Waxman-Bahcall limit on astrophysical neutrinos

E. Waxman & J.N. Bahcall, Phys.Rev. D59, 023002 (1998)
J.N. Bahcall & E. Waxman, Phys.Rev. D64, 023002 (2001)

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Upper bound from cosmic-ray flux (1)

- Cosmic-ray-derived neutrino flux
  - Injection above 10^{17}e $dN_{CR}/dE_{CR} \propto E_{CR}^{-2}$
  - Energy production rate (10^{19}-10^{21}eV)

$$\dot{\varepsilon}_{CR}^{[10^{19},10^{21}]} \sim 5 \times 10^{44}\ \ \mathrm{erg\ Mpc^{-3}\ yr^{-1}}$$

$$E_{CR}^2 \frac{d\dot{N}_{CR}}{dE_{CR}} = \frac{\dot{\varepsilon}_{CR}^{[10^{19},10^{21}]}}{\ln(10^{21}/10^{19})} \approx 10^{44}\ \ \mathrm{erg\ Mpc^{-3}\ yr^{-1}}$$

→

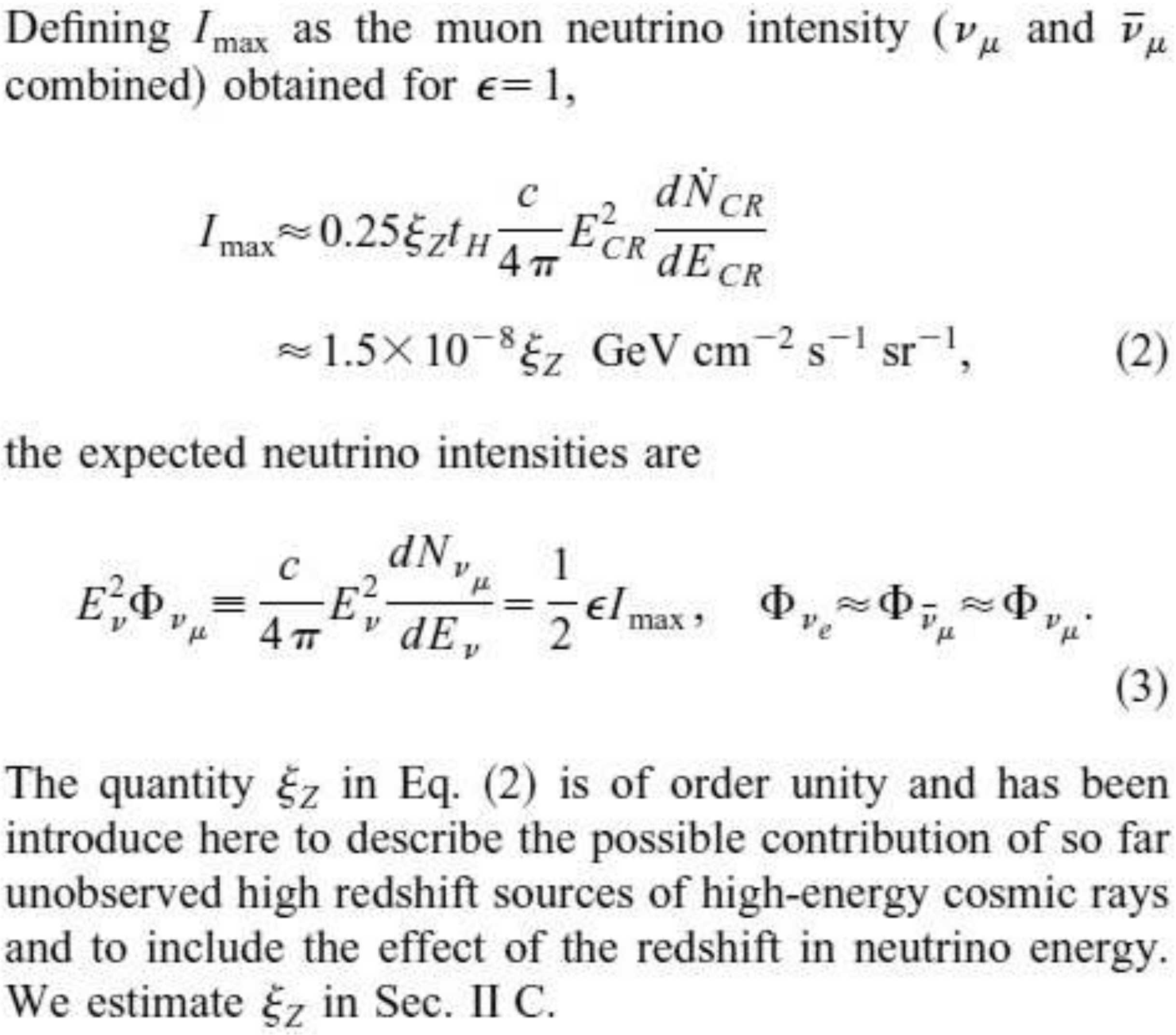
  - Energy density of muon neutrinos

$$E_\nu^2 dN_\nu/dE_\nu \approx 0.25 \epsilon t_H E_{CR}^2 d\dot{N}_{CR}/dE_{CR}$$

where ε is the fraction of energy loss before escaping the source, and t_{H} is the Hubble time.

