the birth of high energy neutrino astrophysics

Two events:
- **First extra-terrestrial source : our Sun** but not at the expected rate : Solar neutrino puzzle

R. Davis pioneer experiment in Homestake Mine in 1966: High threshold radio-chemical (615 t Cl, Cl) neutrino pioneer experiment in 1966 R. Davis in Homestake gold mine) detects only ~1/3 of expected rate in the 60' via the reaction 
\[ ^{37}Cl \, (\nu_e, e^-) \, ^{37}Ar \]
with a reaction threshold \( E_{\nu}^{\text{thr}} = 0.814 \) MeV
Standard solar model called into question. The resolution in 2000 has deep consequences for our understanding of the nature of the neutrino

- **SN1987A: core collapse supernovae**

20 neutrinos detected within 10 seconds with 3 detectors (BAKSAN, Kamiokande-II, IMB)
→ Birth of extra-galactic neutrino astronomy

These neutrinos are “low” energy, in the range ~0.1 - 30 MeV

The observation of ~20 neutrinos within 10 s from the core collapse supernovae SN1987A is remarkable → birth of neutrino astroparticle physics

Reminder : in a core collapse SN type Ib/c, II, most of the binding energy is released into a prompt neutrino burst (99%). Only 1% for the EM burst.

Very roughly : After the gravitational collapse, electron degeneracy pressure not enough to prevent the further collapse → neutronization → inverse beta decay → electron neutrino. The neutron core is very hot and cools down by releasing thermally produced nu-antinu pairs

Supernova direction reconstruction: E.g. Super-K detect them according to inverse beta reaction: anti-nu_e + p → n + positron → cherenkov light, isotropic
A few % of the interactions are elastic scattering: nu_x + e → nu_x + e, which keeps “some” directional information and allows to reconstruct the SN location within few degrees (d=8.6 kpc).

Recently, the neutrino revolution happened : our Sun, a familiar object surrounded by the 50 years old mystery of neutrino deficit, revealed the elusive nature of neutrinos → marks a major step in the birth of astroparticle physics, i.e. by combining astro- and particle- physics, shortly after the first observations of the CMB anisotropies. The connection goes both way.
Traditionally, our knowledge of the sky comes mainly from the observation at various wavelengths. Recent progresses have been made towards longer wavelengths, with the revolution of the CMB observations, objects have been found out to be emitters at ever increasing energies, X-ray, MeV, GeV with satellite observations and now up to 10's of TeV by means of ground telescope arrays, measuring the Cherenkov light emitted by the charged particles of the EM atmospheric shower.
In parallel, Cosmic Rays have been discovered and are measured over 15 orders of magnitude in energy, from MeV to ZeV, by means of various experimental techniques, basically direct detection on board satellites up to 100 TeV and atmospheric shower residuals on surface array above (fluorescence, charged component reaching the ground, Cherenkov light).

Through the measurement of spectral abundances, CR have provided a wealth of knowledge of our environment, notably
- pinpointing toward Fermi 1\textsuperscript{st} order acceleration mechanism and excluding 2\textsuperscript{nd} order (re-acceleration),
- giving serious hints on the morphology of the galaxy

through the study of “cosmic clocks”, spectral fraction of primary CR to spallation products, variable spectral index of primary CR, ... → Standard Leaky Box Model

![Graph showing reacceleration and E-dependence of $\lambda_{\text{esc}}$.](Image)

![Graph showing residence time (combined with $\lambda_{\text{esc}}$) → $\langle p \rangle$.](Image)

![Graph showing $\text{Be}^{7}/\text{B}^{10}$ vs. kinetic energy (GeV/n).](Image)

Fe preferentially interacts instead escape → spectral index closer to injection spectrum.
HE CRs are mainly ions
Power law spectrum
Covers huge energy range
Knee
Ankle
GZK cut-off

Galactic Magnetic Field:
\[ \rho_E \sim B^2 \sim \text{eV/cm}^3 \]

CR spectrum (to the knee):
\[ \rho_E = \frac{4\pi}{c} \int E^2 dN dE \sim \text{eV/cm}^3 \]

One SN / 30 year in our galaxy, each with luminosity \(10^{41}\) erg/s and active for 1000 yr:
\[ L_{SN} \sim 3 \cdot 10^{42}\] erg/s
provide the right power for galactic CR
\[ L_{CR} \sim V_{\text{disk}} \rho_E / \tau \sim 3 \cdot 10^{40}\] erg/s
(where \(\tau \sim \text{few } 10^6\) yr is the average GCR confinement time) up to the knee provided ~few% of released energy is converted into kinetic energy of CR:
Why should we look at the sky with neutrinos:

Because they do provide a complementary information / view on the cosmos, e.g.

They may escape dense environment, contrary to photons / CR
→ they vehiculate a unique information

They may travel without interacting or being deflected over cosmological distances, contrary to photons / CR

By combining the information of these messengers (the astroparticles), it may be possible to recover part of the missing / incomplete / lost / degraded information carried by photons / CR

These high qualities which makes the neutrino unique follow from the fact that it is a weakly interacting, light and neutral particle. Detecting neutrinos is therefore a challenge for the exact same reasons.
Propagation of photons & Gamma astronomy:
- The optical depth is increasing with energy
- Short PeV photons attenuation length
- Above TeV, spectra from close by AGN are affected

Propagation of charged cosmic rays:
Deflection in (extra-)galactic magnetic field scrambling the direction of origin
\[ r_L / \text{kpc} = E_{18} / (Z B_{\mu G}) \]
(This relation should also hold at the source, i.e. \( E_{\text{max}} = ZBL \) and may explain the knee)

Neutrons
\[ E = 1 \text{ EeV} \]
\[ \lambda = \gamma \tau = 8.6 \text{ kpc} = d_{\text{Sun-GC}} \]

Interaction
\[ p + \gamma_{\text{CMB}} \rightarrow \pi + n \]
Mikheyev – Smirnov – Wolfenstein Matter effect:

Exercice.

See any text book. Basically due to the fact that electron neutrinos interacts in a different way than other flavors with matter. While NC interactions are the same for all three flavors, CC interactions differ

→ free propagation and forward scattering interfere, leading to a matter contribution to the oscillation pattern, which takes the form:

\[ \mathcal{H}_e = \frac{4G_F}{\sqrt{2}} \left( \bar{\nu}_e \gamma^\mu \frac{1 - \gamma^5}{2} \nu_\mu \right) \left( \bar{e} \gamma^\nu \frac{1 - \gamma^5}{2} e \right) \]

Routine calculation can be done and show that at energies above ~MeV,

\[ \theta_m = \theta_{\text{sol}} \]

→ experiments like CHLORINE and Kamiokande have measured a solar neutrino flux less than expected in pure vacuum: \[ p_m(\nu_e \rightarrow \nu_e) = \cos^2 \theta_m \]
Neutrino astroparticle physics

ELECTROMAGNETIC SPECTRUM

NEUTRINO SPECTRUM

Produced by
New Particles

Produced by
Ultra-High Energy Cosmic Rays

Limited

Limited

Radio, microwave, IR, Visible, UV, X-rays, gamma rays, VHE gamma rays

Integral neutrino & acoustic

28 Mai 2009 Mathieu Ribordy, 3rd Cycle (intro)
What makes neutrino astronomy possible and goals

- Effective volume quickly increases with energy, from the combination of rising cross section and muon range, fully (up to 10 TeV) and then partly (above) compensating the decline of the flux (for a spectral index $\alpha=2$)

- Above TeV energies, neutrino telescopes can reach an angular resolution $\approx 0.1 - 1^\circ$ ($0.1^\circ$ pour les gammas) $\Rightarrow$ astronomy

- At High energies, atmospheric neutrino flux constitutes an irreducible background for extra-terrestrial neutrino search. Fortunately, this flux is softer than expected from cosmic accelerators (strong shock acceleration, large scale electric fields)

- There exist High Energy guaranteed fluxes which should be in the reach of the current high energy neutrino telescope generation: diffuse galactic neutrinos, predominantly from the higher density disk region; diffuse cosmogenic neutrinos resulting from the GZK interactions of UHE protons with CMB

- High energy neutrino telescopes are dedicated to the detection guaranteed fluxes and aims at revealing hypothetical fluxes as a signature of hadronic acceleration via pp et $p\gamma$ processes. The main ambition is to solve the 100 year old cosmic ray origin controversy (which has not yet been resolved through photon multiwavelength spectral studies, as the extraction of the $\pi^0$ decay component may be drawn in Inverse Compton / Bremsstrahlung components)
Neutrino sources

**Terrestrial sources**
- (anti-) Muon / Electron neutrinos beam from pion decays produced by interaction of CR with the atmosphere → (GeV)
- Nuclear power plants, natural radiactivity → (MeV)
  
  (e.g. $^{40}$K with $\tau_{1/2} = 1.25 \times 10^9$ yr in the crust, $^{14}$C with $\tau_{1/2} = 5530$ yr produced in the high atmosphere according to $n + ^{14}$N $\rightarrow ^{14}$C + p)

**Extra-terrestrial sources**
- Solar fusion → (MeV)
- Supernovae → all type (MeV)
  - Hypothetical from the interaction of CR in galactic or extra-galactic accelerators with surrounding matter and radiation field → (anti-) neutrinos e / $\mu$
  - Supernova remnants, galactic binaries, gamma ray bursts, active galactic nuclei
- Neutrinos over a large spectrum
- Related to the cosmic puzzle
  - Diffuse guaranteed flux: galactic disk (interaction with ISM), cosmogenic from interaction of UHE CR with CMB
  - Exotic particle annihilation: e.g. dark matter WIMP accumulating in the core of the Sun ~100 GeV or in the galactic center
Neutrino interactions

Neutral and Charged current interactions:
- NC and CC
- $\sigma_{\nu - e/N} \sim G_F^2 m_{e/N} E_\nu$ in the range $E_\nu \gg m_{e/N}$ and $E_\nu < M_Z^2 / m_{e/N}$
- $\sigma_{\nu} \sim E_\nu^{0.363} \ (10^{16} \text{ eV} < E_\nu < 10^{21} \text{ eV})$

