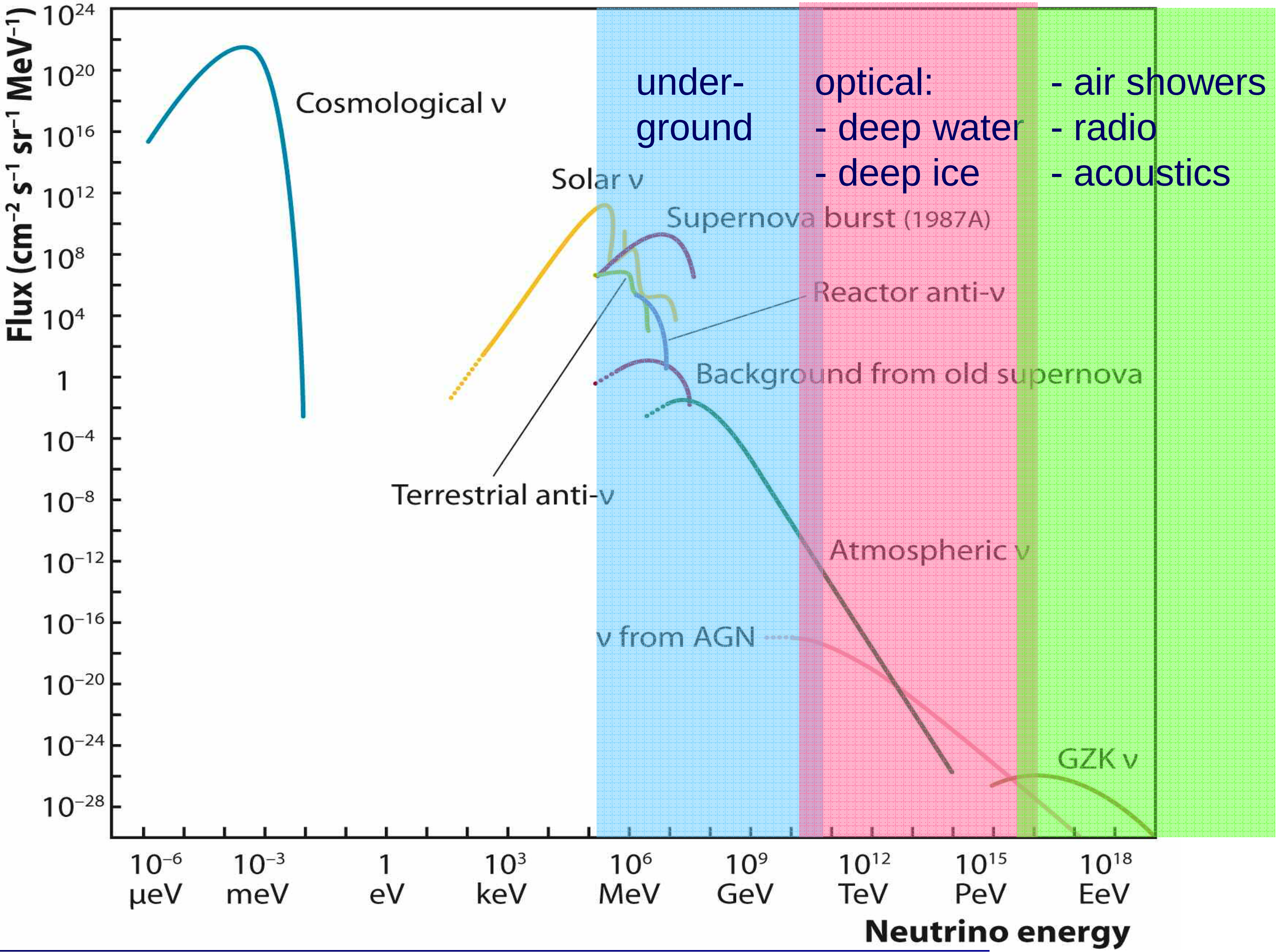
# Neutrino Telescopes

## Status and Perspectives

Christian Spiering
DESY

TeV-III, Venice 2007

# The unified spectrum of neutrinos



# Content

- **Signal expectations**
- **The TeV domain**
  Underwater/ice optical detectors,
  status and perspectives of experiments
- **Some physics results**
  from AMANDA/Baikal
- **PeV and beyond:**
  status and perspectives
- **Summary**

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# Neutrino Production

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

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

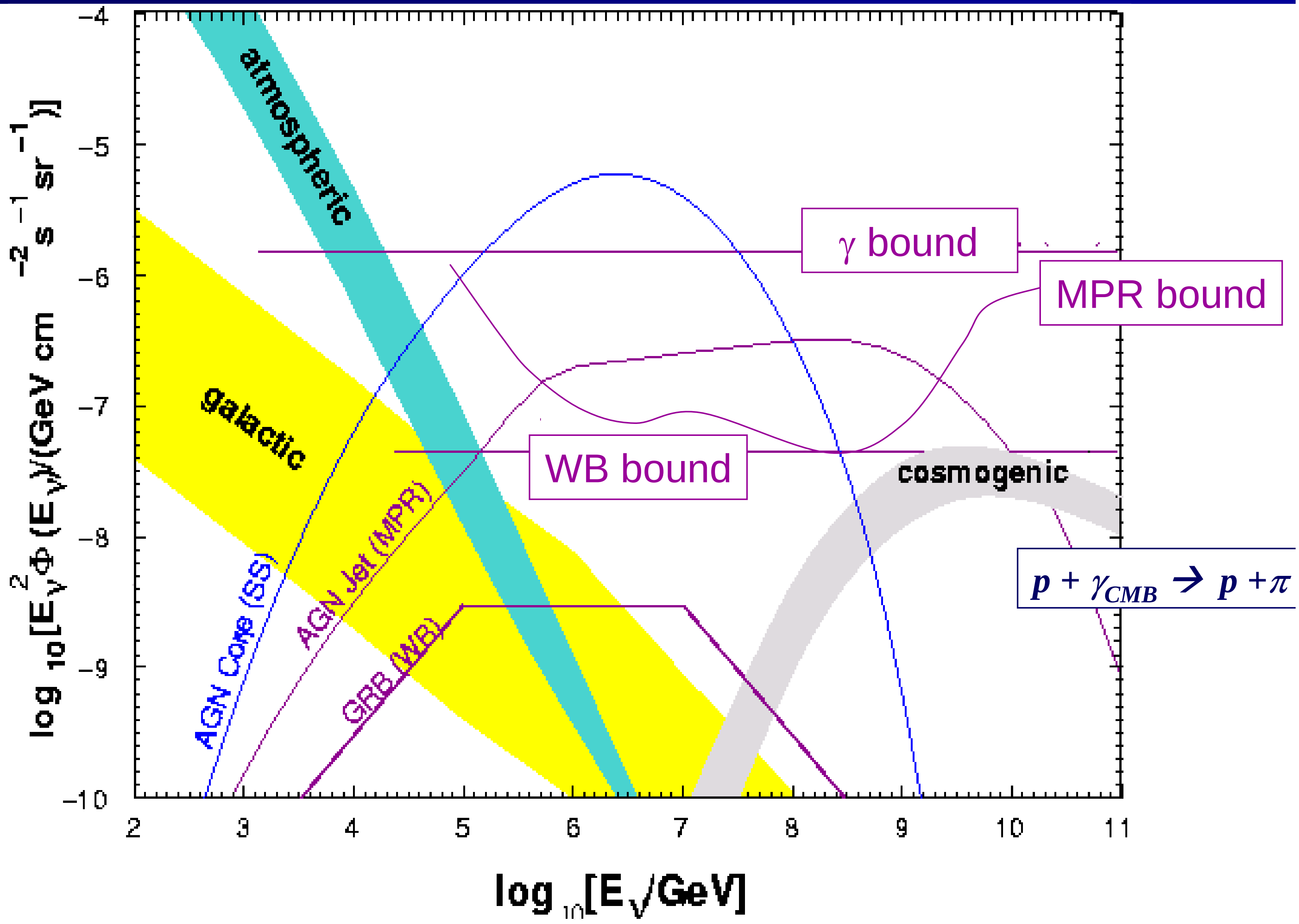
$$\rightarrow e + \nu_e + \nu_\mu$$

$$p + \gamma \rightarrow n + \pi^+$$ **or** $$\rightarrow p + \pi^0$$

$$\rightarrow \mu + \nu \qquad \rightarrow \gamma + \gamma$$

$\nu_e : \nu_\mu : \nu_\tau$ ~1:2:0 turns to 1:1:1 at Earth

# Diffuse Fluxes (1998)



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# Signal predictions: extragalactic sources

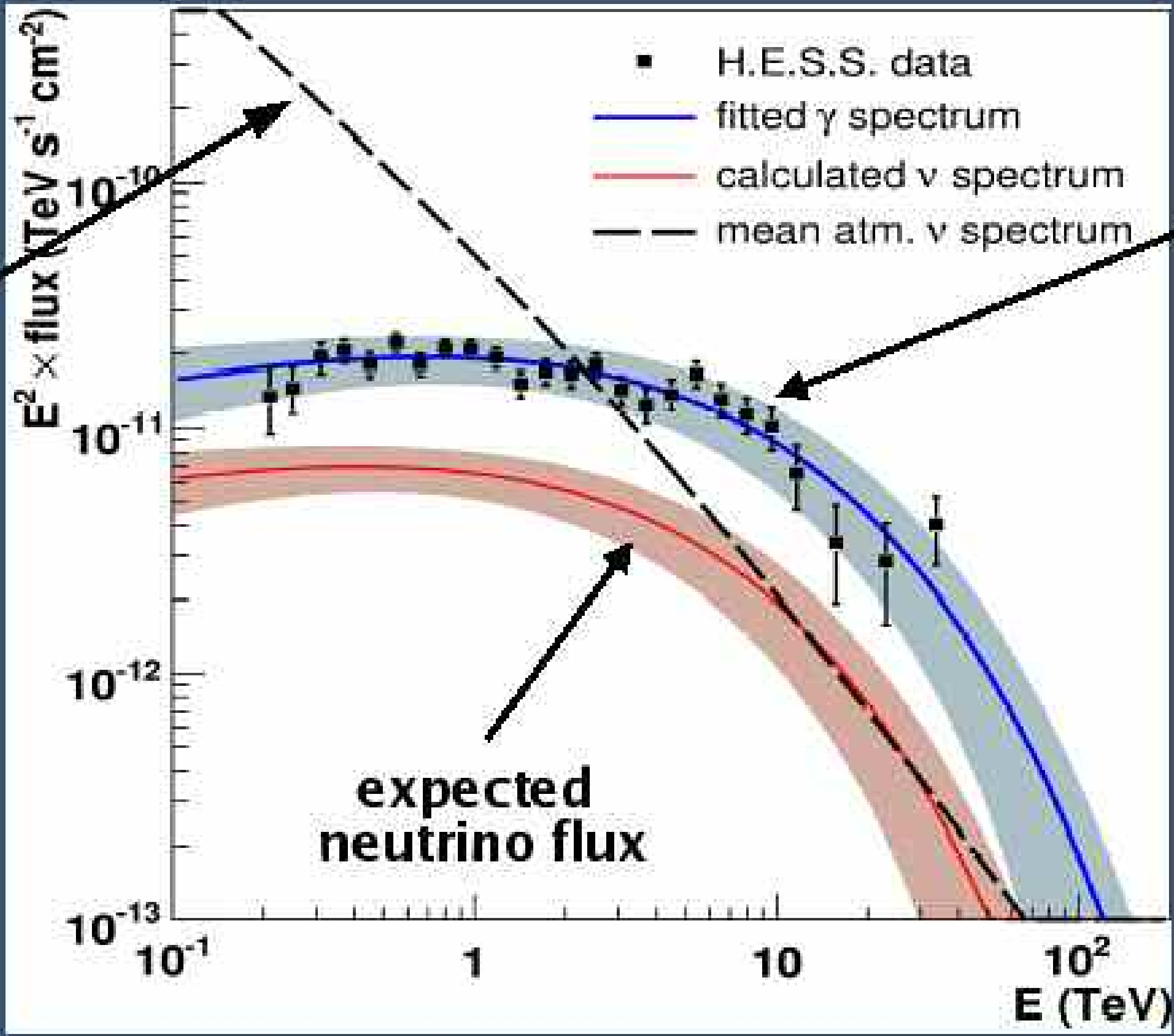
- WB bound corresponds to 100-500 neutrinos per $km^2$·year
- AGN predictions are highly uncertain (many orders of magnitude !) but leave room for hopes
- Several older AGN models dramatically violate even soft upper bounds on diffuse fluxes, as derived from CR
- Fluxes from individual AGN: less constrained
- GRB: various models, benchmark model of Waxman-Bahcall can be easily tested with km3 detectors

# Signal predictions: galactic sources

- Predictions on firmer ground than for AGN
  - Shell-type SNR
  - Pulsar Wind Nebula
  - Compact Binary Systems
- Many papers in the last 2 years:
  - Bednarek and Montaruli 2005
  - Vissani 2006
  - DiStefano 2006
  - Lipari 2006
  - Kappes, Hinton, Stegmann, Aharonian 2007
  - Gabici, Aharonian 2007
  - …
- Unanimous conclusion:
  Cubic kilometer detectors will just scrape the detection region

# Expected ν flux from galactic point sources, example: RXJ 1713-3946

Assume $\pi^0 \rightarrow \gamma$ and calculate related $\pi^\pm \rightarrow \nu$




mean atm. flux (Volkova, 1980, Sov.J.Nucl.Phys., 31(6), 784)

measured γ-ray flux (H.E.S.S.)

C. Stegmann ICRC 2007

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# Neutrino Event Rates (II)

- γ-ray sources with observed cut-off (KM3NeT, 5 years)

| | Type | Dia. [º] | E > 1TeV src | bck | E > 5TeV src | bck |
|---|---|---|---|---|---|---|
| - Vela X | PWN | 0.8 | 9 – 23 | 23 | 5 – 15 | 4.6 |
| - RX J1713.7-3946 | SNR | 1.3 | 7 – 14 | 21 | 2.6 – 6.7 | 8.2 |
| - RX J0852.0-4622 | SNR | 2.0 | 7 – 15 | 104 | 1.9 – 6.5 | 21 |
| - HESS J1825–137 | PWN | 0.3 | 5 – 10 | 9.3 | 2.2 – 5.2 | 1.8 |
| - Crab Nebula | PWN | <0.1 | 4.0 – 7.6 | 5.2 | 1.1 – 2.7 | 1.1 |
| - HESS J1303–631 | NCP | 0.3 | 0.8 – 2.3 | 11 | 0.1 – 0.5 | 2.1 |
| - LS 5039* (INFC) | Binary | <0.1 | 0.3 – 0.7 | 2.5 | 0.1 – 0.3 | 0.5 |

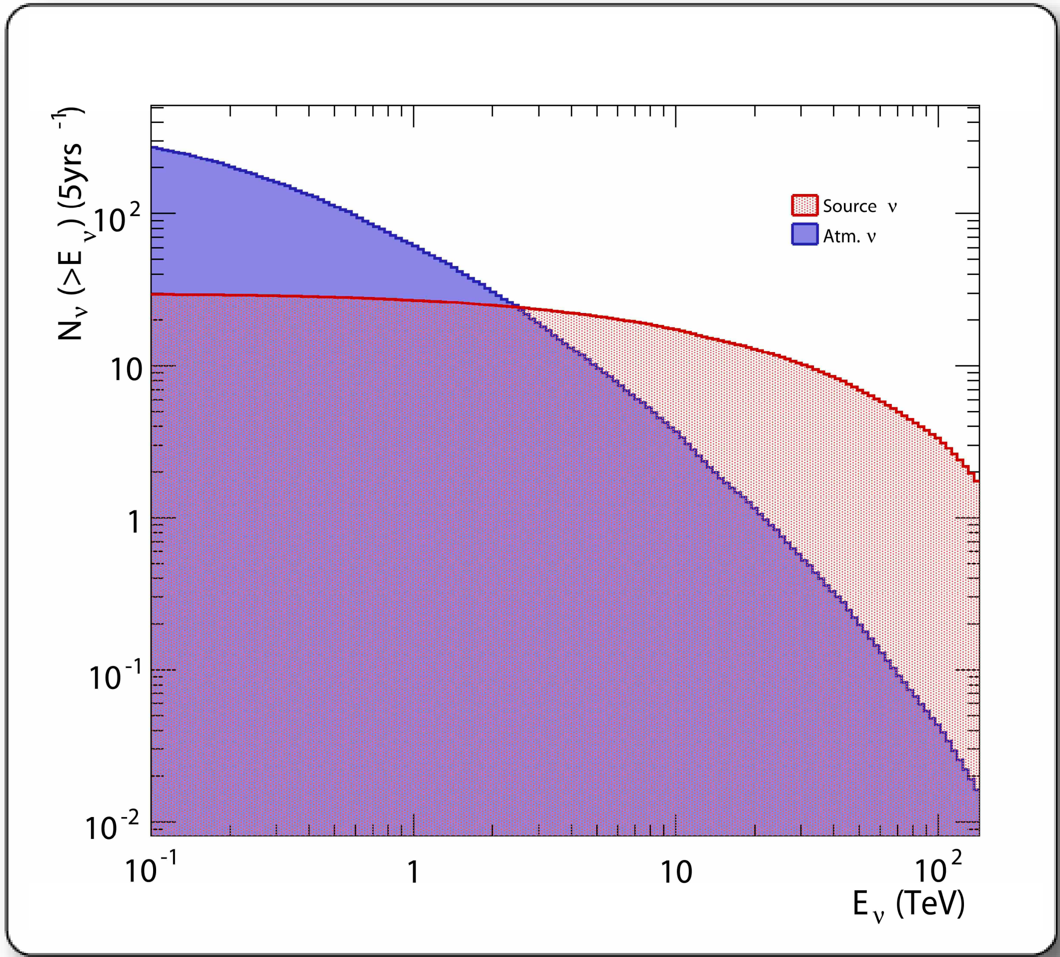
NCP: no counterparts at other wavelength

* no γ-ray absorption

- 23 further γ-ray sources investigated:
  - All γ-ray spectra show no cut-offs (but limited statistics)
  - Event numbers mostly below 1 – 2 in 5 years

Christian Stegmann, Galactic Neutrinos, ICRC 2007

# PKS2105-304 (R. White, ICRC)




R.J.White, ICRC

- PKS2105-304 as measured by H.E.S.S.
- Correcting for γ absorption
- kinematics for ν/γ in source
- KM3NeT with angular resolution 0.5°
- S/Bg (> 1TeV) = 27/61
- S/Bg(> 5TeV)
- =21/10 (→5σ)

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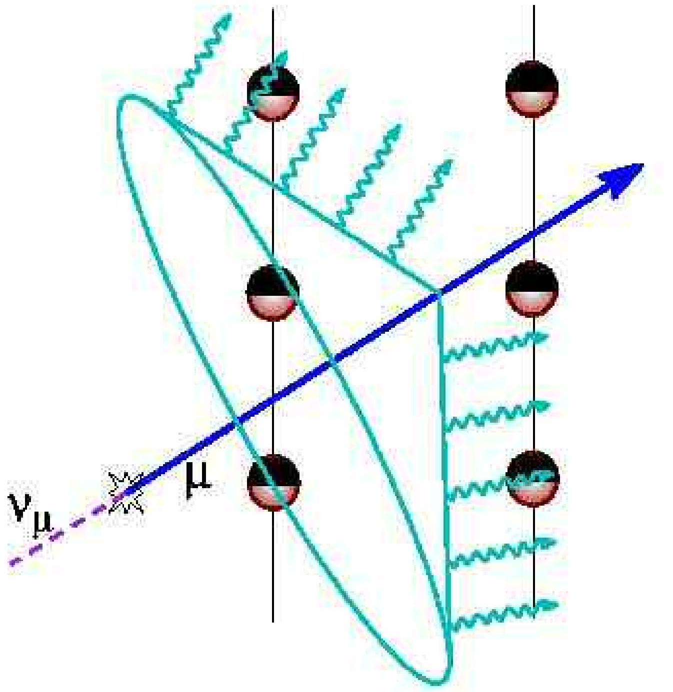
# Conclusions for galactic sources

- No strong need for PeV range
- No strong need for < 1 TeV  and  km³  det.
- Optimum threshold for typical analyses with a km3 detector more like 5 TeV
- Desirable  area  5-10 km²
- But: don‘t forget SN shells in first months after explosion !
- Always to the rescue: hidden sources

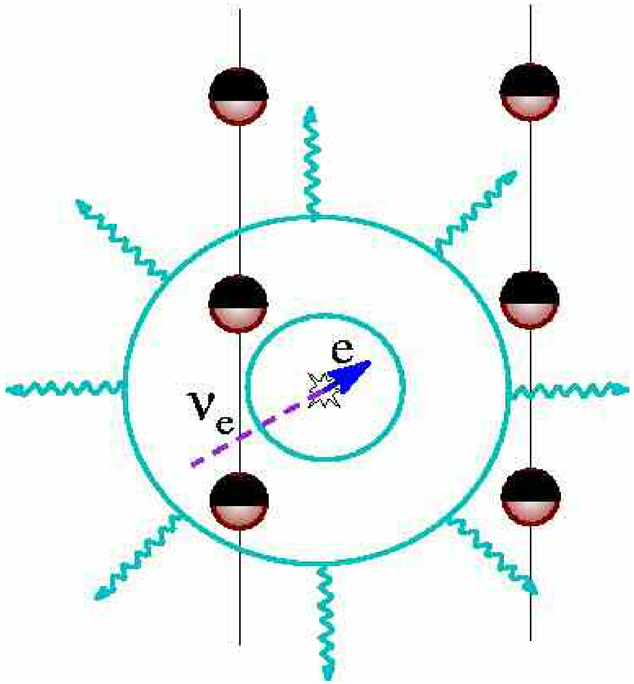
(but they also eventually should be visible at low photon energies !)

