Detection and phenomenology of cosmic neutrinos I

An overview biased towards the Mediterranean Sea

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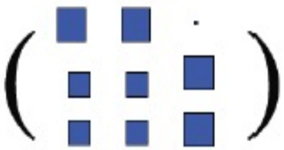
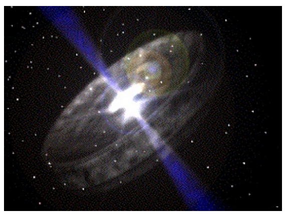
Outline



Introduction to neutrinos

Today's picture

Historical aspects



Neutrino astronomy

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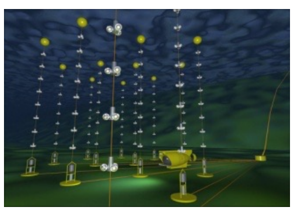
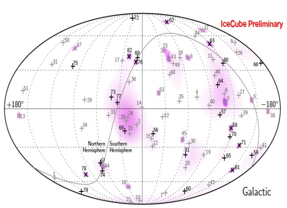
Cosmic neutrino sources



Neutrino telescope

Detection principles

Current telescopes



Selected results

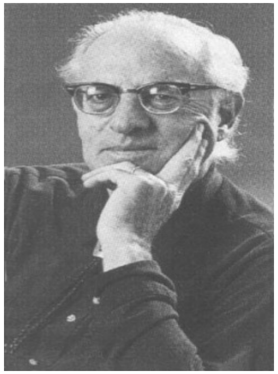
Diffuse Flux, point sources

Multi-messenger search

Future prospects

Reines and Cowan

Cf tutorial



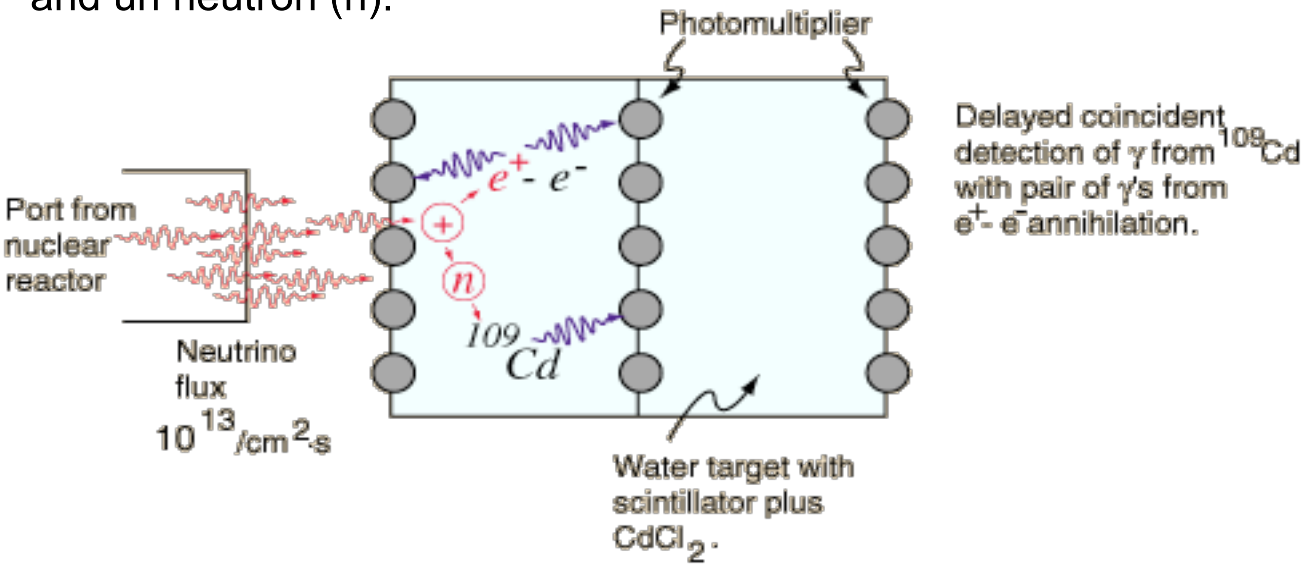
$$p + \overline{\nu} \rightarrow n + e^{+}$$

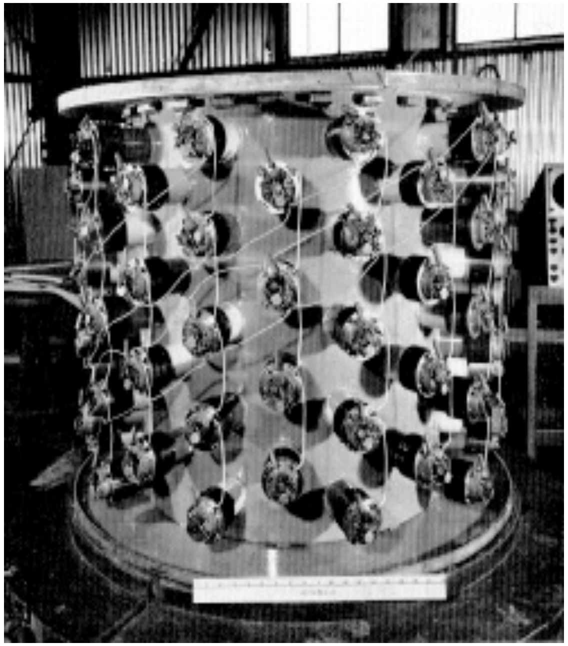
Reaction threshold = 1,8 MeV

1953 : Hanford
300 liters of scintillators only.
Encouraging results, but too high background

'Poltergeist' project

1956 : Savanah River
Target made of 400 liters of water and Cadmium Chlorure.
The neutrino interacts with a proton and undergo a positon (e+) and un neutron (n).





Historical context: birth of the neutrino

H. Bethe (+ R. Bacher) 1936
Nuclear Physics. A:Stationary states of Nuclei

First review about the properties of the neutrino:

- No charge
- Very small mass ($<<m_e$), probably zero
- Spin ½, Fermi statistics
- Very small magnetic moment ($< 1/7000\ \mu_{Bohr}$), if any

There is thus considerable evidence for the neutrino hypothesis. Unfortunately, all this evidence is indirect; and more unfortunately, there seems at present to be no way of getting any direct evidence. At least, it seems practically impossible to detect neutrinos in the *free state*, i.e., *after* they have been emitted by the radioactive atom. There is only *one* process which neutrinos can *certainly* cause. That is the inverse β-process, consisting of the capture of a neutrino by a nucleus together with the emission of an electron (or positron). This process is, however, so extremely rare (§42) that a neutrino has to go, in the average, through 10^{16} km of solid matter before it causes such a process. The present methods of detection must be improved at least by a factor 10^{13} in sensitivity before such a process could be detected.

Neutrino Discovery

1934: Fermi builds a new theory to explain the β decay

This processus can be used to detect (anti)neutrinos!

1934: Bethe & Peierls use the theory to compute the neutrino cross-section

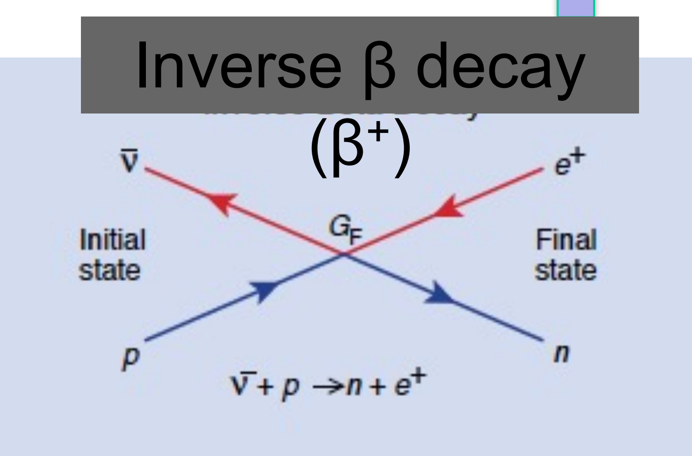
$$\sigma(\bar{\nu}p \rightarrow e^+ n) \simeq \frac{2\pi^2}{\tau_n m_e^5 f} E_e p_e = \frac{2\pi^2 (hc)^3}{\tau_n c (m_e c^2)^5 f} E_e c p_e$$

$f = 1.715$ phase space factor (for $E_{\bar{\nu}}$ close to threshold)

$\tau_n = 886 \pm 8\mathrm{s}$ neutron lifetime

$$\sigma(\bar{\nu}p \rightarrow e^+ n) \simeq 10^{-43} \left(\frac{E_e p_e}{\mathrm{MeV}^2}\right) \times \left(\frac{\tau_n}{886\mathrm{s}}\right) \mathrm{cm}^2$$

TINY !!!



Neutrino Discovery

…How small is 10^{-43} cm^2 ?