Quark – neutrino interactions:
- all flavors through NC + NC
- Electron – neutrino interaction:
  - much smaller than $\nu N$
  - all flavors: NC
  - electronic flavors: CC
    - anti neutrino
      - Glashow resonance
    - neutrino
      - MSW effect from interferences of diagrams with $Z$ and $W$ exchange

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Neutrino oscillation formalism

Similarly to the quark sector (via CKM matrix), neutrino mass eigenstates and weak eigenstates do not coincide (because mass is not zero) but related via the unitary MNS (Maki-Nakagawa - Sakata) mixing matrix $U$:

$$|\nu_{\alpha}\rangle = \sum_{i} U_{\alpha i} |\nu_{i}\rangle$$

$$|\nu_{\beta}\rangle = \sum_{i} U_{\beta i}^* |\nu_{i}\rangle,$$

Orthonormal states:

$$\langle \nu_{i}|\nu_{j}\rangle = \delta_{ij}, \quad \langle \nu_{\alpha}|\nu_{\beta}\rangle = \delta_{\alpha\beta},$$

Unitarity

$$\sum_{i} U_{\alpha i} U_{\beta i}^* = \delta_{\alpha\beta}, \quad \sum_{i} U_{\alpha i} U_{\alpha i}^* = \delta_{\alpha\alpha}$$

Given a neutrino produced with a momentum $p$ in a flavor state $\alpha$ at position $x=0$ and time $t=0$: $|\nu\rangle(0,0) = |\nu_{\alpha}\rangle$. The evolution of mass eigenstates is governed by

$$|\nu_{i}(x,t)\rangle = e^{-iE_{i}t-px}|\nu_{i}\rangle = e^{-i(m_{i}^{2}/2E)t}|\nu_{i}\rangle$$

for relativistic neutrinos. The phase factor depends on the neutrino mass $\rightarrow$ the flavor content of the propagated state may differ from the initial state:

$$|\nu_{\alpha}(x,t)\rangle = \sum_{i} e^{-iE_{i}t-px} U_{\alpha i} |\nu_{i}\rangle = \sum_{i,\beta} U_{\alpha i}^T e^{-i(m_{i}^{2}/2E)t} U_{\beta i} |\nu_{\beta}\rangle$$

The probability of appearance of flavor $\beta$ at distance $L$ is therefore (no CP violating phases):

$$P_{\nu_{\alpha}\rightarrow\nu_{\beta}}(L) = \sum_{i} U_{\alpha i}^2 U_{\beta i}^2 + 2 \sum_{j>i} \cos\left(\frac{\Delta m_{ij}^2 L}{2E}\right) U_{\alpha i} U_{\beta i} U_{\alpha j} U_{\beta j}$$

$$= \delta_{\alpha\beta} - 4 \sum_{j>i} \sin^2\left(\frac{\Delta m_{ij}^2 L}{4E}\right) U_{\alpha i} U_{\beta i} U_{\alpha j} U_{\beta j}$$

There are still many open questions, regarding the neutrino, among which

- Mass
- Dirac or Majorana
Neutrino oscillation formalism

Experimental values:
\[
\Delta m^2_0 \equiv \Delta m_{12} \approx 8 \times 10^{-5} \text{ eV}^2
\]
\[
\Delta m^2_{\text{atm}} = \Delta m_{23} = \Delta m_{13} \approx 2.4 \times 10^{-3} \text{ eV}^2
\]
\[
\theta \equiv \theta_{12} \approx 33^\circ, \; \theta_{\text{atm}} \equiv \theta_{23} \approx 45^\circ, \; \theta_{13} \approx 0^\circ
\]

therefore the MNS matrix takes the values
\[
U = \begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\nu1} & U_{\nu2} & U_{\nu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix} \approx \begin{pmatrix}
c_{12} & s_{12} & 0 \\-
s_{12}/\sqrt{2} & c_{12}/\sqrt{2} & 1/\sqrt{2} \\s_{12}/\sqrt{2} & -c_{12}/\sqrt{2} & 1/\sqrt{2}
\end{pmatrix}
\]

In case of two flavors, this is reduced to
\[
P_{\alpha \to \beta \neq \alpha} = \sin^2(\Delta m^2 L/4E) \sin^2 2\theta
\]

A useful form for the oscillation prob. is
\[
P_{\alpha \to \beta \neq \alpha} = \sin^2\left(1.27 \frac{\Delta m^2}{\text{eV}^2} \frac{L}{\text{km}} \frac{\text{GeV}}{E}\right) \sin^2 2\theta
\]

The corresponding oscillation length
\[
L_{\text{osc}} = 4\pi E / |\Delta m|^2 \approx 2.5 \times 10^{-3} (E / \text{PeV}) (10^{-5} \text{ eV}^2 / |\Delta m|^2) \text{ pc}
\]
is much smaller than astrophysical distances.

In case of propagation over astrophysical distances \((L \gg 4E / |\Delta m|^2)\) and given the source extension and finite energy resolution of the detector \(\sigma(L/E) \gg L/E\), we have
\[
P^{L/E \gg 1/|\Delta m|^2}(L) = \delta_{\alpha \beta} - 2 \sum_{j \neq i} U_{\alpha j} U_{\beta j} U_{\alpha j} U_{\beta j}
\]

Exercice:
Show that the 2-flavor oscillation scheme is satisfying to describe solar and atmospheric neutrino oscillations (Hint: atm. \(E_{\nu} \sim \text{GeV}\), solar: \(E_{\nu} \sim \text{MeV}\))

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Neutrino oscillation formalism

Because of the "special" values taken by $\theta_{23}$ and $\theta_{13}$, the relation between the flux at Earth and the flux at the source (assuming neutrinos from pp or p$\gamma$)

$$\Phi^\text{source}_\nu = \{1/3, 2/3, 0\} \longrightarrow \Phi^\text{Earth}_\nu = \{1/3, 1/3, 1/3\}$$

(where $\Phi = \{\nu_e + \bar{\nu}_e, \nu_\mu + \bar{\nu}_\mu, \nu_\tau + \bar{\nu}_\tau\}$)

i.e equally populated in all three flavors.

Also, following neutron decay (c.f. transparent source model, GZK flux), we have

$$\Phi^\text{n}_\nu = \{1, 0, 0\} \longrightarrow \Phi^\text{n,Earth}_\nu = \{3/5, 1/5, 1/5\} \quad \text{where } \Phi_n = \{\bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau\}$$

This opens new experimental perspectives

- potential source detection with different kinds of signature
- allows to look at very high energy neutrinos with tau flavor, other hindered (see later)
**Glashow resonance, pp, pγ**

*pp versus pp:* in principle, the dominant processes at the source can be distinguished because (notation: $\Phi_\nu = \{\nu_\alpha, \bar{\nu}_\alpha, \nu_\beta, \bar{\nu}_\beta, \nu_\gamma, \bar{\nu}_\gamma\}$):

- $pp \rightarrow \pi^+ \pi^- \rightarrow \Phi_{pp} = \{1/6, 1/6, 1/3, 1/3, 0, 0\}$
- $p\gamma \rightarrow n \pi^+ \rightarrow \Phi_{p\gamma} = \{1/3, 0, 1/3, 1/3, 0, 0\}$

At Earth $\Phi_{\nu_{\text{Earth}}}$ is

- $\Phi_{\nu_{pp}} = \{1/6, 1/6, 1/6, 1/6, 1/6, 1/6\}$
- $\Phi_{\nu_{p\gamma}} = \{4/15, 1/15, 3/15, 2/15, 3/15, 2/15\}$

which are different: anti-electron neutrino flux is relatively smaller in case of $p\gamma$.

Given a detected extra-terrestrial source of PeV neutrinos, the Glashow resonance $\bar{\nu}_e$ around 6.3 PeV (0.7 PeV width) may allow to discriminate the dominant process at work in a cosmic accelerator:

$$\sigma (\bar{\nu}_e + e^- \rightarrow W^- \rightarrow \bar{\nu}_l + 1, \text{ hadrons}) = 5 \cdot 10^{-31} \text{ cm}^{-2}$$

10x bigger than for other flavors ($\sigma < 10^{-32} \text{ cm}^2$).
From 2-body kinematics of pion and 3-body kin. Of muon decay:
- In average, all leptons take $\frac{1}{4}$ of the pion energy (CoM)
- The max energy of the neutrino from pion decay is 42.7% in CoM

This plot shows the pion multiplicity above some energy, for various proton energy from interaction of a high energy proton on a target at rest
The SOUDAN – II is an 700t iron calorimeter experiment in a mine in Minnesota, operating since 1989.

**Particle flux VS slant depth**

**Definition:** The **slant depth** is the integrated column density along the particle trajectory. It increases with increasing zenith angle.

The intensity is decaying exponentially up to ~14 kmwe and then turn into a constant: Neutrinos.

High energy neutrino telescopes are located between 1 – 5 km. At 2 kmwe depth, $\Phi_{\nu} / \Phi_{\mu} \sim 10^{-6}$

→ Muons constitute a background regarding efficiencies of neutrino analyses as they may be mis-identified as traveling upward (i.e. $82^\circ < \theta_{\text{zen}} < 180^\circ$ in this exemple)

![Particle flux VS slant depth diagram](image)
Atmospheric muon / conventional neutrino spectra

Muon / Neutrino spectra can be derived from coupled equations describing the development of an atmospheric shower with MC

There are some analytical and approximate solutions

\[
\frac{d\Phi_\mu}{dE_\mu} \propto E^{-2.7} \left( \frac{1}{1 + \frac{1.1 E_\mu \cos \theta}{\epsilon_{\mu \ell \pm}}} + \frac{0.054}{1 + \frac{1.1 E_\mu \cos \theta}{\epsilon_{K \ell \pm}}} \right)
\]

when muon energy loss are neglected. A similar form also describes the neutrino flux.