# Underwater/Ice: optical telescopes

muon tracks




cascades




| | muon tracks | cascades | |
|---|---|---|---|
| $\sigma_{angle}$ | water < 0.3° | water 3-6° | (at 10 TeV) |
| | ice 0.5-1° | ice ~25° | (at 10 TeV) |
| $\sigma_{energy}$ | 0.3 in log E | 30% in E | (at 10 TeV) |

# Basic parameters of present and planned neutrino telescopes

## Effective ν area:

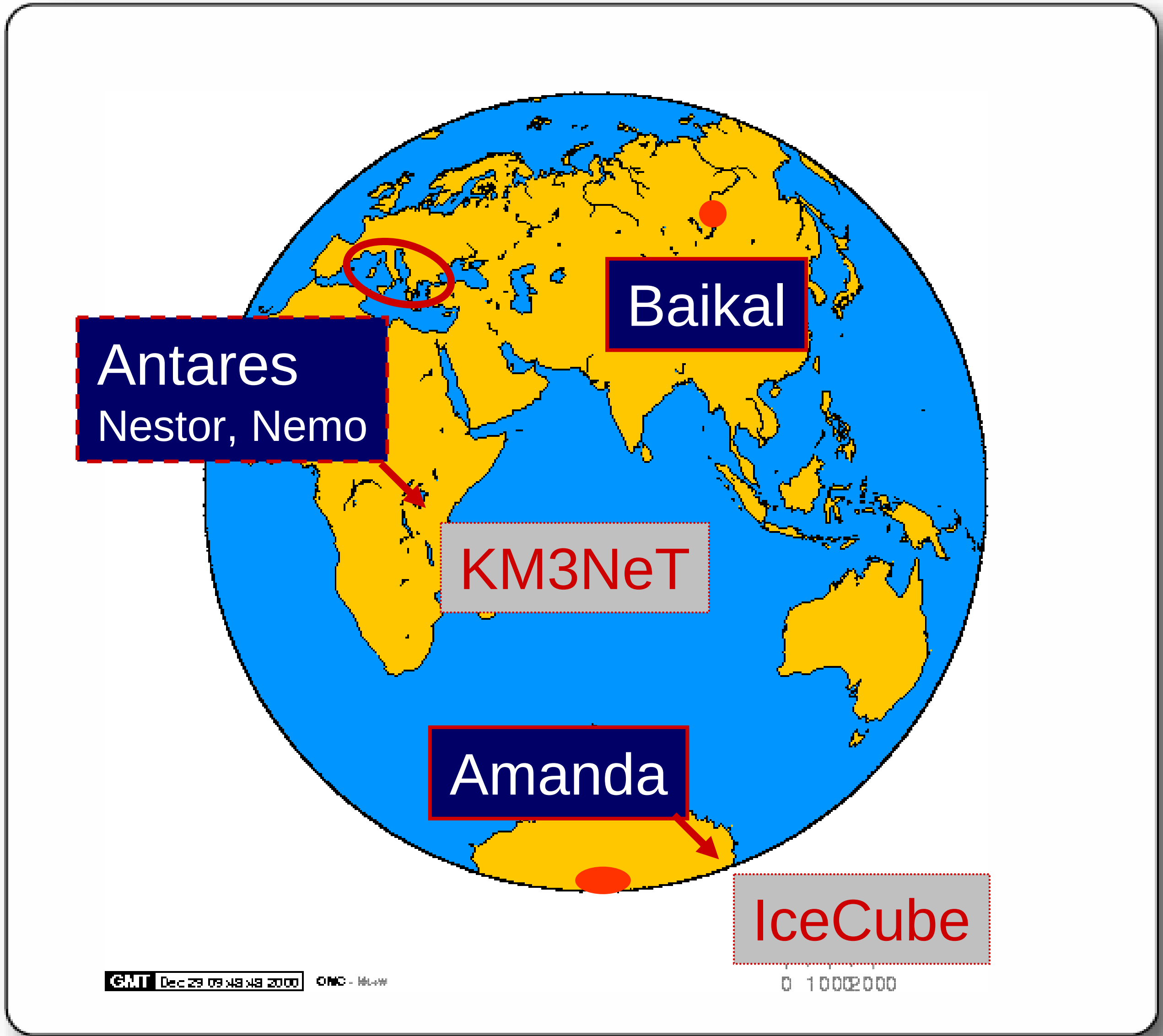
| | | | |
|---|---|---|---|
| ~ 0.1 $m^2$ | @ 10 TeV | Amanda/Antares |
| ~ 4 $m^2$ | @ 100 TeV | Amanda/Antares |
| ~ 20 $m^2$ | @ 100 TeV | IceCube now |
| ~100 $m^2$ | @ 100 TeV | IceCube complete |

## Point source sensitivity:

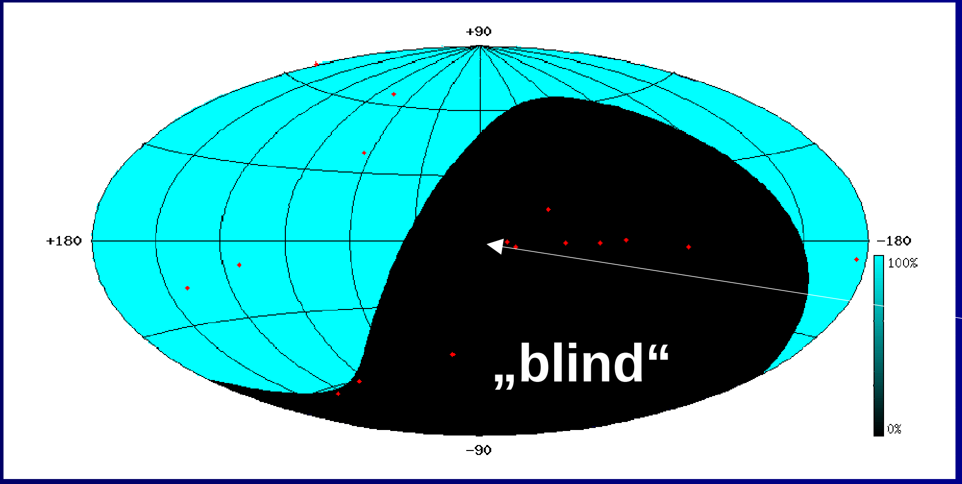
- AMANDA, ANTARES: ~ $3\cdot10^{-10}$ ν / ($cm^2$ s) above 1 TeV
- IceCube, KM3NeT ~ $10^{-11}$ ν / ($cm^2$ s) above 1 TeV

(for 5σ discovery)

# The Projects

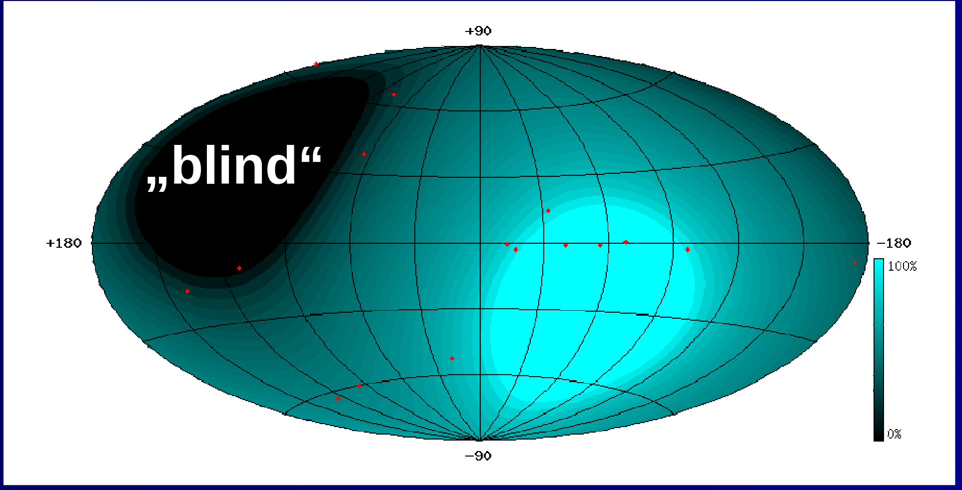


# North and South




## South Pole

Galactic Center




## Mediterranean

# BUT:

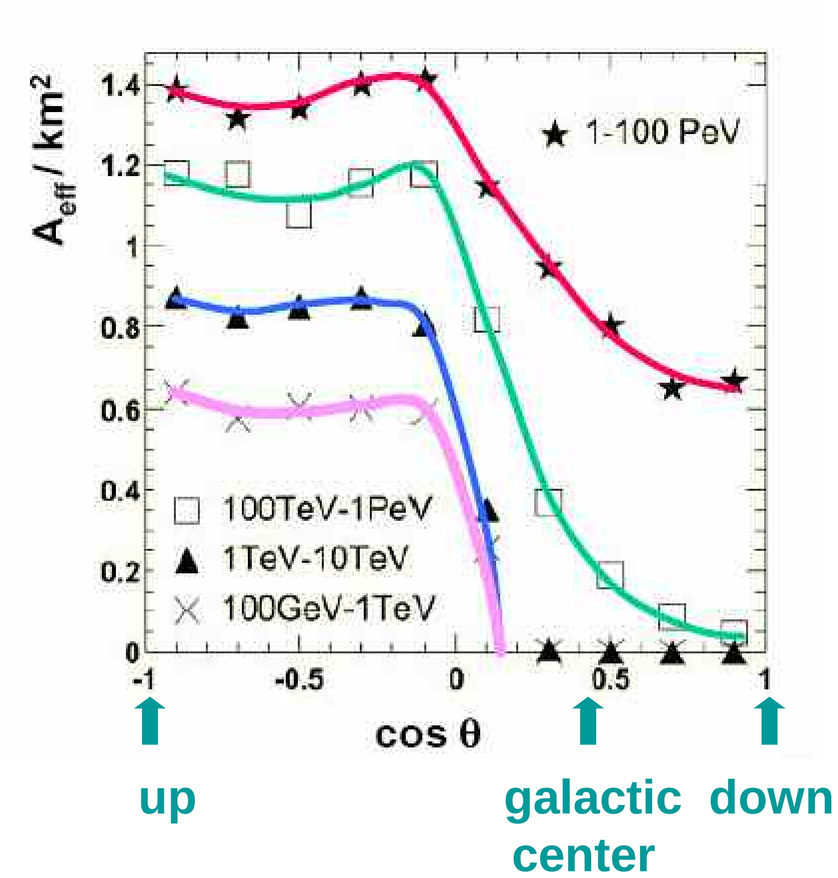
# North and South

- At high energies: much less μ BG from above
  → **look above horizon !**

- At low energies: contained events in large detectors
  → **look above horizon !**

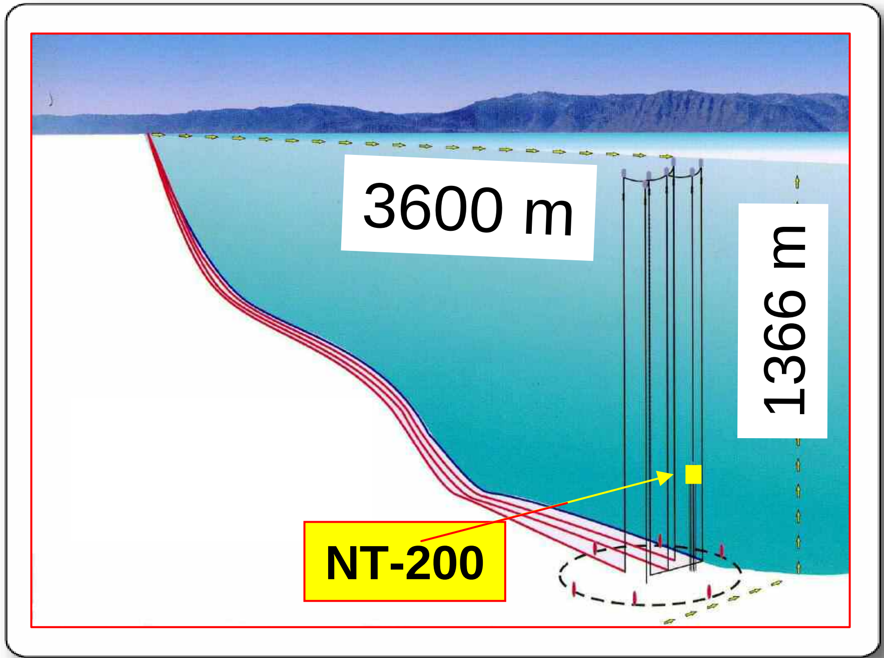
(more below)

**IceCube, after $10^6$ BG reduction**



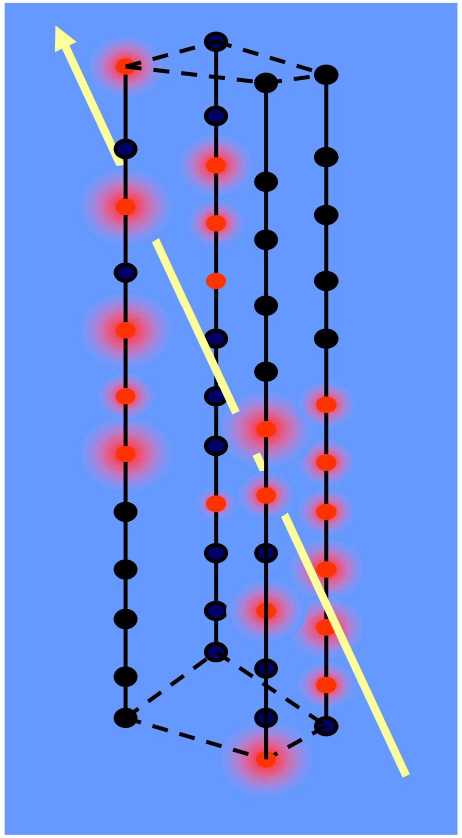
# The Baikal Neutrino Telescope

see talk R. Wischnewski




- 1981 first site explorations
- 1998 NT200 finished

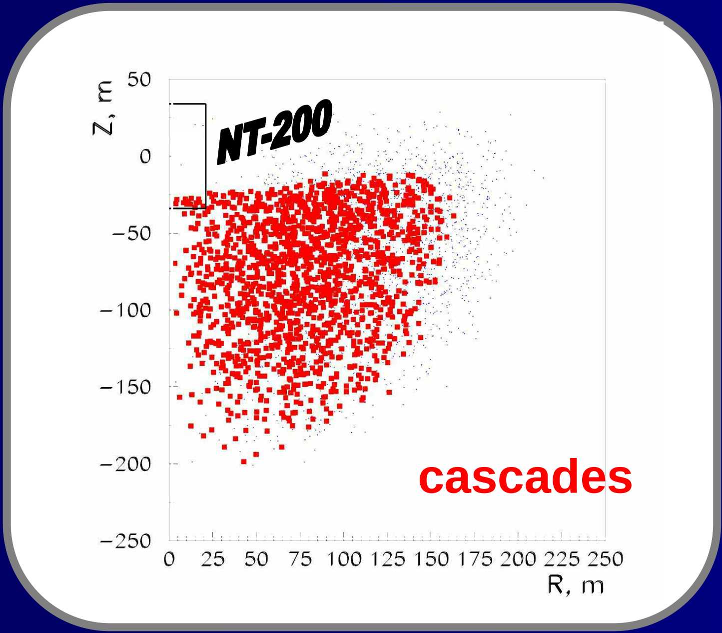
Ice as natural deployment platform

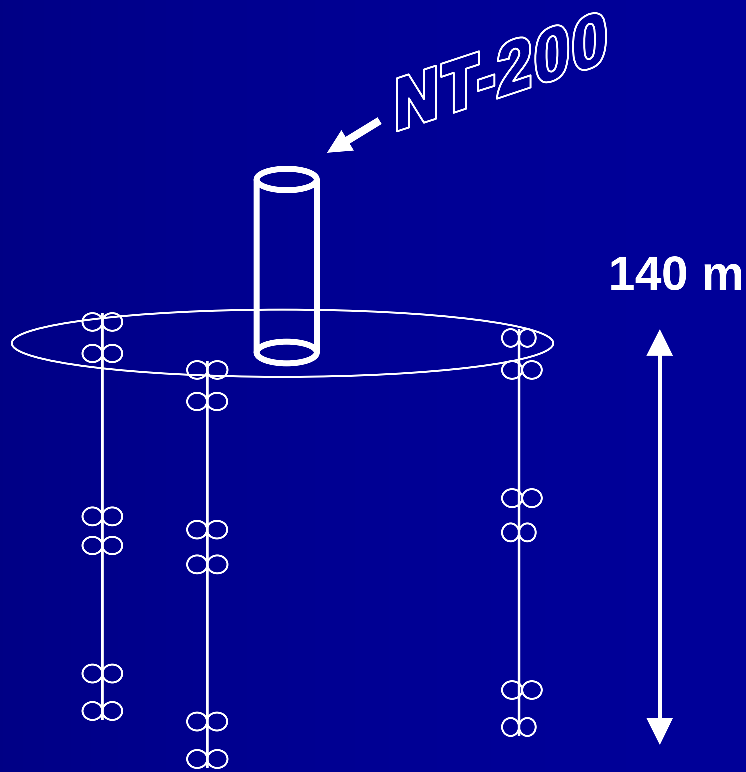


A textbook neutrino event (4-strings 1996)

# From NT200 to NT200+

Detection of high energy cascades outside the instrumented volume



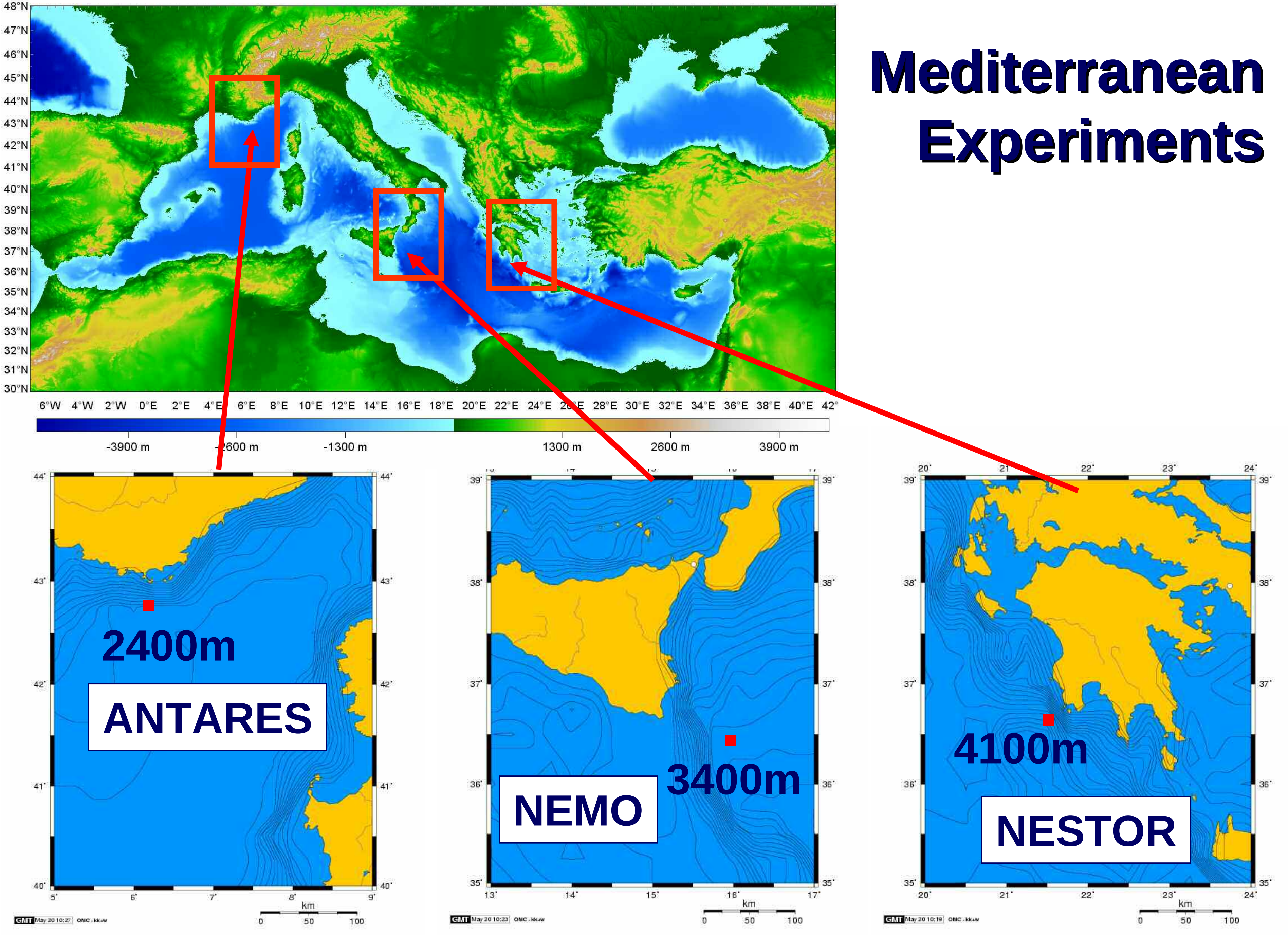




Since 2005: observation volume fenced with 36 PMTs

→ 4 times better sensitivity at high energies

Basic cell for future Gigaton detector

# Mediterranean Experiments

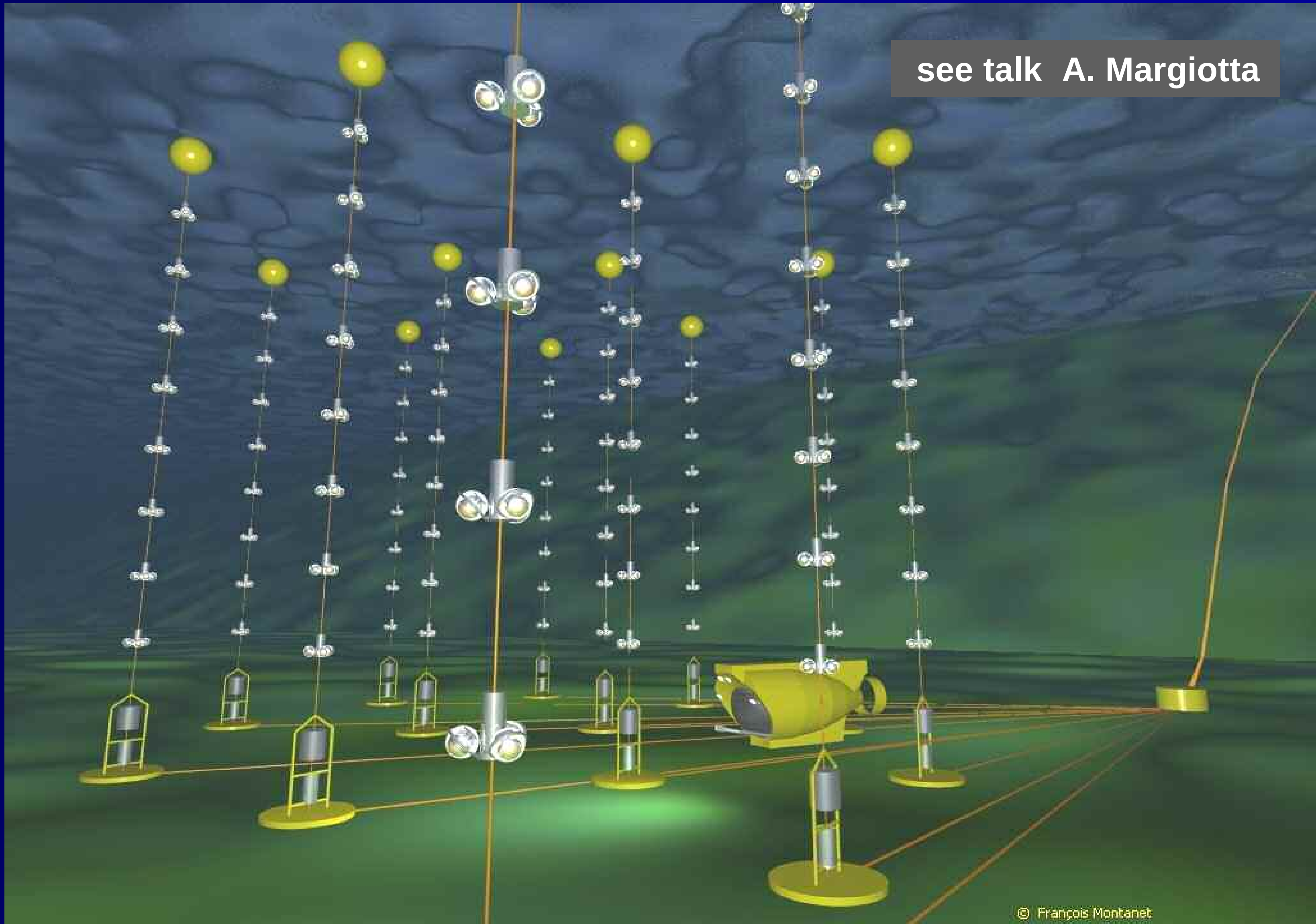


# NESTOR

- project since 1991
- 1 floor deployed in 2004
- took data for a few weeks, then cable defect
- waiting for repair
- 4 floors ready for deployment

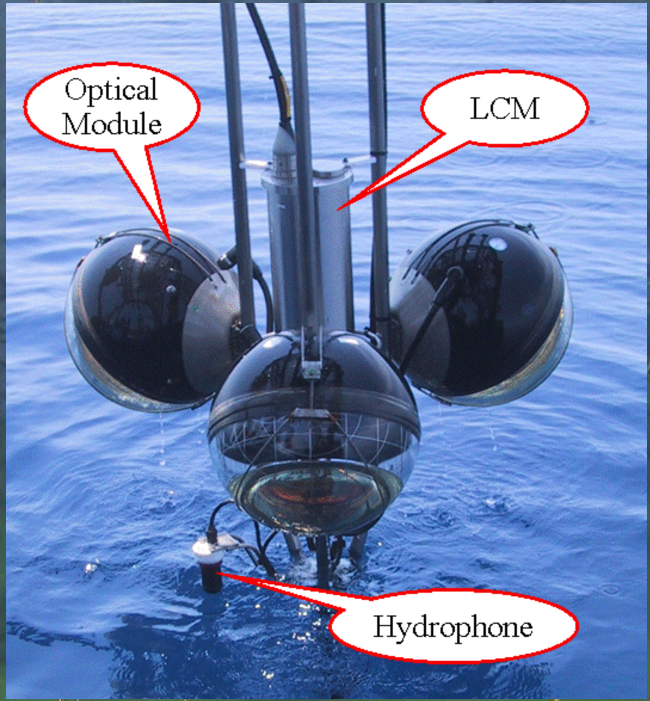
- Plans for 4 floors surrounded by autonomous stations