… What is the mean free path of a neutrino ? $$\lambda = \frac{1}{n\,\sigma}$$ n : density of target (cm^{-3})

σ : cross-section (cm^2)

Assuming water molecules (H_20) as target & inverse beta decay on free protons:

- 2 free protons per H_20 molecule
- 6 x 10^{23} molecules per mol
- 1 cm^3 of H_2O weights 1 gr = 1/18 mol H_2O

contains 1/18 x 6 x 10^{23} x 2 free protons $\simeq 6.7 \times 10^{22} \mathrm{cm}^{-3}$

$$\lambda \simeq \frac{1}{(6.7 \times 10^{22} \mathrm{cm}^{-3})(10^{-43} \mathrm{cm}^2)} = 1.5 \times 10^{20}\ \mathrm{cm}$$

…about 150 light-years !

« I have done a terrible thing. I have postulated a particle that cannot be detected . »

W. Pauli

Early experiments: inverse β decay with reactor neutrinos

Nuclear fission reactors: pure, intense and isotropic sources of (anti)neutrinos!

$^{235}U + n \longrightarrow {}^{140}Ba + {}^{94}Kr + 2n + 200\ MeV$

$$^{140}Ba \xrightarrow{\beta^-(13j,1MeV)} {}^{140}La \xrightarrow{\beta^-(40h,2,2MeV)} {}^{140}Ce$$

$$^{94}Kr \xrightarrow{\beta^-(0,2s,7,5MeV)} {}^{94}Rb \xrightarrow{\beta^-(2,7s,10MeV)} {}^{94}Sr \xrightarrow{\beta^-(75s,3,4MeV)} {}^{94}Y \xrightarrow{\beta^-(19\min,4,9MeV)} {}^{94}Zr$$

- How many antineutrinos are emitted by the above fission reaction ☞6
  <E> 3MeV
- What is the typical thermal power P_t of a nuclear plant? Give the rate of antineutrinos as a function of P_t. A.N

$$6\times\frac{P_t\ MW}{200\ MeV} = 6\times\frac{2700\times10^6\ J\ s^{-1}}{200\times10^6\times1{,}602\times10^{-19}\ J} = 5\times10^{20}\ \overline{\nu}_e s^{-1}$$

→ A typical reactor with thermal power ~2500 MW will produce about **5 10^{20} ν per second**

Early experiments: inverse β decay with reactor neutrinos

Nuclear fission reactors: pure, intense and isotropic sources of (anti)neutrinos!

❖ Neutrino flux is isotropic and attenuates with distance:

$$\boxed{\phi_\nu(\nu/cm^2/s) = \frac{\phi_\nu^0}{4\pi L^2} \simeq \frac{1,6 \times 10^{15}}{L^2} \times \frac{\mathrm{P_{thermal}}}{\mathrm{GW}}}$$

L: distance core-detector (in meters)

→ Place detectors close to the source ! (possibly at different distances from the core)

❖ The precision on emitted neutrino spectrum depends on several parameters:
Reactor fuel composition & burnup, beta decay chains, center of gravity of neutrino emission,
Distance to the reactor core,… (uncertainties ~10% → 1-2% today)

Early experiments: inverse β decay with reactor neutrinos

…How many neutrino events ?

❖ Event rate calculation (thin target approximation) $p+\overline{\nu} \rightarrow n+e^{+}$

$$\boxed{R \equiv N_T \times \phi_\nu \times \sigma}$$

Number of target protons

Neutrino flux (ν's/cm²/s)

Cross-section (cm²)

For 1 ton H_2O detector at distance L(m) from the core:

$$R \simeq (6.7\times 10^{28})\left(\frac{1.6\times 10^{15}}{L^2}\times\frac{P_{thermal}}{GW}\right)\times 10^{-43}\mathrm{cm}^2 \simeq 10\left(\frac{P_{thermal}}{GW}\right)\left(\frac{m_{detector}}{1ton}\right)\left(\frac{1\,m}{L^2}\right)\; s^{-1}$$

$$\left.\begin{array}{l}\text{L=100 m}\\ M_{detector} = \text{1 ton}\\ P_{thermal} = \text{10 GW}\end{array}\right\} \quad R \approx 0.01\,\mathrm{s}^{-1} \approx 900\,\mathrm{day}^{-1}$$

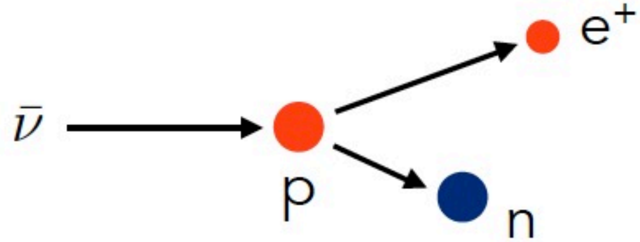
Early experiments: inverse β decay with reactor neutrinos

Neglecting the neutron recoil, one expects:

$$
\begin{aligned}
E_{\bar{\nu}} &\simeq E_{e^+} + (M_n - M_p) \\
&\approx E_{e^+} + 1,293\,\mathrm{MeV} \\
&\approx T_{e^+} + 1,804\,\mathrm{MeV}
\end{aligned}
$$

kinetic energy of outgoing positron: must be positive !

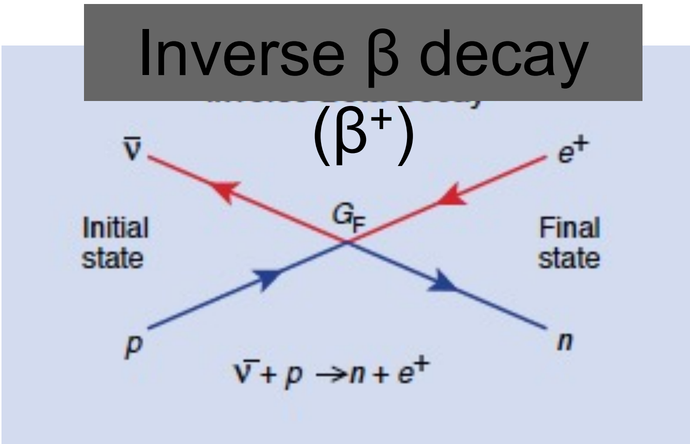
$m_e = 0,511\,\mathrm{MeV}$



Threshold for $\bar{\nu}$ capture:

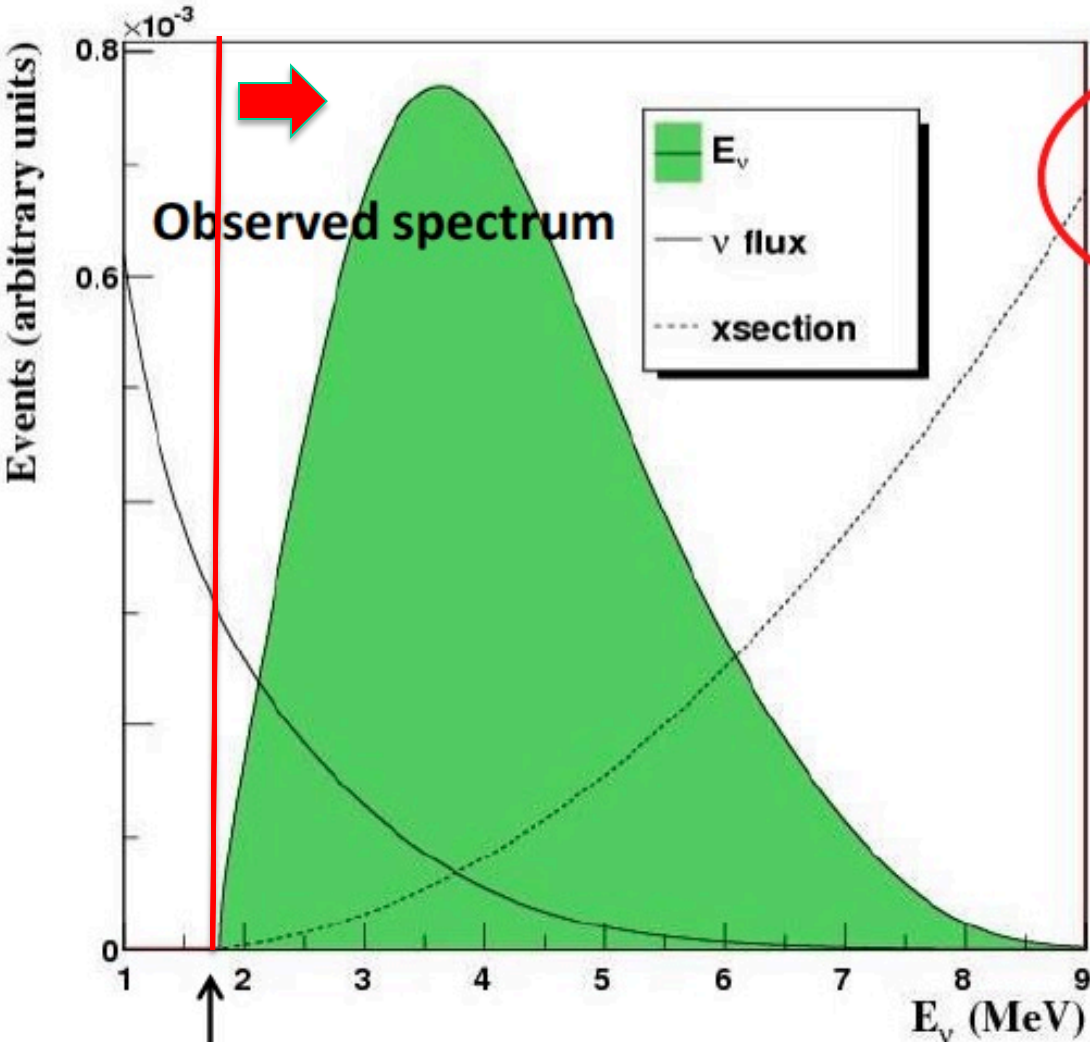
$$\boxed{E_{\bar{\nu}} \gtrsim 1,806\,\mathrm{MeV}}$$