**We notice that:**
- \( \frac{d\Phi_\nu}{dE} \)_{horiz} > \( \frac{d\Phi_\nu}{dE} \)_{vert}, contrary to the isotropic prompt ν-flux as \( \epsilon_{\text{charmed}} \gg \epsilon_{\pi, K} \)
- The spectral index progressively increases from by one unit with increasing energies \( \alpha=2.7 \rightarrow \alpha=3.7 \). This is due to an increased probability of the mother particles to reinteract before decay (\( \chi = \lambda_{\pi/K} = 116 \text{ g/cm}^2 \text{VS } \tau_{\pi/K} \), depends on altitude)

The softening of the atmospheric spectrum is essential for high energy neutrino telescope to do astronomy, leading to a strong reduction of the local background
Atmospheric muons

Following superposition principle (nuclei \( A \) with energy \( E \) behaves as a collection of \( A \) nucleons with energy \( E/A \)):

\[
N_{\mu}^{Fe} > N_{\mu}^{p}
\]

with a softer spectrum for muons from Fe \( \rightarrow \) there is a depth depending on the primary CR energy \( E_{\text{crit}} \) where this relation is inverted (e.g. 1.5 kmwe for 200 TeV primaries).

Cosmic ray composition in the knee region can be studied with the coincident detection of events on the ground and at depth as \( N_{\mu} \) is anti-correlated to \( N_{\nu} \)
- Measure the total light output from muons (simple method)
- Measure the fading of light in the detector (more sophisticated method)

Reminder:
Behavior of the muon density on the ground in the knee region: \( N_{\mu}^{p} \sim E^{1/\alpha} \), where \( \alpha=1+\epsilon \)
Therefore
\[
N_{\mu}^{A} \sim A(E/A)^{1/\alpha} \sim A^{1-1/\alpha} N_{\mu}^{p}, \text{ i.e. } N_{\mu}^{A} / N_{\mu}^{p} = A^{\epsilon} > 1
\]
The prompt neutrino flux results from semi-leptonic decay of $D^+$ (cd), $D^0$s (cu), $D^+_s$ (cs), $\Lambda^+_c$ (udc), ... 

$D_s$ decay is the unique source of tau neutrinos, which may compete with tau neutrinos following oscillations of atm / extra-terrestrial muon neutrinos
Neutrinos interact in the effective volume of the detector

Extra-terrestrial neutrinos may be masked by various background sources
- irreducible
- misidentified events
Neutrino Detection Methodology: detection channels

- High energy neutrino telescopes are all-flavor sensitive
- It may be possible to partly discriminate between flavors in a km$^3$ high energy neutrino telescope

- **NC:** Hadronic cascades from all 3 flavors
- **CC:**
  - Electron neutrino produce EM cascades
  - Muon neutrino produce bright muon tracks
  - Tau neutrino produce distinctive lollipop or double bang signatures above ~PeV

From simulations of the IceCube detector

28 mai 2009 | Mathieu Ribordy, 3rd Cycle (atmospheric neutrinos & neutrino detection)
High Energy Neutrino Detection: Methodology

Charged particles produce Cherenkov light which propagate in a transparent medium (ice, water)
- The energy and incidence direction of the particle is determined via the amount & time pattern of collected light
- With increasing energies, the incidence angle of the neutrino is more accurately determined

Neutrino-induced muon: the mean production energy is \( E_\mu = (1 - \langle y(E_\nu) \rangle) E_\nu \)

where the inelasticity is derived from the differential cross section (below ~10 TeV)

\[
\frac{d\sigma}{dE_\mu} = (0.72 + 0.06 \frac{E_\nu}{E_\mu}) \cdot 10^{-38} \text{ cm}^2 \text{GeV}^{-1}
\]

i.e.: \( \langle E_\mu \rangle = \frac{1}{\sigma} \int_0^{E_\nu} E_\mu \frac{d\sigma}{dE_\mu} dE_\mu \approx \frac{E_\nu}{2} \)

\[ \Rightarrow \langle y(E_\nu) \rangle \approx \frac{1}{2} \]

\[
\Theta_\mu = 1.5^\circ \left( \frac{E_\nu}{\text{TeV}} \right)^{0.363} \nu_{\mu \rightarrow \mu}
\]
Golden channel: Muon neutrinos

Muon energy loss can be parametrized: 

\[
\langle dE_\mu / dx \rangle = -\alpha(E_\mu) - \beta(E_\mu) E_\mu
\]

where \( \alpha = \alpha(E) \) and \( \beta = \beta(E) \) account for ionisation / stochastic energy losses, weakly dependent on energy (a+b logE)

\[
\alpha_{\text{rock}} = 2.4 \text{ MeV} / (\text{g cm}^{-2}) \quad \text{and} \quad \beta_{\text{rock}} = (4 - 5) \cdot 10^{-6} / (\text{g cm}^{-2})
\]

Definition: Critical energy 

\( \varepsilon = \alpha / \beta \approx 500 \text{ GeV} \)

below which ionisation dominates over stochastic energy losses.

Stochastic losses are dramatic events and represent a challenge for high energy neutrino data analysis:

- Bremsstrahlung
- Pair production \( e^+e^- \)
- \( \mu + \text{nucleon} \rightarrow \mu + \text{hadrons} \)
**Golden channel: Muon neutrinos**

- Compared to other neutrino flavor, the muon signature is particularly interesting, with a large increase of the effective volume of a detector $V(E_\mu) \sim A R(E_\mu)$.
- The energy at the interaction is not known in case this occurs outside of the instrumented volume. Propagation unfolding methods allow nevertheless to recover the muon angular distribution and differential flux.
- Combined to the neutrino interaction cross section, detectability is $\sim$cte up to $\sim$10 TeV for extra-terrestrial sources with spectral index $\alpha=2$.

Average muon energy at depth $X$:
$$E_\mu = (E_\mu^0 + \epsilon) e^{\beta x} - \epsilon$$

Muon range:
$$R_\mu = \ln(E_\mu/\epsilon + 1) / \beta$$

Logarithmic increase of the muon range above $\sim$TeV

A vertical muon on the ground needs 375 GeV to reach 1.5 km depth in ice.

Logarithmic increase of the muon range above $\sim$TeV

- Compared to other neutrino flavor, the muon signature is particularly interesting, with a large increase of the effective volume of a detector $V(E_\mu) \sim A R(E_\mu)$.
- The energy at the interaction is not known in case this occurs outside of the instrumented volume. Propagation unfolding methods allow nevertheless to recover the muon angular distribution and differential flux.
- Combined to the neutrino interaction cross section, detectability is $\sim$cte up to $\sim$10 TeV for extra-terrestrial sources with spectral index $\alpha=2$.
Earth screening

At high energy, the Earth is opaque to neutrinos, due to the cross section increase. The neutrino survival probability $P$ along a chord with zenith $\theta$ can be calculated, assuming an Earth density profile.

$$ P_{Earth}(E_{\nu}) = e^{-N_A \sigma_{\nu} E_{\nu} \int \rho(l) dl} $$

Opacity becomes important between 10 – 100 TeV

The shadow factor (the attenuation of an isotropic flux) is

$$ S(E_\nu) = \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} d\cos \theta \exp \left(-z(\theta)/L_{int}(E_\nu)\right) $$

where $z(\theta)$ is the integrated column density along the chord and $L_{int} = \frac{m_p}{\sigma}$.
Earth screening

Examples:
- \( E_\nu = 1 \text{ TeV}: \sigma = 8 \times 10^{-36} \text{ cm}^2 \) \( \Rightarrow P > 95\% \)
- \( E_\nu = 100 \text{ TeV}: \sigma = 3 \times 10^{-34} \text{ cm}^2 \) \( \Rightarrow P > 15\% \)
  (large opacity for \( \theta > 120^\circ \))
- \( E_\nu = 10 \text{ PeV}: \sigma = 2 \times 10^{-33} \text{ cm}^2 \) \( \Rightarrow \) limit the detection potential to 10-20\(^\circ\) below horizon. At the same time, the hemisphere above horizon gradually open to neutrino observations (atm. muon flux decay quickly in this range)

This does not affect as much tau neutrinos which regenerate along their path (very short lifetime \( \tau = 2.9 \times 10^{-13} \text{ s} \)) before losing energy (decay length \( \lambda = 49 \text{ m} / \text{PeV} \)). Nevertheless, their energy is lowered.
Given an astrophysical source of very high energy neutrinos, hidden in \( \mu/e \) neutrino channels, the tau neutrino flux is guaranteed through oscillations \( \Rightarrow \) interesting channel to observe the very high energy neutrino sky.
**Neutrino Detection Methodology:** Rate calculation

Consider neutrino-induced muons & a detector with length \( L \) and cross section \( A = L^2 \). For a particle to be detected, the interaction must occur at a distance \( R_\mu (R_\mu \gg L) \).

Therefore the effective volume is \( V = R_\mu \times A \).

The interaction probability \( P = P_{\nu \rightarrow \mu} (E) \) of a neutrino crossing the volume is approximately given by

\[
R_\mu / \lambda_\nu,
\]

where \( \lambda_\nu (E) \) is the neutrino interaction length.

The number of detected events during a time \( T \) is

\[
N = T A P \Phi = T A_{\text{eff}} \Phi,
\]

where \( \Phi \) is a monochromatic flux normal to \( A \).
Neutrino Detection Methodology: Rate calculation

**Definition:** The effective surface $S_{\text{eff}}$ is the surface of 100% detection efficiency (given a flux of neutrino with energy $E$ through a surface $S$).

It describes the detector potential in a way which is independent of the probed astrophysical models. The neutrino effective area is useful as it combines neutrino propagation/interaction, muon propagation and detector response. The expected outcome of an experiment can therefore be calculated:

$$n_{\text{model}} = \sum_{\alpha=e,\mu,\tau} T_{\text{life}} \int_{E_{\text{th}}} A_{\text{eff}}(E_{\nu_\alpha}, \delta) dE_{\nu_\alpha} d\Omega$$

The outcome from the background must be calculated as well.

