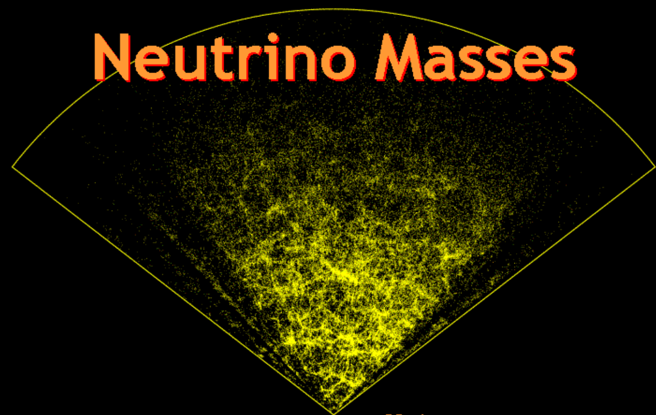
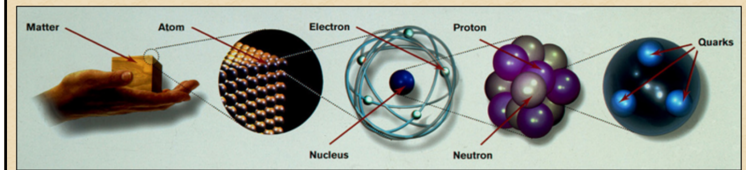
International Heraeus Summer School, 5-16 July 2004, Bad Honnef, Germany

Neutrino Masses

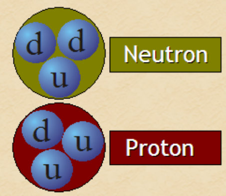


Georg G. Raffelt
Max-Planck-Institut für Physik, München, Germany

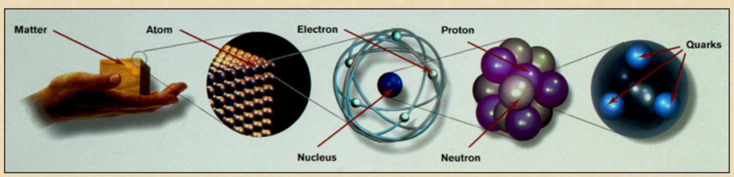
Periodic System of Elementary Particles



Quarks		Leptons	
Charge +2/3	Charge −1/3	Charge −1	Charge 0
Up u	Down d	Electron e	e-Neutrino ν_e

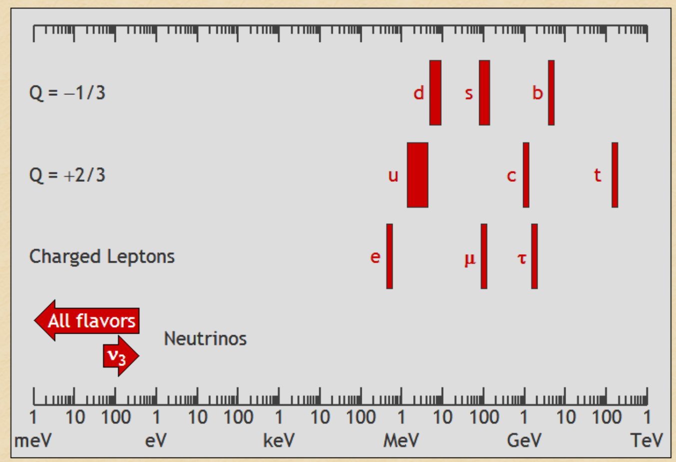


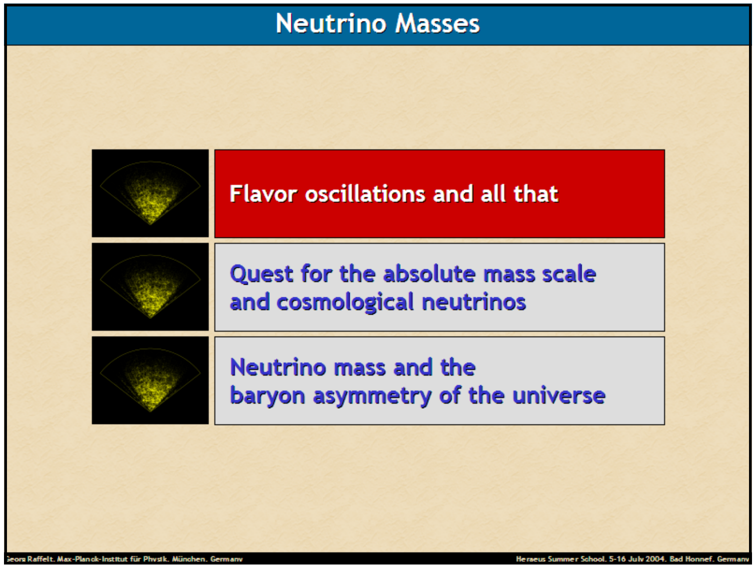
Periodic System of Elementary Particles

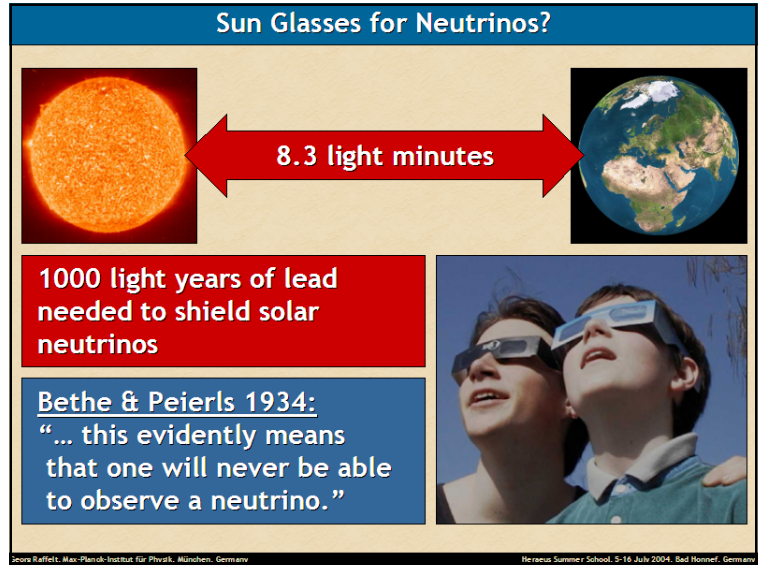


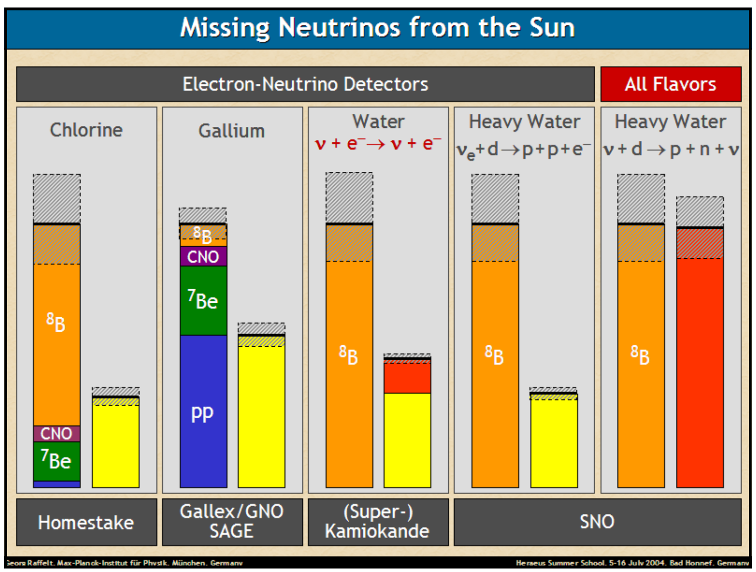
	Quarks		Leptons	
	Charge +2/3	Charge −1/3	Charge −1	Charge 0
1st Family	Up u	Down d	Electron e	e-Neutrino ν_e
2nd Family	Charm c	Strange s	Muon μ	μ-Neutrino ν_μ
3rd Family	Top t	Bottom b	Tau τ	τ-Neutrino ν_τ
	Gravitation			
	Weak Interaction			
	Electromagnetic Interaction			
	Strong Interaction			

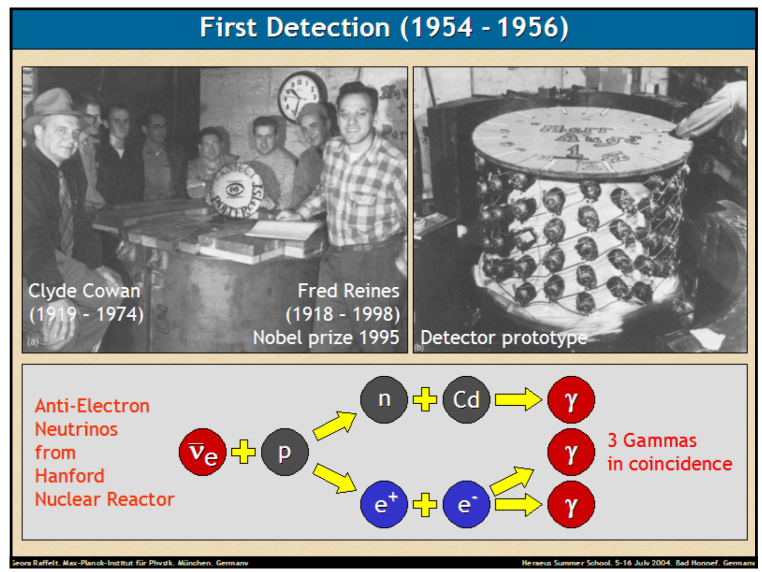
Fermion Mass Spectrum

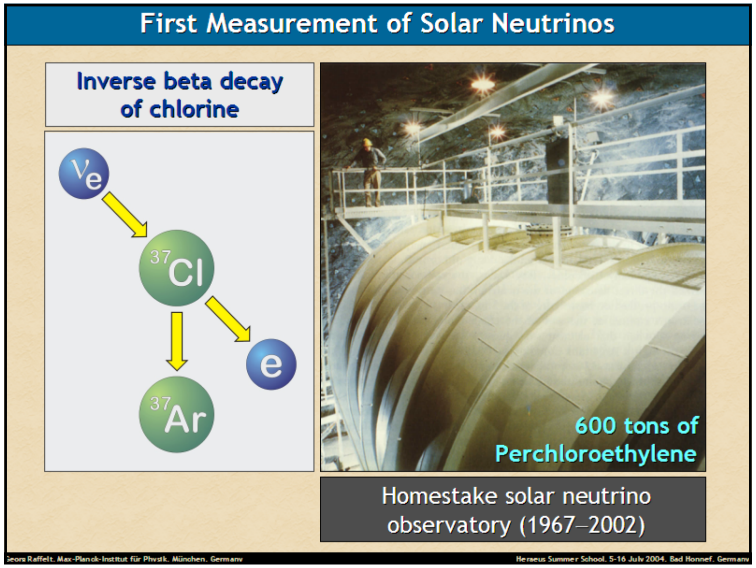


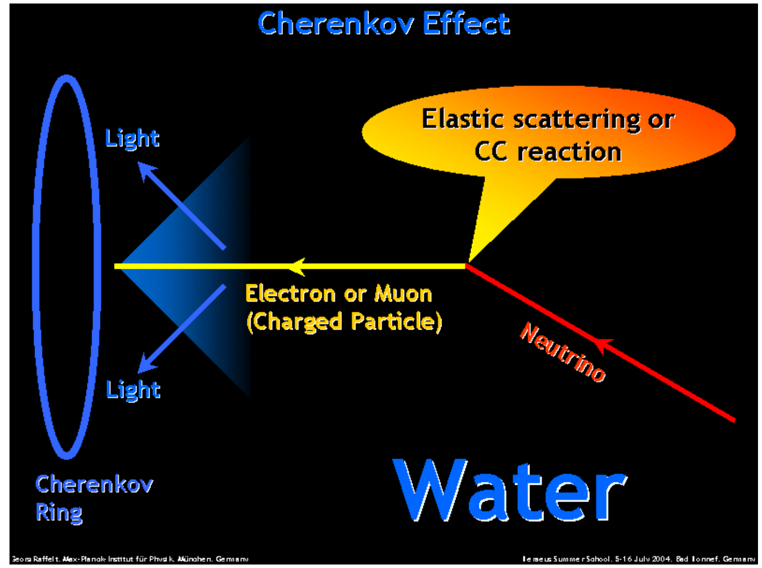

Neutrino Masses
Flavor oscillations and all that
Quest for the absolute mass scale and cosmological neutrinos
Neutrino mass and the baryon asymmetry of the universe
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
Heraeus Summer School, 5-16 July 2004, Bad Honnef, Germany