(taking into account neutron recoil)



$T_S = -Q = -m_p + m_n + m_e = 1,8\ \mathrm{MeV}$

Early experiments: inverse β decay with reactor neutrinos



Neutrinos with E < 1.8 MeV are not detected (threshold for

Inverse β-decay reaction

$\bar{\nu}_e + p \rightarrow e^+ + n$

$\sigma \sim 10^{-43}\ \mathrm{cm}^2$

Typical energy range of reactor neutrinos: 2 – 8 MeV

~1.5 $\bar{\nu}_e$ /fission can be detected

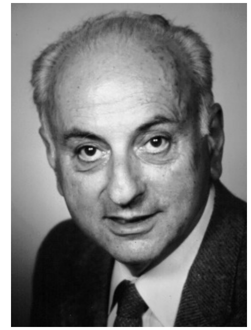
Discovery of muon neutrino

Cf tutorial

1962: Brookhaven experiment

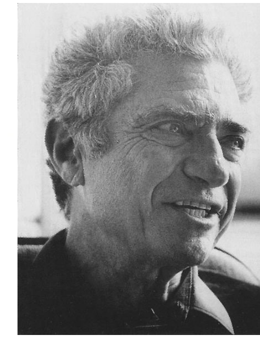
📖 PRL 9, 36-44, 1962

Nobel Prize 1988



M. Schwartz
1932- 2006

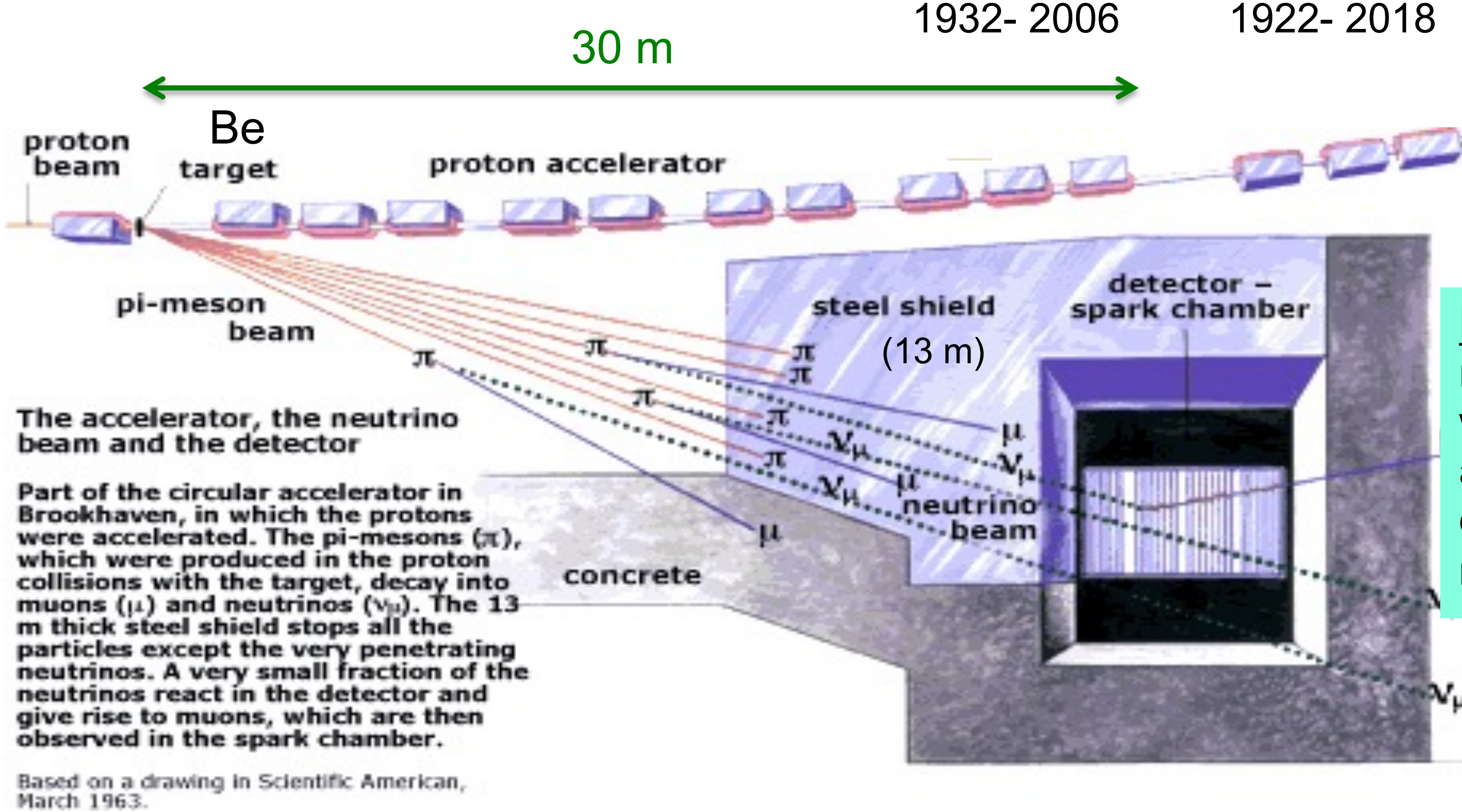
L. Lederman
1922- 2018



J. Steinberger
1921- 2020

AGS 15 GeV Proton Beam

4×10^{11} protons per pulse
3000 pulses per day



__Double challenge__: need a detector with **large mass** & able to **distinguish electrons from muons**

Discovery of muon neutrino

❖ Beam requirements for an event rate of ≈ 1 neutrino interaction/hour:

- **Proton current: I = 3 GeV protons per second on target**
- **Pion production (pion above 2 GeV): $I_\pi = I/10$**
- **Decay probability before hitting shield (L=10m): ≈10%**
- **Detector solid angle (1cm² at L=20m): $d\Omega = 0.25 \times 10^{-6}$ ster**
- **Neutrino flux:** $$\phi_\nu(\nu/\mathrm{cm}^2/\mathrm{s}) \simeq \frac{I}{10}(0.1)\frac{0.25\times 10^{-6}}{2} \approx 10^{-9} I$$

forward production of π

- **Event rate: $m_{detector}$ = 10 tons**

$$R(\mathrm{s}^{-1}) = 10^7 (6\times 10^{23})(10^{-9} I)\sigma \approx 6\times 10^{21} I\sigma(\mathrm{cm}^2)$$

Cross-section at 1 GeV per nucleon: $\sigma \simeq 10^{-38}\,\mathrm{cm}^2$

$$R(\mathrm{s}^{-1}) \approx 6\times 10^{-17} I \quad \Longrightarrow I = \frac{R}{6\times 10^{-17}}$$

Assume 1 event / hour / 10 tons: $$\boxed{I = \frac{3\times 10^{-4}\,\mathrm{s}^{-1}}{6\times 10^{-17}} = 5\times 10^{12}\,\mathrm{p/s}}$$

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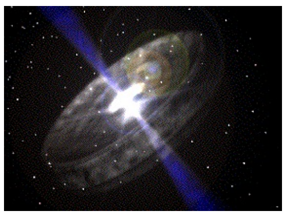

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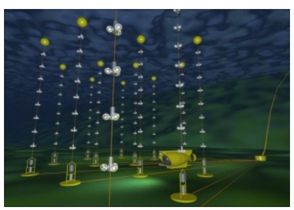
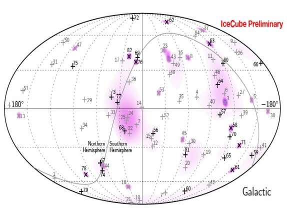