For point source search, $\Omega$ is chosen in a way to maximize the significance (based on binomial statistics) and will depend on the details of an analysis, the corresponding PSF and the kinematics of the neutrino interaction $\Theta_{\nu \nu} \approx 1.6^\circ/\sqrt{E/\text{TeV}}$

The muon and neutrino effective area are related through the identity:

$$\int dE_\nu A^\nu_{\text{eff}}(E_\nu) \frac{d\Phi_\nu}{dE_\nu} = \int dE_\mu A^\mu_{\text{eff}}(E_\mu) \frac{d\Phi_\mu}{dE_\mu}$$

The muon effective area has no simple geometric explanation but can be extracted from the above identity. This is useful to understand the potential of a detector to a given astrophysical model with e.g. increasing the low muon energy cut (a detector measures the muon energy, not the neutrino energy)

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Neutrino Detection Methodology: Rate calculation

The effective surface is precisely derived via simulations

\[ A_{\nu}^{\text{eff}}(E_\nu, \Omega) = \epsilon \cdot V_{gen} \cdot N_A \rho \sigma_\nu(E_\nu) \cdot P_{Earth}(E_\nu, \Omega) \]

where

\[ \epsilon = \frac{N_{\text{sel}}(E_\nu, \Omega)}{N_{gen}(E_\nu, \Omega)} \]

Depend on the differential cross section, muon propagation and analysis
Neutrino Detection Methodology: Rate calculation
Larmor radius is given by \( r_L/Mpc = E_{18}/(Z B_{nG}) \) and can be coherent over large distances → UHE CR may keep track of their direction of origin over \(~100\) Mpc at the highest \( E \)

The Pierre AUGER Observatory:

- **Hybrid** detection of UHECR:
  - 4 fluorescence + 1600 surface detectors (1.5km spacing) for measurement of longitudinal & lateral shower profile → improved energy resolution, cross-calibration, sub-degree angular resolution, improving with \( E \) and shower inclination
  - UHE CR composition
  - UHE CR incidence direction
  - UHE tau neutrino flux (horizontal showers)
  - Exposure depends on \((\alpha, \delta)\), derived from acceptance and lifetime, 3000 km²

Note: **Fluorescence technique:**
- Measurement of Nitrogen scintillation light, \(~3-5\) photons / m (charged particle) at 10-15 km
- The composition is derived from the measurement of \( X_{max} \), the atmospheric depth of the max. development of the shower.

According to the superposition principle (Nuclei \( A \) with energy \( E \) is composed of \( A \) independent nucleons, each carrying a fraction of energy \( E/A \)) and from the Bethe-Heitler shower development toy model, \( X_{max} \) depends logarithmically with the atomic number \( A \) → composition w.r.t. \( E \) can be derived from the statistical studies of \( X_{max} \).

The primary energy can be estimated by integrating the electronic density along the shower axis (from the count of \( ^2\)N fluorescence photons), each electron / positron loosing energy through ionization (i.e. \( E_c/X_0 \sim 2.2\) MeV / (g/cm²), where \( E_c \) is the critical energy, when Bremsstrahlung and ioniation losses are equal and \( X_0 \) is the Bremsstrahlung radiation length).

Provided stereoscopic observation, a better reconstruction of \( E \), impact parameter and incidence direction can be determined.

Notes: **Tau neutrinos**
for nearly horizontal events, the EM component from a hadronic shower is long extinguished. A nearly horizontal tau neutrino can interact directly in the ground or surrounding mountains and decay \((\pi^\tau \nu_\tau \text{ or } e^\nu_e \nu_\nu)\) above the detector: both mode look like a “normal” shower, but horizontal, with large curvature of the front
Astronomy with UHE CR?

27 events with energies in excess of 57 EeV reported by AUGER collaboration, in correlation with AGN's location

Hints toward light composition? At a given energy and compared to other species, protons have max. rigidity and are thus less deflected

Supergalactic plane
(concentration of nearby galaxies & AGN)

AGN Centaurus A, $d=4.3$ Mpc
AUGER UHE CR spectrum measurement

The Universe is opaque to CR with UHE over cosmologically short distances ~ 100 Mpc, the size of our galaxy supercluster, following photo-pion production reactions

\[ p \gamma \rightarrow \Delta^+ \rightarrow \pi^+ n \]
\[ p \gamma \rightarrow \Delta^0 \rightarrow \pi^0 p \]

This results into a degradation of the energy of the nucleons above \( \sim 10^{20} \) eV and is at the origin of the Greisen-Zatsepin-Kuzmin cutoff.

- The GZK cutoff is clearly seen by the experiments AUGER, HiRes
- Charged pion / neutron decay leads to a "cosmogenic" neutrino flux
- The intensity of the flux depends on the UHE CR composition (light is favored by AUGER correlations but only protons unacceptable from elongation rate studies)

**Elongation rate: variation of \( X_{\text{max}} \) w.r.t. \( \log E \)**

According to the superposition principle and the Bether-Heitler toy model for the development of EM showers, we have:

- \( X_{\text{max}} \) grows linearly with \( \log E \)
- \[ \Delta X_{\text{max}} = X_{\text{max}p} - X_{\text{max}A} > 0 \] is a constant
Cosmogenic neutrino flux

Consider a photon \( q = (q, q, 0, 0) \) and a proton

\[
p = (\sqrt{p^2 + m_p^2}, p \cos \theta, p \sin \theta, 0)
\]

The energy threshold of the reaction is

\[
E_{\text{threshold}}^{p\gamma} = \frac{m_n (m_p + m_n/2)}{2 \langle \epsilon_{\text{CMB}} \rangle} \approx 10^{20} \text{ eV}
\]

where \( \langle \epsilon_{\text{CMB}} \rangle = 6.4 \cdot 10^{-4} \text{ eV} \)

The interaction length can be estimated:

\[
\lambda_{\text{GZK}} = (n_y \sigma_{p\gamma})^{-1} \approx 3 \text{ Mpc}
\]

where \( n_y = \int f(\epsilon, T=2.728^\circ \text{K}) \approx 411 \text{ cm}^{-3} \),

\[
\sigma_{p\gamma} \approx 0.25 \text{ mb} \quad \text{and} \quad f(\epsilon, T) = \frac{\epsilon^2}{h^3 c^3 \pi^2 (\epsilon/kT - 1)}
\]

It is clear that one ultra-high energy proton undergoing pion photo-production reactions will produce many UHE neutrinos.
Cosmogenic neutrino flux

Pions from γp interaction will carry a fraction $K_p$ of the incoming proton energy

$$E_\pi(E_p) = K_p(E_p) E_p$$

where $K_p$ is the inelasticity of the reaction

$$K_p = \left(1 + \frac{m_e^2 - m^2}{s}\right) / 2$$

More precisely:

$$\lambda^{-1}_{\text{coll}}(E_p) = \frac{1}{2} \int \frac{d\cos \theta}{s} \int_0^\infty d \epsilon \sigma(E_p, \epsilon, \cos \theta) f(\epsilon, T)$$

$$\lambda^{-1}_{\text{int}}(E_p) = \frac{1}{2} \int \frac{d\cos \theta}{s} \int_0^\infty d \epsilon \sigma(E_p, \epsilon, \cos \theta) f(\epsilon, T) \times K_p(E_p, \epsilon, \cos \theta)$$

Improved

28 Mai 2009    Mathieu Ribordy, 3rd Cycle (UHE CR + neutrinos)
Cosmogenic neutrino flux

Other energy loss processes: adiabatic expansion, pair production

Models depend on assumptions regarding
- Cosmological source evolution
- Source distribution
- Composition
- Injection spectrum (spectral index + cutoff)

Estimate (peak, normalization):
- \( E_\nu \approx 0.05 \times E_p \) \( (E_\pi \approx \frac{1}{4} E_\pi, E_\pi \approx 0.2 E_p) \).
- Number of interaction \(-10\) for a primary proton with \( E_p \sim 10^{21} \) eV
Cosmogenic neutrino flux

Rates strongly depend on composition and can be suppressed by up to 2 orders of magnitude in case of heavy composition

→ detection / non detection by km$^3$

neutrino telescopes may discriminate between these possibilities

Currently, situation is uncertain:
- AUGER composition studies hardly compatible with pure proton
- AUGER correlation hints toward light primaries

L.A. Anchordoqui et al.,

28 Mai 2009
Mathieu Ribordy, 3rd Cycle (UHE CR + neutrinos)
Cosmogenic neutrino flux
UHE neutrino: Alternative detection techniques

Alternative detection techniques
- Acoustic pulse
- Coherent Radio Cherenkov emission in the range 0.2 – 1 GHz. Compton scattering and positron annihilation create a 20% irradiating electron charge excess.

Both, following suggestions of the physicist Askaryan.

<table>
<thead>
<tr>
<th></th>
<th>water</th>
<th>ice</th>
<th>salt</th>
</tr>
</thead>
<tbody>
<tr>
<td>EM optical</td>
<td>- 50 m</td>
<td>- 100 m</td>
<td>- 0</td>
</tr>
<tr>
<td>(Cerenkov)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EM radio</td>
<td>~ 0</td>
<td>- few km</td>
<td>-1 km (?)</td>
</tr>
<tr>
<td>(0.1–1.0 GHz)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>acoustic</td>
<td>-10 km</td>
<td>? (large)</td>
<td>? (large)</td>
</tr>
<tr>
<td>(10kHz)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
UHE neutrino: alternative detection techniques

The thermo-acoustic model was first described by G.A. Askariyan in 1957: A neutrino interacts with a target nucleon, the water producing an electromagnetic/hadronic cascade. The energy deposited in the water leads to a local heating of a few nK along the cascade. This induces a fast expansion of the medium.