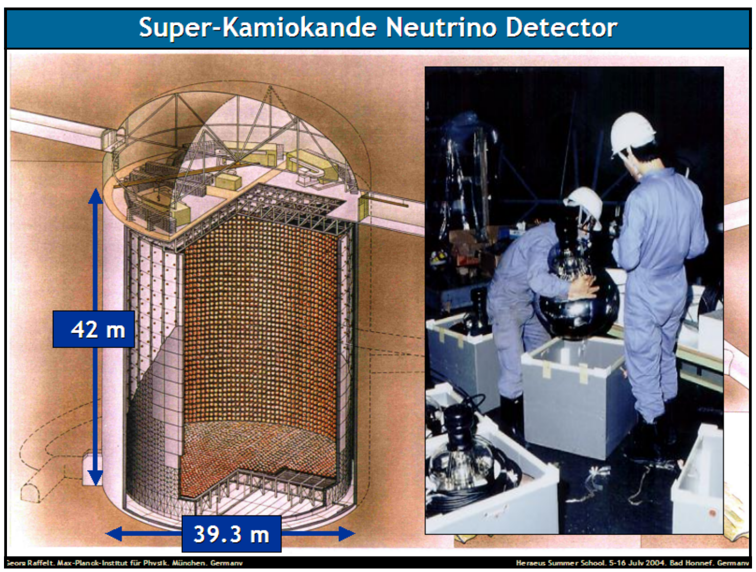

Sun Glasses for Neutrinos?
8.3 light minutes
1000 light years of lead needed to shield solar neutrinos
Bethe & Peierls 1934:
"… this evidently means that one will never be able to observe a neutrino."
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
Heraeus Summer School, 5-16 July 2004, Bad Honnef, Germany

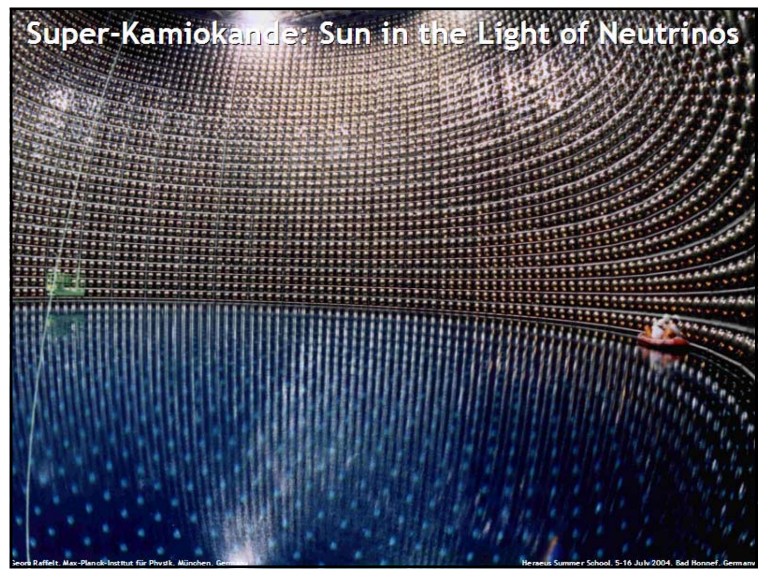

Missing Neutrinos from the Sun
Electron-Neutrino Detectors
All Flavors
Chlorine
Gallium
Water
ν + e⁻ → ν + e⁻
Heavy Water
νe + d → p + p + e⁻
Heavy Water
ν + d → p + n + ν
8B
CNO
7Be
pp
Homestake
Gallex/GNO SAGE
(Super-) Kamiokande
SNO
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
Heraeus Summer School, 5-16 July 2004, Bad Honnef, Germany

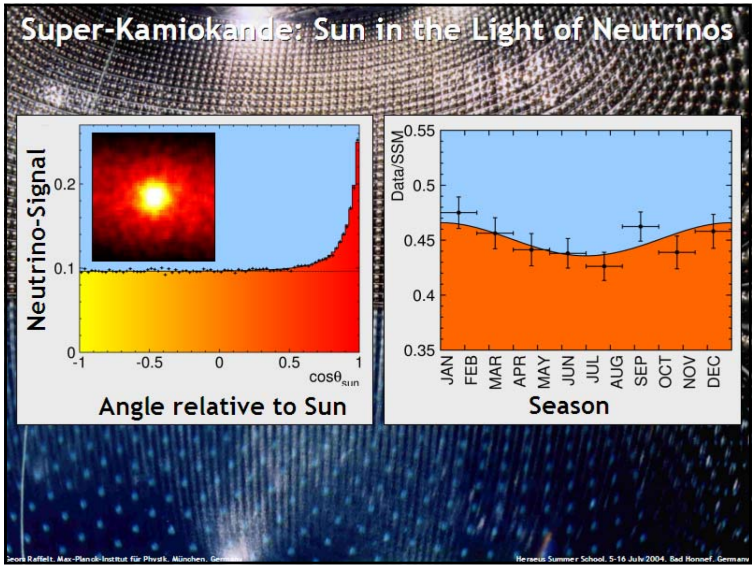

First Detection (1954 - 1956)
Clyde Cowan (1919 - 1974)
Fred Reines (1918 - 1998) Nobel prize 1995
Detector prototype
Anti-Electron Neutrinos from Hanford Nuclear Reactor
ν̄e + p
n + Cd → γ
e⁺ + e⁻ → γ
γ
3 Gammas in coincidence
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
Heraeus Summer School, 5-16 July 2004, Bad Honnef, Germany

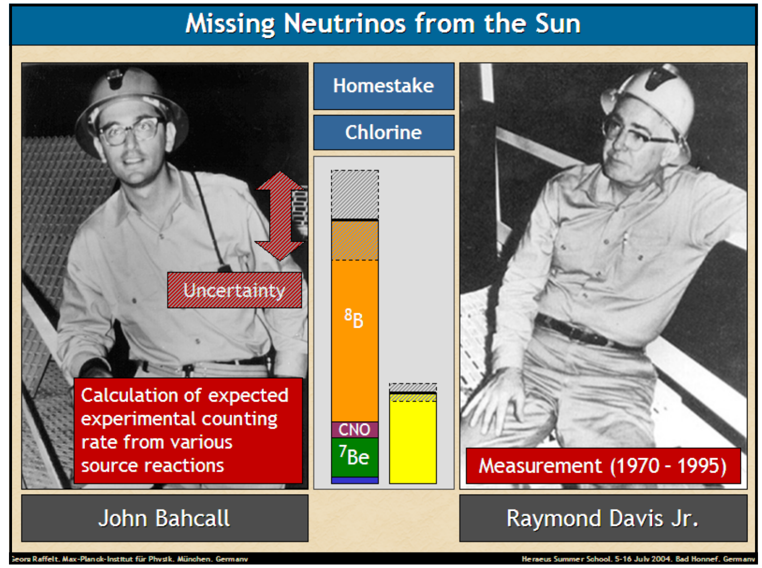

First Measurement of Solar Neutrinos
Inverse beta decay of chlorine
νe
37Cl
e
37Ar
600 tons of Perchloroethylene
Homestake solar neutrino observatory (1967–2002)
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
Heraeus Summer School, 5-16 July 2004, Bad Honnef, Germany

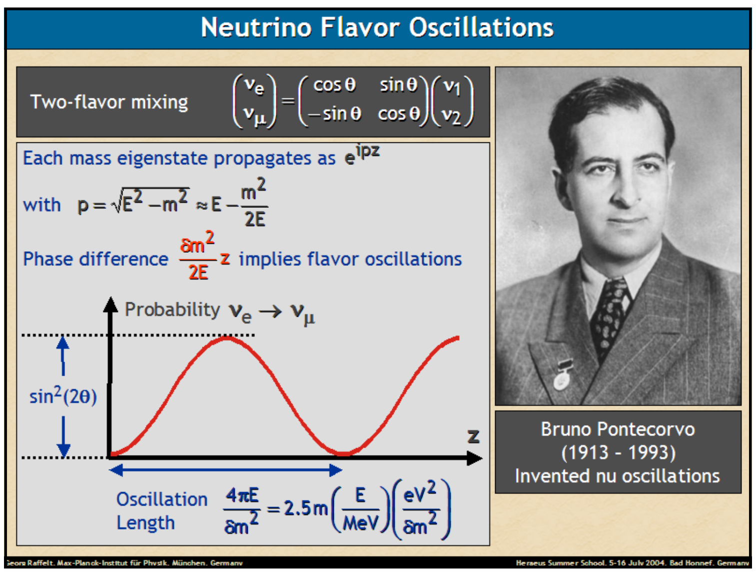

Cherenkov Effect
Light
Elastic scattering or CC reaction
Electron or Muon (Charged Particle)
Neutrino
Light
Cherenkov Ring
Water
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
Heraeus Summer School, 5-16 July 2004, Bad Honnef, Germany

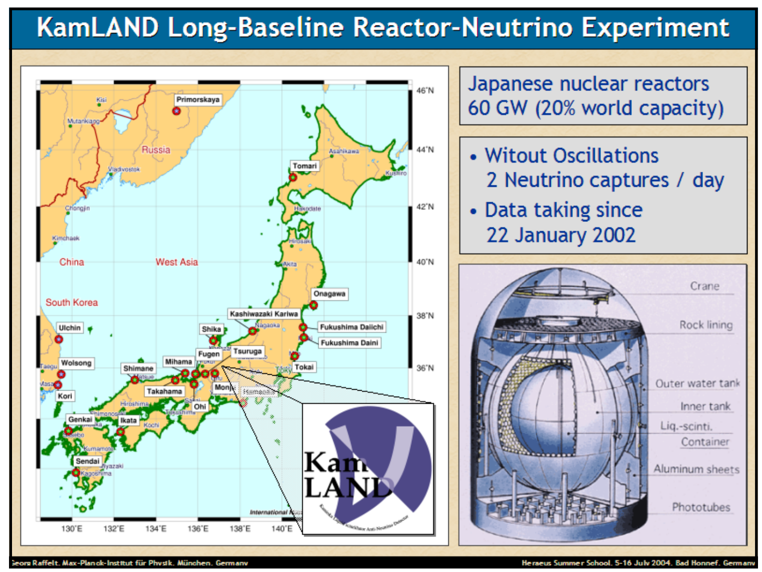

Super-Kamiokande Neutrino Detector
42 m
39.3 m
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
Heraeus Summer School, 5-16 July 2004, Bad Honnef, Germany


Super-Kamiokande: Sun in the Light of Neutrinos
Heraeus Summer School, 5-16 July 2004, Bad Honnef, Germany

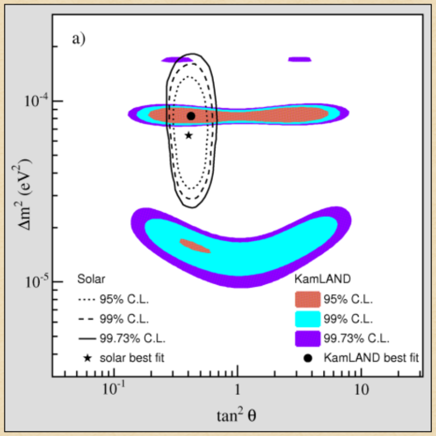

Super-Kamiokande: Sun in the Light of Neutrinos
Neutrino-Signal
0.2
0.1
0
-1
-0.5
0
0.5
1
cosθsun
Angle relative to Sun
Data/SSM
0.55
0.5
0.45
0.4
0.35
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
Season
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
Heraeus Summer School, 5-16 July 2004, Bad Honnef, Germany


Missing Neutrinos from the Sun
Homestake
Chlorine
Uncertainty
8B
CNO
7Be
Calculation of expected experimental counting rate from various source reactions
Measurement (1970 - 1995)
John Bahcall
Raymond Davis Jr.
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
Heraeus Summer School, 5-16 July 2004, Bad Honnef, Germany