# ANTARES

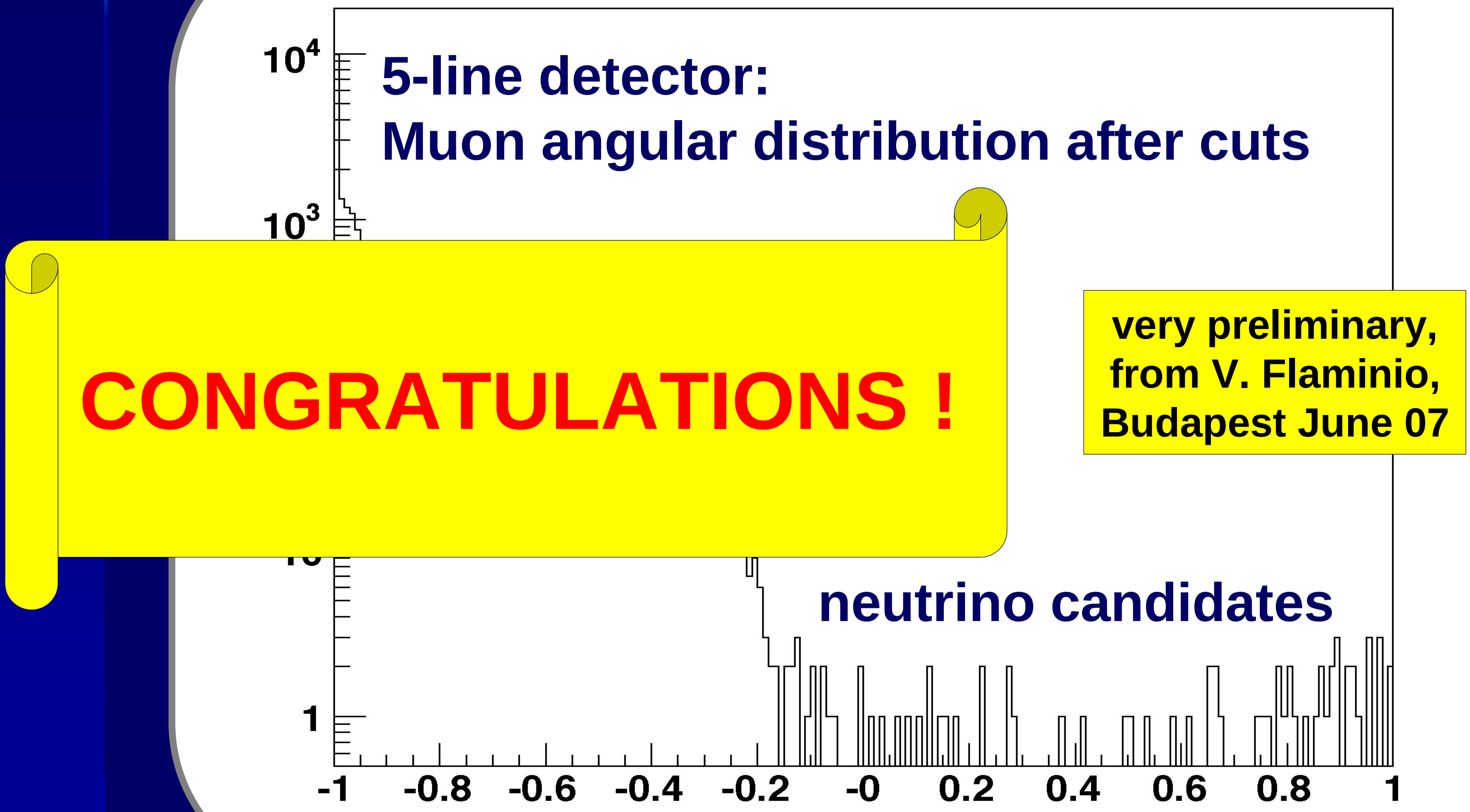


# ANTARES

- Project since 1996
- 12 lines in total
- 2001: cable
- 2002: junction box
- 2005: MILOM test line
- 2007: 7 lines deployed (525 PMTs)
- 5 lines connected and taking data
- Atumn/Jan/Feb: deploy &connect the rest

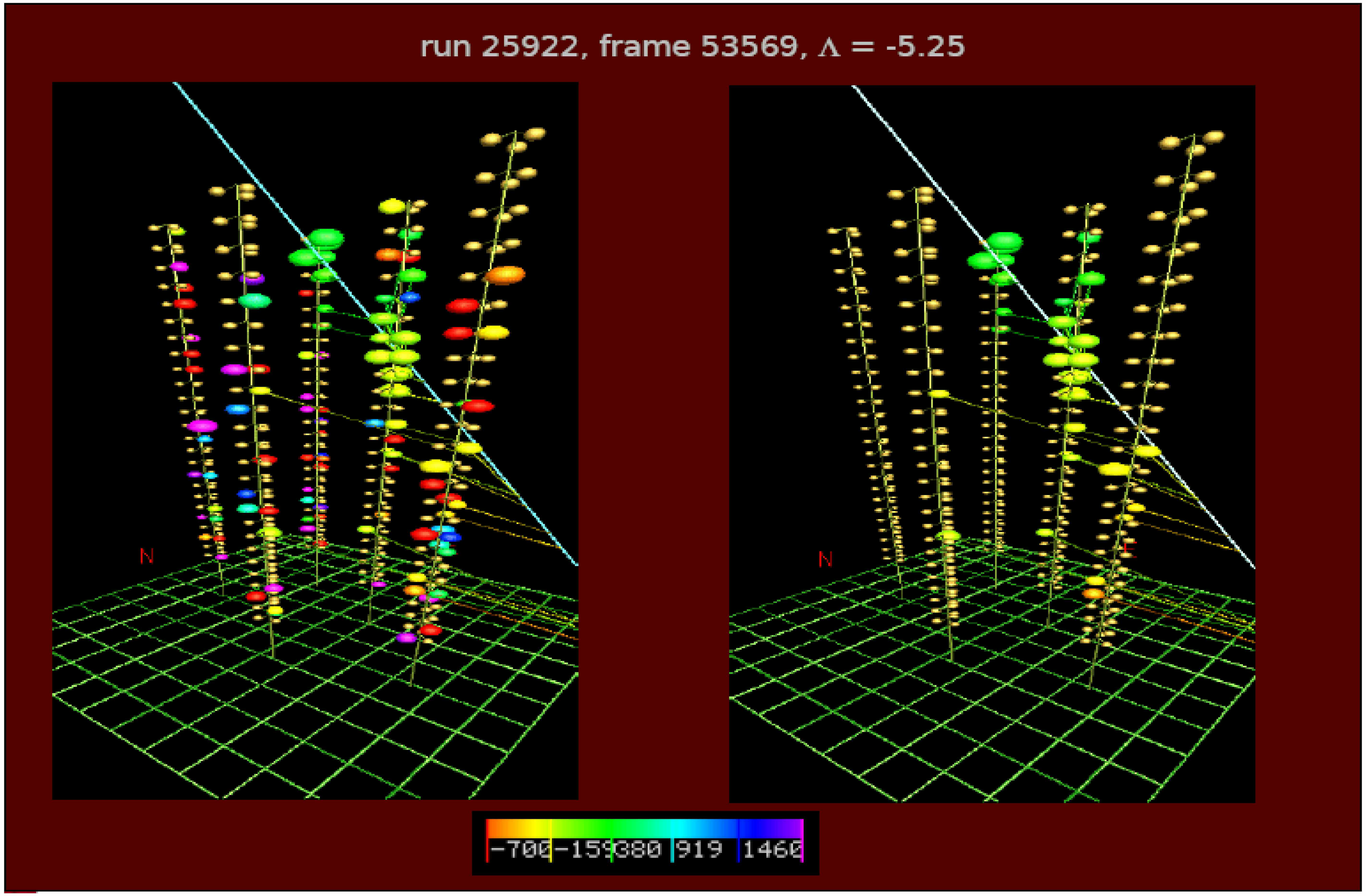


# ANTARES



5-line detector:
Muon angular distribution after cuts
CONGRATULATIONS !
very preliminary, from V. Flaminio, Budapest June 07
neutrino candidates
10^4
10^3
1
-1
-0.8
-0.6
-0.4
-0.2
-0
0.2
0.4
0.6
0.8
1

# ANTARES Neutrino Candidates

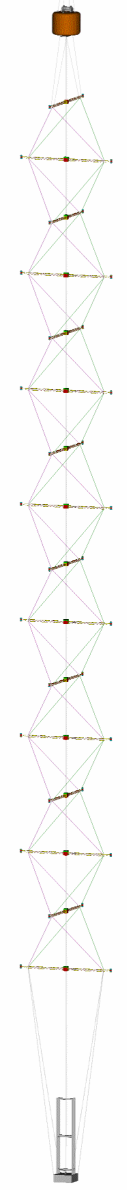


# NEMO

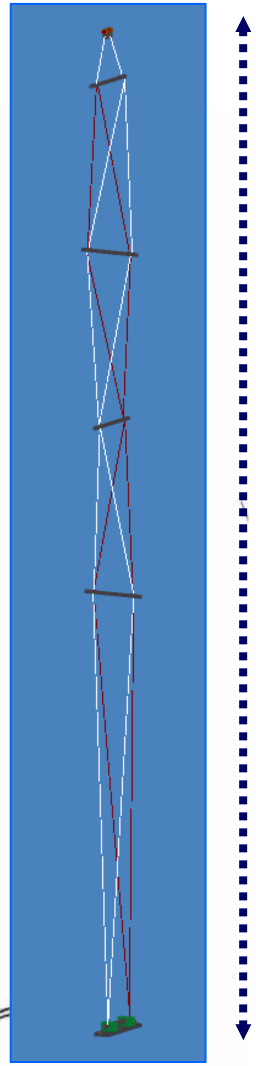
- NEMO Phase-1 (2003-2007)
  *@ LNS Underwater Test Site (2000 m)*
  – Test prototypes of main km3 components
  – Validate installation and connection procedures

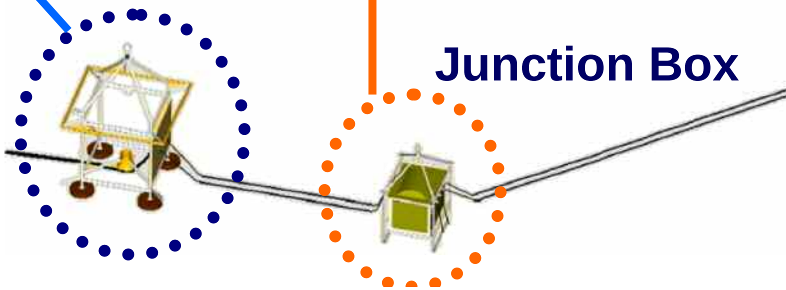
- NEMO Phase-2 (2005-2008)
  *@ Capo Passero Site (3500 m)*
  – Establish infrastructure suitable for a km3 detector
  – Test & validate advanced detector prototypes
  – Long term monitoring of site properties

***tower structure***



# NEMO-Phase 1

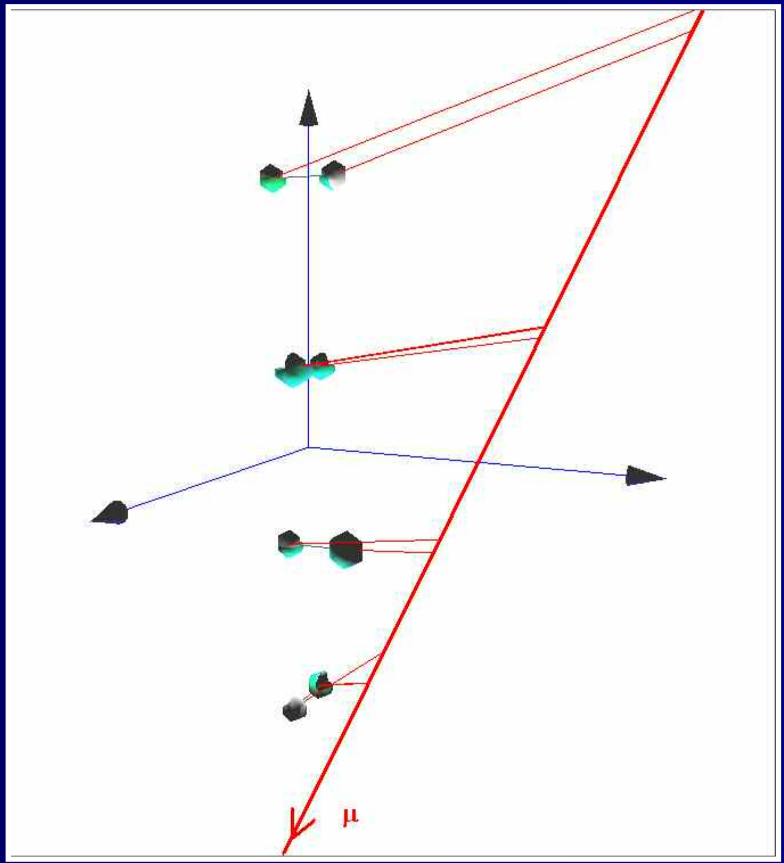


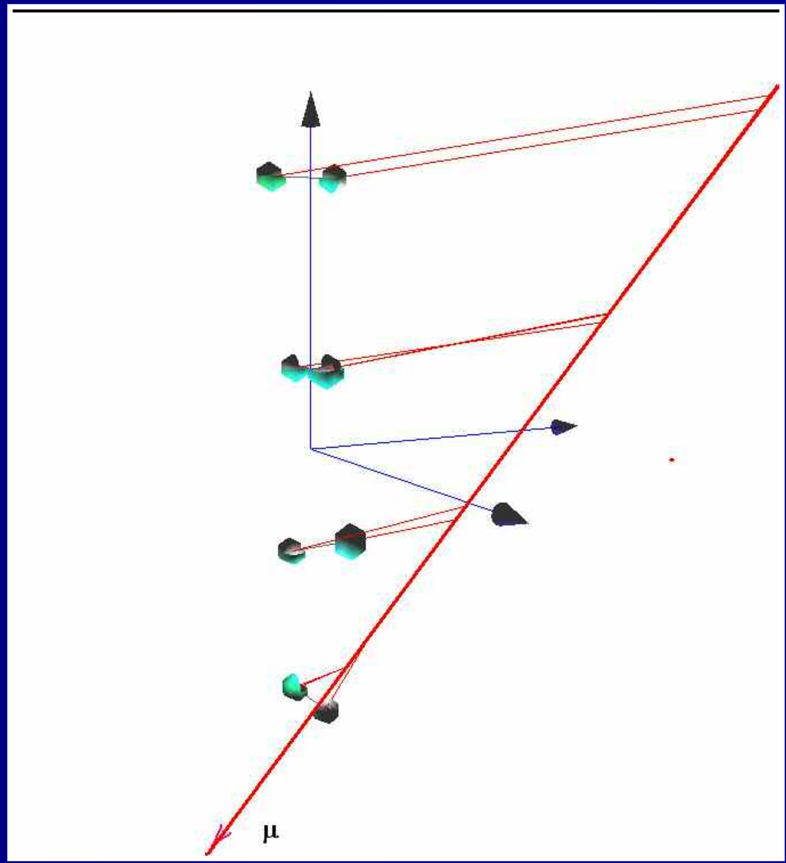



# NEMO Phase-1

## Dec 2006: deployment of tower

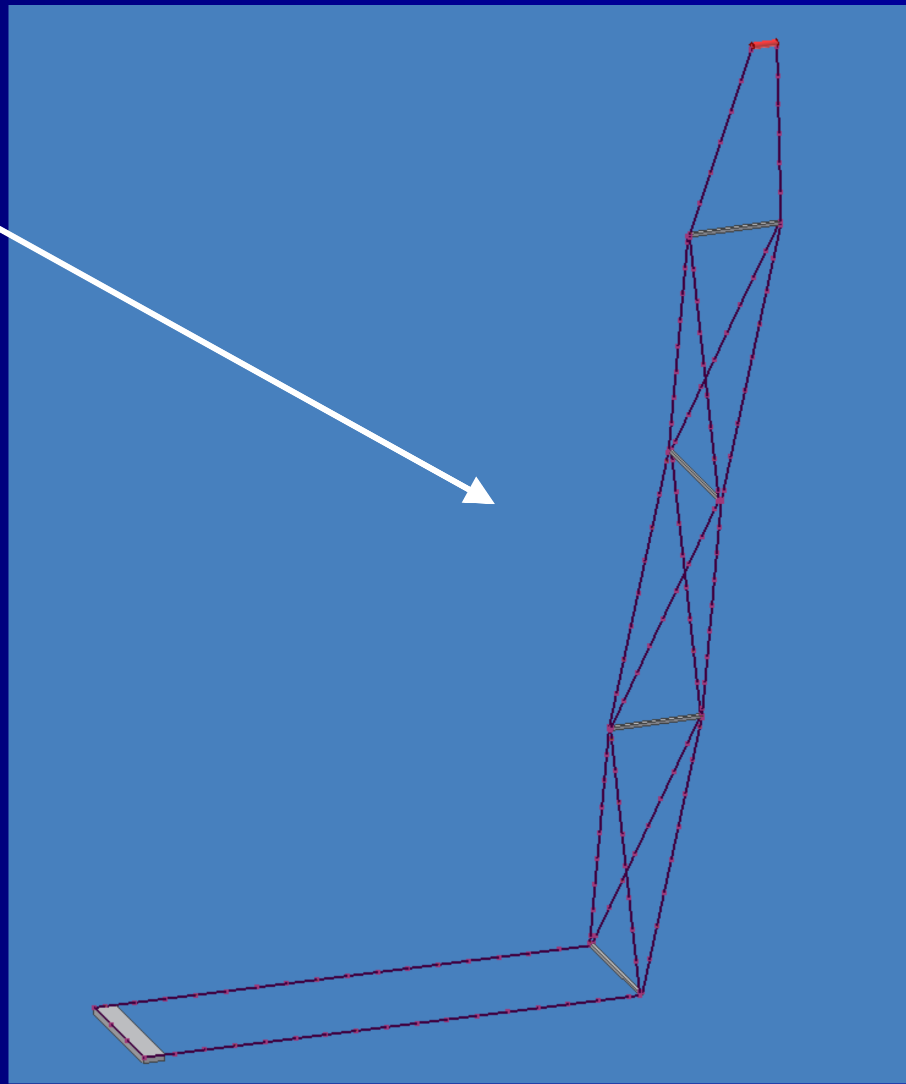
# NEMO downgoing muons (Jan.2007)



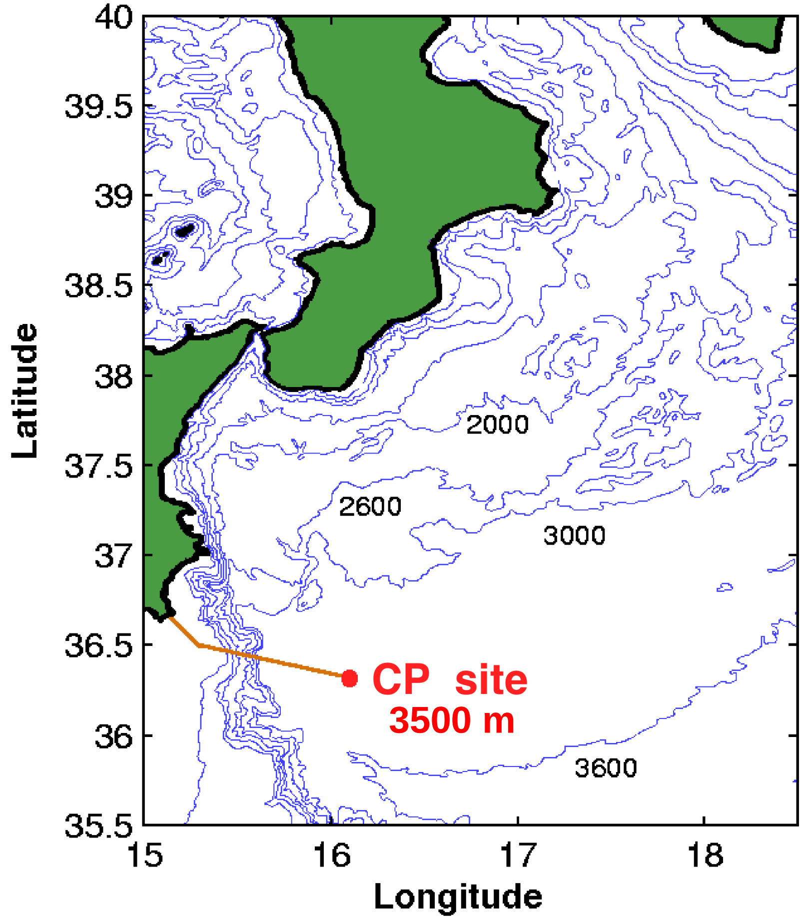
# NEMO-1 present status

- Floors are slowly sinking
- First and second floor now close to seabed
- Reason: deterioration of boy material
- → Add buoyancy
- Learned a lot of important lessons



# NEMO-2

- Full tower, 16 floors
- Same electronics like Phase-1, 2 floors to test new concepts
- 100 km cable, deployment in summer 2007
- Completion of shore station early 2008
- Tower deployment mid 2008



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- Impressing progress for both ANTARES and NEMO within the last 2 years
- Significant technological steps towards cubic kilometer detector

- Declaration of Greece minister: 50 M€ if cubic kilometer detector would be in Greece ….

# KM3NeT

- **A cubic kilometer detector in the Mediterranean**
- **Design study: 2006-2009**
  - Technical Design Report
- **Preparatory phase: 2008-2011**
  (proposal submitted)
  - Political convergence (site)
  - Commitment for construction of funding agencies/ministries
  - Governance and legal structure
  - System prototype
  - Tendering procedures
- **Construction phase: 2010-2013 (??)**
  - Build ≥1 km3 detector

**Targeted budget:**
M€220-250 (ESFRI roadmap)

# Which site ?

Final choice will depend on:

- Depth
- Bioluminescence rate
- Sedimentation, bio-fouling
- Distance from shore
- Sea currents, Earth quake profile
- ……

- Contributions from host country
- Strength of national community
- Global European considerations
- ……

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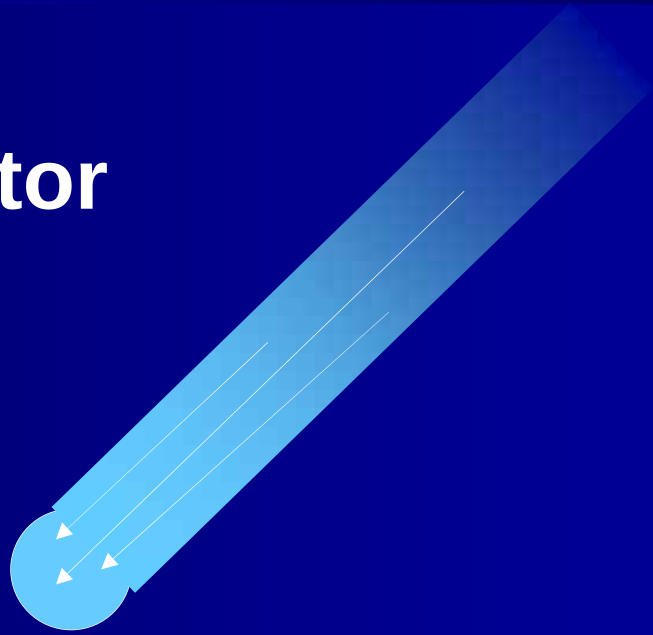
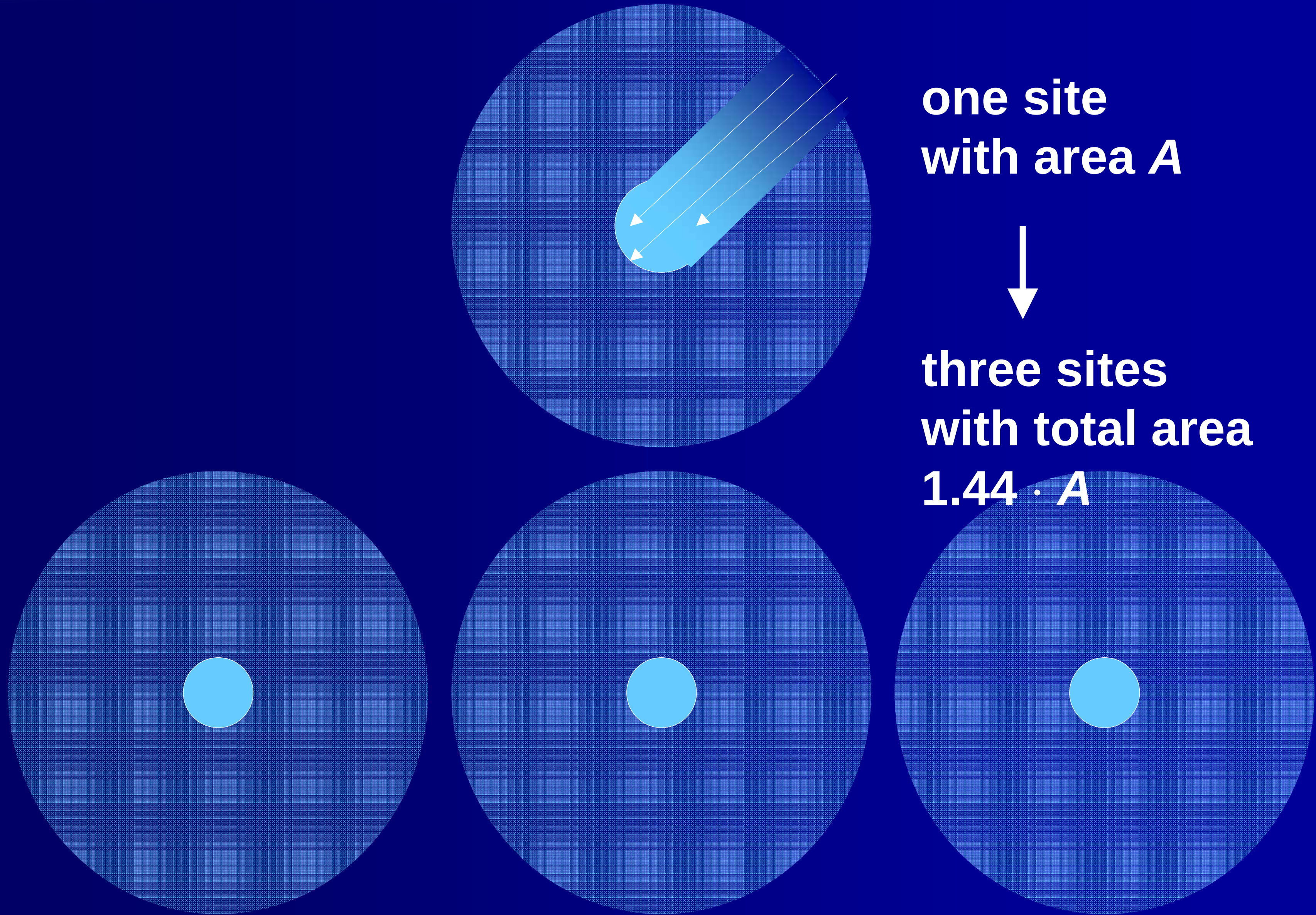
# One big or three smaller detectors ?

