Are Km3 telescopes sufficiently large to observe astrophysical neutrinos?
The idea to observe the Universe using Neutrinos is profoundly fascinating.

The insights about Nature that are possible with this: “New Way” to look at the Sky can be profound.
The idea to observe the Universe using Neutrinos is profoundly fascinating.

The insights about Nature that are possible with this: "New Way" to look at the Sky can be profound.

Neutrino Astronomy is an old "DREAM"

The scientific significance of this idea has been recognized very early after the "invention" of the neutrino.

The "dream" has become a reality with Solar and SuperNova neutrinos [E ~ 0.5 – 30 MeV]
What about “high energy neutrinos”?

Still an open problem ..... 
.... a very difficult challenge ..... 

The “High Energy Universe”:

Fundamental, fascinating question
With many uncertainties and open problems

A century old problem (the origin of cosmic rays)

A “quantum leap” in understanding
Gamma Astronomy [GeV !, TeV !]
[multi-wavelength observations! Radio, X-rays]

Field with great “dynamism”
“The estimate of the neutrino flux may be too low, since regions that produce neutrinos abundantly may not reveal themselves in the types of radiation yet detected”

Kenneth Greisen 1960 (Review on CR) advocating the construction of neutrino telescopes:

The “hunt” for the elusive astrophysical neutrinos.....

Long history of larger and larger detectors:
Baksan Neutrino Observatory
Neutrino Telescopes of growing size.

BAKSAN
MACRO at Gran Sasso (~1000 m²)
BAIKAL
AMANDA at the South Pole (~10⁴ m²)
ANTARES

The "KM³ concept" "The 'natural size' for a neutrino telescope is 1 Km³ of water / ice"
ICECUBE LAB

IceTop
- 81 Stations, each with
- 2 IceTop Cherenkov detector tanks
- 2 optical sensors per tank
- 324 optical sensors

IceCube Array
- 86 strings including 8 DeepCore strings
- 60 optical sensors on each string
- 5160 optical sensors

December, 2010: Project completed, 86 strings

DeepCore
- 8 strings spacing optimized for lower energies
- 480 optical sensors

Eiffel Tower 324 m

Bedrock

125 m string separation
17 m between PMT's

ICECUBE COMPLETED
CONGRATULATIONS!
CONGRATULATIONS !

Extraordinary effort.  
Remarkable technical success.  

Beautiful results!  
(CR anisotropies from down-going muons)
CONGRATULATIONS!

Extraordinary effort.
Remarkable technical success.

Beautiful results!
(CR anisotropies from down-going muons)

..... But still waiting for evidence of
Astrophysical Neutrinos .....

Very interesting upper limits,
But no signal in an exposure of order ($\frac{1}{2}$ Km$^3$ year)
.... yes, yes, of course ....

it is still too early, we have to be patient, more statistics and improved analysis soon! .....
.... yes, yes, of course ....

it is still too early, we have to be patient, more statistics and improved analysis soon! ....

However: let us consider the situation at the present "unstable" moment, soon before the time when the significance of this wonderful concept will be established.

Will virtue be rewarded?
No evidence for Astrophysical Neutrinos in $\frac{1}{2}$ Km3 yr

Disappointment ?

Surprise ?

Problem ?
No evidence for Astrophysical Neutrinos in $\frac{1}{2}$ Km3 yr

Disappointment? ......YES ....OF COURSE !! ....

Surprise? NO. Signals at this level were expected only in optimistic/serendipitous scenarios.

Problem? YES. IceCube (in the present configuration) will only just “scratch the surface” of neutrino astronomy. [there are already lessons to be extracted]
The development of the "Beaded String" concept for neutrino telescopes has improved the sensitivity by two orders of magnitude!

These telescopes could have discovered sources!

The limits [on the diffuse neutrino fluxes] are falsifying physical scenarios that are viable and do have interesting astrophysical significance.
The development of the “Beaded String” concept for neutrino telescopes has improved the sensitivity by two orders of magnitude!

These telescopes could have discovered sources!

The limits [on the diffuse neutrino fluxes] are falsifying physical scenarios that are viable and do have interesting astrophysical significance.

and then...

there is “SERENDIPITY”...
The “princes of Serendip” have not smiled to Francis and Tom and their friends ....

(Perhaps their smile is beyond that corner ?...)

