Most pressing questions

Why 3 neutrinos?

Normal or inverted hierarchy?

CP violation? (after θ_{13})

Nature of the neutrinos, Dirac or Majorana?

Magnetic moment/radiative decays?

Right-handed (sterile) neutrinos?

VHE neutrinos?

What about Big Bang neutrinos?

CP violation

$$P(\nu_e \to \nu_\mu) \neq P(\bar{\nu}_e \to \bar{\nu}_\mu)$$

$$P(\nu_e \to \nu_\mu) \neq P(\nu_\mu \to \nu_e)$$

$$P(\nu_e \to \nu_\mu) \approx \underbrace{s_{23}^2 \sin^2 2\theta_{13} \sin^2(\frac{\Delta m_{13}^2 L}{4E})}_{\text{Atmospheric}} +$$

$$\underbrace{c_{23}^2 \sin^2 2\theta_{12} \sin^2(\frac{\Delta m_{12}^2 L}{4E})}_{\text{Solar}} +$$

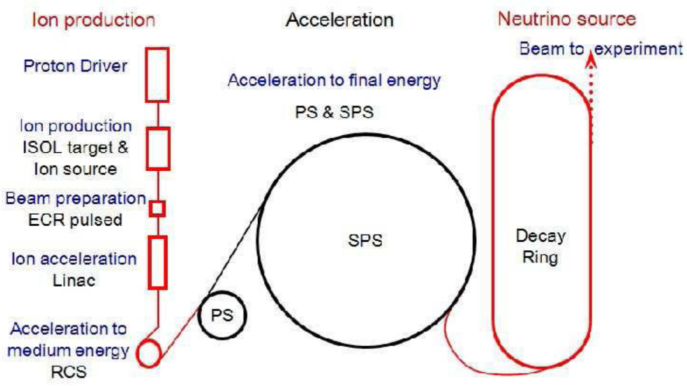
$$\underbrace{\tilde{J} \cos(\delta - \frac{\Delta m_{13}^2 L}{4E}) \frac{\Delta m_{12}^2 L}{4E} \sin(\frac{\Delta m_{13}^2 L}{4E})}_{\text{Interference}}$$

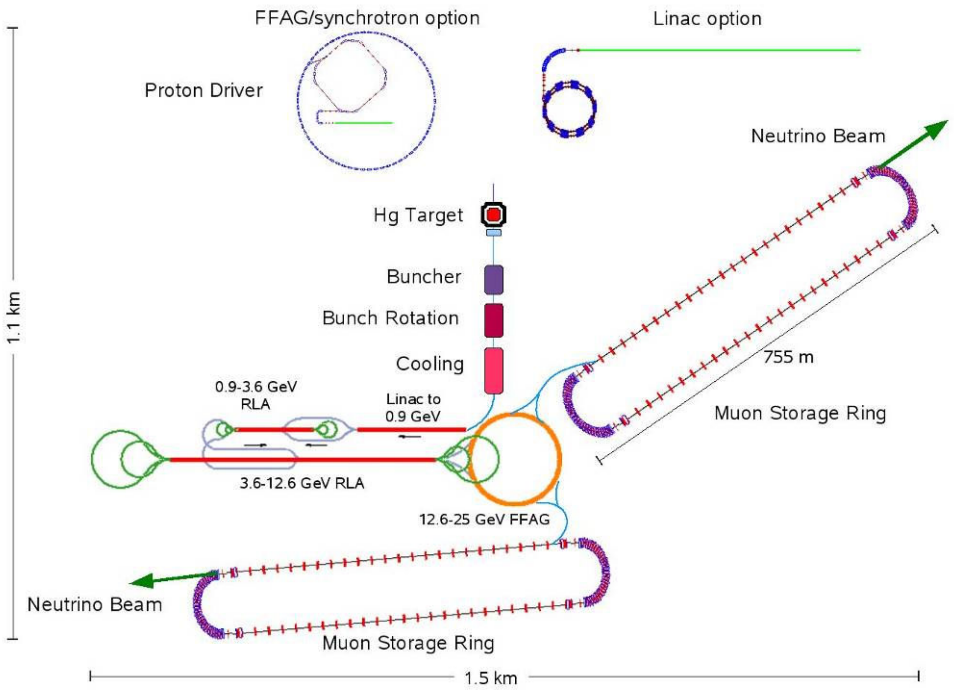
θ_{13} is crucial to test CP violation

If leptonic CP violation is observed, leptogenesis can trigger baryogenesis

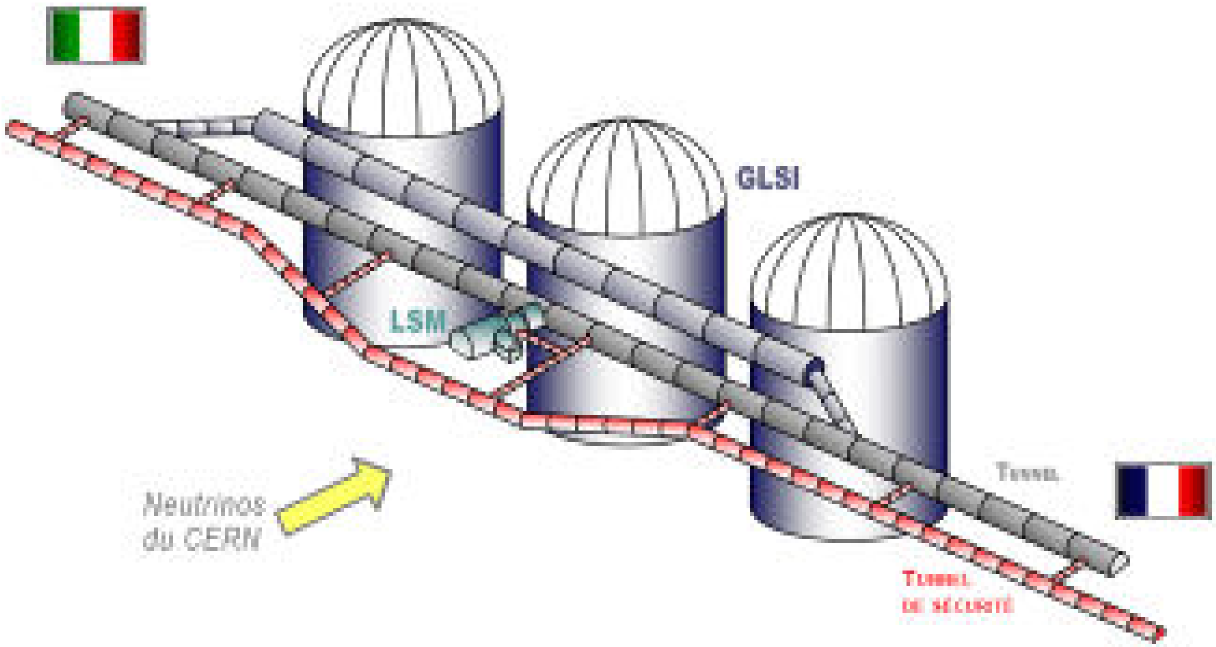
$$J \sim \cos\theta_{13} \sin^2\theta_{13} \sin^2\theta_{23} \sin^2\theta_{12} \sin\delta$$