**Spherical detector**
**radius *r***
**area $A = 2\pi r^2$**



**distribute same # of PMTs to 3 spheres**
**area = $2\pi\, 3^{1/3}\, r^2 = 1.44 \cdot A$**
**→ gain a factor of 44% for muons ?**

# One big or three smaller detectors ?



**one site with area *A***

↓

**three sites with total area $1.44 \cdot A$**

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# .. but

- smaller lever arm
  → worse pointing
- increase spacing
  – with same lever arm get higher threshold
- worse energy sampling
- worse background rejection
- → net effect for $\nu_\mu$ will be smaller than 44%
- cascade events ($\nu_e$, $\nu_\tau$):
  – VOLUME counts
  – with a fixed veto region for contained events, the net effect is negative
- need 3 times the infrastructure and operation cost

# ApPEC Roadmap Recommendation

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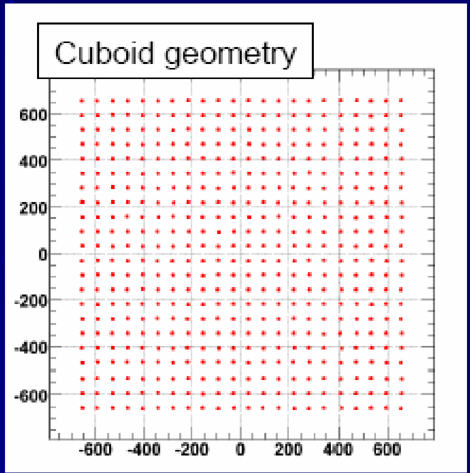
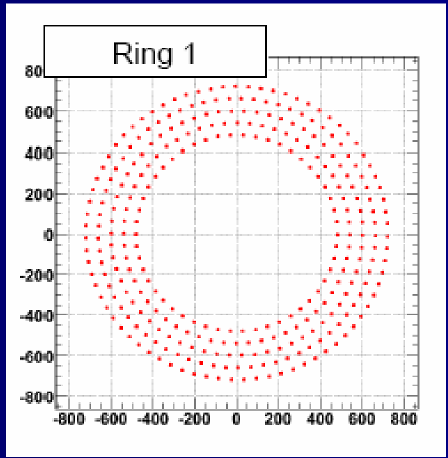
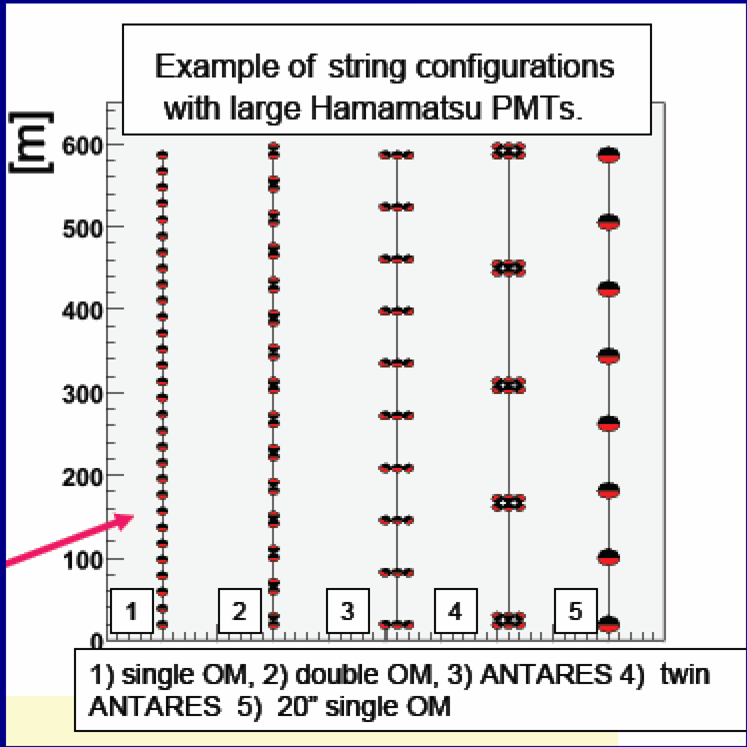
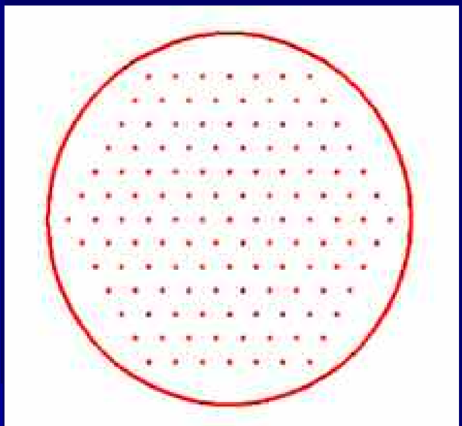
For a complete sky coverage, in particular of the central parts of the Galaxy with many promising sources, we strongly recommend to work towards a cubic kilometre detector in the Northern Hemisphere which will complement the IceCube detector. **Resources for a Mediterranean detector should be pooled in a single, optimized large research infrastructure "KM3NeT".** Start of the construction of KM3NeT is going to be preceded by the successful operation of small scale or prototype detector(s) in the Mediterranean. It's design should also incorporate the improved knowledge on galactic sources as provided by H.E.S.S. and MAGIC gamma ray observations, as well as initial results from IceCube. Still, the time lag between IceCube and KM3NeT detector should be kept as small as possible.

# Simulating configurations



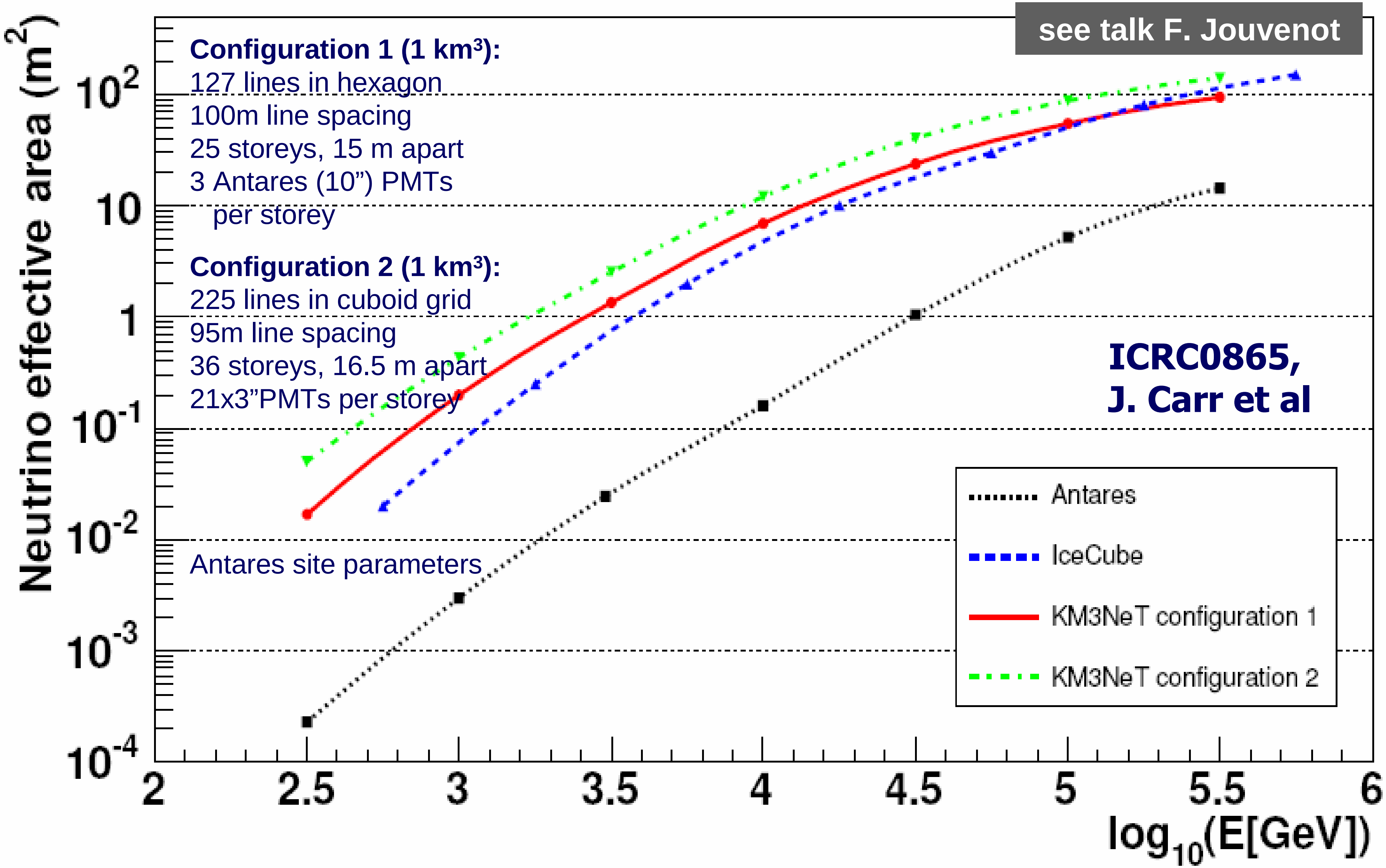



Cuboidial,
Ring,
Hexagon,
Clustered,
IceCube-like
...
Usually with Antares environmental parameters

# KM3NeT neutrino effective area

see talk F. Jouvenot



# R&D on Novel Optical Modules

Segmentation of photo cathode of 10″ PMT



multi-PMTs in one glass sphere

**Ref. ICRC0489, P. Kooijman**

# IceCube

see talks of G.Hill, C.Rott, I.Taboada , M.Tluczykont (IceCube), T. Stanev (IceTop)

# IceCube

## IceTop

Air shower detector

80 pairs of ice

Cherenkov tanks

Threshold ~ 300 TeV

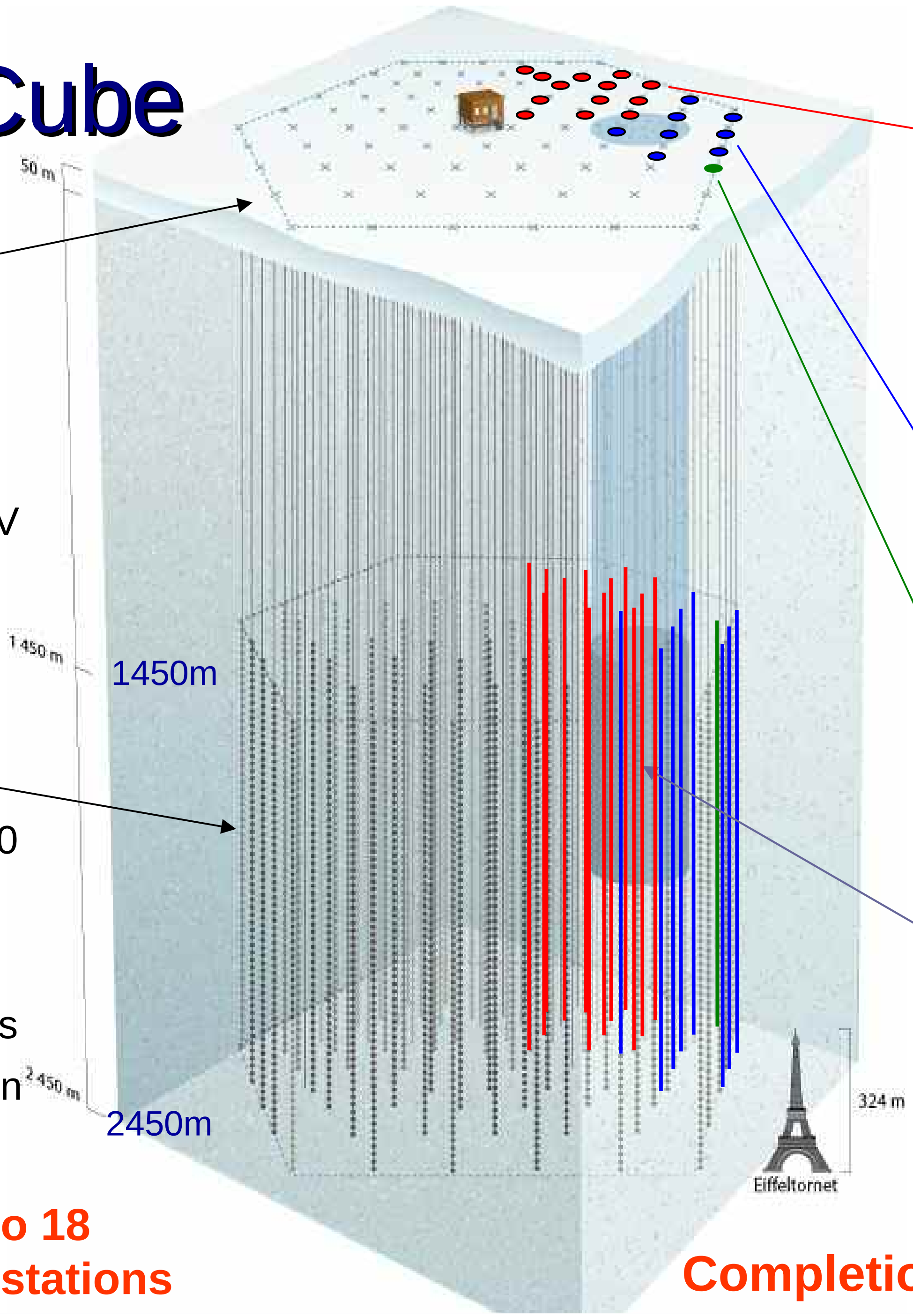
## InIce

Goal of 80 strings of 60

optical modules each

17 m between modules

125 m string separation




2006-2007:

13 strings deployed

2005-2006: 8 strings

2004-2005 : 1 string

AMANDA-II

19 strings

677 modules

AMANDA now operating as part of IceCube

**2007/08: add 14 to 18 strings and tank stations**

**Completion by 2011.**

# IceCube

## IceTop

Air shower detector

80 pairs of ice

Cherenkov tanks

Threshold ~ 300 TeV

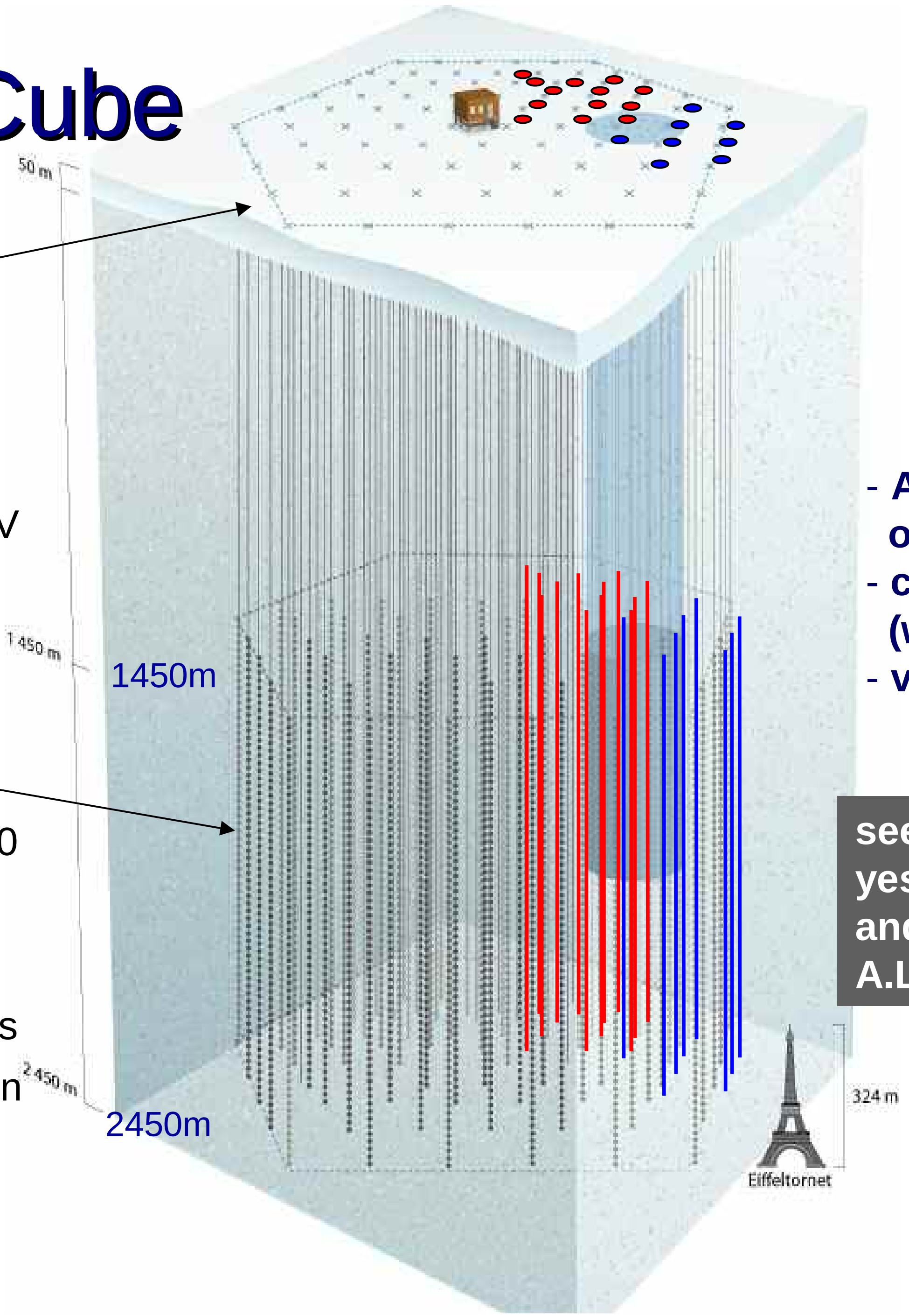
## InIce

Goal of 80 strings of 60

optical modules each

17 m between modules

125 m string separation




## IceTop

- Angular calibration of IceCube
- chemical composition (with IceCube)
- veto for IceCube