Neutrino Flavor Oscillations
Two-flavor mixing
$\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}=\begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$
Each mass eigenstate propagates as e^{ipz}
with $p=\sqrt{E^2-m^2}\approx E-\frac{m^2}{2E}$
Phase difference $\frac{\delta m^2}{2E}z$ implies flavor oscillations
Probability $\nu_e \to \nu_\mu$
$\sin^2(2\theta)$
z
Oscillation Length $\frac{4\pi E}{\delta m^2}=2.5\,\mathrm{m}\left(\frac{E}{\mathrm{MeV}}\right)\left(\frac{\mathrm{eV}^2}{\delta m^2}\right)$
Bruno Pontecorvo
(1913 - 1993)
Invented nu oscillations
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
Heraeus Summer School, 5-16 July 2004, Bad Honnef, Germany


KamLAND Long-Baseline Reactor-Neutrino Experiment
Japanese nuclear reactors
60 GW (20% world capacity)
• Witout Oscillations
2 Neutrino captures / day
• Data taking since
22 January 2002
Russia
China
West Asia
South Korea
Kashiwazaki Kariwa
Fukushima Daiichi
Fukushima Daini
Tokai
Onagawa
Tomari
Kam LAND
Crane
Rock lining
Outer water tank
Inner tank
Liq.-scinti. Container
Aluminum sheets
Phototubes
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
Heraeus Summer School, 5-16 July 2004, Bad Honnef, Germany

Solar & KamLAND Mixing Parameters

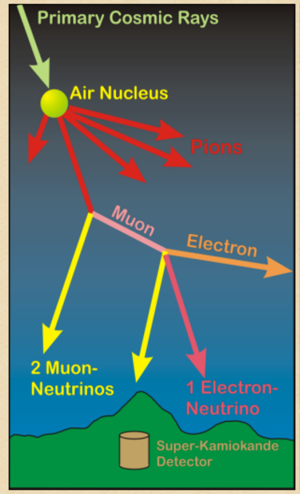


Kamland Collaboration, hep-ex/0406035

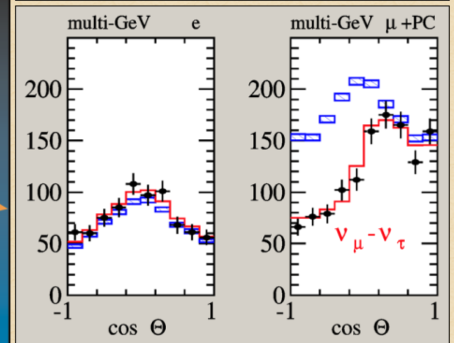
Main features

- Oscillation channel $\nu_e \to \nu_{\mu\tau}$ (not sterile - full flux at SNO)
- Mass ordering normal ("light side" of mixing angle, medium effect crucial for this information)
- Mixing angle large but not maximal (at 5.4 σ after SNO w/salt)
- Good fit to all data

Atmospheric Neutrino Anomaly



Zenith-angle distribution of atmospheric nus in Super-Kamiokande [hep-ex/0210019]



Half of the muon neutrinos from below are missing

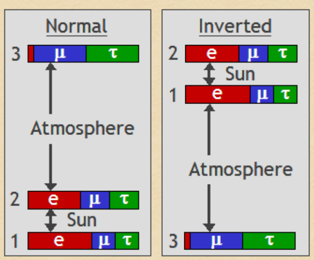
Three-Flavor Neutrino Parameters

Atmospheric/K2K	CHOOZ	Solar/KamLAND	2σ ranges hep-ph/0405172
$37^\circ < \theta_{23} < 54^\circ$	$\theta_{13} < 11^\circ$	$30^\circ < \theta_{12} < 36^\circ$	

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

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

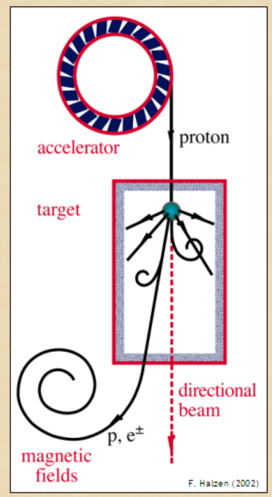
Solar 75–92
Atmospheric 1400–3000
$\Delta m^2/\mathrm{meV}^2$

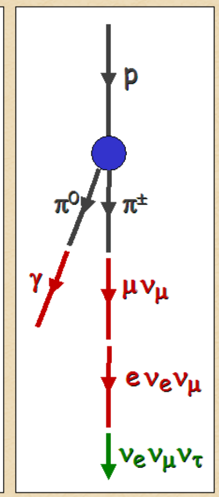


Tasks and Open Questions

- Precision for θ_{12} and θ_{23}
- How large is θ_{13}?
- CP-violating phase δ?
- Mass ordering? (normal vs inverted)
- Absolute masses? (hierarchical vs degenerate)
- Dirac or Majorana?

Neutrino Beams: Heaven and Earth





Target: Protons or Photons

Approx. equal fluxes of photons & neutrinos

Equal neutrino fluxes in all flavors due to oscillations

Upcoming Long-Baseline Experiments

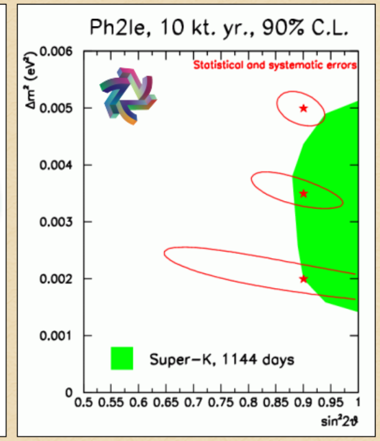
FermiLab-Soudan (MINOS)

CERN - Gran Sasso

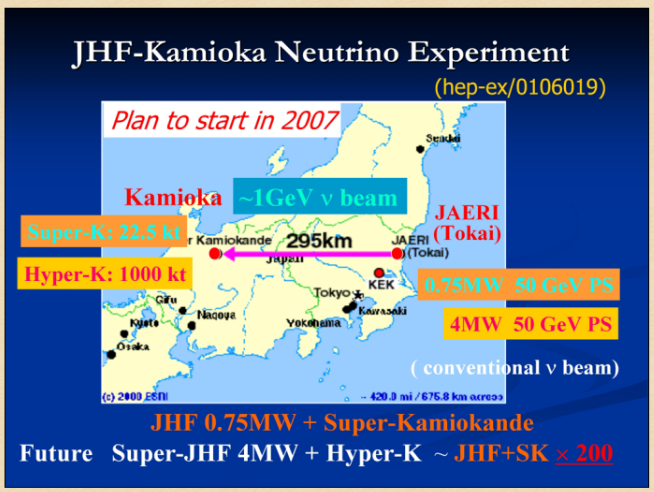
Upcoming Long-Baseline Experiments

FermiLab-Soudan (MINOS)

Sensitivity to Oscillations



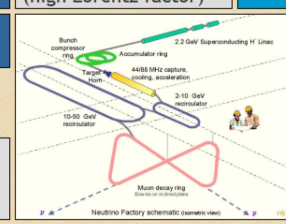
Tokai to Kamioka - T2K (2007)



Y. Itow (ICRR,Univ. Tokyo), ICHEP02 Amsterdam

Long-Baseline Experiments

Nuclear reactors	Nuclear decay	Kamland (2002) Borexino (>2005)	Solar LMA
		2 Chooz (> 2007) Other projects	$\sin^2 2\theta_{13} \lesssim 0.03$
Conventional beams	Proton beam dump	K2K (1999) NuMI, CNGS (2005) T2K (2007)	Precision for atm $\sin^2 2\theta_{13}$ ~ 0.01
Super beams	Primary proton beam > 1 MW	Super-JHF, Super-NuMI, ...	$\sin^2 2\theta_{13}$ ~ 0.001
Beta beams	Nuclear decay (high Lorentz factor)	R&D	$\sin^2 2\theta_{13}$ ~ 0.0001
Neutrino factory	(see schematic)	R&D	CP violation Mass ordering



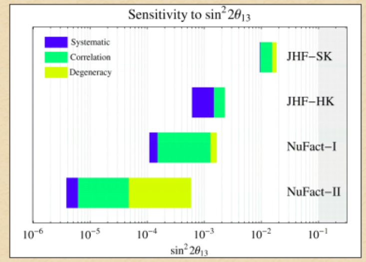
Muon storage ring
$\mu \to e\nu_\mu\bar{\nu}_e$

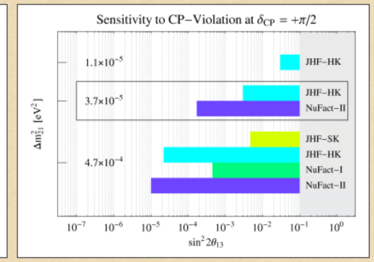
Neutrino Factory Working Group homepage at CERN
http://nfwg.home.cern.ch/nfwg/nufactwg/nufactwg.html

Fiducial Long-Baseline Configurations

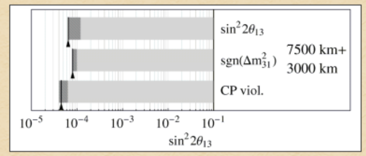
Setup	Baseline	Beam	Detector	Running
JHF-SK	295 km	0.75 MW	Water Cherenkov 23 kt fiducial	ν 5 yr
JHF-HK		4 MW	Water Cherenkov 1000 kt fiducial	ν 2 yr $\bar{\nu}$ 6 yr
NuFact I	3000 km	0.75 MW, E_μ = 50 GeV 10^{20} useful μ decays per year	Magnetized iron calorimeter 10 kt fiducial	ν 2.5 yr $\bar{\nu}$ 2.5 yr
NuFact II		4 MW, E_μ = 50 GeV 5.3×10^{20} useful μ decays per year	Magnetized iron calorimeter 50 kt fiducial	ν 4 yr $\bar{\nu}$ 4 yr

Sensitivity to Θ_{13} and CP violation





Huber, Lindner & Winter: Superbeams vs neutrino factories hep-ph/0204352



Huber & Winter:
Neutrino factories and the "Magic baseline" (hep-ph/0301257)

Clean up degeneracies with two baselines

Three-Neutrino Oscillations with a Long Baseline

The three-flavor oscillation probability at a long-baseline (LBL) experiment can be expanded in the small mixing angle $\sin 2\Theta_{13} < 0.3$

and the small hierarchy parameter $\alpha = \Delta m^2_{21}/\Delta m^2_{31} \approx 0.03$

Other parameters: $\xi = \cos\Theta_{13}\sin 2\Theta_{12}\sin 2\Theta_{23}$, $A = \pm\frac{2\sqrt{2}G_F n_e E}{\Delta m^2_{31}}$, $\Delta = \frac{\Delta m^2_{31} L}{4E}$

Up to α^2 and $\sin^2(2\Theta_{13})$ the transition probability is

$$P(\nu_e \to \nu_\mu) = \sin^2 2\Theta_{13}\sin^2\Theta_{23}\frac{\sin^2[(1-A)\Delta]}{(1-A)^2} \quad (0)$$

$$+\alpha\xi\sin 2\Theta_{13}(\cos\delta\cos\Delta \pm \sin\delta\sin\Delta)\frac{\sin(A\Delta)}{A}\frac{\sin[(1-A)\Delta]}{(1-A)} \quad (1)$$

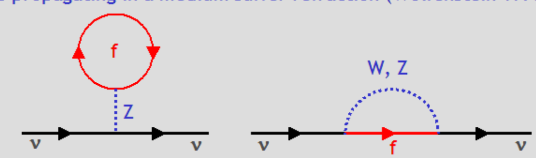
$$+\alpha^2\cos^2\Theta_{23}\sin^2 2\Theta_{12}\frac{\sin^2(A\Delta)}{A^2} \quad (2)$$

Lower sign for $P(\bar{\nu}_\mu \to \bar{\nu}_e)$

(1,2) disappear for "magic baseline" ~ 7500 km where $A\Delta$ ~ 0, assuming a neutrino factory with muon energy ~ 50 GeV

Neutrino Refraction in Media

Neutrinos propagating in a medium suffer refraction (Wolfenstein 1978)



Effect is usually different for different flavors

For small neutrino energies and large matter-antimatter asymmetry of the medium (not true in the early universe)

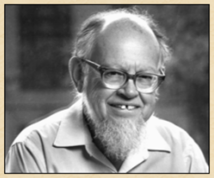
$$(E-V)^2 - p^2 = m^2_{vac}$$

Normal medium, consisting of protons, neutrons (or nuclei), and electrons

$$V = \pm\sqrt{2}G_F n_B \times \begin{cases} -\frac{1}{2}Y_n + Y_e & \text{for } \nu_e \\ -\frac{1}{2}Y_n & \text{for } \nu_\mu, \nu_\tau \end{cases}$$

$$\sqrt{2}G_F n_B = 0.762\times10^{-13}\,\text{eV}\,\frac{\rho}{\text{g cm}^{-3}}$$