Francis Halzen: 1996

Table 1: New windows on the Universe

<table>
<thead>
<tr>
<th>Telescope</th>
<th>Intended use</th>
<th>Actual results</th>
</tr>
</thead>
<tbody>
<tr>
<td>optical (Galileo)</td>
<td>navigation</td>
<td>moons of Jupiter</td>
</tr>
<tr>
<td>radio (Jansky)</td>
<td>noise</td>
<td>radio galaxies</td>
</tr>
<tr>
<td>optical (Hubble)</td>
<td>nebulae</td>
<td>expanding Universe</td>
</tr>
<tr>
<td>microwave (Penzias-Wilson)</td>
<td>noise</td>
<td>3K cosmic background</td>
</tr>
<tr>
<td>X-ray (Giacconi...)</td>
<td>moon</td>
<td>neutron stars...</td>
</tr>
<tr>
<td>radio (Hewish, Bell)</td>
<td>scintillations</td>
<td>pulsars</td>
</tr>
<tr>
<td>γ-ray (???)</td>
<td>thermonuclear explosions</td>
<td>γ-ray bursts</td>
</tr>
</tbody>
</table>

**Neutrino Telescopes**  
{SNR, AGN,...}  
{???,}
\( \frac{1}{2} \text{ Km}^3 \text{-year exposure and no neutrinos ...} \)

Surprise? Not Really.

Table 5

<table>
<thead>
<tr>
<th>Muon energy</th>
<th>Events per year in 0.1 km²</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ref. [72]</td>
</tr>
<tr>
<td>Atmospheric (angle averaged, per steradian)</td>
<td></td>
</tr>
<tr>
<td>&gt; 1 GeV</td>
<td>7800</td>
</tr>
<tr>
<td>&gt; 1 TeV</td>
<td>129</td>
</tr>
<tr>
<td>Atmospheric in 1° circle, Ref. [75]</td>
<td></td>
</tr>
<tr>
<td>&gt; 1 GeV</td>
<td>12.6</td>
</tr>
<tr>
<td>&gt; 1 TeV</td>
<td>0.21</td>
</tr>
<tr>
<td>Extraterrestrial fluxes (angle averaged)</td>
<td></td>
</tr>
<tr>
<td>( \phi_\nu = 2.7 \times 10^{-5} (E_\nu/\text{GeV})^{-1.7} \text{ cm}^{-2} \text{ s}^{-1} )</td>
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</tr>
<tr>
<td>&gt; 1 GeV</td>
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</tr>
<tr>
<td>&gt; 1 TeV</td>
<td>4.3</td>
</tr>
<tr>
<td>( \phi_\nu = 4.0 \times 10^{-8} (E_\nu/\text{GeV})^{-1} \text{ cm}^{-2} \text{ s}^{-1} )</td>
<td></td>
</tr>
<tr>
<td>&gt; 1 GeV</td>
<td>8.8</td>
</tr>
<tr>
<td>&gt; 1 TeV</td>
<td>5.0</td>
</tr>
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<tr>
<td>Astrophysical point sources (( E_\mu &gt; 1 \text{ TeV} ))</td>
<td></td>
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<tr>
<td>Galactic source (Eq. 37)/100</td>
<td></td>
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<tr>
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</tr>
<tr>
<td>500 GeV WIMPS from ( \odot )</td>
<td></td>
</tr>
<tr>
<td>AGN</td>
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</tr>
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<td>plane of galaxy</td>
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<tr>
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<tr>
<td></td>
<td>θ = 0.05</td>
</tr>
<tr>
<td>&gt; 2.6</td>
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<td>&gt; 0.21</td>
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### Reasonable prediction [at the time]

But overestimates (by factor of 10).

#### Extraterrestrial fluxes (angle averaged)

- \( \phi_\nu = 2.7 \times 10^{-5} (E_\nu/\text{GeV})^{-1.7} \text{ cm}^{-2} \text{ s}^{-1} \)
- \( \phi_\nu = 4.0 \times 10^{-8} (E_\nu/\text{GeV})^{-1} \text{ cm}^{-2} \text{ s}^{-1} \)

#### Astrophysical diffuse fluxes (per steradian)

- \( > 1 \text{ GeV} \) plane of galaxy
  - 12–20
  - 80–200
- \( > 1 \text{ TeV} \)
  - 1.5–3.0
  - 40–200

#### Astrophysical point sources (\( E_\mu > 1 \text{ TeV} \))

- Galactic source (Eq. 37)/100
- Extragalactic source
  - 2.6
  - 0.1–10

#### 500 GeV WIMPS from \( \odot \)

- 20

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<tr>
<td>with abs.</td>
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<tr>
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<td>3.8</td>
</tr>
<tr>
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Reasonable prediction [at the time]
But overestimates (by factor of 10).

