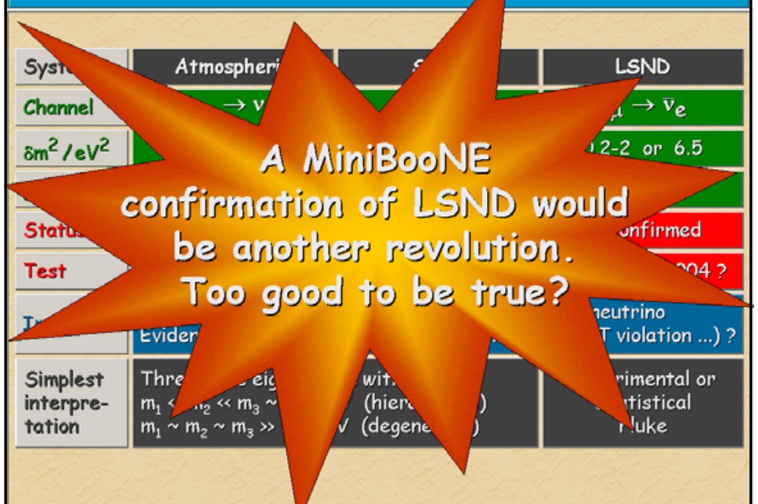
Status of Evidence for Neutrino Oscillations

System	Atmospheric	Solar	LSND
Channel	$\nu_\mu \to \nu_\tau$	$\nu_e \to \nu_{\mu\tau}$	$\bar\nu_\mu \to \bar\nu_e$
$\delta m^2 / eV^2$	$(1.5-4)\times 10^{-3}$	LMA $(0.2-2)\times 10^{-4}$	0.2-2 or 6.5
$\sin^2 2\theta$	0.9–1	0.2–0.6	0.001–0.03
Status	Established	Established	Unconfirmed
Test	Long Baseline	KamLAND 12/2002	MiniBooNE 2004 ?
Implication	Mutually inconsistent, even with a sterile neutrino Evidence for physics beyond flavor oscillations (CPT violation ...) ?		
Simplest interpre-tation	Three mass eigenstates with $m_1 \ll m_2 \ll m_3 \sim 50$ meV (hierarchical) $m_1 \sim m_2 \sim m_3 \gg 50$ meV (degenerate)		Experimental or Statistical Fluke

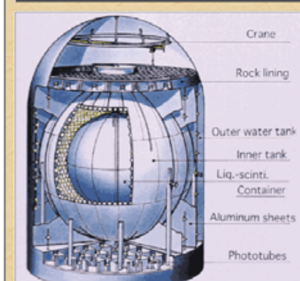
Status of Evidence for Neutrino Oscillations



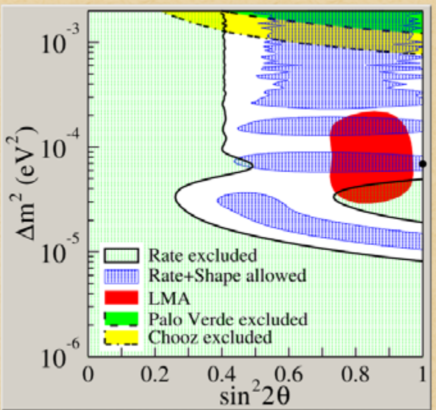
Kamland Reactor Neutrino Experiment (Japan)

Japanese nuclear reactors
60 GW (20% world capacity)

- Witout Oscillations
  2 Neutrino captures / day
- Data taking since
  22 January 2002



Kamland Reactor Neutrino Experiment (Japan)



Japanese nuclear reactors
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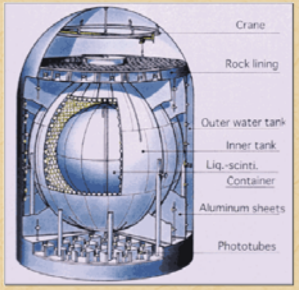


First Kamland results earlier this week at "Texas in Tuscany" and hep-ex/0212021

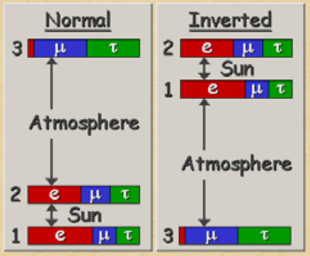
Three-Flavor Neutrino Parameters (Ignoring LSND)

