Topical Seminar on Frontiers of Particle Physics 2002: Neutrinos and Cosmology
Yun Hu Holiday Resort of Mi Yun, Beijing, China (20-25 August 2002)

Neutrino Astrophysics

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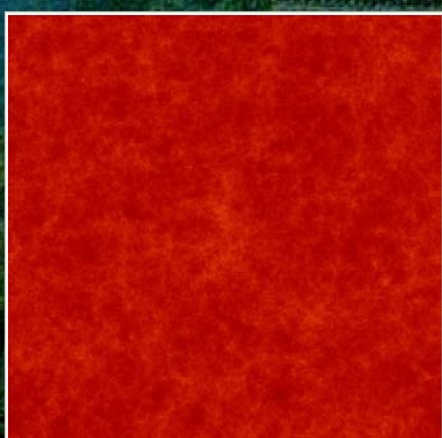
Lecture I: Physics with Supernovae



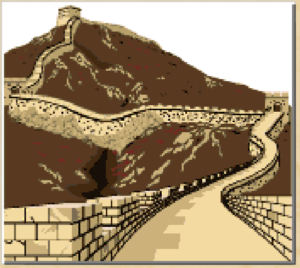
Lecture II: Cosmological Neutrinos

Status of Evidence for Neutrino Oscillations

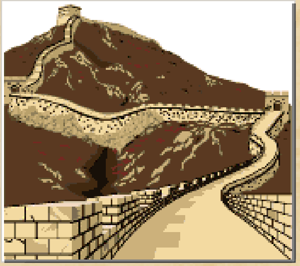
System	Atmospheric	Solar	LSND
Channel	$\nu_\mu \to \nu_\tau$	$\nu_e \to \nu_{\mu\tau}$	$\overline{\nu}_\mu \to \overline{\nu}_e$
$\delta m^2 / eV^2$	$(1.5-4)\times 10^{-3}$	LMA $(0.2-2)\times 10^{-4}$	0.2-2
$\sin^2 2\theta$	0.9–1	0.2–0.6	0.001–0.03
Status	Established	Established	Unconfirmed
	Mutually inconsistent with 3 mass eigenstates		
Test	Long Baseline (K2K)	KamLAND 2002 ?	MiniBooNE 2004 ?
Simplest interpre-tation	Three mass eigenstates with $m_1 \ll m_2 \ll m_3 \sim 50$ meV (hierarchical) $m_1 \sim m_2 \sim m_3 \gg 50$ meV (degenerate)		Experimental Fluke

What is the absolute neutrino mass scale m_ν?

Lecture II: Cosmological Neutrinos

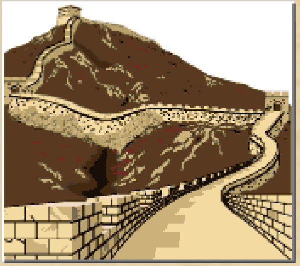


Neutrino Dark Matter and Cosmic Structure Formation



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

Cosmological Limit on Neutrino Masses

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

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

m_ν < 40 eV For all stable flavors

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

REST MASS OF MUONIC NEUTRINO AND COSMOLOGY

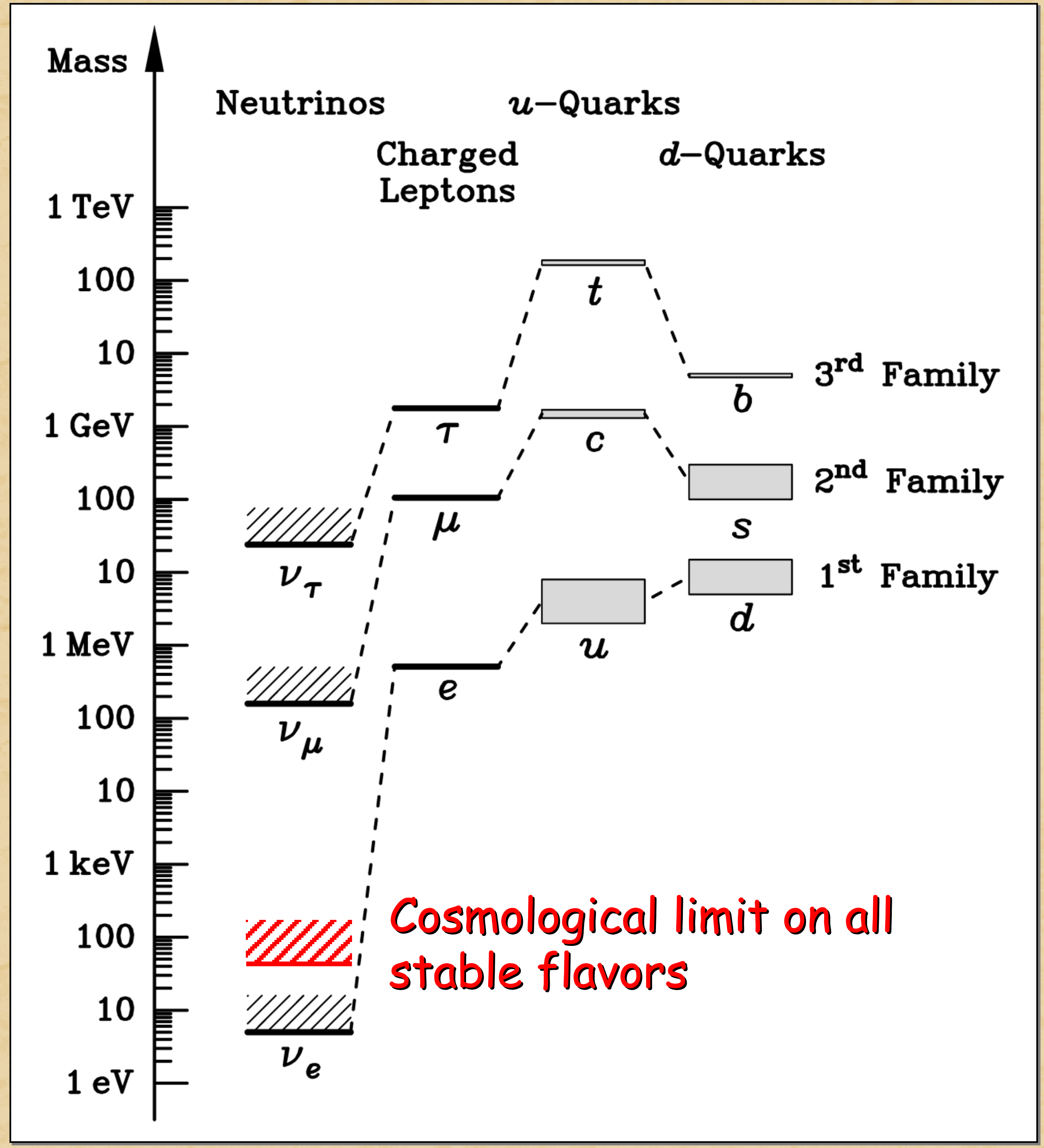
S. S. Gershtein and Ya. B. Zel'dovich
Submitted 4 June 1966
ZhETF Pis'ma 4, No. 5, 174-177, 1 September 1966

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

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

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

Fermion Mass Spectrum



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):

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

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; $T(z_{\rm eq}) = T_r(z_{\rm eq}) = T_\nu(z_{\rm eq}) = T_e(z_{\rm eq}) \cdots =$ the common temperature of radiation, neutrinos, electrons, etc., at the latest epoch characterized by redshift $z_{\rm eq}$ when they may be assumed to have been in thermal equilibrium; $kT(z_{\rm eq}) \simeq 1$ MeV.

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

$$n_{\nu i}(z_{\rm eq}) \simeq 0.183[T(z_{\rm eq})/hc]^3\,. \qquad (2)$$

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 $\sim V(z_{\rm eq})/V(z) = [(1 + z)/(1 + z_{\rm eq})]^3$. Noting that $(1 + z_{\rm eq})/(1 + z) = T_r(z_{\rm eq})/T_r(z)$, the number density at the present epoch ($z = 0$) is given by

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

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

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Almost 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 Fermi gas

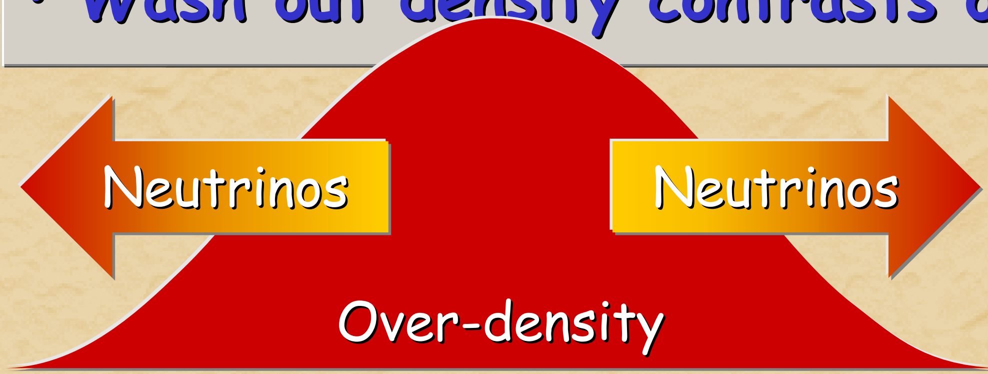
$$\rho_{max} = m_\nu\, n_{max} = m_\nu\, p_{max}^3/3\pi^2 = m_\nu\, (m_\nu v_{escape})^3/3\pi^2$$

$m_\nu > 20 - 40$ eV Spiral galaxies

More restrictive from dwarf galaxies
$m_\nu > 100 - 200$ eV

Neutrino Free Streaming (Collisionless Phase Mixing)

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

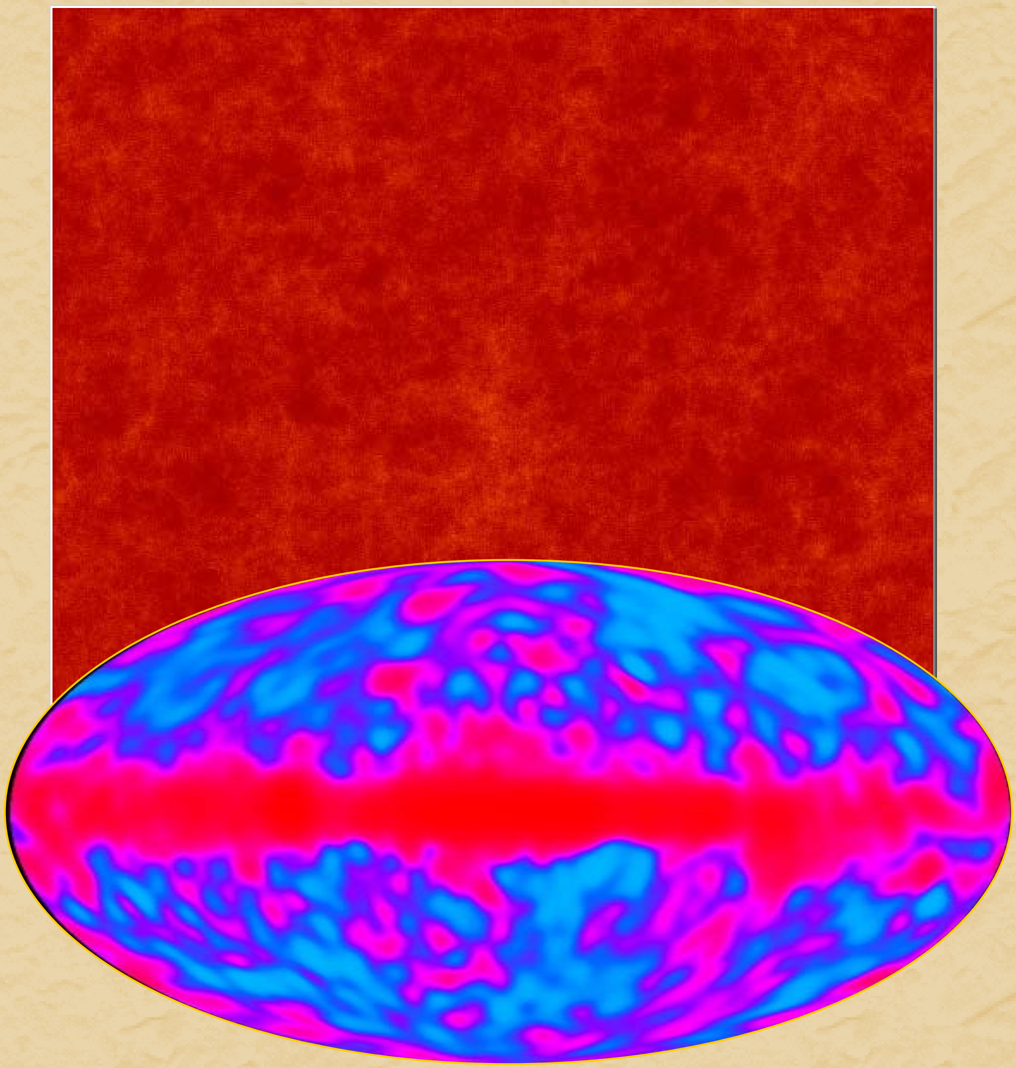


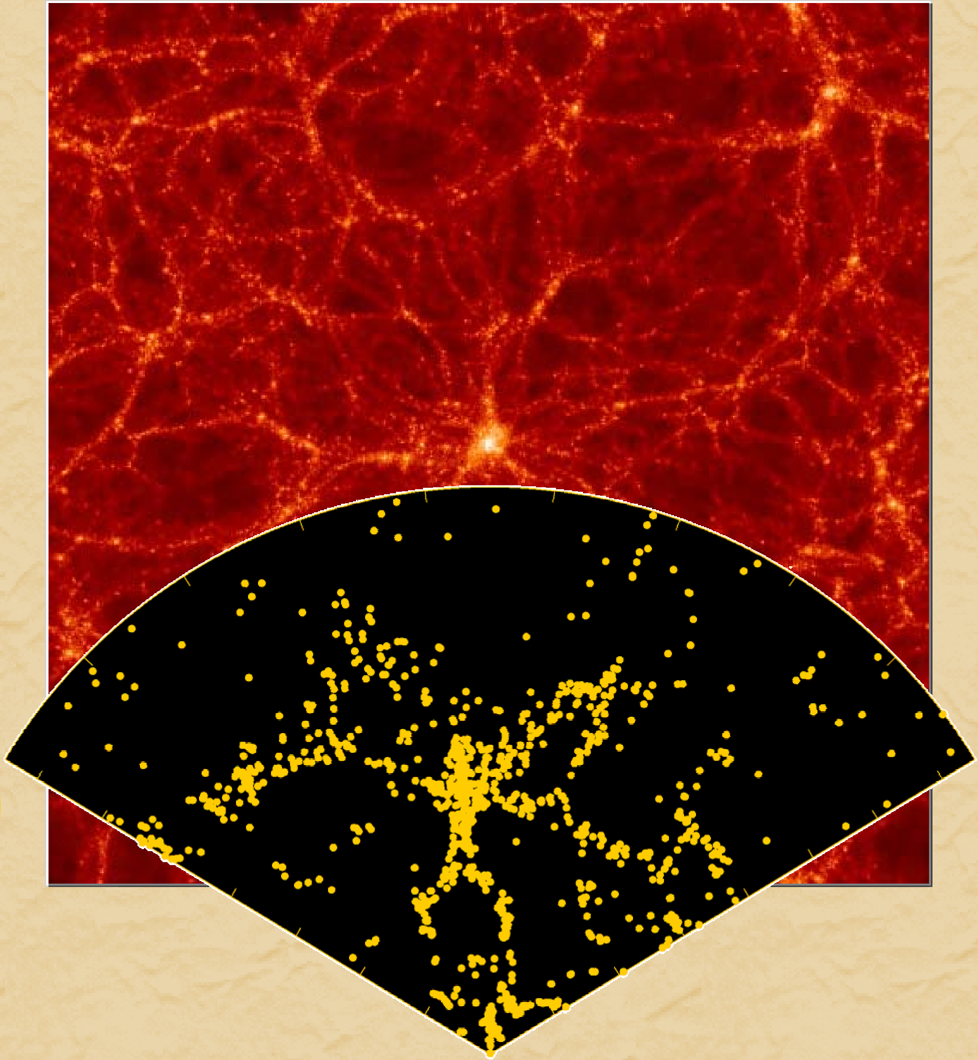
- Nus are "Hot Dark Matter"
- Ruled out by structure formation