Super beams, beta beams, ν factories





New detectors



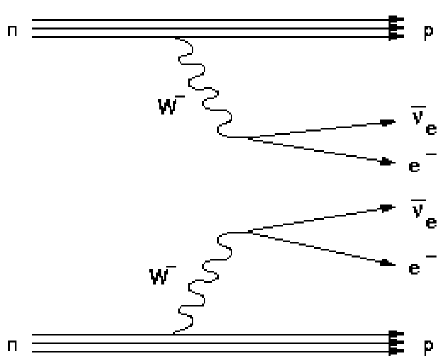
LAGUNA study for Large scale underground laboratory (1’000’000 m3)

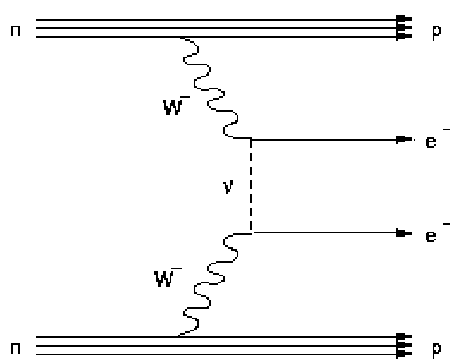
Dirac or Majorana neutrinos

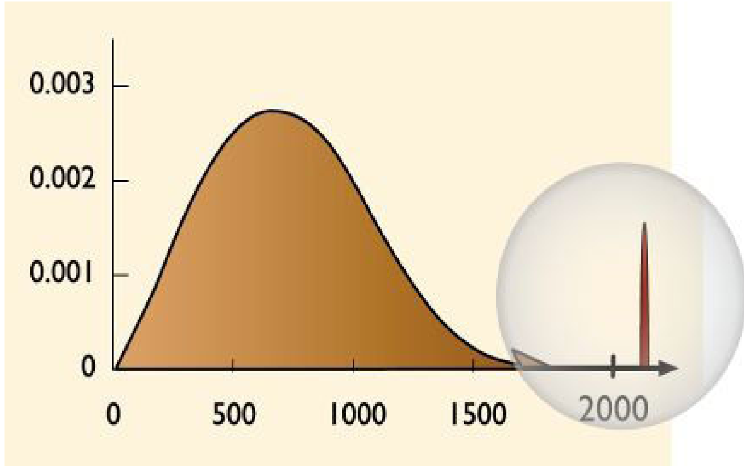
- Complexity of the neutrino nature
  - *LH ν gives LH e^-*
  - *RH anti-ν gives RH e^+*
- Mass term in Lagrangian mixes RH and LH terms
- Two possibilities:
  - existence of a ν_R (Dirac neutrino)
  - or association of ν and anti-ν (Majorana neutrino)
- *Identical consequences if 0 mass*
- Is the ν its own antiparticle?

Double β decays

- *With or without neutrino, this is the question !*







With neutrinos, already seen

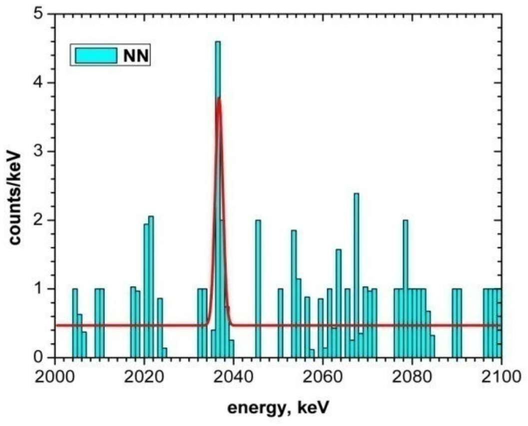
Without neutrinos, 2 e^- carry all available energy

Extremely rare!

Detectors

Two techniques:

Calorimeters (Ge)
or spectrometers

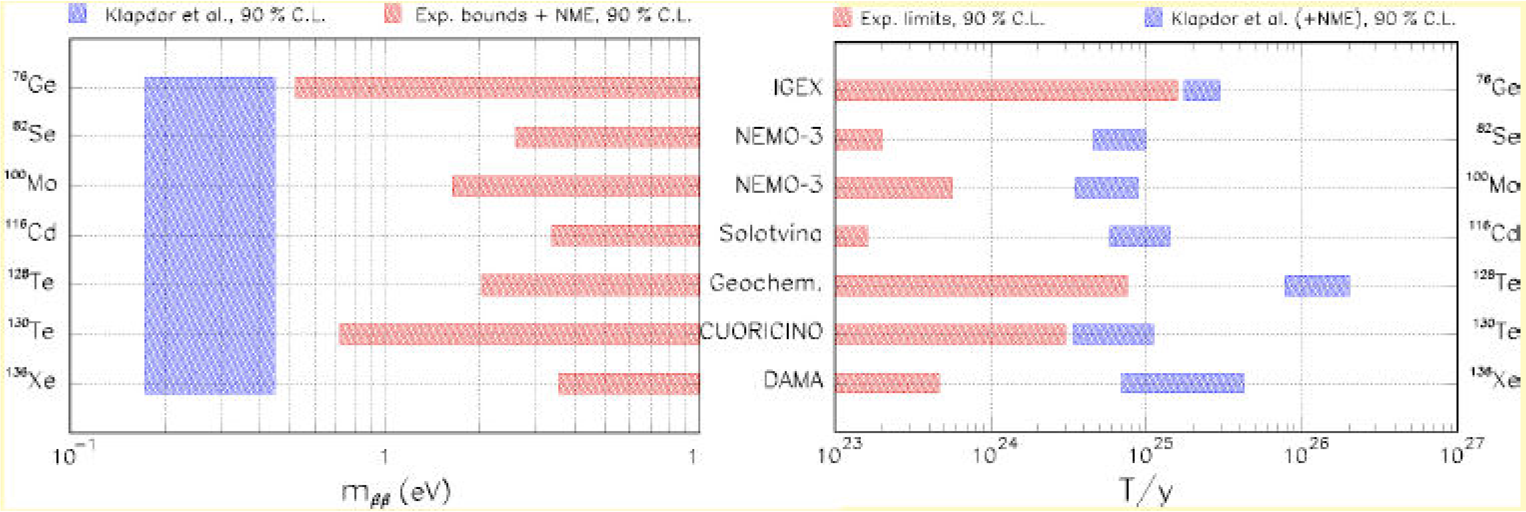


Heidelberg-Moscow

Nemo3

Present limits

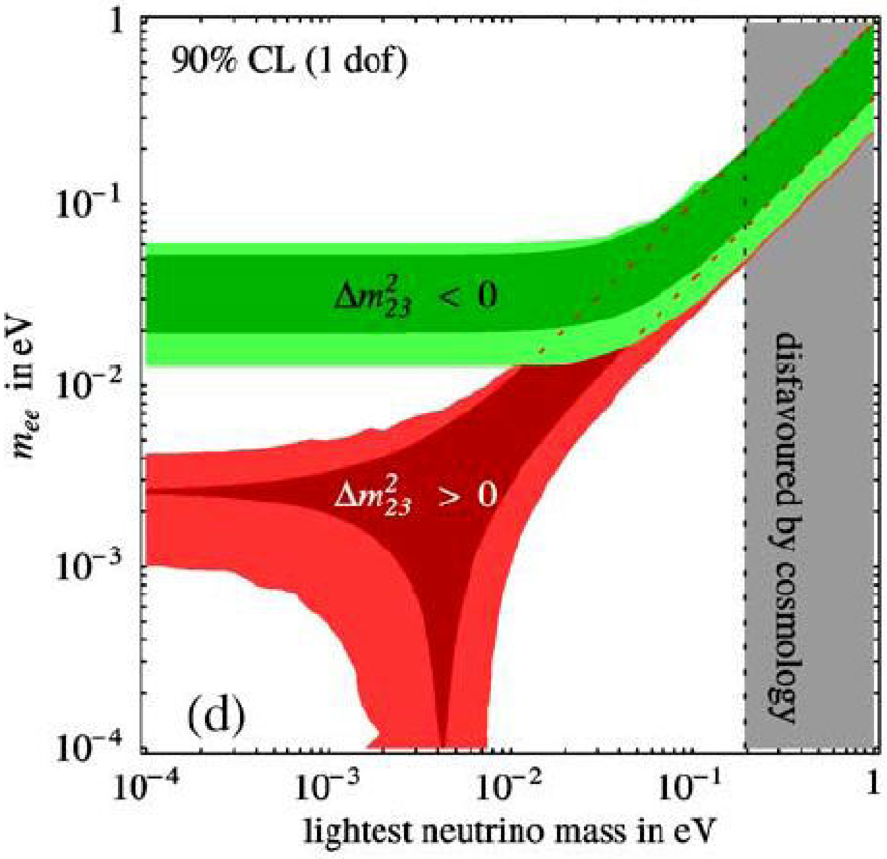
$$m_{\beta\beta} = \Sigma\, U^2\, m_i$$



Level reached ~ 1 eV

Next generation ~ 0.1 eV

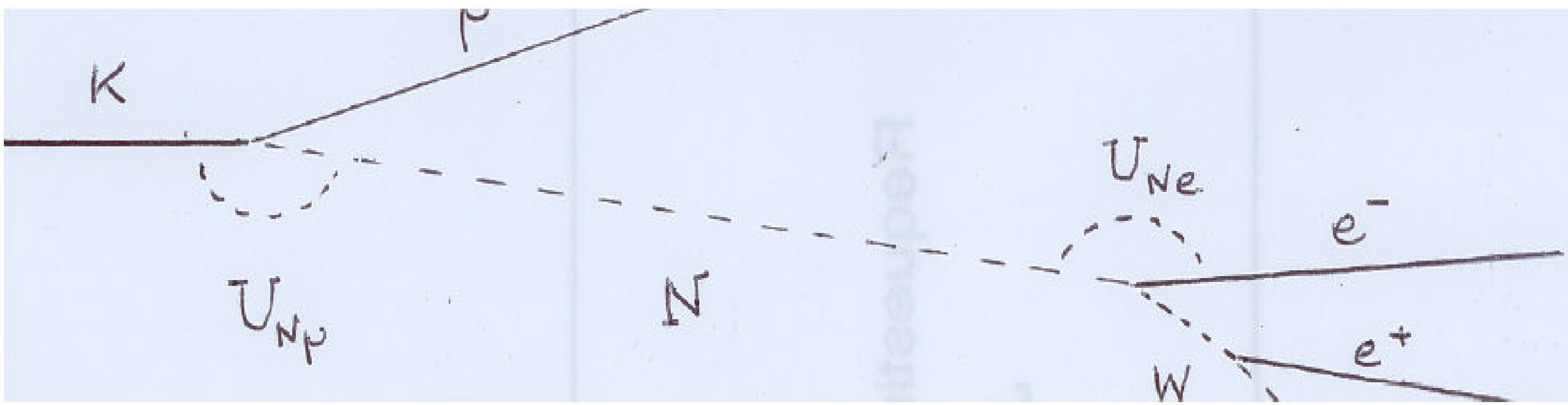
Correlations



Right-handed (Sterile) neutrinos

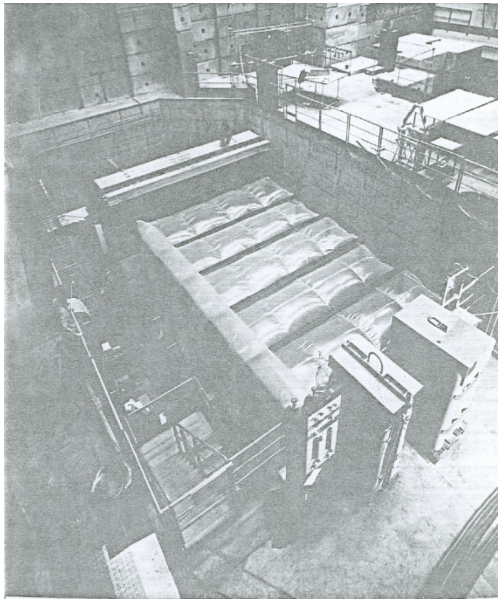
- *See-saw* formula for active neutrinos $m_\nu = M^D (1/M_M)(M^D)^T$
  - Majorana mass M_M
  - Dirac mass $M_D = fv$ $v = 174$ GeV vac. exp. val. of Higgs field