Neutrino Oscillations in Matter



Lincoln Wolfenstein

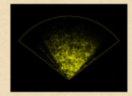
Neutrinos in a medium suffer flavor-dependent refraction (PRD 17:2369, 1978)

In Earth or Sun weak potential of order 10^{-13} eV

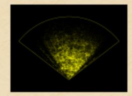
$$i\frac{\partial}{\partial z}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \left[\frac{M^2}{2E} + \sqrt{2}G_F\begin{pmatrix} n_e - \frac{1}{2} n_n & 0\\ 0 & -\frac{1}{2} n_n\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

- "Level crossing" possible in a medium with a gradient (MSW effect)
  - For solar nus large flavor conversion anyway due to large mixing
  - Still important for 13-oscillations in supernova envelope
- Breaks degeneracy between Θ and $\pi/2-\Theta$ (dark vs light side)
  - 12 mass ordering for solar nus established
  - 13 mass ordering (normal vs inverted) at future LBL or SN
- Discriminates against sterile nus in atmospheric oscillations
- CP asymmetry in LBL, to be distinguished from intrinsic CP violation
- Prevents flavor conversion in a SN core and within shock wave
- Strongly affects sterile nu production in SN or early universe

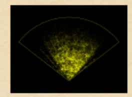
Neutrino Masses



Flavor oscillations and all that



Quest for the absolute mass scale and cosmological neutrinos

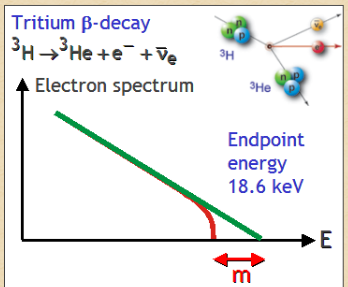


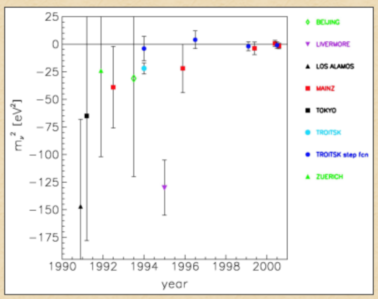
Neutrino mass and the baryon asymmetry of the universe

Tritium Endpoint Spectrum

Tritium β-decay

$^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$





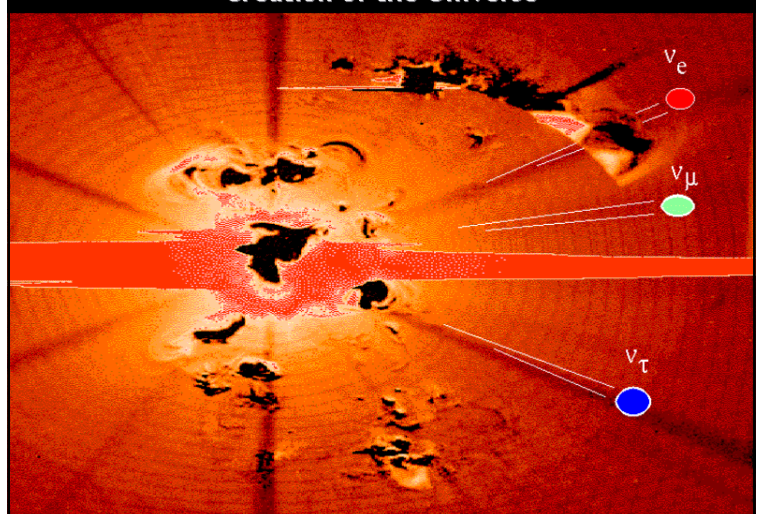
Currently best limits from Mainz and Troitsk experiments

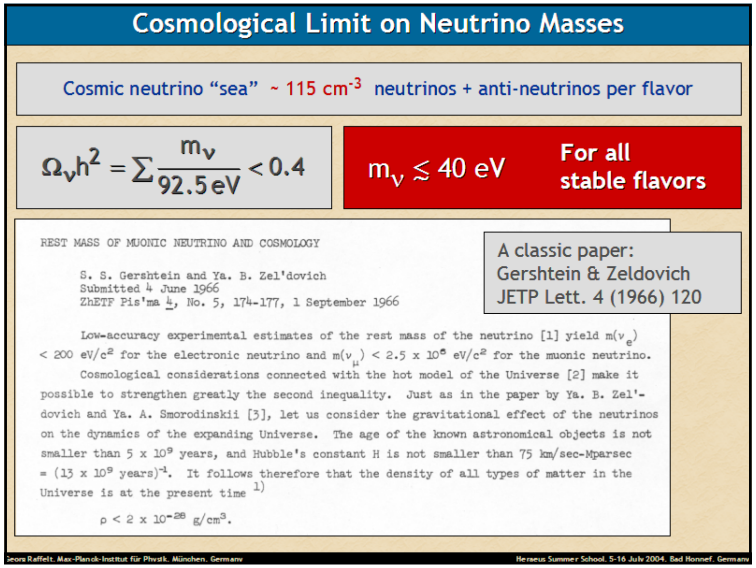
m < 2.2 eV (95% CL)

- Scaled-up spectrometer (KATRIN) is expected to reach 0.2 eV
- Currently under construction
- Measurements to begin 2007

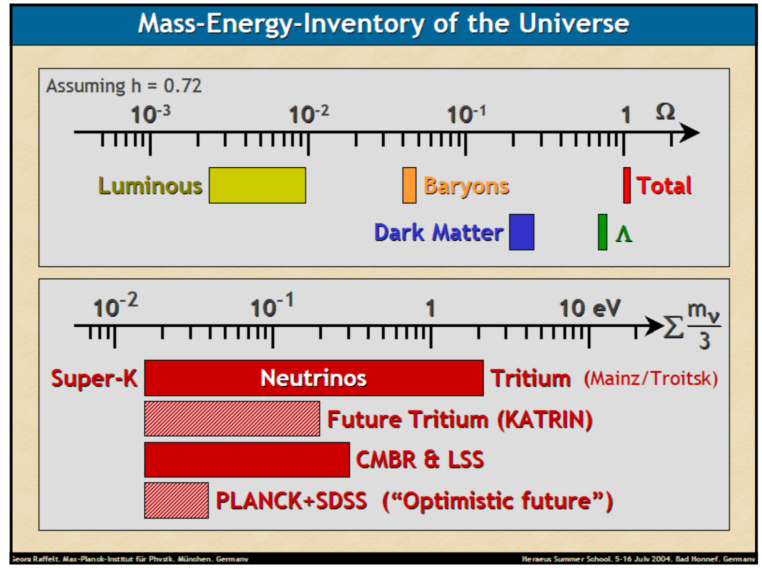
http://ik1au1.fzk.de/~katrin

Creation of the Universe

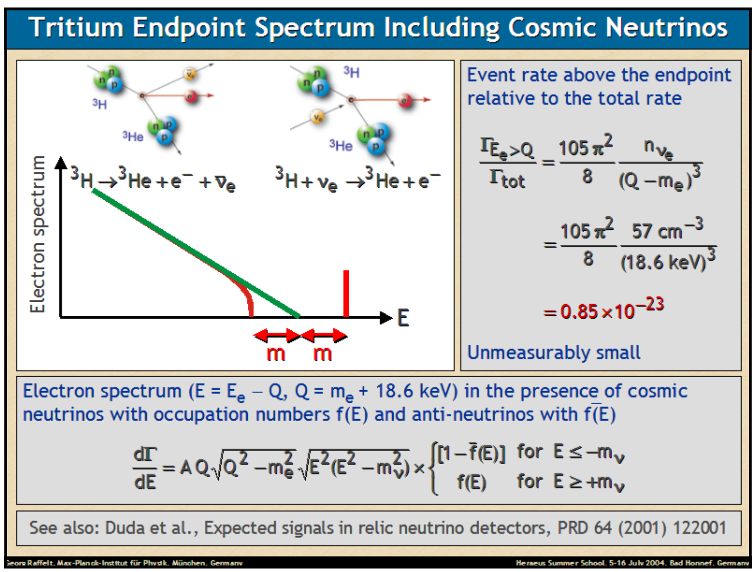




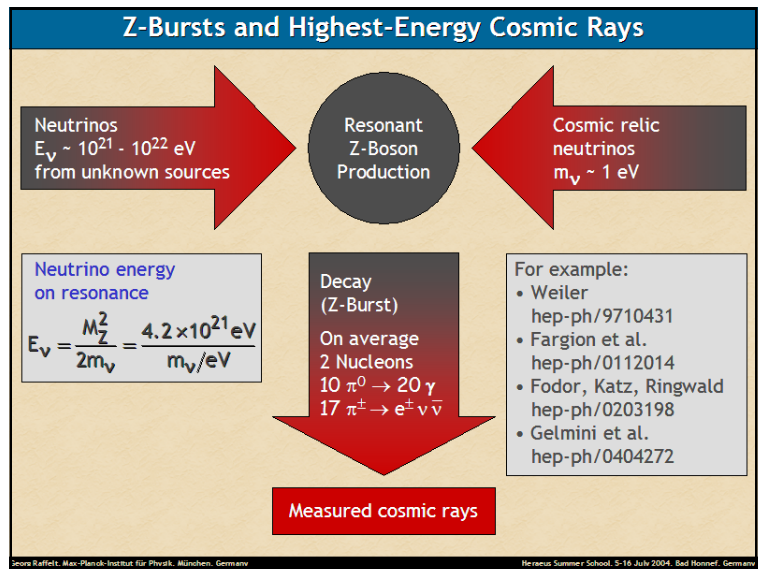
Cosmological Limit on Neutrino Masses
Cosmic neutrino "sea" ~ 115 cm^{-3} neutrinos + anti-neutrinos per flavor
$\Omega_\nu h^2 = \sum \frac{m_\nu}{92.5\,\mathrm{eV}} < 0.4$
$m_\nu \lesssim 40$ eV
For all stable flavors
REST MASS OF MUONIC NEUTRINO AND COSMOLOGY
S. S. Gershtein and Ya. B. Zel'dovich
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 x 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)
$\rho < 2 \times 10^{-28}$ g/cm^3.
A classic paper:
Gershtein & Zeldovich
JETP Lett. 4 (1966) 120
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
Heraeus Summer School, 5-16 July 2004, Bad Honnef, Germany



Mass-Energy-Inventory of the Universe
Assuming h = 0.72
10^{-3} 10^{-2} 10^{-1} 1 Ω
Luminous
Baryons
Total
Dark Matter
Λ
10^{-2} 10^{-1} 1 10 eV $\sum \frac{m_\nu}{3}$
Super-K
Neutrinos
Tritium (Mainz/Troitsk)
Future Tritium (KATRIN)
CMBR & LSS
PLANCK+SDSS ("Optimistic future")
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
Heraeus Summer School, 5-16 July 2004, Bad Honnef, Germany

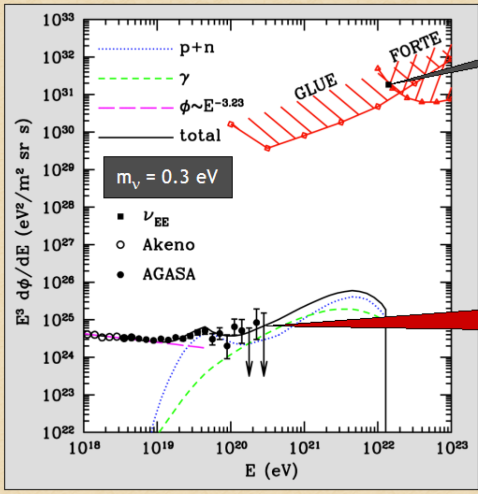


Tritium Endpoint Spectrum Including Cosmic Neutrinos
^{3}H
^{3}He
$^3H \to {}^3He + e^- + \bar\nu_e$
$^3H + \nu_e \to {}^3He + e^-$
Electron spectrum
E
m m
Event rate above the endpoint relative to the total rate
$\frac{\Gamma_{E_e>Q}}{\Gamma_{tot}} = \frac{105\pi^2}{8}\frac{n_{\nu_e}}{(Q-m_e)^3}$
$= \frac{105\pi^2}{8}\frac{57\,\mathrm{cm}^{-3}}{(18.6\,\mathrm{keV})^3}$
$= 0.85\times10^{-23}$
Unmeasurably small
Electron spectrum ($E = E_e - Q$, $Q = m_e$ + 18.6 keV) in the presence of cosmic neutrinos with occupation numbers f(E) and anti-neutrinos with $\bar f(E)$
$\frac{d\Gamma}{dE} = A\,Q\sqrt{Q^2-m_e^2}\,\sqrt{E^2(E^2-m_\nu^2)}\times\begin{cases}[1-\bar f(E)] & \text{for } E\le -m_\nu\\ f(E) & \text{for } E\ge +m_\nu\end{cases}$
See also: Duda et al., Expected signals in relic neutrino detectors, PRD 64 (2001) 122001
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
Heraeus Summer School, 5-16 July 2004, Bad Honnef, Germany



