NEUTRINOS IN COSMOLOGY AND PONTECORVO INSIGHT

A.D. Dolgov

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Pioneering works on cosmological implications of neutrinos:

B. Pontecorvo, Ya. Smorodinsky, JETF, 41 (1961) 239;

B. Pontecorvo, Uspekhi Fiz. Nauk, 79 (1963) 1.

"In macroscopic phenomena neutrinos probably play an essential role."

Neutrino is the second most abundant particle in the universe after photons of CMB (maybe, also after axions, if they exist).

Gerstein-Zeldovich bound as well as modern precise cosmological bounds on neutrino mass originated from Pontecorvo ideas. An analysis of CMB and LSS allows today to put the limit:

$$\sum m_{\nu_j} < (\sim 1\mathrm{eV}),$$

an order of magnitude stronger than direct experiment.

Our (Vysotsky, Dolgov, Zeldovich, 1977) and Lee and Weinberg (1977) bound on hypothetical heavy neutrino mass:

$$m_{L^0} > 2\,\mathrm{GeV}$$

also arose from the Pontecorvo observations.
Such heavy neutral lepton, if stable, is a popular condidate for CDM particle.

Neutrino oscillations, suggested by Pontecorvo, have an important impact on cosmology: BBN, WDM, cosmological lepton asymmetry.

Description of oscillations in the hot and dense primeval plasma is technically much more complicated than e.g. description of oscillations in less violent environment as e.g. inside the Earth or the Sun.

Neutrino oscillations in “normal” medium are well described by the Schroedinger equation:

$$i\partial_t \Psi = \mathcal{H}\, \Psi,$$

where the Hamiltonian contains refraction index (effective potential) to describe interaction with medium:

$$V^a_{eff} = \pm C_1 (n - \bar{n}) + C^a_2 G^2_F T^4 E/\alpha,$$

(Nötzold, Raffelt, 1988).

In the early universe (and in the final stage of supernova explosion) breaking of coherence is 100% important and one needs to use density matrix formalism, (AD, 1981):

$$\dot{\rho} = i\left[\mathcal{H}_m + V_{eff}, \rho\right] + I_{coll}(\rho).$$

Quite complicated nonlinear matrix integro-differential equation, can be solved numerically and in some realistic cases even analytically (!!!).

Sterile neutrino mixed with active ones can be produced by oscillations in the early universe (R. Barbieri, AD):

$$\dot{\rho}_{ss} \approx \sin^2\theta_m \,(\Gamma_W/4)\, f_{eq}.$$

Accurate solution of kinetic equation (AD, 2002) found factor 2 error of previous works.

Sterile neutrinos produced by this mechanism are the best candidates for WDM (Dodelson, Widrow).

Distortion of neutrino spectrum (AD, M. Fukugita, 1992), due to residual annihilation of hot e^+e^- into $\bar{\nu}\nu$ practically unobservable in BBN but potentially observable in CMB (Planck), $N_\nu = 3 \rightarrow 3 + 0.03 + 0.01$
(the last 0.01 comes from plasma effects).
Analytical calculations:

$$\frac{\delta f}{f} \approx 3 \times 10^{-4} \frac{E}{T} \left(\frac{11E}{T} - 3 \right)$$

Agree with precise numerical solution of kinetic equations (AD, Hansen, Semikoz, 1997).