Formation of Structure

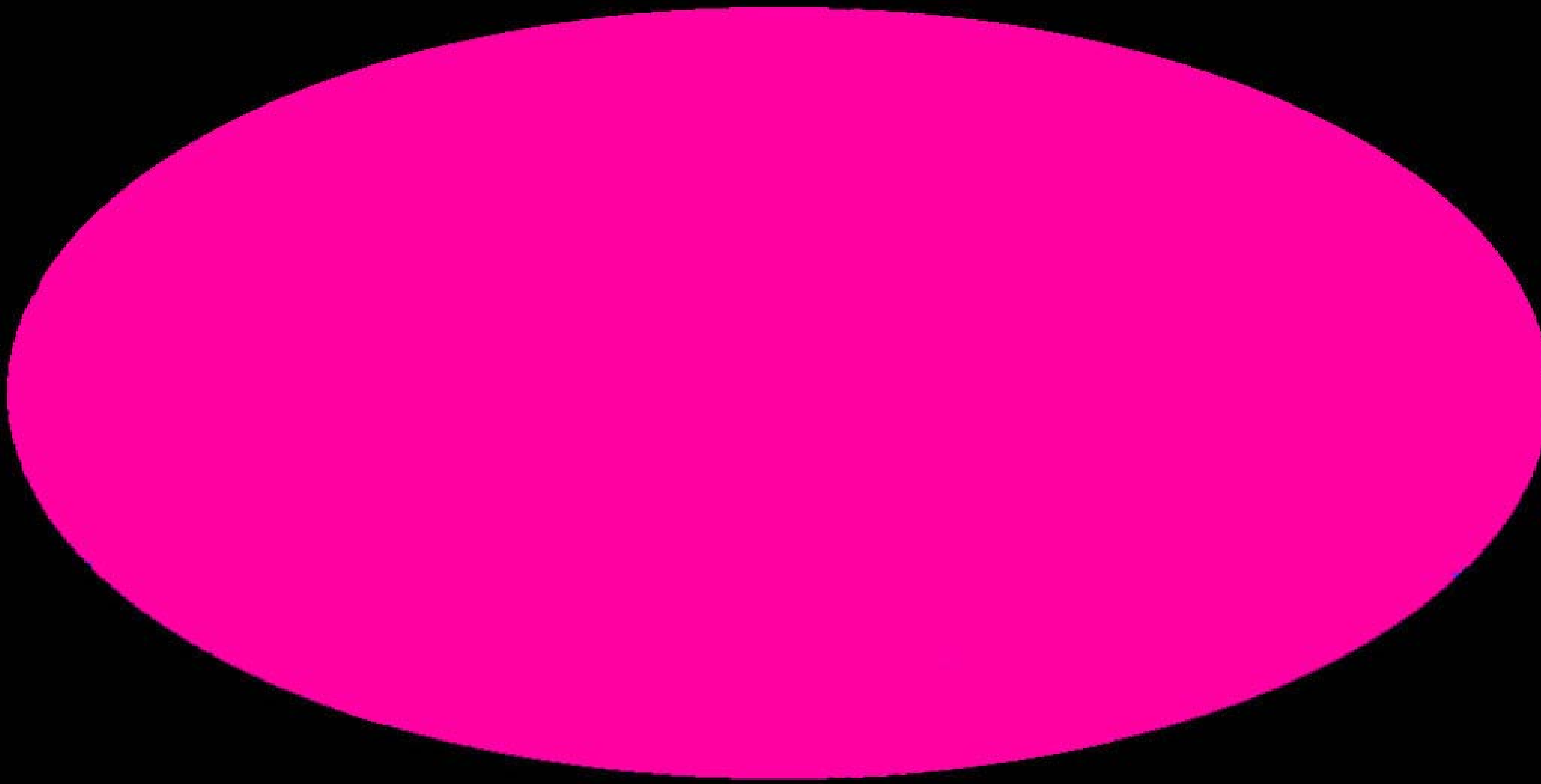
Numerical Simulation Max-Planck-Institut für Astrophysik, Garching

Smooth → Structured



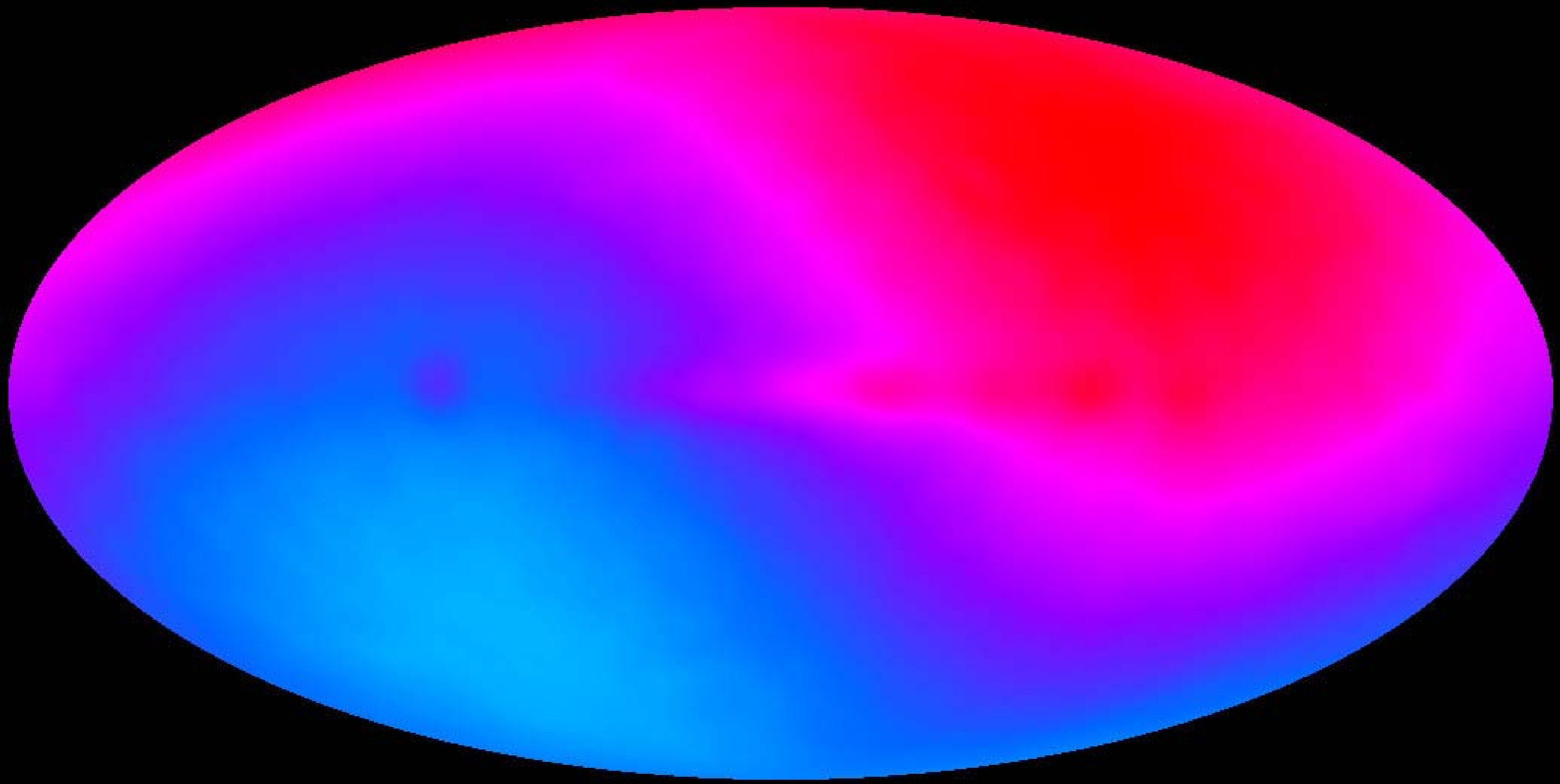


COBE Sky Map of the CMBR Temperature



T = 2.728 K (uniform on the sky)

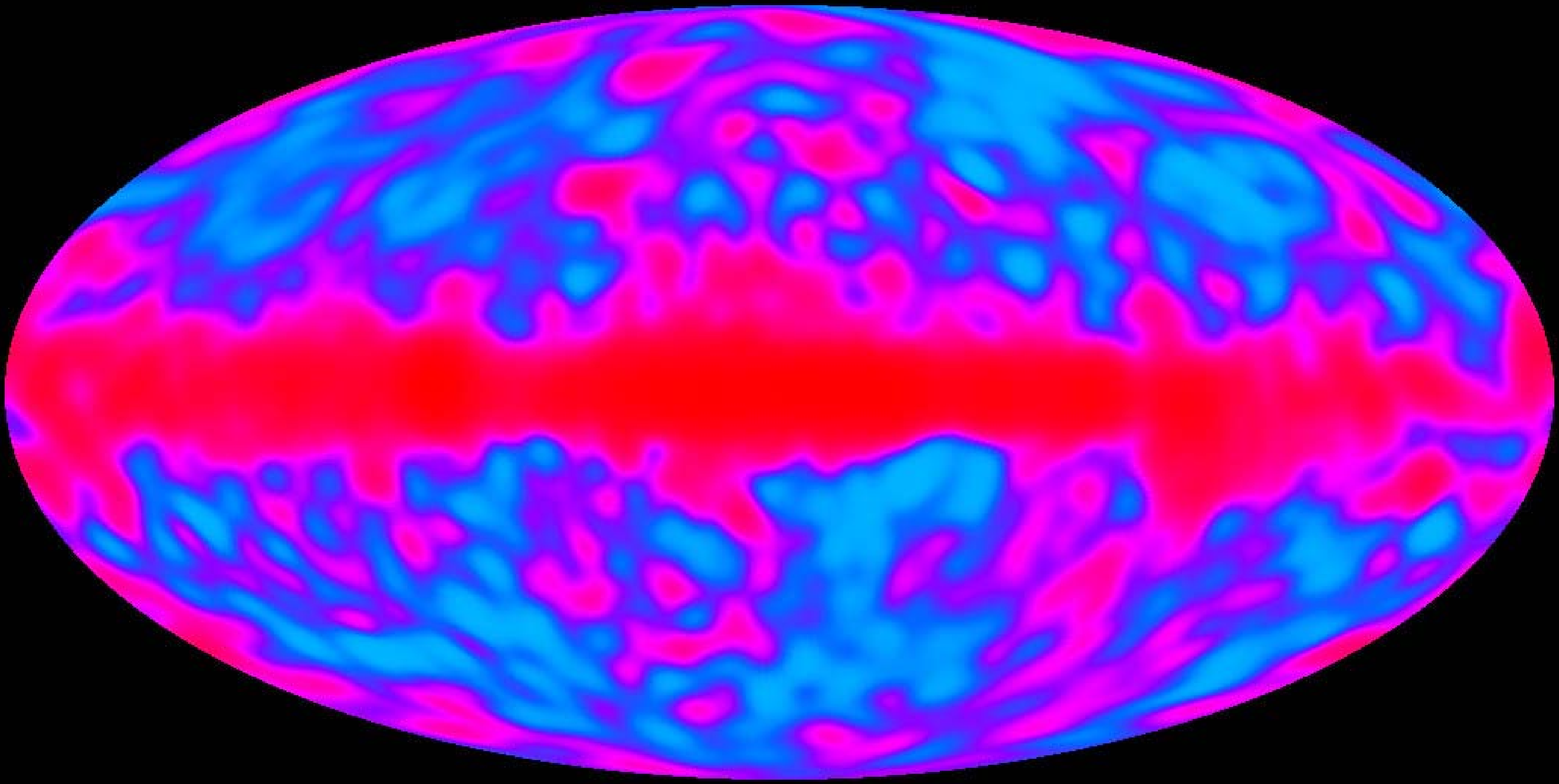
COBE Sky Map of the CMBR Temperature



Dynamical range $\Delta T = 3.353$ mK

Dipole temperature distribution from Doppler effect due to our motion relative to the cosmic frame