Atmospheric	Chooz Limit	Solar	3σ ranges
$32^\circ < \theta_{23} < 60^\circ$	$\theta_{13} < 14^\circ$	$27^\circ < \theta_{12} < 41^\circ$	hep-ph/0211054

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & & \\ & c_{23} & s_{23}\\ & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & & e^{-i\delta}s_{13}\\ & 1 & \\ -e^{i\delta}s_{13} & & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$c_{12} = \cos\theta_{12}$ etc., δ CP-violating phase

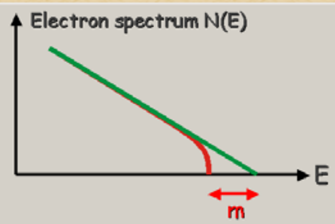
Solar 24 - 240
Atmospheric 1400 - 6000
$\Delta m^2/\mathrm{meV}^2$



Cosmology →

Tasks and Open Questions
- Precision for θ_{12} and θ_{23} ($\theta_{12} < 45^\circ$ and $\theta_{23} = 45^\circ$?)
- How large is θ_{13}?
- CP-violating phase?
- Mass ordering? (normal vs inverted)
- Absolute masses? (hierarchical vs degenerate)
- Dirac or Majorana?

Tritium Endpoint Spectrum



Tritium Beta Decay

$$^3H \to {}^3He + e^- + \bar\nu_e$$

Endpoint energy 18.6 keV

Mainz Experiment, PLB 460 (1999) 219
m < 2.8 eV (95% CL)

Troitsk Experiment, ibid. 227
m < 2.5 eV (95% CL)

These experiments have reached 2.2 eV (Neutrino 2002)

Scaled-up spectrometer (KATRIN) may reach 0.3 eV
Currently in preparation - Results in > 5 years

Cosmological Limit on Neutrino Masses

Cosmic neutrino "sea" ~ 112 cm^{-3} neutrinos + anti-neutrinos per flavor

$$\Omega_\nu h^2 = \sum \frac{m_\nu}{94\,\mathrm{eV}} < 0.4$$

m_ν < 40 eV — For all stable flavors

REST MASS OF MUONIC NEUTRINO AND COSMOLOGY

S. S. Gershtein and Ya. B. Zel'dovich
Submitted 4 June 1966
ZhETF Pis'ma 4, No. 5, 174-177, 1 September 1966

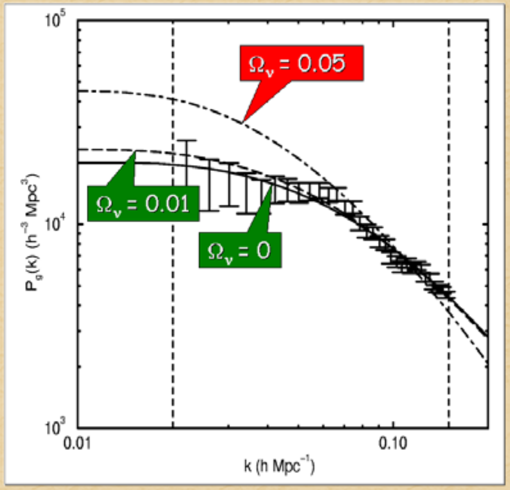
Low-accuracy experimental estimates of the rest mass of the neutrino [1] yield $m(\nu_e) < 200$ eV/c^2 for the electronic neutrino and $m(\nu_\mu) < 2.5 \times 10^6$ eV/c^2 for the muonic neutrino.

