# The evolution and decay of hadronic inhomogeneities in the early universe


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(Work done in collaboration with

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Based on arXiv : 180506241

COSMO 2018

Daejeon, Korea

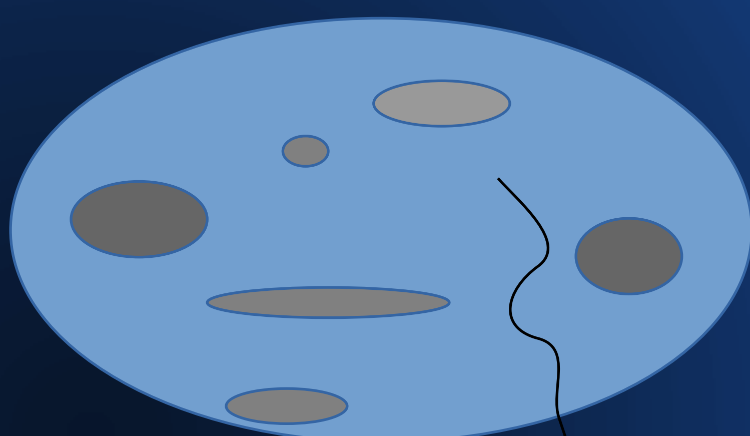
August 27 - 31, 2018.

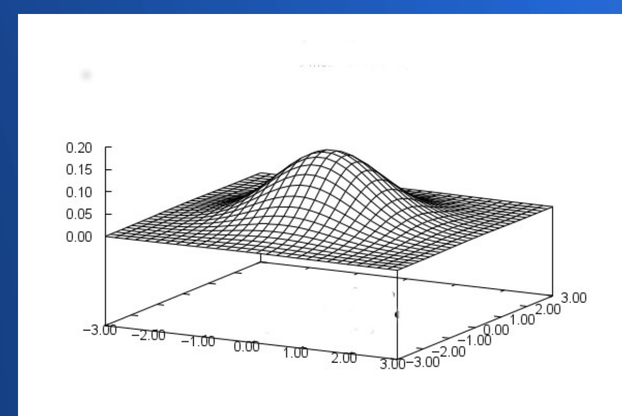
# Plan of the talk

- Brief description of baryon inhomogeneities
- Previous studies of their decay
- Diffusion coefficient of nucleons in presence of muons
- Decay of inhomogeneities in multiparticle plasmas
- Effect on neutrino chemical potential
- Summary
- Acknowledgements

# Baryon inhomogeneities

- Generated by the trapping of a higher density of baryon number in small regions after the quark – hadron phase transition.
- They can be formed irrespective of the order of the phase transition





# Decay of Baryon Inhomogeneities

- Decay due to the diffusion of neutrons and protons from higher density regions to lower density regions
- Decay is important as the neutron/proton ratio is a crucial input to the big bang nucleosynthesis calculations
- Plasma consists predominantly of leptons, neutrons and protons
- Previously diffusion of neutrons and protons were studied in such a plasma
- Collision with muons was neglected as their contribution is considered to be too small

# Can we really neglect muons ?

- Inhomogeneities formed from collapsing Z(3) domain walls lead to accumulation of a large number of strange quarks
- Hadronization of these inhomogeneities result in hyperons
- Hyperons decay into pions and muons
- Metastable quark nuggets emit kaons which decay to muons

# Diffusion Coefficients

- We calculate the diffusion coefficient of neutrons in the presence of muons
- Since it is a multiparticle plasma, average diffusion coefficient is given by

$$\frac{(1 - x_i)}{D_i} = \sum_{i \neq j} \frac{x_j}{D_{ij}}$$

- If N be the total number of particles then $x_i = \frac{n_i}{N}$

# Calculation of Diffusion Coefficients

We obtain the diffusion constants from the scattering cross – section of the particles

$$D_{ne} = \frac{\mathrm{M}^2}{32\mathrm{m}^3}\,\frac{1}{\alpha\kappa^2}\,\frac{\mathrm{e}^{\frac{1}{\mathrm{T}}}}{\mathrm{T}\,\mathrm{f}(\mathrm{T})}$$