COBE Sky Map of the CMBR Temperature

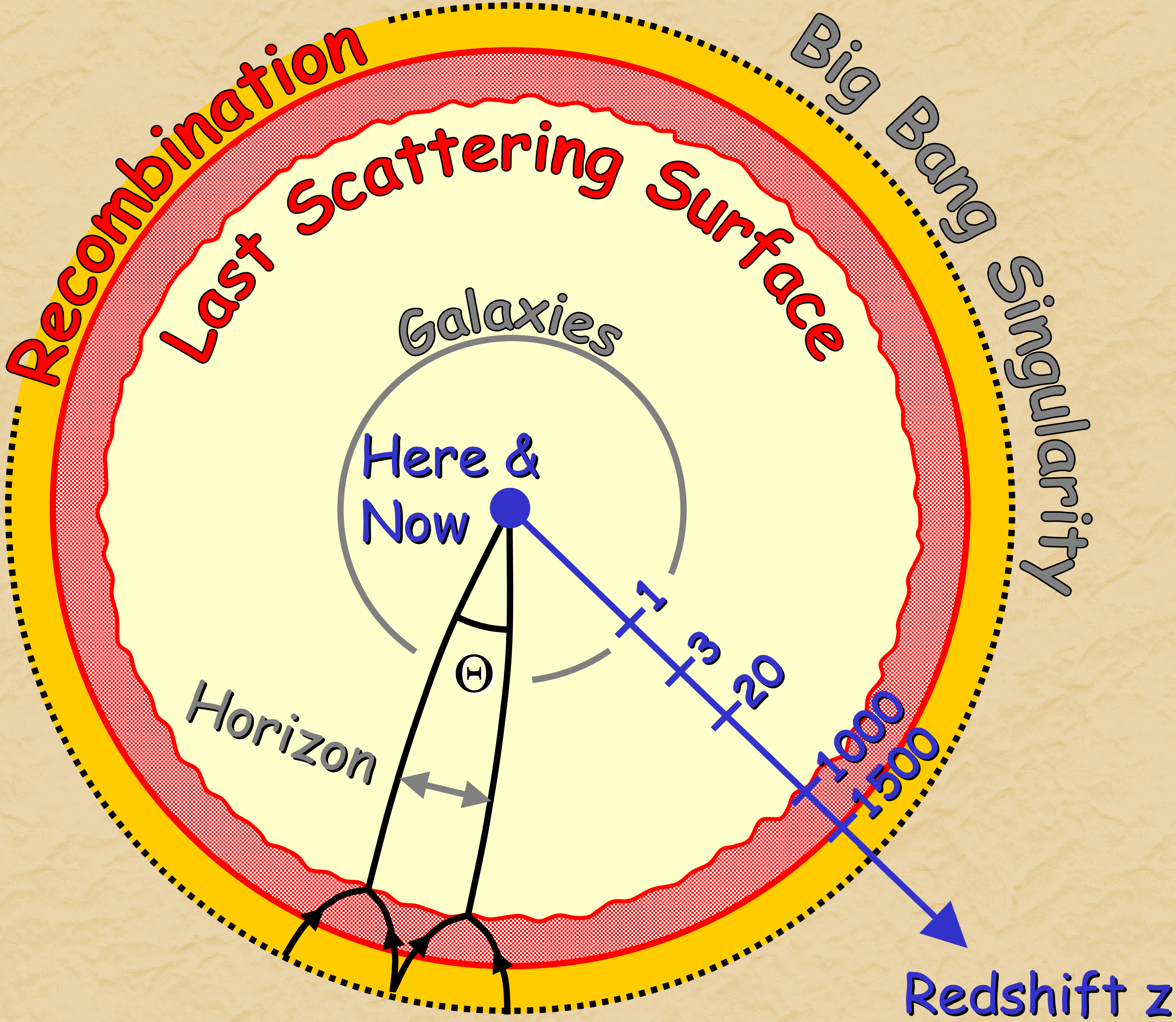


Dynamical range $\Delta T = 18\ \mu K$

Primordial temperature fluctuations

our motion relative to the cosmic frame

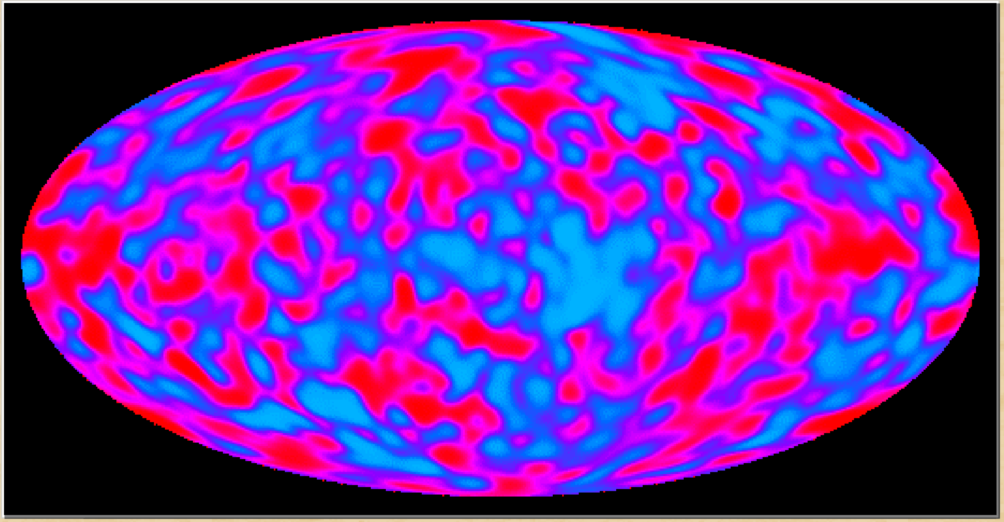
Last Scattering Surface



Power Spectrum of CMBR Temperature Fluctuations

Sky map of CMBR temperature fluctuations

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

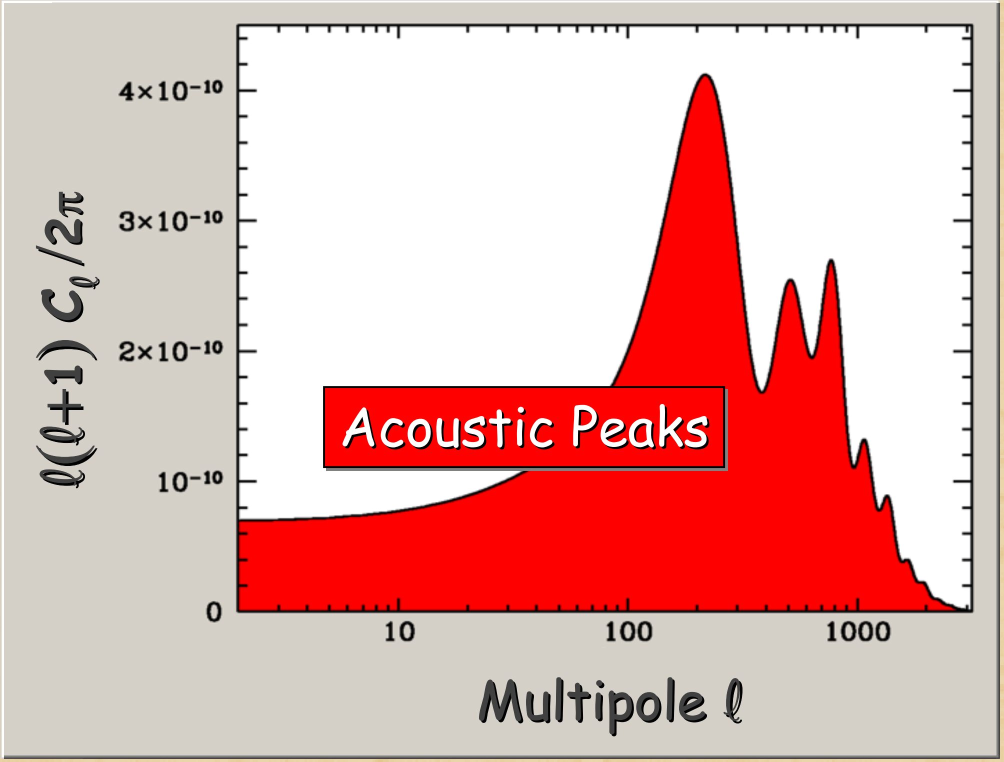


Multipole expansion

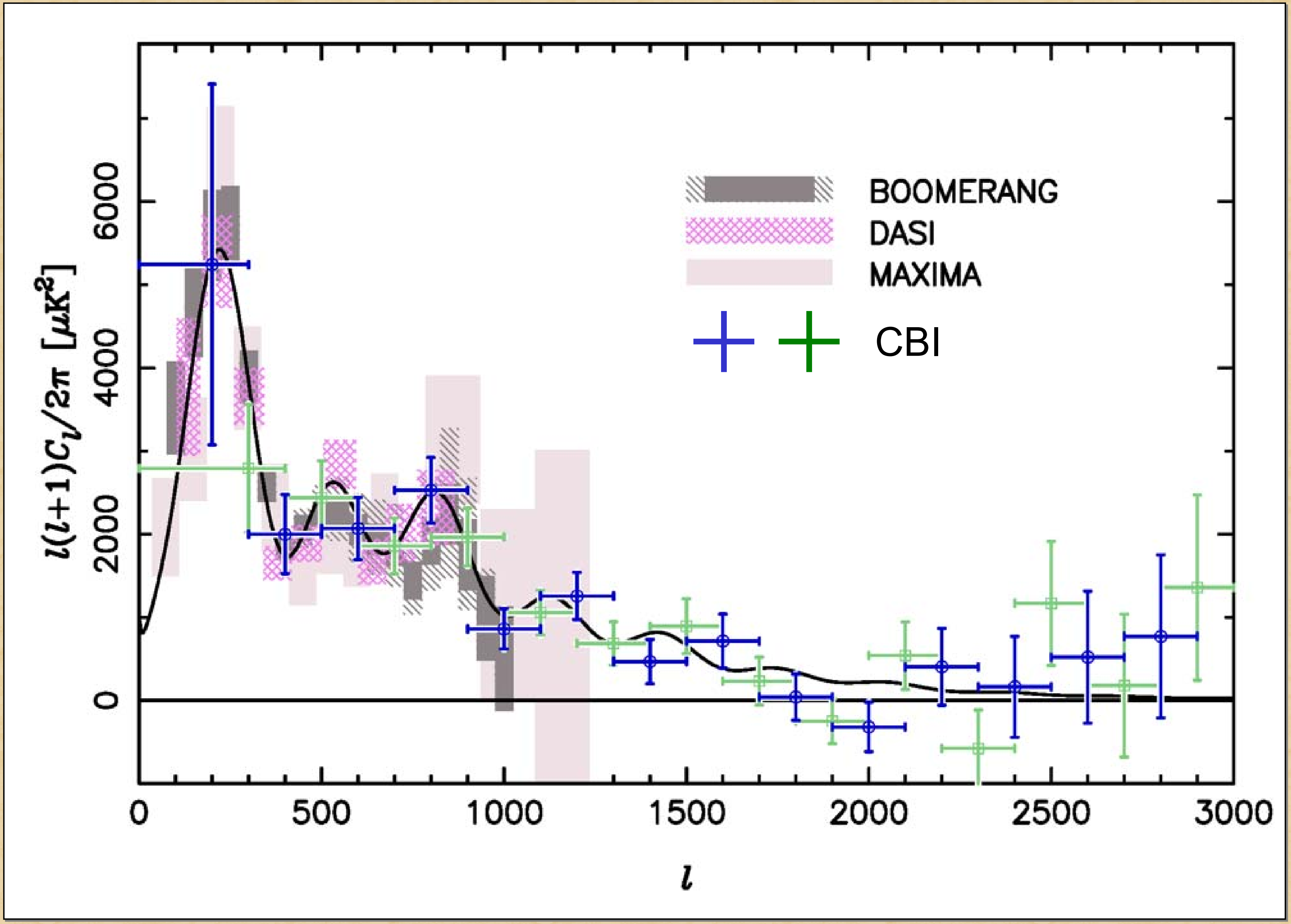
$$\Delta(\theta,\varphi) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\theta,\varphi)$$

Angular power spectrum

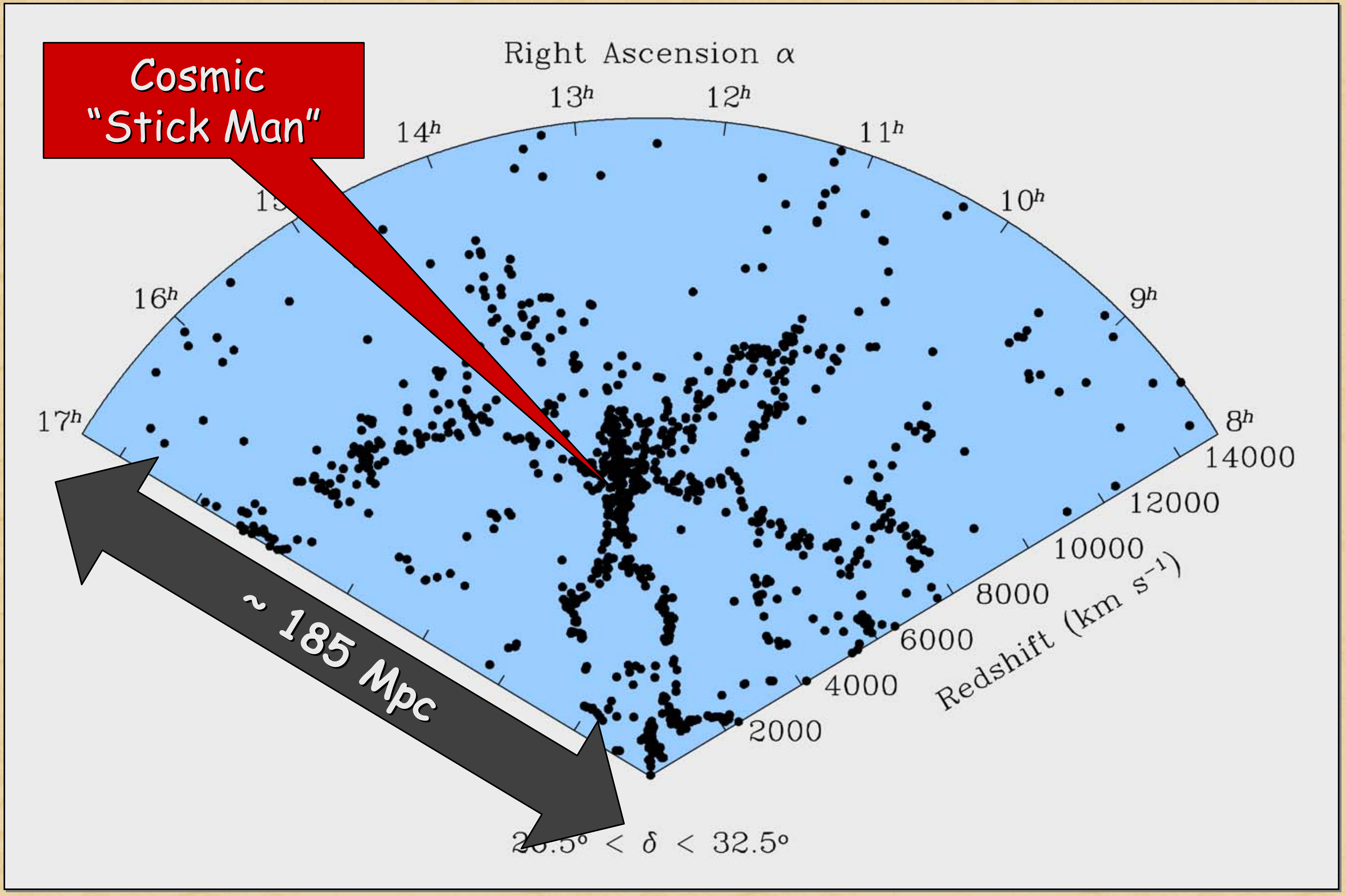
$$C_\ell = \left\langle a_{\ell m}^* a_{\ell m} \right\rangle = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} a_{\ell m}^* a_{\ell m}$$



Multiple Peaks in CMBR Angular Power Spectrum

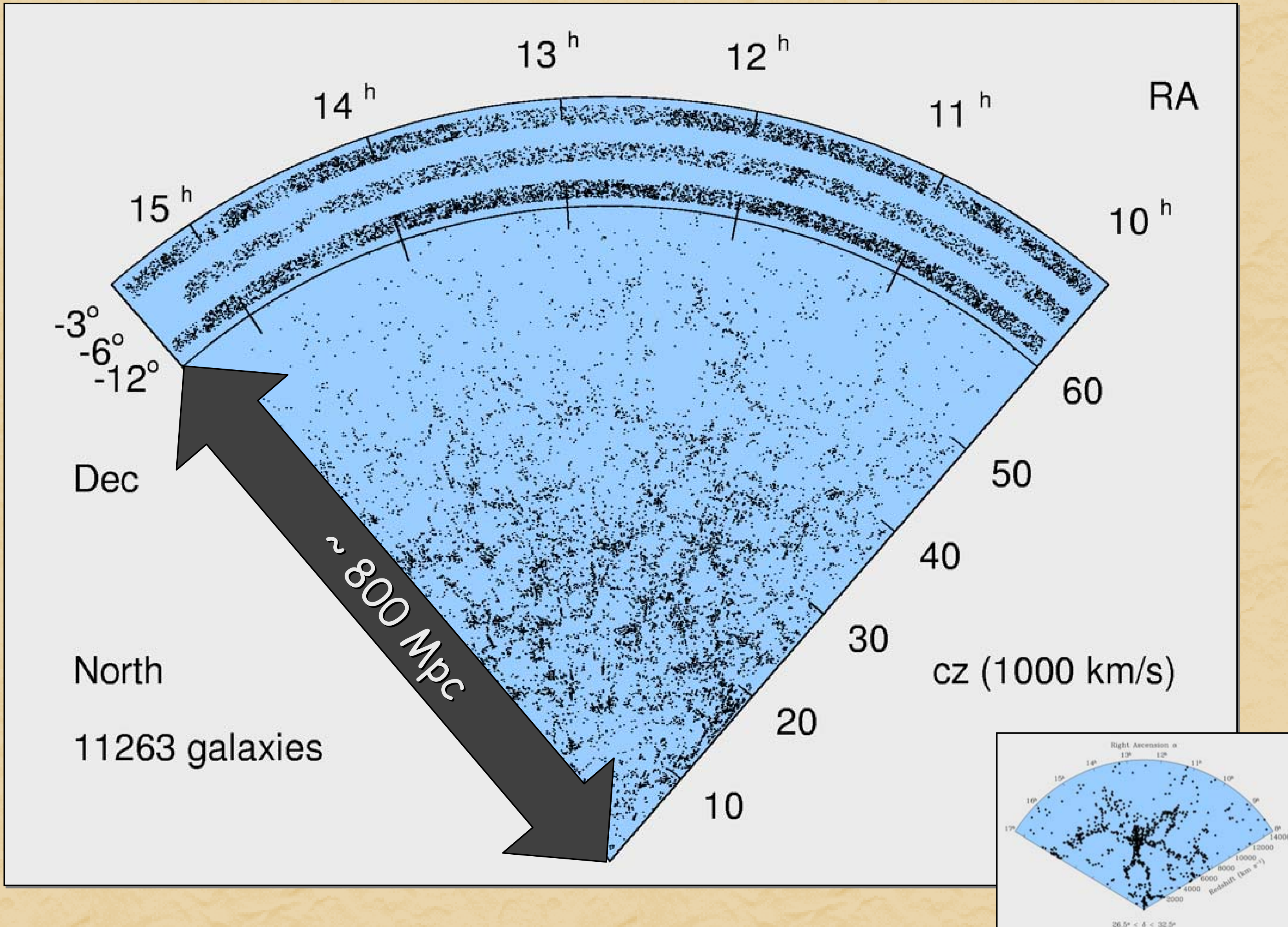


A Slice of the Universe

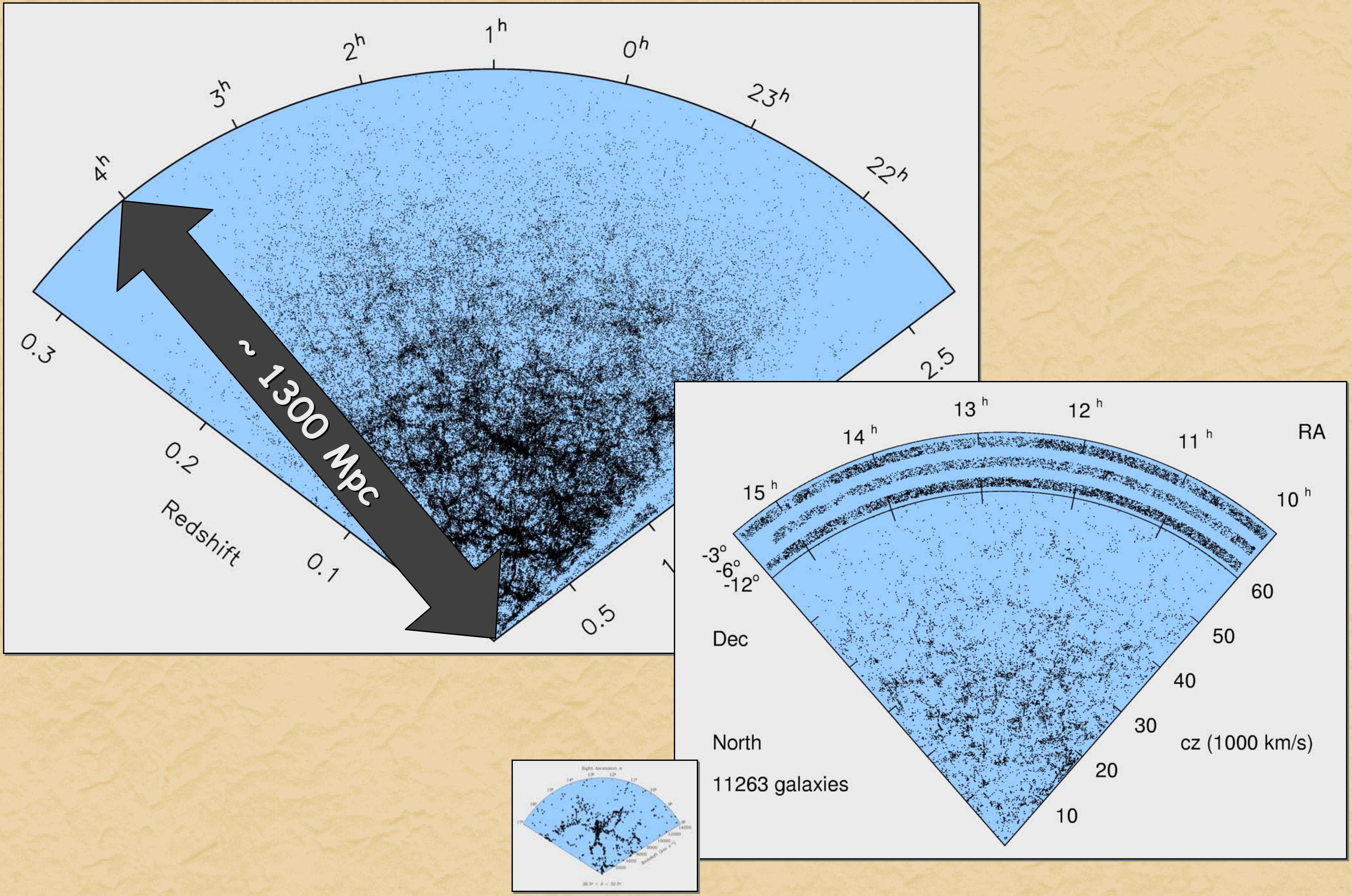


Galaxy distribution from the CfA redshift survey
[ApJ 302 (1986) L1]

Las Campanas Redshift Survey



2dF Galaxy Redshift Survey (15 May 2002)



2dF Galaxy Redshift Survey

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

Power Spectrum of Density Fluctuations

Field of density fluctuations

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

Fourier transform

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

Power spectrum essentially square of Fourier transform

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

with $\hat{\delta}$ the delta function

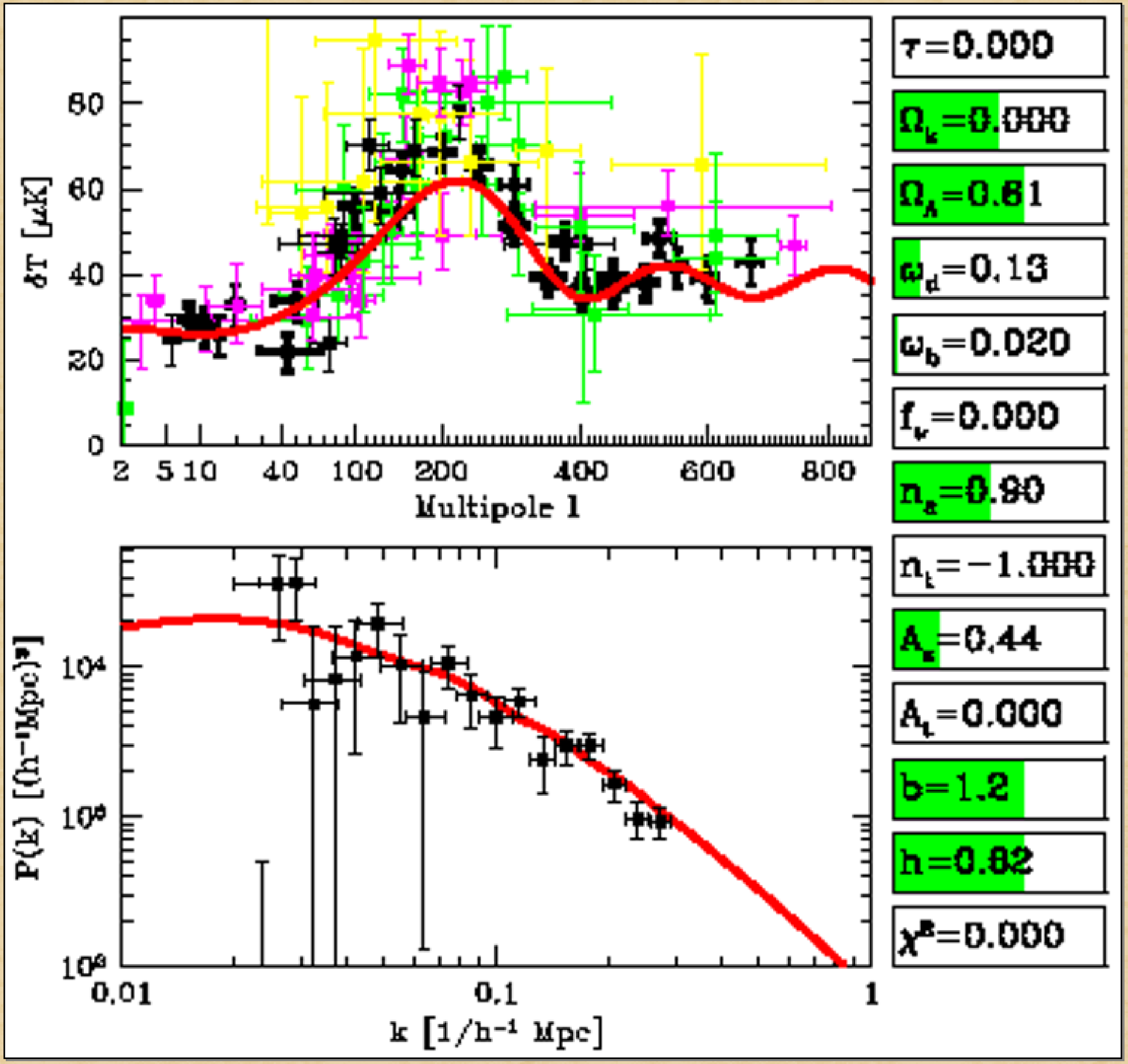
Power spectrum is Fourier transform of two-point correlation function