Now: natural questions:
1. What is the meaning of the new limits.
2. Can one make better predictions today?
3. Are there "guaranteed" sources

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| 500 GeV WIMPS from ⊙ | 20 |

500 GeV WIMPS from ⊙

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Reasonable prediction [at the time]
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Now: natural questions:
1. What is the meaning of the new limits.
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3. Are there "guaranteed" sources

What if 2 years from now no signals?
Which directions should one follow?

[are these legitimate/appropriate questions?]
For the “KM³ concept”

the “moment of truth” has arrived.

Difficult choices for the proponents of a neutrino detector of similar conception in the Mediterranean Sea

[looking at the Southern hemisphere of the celestial sphere]
Projects in the Mediterranean

- **ANTARES**: 2400m
- **NEMO**: 3400m
- **NESTOR**: 4100m
Possible structure of a “KM3” detector in the Mediterranean Sea:

“tower” [6 PMT's]

127 towers (180 m)

Detection Unit layout.
A detector in the Mediterranean Sea has one crucial advantage with respect to IceCube at the South Pole:

A view of the CENTER of our GALAXY
Galactic Center
Galactic sources

In principle also a better angular resolution for the muon direction (less scattering in water).

Therefore smaller integration cone in the study of point sources: smaller background.
For a neutrino telescope in the Mediterranean, to obtain [after a very important effort] only Upper Limits on astrophysical neutrinos [several years after IceCube] would be a VERY unsatisfactory result.
For a neutrino telescope in the Mediterranean, to obtain [after a very important effort] only Upper Limits on astrophysical neutrinos [several years after IceCube] would be a VERY unsatisfactory result.

How does one protects him/her self from this danger?

One can make the telescope bigger.... [but how much bigger ?]

What are the most interesting scientific goals? What is the best design (for these goals)?

Should one perhaps change the concept? Different technique (acoustic, radio, taus)
We talk about:

NEUTRINO ASTRONOMY
We talk about:

NEUTRINO ASTRONOMY

But really there are several

Radio-astronomy
Optical-astronomy
X-ray astronomy
......

NEUTRINO ASTRONOMIES

$10^{10} \, \text{eV} \lesssim E_{\nu} \lesssim 10^{21} \, \text{eV}$

Very broad energy range
$E_\nu \sim [10^{10} \div 10^{12}] \text{ eV}$  

Dark Matter

$E_\nu \sim [10^{13} \div 10^{14}] \text{ eV}$  

Point sources

$E_\nu \sim [10^{14} \div 10^{17}] \text{ eV}$  

GRB [exploration]

$E_\nu \sim [10^{17} \div 10^{20}] \text{ eV}$  

Cosmogenic Neutrinos

$E_\nu \gtrsim 10^{20} \text{ eV}$  

“Exotic” (TD decay...)
EXTRA-GALACTIC NEUTRINOS

Main candidate sources

Intimate relation with UHECR [extragalactic cosmic rays]
The 3-dimensional lampposts ensemble "paradox" [Kepler – Olbers paradox].

Linear sequence of lampposts: Most of the light you receive from the nearest lamppost 3D ensemble of lampposts: [Euclidean static space] Light diverges!
Homogeneous (in average) density of sources: spherical shells between radii: 1, 2, 3, 4, ....

All spherical shells contribute equally.: DIVERGENCE!

\[
\left( \frac{1}{4\pi R^2} \right) \quad (4\pi R^2 \Delta R)
\]
Homogeneous (in average) density of sources: spherical shells between radii: 1, 2, 3, 4, ....

All spherical shells contribute equally.: DIVERGENCE!

\[
\left( \frac{1}{4\pi R^2} \right) (4\pi R^2 \Delta R)
\]

Divergence cured
By cosmological effects

\[
R_{\text{Hubble}} = \frac{c}{H_0} \approx 3 \text{ Gpc}
\]
Solution of the Paradox:
The expansion of the universe.

Cosmological effects “cut” the integration
For \( r > c/H_0 \)
Solution of the Paradox:
The expansion of the universe.

Cosmological effects “cut” the integration
For $r > c/H_0$

LARGEST extragalactic signal comes from large distances, dominated by the sum of many very faint unresolved sources.