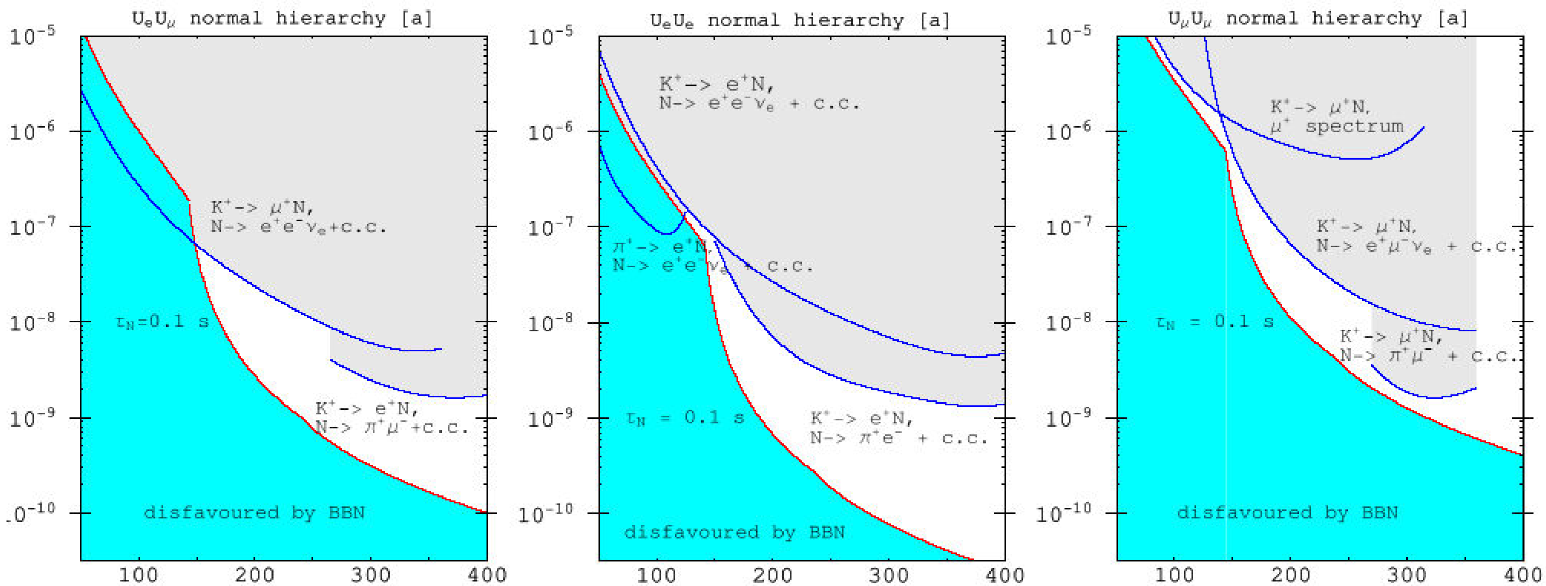
  New model : νMSM f small, N_1 (10 keV), N_2, N_3 (100 MeV-1 GeV)



Limits

A massless detector for massive neutrinos (1984)





E.M. interactions of neutrinos

1) Magnetic moment

$\mu(\nu_e) < 10^{-11}\mu_B$ (theory $10^{-19}\mu_B$ for 1 eV mass)

2) Radiative decays

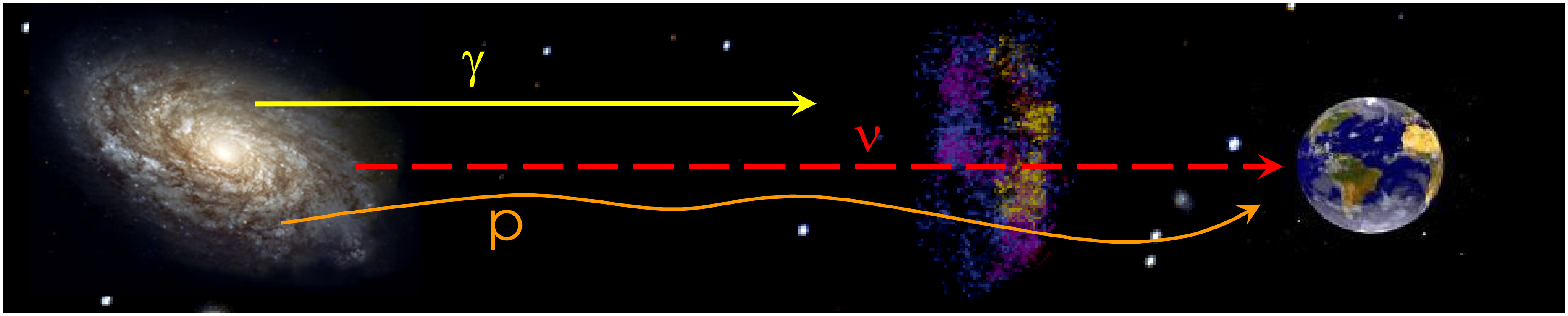
- Mass hierarchy $E_\gamma = E_\nu/2$
- SN anti-ν_e $\tau/m > 6\ 10^{15}$ s/eV
- Los Alamos ν_μ $\tau/m > 15{,}4$ s/eV
- Degenerated masses $E_\gamma = E_\nu\ \delta m^2/m^2 = 2\ E_\nu\ \delta m/m$
- Bugey anti-ν_e $\tau/m > 2\ 10^{-4}$ s/eV if $\delta m/m > 10^{-7}$
- Solar eclipse ν_μ $\tau/m > 100$ s/eV if $\delta m^2 \sim 10^{-5}$ eV^2

3) Stimulated conversion

Neutrino astronomy

Astroparticles « par excellence », protons feel magnetic fields and GZK mechanism. Photons interact with I.R. background

Only neutrinos can reach from the frontiers of the Universe, but weak cross-sections mean huge detectors



Up to now, only two sources seen in the sky:

- *The Sun and the supernova 1987A*

⇒ Towards a neutrino sky map

Predictions?

- *Presumably protons are accelerated in SN remnants (10^{15} eV)*
- *Also in jets, in particular in AGN (10^{18} eV)*
- *On their way, protons interact giving π^0 and $\pi^\pm$.*

- Sure contribution: from GZK suppression

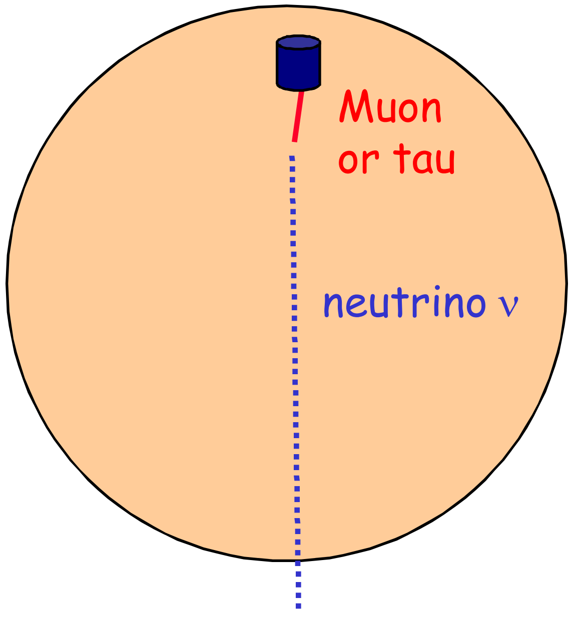
$$p + \gamma \rightarrow \Delta \rightarrow n\,\pi$$

- At production, 2 ν_μ for 1 ν_e
- On earth, after oscillations, equal fluxes of ν_e, ν_μ, ν_τ

- *Detectors 10000 bigger than SuperK are necessary.*
- Only possible in instrumenting existing media: Antarctic ice or sea(lake) water.