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

where $x = x_2 - x_1$

Gaussian random field fully characterized by power spectrum

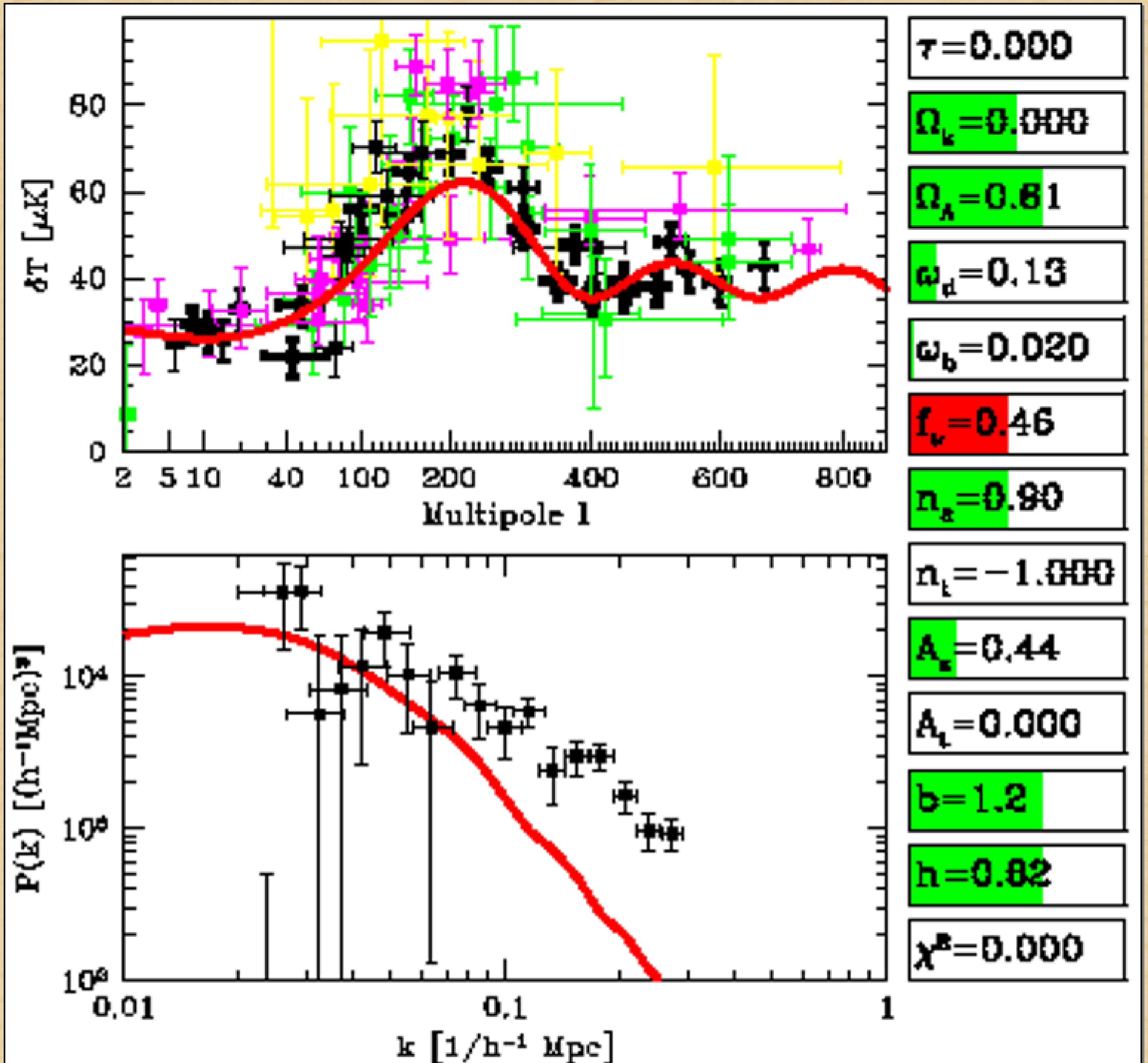
Fitting the Cosmological Model - Neutrinos



- Ionization parameter
- Curvature
- Cosmological constant
- Dark Matter ($\Omega_M h^2$)
- Baryons ($\Omega_B h^2$)
- **Neutrino DM fraction**
- 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

Fitting the Cosmological Model - Neutrinos



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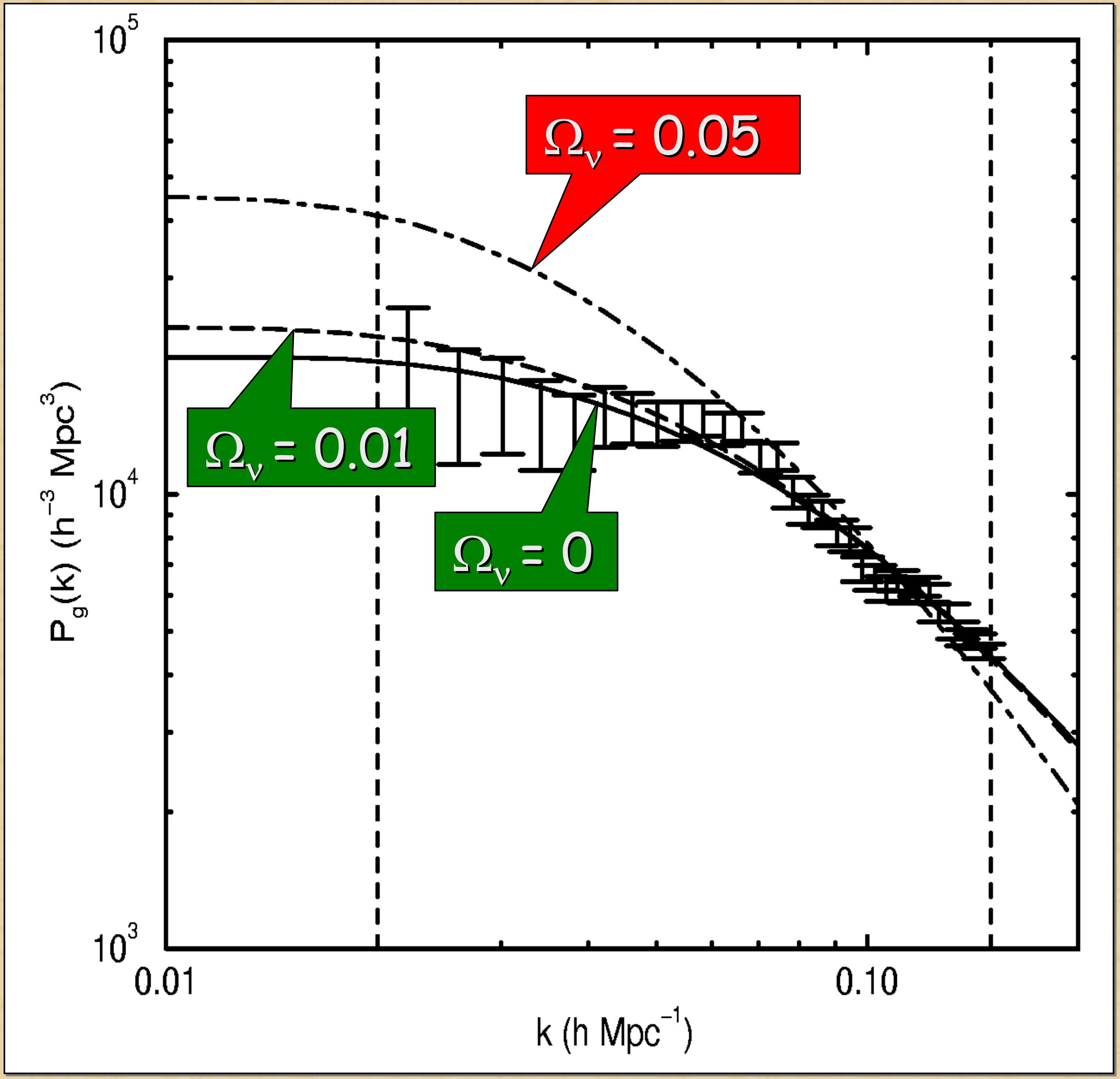
Neutrino Mass Limit from 2dF Galaxy Survey



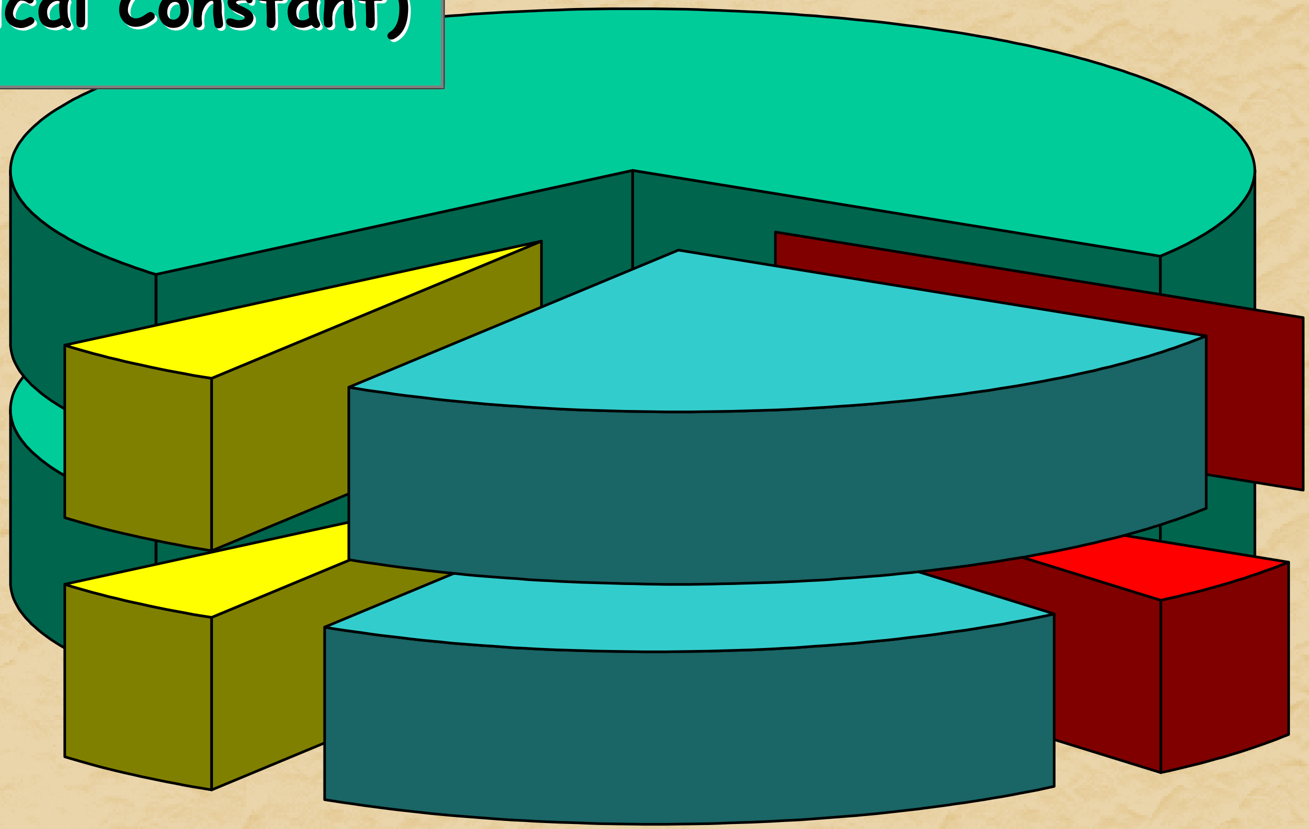
Elgaroy et al., astro-ph/0204152

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

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

Matter Inventory of the Universe

Dark Energy ~ 70%
(Cosmological Constant)



Baryonic Matter ~ 5%
(~10% of this luminous)

Dark Matter
~ 25%

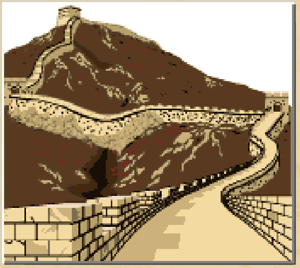
Neutrinos
min. 0.1%
max. 6%

Neutrino Mass Limits and Future Sensitivity

Tritium endpoint	Mainz/Troitsk	2.5 eV
	KATRIN	0.3 eV
Supernova Nus 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	0.8 eV
	Sloan Digital Sky Survey	0.3 eV

- Assume 3 mass eigenstates with very small mass differences as indicated by atmospheric and solar neutrinos
- The cosmological limit refers to $m_\nu = \Sigma\, m_\nu/3$

Lecture II: Cosmological Neutrinos



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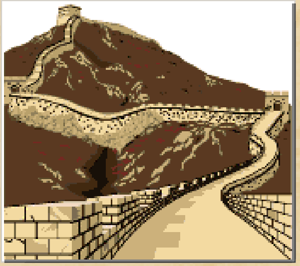
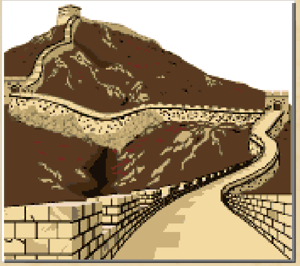
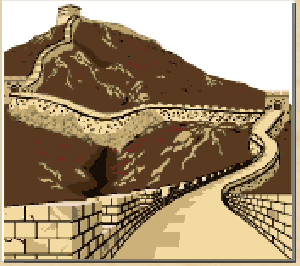


Neutrino Chemical Potentials, Big-Bang Nucleosynthesis, and Flavor Oscillations



Highest-Energy Cosmic Rays and the Cosmic Neutrino Sea



Massive Neutrinos and the Cosmic Baryon Asymmetry

How Many Relic Neutrinos?

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

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

Thermal Neutrino Distribution

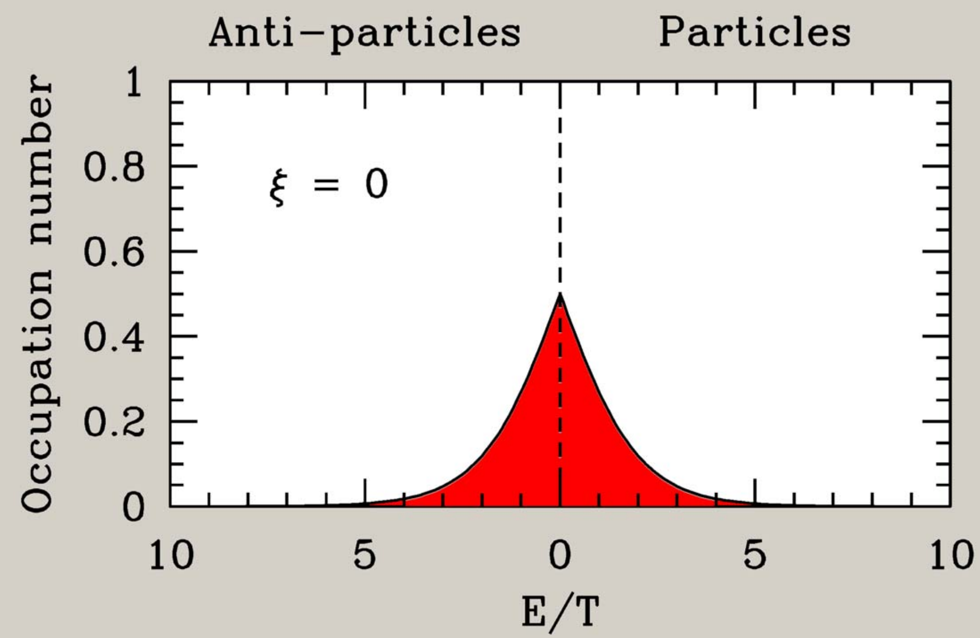
Fermi-Dirac distribution

- 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

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

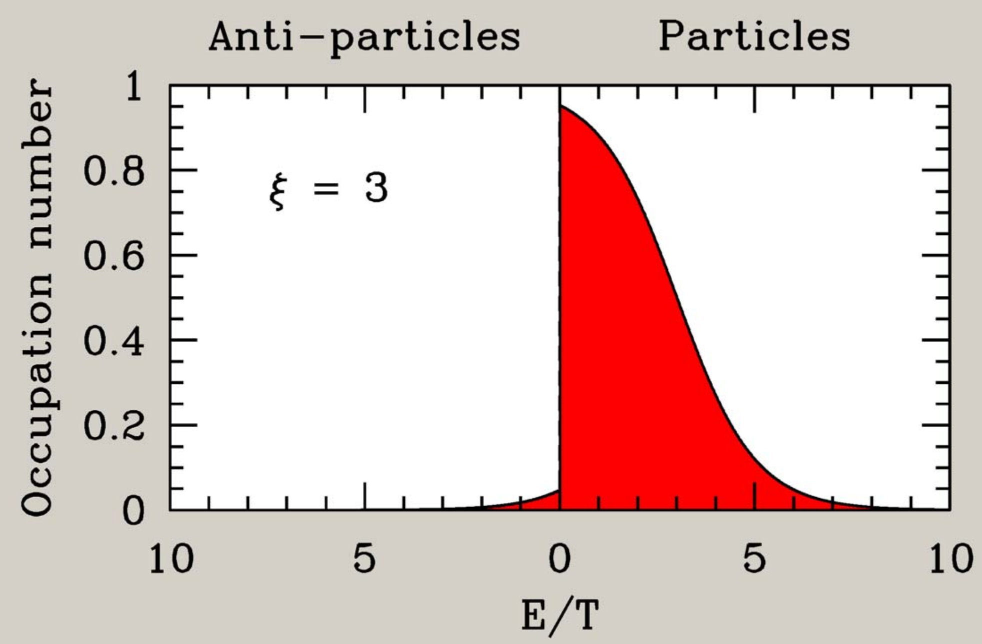
$$= \frac{3\zeta_3}{2\pi^2} T_\nu^3 \left[1 + \frac{2\ln(2)}{3\zeta_3}\xi^2 + \frac{1}{72\zeta_3}\xi^4 + \ldots\right]$$