Cosmological considerations connected with the hot model of the Universe [2] make it possible to strengthen greatly the second inequality. Just as in the paper by Ya. B. Zel'dovich and Ya. A. Smorodinskii [3], let us consider the gravitational effect of the neutrinos on the dynamics of the expanding Universe. The age of the known astronomical objects is not smaller than 5 x 10^9 years, and Hubble's constant H is not smaller than 75 km/sec-Mparsec = (13 x 10^9 years)$^{-1}$. It follows therefore that the density of all types of matter in the Universe is at the present time 1)

$$\rho < 2 \times 10^{-28}\ \mathrm{g/cm^3}.$$

A classic paper:
Gershtein & Zeldovich
JETP Lett. 4 (1966) 120

Neutrino Mass Limit from 2dF Galaxy Survey



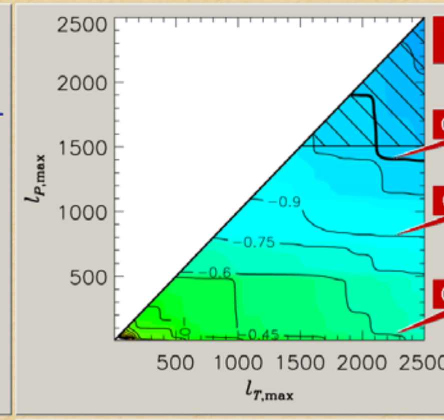
Elgarøy et al., astro-ph/0204152

$\Sigma\, m_\nu < 2.2$ eV at 95% CL (statistical)

Depends on priors for other parameters

Similar limits based on the 2dF survey
- Hannestad astro-ph/0205223
- Lewis & Bridle astro-ph/0205436

PLANCK Sensitivity to Neutrino Mass

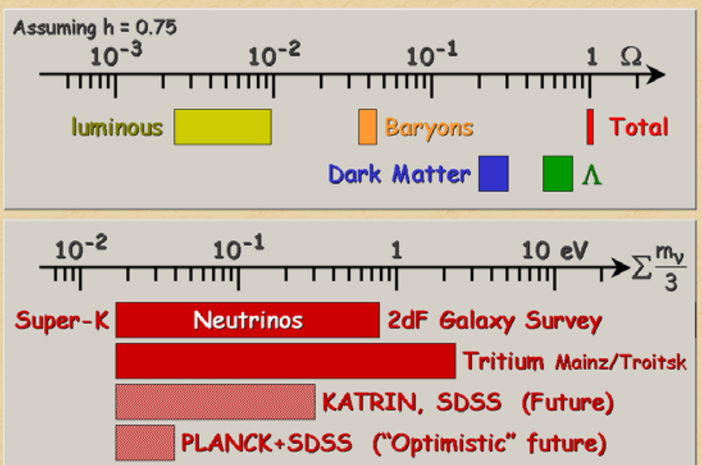


Maximum polarization multipole that can be measured to cosmic-variance precision

Maximum temperature multipole that can be measured to cosmic-variance precision

Steen Hannestad astro-ph/0211106

Mass-Energy-Inventory of the Universe

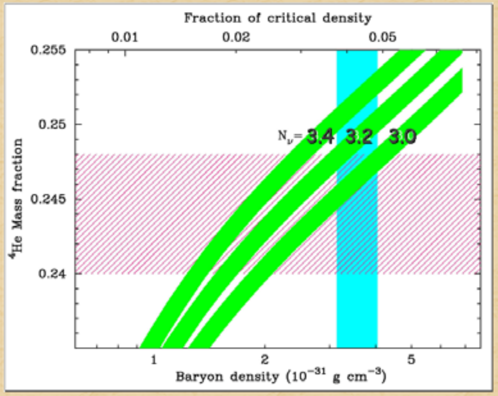


How Many Relic Neutrinos?

Standard thermal population in one flavor $n_{\nu\bar\nu} = \frac{3}{11} n_\gamma \approx 112\,\mathrm{cm}^{-3}$

Additional active neutrinos beyond standard population of ν_e, ν_μ, ν_τ	Additional families	Excluded by Z^0 width ($N_\nu = 3$)
	Chemical potentials for ν_e, ν_μ, ν_τ	Possible
Sterile (right-handed) states. Populated by $\nu_L \to \nu_R$ transitions	Dirac mass	Not effective in eV range
	Right-handed currents	Excluded by energy loss of SN 1987A
	Electromagnetic dipole moments	Excluded by energy loss of globular cluster stars
	Oscillations/collisions	Hot/warm/cold DM possible

BBN Limits on Neutrino Flavors



Burles, Nollett & Turner, astro-ph/9903300

- At BBN one flavor contributes about 16% to cosmic mass-energy density
- Extra flavors modify expansion parameter accordingly

