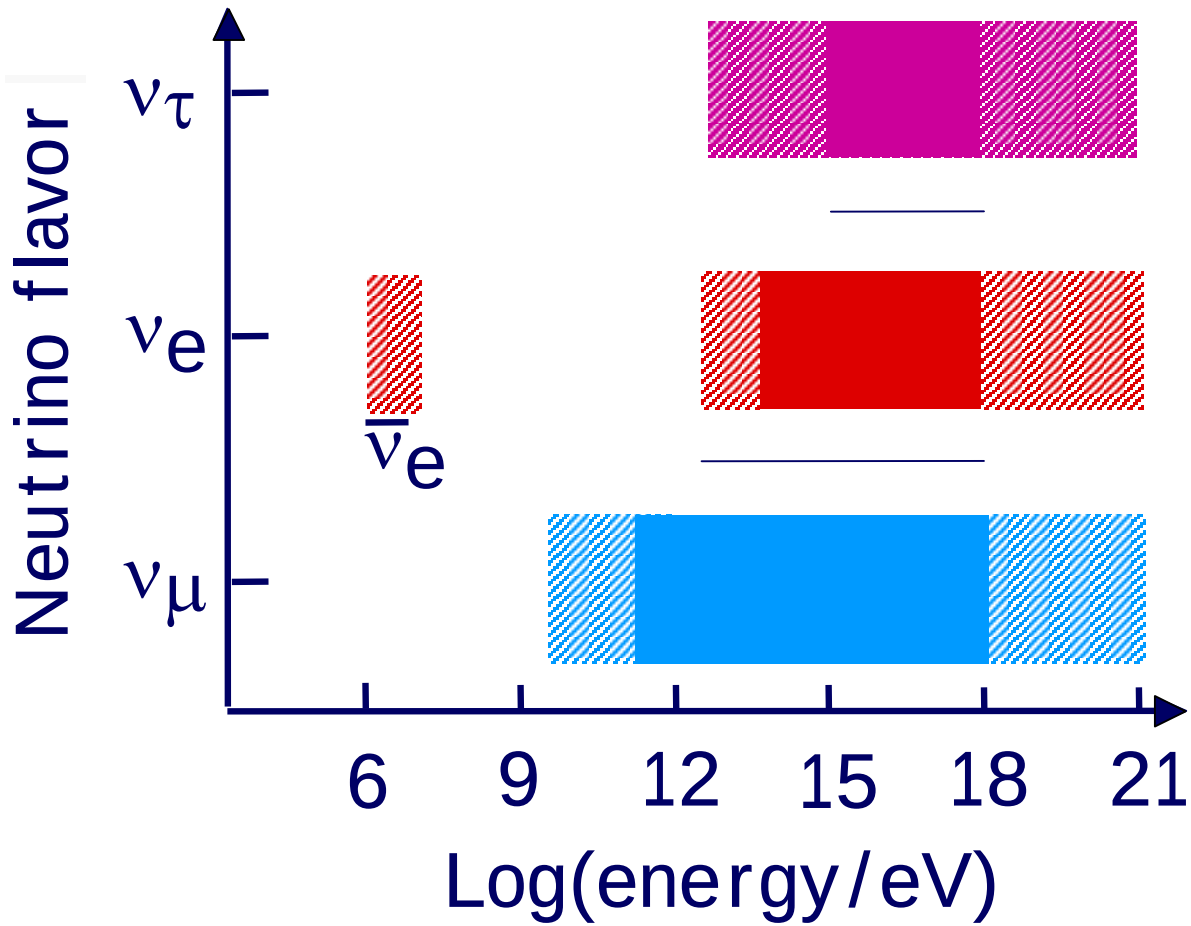
Japan

- Chiba university, Japan

New Zealand