[0.25 factor: ½ for neutral and charged pions, another ½ for pion decay]

Upper bound from cosmic-ray flux (2)



Defining $I_{\rm max}$ as the muon neutrino intensity (ν_μ and $\bar{\nu}_\mu$ combined) obtained for $\epsilon = 1$,

$$I_{\rm max} \approx 0.25 \xi_Z t_H \frac{c}{4\pi} E_{CR}^2 \frac{d\dot{N}_{CR}}{dE_{CR}} \approx 1.5 \times 10^{-8} \xi_Z \ \mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}, \qquad (2)$$

the expected neutrino intensities are

$$E_\nu^2 \Phi_{\nu_\mu} \equiv \frac{c}{4\pi} E_\nu^2 \frac{dN_{\nu_\mu}}{dE_\nu} = \frac{1}{2} \epsilon I_{\rm max}, \quad \Phi_{\nu_e} \approx \Phi_{\bar{\nu}_\mu} \approx \Phi_{\nu_\mu}. \qquad (3)$$

The quantity ξ_Z in Eq. (2) is of order unity and has been introduce here to describe the possible contribution of so far unobserved high redshift sources of high-energy cosmic rays and to include the effect of the redshift in neutrino energy. We estimate ξ_Z in Sec. II C.

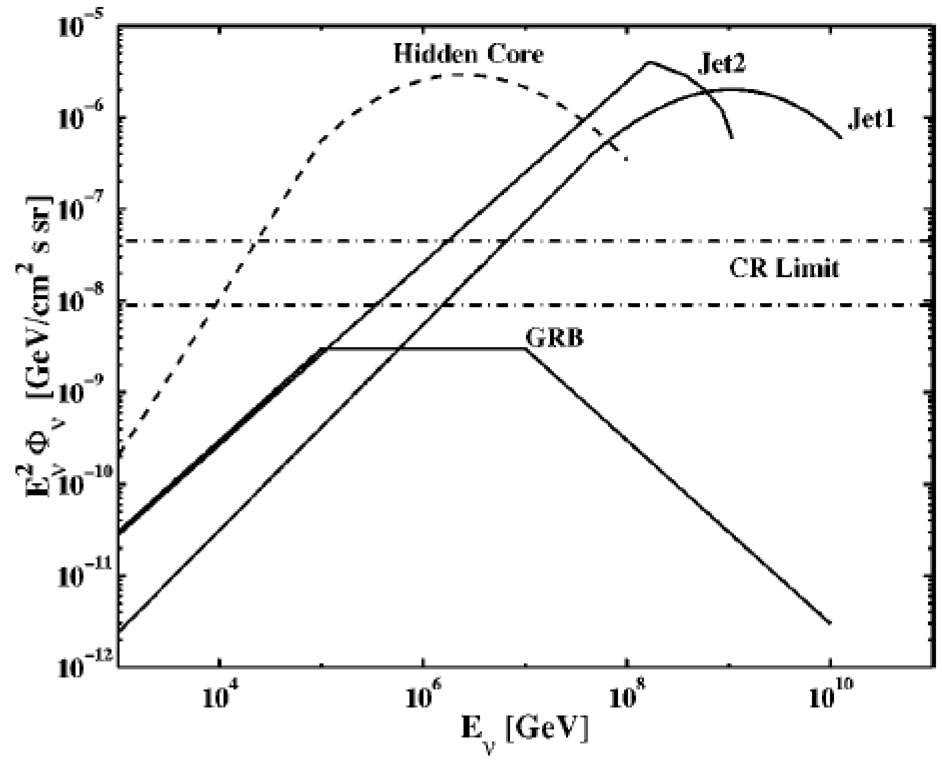


FIG. 1. Comparison of muon neutrino intensities (ν_μ and $\bar{\nu}_\mu$ combined) predicted by different models with the upper bound implied by cosmic ray observations. The dash-dotted lines give the upper bound, Eq. (2), corrected for neutrino energy loss due to redshift and for possible redshift evolution of the cosmic-ray generation rate. The lower line is obtained assuming no evolution, and the upper line assuming rapid evolution similar to the evolution of the quasi-stellar object (QSO) luminosity density. The AGN jet model predictions are taken from Ref. [4] (labeled ''Jet1'' and ''Jet2''). The GRB intensity is based on the estimate presented in this paper, following [3]. The AGN hidden-core conjecture, which produces only neutrinos and to which the upper bound does not apply, is taken from [6].

