Neutrino Telescopes

An experimental overview

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The Dark Side of the Universe
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Against Common Wisdom

- Statement # 1:

Neutrino Telescopes are not experiments …they are "a way of life"!

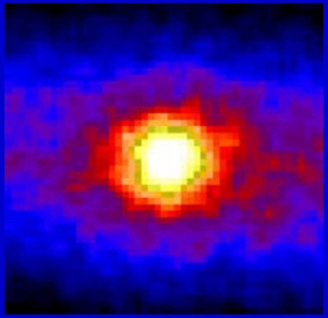
- Enter R&D phase as a graduate student
- Participate in the design of the detector as a PhD student
- During your first post-doc you help writing the TDR
- Start construction during your second post-doc
- Keep on building it during your third post-doc (Spanish physicist)
- Come back home during the first data taking
- Try to understand the data as a Tenure Track-er
- Get permanent position (if you understand the data)
- Get promoted (if you beat the Waxman&Bahcall limit)
- Get full Professorship (if you find one single source)
- But most likely, retire during the construction phase of the mythical "kilometre cube"

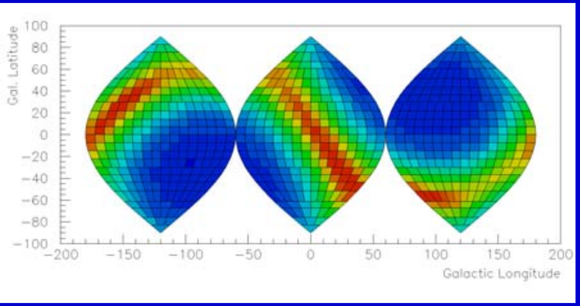
Against Common Wisdom (cont'ed)

- Statement # 2:

  Neutrino Telescopes do not operate yet

  - False! Kamiokande and Superkamiokande <u>are</u> ν-Telescopes!

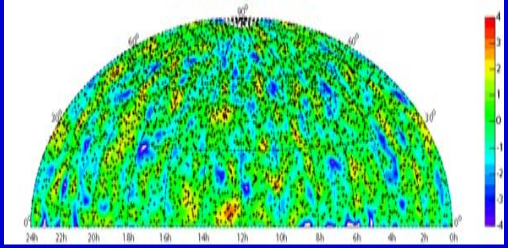




Well…

High energy Neutrino Telescopes do not operate yet

- False! AMANDA and BAIKAL are operating.



Against Common Wisdom (cont'ed)

- Statement # 2 bis:

Neutrino Telescopes <u>sensitive enough</u> will take years to be operational

  - False! IceCube's schedule is awesome and KM3's is aggressive too

- Statement # 3:

Neutrino Telescopes do not have a clear physics case…

  - False (at least according to theorists!)
    - HE Astrophysics, dark matter, ν-oscillations, breakdown of equivalence principle, breakdown of Lorentz invariance, study of MSW resonance, quantum decoherence, magnetic monopoles, Q-balls, whys (what-have-you's)…

and who knows, we are opening a new window to the Universe

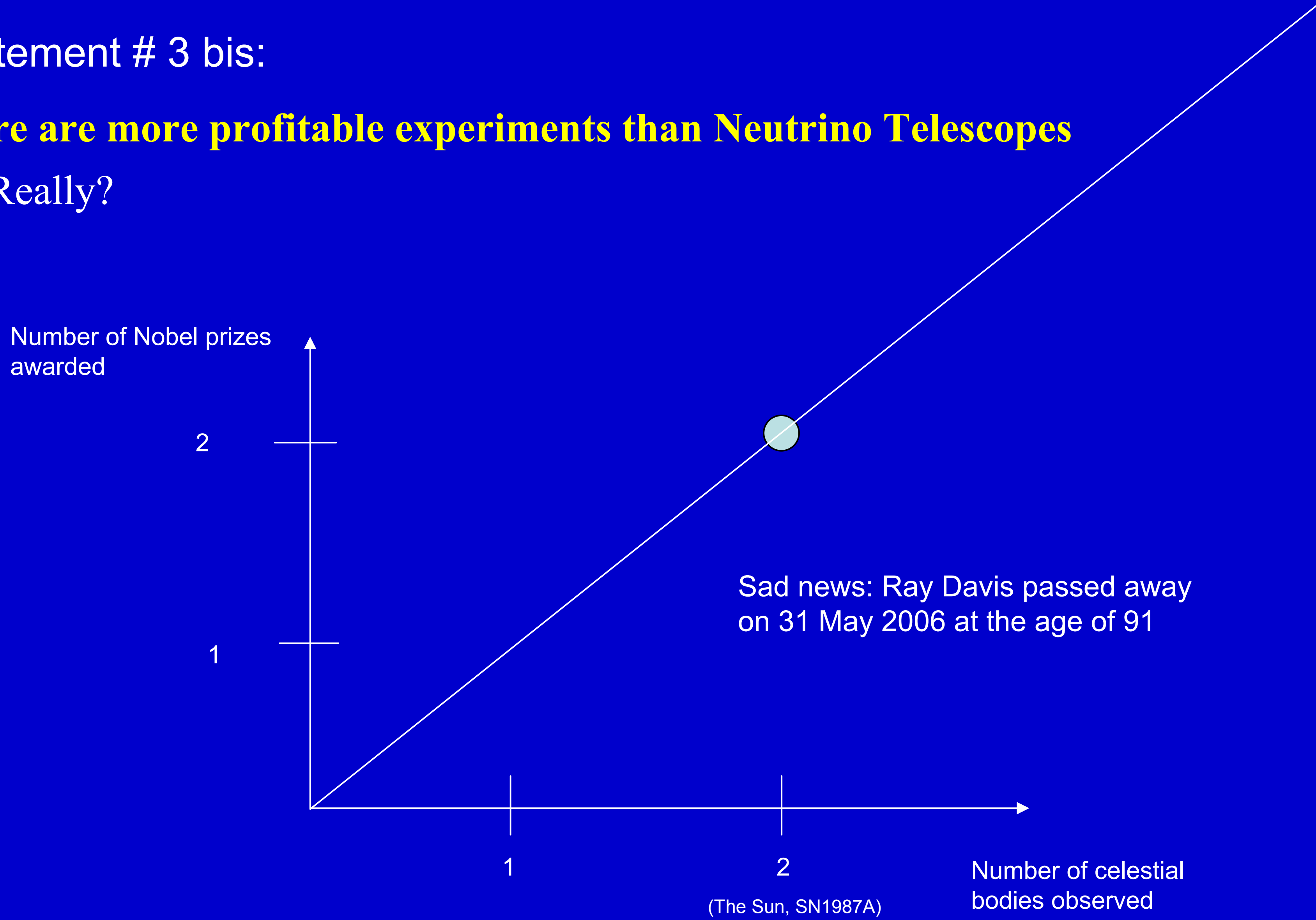
(astrophysicists: "c'mmon, at most you'll just make a little hole in the wall")

Against Common Wisdom (cont'ed)

- Statement # 3 bis:

There are more profitable experiments than Neutrino Telescopes

- Really?



Sad news: Ray Davis passed away on 31 May 2006 at the age of 91

Detection of extra-terrestrial neutrinos

Detection of the products produced in CC and NC interactions (muons, EM showers)

(Disclaimer: I will only cover "optical" neutrino telescopes)

Optical Cherenkov radiation

In Ice

AMANDA B-10
AMANDA II

IceCube

In water

Baikal

ANTARES
NEMO
NESTOR

KM3NeT

Atmospheric showers

Earth based

Auger
Hi-res
Fly's eye

In space

EUSO
OWL

Radio emission

Earth based

RICE
GLUE
SalSA
CODALEMA

In space

ANITA
FORTE

Acoustic detection

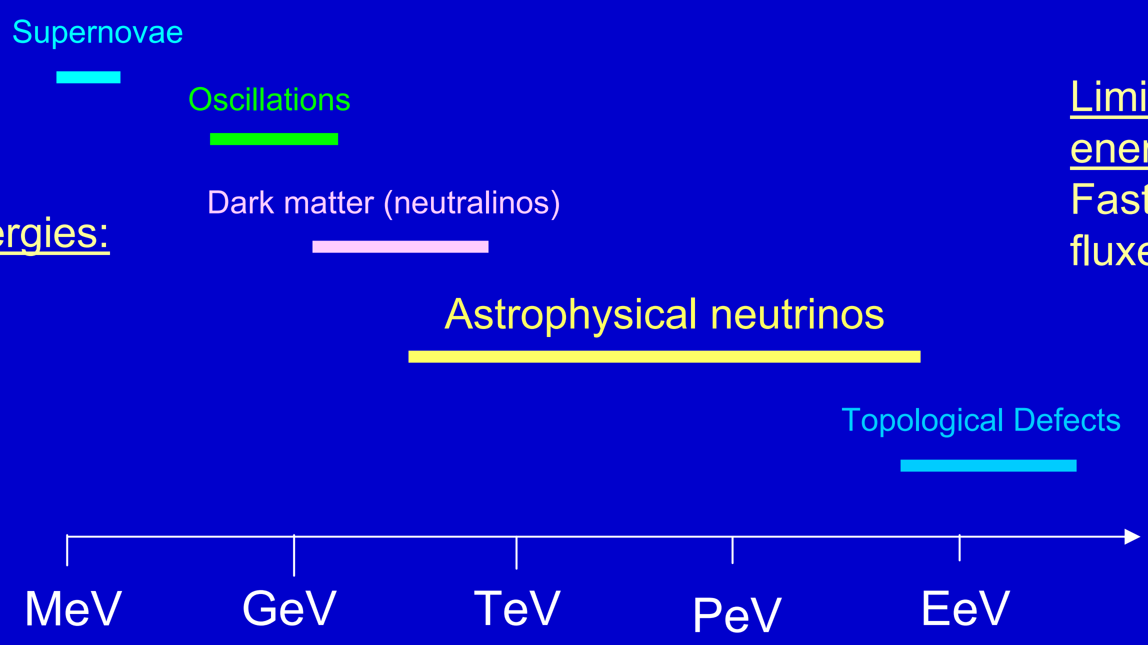
SAUND
SADCO (Greece)
ANTARES R&D
IceCube R&D
AUTEC
AGAM

Scientific Scope

- Astrophysics:
  - Hadronic vs Leptonic sources
  - Origin of VHE Cosmic ray origin
- Particle Physics:
  - Indirect search of dark matter
  - Oscillations
- Other
  - Monopoles, top-down scenarios, SUSY Q-balls, etc

Detector size

<u>Limitation at high energies:</u>
Fast decreasing fluxes E^{-2}, E^{-3}



<u>Limitation at low energies:</u>
-Short muon range
-Low light yield
-^{40}K (in water)

Detector density

Production Mechanism

- Neutrinos are expected to be produced in the interaction of high energy nucleons with matter or radiation:

$$N + X \rightarrow \pi^{\pm}(K^{\pm}\ldots) + Y \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu}) + Y$$

$$\downarrow$$

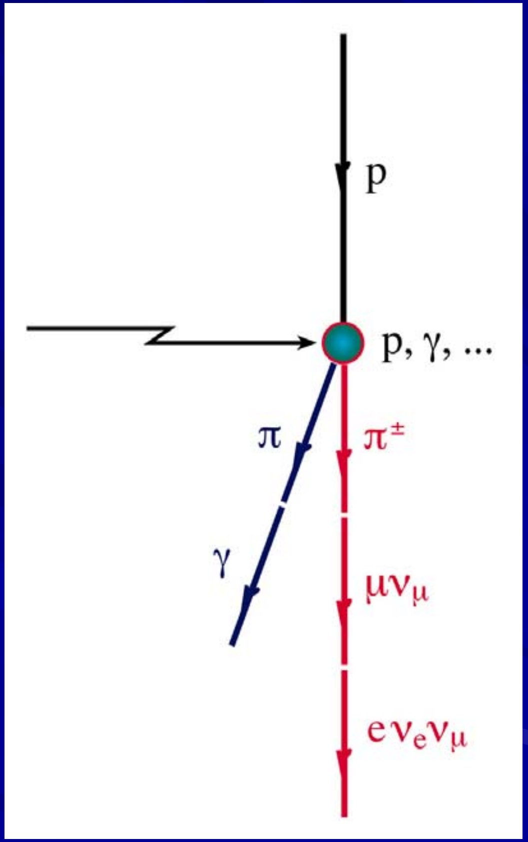
$$e^{\pm} + \bar{\nu}_e(\nu_e) + \bar{\nu}_{\mu}(\nu_{\mu})$$

Cosmic rays

- Moreover, gamma production is also associated in this scenario:

$$N + X \rightarrow \pi^{0} + Y \rightarrow \gamma\,\gamma + Y$$

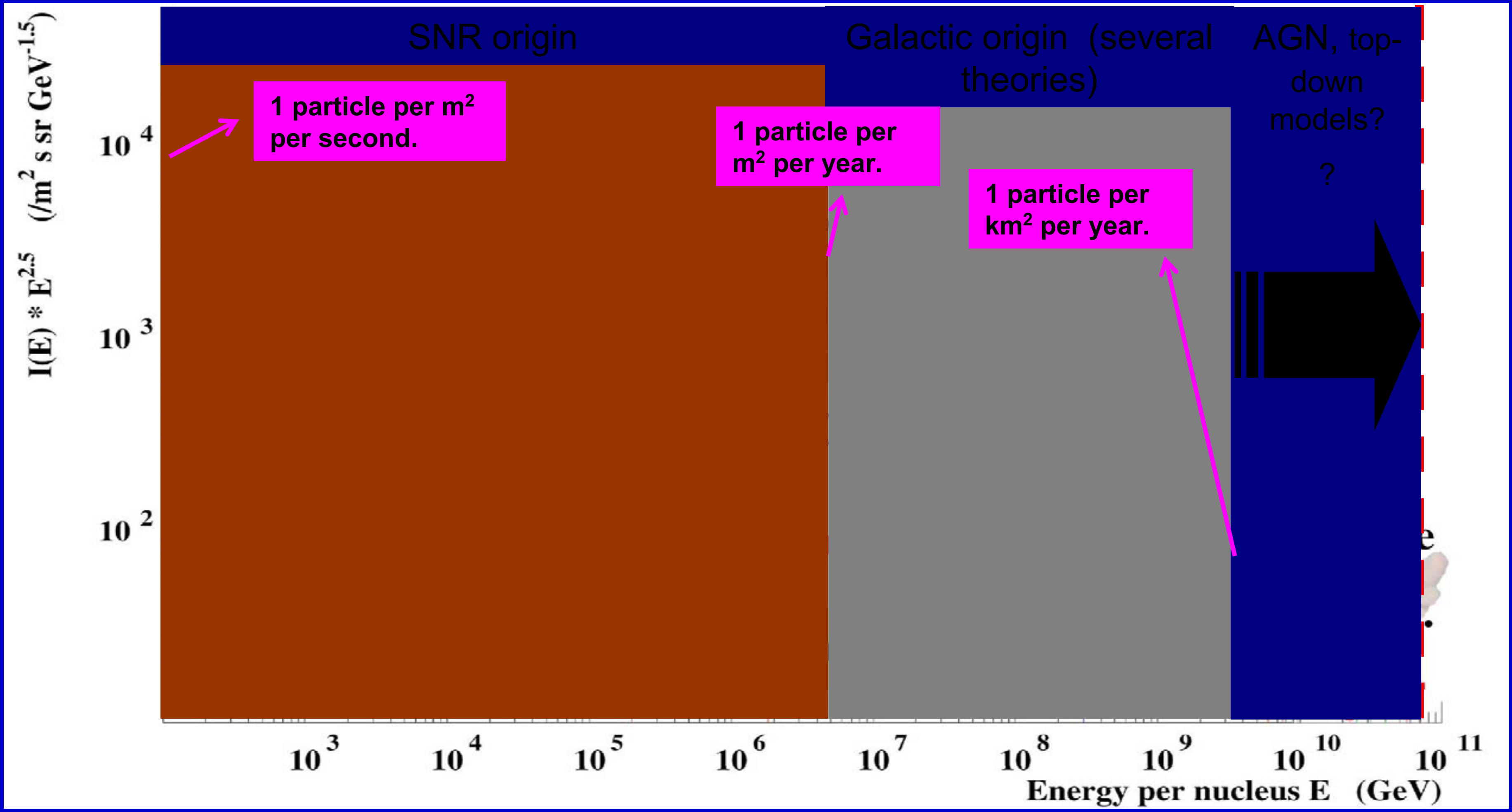
Gamma ray astronomy



Cosmic Ray spectrum

- We do see cosmic Rays accelerated at to very high energy

GZK cut-off: end of the cosmic ray spectrum??



Astrophysical Sources

- **Extra-galactic sources**: most powerful sources in the Universe
  - AGNs
  - GRBs

- **Galactic sources**: these are near objects (few kpc) so the luminosity requirements are much lower.
  - Micro-quasars
  - Supernova remnants
  - Magnetars

■ …EG …

• U… HE … iffuse flux can be established.

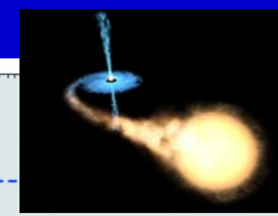
• From the isotropic gamma ray background.

