Neutrino Spin Flavor Oscillations in the Intergalactic Medium

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Plan of talk

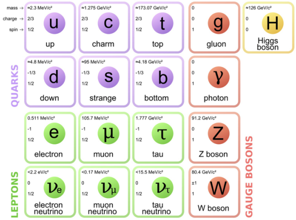
1. SM and its limitations
2. Neutrino Oscillations
3. Spin Flavor Oscillations
4. Effects of Intergalactic magnetic field on Neutrinos
5. Conclusions

Based on *"Cosmic neutrino flux and spin flavor oscillations in intergalactic medium"*, Ashutosh Kumar Alok, NRSC and Arindam Mandal, Phys. Lett. B 839, 137791 (2023).

SM and its limitations

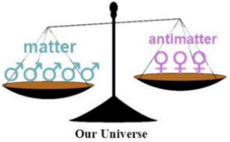
Sometimes regarded as
theory of almost everything!

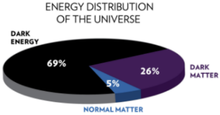
$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

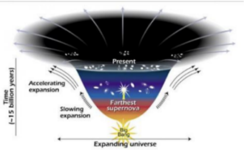


Why SM is not a complete theory?

SM fails to account for the matter-antimatter asymmetry of the Universe
SM does not include gravity
SM includes no dark matter and dark energy candidates







We need to look for physics beyond Standard Model!

Neutrinos in the SM

- Only neutral fermions in the SM
- Neutrinos do not feel a strong force or electromagnetic force
- Massless, move with the speed of light and neutrinos are always left handed (opposite for anti-neutrinos)

- Trillions of neutrinos pass per second through you for every second of your life!
- They come from the sun, atmosphere, natural radioactivity in the Earth, and the relic neutrinos from the Big Bang
- Even a light year of lead (six trillion miles) would only stop half of the neutrinos flying through it

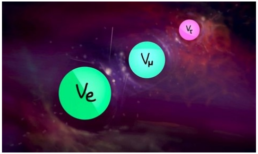
UBIQUITOUS BUT MYSTERIOUS PARTICLES!

Neutrino Oscillations

It is a quantum mechanical phenomenon, first proposed by Bruno Pontecorvo in 1957, followed by Maki, Nakagawa & Sakata in 1962, which successfully explained the famous Solar Neutrino Anomaly.

- ν_e, ν_μ and ν_τ are flavor eigenstates, not mass eigenstates
- Interference of different massive neutrinos
- Oscillations between different active neutrino flavors are possible if neutrinos are massive and mixed

$$\nu_e = \nu_1 cos\theta + \nu_2 sin\theta$$
$$\nu_\mu = - \nu_1 sin\theta + \nu_2 cos\theta$$



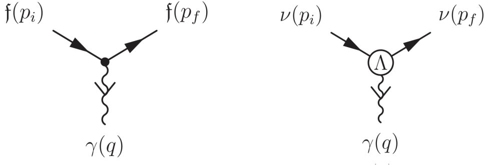
Noble Prize in 2015 has been awarded to T. Kajita (SuperK collab.) and A.B. McDonald (SNO collab.) for the discovery of neutrino oscillations which confirms that neutrinos have mass.

Electromagnetic (EM) properties of neutrinos

- A finite neutrino mass would lead to EM properties: First mentioned by Pauli in 1930
- Such interactions can arise due to the quantum loop effects

$$H_{em}^{(\nu)}(x) = \bar{\nu}(x)\ \Lambda_\mu\ \nu(x)\ A^\mu(x)$$

where Λ_μ is a vertex function in which neutrino EM properties are contained



$$\Lambda_\mu(q) = f_Q(q^2)\ \gamma_\mu \text{ - } f_M(q^2)\ \iota\sigma_{\mu\nu}\gamma^\nu + f_E(q^2)\sigma_{\mu\nu}\gamma^\nu\gamma_5 + f_A(q^2)\ (q^2\gamma_\mu - q_\mu q)\gamma_5$$

where f_Q, f_M,f_E, and f_A are real charge, dipole magnetic and electric, and anapole moment form factors. [Giunti & Studenikin 2015]

In the Minimal Extended SM (MESM) with Right-handed neutrinos (SM allowing neutrinos to be massive), finite value of neutrino magnetic moment is allowed.

