Neutrino Telescopes

An experimental overview

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The Dark Side of the Universe
June 20–24, 2006, U.A.M., Madrid
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 are 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 sensitive enough 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, $\nu$-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’mon, 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?

Number of celestial bodies observed

Number of Nobel prizes awarded

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

(The Sun, SN1987A)
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
- AMANDA B-10
- AMANDA II
- IceCube

Atmospheric showers
- Baikal
- ANTARES
- NEMO
- NESTOR
- KM3NeT

Radio emission
- Auger
- Hi-res
- Fly’s eye
- EUSO
- OWL

Acoustic detection
- RICE
- GLUE
- SaLSA
- CODALEMA
- ANITA
- FORTE
- 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

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

Limitation at high energies:
Fast decreasing fluxes $E^{-2}$, $E^{-3}$

Detector size

Detector density

Supernovae
Oscillations
Dark matter (neutralinos)
Astrophysical neutrinos
Topological Defects

Energy scales:
- MeV
- GeV
- TeV
- PeV
- EeV
Production Mechanism

- Neutrinos are expected to be produced in the interaction of high energy nucleons with matter or radiation:
  \[ N + X \rightarrow \pi^\pm (K^\pm ...)+Y \rightarrow \mu^\pm + \nu_\mu (\bar{\nu}_\mu) + Y \]

- Moreover, gamma production is also associated in this scenario:
  \[ N + X \rightarrow \pi^0 + Y \rightarrow \gamma \gamma + Y \]
Cosmic Ray spectrum

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

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

SNR origin

Galactic origin (several theories)

1 particle per m²

1 particle per m² per year.

1 particle per km² per year.

AGN, top-down models?
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

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E\(^2\) dΦ/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\(^2\) dΦ/dE < 4.5 × 10\(^{-8}\) GeV cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\)
  - **MPR**: E\(^2\) dΦ/dE < 2 × 10\(^{-6}\) – 4.5 × 10\(^{-8}\) GeV cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\)

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

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 km$^3$ detector ντ identification will be possible. A very wide energy range can be covered looking in different directions.

1.2 TeV muon traversing the detector.

- 1 km at 300 GeV
- 25 km at 1 PeV
- 5-10 m long diameter ~10 cm

track cascade
PhD students are so brave!
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 < $E_{\nu}$ < PeV:
- Directionality + energy-related variables to reject atm $\mu$ background
- Confined to up-going tracks
- High-quality tracks

**UHE:** $E_{\nu}$ > PeV:
- Earth opaque. Search in the upper hemisphere and close to the horizon
- Bright events: many hit OMs with several hits/OM

**Cascades:** TeV < $E_{\nu}$ < PeV
- $4\pi$ search
- Background: brehmm. from down-going muons

Arrival time
Amplitude
Diffuse Flux Limits

1: B10, 97, ↑μ
3: A-II, 2000, cascade
4: B10, 97, UHE
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 vs detected from Northern Hemisphere
3438 atmospheric vs expected

The largest fluctuation (3.4σ) is compatible with atmospheric background
Specific point-like source searches

- Some other specific searches are being made or will be made:
  - Stacking sources: Combine source types. Preliminary: no excess found.
  - Transient sources (multi-wavelength observations in X-rays and gamma-rays of TeV blazars, microquasars, and variable sources from EGRET).
  - GRBs follow-up.

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

- A posteriori search: undefined probability of random coincidence.

Source: 1ES 1959+650 \( n_{\text{max}} (40 \text{d}) = 2 \), \( n_{\text{av}} (4 \text{y}) = 5 \), \( n_{\text{bp}} (4 \text{y}) = 3.71 \)
Neutralino Search

From the Sun

- 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)

From the Earth

- The Sun is the most promising source of neutralinos.
- Neutralino density in the Earth is diminished the effect of the Sun mass.

More Info?
IceCube

IceTop

air shower array

IceCube:
- 80 strings with 60 optical modules
- 17 m between optical modules
- 125 m between strings
- 1 km

Presently installed:

IceTop:
- 4 + 12 stations
- 16+48 optical modules

IceCube:
- 1 + 8 strings
- 60+480 optical modules

AMANDA:
- 19 strings, 677 optical modules in total
- ø 200 m, height 500 m
Drilling time

AMANDA’s string 19

ICECUBE

2450 m
Neutrino Telescopes in the World

ANTARES + NEMO + NESTOR → KM3NeT

DUMAND
ANTARES
NESTOR
NEMO
Lake Baikal

AMANDA
South Pole
IceCube

km³ projects
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) with 12 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 km$^3$: 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

Test site at 2000 m depth operational. Funding ok. Completion expected by 2006.