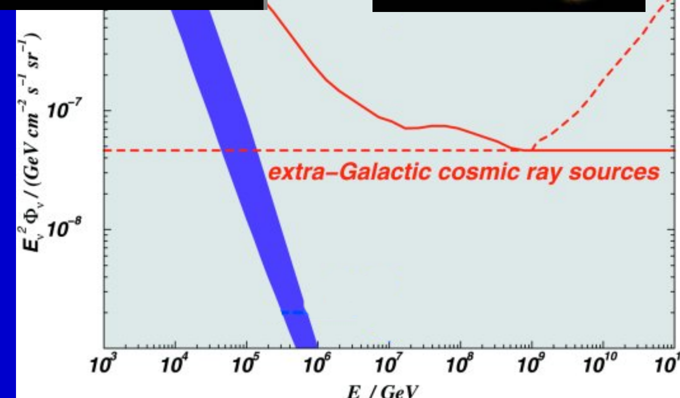
$E^2\, d\Phi/dE < 10^{-6}$ GeV cm^{-2} s^{-1} sr^{-1}

• The limit from cosmic ray fluxes depends on the assumptions on the source*:

WB: $E^2\, d\Phi/dE < 4.5\times10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}

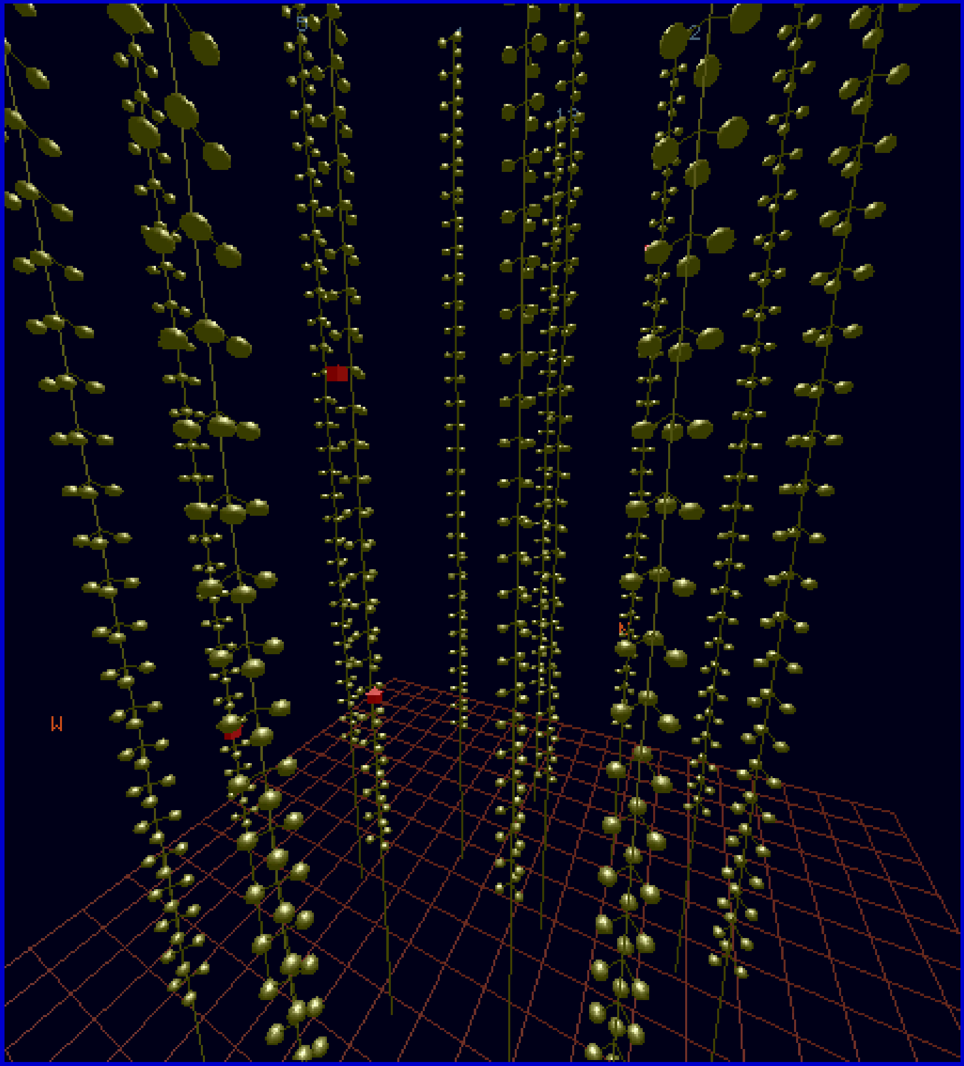
MPR: $E^2\, d\Phi/dE < 2\times10^{-6} - 4.5\times10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}





*Oscillations reduce these limits in a factor two: 1:2:0 → 1:1:1

Detection Principle

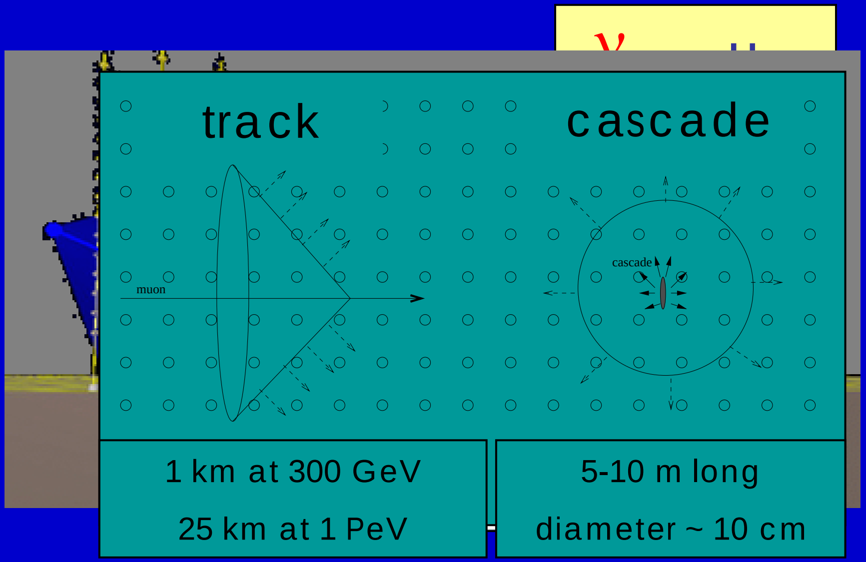


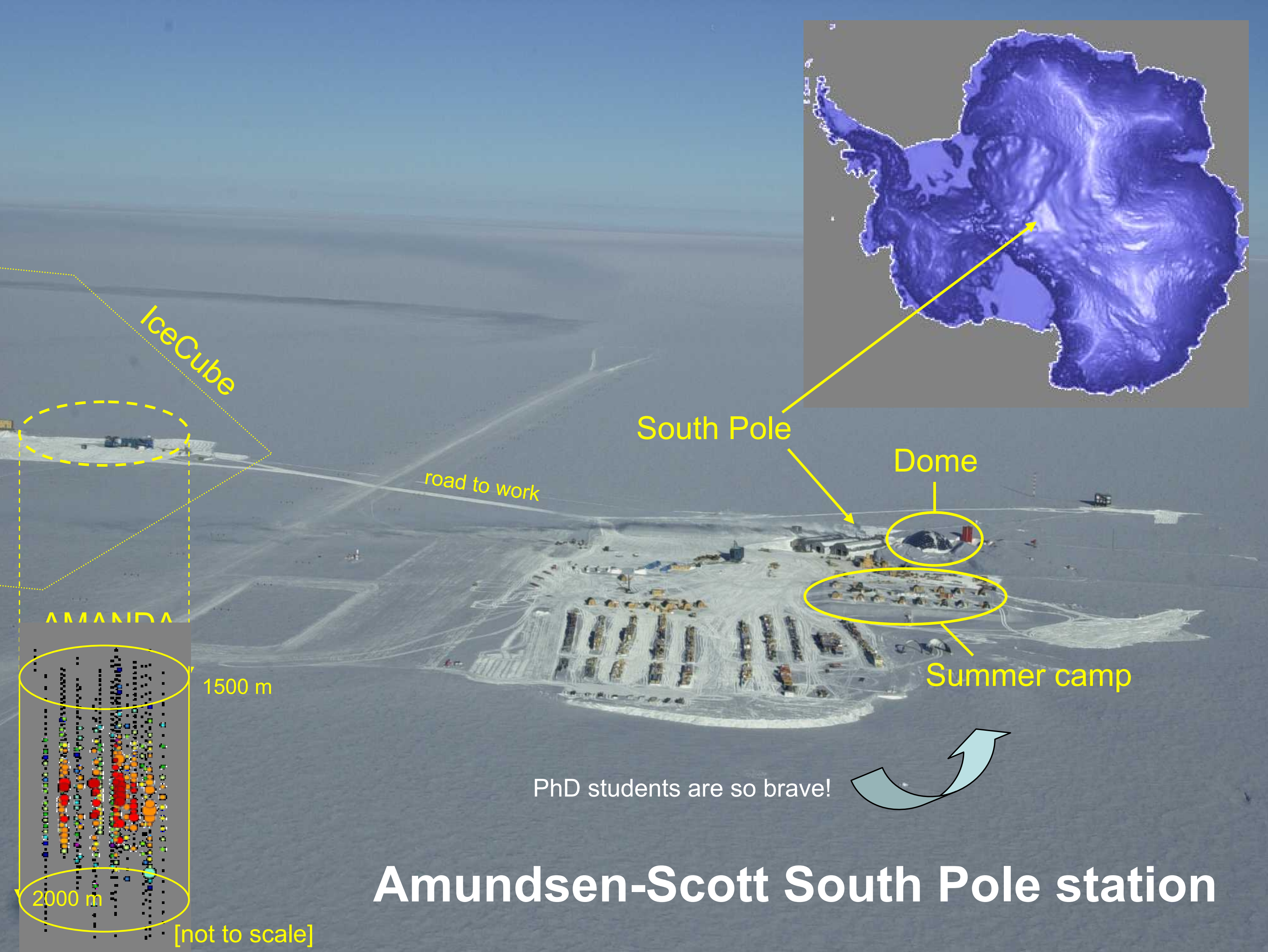
1.2 TeV muon traversing the detector.

The neutrino is detected by the Cherenkov light emitted by the muon produced in the CC interaction.

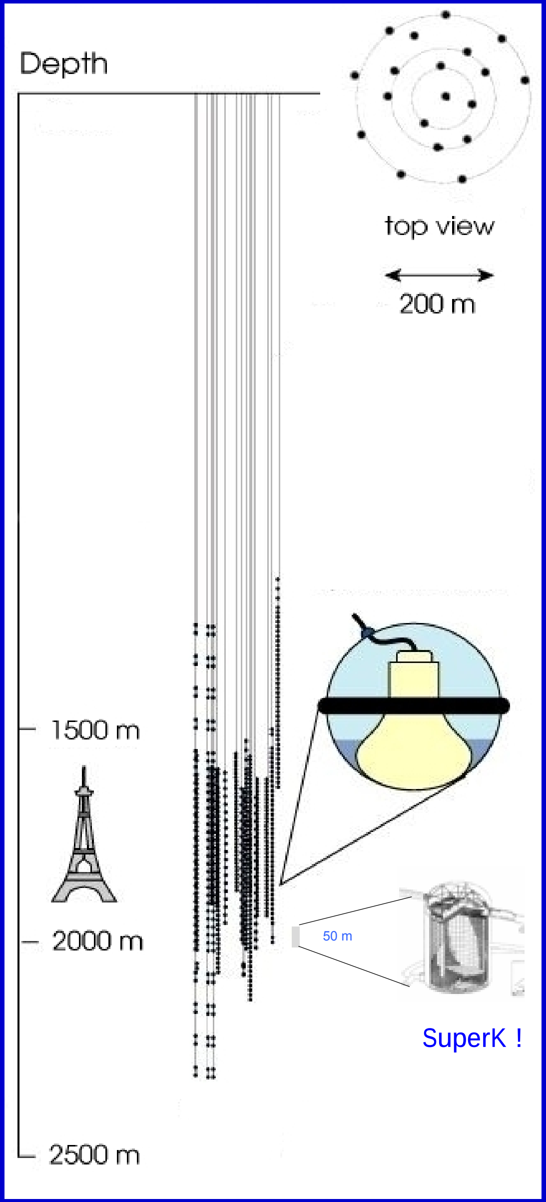
Detection of cascades is also possible. In a km3 detector ν_τ identification will be possible

A very wide energy range can be covered looking in different directions




IceCube
road to work
South Pole
Dome
Summer camp
1500 m
2000 m
[not to scale]
PhD students are so brave!
Amundsen-Scott South Pole station

AMANDA Detector

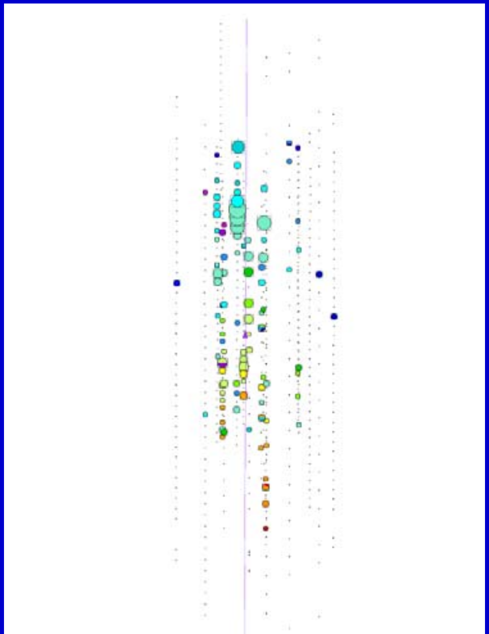


1997-99: **AMANDA-B10**
(inner lines of AMANDA-II)

- 10 strings
- 302 PMTs

Since 2000: **AMANDA-II**

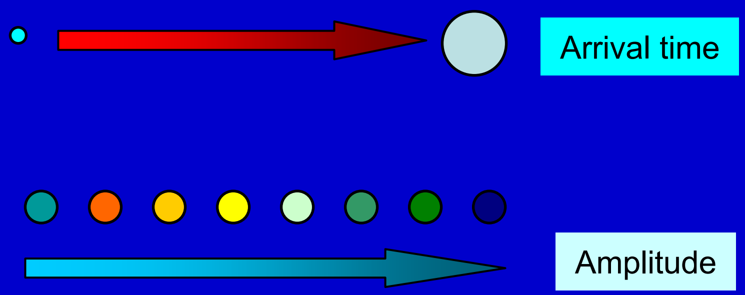
- 19 strings
- 677 OMs
- 20-40 PMTs / string



•**HE**: TeV < E_ν < PeV:
•Directionality + energy-related variables to reject atm μ background
•Confined to up-going tracks
•High-quality tracks

•**UHE:** E_ν > P eV:
•Earth opaque. Search in the upper hemisphere and close to the horizon
•Bright events: many hit OMs with several hits/OM

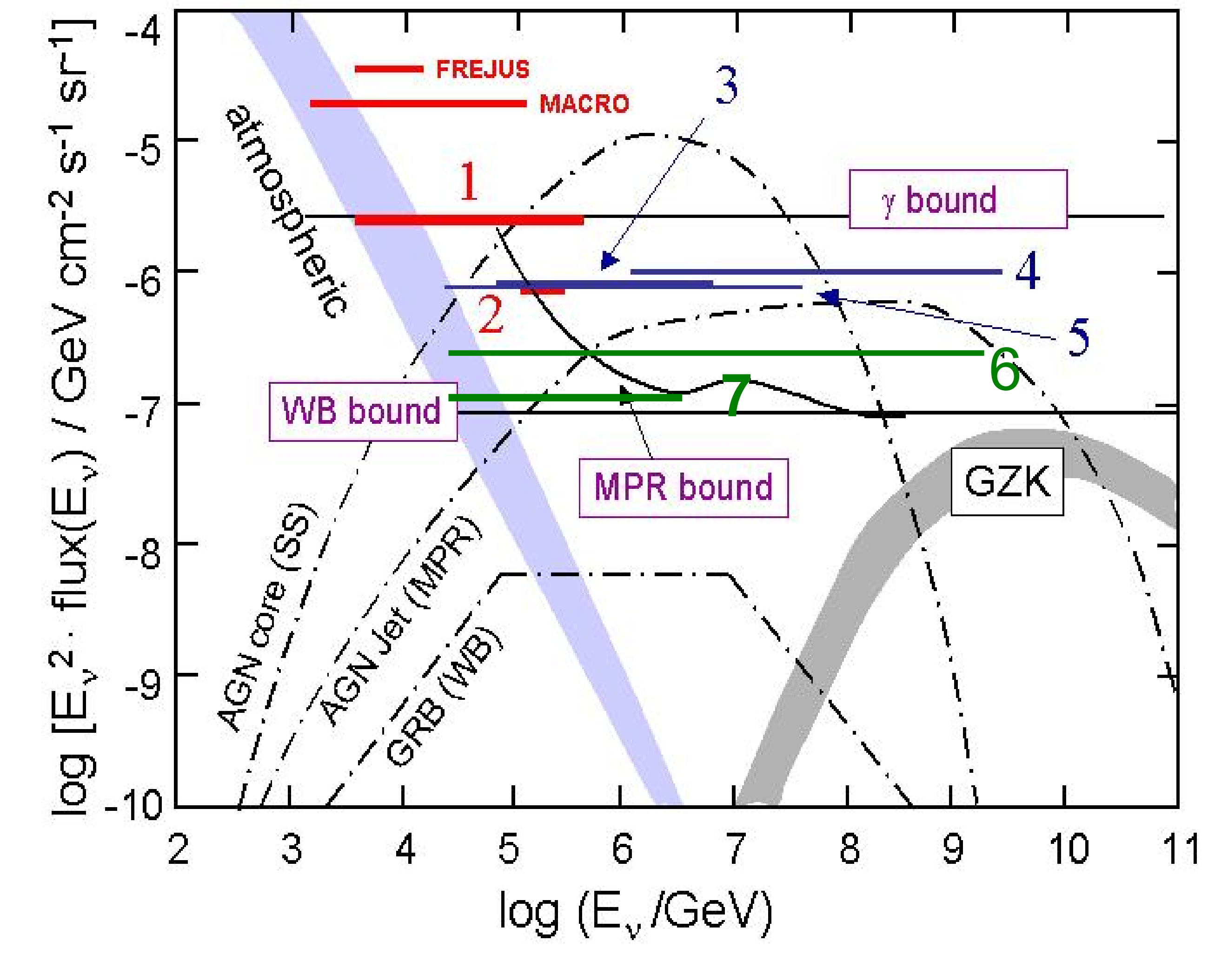
•**Cascades:** TeV < E < PeV
•4π search
•Background: brehmm. from down-going muons



Diffuse Flux Limits

all-flavor limits

1:1:1 flavor flux ratio



AMANDA

1: B10, 97, ↑μ
2: A-II, 2000, unfold.
3: A-II, 2000, cascade
4: B10, 97, UHE
6: A-II, 2000, UHE sensit.
7: A-II, 2000-03 ↑μ sensit.