Electromagnetic (EM) properties of neutrinos

In the MESM, the magnetic moment can be written as

$$\mu_\nu = \frac{3eG_F m_\nu}{8\pi^2\sqrt{2}} \approx 3.2x10^{-19} \frac{m_\nu}{1eV} \mu_B$$

$\mu_B \rightarrow$ Bohr Magneton [Lee & Shrock 1977, Shrock & Fujikawa 1980]

Measurements on Neutrino Magnetic moment

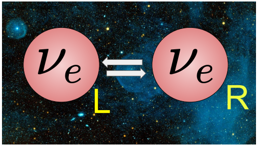
- Terrestrial Experiments: $\mu_\nu \sim 10^{-11}\ \mu_B$ [TEXONO 2006, Borexino 2017, GEMMA 2007], $\mu_\nu \sim 10^{-12}\ \mu_B$ [XENON1T 2022]
- Astrophysical Bounds: d.o.f. in BBN, stellar cooling via plasmon decay, cooling of SN1987a, Red giant Luminosity etc [Brdar, Greljo, Kopp and Opferkuch 2020]

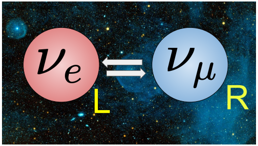
μ_ν can be enhanced up to these levels in a number of new physics models!

The study of Neutrino EM properties is important as they are directly related to fundamental particle physics!

Spin Flavor Oscillations

- Idea was introduced by Voloshin, Vysotsky and Okun in 1986 to explain solar neutrino deficit
- Due to μ_ν, neutrinos can interact with magnetic fields
- μ_ν induces an LH to RH neutrino(and vice-versa) transition due to helicity Flip when placed in a magnetic field - Spin Flip Precession
- Flavor oscillations will also subsist during the passage through an external magnetic field -Flavor oscillations
- As a result, both spin and flavor oscillations can proliferate during their propagation - " Spin Flavor oscillations"





Larger effects can be seen in the astrophysical set-ups!

Intergalactic Magnetic Field

- Several measurements show that such fields do exist: Omnipresent
- Spans over astonishingly large scales : Interstellar as well as Intergalactic
- Magnetic energy contributions coming from individual galaxies are being stored in the intergalactic separations (μG or less)

Measurements on IG Magnetic fields

- Interstellar magnetic field of the Milky Way is measured to be 2.93 μG within a small uncertainty [Zirnstein et al 2016]
- The first direct measurement of the magnetic field strength in the Coma Cluster is about 2 μG spanning over a scale of 13-40 kpc [Kim et al 1990]
- Even found in the voids with a strength of $\sim 10^{-16} G$ extending coherently over Mpc scales [Vachaspati 2021, Subramanian 2016]

Although this field is small ($O(\mu\mathrm{G})$ or less), this can effectuate observable spin-flavor oscillations since the neutrinos can travel a very large distance in the interstellar and intergalactic field!

SFP in IG magnetic field

- The Dirac equation obeyed by neutrinos in the presence of a magnetic field is

$$(\gamma_\mu p^\mu - m_i - \mu_i \boldsymbol{\Sigma B})\nu_i^s(p) = 0$$

$\nu_i^s \rightarrow$ wave function of neutrino of i-th mass eigenstate
$s \rightarrow$ eigenvalues of the spin operator which commutes with the Hamiltonian

- The spin-flavor oscillation probability can be written as,

$$P_{\alpha\beta}^{hh'}(x) = |\langle \nu_\beta^{h'}(0)|\nu_\alpha^h(x)\rangle|^2$$

- For a neutrino flux traversing a very large distance, the probability is averaged out to,

$$P_{\alpha\beta}^{hh'}(x) = \delta_{\alpha\beta}\delta_{hh'} - 2\sum_{\{i,j,s,s'\}} \mathrm{Re}([A_{\alpha\beta}^{hh'}]_{i,j,s,s'}) \,.$$

where $[A_{\alpha\beta}^{hh'}]_{i,j,s,s'} = U_{\beta i}^* U_{\alpha i} U_{\beta j} U_{\alpha j}^* (C_{is}^{h'h})(C_{is}^{h'h})^*$, $C_{is}^{h'h} = \langle \nu_i^{h'}|\hat{P}_i^s|\nu_i^h\rangle$ and $U^{'}s$ are the PMNS matrix elements.

SFP in IG magnetic field

- The flux of neutrinos passes through an omnipresent intergalactic magnetic field: may undergo spin-flavor oscillations
- Some crucial effect on active neutrino flux is expected!
- The active neutrino flux on earth from a very distant source can be obtained as,

$$\Phi_{\beta}^{\oplus} = \sum_{\alpha} P_{\alpha\beta}^{LL} \Phi_{\alpha}^{s},$$

$\Phi^{\oplus} \rightarrow$ flux on earth
$\Phi^{s} \rightarrow$ flux at the source

- The process of averaging out the probablity is subject to the number of cycles completed by the oscillation waveforms

SFP in IG magnetic field

- The phase of oscillations ϕ is composed of two different phases, $\phi = \phi_v + \phi_B$