Shore station 2.5 km e.o. Cable with double steel shield 21 km e.o. Cable with single steel shield. 5 km e.o. cable.

Geoseismic station SN-1 (INGV). 5 km e.o. cable.

¾ 10 optical fibres standard ITU-T G-652 ¾ 6 electrical conductors Φ 4 mm².

NEMO Phase I
The ANTARES detector

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

~60-75 m

Junction Box

Horizontal layout

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

Buoy

Storey

100 m

40 km to shore
Some ANITA components

The ANITA 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 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. The Hydrophone (Rx) for positioning.
Site evaluation results

- **Water properties.**

<table>
<thead>
<tr>
<th></th>
<th>blue (470 nm)</th>
<th>UV (370 nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_{\text{abs}}$</td>
<td>$60 \pm 8$ m</td>
<td>$26 \pm 2$ m</td>
</tr>
</tbody>
</table>
| $\lambda_{\text{scat(eff)}}$ | $265 \pm 30$ m | $120 \pm 4$ m |}

- **Biofouling.**

  At 90° a global loss of ~1.5% is expected in one year with a saturation tendency.

- **Optical background.**

  Continuous component due to $^{40}$K decay (salt) and bacteria colonies. Burst (20% over baseline) due to bioluminescence abyssal creatures.
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 1 deployment

February 2006

March 2006
Data from ~2500 m below sea level

- Site properties:

  - Example of data taking rate
  - Baseline evolution with time

  - Baseline
  - Bursts

  - Currents < 20 cm/s
    ~5 cm/s on average

  - Water current velocity evolution with time

  - Seasonal variations
    ~60 kHz
    ~120 kHz

  - Correlation with currents has been noticed

  - 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.](image1)

- Charge Calibration:

  ![WF signal example.](image2)

  ![Evolution with time of the normalized charge.](image3)
Data from ~2500 m below sea level

Time Calibration:

- Internal LED $\Delta t$ evolution with time
- $^{40}$K coincidences between OMs.

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

OM signal – beacon PMT time difference for each OM.
Line 1 calibration

\[ \sigma = 2.6 \text{ ns} \]

\[ \sigma = 0.7 \text{ ns} \]

Number of events [arbitrary units]

$\Delta t$ [ns]
First (downgoing) muons detected
First muons reconstructed with Line 1

<table>
<thead>
<tr>
<th>Run / Event</th>
<th>Zenith angle</th>
<th>Fit probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>21240 / 12505</td>
<td>$\theta = 101^\circ$</td>
<td>$P(\chi^2, ndf) = 0.88$</td>
</tr>
<tr>
<td>21240 / 12527</td>
<td>$\theta = 172^\circ$</td>
<td>$P(\chi^2, ndf) = 0.94$</td>
</tr>
<tr>
<td>21240 / 12845</td>
<td>$\theta = 72^\circ$</td>
<td>$P(\chi^2, ndf) = 0.37$</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>Data set</th>
<th># of days</th>
<th>Channel</th>
<th>Limit/Sensitivity $\Phi E^2$ (GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$)</th>
<th>Energy range</th>
<th>assumptions</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMANDA II 2000 Unfolding</td>
<td>197</td>
<td></td>
<td>2.6 x 10-7</td>
<td>100 TeV &lt; E &lt; 300 TeV</td>
<td>$\nu_e \nu_x \nu_\tau = 1:1:1$</td>
<td>ditto</td>
</tr>
<tr>
<td>AMANDA II</td>
<td>807</td>
<td>Upward going muons</td>
<td>9.5 x 10-8</td>
<td>13 TeV &lt; E &lt; 3.2 PeV</td>
<td>ditto</td>
<td></td>
</tr>
<tr>
<td>AMANDA II 2000</td>
<td>174</td>
<td>Cascades</td>
<td>8.6 x 10-7</td>
<td>50 TeV &lt; E &lt; 5 PeV</td>
<td>All 3 flavours</td>
<td></td>
</tr>
<tr>
<td>AMANDA B10 1997</td>
<td></td>
<td>UHE</td>
<td>9.9 x 10-7</td>
<td>1 PeV &lt; E &lt; 3 EeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AMANDA II 2000</td>
<td>174</td>
<td>UHE</td>
<td>3.8 x 10-7</td>
<td>0.2 PeV &lt; E &lt; 2 EeV</td>
<td>All 3 flavours</td>
<td>Sensitivity</td>
</tr>
</tbody>
</table>
**ν telescope : unresolved sources?**

From P. Desiati
PANIC 05

Neutrinos from single steady sources may be as many as background.

