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SMR.1508 - 35

SUMMER SCHOOL ON PARTICLE PHYSICS

16 June - 4 July 2003

ASTROPARTICLE PHYSICS

Lecture IV

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HIGH ENERGY NEUTRINO ASTRONOMY

VHE : $E_\nu \gtrsim 1\,\mathrm{TeV}$

UHE : $E_\nu > \frac{m_W^2}{2m_e} = 6.3 \cdot 10^6\,\mathrm{GeV}$

SUPERGZK: $E_\nu > 1 \cdot 10^{10}\,\mathrm{GeV}$

BASICS OF HE NEUTRINO ASTROPHYSICS

HE NEUTRINO PRODUCTION

- PP AND Pγ INTERACTION OF ACCELERATED PROTONS

$p + p \to \pi^{\pm}(K^{\pm}) + all$, $\pi^{\pm} \to \nu$

HE NEUTRINO ASTRONOMY

$E_\nu \gtrsim 1\,TeV$

$p + \gamma \to \pi^{\pm}(K^{\pm}) + all$, $\pi^{\pm} \to \nu$

VHE NEUTRINO ASTRONOMY

$$E_\nu \gtrsim 0.05\,\frac{m_\pi m_p}{\epsilon_{\gamma,tar}} \sim 10^7 - 10^8\,\frac{1\,eV}{\epsilon_{\gamma,tar}}\,GeV$$

- ANNIHILATION OF DM PARTICLES

$\chi + \chi \to \pi^{\pm}(K^{\pm}) + all$, $\pi^{\pm} \to \nu$

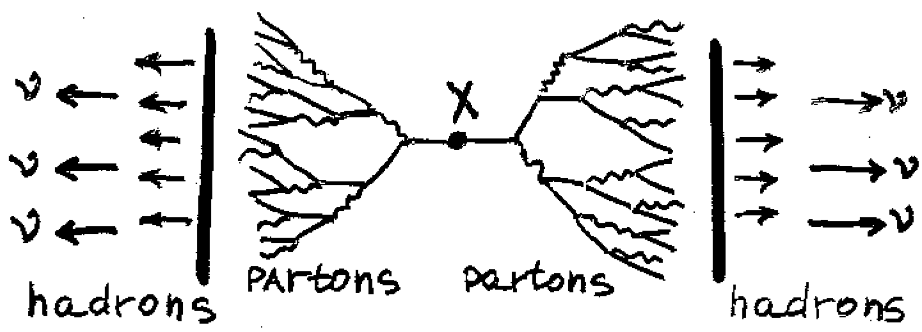
$E_\nu \lesssim m_\chi \lesssim 1\,TeV$

- DECAY OF SUPERHEAVY PARTICLES

$X \to \pi^{\pm}(K^{\pm}) + all$

UHE NEUTRINO ASTRONOMY

$E_\nu^{max} \sim 5 \cdot 10^{-2}\, m_X$



NEUTRINO DETECTION

FOUR REMARKABLE REACTIONS

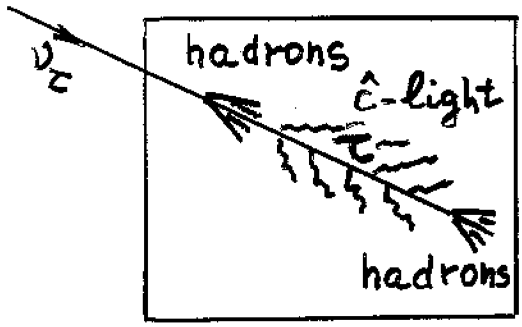
- $\nu_\mu + N \to \mu + all$ — SEARCH FOR DISCRETE SOURCES

- $\bar{\nu}_e + e \to W^- \to hadrons$ — MONOENERGETIC SHOWERS

  $$E_0 = \frac{m_W^2}{2m_e} = 6.3 \cdot 10^6 \text{ GeV}$$

  LARGE CROSS-SECTION

- $\nu_\tau + N \to \tau + hadrons$ — THREE SIGNALS:



PROMPT HADRONS,

CHERENKOV LIGHT FROM τ

HADRONS FROM τ-DECAY

- Z - BURSTS — SIGNAL FROM SPACE

  $$\nu + \bar{\nu}_{DM} \to Z^0 \to hadrons \qquad E_0 = \frac{m_Z^2}{2m_\nu} = 4 \cdot 10^{12} \left(\frac{1 eV}{m_\nu}\right) \text{ GeV}$$

NEUTRINO CROSS-SECTIONS

νN CROSS-SECTION

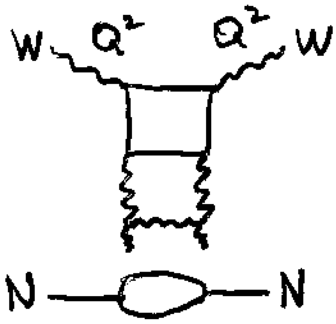
- PERTURBATIVE AND NON-PERTURBATIVE QCD

$$\frac{d^2\sigma_{cc}}{dx\,dy} = \frac{G_F^2 s}{\pi}\left(\frac{m_W^2}{Q^2+m_W^2}\right)^2 \mathcal{F}(x,y,Q^2)$$

$$\mathcal{F} = \frac{1}{2}\left[1+(1-y)^2\right]F_2(x,Q^2) - \frac{1}{2}y^2 F_L(x,Q^2) \pm y\left(1-\frac{y}{2}\right)xF_3(x,Q^2)$$

$x_{eff} \sim m_W^2/S \sim 3\cdot 10^{-7}(10^{10}\,\mathrm{GeV}/E_\nu)$ IS TOO SMALL.

$$F(x,Q^2) \sim \begin{cases} (\ln Q^2)\, x^{-0.5} & \text{PERT DGLAP} \\ \sqrt{Q^2}\, x^{-0.5} & \text{BFKL} \end{cases}$$



Kwiecinski et al FIG

- PHYSICS BEYOND SM (EXTRA DIMENSIONS)

EXCHANGE BY MASSIVE $\left(\frac{n^2}{R^2}\right)$ KK GRAVITONS $(\sigma \sim s^2)$

$$s \gg M^2: \quad \sigma_{\nu N} \sim \frac{4\pi s}{M^4} \sim 10^{-27}\left(\frac{M}{1\,\mathrm{TeV}}\right)^{-4}\left(\frac{E}{10^{11}\,\mathrm{GeV}}\right)\ \mathrm{cm}^2$$

RESONANCE INTERACTION

$\bar{\nu}_e + e \to W^- \to$ hadrons

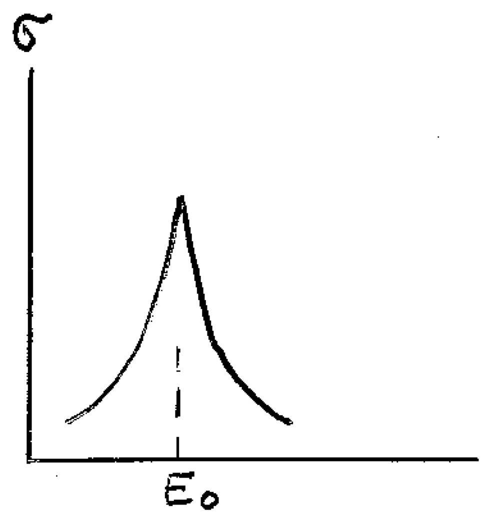
V.B., Gazizov 1977

$E_0 = m_W^2/2m_e = 6.3\cdot 10^6$ GeV

RATE OF RESONANCE EVENTS:

$$\nu_{res} = 2\pi N_e \sigma_{eff} E_0 I_{\bar{\nu}_e}(E_0)$$

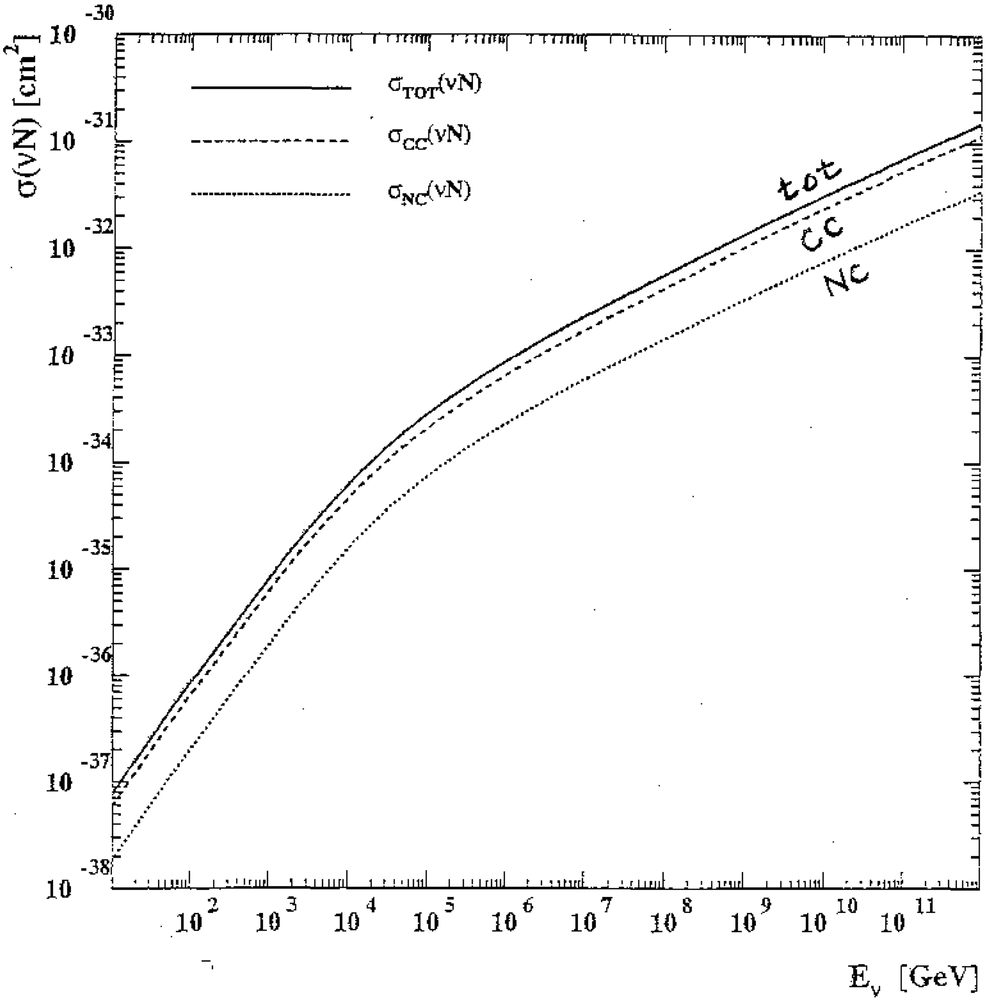
solid angle (2π); number of electrons in the detector (N_e)



$\sigma_{eff} = (3\pi/2)G_F = 3.0\cdot 10^{-32}\ \mathrm{cm}^2$

Kwiecinsky, Martin, Staso 2000

COMBINED DGLAP/BFKL



ROLE OF NEUTRINO OSCILLATIONS

OSCILLATION IS EFFECTIVE

$$P_{\nu_\mu \to \nu_\tau} = \frac{1}{2} \sin^2 2\theta \sin^2 \frac{r}{L(E)}$$

$$L(E) = \frac{4E}{\Delta m^2} \simeq 1 \left(\frac{E}{10^{11}\,\mathrm{GeV}}\right) \left(\frac{3 \cdot 10^{-3}\,\mathrm{eV}^2}{\Delta m^2}\right) \,\mathrm{pc}$$

SINCE $L_{osc} \ll r_{source}$ THE FLAVOR RATIO AT UHE

$$\nu_\mu : \nu_\tau = 1 : 1$$

$\bar{\nu}_e$ AND ν_τ ARE INEFFICIENTLY PRODUCED IN ACCELERATOR SOURCES

$$p + \gamma \to \Delta^+ \to p + \pi^0$$

$$\Delta^+ \to n + \pi^+$$

$$\pi^+ \to \mu^+ + \nu_\mu$$

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

$$P_{\bar{\nu}_\mu \to \bar{\nu}_e} = 2 |U_{e2}|^2 |U_{\mu 2}|^2 \left(1 - \cos \frac{\Delta m^2_{21} r}{2E}\right) \quad \text{if } U_{e3} = 0$$

FOR BIMAXIMAL MIXING $U_{e2} = \frac{1}{\sqrt{2}}$, $U_{\mu 2} = \frac{1}{2}$

$\langle P_{\bar{\nu}_\mu \to \bar{\nu}_e} \rangle = \frac{1}{4}$ AND $\bar{\nu}_\mu : \bar{\nu}_\tau : \bar{\nu}_e = 1 : 1 : \frac{1}{2}$

HE NEUTRINOS FROM EPOCHS WITH LARGE z

(TD AND DECAY OF SUPERHEAVY PARTICLES)

- ABSORPTION OF HE NEUTRINOS

$\nu + \bar{\nu} \to f + \bar{f}$ $\quad f = e, \mu, \tau, u, d, s \ldots$

$$z_{abs} = 7.9 \cdot 10^4 (E_{\nu 0}/1\,\mathrm{TeV})^{-1/3}$$

$E_{\nu 0}$ IS ENERGY AT $z = 0$

- NUCLEOSYNTHESIS BOUND

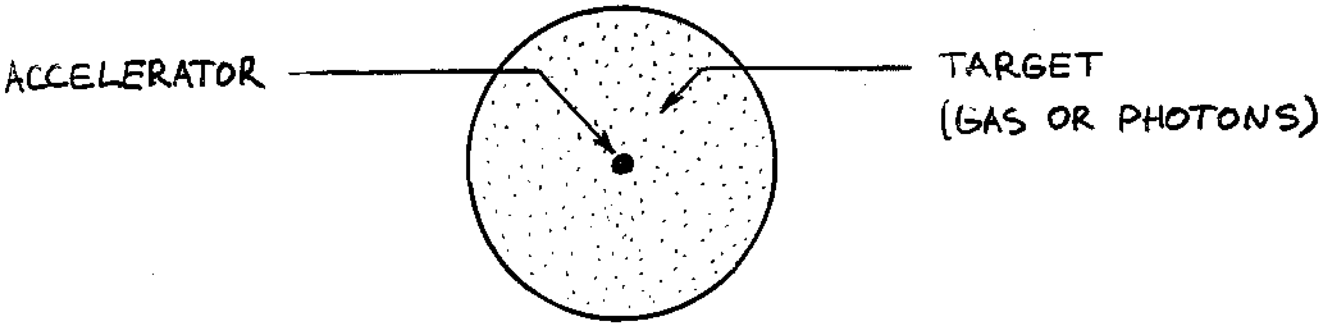
NEUTRINO FLUXES ARE STRONGLY RESTRICTED BY PRODUCTION OF $D/^3He$ AFTER BBN ($t > 1 - 100\,s$)

$$\nu + \bar{\nu}_{DM} \to \pi^0 \to \gamma \to \text{(CASCADE)} \to \text{MeV photons} \quad \gamma + {}^4He \to D, {}^3He$$