Baikal

5: 98-03, casc.

Limits for other flux predictions:
Cuts optimized for each case.
Expected limit from a given model compared with observed limit.

Some AGN models excluded at 90% CL :

Szabo-Protehoe 92

Stecker, Salamon. Space Sc. Rev. 75, 1996

Protehoe. ASP Conf series, 121, 1997

More info?

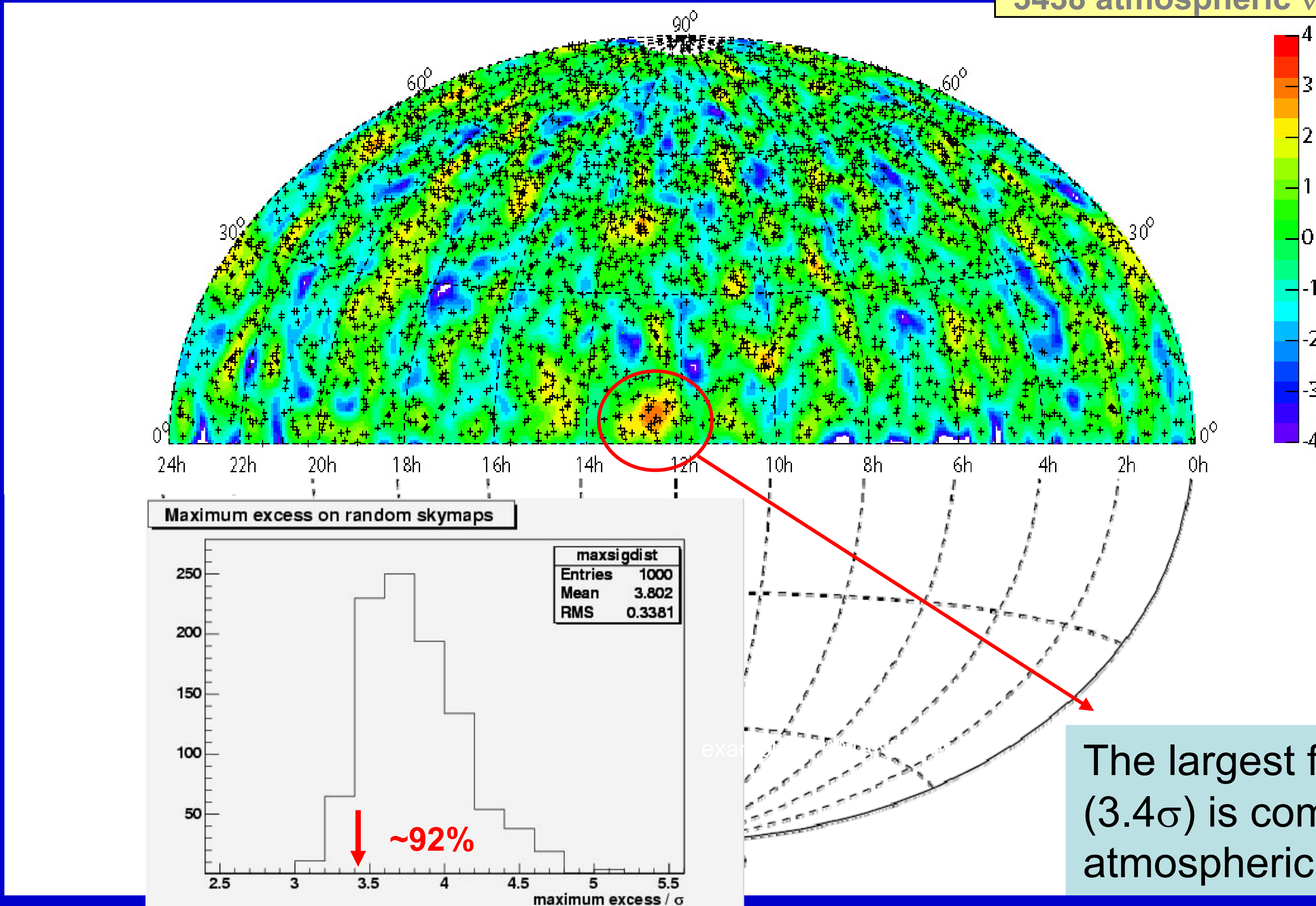
Neutrino Sky Map

AMANDA has provided the first neutrino sky map of the Northern Hemisphere

2000-2003 (807 days)

3329 νs detected from Northern Hemisphere

3438 atmospheric νs expected



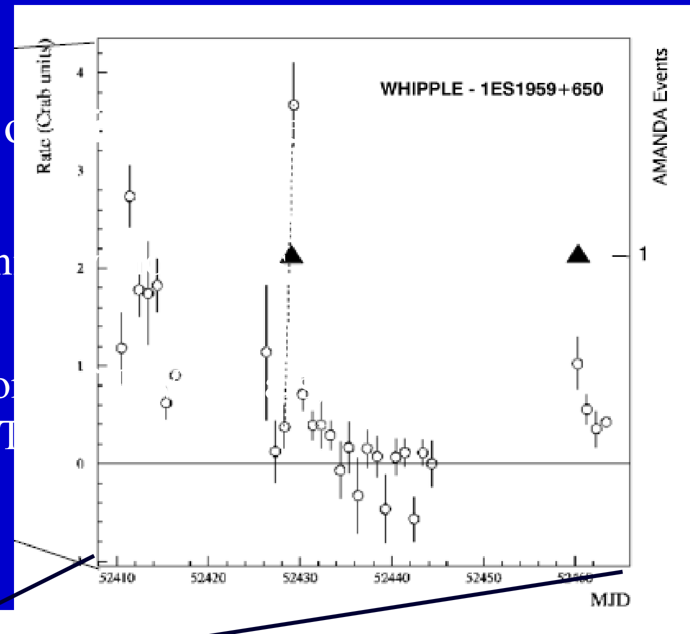
The largest fluctuation (3.4σ) is compatible with atmospheric background

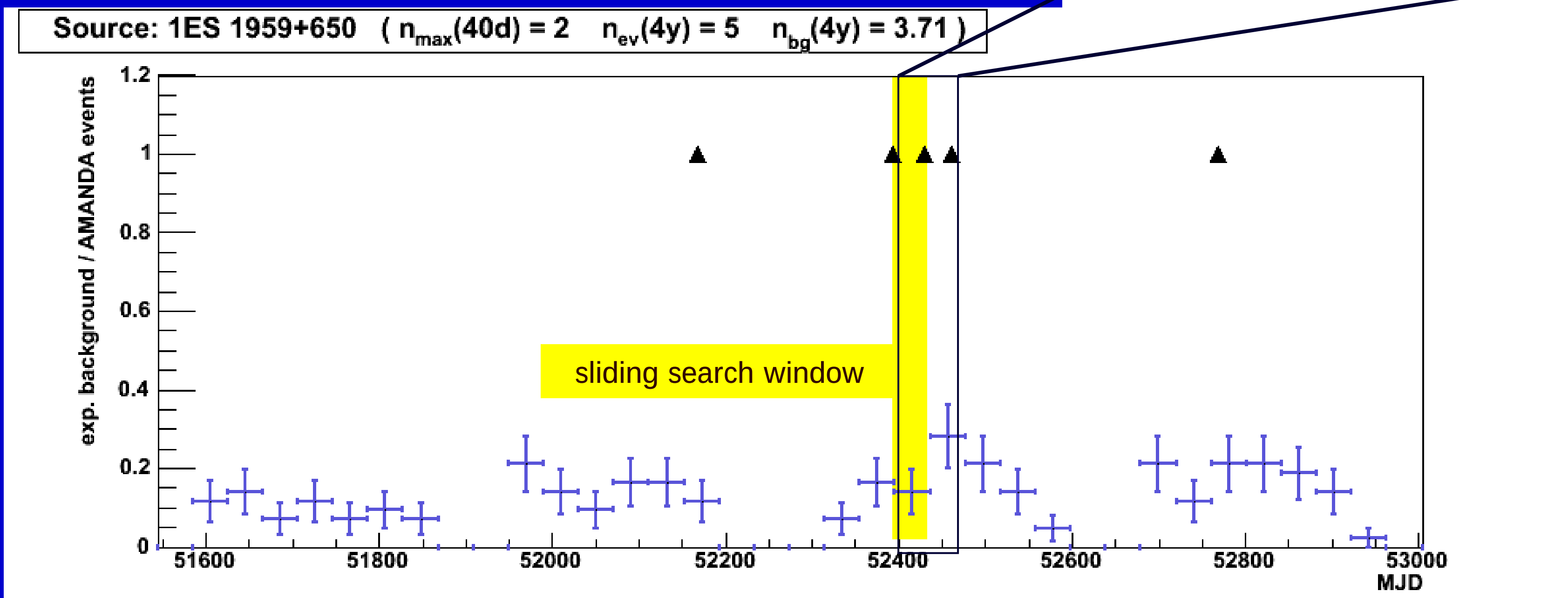
Specific point-like source searches

- Some other specific searches are being made o
  - Stacking sources: combine source types. Prelim
  - Transient sources (multi-wavelength observatio
  - microquasars and variable sources from EGRET
  - GRBs follow-up.

- Three events in 66 days within the period of a mayor 1ES 1959+650 burst (orphan flare: γs but no X-rays)

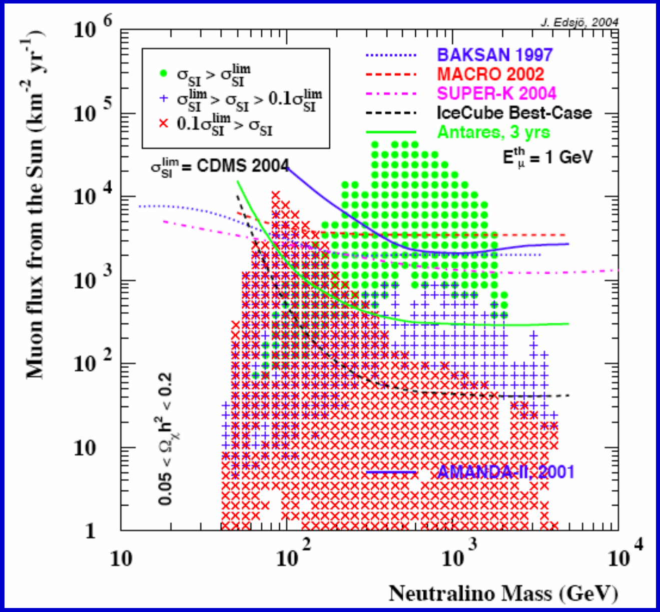
- A posteriori search → undefined probability of random coincidence.



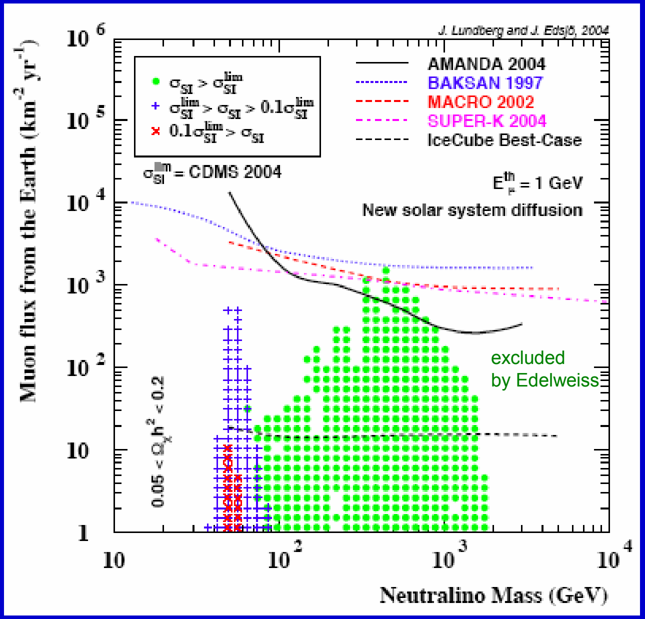


More Info?

Neutralino Search



From the Sun



From the Earth

- Direct and indirect methods probe the WIMP distributions in the solar system at different epochs.
- They are sensitive to different parts of the velocity distribution (direct → high energy recoils; indirect → high capture rate → low energy)

- The Sun is the most promising source of neutralinos.

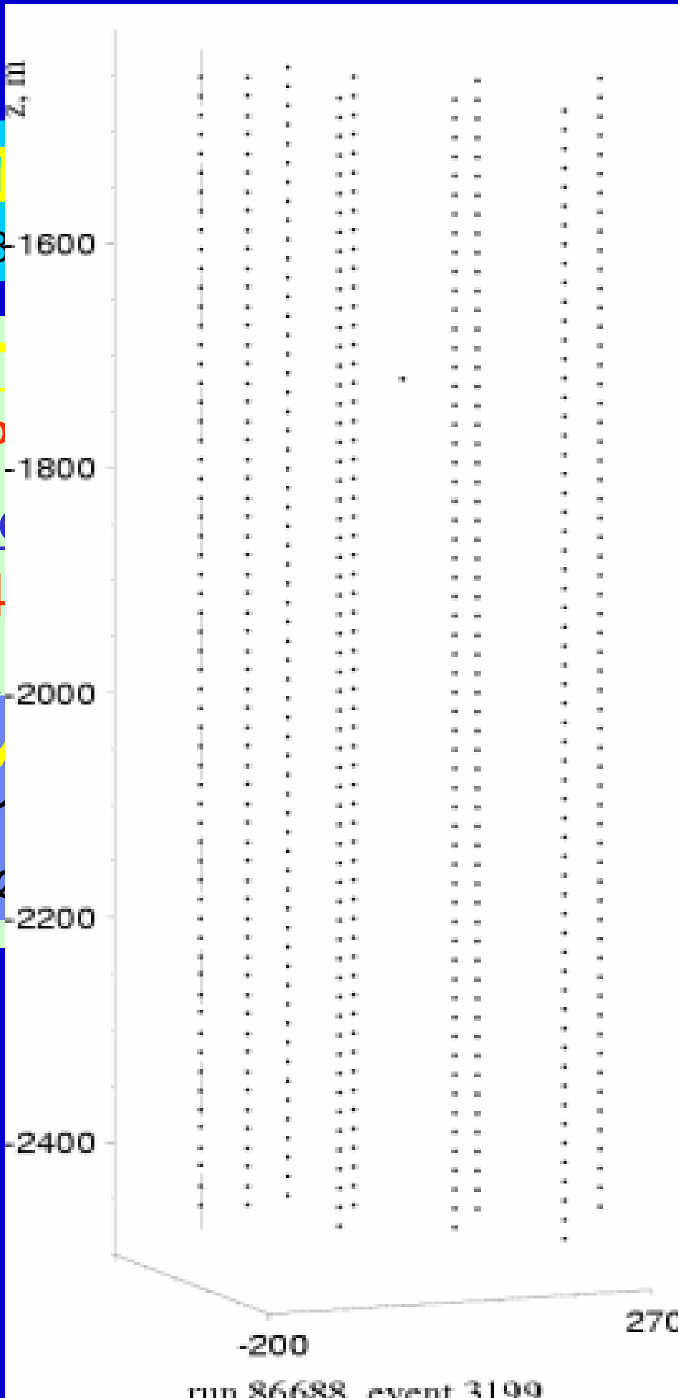
- Neutralino density in the Earth is diminished the effect of the Sun mass.