“DIFFUSE ISOTROPIC” flux
CEN A
the closest AGN: (3.5 Mpc)
3 events within 3 degrees
13 events within 18 degrees

Point source of UHCR?
Point source of neutrinos??

AUGER data
E > 57 EeV

November 2008 (13 + 14 events)
Update September 2010 (+42 events)
3, 20 degrees circles
Say one observes \( N_0 \approx 1 \) events from CEN A in IceCube.

What are the implications for the diffuse flux?
Say one observes \( N_0 \approx 1 \) events from CEN A in IceCube.

What are the implications for the diffuse flux?

If you have 1 CEN A, you have infinitely many others essentially identical sources distributed in the universe, each contributing to the neutrino event rate in IceCube.

If the comoving volume that contains 1 “CEN A-like” source is a sphere of radius \( R_0 \)

Then the total number of events from all CEN A-like sources is:

\[
N_{\text{all}} = N_0 \left( \frac{R_{\text{Hubble}}}{R_0} \right)^\xi \alpha
\]
The quantity $\xi_\alpha$ is an adimensional number of order unity.

\[ \xi_\alpha = \int_0^\infty \frac{dz}{\sqrt{\Omega_m} (1 + z)^3 + \Omega_\Lambda} \frac{dL}{L(0)} (1 + z)^{-\alpha} \frac{L(z)}{L(0)} \]

Depends on:
[1] Cosmological parameters $\Omega_m$, $\Omega_\Lambda$
[2] The spectral shape [power law index]
   (may be CEN-A-like sources are more/less abundant or more/powerful at different epochs)

\[ \xi_\alpha \simeq 0.53 - 0.22 (\alpha - 2) \quad \text{No source evolution} \]
\[ \xi_\alpha \simeq 2.2 - 1.23 (\alpha - 2) \quad \text{Source evolution} \]
Most “natural choice”

\[ R_0 \sim d_{\text{Cen A}} \]

\[ N_0 \sim 1 \implies N_{\text{diffuse}} \sim 1000 \ \xi \]

Cen A “specially” close

\[ R_0 \sim 10 \ d_{\text{Cen A}} \]

\[ N_0 \sim 1 \implies N_{\text{diffuse}} \sim 100 \ \xi \]
\[ R_0 \approx d_{\text{Cen A}} \quad \text{Most "natural choice"} \]

\[ N_0 \approx 1 \implies N_{\text{diffuse}} \approx 1000 \, \xi \]

\[ R_0 \approx 10 \, d_{\text{Cen A}} \quad \text{Cen A "specially" close} \]

\[ N_0 \approx 1 \implies N_{\text{diffuse}} \approx 100 \, \xi \]

\[ N_{\text{diffuse}} \lesssim 50 \, [\text{Km}^3\text{yr}]^{-1} \quad \text{Limit from IceCube 40} \]
MonteCarlo Energy Spectrum of Neutrinos Observable in IceCube.

![Graph showing energy spectrum of atmospheric and astrophysical neutrinos.](image)
Neutrino Energy

Reconstructed Neutrino Energy

[From Muon Radiation]

\[-\frac{dE}{dX} \simeq \alpha + \frac{E}{\lambda_\mu} = \alpha \left(1 + \frac{E}{\varepsilon_\mu}\right)\]
A Search for a Diffuse Flux of Astrophysical Muon Neutrinos with the IceCube 40-String Detector

No excess over atmospheric neutrinos
Diffuse neutrino flux limit:

\[ \phi_{\nu_{\mu}}(E) E^2 \leq 8.9 \times 10^{-9} \frac{\text{GeV}}{\text{cm}^2 \text{ s sr}} \]

\[ N_{\mu \uparrow} \simeq 2\pi \left[ A \ t \right] \Phi_{\nu_{\mu}} \ (\geq 1 \ \text{TeV}) \ \langle \varepsilon_{\nu \to \mu} \rangle \]

\[ \langle \varepsilon_{\nu \to \mu} \rangle \simeq 3 \times 10^{-6} \]

\[ N_{\mu \uparrow} \simeq 50 \ \frac{\text{events}}{\text{Km}^2 \ \text{yr}} \]
Existing (published) limit on the diffuse neutrino flux implies:

\[ \mathcal{L}_\nu \lesssim 1.2 \times 10^{36} \ \frac{\text{erg}}{\text{decade s Mpc}^3} \]

\[ \mathcal{L}_{\text{SN}}^{\text{kin}} \approx 3 \times 10^{40} \ \text{erg}/(\text{Mpc}^3 \text{s}) \]

\[ \mathcal{L}_{\text{AGN}}^{\text{bolometric}} \approx 2 \times 10^{40} \left( \frac{\text{erg}}{\text{s Mpc}^3} \right) \]
Diffuse contribution

