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 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 Γ_ν/Γ_ℓ = 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 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 $e^+e^- \rightarrow \nu\overline{\nu}\gamma$. All are obtained from LEP runs in the E^{ee}_{cm} range 88–189 GeV.

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
2.92±0.07 OUR AVERAGE				
2.69±0.13±0.11	ABBIENDI,G	00D	OPAL	1998 LEP run
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
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 terrestial experiments, see DENEGRI 90. Also see "Big-Bang Nucleosynthesis" in this *Review*.

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
< 3.6	[2] CYBURT	01	COSM	
<17	[3] HANNESTAD	01C	COSM	
< 9	[4] KNELLER	01	COSM	
$2<N_\nu<4$	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; ≥ 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	[5] SHVARTSMAN	69		Cosmology
	HOYLE	64		Cosmology

[2] Limit on the number of neutrino types based on ^{4}He abundance assuming a baryon density fixed by the recent CMB data. Limit relaxes to 5.9 if D/H is used instead of ^{4}He. More than two light ($m<1$ MeV) neutrino types have been assumed.

[3] Limit on the number of neutrino types based solely on microwave background anisotropy data.

[4] Limit on the number of neutrino types based on combination of microwave background anisotropy data and degenerate big bang nucleosynthesis.

[5] 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	[6] OLIVE	81C	COSM
<20	[6] STEIGMAN	79	COSM

[6] 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.

VALUE (eV)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<$ 1.8	[7] ELGAROY	02	ASTR	2dF Galaxy Redshift Survey
$<$ 3.0	[8] HANNESTAD	02C	ASTR	2dF Galaxy Redshift Survey
$<$ 0.9	[9] LEWIS	02	COSM	
$<$ 4.2	[10] WANG	02	COSM	CMB
$<$ 2.7	[11] FUKUGITA	00	COSM	
$<$ 5.5	[12] CROFT	99	ASTR	Ly α power spec
$<$180	SZALAY	74	COSM	
$<$132	COWSIK	72	COSM	
$<$280	MARX	72	COSM	
$<$400	GERSHTEIN	66	COSM	

[7] ELGAROY 02 constrains the fractional contribution of neutrinos to the total matter density in the Universe from the power spectrum of fluctuations derived from the 2 Degree Field Galaxy Redshift Survey. Assumes $\Omega_{matter} < 0.5$ and a spectal index of 1.0. Limit softens to $m_\nu < 2.2$ eV for n=1.0 $\pm$ 0.1.

[8] HANNESTAD 02C constrains the fractional contribution of neutrinos to the total matter density in the Universe combining data from the CMB and the 2 Degree Field Galaxy Redshift Survey. Limit strengthens to 2.5 eV when data from SNIa observations, big-bang nucleosynthesis, and HST Key project are included.

[9] LEWIS 02 constrains the total mass of neutrinos from the power spectrum of fluctuations derived from the CMB, HST Key project, 2dF galaxy redshift survey, supernovae type Ia, and BBN.

[10] WANG 02 constrains the total mass of neutrinos from the power spectrum of fluctuations derived from the CMB and other cosmological data sets such as galaxy clustering and the Lyman α forest.

[11] 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.

[12] CROFT 99 result based on the power spectrum of the Ly α forest. If $\Omega_{matter} < 0.5$, the limit is improved to $m_\nu < 2.4$ (Ω_{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*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<$100–200	[13] OLIVE	82	COSM	Dirac ν
$<$200–2000	[13] OLIVE	82	COSM	Majorana ν

[13] 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*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$>$ 10	[14] OLIVE	82	COSM	G_R/G_F <0.1
$>$100	[14] OLIVE	82	COSM	G_R/G_F <0.01

[14] These results apply to heavy Majorana neutrinos and are summarized by the equation: m_ν >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

ELGAROY	02	PRL 89 061301	O. Elgaroy *et al.*	
HANNESTAD	02C	PR D66 125011	S. Hannestad *et al.*	
LEWIS	02	PR D66 103511	A. Lewis, S. Bridle	
WANG	02	PR D65 123001	X. Wang, M. Tegmark, M. Zaldarriaga	
CYBURT	01	ASP 17 87	R.H. Cyburt, B.D. Fields, K.A. Olive	
HANNESTAD	01C	PR D64 083002	S. Hannestad *et al.*	
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ABREU	00Z	EPJ C17 53	P. Abreu *et al.*	(DELPHI Collab.)
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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	
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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)
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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)
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)
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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+)
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VYSOTSKY	77	JETPL 26 188 Translated from ZETFP 26 200.	M.I. Vysotsky, A.D. Dolgov, Y.B. Zeldovich	(ITEP)
SZALAY	76	AA 49 437	A.S. Szalay, G. Marx	(EOTV)
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MARX	72	Nu Conf. Budapest	G. Marx, A.S. Szalay	(EOTV)
PEEBLES	71	Physical Cosmology Princeton Univ. Press (1971)	P.Z. Peebles	(PRIN)
SHVARTSMAN	69	JETPL 9 184 Translated from ZETFP 9 315.	V.F. Shvartsman	(MOSU)
GERSHTEIN	66	JETPL 4 120 Translated from ZETFP 4 189.	S.S. Gershtein, Y.B. Zeldovich	(KIAM)
HOYLE	64	NAT 203 1108	F. Hoyle, R.J. Tayler	(CAMB)