Z-Bursts and Highest-Energy Cosmic Rays
Neutrinos
$E_\nu \sim 10^{21}$ - 10^{22} eV
from unknown sources
Resonant Z-Boson Production
Cosmic relic neutrinos
m_ν ~ 1 eV
Neutrino energy on resonance
$E_\nu = \frac{M_Z^2}{2m_\nu} = \frac{4.2\times10^{21}\,\mathrm{eV}}{m_\nu/\mathrm{eV}}$
Decay (Z-Burst)
On average
2 Nucleons
10 $\pi^0 \to 20\,\gamma$
17 $\pi^\pm \to e^\pm\,\nu\,\bar\nu$
Measured cosmic rays
For example:
• Weiler hep-ph/9710431
• Fargion et al. hep-ph/0112014
• Fodor, Katz, Ringwald hep-ph/0203198
• Gelmini et al. hep-ph/0404272
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
Heraeus Summer School, 5-16 July 2004, Bad Honnef, Germany

Lower Limit on Required Neutrino Mass



Required neutrino flux

For m_ν < 0.3 eV, expect too many events above AGASA endpoint

Gelmini, Varieschi, Weiler
hep-ph/0404272

Weakly Interacting Particles as Dark Matter

THE ASTROPHYSICAL JOURNAL, 180: 7–10, 1973 February 15
© 1973. The American Astronomical Society. All rights reserved. Printed in U.S.A.

GRAVITY OF NEUTRINOS OF NONZERO MASS IN ASTROPHYSICS

R. COWSIK* AND J. MCCLELLAND
Department of Physics, University of California, Berkeley
Received 1972 July 24

ABSTRACT

If neutrinos have a rest mass of a few eV/c^2, then they would dominate the gravitational dynamics of the large clusters of galaxies and of the Universe. A simple model to understand the virial mass discrepancy in the Coma cluster on this basis is outlined.

Subject headings: cosmology — galaxies, clusters of — neutrinos

The possibility of a finite rest mass for the neutrinos has fascinated astrophysicists (Kuchowicz 1969). A recent discussion of such a possibility has been in the context of the solar-neutrino experiments (Bahcall, Cabibbo, and Yahil 1972). Here we wish to point out some interesting consequences of the gravitational interactions of such neutrinos. These considerations become particularly relevant in the framework of big-bang cosmologies which we assume to be valid in our discussion here.

In the early phase of such a Universe when the temperature was ~1 MeV, several processes of neutrino production (Ruderman 1969) would have led to copious production of neutrinos and antineutrinos (Steigman 1972; Cowsik and McClelland 1972). Conditions of thermal equilibrium allow an easy estimate of their number densities (Landau and Lifshitz 1969):

$$n_{\nu i} = \frac{1}{\pi^2 \hbar^3} \int_0^\infty \frac{p^2 dp}{\exp[E/kT(z_{eq})] + 1} . \quad (1)$$

Here $n_{\nu i}$ = number density of neutrinos of the *i*th kind (notice that in writing this expression we have assumed that both the helicity states are allowed for the neutrinos because of finite rest mass); $E = c(p^2 + m^2c^2)^{1/2}$; k = Boltzmann's constant; $T(z_{eq}) = T_\nu(z_{eq}) = T_r(z_{eq}) = T_e(z_{eq}) \cdots$ = the common temperature of radiation, neutrinos, electrons, etc., at the latest epoch characterized by redshift z_{eq} when they may be assumed to have been in thermal equilibrium; $kT(z_{eq}) \simeq 1$ MeV.

Since the masses of the neutrinos are expected to be small, $kT(z_{eq}) \gg m_{\nu i}c^2$, in the extreme-relativistic limit equation (1) reduces to

$$n_{\nu i}(z_{eq}) \simeq 0.183[T(z_{eq})/\hbar c]^3 . \quad (2)$$

As the Universe expands, only the neutrinos (in contrast to all other known particles) survive annihilation because of extremely low cross-sections (deGraff and Tolhock 1966), and their number density decreases with increasing volume of the Universe, simply as $\sim V(z_{eq})/V(z) = [(1 + z)/(1 + z_{eq})]^3$. Noting that $(1 + z_{eq})/(1 + z) = T_r(z_{eq})/T_r(z)$, the number density at the present epoch ($z = 0$) is given by

$$n_{\nu i}(0) = n_{\nu i}(z_{eq})/(1 + z_{eq})^3 \simeq 0.183[T_r(0)/\hbar c]^3 \simeq 300\ cm^{-3} , \quad (3)$$

* On leave from the Tata Institute of Fundamental Research, Bombay, India.

7

More than 30 years ago, beginnings of the idea of weakly interacting particles (neutrinos) as dark matter

Massive neutrinos are no longer a good candidate (hot dark matter)

However, the idea of weakly interacting massive particles as dark matter is now standard

What is wrong with neutrino dark matter?

Galactic Phase Space ("Tremaine-Gunn-Limit")

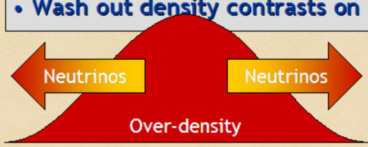
Maximum mass density of a degenerate Fermi gas

$$\rho_{max} = m_\nu \underbrace{\frac{p_{max}^3}{3\pi^2}}_{n_{max}} = \frac{m_\nu (m_\nu v_{escape})^3}{3\pi^2}$$

m_ν > 20 – 40 eV	Spiral galaxies
m_ν > 100 – 200 eV	Dwarf galaxies

Neutrino Free Streaming (Collisionless Phase Mixing)

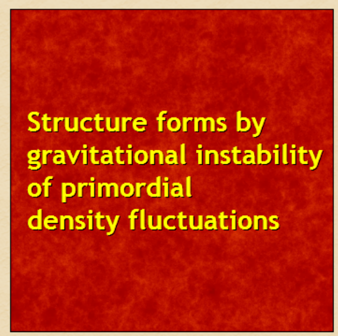
- **At T < 1 MeV neutrino scattering in early universe ineffective**
- **Stream freely until non-relativistic**
- **Wash out density contrasts on small scales**

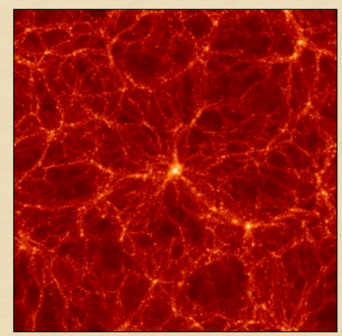


- **Nus are "Hot Dark Matter"**
- **Ruled out by structure formation**

Formation of Structure

Smooth → Structured





Power Spectrum of Density Fluctuations

Field of density fluctuations

$$\delta(x) = \frac{\delta\rho(x)}{\bar{\rho}}$$

Fourier transform

$$\delta_k = \int d^3x\, e^{-ik\cdot x}\, \delta(x)$$

Power spectrum essentially square of Fourier transformation

$$\langle \delta_k \delta_{k'} \rangle = (2\pi)^3 \hat{\delta}(k-k')\, P(k)$$

with $\hat{\delta}$ the δ-function

Power spectrum is Fourier transform of two-point correlation function ($x = x_2 - x_1$)

$$\xi(x) = \langle \delta(x_2)\delta(x_1) \rangle = \int \frac{d^3k}{(2\pi)^3}\, e^{ik\cdot x}\, P(k)$$

$$= \int \frac{d\Omega}{4\pi} \frac{dk}{k}\, e^{ik\cdot x} \underbrace{\frac{k^3 P(k)}{2\pi^2}}_{\Delta^2(k)}$$

Gaussian random field (phases of Fourier modes δ_k uncorrelated) is fully characterized by the power spectrum

$$P(k) = |\delta_k|^2$$

or equivalently by

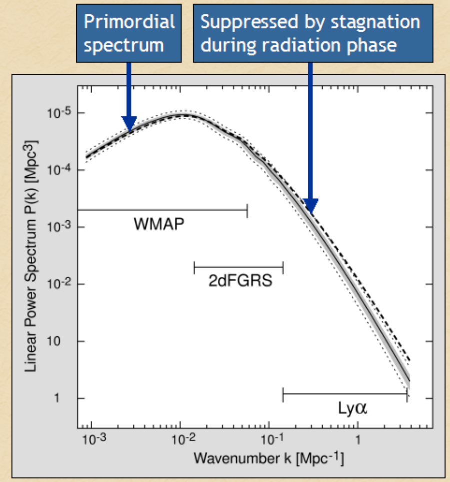
$$\Delta(k) = \left(\frac{k^3 P(k)}{2\pi^2}\right)^{1/2} = \frac{k^{3/2}|\delta_k|}{\sqrt{2\pi}}$$

Processed Power Spectrum in Cold Dark Matter Scenario

Primordial spectrum usually assumed to be of power-law form

$$P(k) = |\delta_k|^2 \propto k^n$$

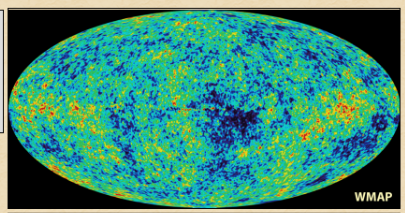
Harrison-Zeldovich ("flat") spectrum $n = 1$ expected from inflation (may be slightly less than 1, depending on details of inflationary phase)



Power Spectrum of CMBR Temperature Fluctuations

Sky map of CMBR temperature fluctuations

$$\Delta(\theta,\varphi) = \frac{T(\theta,\varphi) - \langle T \rangle}{\langle T \rangle}$$

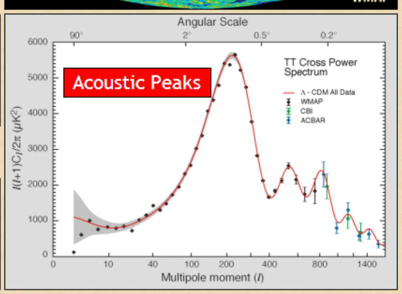


Multipole expansion

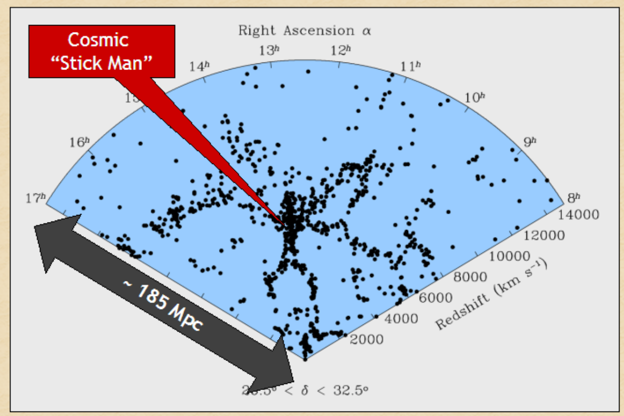
$$\Delta(\theta,\varphi) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\theta,\varphi)$$

Angular power spectrum

$$C_\ell = \langle a^*_{\ell m} a_{\ell m} \rangle = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} a^*_{\ell m} a_{\ell m}$$