Jet1: Mannheim (1995)
Jet2: Halzen&Zas (1997)
Hidden Core: Stecker et al. (1991)

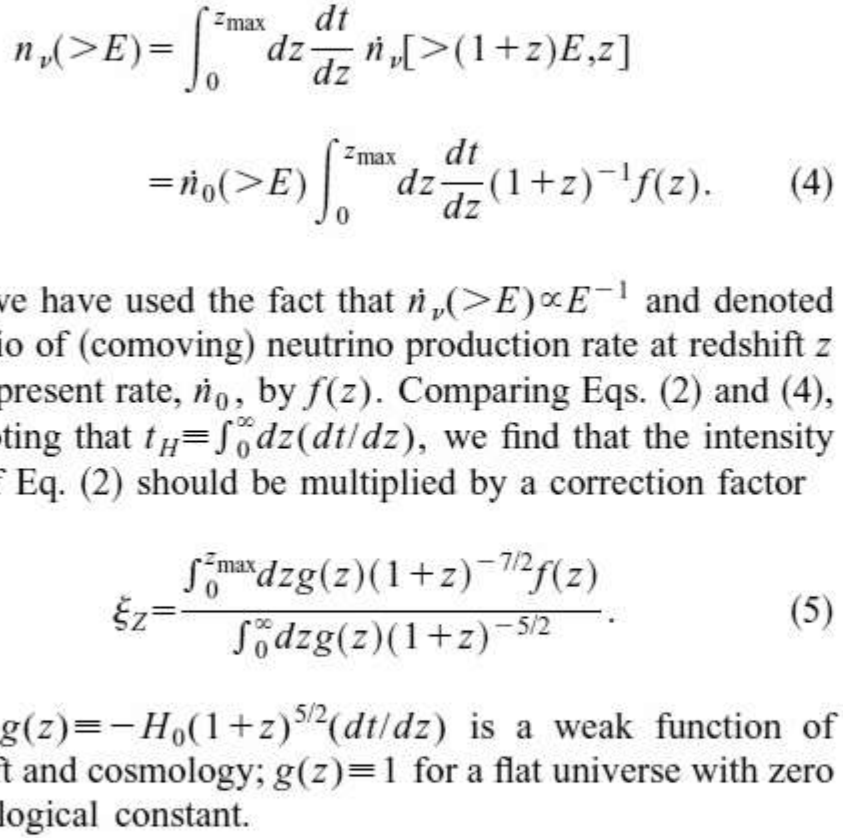
← $\boldsymbol{I}_{\text{max}}$

The intensity I_{max} is an upper bound to the intensity of high-energy neutrinos produced by photo-meson interaction in sources of size not much larger than the proton photo-meson mean-free-path.

Clearly, higher neutrino intensities may be produced by sources where the proton photo-meson “optical depth” is much higher than unity, in which case only the neutrinos escape the source (“hidden core” models). But, there is no experimental reason to assume them…

Evolution and redshift losses

- Due to energy losses, $E>10^{18}$eV protons produced at $z>1$ would be observed as $\sim10^{18}$eV.
- Modification factor ξ_z



$$n_\nu(>E)=\int_0^{z_{\max}} dz\frac{dt}{dz}\,\dot n_\nu[>(1+z)E,z]$$

$$=\dot n_0(>E)\int_0^{z_{\max}} dz\frac{dt}{dz}(1+z)^{-1}f(z). \qquad (4)$$

Here we have used the fact that $\dot n_\nu(>E)\propto E^{-1}$ and denoted the ratio of (comoving) neutrino production rate at redshift z to the present rate, $\dot n_0$, by $f(z)$. Comparing Eqs. (2) and (4), and noting that $t_H\equiv\int_0^\infty dz(dt/dz)$, we find that the intensity $I_{\max}$ of Eq. (2) should be multiplied by a correction factor

$$\xi_Z=\frac{\int_0^{z_{\max}}dz\,g(z)(1+z)^{-7/2}f(z)}{\int_0^\infty dz\,g(z)(1+z)^{-5/2}}. \qquad (5)$$

Here, $g(z)\equiv-H_0(1+z)^{5/2}(dt/dz)$ is a weak function of redshift and cosmology; $g(z)\equiv1$ for a flat universe with zero cosmological constant.

ξ_z ~3 for QSO-like evolution

ξ_z~0.6 for no evolution

Berezinsky et al., Phys. Rev. D74, 043005 (2006)