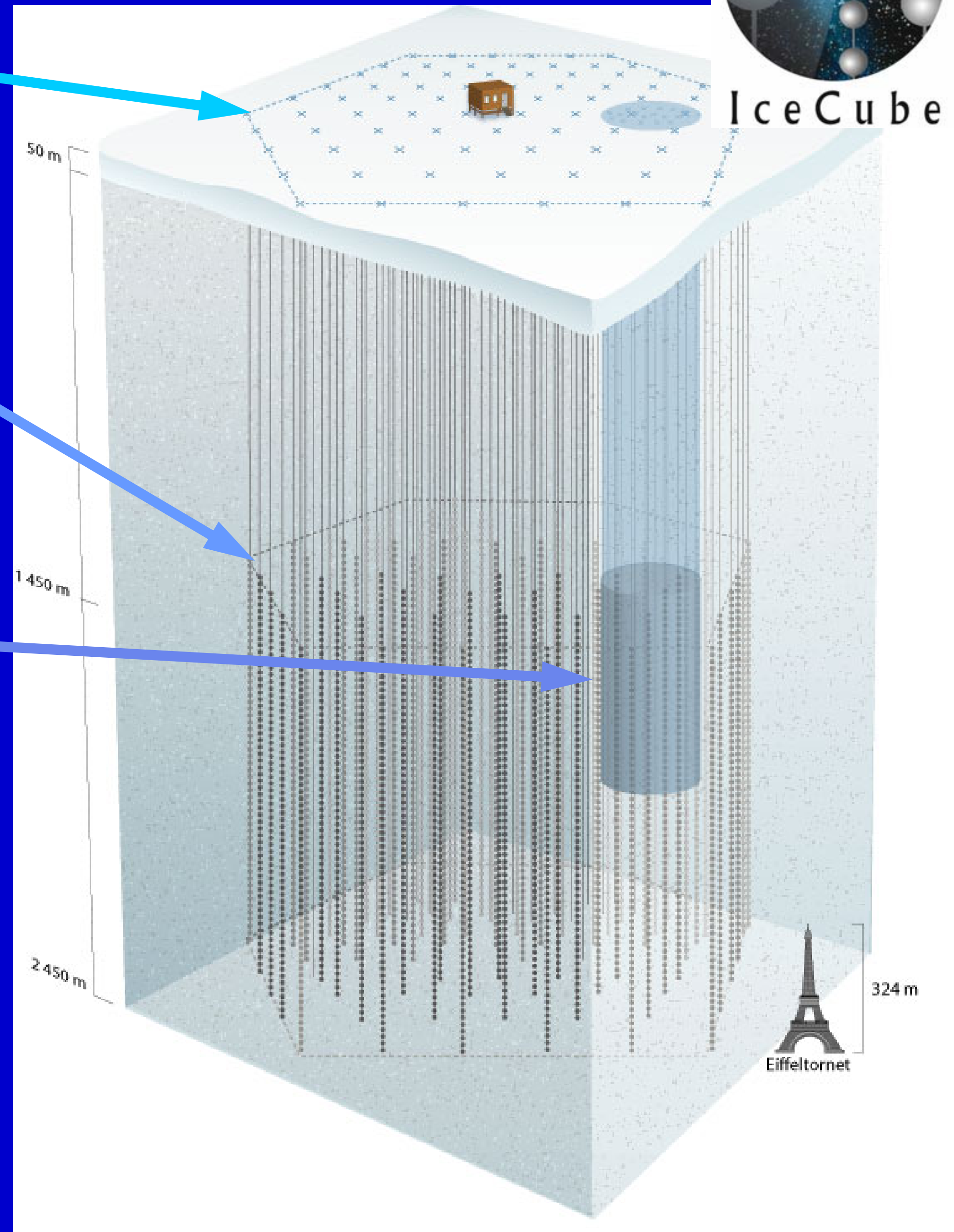
More Info?

eCube

ules

s

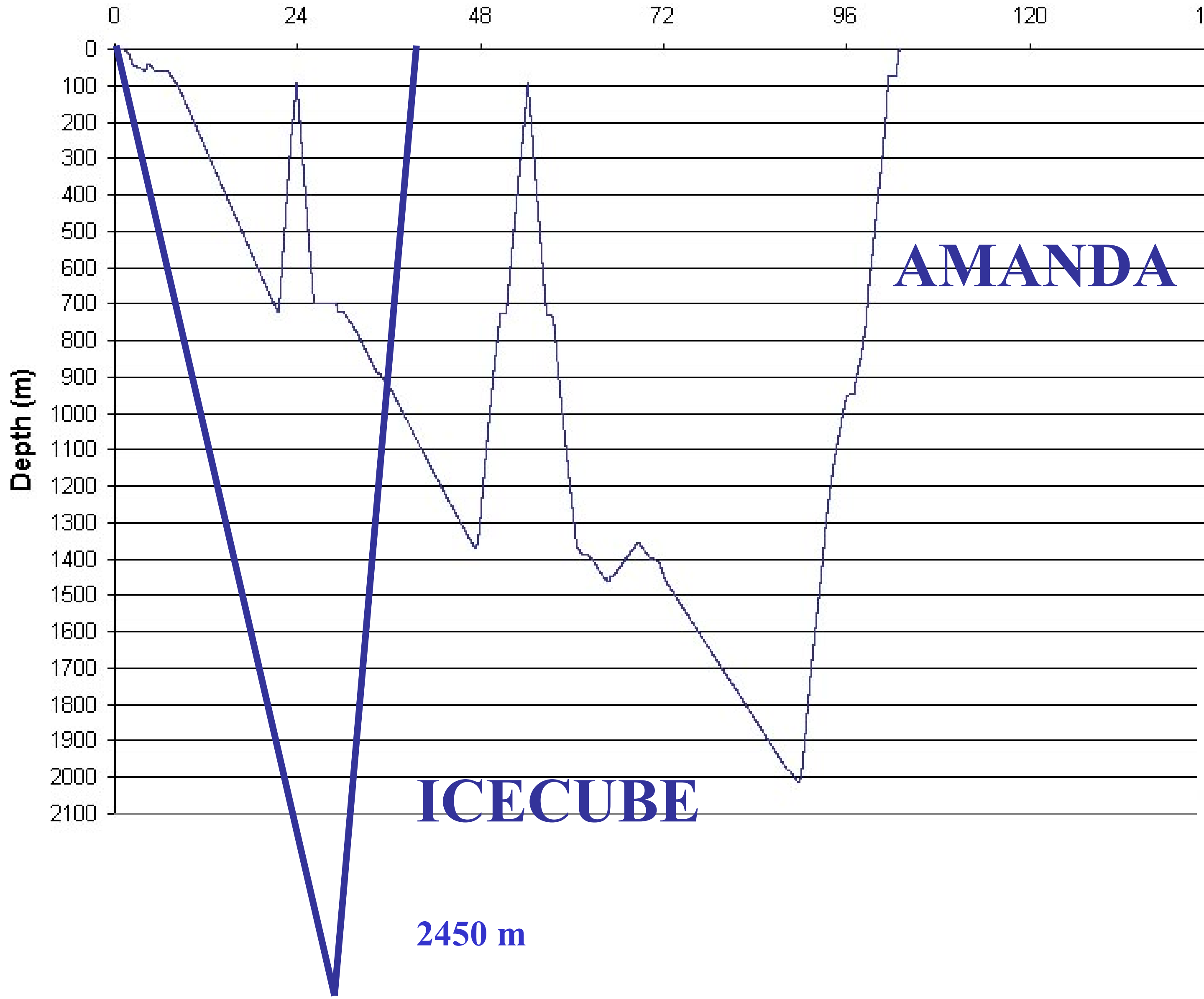


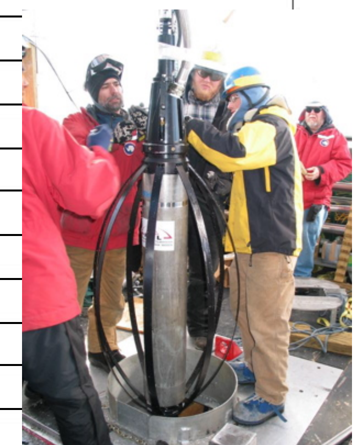


IceCube

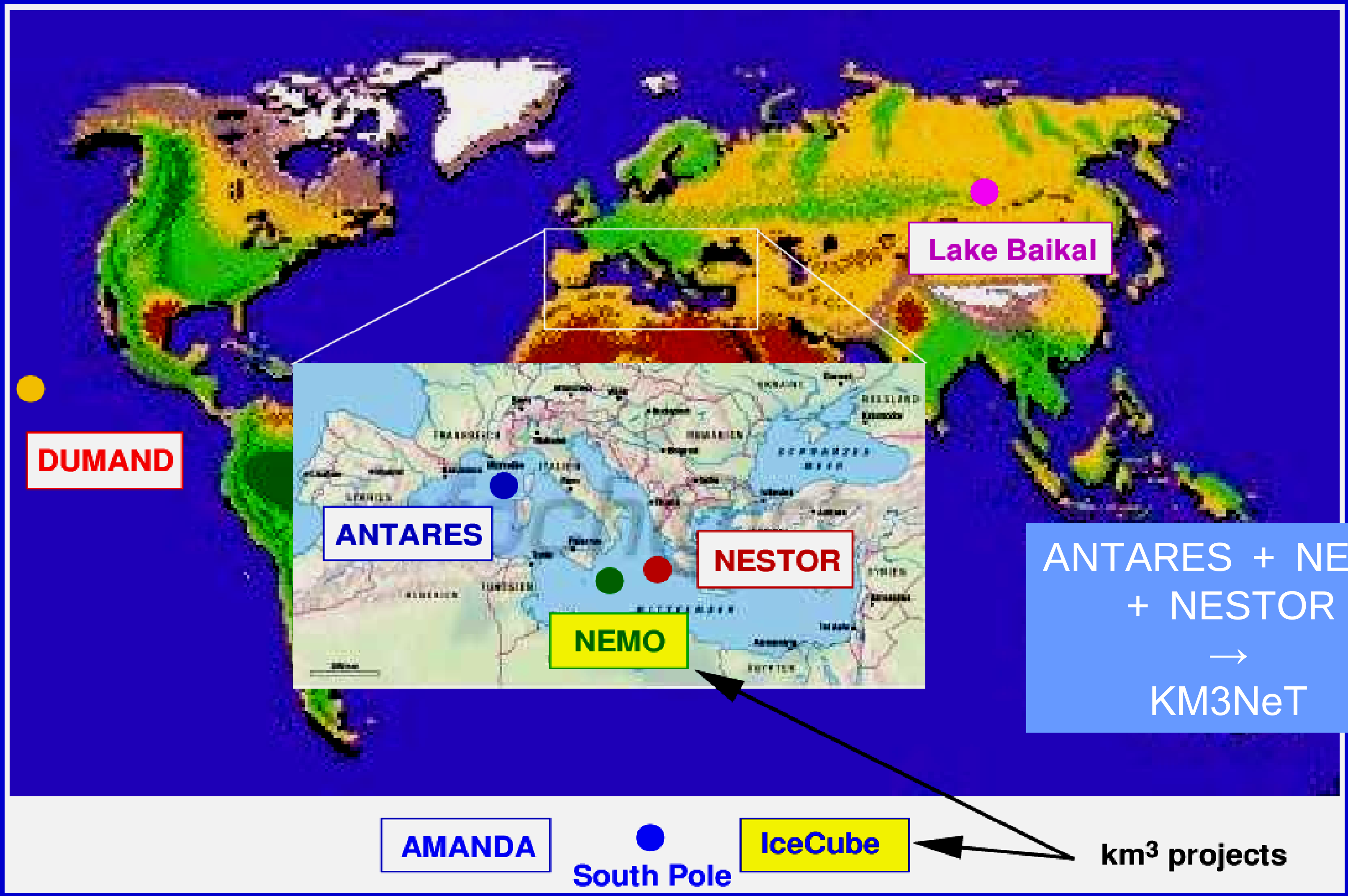
Drilling time

AMANDA's string 19





Neutrino Telescopes in the World



ANTARES + NEMO + NESTOR → KM3NeT

NESTOR: Rigid Structures Forming Towers

- Tower based detector (titanium structures).
- Dry connections (recover−connect−redeploy).
- Up- and downward looking PMs.
- 3800 m deep.
- First floor (reduced size) deployed & operated in 2003.

Plan: Tower(s) with12 floors

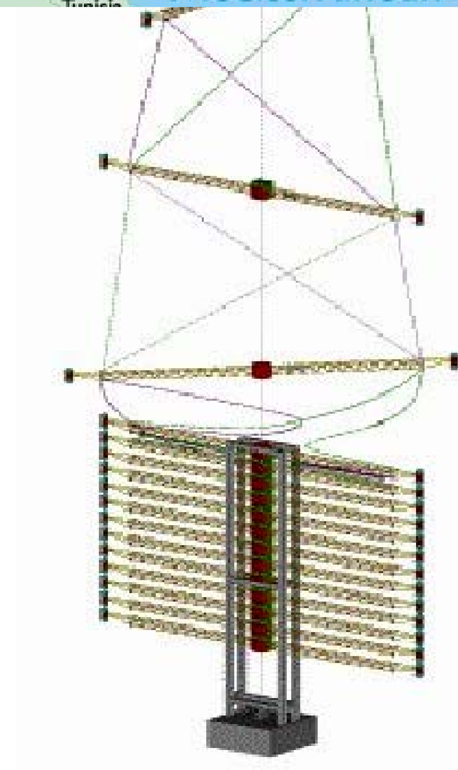
→ 32 m diameter

→ 30 m between floors

→ 144 PMs per tower

The NEMO Project

- Extensive site exploration (Capo Passero near Catania, depth 3500 m);
- R&D towards km³: architecture, mechanical structures, readout, electronics, cables ...;
- Simulation.

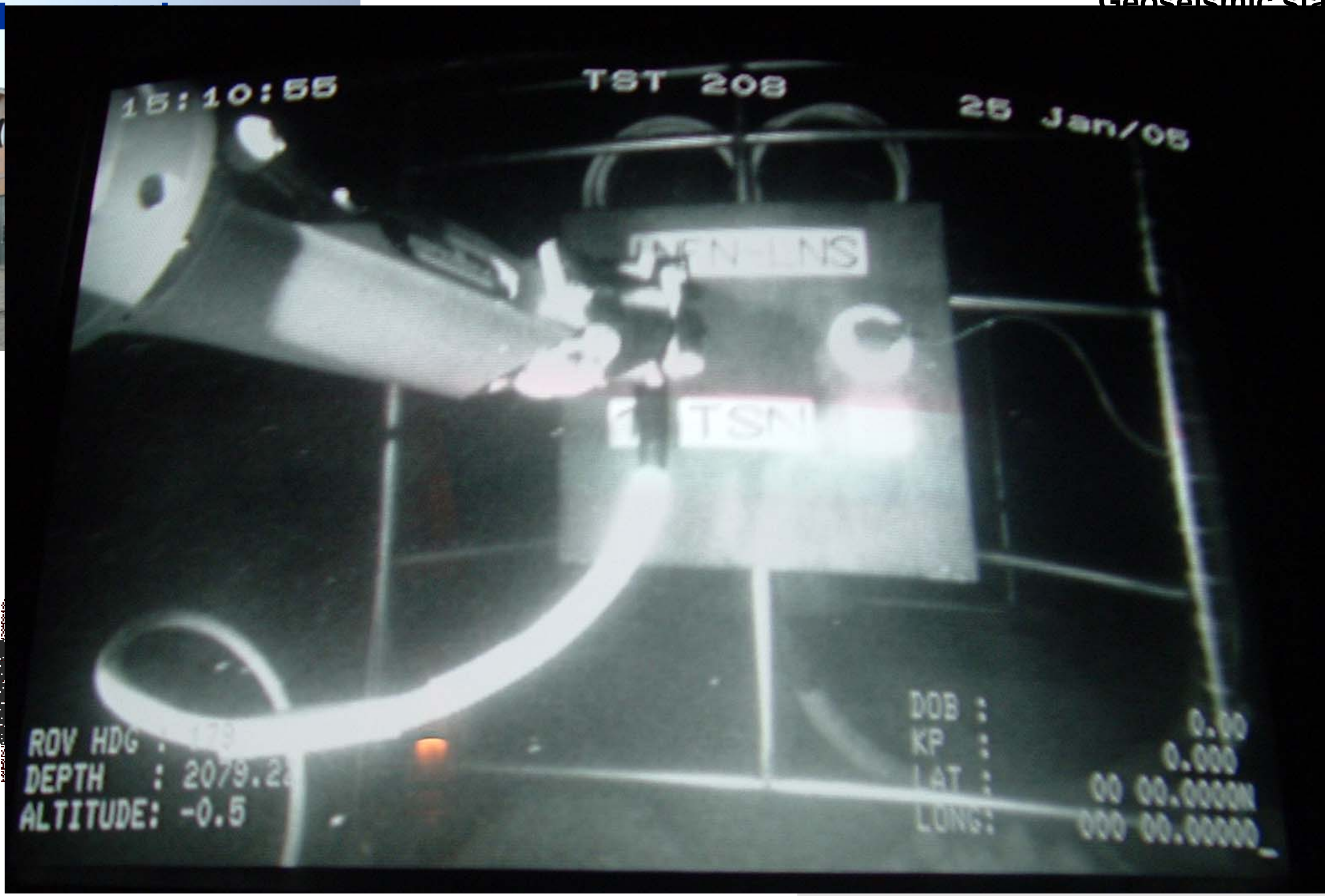


Example: Flexible tower

- 16 arms per tower, 20 m arm length, arms 40 m apart;
- 64 PMs per tower;
- Underwater connections;
- Up- and downward-looking PMs.

NEMO Phase I

Geoseismic station



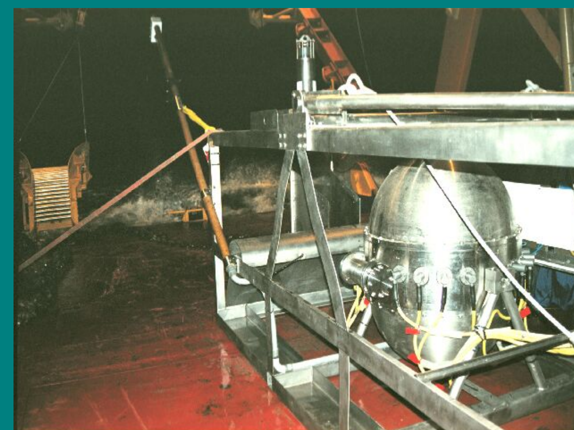
The ANTARES detector

• 12 strings (900 PMTs)
• 25 floors / string
• 3 PMTs / floor

Buoy

Storey

14.5 m

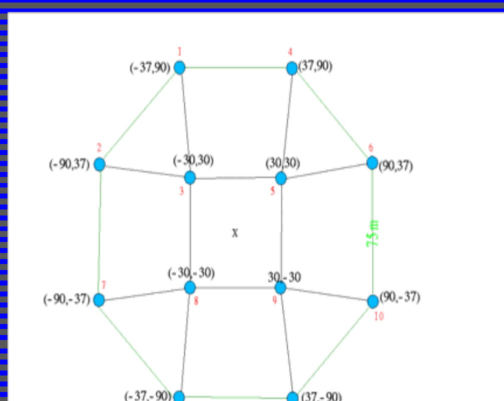


It receives power from shore station and distributes it to the lines. Data and control signals are also transmitted via the JB.

