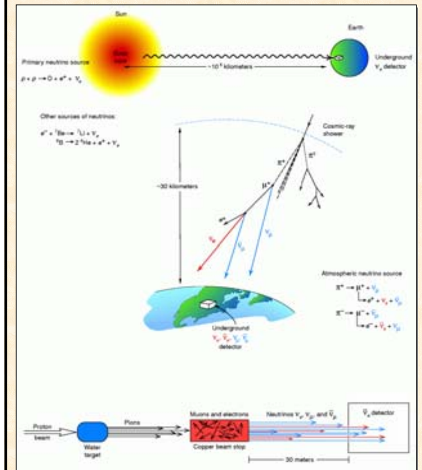
Neutrino Masses in Astrophysics and Cosmology

Georg Raffelt (Max-Planck-Institut für Physik, München)

Evidence for Neutrino Oscillations



- Solar Neutrinos
- Atmospheric Neutrinos
- LSND Experiment

Status of Evidence for Neutrino Oscillations

System	Atmospheric	Solar	LSND
Channel	$\nu_\mu \to \nu_\tau$	$\nu_e \to \nu_{\mu\tau}$	$\bar\nu_\mu \to \bar\nu_e$
$\delta m^2 / eV^2$	$(1.5-4)\times10^{-3}$	LMA $(0.2-2)\times10^{-4}$	0.2-2
$\sin^2 2\theta$	0.9-1	0.2-0.6	0.001-0.03
Status	Established	Established	Unconfirmed
	Mutually inconsistent with 3 mass eigenstates		
Test	Long Baseline	KamLAND 2002 ?	MiniBooNE 2003/4?
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)		Wrong

What is the absolute neutrino mass scale m_ν?

Neutrino Masses in Astrophysics and Cosmology

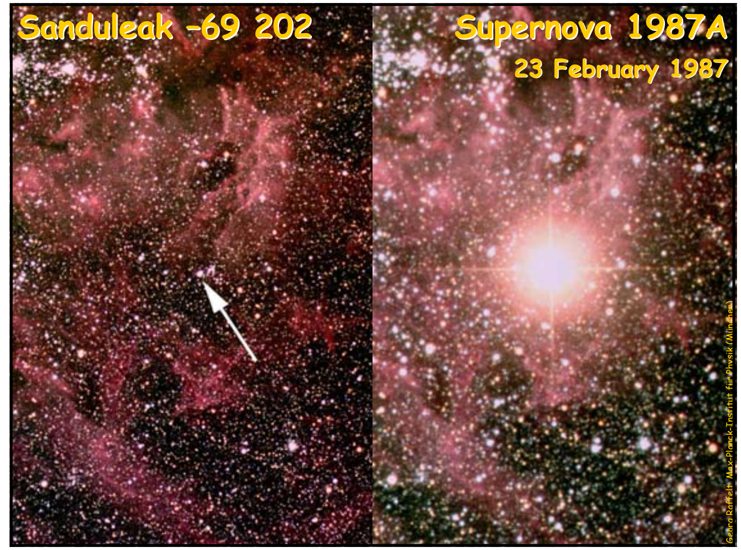

Time-Of-Flight Sensitivity with Supernova Neutrinos

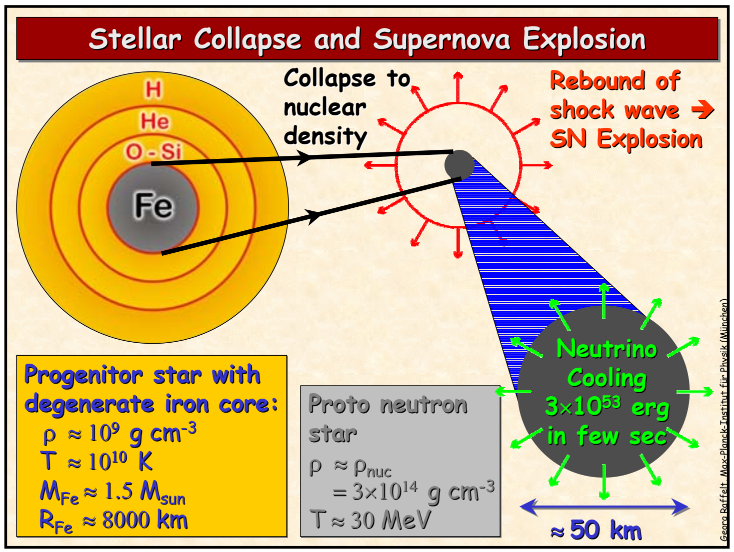

Neutrino Dark Matter and Cosmic Structure Formation


Neutrino Chemical Potentials, Big-Bang Nucleosynthesis, and Flavor Oscillations


Highest-Energy Cosmic Rays and the Cosmic Neutrino Sea


Massive Neutrinos and the Cosmic Baryon Asymmetry





Core Collapse Supernova Energetics

Liberated gravitational binding energy of neutron star:

$E_b \approx 3 \times 10^{53}$ erg $\approx$ 17% $M_{SUN}c^2$

This shows up as

99%	Neutrinos
1%	Kinetic energy of explosion (1% of this into cosmic rays)
0.01%	Photons (outshine host galaxy)

Neutrino luminosity

$L_\nu \approx 3\times10^{53}$ erg / 3 sec $\approx 3\times10^{19}\ L_{SUN}$

While it lasts, outshines the photon luminosity of the entire visible universe!

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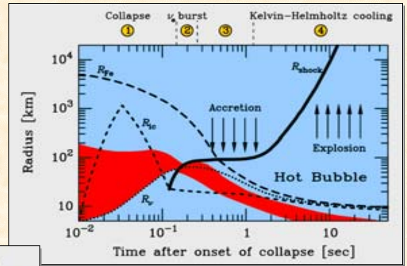
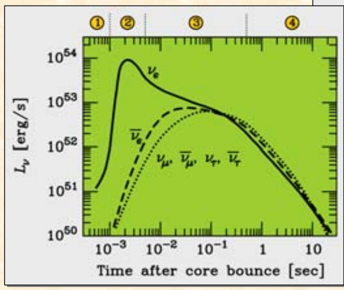
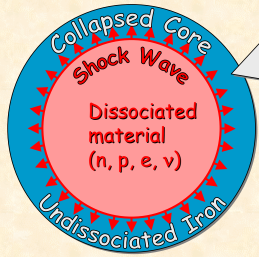
Supernova Neutrino Signal

1. Collapse (infall phase)
2. Shock break out
3. Matter accretion
4. Kelvin-Helmholtz cooling



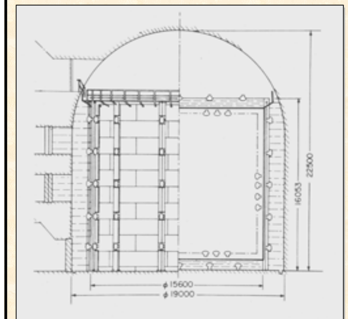


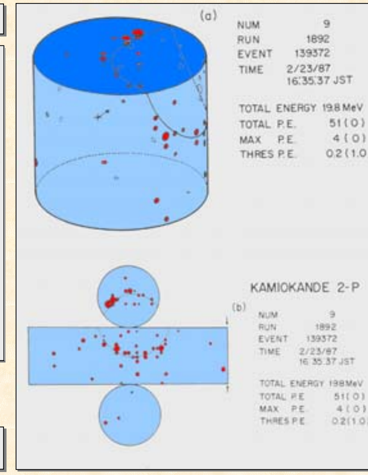


Traps neutrinos and lepton number of outer core layers

SN 1987A Event No.9 in Kamiokande

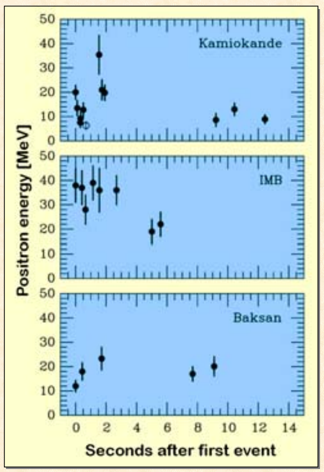
Kamiokande Detector





Hirata et al., PRD 38 (1988) 448

Neutrino Signal of Supernova 1987A



Kamiokande (Japan)
Water Cherenkov detector
Clock uncertainty ±1 min

Irvine-Michigan-Brookhaven (USA)
Water Cherenkov detector
Clock uncertainty ±50 ms

Baksan Scintillator Telescope (Soviet Union)
Clock uncertainty +2/-54 s

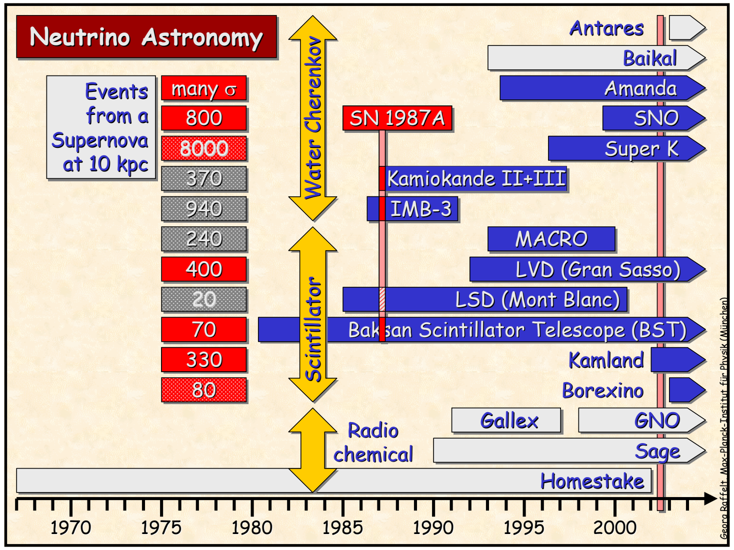
Within clock uncertainties, signals are contemporaneous