UHE proton energy loss

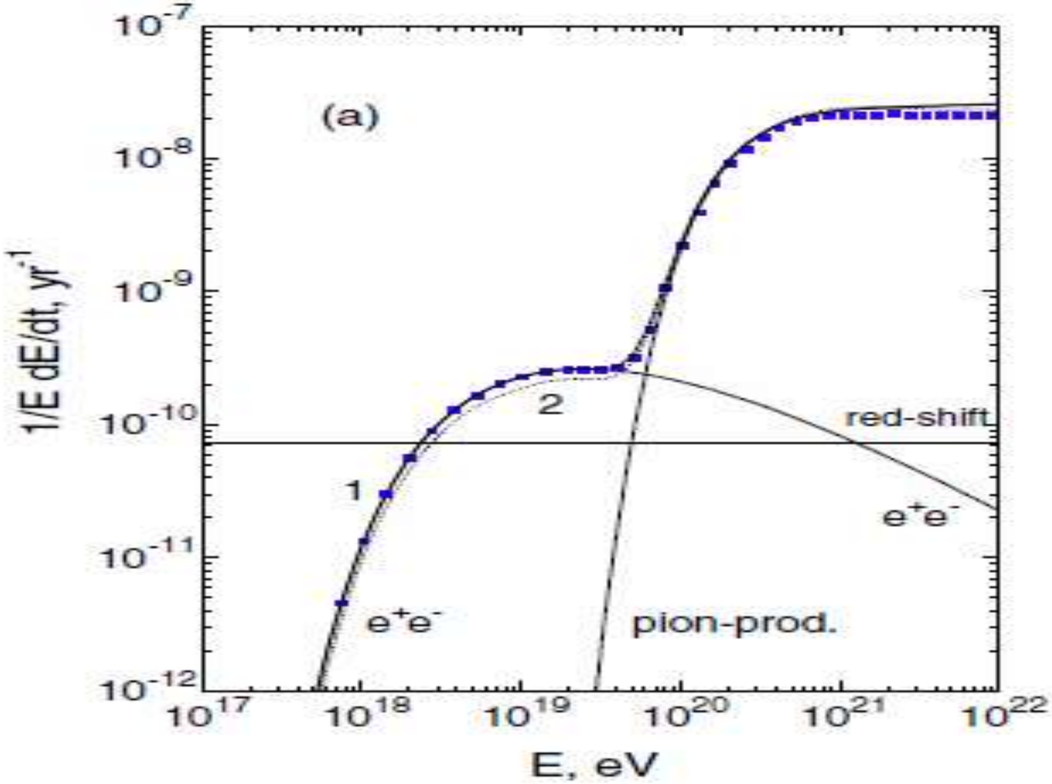
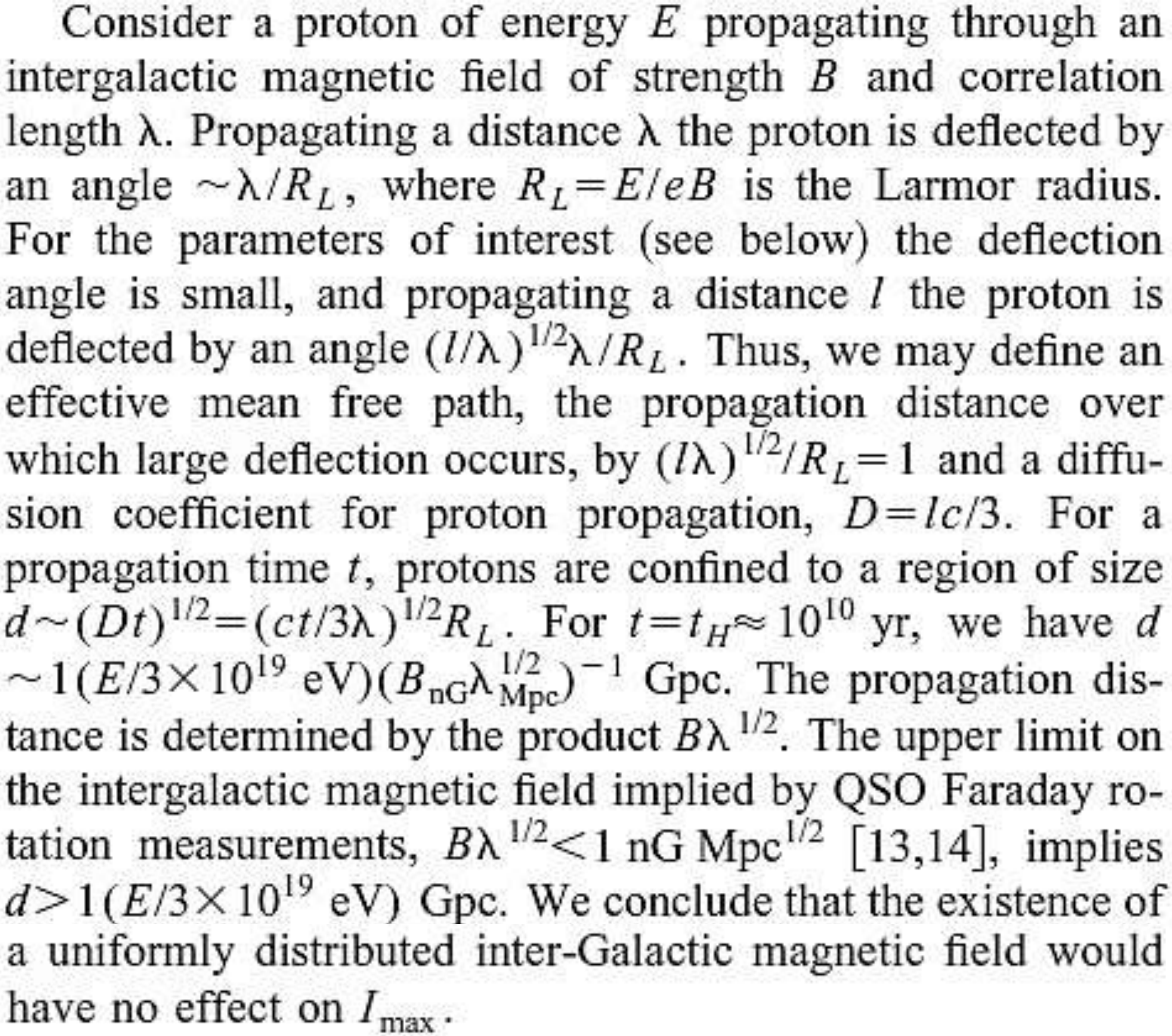


FIG. 1 (color online). (a) UHE proton energy losses $E^{-1}dE/dt$ at $z - 0$ (present work: curve 1; Berezinsky and Grigorieva (1988) [50]: curve 2; Stanev *et al.* 2000 [51]: black squares). The line "redshift" ($H_0 - 72$ km/s Mpc) gives adiabatic energy losses. Note two important energies $E_{\mathrm{eq1}} - 2.37 \times 10^{18}$ eV, where adiabatic and pair- production energy losses become equal, and $E_{\mathrm{eq2}} - 6.05 \times 10^{19}$ eV, where pair-production and photopion production energy losses are equal. The latter is one of the characteristics of the GZK cutoff. (b) The derivative $db_0(E)/dE$, where $b_0(E) - -dE/dt$ at present epoch $z - 0$, (solid curve) in comparison with $\beta_0(E) - -E^{-1}dE/dt$ (dashed curve).