VHE neutrino detection

- Small fluxes but cross-section increases (although not linear anymore)



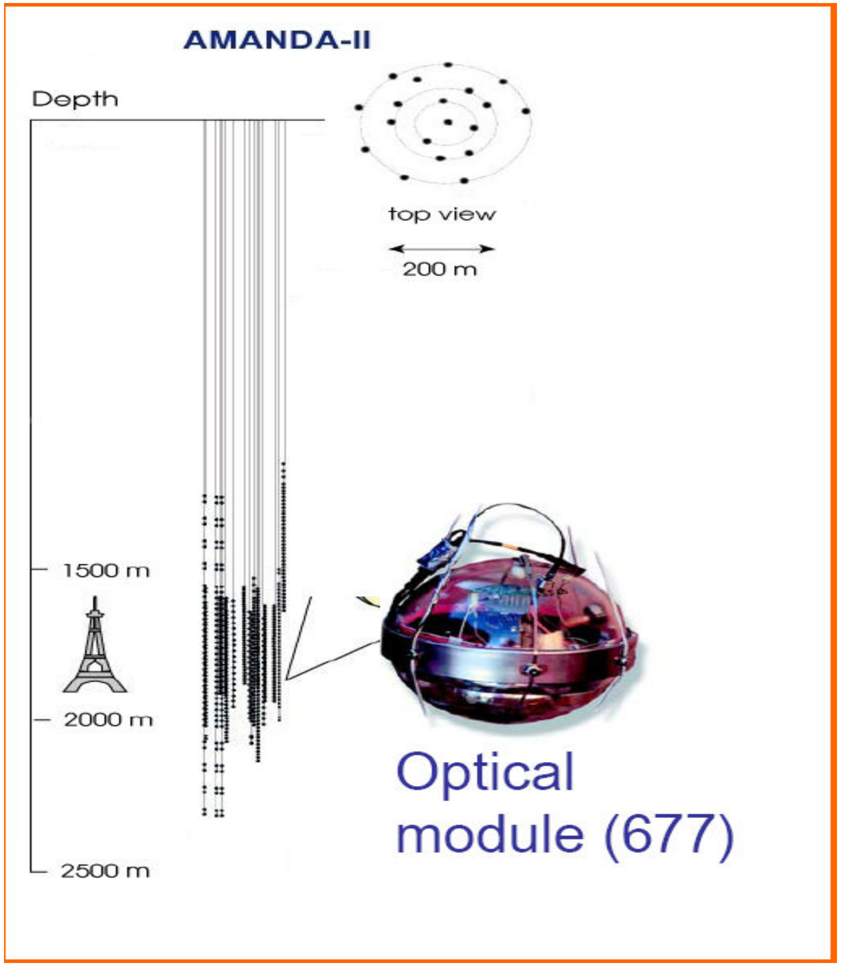
Generated μ ou τ can cross large distances in matter: few km for μ in rock, up to 30 km for τ

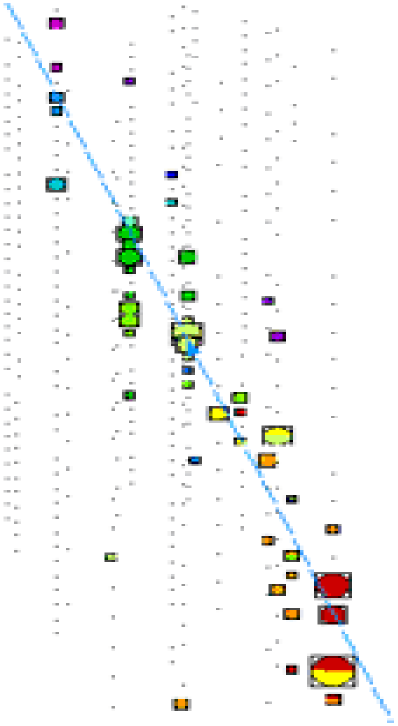
Catastrophic bremsstrahlung

At the South pole

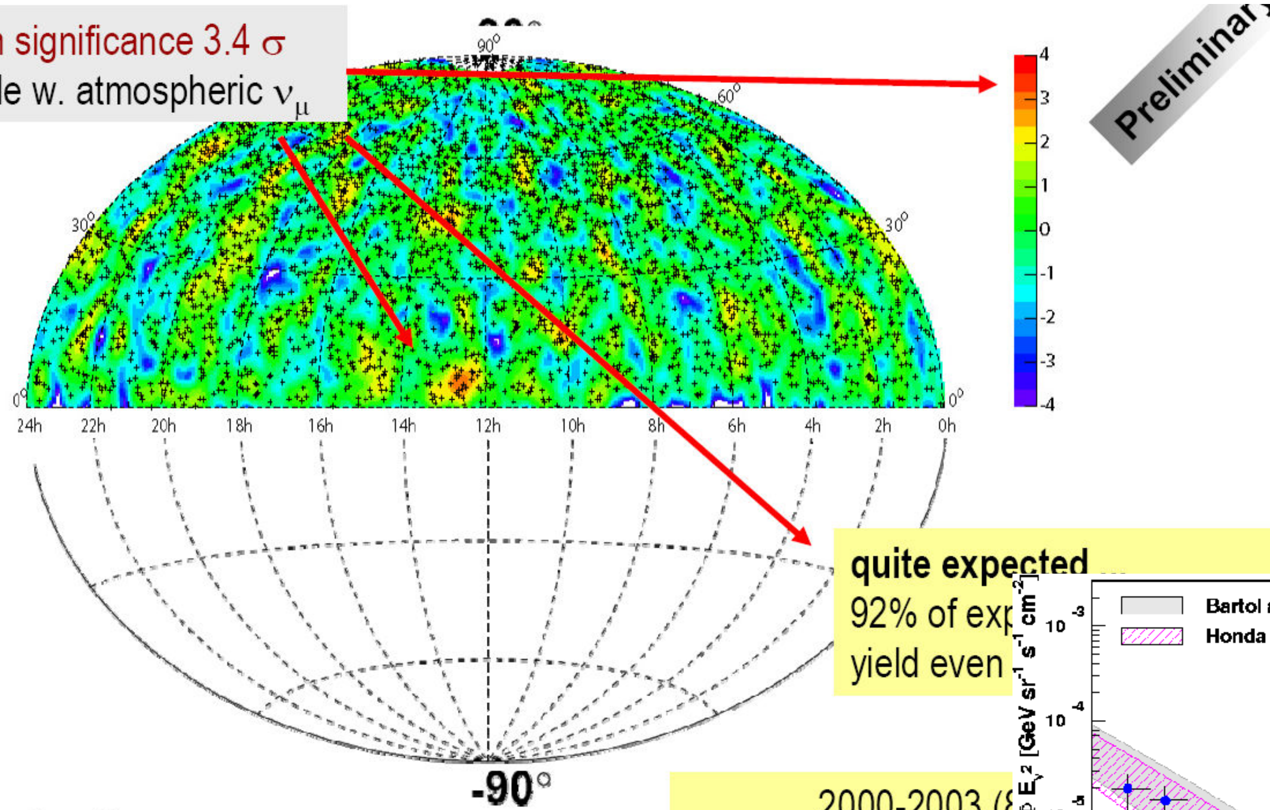
- Cables with photomultiplier tubes are lowered in deep holes excavated in ice.
- *Detection technique again based on light produced by Cerenkov effect.*
- AmandaB has already given results
  - volume 500 m high by100 m section.
- Icecube in construction.
- Already 59/80 strings holding 60 PMs
- Will be 1 km^3 big
- *Such an apparatus observes the Northern hemisphere because cosmic muon background is enormous.*