Neutrino telescope

Detection principles

Current telescopes



Selected results

Diffuse Flux

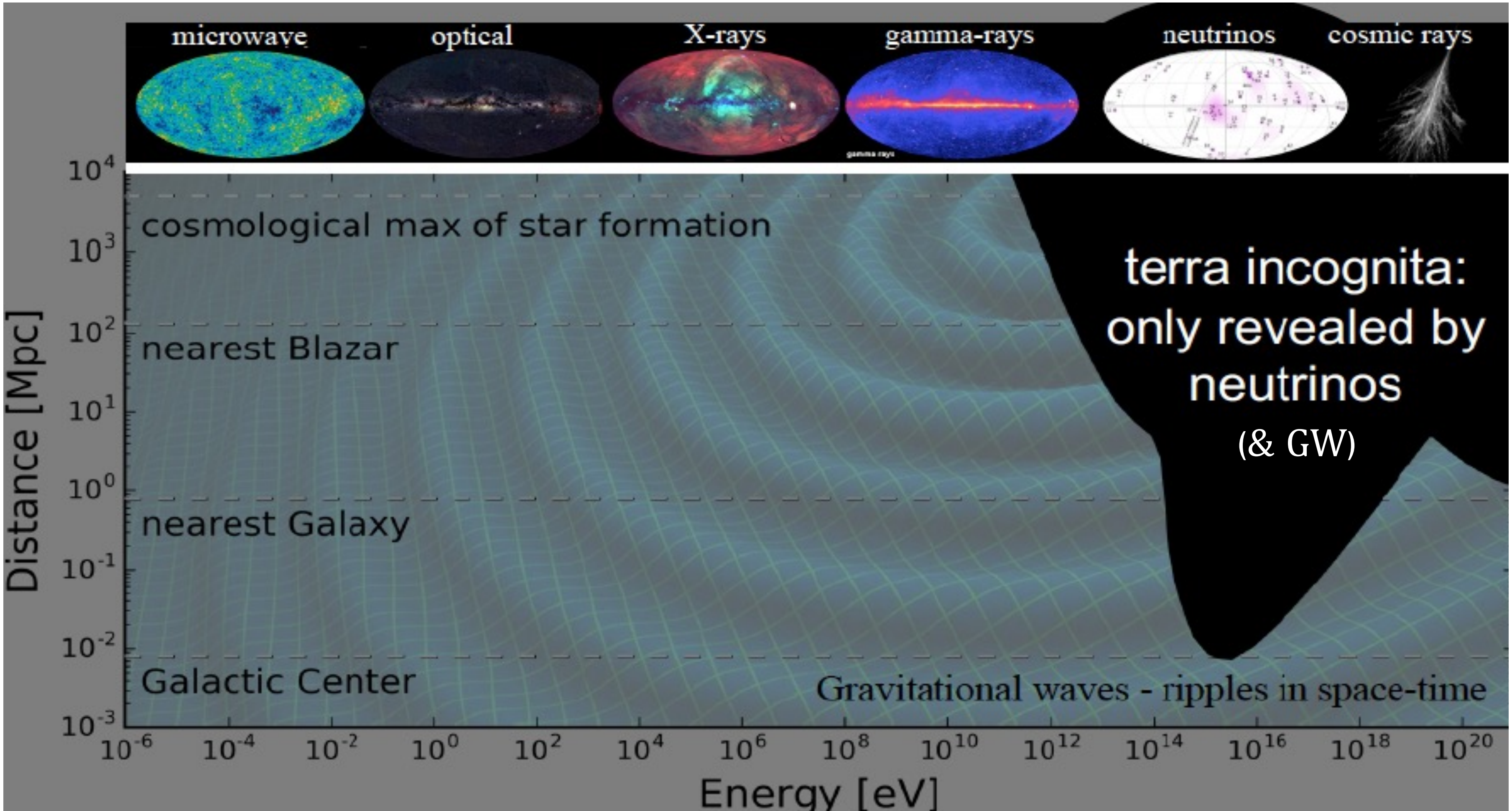
Search for point sources

Multi-messenger search

Future prospects

Multi-messenger astronomy

Cf tutorial



Neutrinos

✓Transient sources ✓Core of astrophysical bodies

✓ Point source ✓Cosmological distance

⇒ Signature of hadronic acceleration

From F. Halzen

Horizons of HE astroparticle astronomy

EXERCICES:

1. ***What is the distance that a neutron of 10^{18} eV would travel?***

$$\tau_0 = 885.7s \approx 15\min \Rightarrow \tau_{lab} = \gamma\tau_0 = \frac{E}{m}\tau_0 \approx \frac{10^{18}}{10^9}\tau_0$$

$$\boxed{D = \frac{\tau_{lab}}{c} \approx 9\text{kpc}}$$

2. ***Consider the process $\gamma_{HE}\gamma_{CMB}\rightarrow e^-e^+$. Try to estimate the energy of the HE photon for which the interaction length will be minimal. Is it compatible with the plot shown before?.***

$$\left\{(E_1+E_2)^2 - (\vec{p_1}+\vec{p_2})^2\right\}_{lab} = \left\{(m_1+m_2)^2 - (\vec{0}+\vec{0})^2\right\}_{cm} = 4m_e^{\ 2}$$

$$2(E_1E_2 - \vec{p_1}.\vec{p_2}) = 2E_1E_2(1-\cos\theta)$$

The minimum energy is required for head-on collision ($\theta=\pi$) $\quad \Rightarrow E_2 \geq \frac{m_e^{\ 2}}{E_1}$

Energy of black body spectrum $h\nu/kT = 2.82$ $\quad \boxed{\Rightarrow E_1 \approx 6.10^{-4}\,\text{eV} \Rightarrow E_2 \approx 4.10^{14}\,\text{eV}}$

But we should consider the increase of the cross section near the threshold, that will slightly shift the result towards higher value. Far above threshold: $\quad \sigma_{\gamma\gamma} \propto \frac{1}{E_1}$

3. ***What can you say about the $\gamma_{HE}\gamma_{CMB}\rightarrow\mu^-\mu^+$.process ?***

Same as above with $m_\mu \approx 200\ m_e$ $\quad \boxed{\Rightarrow E_2 \approx (200)^2 4.10^{14}\,\text{eV} \approx 1.6.10^{19}\,\text{eV}}$

Competion with $\gamma_{HE}\gamma_{radio}\rightarrow e^-e^+$ but cross section and photon density smaller.

Horizons of HE astroparticle astronomy

Charged nuclei also interact with the diffuse photon fields : **GZK cut-off**

- absorbed by photo production of Δ resonance:

$$p + \gamma_{CMB} \rightarrow \Delta \rightarrow \pi + p$$

- At energy threshold:

$$2E_p E_{CMB} > (m_\Delta^2 - m_p^2) = 50x10^{18} = 5x10^{19}\, eV$$

- Absorption length:

$$(n_{CMB} = 400/cm^3; \sigma_p \gamma_{CMB} = 10^{-28} cm^2)$$

$$\lambda_{\gamma p} = (n_{CMB} \sigma_{p+\gamma_{CMB}})^{-1} \simeq 10 Mpc$$

Radiochemical experiments

Cf tutorial

1968: First detection of solar ν_e – The Homestake experiment

…v2 of Davis' experiment!

Homestake gold mine, South Dakota, USA
1480m underground

615 tons C_2Cl_4 (Perchloroethylene)
~ 380 000 litres(cheap, commercially available)

$\nu_e + {}^{37}Cl \longrightarrow {}^{37}Ar + e^-$

$\hookrightarrow {}^{37}Cl \quad (T_{1/2}=35\ d)$

$E_{threshold}$=0.8 MeV >E_{pp}

→ Mainly sensitive to ^{7}Be neutrinos

Principle of a cycle :

-Exposition (~2 months)
-Extraction of the produced Ar

-Counting
Observation of Ar disintegration (e_{AUGER}):
Energy deposit and signal rise time

Solar neutrino production and first detection

$m_e(MeV)$	$m_p(MeV)$	$m_n(MeV)$	Sun-Earth distance	Sun Luminosity	Sun Mass	Sun radius
0.511	938.272	939.565	$d_\odot = 1.5\,10^{11} m$	$L_\odot = 3.8\,10^{26} W$	$M_\odot = 2\,10^{30}$ kg	$R_\odot = 7.0 \cdot 10^{10}$ cm

The production of neutrinos inside the Sun mostly results from the chain reactions initiated by hydrogen fusion into helium (so-called "p-p chain", see Figure 1). The resulting neutrino fluxes on Earth are shown in Figure 2.

