Citation: D.E. Groom *et al.* (Particle Data Group), Eur. Phys. Jour. **C15**, 1 (2000) and 2001 partial update for edition 2002 (URL: http://pdg.lbl.gov)

# Number of Neutrino Types and Sum of Neutrino Masses

The neutrinos referred to in this section are those of the Standard SU(2)×U(1) Electroweak Model possibly extended to allow nonzero neutrino masses. Light neutrinos are those with $m < m_Z/2$. The limits are on the number of neutrino mass eigenstates, including $\nu_1$, $\nu_2$, and $\nu_3$.

## A REVIEW GOES HERE – Check our WWW List of Reviews

### Number from $e^+e^-$ Colliders

#### Number of Light $\nu$ Types

Our evaluation uses the invisible and leptonic widths of the $Z$ boson from our combined fit shown in the Particle Listings for the $Z$ Boson, and the Standard Model value $\Gamma_\nu/\Gamma_\ell$ = 1.9908 ± 0.0015.

| *VALUE* | *DOCUMENT ID* | | *TECN* |
|---|---|---|---|
| **2.994±0.012 OUR EVALUATION** | Combined fit to all LEP data. | | |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | |
| 3.00 ±0.05 | [1] LEP | 92 | RVUE |

[1] Simultaneous fits to all measured cross section data from all four LEP experiments.

#### Number of Light $\nu$ Types from Direct Measurement of Invisible $Z$ Width

In the following, the invisible $Z$ width is obtained from studies of single-photon events from the reaction $e^+e^- \rightarrow \nu\overline{\nu}\gamma$. All are obtained from LEP runs in the $E^{ee}_{\rm cm}$ range 88–189 GeV.

| *VALUE* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|
| **3.00±0.07 OUR AVERAGE** | | | | |
| 2.84±0.15±0.14 | ABREU | 00Z | DLPH | 1997–1998 LEP runs |
| 3.01±0.08 | ACCIARRI | 99R | L3 | 1991–1998 LEP runs |
| 2.89±0.32±0.19 | ABREU | 97J | DLPH | 1993–1994 LEP runs |
| 3.23±0.16±0.10 | AKERS | 95C | OPAL | 1990–1992 LEP runs |
| 2.68±0.20±0.20 | BUSKULIC | 93L | ALEP | 1990–1991 LEP runs |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| 3.1 ±0.6 ±0.1 | ADAM | 96C | DLPH | $\sqrt{s}$ = 130, 136 GeV |

### Limits from Astrophysics and Cosmology

#### Number of Light $\nu$ Types

("light" means < about 1 MeV). See also OLIVE 81. For a review of limits based on Nucleosynthesis, Supernovae, and also on terrestial experiments, see DENEGRI 90. Also see "Big-Bang Nucleosynthesis" in this *Review*.

| *VALUE* | *DOCUMENT ID* | *COMMENT* |
|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | |

| | | | |
|---|---|---|---|
| $2 < N_\nu < 4$ | LISI | 99 | BBN |
| $< 4.3$ | OLIVE | 99 | BBN |
| $< 4.9$ | COPI | 97 | Cosmology |
| $< 3.6$ | HATA | 97B | High D/H quasar abs. |
| $< 4.0$ | OLIVE | 97 | BBN; high $^4$He and $^7$Li |
| $< 4.7$ | CARDALL | 96B | Cosmology, High D/H quasar abs. |
| $< 3.9$ | FIELDS | 96 | Cosmology, BBN; high $^4$He and $^7$Li |
| $< 4.5$ | KERNAN | 96 | Cosmology, High D/H quasar abs. |
| $< 3.6$ | OLIVE | 95 | BBN; $\geq 3$ massless $\nu$ |
| $< 3.3$ | WALKER | 91 | Cosmology |
| $< 3.4$ | OLIVE | 90 | Cosmology |
| $< 4$ | YANG | 84 | Cosmology |
| $< 4$ | YANG | 79 | Cosmology |
| $< 7$ | STEIGMAN | 77 | Cosmology |
| | PEEBLES | 71 | Cosmology |
| $< 16$ | [2] SHVARTSMAN | 69 | Cosmology |
| | HOYLE | 64 | Cosmology |

[2] SHVARTSMAN 69 limit inferred from his equations.

