GERSHTEIN-ZELDOVICH BOUND AND COSMOLOGICAL RESTRICTIONS ON NEUTRINO MASS

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COSMOLOGY AND ASTROPHYSICS AT HIGH ENERGIES

(dedicated to 90th anniversary of Ya. B. Zeldovich)

Presently telescopes allow to weight neutrinos more accurately then direct experiments.

Tritium decay experiments (Troitsk, Meinz):

$$m_{\nu_e} < (2-3)\ \mathrm{eV}$$

Neutrino oscillation data:

$$\delta m^2_{solar} = (5.4-9.5)\cdot 10^{-5}\ \mathrm{eV}^2$$
$$\delta m^2_{atm} = (1.2-4.8)\cdot 10^{-3}\ \mathrm{eV}^2$$

Hence:

$$\boxed{m_\nu > 5\cdot 10^{-2}\,\mathrm{eV}}$$

2β-decay (Heidelberg-Moscow): $\mathbf{m_\nu > 0.1}\mathrm{eV}$(?) - Majorana mass.

Astronomy is sensitive now to

$$\boxed{m_\nu \sim (\text{a few})\times 0.1\ \ \mathrm{eV}.}$$

based on combined data on LSS and CMBR.

Derivation of GZ bound.

At $T > 1$ MeV thermal equilibrium between $\nu, e^{\pm}, \gamma$:

$$n_{\nu} = (3/8) n_{\gamma}$$

for each left-handed neutrino flavor, $\nu_e, \nu_{\mu}, \nu_{\tau}$. Assumed vanishing charge asymmetry, i.e.

$$n_{\nu} = n_{\bar{\nu}}.$$

At $T \leq m_e$ photons are heated by e^+e^--annihilation, while ν are decoupled. It leads to the present-day neutrino number density:

$$n_{\nu} + n_{\bar{\nu}} = (3/11) n_{\gamma} = 112/\mathrm{cm}^3$$

Hence:

$$\sum_a m_{\nu_a} < 94\,\mathrm{eV}\,\Omega_m h^2$$

For $\Omega_m < 0.3$ and $h = 0.7$:

$$\sum_a m_{\nu_a} < 14\,\mathrm{eV}$$

Detailed analysis of LSS observational data together with **measured** spectrum of density perturbations from the angular fluctuations of CMBR allows to strengthen the bound down to

$$\sum_a m_{\nu_a} < (0.4 - 1)\,\mathrm{eV}$$

The necessary input for this result are **GZ** calculations of the present day number density of relic neutrinos.

Historical remarks

GZ-bound derived in:
REST MASS OF MUONIC NEUTRINO AND COSMOLOGY
By S.S. Gershtein, Ya.B. Zeldovich,
Pisma Zh. Eksp. Teor. Fiz. v.4, 174, 1966
English translation: JETP Lett. v.4, 120, 1966.

Usually quoted:
R. Cowsik, J. McClelland
AN UPPER LIMIT ON THE NEUTRINO REST MASS
Phys. Rev. Lett. v.29, 669, 1972.
Effects of photon heating are not accounted for and 2 spin states of neutrinos are assumed to be equally abundant.

HEAVY NEUTRINOS: Lee-Weinberg equation, 1971, in Zeldovich, Okun, Pikel'ner, 1964; mass limit LW (1971), VDZ (1971).

IS IT POSSIBLE TO AVOID GZ BOUND?

1. **Thermal equilibrium in the early universe** - OK in the standard model. Can be broken if T was never larger than MeV.
2. **Nonvanishing lepton asymmetry** - results in stronger bound.
3. **Extra heating of photon plasma below MeV**. Care should be taken of BBN and spectrum of CMBR.
4. **Neutrino stability at cosmological time scale:** $\tau_\nu \geq t_u \sim 10^{10}$ years. Difficult to make smaller life-time. New interactions are necessary.
5. **New interactions which could lead to strong annihilation of $\bar\nu\nu$.** Very light or massless boson is needed.
6. **Right-handed neutrinos** - result in stronger bound.