…ction Box

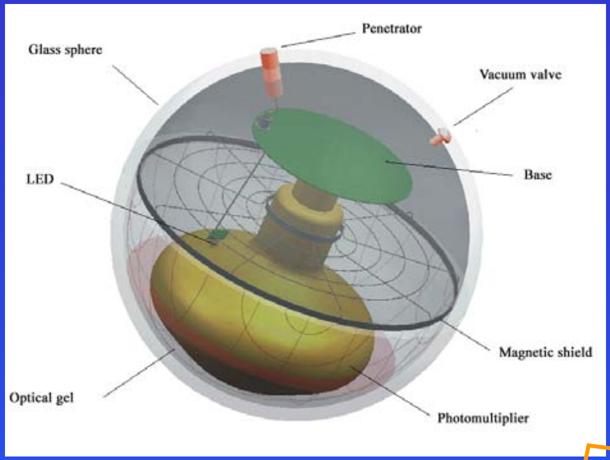
100 m

40 km to shore



Horizontal layout

Some ANTARES components



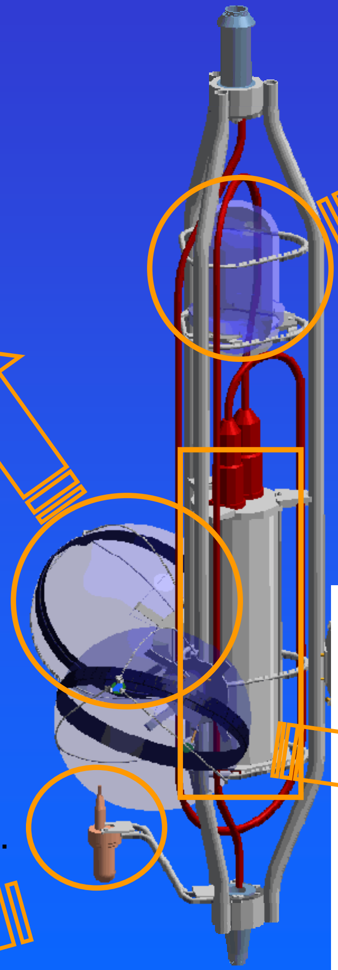
The ANTARES 10'' PMT is housed in the **Optical Module.**

A glass sphere protects it from high pressures.

A μ-metal cage shields against the Earth magnetic field.

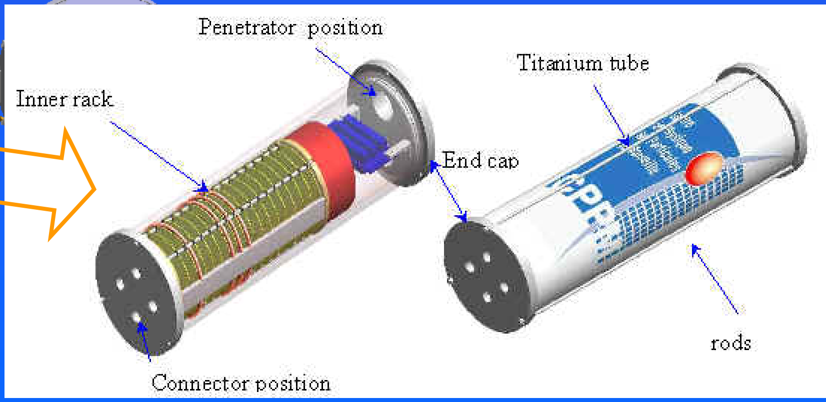
The **Hydrophone (Rx)** for positioning.

The Storey



The **LED Beacon** for time calibration purposes.

The **Local Control Module** houses, in a titanium frame, the electronic cards devised for the readout of the three OMs .

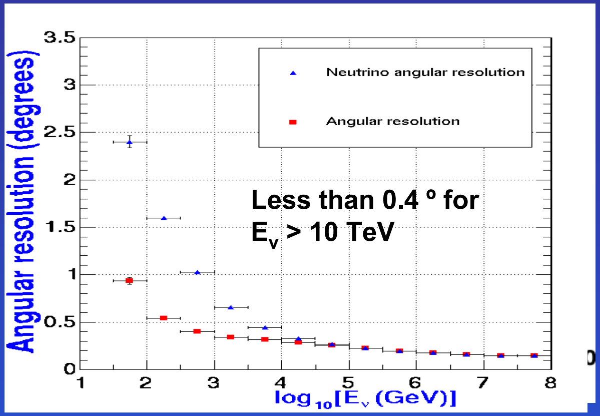


Site evaluation results

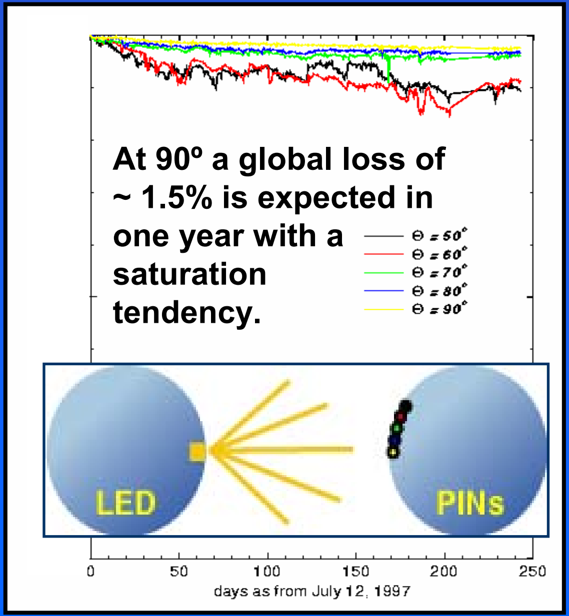
- Water properties.

	blue (470 nm)	UV (370 nm)
λ_{abs}	60 ± 8 m	26 ± 2 m
$\lambda_{sct(eff)}$	265 ± 30 m	120 ± 4 m

$$\lambda_{scat(eff)} = \frac{\lambda_{scat}}{1 - \langle \cos\theta \rangle}$$



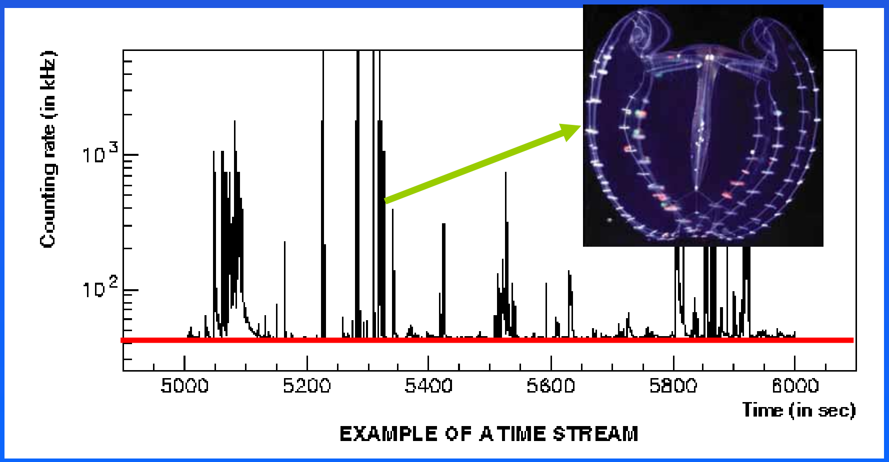
- Biofouling.



- Optical background.

Continuous component due to ^{40}K decay (salt) and bacteria colonies.

Burst (20% over baseline) due to bioluminiscense abyssal creatures.

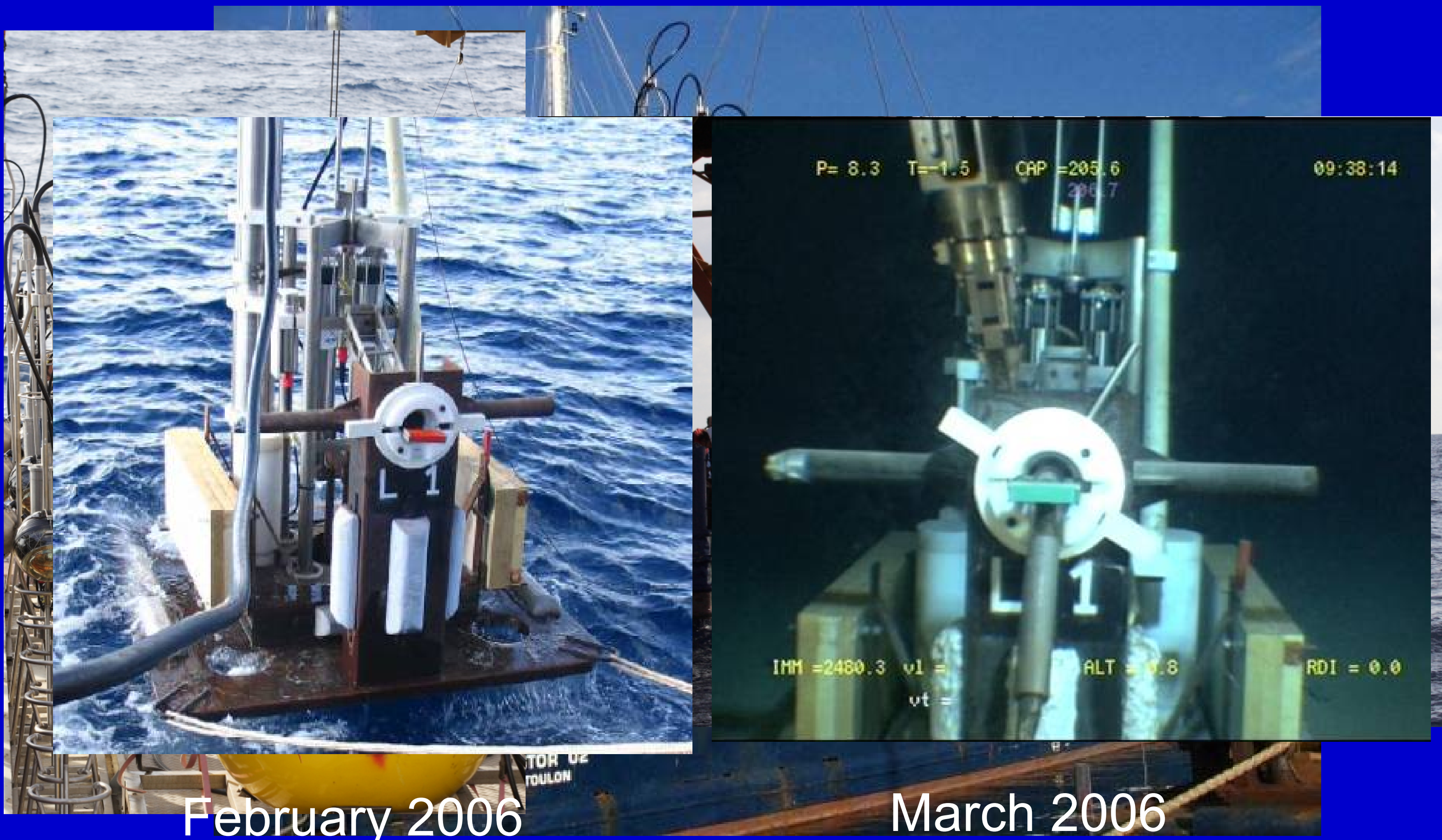


ANTARES status

- Presently taking data from two lines in the water.
  - Full Line 1 and Mini-Instrumentation Line
  - + Junction Box, Electro-optical cable, Shore Station, DAQ, Slow Control, calibration systems…

Line anchor

Line 1 deployment

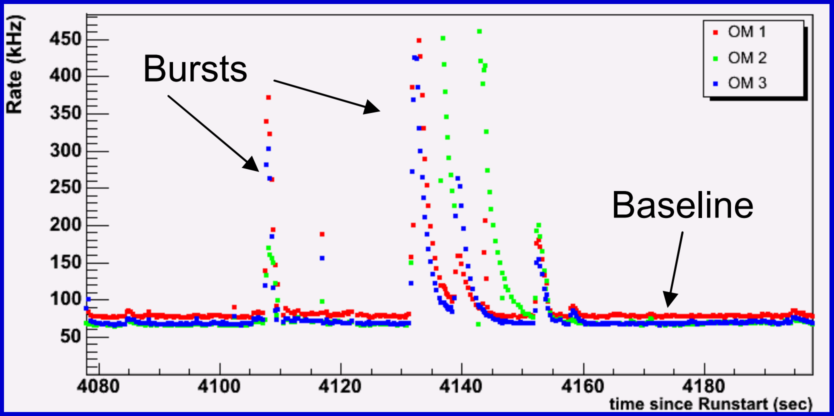


February 2006

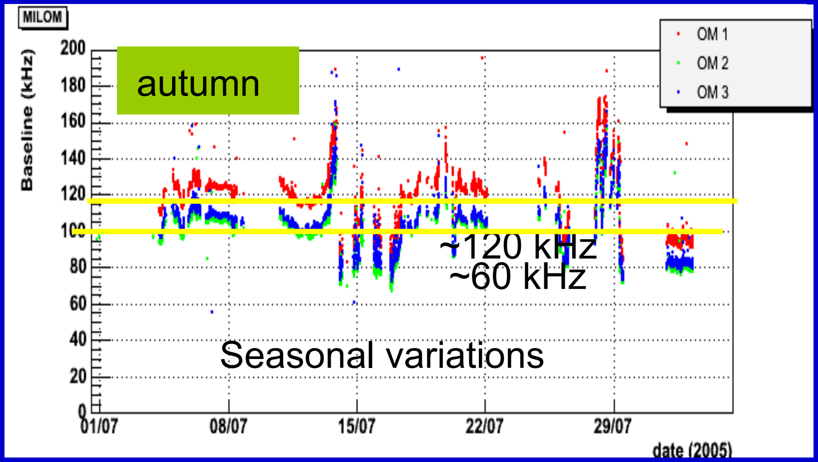
March 2006

Data from ~2500 m below sea level

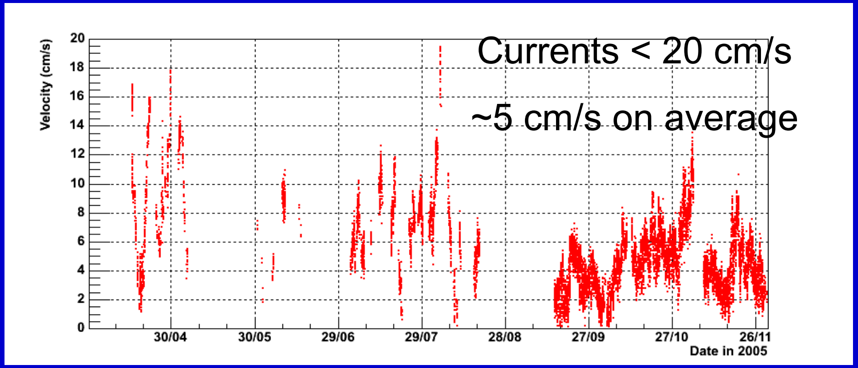
- Site properties:



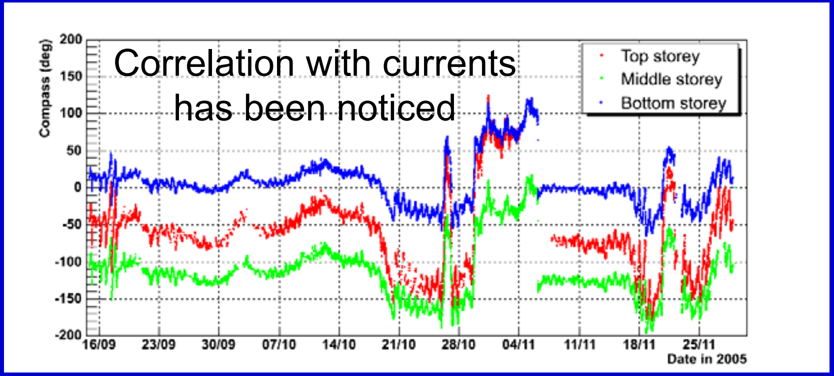
Example of data taking rate



Baseline evolution with time



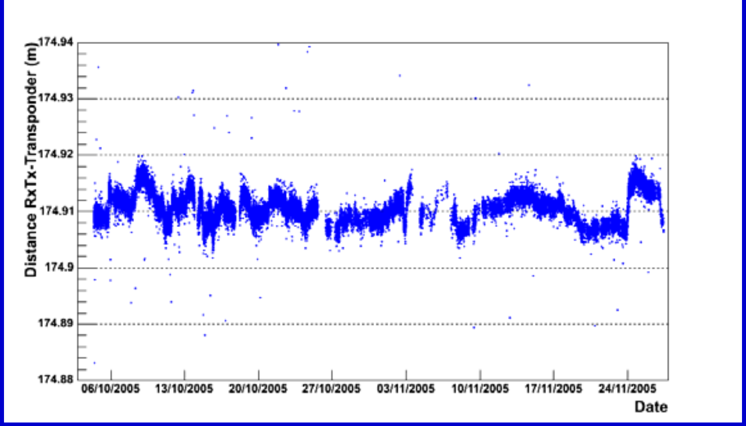
Water current velocity
evolution with time