CASCADE

NEUTRINO SOURCES

- ACCELERATOR SOURCES

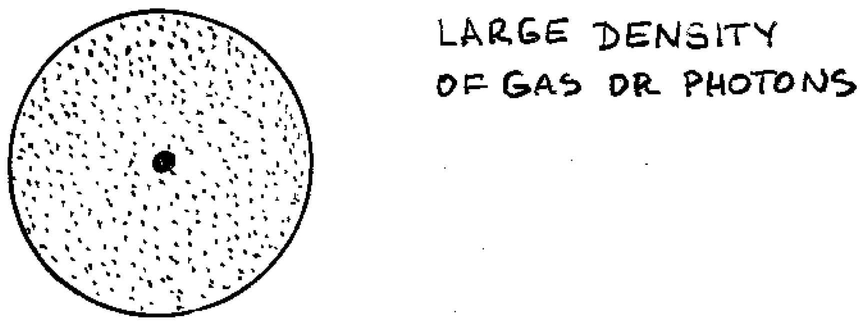


- NON-ACCELERATOR SOURCES

ANNIHILATION $X + \bar{X} \to (\pi^{\pm}, K^{\pm}) \to \nu$

DECAY $X \to$ PARTON CASCADE $\to \pi^{\pm}, K^{\pm} \to \nu$

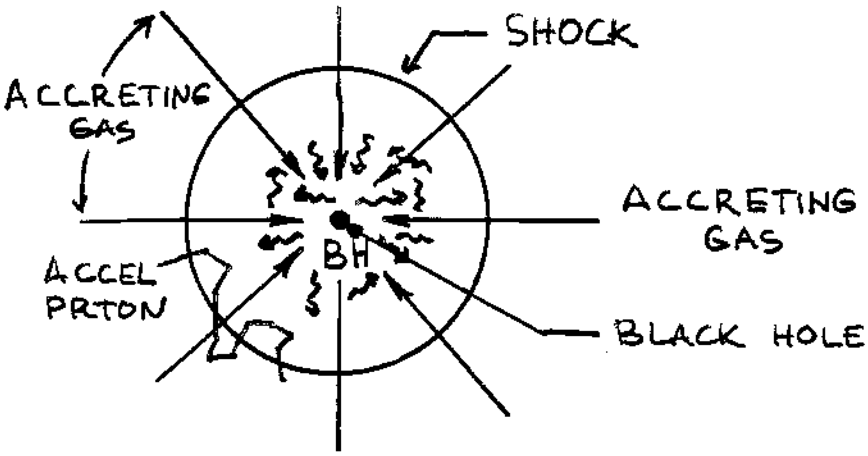
- HIDDEN SOURCES



ACCELERATION SOURCES

HE ν's FROM RADIO-QUIET AGN

STECKER MODEL 1992



- STANDING SHOCK AT $R_{sh} \sim 20\, r_g$
- PROTONS ARE ACCELERATED AND DRAGGED DOWNSTREAM

$$Q_{Prod}(E) \sim E^{-2}, \quad \int_0^{E_m} Q_{Prod}(E)\, E\, dE = \eta\, G M_{bh} \dot{M} / R_{sh}$$

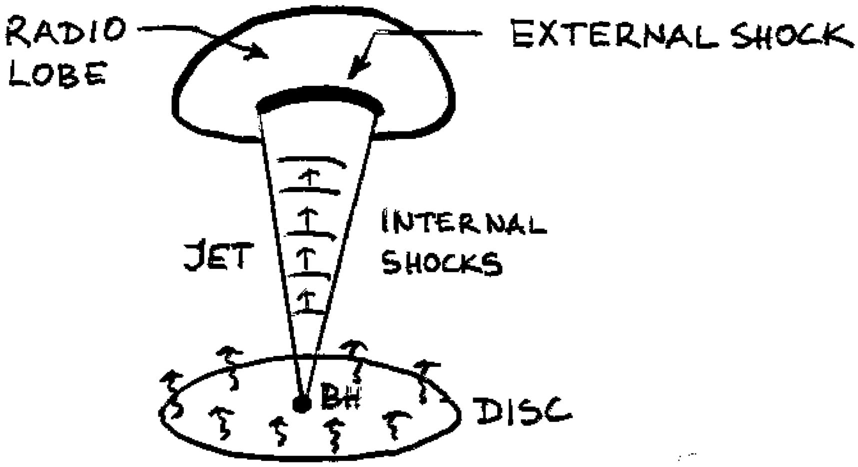
- DENSITY OF X-RAY PHOTONS, $n_X(\varepsilon)$, – OBSERVATIONS
- NEUTRINO PRODUCTION: $p + \gamma_X \Rightarrow \pi + all$
- NON-TRANSPARENCY FOR γ WITH $E_\gamma \gtrsim 1\,\mathrm{MeV}$

$$\gamma + \gamma_X \rightarrow e^+ + e^-$$

HE ν's FROM RADIO-LOUD (JET) AGN

Mannheim 1995

Atoyan, Dermer 2001

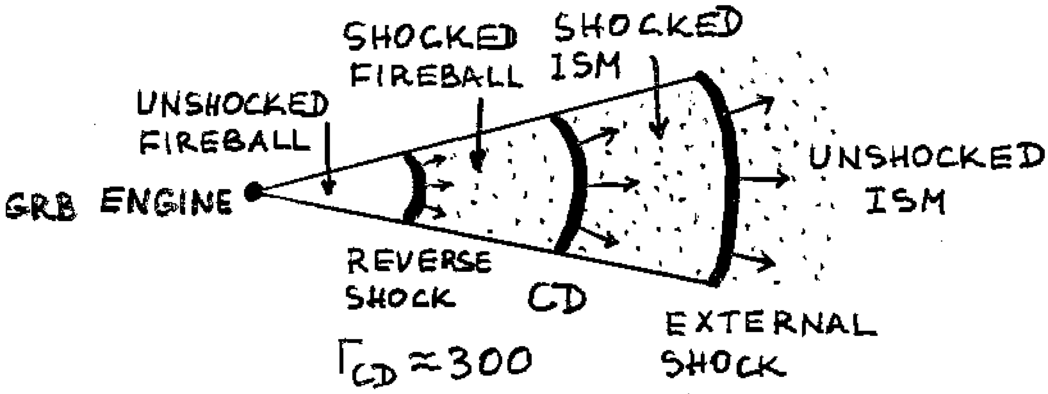


TRANSPARENT FOR HE γ'S

- NEUTRINO PRODUCTION: $p + \gamma_{tar} \rightarrow \pi^{\pm} + all$
- TARGET PHOTONS: SYNCHROTRON AND IC
- WITH PROTON LUMINOSITY $L_p = 2 \cdot 10^{48}$ erg/s 3C 379 CAN BE DETECTED BY $1\,km^3$ DETECTOR AT RATE $\sim 1\,yr^{-1}$ (Atoyan, Dermer)
- DIFFUSE FLUX CAN BE DETECTABLE

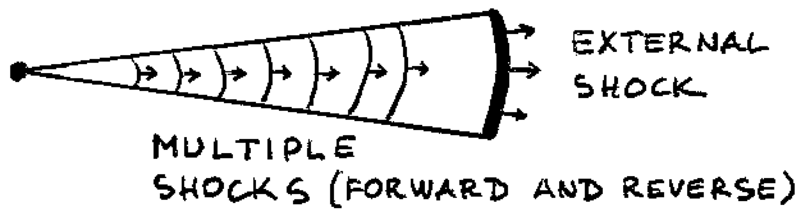
GRBs

- **EXTERNAL SHOCK** (M. Vietri 1995)



  - PROBLEMS WITH ACCELERATION
  - ν-FLUX IS UNDETECTABLE BY $1\,km^3$ DETECTOR (Dermer 02)

- **INTERNAL SHOCKS** (Waxman, Bahcall 1995)



- COLLISIONS OF SHOCKS $\longrightarrow$ TURBULENCE
- EQUIPARTITION MAGN FIELD $(B'_{eq})^2/8\pi = \epsilon_B \omega'_\gamma$
- ACCELERATION OF PROTONS $N_p(E) \sim E^{-2}$; $W_p \sim W_{GRB}$
- $E_{p,max}$: Larmor rad $r'_H \sim r'_{hor} \sim c\tau'_{GRB}$
- $p\gamma$-COLLISIONS : $\sigma_{p\gamma} n'_\gamma c\tau' \sim 1$

$$W_\nu \sim W_p \sim W_{GRB}$$

$$N_\nu(E) \sim \frac{W_{GRB}}{\ln E_{max}/E_{min}} E^{-2}$$

DETECTABILITY OF GRBs

- SINGLE GRB WITH FLUENCE S_ν

$$F_{\nu_\mu+\bar{\nu}_\mu}(>E)=\frac{1}{2}\,\frac{S_\nu}{E\,\ln E_{max}/E_{min}}$$