Magnetic fields (1)

- Sources in which protons are confined by ***B***: neutrons produced in photo-pion production can escape and decay!
- Uniformly distributed intergalactic magnetic fields may limit CR propagation distance: but integration over time yields the same result if the CR production rate is homogeneous.
  - Even if it is inhomogeneous, strong ***B*** is required which is inconsistent with observations.



Consider a proton of energy E propagating through an intergalactic magnetic field of strength B and correlation length λ. Propagating a distance λ the proton is deflected by an angle $\sim\lambda/R_L$, where $R_L = E/eB$ is the Larmor radius. For the parameters of interest (see below) the deflection angle is small, and propagating a distance l the proton is deflected by an angle $(l/\lambda)^{1/2}\lambda/R_L$. Thus, we may define an effective mean free path, the propagation distance over which large deflection occurs, by $(l\lambda)^{1/2}/R_L = 1$ and a diffusion coefficient for proton propagation, $D = lc/3$. For a propagation time t, protons are confined to a region of size $d\sim(Dt)^{1/2} = (ct/3\lambda)^{1/2}R_L$. For $t = t_H \approx 10^{10}$ yr, we have $d \sim 1(E/3\times10^{19}\text{ eV})(B_{\text{nG}}\lambda^{1/2}_{\text{Mpc}})^{-1}$ Gpc. The propagation distance is determined by the product $B\lambda^{1/2}$. The upper limit on the intergalactic magnetic field implied by QSO Faraday rotation measurements, $B\lambda^{1/2} < 1\text{ nG Mpc}^{1/2}$ [13,14], implies $d > 1(E/3\times10^{19}\text{ eV})$ Gpc. We conclude that the existence of a uniformly distributed inter-Galactic magnetic field would have no effect on $I_{\max}$.

Magnetic fields (2)

- ***B*** in large scale structure
  - Galaxy clusters
    - $B\sim 1\mu$G, $\lambda\sim 10$kpc in the central 0.5Mpc region
    - $d\sim 10(E/3\times 10^{19}$eV)Mpc and not confined
  - Filaments and sheets
    - Particles escape faster than the Hubble time

$$t_e \sim L^2/cR_L = 10^7 \ (L/1\ \mathrm{Mpc})^2 \ (B/0.1\ \mu\mathrm{G}) \ (E/3\times 10^{19}\ \mathrm{eV}) \ \mathrm{yr}.$$

  - Local supercluster
    - $B\sim 0.1\mu$G, $\lambda\sim 10$Mpc, so $t_e << t_H$
    - If confined, local CR flux is higher than average and upper bound on neutrino intensity is lower.

AGN jet models

- Proton injection $\propto E_p^{-2}$
- Proton photo-meson optical depth $\propto E_p$
- $\therefore$Resulting neutrino spectrum $\propto E_\nu^{-1}$ (as far as optical depth is small)
- $E_\nu^{max} \sim 0.05\, E_p^{max} \sim 10^{19}$eV
- Accompanying gamma-ray emission
  - Gamma-ray blazars (But there are also leptonic emission models!)
    - Observed power-law spectrum → opt. depth is small!
  - Extragalactic diffuse gamma-ray emission

Gamma-ray bursts (1)

- Neutrinos at energies ~10^{14}eV
  - If GRBs are the source of UHECR,

$$E_\nu^2 \Phi_{\nu_\mu} \approx E_\nu^2 \Phi_{\bar{\nu}_\mu} \approx E_\nu^2 \Phi_{\nu_e} \approx \frac{1}{2} f_\pi I_{\max}$$

$$\approx 1.5 \times 10^{-9} \left(\frac{f_\pi}{0.2} \right) \min\{1, E_\nu / E_\nu^b\} \ \text{GeV cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}, \quad E_\nu^b \approx 10^{14} \ \text{eV}.$$

where f_π (~0.2) is the fraction of energy lost to pion production by protons, and $E^b{}_\nu$ (~5×10^{14}eV$[\Gamma/300]^2[E^b{}_\gamma/1\text{MeV}]^{-1}$) is the break energy.

  - This is consistent with the observed gamma-ray fluence.

