Exploring the Universe with Very High Energy Neutrinos
Exploring the high-energy universe

(source) galactic magnetic fields

Flux (GeV^{-1} m^{-2} s^{-1} sr^{-1})

Cosmic-ray spectrum

energy (eV)

LHC (beam energy)
Exploring the high-energy universe

source

p

(inter-) galactic magnetic fields

γ

ν

Vela junior in gamma-rays (H.E.S.S.)

Cosmic-ray spectrum

Flux (GeV$^{-1}$ m$^{-2}$ s$^{-1}$ sr$^{-1}$)

energy (eV)

10$^9$ 10$^{12}$ 10$^{15}$ 10$^{18}$ 10$^{21}$

10$^{-27}$ 10$^{-21}$ 10$^{-15}$ 10$^{-9}$ 10$^{-3}$ 10$^3$

LHC (beam energy)
Neutrinos and photons from cosmic-ray accelerators

- **p** → **p(γ)**
- **π⁺ + X** → **μ⁺ + (ν_μ + ν_e)**
- **π⁰ + X** → **γ + γ**

- **γ**
- **e**
- **γ**

- **synchrotron**
- **CMB, IR synchrotron . . .**

- **p**
- **π**
- **μ**
- **e**
- **ν**

- high-energy (> 0.1 TeV) secondary particles
- pionic neutrinos
- pionic gammas
- inverse Compton
Detection of high-energy neutrinos

- Detection & reconstruction via Cherenkov light of secondary particles → transparent detection media
- Low fluxes require huge detection volumes → natural abundances of ice or water (lakes, oceans, Antarctic ice)

Time & position of hits

- \(\mu\) trajectory → \(\nu\) trajectory

Light intensity

- 

Energy

\[\nu_\mu + N \rightarrow \mu + X\]
Current neutrino telescope projects

**ANTARES**
- instr. vol. = 0.01 km³

**ICECUBE**
- instr. vol. = 1 km³

**Baikal**
- instr. vol. = 0.0001 km³ (up to 0.01 km³ effective)

**KM3NeT**
- instr. vol. = 0.0001 km³ (up to 0.01 km³ effective)
- (phase 1)

**GVD**

ATP & Cosm. Session:
- Wed 9:00: GVD status

ATP & Cosm. Session:
- Wed 9:18: Recent results
- Wed 9:35: Dark Matter

ATP & Cosm. Session:
- Wed 9:48: Status & goals

ATP & Cosm. Session:
- Wed 9:00: Astroph. neutrinos
- Wed 9:48: Status & goals
Neutrino signatures

Track-like

- Good angular resolution in ice (IceCube) ~ 0.5° for E > 10 TeV
- Sensitive volume > instrumented volume

Cascade-like

- Good energy resolution in ice (IceCube) < 10% for E > 10 TeV
- Reduced angular resolution in ice (IceCube) > $O(10°)$
- Sensitive volume ≈ instrumented volume
Atmospheric muons and neutrinos

\[
E^2 \Phi_\nu [\text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}] = 10^{-1} \quad 10^{-2} \quad 10^{-3} \quad 10^{-4} \quad 10^{-5} \quad 10^{-6} \quad 10^{-7} \quad 10^{-8} \quad 10^{-9}
\]

\[
\log_{10} (E_\nu [\text{GeV}]) = -1 \quad 0 \quad 1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6 \quad 7
\]

**Conventional**
- $\nu_e$
- $\nu_\mu$

**Cosmic ray** (p)
- $\pi$
- $\mu$
- $e$
- $\nu_\mu$
- $\nu_e$

\[\Phi \sim E^{-3.7}\]
Atmospheric muons and neutrinos

\begin{align*}
\text{conventional } \nu_e / \text{conventional } \nu_\mu
\end{align*}

\begin{align*}
\Phi \sim E^{-2.7}
\end{align*}

\begin{align*}
\text{conventional } \nu_e, \mu
\end{align*}

\begin{align*}
\Phi \sim E^{-3.7}
\end{align*}

\begin{align*}
\text{charm } \nu_\mu, \nu_e
\end{align*}

\begin{align*}
\text{cosmic ray (p)}
\end{align*}

\begin{align*}
\text{conventional}
\end{align*}
Atmospheric muons and neutrinos
Atmospheric muons and neutrinos

\[ E^2 \Phi_\nu \ [\text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}] \]

\[ \log_{10} (E_\nu \ [\text{GeV}]) \]