Given a deposited energy $\epsilon(\vec{r}, t)$, the pressure can be calculated

$$p(\vec{r}, t) = \frac{\alpha}{4\pi C_p} \int \frac{d^3 r'}{|\vec{r} - \vec{r}'|} \frac{\partial^2}{\partial t^2} \epsilon(\vec{r}', t - |\vec{r} - \vec{r}'|/c_s)$$

where $\alpha$ is the thermal expansion coefficient, $C_p$ the specific heat capacity and $c_s$ the speed of sound. The pressure pulse amplitude depends on the Grüneisen parameter $\gamma = c_s^2 \alpha / C_p$, which depends on the medium

<table>
<thead>
<tr>
<th></th>
<th>ocean</th>
<th>salt</th>
<th>South Pole ice</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c$ (m/s)</td>
<td>1530</td>
<td>4560</td>
<td>3920</td>
</tr>
<tr>
<td>$\beta$ (K)</td>
<td>25.5e-5</td>
<td>11.6e-5</td>
<td>12.5e-5</td>
</tr>
<tr>
<td>$C_p$ (J/kg/K)</td>
<td>3900</td>
<td>839</td>
<td>1720</td>
</tr>
<tr>
<td>$f_{max}$ (kHz)</td>
<td>7.7</td>
<td>42</td>
<td>20</td>
</tr>
<tr>
<td>$\gamma = c_s^2 \alpha / C_p$</td>
<td>0.153</td>
<td>2.87</td>
<td>1.12</td>
</tr>
</tbody>
</table>
UHE neutrino: alternative detection techniques

Background noise + experimental issue:
- Ocean noisy
- Salt impure + expensive drilling
- Ice: Attenuation length may be shorter than theoretical prediction (grain size). Noise level is low < 10 mPa and signal 7 times larger than in water.

Current activities:
- Measurements in salt
- Arrays in water at Bahamas (SAUND), Scottish Isles (ACORNE), Mediterranean Sea (ONDE, AMADEUS), Lake Baikal
- Array in ice at South Pole (SPATS)
- New ideas: Ross Ice Shelf, Dead Sea

28 Mai 2009    Mathieu Ribordy, 3rd Cycle (UHE CR + neutrinos)
UHE neutrino: alternative detection techniques

SAUND – II: reconstruction
Lightbulbs dropped from a boat pop at ~100 m depth

“Physics” run started
Summer 2006
**UHE neutrino: alternative detection techniques**

**Coherent radio Cerenkov emission:** based on the Aska’rian effect

- EM shower develop a charge asymmetry mainly due to the following processes:

<table>
<thead>
<tr>
<th>Process</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. shower photons interact with atomic electrons via Compton scattering</td>
<td>$\gamma + e_{\text{atom}}^+ \rightarrow \gamma + e^+$</td>
</tr>
<tr>
<td>2. shower positrons interact with atomic electrons via Bhabha scattering</td>
<td>$e^+ + e_{\text{atom}}^- \rightarrow e^+ + e^-$</td>
</tr>
<tr>
<td>3. or via annihilation in-flight, reducing the positron mean free path</td>
<td>$e^+ + e_{\text{atom}}^- \rightarrow \gamma$</td>
</tr>
<tr>
<td>4. shower electrons interact with atomic electrons via Møller scattering</td>
<td>$e^- + e_{\text{atom}}^+ \rightarrow e^- + e^-$</td>
</tr>
</tbody>
</table>

Enhancing the charged current.

- At radio wavelength, the Cerenkov radiation becomes comparable to the dimension of the shower, so that the Cerenkov emission from the excess charge becomes coherent → amplification of the radiation in the radio waves
- This compensates the suppressed emission at these wavelengths
UHE neutrino: alternative detection techniques

**Coherent radio Cerenkov emission:** based on the other excellent idea from Aska'rian:

A UHE event will induce an e/γ shower,

![Image of a shower](image.png)

In electron-gamma shower in matter, there will be ~20% more electrons than positrons.

- **Compton scattering:** \( \gamma + e_{\text{(at rest)}} \rightarrow \gamma + e^- \)
- **Positron annihilation:** \( e^+ + e^-_{\text{(at rest)}} \rightarrow \gamma + \gamma \)

Excess charge moving faster than \( c/n \) in matter emit **Cherenkov Radiation**, radiation power \( \sim \nu \).

In dense material \( R_{\text{Moliere}} \sim 10\text{cm} \) (radius of EM shower containment).

- \( \lambda << R_{\text{Moliere}} \) (optical case), **random phases** \( \Rightarrow P \propto N \)
- \( \lambda >> R_{\text{Moliere}} \) (microwaves), **coherent** \( \Rightarrow P \propto N^2 \)
UHE neutrino: alternative detection techniques

ANTIA, a balloon-borne experiment, has set the best limits so far on UHE neutrino following a 35d flight in 2006-07.
UHE neutrino: alternative detection techniques

Other experiments include:

- **GLUE**, the Goldstone Lunar Ultra high energy neutrino Experiment (California)
  
  2 radio telescopes separated by 20 km looking at the Moon surface regolith, attenuation length of about ~20m at 2GHz, 123 hours lifetime

  Sensitive over a surface of >100’000 km², for interactions down to ~20m, $[V\Delta\Omega]_{eff} \approx 600$ km³-sr

- **FORTE**: Fast On-orbit Recording of Transient Events satellite
  
  Records bursts of electromagnetic waves arising from near the Earth’s surface in the radio frequency range of 30 to 300 MHz

  Observe Greenland ice sheet, $2 \times 10^6$ km³
  $[V\Delta\Omega]_{eff} \approx 100'000$ km³-sr

- **RICE**, antennas bound to AMANDA strings
UHE neutrino: alternative detection techniques

Future:

- ARIANNA, cover gap between $10^{17}$-$10^{18}$ eV
  100x100 station array, 30 x 30 km$^2$
  Ross Ice Shelf, ~624 m thick
- SALSA in salt domes
High Energy Neutrino telescopes

**Water Cherenkov detector:**
ANTARES, NESTOR, BAIKAL, KM3Net project, located in the Mediterranean and Baikal lake (Northern hemisphere)

**Ice Cherenkov detector:**
AMANDA, IceCube located at the South Pole (Southern hemisphere)

→ different FoV (permanently the northern sky at the South Pole)
Northern hemisphere detectors have a direct view of the galactic center

Also systematics, medium properties are different, e.g
- while pointing resolution is better in water (0.1° instead of 1°), the energy resolution is better in ice (better calorimeter)
<table>
<thead>
<tr>
<th>detector</th>
<th>depth [km]</th>
<th>λ_{abs} [m]</th>
<th>λ_{scatt} [m]</th>
<th>PMT noise rate [kHz]</th>
<th>Volume [km³]</th>
<th>Energy range [GeV]</th>
<th>#OM</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMANDA 2002</td>
<td>1.5</td>
<td>150</td>
<td>30</td>
<td>1</td>
<td>0.03</td>
<td>10^{2-10^7}</td>
<td>600</td>
</tr>
<tr>
<td>ICECUBE 2011</td>
<td>2</td>
<td>150</td>
<td>30</td>
<td>1</td>
<td>1</td>
<td>10^{1.5-10^9}</td>
<td>5000</td>
</tr>
<tr>
<td>BAIKAL 1998 (2005)</td>
<td>1</td>
<td>25</td>
<td>50</td>
<td>1</td>
<td>0.01</td>
<td>10^{3-10^7}</td>
<td>228 (NT-200+)</td>
</tr>
<tr>
<td>ANTARES 2008</td>
<td>2.5</td>
<td>40</td>
<td>110</td>
<td>30</td>
<td>0.03</td>
<td>10^{1.5-10^7}</td>
<td>900</td>
</tr>
<tr>
<td>NESTOR</td>
<td>4</td>
<td>40</td>
<td>110</td>
<td>30</td>
<td></td>
<td></td>
<td>15 (1 floor)</td>
</tr>
<tr>
<td>KM3NET</td>
<td>?</td>
<td>40</td>
<td>110</td>
<td>30</td>
<td>1</td>
<td>10^{1.5-10^9}</td>
<td>?</td>
</tr>
</tbody>
</table>
- The NESTOR project in the ionian sea. Currently a floor is operating (since 2003) at a depth of 4000m.

- At larger depth, exponential suppression of the atmospheric muon background, largely enhancing the sensitivity

- Next step: deploy some additional floors + surrounding strings
Optical background:

\[ ^{40}\text{K} \rightarrow ^{40}\text{Ca} + e^+ + \bar{\nu}_e \quad (BR = 89.3) \]
\[ ^{40}\text{K} + e^- \rightarrow ^{40}\text{Ar} + \nu_e + \gamma (1.46 \text{ MeV}) \quad (BR = 10.7) \]

with the photon which may eventually lead to an electron above Cherenkov radiation threshold through Compton scattering.

Bacterial bioluminescence and light flashes by animals decrease with depth. It produces burst demultiplying by 10 the count rate.

Current, sedimentation

→ under control
Attenuation length is strongly determined by the absorption length.

Scattering lengths are much longer, between 100 and 300m → mainly direct photons are detected, providing therefore an excellent angular resolution in the Mediterranean, ~0.1° for high energy neutrinos.
KM3NET
- watch the galactic center
- complementary to IceCube
Sky coverage in Galactic coordinates for a detector located in the Mediterranean Sea and at the South Pole. The shading indicates the visibility for a detector in the Mediterranean with $2\pi$ downward coverage; dark (light) areas are visible at least 75% (25%) of the time. The locations of recently observed sources of high energy $\gamma$-rays are also indicated.
Deployed at large depth
- Ice clarity
- Atmospheric muon background reduction
IceTop
Air shower detector
threshold ~ 300 TeV

DeepCore
6 additional strings
60 Optical Modules
7 or 10 m between Modules
72 m between Strings

InIce
70-80 Strings
60 Optical Modules
17 m between Modules
125 m between Strings

IceCube has 60x the instrumented volume of AMANDA
Downward / Upward going muons: IC background rejection factor of 1 million required

<table>
<thead>
<tr>
<th>Strings</th>
<th>Year</th>
<th>Livetime</th>
<th>μ rate</th>
<th>ν rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>IC9</td>
<td>2006</td>
<td>137 days</td>
<td>80 Hz</td>
<td>1.7 / day</td>
</tr>
<tr>
<td>IC22</td>
<td>2007</td>
<td>275 days</td>
<td>550 Hz</td>
<td>28 / day</td>
</tr>
<tr>
<td>IC40*</td>
<td>2008</td>
<td>~365 days</td>
<td>1000 Hz</td>
<td>110 / day</td>
</tr>
<tr>
<td>IC80*</td>
<td>2011</td>
<td>~365 days</td>
<td>1650 Hz</td>
<td>220 / day</td>
</tr>
</tbody>
</table>
IceCube Deep Core