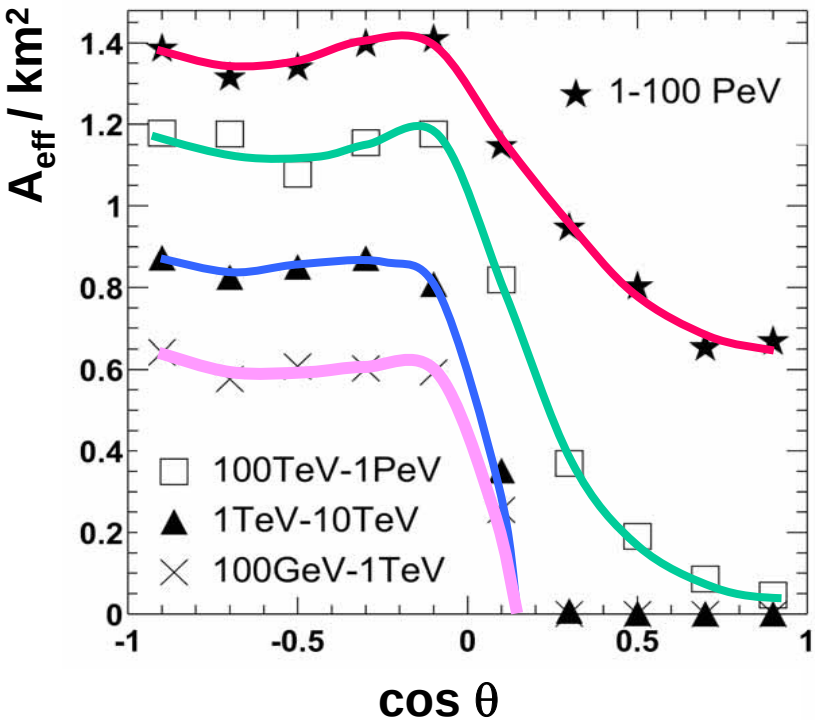
University of Canterbury, Christchurch, NZ