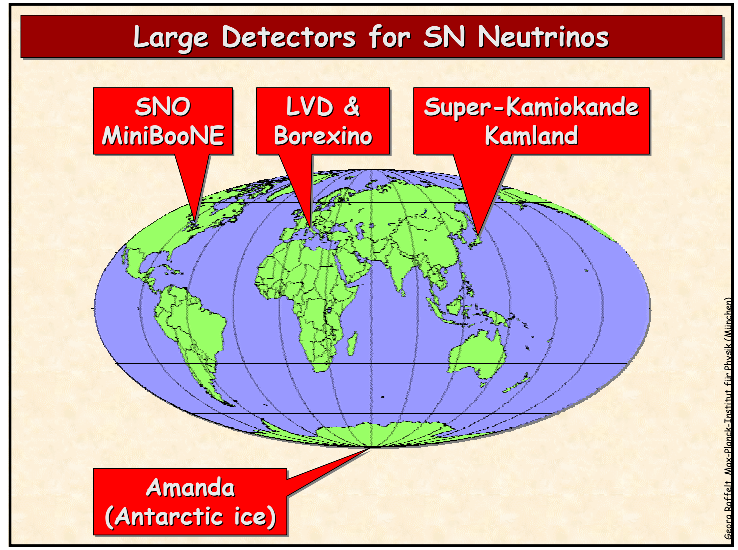
Neutrino Limits by Intrinsic Signal Dispersion

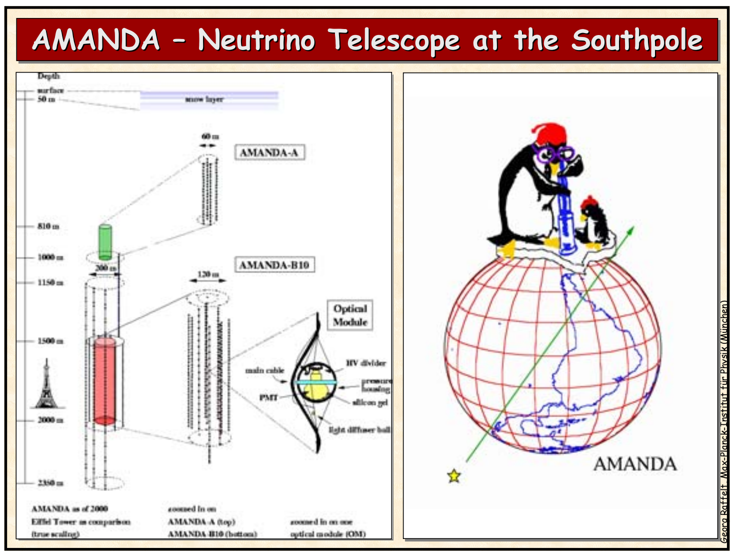
Time-of-flight delay of massive neutrinos

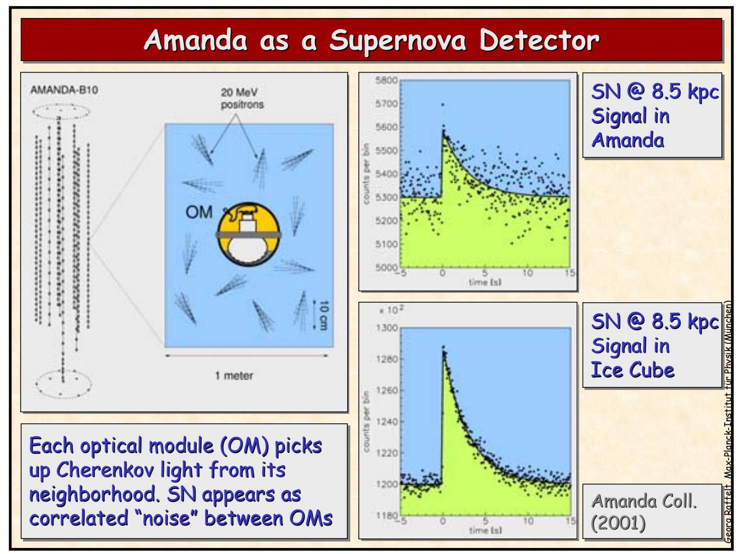
$$\Delta t = 2.57\,\mathrm{s}\left(\frac{D}{50\,\mathrm{kpc}}\right)\left(\frac{10\,\mathrm{MeV}}{E_\nu}\right)^2\left(\frac{m_\nu}{10\,\mathrm{eV}}\right)^2$$

SN 1987A	$E \approx 20$ MeV, $\Delta t \approx 10$ s, $D \approx 50$ kpc	$m_{\nu_e} < 20$ eV
	Detailed maximum-likelihood analysis similar result In 1987 competitive with tritium end-point limits	
Future Galactic SN (Super-K)	$D \approx 50$ kpc, Rise-time 0.01 s	
	Sensitivity approximately	$m_{\nu_e} \sim 3$ eV

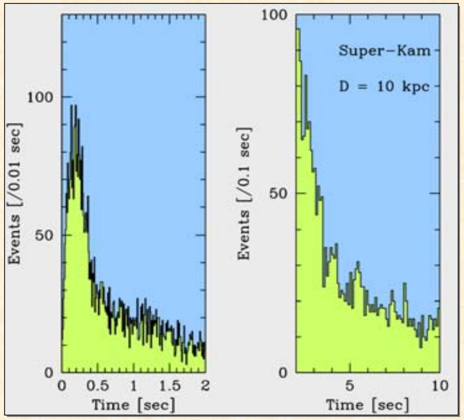

Neutrino Astronomy
Events from a Supernova at 10 kpc
many σ
800
8000
370
940
240
400
20
70
330
80
Water Cherenkov
Scintillator
Radio chemical
SN 1987A
Antares
Baikal
Amanda
SNO
Super K
Kamiokande II+III
IMB-3
MACRO
LVD (Gran Sasso)
LSD (Mont Blanc)
Baksan Scintillator Telescope (BST)
Kamland
Borexino
Gallex
GNO
Sage
Homestake
1970
1975
1980
1985
1990
1995
2000
Georg Raffelt, Max-Planck-Institut für Physik (München)


Large Detectors for SN Neutrinos
SNO MiniBooNE
LVD & Borexino
Super-Kamiokande Kamland
Amanda (Antarctic ice)
Georg Raffelt, Max-Planck-Institut für Physik (München)


AMANDA - Neutrino Telescope at the Southpole
AMANDA-A
AMANDA-B10
Optical Module
AMANDA
Georg Raffelt, Max-Planck-Institut für Physik (München)


Amanda as a Supernova Detector
AMANDA-B10
20 MeV positrons
OM
10 cm
1 meter
SN @ 8.5 kpc Signal in Amanda
SN @ 8.5 kpc Signal in Ice Cube
Each optical module (OM) picks up Cherenkov light from its neighborhood. SN appears as correlated "noise" between OMs
Amanda Coll. (2001)
Georg Raffelt, Max-Planck-Institut für Physik (München)

Galactic Supernova Signal in Super-Kamiokande

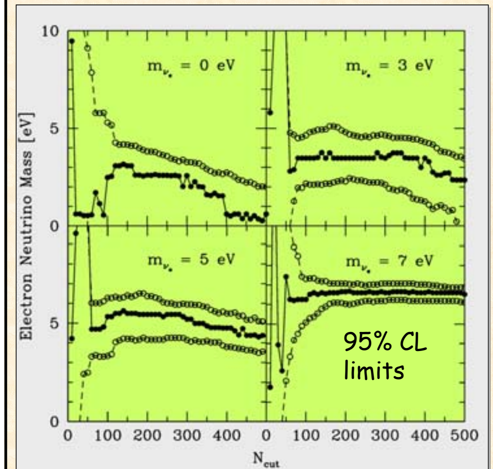


Monte-Carlo simulation for Super-K signal of SN at 10 kpc, based on a numerical model with Livermore code

Total of about 8300 events for t < 18 s

Totani, Sato, Dalhed & Wilson, ApJ 496 (1998) 216

Neutrino Mass from a Future Galactic SN

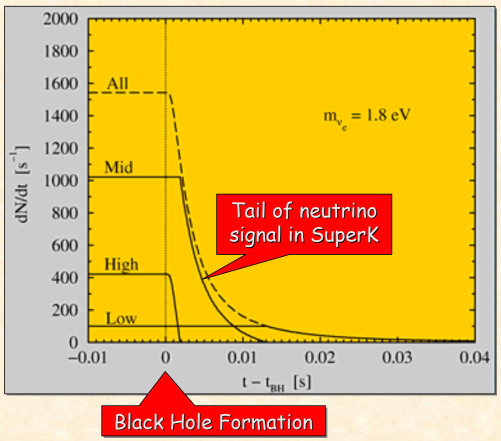


Use correlation between energy & time of arrival as a statistical measure of first N_{cut} events in Monte Carlo simulation of SN signal in SuperK

For SN at 10 kpc sensitive to approx. 3 eV

T.Totani, PRL 80 (1998) 2040

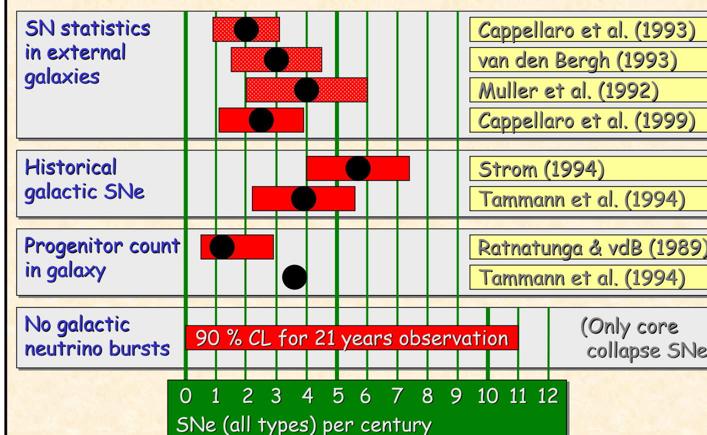
SN Neutrino Mass from Early Black Hole Formation



Beacom, Boyd & Mezzacappa, hep-ph/0006015

Super-Kamiokande sensitivity $m_\nu \sim 1.8$ eV

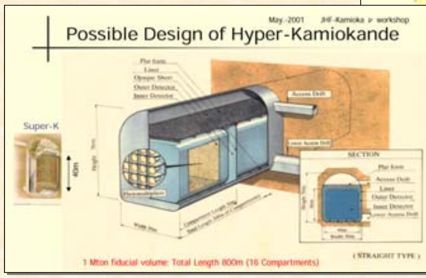
Estimates of the Galactic SN Rate



The Future: A Megatonne Detector?