FORMATION OF LARGE SCALE STRUCTURE

Theoretical input:

1. **Spectrum of primordial fluctuations**. Usually assumed flat, **Harrison-Zeldovich** type. Predicted by inflation. Confirmed by CMBR at large scales $\geq 10 Mpc$.

2. **Properties of dark matter**. Usually non-interacting **CDM+Lambda**.

3. **Analytical calculations** at **linear regime**, when $\delta\rho/\rho \ll 1$. Standard physics: GR and hydrodynamics. Is not distorted at large scales accessible to CMBR.

4. **Numerical simulations** at **nonlinear regime**, when $\delta\rho/\rho \geq 1$. Necessary at smaller scales, ~ 10 Mpc.

PROBLEMS: M. Kamionkowsky, yesterday talk.

Neutrino role in LSS formation

Very large **free-streaming length**:

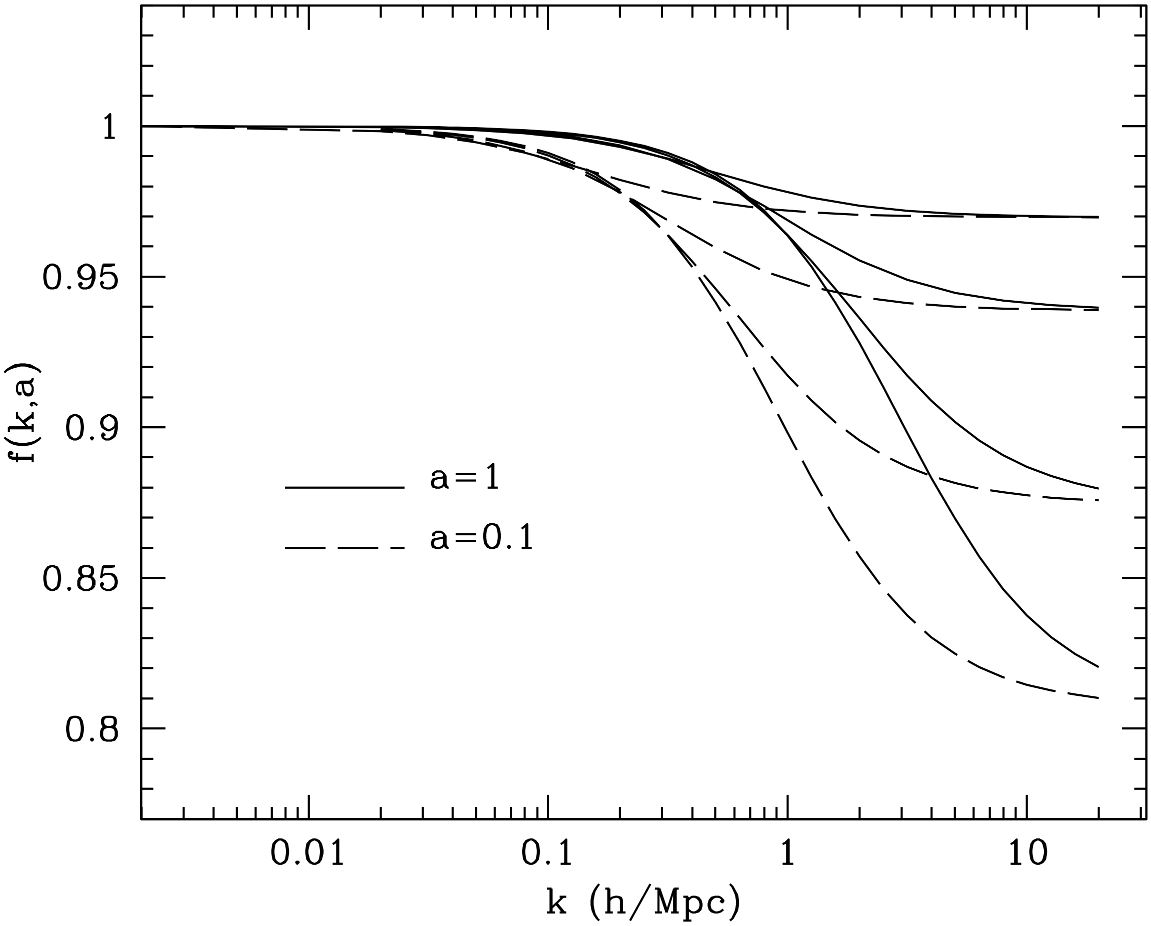
$$l_{FS} \approx 250\,\mathrm{Mpc}\;(\mathrm{eV}/m_\nu)$$