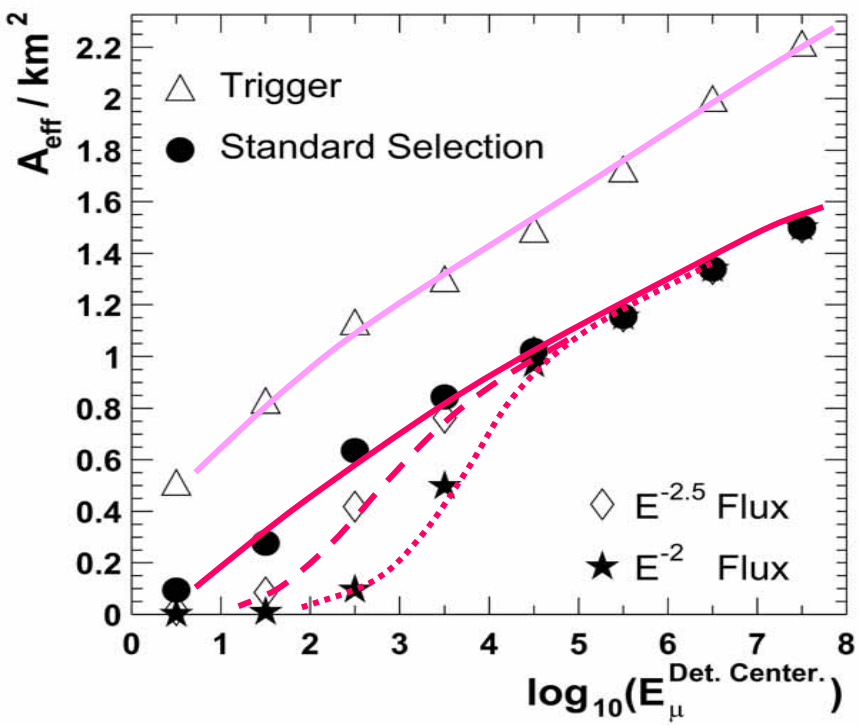
Neutrino ID, Energy, and Angle



- Filled area: particle id, direction, energy
- Shaded area: energy only

Effective Area of IceCube

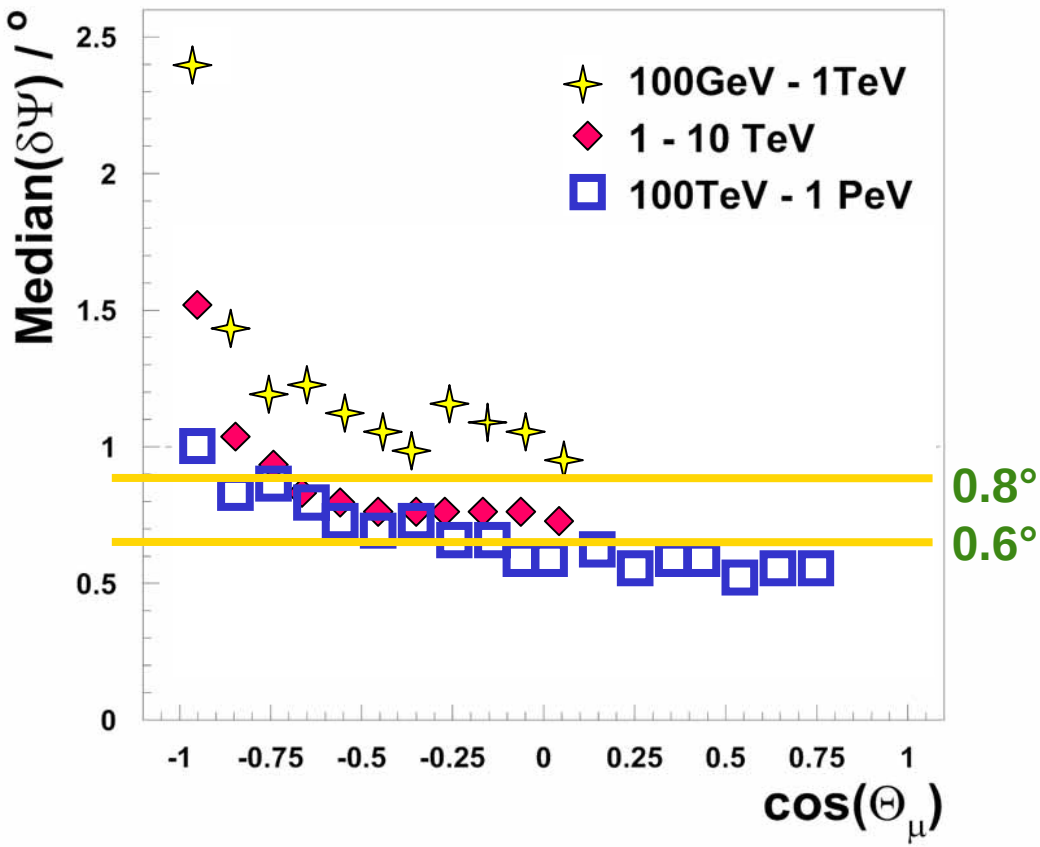




Effective area vs. zenith angle (downgoing muons rejected)

Effective area vs. muon energy (trigger, atm μ, pointing cuts)