**see talk of T.Stanev yesterday**
**and today**
**A.Leisos for SEATOP**

# IceCube

## IceTop

Air shower detector

80 pairs of ice

Cherenkov tanks

Threshold ~ 300 TeV

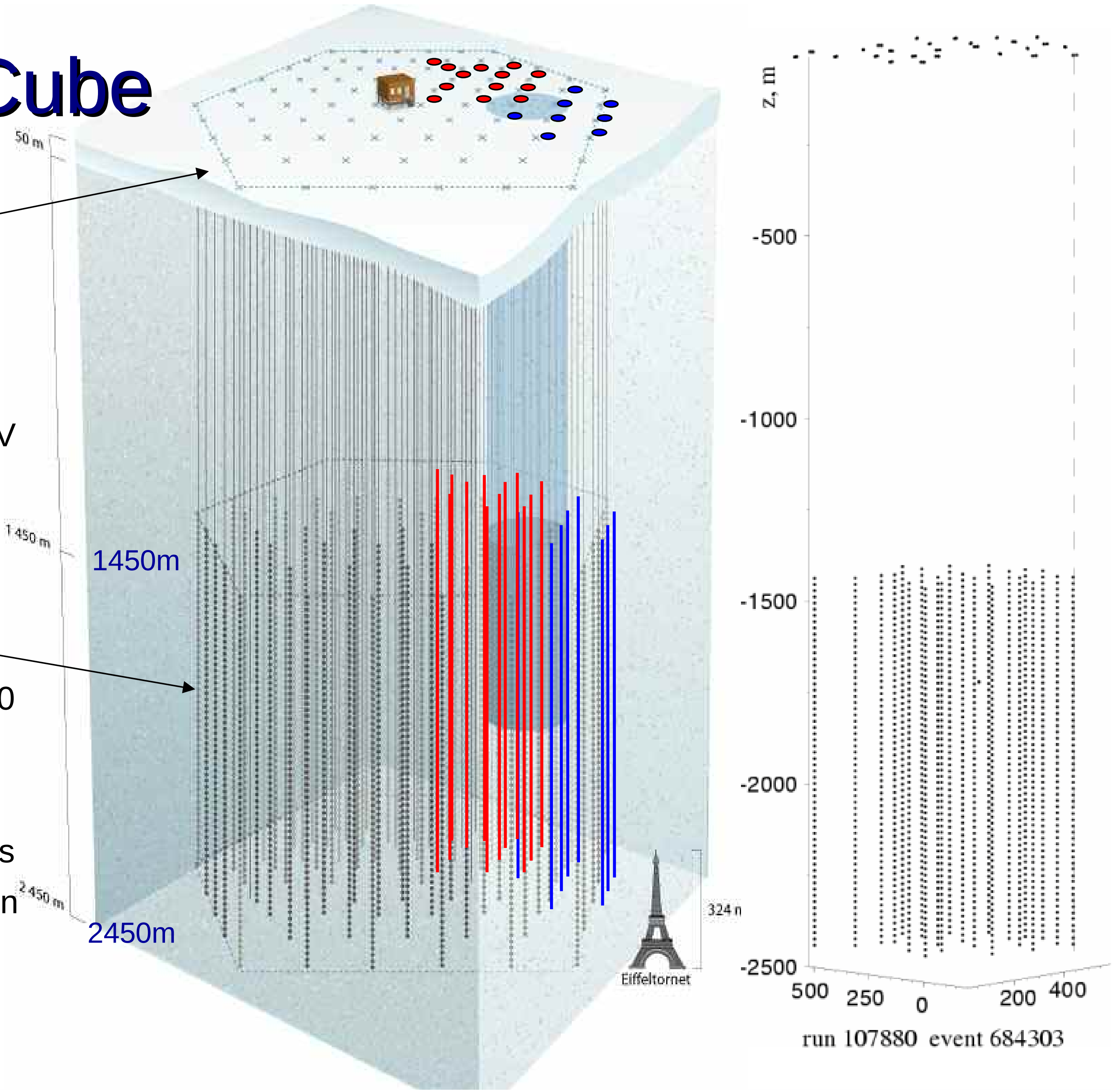
## InIce

Goal of 80 strings of 60

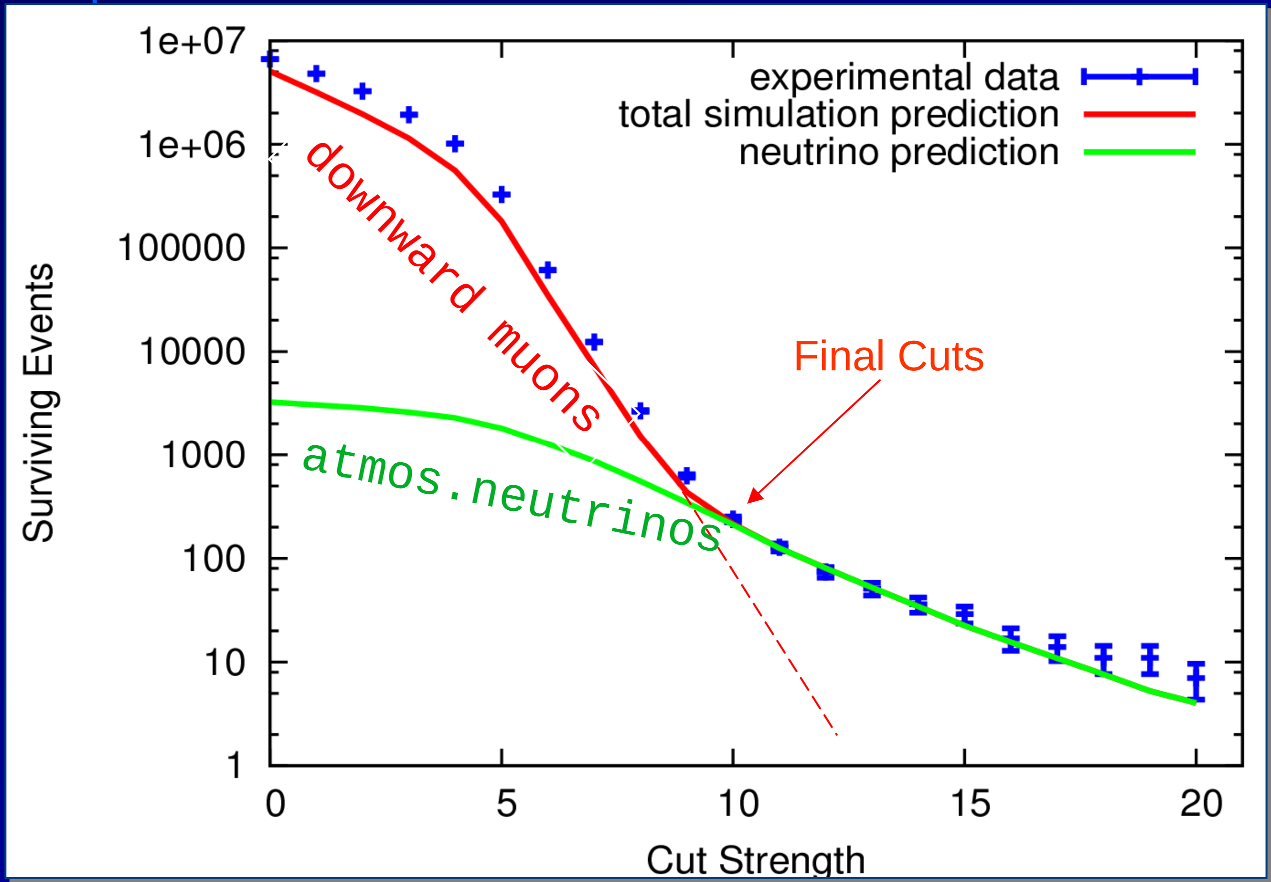
optical modules each

17 m between modules

125 m string separation



# Neutrinos in IC9

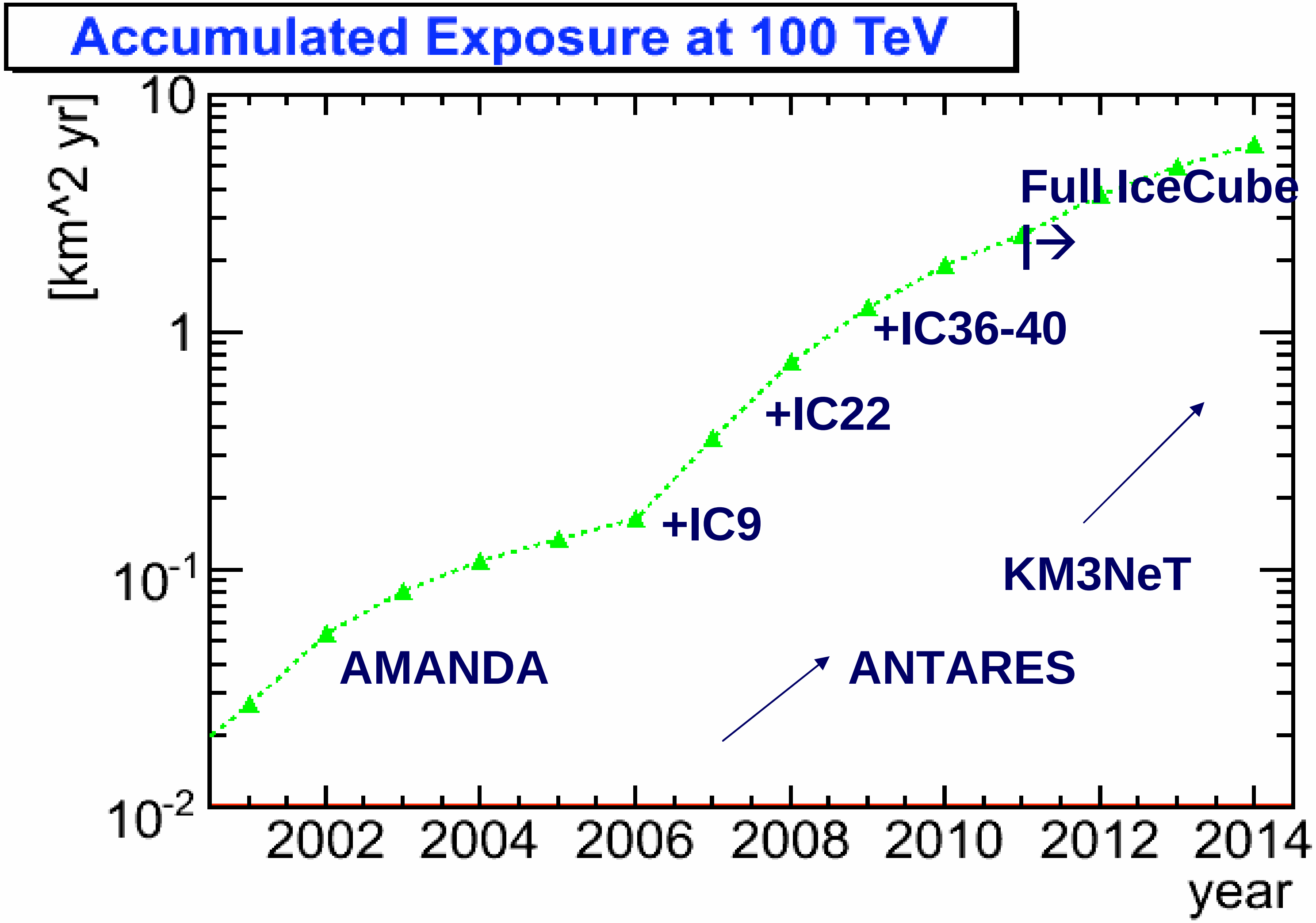



Achterberg et al. astro-ph/0705.1781

- 9-string data (2006)
- Cosmic ray background seen with weak cuts
- Atmospheric neutrinos seen with strong cuts
- Agreement in event rate over 6 decades

# IceCube Laboratory and Data Center

# Growth of IceCube

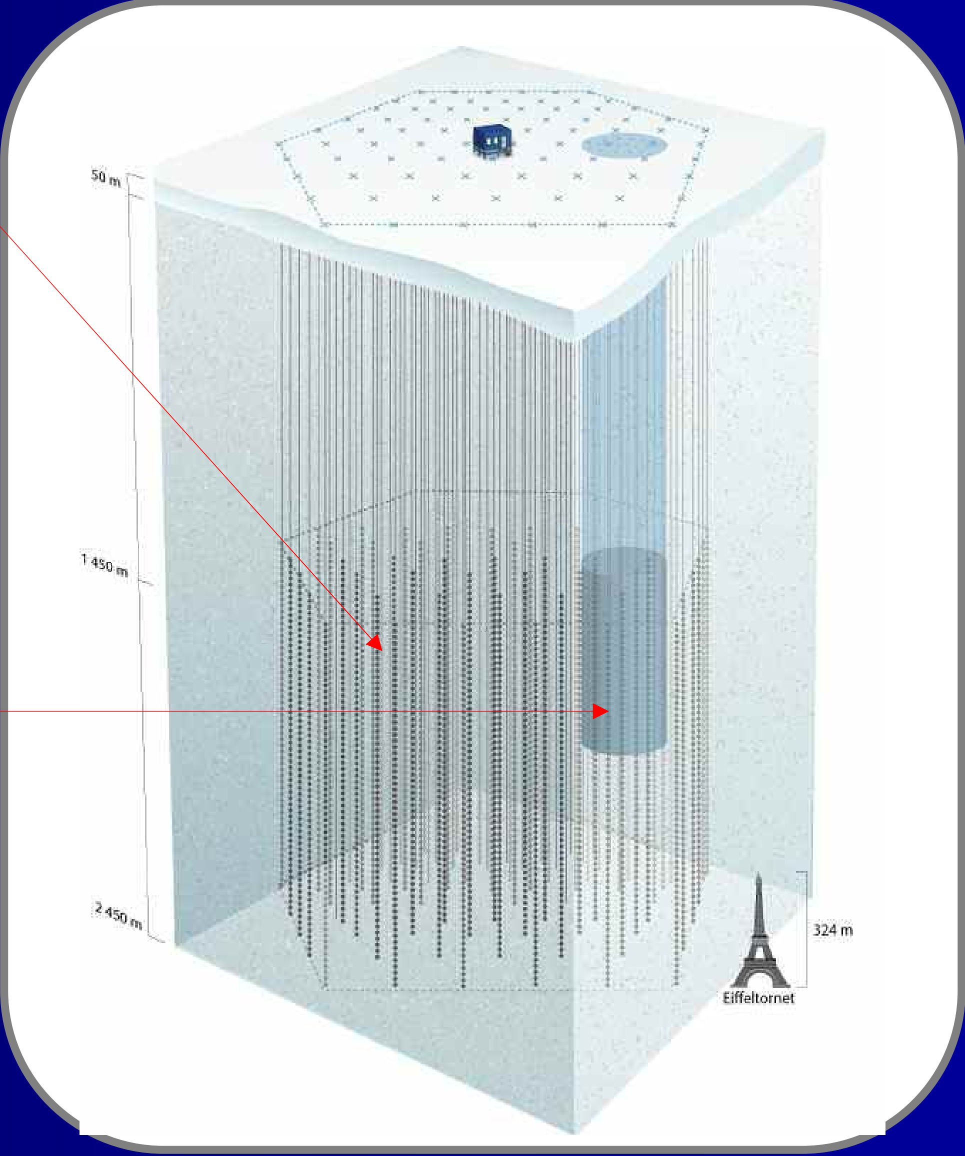


# AMANDA as low energy subdetector of IceCube

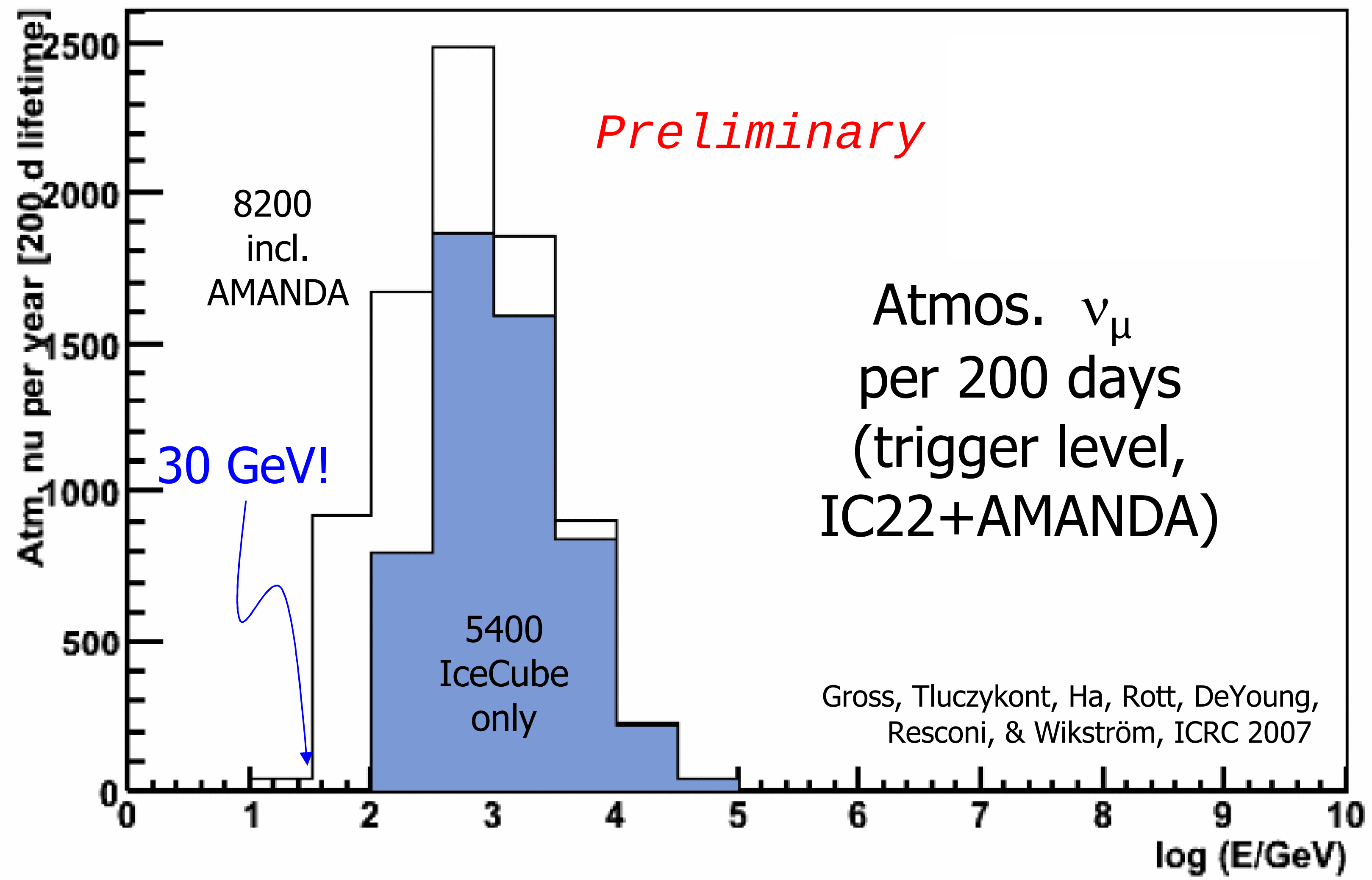
IceCube
threshold 100 GeV

IceCube with
Amanda 30 GeV

Amanda without
IceCube 50 GeV



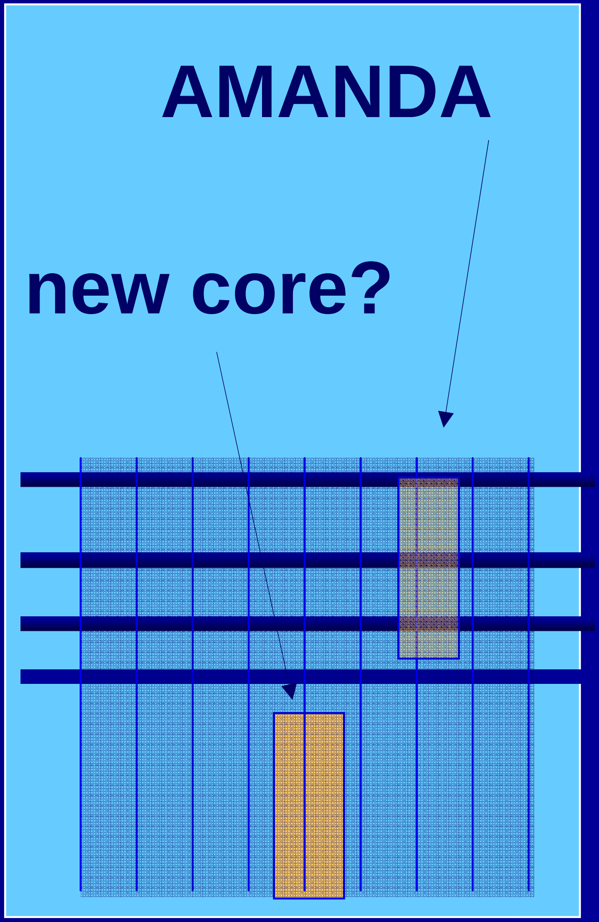
# Effect on 22-string detector



# A new low energy subdetector for IceCube ?

see talk of C.Rott

- 6 strings each with 40 PM, spaced by 10 m
- better veto from top
- located in best ice (below 2100 m exceptionally clear)
- uses IceCube technology
- considerably better performance at low energy
- see talk of Carsten Rott this afternoon



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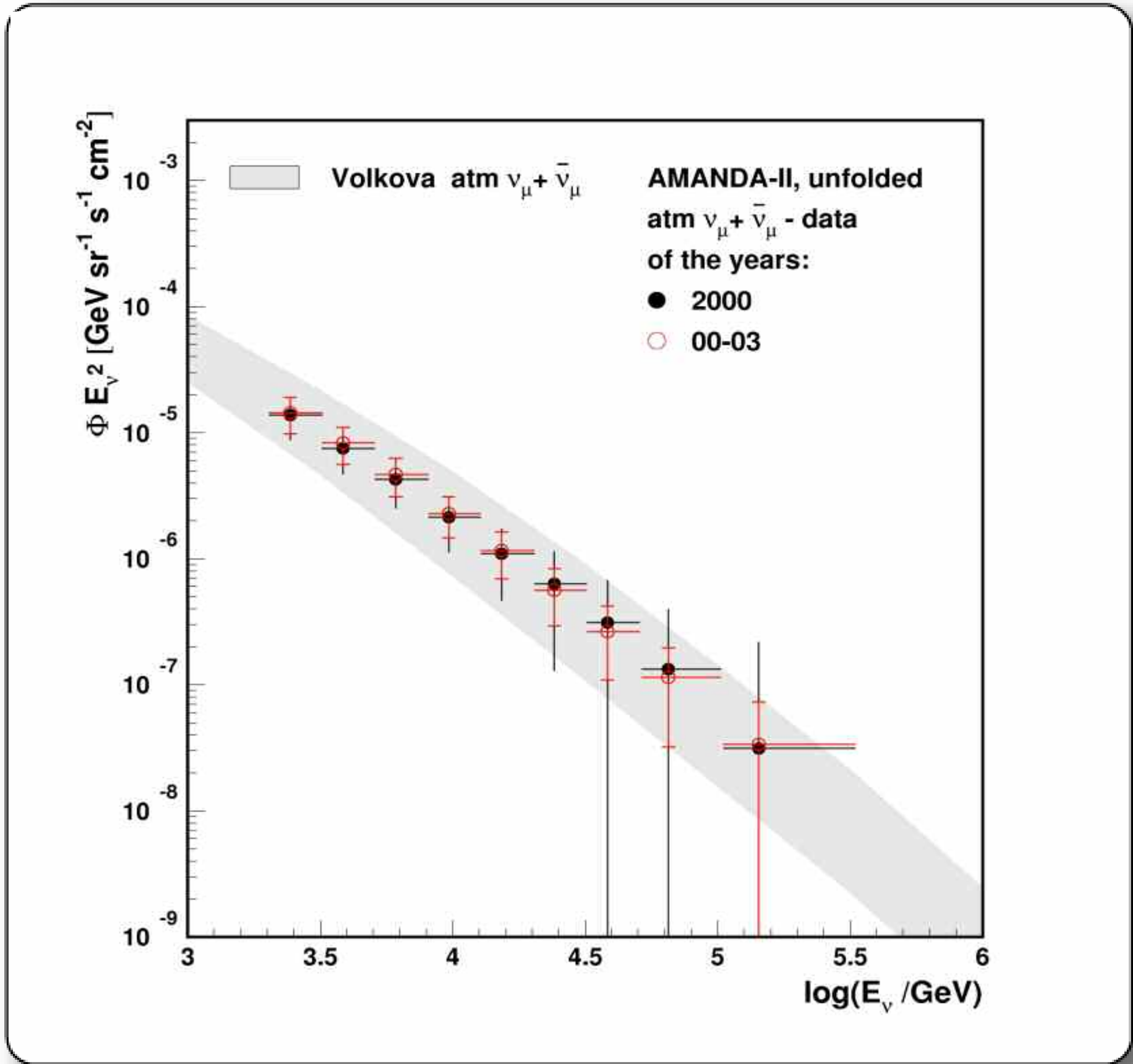
# Some Physics Results

(see afternoon sessions)

# Physics from Baikal & AMANDA

- Atmospheric neutrinos
- Point sources
- Diffuse fluxes
- Coincidences with GRB
- Supernova Bursts & SNEWS
- Cosmic ray search with IceTop/IceCube
- WIMP indirect detection
- Magnetic monopoles and other exotic particles
- Test of basic physics laws
- .....