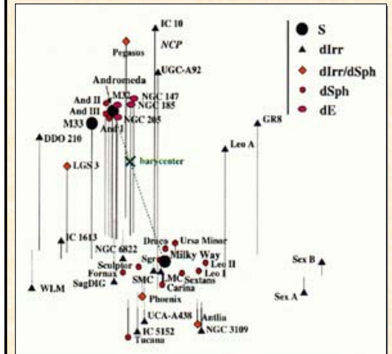
Megatonne detector motivated by
- Long baseline neutrino oscillations
- Proton decay
- Atmospheric neutrinos
- Solar neutrinos
- Supernova neutrinos

(~10^5 events for SN at 10 kpc)

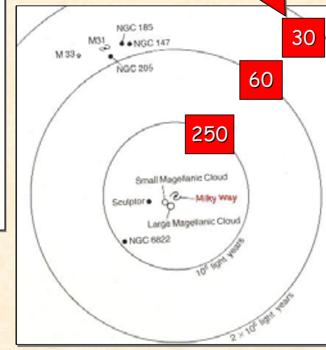


Similar discussions in
- USA (UNO project)
- Europe (Frejus Tunnel)

Local Group of Galaxies



Events in a detector with 30 x SuperK fiducial volume (8000 events in SK at 10 kpc)



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Brightest Members of Local Group

	Type	Lum	D kpc	Neutrino events	SN (all types) per century
Milky Way	S(B)bc	1	8.5	330,000	1-6
LMC	Ir	0.11	50	9,600	0.1 / 0.23 / 0.49
SMC	Ir	0.030	60	6,600	0.065 / 0.12
NGC 6822	Ir	0.011	500	96	0.04
IC 10 (UGC 192)	Ir	0.015	660	55	0.082-0.11
NGC 205	Sph	0.016	760	42	
M32 (NGC 221)	E2	0.017	760	42	
Andromeda (M31)	Sb	1.3	760	42	0.9 / 1.21 / 1.25
Triangulum (M33)	Sc	0.16	790	38	0.28 / 0.35 / 0.68

- Luminosity: Visual in units of the Milky Way
- Neutrino events in 30 x SK fiducial vol. (8000 events in SK for SN at 10 kpc)
- Refs. for SN rates in Pavlidou & Fields, Ap. J. 558 (2001) 63.

Georg Raffelt, Max-Planck-Institut für Physik (München)

Neutrino Limits by Intrinsic Signal Dispersion

Time-of-flight delay of massive neutrinos

$$\Delta t = 2.57\,\mathrm{s}\left(\frac{D}{50\,\mathrm{kpc}}\right)\left(\frac{10\,\mathrm{MeV}}{E_\nu}\right)^2\left(\frac{m_\nu}{10\,\mathrm{eV}}\right)^2$$

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	Detailed maximum-likelihood analysis similar result In 1987 competitive with tritium end-point limits	
Future Galactic SN (Super-K)	$D \approx 50$ kpc, Rise-time 0.01 s	
	Sensitivity approximately	$m_{\nu_e} \sim 3$ eV
Future SN in Andromeda (Megatonne)	$D \approx 750$ kpc, $\Delta t \approx 10$ s	
	Sensitivity approximately	$m_{\nu_e} \sim 1$-2 eV

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Neutrino Mass and SNe – Good or Bad News?

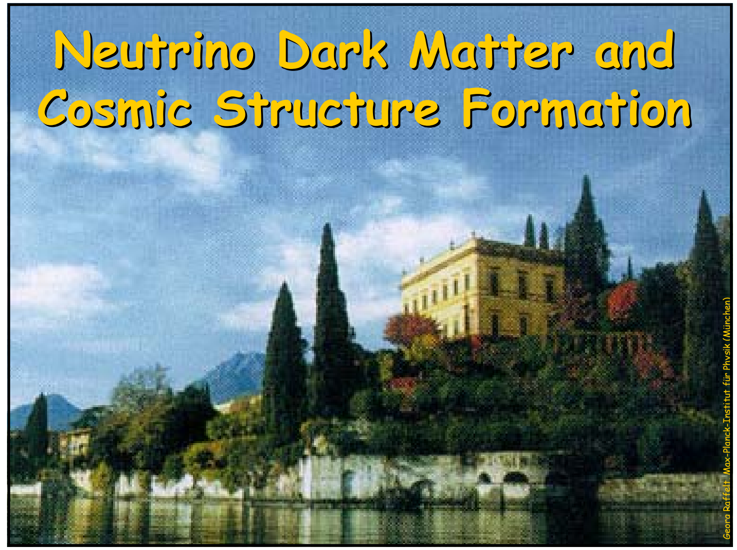
Tritium Limits < 2-3 eV
Future < 0.3 eV
Cosmological LSS similar limits
Oscillations: All mass differences < 0.1 eV

→ All active flavors likely to have sub-eV masses or less

Supernova time-of-flight dispersion

$$\Delta t = 0.46\,\mathrm{ms}\left(\frac{D}{10\,\mathrm{kpc}}\right)\left(\frac{10\,\mathrm{MeV}}{E_\nu}\right)^2\left(\frac{m_\nu}{0.3\,\mathrm{eV}}\right)^2$$

→ Measure pristine neutrino light curve, unspoilt by dispersion effects



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Cosmological Limit on Neutrino Masses

Cosmic neutrino "sea":
Approximately 112 cm^{-3} neutrinos + antineutrinos per flavor

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

m_ν < 40 eV For all stable flavors

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

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 $m(\nu_e) < 200\ \mathrm{eV}/c^2$ for the electronic neutrino and $m(\nu_\mu) < 2.5 \times 10^6\ \mathrm{eV}/c^2$ 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 5×10^9 years, and Hubble's constant H is not smaller than 75 km/sec-Mparsec $= (13 \times 10^9\ \mathrm{years})^{-1}$. It follows therefore that the density of all types of matter in the Universe is at the present time [1)]

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

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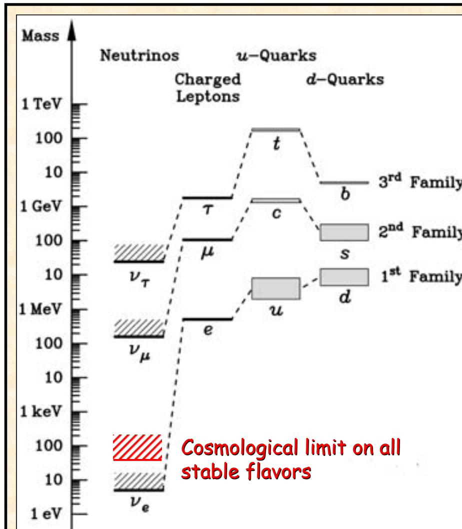

Fermion Mass Spectrum

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Weakly Interacting Particles as Dark Matter

THE ASTROPHYSICAL JOURNAL, 180: 7–10, 1973 February 15

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 ith 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; $T(z_{eq}) = T_\gamma(z_{eq}) = T_\nu(z_{eq}) = T_e(z_{eq}) \cdots$ = 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 $(1+z_{eq})/(1+z) = T_\gamma(z_{eq})/T_\gamma(z)$, the number density at the present epoch ($z = 0$) is given by

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

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

7

Almost 30 years ago:

Beginnings of the idea of weakly interacting particles (neutrinos) as dark matter.

Massive neutrinos are no longer thought to be a good dark matter candidate.

However, the idea of weakly interacting massive particles constituting the cosmic dark matter is now standard.

What is wrong with neutrino dark matter?

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

Maximum mass density of a Fermi gas:

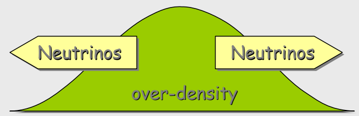
$$\rho_{max} = m_\nu\, n_{max} = m_\nu\, p_{max}^3/3\pi^2 = m_\nu\, (m_\nu v_{escape})^3/3\pi^2$$

m_ν > (20 – 40) eV

Spiral galaxies, more restrictive from dwarf galaxies: m_ν > 100-200 eV

➔ **Neutrino Free Streaming (Collisionless Phase Mixing)**

At T < 1 MeV neutrino scattering ineffective, stream freely until nonrelativistic, wash out density contrasts on small scales.



Neutrinos are "Hot Dark Matter", excluded by structure formation

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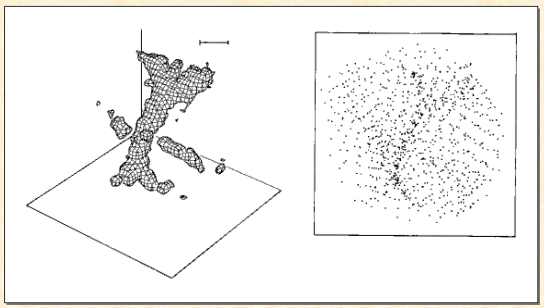
Hot dark matter ruled out in 1983



1000 particle simulation by Frenk, White & Davis, ApJ 271 (1983) 417

The coherence length of the neutrino distribution … is too large to be consistent with the observed clustering scale of galaxies …
The conventional neutrino-dominated picture appears to be ruled out.
[White, Frenk & Davis, ApJ 274 (1983) L1]