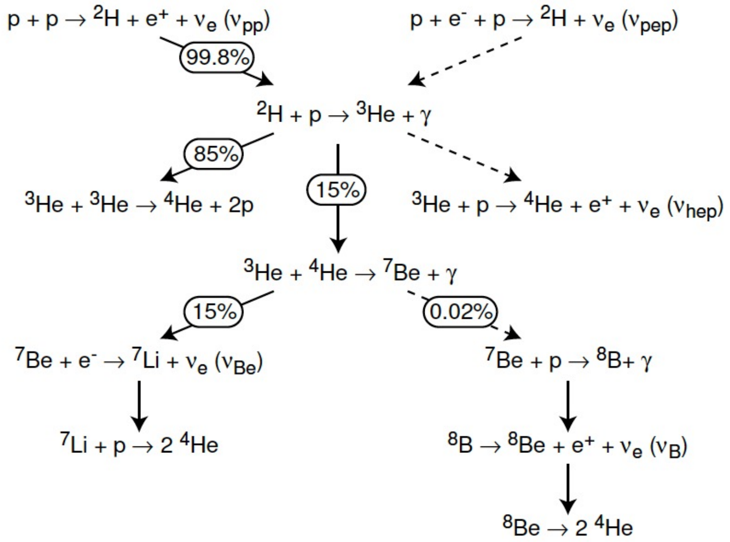


Figure 1: Schemes of the nuclear reactions of the p-p chain. The neutrinos produced by the different fusion processes are labelled ν_{pp}, ν_{pep}, ν_{hep}, ν_{Be} and ν_B.

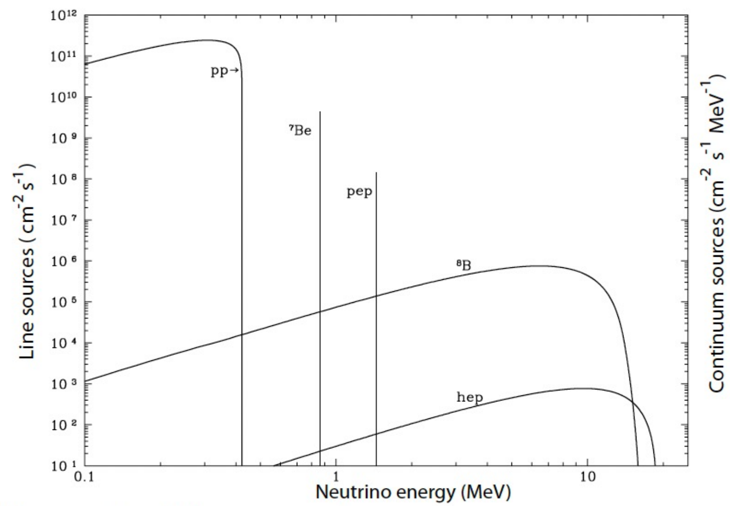


Figure 2: Solar neutrino energy spectra as predicted by the standard model of the Sun.

(a) For each of the reactions producing ν_{pp}, ν_{pep}, ν_{hep}, ν_{Be} and ν_B, justify the shape of the corresponding neutrino spectrum at Earth given in Figure 2. [0.5]

Solar neutrino production and first detection

(b) Estimate the energy of the ν_{pep} neutrinos and the maximum energy of the ν_{pp} neutrinos. Make sure that your answers are compatible with what is shown in Figure 2. We give the binding energy (defined as the energy needed to dissociate the nucleons of a nucleus) of deuterium $B({}^2_1\mathrm{H} \equiv D \equiv d) = 2,225$ MeV.

(c) The first detection of solar neutrinos was made by the Homestake experiment, taking advantage of the reaction:

$$\nu_e + {}^{37}_{17}Cl \rightarrow {}^{37}_{18}Ar + e^- \tag{1}$$

The incoming neutrino flux was computed by counting the number of ${}^{37}_{18}Ar$ atoms produced inside the detector. Compute the minimum neutrino energy needed to undergo reaction 1. What neutrinos of the p-p chain was the experiment sensitive to? We give the following excesses of mass: $\Delta({}^{37}_{17}\mathrm{Cl}) = -31,760$ MeV and $\Delta({}^{37}_{18}\mathrm{Ar}) = -30,946$ MeV.

(d) The produced ${}^{37}_{18}Ar$ nuclei are detected thanks to their radioactive decay into ${}^{37}_{17}\mathrm{Cl}$. What are the possible decay modes? Justify your answer.

(e) Describe how the produced ${}^{37}_{18}Ar$ atoms were counted. What were the main sources of background for the Chlorine experiment?

The SNO experiment (optional)

The Sudbury Neutrino Observatory experiment started to take data in 1999. It is a real time Cherenkov detector filled with 1000 tons of heavy water (D_2O) placed in a transparent acrylic spherical tank (12 m diameter) and surrounded by 9600 photomultipliers covering 100% of the spherical surface.
The presence of heavy water allows several reactions providing acces to all known active flavors:

$$\begin{aligned}
\textbf{(CC)} &: \nu_e + d \to e^- + p + p \\
\textbf{(ES)} &: \nu_x + e^- \to \nu_x + e^- \\
\textbf{(NC)} &: \nu_x + d \to \nu_x + p + n
\end{aligned}$$

where ν_x can be ν_e, ν_μ or ν_τ.

(a) i. Explain qualitatively why the cross section of the (ES) process is ~ 6 times higher for ν_e's than for ν_μ's or ν_τ's. Draw the Feynman diagrams of the possible reactions. [0.5]

ii. What is the signature of the (NC) process in the detector? [0.5]

The SNO experiment (optional)

(b) We now consider only the (CC) process which gives access to the ν_e flux[1].

i. Why does the reaction only occur with ν_e's? [0.5]

ii. Assuming a flux of $\Phi_{\nu_e} = 5.8\,10^6$ cm^{-2}s^{-1} and an average cross section $\sigma_{CC} = 1.8\,10^{-42}$ cm^2, estimate the rate of interactions inside the detector. A molar mass of 20 g.mol^{-1} can be considered for heavy water. [1]

iii. The electron energy loss in heavy water is $dE/dx = 2\,\mathrm{MeV\,cm^{-1}}$. Give an estimate of the number of Cherenkov photons produced for a 10 MeV electron? What is the value of the Cherenkov angle in heavy water ($n_{D_20} = 1.33$)? [1]

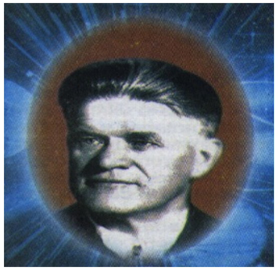
iv. Suppose that the interaction happens right in the middle of the detector producing a 10 MeV electron. Describe the topological pattern of the hit photomultipliers. Estimate the number of photomultipliers producing a signal, assuming a collection efficiency ϵ =20%. [1]

v. According to 3)b)iii), the number of generated photons is proportional to the electron energy. Thus, the energy resolution is given by the statistical fluctuations of the number of Cherenkov photons. Deduce the relation giving the energy resolution $\Delta E/E$ as a function of the energy E. [1]

(c) What have been the consequences of the results provided by the SNO experiment. Briefly desribe the situation concerning the solar neutrino problem right after these results. [1]

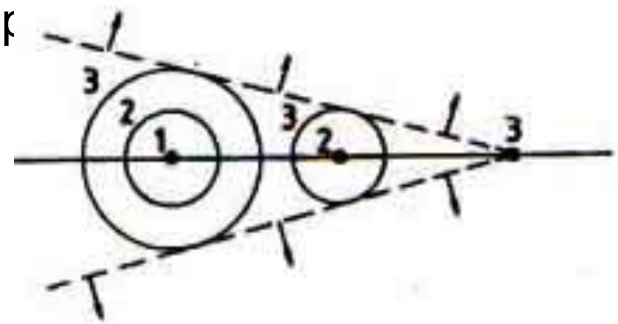
Real-time detection: water Cherenkov

Cf tutorial

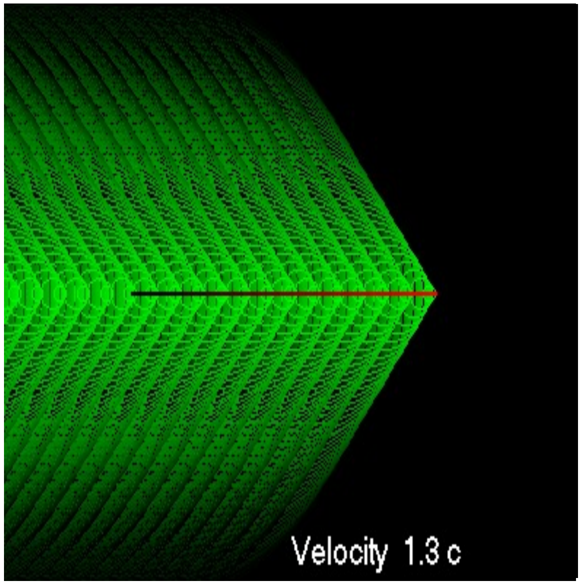


Coherent emission of light produced by relativistic charged particles, observable in a transparent medium