“horizon”

“Resolved” sources

Relation between
The diffuse flux
And the detected Point Sources
If Ice-Cube does not discover “soon” a diffuse flux, the observation of extragalactic-point-sources become improbable.
\[ \phi_{\text{inclusive}} \propto \mathcal{L} = n_{\text{sources}} \quad L \]

\[ \phi_{\text{source}} \propto \frac{L}{r^2} \quad \implies \quad r_{\text{horizon}} \propto \sqrt{L} \quad \sqrt{A} \quad t \]

\[ N_{[\text{det \ sources}]} = n_{\text{sources}} \quad \left( \frac{4\pi}{3} \quad r_h^3 \right) \]

\[ N_{[\text{det \ sources}]} \equiv N_{\text{sources}}[\langle n_\mu \rangle \geq 1] \]

\[ N_{[\text{det \ sources}]} \propto \frac{\mathcal{L}}{L} \quad \left( \sqrt{L} \right)^3 \]
$N_{[\text{det sources}]} \propto \frac{L}{\bar{L}} (\sqrt{L})^3$

Obtain from diffuse flux

Estimate from Astrophysical considerations.

$N_{[\text{det sources}]} \sim 1.2 \, L_{35} \sqrt{L_{45}} \, (A t)_{Km^2yr}^{3/2}$
We know there are extragalactic neutrinos because there are (extra galactic) cosmic rays, and the sources of CR are also sources of neutrinos.

A more precise prediction requires a model for the CR production (and source).

AGN 's
GRB's
[or something else]
ACTIVE GALACTIC NUCLEI

- Narrow Emission Line Region
- Jet
- Dust Torus
- Broad Emission Line Region
- Accretion Disk
- Black Hole
GRB: associated with a subset of SN Stellar Gravitational Collapse

\[ \Gamma > 100 \]
Extraordinary Large (beamed) Energy Output
41 GRB used by AMANDA [Waxman/Bahcall model]

Photon detection

Neutrino assumed spectrum
GRB $\nu$'s: IC40 constraints

- No $\nu$'s for 117 GRBs ($\sim1$ expected, at 90\%CL $<2$)
- IC is achieving relevant sensitivity
Gamma Ray bursts are obviously VERY attractive as a neutrino source!

[time coincidence with event visible in photons up to very large redshift !!]
Gamma Ray bursts are obviously VERY attractive as a neutrino source!

[time coincidence with event visible in photons up to very large redshift !!]

Prediction from GRB has been forcefully motivated [talks of E.Waxman, S.Razzaque] but remains [warning : personal opinion !] very speculative. [possible problems with energy budget?]

Can the model be falsified with Neutrino Data? [possible, but some room to “escape”]
What will we learn?

- Detection: highly informative
  - Identify CR source
  - Strong support: Baryon dissipation
  - Fundamental/ν physics

- Non-detection: ambiguous
  - $10/km^2\text{yr}$ is an order of mag. (proportional to $\zeta \times dQ/dE \times f_\pi$)
  - Significant non-detection ($\ll 10/km^2\text{yr}$, $\ll 1\nu/100\text{GRB}$)
    Poynting jet (no p)
    or
    Dissipation mechanism (eg no p acceleration to relevant E)
    or
    Radiation mechanism ($\Rightarrow f_\pi \ll 0.2$)

From E.Waxman talk

Question: how can one falsify this model!?
Neutrino Point Sources
Prediction of the neutrino Flux from the photon flux [+ additional information]

Multi-wavelength observations

\[ \phi_{\gamma}(E) \]

Astrophysical source

\[ \phi_{\nu}(E) \]

Earth
$$\phi_{\gamma}^{\text{leptonic}}(E) + \phi_{\gamma}^{\text{hadronic}}(E)$$

Possible absorption in the source

Propagation effects (extragalactic)

$$\phi_{\gamma}(E)$$

Earth

Energy extrapolation

Flavor oscillations (good theoretical control)

Astrophysical source
Astrophysical Object containing:

Populations of relativistic protons, Nuclei electrons/positrons

Emission of:

Γ αµ µ α rays
Neutrinos
Cosmic Rays
$p + \text{target} \rightarrow \text{many particles}$

$\rightarrow p(n) + \pi^+ + \pi^- + \pi^0$

$\mu^+ + \nu_\mu \rightarrow \gamma + \gamma$

$e^+ + \nu_e + \bar{\nu}_\mu$

“Hadronic Emission”

$e^+ + B \rightarrow e^+ + \gamma_{\text{synchrotron}}$

“Leptonic Emission”

$e^+ + \gamma_{\text{soft}} \rightarrow e^+ + \gamma_{\text{Inverse Compton}}$
1. Neglect photon absorption in propagation from source

2. Neglect photon absorption INSIDE the source

Rule of thumb:

Summing over all 6 neutrino types (2 * 3 flavors)

1 "hadronic-photon" $\approx$ 1 Neutrino

"Counting + Energy spectra"

$p + p \rightarrow \pi^+ + \pi^- + \pi^0 + K^+ + K^- + \ldots$

$\rightarrow \mu^+ (\nu_\mu)$

$\rightarrow e^+ (\nu_e \bar{\nu}_\mu)$

Very very naively $2 * 3$ / $1*2$ wrong!
Exact Power Law spectra: \( K E^{-\alpha} \)

\[
\frac{\phi(\nu)}{\phi(\gamma)}
\]

Before \( \nu \) Oscillations

\[
\{\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau\} \simeq \{1 + \epsilon, 1 - \epsilon, 2, 2, 0, 0\}
\]
Effect of Neutrino Oscillations

\[ \langle P(\nu_\alpha \to \nu_\beta) \rangle = \langle P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \rangle = \sum_j |U_{\alpha j}|^2 |U_{\beta j}|^2 \]

\[
\approx \begin{pmatrix}
0.6 & 0.2 & 0.2 \\
0.2 & 0.4 & 0.4 \\
0.2 & 0.4 & 0.4 \\
\end{pmatrix}
\quad (1)
\]

Before Oscillations

\{\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau\} \approx \{1 + \epsilon, 1 - \epsilon, 2, 2, 0, 0\}

After Oscillations

\{\nu_e + \bar{\nu}_e, \nu_\mu + \bar{\nu}_\mu, \nu_\tau + \bar{\nu}_\tau\} = \{1, 1, 1\}
\[ \phi_\nu(E) = \frac{1}{4 \pi r^2} \left[ \frac{L^{\text{decade}}(E_*)}{\ln 10} \right] E^{\frac{\alpha - 2}{2}} E^{-\alpha} \]
Neutrino induced Muon signal

\[ \Phi_{\mu \uparrow} \simeq (1 \div 5) \left[ \frac{\phi_\nu(\geq 1 \text{ TeV})}{10^{-11} \text{ (cm}^2\text{s})^{-1}} \right] \text{ (Km}^2\text{ yr})^{-1} \]

Energy Response:
Peak @ 20 TeV
From the Neutrino Flux to the Muon induced signal.

\[ N_{\mu} \uparrow \approx 7.5 \times \left( \frac{L}{10^{34} \text{ erg/s}} \right) \left( \frac{\text{Kpc}}{r} \right)^2 \left( \frac{A t}{\text{Km}^2 \text{ year}} \right) \]

\[ N_{\mu} \uparrow \approx 0.4 \times \left( \frac{L}{10^{46} \text{ erg/s}} \right) \left( \frac{A t}{\text{Km}^2 \text{ year}} \right) \frac{1}{z^2} \]
Line: 1 (muon event)/(km² yr)

How many sources Are here ??!

Galaxy

Cen A  Mrk 421/501  z = 1
Very direct connection with TeV Gamma Astronomy!!

A field that in the last few years has been collecting remarkable results.

We have (HESS) a scan of the Milky Way disk! We know which one are the brightest TeV sources in our Galaxy, and the luminosity of these sources.

SNR
Pulsars
Pulsars Wind Nebulae
$\mu$ Quasars
15 New Sources + 3 Known

"SCAN" of the Galactic Plane
Table 3. Galactic sources.

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* Flux in the unit of $10^{-12}$ cm$^{-2}$ s$^{-1}$ TeV$^{-1}$ at 1 TeV.

Table 4. Galactic sources—continued.