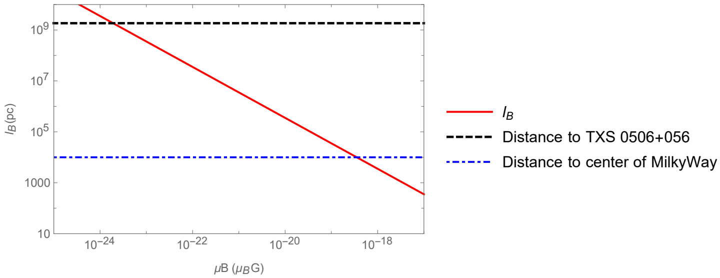
$$\phi = \left[\frac{\Delta m_{ij}^2}{2p} + \mu_\nu (s - s') B_\perp\right] x$$

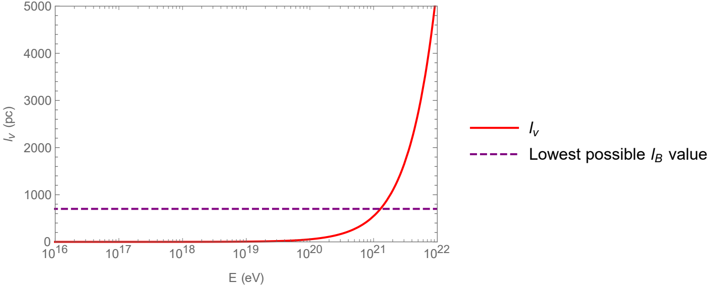
- The probability is sum of terms like $(\sin^2 \phi_v)(\sin^2 \phi_B)$, which forms a modulated waveform

- The oscillation length corresponding to each of them is given by $l_v = \frac{\pi}{\omega_v}, \quad l_B = \frac{\pi}{\omega_B}$

Probability can be averaged out iff $n = \frac{x}{l_v / l_B} \gg 1$ [$n = 100$ (at least)]

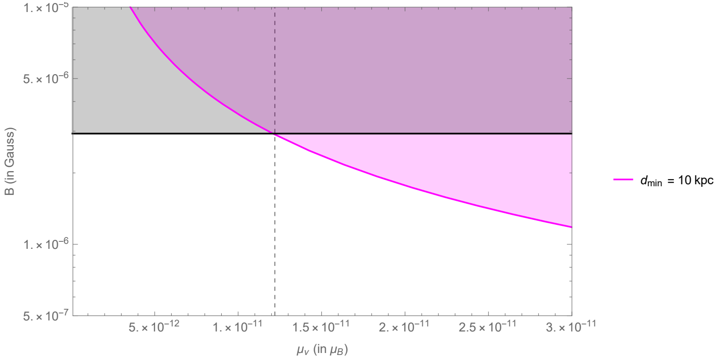
SFP in IG magnetic field





SFP in IG magnetic field

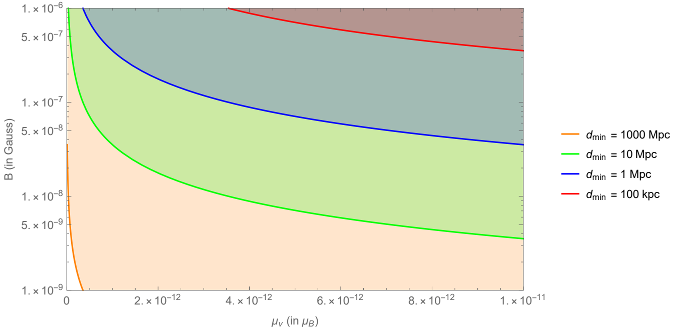
- For sources lying within the Milky Way Galaxy,



- Averaging out is not possible with the current upper limit of $\mu_\nu \sim 10^{-12}\mu_B$
- Neutrinos do not undergo spin-flip oscillations!

SFP in IG magnetic field

- For larger distances, we find that half of the active neutrinos becomes sterile neutrinos



- The flux of neutrinos from sources located above the distances of several kiloparsecs from Earth is reduced by half!
- However, if the current upper limit of the μ_ν is improved to approximately $10^{-13}\mu_B$, the reduction of cosmic neutrino flux remains unattainable, even when neutrinos traverse the entire length of the visible universe

Conclusions

- The cosmic neutrinos usually perambulate gargantuan scales in the extragalactic universe having a magnetic field
- If neutrinos have a finite magnetic moment (μ_ν) owing to quantum loop corrections, this may result in spin-flavor oscillations, which can affect the cosmic neutrino flux
- The reduction of flux by a factor of half, is satisfied for the neutrino sources lying at a distance of several kpcs from the earth
- The reduction of cosmic neutrino flux is not possible if the current upper limit of μ_ν is improved up to $\sim 10^{-13}\,\mu_{\mathrm{B}}$ even if the neutrinos travel through the entire length of the visible universe

  For a magnetic moment in this range, the effect of spin flavor oscillations can be safely neglected!


THANK
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