Thermal Neutrino Distribution

Fermi-Dirac distribution

- Temperature T
- Chemical potential μ
  - +μ Particles
  - −μ Anti-particles

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



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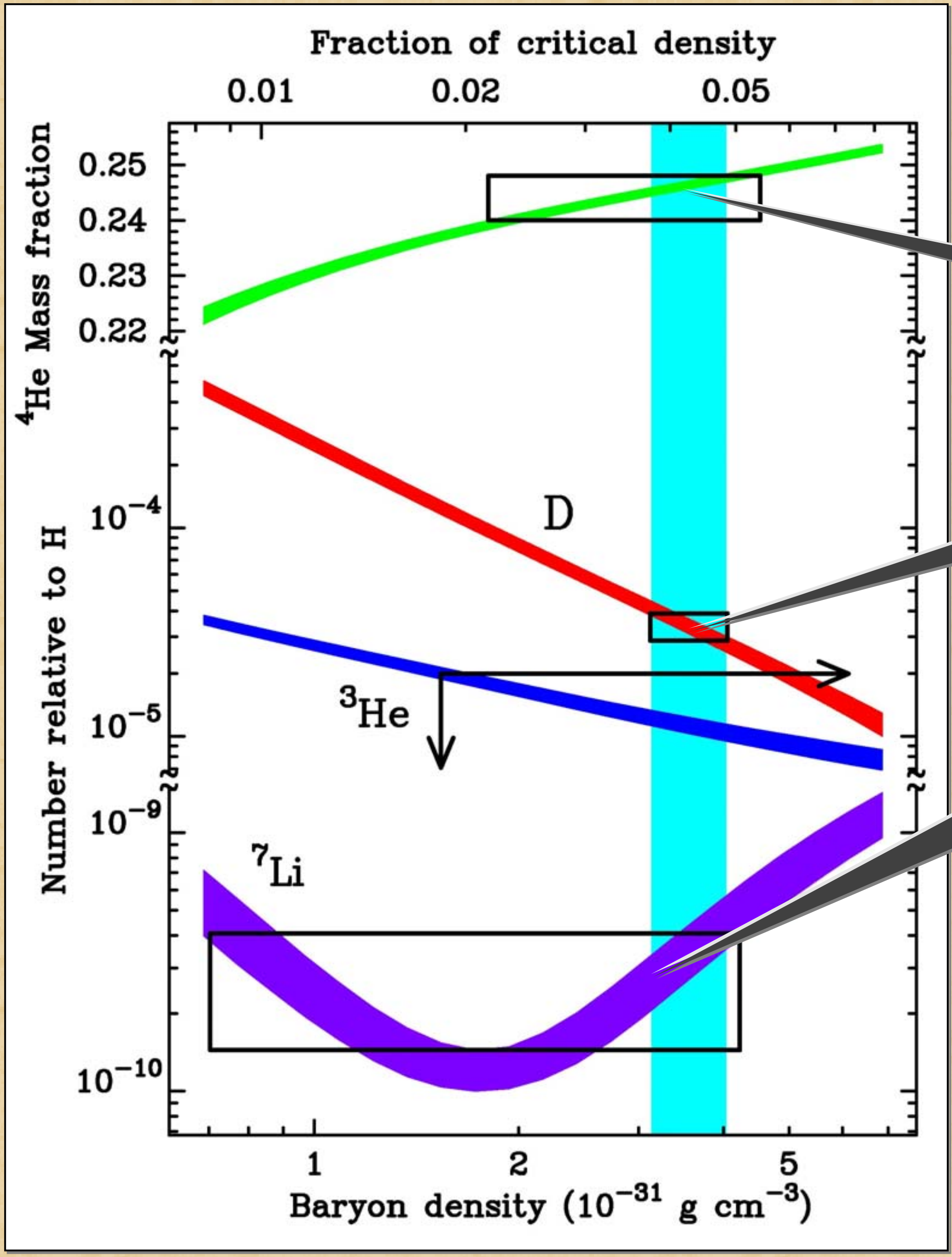
BBN Concordance



Burles, Nollett & Turner
astro-ph/9903300

Helium 4

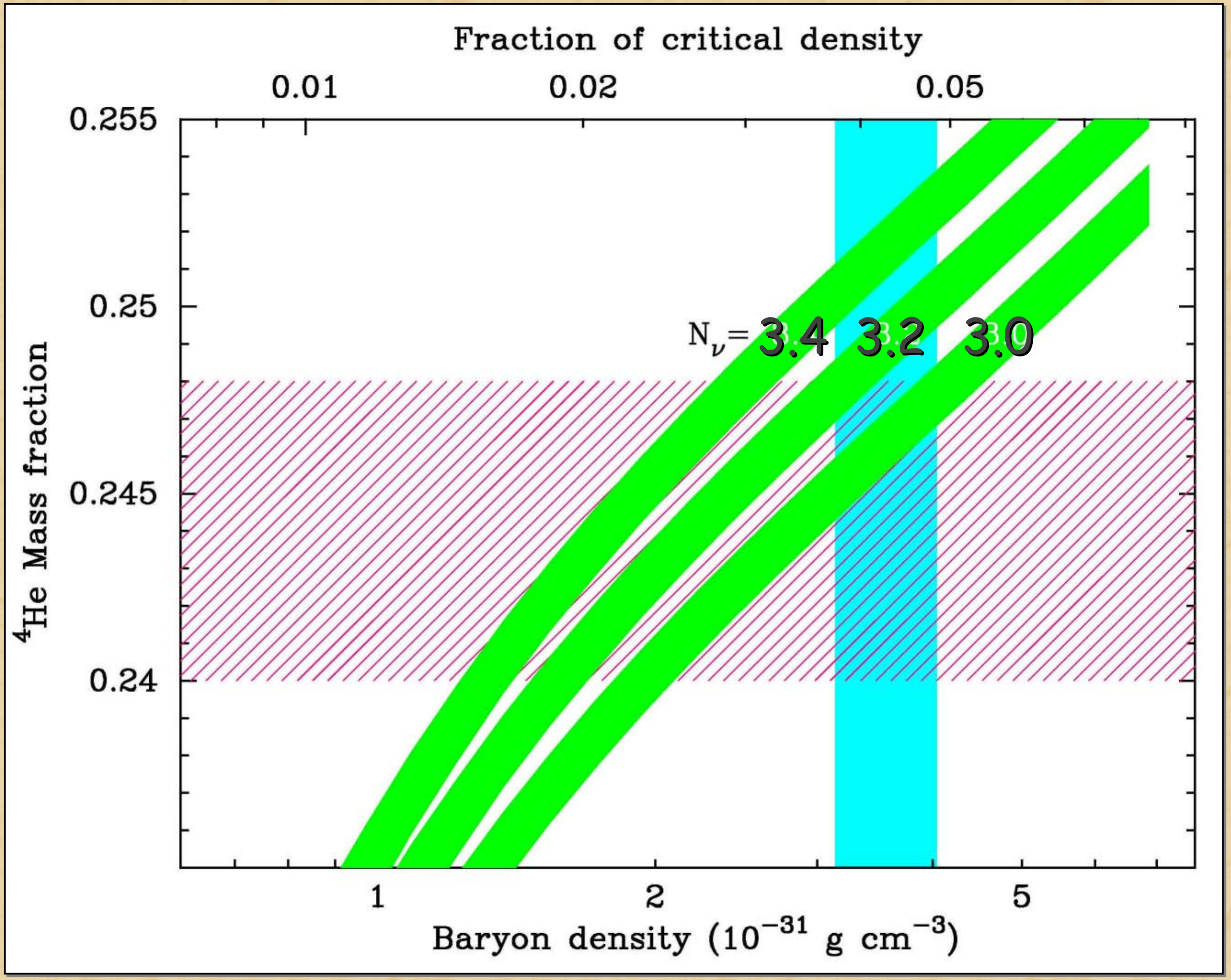
Deuterium

Lithium

Cosmic baryon density implied by deuterium

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

BBN Limits on Neutrino Flavors



Burles, Nollett & Turner, astro-ph/9903300

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

Conservative limit

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

BBN and Neutrino Chemical Potentials

Expansion Rate Effect (all flavors)

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

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

Beta equilibrium effect for electron flavor

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

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

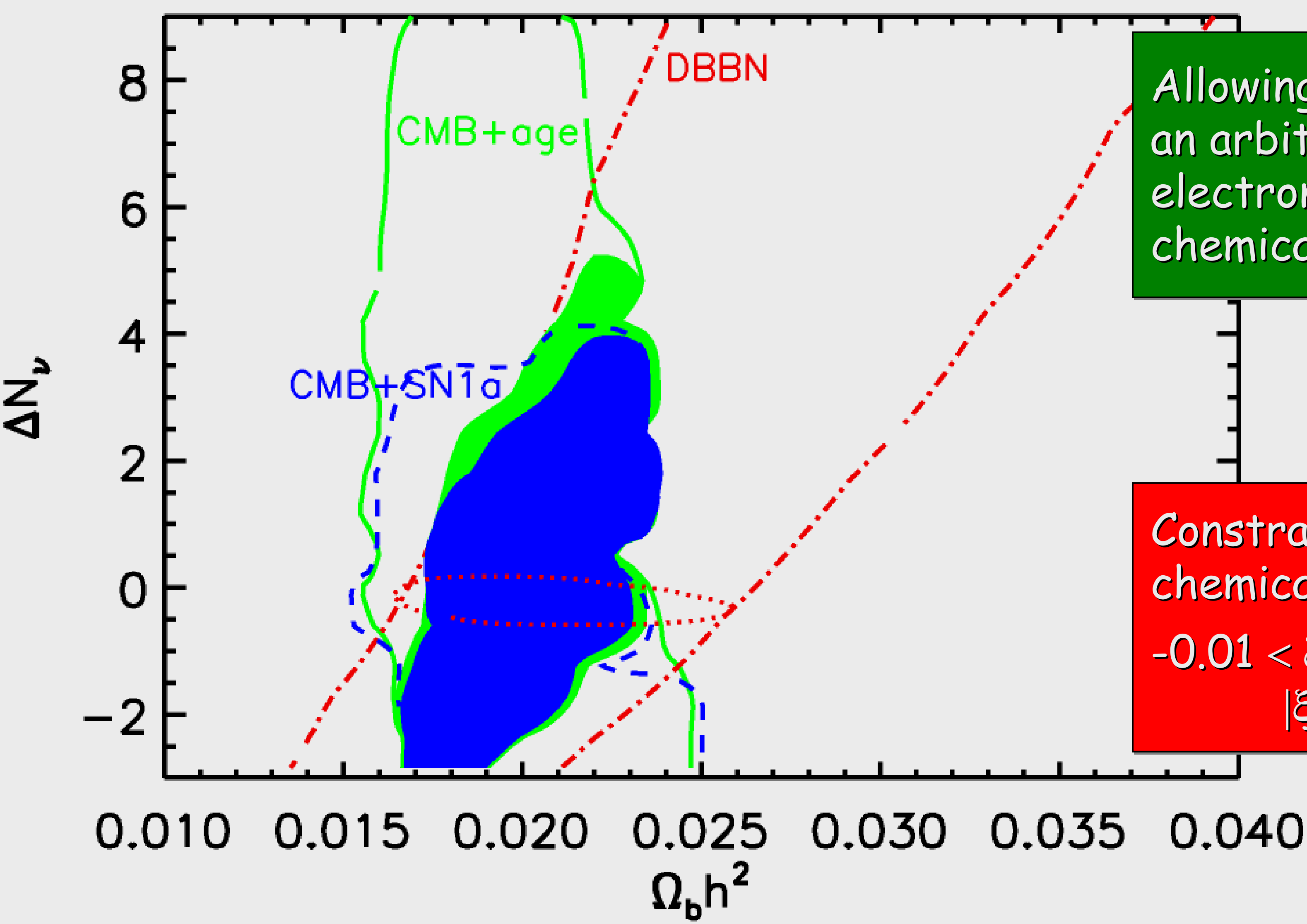
$$\frac{n}{p} = e^{-(m_n - m_p)/T - \xi_{\nu_e}}$$

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

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

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

Limits on Radiation Density



Allowing for an arbitrary electron neutrino chemical potential

Constraints on nu chemical potentials

$-0.01 < \xi_{\nu_e} < 0.25$

$|\xi_{\nu_{\mu,\tau}}| < 2.9$

Hansen et al., astro-ph/0105385

Chemical Potentials and Flavor Oscillations

Flavor mixing (neutrino oscillations)

Flavor lepton numbers not conserved

Only one common nu chemical potential

Stringent $\xi_{\nu e}$ limit applies to all flavors

$|\xi_{\nu e,\mu,\tau}| < 0.07$

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

Cosmic neutrino density close to standard value

Flavor equilibrium before n/p freeze out?

yes	Solar LMA solution
maybe	LOW (depends on Θ_{13})
no	Solar SMA solution

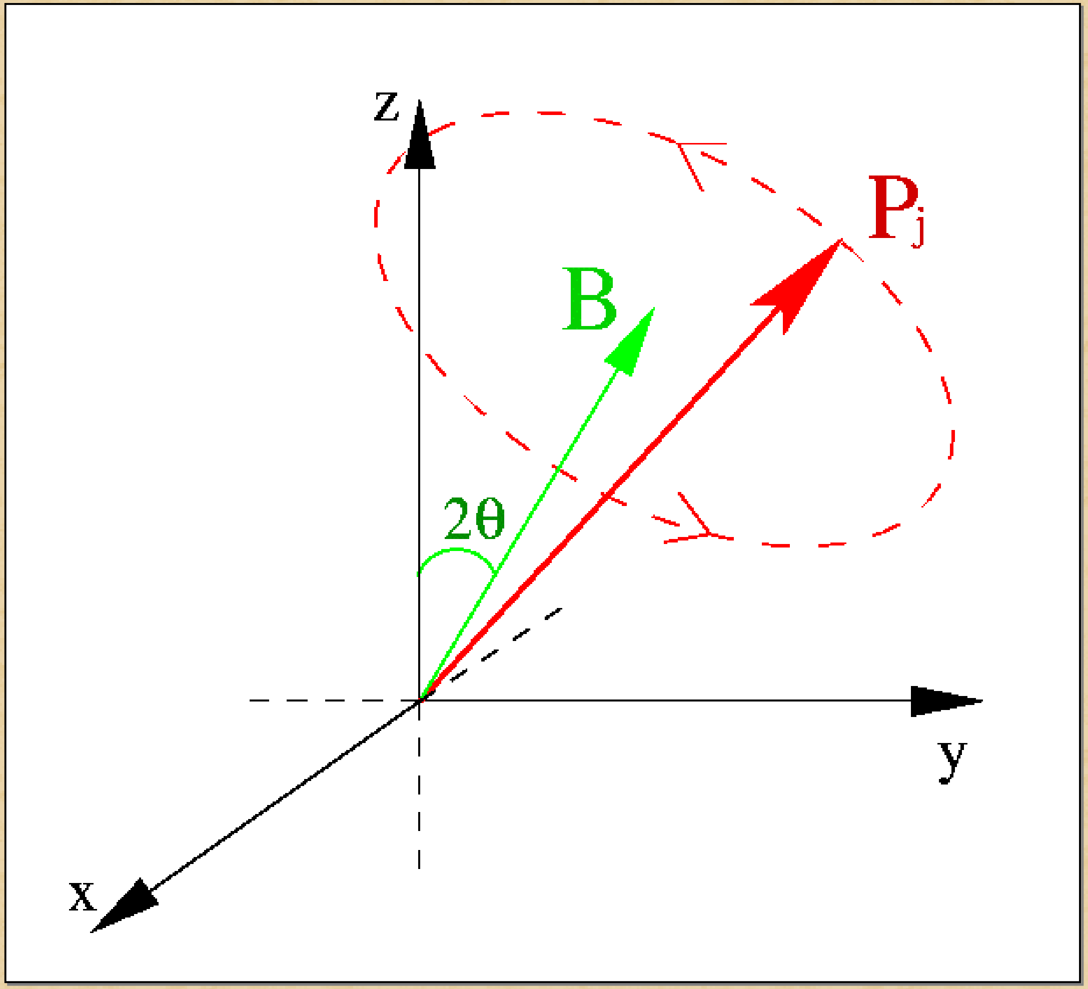
- Our knowledge of the cosmic nu density depends on the solution of the solar neutrino problem
- KamLAND most relevant experiment