Gamma-ray bursts (2)

- Neutrinos at high energy $>10^{16}$eV
  - Neutrinos are produced by decay of π&μ
  - Synchrotron loss suppression

$$\frac{E^s_{\nu_\mu(\bar{\nu}_\mu,\nu_e)}}{E^b_\nu} \approx (\xi_B L_{\gamma,51}/\xi_e)^{-1/2}\Gamma^2_{300}\Delta t_{\mathrm{ms}}(E^b_\gamma/1\ \mathrm{MeV}) \times \begin{cases} 10 & \text{for } \bar{\nu}_\mu, \nu_e, \\ 100 & \text{for } \nu_\mu. \end{cases}$$

$$\therefore \quad E^2_\nu \Phi_{\nu_\mu(\bar{\nu}_\mu,\nu_e)} \approx 1.5\times 10^{-9}\left(\frac{f_\pi}{0.2}\right) \times \left[\frac{E_\nu}{E^s_{\nu_\mu(\bar{\nu}_\mu,\nu_e)}}\right]^{-2} \ \mathrm{GeV\ cm^{-2}\ s^{-1}\ sr^{-1}},$$

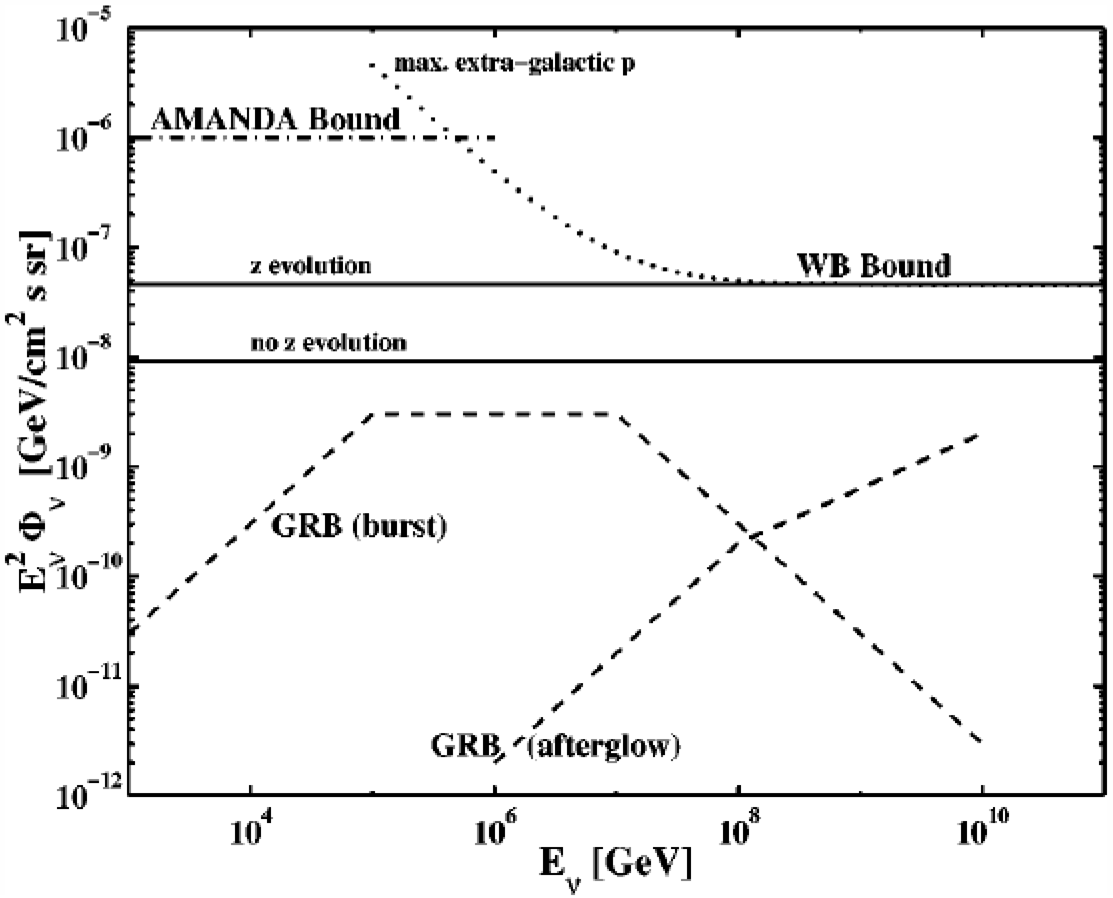
$$E_\nu \gg E^s_\nu.$$

Discussion

- Neutrino flux limit: ~1/km^2/yr
- AGN jet model assumptions may be wrong:
  1. AGN jets produce diffuse gamma-ray background
  2. Gamma-rays are due to decay of π^0 produced in photo-meson production of accelerated protons
  - Ex. Mrk 421: inverse Compton?