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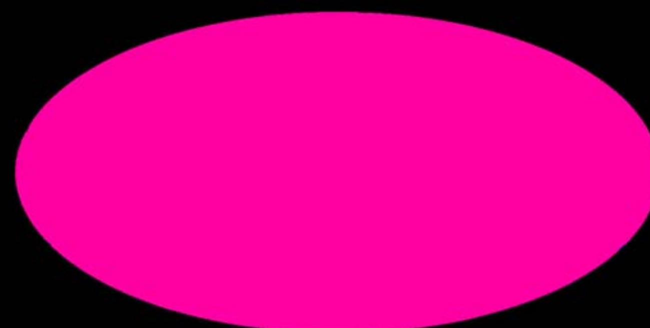
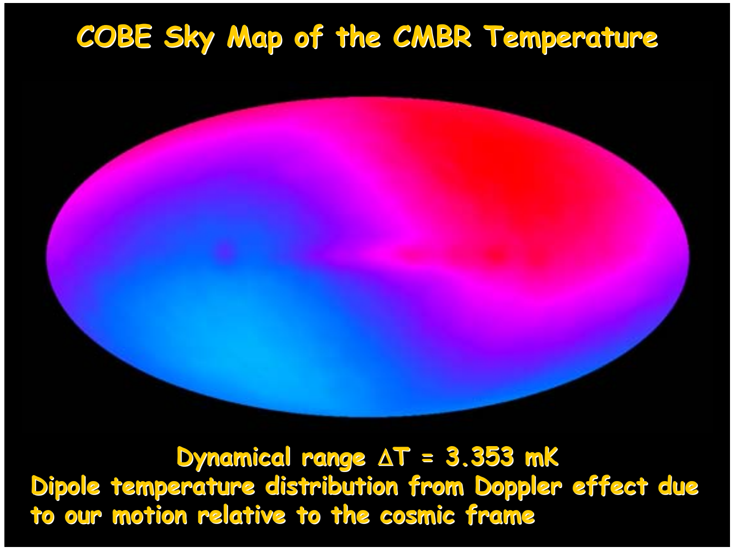
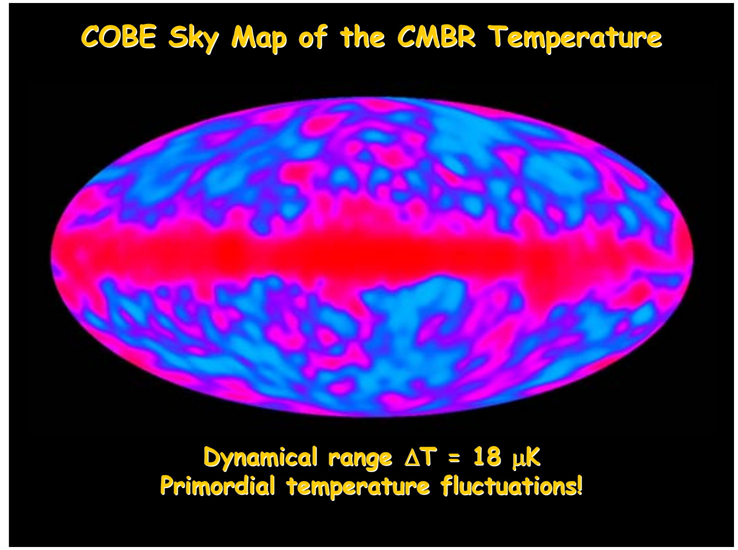
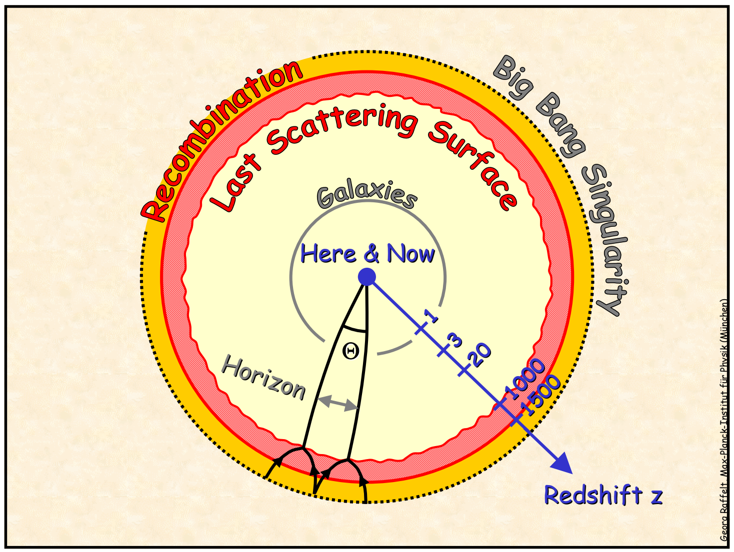
COBE Sky Map of the CMBR Temperature

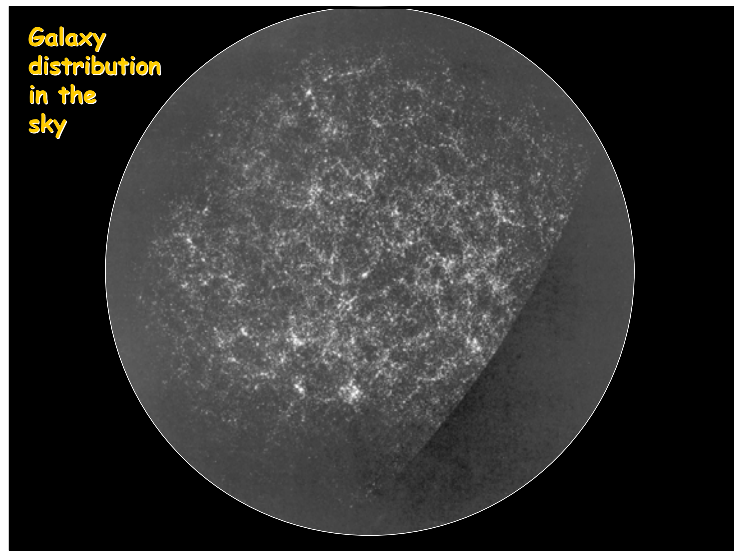


T = 2.728 K (uniform on the sky)


COBE Sky Map of the CMBR Temperature
Dynamical range ΔT = 3.353 mK
Dipole temperature distribution from Doppler effect due to our motion relative to the cosmic frame


COBE Sky Map of the CMBR Temperature
Dynamical range ΔT = 18 μK
Primordial temperature fluctuations!

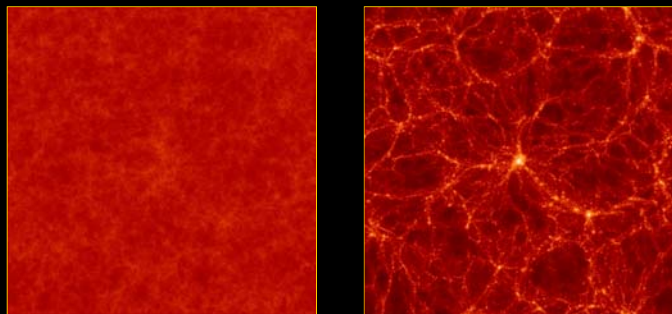

Recombination
Last Scattering Surface
Big Bang Singularity
Galaxies
Here & Now
Horizon
Θ
1
3
20
1000
1500
Redshift z


Galaxy distribution in the sky

Formation of Structure

[Numerical Simulation Max-Planck-Institut für Astrophysik, Garching]

Smooth ➔ Structured



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Power Spectrum of Density Fluctuations

Power Spectrum

Field of Density Fluctuations:

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

Fourier Transform:

$$\delta(\mathbf{k}) = \int d^3\mathbf{x}\, e^{-i\mathbf{k}\cdot x}\delta(\mathbf{x})$$

Power Spectrum:

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

with $\hat\delta$ the delta function

Two-Point Correlation Function:

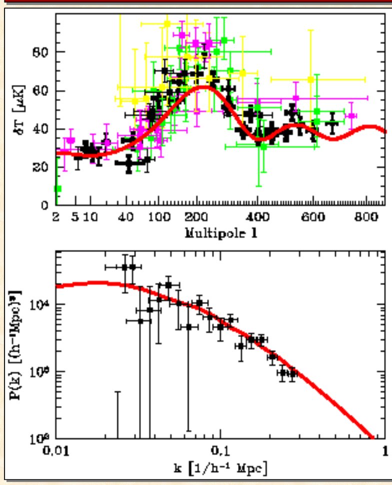
$$\xi(\mathbf{x}) = \langle\delta(\mathbf{x}_2)\delta(\mathbf{x}_1)\rangle = \int\frac{d^3\mathbf{k}}{(2\pi)^3}\,e^{i\mathbf{k}\cdot\mathbf{x}}\,P(\mathbf{k})$$

where $\mathbf{x} = \mathbf{x}_2 - \mathbf{x}_1$.

Gaussian random field fully characterized by power spectrum

Georg Raffelt, Max-Planck-Institut für Physik (München)

Fitting the Cosmological Model - Neutrinos

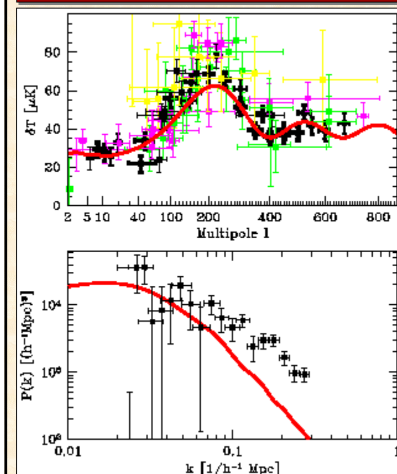


τ=0.000	Ionization parameter
Ω_k=0.000	Curvature
Ω_Λ=0.61	Cosmological constant
ω_d=0.13	Dark Matter ($\Omega_M h^2$)
ω_b=0.020	Baryons ($\Omega_B h^2$)
f_ν=0.000	Neutrino fraction of DM
n_s=0.90	Scalar power-law index
n_t=−1.000	Tensor power-law index
A_s=0.44	Scalar Amplitude
A_t=0.000	Tensor Amplitude
b=1.2	Biasing parameter
h=0.62	Hubble constant
χ^2=0.000	

Max Tegmark, www.hep.upenn.edu/~max/concordance.html

Georg Raffelt, Max-Planck-Institut für Physik (München)

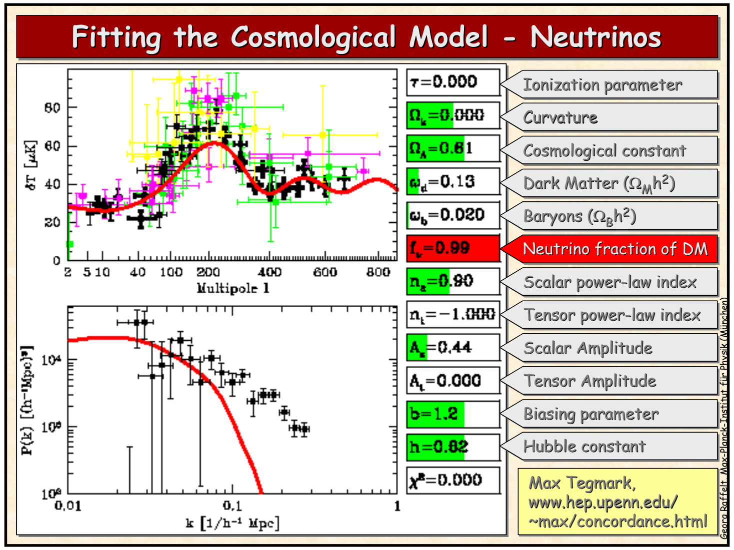
Fitting the Cosmological Model - Neutrinos