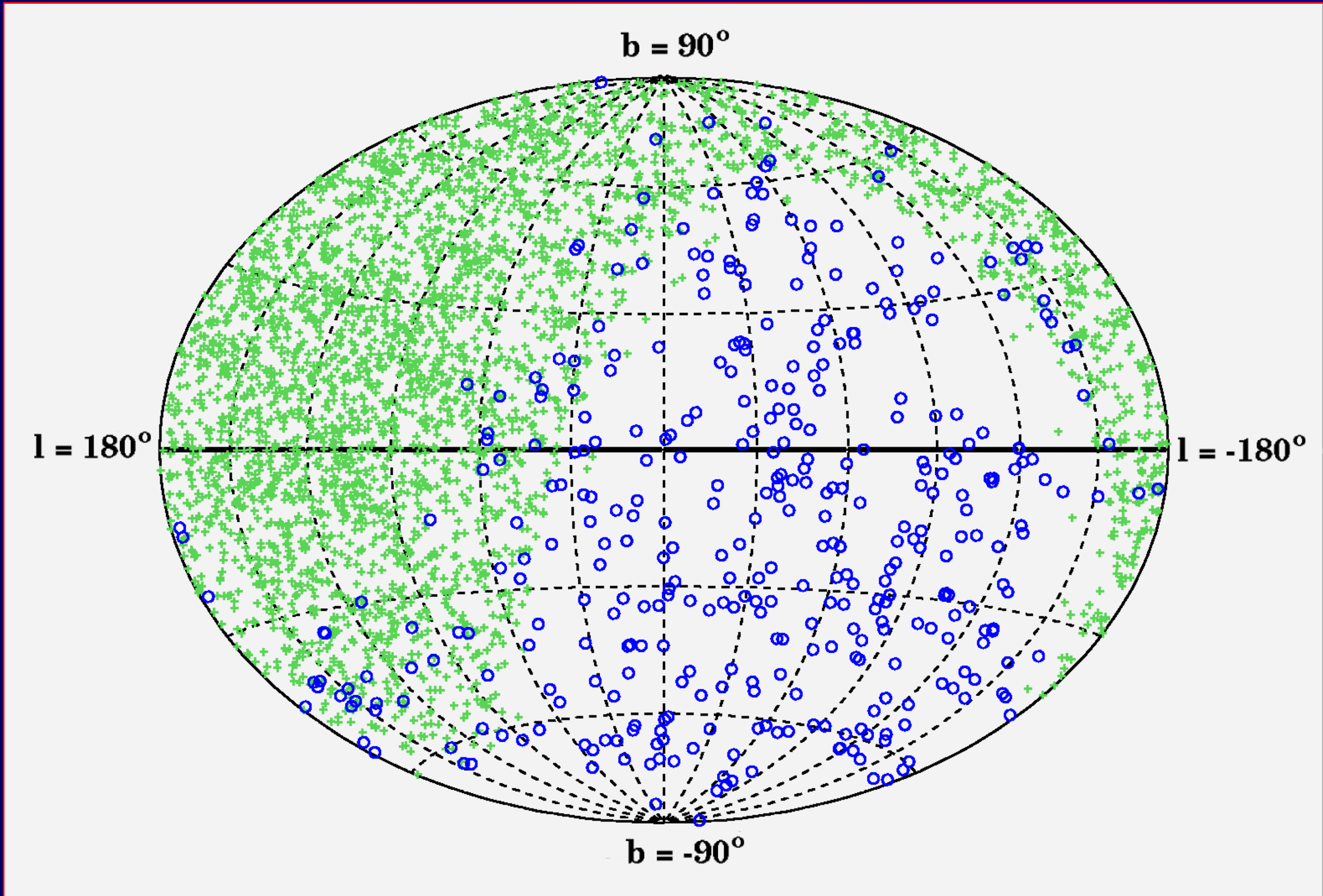
# Atmospheric neutrinos



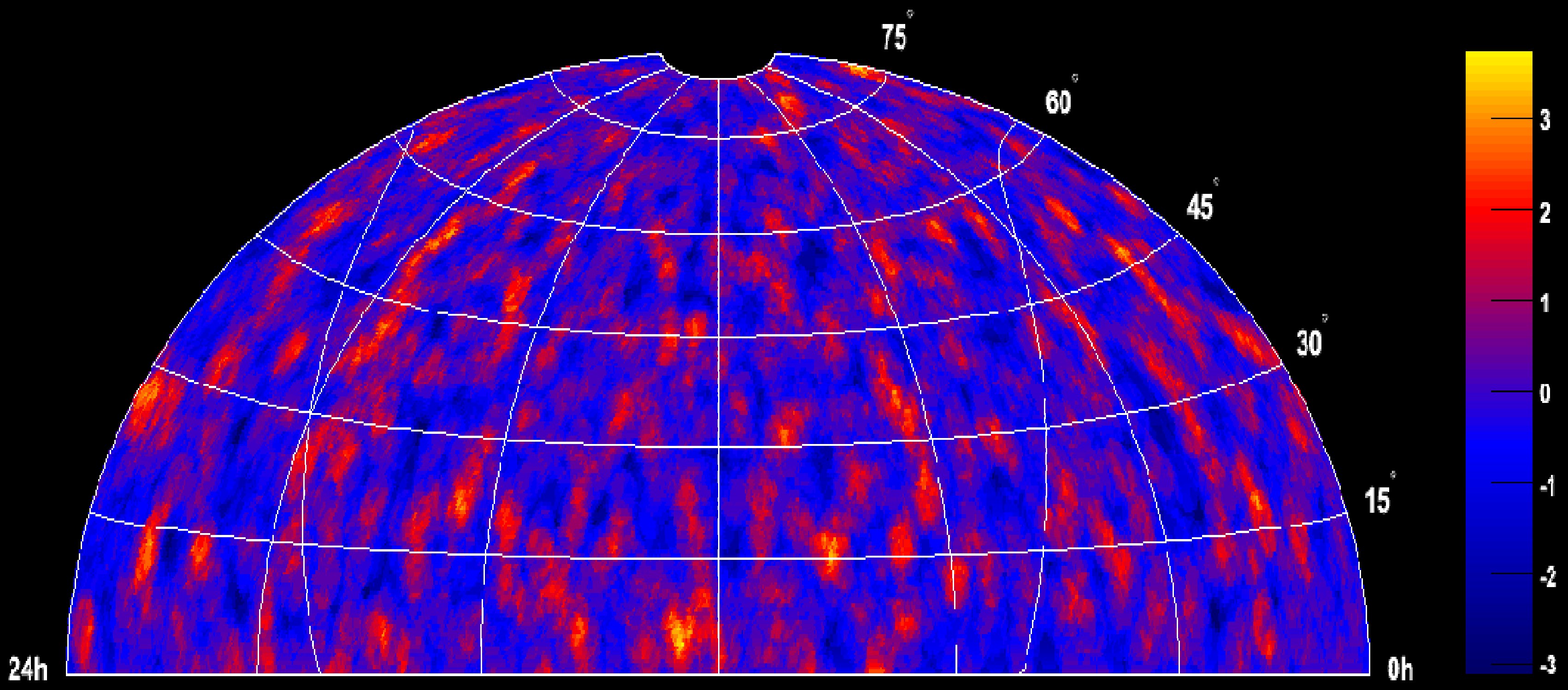

**K. Münich**
**RICAP 2007**

**spectrum measured up to 100 TeV**

# Search for steady point sources: AMANDA and Baikal



# Search for steady point source




AMANDA-II: 2000-2004 (1001 live days) 4282 ν from Northern hemisphere

No significant excess found

# Multi-Messenger Analyses

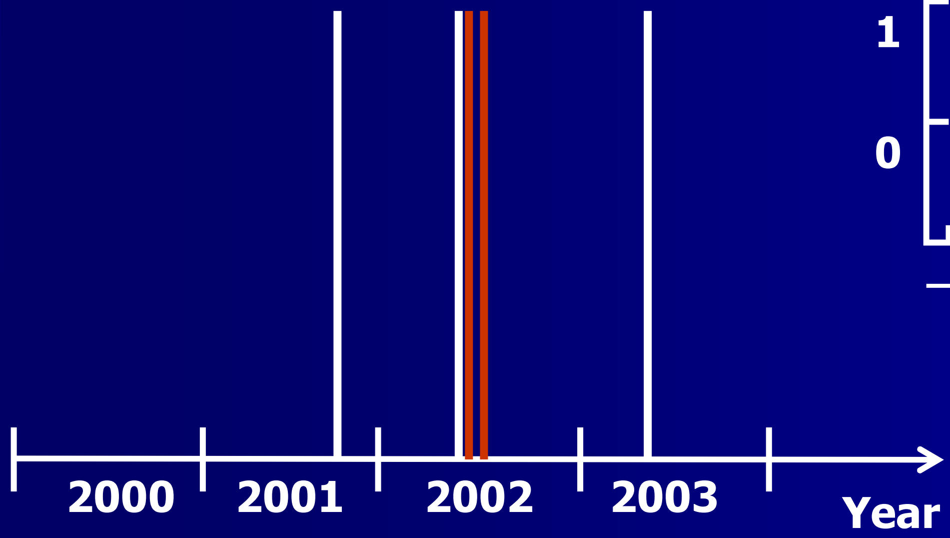
see talk M.Tluczikont

- Any source selection using information from optical, X-ray, gamma data
- Reducing trial factors
- Stacking analyses
- Transient sources
  - Searching around GRB signals from satellite data (see below)
  - Target of Opportunity programs (like AMANDA/MAGIC)
  - GRB candidate follow-up by optical telescopes

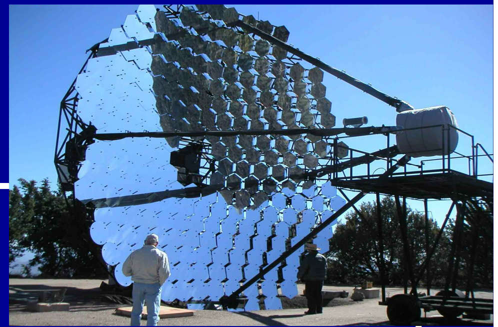
see talk M.Kowalski

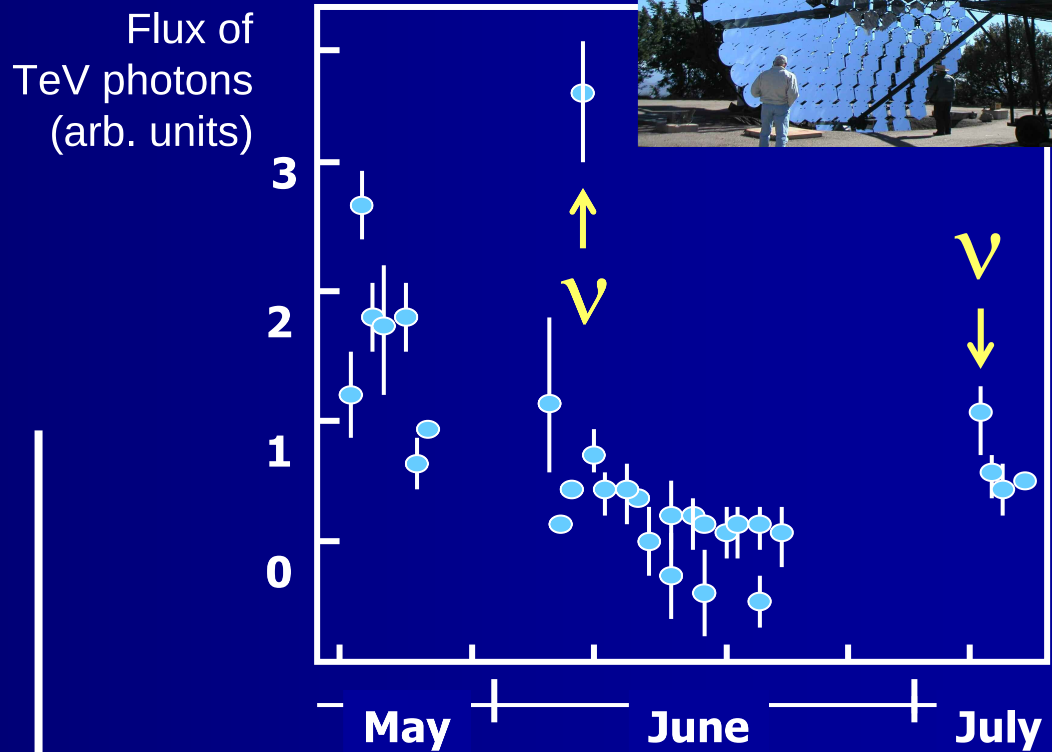
# ES 1959+650

Arrival time of neutrinos from the direction of the AGN ES1959+650

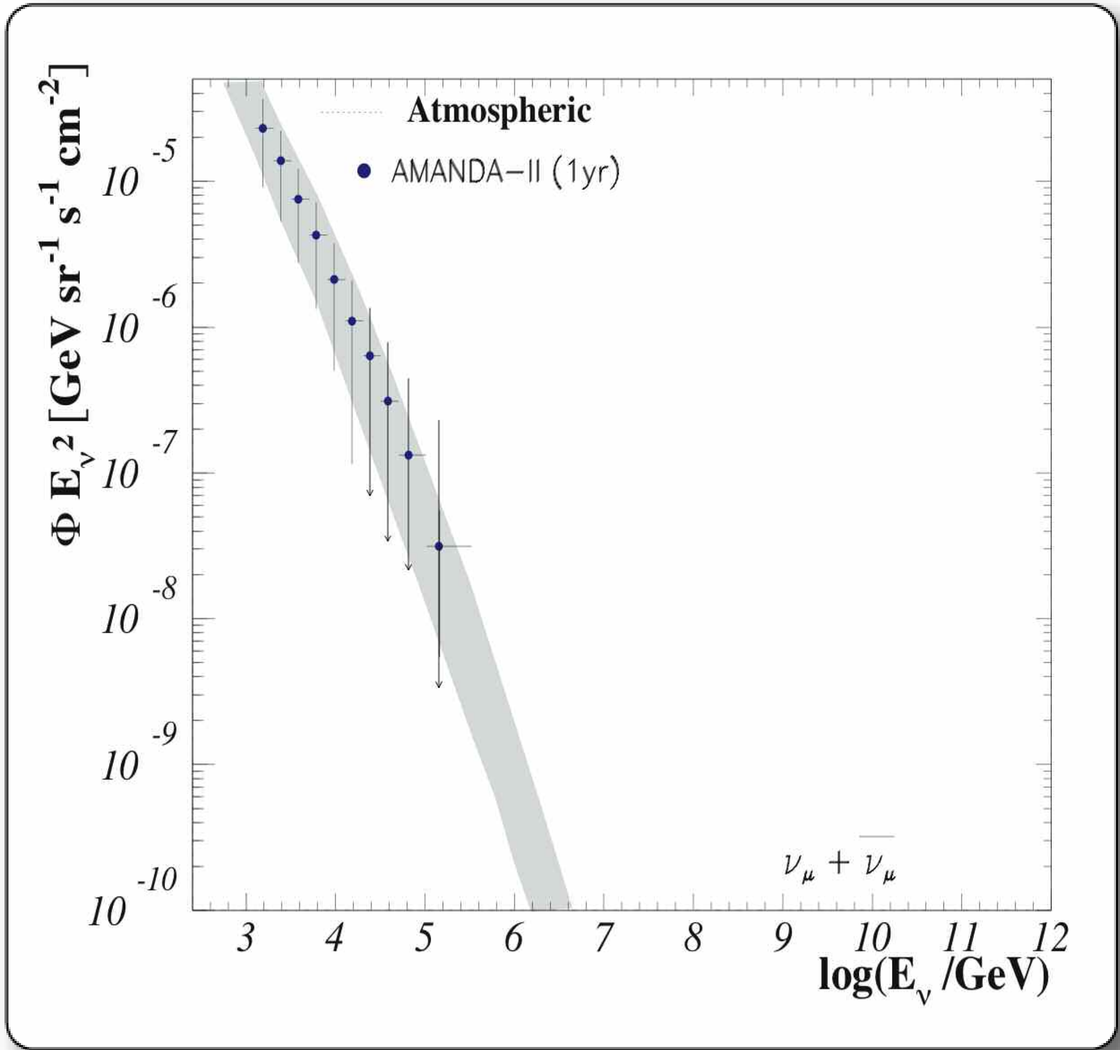



WHIPPLE





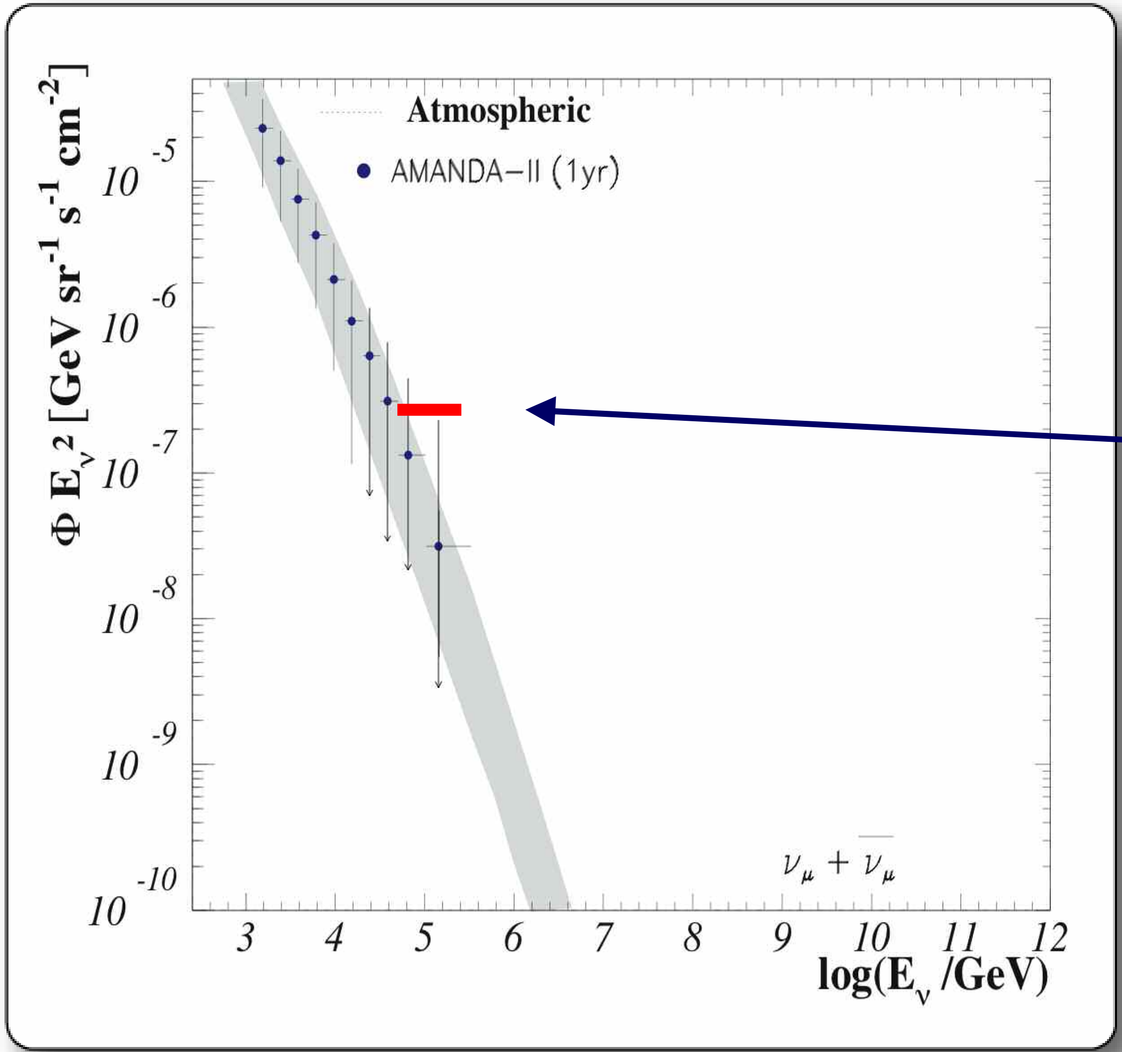
# Diffuse fluxes




- Atmospheric neutrinos behave like $E^{-3.7}$
- Typical extraterrestrial fluxes behave like $E^{-2}$

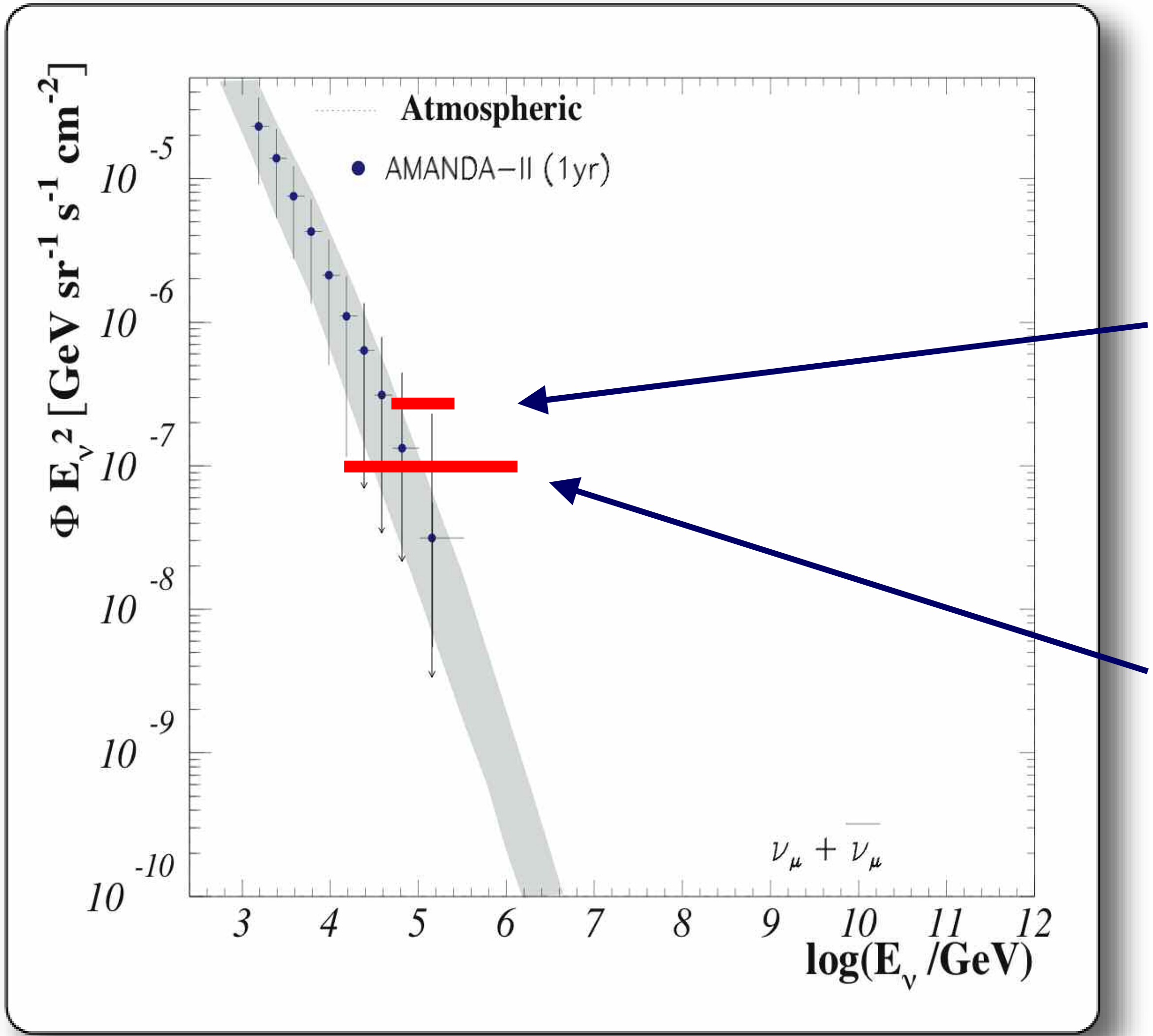
see talk of Gary Hill

# Limit on diffuse extraterrestrial fluxes



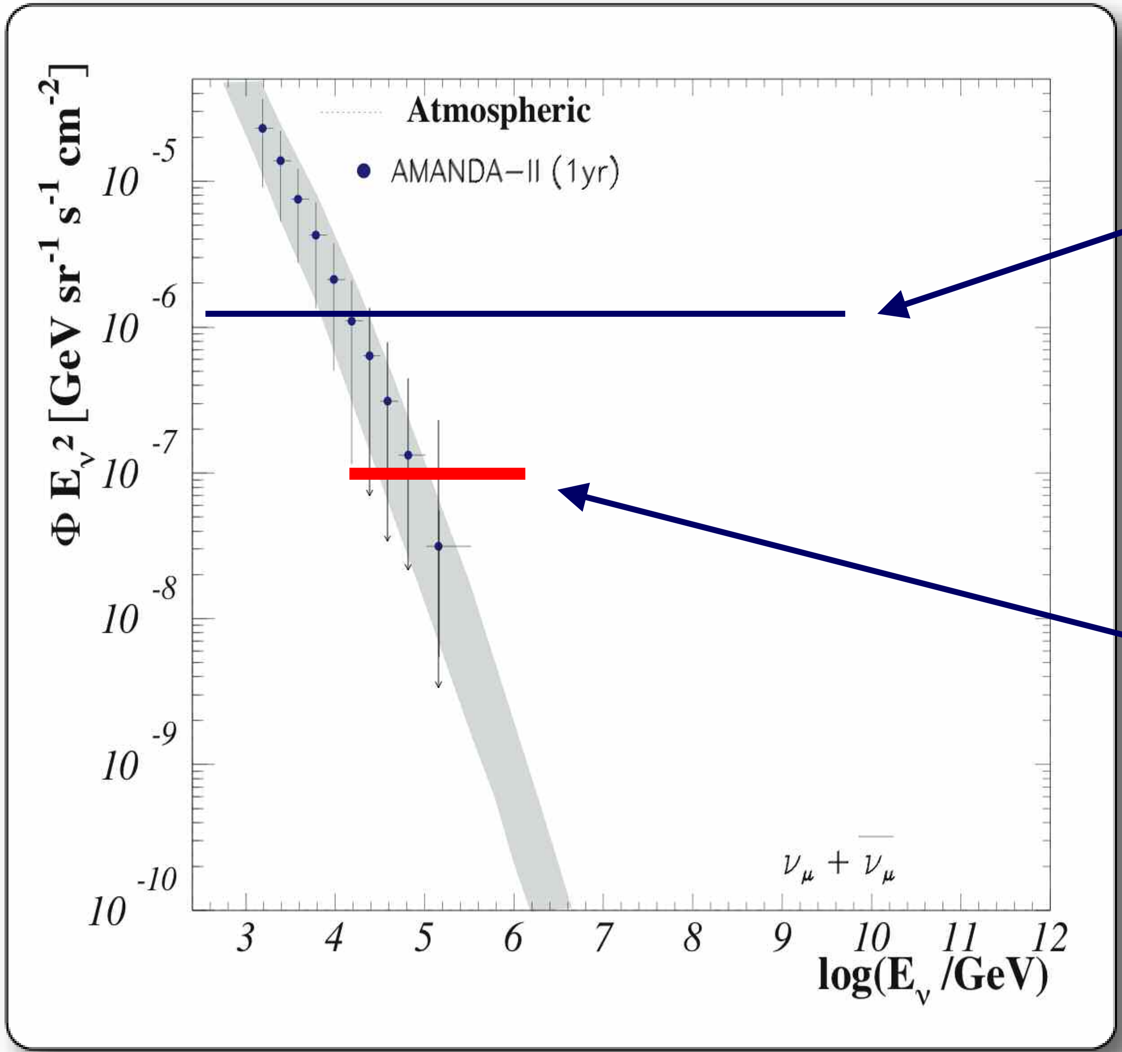

- Atmospheric neutrinos behave like $E^{-3.7}$
- Typical extraterrestrial fluxes behave like $E^{-2}$
- From this method and one year data we exclude $E^{-2}$ fluxes with $\Phi \cdot E^2 > 2.7 \cdot 10^{-7}$ GeV sr$^{-1}$ s$^{-1}$ cm$^{-2}$