- **Stacking source analysis (2000)**
  - Limit / source
    - \( \varphi \) \( [10^{-3} \text{ cm}^{-2} \text{s}^{-1}] \)
  - Single point source sensitivity (4 yrs)

- **Time-correlation with transient phenomena (2000-03)**
  - Known active flaring periods of TeV gamma sources
  - If neutrinos in coincidence with gamma emission

<table>
<thead>
<tr>
<th>Source</th>
<th>EM light curve source</th>
<th>Livetime @ high activity</th>
<th>#events in high state</th>
<th>Expected backgr. in high state</th>
</tr>
</thead>
<tbody>
<tr>
<td>Markarian 421</td>
<td>ASM/RXTE</td>
<td>141 days</td>
<td>0</td>
<td>1.63</td>
</tr>
<tr>
<td>1ES1959+650</td>
<td>ASM/RXTE</td>
<td>283 days</td>
<td>2</td>
<td>1.56</td>
</tr>
<tr>
<td>Cygnus X-3</td>
<td>Ryle Telesc.</td>
<td>114 days</td>
<td>2</td>
<td>1.37</td>
</tr>
</tbody>
</table>

- **Time-rolling search over 2000-03 period**
  - Optimized angular search bin: 2.25°-3.75°

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

Search neutrinos in time-space coincidence with GRB:

- \( \nu_\mu \) 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

No signal detected therefore limits assigned.
AGNs: Stacking source analysis

- 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.

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

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

Table 3

Results for the year 2000 data: Number of sources $N_{src}$, measured number of events $N_{\nu}^{obs}$, the corresponding background $N_{\nu}^{bg}$ 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 $10^{-8}$ cm$^{-2}$ s$^{-1}$. $f_{lim}/N_{src}$ represents the limit per source.
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

<table>
<thead>
<tr>
<th>Source</th>
<th>#events (4 years)</th>
<th>Expected background (4 years)</th>
<th>Period duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Markarian 421</td>
<td>6</td>
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</table>

sources: TeV blazars, microquasars and variable sources from EGRET
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.

\[ \Gamma_{\text{ann}} = \frac{\sigma_{\text{ann}} \nu \rho^2}{m^2} \]

- \( \Gamma_{\text{ann}} \): annihilation rate per unit of volume
- \( \sigma_{\text{ann}} \): neutralino-neutralino cross-section
- \( \nu \): relative speed of the annihilating particles
- \( \rho \): neutralino mass density
- \( m \): neutralino mass
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.
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:

\[
\chi\chi \rightarrow l^+l^-, W^+W^-, Z^0Z^0, H_{1,2}^0H_3^0, Z^0H_{1,2}^0, W^\pm H^{\mp}
\]
Energy spectrum

- Production by secondaries: continuum energy spectrum.
- Typically, neutrinos get \( \sim 1/10 \) of the neutralino mass → \( E_\nu \sim \text{GeV} – \text{TeV} \)
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)
Detecting neutralinos from the Earth is challenging, due to the depleting effect of the gravitational potential from the Sun.

Lundberg and Edsjo, 2003

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.
Complementary experiments
Sky View

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

AMANDA
South Pole

0.5 \pi \text{ sr} \text{ instantaneous common view}
1.5 \pi \text{ sr} \text{ 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 $\rightarrow$ 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: \( \lambda_{\text{abs}} \sim 60 \pm 8 \text{ m (470 nm)} \)
\( \lambda_{\text{abs}} \sim 26 \pm 2 \text{ m (370 nm)} \)

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

\[
\lambda_{\text{eff}} = \frac{\lambda_{\text{sc}}}{1 - \langle \cos \theta \rangle}
\]

Average optical ice parameters:
\( \lambda_{\text{abs}} \sim 110 \text{ m @ 400 nm} \)
\( \lambda_{\text{sca}} \sim 20 \text{ m @ 400 nm} \)
Complementarity