

Number of Neutrino Types and Sum of Neutrino Masses

The neutrinos referred to in this section are those of the Standard $SU(2)\times U(1)$ 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 ν_1 , ν_2 , and ν_3 .

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Number from e^+e^- Colliders

Number of Light ν 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 $\Gamma_\nu/\Gamma_\ell = 1.9908 \pm 0.0015$.

<u>VALUE</u>	<u>DOCUMENT ID</u>	<u>TECN</u>
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
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¹ Simultaneous fits to all measured cross section data from all four LEP experiments.

Number of Light ν 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 $e^+e^- \rightarrow \nu\bar{\nu}\gamma$. All are obtained from LEP runs in the E_{cm}^{ee} range 88–189 GeV.

<u>VALUE</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
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 ν Types

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

<u>VALUE</u>	<u>DOCUMENT ID</u>	<u>COMMENT</u>
• • • 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 ^4He and ^7Li
< 4.7	CARDALL	96B	Cosmology, High D/H quasar abs.
< 3.9	FIELDS	96	Cosmology, BBN; high ^4He and ^7Li
< 4.5	KERNAN	96	Cosmology, High D/H quasar abs.
< 3.6	OLIVE	95	BBN; ≥ 3 massless ν
< 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

<u>VALUE</u>	<u>DOCUMENT ID</u>	<u>TECN</u>
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• • • 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.

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Limit on Total ν 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.

<u>VALUE (eV)</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
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• • • 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 α 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 σ_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 α forest. If $\Omega_{\text{matter}} < 0.5$, the limit is improved to $m_\nu < 2.4 (\Omega_{\text{matter}}/0.17-1)$ eV.

Limits on MASSES of Light Stable Right-Handed ν (with necessarily suppressed interaction strengths)

VALUE (eV)	DOCUMENT ID	TECN	COMMENT
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• • • We do not use the following data for averages, fits, limits, etc. • • •

<100–200	⁶ OLIVE	82	COSM Dirac ν
<200–2000	⁶ OLIVE	82	COSM Majorana ν

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

Limits on MASSES of Heavy Stable Right-Handed ν (with necessarily suppressed interaction strengths)

VALUE (GeV)	DOCUMENT ID	TECN	COMMENT
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• • • 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: $m_\nu > 1.2 \text{ GeV} (G_F/G_R)$. 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 <i>et al.</i>	(DELPHI Collab.)
FUKUGITA	00	PRL 84 1082	M. Fukugita, G.C. Liu, N. Sugiyama	
ACCIARRI	99R	PL B470 268	M. Acciarri <i>et al.</i>	(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 <i>et al.</i>	(DELPHI Collab.)
COPI	97	PR D55 3389	C.J. Copi, D.N. Schramm, M.S. Turner	(CHIC)
HATA	97B	PR D55 540	N. Hata <i>et al.</i>	(OSU, PENN)
OLIVE	97	ASP 7 27	K.A. Olive, D. Thomas	(MINN, FLOR)
ADAM	96C	PL B380 471	W. Adam <i>et al.</i>	(DELPHI Collab.)
CARDALL	96B	APJ 472 435	C.Y. Cardall, G.M. Fuller	(UCSD)
FIELDS	96	New Ast 1 77	B.D. Fields <i>et al.</i>	(NDAM, CERN, MINN+)
KERNAN	96	PR D54 3681	P.S. Kernan, S. Sarkar	(CASE, OXFTP)
AKERS	95C	ZPHY C65 47	R. Akers <i>et al.</i>	(OPAL Collab.)
OLIVE	95	PL B354 357	K.A. Olive, G. Steigman	(MINN, OSU)
BUSKULIC	93L	PL B313 520	D. Buskalic <i>et al.</i>	(ALEPH Collab.)
LEP	92	PL B276 247	LEP Collabs.	(LEP, ALEPH, DELPHI, L3, OPAL)
WALKER	91	APJ 376 51	T.P. Walker <i>et al.</i>	(HSCA, OSU, CHIC+)
DENEGRI	90	RMP 62 1	D. Denegri, B. Sadoulet, M. Spiro	(CERN, UCB+)
OLIVE	90	PL B236 454	K.A. Olive <i>et al.</i>	(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 <i>et al.</i>	(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 <i>et al.</i>	(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 <i>et al.</i>	(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	S.S. Gershtein, Y.B. Zeldovich	(KIAM)
		Translated from ZETFP 4 189.		
HOYLE	64	Nature 203 1108	F. Hoyle, R.J. Tayler	(CAMB)