# Limit on diffuse extraterrestrial fluxes



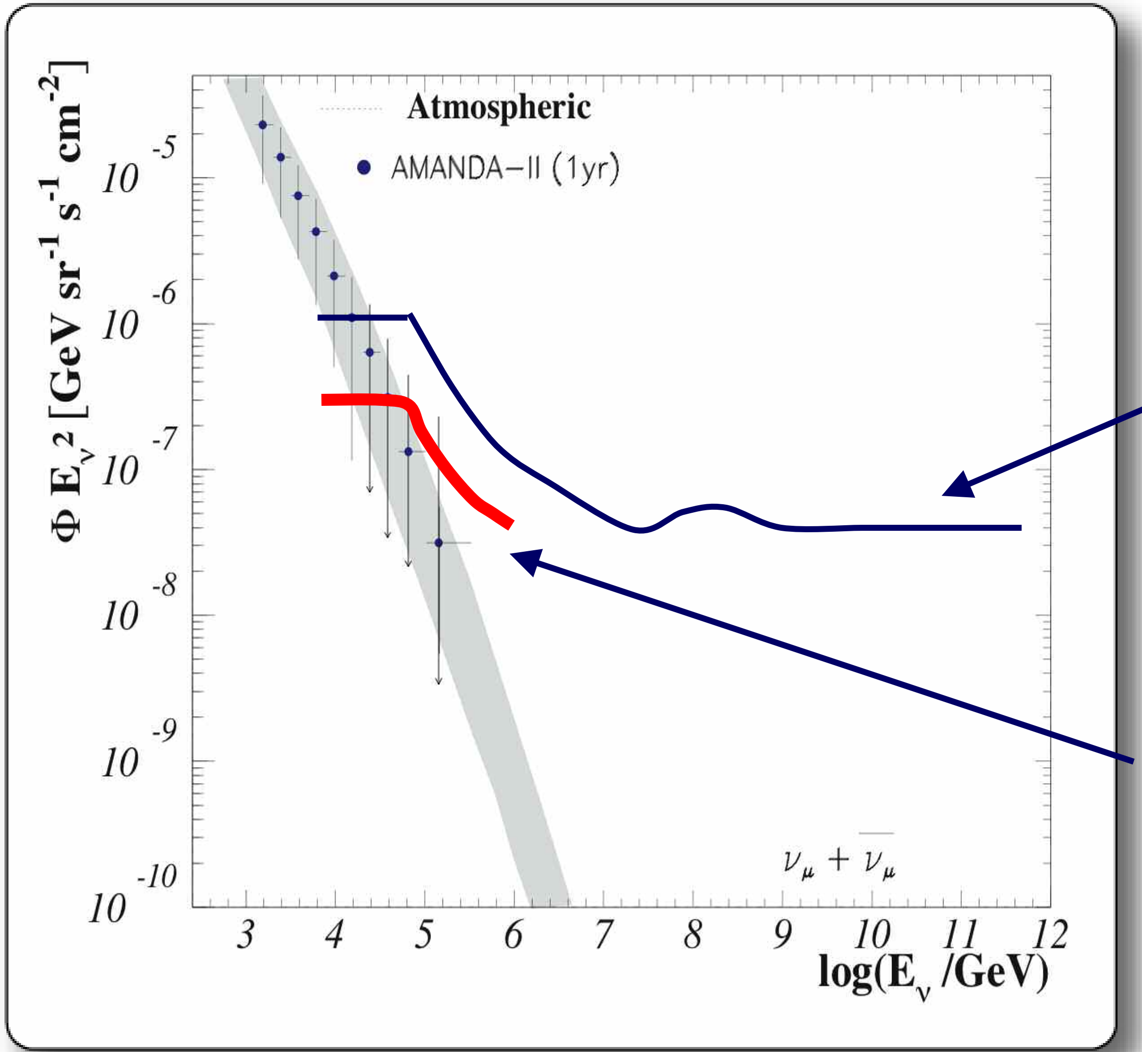

- From this method and one year data we exclude $E^{-2}$ fluxes with $\Phi \cdot E^2 > 2.7 \cdot 10^{-7}$ GeV sr$^{-1}$ s$^{-1}$ cm$^{-2}$
- With 4 years and improved methods we are now at $\Phi \cdot E^2 > 8.8 \cdot 10^{-8}$ GeV sr$^{-1}$ s$^{-1}$ cm$^{-2}$

# Experimental limits & theoretical bounds



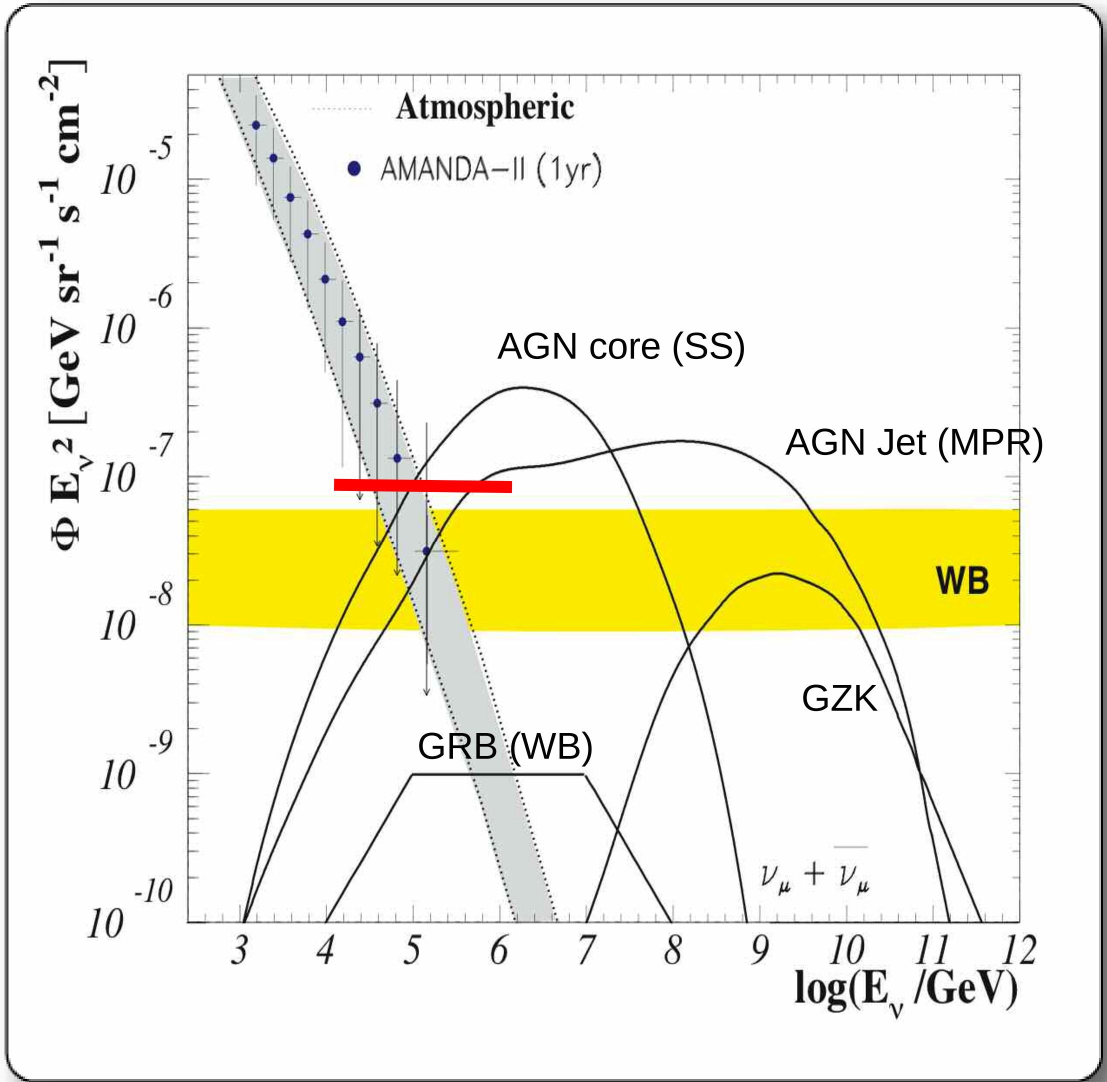

- MPR bound, no neutron escape (gamma bound)
- Factor 11 below MPR bound for sources opaque to neutrons

# Experimental limits & theoretical bounds

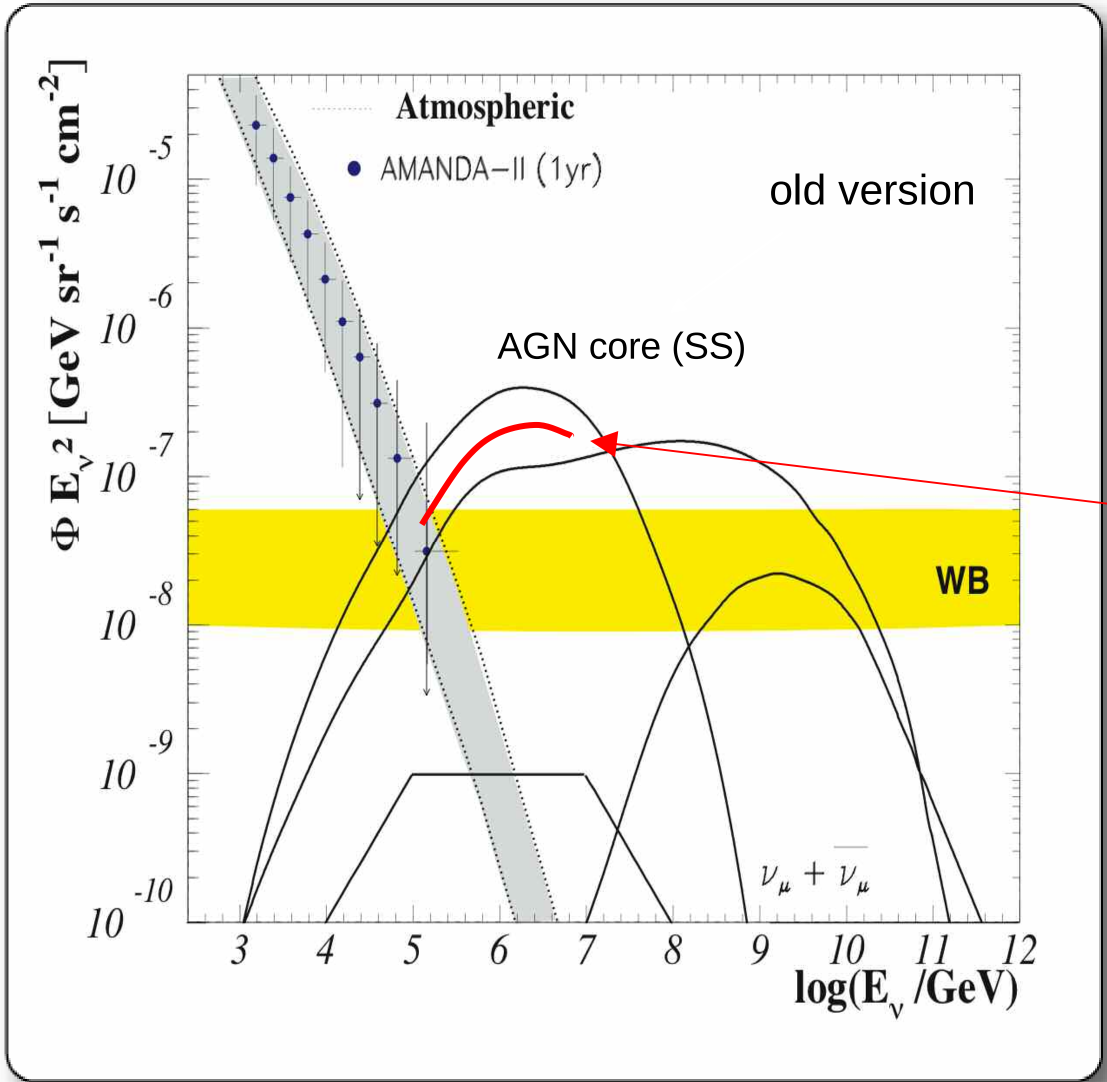



- MPR bound, neutrons escape (CR bound)
- Factor 4 below MPR bound for sources transparent to neutrons

# Experimental limits & theoretical bounds

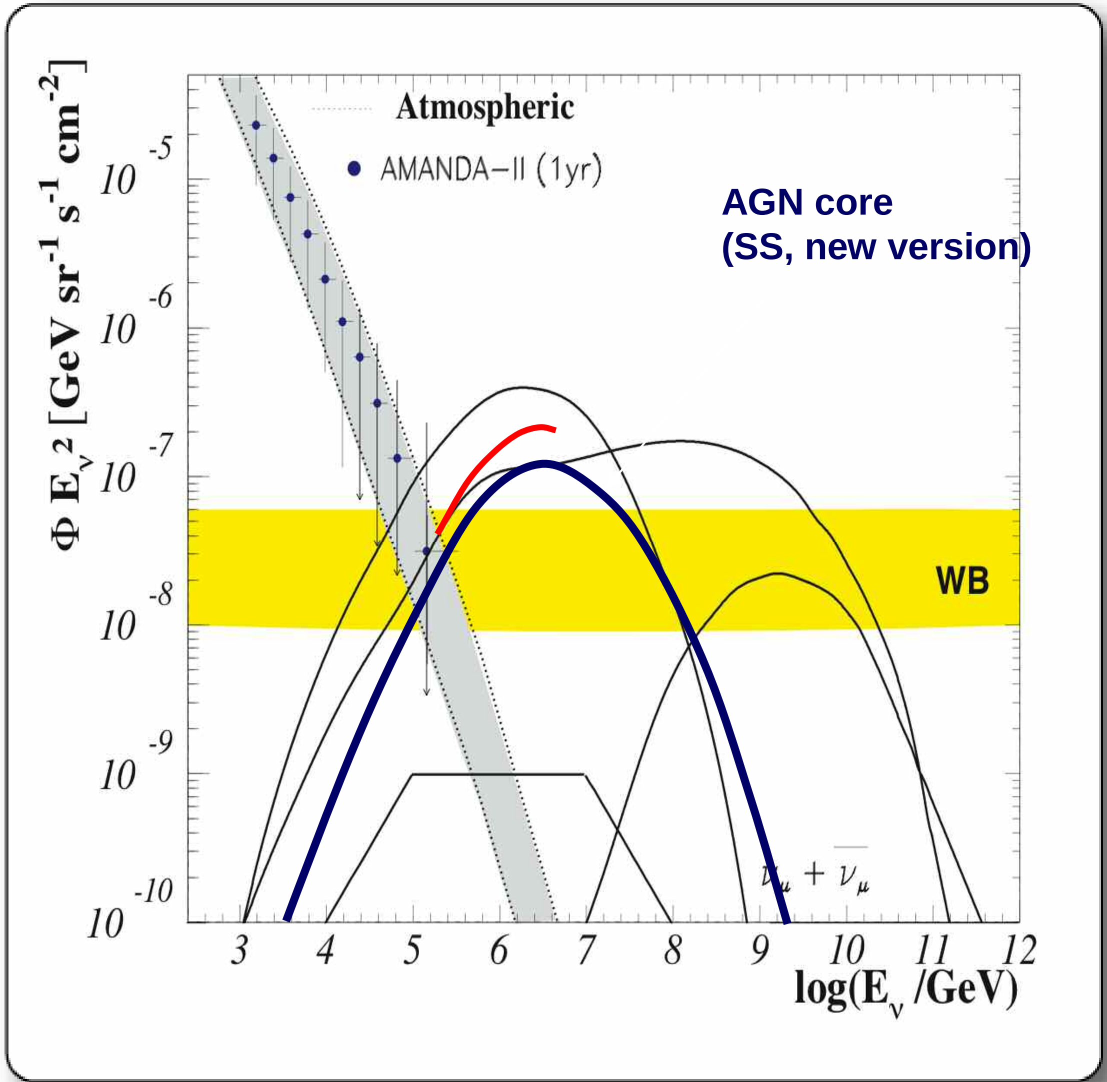


# Experimental limits & theoretical bounds




**„old“ Stecker model excluded**

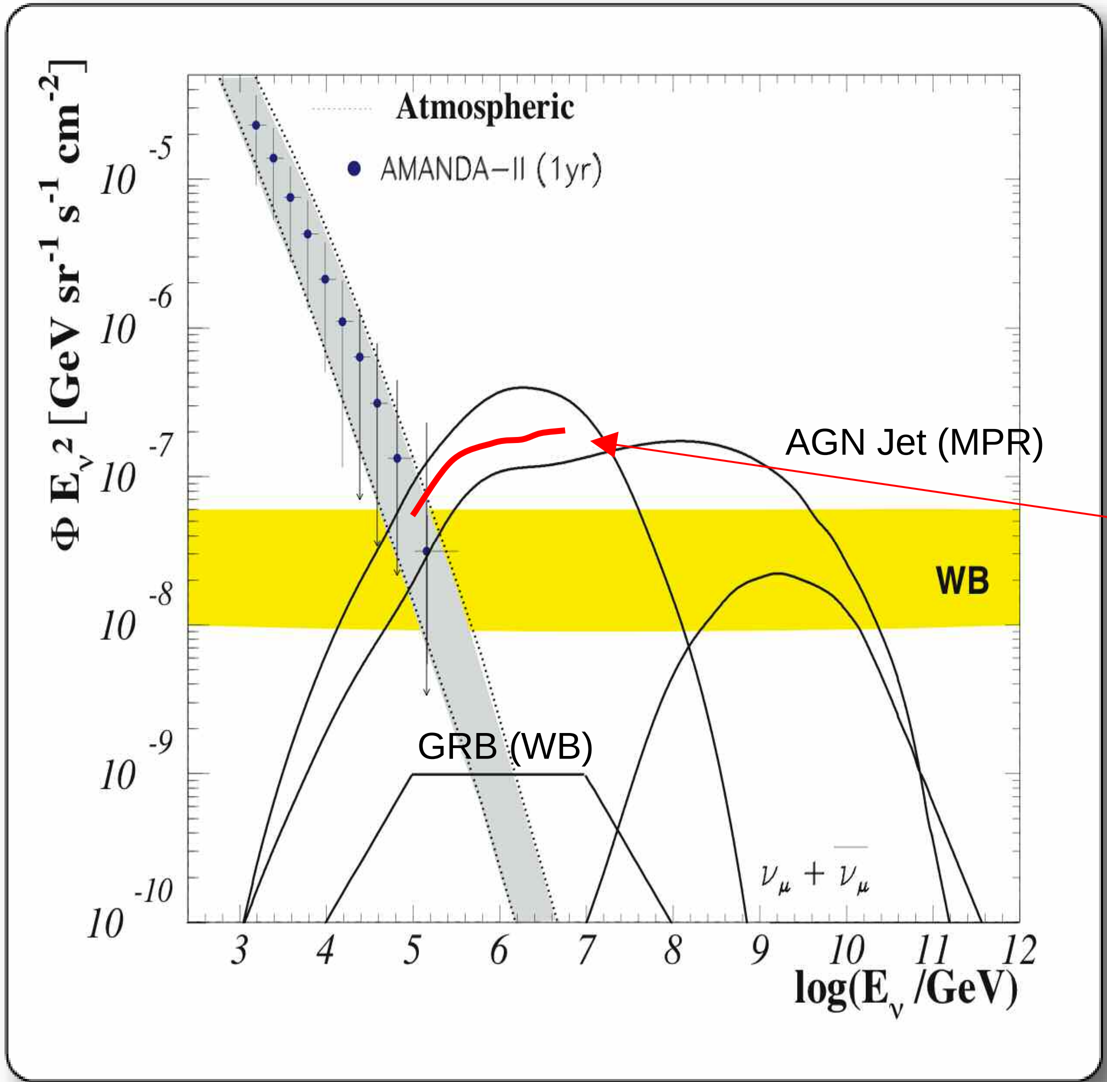
# Experimental limits & theoretical bounds




**„new“**
**Stecker model**
**not excluded**

**(MRF = 1.9)**

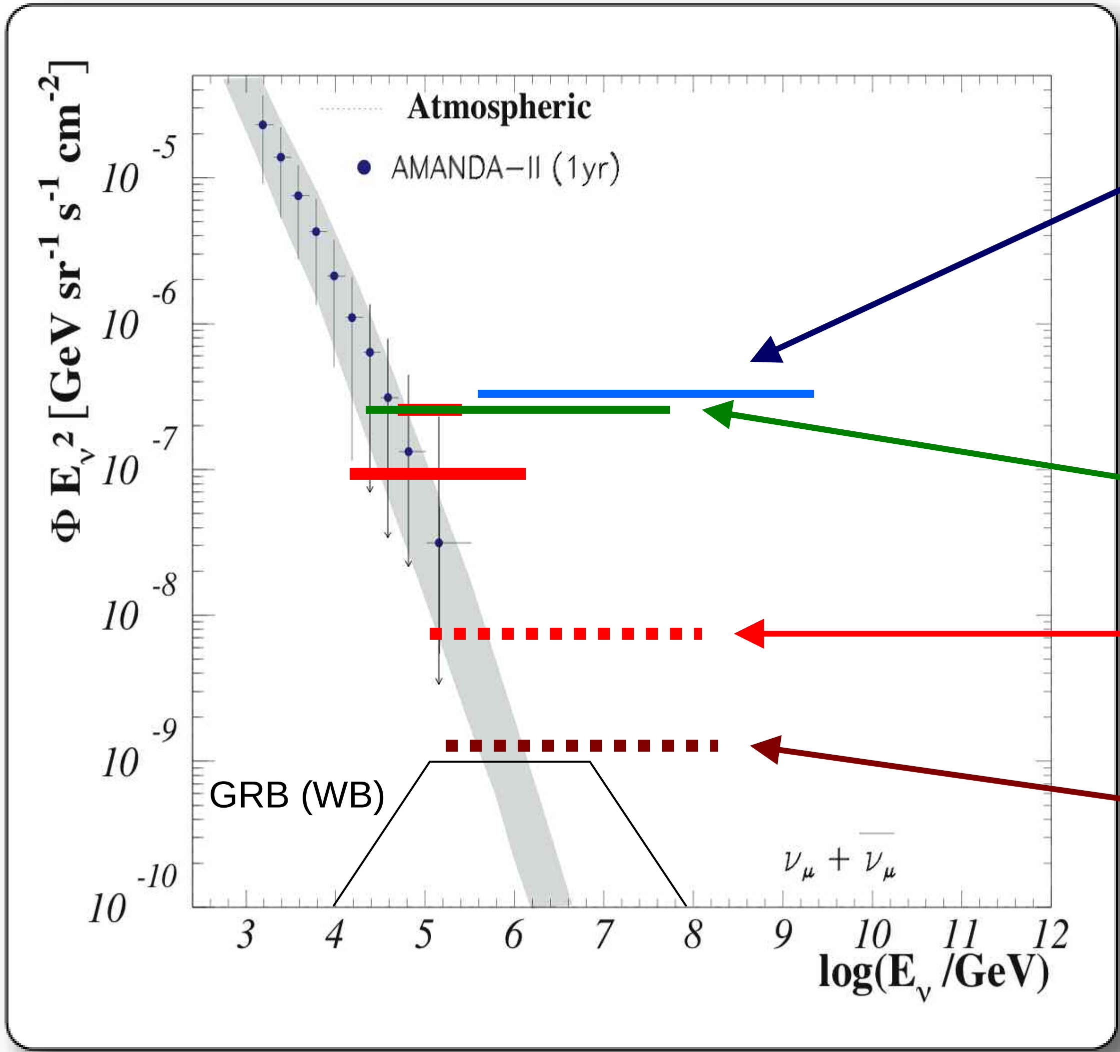
# Experimental limits & theoretical bounds