In neutrino dominated universe the structures below this scale are erased.

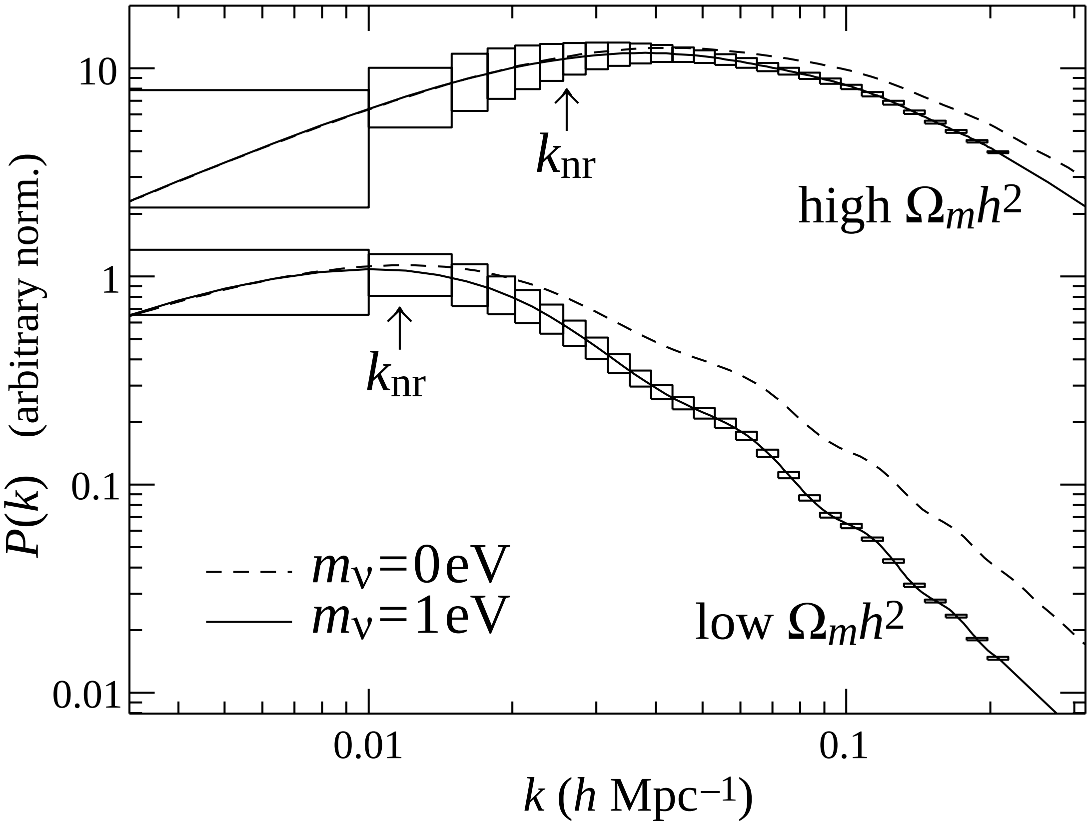
If neutrinos are sub-dominant they lead to:

1. Suppression of power at small scales.
2. Delayed formation of structures. Ly-α clouds at high red-shifts, $z \geq 1$ are sensitive to light massive neutrinos.