Conservative limit
$|\Delta N_{eff}| < 1$

BBN and Neutrino Chemical Potentials

Expansion Rate Effect (all flavors)

Energy density in one neutrino flavor with degeneracy parameter $\xi = \eta/T$

$$\rho_{\nu\bar\nu} = \frac{7\pi^2}{120} T_\nu^4 \left[1 + \underbrace{\frac{30}{7}\left(\frac{\xi}{\pi}\right)^2 + \frac{15}{7}\left(\frac{\xi}{\pi}\right)^4}_{\Delta N_{eff}} \right]$$

Beta equilibrium effect for electron flavor

$n + \nu_e \leftrightarrow p + e^-$

Helium abundance essentially fixed by n/p ratio at beta freeze-out

$$\frac{n}{p} = e^{-(m_n - m_p)/T - \xi_{\nu_e}}$$

Effect on helium equivalent to $\Delta N_{eff} \sim -18\,\xi_{\nu e}$

$|\Delta N_{eff}| < 1$ → $|\xi_{\nu e}| < 0.06$

- ν_e beta effect can compensate expansion-rate effect of $\nu_{\mu,\tau}$
- No significant BBN limit on neutrino number density

Chemical Potentials and Flavor Oscillations

Flavor mixing (neutrino oscillations)

Flavor lepton numbers not conserved

Only one common nu chemical potential

Stringent $\xi_{\nu e}$ limit applies to all flavors $|\xi_{\nu e,\mu,\tau}| < 0.07$

Extra neutrino density $\Delta N_{eff} < 0.0064$

Cosmic neutrino density close to standard value

Flavor equilibrium before n/p freeze out?	
yes	Solar LMA solution
maybe	LOW (depends on Θ_{13})
no	SMA or VAC

- Our knowledge of the cosmic nu density depends on the solution of the solar neutrino problem
- KamLAND most relevant experiment

- Lunardini & Smirnov, hep-ph/0012056
- Dolgov, Hansen, Pastor, Petcov, Raffelt & Semikoz, hep-ph/0201287
- Abazajian, Beacom & Bell, astro-ph/0203442
- Wong, hep-ph/0203180

Baryogenesis in the Early Universe

Andrei Sakharov
1921 - 1989

Sakharov conditions for creating the Baryon Asymmetry of the Universe (BAU)
- C and CP violation
- Baryon number violation
- Deviation from thermal equilibrium

Particle-physics standard model
- Violates C and CP
- Violates B and L by EW instanton effects (B − L conserved)

- However, electroweak baryogenesis not quantitatively possible within particle-physics standard model
- Works in SUSY models for small range of parameters

A.Riotto & M.Trodden: Recent progress in baryogenesis
Ann. Rev. Nucl. Part. Sci. 49 (1999) 35

Leptogenesis by Majorana Neutrino Decays

A classic paper

Volume 174, number 1 PHYSICS LETTERS B 26 June 1986

BARYOGENESIS WITHOUT GRAND UNIFICATION

M. FUKUGITA
Research Institute for Fundamental Physics, Kyoto University, Kyoto 606, Japan

and

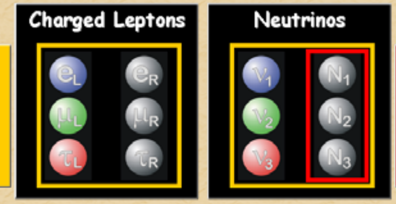
T. YANAGIDA
Institute of Physics, College of General Education, Tohoku University, Sendai 980, Japan and Deutsches Elektronen-Synchrotron DESY, D-2000 Hamburg, Fed. Rep. Germany

Received 8 March 1986

A mechanism is pointed out to generate cosmological baryon number excess without resorting to grand unified theories. The lepton number excess originating from Majorana mass terms may transform into the baryon number excess through the unsuppressed baryon number violation of electroweak processes at high temperatures.