**still above AGN jet (MPR)**

**(MRF ~ 2.3)**

# Limit on diffuse extraterrestrial fluxes




**AMANDA HE analysis** *2003*

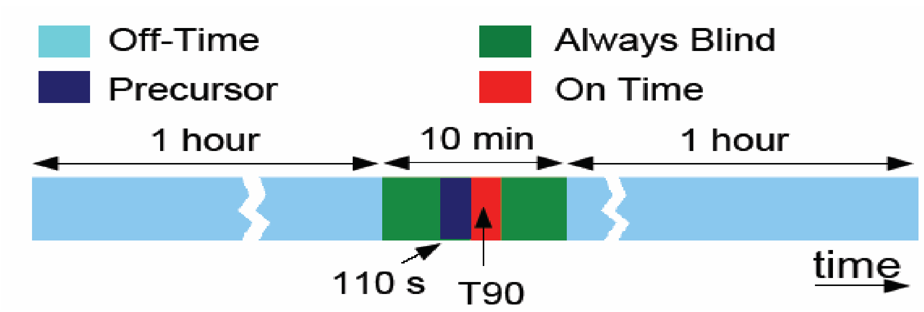
**Baikal** *2006*

**IceCube muons, 1 year** *2009*

**Icecube, muons & cascades 4 years** *2013*

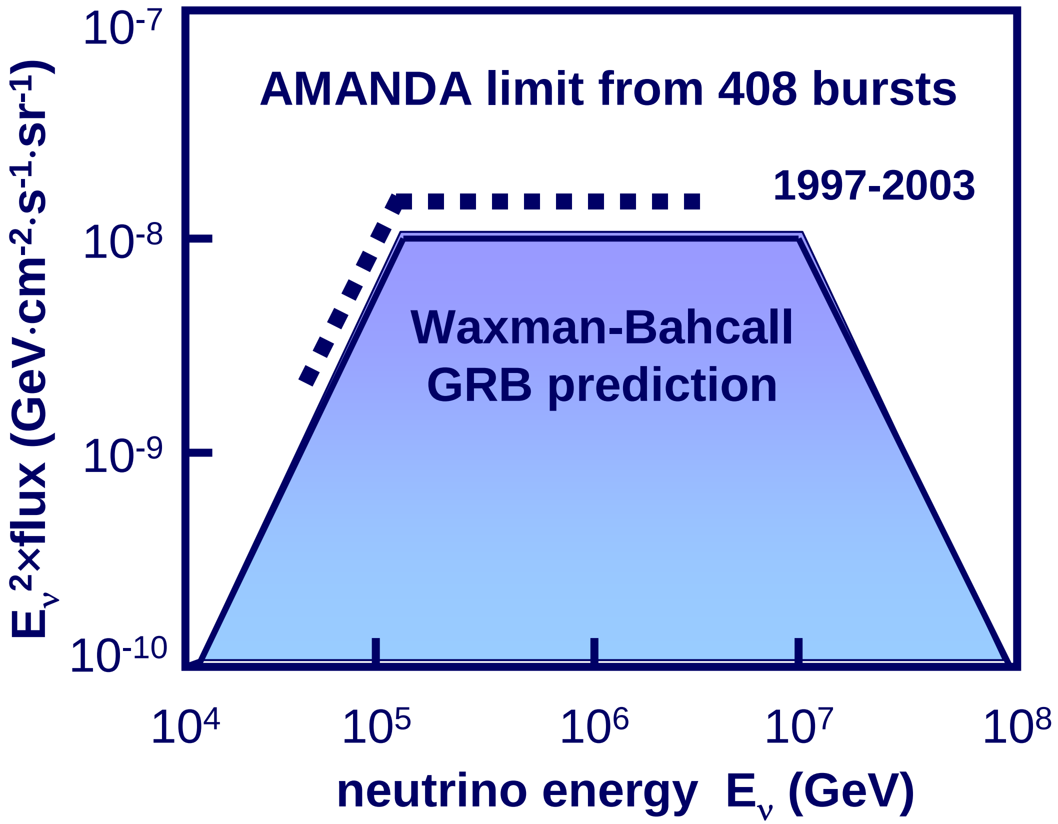
# Coincidences with GRB

see talk of I. Taboada

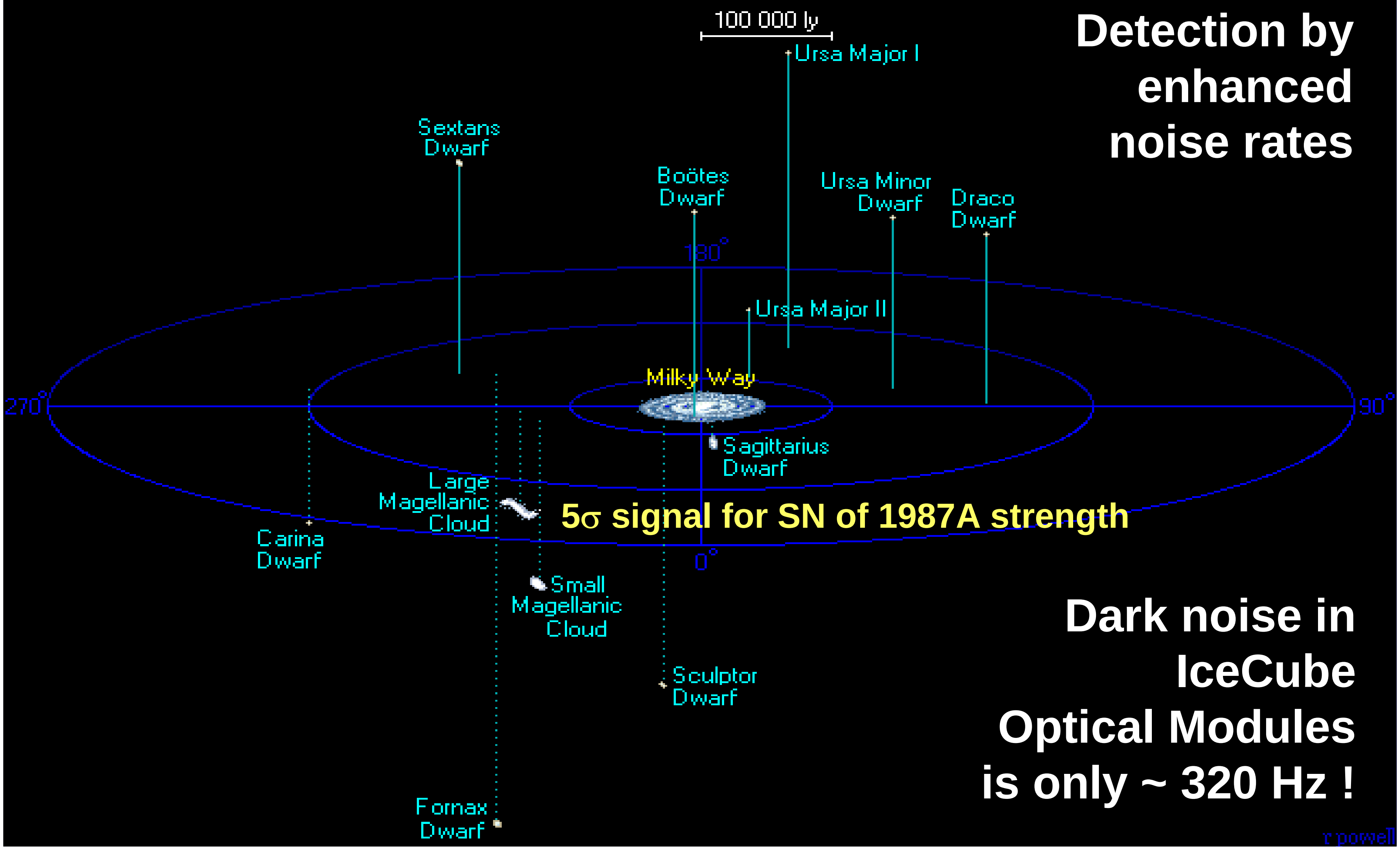



Check for coincidences with
**BATSE, IPN, SWIFT**

- close to WB within < factor 2
- with IceCube: test WB within a few months



# Supernova in IceCube




**Detection by enhanced noise rates**

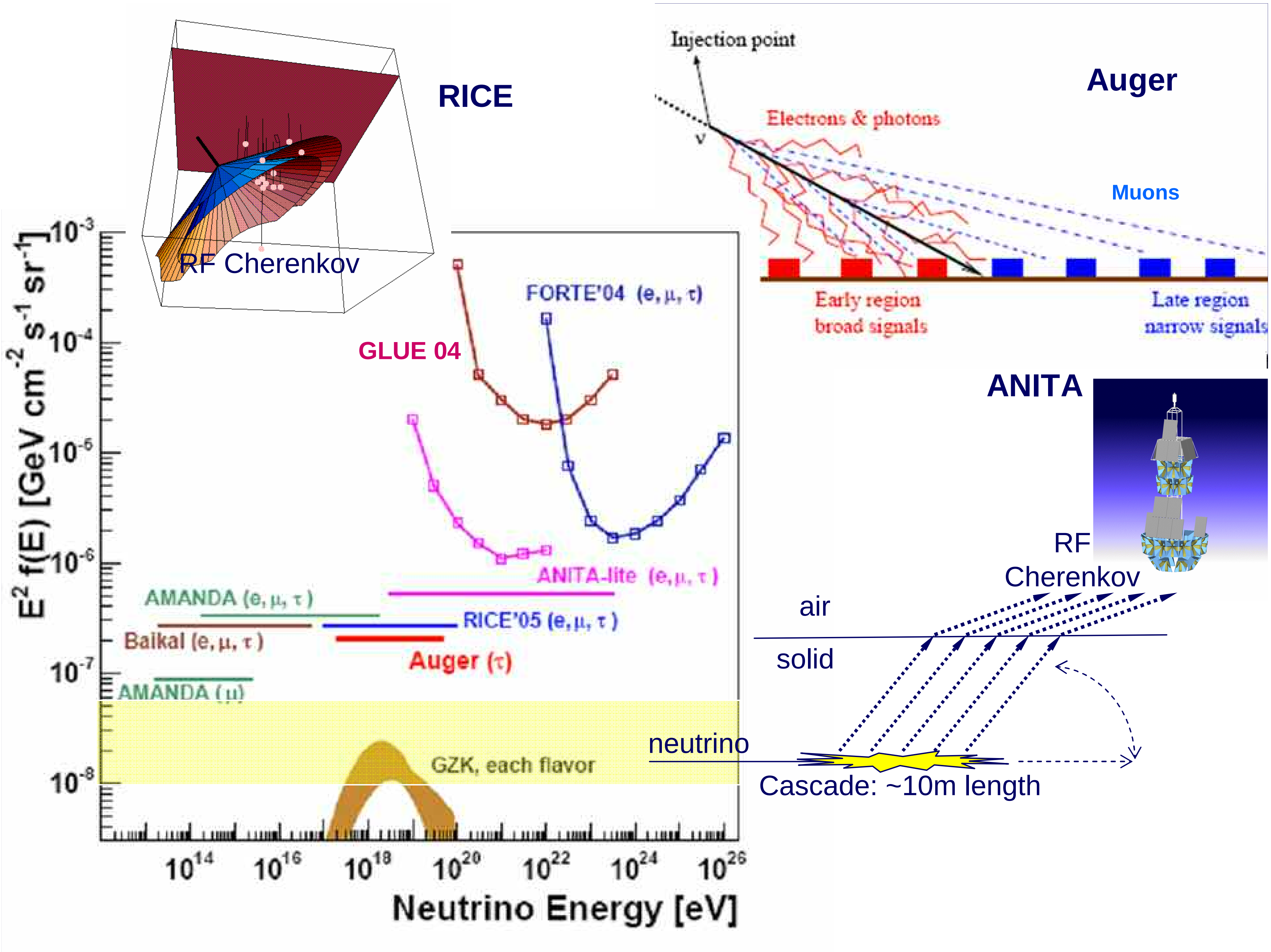
**5σ signal for SN of 1987A strength**

**Dark noise in IceCube Optical Modules is only ~ 320 Hz !**

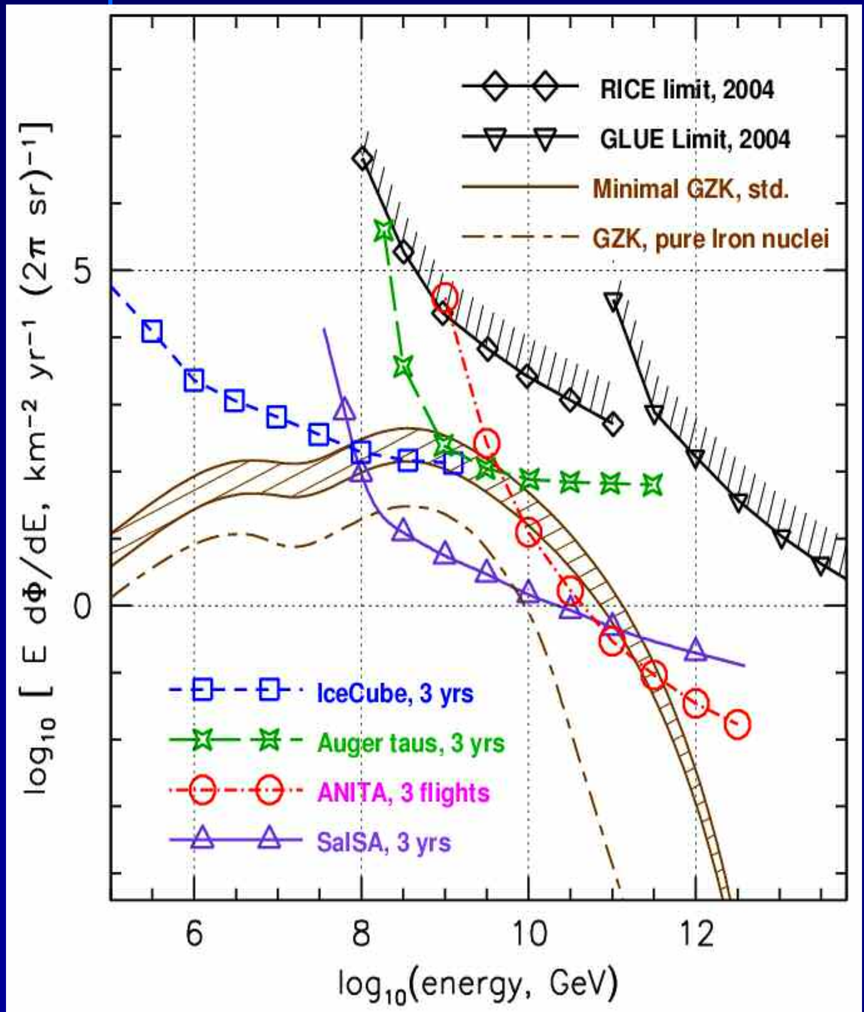
# PeV and beyond

# Overview

- *Radio in ice:*
  - **RICE, ANITA**, AURA, ARIANNA-type (all Antarctica), SALSA (salt)
- *Radio in Moon:*
  - **GLUE, NuMOON**, …
- *Radio in air:*
  - **FORTE** (from space), LOPES, …
- *Horizontal air showers:*
  - **AGASA, HiRES, Auger,** EUSO, …
- *Acoustic detection:*
  - **SAUND** (Caribbean), SPATS (South Pole), AMADEUS & others (Mediterranean), Baikal, SALSA (salt dome), Permafrost (Siberia), …

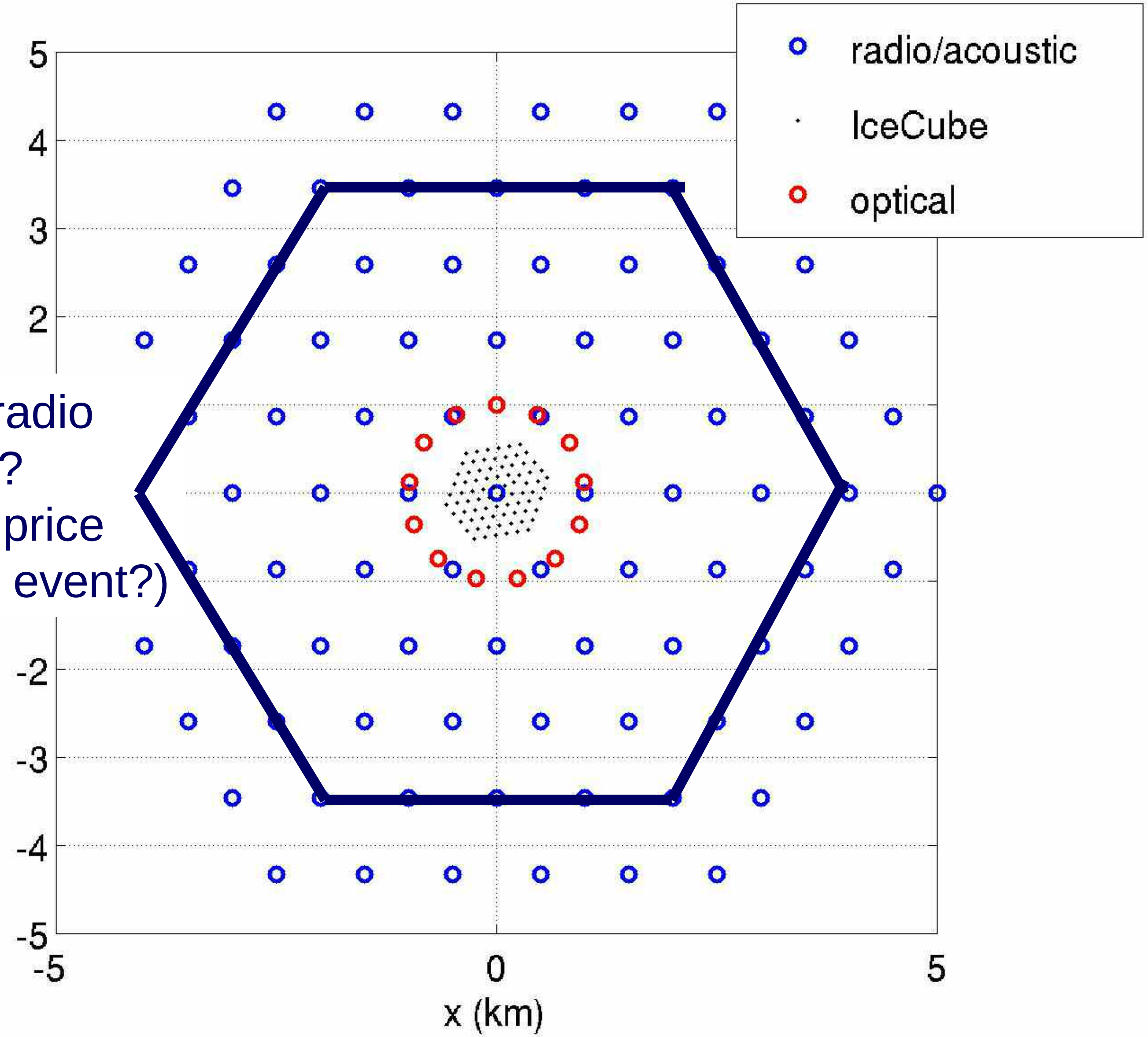

RICE
RF Cherenkov
Auger
Injection point
Electrons & photons
Muons
Early region
broad signals
Late region
narrow signals
ANITA
RF
Cherenkov
air
solid
neutrino
Cascade: ~10m length
FORTE'04 (e, μ, τ)
GLUE 04
ANITA-lite (e, μ, τ)
AMANDA (e, μ, τ)
RICE'05 (e, μ, τ)
Baikal (e, μ, τ)
Auger (τ)
AMANDA (μ)
GZK, each flavor
E² f(E) [GeV cm⁻² s⁻¹ sr⁻¹]
Neutrino Energy [eV]

# Present and projected limits and event numbers




- RICE limits, 3500 hours
- GLUE limits, 120 hours
- ANITA sensitivity, 45 days total:
  - ~5 to 30 GZK neutrinos
- IceCube: high energy cascades
  - ~1.5-3 GZK events in 3 years
- Auger: tau neutrino decay events
  - ~1 GZK event per year?

# Possible HE-Extensions to IceCube ?




surface radio stations ? (smaller price per GZK event?)

# Event numbers

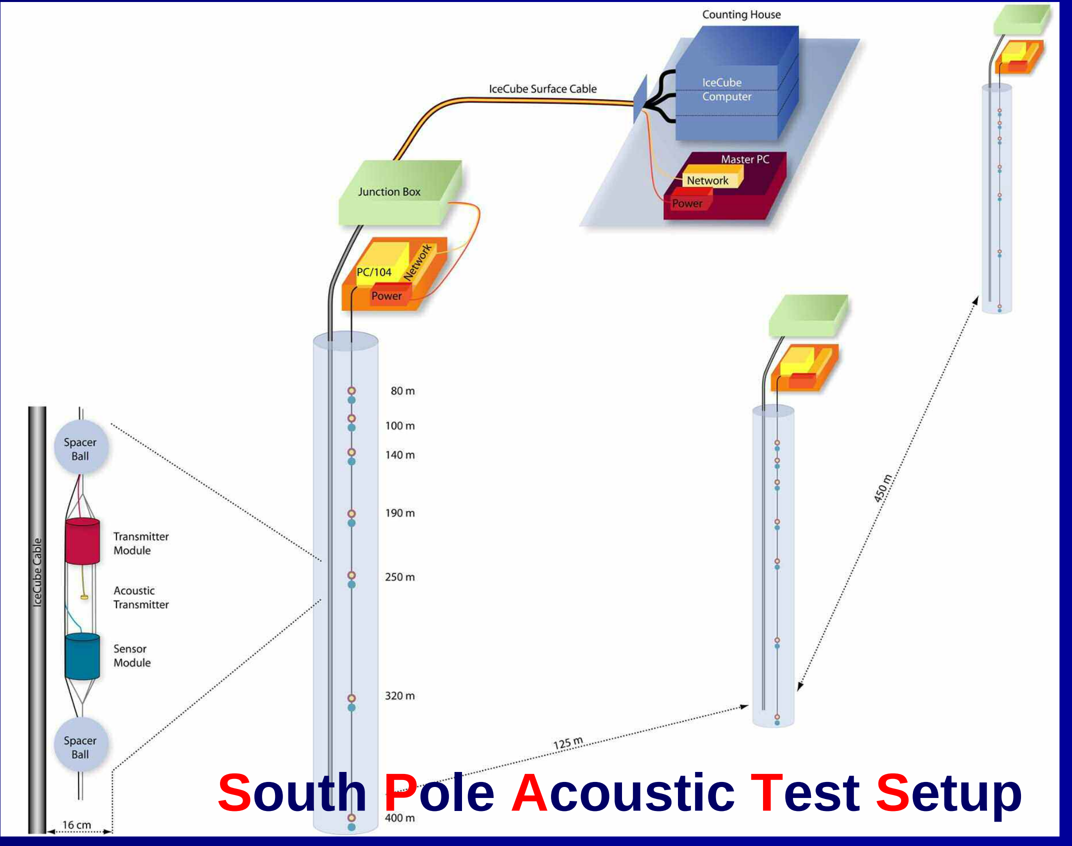
| Detection option | GZK events/year*) |
|---|---|
| **IceCube** | **0.7** |
| **Optical** (IceCube + ring) | **1.2** |
| **Radio** | **12.3** |
| **Acoustic** | **16.0** |
| **Optical + Radio** | **0.2** |
| **Optical + Acoustic** | **0.3** |
| **Radio + Acoustic** | **8.0 !!!** |
| **Opt.+Rad.+Acou.** | **0.1** |
| **TOTAL** | **21.1** |

***Numbers calculated, folding effective volumes with ESS GZK neutrino flux model**

# Installed in last season and under evaluation:

- 3 test strings acoustics **SPATS**

  test:
  - noise
  - attenuation length
  - refraction




see talks of F. Descamps and D.Williams

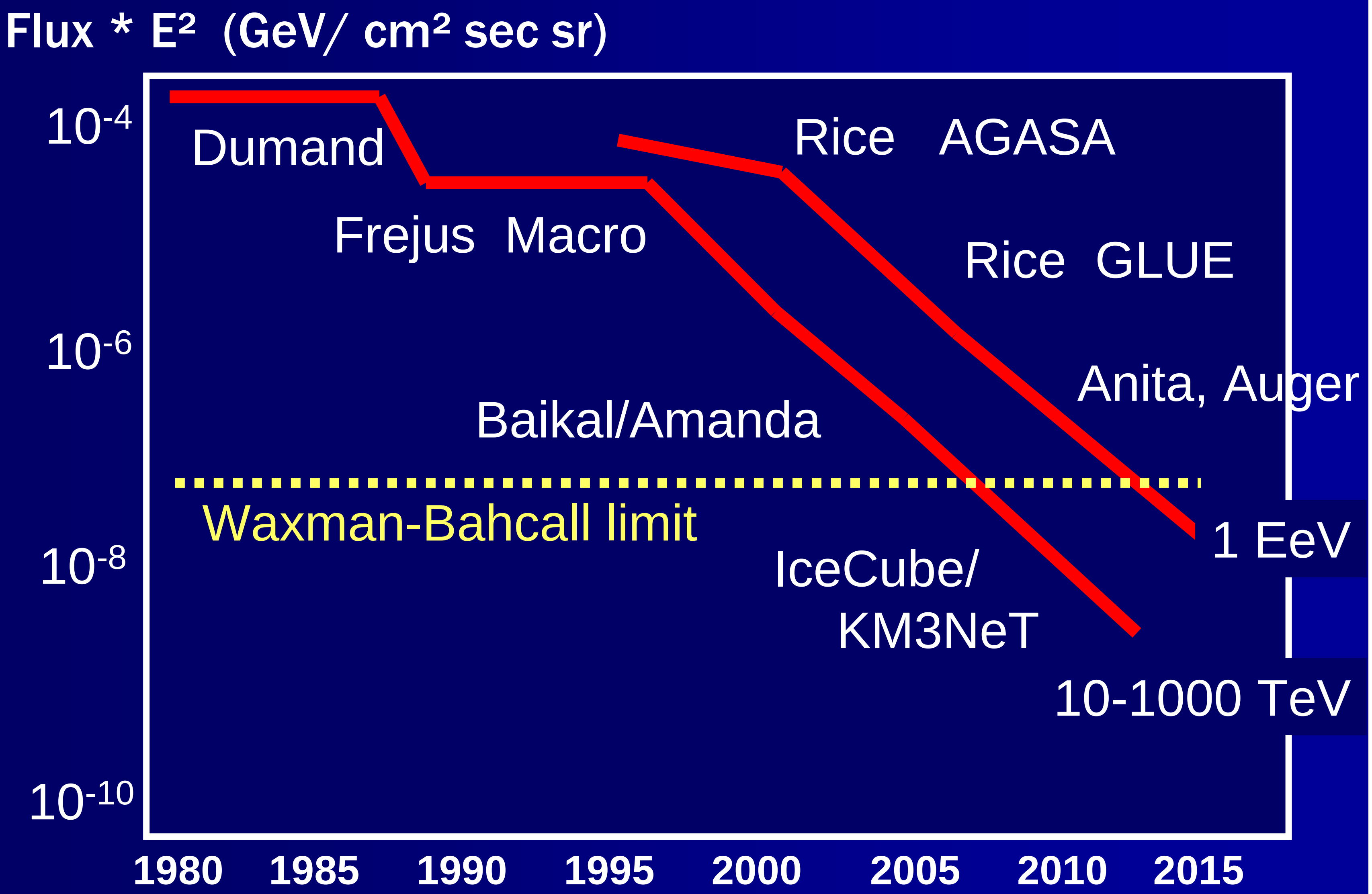
3 test strings radio **AURA**

(Askaryan Underice Radio Array)

$\nu_{Tel}$

# Summary

# Sensitivity to HE diffuse neutrino fluxes



ν Tel

- tremendous technological progress over last decade
- no positive detection yet, but already testing (optimistic) bounds
- IceCube reaches 1 km$^3$ × year by early 2009
- entering region with realistic discovery potential
- IceCube (and HESS) will hopefully consolidate the physics case for KM3NeT
- ready for the next Supernova
- addressing also a wide range of particle physics questions
- Vigorous activity at extreme energies (GZK)

# Will the curtain go up before 100 years after Hess' discovery ?