The Neutrino – Gamma Ray Connection

- The gamma – neutrino link
- Neutrino telescopes: facts and vision
- The KM3NeT Design Study, history and future
- Operational options
- Conclusions and Outlook

Uli Katz
Univ. Erlangen

CTA Meeting, Paris, 01–02.03.2007
Hadronic acceleration, neutrinos and gammas

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

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

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

- Simultaneously, gamma production takes place:

\[
N + X \rightarrow \pi^0 + Y \rightarrow \gamma \gamma + Y
\]

- Cosmic ray acceleration yields neutrinos and gammas with similar abundance and energy spectra!
Astro- and Particle Physics with Neutrinos

Neutrino Oscillations:
- Direction
- Energy
- Flavor

Low-energy limit:
- detector sensitivity
- background

- Dark matter search (WIMPs): Direction, Energy
- Astrophysical point sources: Direction, (Energy), Time

High-energy limit:
- neutrino flux decreases like $E^{-n}$ ($n \approx 2$)
- large detection volume needed.

Direct $\nu \rightarrow \gamma$ connection

Diffuse cosmic neutrino flux: (Direction), Energy

GeV TeV PeV EeV $E_{\nu}$

... and also:
- GZK neutrinos
- Z bursts
- magnetic monopoles
- topological defects
- top-down scenarios
- supernova detection
- ...

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Example: ν’s from Supernova Remnants

- **Example:** SNR RX J1713.7-3946 (shell-type supernova remnant)

- **H.E.S.S.:** $E_\gamma = 200 \text{ GeV} – 40 \text{ TeV}

- **W. Hofmann, ICRC 2005**

- **Acceleration beyond 100 TeV.**

- **Power-law energy spectrum, index ~2.1–2.2.**

- **Spectrum points to hadron acceleration $\rightarrow$ ν flux $\sim$ γ flux**

- **Typical ν energies: few TeV**
Sky Coverage of Neutrino Telescopes

Observed sky region in galactic coordinates assuming efficiency for downward hemisphere.

→ We need Northern \( \nu \) telescopes to cover the Galactic Plane

Mediterranean site:

>75% visibility

>25% visibility
Precise $\nu$ Flux Predictions from $\gamma$ ray Mmt’s!

A. Kappes et al., astro-ph 0607286

mean atm. flux

$E^2 \times \text{flux \ (TeV}^2 \text{s}^{-1} \text{cm}^{-2})$

- $1 \sigma$ error bands include systematic errors (20% norm., 10% index & cut-off)

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# Expected signals

A. Kappes et al., astro-ph 0607286

<table>
<thead>
<tr>
<th>Type</th>
<th>Type</th>
<th>$\varnothing$ [°]</th>
<th>$E_\nu &gt; 1$ TeV</th>
<th>$E_\nu &gt; 5$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vela X</td>
<td>PWN</td>
<td>0.8</td>
<td>9 – 23</td>
<td>5 – 15</td>
</tr>
<tr>
<td>RX J1713.7–3946</td>
<td>SNR</td>
<td>1.3</td>
<td>7 – 14</td>
<td>2.6 – 6.7</td>
</tr>
<tr>
<td>HESS J1825–137</td>
<td>PWN</td>
<td>0.3</td>
<td>5 – 10</td>
<td>2.2 – 5.2</td>
</tr>
<tr>
<td>Crab Nebula</td>
<td>PWN</td>
<td>&lt;0.1</td>
<td>4.0 – 7.6</td>
<td>1.1 – 2.7</td>
</tr>
<tr>
<td>HESS J1303–631</td>
<td>NCP</td>
<td>0.3</td>
<td>0.8 – 2.3</td>
<td>0.1 – 0.5</td>
</tr>
<tr>
<td>LS 5039* (INFC)</td>
<td>Binary</td>
<td>&lt;0.1</td>
<td>0.3 – 0.7</td>
<td>0.1 – 0.3</td>
</tr>
</tbody>
</table>

NCP: No counterpart at other wavelengths

*no $\gamma$-ray absorption

- Neutrino astronomy is a **low-statistics domain**!
- Sensitivity to galactic sources in reach $\rightarrow$ important design criterion
- Enhanced signals/sensitivity for
  - transient sources
  - opaque sources
  - sources at higher energies ("PeVatrons")

Even few neutrinos from unambiguously identified source would be a scientific breakthrough!
The Principle of Neutrino Telescopes

**Role of the Earth:**
- Screening against all particles except neutrinos.
- Atmosphere = target for production of secondary neutrinos.

**Cherenkov light:**
- In water: $\theta_C \approx 43^\circ$
- Spectral range used: $\sim$ 350-500nm.

**Angular resolution in water:**
- Better than $\sim$0.3° for neutrino energy above $\sim$10 TeV, 0.1° at 100 TeV
- Dominated by angle($\nu, \mu$) below $\sim$10 TeV ($\sim$0.6° at 1 TeV)
The Neutrino Telescope World Map

ANTARES + NEMO + NESTOR join their efforts to prepare a km
3-scale neutrino telescope in the Mediterranean

Design Study
IceCube: a km³ Detector in the Antarctic Ice

- Meanwhile 22 strings installed (~ 30%)
- Data taking in progress
ANTARES: A Pilot Project in the Mediterranean

- String-based detector;
- Underwater connections by deep-sea submersible;
- Downward-looking photomultipliers (PMs), axis at 45° to vertical;
- 2500 m deep;
- Jan 2007: 5 strings deployed and connected, data taking in progress
Progress in the Mediterranean Sea

- **ANTARES:**
  5 lines operational, first atmospheric muon events observed with all lines.

- **NEMO:**
  Successful test deployment, data taking

- **NESTOR:**
  Prototype module operated in 2003.