J.N. Bahcall & E. Waxman, Phys.Rev. D64, 023002 (2001)

Revised upper bound vs GRB



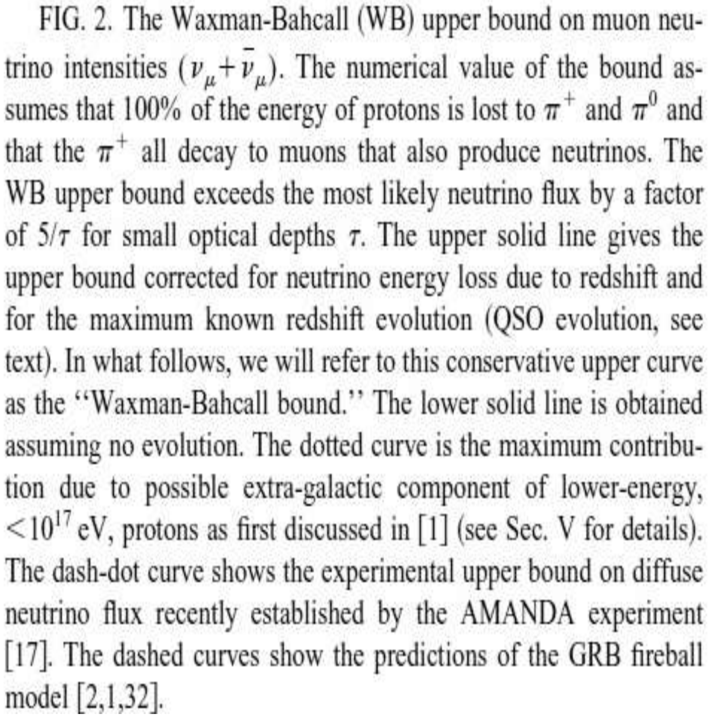


FIG. 2. The Waxman-Bahcall (WB) upper bound on muon neutrino intensities ($\nu_\mu+\bar{\nu}_\mu$). The numerical value of the bound assumes that 100% of the energy of protons is lost to π^+ and π^0 and that the π^+ all decay to muons that also produce neutrinos. The WB upper bound exceeds the most likely neutrino flux by a factor of $5/\tau$ for small optical depths τ. The upper solid line gives the upper bound corrected for neutrino energy loss due to redshift and for the maximum known redshift evolution (QSO evolution, see text). In what follows, we will refer to this conservative upper curve as the "Waxman-Bahcall bound." The lower solid line is obtained assuming no evolution. The dotted curve is the maximum contribution due to possible extra-galactic component of lower-energy, $<10^{17}$ eV, protons as first discussed in [1] (see Sec. V for details). The dash-dot curve shows the experimental upper bound on diffuse neutrino flux recently established by the AMANDA experiment [17]. The dashed curves show the predictions of the GRB fireball model [2,1,32].

J.N. Bahcall & E. Waxman, Phys.Rev. D64, 023002 (2001)