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a Flux in the unit of $10^{-12}$ cm$^{-2}$ s$^{-1}$ TeV$^{-1}$ at 1 TeV.

b Spectral index $\Gamma$ when fitted by $E^{-\gamma}$. See text for details.

c: point-like, e: extended. m: morphological structure studied.
**Table 3. Galactic sources.**

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CRAB Nebula
SNR: RX 1713.7 -3946 (SN 393A)
SNR: R0952-4622 (Vela

**Table 4. Galactic sources—continued.**

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<td>1.8</td>
<td>e</td>
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<td>G29 17 47</td>
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<td>e</td>
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<tr>
<td>G30 18 00</td>
<td>-24 00</td>
<td>1.9</td>
<td>2.5</td>
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<td>SNR? W28</td>
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<td>G31 18 04</td>
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<tr>
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<td>-19 18</td>
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<td>2.2</td>
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<td>-13 44</td>
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<td>m</td>
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<tr>
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<tr>
<td>G44 19 12</td>
<td>+10 10</td>
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<td>2.1</td>
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<td>+58 49</td>
<td>0.7</td>
<td>2.5</td>
<td>p?</td>
<td>SNR Cas A</td>
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</tr>
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</table>

\(a\) Flux in the unit of \(10^{-12}\) cm\(^{-2}\) s\(^{-1}\) TeV\(^{-1}\) at 1 TeV.

\(b\) Spectral index \(\Gamma\) when fitted by \(E^{-\Gamma}\). See text for details.

\(c\) p: point-like, e: extended, m: morphological structure studied.
## Table 5. Extragalactic sources.

| E1  | 02 32 53.2 | +20 16 21 | 0.62 | 2.5 | 0.140 | 1ES 0229+200 |
| E2  | 03 49 23.0 | −11 58 38 | 0.45 | 3.1 | 0.188 | 1ES 0347−121 |
| E3  | 05 50 40.8 | −32 16 18 | ~0.3 | 2.8 | 0.069 | PKS 0548-322 |
| E4  | 10 15 04.1 | +49 26 01 | ~0.3 | 4.0 | 0.212 | 1ES 1011+496 |
| E5  | 11 03 37.7 | −23 29 31 | 0.4  | 2.9 | 0.186 | 1ES 1101−232 |
| E6  | 11 04 27.6 | +38 12 54 | 12−97 | 2.4−3.1(3) | 0.031 | Mkn 421 |

| E7  | 11 36 26.4 | +70 07 28 | 0.9  | 3.3 | 0.046 | Mkn 180 |
| E8  | 12 21 22.1 | +30 10 37 | 1.3  | 3.0 | 0.182 | 1ES 1218+304 |
| E9  | 12 30 54.4 | +12 24 17 | ~1   | 2.9 | 0.004 | M87 |
| E10 | 12 56 11.1 | −05 47 22 | e    |     | 0.536 | 3C279 |
| E11 | 14 28 32.7 | +42 40 20 | 1−2  | 2.6−3.7 | 0.129 | H 1426+428 |
| E12 | 15 55 43.2 | +11 11 21 | 0.1−0.2 | 4.0 | 0.36? | PG1553+113 |
| E13 | 16 53 52.1 | +39 45 37 | 0.5−100 | 1.9−2.3(5) | 0.034 | Mkn 501 |
| E14 | 19 59 59.9 | +65 08 55 | 4−120 | 2.7−2.8 | 0.047 | 1ES 1959+650 |

| E15 | 20 09 29.3 | −48 49 19 | 0.2  | 4   | 0.071 | PKS 2005-489 |
| E16 | 21 58 52.7 | −30 13 18 | 2−3  | 3.3−3.4 | 0.116 | PKS 2155-304 |
| E17 | 22 02 43.3 | +42 16 40 | ~0.3 | 3.6 | 0.069 | BL Lacetae |
| E18 | 23 47 06.0 | +51 42 30 | 1−5  | 2.3−2.5 | 0.044 | 1ES 2344+514 |
| E19 | 23 59 07.9 | −30 37 41 | ~0.3 | ~3.1 | 0.165 | H 2356−309 |

---

*a* Flux in the unit of \(10^{-12} \text{ cm}^{-2} \text{ s}^{-1} \text{ TeV}^{-1}\) at 1 TeV.

*b* Spectral index \(\Gamma\) when fitted by \(E^{-\Gamma}\).