## Number Coupling with Less Than Full Weak Strength

| VALUE | DOCUMENT ID | | TECN |
|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | |
| $< 20$ | [3] OLIVE | 81C | COSM |
| $< 20$ | [3] STEIGMAN | 79 | COSM |

[3] Limit varies with strength of coupling. See also WALKER 91.

---

# A REVIEW GOES HERE – Check our WWW List of Reviews

---

## Limit on Total $\nu$ MASS, $m_{tot}$

(Defined in the above note), of effectively stable neutrinos (i.e., those with mean lives greater than or equal to the age of the universe). These papers assumed Dirac neutrinos. When necessary, we have generalized the results reported so they apply to $m_{tot}$. For other limits, see SZALAY 76, VYSOTSKY 77, BERNSTEIN 81, FREESE 84, SCHRAMM 84, and COWSIK 85.

| VALUE (eV) | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| $< 2.7$ | [4] FUKUGITA | 00 | COSM | |
| $< 5.5$ | [5] CROFT | 99 | ASTR | Ly $\alpha$ power spec |
| $< 180$ | SZALAY | 74 | COSM | |
| $< 132$ | COWSIK | 72 | COSM | |
| $< 280$ | MARX | 72 | COSM | |
| $< 400$ | GERSHTEIN | 66 | COSM | |

[4] FUKUGITA 00 is a limit on neutrino masses from structure formation. The constraint is based on the clustering scale $\sigma_8$ and the COBE normalization and leads to a conservative limit of 0.9 eV assuming 3 nearly degenerate neutrinos. The quoted limit is on the sum of the light neutrino masses.

[5] CROFT 99 result based on the power spectrum of the Ly $\alpha$ forest. If $\Omega_{matter} < 0.5$, the limit is improved to $m_\nu < 2.4$ ($\Omega_{matter}$/0.17–1) eV.

## Limits on MASSES of Light Stable Right-Handed $\nu$ (with necessarily suppressed interaction strengths)

| *VALUE* (eV) | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| <100–200 | [6] OLIVE | 82 | COSM | Dirac $\nu$ |
| <200–2000 | [6] OLIVE | 82 | COSM | Majorana $\nu$ |

[6] Depending on interaction strength $G_R$ where $G_R < G_F$.

## Limits on MASSES of Heavy Stable Right-Handed $\nu$ (with necessarily suppressed interaction strengths)

| *VALUE* (GeV) | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| > 10 | [7] OLIVE | 82 | COSM | $G_R/G_F$ <0.1 |
| >100 | [7] OLIVE | 82 | COSM | $G_R/G_F$ <0.01 |

[7] These results apply to heavy Majorana neutrinos and are summarized by the equation: $m_\nu$ >1.2 GeV ($G_F/G_R$). The bound saturates, and if $G_R$ is too small no mass range is allowed.