See-Saw Model for Neutrino Masses

Dirac masses from coupling to standard Higgs field ϕ



Heavy Majorana masses $M_j > 10^{10}$ GeV

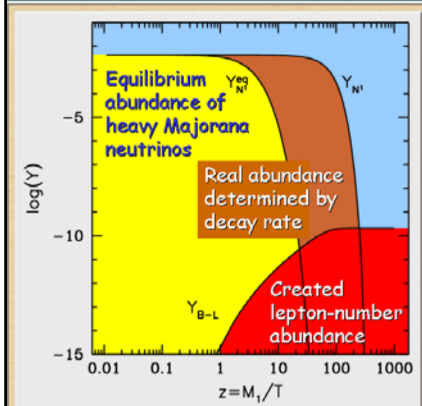
Lagrangian for particle masses

$$\mathcal{L}_{mass} = -\bar{\ell}_L \phi g_\ell e_R - \bar{\ell}_L \phi g_\nu N_R - \frac{1}{2}\overline{N_R^c} M N_R + h.c.$$

Light Majorana mass

$$(\bar{\nu}_L \;\; \bar{N}_R)\begin{pmatrix} 0 & g_\nu\langle\phi\rangle \\ g_\nu\langle\phi\rangle & M \end{pmatrix}\begin{pmatrix}\nu_L \\ N_R\end{pmatrix} \xrightarrow{\text{Diagonalize}} (\bar{\nu}_L \;\; \bar{N}_R)\begin{pmatrix} \frac{g_\nu^2\langle\phi\rangle^2}{M} & 0 \\ 0 & M \end{pmatrix}\begin{pmatrix}\nu_L \\ N_R\end{pmatrix}$$

Leptogenesis by Out-of-Equilibrium Decay



CP-violating decays by interference of tree-level with one-loop diagram

$$\Gamma_{Decay} = g_\nu^2 \frac{M}{8\pi}$$

W. Buchmüller & M. Plümacher: Neutrino masses and the baryon asymmetry Int. J. Mod. Phys. A15 (2000) 5047-5086

Leptogenesis by Majorana Neutrino Decays

In see-saw models for neutrino masses, out-of-equilibrium decay of right-handed heavy Majorana neutrinos provides source for CP- and L-violation

Cosmological evolution:
- B = L = 0 early on
- Thermal freeze-out of heavy Majorana neutrinos
- Out-of-equilibrium CP-violating decay creates net L
- Shift L excess into B by sphaleron effects

Sufficient deviation from equilibrium distribution of heavy Majorana neutrinos at freeze-out → Limits on Yukawa couplings → Limits on masses of ordinary neutrinos

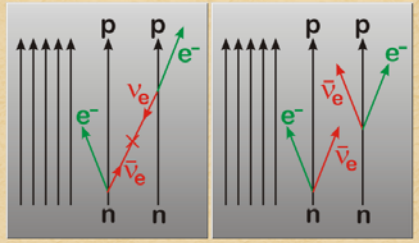
Requires Majorana neutrino masses below 0.2 eV
Buchmüller, Di Bari & Plümacher, PLB 547 (2002) 128 [hep-ph/0209301]

Leptogenesis – A Popular Research Topic

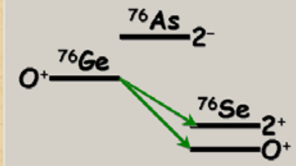
- Fukugita & Yanagida, PLB 174 (1986) 45
- Langacker, Peccei & Yanagida, Mod. Phys. Lett. A 1 (1986) 541
- Campbell, Davidson & Olive, NPB 399 (1993) 111
- Gherghetta & Jungmann, PRD 48 (1993) 1546
- Muryama & Yanagida, PLB 322 (1994) 349
- Worah, PRD 53 (1996) 3902
- Jeannerot, PRL 77 (1996) 3292
- Dine, Randall & Thomas, NPB 458 (1996) 291
- Buchmüller & Plümacher, PLB 389 (1996) 73
- Lazarides, Schaefer & Shafi, PRD 56 (1997) 1324
- Ma & Sarkar, PRL 80 (1998) 5716
- Plümacher, NPB 530 (1998) 207
- Flanz & Paschos, PRD 58 (1998) 113009
- Lazarides & Shafi, PRD 58 (1998) 071702
- Akhmedov, Rubakov & Smirnov, PRL 81 (1998) 1562
- Carlier, Frére & Ling, PRD 60 (1999) 096003
- Giudice, Peloso, Riotto & Tkachev, JHEP 9908 (1999) 014
- Berger & Brahmachari, PRD 60 (1999) 073009
- Ellis, Lola & Nanopoulos, PLB 452 (1999) 87
- Barbieri, Creminelli, Strumia & Tetradis, NPB 575 (2000) 61
- Frére, Ling, Tytgat & v.Elewyck, PRD 60 (1999) 016005
- Dick, Lindner, Ratz & Wright, PRL 84 (2000) 4039
- Lalakulich, Paschos & Flanz, PRD 62 (2000) 053006
- Asaka, Hamaguchi, Kawasaki & Yanagida, PRD 61 (2000) 083512
- Berger, PRD 62 (2000) 013007
- Hambye, Ma & Sarkar, PRD 62 (2000) 015010
- Mangano & Miele, PRD 62 (2000) 063514
- Goldberg, PLB 474 (2000) 389
- Rangarajan & Mishra, PRD 61 (2000) 043509
- Hirsch & King, PRD 64 (2001) 113005
- Falcone & Tramontano, PRD 63 (2001) 073007
- Bastero-Gil & King, PRD 63 (2001) 123509
- Joshipura, Paschos & Rodejohann, NPB 611 (2001) 227
- Branco, Morozumi, Nobre & Rebelo, NPB 617 (2001) 475
- Hambye, Ma & Sarkar, NPB 602 (2001) 23
- AND MANY MORE ...