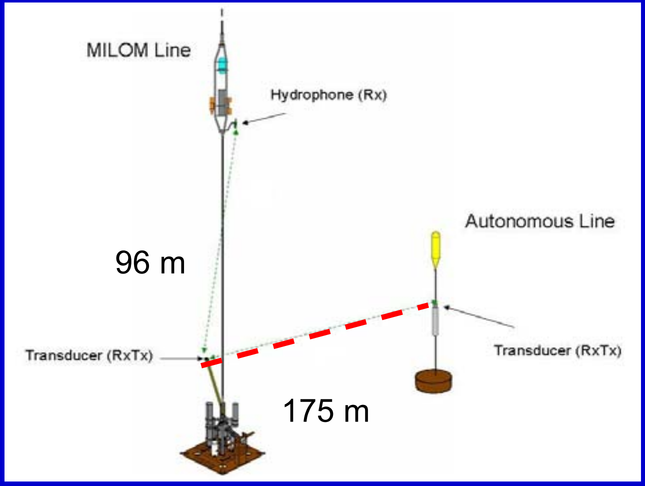
Heading of the three MILOM storeys

Data from ~2500 m below sea level

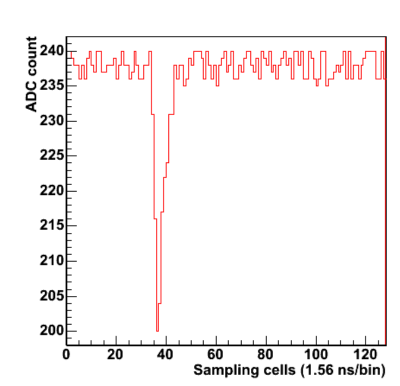
- Spatial Calibration:



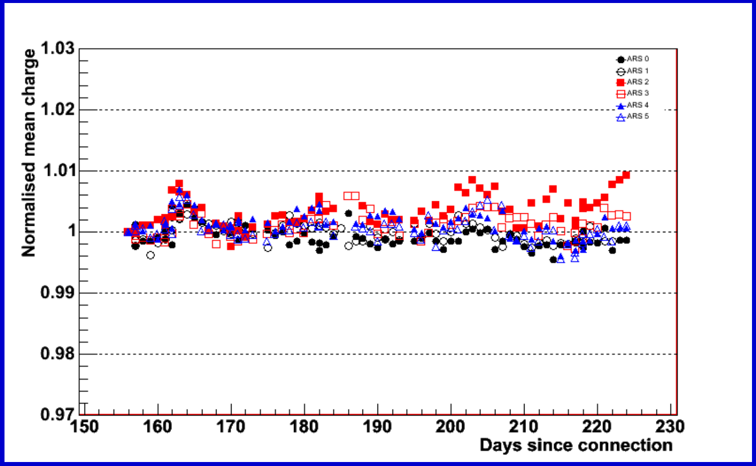
Distance from autonomous line (RxTx) to MILOM RxTx, evolution with time.



- Charge Calibration:



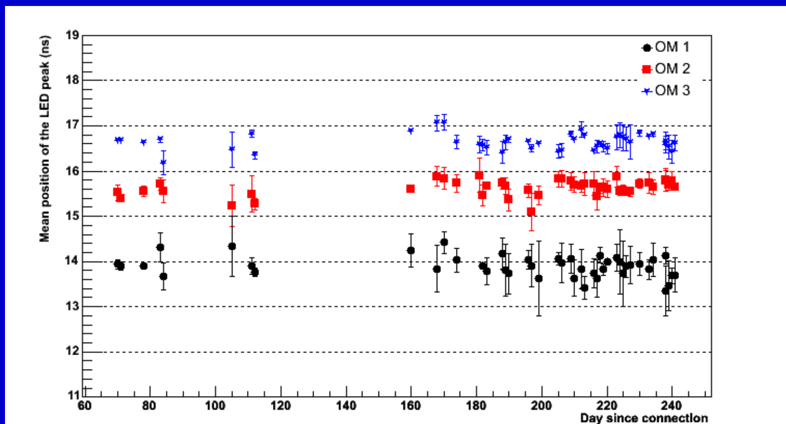
WF signal example.



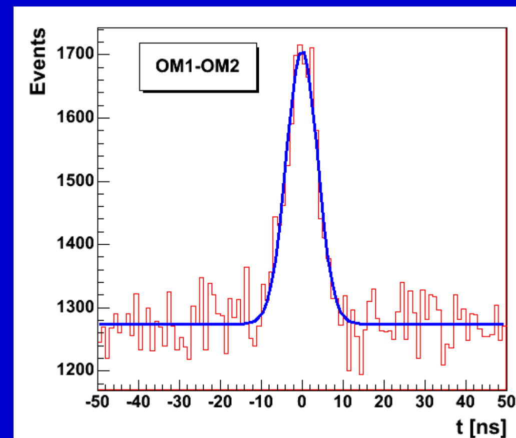
Evolution with time of the normalized charge.

Data from ~2500 m below sea level

- Time Calibration:

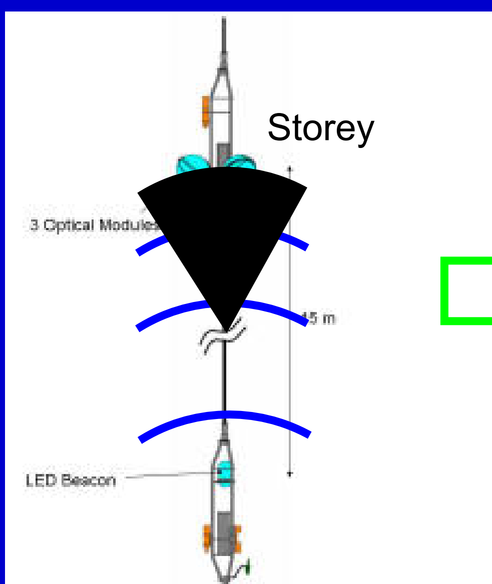


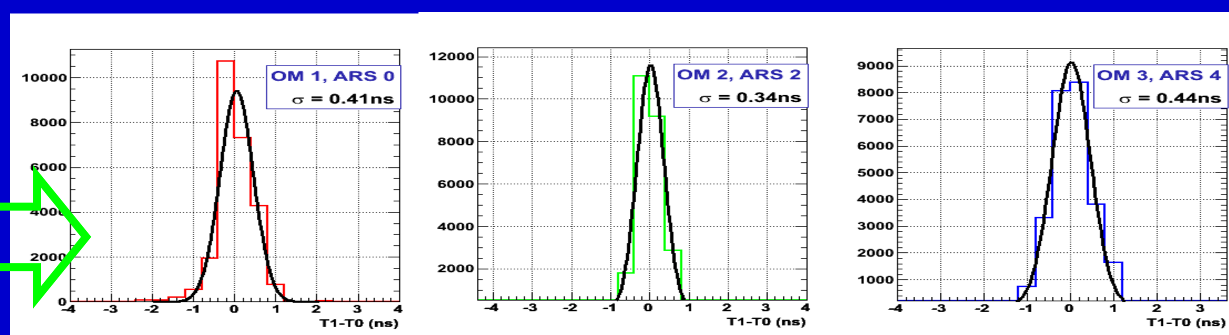
Internal LED Δt evolution with time



The rate measured of these coincidences is ~13 Hz (in agreement with the estimations).

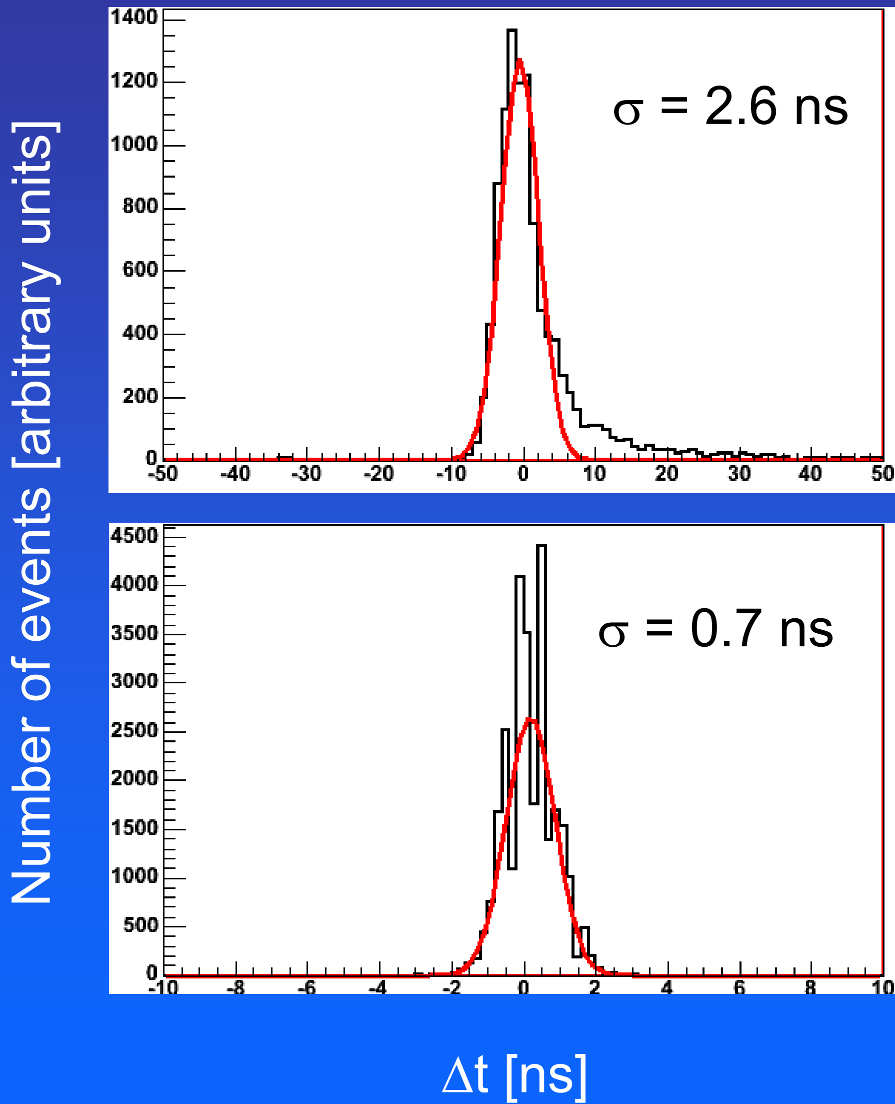
^{40}K coincidences between OMs.

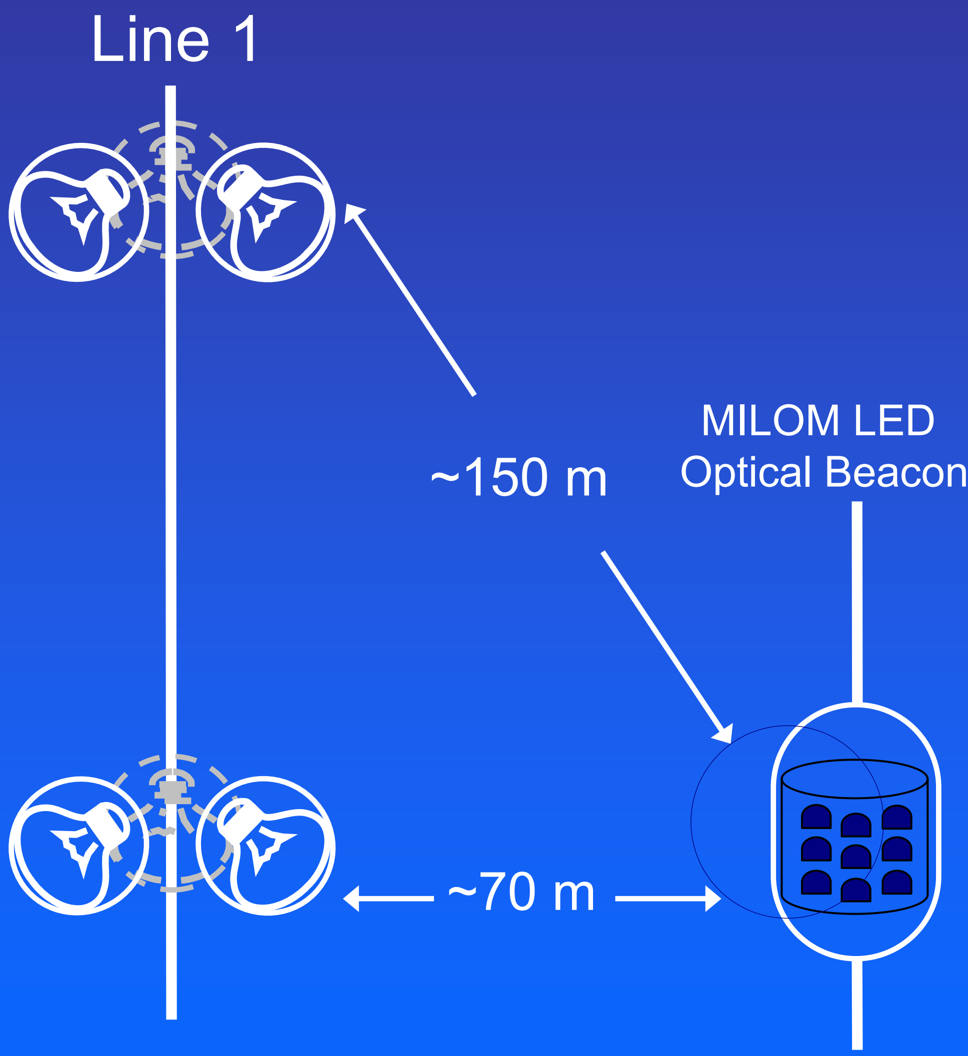




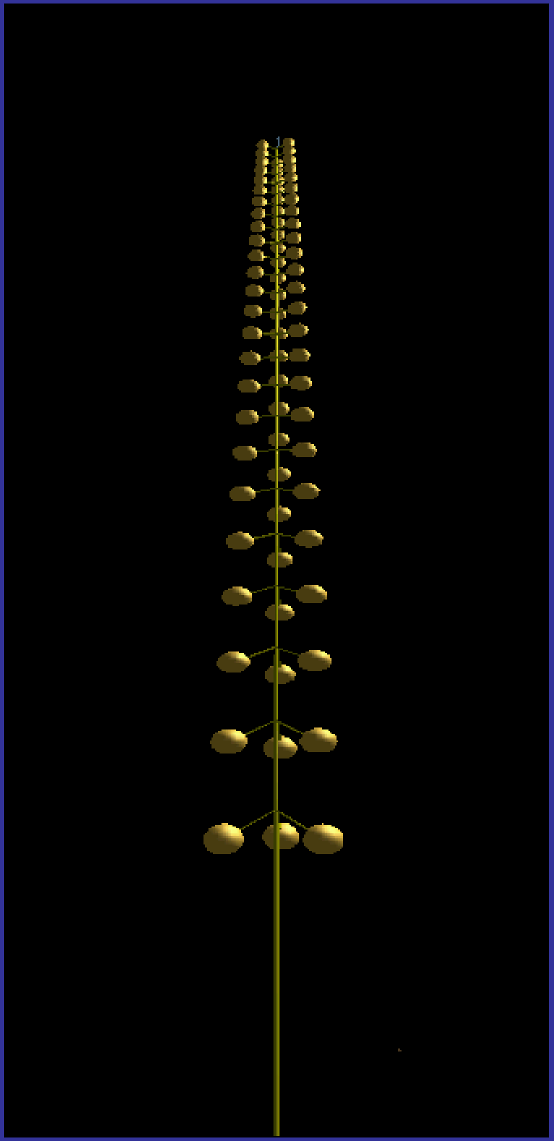
OM signal – beacon PMT time difference for each OM.