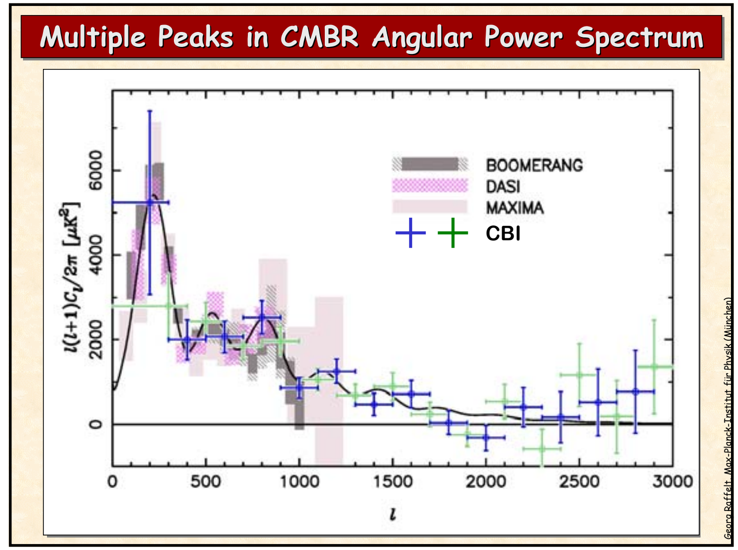


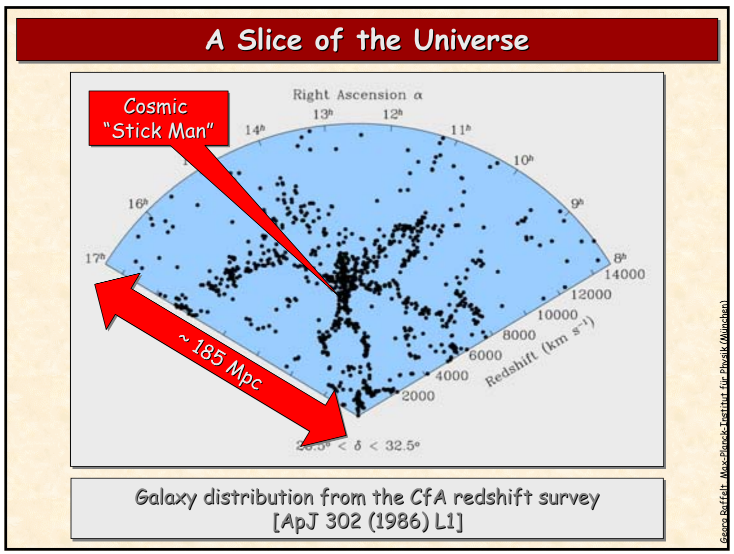
τ=0.000	Ionization parameter
Ω_k=0.000	Curvature
Ω_Λ=0.61	Cosmological constant
ω_d=0.13	Dark Matter ($\Omega_M h^2$)
ω_b=0.020	Baryons ($\Omega_B h^2$)
f_ν=0.36	Neutrino fraction of DM
n_s=0.90	Scalar power-law index
n_t=−1.000	Tensor power-law index
A_s=0.44	Scalar Amplitude
A_t=0.000	Tensor Amplitude
b=1.2	Biasing parameter
h=0.62	Hubble constant
χ^2=0.000	

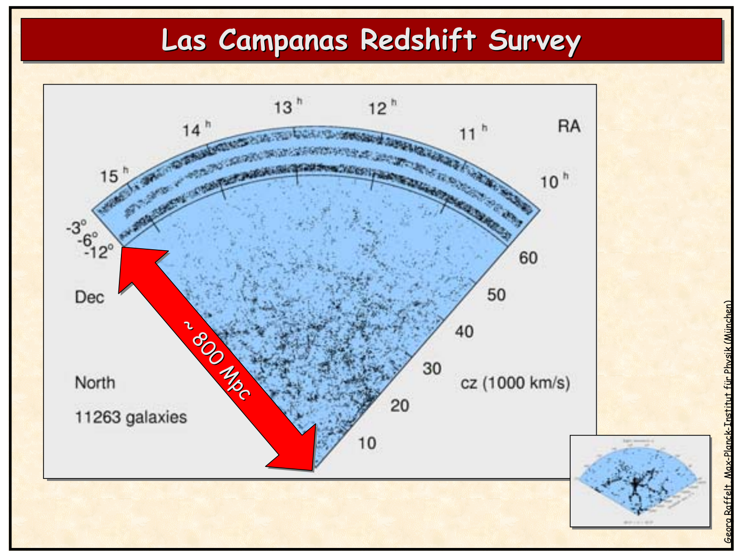
Max Tegmark, www.hep.upenn.edu/~max/concordance.html

Georg Raffelt, Max-Planck-Institut für Physik (München)

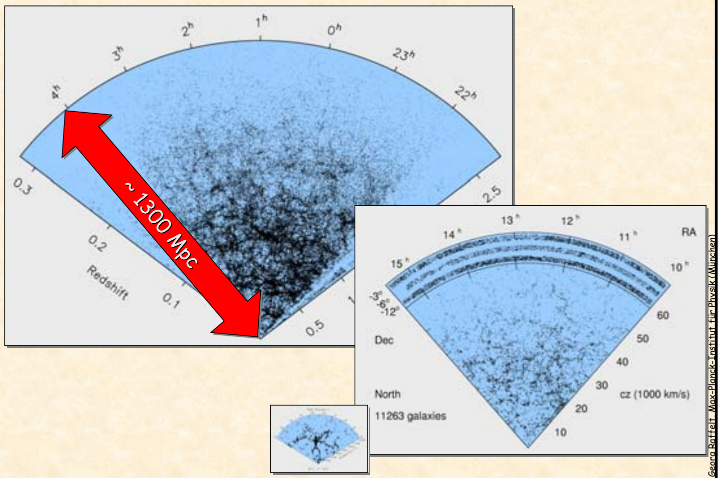

Fitting the Cosmological Model - Neutrinos
Multipole l
k [1/h⁻¹ Mpc]
τ=0.000
Ionization parameter
Curvature
Cosmological constant
Dark Matter ($\Omega_M h^2$)
Baryons ($\Omega_B h^2$)
Neutrino fraction of DM
Scalar power-law index
Tensor power-law index
Scalar Amplitude
Tensor Amplitude
Biasing parameter
Hubble constant
Max Tegmark,
www.hep.upenn.edu/
~max/concordance.html


Multiple Peaks in CMBR Angular Power Spectrum
BOOMERANG
DASI
MAXIMA
CBI
$l(l+1)C_l/2\pi$ [μK^2]
l

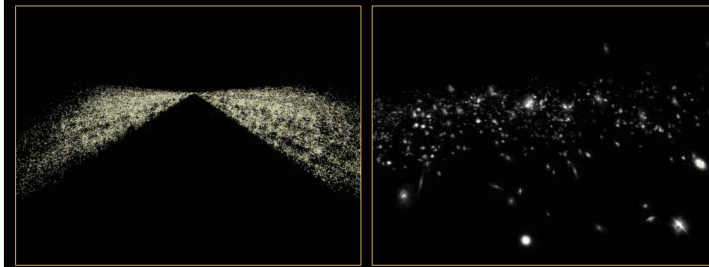

A Slice of the Universe
Cosmic
"Stick Man"
Right Ascension α
~ 185 Mpc
Redshift (km s⁻¹)
Galaxy distribution from the CfA redshift survey
[ApJ 302 (1986) L1]


Las Campanas Redshift Survey
RA
Dec
North
11263 galaxies
cz (1000 km/s)
~ 800 Mpc

2dF Galaxy Redshift Survey (15 May 2002)

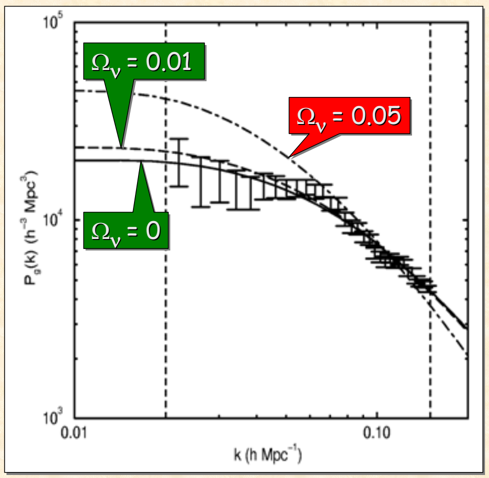


2dF Galaxy Redshift Survey



Animations from 2dFGRS Homepage http://www.mso.anu.edu.au/2dFGRS/

Neutrino Mass Limit from 2dF Galaxy Survey



Elgaroy et al., astro-ph/0204152

$\Sigma m_\nu < 2.2$ eV at 95% CL

For a similar limit based on the 2dF data see Hannestad, astro-ph/0205223

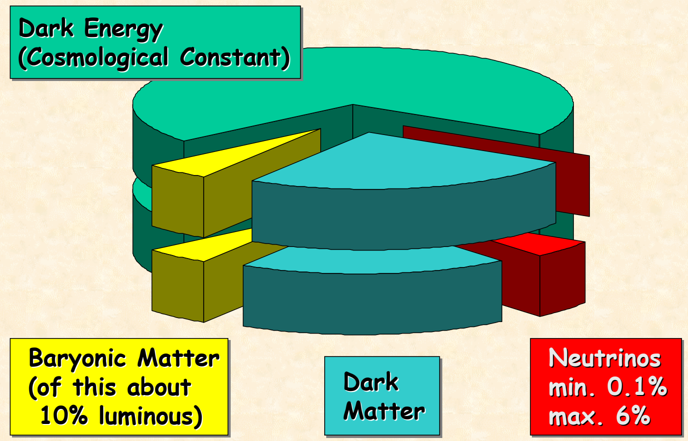
Neutrino Mass Limits from Cosmic Structure