The charged particles polarize the molecules of the medium, which then turn back rapidly to their ground state, emitting radiation in the



$$\cos\theta_c = \frac{1}{\beta n}$$

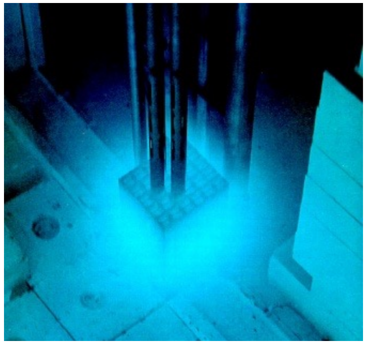


Cherenkov emission angle depends on the refraction index of the medium

Water → $\vartheta \cong 41°$

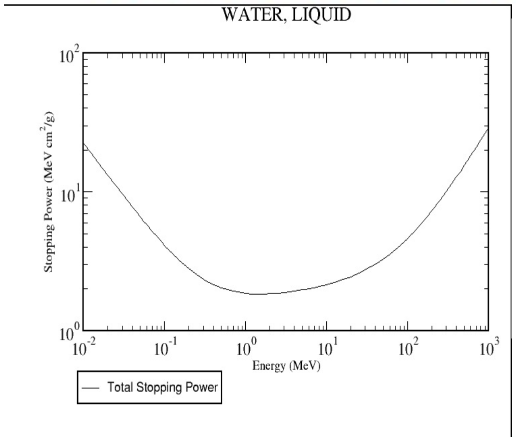
Number of Cherenkov photons emitted in the range 400 – 700 nm:

$$N_C \approx 5\cdot 10^4\left(1-\frac{1}{\beta^2 n^2}\right) \approx 5\cdot 10^4 \sin^2\theta_c \left(\text{photons m}^{-1}\right)$$



Exercise

Q: Estimate the vertex resolution for a water Cherenkov detector for a 10 MeV electron produced by the elastic scatter of a solar neutrino. Assume 40% of the detector walls are covered by PMT's and that the PMT's have an average of 25% efficiency.

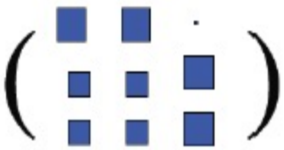


A 10 MeV electron will go ~5cm in water.
The number of emitted photons will be [500 x $\sin^2 \theta_c$ x 5 = 1120.]
Of those (0.4x0.25)=0.1 will be detected. So 112 photons, each with a timing resolution 2 ns, about 60 cmx1.33 = 80 cm.
This gives a final resolution 80/sqrt(112) = 7.5 cm

Q: Compare the detection efficiencies for the Kamiokande (20% photocathode coverage) and IMB-1 (1% photocathode coverage) for a 15 MeV super-nova neutrino

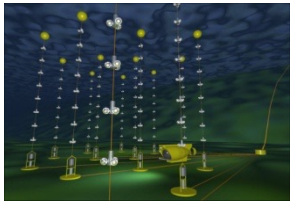
A: 15 MeV corresponds to abou 1680 photons which is about 0.6 detected photons on average in IMB and 80 in Kamiokande. Efficiency for detection is roughly 1-exp(-4) = 98% for IMB and 1-exp -80 = 100 % for Kamiokande.

Outline

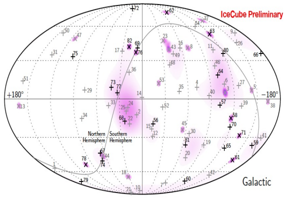


Introduction to neutrinos
Today's picture
Historical aspects

Neutrino astronomy
Scientific motivations
Historical aspects
Cosmic neutrino sources



Neutrino telescope
Detection principles
Current telescopes



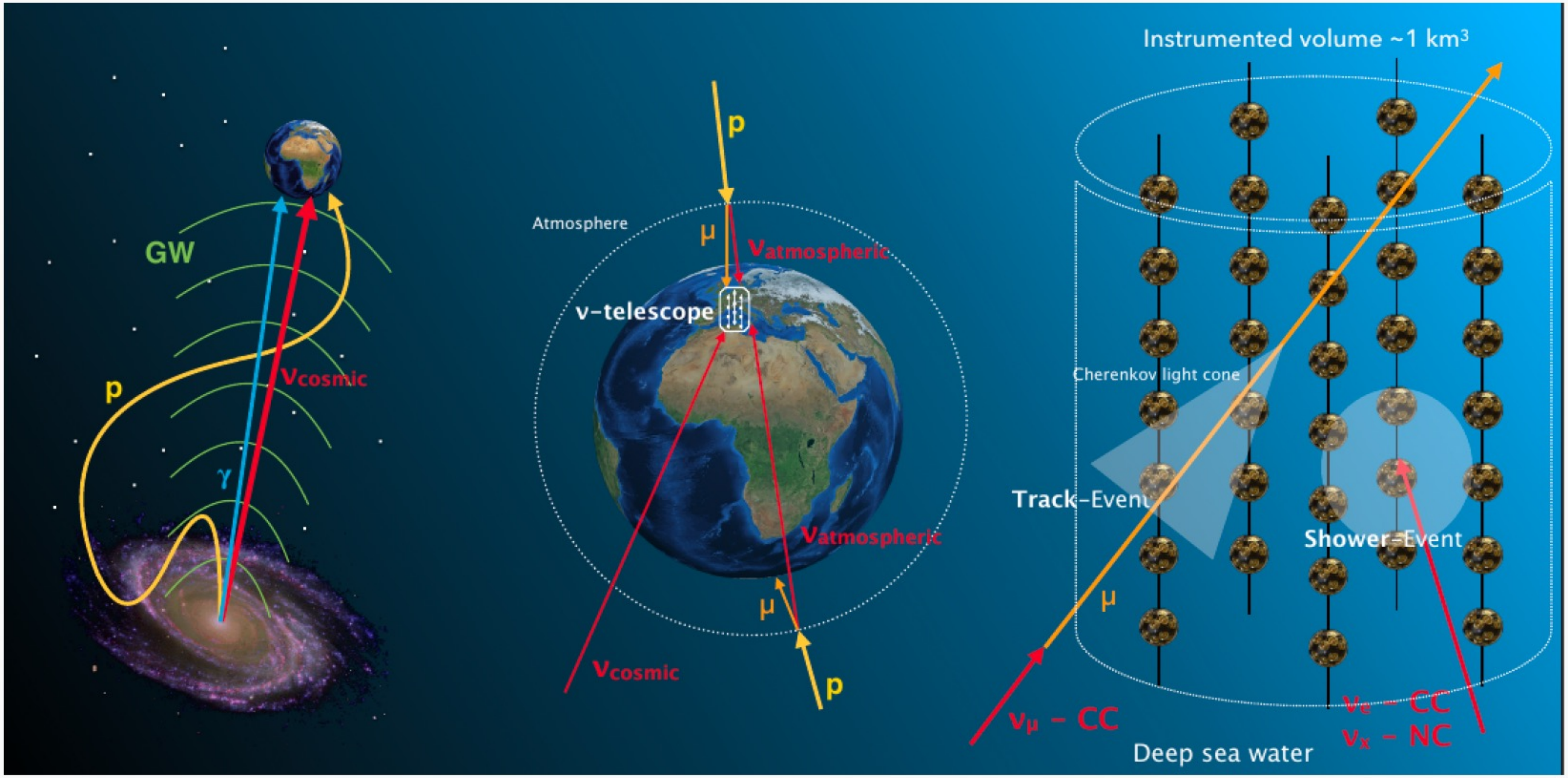
Selected results
Diffuse Flux
Search for point sources
Multi-messenger search

KM3NeT

Future prospects

In short

Cf tutorial



Atmospheric neutrinos detectors

$m_\mu(MeV)$	Lifetime τ_μ (s)	Lifetime τ_τ (s)	m_{Earth} (kg)	R_{Earth}(km)
105.7	2.2 10^{-6}	2.9 10^{-13}	5 10^{24}	6370

1.1 Atmospheric neutrinos

a. Briefly describe how atmospheric neutrinos are produced. Which are the main sources of uncertainties on their flux?

b. Let us consider only positively charged mesons. The neutrino production is dominated by the decay $\pi^+ \to \mu^+ \nu_\mu$.

   (a) We recall that the fraction of particles decaying within a distance L can be written as $(1 - e^{-L/\lambda})$. Explain this relation. What is λ in this context? Give its expression as a function of the energy E of the decaying particle.

   (b) In this process, ν_e and $\bar{\nu}_\mu$ are also produced. How?

   (c) Give a simple estimate of their relative abundance with respect to the ν_μ's as a function of their traveled distance L and the other relevant quantities.

c. Atmospheric neutrinos contain both ν_μ and $\bar{\nu}_\mu$ from $\pi^\pm$, $K^\pm$ decays. Evaluate the ratio $R = \frac{\nu_e + \bar{\nu}_e}{\nu_\mu + \bar{\nu}_\mu}$ assuming $L = 20$ km and for $E_\mu = 2,\ 20,\ 2000$ GeV. Comment on its evolution with E_ν.

Atmospheric neutrinos detectors

1.2 Neutrino telescopes

Neutrino telescopes detect secondary muons produced in deep inelastic interactions :

$$\nu_\mu \, N \to \mu \, X \tag{1}$$

where N denotes a nucleon.