Line 1 calibration

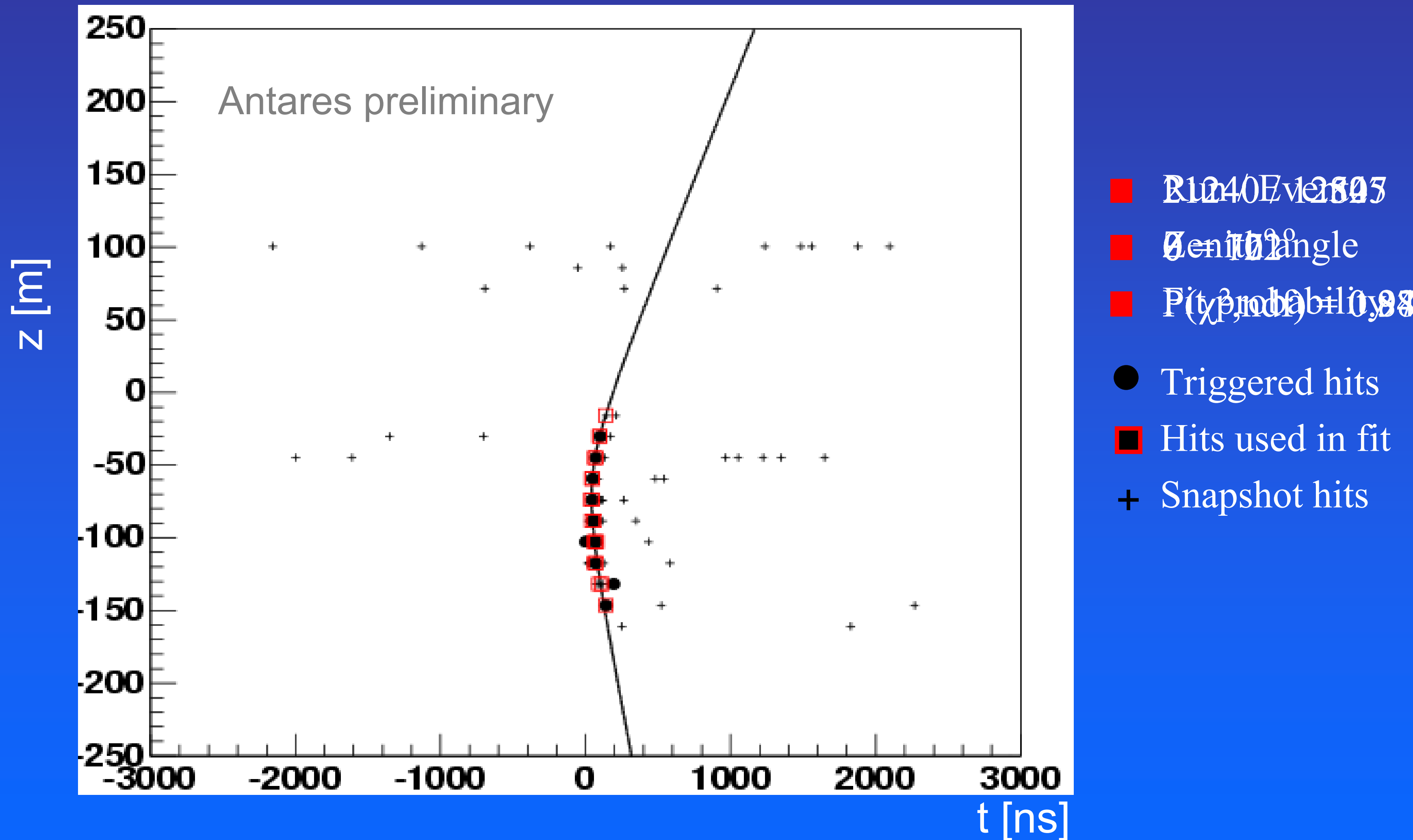




First (downgoing) muons detected



First muons reconstructed with Line 1



Conclusions

- The recent past of neutrino astrophysics is extremely bright (ν oscillations, confirmation of solar model, direct detection of supernova collapse)
- High energy Neutrino Telescopes are presently operating. The technique is proven and the limits obtained are meaningful
- New, bigger and more sensitive telescopes will soon operate
- Other detection techniques (radio, acoustic) might sizeably increase our sensitivity

Surprises might be round the corner…

“Copyleft” (credits)

I borrowed slides from:

- P. Desiati
- AMANDA/IceCube collaboration
- J.D. Zornoza
- U. Katz (and through him from Nestor and Nemo)
- F. Salesa
- J.A. Aguilar
- myself (I even copied myself)

END OF TALK

HYPERLINKS

AMANDA diffuse flux limits

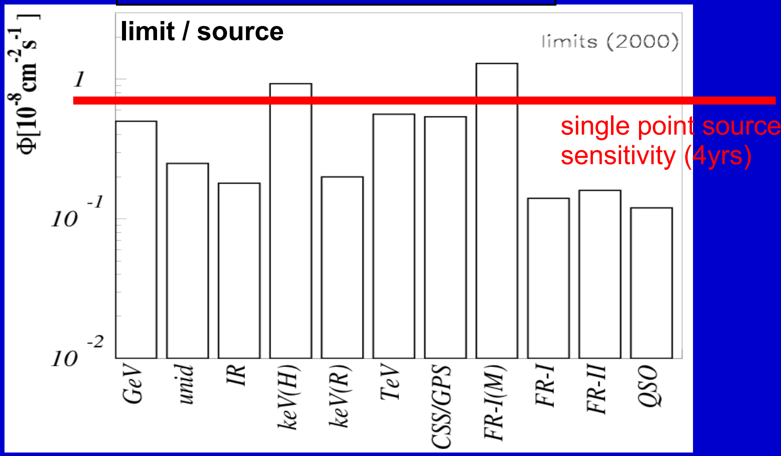
Data set	**# of days**	**Channel**	**Limit/Sensitivity** ΦE^2 ($GeV\ cm^{-2}\ s^{-1}\ sr^{-1}$)	**Energy range**	**assumptions**	**Comments**
					$\nu_e:\nu_\mu:\nu_\tau=1:1:1$	
AMANDA II 2000 Unfolding	197		2.6 x 10-7	100 TeV < E < 300 TeV	ditto	
AMANDA II	807	Upward going muons	9.5 x 10-8	13 TeV < E < 3.2 PeV	ditto	
AMANDA II 2000	174	Cascades	8.6 x 10-7	50 TeV < E < 5 PeV		All 3 flavours
AMANDA B10 1997		UHE	9.9 x 10-7	1 PeV < E < 3 EeV		
AMANDA II 2000	174	UHE	3.8 x 10-7	0.2 PeV < E < 2 EeV		All 3 flavours Sensitivity

ν telescope : unresolved sources ?

From P. Desiati
PANIC 05

neutrinos from single steady sources may be as many as background

stacking source analysis (2000)



time-correlation with transient phenomena (2000-03)
known active flary periods of TeV gamma sources

if neutrinos in coincidence with gamma emission

Source	EM light curve source	Livetime @ high activity	#events in high state	Expected backgr. in high state
Markarian 421	ASM/RXTE	141 days	0	1.63
1ES1959+650	ASM/RXTE	283 days	2	1.59
Cygnus X-3	Ryle Telesc.	114 days	2	1.37

time-rolling search over 2000-03 period
optimized angular search bin : 2.25°-3.75°

Source	#events (4 years)	Expected backgr. (4 years)	Period duration	#doublets	Chance probability
Markarian 421	6	5.58	40 d	0	1
1ES1959+650	5	3.71	40 d	1	0.34
3EG J1227+4302	6	4.37	40 d	1	0.43
QSO 0235+164	6	5.04	40 d	1	0.52
Cygnus X-3	6	5.04	20 d	0	1
GRS 1915+105	6	4.76	20 d	1	0.32
GRO J0422+32	5	5.12	20 d	0	1

search neutrinos in time-space coincidence with GRB

- ν_μ and all-flavor searches with Waxman-Bahcall spectrum
- all-flavor rolling-time search with WB spectrum 1 and 100 s time windows
- GRB030329 case with specific spectrum based on observed electromagnetic parameters (Band fit, red shift): `astro-ph/0510336`
- SGR 1806-20 (Dec 27th 2004): `astro-ph/0503348` muons from gamma interaction in atmosphere

no signal detected therefore limits assigned

From J.D. Zornoza
CRIS 06

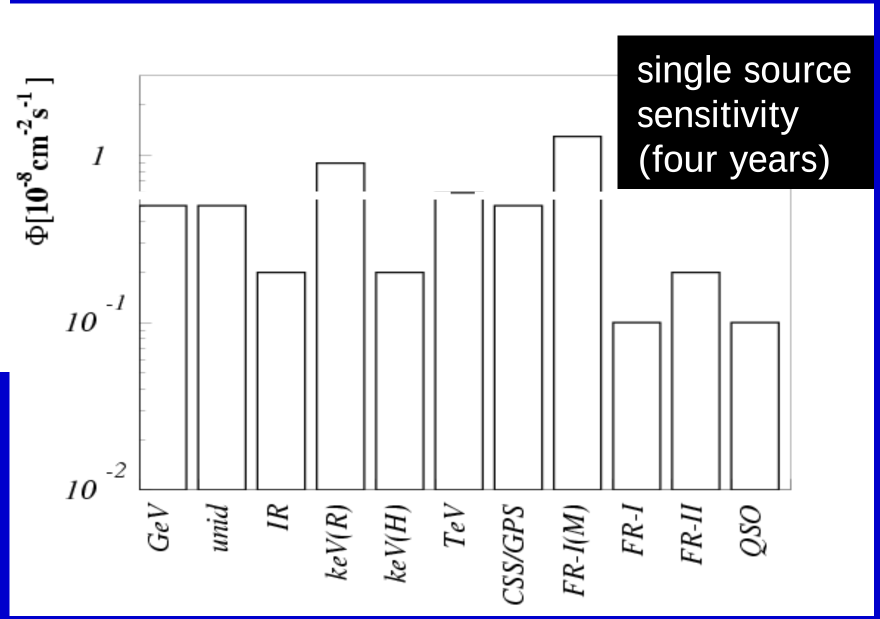
AGNs: Stacking source analysis

sample	N_{src}	N_ν^{obs}	N_ν^{bg}	n_{lim}	f_{lim}	f_{lim}/N_{src}
IR blazars	11	7	10.17	3.0	2.0	0.18
keV blazars (ROSAT)	8	4	6.68	2.4	1.6	0.2
keV blazars (HEAO-A)	3	2	2.47	3.5	2.8	0.9
GeV blazars	8	6	5.3	6.3	4.0	0.5
unid. GeV sources	22	15	14.9	7.6	5.6	0.25
TEV blazars	5	4	4.53	4.1	2.8	0.56
GPS and CSS	8	7	6.14	6.4	4.3	0.54
FR-I galaxies	1	0	0.56	1.9	1.3	1.3
FR-I without M87	20	9	11.50	3.9	2.7	0.14
FR-II galaxies	17	10	13.42	3.7	2.7	0.16
radio-weak quasars	11	4	7.55	1.9	1.3	0.12

preliminary

Table 3
Results for the year 2000 data: Number of sources N_{src}, measured number of events N_ν^{obs}, the corresponding background N_ν^{bg} and the 90% C.L. limits on the event counts (n_{lim}) and on the integral flux for an E^{-2} spectrum above 10 GeV (f_{lim}) in units of $10^{-8}\text{cm}^{-2}\ \text{s}^{-1}$. f_{lim}/N_{src} represents the limit per source.

- ❑ Neutrino astronomy could be the key for establishing the hadronic/leptonic origin of the HE photons from AGNs.
- ❑ Stacking-source analysis: The flux from AGNs of the same type integrated to enhance the statistics.



- ❑ No significant excess has been found.
- ❑ The stacking approach improves the one source limit by a factor three, typically.

From J.D. Zornoza
CRIS 06

Transient sources

- When the variable character of the source is evident, but the EM observations are limited, we can use the sliding-window technique.
- For the time-rolling source search, events in a sliding time window are searched:
  - Galactic: 20 days
  - Extragalactic: 40 days

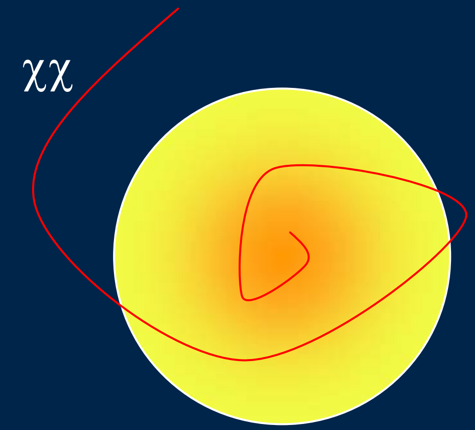
	Source	#events (4 years)	Expected background (4 years)	Period duration
Extragalactic	Markarian 421	6	5.58	40 d
	1ES1959+650	5	3.71	40 d
	3EG J1227+4302	6	4.37	40 d
	QSO 0235+164	6	5.04	40 d
Galactic	Cygnus X-3	6	5.04	20 d
	GRS 1915+105	6	4.76	20 d
	GRO J0422+32	5	5.12	20 d

sources: TeV blazars, microquasars and variable sources from EGRET

From J.D. Zornoza
DMDE06

Detection in the Sun / Earth

- Neutralinos would scatter elastically in the Sun or Earth and become gravitationally trapped.
- Neutralinos would annihilate producing standard model particles.
- Among the annihilation products, only neutrinos can reach us.

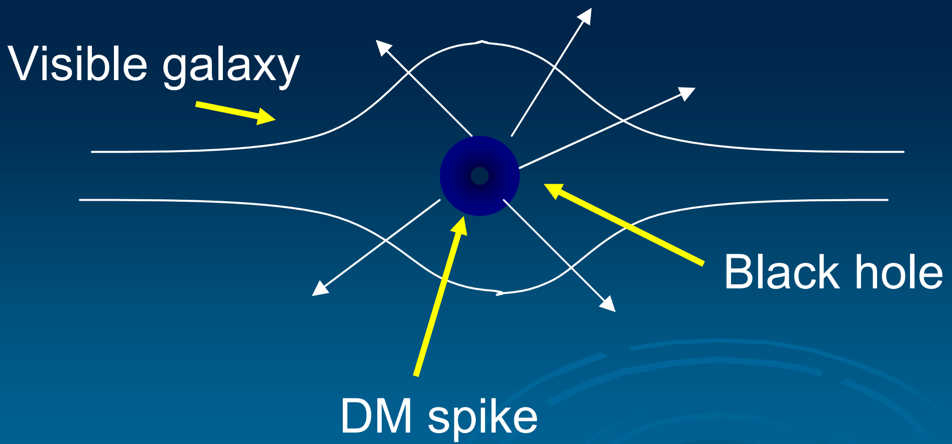


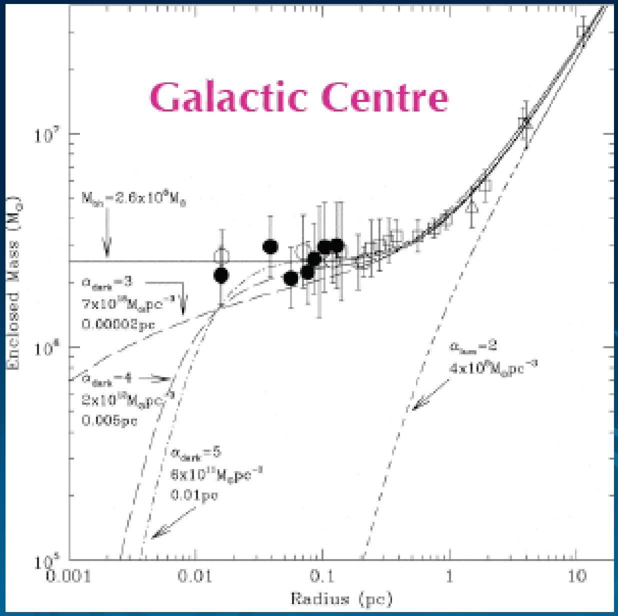
$$\Gamma_{ann} = \frac{\sigma_{ann} v \rho^2}{m^2}$$

Γ_{ann}: annihilation rate per unit of volume
σ_{ann}: neutralino-neutralino cross-section
v: relative speed of the annihilating particles
ρ: neutralino mass density
m: neutralino mass

Galactic Center

- Neutralinos could also concentrate in the Galactic Center.
- The super-massive black hole there would enhance the neutralino density
- If there is such a spike of dark matter, a signal of neutrinos, gamma rays and radio waves could be detected.





