ニュートリノ質量、暗黒物質、物質・反物質非対称性と右巻きニュートリノ

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Outline

- Phenomena beyond SM
  1. Neutrino mass
  2. Dark matter
  3. Matter and Anti-matter asymmetry
- Explanation by right-handed neutrinos
Mass in Standard Model

Left-handed: \[\begin{pmatrix} \nu_L \end{pmatrix} \]

Right-handed: \[\begin{pmatrix} \nu_R \end{pmatrix} \]

- Mass term in SM
electron: \[-\mathcal{L}_{mass} = y \bar{L}_L \Phi e_R + h.c.\]

\[m(\bar{e}_L e_R + \bar{e}_R e_L)\]

neutrino: \[-\mathcal{L}_{mass} = y \bar{L}_L \tilde{\Phi} \nu_R + h.c.\]

\(\nu_R\) is not in SM, so neutrino mass = 0
Motivation

ν mass by experiment:

\( m_2^2 - m_1^2 = (0.00868\text{eV})^2 \)
\( m_3^2 - (m_2^2 + m_1^2)/2 = (0.0494\text{eV})^2 \)

\( \nu_R \) can explain **neutrino mass**

Problem in cosmology:

- Dark matter
- Matter-anti-matter asymmetry

Q. All solved by \( \nu_R \)?

A. **YES** (Conclusion)
Neutrino mass

General mass term

\[-\mathcal{L}_{\text{mass}} = \frac{1}{2} \left( \nu_L \nu^c_R \right) \begin{pmatrix} M_L & yv \\ y^T v & M_R \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix} + \text{h.c.} \]

Block diagonalization \((M_L, yv \ll M_R)\)

\[
\begin{pmatrix} m_\nu & 0 \\ 0 & M_N \end{pmatrix} \quad m_\nu = M_L - v^2 y M_R^{-1} y^T \quad (0) : \text{light}
\]

\[
\tilde{M}_N \simeq M_R \quad : \text{heavy}
\]

\(m_\nu\) and \(M_N\) are diagonalized by mixing matrix \(U, V\)

\[
m_\nu^{\text{diag}} = U^\dagger m_\nu U^* \\
M_N^{\text{diag}} = V^\dagger M_R V^*
\]
Interaction of $v_R$

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- $\nu_R$ interact weakly by mixing with $\nu_L$ $\rightarrow$ Dark matter

Life time: $\tau \sim 10^7 \tau_U$ (for $M_1 = 7\text{keV}, \Theta_1^2 = 10^{-10}$)
Production of $\nu_{R1}$ DM

Assumption 1: $\nu_R$ were in thermal equilibrium
-> Introduce new gauge interaction
   (e.g., Left-right model, GUT)
-> DM is thermal relic

Advantage of thermal relic:
1. No need for assuming initial abundance of $\nu_R$
2. Simple calculation of abundance today
3. Colder than other mechanism (‘94 Dodelson, Widrow)
   -> weaker constraint from Ly-\(\alpha\)
Production of $v_{R1}$ DM

- Problem of thermal relic: Over production

$$\frac{n_{N_1}}{s} = \frac{1}{g_s} \frac{135 \zeta(3)}{4\pi^4} : \text{constant}$$

$$\Omega_{N_1} \gtrsim 10\Omega_{DM}$$

$$\gg \Omega_{DM} \sim 0.3$$

- Solution: Diluted by Entropy production

$$s \rightarrow \frac{S_{after}}{S_{before}} s$$

Assumption 2: $v_{R2}$ decay produce entropy

$$\frac{S_{after}}{S_{before}} \sim 10$$
Thermal history

\[ T_{\text{freeze out}} \]

\[ T_{f} \]

\[ N_{2} \text{ decay} \]

\[ \rho_{\text{DM}}/M_{1} \]

\[ 0.416/g_{*f} \]

\[ 0.86 \times 10^{-10} \]

\[ M_{2} > 10^{9} \text{GeV} \]

\[ T_{\text{decay}} > 10^{6} \text{GeV} \]

\[ T_{0} \]

\[ v_{R1}, v_{R2} \text{ was in equilibrium} \]