Since both electrons and muons are similar in their interaction with the neutron, the difference in their diffusion constants will be by a factor and the difference in their masses

# Calculation of Diffusion Coefficient

Differential Cross section of the neutron and the muon is given by

$$\frac{d\sigma}{d\Omega} \approx K \frac{\alpha^2\kappa^2}{4\,M^2}\left[1 + \ cosec^2\,{}^{\theta}\!/_{2}\right]$$

The diffusion coefficient is :

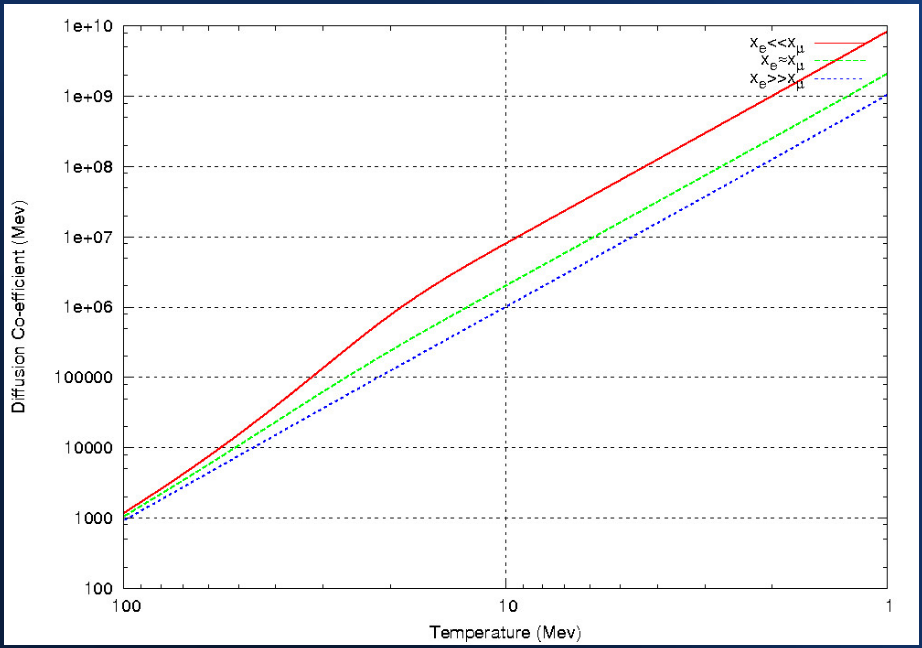
Here T' depends on mass of muon

$$D_{n\mu} = \frac{\mathrm{M}^2}{32\mathrm{m}^3}\,\frac{1}{\alpha\kappa^2}\,\frac{\mathrm{e}^{\frac{1}{\mathrm{T}'}}}{\mathrm{T}\ \mathrm{f}(\mathrm{T}')}$$

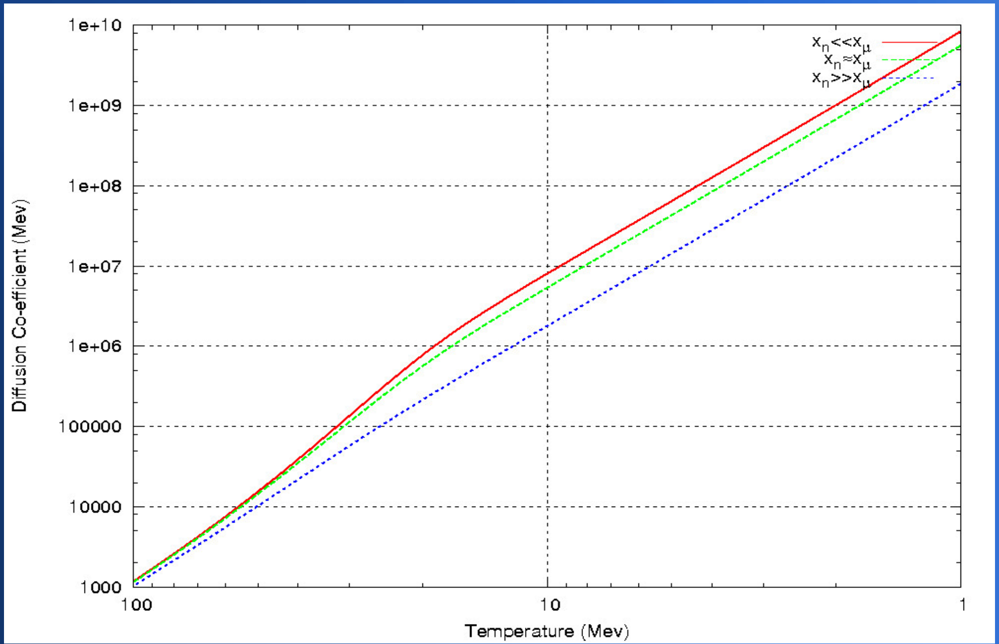
Since the net diffusion constant depends on the densities of the particles we keep the density of one particle constant