An *ad hoc* modification of perturbation spectrum could mimic the presence of massive neutrinos and no mass bound would be obtained



Growth rate $f \equiv d\log\delta/d\log a$, in four flat C+HDM models at $a = 1$ (solid) and 0.1 (dashed) with different neutrino masses: $m_\nu =$ 1.2, 2.3, 4.6, 6.9 eV (from top down), corresponding to $\Omega_\nu = 0.05, 0.1, 0.2, 0.3$. At small k, the CDM density field grows with the same rate ($\delta \propto a$) as in the standard CDM model. **At large k, the growth rate is suppressed**. (From Ma, 1999.)



Effect of 1 eV neutrino on BRG power spectrum compared with expected precision of the SDSS (1σ error boxes Upper: $\Omega_m = 1$, $h = 0.5$, $\Omega_b h^2 = 0.0125$, $n = 1$ Lower: the same but for an $\Omega_m = 0.2$, $h = 0.65$. (From Hu et al, 1997.)

The effect is most pronounced at small scales (and high z, previous figure).

Massive neutrinos and CMBR

Angular spectrum of CMBR does not feel directly presence of light neutrinos - they are practically relativistic at recombination.

CMBR allows to measure perturbation spectrum and fit it to spectrum derived from LSS in the common range of wave lengths.

Scales available to CMBR:

$$300\,\mathrm{Mpc} < d < 10/h\,\mathrm{Mpc}$$

(low accuracy at large d because of cosmic variance).

LSS: Spectrum at small scales (sensitive to neutrinos) is strongly distorted at non-linear regime.

Ly-α at $z = 2 - 4$, scales about 1 Mpc; evolution is non-negligible but manageable.

SDSS: 3600 QSO at $z > 2.2$, high accuracy.

BEST LIMIT from combined CMBR, LSS, and Ly-α:

$$\sum m_{\nu_a} < 0.42\,\mathrm{eV}$$

Various recent limits on the neutrino mass from cosmology and the data sets used in deriving them:

1: WMAP data
2: Other CMB data
3: 2dF data
4: Constraint on σ_8
5: SDSS data
6: Constraint on H_0
7: Constraint from Lyman-α forest.

WMAP: $\Sigma m_\nu <$**0.69 eV**, from 1-4,6, 7
Hannestad: $\Sigma m_\nu <$**1.01 eV**, from 1-3,6
Allen et al: $\Sigma m_\nu < 0.56^{+0.3}_{-0.26}$ **eV**, from 1-4,6
SDSS: $\Sigma m_\nu <$**1.8 eV**, from 1,5
Barger et al. $\Sigma m_\nu <$ **0.75 eV**, from 1-3,5,6
Crotty et al: $\Sigma m_\nu <$ **1.0 eV** from 1-3,5 (6)
Seljak et al. $\Sigma m_\nu <$**0.42 eV** 1,2,4-7
Fogli et al. $\Sigma m_\nu <$**0.5 eV**, from 1-7
Hannestad: $\Sigma m_\nu <$**0.65 eV**, from 1,5-7.

CONCLUSION

1. All bounds quoted above are based on the calculations of the present day number density of ν by GZ.

2. More restrictive results, i.e. $\Sigma m_\nu < 1-0.42$ eV are based on analysis of LSS at relatively small scales plus CMBR to shift degeneracy of parameters.

3. With almost equal neutrino masses (from oscillation experiments) one can conclude: $m_\nu < 0.33 - 0.14$ eV.

4. Direct experiment project, KATRIN, may approach this accuracy. Do we need it?

5. Possible ways to violate the limit:

a) From particle physics: new particles or stronger ν-interactions;

b) From cosmology: unusual spectrum of perturbations at small scales;

$\mathbf{w} = \mathbf{w}(\mathbf{t})$.

WHAT ELSE?