- 6 dedicated strings
- 1 installed in IC59
- Together with IC strings from the baseline configuration, this is a 13-string densely instrumented core

- IceCube / Deep Core DOMs surrounding the lower Deep Core region used as a VETO

Science: E.g.
- Explore the southern neutrino sky
- Improve WIMP search to lower masses
- Soft point sources (identify short tracks from low energy muons)
ICECUBE HIGH ENERGY NEUTRINO TELESCOPE

- up/down $\approx 10^{-6}$ $\Rightarrow$ background mostly from misreconstructed atmospheric muon
- muon range scales with $\log(E_\mu)$
- $\sigma^{CC}/E_\mu \approx$ cte up to 10 TeV
- IceCube angular resolution $\sim 1^\circ$

Neutrino flavor

$\nu_e$

IceCube flavor ID, $\nu_e$
direction, energy

IceCube triggered, partial reconstruction

$\nu_\mu$

Full flavor ID

Log(ENERGY/TeV)

6 9 12 15 18 21

TeV

$\nu_\tau$

$\nu_\mu$

$\nu_e$

$\nu_\tau$

supernovae

showers vs tracks

IceCube flavor ID, $\nu_e$
direction, energy

IceCube triggered, partial reconstruction

$\nu_\mu$

Full flavor ID

$\nu_\tau$

$\nu_e$

$\nu_\tau$

Full flavor ID

$\nu_\mu$

$\nu_\tau$

$\nu_e$

$\nu_\tau$

$\nu_e$

$\nu_\tau$

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$\nu_\tau$

$\nu_e$

$\nu_\tau$
Moon Shadow

4.2σ deficit of events from direction of moon in the IceCube 40-string detector (3 months of data) confirms pointing accuracy.

Absolute pointing calibration

Angular resolution:
- IceCube 22 < 1.5°
- IceCube 80 < 1°

observed: 88202 events
expected: 89521.6 events
deficit: -1319.62 events
error: 315.265 events
significance: -4.18576 σ
Muons are not minimum ionizing over sensitive range of IceCube, which allows for “accurate” energy reconstruction. The abundant signal collected from high energy can be exploited to improve the angular resolution.
IceCube reconstruction sensitive to optical properties of the ice!
→ Determine light absorption & scattering length vs. depth:
  • LED, laser light sources
  • ‘Dust logger’ profiles dust
The Dust Logger

- Vostok calcium: meter to several meter resolution
- AMANDA scattering at 400 nm: 5-10 m resolution
- IceCube Dust Log (2005): 2-3 mm resolution
Are the dust layers horizontal?
**Event reconstruction**

Log likelihood minimization proceeds via the measurements of Cherenkov photon density and arrival time.

Following a hypothesis for the event topology (track, shower, composite), the photon time residuals (to which correspond a PDF) are calculated.

This PDF depends on distance, incidence and surrounding ice as well, to properly account on absorption, scattering and angular sensitivity of the phototubes.

\[ \theta_{\nu \tau} = 1.5^\circ \cdot (E_\nu / \text{TeV})^{-0.6} \]

0(km) long muon tracks
**Km$^3$-scale neutrino telescopes:**

- Effective area for muon detection is of order 1 km$^2$ at ~TeV
- Above ~PeV, the galactic center progressively open to observation, the CR muon background is weak and can be discriminated
  - No single muon events but muon bundle events, with a fading light pattern reflecting the dying muons along the bundle trajectory
  - Some muons in the bundle at some distance from the core

**Simulation of IceCube:**

- Assuming a $E^2 \nu_\mu$ spectrum
- After some quality selection for CR-induced background suppression

---

28 Mai 2009  Mathieu Ribordy, 3rd Cycle (detectors)
UHE CR sources

- **Hidden source:**

  CR + radiation do not escape the source (confined + interact)
  
The neutrino flux is arbitrary large, not constrained.

  Such a source would not explain the existence of UHE CR and not be revealed by conventional astronomy

  → transparent source model
The transparent source model explains UHE CR component and associates to it neutrinos and radiation. In this model, accelerated protons interact with surrounding radiation field and photo-produce charged and neutral pions via

\[ p\gamma \rightarrow \Delta^+ \rightarrow p\pi_0 \quad (\text{BR} = 2/3) \quad \text{and} \quad p\gamma \rightarrow \Delta^+ \rightarrow n\pi^+ \quad (\text{BR} = 1/3) \]

While secondary protons remain confined in the acceleration region, neutrons and neutral products from pion decay \((2\gamma, 3\nu)\) escape → the luminosity is distributed into

- Charged protons (once the neutron decay)
- Photons
- Neutrinos

according to

\[ E_n = 0.8 E_p, \quad E_\gamma = 0.1 E_p, \quad E_\nu = 0.05 E_p \]

Therefore,

\[ \int_{E_{\nu,min}}^{E_{\nu,max}} E_\nu \frac{dN_\nu}{dE_\nu} = K \int_{E_{\gamma,min}}^{E_{\gamma,max}} E_\gamma \frac{dN_\gamma}{dE_\gamma} \]

with \(K_{\gamma\nu} = 4\)

The neutrino flux from this generic transparent source is referred to as Waxman-Bahcall flux.
Transparent source model

UHECR flux

• Injection spectral index $\alpha=2$,
• $E^2 \frac{d\Phi}{dE} = 10^{-8} \text{ GeV cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1} @ E = 2 \times 10^{19} \text{ eV}$

$\Rightarrow$ energy density of this component ($10^{19} - 10^{21} \text{ eV}$):

$$\rho_E \sim 3 \times 10^{-19} \text{ erg cm}^{-3}$$

corresponds to an injection rate (over a Hubble time $\sim 10 \text{ Gyr}$):

$$\frac{dE}{dt} \sim 3 \times 10^{37} \text{ erg/s} / \text{ Mpc}^3$$

The coincidence between the injection rate:

• The AGN density ($\sim 1 \text{ AGN} / (200 \text{ Mpc})^3$) and their typical EM luminosity $L_{\text{AGN}} \sim 2 \times 10^{44} \text{ erg/s}$

• The frequency of occurrence of GRB ($\sim 1 \text{ GRB} / \text{ hr in } V_{\text{univ}} \sim 10^{11} \text{ Mpc}^3$) and an energy release of $\sim 2 \times 10^{52} \text{ erg}$ (isotropic value; same also true if beamed events: an energy decrease compensated by a rate increase)

explains why they have emerged as the leading candidates for the cosmic ray accelerators. The coincidence is also consistent with the transparent source model.

28 Mai 2009 Mathieu Ribordy, 3rd Cycle (sources)

EM output:
AGN: $2 \times 10^{44} \text{ erg/s} / (200 \text{ Mpc})^3 = 2.5 \times 10^{37} \text{ erg/s} / \text{ Mpc}^3$
GRB: $2 \times 10^{52} \text{ erg} / 10^{11} \text{ Mpc}^3 / \sim 3600 \text{ s} \sim 5 \times 10^{37} \text{ erg/s} / \text{ Mpc}^3$

Density $\rho_E = c/4\pi \times \text{ integral of } \{ E \text{ Flux } dE \}$
Injection rate: $\frac{dE}{dt} = \rho_E / t_H \sim 10^{55} \text{ erg} / \text{ Mpc}^3 / 3 \times 10^{17} \text{ s} = 3 \times 10^{37} \text{ erg/s} / \text{ Mpc}^3$
Let's assume that $\rho_E \sim 3 \cdot 10^{-19}$ erg cm$^{-3}$, observed in CR and EM also holds for neutrinos:

$$\int E \frac{d\phi}{dE}(E) \, dE = c \rho_E / 4 \pi$$

$$\rightarrow E^3 \frac{d\phi}{dE}(E) \, dE \sim 5 \cdot 10^{-8} \text{GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$$

Note:
- The neutrino flux can be larger due to GZK (depletes UHECR and produce $\nu$) partly compensated by
- In $p\gamma$, $E_{\nu\mu} \sim \frac{1}{4} E_\pi$ following the decay chain: $\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$
is oscillated, reducing further the muon neutrino flux

Note: This WB flux is known as the WB upper bound derived under the assumption of a semi-transparent source: CR can escape after losing a fraction of their energy in photo-pion production interactions.

Generic comment: High energy $\gamma$-rays may remain trapped in the source (optically deep) and cascade down to lower energy. Hard neutrino fluxes are not necessarily excluded. A measurement of the bolometric luminosity provides constraints on the neutrino flux.
Note that the torus unresolved as well (<1pc from closest AGN)
The inner radius of the torus is of order 0.1 pc. Deeper inside, dust is vaporized
given the central engine luminosity. The accretion process is limited by radiation
pressure according to Eddington luminosity, in the case of isotropic
emission/accretion. This limit can be overcome if accretion / emission happen in
different region surrounding the SMBH

Relativistic jets are observed but not well understood

Our own galaxy, the Milky Way is an AGN, but weak and not obscured by torus (no
line). Do not reach Eddington luminosity, maybe due to the lack of fuel

Observe broad band spectrum IR – X-ray, thermal: optical – X-ray from the
accretion disk and IR from reemission
Active Galactic Nuclei

Particle acceleration
- shock acceleration in the jet?
- large scale electric field at the base of the jet?