Revised upper bound vs AGN

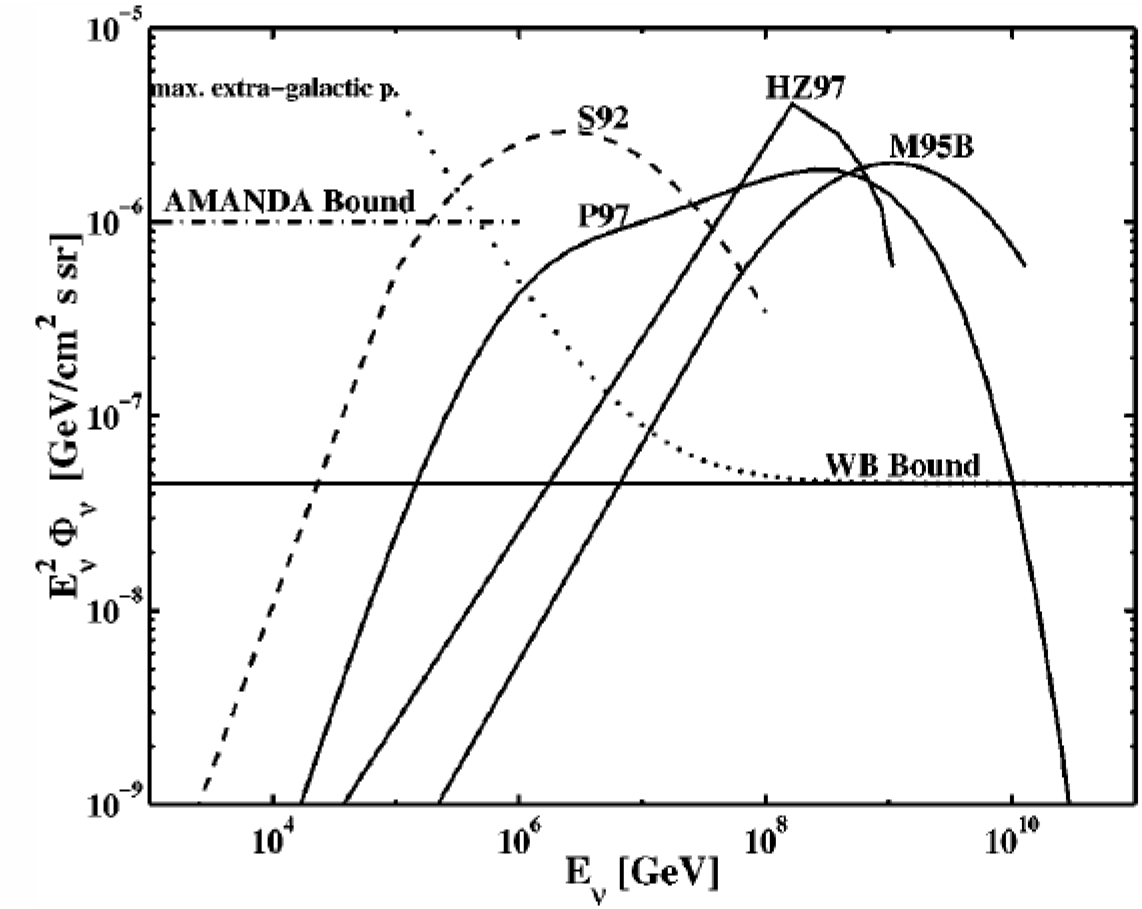
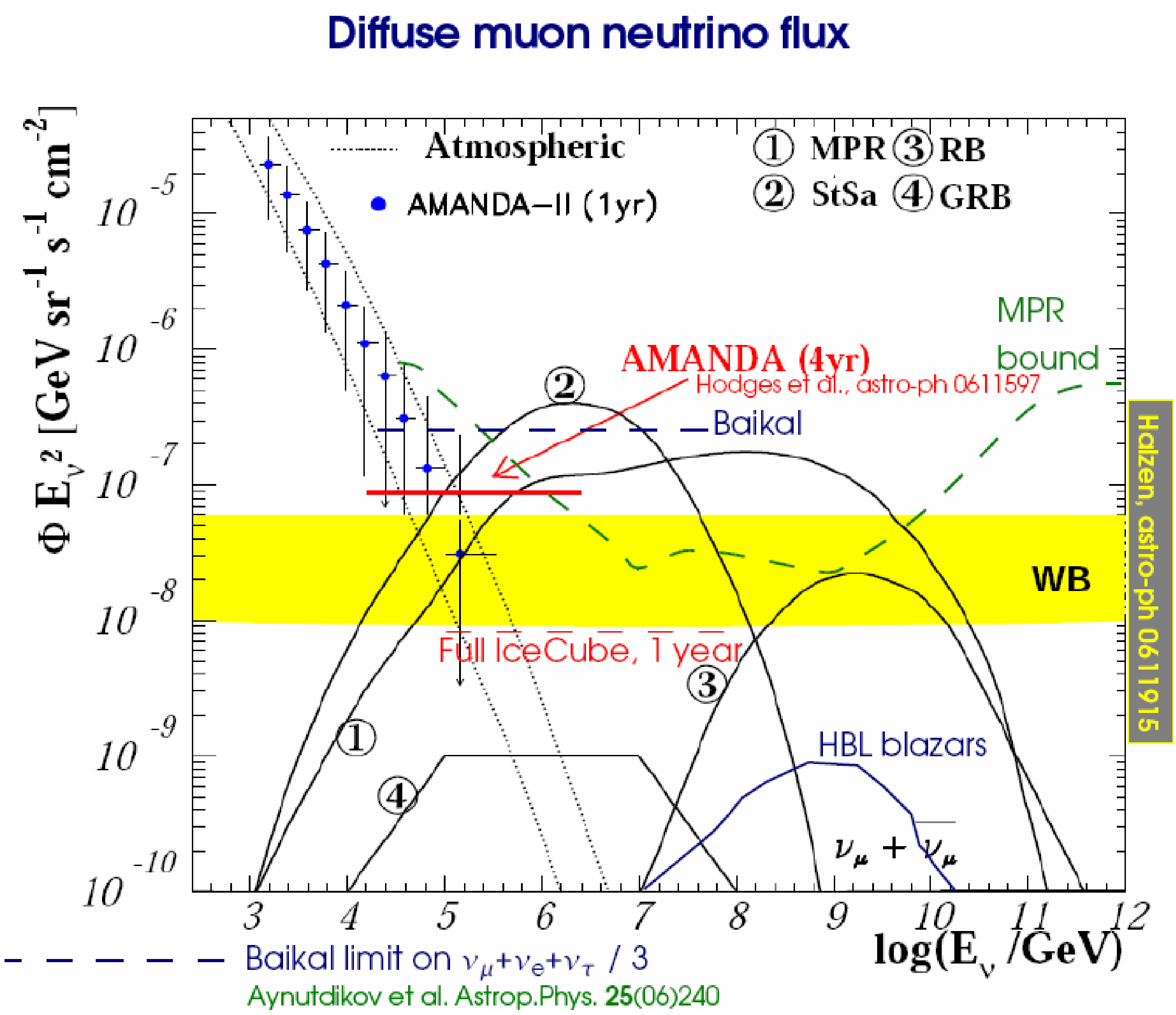


FIG. 3. The Waxman-Bahcall (WB) upper bound on muon neutrino intensities ($\nu_\mu + \bar{\nu}_\mu$) (solid line) compared to predictions of representative AGN jet models, taken from the earlier papers of Mannheim [42] (marked M95B in the figure), Protheroe [43] (P97), and Halzen and Zas [44] (HZ97). The AGN models were normalized so that the calculated gamma-ray flux from π^0 decay fits the observed gamma-ray background. The AGN hidden-core conjecture (S92), to which the WB upper bound does not apply due to high photo-meson optical depth of the source, is taken from [14]. Note that this conjecture is already ruled out by the AMANDA upper bound [17].

高エネルギーニュートリノ観測の現状



Baikal limit on $\nu_\mu+\nu_e+\nu_\tau$ / 3

Aynutdikov et al. Astrop.Phys. **25**(06)240