# Density dependency of the diffusion coefficients

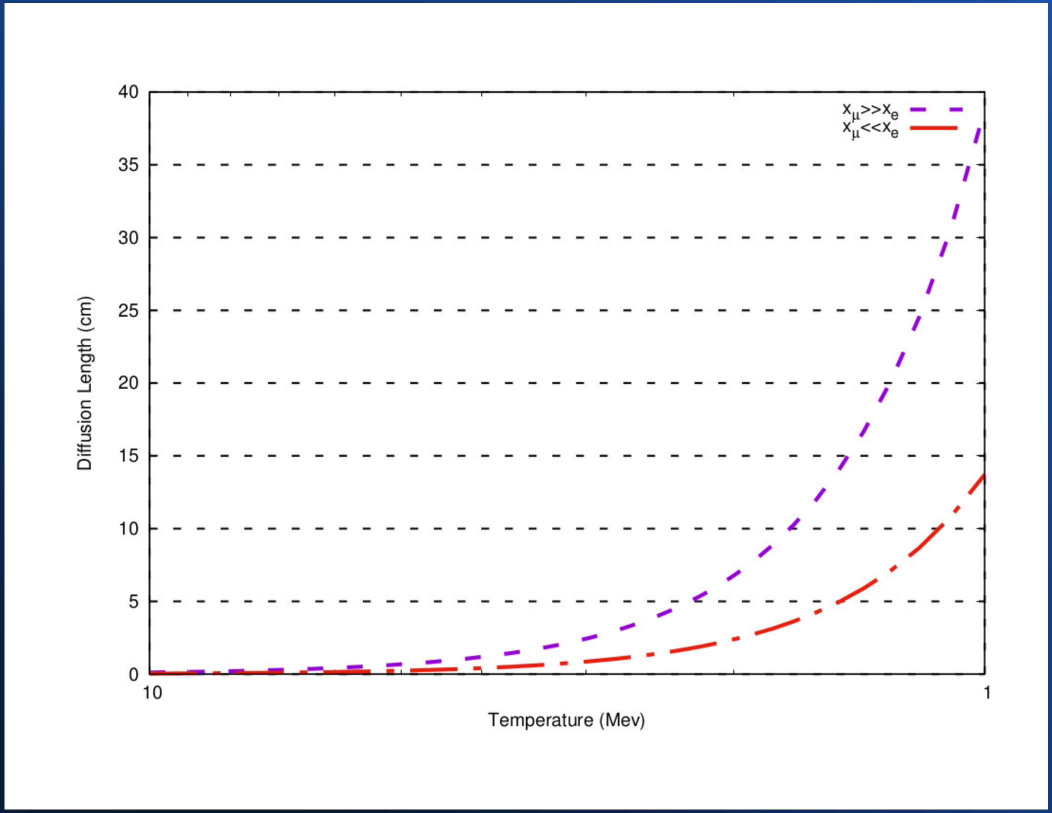
Neutron density is kept constant




Electron density is kept Constant



# The Diffusion Length




We also calculate the Diffusion length of the neutrons in the nucleon, electron and muon plasma

# Decay of overdensities

We assume the over densities to be Gaussian and evolve them using the diffusion equation