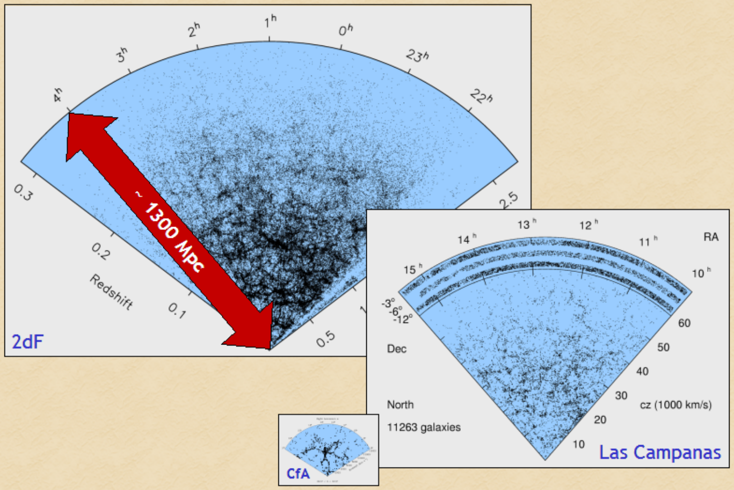


A Slice of the Universe

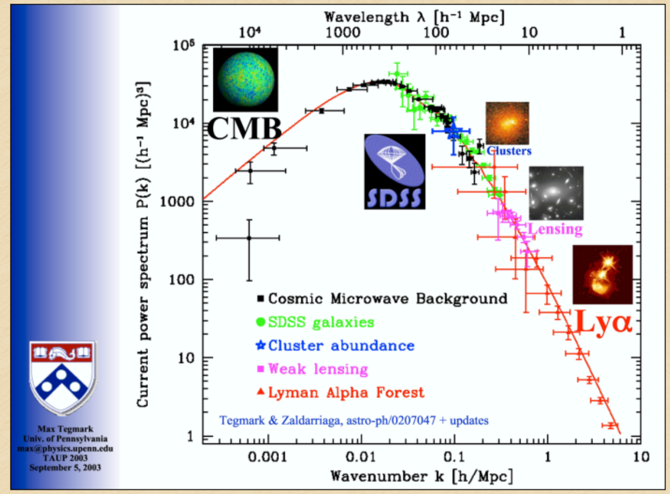


Galaxy distribution from the CfA redshift survey [ApJ 302 (1986) L1]

2dF Galaxy Redshift Survey (15 May 2002)

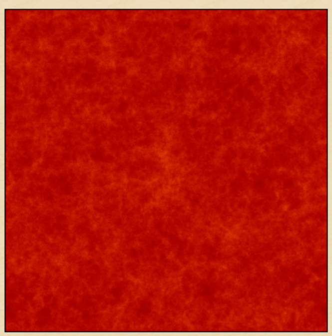


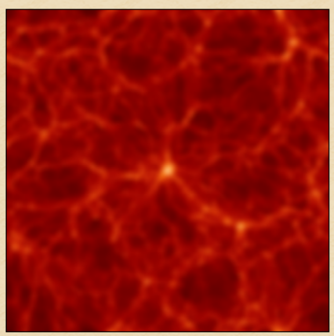
Power Spectrum of Cosmic Density Fluctuations



Formation of Structure

Smooth → Structured

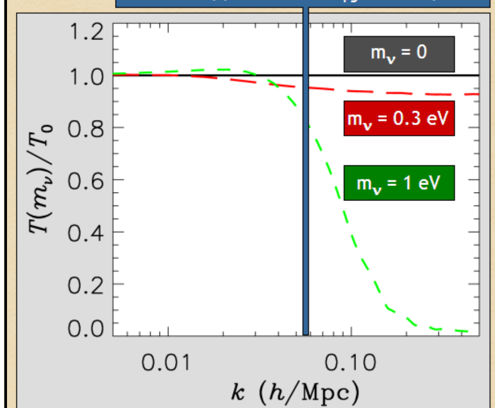




A fraction of hot dark matter suppresses small-scale structure

Neutrino Free Streaming - Transfer Function

Power suppression for $\lambda_{FS} \lesssim 100$ Mpc/h



Transfer function

$P(k) = T(k)\, P_0(k)$

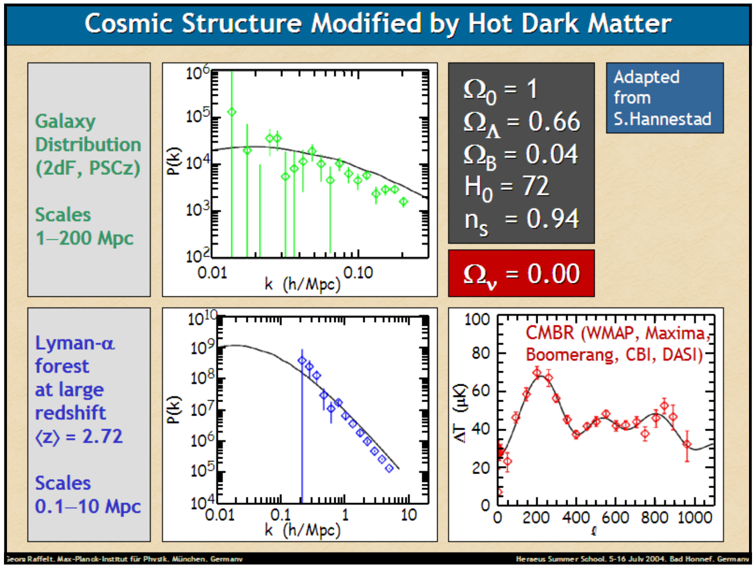
Effect of neutrino free streaming on small scales

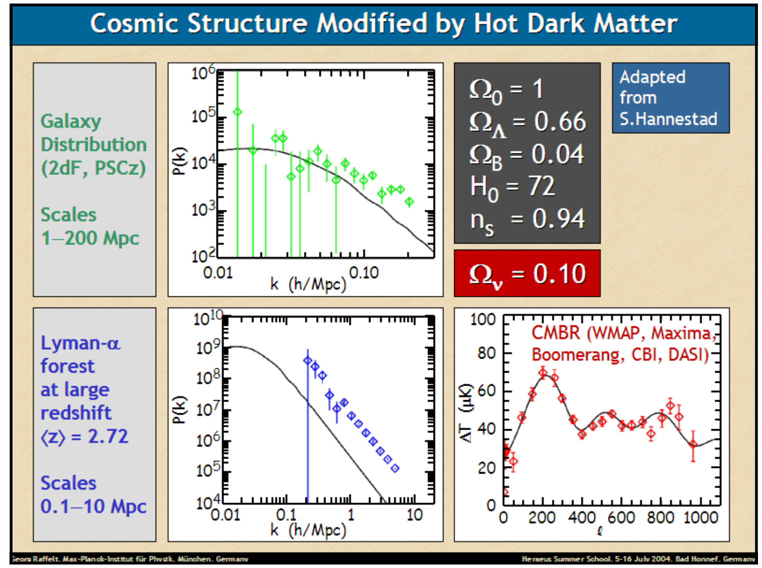
$T(k) = 1 - 8\Omega_\nu/\Omega_M$

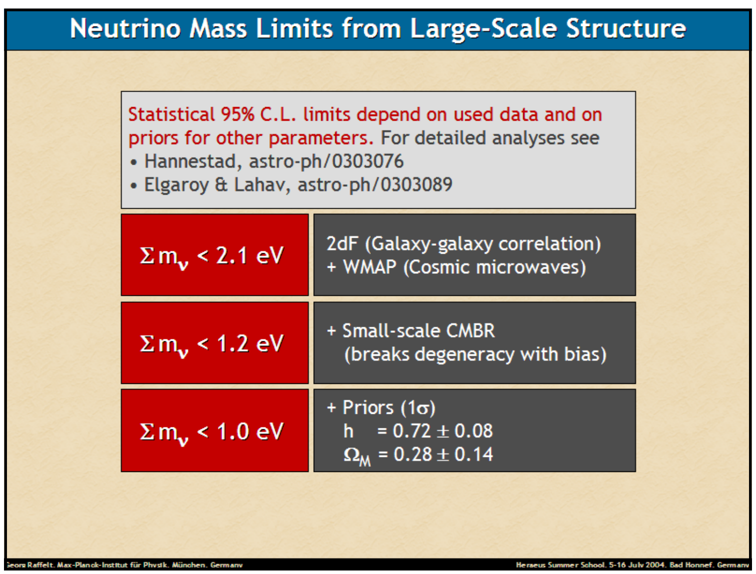
valid for

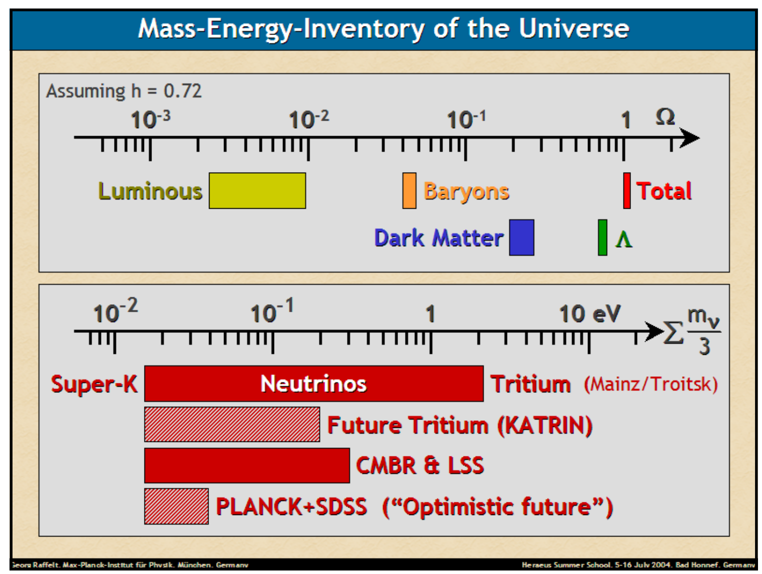
$8\Omega_\nu/\Omega_M \ll 1$

Hannestad, Neutrinos in Cosmology, hep-ph/0404239


Cosmic Structure Modified by Hot Dark Matter
Galaxy Distribution (2dF, PSCz)
Scales 1–200 Mpc
P(k)
k (h/Mpc)
Lyman-α forest at large redshift ⟨z⟩ = 2.72
Scales 0.1–10 Mpc
$\Omega_0 = 1$
$\Omega_\Lambda = 0.66$
$\Omega_B = 0.04$
$H_0 = 72$
$n_s = 0.94$
Adapted from S.Hannestad
$\Omega_\nu = 0.00$
CMBR (WMAP, Maxima, Boomerang, CBI, DASI)
ΔT (μK)
ℓ
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
Heraeus Summer School, 5-16 July 2004, Bad Honnef, Germany


Cosmic Structure Modified by Hot Dark Matter
Galaxy Distribution (2dF, PSCz)
Scales 1–200 Mpc
P(k)
k (h/Mpc)
Lyman-α forest at large redshift ⟨z⟩ = 2.72
Scales 0.1–10 Mpc
$\Omega_0 = 1$
$\Omega_\Lambda = 0.66$
$\Omega_B = 0.04$
$H_0 = 72$
$n_s = 0.94$
Adapted from S.Hannestad
$\Omega_\nu = 0.10$
CMBR (WMAP, Maxima, Boomerang, CBI, DASI)
ΔT (μK)
ℓ
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
Heraeus Summer School, 5-16 July 2004, Bad Honnef, Germany

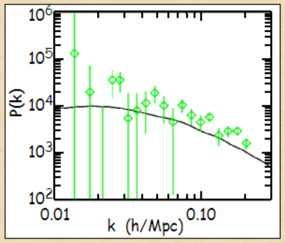

Neutrino Mass Limits from Large-Scale Structure
Statistical 95% C.L. limits depend on used data and on priors for other parameters. For detailed analyses see
• Hannestad, astro-ph/0303076
• Elgaroy & Lahav, astro-ph/0303089
$\Sigma m_\nu < 2.1$ eV
2dF (Galaxy-galaxy correlation) + WMAP (Cosmic microwaves)
$\Sigma m_\nu < 1.2$ eV
+ Small-scale CMBR (breaks degeneracy with bias)
$\Sigma m_\nu < 1.0$ eV
+ Priors (1σ) h = 0.72 ± 0.08 Ω_M = 0.28 ± 0.14
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
Heraeus Summer School, 5-16 July 2004, Bad Honnef, Germany


Mass-Energy-Inventory of the Universe
Assuming h = 0.72
10^{-3}
10^{-2}
10^{-1}
1
Ω
Luminous
Baryons
Total
Dark Matter
Λ
10^{-2}
10^{-1}
1
10 eV
$\Sigma \frac{m_\nu}{3}$
Super-K
Neutrinos
Tritium (Mainz/Troitsk)
Future Tritium (KATRIN)
CMBR & LSS
PLANCK+SDSS ("Optimistic future")
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
Heraeus Summer School, 5-16 July 2004, Bad Honnef, Germany

Cosmic Structure Modified by Additional Radiation

Galaxy Distribution (2dF, PSCz)