Shocks

Downstream region: particle advected from the shock

Advedted particles downstream may eventually interact with dust from the torus / accretion disk and produce neutrinos

Particles also escape the acceleration region when the magnetic field is not strong enough to confine them further (to higher energies).
AGN neutrinos (1)

- **blazar AGN:** jets toward observer. Blobs (magnetic field, charged particles) travel along the jet with relativistic factor $\gamma > 10$ (observer frame) $\rightarrow$ relativistic 1st order Fermi acceleration
- The model assumes that hadronic acceleration occurs in the jet, at the origin of the UHE CR flux
- In the blob frame, with size $R' = \gamma R$, particles have energy $E' = E/\gamma$ (relativistic Doppler effect on time & energy)
- TeV observed variability on time scale of as short as $10^3$ s $\rightarrow$ the size of the blob is constrained to

$$R' = \gamma R = \gamma c \Delta t \sim 10^{-4} - 10^{-3} \text{ pc} \quad (10 < \gamma < 100)$$

therefore there are small transient structure
- Photons with $E_\gamma = 15$ TeV are observed, as well as a UV bump ($\epsilon_\gamma \sim 10$ eV), therefore the $E_\gamma = 15$ TeV photons must be below the $\gamma \gamma \rightarrow e^+e^-$ production threshold in the blob rest frame, i.e.:

$$\epsilon_\gamma E_\gamma < m_e^2 \rightarrow \epsilon_\gamma E_\gamma < \gamma^2 m_e^2 \rightarrow \gamma > 25$$

---

Reminder:
- Combining Doppler with time dilation:
  - Observer measure $\Delta t$ between 2 flashes.
  - Lorentz transform: $\Delta t$ is dilated by $\gamma$
  - Doppler effect when aligned with the jet: time is “contracted” by $\gamma$
    $\rightarrow$ so time is “contracted” for the observer, i.e.

$$\Delta t = \gamma \Delta t' / \gamma^2 = \Delta t' / \gamma$$

and the size of the blob in its rest frame is

$$R' = c \Delta t' = \gamma c \Delta t$$

- The energy of photons of a moving blob towards the observer is given directly by the relativistic Doppler factor: $E = 2\gamma E'$
i.e.: we get the fireball photon number density from

The measured luminosity is increased by a factor $\gamma$: $L = \gamma L'$ and from the previous relation: $R' = \gamma c \Delta t$.

For the reaction threshold, see chapter on UHE CR.
AGN neutrinos (3)

- Through $p\gamma$ interaction, protons loose an energy fraction $f_p$ by crossing the blob of size $R'$ and density $n'_\gamma$:
  \[ f_p = R' / \lambda_{p\gamma} \langle \chi_{p\rightarrow x} \rangle = R' n'_\gamma \sigma_{p\gamma\rightarrow x} \langle \chi_{p\rightarrow x} \rangle = 0.3 \]
  \[(R' = \lambda_{p\gamma} = 10^{14} \text{ cm}, \sigma_{p\gamma\rightarrow x} = 10^{-26} \text{ cm}^2)\]

- Neutrino flux can now be estimated, assuming that AGN are at the origin of the UHE CR flux beyond the ankle. The injection rate of UHE CR in the universe is $dE / dt \sim 10^{44-45} \text{ erg / Mpc}^3 / \text{ yr}$:
  \[ \Phi_\nu = (c/4\pi)(u_\nu/E_\nu) = (c/4\pi E_\nu) (1/2 f_p t_H dE/dt) \sim 10^{-15} \text{ cm}^2 \text{ s}^{-1} \]
  \(\frac{1}{2}\) of $\pi$ energy transferred to $\nu_\mu$
  (the energy density in the neutrino component $u_\nu$ is a fraction $f_\pi$ of the UHE CR energy density)

- The probability of detection of a EeV neutrino is:
  \[ P_{\nu\rightarrow \mu} = R_\mu / \lambda_{\nu\rightarrow \mu} = 6\% \]
  (neutrino interacting within the muon range distance to the detector)

Therefore the expected number of detected events is $N_\mu \sim 10 \text{ km}^{-3} \text{ yr}^{-1}$.
**pp interaction**

In this model, accelerated protons interact with surrounding matter

\[
\text{pp} \rightarrow \text{pp}\pi_0 \quad \text{and} \quad \text{pp} \rightarrow \text{pn}\pi^+
\]

with \( E_\pi = \frac{E_p}{3} \)

Protons remain confined as in the transparent source model, neutrons and neutral products from pion decay (2\(\gamma\), 3\(\nu\)) escape. The luminosity is shared between the EM, CR and neutrino components according to

\[
\int_{E_{\gamma,\text{max}}}^{E_{\gamma,\text{max}}} \frac{dN_\gamma}{dE_\gamma} dE_\gamma = K \int_{E_{\nu,\text{max}}}^{E_{\nu,\text{max}}} \frac{dN_\nu}{dE_\nu} dE_\nu
\]

with \( K_{\text{pp}} = 1 \)

In contrast to \( p\gamma \), besides a lower pion production threshold, the pp reaction also enhances the energy ending up in the neutrino component.
SN count rate estimate:
10 MeV neutrino cross section is \( \sigma \sim 10^{-40} \) cm\(^2\).
Therefore the interaction length in a medium with \( \rho = 1 \) g/cm\(^3\) is
\[ \lambda_{\text{int}} = \frac{m_p}{\rho \sigma} \sim 1.6 \times 10^{11} \text{ km}, \]
i.e. the interaction prob. in a km detector is \( P_{\text{int}} \sim 0.6 \times 10^{-11} \).

The flux of anti-electron neutrinos at Earth for a SN occurring at \( D = 10 \) kpc = \( 3 \times 10^{22} \) cm is \( \Phi \sim (10^{57}/6) / 4\pi D^2 = 2 \times 10^{10} \) cm\(^2\) Hz.

The number of interaction in the detector is \( \rho_{\text{int}} = \Phi P_{\text{int}} \sim 10^9 \) [km\(^{-3}\)] each producing 3000 Cherenkov photons which will propagate about \( \lambda_{\text{att}} = 30 \) m and eventually hit phototubes with diameter 30 cm.

The phototube density (DOM) is \( \rho_{\text{DOM}} \sim 5000 \) km\(^{-3}\), i.e. each DOM cover a sphere with radius of approx. \( \lambda_{\text{att}} \) for IceCube. The fraction of the solid angle covered by a DOM at 30 m is \( \Omega_{\text{DOM}} / \Omega_{\text{30m}} \sim 1/2 \times 10^{-5} \).

We can now estimate the number of additional counts per DOM due to SN explosion:
\[ N_{\text{count}} = \text{Q.E.} \times 3000/e \times \frac{\rho_{\text{DOM}} \times \Omega_{\text{DOM}}}{\Omega_{\text{30m}}} \times \lambda_{\text{int}} \]
\[ = 0.2 \times 3000/e \times 0.2 \times 10^6 \times \frac{1}{2} \times 10^{-5} \]
\[ \sim 200 \text{ counts over 10 s}, \text{i.e. few 10's of Hz increase per DOMs.} \]
Dark matter

The cosmological standard model is motivated by observational pillars:
- Galaxy recession
- Isotropy of the Microwave Background
- Large scale homogeneity
- Big bang nucleosynthesis: Light element abundances

and is funded on the theoretical assumptions
- Cosmological principle validity:
  - Generic position + isotropy imply homogeneity + existence of comobile observers
  - Physics law universality
  - Large scale dynamics according to GR

Today, the critical density takes the value \( \rho_c \approx 10^{-29} \text{g/cm}^3 \approx 0.5 \cdot 10^{-6} \text{GeV/cm}^3 \)

Galactic rotation curves \( \rightarrow \) dark matter
SN 1a + CMB \( \rightarrow \) dark energy

<table>
<thead>
<tr>
<th>Baryonic matter</th>
<th>Dark matter</th>
<th>Dark energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>~4%</td>
<td>~27%</td>
<td>~70%</td>
</tr>
</tbody>
</table>

Candidate for dark matter: Weakly Interacting Massive Particle (WIMP) with mass > 45 GeV.

WIMP decouple from other forms of energy when anihilation/production rate processes falls below the expansion rate. To explain galactic rotation curves, we introduce a WIMP halo of density \( \rho_x \approx 0.4 \text{GeV cm}^{-2} \text{cm}^{-3} \) in corotation with the galaxy \( v_x \approx 300 \text{km/s} \)
Dark matter

We can now calculate the corresponding number density and flux

\[ n_x = 8 \cdot 10^{-4} \left( \frac{500 \text{ GeV/c}^2}{m_x} \right) \text{ cm}^{-3} \]

\[ \phi_x = n_x \nu_x = 2 \cdot 10^{-4} \left( \frac{500 \text{ GeV/c}^2}{m_x} \right) \text{ cm}^{-2} \text{ s}^{-1} \]

We then derive the solar WIMP capture cross section (WIMP are gravitationally trapped by successive scatterings), under the assumption of a weak interaction exchange of a neutral weak boson between the WIMP and a quark in the nucleon \( \sigma_{\text{WN}} = (G_F m_N)^2 / m_Z^2 \)

\[ \sigma_{\text{sun}} = \frac{m_{\text{sun}}}{m_N} \sigma_{\text{WN}} = 1.2 \cdot 10^{57} \times 0.5 \cdot 10^{-41} \text{ cm}^2 \]

The capture rate takes the value \( \Gamma_{\text{cap}} = \phi_x \sigma_{\text{sun}} = 1.2 \cdot 10^{30} \text{ s}^{-1} \) for \( m_x = 500 \text{ GeV/c}^2 \)

To finally calculate the rate of solar neutrino of dark matter origin annihilating in the center of the Sun, we assume a steady state where capture and annihilation of WIMPS are in equilibrium. The dominant annihilation channel is into weak bosons, each producing muon neutrinos with a branching ratio around 10%, \( \chi \chi \rightarrow WW \rightarrow \mu \nu_{\mu} \), each carrying about half of the neutralino energy. The neutrino generation rate is therefore related to the capture rate \( \Gamma_{\nu} = \Gamma_{\text{cap}}/10 = 1.2 \cdot 10^{29} \text{ s}^{-1} \) and the flux at earth is given by

\[ \phi_{\nu} = \frac{\Gamma_{\nu}}{4\pi d^2} \approx 0.5 \cdot 10^{-8} \text{ cm}^{-2} \text{ s}^{-1} \text{ where } d = 1 \text{ a.u.} \]

\( \sigma_{\text{WN}} \) is an “effective” cross section, smaller than the scattering cross section:

It accounts for the fact that the WIMP (Maxwell distribution of velocity) has to lose a fraction of its energy in order to be trapped in the gravitational potential of the Sun.
Dark matter

Considering roughly half of the neutrino energy is transferred to the muon (i.e. $E_\mu \approx 100$ GeV, interaction inelasticity is approximately 50%), the neutrino-induced muon event rate in the IceCube neutrino telescope at the South Pole with a cross section of $1 \text{ km}^2$ is therefore given ($\sigma_{\nu \rightarrow \mu} = 0.7 \times 10^{-36} \text{ cm}^2$, $R_\mu \approx 300 \text{ m}$) by:

$$N_{\text{event}} \approx 10^{18} \phi_\nu N_A \rho_{\text{ice}} \sigma_{\nu \rightarrow \mu} R_\mu \approx 15 \text{ yr}^{-1}.$$  

The atmospheric neutrino background is quite high at these « low » energies, $N_{\text{BG}} \sim 2-3 \text{ / square degrees / yr}$ and the neutrino-induced muon flux from solar WIMP annihilation is quite diffuse (from kinematics of the interaction, the typical angle between the outgoing muon and the incoming neutrino is $\sim 5^\circ$, much larger than the angular size of the Sun). Chasing a signal over background excess in km-scale high energy neutrino telescopes will require few years lifetime and good detection efficiency.