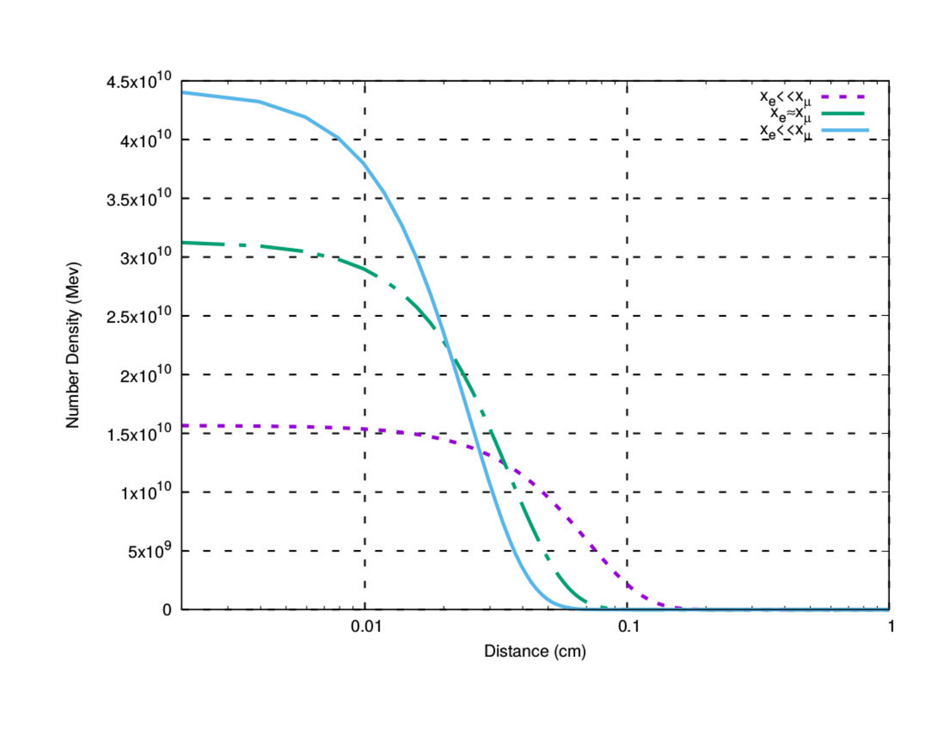
The decay of the over density is studied with respect to both space and time

Diffusion coefficient is dependent on time so the equation is solved numerically

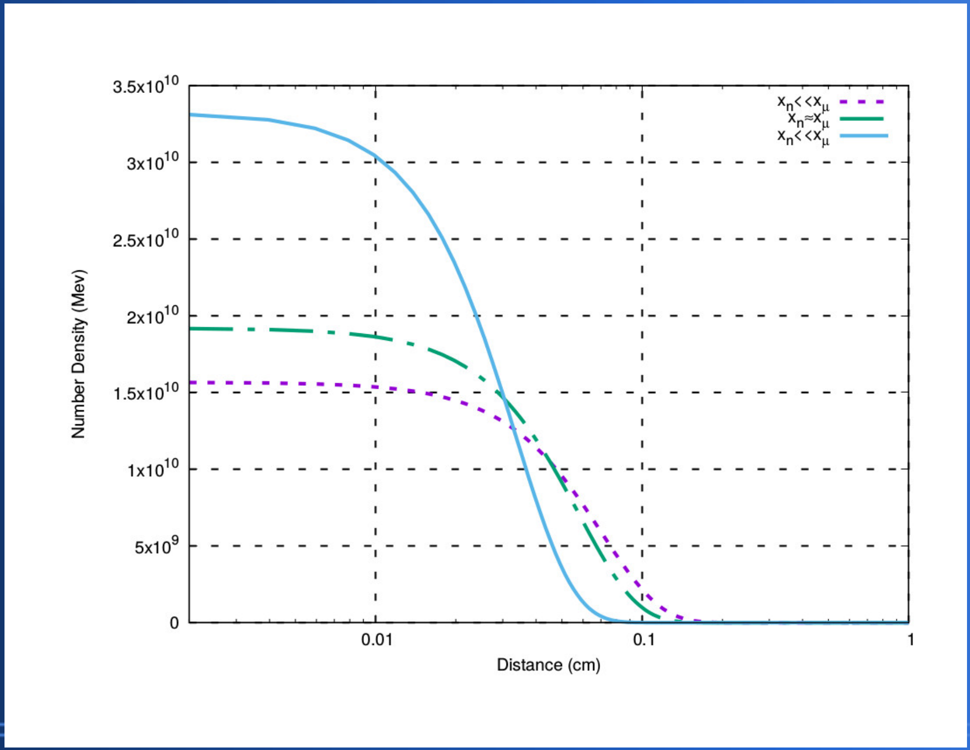
$$\frac{D(t)}{a^2}\frac{\partial^2 n(x,t)}{\partial x^2} = \frac{\partial n(x,t)}{\partial t} = -\lambda^2$$