1.2.1 Neutrino journey through the Earth

The cross section per nucleon of process (1) can be parameterized for neutrinos as:

$$\sigma_{\nu N} = 0.67 \times 10^{-38} \frac{E_\nu}{\mathrm{GeV}} \, \mathrm{cm}^2/\mathrm{nucleon}$$

a. Assuming an average mass density $\langle \rho \rangle$ for the Earth, compute the neutrino mean free path Λ, as a function of its energy. Show that it doesn't depend on the nature of the target (molar mass) but only on its density.

b. Give an expression of the transmission probability T of neutrinos through the Earth as a function of the neutrino energy E_ν and the neutrino path length (as defined by the expression $L_\nu = 2R_{\mathrm{Earth}} \cos(\theta_\nu)$ where θ_ν is the zenith angle of the neutrino).

c. Deduce at which energy the Earth becomes opaque to neutrinos? (Indication : consider, as a criterion for opacity, $T = 1/e$ in the vertical case).

Atmospheric neutrinos detectors

1.2.2 Neutrino induced muon journey through matter

The average energy loss of muons of energy E_μ traveling through matter can be written as :

$$\left\langle \frac{dE_\mu}{dX} \right\rangle = -\left(\alpha + \beta E_\mu\right) \tag{2}$$

with $\alpha \simeq 2,2$ MeV.g^{-1}.cm^2 (ionization term) and $\beta \simeq 4 \times 10^{-6}$ g^{-1}.cm^2 (radiation term).

a. Compute, using relation (2) the distance λ_μ travelled in water by a muon of energy $E_\mu = 40$ TeV before it looses all its energy. Give both a literal and numerical result.

b. To first order, do muons of such typical energies decay before loosing their energy?

c. *Facultative (bonus):* Would you conclude the same for a τ lepton? How would this modify your answer to question 1.2.1.c in the case of ν_τ neutrinos?

1.2.3 Neutrino effective surface

Let us consider a spherical[1] detector of total surface S_D. All the muons produced in the volume $V_{\text{eff}} = S_D/4 \times \lambda_\mu$, defined as the surface seen by the muon, times the muon mean free path λ_μ, will be detected.

a. The detection rate can be written as $R = \int \frac{d\Phi}{dE}(E) S_{\text{eff}}(E,\theta) dE d\theta$ where $\frac{d\Phi}{dE}(E)$ is the incoming neutrino flux at Earth and $S_{\text{eff}}(E,\theta)$ is referred to as the neutrino effective surface for a neutrino of energy E and arrival direction θ. Deduce an expression of $S_{\text{eff}}(E,\theta)$ as a function of the parameters introduced earlier along section 1.2.

b. Give an estimate of the effective surface for a ~40 TeV neutrino, assuming $E_\mu \approx E_\nu$ and $S_D = 0.1\text{km}^2$.

1.2.4 Detection units

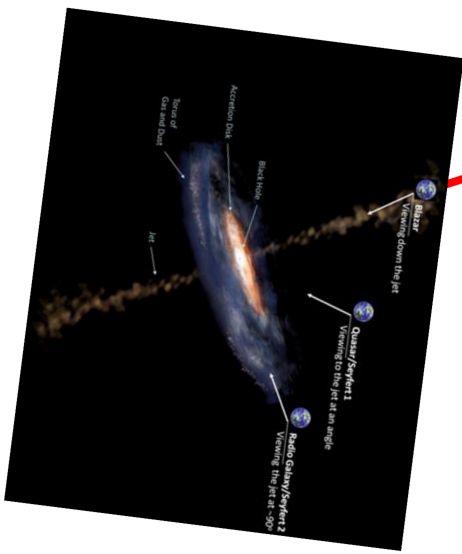
Let us consider a $1\,\text{km}^3$(instrumented volume) neutrino telescope, made of 10" (1 inch= 2.54 cm) diameter photomultipliers (PMT) with a collection efficiency $\epsilon = 0.2$. The N_{PMT} form a 3D array sensitive to the Cherenkov light produced by the passage of muon trough matter. The number of photoelectrons needed to reconstruct the muon trajectory is $N_{p.e} = 100$.

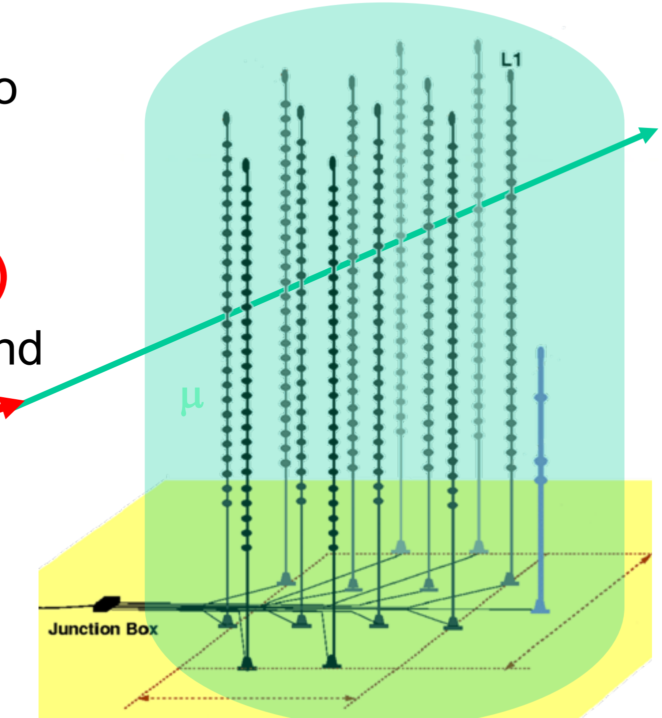
a. The absorption length in water is $\lambda \approx 50$ m in the 400-500 nm range. We denote V_{eff}^{γ} the photon effective detection volume as defined by the λ first meters in front of the PMTs. We thus consider that one photon falling into this volume can produce a photoelectron with a probability ϵ. What is the ratio R of this overall volume over the instrumented volume?

b. Estimate the number of optical sensors N_{PMT} needed to reconstruct the trajectory of a muon passing through the detector (1 km path length). Comment on your result.

Detecting cosmic ν

- **Event rate (s^{-1}) in the detector in a time T**: neutrino detection through CC interaction with production of a charged lepton
- **Neutrino spectrum from the source (ν/cm² s GeV)**
- **Neutrino- effective area (cm²).** Different for track and shower events





Instrumented detector D<R_μ

$$\frac{N_\nu}{T} = \int dE \cdot \frac{d\Phi_\nu}{dE} \cdot A_\nu^{eff}(E)$$

Example: neutrinos from a Galactic source

- TeV γ-rays and ν's can be produced from **photoproduction** hadronic processes:

  $p + \gamma \rightarrow \Delta^+ \rightarrow \pi^o + p \qquad p + \gamma \rightarrow \Delta^+ \rightarrow \pi^+ + n$

- The same occurs in beam-dump collisions of CRs with matter

  $p + p \rightarrow$ many hadrons (mostly π^+, π^-, π^o)

- Then, neutral mesons decay in **photons**: $\pi^o \rightarrow \gamma\gamma$
- While charged mesons decay in **neutrinos**:

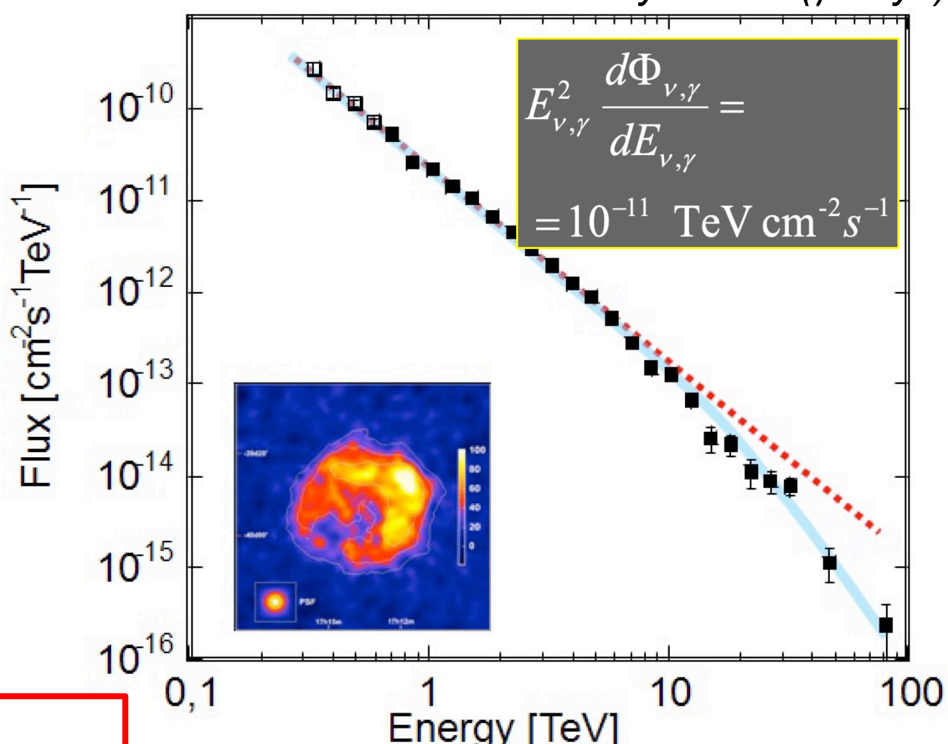
$\pi^+ \rightarrow \nu_\mu + \mu^+ \qquad \mu^+ \rightarrow \nu_\mu + \nu_e + e^+$

