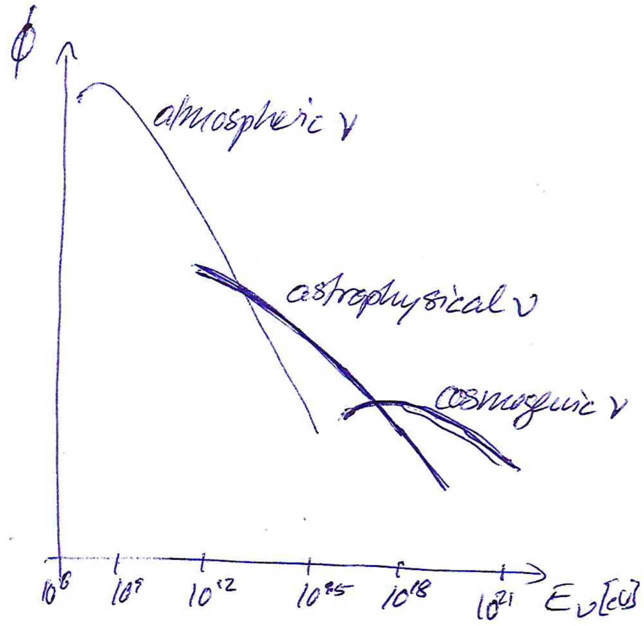
High-energy neutrino telescopes

Neutrino fluxes at >TeV energies



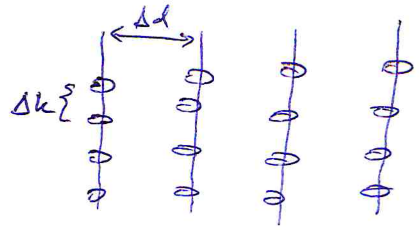
- Astrophysical ν's
  - galactic sources: $E_\nu \lesssim$ PeV (knee) from Supernova remnants
  - extragalactic sources:
    - Active galactic Nuclei, Gamma Ray Bursts } point sources, time-variation?
    - Starburst galaxies – diffuse flux
- Cosmogenic ν's
  - $p+\gamma \to \Delta^+$ with CMB
    $\hookrightarrow \pi^+ n$
    $\hookrightarrow \mu^+ \nu_\mu$
- Particle physics: decay of heavy particles, cosmological defects etc.
- Backgrounds:
  - atmospheric μ's: $\phi_\mu \sim 10^6 \phi_\nu$ → underground detectors
    → rising tracks
  - atmospheric ν's: dominate up to TeV level

Observables

- point sources (local excess over BG)
- energy spectrum → source, acceleration mechanism
- flavor composition → acc. mechanism, e.g.
  - π/K decay: $\nu_e : \nu_\mu : \nu_\tau \equiv 1:2:0$
  - n decay: $1:0:0$

  note: oscillation changes ratio, e.g. $1:2:0 \to 1:1:1$
- time-correlation with transient sources (e.g. GRBs)

Basic detector layout



- regularly spaced PMTs (in pressure capsules) in natural water/ice volumes
  → instrumentation of large volumes! (1 km³)
- PMTs arrayed on strings: $\Delta h \sim 5\,m$, $\Delta d \sim 20\,m$
  → density determines energy threshold

Neutrino interactions

- TeV energies → deep inelastic scattering

  (CC) $\overset{(-)}{\nu}_\ell N \to \ell^\mp X$ → small hadronic cascade + <u>lepton track</u> ← ν_μ
  + em cascade ← ν_e

  (NC) $\overset{(-)}{\nu}_\ell N \to \overset{(-)}{\nu}_\ell X$ → cascade

- cross section for $CC\,\nu_\mu$:

$$\frac{d\sigma}{dx\,dy} = \frac{2 G_F^2 M_N E_\nu}{\pi} \left(\frac{M_W^2}{Q^2 + M_W^2}\right) \cdot x \cdot \begin{cases} d(x,Q^2) + (1-y)^2\,\bar{u}(x,Q^2) & \text{for } \nu_\mu \\ (1-y)^2\,u(x,Q^2) + \bar{d}(x,Q^2) & \text{for } \bar{\nu}_\mu \end{cases}$$

(↑ coupling; ↑ propagator)

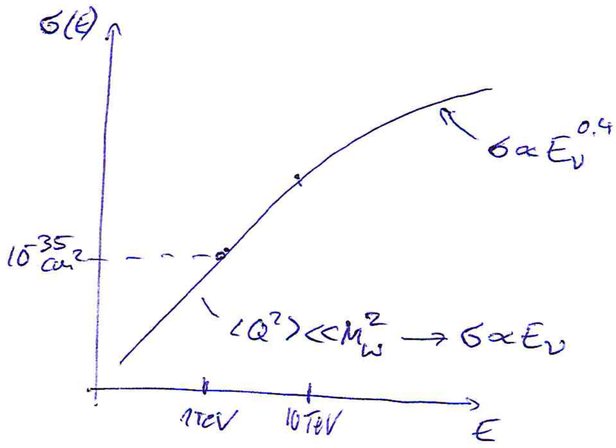
x, y Bjorken scale variables: x – fraction of nucleon momentum carried by quark; y – fraction of neutrino momentum transferred

$Q^2 = 2xy E_\nu M_N$ – four-momentum transferred

$\overset{(-)}{d}(x,Q^2)$, $\overset{(-)}{u}(x,Q^2)$ – parton distributions in nuclei

$\sigma_{tot}(E_\nu \simeq 1\,TeV) \approx 10^{-35}\,cm^2$

<u>note</u>: $\sigma(\nu_\mu) \approx 2 \cdot \sigma(\bar{\nu}_\mu)$
for target of protons + neutrons



- limit for directional reconstruction of ν direction from μ track:

$$\langle \Theta_{\nu,\mu} \rangle \approx \frac{0.7^\circ}{(E_\nu[TeV])^{0.6}}$$

+ muon resolution effects

- muon track length $\tilde{\propto}$ energy → long tracks at high energies
  → effective detection volume much larger
  → probability of detection: 10^{-6} for $E_\nu \sim 1\,TeV$
  but: Earth becomes opaque for PeV ν's ...