Scales 1–200 Mpc



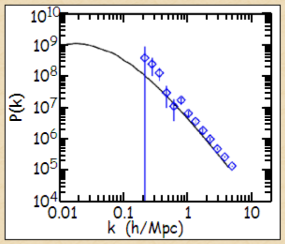
$\Omega_0 = 1$
$\Omega_\Lambda = 0.66$
$\Omega_B = 0.04$
$H_0 = 72$
$n_s = 0.94$

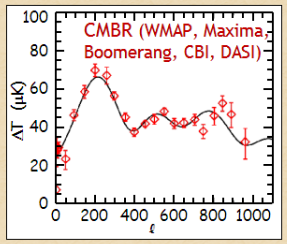
Adapted from S.Hannestad

$N_\nu = 3$

Lyman-α forest at large redshift ⟨z⟩ = 2.72

Scales 0.1–10 Mpc

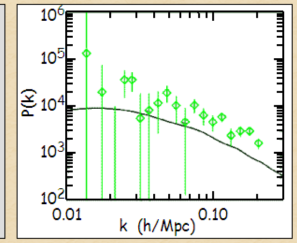




Cosmic Structure Modified by Additional Radiation

Galaxy Distribution (2dF, PSCz)

Scales 1–200 Mpc



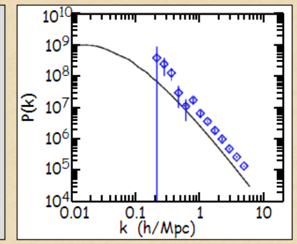
$\Omega_0 = 1$
$\Omega_\Lambda = 0.66$
$\Omega_B = 0.04$
$H_0 = 72$
$n_s = 0.94$

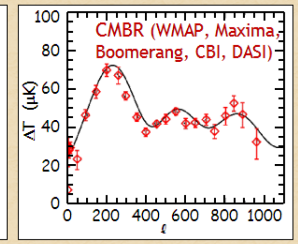
Adapted from S.Hannestad

$N_\nu = 7$

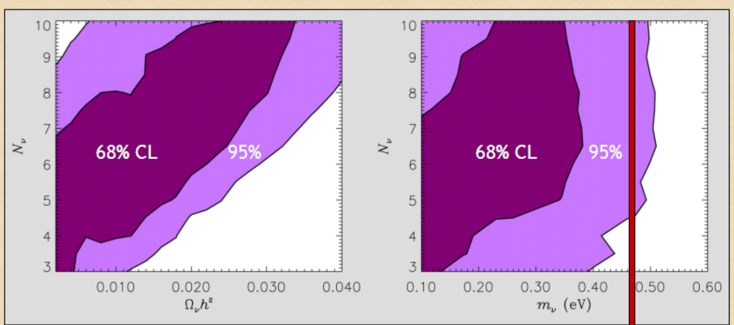
Lyman-α forest at large redshift ⟨z⟩ = 2.72

Scales 0.1–10 Mpc





Neutrino Masses vs. Radiation Density



Neutrino mass limit almost independent of the neutrino number density

Hannestad & Raffelt, Cosmological mass limits on neutrinos, axions, and other light particles, hep/ph0312154

Evidence for Presence of Cosmic Neutrinos

CMBR and LSS data, with different priors, provide allowed range (95% CL) on radiation density, expressed in terms of effective neutrino flavors N_{eff}

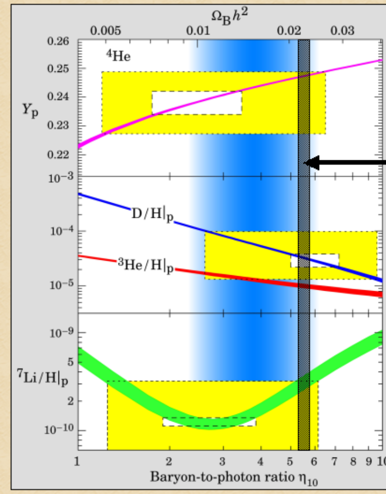
$1.4 < N_{eff} < 8.5$	Crotty, Lesgourgues, Pastor [hep-ph/0402049]
$0.9 < N_{eff} < 7.0$	Hannestad [astro-ph/0303076]
$1.9 < N_{eff} < 6.6$	Pierpaoli [astro-ph/0302465]
$0.9 < N_{eff} < 8.3$	Barger et al. [hep-ph/0305075]

Presence of cosmic neutrinos indicated with high significance, independently of big-bang nucleosynthesis

Helium Synthesis - Three Easy Steps

t (sec)	T (MeV)	Step	Relation	Result
		β equilibrium	$p+e^- \leftrightarrow n+\nu_e$ $p+\bar\nu_e \leftrightarrow n+e^+$	$\frac{n}{p}=\exp\left(-\frac{m_n-m_p}{T}\right)\approx 1$ $m_n-m_p=1.293\,\mathrm{MeV}$
1	1	β freeze-out	$\frac{n}{p}\approx\frac{1}{6}$	β rates fall below expansion rate H
		• Neutron decay • Nuclear statist. equilibrium	$n_n \propto \exp\left(\frac{-t}{\tau_n}\right)$ $\tau_n = 886\,\mathrm{sec}$	$2p+2n \leftrightarrow {}^4He+\gamma$ Helium suppressed by large entropy
100	0.1	Neutrons freeze in helium	$\frac{n}{p}\approx\frac{1}{7}$	Helium mass fraction $Y_p \approx 25\%$
		Thermonuclear reaction chains	Production and destruction of traces of D, ^3He, ^6Li, ^7Li, ^7Be	
10^4	0.01	All done		

BBN Predictions



Helium

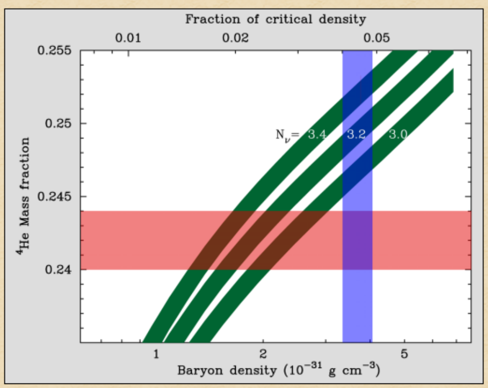
Deuterium

Lithium

Implied by CMBR and large-scale structure

Review of Particle Properties

BBN Limits on Neutrino Flavors



With the baryon density known, the observed helium mass fraction measures the expansion rate at nucleosynthesis

$$H=\sqrt{\frac{4\pi^3}{45}g_*}\,\frac{T^2}{m_{Pl}}$$

$$g_* = 2+\frac{7}{8}(4+2N_\nu)$$

At BBN one flavor contributes about 16% to cosmic mass-energy so that

$$\Delta Y_p \approx 0.012\,\Delta N_\nu$$

Measured value

$$Y_p = 0.242 \pm 0.002$$

(only statistical error)

- Slight tension between measured and predicted helium abundance
- Certainly no evidence for additional radiation

How Many Relic Neutrinos?

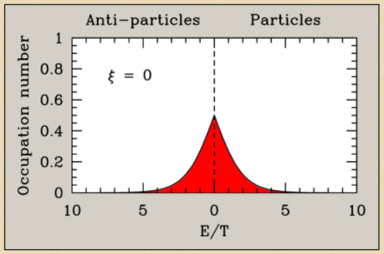
Standard thermal population in one flavor $n_{\nu\bar\nu}=\frac{3}{11}n_\gamma \approx 115\,\mathrm{cm}^{-3}$

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	Constrained by energy loss of SN 1987A
	Electromagnetic dipole moments	Constrained by energy loss of globular cluster stars
	Oscillations/collisions	Hot/warm/cold DM possible

Thermal Neutrino Distribution with Chemical Potential

Fermi-Dirac distribution
- Temperature T
- Chemical potential μ
  - $+\mu$ Particles
  - $-\mu$ Anti-particles

$$f_p = \frac{1}{\exp\left(\frac{E-\mu}{T}\right)+1}$$



Degeneracy parameter $\xi = \frac{\mu}{T}$ Invariant under cosmic expansion

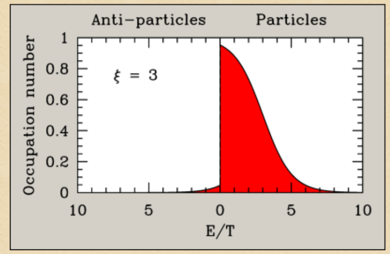
Number density

$$n_{\nu\bar{\nu}} = \int dE \frac{4\pi}{(2\pi)^3}\left(\frac{E^2}{1+\exp(E/T-\xi)} + \frac{E^2}{1+\exp(E/T+\xi)}\right)$$
$$= \frac{3\zeta_3}{2\pi^2} T_\nu^3 \left[1 + \frac{2\ln(2)}{3\zeta_3}\xi^2 + \frac{1}{72\zeta_3}\xi^4 + \ldots\right]$$

Thermal Neutrino Distribution with Chemical Potential

Fermi-Dirac distribution
- Temperature T
- Chemical potential μ
  - $+\mu$ Particles
  - $-\mu$ Anti-particles

$$f_p = \frac{1}{\exp\left(\frac{E-\mu}{T}\right)+1}$$



Degeneracy parameter $\xi = \frac{\mu}{T}$ Invariant under cosmic expansion

Number density

$$n_{\nu\bar{\nu}} = \int dE \frac{4\pi}{(2\pi)^3}\left(\frac{E^2}{1+\exp(E/T-\xi)} + \frac{E^2}{1+\exp(E/T+\xi)}\right)$$
$$= \frac{3\zeta_3}{2\pi^2} T_\nu^3 \left[1 + \frac{2\ln(2)}{3\zeta_3}\xi^2 + \frac{1}{72\zeta_3}\xi^4 + \ldots\right]$$

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 $\Delta N_{eff} \sim -18\,\xi_{\nu e}$

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

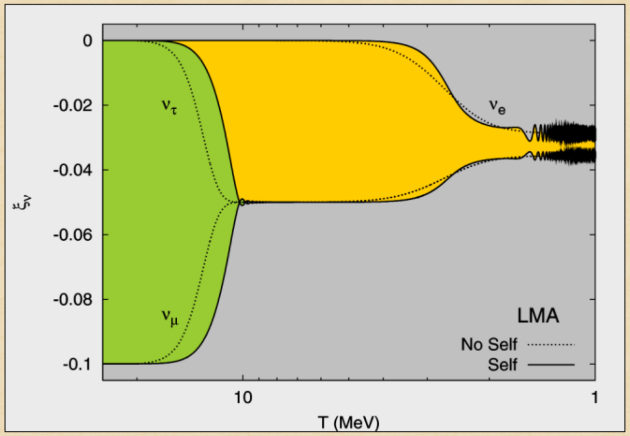
Chemical Potentials and Flavor Oscillations

- Flavor mixing (neutrino oscillations)
- Flavor lepton numbers not conserved
- Only one common neutrino 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 for solar LMA solution
- Our knowledge of the cosmic neutrino density depends on measured oscillation parameters

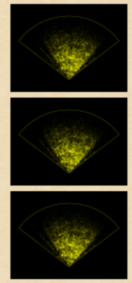
- Lunardini & Smirnov, hep-ph/0012056
- Dolgov, Hansen, Pastor, Petcov, Raffelt & Semikoz, hep-ph/0201287
- Abazajian, Beacom & Bell, astro-ph/0203442
- Wong, hep-ph/0203180

Flavor Equilibration: LMA Solution

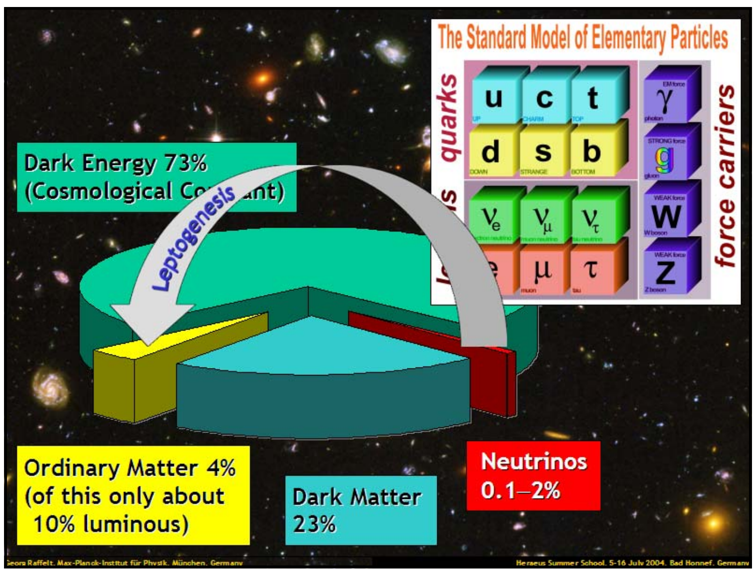


Dolgov, Hansen, Pastor, Petcov, Raffelt & Semikoz, hep-ph/0201287

Neutrino Masses



- Flavor oscillations and all that
- Quest for the absolute mass scale and cosmological neutrinos
- Neutrino mass and the baryon asymmetry of the universe



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

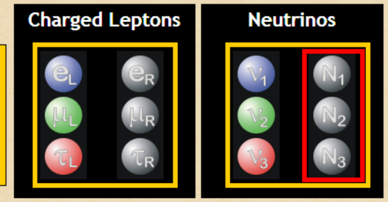
Received 8 March 1986

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.