$\pi^- \rightarrow \nu_\mu + \mu^- \qquad \mu^- \rightarrow \nu_\mu + \nu_e + e^-$

- In all cases, at first order:

$$\frac{d\Phi_\nu}{dE} \cong \frac{d\Phi_\gamma}{dE} 10^{-11} E^{-2}\ \text{TeV cm}^{-2}\text{s}^{-1}$$

RX J1713.7-3946 *seen by HESS (γ–rays)*



Detector effective area

$$A_\nu^{eff}(E) = A \cdot P_{\nu\to\mu}(E, E_\mu) \cdot \epsilon_{det} \cdot e^{-\sigma(E)\cdot\rho\cdot N_A\cdot Z(\theta)}$$

- The effective area, $A_\nu^{eff}(E)$ of a NT corresponds to the quantity that, convoluted with the neutrino flux, gives the event rate.
- The A_{eff} depends on the **neutrino flavor and interaction type** (if the interaction yields a track- or shower-like, the latter either through a CC or NC interaction); on the neutrino **energy** and incoming **direction**; on the **status** of the detector; and on the **cuts** that each particular analysis uses for the suppression of the background.
- A is the geometrical area of the detector (the surface of the instrumented volume)
- $P_{\nu\to\mu}$ represents the probability that a neutrino with energy E produces a muon arriving with a residual threshold energy E_μ at the detector.
- ϵ_{det} is the detector efficiency (only determined through Monte Carlo)
- The $e^{-\sigma(E)\cdot\rho\cdot N_A\cdot Z(\theta)}$ term takes in the account the Earth absorption;
- In the following, we describe the ingredients necessary to construct, in a simplified analytic method A_{eff} for the ν_μ CC channel, assuming only dependence on energy E_ν .
- Only detailed and dedicated Monte Carlo simulations can determine A_{eff}

The $P_{\nu\rightarrow\mu}$ term in the effective area

- $P_{\nu\rightarrow\mu}(E,E_\mu)$ = Probability that a ν induces a muon reaching the detector:

$$P_{\nu\rightarrow\mu}(E,E_\mu) = \sigma_{\nu\mu}\times n\,(cm^{-3})\times R\,(cm)$$

- The neutrino CC cross-section can be parameterized as

$$\sigma_{\nu\mu} \cong 10^{-35}\left(\frac{E}{TeV}\right)(cm^2)$$

- Roughly, half of the neutrino energy is transferred
- The target number density is $n \cong 10^{23}\ cm^{-3}$;
- The muon range R depends on the muon energy,
- In the high energy limit the muon range $R = \int(\frac{dE}{dx})^{-1}\,dx \cong 10^6$ cm;
- Thus, and estimate of the probability is:

$$P_{\nu\rightarrow\mu}(E,E_\mu) = 10^{-35}\left(\frac{E}{TeV}\right)\times 10^{23}(cm^{-3})\times 10^{6}(cm) = 10^{-6}\left(\frac{E}{TeV}\right)$$

Detector effective area

$$A_\nu^{eff}(E) = A \cdot P_{\nu\to\mu}(E, E_\mu) \cdot \epsilon_{det} \cdot e^{-\sigma(E)\cdot\rho\cdot N_A\cdot Z(\theta)}$$

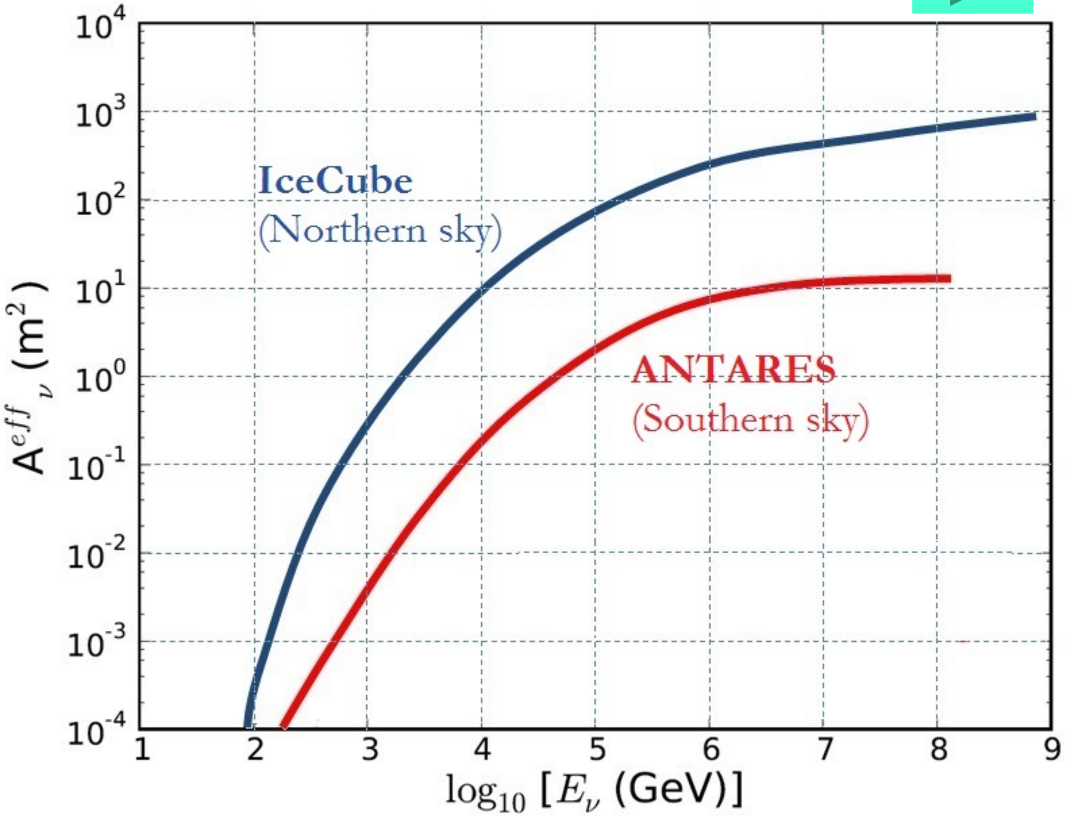
- The effective area, $A_\nu^{eff}(E)$ of a NT corresponds to the quantity that, convoluted with the neutrino flux, gives the event rate.
- In a detector with projected surface: A =1 km^2=10^{10} cm^2:
- Under very simple assumption for $\nu \to \mu$: $P_{\nu\to\mu} \cong 10^{-6}\left(\frac{E}{TeV}\right)$;
- For a perfect detector: $\epsilon_{det} = 1$
- Neglecting the Earth absorption: $e^{-\sigma(E)\cdot\rho\cdot N_A\cdot Z(\theta)} = 1$

$$\boxed{A_\nu^{eff} = A \cdot P_{\nu\to\mu} \cdot \epsilon \cong 10^4 \left(\frac{E}{\mathrm{TeV}}\right) [\mathrm{cm}^2] = 1 \left(\frac{E}{\mathrm{TeV}}\right) [\mathrm{m}^2]}$$

- **Under our simple estimates, the effective area of a neutrino telescope of 1 km^2 area for neutrinos of 1 TeV is ~1 m^2. It increases with increasing energy**

«Real» effective areas

- Neutrino effective area as a function of the true simulated neutrino energy obtained for the events selected by the IceCube and ANTARES detectors.
- A full Monte Carlo simulation is necessary to describe the triggering, tracking and selection efficiencies of the two detectors (term ϵ_{det} in the effective area)
- The plots refer to the ν_μ channel for upgoing particles, selected in order to have angular resolution <1° and small contamination of atmospheric muons



Number of expected events in a NT

$$\frac{N_\nu}{T} = \int dE \cdot \frac{d\Phi_\nu}{dE} \cdot A_\nu^{eff}(E)$$

- Let us merge all the above information to have the event rate N_ν/T;
- The cosmic signal is provided by the neutrino flux from the galactic source i

$$\frac{d\Phi}{dE} = 10^{-11}\ /E^2 \quad [\mathrm{TeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$$

- The effective area is of the order of **~1 m²** at 1 TeV and increases with energ

- Integrating the event rate formula between 1 TeV and 100 TeV, we obtain

$$N_\nu = T\int_1^{100} \frac{10^{-11}}{E^2} \cdot 10^4\ E\ \cdot dE = T \cdot 10^{-7}\ln(100)$$

- For T=1y=3 10^7 s, this corresponds **to**
  $N_\nu =$ **some event/y**
- (depends on the value of detector efficiency ϵ_{det}).