- Global fits to CMBR and LSS data,
- 3 flavors of equal-mass neutrinos

$m_\nu < 2.8$ eV at 95% CL	Novosyadlyj, Durrer & Apunevych, astro-ph/0011055
$m_\nu < 1.4$ eV at 95% CL	Wang, Tegmark & Zaldarriaga, astro-ph/0105091
$m_\nu < 0.8$ eV at 95% CL	Elgaroy et al., astro-ph/0204152 Hannestad, astro-ph/0205223

For similar older limits see
- Croft, Hu & Davé, PRL 83 (1999) 1092
- Fukugita, Liu & Sugiyama, PRL 84 (2000) 1082
- Gawiser, astro-ph/0005475

Matter Inventory of the Universe



Neutrino Mass Limits and Future Sensitivity

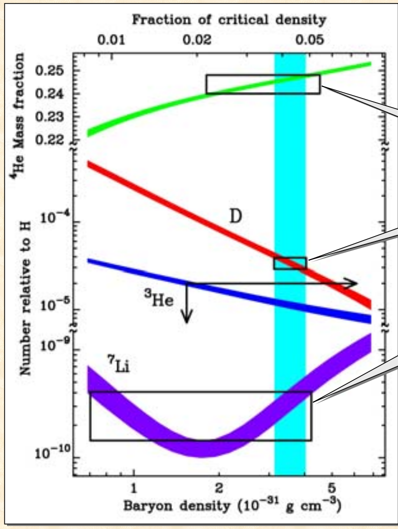
Tritium endpoint	Mainz/Troitsk	2.5 eV
	KATRIN	0.3 eV
Supernova Neutrinos Time-of-flight	SN 1987A	20 eV
	Super-Kamiokande	3 eV
	with black hole	2 eV
	with gravity waves	1 eV
Cosmic structure	2DF Redshift Survey	$m_\nu < 0.8$ eV
	Sloan Digital Sky Survey	$m_\nu < 0.3$ eV

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	o.k.
Sterile (right-handed) states, populated by $\nu_L \to \nu_R$	
Dirac mass	Too small in eV range
Electromagnetic dipole moments	Excluded by energy loss of globular cluster stars
Right-handed currents	Excluded by energy loss of SN 87A
Oscillations/collisions	o.k., hot/warm DM possible

BBN Concordance



[astro-ph/9903300]

Helium 4

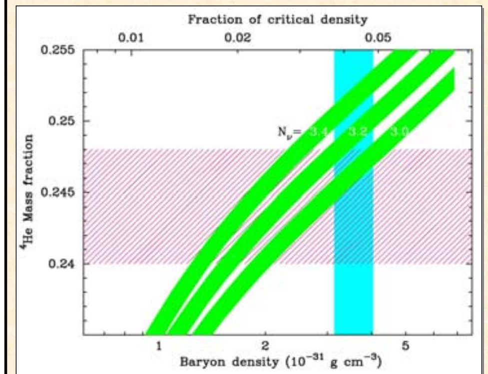
Deuterium

Lithium

Cosmic baryon density implied by deuterium abundance:

$\Omega_B h^2 = 0.019 \pm 0.0024$

BBN Limits on Neutrino Flavors



[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:

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

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

Numerically effect on helium analogous to $\Delta N_{eff} \sim -18\,\xi_{\nu e}$.

$|\Delta N_{eff}| < 1 \;\Rightarrow\; |\xi_{\nu e}| < 0.057$

Beta effect of ν_e can compensate expansion-rate effect of ν_μ or ν_τ
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 chemical potential ξ
- Stringent $\xi_{\nu e}$ limit applies to all flavors
- For all flavors $|\xi_{\nu e,\mu,\tau}| < 0.07$
- Extra neutrino density $\Delta N_{eff} < 0.0064$
- Cosmic neutrino density very close to standard value. Neutrino-mass experiments indeed measure or constrain cosmic neutrino density

Chain of arguments only valid if relaxation to flavor equilibrium obtains before n/p freeze-out, i.e. before T ~ 1 MeV

Flavor Equilibrium Before N/P Freeze-Out ?

yes	• Atmospheric neutrinos: Maximally mixed $\nu_\mu \to \nu_\tau$ oscillations • Solar neutrinos by LMA solution
maybe	Solar LOW solution (Quasi-equilibrium depends on unknown third mixing angle 13)
no	Solar SMA solution

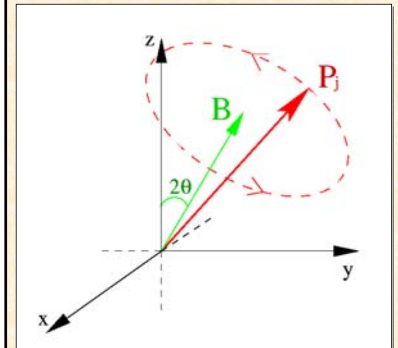
Our knowledge of the cosmic neutrino density depends on the solution of the solar neutrino problem: KamLAND most relevant current experiment

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

Two-Flavor Neutrino Oscillations

Evolution of neutrino ensemble described in terms of density matrices:

$$f_p \to \rho_p = \begin{pmatrix} f_p^e & f_p^{\mu e} \\ f_p^{e\mu} & f_p^{\mu} \end{pmatrix} = \frac{1}{2}\left(f_p + \vec\sigma\cdot\vec P_p\right)$$



Flavor oscillations in vacuum:

$$\partial_t \vec P_p = \frac{\delta m^2}{2p}\vec B \times \vec P_p$$

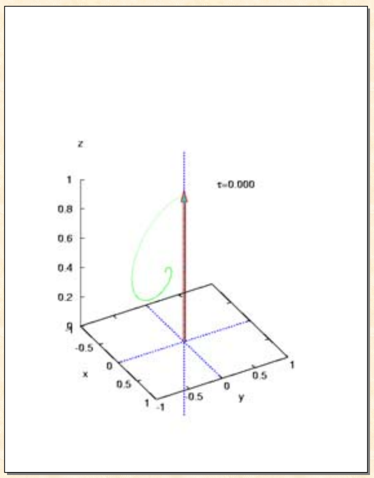
with

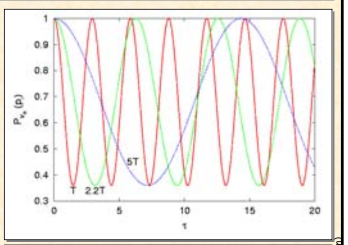
$$\vec B = \begin{pmatrix} \sin 2\theta \\ 0 \\ \cos 2\theta \end{pmatrix}$$

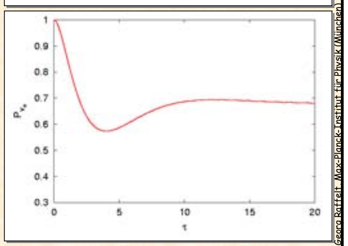
and

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}\begin{pmatrix} \nu_1 \\ \nu 2 \end{pmatrix}$$

Vacuum Oscillations with Distribution of Energies

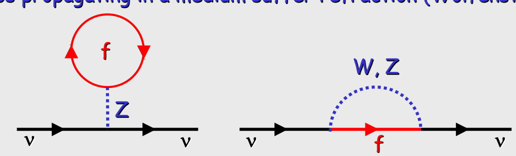






Two-Flavor Oscillations in Media

Neutrinos propagating in a medium suffer refraction (Wolfenstein 1978)

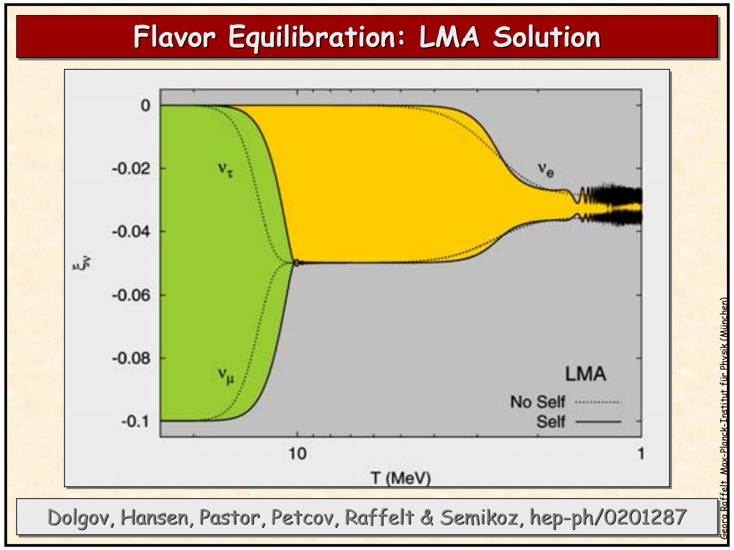


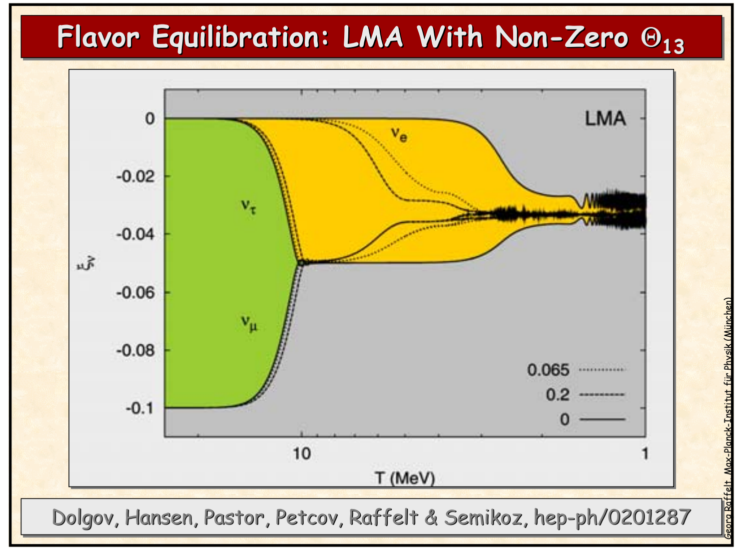
Effect is usually different for different flavors