Waxman&Bahcall upper bound

astrophysical neutrinos \( \Phi \sim E^{-2} \)

conventional \( \Phi \sim E^{-3.7} \)

cosmic ray (p)

charm

\( c,(b) \)

\( e,\mu \)

\( \nu_{e,\mu} \)

\( \nu_\mu \)

\( \nu_e \)

IceCube \( \nu_\mu \)

Frejus \( \nu_\mu, \nu_e \)

Frejus unfolding

forward folding

AMANDA \( \nu_\mu \)

conventional \( \nu_\mu, \nu_e \)

conventional \( \nu_\mu \)

conventional \( \nu_e \)

\( \Delta \nu_e \)

Super-K \( \nu_\mu \)

\( \Phi \sim E^{-2.7} \)
Atmospheric muons and neutrinos

- Atmospheric muons
- Muons induced by atmospheric neutrinos
- Up-going
- Down-going

\[ \Phi \sim E^{-2.7} \]

\[ \Phi \sim E^{-3.7} \]

Cosmic ray (p) → e, μ → ν_{e,μ} → charm

\[ c,(b) \]
"Classical" picture of neutrino astronomy

Search for point sources

**IceCube**
- 1373 days
- ~180,000 $\nu$ (up-going)
- High atmospheric muon background $\rightarrow$ 1 PeV energy threshold
- P-value (post-trial) = 23%

**ANTARES**
- 1338 days
- ~5500 $\nu$ (up-going)
- Significance maps (equatorial coordinates)
- P-value (post-trial) = 2.7%

Alexander Kappes, ICHEP 2014, Valencia. 9.7.2014
Point sources: Sensitivities & upper limits

90% CL sensitivity / upper limits for $E^{-2}$ spectrum

Galactic γ-ray sources

Galactic Center

discovery region

$E^2 \times \text{flux [TeV cm}^{-2} \text{ s}^{-1}]$

$\sin(\delta)$

MACRO

ANTARES
ApJL 786 (2014)

IceCube
Point sources: Sensitivities & upper limits

90% CL sensitivity / upper limits for $E^{-2}$ spectrum

Galactic γ-ray sources

Galactic Center

discovery region

$10^2 \text{ GeV} < E_{\nu} \leq 10 \text{ TeV}$

$10 \text{ TeV} < E_{\nu} \leq 1 \text{ PeV}$

$1 \text{ PeV} < E_{\nu} \leq 1 \text{ EeV}$

$0.1 - 10 \text{ TeV}$

$1 \text{ PeV} - 1 \text{ EeV}$

Alexander Kappes, ICHEP 2014, Valencia. 9.7.2014
Neutrinos from gamma-ray bursts

Gamma-ray bursts (GRBs)
- duration 0.1–100 s
- jets with Lorentz factor \( \Gamma > 300 \)
- candidates for ultra-high-energy cosmic rays

example GRB neutrino spectrum

\[ E^2 \times dN/dE \text{ (GeV cm}^{-2}\text{)} \]

- \( \Gamma = 300 \)
- \( \Gamma = 500 \)
- \( \Gamma = 1400 \)

timing/localization from satellites

\( \gamma \)

low background

Earth

break energy

Alexander Kappes, ICHEP 2014, Valencia. 9.7.2014
Neutrinos from gamma-ray bursts

Gamma-ray bursts (GRBs)
- duration 0.1–100 s
- jets with Lorentz factor $\Gamma > 300$
- candidates for ultra-high-energy cosmic rays

IceCube: analysis of 506 GRBs → no correlation

Are GRBs really cosmic-ray sources?