# Decay of overdensities (At constant temperature)

Neutron density is kept constant

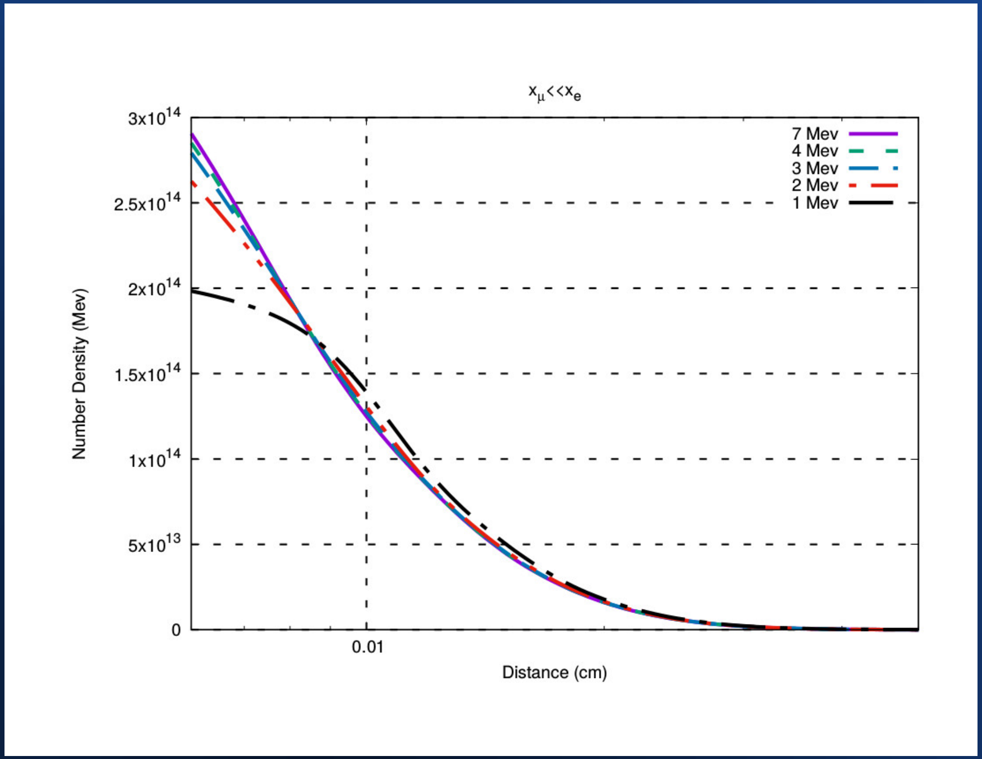



Electron density is kept constant

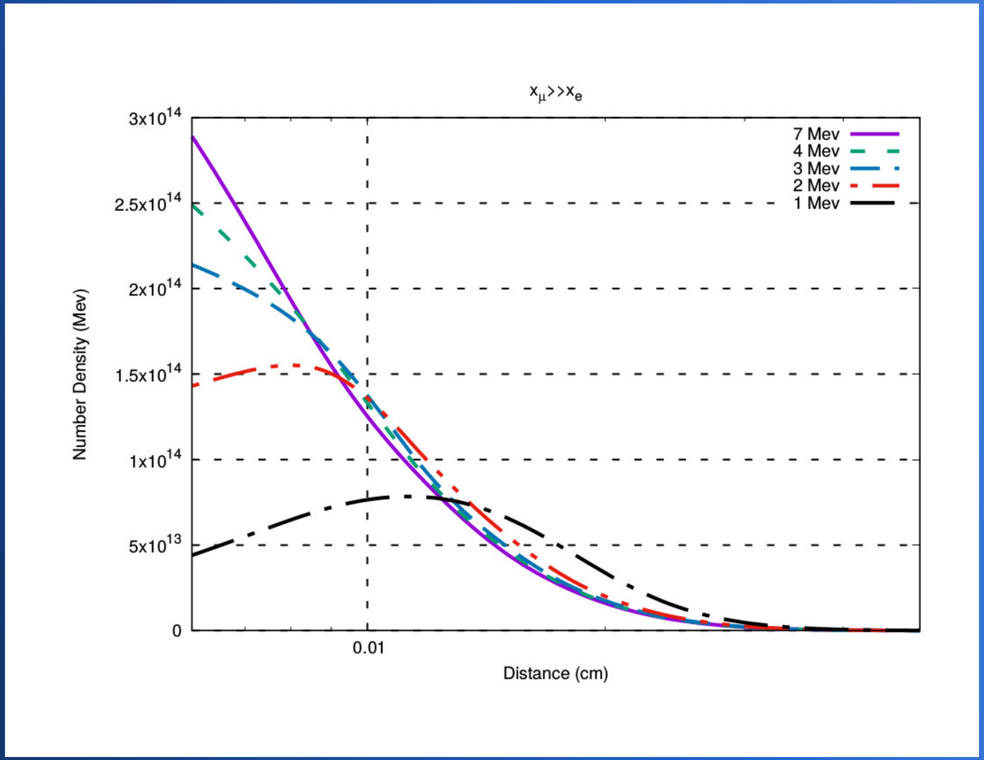


# Decay of overdensities (As temperature decreases)

In Electron Rich Plasma




In Muon Rich Plasma



# Generation of neutrinos

Hyperon decay leads to generation of pions and muons as well as neutrinos

Eg : $\Omega^-$ can decay into charged kaon and $\Lambda$. The decay of $K^-$ will generate a $\nu_\mu$

Similarly $\nu_e$ can also be generated

Chemical potential of the neutrinos are an important input to nucleosynthesis calculations