NUMBER OF HE MUONS IN $1\,km^3$ DETECTOR:

FOR $S_\nu \le S_{GRB}^{max} = 1\cdot 10^{-4}\,erg/cm^2$

$$N_\mu < 0.1 \quad \text{AT } E_\mu \ge 1\,TeV$$

- DIFFUSE FLUX FROM GRBs

$$I_\nu(>E)=\frac{ct_0}{4\pi}\,\frac{\mathcal{L}_\nu(0)}{E\,\ln E_{max}/E_{min}}\,K_{evol}$$

LOCAL NEUTRINO EMISSIVITY $\mathcal{L}_\nu(0) < \mathcal{L}_{GRB}(0) = 1\cdot 10^{43}\,\frac{erg}{Mpc^3\,yr}$

EVOLUTION FACTOR

$$K_{evol}=\int_0^{z_{max}} dz\,\frac{f_{ev}(z)}{(1+z)^{7/2}}$$

FOR $1\,km^3$ DETECTOR

$$N_\mu < 4.4\,K_{evol}\ yr^{-1}$$

TIME AND POSITION CORRELATION WITH GRBs !

BRIGHT PHASE

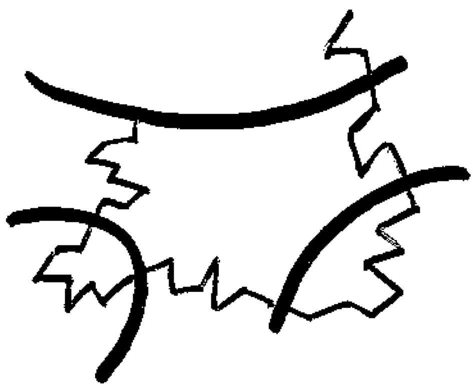
BASED ON REIONIZATION DETECTED BY WMAP

BURST OF MASSIVE STAR FORMATION AT $z \sim 10-20$

DURATION $\tau \sim (1-3) \cdot 10^{7}$ yr

ENERGY RELEASE $W \sim 3 \cdot 10^{61}$ erg/galaxy

ACCELERATION: MULTIPLE SCATTERING ON DIFFERENT SHOCKS

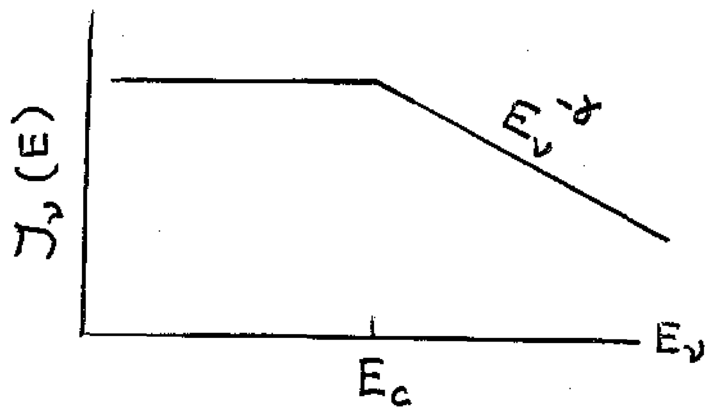


$$J_g(E) \sim E^{-\gamma_g}$$
$$\gamma_g \approx 1$$

NEUTRINO PRODUCTION: $p + \gamma_{CMB} \to \pi^{\pm} + N$

$\varepsilon_{CMB} = 6.3 \cdot 10^{-4} (1+z)$ eV; $n_{CMB} \approx 400 (1+z)^3$ cm^{-3}

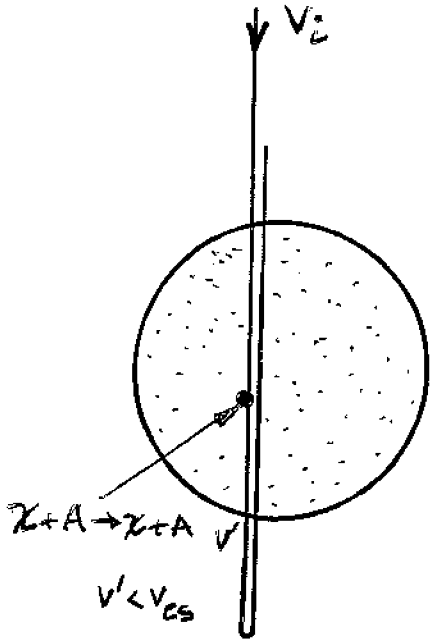
SPECTRUM AND ENERGIES



$$E_c = 6.1 \cdot 10^{6} \left(\frac{20}{1+z_{rei}} \right)^2 \text{ GeV}$$

NON-ACCELERATOR SOURCES

NEUTRALINO ANNIHILATION IN THE SUN AND EARTH



- CAPTURING OF χ BY SUN AND EARTH

Press, Spergel 1985

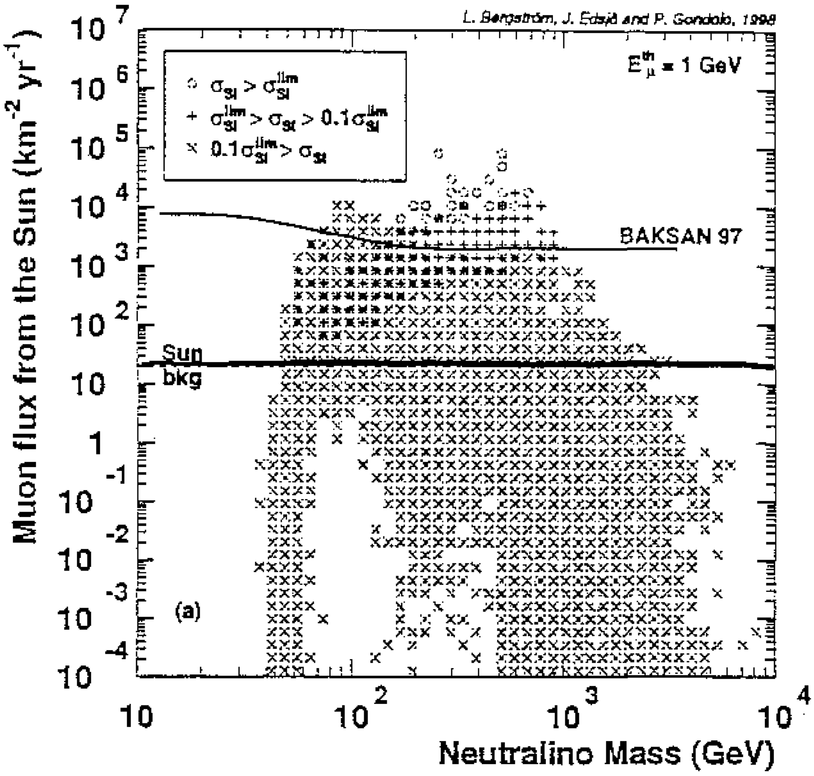
$$V_{es} = \left(\frac{2GM}{R}\right)^{1/2} = \begin{cases} 618 \text{ km/s} & \text{SUN} \\ 11 \text{ km/s} & \text{EARTH} \end{cases}$$

$$\chi + A \to \chi' + A' \qquad v' < v_{es}$$

- NEUTRINO PRODUCTION

$$\chi + \chi \to q + \bar{q} \to \text{PARTON CASCADE} \to \pi \to \nu$$

MUONS FROM SUN



DIFFUSE FLUXES

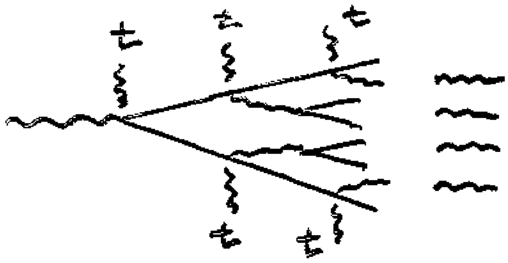
UPPER LIMITS

1. CASCADE UPPER LIMIT (V.B., A. SMIRNOV 1976)

E-M CASCADE ON TARGET PHOTONS

$\gamma + \gamma_{tar} \rightarrow e^+ + e^-$

$e + \gamma_{tar} \rightarrow e' + \gamma'$



diffuse extragal. γ
0.01 – 100 GeV

$$\omega_{cas} > \omega_\nu(>E) = \frac{4\pi}{c}\int_E^\infty E I_\nu(E)dE > \frac{4\pi}{c} E \int_E^\infty I_\nu(E)dE \equiv \frac{4\pi}{c} E I_\nu(>E)$$

$$E^2 I_\nu(E) \le \frac{c}{4\pi}\,\omega_{cas}$$

EGRET: $\omega_{cas} \lesssim 2\cdot 10^{-6}\ \text{eV/cm}^3$

2. CR UPPER LIMITS

WB UPPER LIMIT

ASSUMPTIONS:

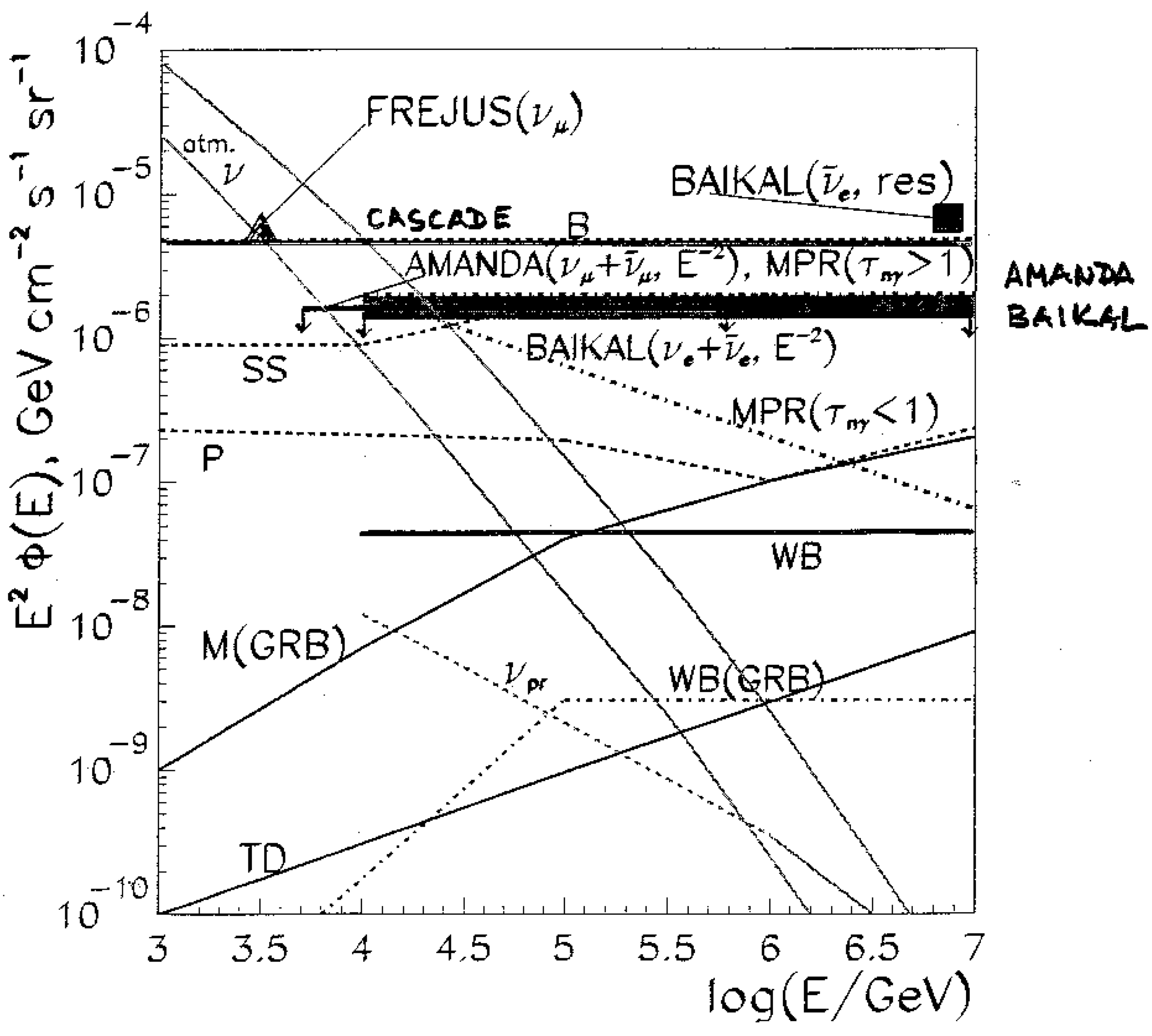
- FREE ESCAPE OF HE PROTONS
- $1/E^2$ GENERATION SPECTRUM
- NORMALIZATION TO OBSERVED FLUX AT $10^{19} - 10^{20}$ eV

MPR UPPER LIMIT

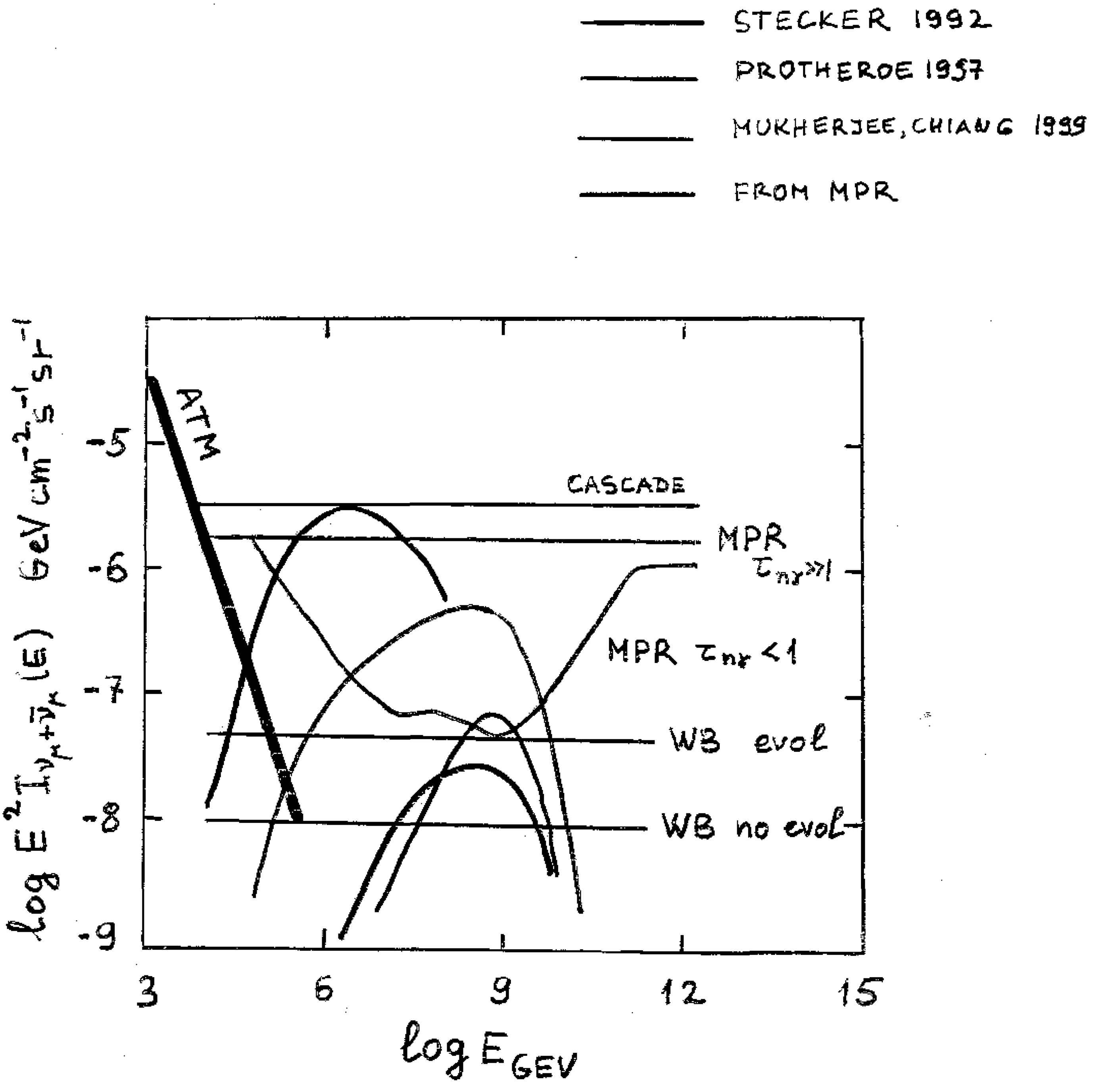
ASSUMPTIONS:

- VALID FOR AGN JETS AND GRBs WITH VARIOUS OPTICAL DEPTH $\tau_{n\gamma}$
- MAXIMUM PROTON ENERGY: $10^6 < E_{max} < 3\cdot 10^{13}$ GeV

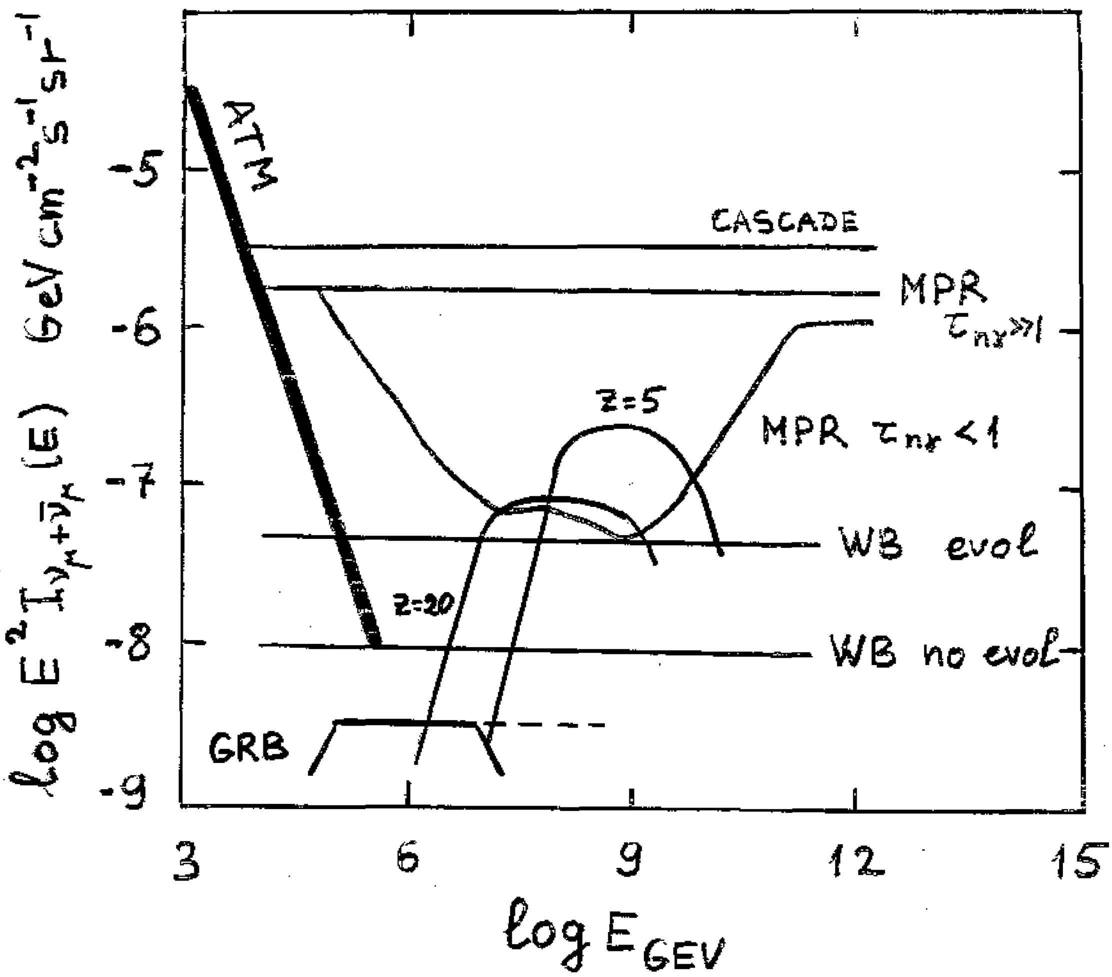
Upper Limit on Diffuse Neutrino Flux
NT-200 (234 days) + NT-96 (70 days)



AGN


STECKER 1992
PROTHEROE 1997
MUKHERJEE, CHIANG 1999
FROM MPR
ATM
CASCADE
MPR
$\tau_{n\gamma} \gg 1$
MPR $\tau_{n\gamma} < 1$
WB evol
WB no evol
-5
-6
-7
-8
-9
3
6
9
12
15
$\log E^2 I_{\nu_\mu+\bar{\nu}_\mu}(E)$ GeV cm^{-2} s^{-1} sr^{-1}
$\log E_{GEV}$

GRBs AND BRIGHT PHASE



HE NEUTRINO DETECTORS

- EXISTING:

  BAIKAL, AMANDA

- AT CONSTRUCTION:

  ANTARES, NESTOR

- FUTURE

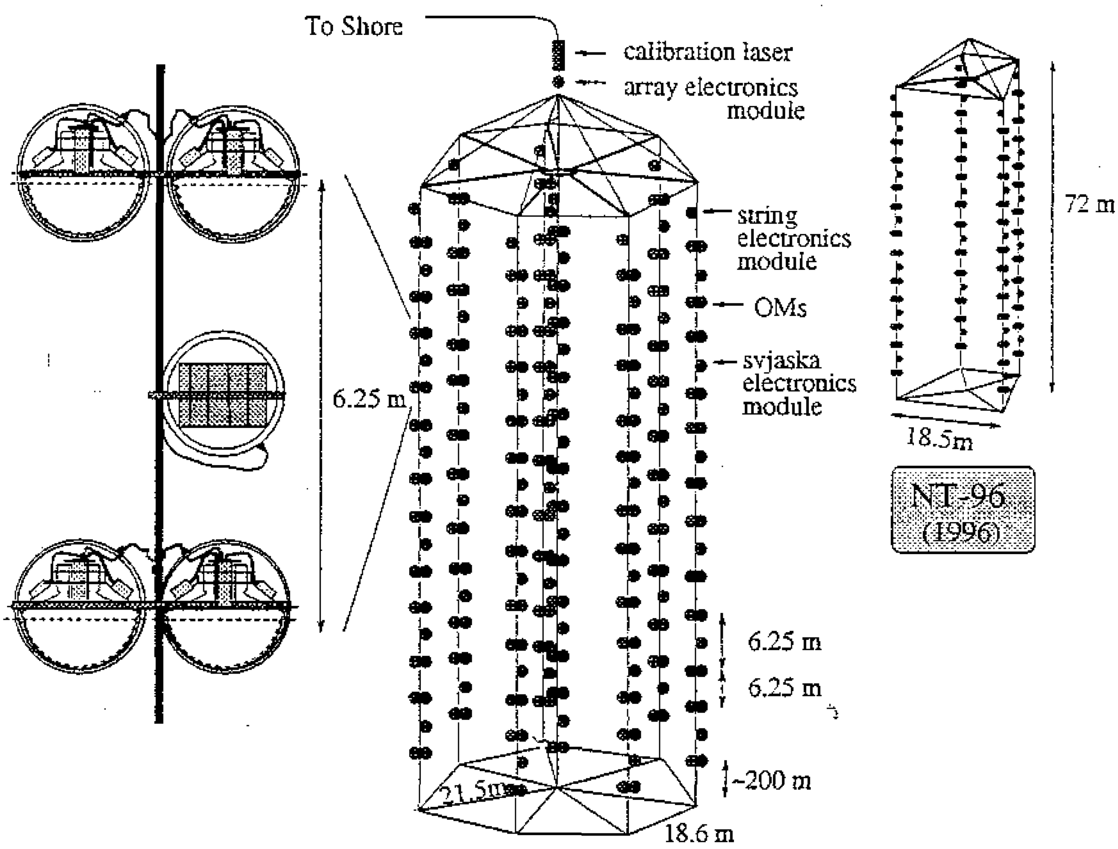
  ICE: $1 km^3$ ICECUBE

  SPACE: EUSO, OWL

  ACOUSTIC AND RADIO

BAIKAL NEUTRINO TELESCOPE NT

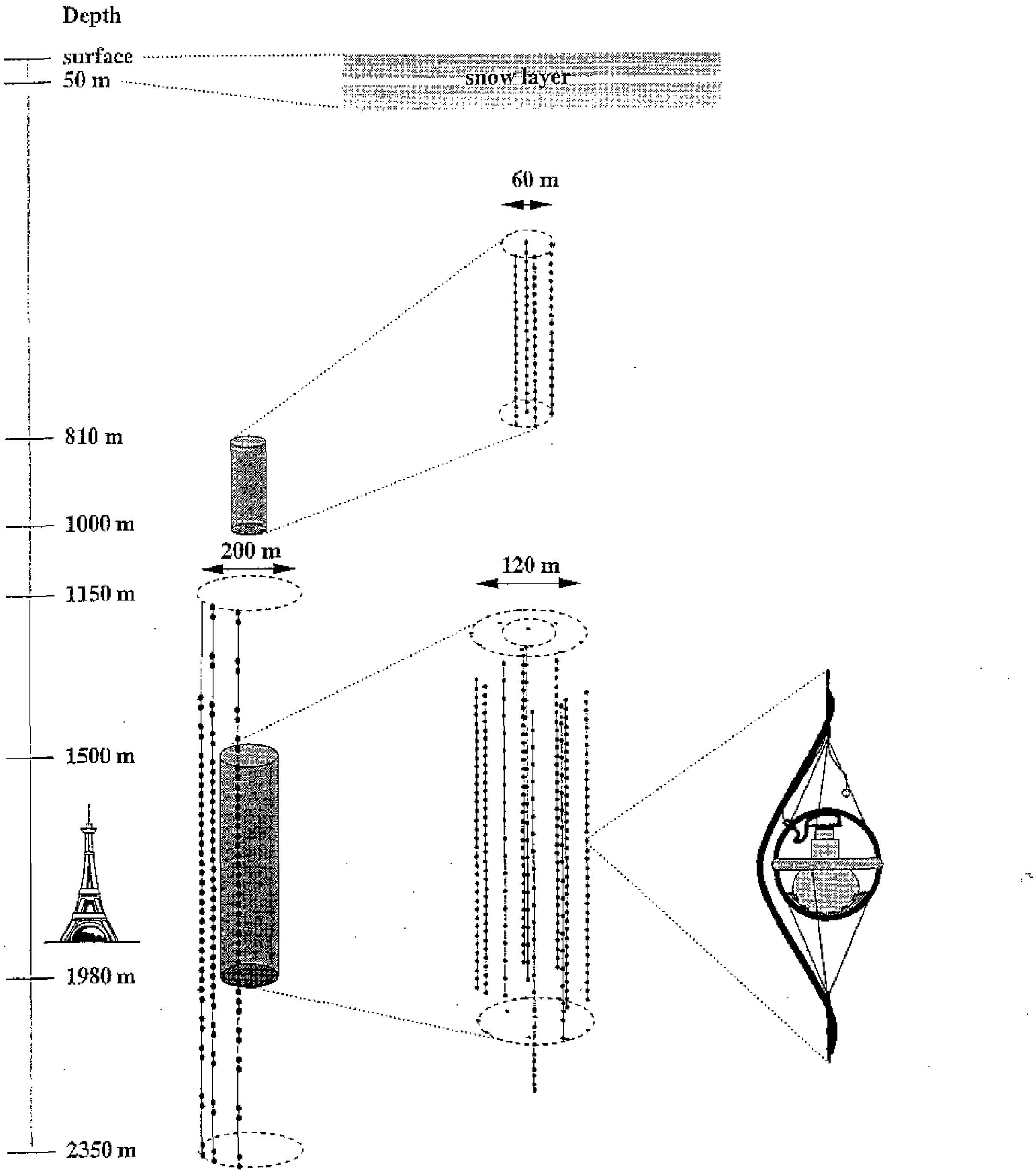
ical modules on 8 strings



Data from NT-96: 12 events for 70 effective days

AMANDA

302 modules on 10 strings at 1500-2000 m



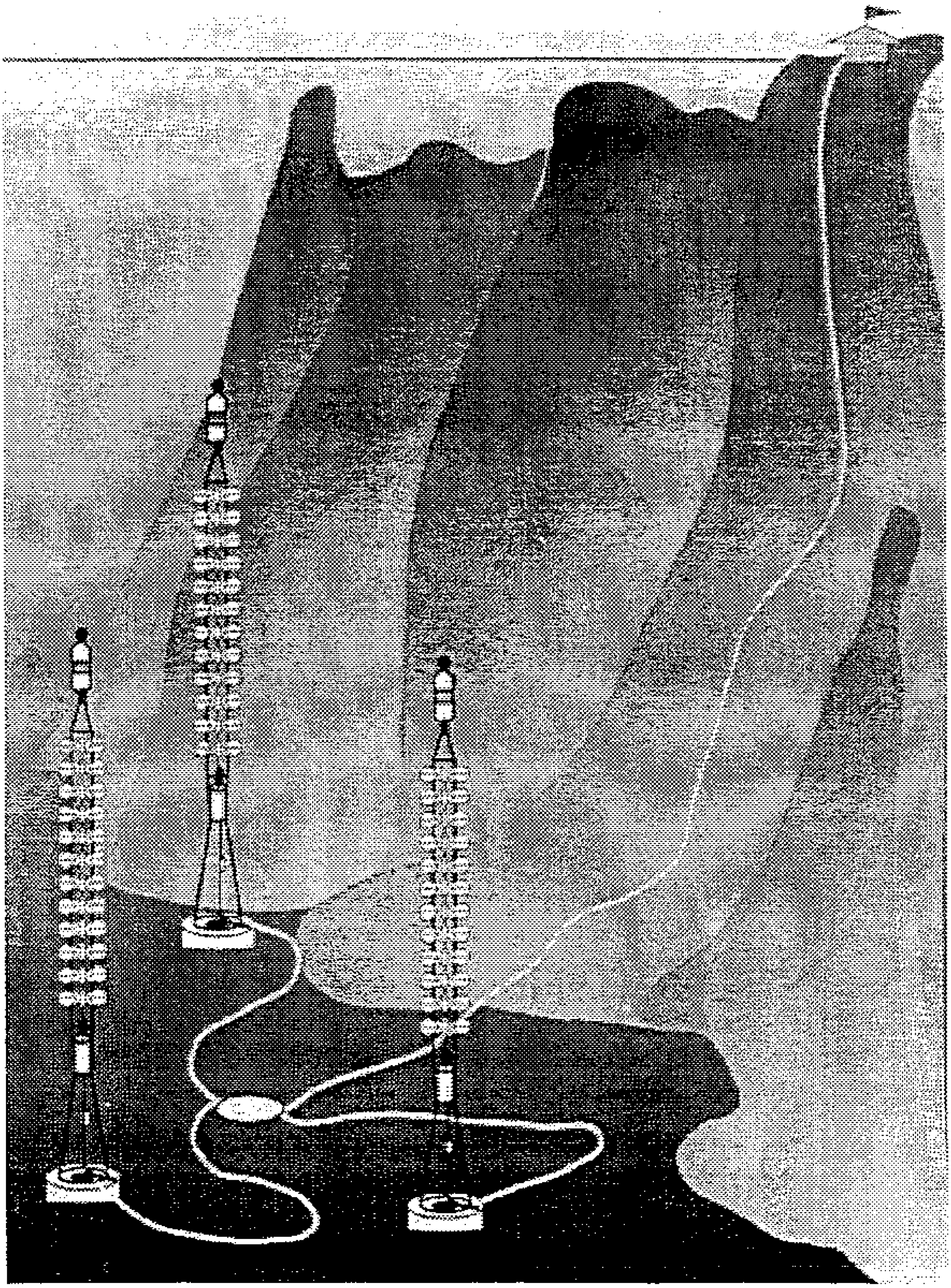
AMANDA as of 1998
Eiffel Tower as comparison
(true scaling)

zoomed in on
AMANDA-A (top)
AMANDA-B10 (bottom)