- **KM3NeT:** Upcoming.
KM3NeT Design Study: The last years

Design Study for a Deep-Sea Facility in the Mediterranean for Neutrino Astronomy and Associated Sciences

- Proposal submitted to EU 04.03.2004.
- Confirmation that Design Study will be funded (Sept. 2004).
- KM3NeT on ESFRI list of Opportunities, March 2005.
- 2nd VLVνT Workshop, Catania, 08-11.11.2005.
- Design Study contract signed, Jan. 2006 (9 M€ from EU, ~20 M€ overall).
- Start of Design Study project, 01.02.2006.
- Kick-off meeting, Erlangen, April 2006.
- First year report, due 15.03.2007.

And: Essential progress of ANTARES, NEMO and NESTOR in this period!
KM3NeT Design Study: Participants

- **Cyprus**: Univ. Cyprus
- **France**: CEA/Saclay, CNRS/IN2P3 (CPP Marseille, IréS Strasbourg, APC Paris-7), Univ. Mulhouse/GRPHE, IFREMER
- **Germany**: Univ. Erlangen, Univ. Kiel
- **Greece**: HCMR, Hellenic Open Univ., NCSR Demokritos, NOA/Nestor, Univ. Athens
- **Ireland**: Dublin Institute of Advanced Studies (since 1.Nov.2006)
- **Italy**: CNR/ISMAR, INFN (Univs. Bari, Bologna, Catania, Genova, Napoli, Pisa, Roma-1, LNS Catania, LNF Frascati), INGV, Tecnomare SpA
- **Netherlands**: NIKHEF/FOM (incl. Univ. Amsterdam, Univ. Utrecht, KVI Groningen)
- **Spain**: IFIC/CSIC Valencia, Univ. Valencia, UP Valencia
- **UK**: Univ. Aberdeen, Univ. Leeds, Univ. Liverpool, Univ. Sheffield

Particle/Astroparticle institutes (29+1) – Sea science/technology institutes (7) – Coordinator
The KM3NeT Design Study work packages

- **WP1**: Management of the Design Study
- **WP2**: Physics analysis and simulation
- **WP3**: System and product engineering
- **WP4**: Information technology
- **WP5**: Shore and deep-sea infrastructure
- **WP6**: Sea surface infrastructure
- **WP7**: Risk assessment and quality assurance
- **WP8**: Resource exploration
- **WP9**: Associated sciences
The KM3NeT Vision

- KM3NeT will be a multidisciplinary research infrastructure:
  - Data will be publicly available;
  - Implementation of specific online filter algorithms will yield particular sensitivity in predefined directions → non-KM3NeT members can apply for observation time;
  - Data will be buffered to respond to GRB alerts etc.
  - Deep-sea access for marine sciences.
- KM3NeT will be a pan-European project
  - 8+1 European countries involved in Design Study;
  - Substantial funding already now from national agencies.
- KM3NeT will be constructed in time to take data concurrently with IceCube.
- KM3NeT will be extendable.

Target price tag: 200 M€/km³ or less
KM3NeT: Path to Completion

**Time schedule (partly speculative & optimistic):**

<table>
<thead>
<tr>
<th>Date</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>01.02.2006</td>
<td>Start of Design Study</td>
</tr>
<tr>
<td>Fall 2007</td>
<td>Conceptual Design Report</td>
</tr>
<tr>
<td>February 2009</td>
<td>Technical Design Report</td>
</tr>
<tr>
<td>2008-2010</td>
<td>Preparatory Phase in FP7</td>
</tr>
<tr>
<td>2010-2012</td>
<td>Construction</td>
</tr>
<tr>
<td>2011-20xx</td>
<td>Data taking</td>
</tr>
</tbody>
</table>

Call for Preparatory Phase projects published in Dec. 2006, restricted to ESFRI projects.
Gamma—Neutrino: Operational Options

- **“Target of opportunity”:**
  - Neutrino triggers gamma
    [e.g. IceCube/MAGIC cooperation, E. Bernardini]
  - Neutrino triggers optical (then gamma?)
    [see e.g. M. Kowalski, A. Mohr, astro-ph/0701618]
  - Gamma/optical triggers neutrino
    [KM3NeT: direction-dependent event filters, details yet to be worked out]

- **Multimessenger investigations**
  - Correlated analysis of data, requires data access, standardized data formats, agreements, etc.
    → question of policy and resources!
  - Feedback on design decisions?
Example: IceCube—MAGIC cooperation

Target of opportunity test run, Sept-Dec '06

AMANDA on-line filter selected events consistent with any of five γ sources (sometimes) accessible to MAGIC and sent alerts.

MAGIC took on-source data when possible (for five alerts)

Once final neutrino background determined, results will be exchanged and compared with pre-determined thresholds for γ rate.

Neutrino events by themselves are consistent with prel. background estimates.

Need to develop procedure and statistical treatment further.

Presented at WIN07, Kolkata, India, January 2007
Conclusions and Outlook

- There is an **intrinsic gamma—neutrino connection** in TeV+ astroparticle physics that is worth while to be explored.

- The neutrino telescope projects IceCube (Antarctica) and ANTARES, NEMO and NESTOR (Mediterranean Sea) have proven the feasibility of large-scale deep-sea neutrino telescopes.

- **Exciting data** from these experiments can be expected in the near future.

- ANTARES, NEMO and NESTOR have **united their efforts** to prepare together the future, km³-scale deep-sea detector KM3NeT. The EU-funded **KM3NeT Design Study (2006-09)** provides substantial resources for an intense 3-year R&D phase.

- Efforts coordinated between the gamma and the neutrino communities may yield **increased sensitivity** and open **additional options**.