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

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

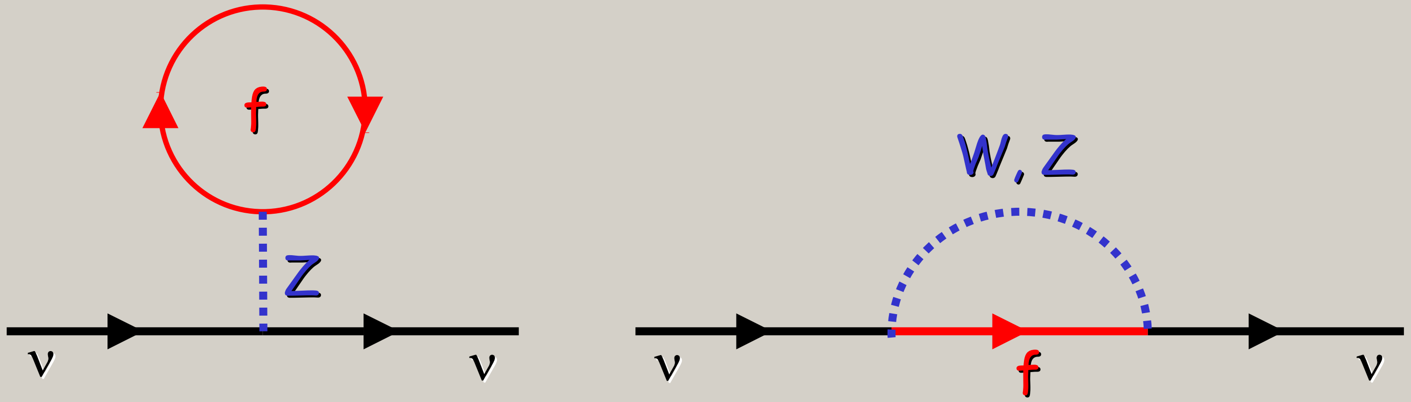
$$\vec{B} = \begin{pmatrix} \sin 2\theta \\ 0 \\ \cos 2\theta \end{pmatrix}$$

and

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}\begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Two-Flavor Oscillations in Media

Neutrinos propagating in a medium suffer refraction (Wolfenstein 1978)



Effect is usually different for different flavors

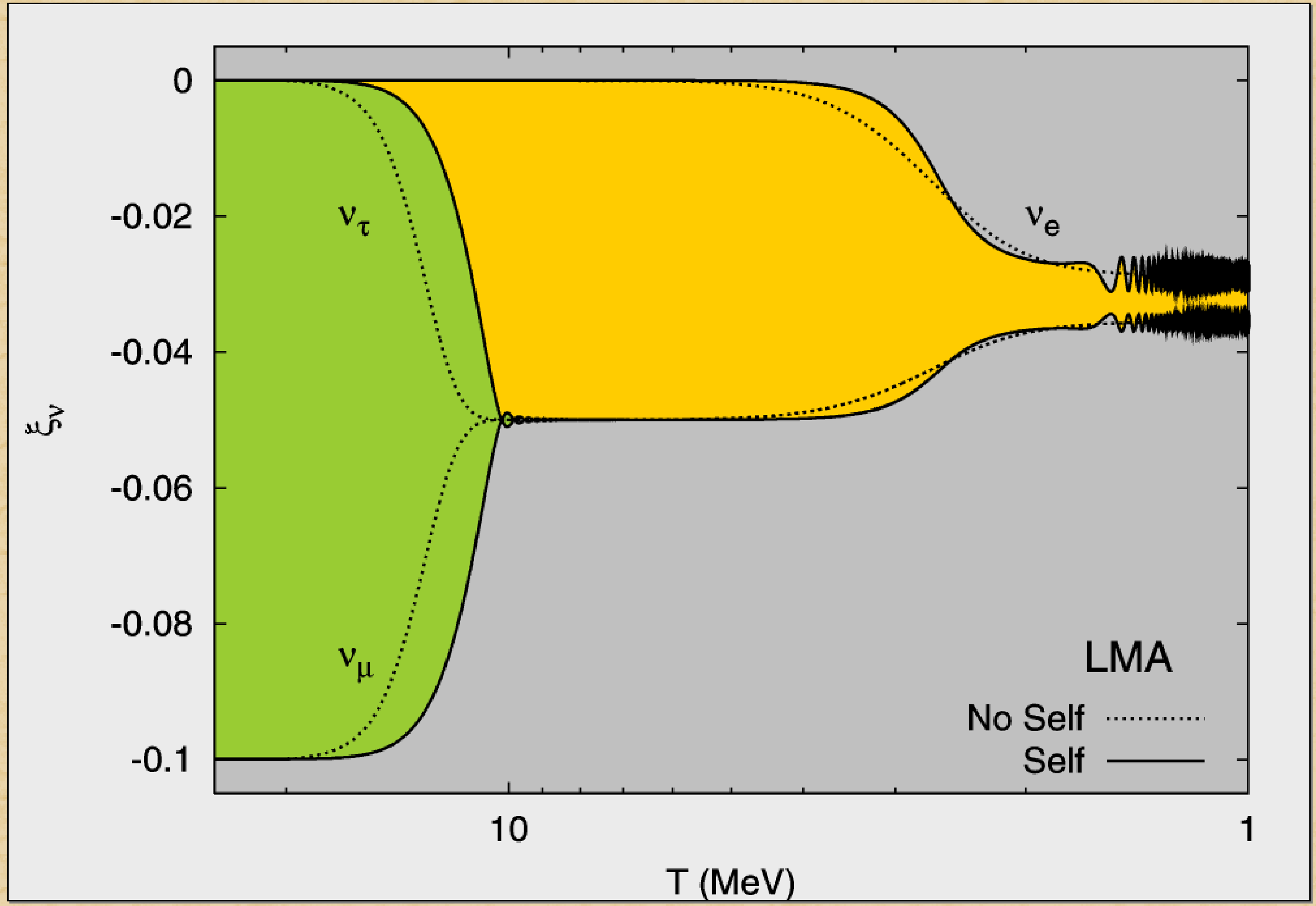
Equation of motion in early universe (ignoring neutrino background)

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

with ρ_e the e^+e^- energy density

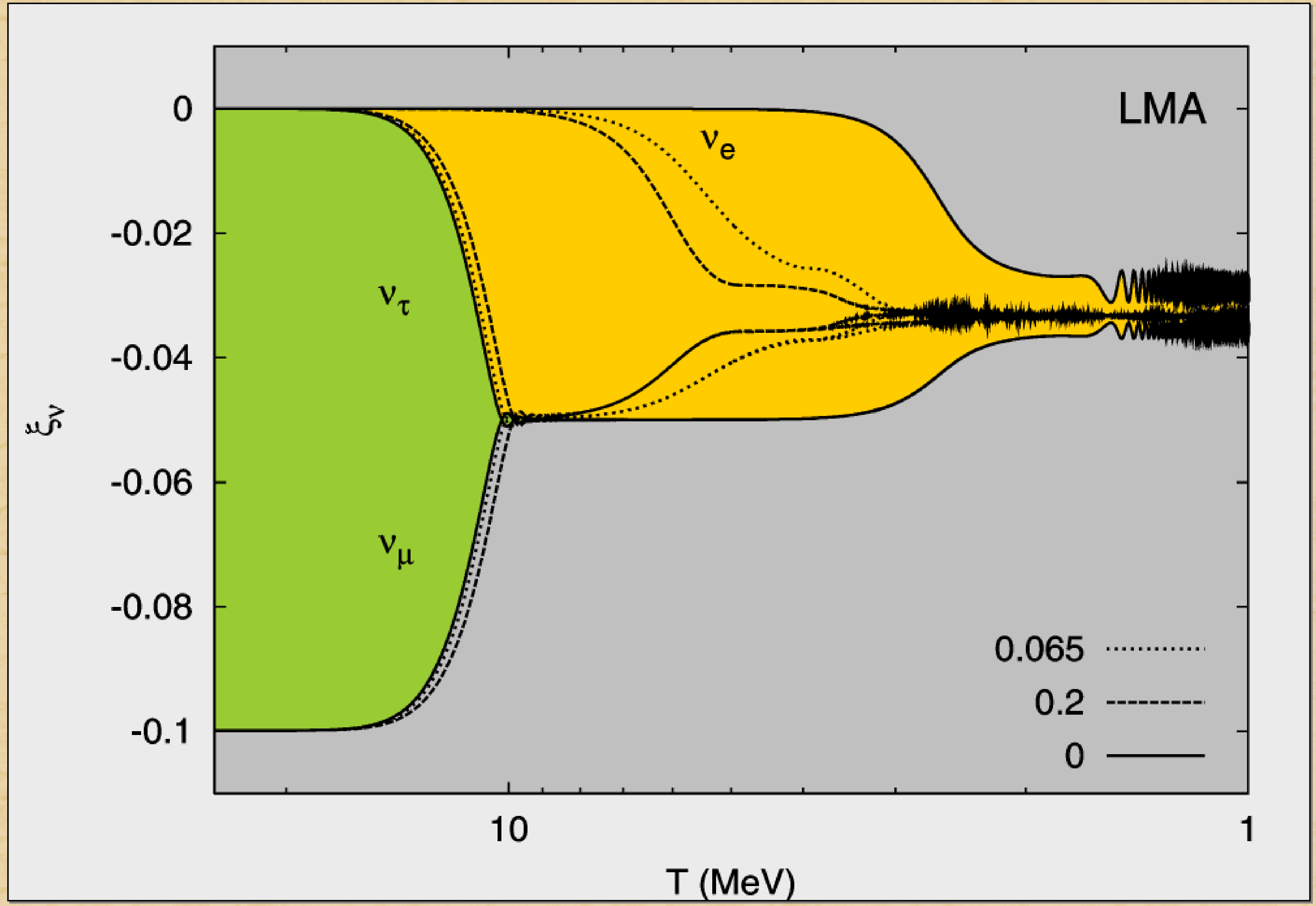
Oscillations begin when background medium is sufficiently diluted to avoid large medium effect compared to vacuum mixing

Flavor Equilibration: LMA Solution



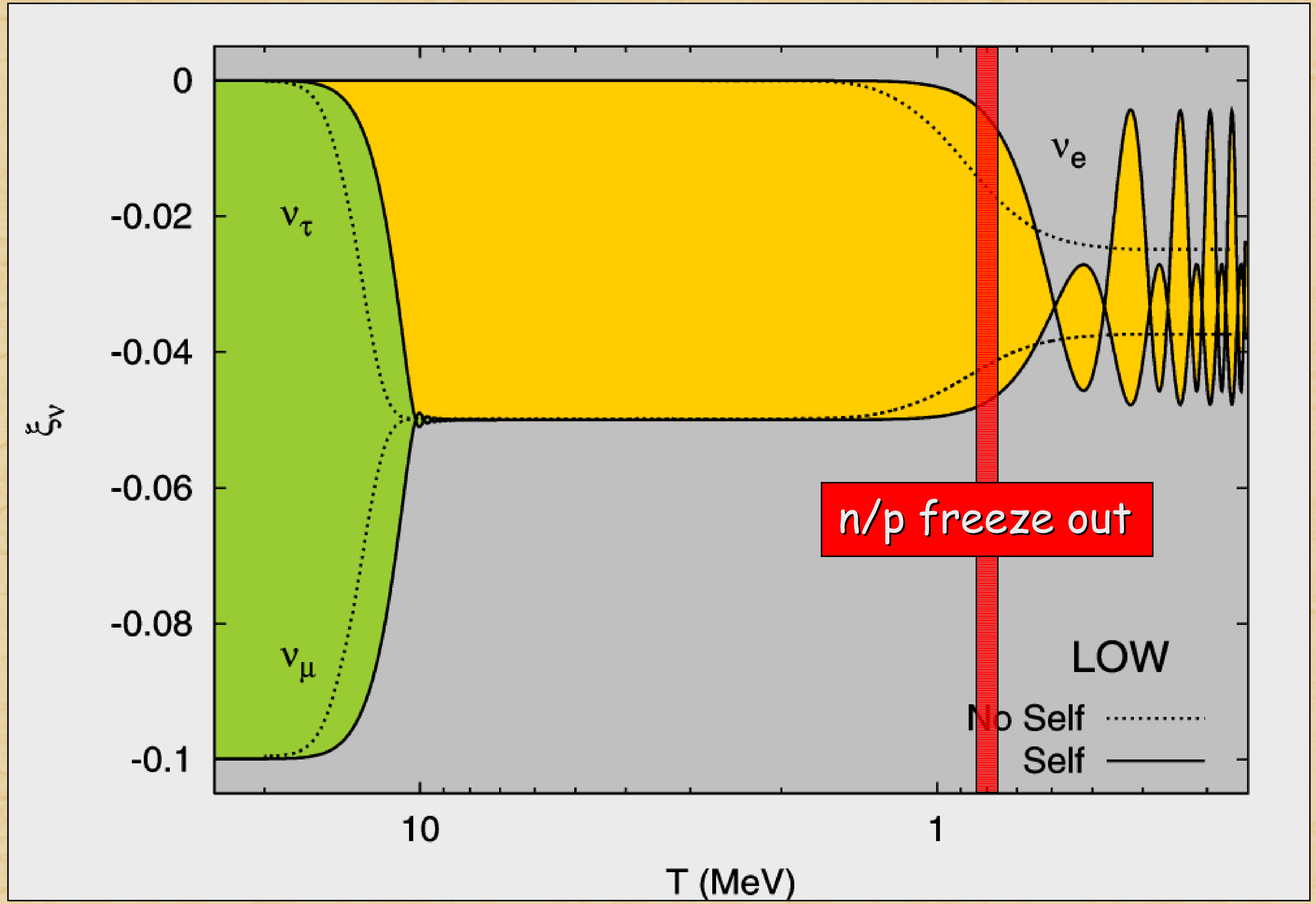
Dolgov, Hansen, Pastor, Petcov, Raffelt & Semikoz, hep-ph/0201287

Flavor Equilibration: LMA With Non-Zero Θ_{13}



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

Flavor Equilibration: LOW Solution



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

Synchronized Oscillations by Self-Interactions

Equation of motion in early universe with neutrino background

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

neutrinos

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

anti-neutrinos

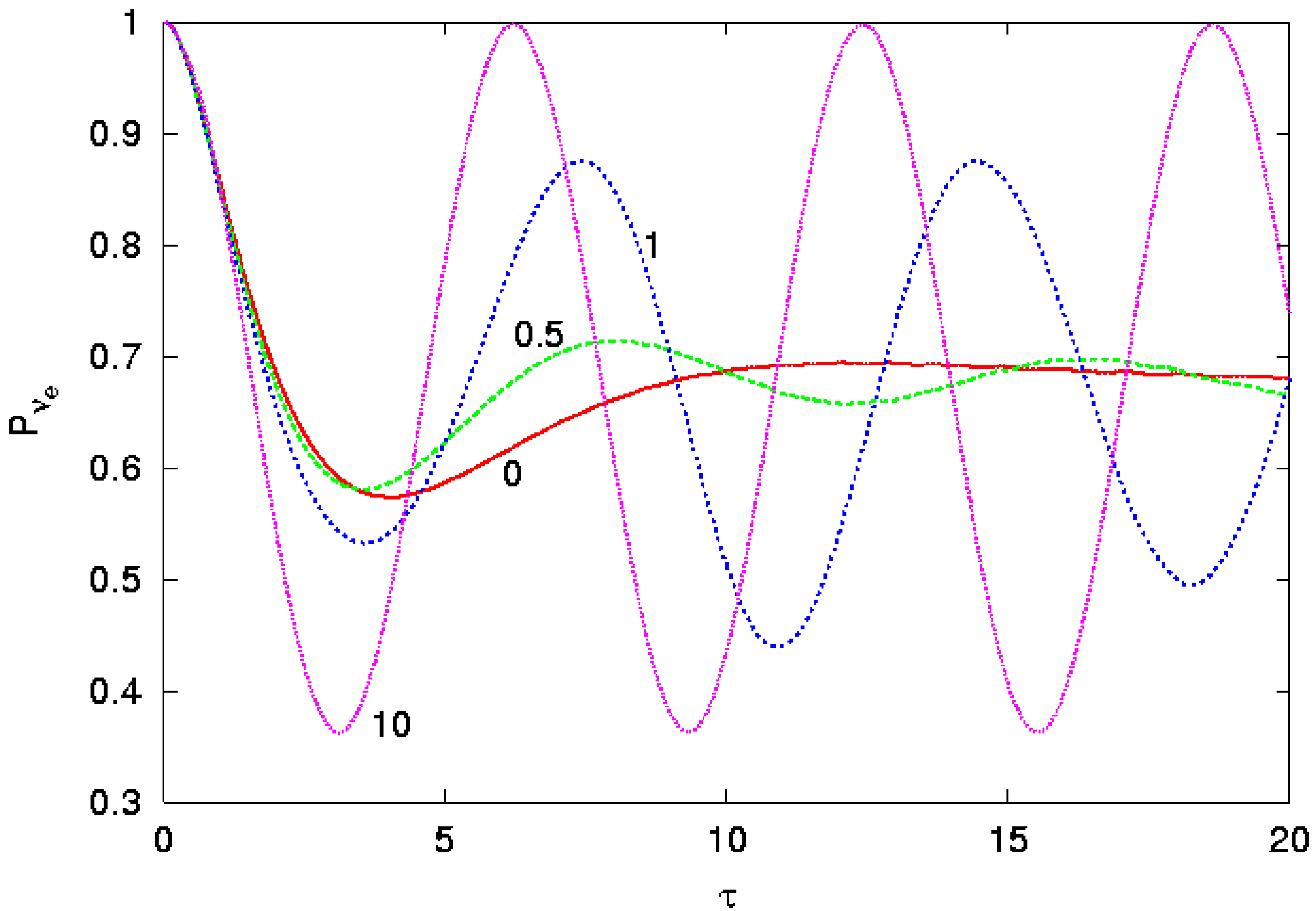
with the integrated neutrino polarization vectors

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

- "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.