<table>
<thead>
<tr>
<th>$\varepsilon_b$ (GeV)</th>
<th>$\varepsilon_b^{\Phi_{\nu_b}}$ (GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^4$</td>
<td>$10^{-7}$</td>
</tr>
<tr>
<td>$10^5$</td>
<td>$10^{-8}$</td>
</tr>
<tr>
<td>$10^6$</td>
<td>$10^{-9}$</td>
</tr>
<tr>
<td>$10^7$</td>
<td></td>
</tr>
</tbody>
</table>

Neutrino break energy $\varepsilon_b$ (GeV)
- low $\Gamma$ ~ 100
- high $\Gamma$ ~ 2000

Ahlers et al.
Waxman-Bahcall

Exclusion CL (%)
- 90%
- 68%
- 50%
Neutrinos from above – the power of veto

- Accept events with no light in veto layer + large signal in fiducial volume → cosmic neutrinos
- Reject events with light in veto layer → atmospheric muons

First idea: Schönert et al., PRD (2009)
Neutrinos from above – the power of veto

First idea: Schönert et al., PRD (2009)

- Accept events with no light in veto layer + large signal in fiducial volume → cosmic neutrinos
- Reject events with light in veto layer → atmospheric muons
- Self-veto of atmospheric neutrinos through accompanying muons!
  (muons can range out at low energies)
The Breakthrough
Discovery of cosmic neutrinos with IceCube

- 2 years data: 28 events observed (background $10.6^{+5.0}_{-3.6} \rightarrow 4.2\sigma$) → IceCube, Science (2013)
- 2+1 year data: observed 28+9 events (background $15.0^{+7.2}_{-4.5}$)
  - 2-d fit (zenith+energy) → $5.7\sigma$ rejection of atmospheric-only hypothesis
  - compatible with isotropic flux with flavor ratio (1:1:1)
  - best-fit astrophysical $E^{-2}$ flux: $E^2\Phi = 10^{-8}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ (best-fit slope $E^{-2.3}$)

IceCube, arXiv:1405.5303 (2014) accepted by PRL
Can we identify sources?

IceCube skymap

- no indication for individual sources
- no correlation with Galactic plane
- extra-galactic origin likely
Can we identify sources?

IceCube skymap

- no indication for individual sources
- no correlation with Galactic plane
- extra-galactic origin likely

- 7 cascades in “hot-spot” → low angular resolution
- ANTARES search for source with width 0° – 3° → source < 0.5° excluded

hot-spot (7 events) flux prediction
Gonzalez-Garcia et al. (2013)

Other channels and experiments

- IceCube: 3.9 $\sigma$ from up-going muon neutrinos (2 years, preliminary)
- IceCube: muon neutrinos unfolding (IC79, preliminary)
- ANTARES upper limit (90% CL) (F. Folger, IDM-TeVPA 2014)
Other channels and experiments

IceCube: 3.9σ from up-going muon neutrinos (2 years, preliminary)

IceCube: muon neutrinos unfolding (IC79, preliminary)

ANTARES upper limit (90% CL)
(F. Folger, IDM-TeVPA 2014)

flux from veto analysis
Source candidates

- Honda + ERS Atmos. $\nu_\mu$
- Waxman Bahcall 2013
- Blazars Stecker 2005 $\nu_\mu \times 3$
- Loeb Waxman Starburst 2006
- IC59 Diffuse $\nu_\mu$ Limit $\times 3$
- IC79 $\nu_\mu$ Unfolding (preliminary)
- IceCube 2012 All Flavor Limit

Flux from veto analysis
Source candidates

$E_{\nu}^2 \frac{d^2N_{\nu}}{dE_{\nu}}$ [GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$]