Neutrinoless ββ Decay

0ν mode, enabled by Majorana mass | Standard 2ν mode



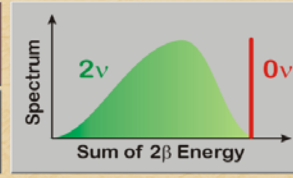
Some nuclei decay only by the ββ mode, e.g.



Half life ~ 10^{21} yr

Measured quantity $|m_{ee}| = \left|\sum_{i=1}^{N} \lambda_i |U_{ei}|^2 m_i\right|$

Best limit from ^{76}Ge $|m_{ee}| < 0.35\,\mathrm{eV}$



Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
From Here to Infinity, Oxford, England, 13-15 December 2002

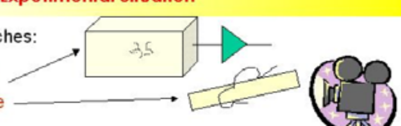
Summary of Current Neutrinoless ββ Decay Limits

O.Cremonesi at Neutrino 2002

0ν2β Experimental Situation

2 main experimental approaches:

- Active Source
- Passive Source



Best 0ν2β results involve active source experiments

Experiment	Isotope	$T_{1/2}^{0\nu}$ (y)	$\langle m_\nu \rangle$ (eV)
You Ke et al. 1998	^{48}Ca	$> 9.5 \times 10^{21}$ (76%)	< 8.3
Klapdor-Kleingrothaus 2001	^{76}Ge	$> 1.9 \times 10^{25}$	< 0.35
Aalseth et al 2002		$> 1.57 \times 10^{25}$	< 0.33 - 1.35
Elliott et al. 1992	^{82}Se	$> 2.7 \times 10^{22}$ (68%)	< 5
Ejiri et al. 2001	^{100}Mo	$> 5.5 \times 10^{22}$	< 2.1
Danevich et al. 2000	^{116}Cd	$> 7 \times 10^{22}$	< 2.6
Bernatowicz et al. 1993	$^{130/128}Te^*$	$(3.52 \pm 0.11) \times 10^{-4}$	< 1.1 – 1.5
Bernatowicz et al. 1993	$^{128}Te^*$	$> 7.7 \times 10^{24}$	< 1.1 – 1.5
Mi DBD – ν 2002	^{130}Te	$> 2.1 \times 10^{23}$	< 0.85 – 2.1
Luescher et al. 1998	^{136}Xe	$> 4.4 \times 10^{23}$	< 1.8 – 5.2
Belli et al. 2001	^{136}Xe	$> 7 \times 10^{23}$	< 1.4 – 4.1
De Silva et al. 1997	^{150}Nd	$> 1.2 \times 10^{21}$	< 3
Danevich et al. 2001	^{160}Gd	$> 1.3 \times 10^{21}$	< 26

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Summary of Future ββ Decay Projects