Equilibration of lepton asymmetry of all neutrino flavors if LMQ solution is realized (AD et al, 2002).
BBN bounds on cosmological lepton asymmetry:

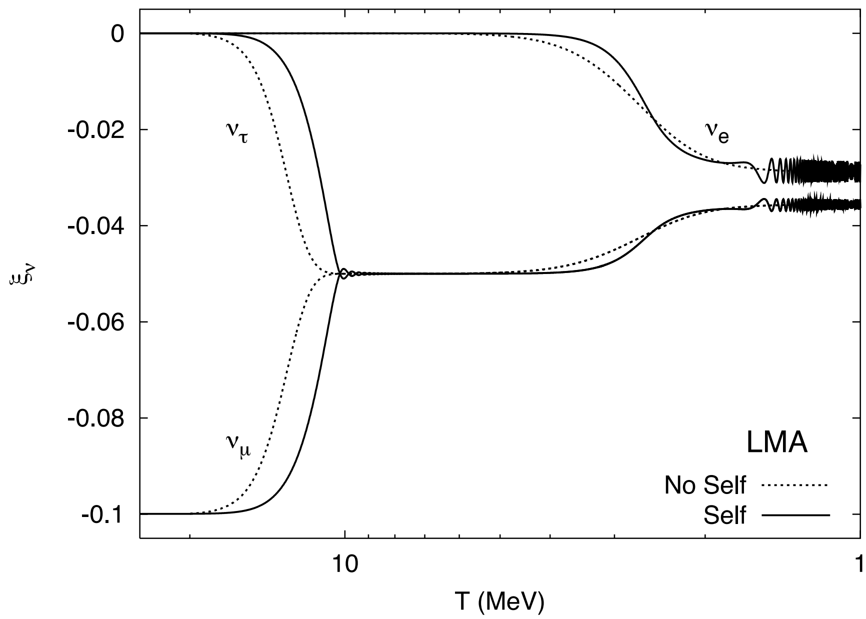
$$|\xi_e| < 0.1, \quad \xi_{\mu,\tau} < 2 - 3,$$

where $\xi = \mu/T$.
Strong mixing of all active neutrinos leads to $\xi_e = \xi_\mu = \xi_\tau$ and

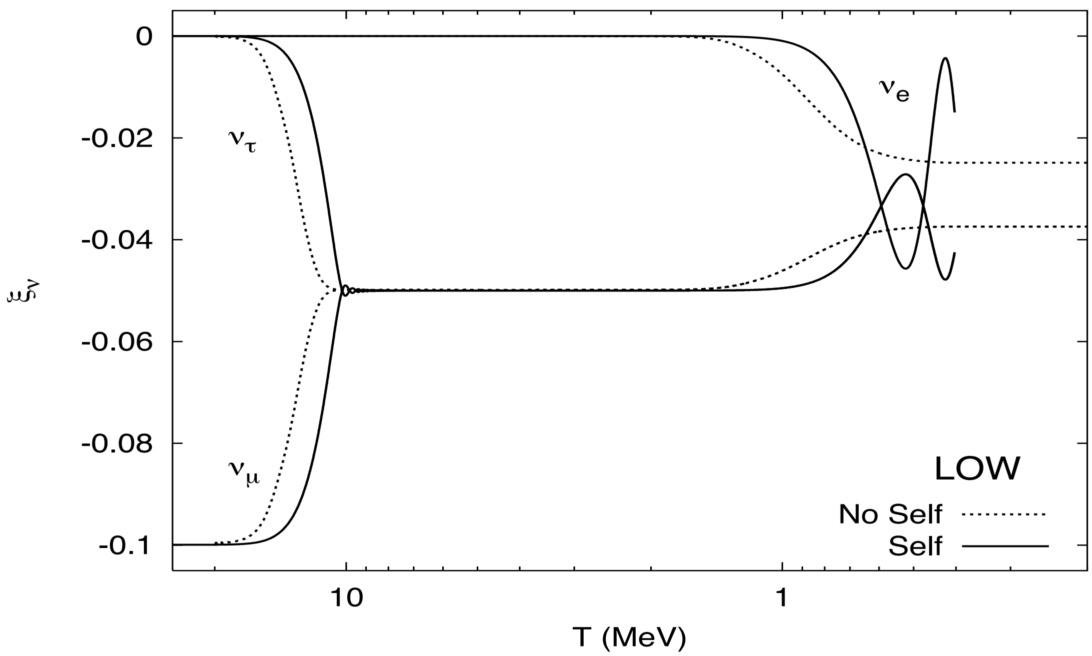
$$|\xi_a| < 0.07.$$

Interactions with majorons can lift this bound (AD, F.Takahashi). The asymmetry would be cosmologically essential if $\xi \sim 1$.