*c* Red shift.
TeV Galactic Sources  
Measured by HESS, MAGIC  

Have FLUX:  
\[ \text{Flux} \left( E_\gamma > 1 \, \text{TeV} \right) = 0.11 - 2.1 \]

UNIT: \( 10^{-11} \left( \text{cm}^2 \, \text{s} \right)^{-1} \)

Three Brightest sources in the TeV sky:  
CRAB NEBULA  
2 young SNR  
Vela Junior  
RX 1713.7-3946
\[ \Phi(E > 1 \text{ TeV}) \approx 10^{-11} \text{ (cm}^2 \text{ s})^{-1} \]

TeV Photons in a Cherenkov Telescope

\[ \sim 10 \text{ events/hour} \]

Up-going muons Neutrino telescope

\[ \phi(E) \propto E^{-2} \]

\[ \sim 2 \text{ events/Km}^2 \text{ yr} \]
\( \langle \phi_{\mu} \rangle \) (km\(^2\) yr\(^{-1}\))

\( \phi_{\nu}(> 1 \, \text{TeV}) = 10^{-11} \, \text{cm}^{-2} \, \text{s}^{-1} \)

\( \alpha = 2.2 \)
IF TEV emission of the brightest TeV sources is of hadronic nature

Detection with neutrinos is within reach ..... Few events / (km2 yr)

...but

NOT EASY !
BACKGROUND

Atmospheric Neutrinos

- Thin lines: Atmospheric $\nu$
- Integration Angle: $0.3^\circ$
- Thick lines: $\phi_\nu = K E^{-2.2}$
- $[cos\theta_{zenith} = 0, -1]$
Angular Distribution of the Neutrino-induced Muons

\[ \alpha = 2.2 \]

- 50% (red dashed line)
- 75% (blue dotted line)
- 90% (red dashed-dotted line)
- Optimum (black line)

Cone Radius (degrees) vs. \( E_\mu \) (GeV)
SuperNova RX J1713.7-3946

Discovered in 1996 by the Roentgen Satellite (Rosat)

Foreground star

Point Source (Neutron Star)
Observations of the young Supernova remnant RX J1713.7–3946 with the Fermi Large Area Telescope

astro-ph/1103.5727. 29th March 2011

Favors leptonic interpretation.
Critical Question:

Can Multi-wavelength Observations Identify the origin of the emission?
Neutrino Astronomy should be considered in the context of the scientific programs toward the understanding of the “High Energy Universe”.

What is the significance of the observations of a small number of neutrinos from several sources?

[Can the hadronic nature of the emission be established without neutrinos, from multiwavelength observations?]

Power of discrimination is widely considered as important
What about “ABSORBED SOURCES?”

(Much) Higher flux in neutrinos than in photons?

Best cases for making a bet:

- GALACTIC CENTER (of course!)
- MicroQuasars

..... Surprises? ......
GALACTIC CENTER

Colors: H.E.S.S.
Contours: Radio

Angular distribution

Point-like core
Extended tail
Similar to NFW profile
MICROQUASARS

GRS 1915+105

Galactic binary system with one stellar mass black hole

Symmetric emission of Plasma "blobs"

Detection in Radio (VLBI)
Geometry of the emission of the two jets

Intense radiation field
Of the companion star
Absorbs TeV photons [?]
Neutrino Astronomy

\[ E_\nu \sim [10^{10} \div 10^{12}] \text{ eV} \]

\[ E_\nu \sim [10^{13} \div 10^{14}] \text{ eV} \]

\[ E_\nu \sim [10^{14} \div 10^{17}] \text{ eV} \]

\[ E_\nu \sim [10^{17} \div 10^{20}] \text{ eV} \]

\[ E_\nu \gtrsim 10^{20} \text{ eV} \]

**Dark Matter**

**Point sources**

**GRB [exploration]**

**Cosmogenic Neutrinos**

“Exotic” (TD decay...)**
Additional Topics for a complete discussion:

- Atmospheric Neutrinos
- Cosmogenic “GZK” Neutrinos
- Exotic Physics Neutrinos (Top-Down Models)
- Dark Matter Annihilation Neutrinos (from the Sun or the Center of the Earth)
- “Interdisciplinary studies”
Final comments (instead of conclusions)
Final comments (instead of conclusions)

Best Wishes to the Observers !!
The interest of Neutrino Astronomy is remarkable.

The difficulties are great.

Detector optimization requires identifying “Physics priorities”

Focus on Galactic Sources
Deeper searches for Extra-galactic Sources
Search for GRB emission
“GZK” cosmogenic neutrinos.

Better angle, energy (for muon) resolution

Very large “sparse” detectors?