# Neutrino Degeneracy parameters

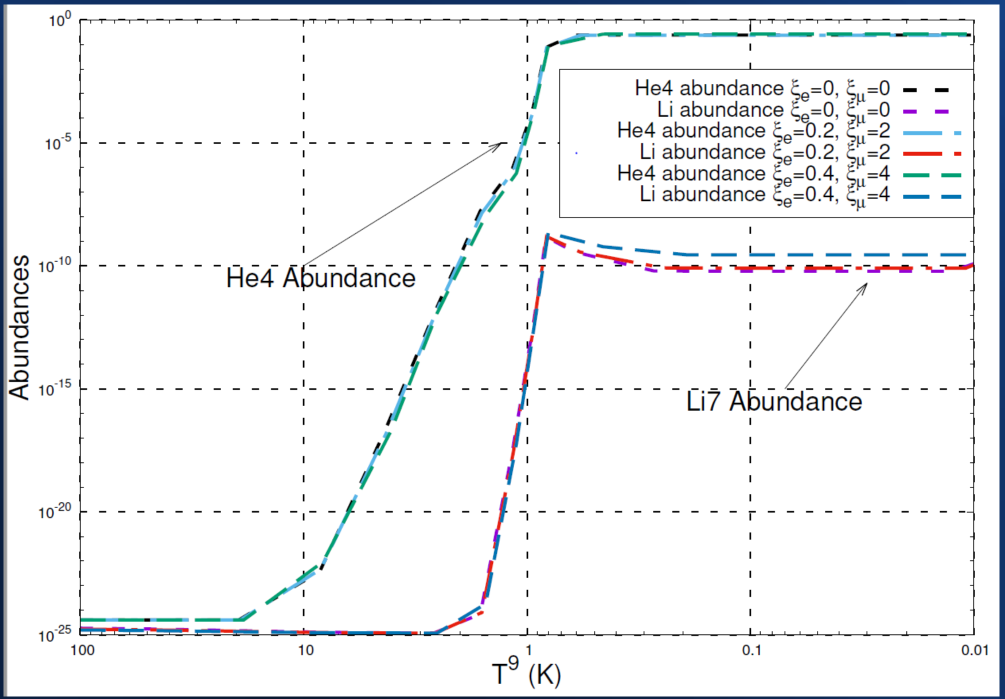
The lepton numbers are given by

$$L_{\nu_i} \approx \frac{\Pi^2}{12\zeta(3)}\left(\frac{T_\nu}{T_\gamma}\right)^3\left(\underbrace{\xi_i}_{\text{Chemical Potential}} + \frac{\xi_i^3}{2\Pi^2}\right)$$

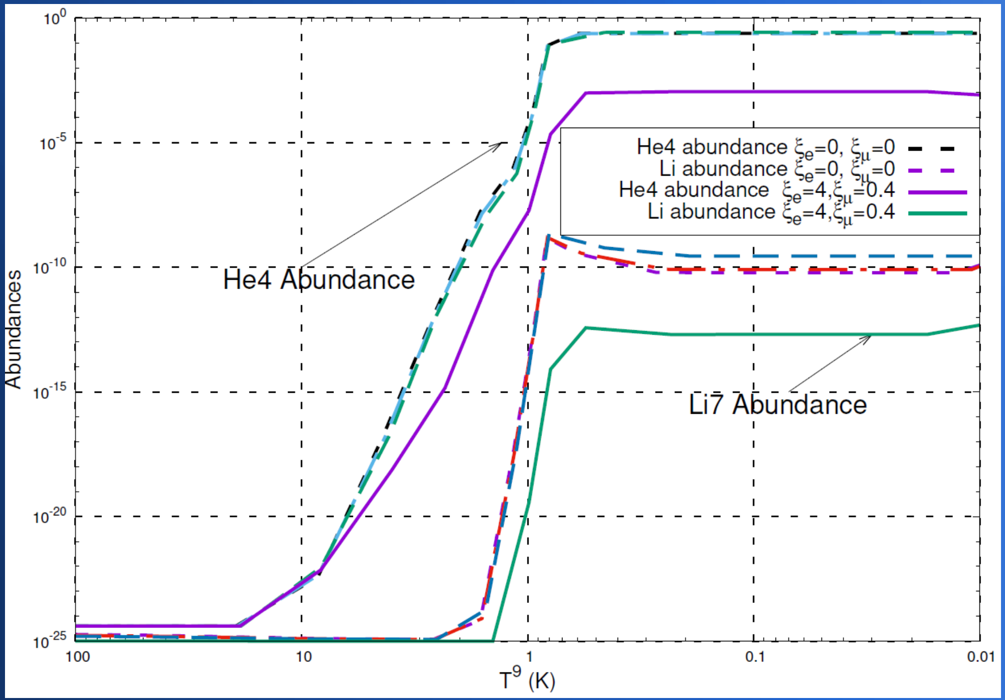
Thus if $L_{\nu\mu} > L_{\nu e}$ or vice versa, nucleosynthesis results would be affected by such inhomogeneities

# Comparison of abundances

Muon neutrino > Electron neutrino




Electron neutrino > Muon neutrinos



# Conclusions

- Baryonic inhomogeneities decay faster in a muon rich plasma compared to an electron rich plasma
- Inhomogeneities generated for scenarios where the strange quarks are selectively filtered will decay before nucleosynthesis
- A large muon neutrino degeneracy parameter will make insignificant changes to the production of the primordial elements
- However Inhomogeneities which enhances the electron degeneracy factor should be studied further as they affect the primordial abundances significantly

# Main References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# Acknowledgements


- We have used a publicly available standard code of nucleosynthesis based on the Wagoner – Kawano code and modified by S. Dodelson to study the primordial abundances.
- Department of Science and Technology, India (PURSE Grant)