Matter profile in the GC

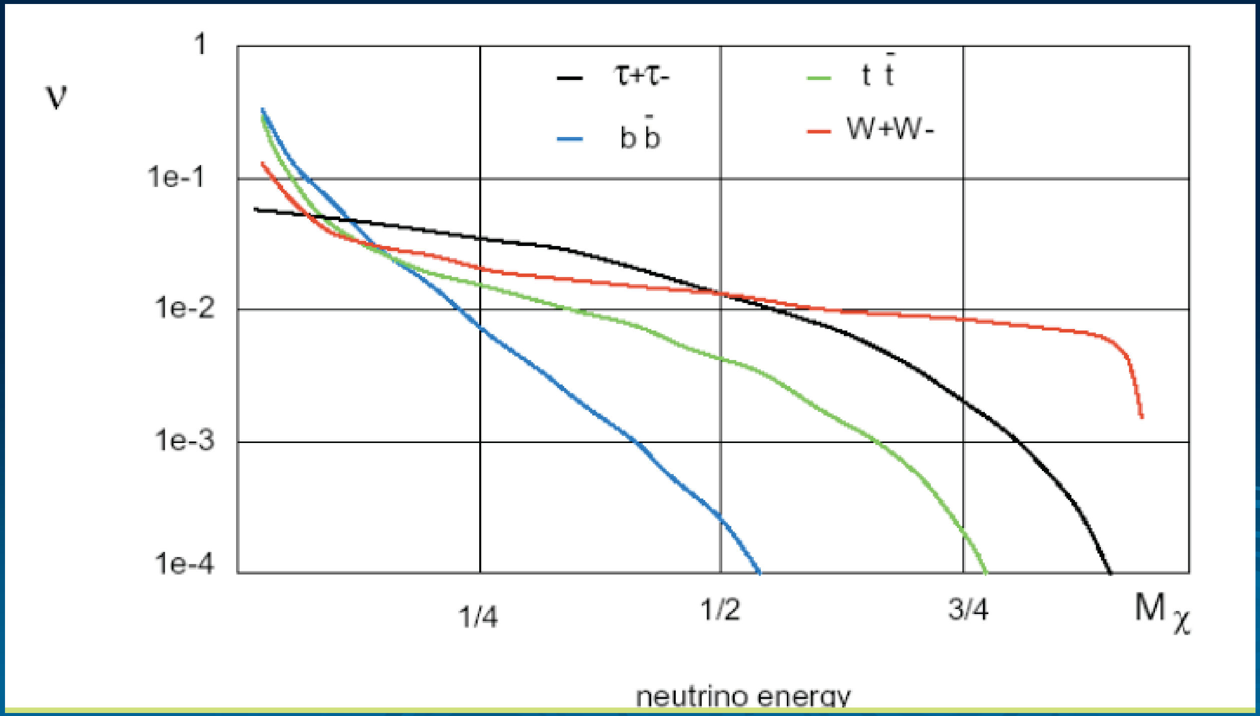
Annihilation process

- All three flavors are produced in the neutralino annihilation
- Direct production suppressed (Majorana particle) but they are also produced as secondaries.
- Neutralino decay in pair-wise mode:

$$\chi\chi \to l^+l^-,\ W^+W^-,\ Z^0Z^0,\ H^0_{1,2}H^0_3,\ Z^0H^0_{1,2},\ W^\pm H^\mp$$

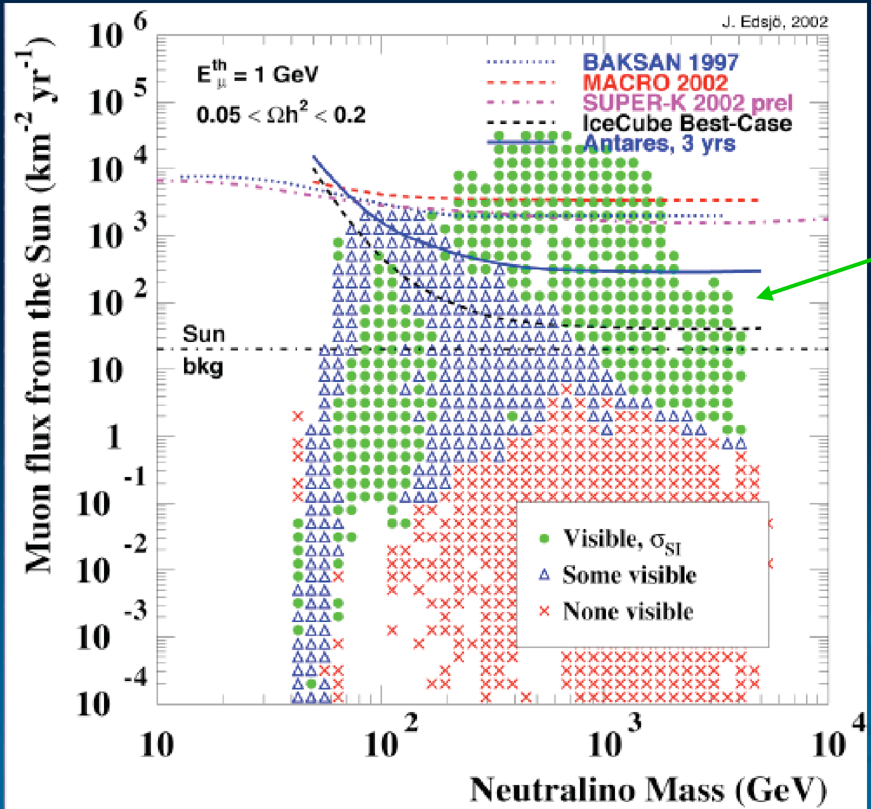
Energy spectrum

- Production by secondaries: continuum energy spectrum.
- Typically, neutrinos get ~1/10 of the neutralino mass → E_ν ~ GeV – TeV



Neutralinos from the Sun

- The Sun is the most promising source of neutralinos.
- Being at intermediate latitudes, ANTARES will have a good visibility of the Sun (from the South Pole, it never gets very high in the horizon)



excluded
by Edelweiss

Neutralinos from the Earth

Lundberg and Edsjo, 2003

Gaussian approximation

Diffusion in the Solar System

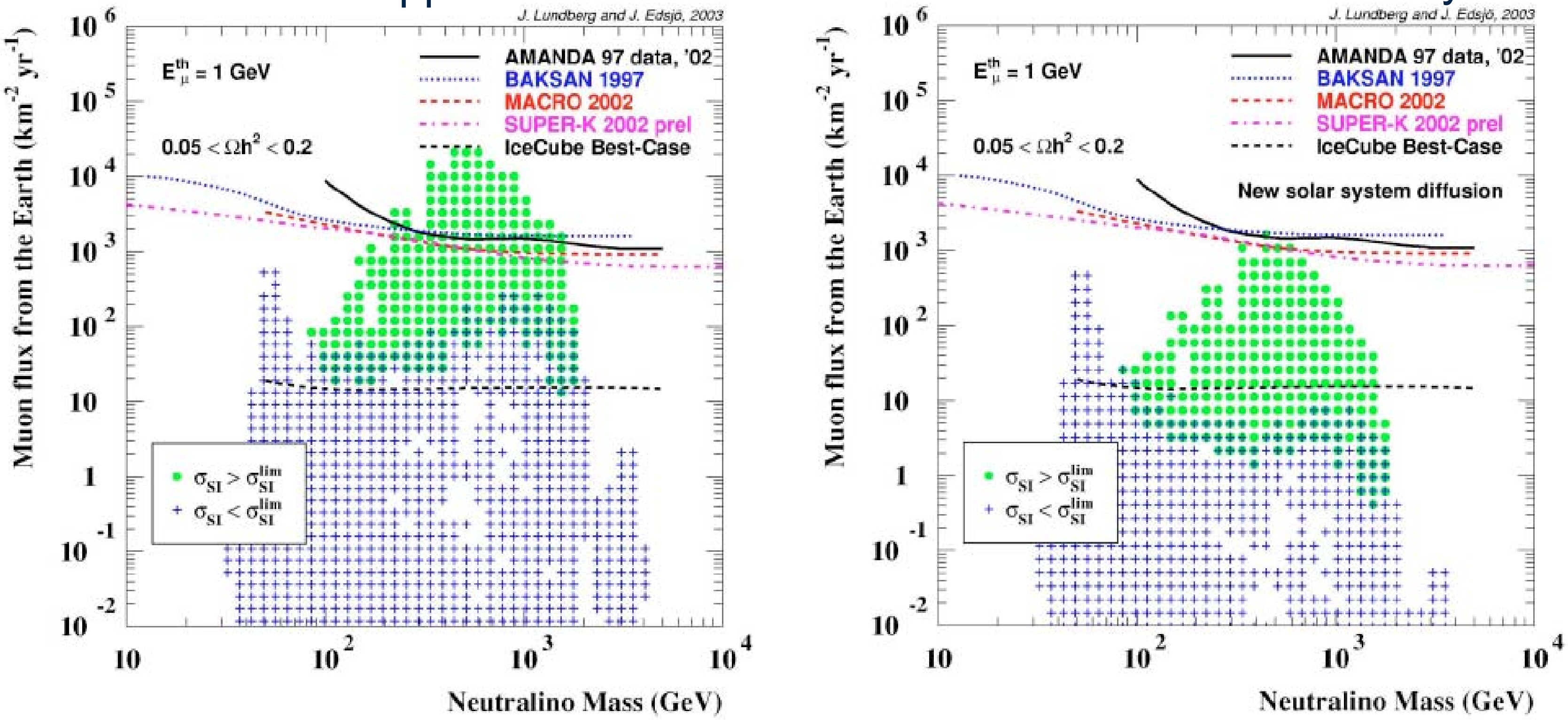
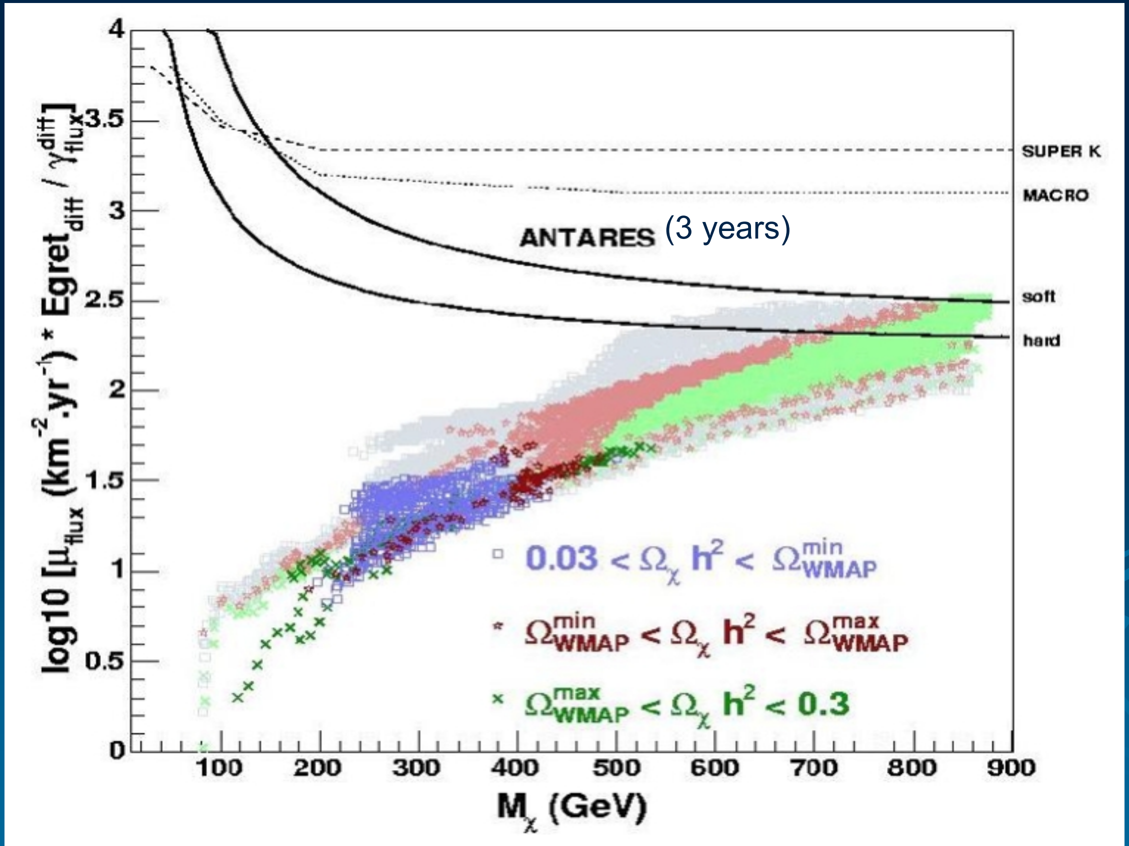


FIG. 16. (Color online). In the left panel we show the neutrino-induced muon fluxes in the standard Gaussian approximation, whereas in the right panel we show the fluxes based on our new estimate of the WIMP diffusion in the solar system. We also show the current limits of a few neutrino telescopes and an optimistic estimate for the future IceCube sensitivity. The current direct detection limit by the Edelweiss experiment [25] is also shown. Models that are excluded by Edelweiss are indicated by green circles, whereas models that are not excluded are indicated with blue crosses.

Neutralinos from the Galactic Center

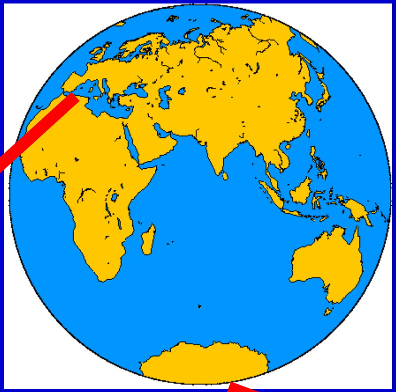
- ANTARES will be the neutrino telescope with better visibility of the Galactic Center.
- The rates to detect depend critically on the DM profile, which is still under debate.

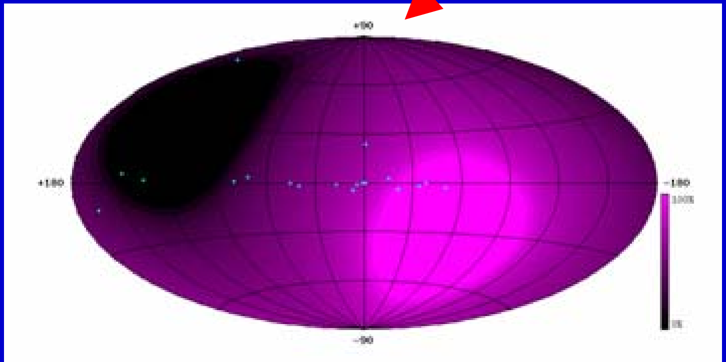


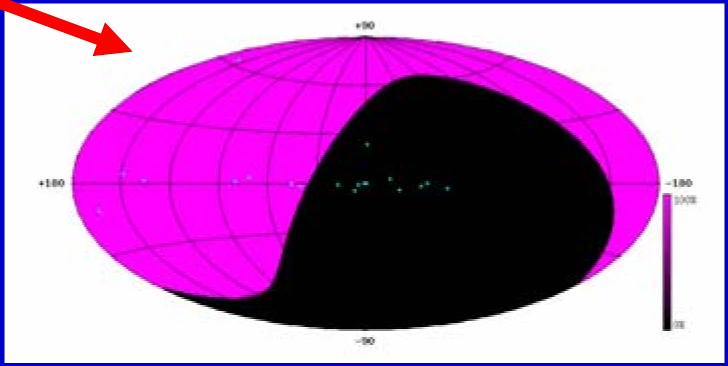
hep-ph/0404175

Complementary experiments

Sky View







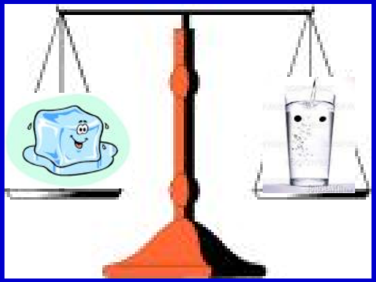
ANTARES
43° North
2/3 of time: Galactic Centre

AMANDA
South Pole

0.5 π sr instantaneous common view
1.5 π sr common view per day

Ice vs. Sea

- Very large volumes of medium transparent to Cherenkov light are needed:
  - Ocean, lakes…
  - Antarctic ice
- Advantages of oceans:
  - Larger scattering length → better angular resolution
  - Weaker depth-dependence of optical parameters
  - Possibility of recovery
  - Changeable detector geometry
- Advantages of ice:
  - Larger absorption length
  - No bioluminescence, no ^{40}K background, no biofouling
  - Easier deployment
  - Lower risk of point-failure
- Anyway, a detector in the Northern Hemisphere in necessary for complete sky coverage (Galactic Center!), and it is only feasible in the ocean.



Comparison of Optical Parameters

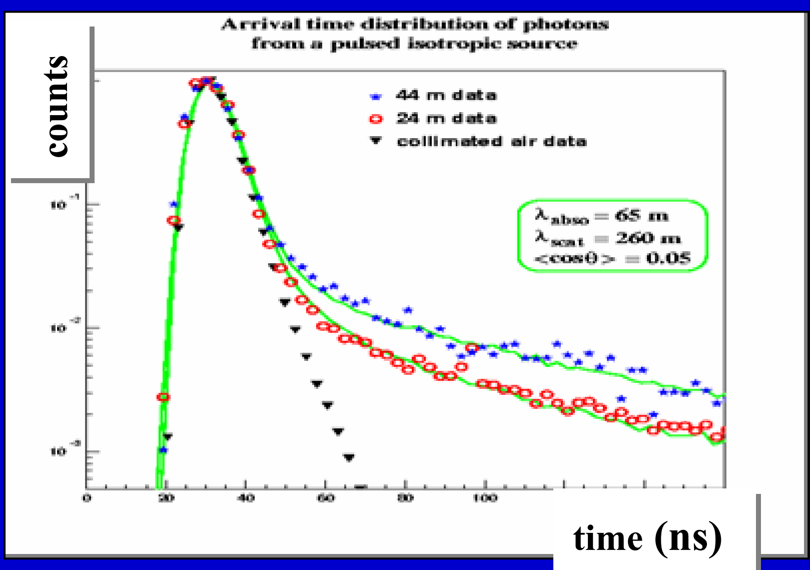
water transparency: $\lambda_{abs} \sim 60 \pm 8$ m (470 nm)
$\lambda_{abs} \sim 26 \pm 2$ m (370 nm)

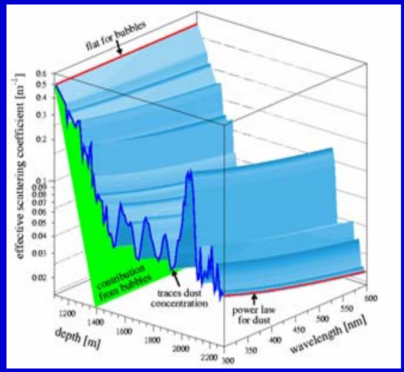
light scattering : $\lambda_{eff} \sim 300$ m (470 nm)
$\lambda_{eff} \sim 100$ m (370 nm)

$$\lambda_{eff} = \frac{\lambda_{sc}}{1 - \langle \cos\theta \rangle}$$

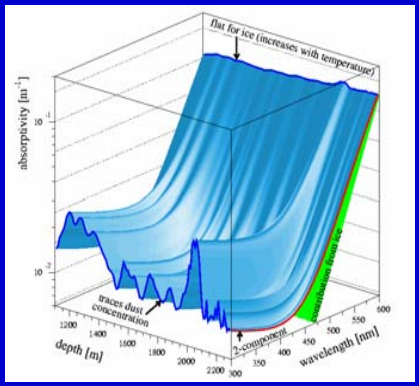
Average optical ice parameters:

$\lambda_{abs} \sim 110$ m @ 400 nm
$\lambda_{sca} \sim 20$ m @ 400 nm





Scattering



Absorption

Complementarity