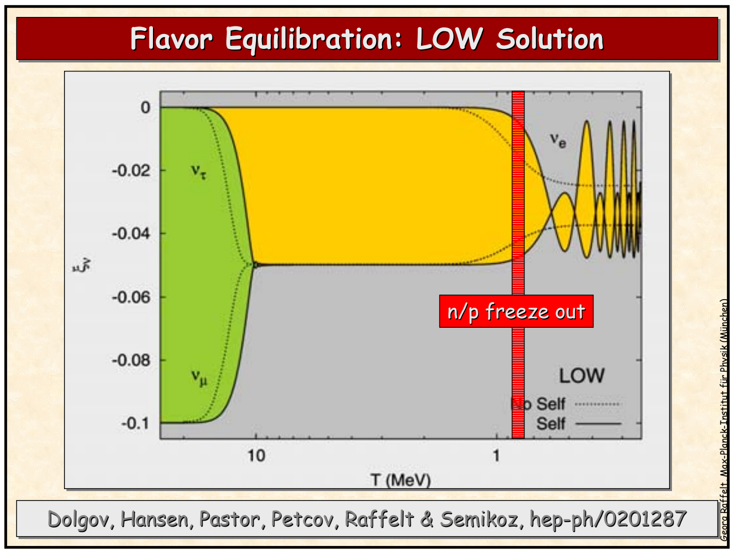
Equation of motion in early universe (ignoring neutrino background)

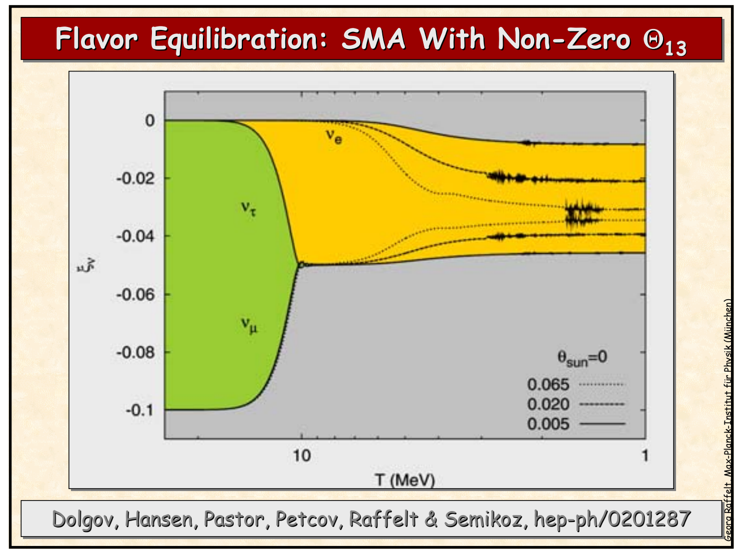
$$\partial_t \vec P_p = \left(\frac{\delta m^2}{2p}\vec B - \frac{8\sqrt{2}G_F p}{3m_W^2}\rho_e \vec z\right)\times \vec P_p \qquad \text{with } \rho_e \text{ the } e^+e^- \text{ energy density}$$

Oscillations begin when background medium is sufficiently diluted to avoid large medium effect compared to vacuum mixing


Flavor Equilibration: LMA Solution
0
-0.02
-0.04
-0.06
-0.08
-0.1
ξ_ν
ν_τ
ν_μ
ν_e
LMA
No Self
Self
10
1
T (MeV)
Dolgov, Hansen, Pastor, Petcov, Raffelt & Semikoz, hep-ph/0201287


Flavor Equilibration: LMA With Non-Zero Θ_{13}
0
-0.02
-0.04
-0.06
-0.08
-0.1
ξ_ν
ν_e
ν_τ
ν_μ
LMA
0.065
0.2
0
10
1
T (MeV)
Dolgov, Hansen, Pastor, Petcov, Raffelt & Semikoz, hep-ph/0201287


Flavor Equilibration: LOW Solution
0
-0.02
-0.04
-0.06
-0.08
-0.1
ξ_ν
ν_τ
ν_μ
ν_e
n/p freeze out
LOW
No Self
Self
10
1
T (MeV)
Dolgov, Hansen, Pastor, Petcov, Raffelt & Semikoz, hep-ph/0201287


Flavor Equilibration: SMA With Non-Zero Θ_{13}
0
-0.02
-0.04
-0.06
-0.08
-0.1
ξ_ν
ν_e
ν_τ
ν_μ
$\theta_{sun}=0$
0.065
0.020
0.005
10
1
T (MeV)
Dolgov, Hansen, Pastor, Petcov, Raffelt & Semikoz, hep-ph/0201287

Synchronized Oscillations by Self-Interactions

Equation of motion in early universe with neutrino background

$$\partial_t \mathbf{P}_p = +\left(\frac{\delta m^2}{2p}\mathbf{B} - \frac{8\sqrt{2}G_F p}{3m_W^2}\rho_e \mathbf{z}\right)\times \mathbf{P}_p + \sqrt{2}G_F(\mathbf{P}-\bar{\mathbf{P}})\times \mathbf{P}_p \quad \text{neutrinos}$$

$$\partial_t \bar{\mathbf{P}}_p = -\left(\frac{\delta m^2}{2p}\mathbf{B} - \frac{8\sqrt{2}G_F p}{3m_W^2}\rho_e \mathbf{z}\right)\times \bar{\mathbf{P}}_p + \sqrt{2}G_F(\mathbf{P}-\bar{\mathbf{P}})\times \bar{\mathbf{P}}_p \quad \text{anti-neutrinos}$$

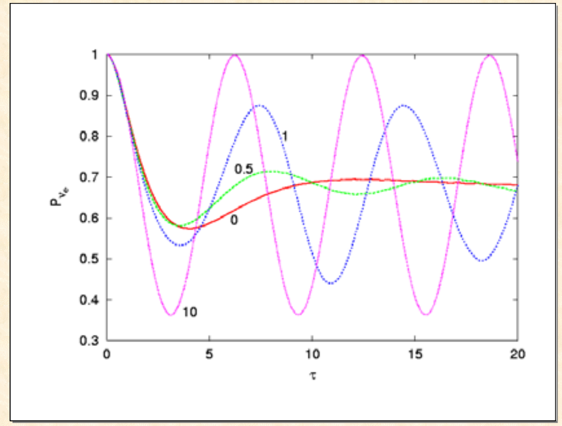
with the integrated neutrino polarization vectors

$$\mathbf{P} = \int \frac{d^3p}{(2\pi)^3}\mathbf{P}_p \quad \text{and} \quad \bar{\mathbf{P}} = \int \frac{d^3p}{(2\pi)^3}\bar{\mathbf{P}}_p$$

"Magnetic field" caused by neutrinos themselves much larger than vacuum or medium terms.
Couples "magnetic moments" to one large dipole which precesses with a single frequency.

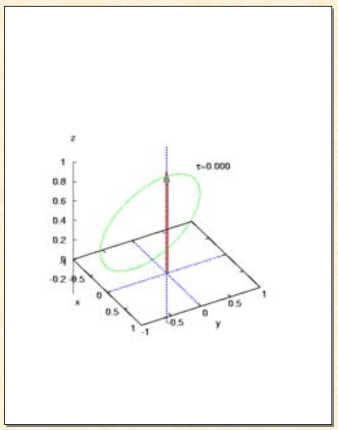
Pastor, Raffelt & Semikoz, PRD 65 (2002) 053011

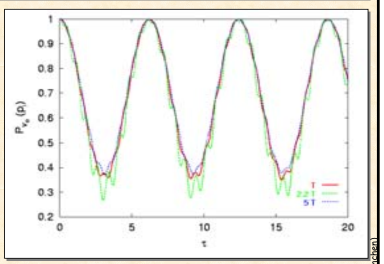
Synchronized Oscillations by Self-Interactions



Pastor, Raffelt & Semikoz, PRD 65 (2002) 053011

Synchronized Oscillations by Self-Interactions





Pastor, Raffelt & Semikoz, PRD 65 (2002) 053011

Zero-Frequency Synchronized Oscillations

Synchronized oscillation frequency, assuming all polarization vectors initially parallel or antiparallel to z-axis

$$\omega_{synch} = \frac{\int \frac{d^3p}{(2\pi)^3}\frac{\delta m^2}{2p}\left(P_p + \bar{P}_p\right)}{\left|\int \frac{d^3p}{(2\pi)^3}\left(P_p - \bar{P}_p\right)\right|}$$

Only neutrinos (no anti-neutrinos):

$$\omega_{synch} = \frac{\delta m^2}{2}\left\langle \frac{1}{p}\right\rangle$$

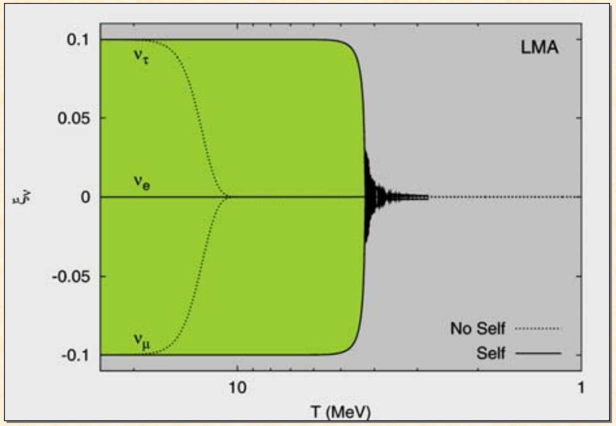
Equal distribution of neutrinos of one flavor and anti-neutrinos of the other:

$$\omega_{synch} = 0$$

Oscillations completely suppressed

Pastor, Raffelt & Semikoz, PRD 65 (2002) 053011

Flavor Equilibration: LMA and $\xi(\nu_\mu) = -\xi(\nu_\tau)$



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

Zero-Frequency Synchronized Oscillations

In a three-flavor system with dominant self-term, oscillations are suppressed (or infinitesimally slow) when

$$|\xi(\nu_e)| = |\xi(\nu_\mu)| = |\xi(\nu_\tau)|$$

Therefore, "equilibrium" in a strict sense not assured, but in that case number densities anyway equal between all flavors.

This situation requires a nonvanishing total lepton number.
If total lepton number is zero, oscillation suppression by self-term not possible.