Angular Resolution as a Function of Zenith Angle

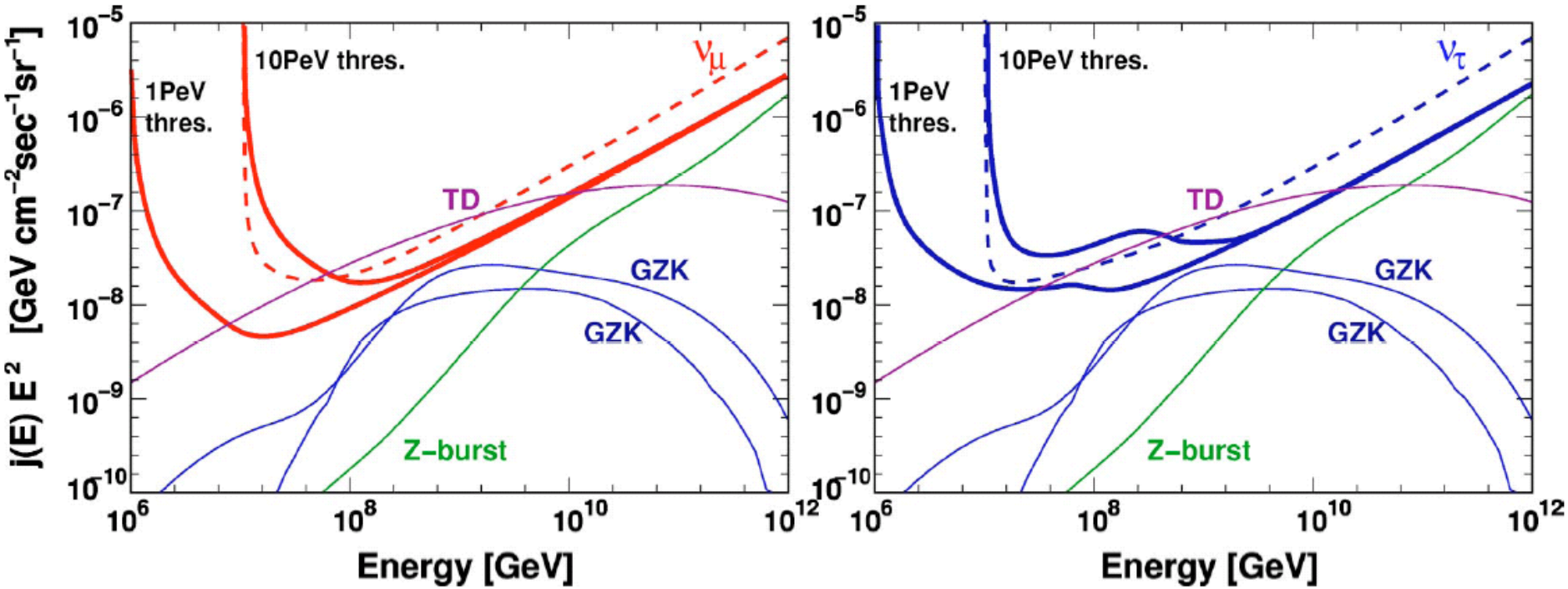


Waveform information not used. Will improve resolution for high energies !