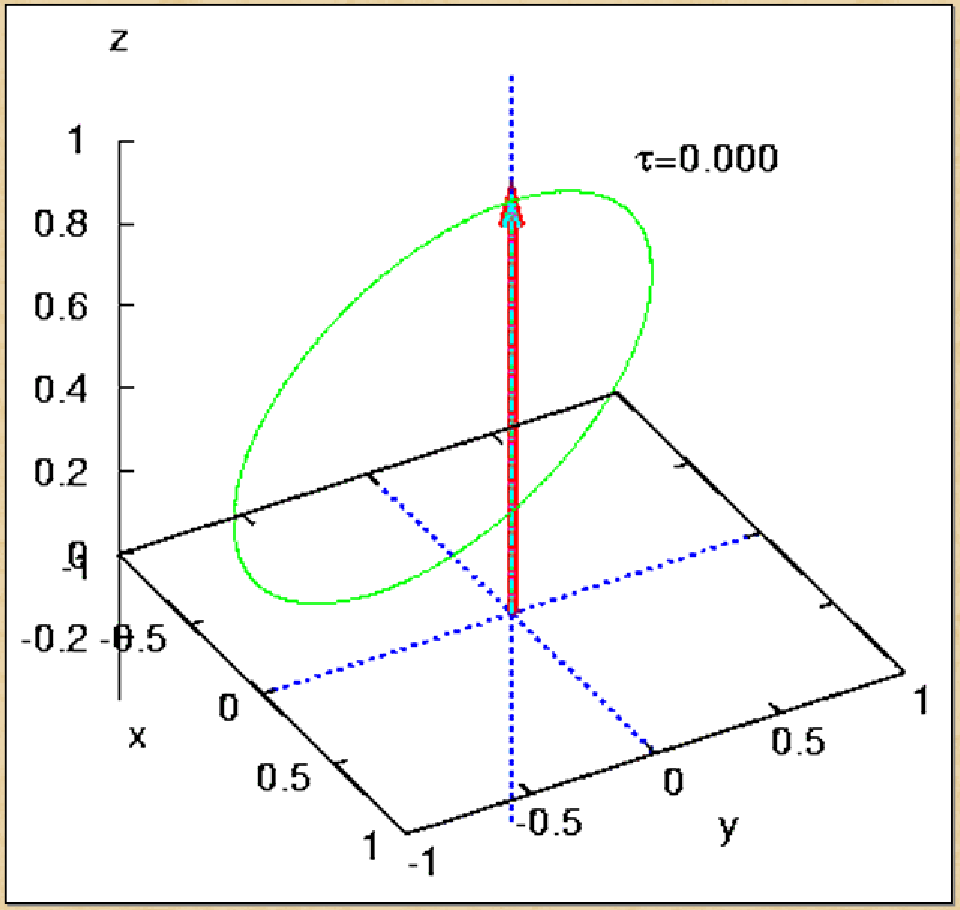
Pastor, Raffelt & Semikoz, PRD 65 (2002) 053011

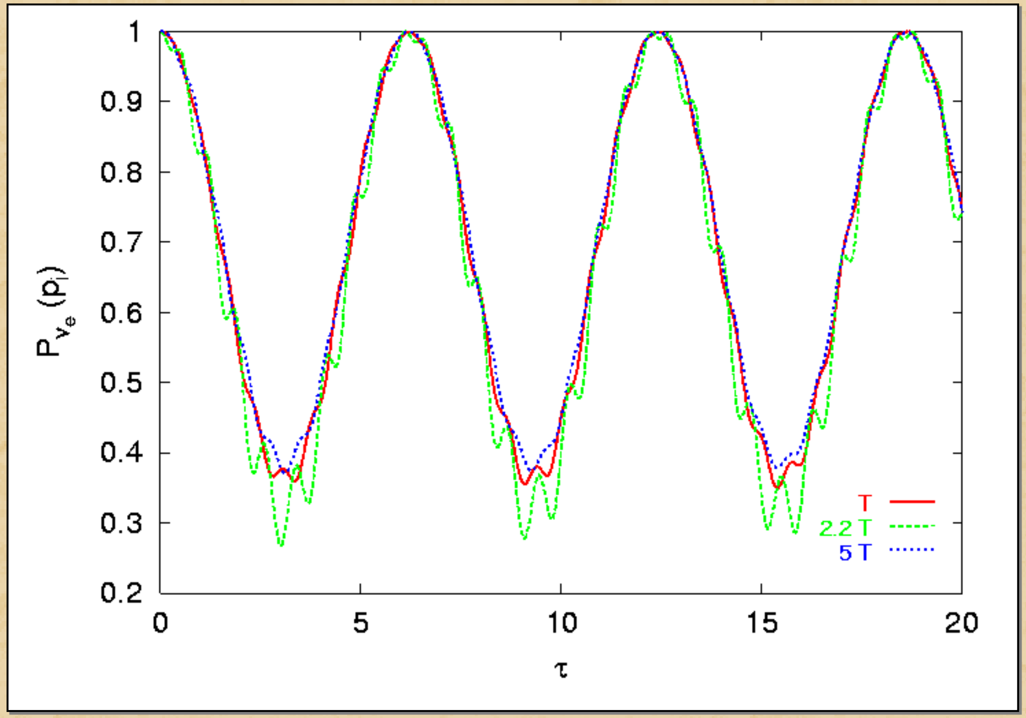
Synchronized Oscillations by Self-Interactions



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

Synchronized Oscillations by Self-Interactions





Individual modes precess around large common dipole moment

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

Zero-Frequency Synchronized Oscillations

Synchronized oscillation frequency, assuming all P vectors start 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

$$\omega_{synch} = 0$$

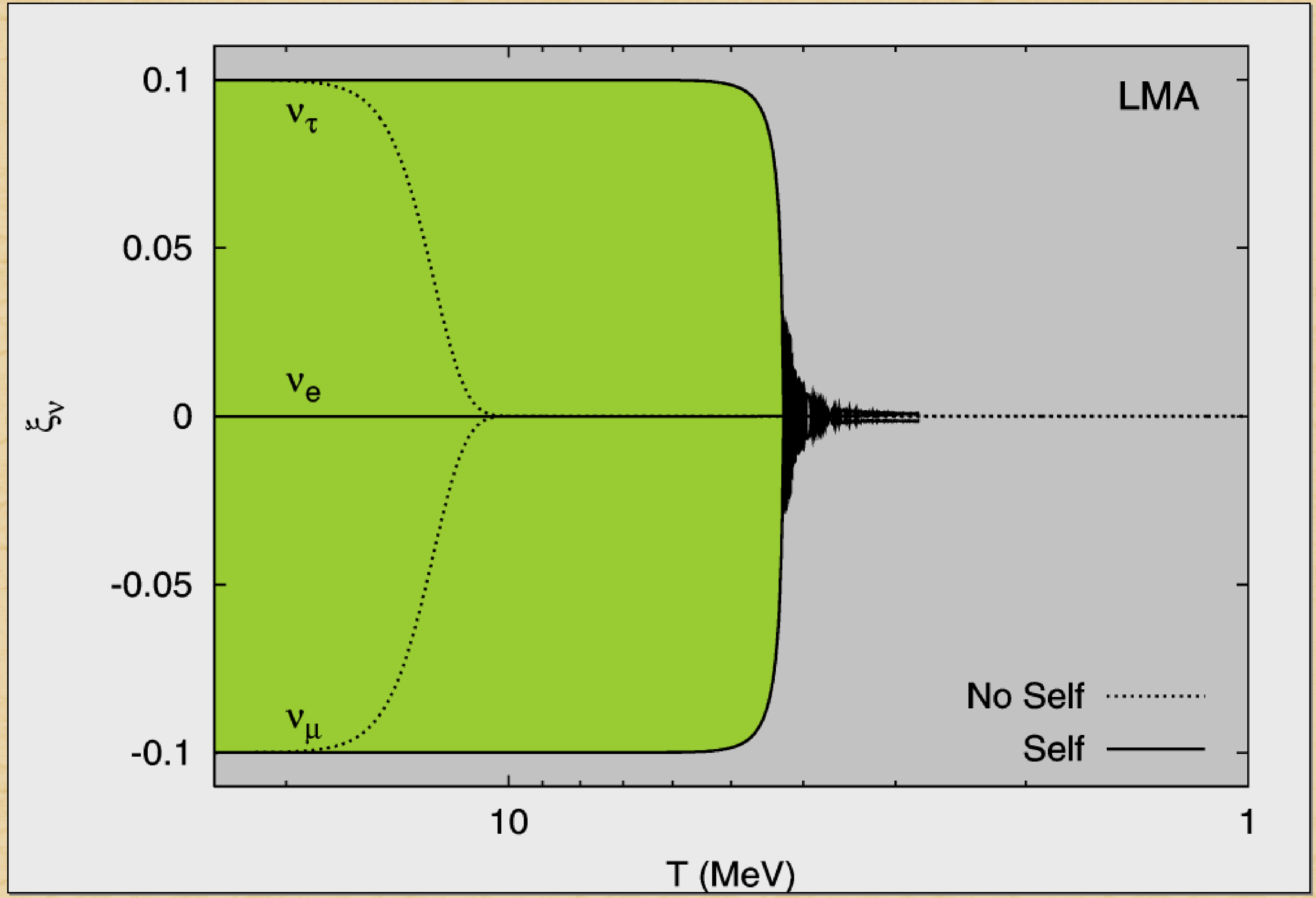
Oscillations completely suppressed

In a three-flavor system, oscillations are suppressed (infinitesimally slow) when

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

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

Summary

Confirmation of solar LMA solution by Kamland

↓

De-facto neutrino flavor equilibrium before BBN

BBN limit on effective number of nu flavors

↓

Cosmic nu density within 1% of standard value

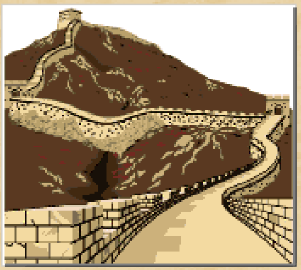
↓

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

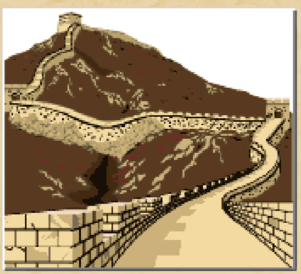
- Laboratory measurements of m_ν imply Ω_ν
- Structure-formation limits on Ω_ν directly constrain m_ν

Lecture II: Cosmological Neutrinos

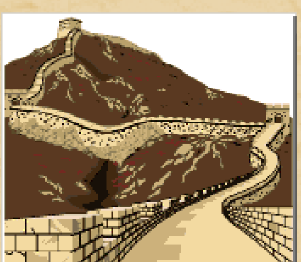
Neutrino Dark Matter and
Cosmic Structure Formation



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

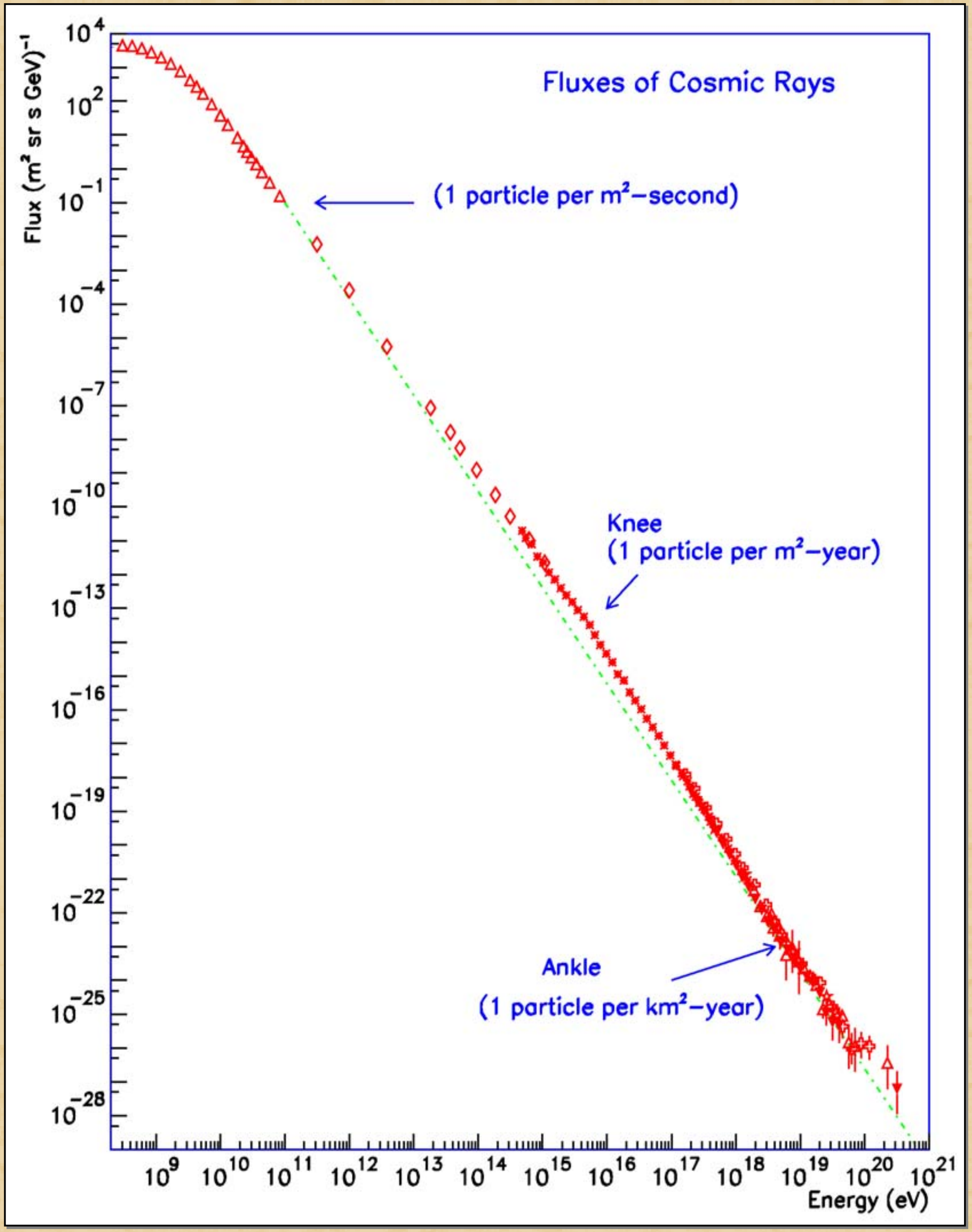


**Highest-Energy Cosmic Rays
and the Cosmic Neutrino Sea**



Massive Neutrinos and the
Cosmic Baryon Asymmetry

Global Cosmic Ray Spectrum



Greisen-Zatsepin-Kuzmin (GZK) Cutoff

END TO THE COSMIC-RAY SPECTRUM?

Kenneth Greisen

Cornell University, Ithaca, New York

(Received 1 April 1966)

PRL 16 (1966) 748

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

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

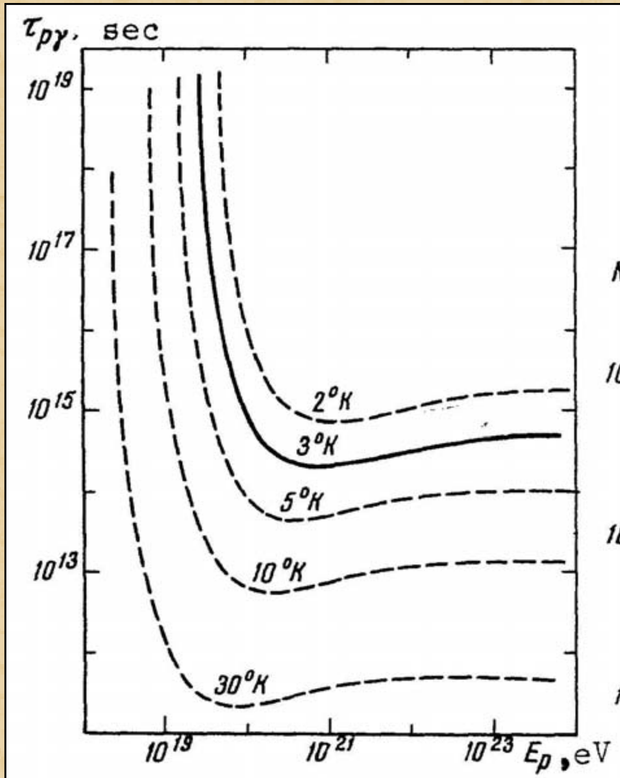


Fig. 1

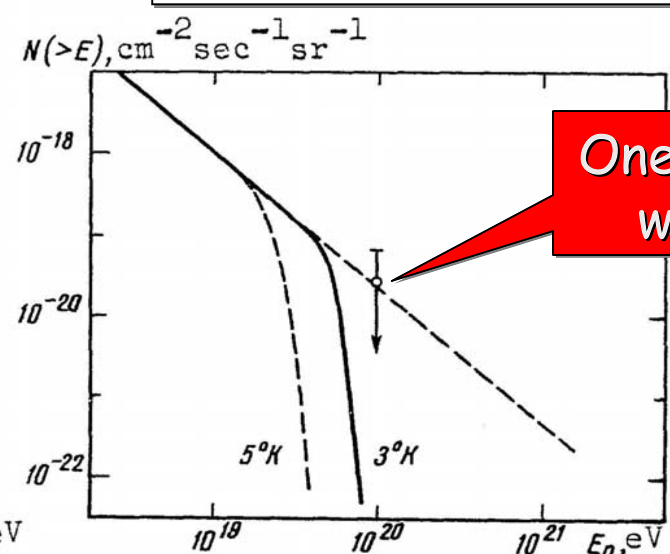
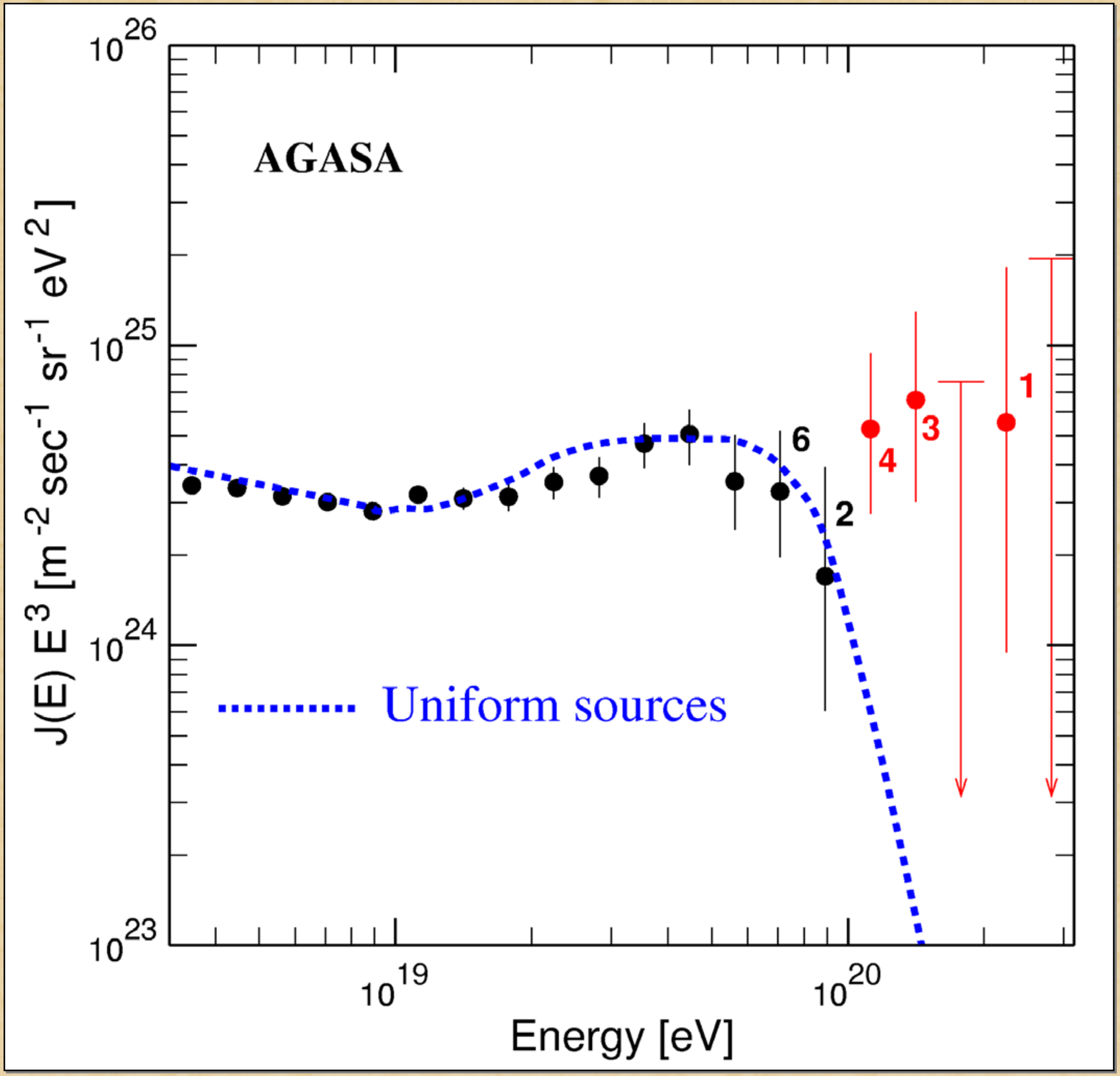