## REFERENCES FOR Limits on Number of Neutrino Types and Sum of Neutrino Masses


ABREU 00Z EPJ C17 53 P. Abreu *et al.* (DELPHI Collab.)
FUKUGITA 00 PRL 84 1082 M. Fukugita, G.C. Liu, N. Sugiyama
ACCIARRI 99R PL B470 268 M. Acciarri *et al.* (L3 Collab.)
CROFT 99 PRL 83 1092 R.A.C. Croft, W. Hu, R. Dave
LISI 99 PR D59 123520 E. Lisi, S. Sarkar, F.L. Villante
OLIVE 99 ASP 11 403 K.A. Olive, D. Thomas
ABREU 97J ZPHY C74 577 P. Abreu *et al.* (DELPHI Collab.)
COPI 97 PR D55 3389 C.J. Copi, D.N. Schramm, M.S. Turner (CHIC)
HATA 97B PR D55 540 N. Hata *et al.* (OSU, PENN)
OLIVE 97 ASP 7 27 K.A. Olive, D. Thomas (MINN, FLOR)
ADAM 96C PL B380 471 W. Adam *et al.* (DELPHI Collab.)
CARDALL 96B APJ 472 435 C.Y. Cardall, G.M. Fuller (UCSD)
FIELDS 96 New Ast 1 77 B.D. Fields *et al.* (NDAM, CERN, MINN+)
KERNAN 96 PR D54 3681 P.S. Kernan, S. Sarkar (CASE, OXFTP)
AKERS 95C ZPHY C65 47 R. Akers *et al.* (OPAL Collab.)
OLIVE 95 PL B354 357 K.A. Olive, G. Steigman (MINN, OSU)
BUSKULIC 93L PL B313 520 D. Buskulic *et al.* (ALEPH Collab.)
LEP 92 PL B276 247 LEP Collabs. (LEP, ALEPH, DELPHI, L3, OPAL)
WALKER 91 APJ 376 51 T.P. Walker *et al.* (HSCA, OSU, CHIC+)
DENEGRI 90 RMP 62 1 D. Denegri, B. Sadoulet, M. Spiro (CERN, UCB+)
OLIVE 90 PL B236 454 K.A. Olive *et al.* (MINN, CHIC, OSU+)
COWSIK 85 PL 151B 62 R. Cowsik (TATA)
FREESE 84 NP B233 167 K. Freese, D.N. Schramm (CHIC, FNAL)
SCHRAMM 84 PL 141B 337 D.N. Schramm, G. Steigman (FNAL, BART)
YANG 84 APJ 281 493 J. Yang *et al.* (CHIC, BART)
OLIVE 82 PR D25 213 K.A. Olive, M.S. Turner (CHIC, UCSB)
BERNSTEIN 81 PL 101B 39 J. Bernstein, G. Feinberg (STEV, COLU)
OLIVE 81 APJ 246 557 K.A. Olive *et al.* (CHIC, BART)
OLIVE 81C NP B180 497 K.A. Olive, D.N. Schramm, G. Steigman (EFI+)
STEIGMAN 79 PRL 43 239 G. Steigman, K.A. Olive, D.N. Schramm (BART+)
YANG 79 APJ 227 697 J. Yang *et al.* (CHIC, YALE, VIRG)
STEIGMAN 77 PL 66B 202 G. Steigman, D.N. Schramm, J.R. Gunn (YALE, CHIC+)
VYSOTSKY 77 JETPL 26 188 M.I. Vysotsky, A.D. Dolgov, Y.B. Zeldovich (ITEP)
Translated from ZETFP 26 200.
SZALAY 76 AA 49 437 A.S. Szalay, G. Marx (EOTV)
SZALAY 74 APAH 35 8 A.S. Szalay, G. Marx (EOTV)
COWSIK 72 PRL 29 669 R. Cowsik, J. McClelland (UCB)
MARX 72 Nu Conf. Budapest G. Marx, A.S. Szalay (EOTV)
PEEBLES 71 Physical Cosmology P.Z. Peebles (PRIN)
Princeton Univ. Press (1971)
SHVARTSMAN 69 JETPL 9 184 V.F. Shvartsman (MOSU)
Translated from ZETFP 9 315.

| | | | | |
|---|---|---|---|---|
| GERSHTEIN | 66 | JETPL 4 120<br>Translated from ZETFP 4 189. | S.S. Gershtein, Y.B. Zeldovich | (KIAM) |
| HOYLE | 64 | Nature 203 1108 | F. Hoyle, R.J. Tayler | (CAMB) |