Amanda


AMANDA-II
Depth
top view
200 m
1500 m
2000 m
2500 m
Optical
module (677)



Maximum significance 3.4 σ
compatible w. atmospheric ν_μ



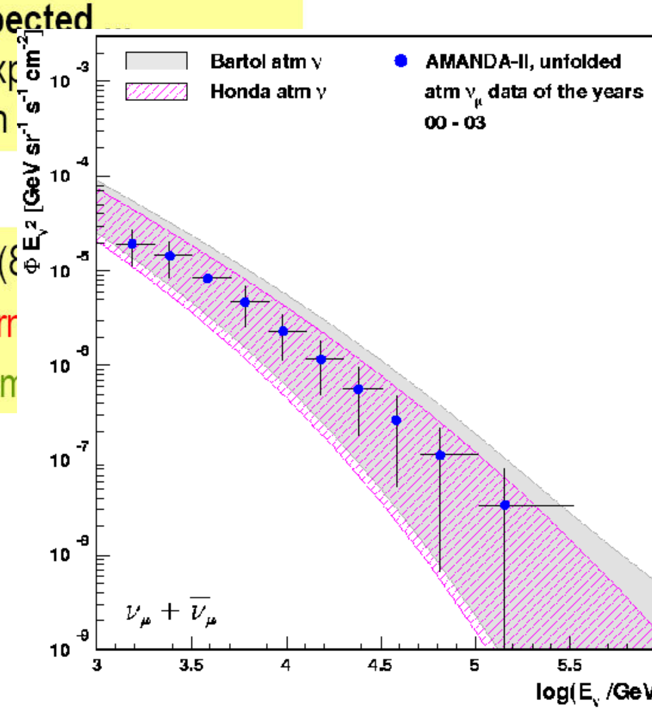
quite expected ...
92% of exp
yield even