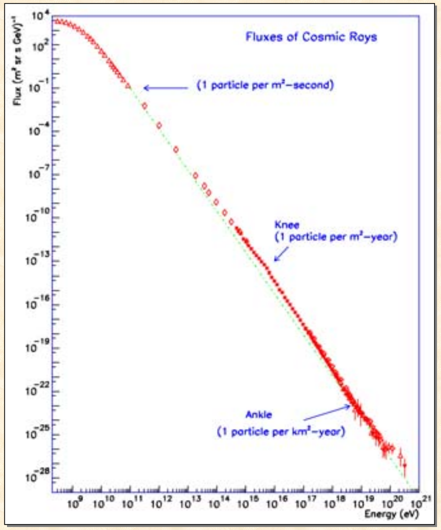
Dolgov, Hansen, Pastor, Petcov, Raffelt & Semikoz, hep-ph/0201287

Summary

If KamLAND confirms LMA solar oscillation solution, BBN implies that the total number density of relic neutrinos agrees with the standard value to better than 1%

Strict relation between cosmological limits on hot dark matter component and neutrino mass

Global Cosmic Ray Spectrum



Greisen-Zatsepin-Kuzmin (GZK) Cutoff

$p + \gamma \to \Delta^+ \to p + \pi^0$

END TO THE COSMIC-RAY SPECTRUM?

Kenneth Greisen

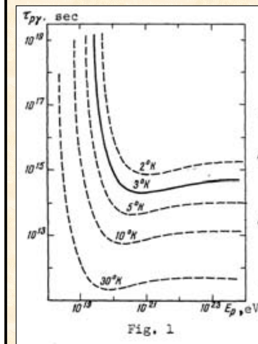
Cornell University, Ithaca, New York
(Received 1 April 1966)

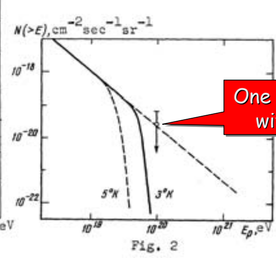
PRL 16 (1966) 748

UPPER LIMIT OF THE SPECTRUM OF COSMIC RAYS

G. T. Zatsepin and V. A. Kuz'min
P. N. Lebedev Physics Institute, USSR Academy of Sciences
Submitted 26 May 1966
ZhETF Pis'ma 4, No. 3, 114-117, 1 August 1966

JETP Lett. 4 (1966) 78



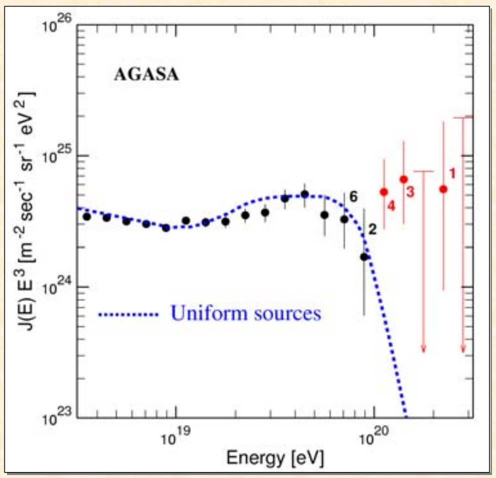


One event (1962) with 10^{20} eV

Georg Raffelt, Max-Planck-Institut für Physik (München)

Spectrum of Highest-Energy AGASA Events

astro-ph/0008102



Georg Raffelt, Max-Planck-Institut für Physik (München)

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
$m_\nu \sim 1$ eV

Neutrino energy on resonance

$$E_\nu = \frac{M_Z^2}{2m_\nu} = \frac{4.2\times10^{21}\,\mathrm{eV}}{m_{\mathrm{eV}}}$$

Decay (Z-Burst)
2 Nucleons
$10\ \pi^0 \to 20\ \gamma$
$17\ \pi^\pm \to e^\pm\ \nu\ \underline{\nu}$

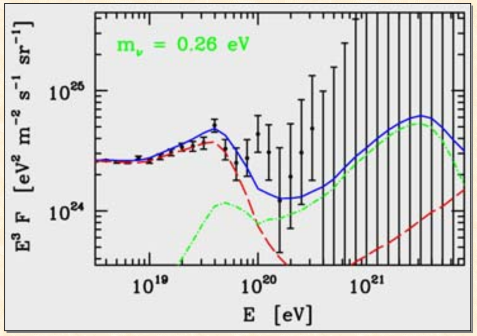
Measured cosmic rays

For example:
- Weiler hep-ph/9710431;
- Fargion et al. hep-ph/0112014
- Fodor, Katz, Ringwald hep-ph/0203198;

Georg Raffelt, Max-Planck-Institut für Physik (München)

Fitting the Cosmic Ray Spectrum with Z-Bursts

Cosmic ray spectrum near cutoff can be fit for a wide range of allowed neutrino masses



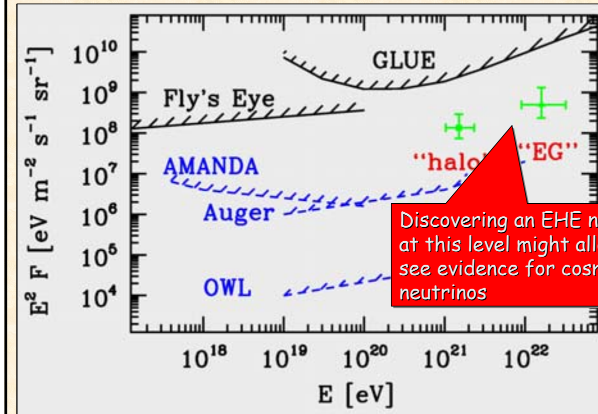
Fodor, Katz & Ringwald, hep-ph/0203198

Main problems:

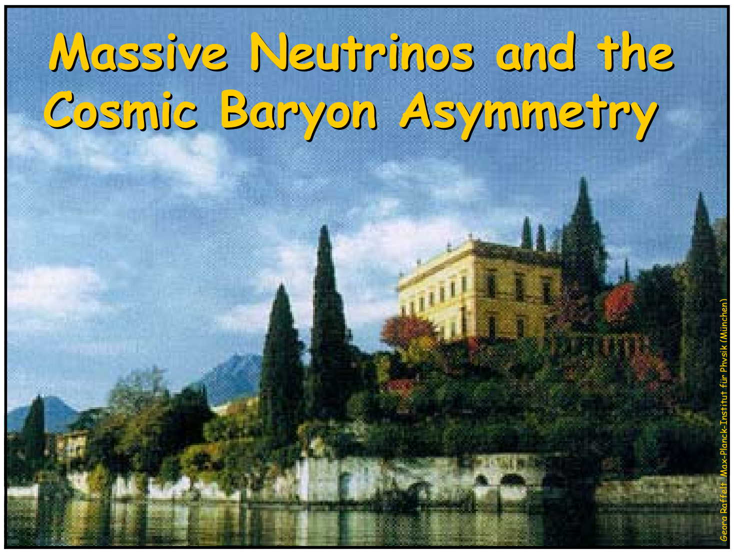
- Huge source flux of EHE neutrinos required
- No plausible sources known
- Accompanying photons must be perfectly obscured

Kalashev et al. hep-ph/0112351

Discovery Potential for Required Neutrino Fluxes



Fodor, Katz & Ringwald, hep-ph/0203198



Baryogenesis in the Early Universe

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 B and L by electroweak instanton effects
- Conserves B − L

In cosmological evolution

- Pre-existing B+L erased at EW phase transition
- Creation of BAU at phase transition not possible, except for special parameters in SUSY models

Leptogenesis by Majorana Neutrino Decays

A classic paper:

Volume 174, number 1 PHYSICS LETTERS B 26 June 1986

BARYOGENESIS WITHOUT GRAND UNIFICATION

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and

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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

	Charged Leptons	Neutrinos	
Dirac masses from coupling to standard Higgs field ϕ	e_L, μ_L, τ_L / e_R, μ_R, τ_R	ν_1, ν_2, ν_3 / N_1, N_2, N_3	Heavy Majorana masses M_j

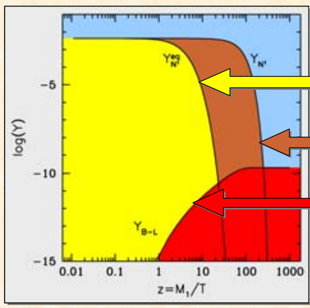
Lagrangian for particle masses:

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

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

Light Majorana mass: $\frac{g_\nu^2\langle\phi\rangle^2}{M}$

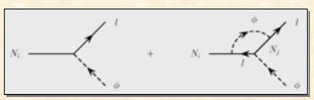
Leptogenesis by Out-of-Equilibrium Decay



Equilibrium abundance of heavy Majorana neutrinos

Real non-equilibrium abundance determined by decay rate

Lepton-number abundance created by CP-violating decays



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

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

Connection to Neutrino Mass

$\Gamma_{Decay} = g_\nu^2 \frac{M}{8\pi}$	Decay rate of heavy Majorana neutrino
$H \approx \sqrt{g_{eff}}\,\frac{T^2}{m_{Pl}}$	Cosmic expansion rate
$\Gamma_{Decay} < H\vert_{T=M}$	Requirement for strong deviation from equilibrium ...
$g_\nu^2 \frac{M}{8\pi} < \sqrt{g_{eff}}\,\frac{M^2}{m_{Pl}}$	
$\frac{g_\nu^2}{M} < \frac{8\pi\sqrt{g_{eff}}}{m_{Pl}}$	
$m_\nu = \frac{g_\nu^2\langle\phi\rangle^2}{M} < \frac{8\pi\sqrt{g_{eff}}}{m_{Pl}}\langle\phi\rangle^2 \sim 10^{-3}\,\mathrm{eV}$	... translates into a limit on the observable neutrino mass

Leptogenesis by Majorana Neutrino Decays

In see-saw models of neutrino masses, right-handed heavy Majorana neutrinos provide source for L-violation

Cosmological evolution:
- B = L = 0 early on
- Thermal freeze-out of heavy Majorana neutrinos
- Out-of-equilibrium decay creates net L
- Shift L excess into B at EW phase transition

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

Consistent with hierarchical masses below 0.1 eV

Leptogenesis – A Popular Research Topic

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AND MANY MORE ...

Conclusions

Future galactic SN signal is
- Sensitive to ~ 1-3 eV mass
- But not sub-eV range

Large-scale galaxy redshift surveys:
- Best limit of $m_\nu < 0.8$ eV,
- Future sensitivity ~ 0.3 eV

If solar LMA solution applies, cosmic neutrino number density precisely determined by BBN

If highest-E cosmic-ray neutrinos are found, Z-bursts provide handle on m_ν

Majorana neutrino masses in the favored range may indicate a leptogenesis scenario for generating cosmic baryon asymmetry