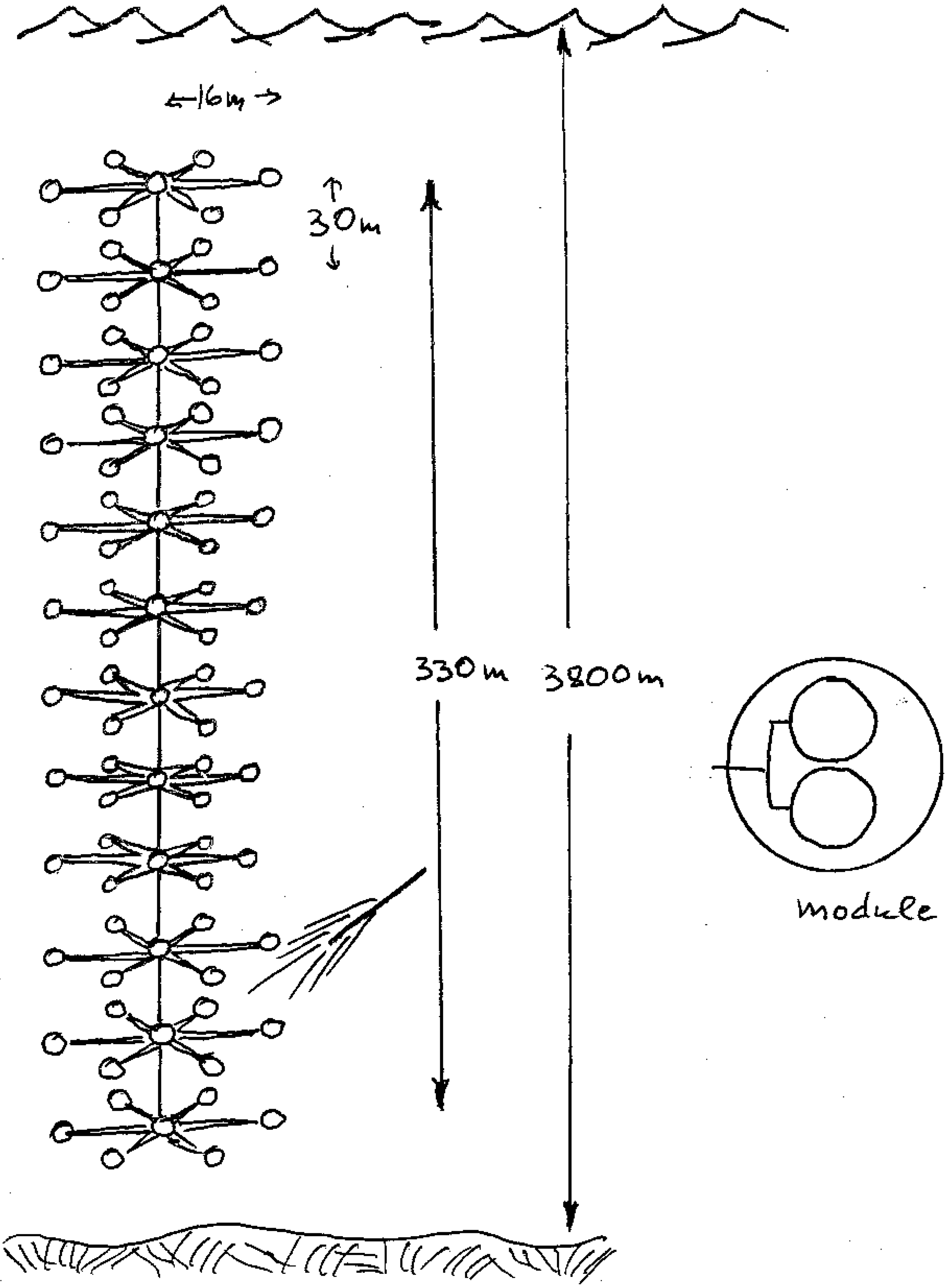
zoomed in on one
optical module (OM)

Figure 7: Configuration of Antarctic Muon And Neutrino Detector Array (AMANDA) in 1998.

ANTARES (PROJECT)



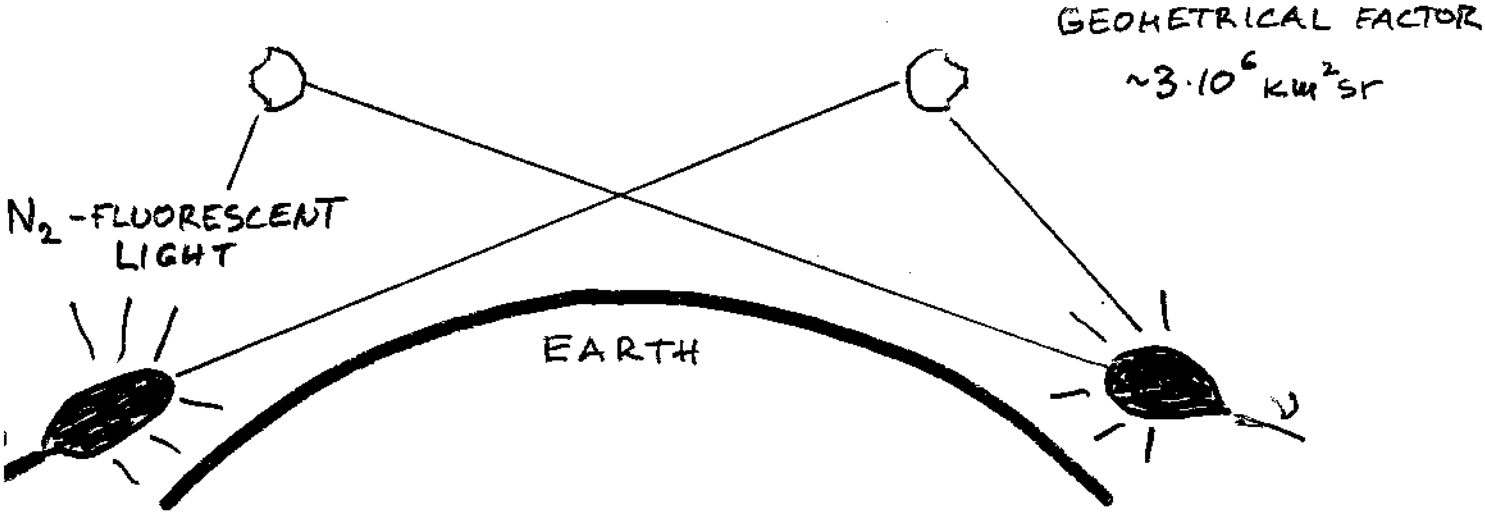
NESTOR



7 towers

SATELLITE OBSERVATIONS

AIRWATCH AND OWL PROJECTS



SATELLITE OBSERVATIONS

AIRWATCH AND OWL PROJECTS