→ above 1 TeV, resolution ~ 0.6 - 0.8 degrees for most zenith angles

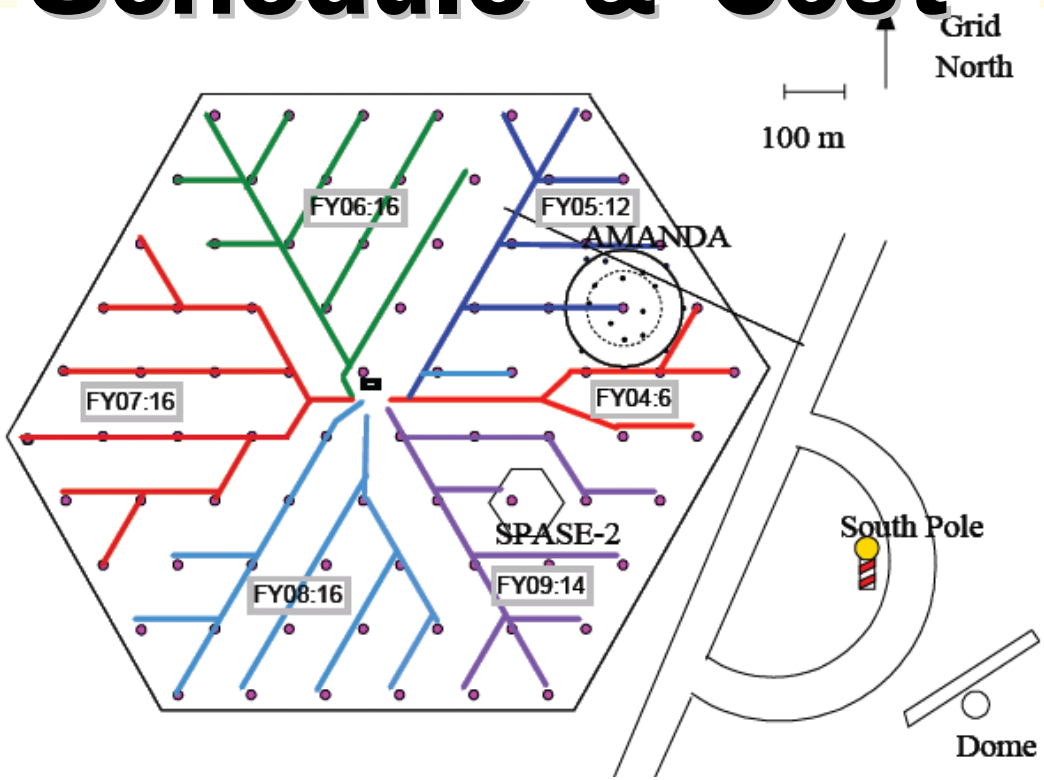
EHE neutrino sensitivities

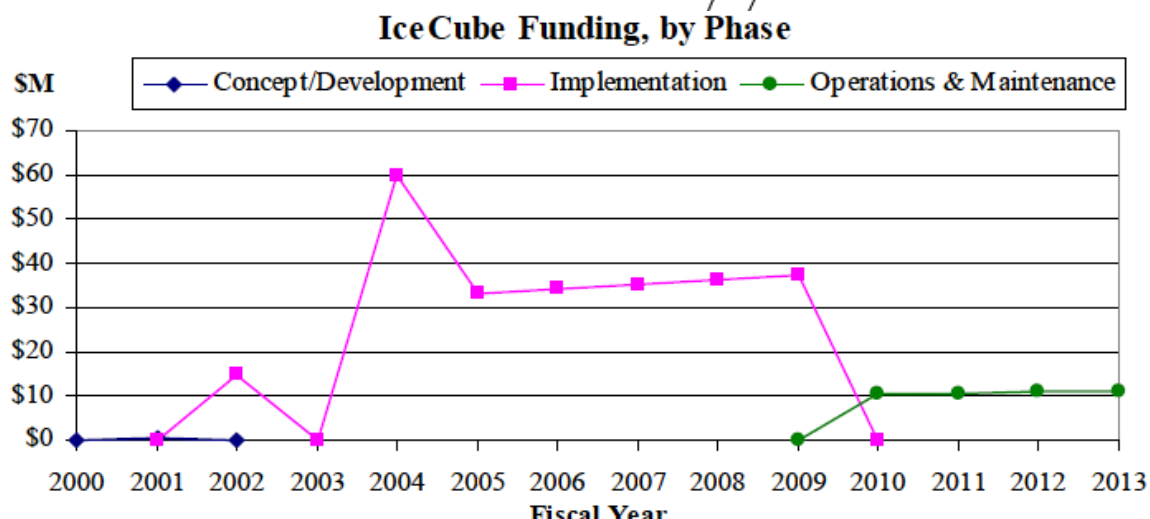
90% C.L. for 10 year observation



S. Yoshida et al., PRD 69, 103004(2004)

Schedule & Cost





Summary and Comments

- Physics objectives : very interesting and important ⇒ promote the high energy neutrino detection projects.
- Current status : prototype detector modules operated, ongoing R&D work and construction for next generation km^3-scale or larger detectors
- Ashra
  - Some techniques are challenging.
  - Need further feasibility study
- IceCube
  - feasibility proof of neutrino telescopy
  - on going construction as a first km^3 neutrino telescope
  - hope more contribution from Japan