cluster search radius
etween 2.25° - 3.75° w.r.t.
the declination

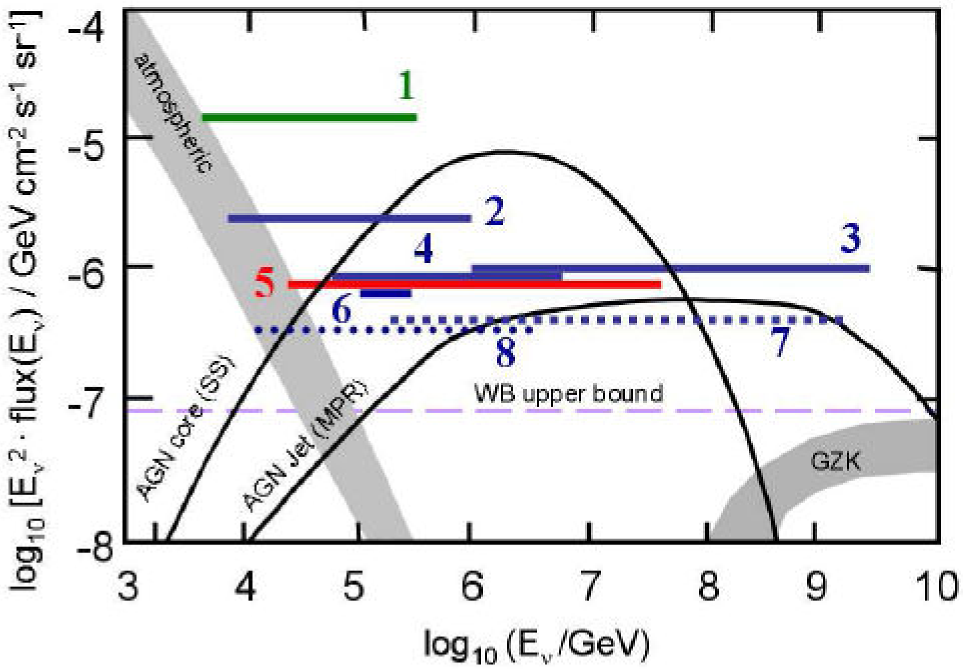
2000-2003 (8

3329 μ from northern

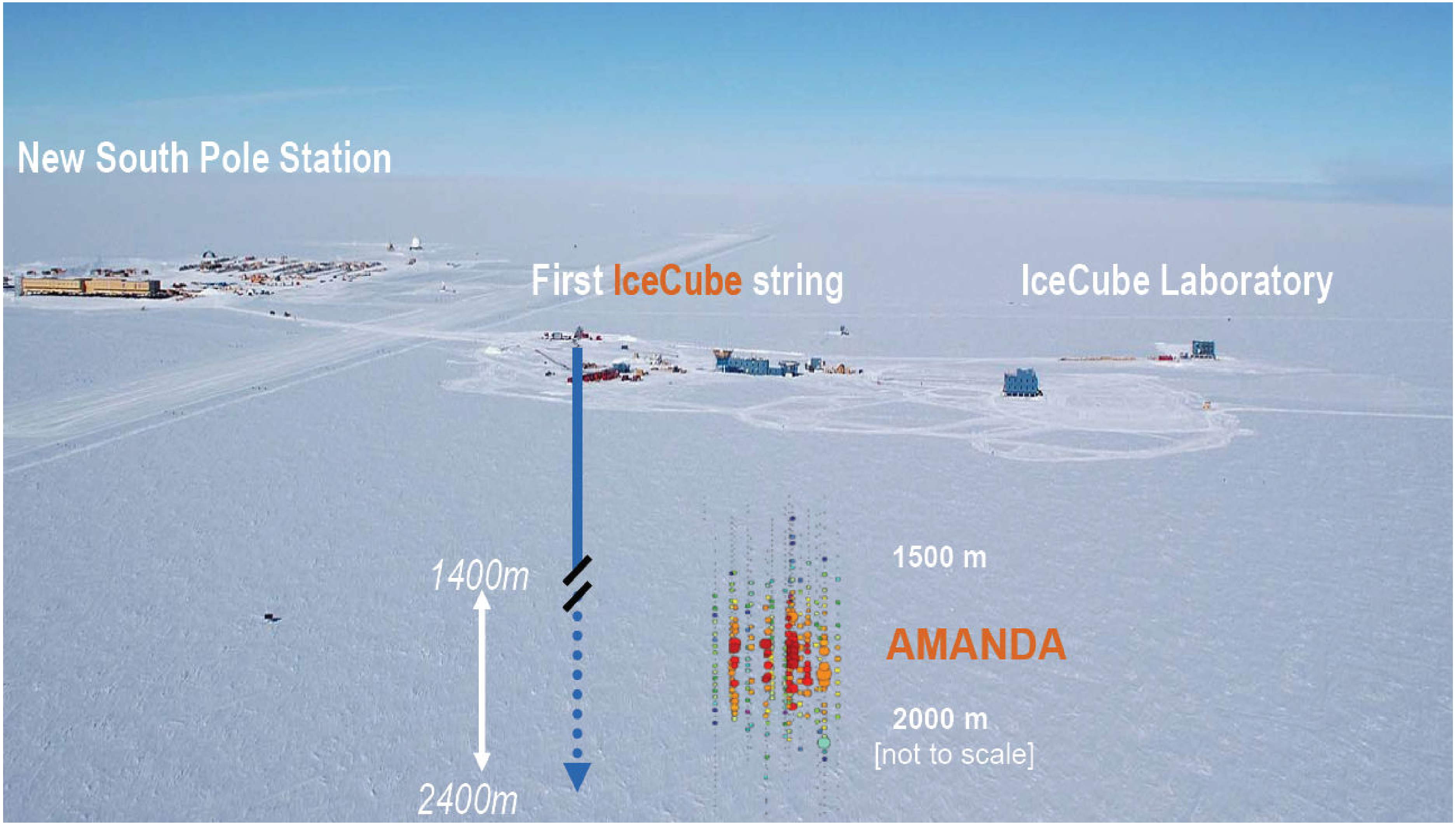
3438 μ expected from



Existing limits



IceCube

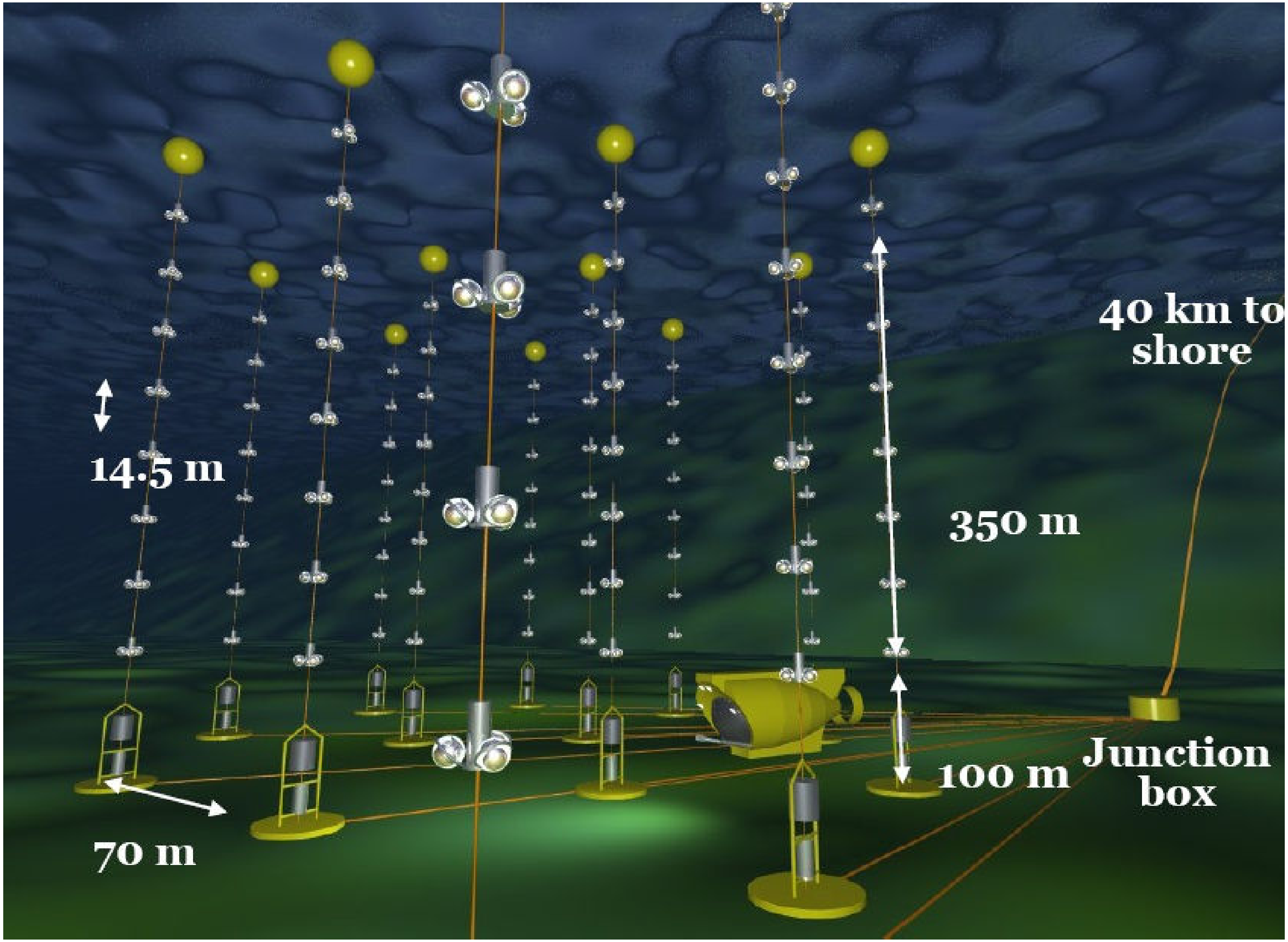


New South Pole Station
First IceCube string
IceCube Laboratory
1400m
2400m
1500 m
AMANDA
2000 m
[not to scale]