- Detection via Cherenkov light
  - light yield for $\lambda \in [400; 700]$ nm: ~200 photons/cm track length
  - light propagation: $N(r) = N_0 e^{-r/L}$

$$\frac{1}{L} = \frac{1}{L_a} + \frac{1}{L_s}$$

L_a → absorption → light lost

L_s → scattering → light delayed → effective length for isotropisation L_{eff}

medium	L_a	L_{eff}	
water	20-70m	150-400m	→ better timing/reco
ice	100-150m	20-40m	→ better light yield

Track event reconstruction

- muons from $CC\nu_\mu$ (low fraction of $CC\nu_\tau \to \tau \to \mu \nu_\mu \nu_\tau$)
- enlarged effective detection volume (track length $\propto E_\mu$)
  IceCube: x10 instrumented volume @ 100TeV
- muon energy loss: $-\frac{dE_\mu}{dx} = a + bE_\mu$
  - a: 2MeV/cm — minimum ionization ($\beta=1$)
  - bE_μ: $3.5 \cdot 10^{-6} \cdot E_\mu$/cm — pair production / bremsstrahlung, photonuclear reactions → dominant for $E_\mu \gtrsim 1$TeV

→ energy estimate based on $\frac{dE}{dx}$ even for partially contained tracks!
→ additional accuracy if initial shower is contained ↳ $\sigma(\log E) \sim 0.3$

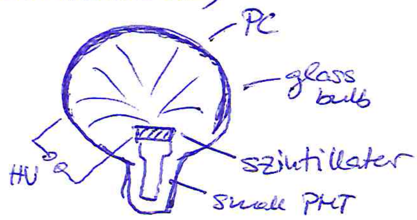
- background: cosmic muons ⟷ downward-going
  ↳ mis-reco as upward-going $\stackrel{!}{\lesssim} 10^{-6}$!

Cascade event reconstruction

- hadronic and e.m. showers from NC, $CC\nu_e$, $CC\nu_\tau$ (most)
- length $\propto \log(E_\nu)$: length: 5-20m, ⌀~10-20 cm → "point-like"
- events are contained: effective ≡ instrumented detection volume
  total amount of light ∝ energy
  → potentially better E resolution than tracks
  $\sigma E \sim 0.3$
- low angular resolution: 15° @ 100 TeV in IceCube

Experiments

- **Baikal neutrino telescope** (1980–today)
  - 8 strings, 192 modules of 2 PMTs each → coincidence for noise suppression (bioluminescence)
  - $h = 72m$, $\phi = 43m$, depth $= 1.1km$
  - QUASAR hybrid PMTs
  - energy threshold for muons: 15GeV
  - ca. 400 upward tracks observed in 5yrs



- **ANTARES** @ Mediterranian (Tolouse, 2002–today)
  - 12 strings, 25 storeys of 3 PMTs each
  - $h = 500m$, $\phi = 300m$, depth $= 2.5km$
    ↳ anchored to sea floor
  - excellent track reconstruction: $\Delta\vartheta = 0.2° @ 1TeV$
  - limits for indirect dark matter searches etc.

- **IceCube** @ Antarctica (2005–2010–today)
  - 86 strings, 60 DOMs each ($\Delta h \sim 20m$) + 320 DOMs in IceTop array
  - depth: 1450m, $h = 1000m$
  - ice quality varies with depth (bubbles → dust)
  - muon angular resolution: 1° @ TeV
  - low dark rates: ~100Hz → SN search

- Results from IceCube:
  - 2013 First evidence for cosmic neutrinos in TeV–PeV range
  - background: atmospheric muons (from above) + atmospheric neutrinos
    ↳ from π/K decay: high energy, μ cannot decay → mostly ν_μ; $\nu_e/\nu_\mu \sim 4\%$
    ↳ from charm decay: $\nu_e : \nu_\mu = 1:1$ expected, but low contribution
  ⇒ background much lower for ν_e/cascade-like events

- based on 3yrs of data:

  Σ 129 cascades
  8 tracks

  energy threshold: up-going 5 TeV / down-going 20 TeV

- fit with signal & background spectra

  signal: $\phi_\alpha(E_\nu) = 3\phi_0 f_{\alpha,\oplus} \left(\frac{E}{100\,\text{TeV}}\right)^{-\gamma}$

  α: flavor
  ϕ_0: flux at 100 TeV
  f_α: flavor ratio
  γ: spectral index

  $\longrightarrow \phi_0 = (2.3 \pm 0.4) \times 10^{-18} \frac{1}{\text{GeV} \cdot \text{cm}^2 \cdot \text{s} \cdot \text{sr}}$

  $\gamma = 2.6 \pm 0.15$

  flavor ratio:

  $f_e : f_\mu : f_\tau = (0 : 0.2 : 0.8)_\oplus$

  but: large uncertainties, compatible with $(1:1:1)_\oplus$ and all others

Future projects:

- ANTARES $\rightarrow$ KM3NET (several km^3)
- IceCube $\rightarrow$ HEX (10 km^3)
- low-energy extensions: DeepCore in IceCube $\rightarrow$ atm. ν oscillations
  PINGU, ORCA