Georg Raffelt, Max-Planck-Institut für Physik, München, Germany — Heraeus Summer School, 5-16 July 2004, Bad Honnef, Germany

See-Saw Model for Neutrino Masses

Dirac masses from coupling to standard Higgs field ϕ



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

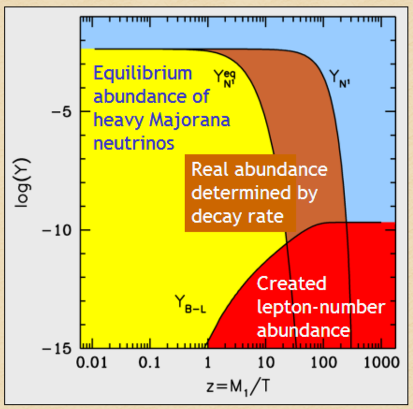
Lagrangian for particle masses: $\mathcal{L}_{\rm mass} = -\bar{\ell}_L \phi g_\ell e_R - \bar{\ell}_L \tilde{\phi} g_\nu N_R - \frac{1}{2}\bar{N}_R^c M N_R + \text{h.c.}$

Light Majorana mass

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

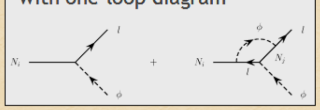
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany — Heraeus Summer School, 5-16 July 2004, Bad Honnef, Germany

Leptogenesis by Out-of-Equilibrium Decay



M. Fukugita & T. Yanagida: Baryogenesis without Grand Unification Phys. Lett. B 174 (1986) 45

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



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

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

Georg Raffelt, Max-Planck-Institut für Physik, München, Germany — Heraeus Summer School, 5-16 July 2004, Bad Honnef, Germany

Leptogenesis by Majorana Neutrino Decays

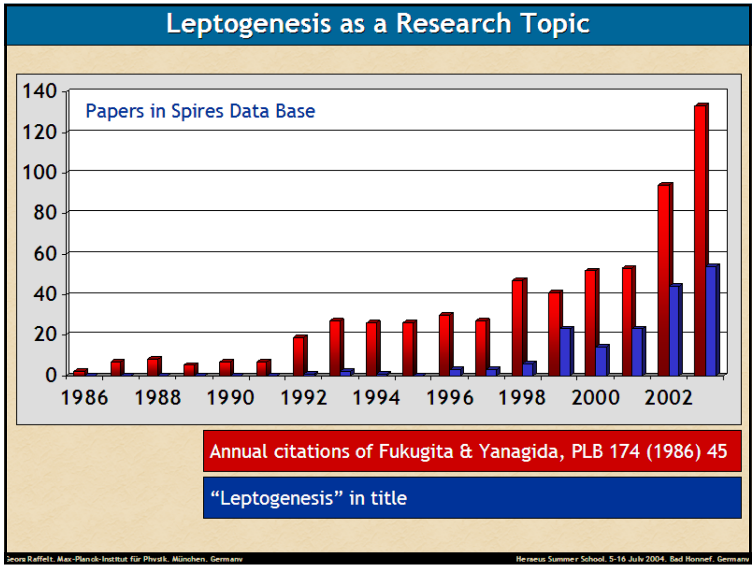
In see-saw models for neutrino masses, out-of-equilibrium decays of right-handed heavy Majorana neutrinos provide source for CP- and L-violation

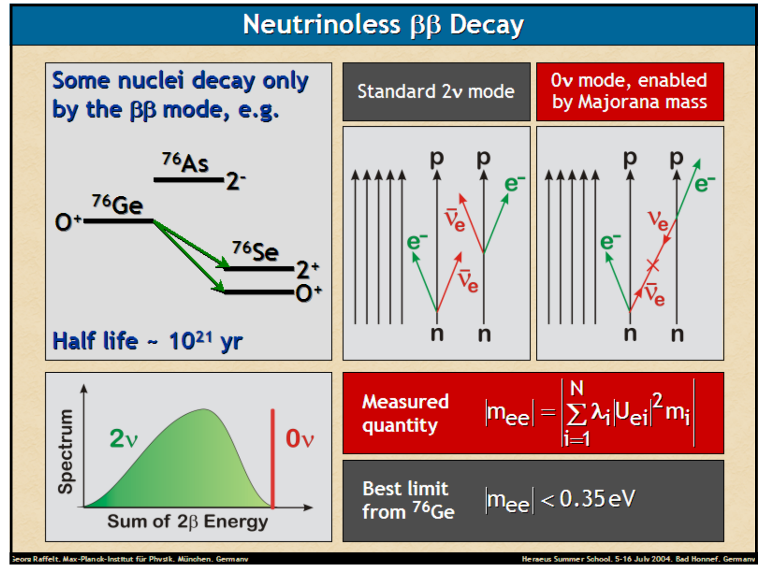
Cosmological evolution
- B = L = 0 early on
- Thermal freeze-out of heavy Majorana neutrinos
- Out-of-equilibrium CP-violating decay creates net L
- Shift L excess into B by sphaleron effects

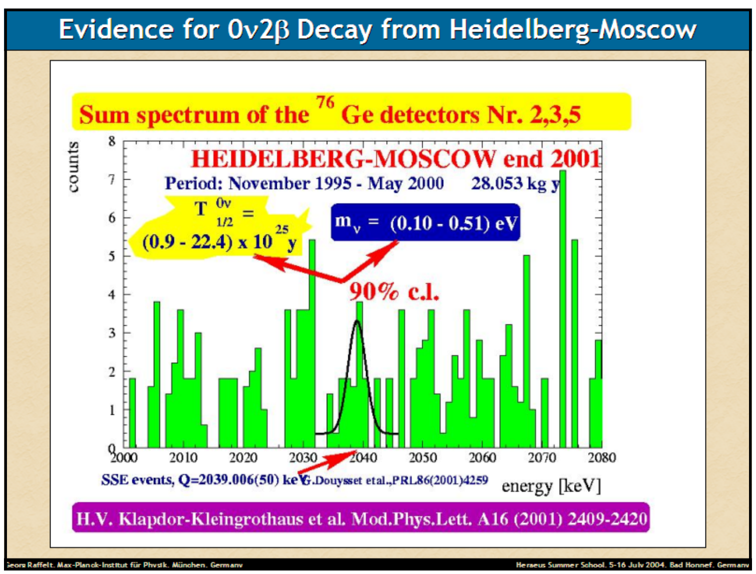
Sufficient deviation from equilibrium distribution of heavy Majorana neutrinos at freeze-out → Limits on Yukawa couplings → Limits on masses of ordinary neutrinos

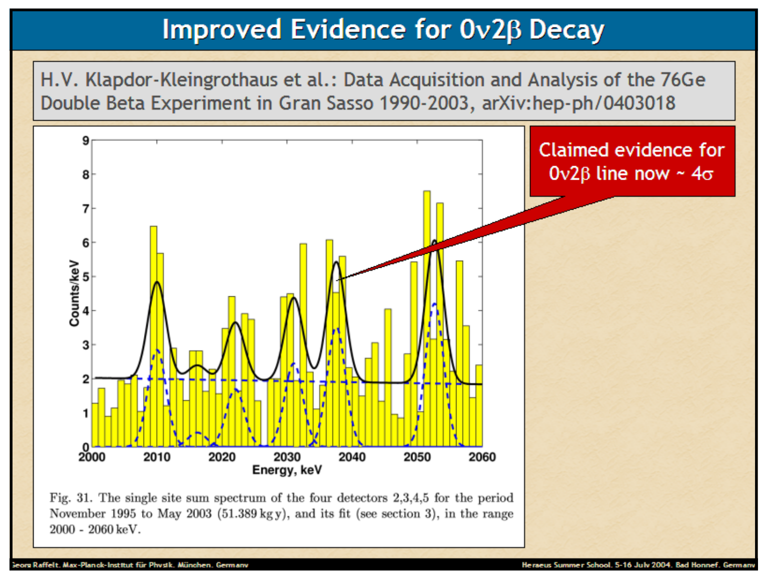
Requires Majorana neutrino masses below 0.1 eV
Buchmüller, Di Bari & Plümacher, hep-ph/0209301 & hep-ph/0302092

Georg Raffelt, Max-Planck-Institut für Physik, München, Germany — Heraeus Summer School, 5-16 July 2004, Bad Honnef, Germany

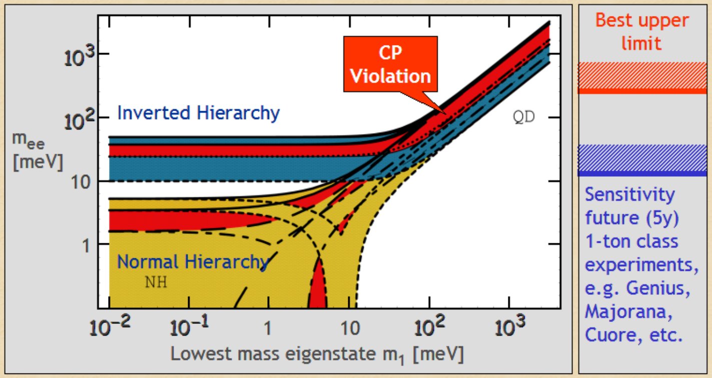

Leptogenesis as a Research Topic
Papers in Spires Data Base
140
120
100
80
60
40
20
0
1986
1988
1990
1992
1994
1996
1998
2000
2002
Annual citations of Fukugita & Yanagida, PLB 174 (1986) 45
"Leptogenesis" in title
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
Heraeus Summer School, 5-16 July 2004, Bad Honnef, Germany


Neutrinoless ββ Decay
Some nuclei decay only by the ββ mode, e.g.
^{76}As
2$^-$
^{76}Ge
0$^+$
^{76}Se
2$^+$
0$^+$
Half life ~ 10^{21} yr
Standard 2ν mode
0ν mode, enabled by Majorana mass
p p
n n
e$^-$
$\bar{\nu}_e$
ν_e
Spectrum
2ν
0ν
Sum of 2β Energy
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
Heraeus Summer School, 5-16 July 2004, Bad Honnef, Germany


Evidence for 0ν2β Decay from Heidelberg-Moscow
Sum spectrum of the ^{76}Ge detectors Nr. 2,3,5
HEIDELBERG-MOSCOW end 2001
Period: November 1995 - May 2000
28.053 kg y
$T^{0\nu}_{1/2}$ = (0.9 - 22.4) x 10^{25} y
m_ν = (0.10 - 0.51) eV
90% c.l.
counts
energy [keV]
SSE events, Q=2039.006(50) keV G.Douysset et al., PRL86(2001)4259
H.V. Klapdor-Kleingrothaus et al. Mod.Phys.Lett. A16 (2001) 2409-2420
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
Heraeus Summer School, 5-16 July 2004, Bad Honnef, Germany


Improved Evidence for 0ν2β Decay
H.V. Klapdor-Kleingrothaus et al.: Data Acquisition and Analysis of the 76Ge Double Beta Experiment in Gran Sasso 1990-2003, arXiv:hep-ph/0403018
Claimed evidence for 0ν2β line now ~ 4σ
Counts/keV
Energy, keV
Fig. 31. The single site sum spectrum of the four detectors 2,3,4,5 for the period November 1995 to May 2003 (51.389 kg y), and its fit (see section 3), in the range 2000 - 2060 keV.
Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
Heraeus Summer School, 5-16 July 2004, Bad Honnef, Germany

Effective Majorana Mass in Plausible Scenarios



Pascoli & Petcov, hep-ph/0310003 & hep-ph/0205022
See also Feruglio, Strumia & Vissani, hep-ph/0201291
Klapdor-Kleingrothaus, Päs & Smirnov, hep-ph/0103076, and others