For higher WIMP masses, the potential slowly (fading atmospheric neutrino background) degrades due the the decreasing statistic. For lower WIMP masses, it degrades (first slowly, down to $m_{\text{WIMP}} \sim 100$ GeV and then quickly) due to the increasing atmospheric neutrino background, the reduced detector efficiency (identification of short muon tracks) and the decreasing neutrino interaction cross section $\sigma_{\nu p}$. 

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Dark matter with ICECUBE

Measurement of the neutrino-induced muon flux from the direction of the Sun and center of the Earth.

This can be compared to other experiments by converting it into annihilation cross sections.
Digression: Measuring the Earth density: Earth tomography with high energy neutrinos

Following Cavendish weighing the Earth, current knowledge on Earth’s interior is based on indirect methods based on the study of seismic wave propagation.

Neutrinos could provide concurrent and direct information on the Earth density:

- Earth is partially opaque at energies above ~10 TeV
- Few 100’s of atmospheric neutrino will be detected above 10 TeV (muon reconstructed energy) per year in a cubic km

![Diagram of Earth density measurement](image)

\[ f(\theta) = \int_{0}^{2\pi} \rho(z) \, d\theta = \int_{0}^{\pi} \frac{\rho(r) \, dr}{\sqrt{1 - (R/r)^2 \sin^2 \theta}} \]

where \( f(\theta) \) is the integrated density along a chord \( 0 < z < 2R\cos\theta \), and \( \rho \) is the density.

This relation \( f(\theta) \) can be (analytically) inverted, providing a mean to measure \( \rho(r) \).

After 10 years, a km³ neutrino telescope would definitely distinguish between PREM and homogeneous (Gonzales-Garcia et al., Phys.Rev.Lett.100:061802,2008).
Neutrino Flux from AGNs

- Fermi recently published a first AGN catalog: a large number of AGN flux in quiescent state are now characterized around GeV with unprecedented precision.
- Multiwavelength spectra are commonly interpreted in the framework of SSC/SEC model classes: Accelerated electrons accompanied by synchrotron radiation (X-ray component). GeV – TeV radiation generated by IC scattering on low energy photons (Synchrotron / External).
- Alternatively, consider a hadronic model ($\pi^0$ decay) at the origin of the observed multiwavelength spectrum, i.e. via $p\gamma$ or $pp$, where $\gamma$ are soft background photons and proton spectrum originates from acceleration processes in jets (1st order Fermi $\Gamma_p \sim 2$) or close to the central engine via large scale electric field ($\Gamma_p \sim 1$):
  - (a) $pp$ with $\Gamma_p \sim 1$, generate a hard $\gamma$-spectrum
  - (b) photo-pion production via $p\gamma$: energy threshold at $68 \, (E_\gamma / \text{eV}) \, \text{PeV}$
    \[ \rightarrow \text{ generate a hard } \gamma\text{-spectrum} \]
  - (c) $pp$ with $\Gamma_p \sim 2$ : produce a broad band photon spectrum

While the observed spectrum can be readily accounted for in case (c), in case (a) and (b), $\gamma$-ray emission may be produced by $e^+e^-$ pairs from $p$ interaction and $\gamma$-initiated EM cascade.

Note that at Fermi energies (max. $\sim 100$ GeV), the spectrum is not attenuated by propagation over cosmological distances, contrary to >TeV energies.

Electronic multiwavelength spectra: 3 processes: BS, IC, synchrotron
We have the useful “identities”

$<E_\gamma> \sim E_\gamma / 3$ for BS with $\Gamma_\gamma = \Gamma_e$

$<E_\gamma>/\text{MeV} \sim \frac{1}{2} \, (E_\gamma / \text{TeV})^2 \, (B/G)$ for synchrotron

Emissivity: $I(\nu) \sim B^{\alpha + 1} \, \nu^{-\alpha}$ where $\alpha = (p - 1)/2$ and $dn_e/dE \sim E^p$ (power emitted per unit volume and frequency).

Synchrotron spectrum peaks close to the critical frequency $\nu_c$.

In a monochromatic approximation: $I(\nu)d\nu = -(dE/d\nu) \, n(E) \, dE$, i.e we obtain $I(\nu) \sim \nu^{-(p-1)/2}$ which is an exact result for $p=2$.

IC spectrum also quite strongly peaks at $E_\gamma = \gamma^2 E_\gamma$.

This is roughly the origin of the multiwavelength spectra.
**Multimessenger**: In the light of the first AGN Fermi catalog

Hadronic model of blazar activity case (c): the broad-band spectrum is generated by pp interaction. We have:

- gamma-ray flux and spectral index ~ neutrino flux and spectral index
- we can directly compare neutrino telescope potential to the diagram below.

It is interesting to note that while IceCube under construction has never observed excess until now (22 string detector), the completed IceCube array will in this model of activity see some blazar sources after one year of operation.

IceCube discovery curve after 3 years of operation, for different declination (Earth opacity)
Multimessenger with IceCube:

Active approach: $\nu \rightarrow \gamma$: a “neutrino” event triggers astronomical observations

- ROTSE optical telescopes
- VERITAS / MAGIC TeV gamma-ray telescopes

Release of an alert in case of neutrino multiplet observations with ICECUBE within certain time and angular windows

- ICECUBE in SNEWS

“Passive” approach: $\gamma \rightarrow \nu$: offline analysis following peculiar events observed by the astronomical community

- Individual steady point source search based on source catalogues
- Stacking steady point source analyses:
  - Point source from restricted time windows (based on the paradigm of a correlated enhanced neutrino / photon emission)

These methods aims at improving the discovery potential by reducing the background, as compared to a random search of point source from an excess in the neutrino map

- GRB’s stacking analysis (observed with BATSE, SWIFT)
- Individual bright GRB’s
Optical Follow Up

With IceCube:

• Coincident triggers are selected for further CPU intensive reconstructions. If coming from same direction in the sky, an alert is sent to the ROTSE array.

• Quality cuts, time and space windows are set to allow ~30 random coincidences per year.
  • $4^\circ$ angular window
  • 100 ns time window
  • $1.85^\circ \times 1.85^\circ$ ROTSE FoV well matched to IC psf

• Increased sensitivity to transients
  • Supernova (id: rising lightcurve)
  • Gamma-Ray Burst (id: afterglow)
  • Gamma-Dark Bursts (id: orphan afterglows)

could be a precursor to icecube sending gcn alerts
**Gamma Ray Burst**

- Release of ~1 solar mass energy in $1 - 10$ s
- Variability time scale $\sim$ms $\rightarrow$ compact source
- Rare and cosmological events: 1 burst / $10^6$ yr /galaxy for isotropic emission, with spectral index $2$ above $0.1 - 1$ MeV and $1$ below. The rate should be increased by the beaming factor and is ~ consistent with SN rate
- Relativistically expanding shell powered and accelerated by radiation pressure up to bulk Lorentz factor $\Gamma$. Afterwards the energy is released as the optical depth for pair production becomes $< 1$ : The observer detects boosted energy emitted over contracted time $\rightarrow$ compactness problem solved

- blue shifted X-ray photons are MeV in observer frame
- observed variability time scale of order ms corresponds to a region of size $\Gamma^2 c \delta t$ (relativistic Doppler factor)

Requiring an optical depth $< 1$ leads to the requirement of $\Gamma \geq 100$ for typical bursts.

Efficient 1st order Fermi acceleration taking place around the multiple shocks from the fireball with differential velocity. Accelerated protons produce a broken power law spectrum neutrinos through $p\gamma$ (which becomes soft at high energy due to $\pi, \mu$ synchrotron radiations)

Note that there are two reference frames :
- observer and central engine (neglect cosmological redshift)
- rest frame of the relativistically expanding shell

Besides the times associated to the 2 reference frames, a 3rd “Doppler” time come into play as the fireball is expanding toward the observer.

The Waxman-Bahcall neutrino spectrum has spectral index $2$ between $0.1$ and $10$ PeV, $1$ below, $3$ above. The raise is related to the observed MeV break energy.
Neutrinos in coincidence with gamma-ray bursts?
SNR proton acceleration?

- 1st order Fermi acceleration: Electrons (protons ?) accelerated to ~100 TeV
- Synchrotron losses are supposedly not dominant at these energies, provided $B \sim \text{few} \, \mu \text{G}$
- Limiting factor is the expanding shock lifetime $T \sim 1000 \text{ yr} \sim$ the time it takes the expanding shell to sweep through its own mass of the ISM ($T$, given $10 \, M_\odot$, $v \sim 0.02c$, $\rho_{\text{ISM}} \sim m_p/cm^3$)

- In presence of nearby molecular clouds → pp interaction may occur → $\nu$ production
SNR proton acceleration?

Signature from p0 decay?
Do not seem confirmed
Galactic binaries

Bursting activity on hr/day scale
Sampled on 0.25 degree grid in both right ascension and declination

Some remarks about the hot spot:
- Non significant when the significance is calculated without accounting for energy
- The events are mostly in the lower part of the detector, where ice is clearer, not really in agreement with MC expectations

IceCube is now analyzing the IceCube data from the 2008-2009 campaign, in a 40 string configuration. This may help to clear the situation