Evolution of lepton charge asymmetry for LMA solution to solar anomaly.



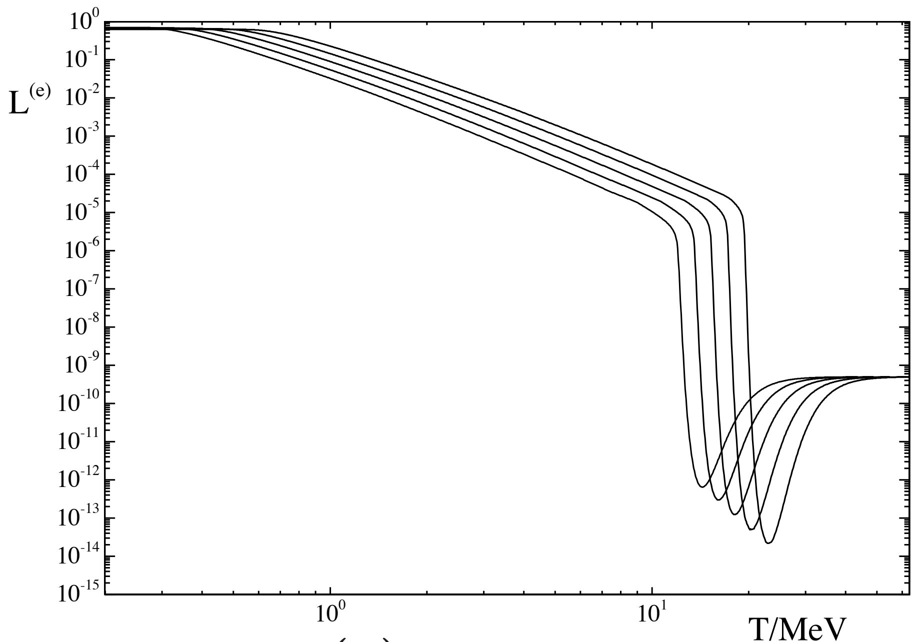
Evolution of lepton charge asymmetry for LOW solution to solar anomaly.



Generation of large lepton asymmetry Foot, Thomson, Volkas, numerically; contradictions with some other papers; AD - analytically.

Due to charge asymmetric term in the refraction index the evolution equation becomes nonlinear and if MSW resonance is realized, leptonic charge asymmetry might rise from 10^{-9} to almost 1.

Resonance generation of lepton asymmetry



Evolution of $L^{(e)} = 2L_{\nu_e} + \eta$ for $\nu_e \to \nu_s$ oscillations with $\sin^2 2\theta_0 = 10^{-8}$ and, from left to right, $\delta m^2/eV^2 = -0.25, -0.5, -1.0, -2.0, -4.0$. The initial $L_{\nu_e} = 0$ is taken and $\eta = 5 \times 10^{-10}$ is assumed. The low temperature evolution is weakly dependent on these values.

Breaking of spin-statistics theorem (AD and Smirnov, 2005)

Neutrinos may condense in the universe and make both CDM and HDM.

Choice for DM: either old physics and new particles or new physics and old particles.

Fundamental theory is still lacking.

2-beta decay search.

Maybe neutrinos are messenger from new world with broken sacred principles: Lorentz, CPT, etc...

Conclusion

Our universe would be completely different without neutrinos and maybe even not fit for life.

Neutrinos brought many discoveries and hopefully will bring more.

B.M. Pontecorvo anticipated impressive new physical phenomena and methods of their observation.

Maybe neutrinos give us the best chance for discovery of more new physics.