Fig. 2

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

JETP Lett. 4 (1966) 78

Spectrum of Highest-Energy AGASA Events



astro-ph/0008102

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

Decay
(Z-Burst)

On average
2 Nucleons
$10\ \pi^0 \to 20\ \gamma$
$17\ \pi^\pm \to e^\pm\ \nu\ \underline{\nu}$

Measured cosmic rays

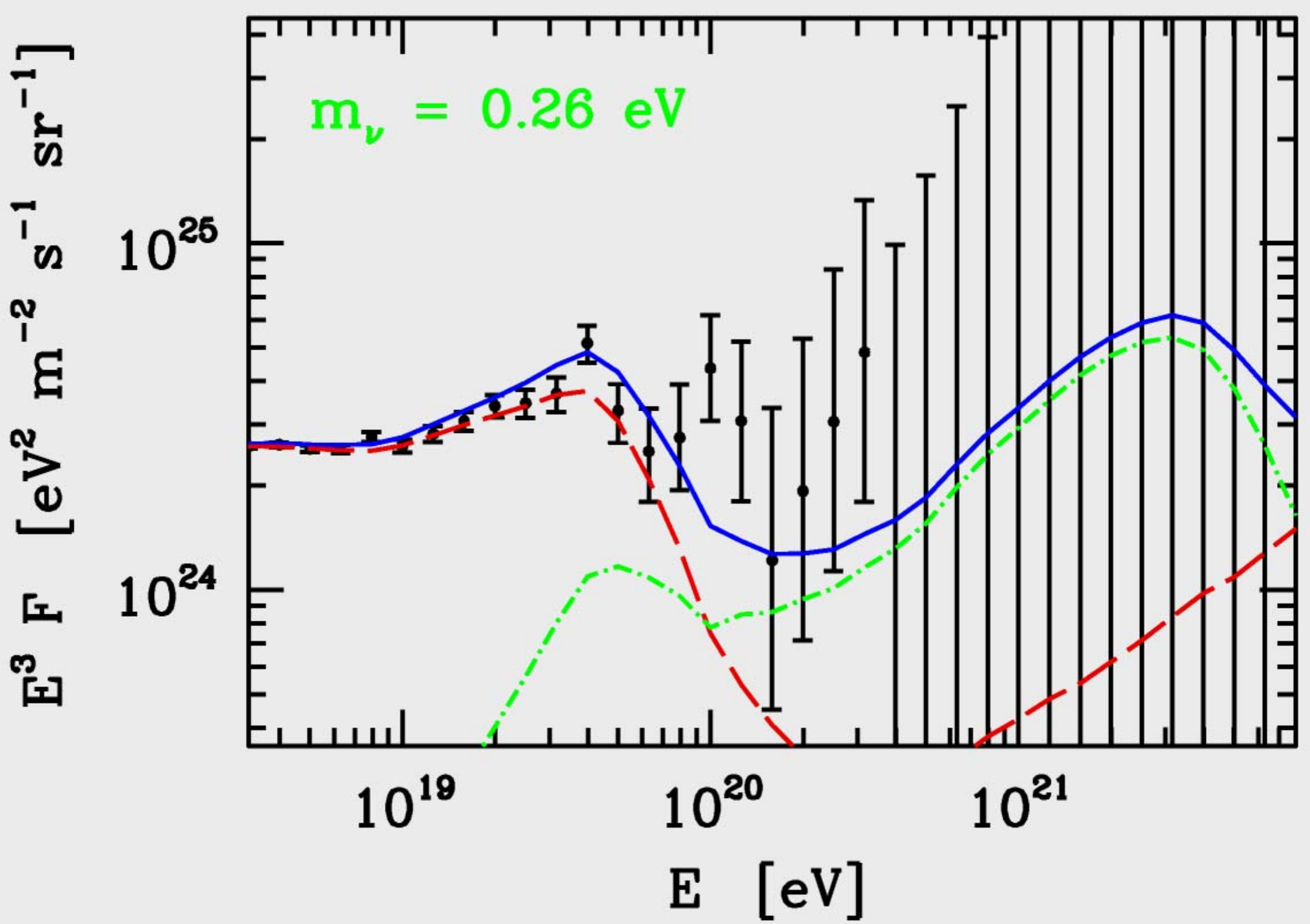
Neutrino energy on resonance

$$E_\nu = \frac{M_Z^2}{2m_\nu} = \frac{4.2\times 10^{21}\,\mathrm{eV}}{m_{\mathrm{eV}}}$$

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

Fitting the Cosmic Ray Spectrum with Z-Bursts

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



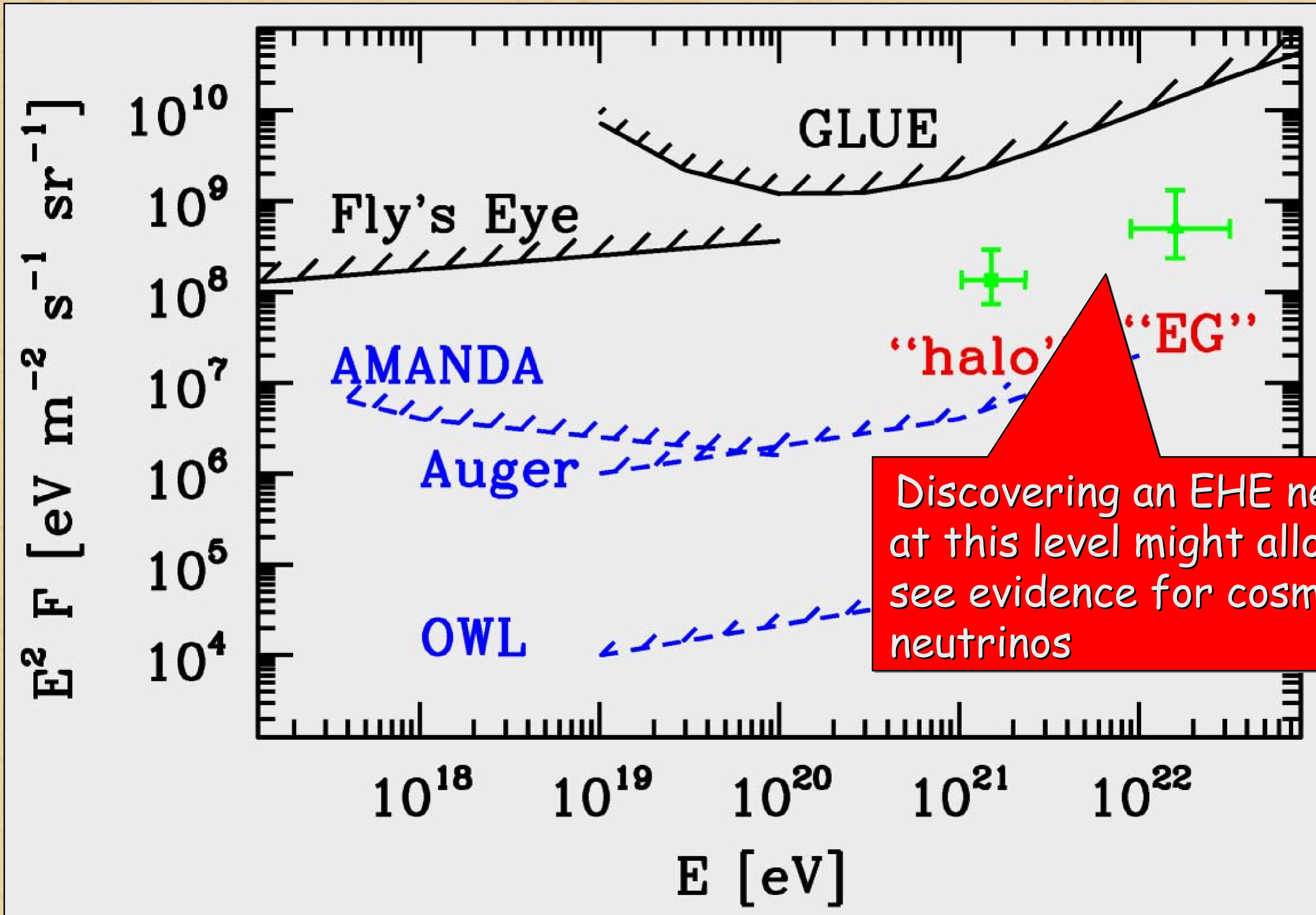
Main problems

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

Kalashev et al.
hep-ph/0112351

Fodor, Katz & Ringwald, hep-ph/0203198

Discovery Potential for Required Neutrino Fluxes

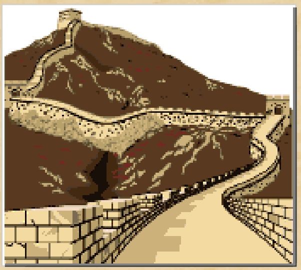


Discovering an EHE neutrino flux at this level might allow one to see evidence for cosmic relic neutrinos

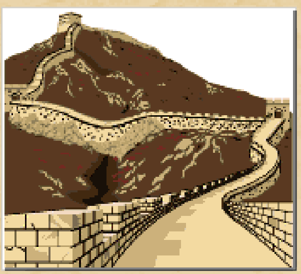
Fodor, Katz & Ringwald, hep-ph/0203198

Lecture II: Cosmological Neutrinos

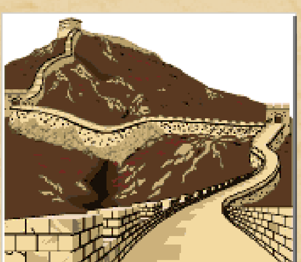
Neutrino Dark Matter and Cosmic Structure Formation



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

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

Another classic paper

Volume 174, number 1 PHYSICS LETTERS B 26 June 1986

BARYOGENESIS WITHOUT GRAND UNIFICATION

M. FUKUGITA

Research Institute for Fundamental Physics, Kyoto University, Kyoto 606, Japan

and

T. YANAGIDA

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

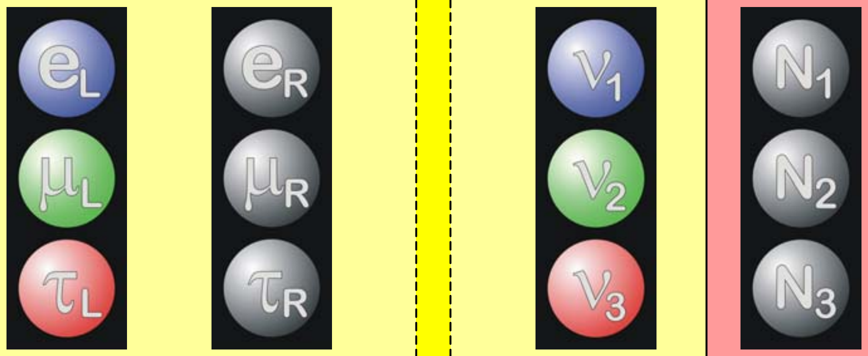
Received 8 March 1986

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

See-Saw Model for Neutrino Masses

Charged Leptons	Neutrinos

Dirac masses from coupling to standard Higgs field ϕ



Heavy Majorana masses M_j

Lagrangian for particle masses

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

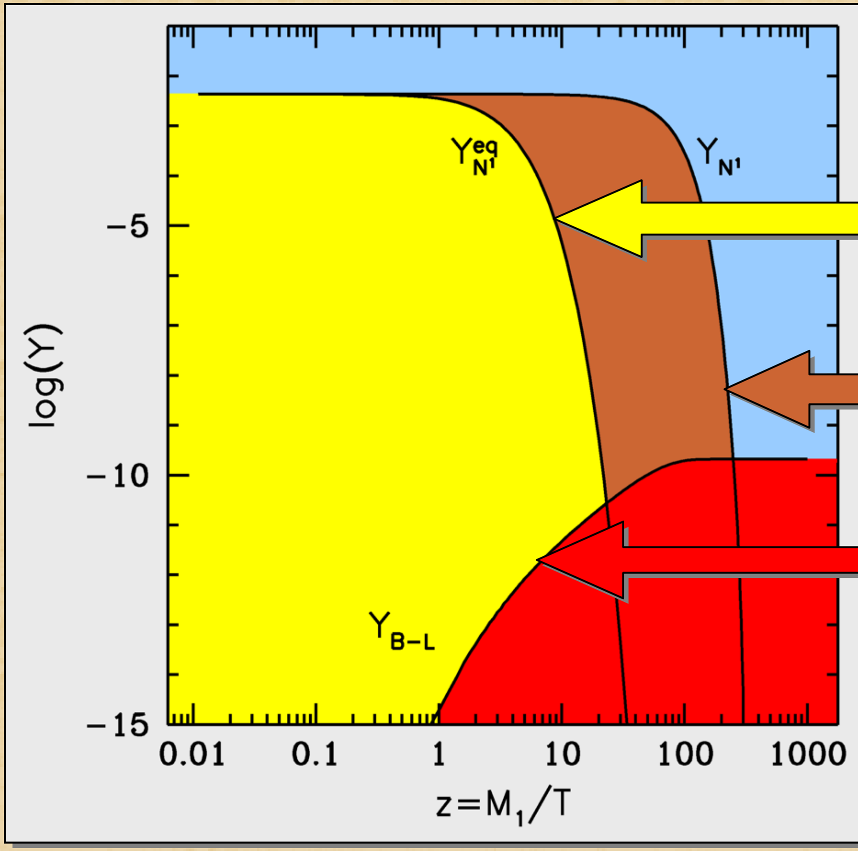
$$\begin{pmatrix} \overline{\nu}_L & \overline{N}_R \end{pmatrix} \begin{pmatrix} 0 & g_\nu \langle\phi\rangle \\ g_\nu \langle\phi\rangle & M \end{pmatrix} \begin{pmatrix} \nu_L \\ N_R \end{pmatrix}$$

Diagonalize

Light Majorana mass

$$\begin{pmatrix} \overline{\nu}_L & \overline{N}_R \end{pmatrix} \begin{pmatrix} \frac{g_\nu^2 \langle\phi\rangle^2}{M} & 0 \\ 0 & M \end{pmatrix} \begin{pmatrix} \nu_L \\ N_R \end{pmatrix}$$

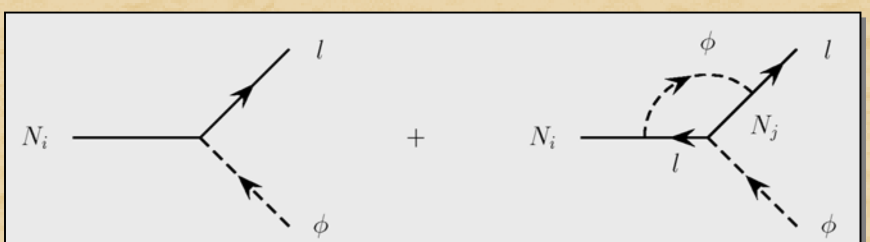
Leptogenesis by Out-of-Equilibrium Decay



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

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

Connection to Neutrino Mass

$\Gamma_{\rm Decay} = g_\nu^2 \frac{M}{8\pi}$	Decay rate of heavy Majorana neutrino
$H \approx \sqrt{g_{\rm eff}} \frac{T^2}{m_{\rm Pl}}$	Cosmic expansion rate
$\Gamma_{\rm Decay} < H\|_{T=M}$	Requirement for strong deviation from equilibrium ...
$g_\nu^2 \frac{M}{8\pi} < \sqrt{g_{\rm eff}} \frac{M^2}{m_{\rm Pl}}$	
$\frac{g_\nu^2}{M} < \frac{8\pi\sqrt{g_{\rm eff}}}{m_{\rm Pl}}$	
$m_\nu = \frac{g_\nu^2 \langle\phi\rangle^2}{M} < \frac{8\pi\sqrt{g_{\rm eff}}}{m_{\rm Pl}} \langle\phi\rangle^2 \sim 10^{-3}\,{\rm eV}$	... 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 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 *light* neutrino masses

Consistent with hierarchical masses below 0.1 eV

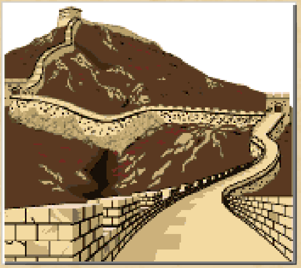
Leptogenesis – A Popular Research Topic

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

Conclusions of Lecture II

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 suggest a leptogenesis scenario
for generating cosmic baryon asymmetry