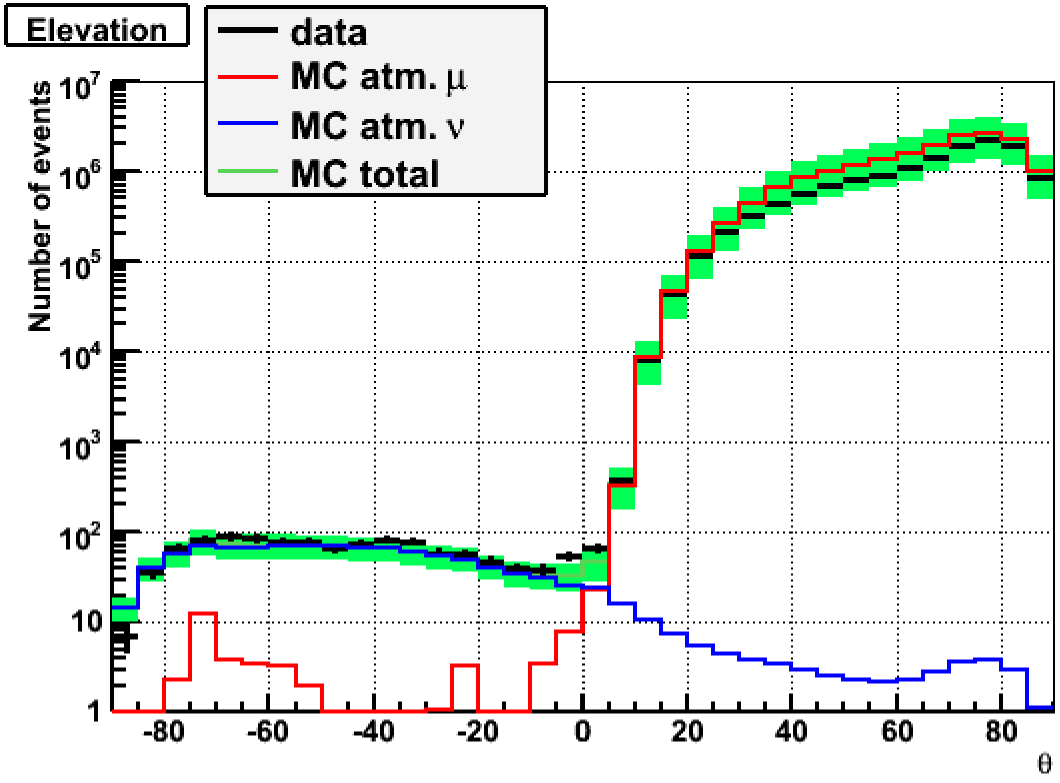
In the Mediterranean sea

- Antarès uses sea water as target. Advantage: less diffusion, better angular resolution
- Cables anchored 2,5 km deep, 30 storeys of 3 PMs spaced15m.
- 12 lines are operational
- 350m high with section 100m x 100m
- *Complementarity to Amanda/Icecube:*
- *Antarès will observe the Southern hemisphere (galactic center).*
- Towards a km^3 detector in the Medditeranean sea.

Antarès



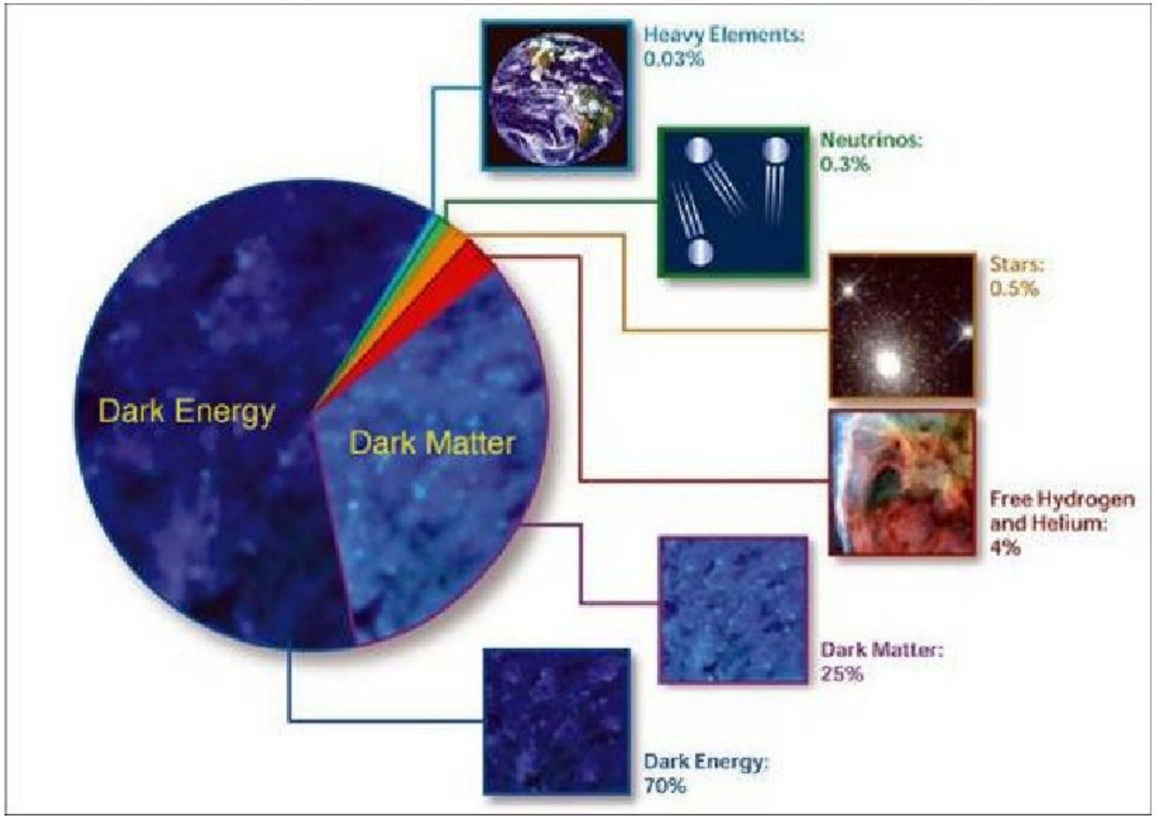
Completed May 2008



Still beyond?

- Large volumes, but statistics very limited.
- Efficient detection of muons and taus of VHE
  Energy measurement and angular information OK
- But earth is opaque above 10^{14} eV
- Auger or JEM-EUSO allow the search of skimming neutrinos from 10^{18} eV to 10^{20} eV.
- Other techniques are investigated: radio emission or sound.
- *Radio detection already attempted: Rice at South Pole (moon shadow). Coming, Anita, Codalema…*

Big bang neutrinos



Conclusions

Very rich domain of physics. Important progresses recently achieved: neutrinos have masses

$m(\nu_\tau) = 50$ meV, $m(\nu_\mu) = 9$ meV, $m(\nu_e) = ?$

They represent ≈ 0,5% of the energy content of the Universe.

Large experimental program still ahead

Solution to the matter-antimatter asymetry?

Solution to the missing mass problem?

Solution to the dark energy problem?

Future will tell.

The most incomprehensible of our story is that the Universe is comprehensible.

A. Einstein