O.Cremonesi at Neutrino 2002

Future projects

Experiment	Author	Isotope	Detector description	$T^{0\nu}_{1/2}$(y)	$\langle m_\nu \rangle$*
COBRA	Zuber 2001	^{130}Te	10 kg CdTe semiconductors	1×10^{24}	0.71
CUORICINO	Arnaboldi et al 2001	^{130}Te	40 kg of TeO_2 bolometers	1.5×10^{25}	0.19
NEMO3	Sarazin et al 2000	^{100}Mo	10 kg of bb(0n) isotopes (7 kg Mo) with tracking	4×10^{24}	0.56
CUORE	Arnaboldi et al. 2001	^{130}Te	760 kg of TeO_2 bolometers	7×10^{26}	0.027
EXO	Danevich et al 2000	^{136}Xe	1 t enriched Xe TPC	8×10^{26}	0.052
GEM	Zdesenko et al 2001	^{76}Ge	1 t enriched Ge diodes in liquid nitrogen + water shield	7×10^{27}	0.018
GENIUS	Klapdor-Kleingrothaus et al 2001	^{76}Ge	1 t enriched Ge diodes in liquid nitrogen	1×10^{28}	0.015
MAJORANA	Aalseth et al 2002	^{76}Ge	0.5 t enriched Ge segmented diodes	4×10^{27}	0.025
DCBA	Ishihara et al 2000	^{150}Nd	20 kg enriched Nd layers with tracking	2×10^{25}	0.035
CAMEO	Bellini et al 2001	^{116}Cd	1 t $CdWO_4$ crystals in liquid scintillator	$> 10^{26}$	0.069
CANDLES	Kishimoto et al	^{48}Ca	several tons of CaF_2 crystal in liquid scintillator	1×10^{26}	
GSO	Danevich 2001	^{160}Gd	2 t Gd_2SiO_5:Ce cristal scintillator in liquid scintillator	2×10^{26}	0.065
MOON	Ejiri et al 2000	^{100}Mo	34 t natural Mo sheets between plastic scintillator	1×10^{27}	0.036
Xe	Caccianiga et al 2001	^{136}Xe	1.56 t of enriched Xe in liquid scintillator	5×10^{26}	0.066
XMASS	Moriyama et al 2001	^{136}Xe	10 t of liquid Xe	3×10^{26}	0.086

* Staudt, Muto, Klapdor-Kleingrothaus Europh. Lett 13 (1990) 31

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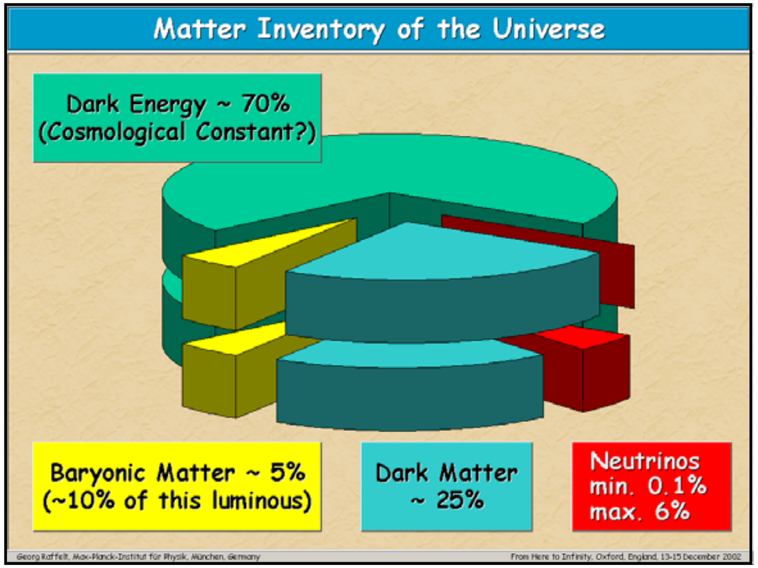
Matter Inventory of the Universe
Dark Energy ~ 70%
(Cosmological Constant?)
Baryonic Matter ~ 5%
(~10% of this luminous)
Dark Matter
~ 25%
Neutrinos
min. 0.1%
max. 6%
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
From Here to Infinity, Oxford, England, 13-15 December 2002