- Honda + ERS Atmos. $\nu_{\mu}$
- Waxman Bahcall 2013
- Blazars Stecker 2005 $\nu_{\mu} \times 3$
- Loeb Waxman Starburst 2006
- IC59 Diffuse $\nu_{\mu}$ Limit $\times 3$
- IC79 $\nu_{\mu}$ Unfolding (preliminary)
- IceCube 2012 All Flavor Limit

flux from veto analysis
Source candidates

- Honda + ERS Atmos. $\nu_\mu$
- Waxman Bahcall 2013
- Loeb Waxman Starburst 2006
- IC59 Diffuse $\nu_\mu$ Limit × 3
- IC79 $\nu_\mu$ Unfolding (preliminary)
- IceCube 2012 All Flavor Limit

flux from veto analysis

IceCube upper GRB limit

IceCube upper GRB limit (preliminary)
Source candidates

flux from veto analysis
Future strategies

- Continue search for neutrino sources (further improve detector capabilities)

- Increase multimessenger strategies with other instruments (X-ray, gamma, radio) in particular for transient sources

- After 10 years of IceCube data-taking
  - Muon neutrinos (point source searches)
    ~90 astrophysical $\nu_\mu$ above 100 TeV
  - Cascade events (energy spectrum/flavor composition)
    ~100 events above 60 TeV
    ~10 events above 1 PeV

→ need significantly more events
Possible strategies for a next-generation IceCube

- In-ice detector of 5–10 km$^3$ with increased spacing → higher energy threshold
- Extended surface veto (~100 km$^2$) to reject atmospheric showers (muons/neutrinos) → increases fiducial volume significantly

Artist conception

current IceCube with surface veto (preliminary)

% increase signal events compared to North

Flux: $47.4 \times 10^{-8} \ E^{-2.3}$

Cosmic flux: +75% >100 TeV

radius of surface veto array

5 km
KM3NeT – Next generation neutrino telescope in the Mediterranean Sea

New Research Infrastructure

- network of cabled observatories
- innovative sensor design with $31 \times 3''$ PMTs ($3 \times$ sensitive area $10''$ PMT)
- instr. vol. $3–6 \text{ km}^3$ (12,000 sensors)

Phased implementation

- **Phase 1**: proof of feasibility ($31 \text{ M€}$, funded)
- **Phase 1.5**: measure IceCube signal ($+50–60 \text{ M€}$, Letter of Intent)
- **Phase 2**: neutrino astronomy ($+140–160 \text{ M€}$, ESFRI roadmap)

KM3NeT phase 1.5: measurement of IceCube cosmic $\nu$ flux

Significance ($\sigma$)
KM3NeT – Next generation neutrino telescope in the Mediterranean Sea

New Research Infrastructure

- network of cabled observatories
- innovative sensor design with $31 \times 3''$ PMTs ($3 \times$ sensitive area $10''$ PMT)
- instr. vol. $3\text{–}6 \text{ km}^3$ (12,000 sensors)

Phased implementation

- Phase 1: proof of feasibility ($31 \text{ M}\text{€}$, funded)
- Phase 1.5: measure IceCube signal (+50\text{–}60 \text{ M}\text{€}, Letter of Intent)
- Phase 2: neutrino astronomy (+140\text{–}160 \text{ M}\text{€}, ESFRI roadmap)

---


Alexander Kappes, ICHEP 2014, Valencia. 9.7.2014
Summary

- IceCube has taken first steps towards high-energy neutrino astronomy
  - discovery of an isotropic cosmic flux at $E^2 \Phi = 10^{-8}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$
  - up to now no indication for point sources or correlation with extended sources
  - many theoretical speculations

- Lack of neutrinos from GRBs in IceCube → pressure on models that have GRBs as major sources of the ultra-high energy cosmic rays

- The fun just started, many things to explore and discover in the future
  → expanding capabilities of current detectors
  → next-generation detectors on the way
The PeV neutrinos

Ernie
\( E = 1.1 \text{ PeV}, \theta = 23^\circ \)

Bert
\( E = 1.0 \text{ PeV}, \theta = 62^\circ \)

Big Bird
\( E = 2.0 \text{ PeV}, \theta = 34^\circ \)