\[ v_{R2} \text{ decay produce baryon and dilute } v_{R1} \]

\[ ('13 \text{ Bezrukov,Kartavtsev,Lindner}) \]

parameters considering \( m_{\nu} \) (this work)
Entropy production

Ratio of entropy before and after $v_{r2}$ decay:

$$10 \sim \frac{S_{after}}{S_{before}} \propto \frac{1}{\sqrt{\Gamma_{N_2}}}$$

$$\Gamma_{N_2} = \frac{(\tilde{y}^\dagger \tilde{y})_{22}}{8\pi} M_2$$

$$(\tilde{y}^\dagger \tilde{y})_{22} = 1.1 \times 10^{-14} \left( \frac{\text{keV}}{M_1} \right)^2 \left( \frac{M_2}{10^9 \text{GeV}} \right)$$ (1)
Matter-antimatter asymmetry

$N_2$ decays into lepton and anti-lepton

$$\epsilon \propto \frac{N_I}{L_{\alpha}} \Phi \quad \frac{\tilde{y}_{\alpha I}}{\tilde{y}_{\alpha I}^*} \frac{\Phi^*}{L_{\alpha}}$$

Ratio: $1,000,000,000$ : $1,000,000,001$

Baryon number:

$$\frac{n_B}{s} = -1.4 \times 10^{-4} \epsilon \left(\frac{\text{keV}}{M_1}\right)$$

By 1-loop calculation of $\epsilon$,

$$\text{Im}[\langle \tilde{y}^\dagger \tilde{y} \rangle_{32}^{2}] = 1.66 \times 10^{-19} \frac{\text{keV}}{M_1} \frac{M_2}{10^9 \text{GeV}} \frac{1}{g(M_3^2/M_2^2)}$$

(2)
Parameter

\[-\mathcal{L}_{\text{mass}} = \frac{1}{2} \left( \nu_L \bar{\nu}_R \right) \begin{pmatrix} M_L & yv \\ y^T v & M_R \end{pmatrix} \begin{pmatrix} \nu^c_L \\ \nu_R \end{pmatrix} + \text{h.c.} \]

Condition:
1. Neutrino mass

\[ m_\nu = M_L - v^2 y M_R^{-1} y^T \quad (0) \]

2. Dark matter

\[(\tilde{y}^\dagger \tilde{y})_{22} = 1.1 \times 10^{-14} \left( \frac{\text{keV}}{M_1} \right)^2 \left( \frac{M_2}{10^9 \text{GeV}} \right) \quad (1) \]

3. Matter asymmetry

\[ \text{Im}[(\tilde{y}^\dagger \tilde{y})_{32}^2] = 1.66 \times 10^{-19} \frac{\text{keV}}{M_1} \frac{M_2}{10^9 \text{GeV}} \frac{1}{g(M_3^2/M_2^2)} \quad (2) \]
Result

Masses of $\nu_R$: 
\[ M_1 \sim \text{keV}, \quad M_2 \gtrsim 10^9 \text{GeV} \]

Yukawa coupling: 
\[ \tilde{y}_\nu = iV_\nu (X_\nu^{\text{diag}})^{1/2} R (M_R^{\text{diag}})^{1/2} \]

\[ X_\nu \equiv m_\nu - M_L, \quad X_\nu^{\text{diag}} = V_\nu^\dagger X_\nu V_\nu^* \quad R \sim \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \]

Mixing of $N_1$

\[ \Theta_1^2 = \frac{(\tilde{y}y)_{11} v^2}{M_1^2} = \frac{X_2 + X_3 |R_{31}|^2}{M_1} \]
Constraints on $\nu_{R1}$ DM

Figure 2: Constraints on $\nu_{R1}$ DM with a red dot indicating detection at 7 keV. The green area represents $10^{-5}$ eV, the blue area represents $10^{-7}$ eV, and the purple area represents $10^{-9}$ eV. The red region represents $\Omega_{N1} > \Omega_{DM}$. The equation $X_2 + X_3 | R_{31} |^2 = 10^{-9}$ eV is also shown.

References:

Summary

Model:
• **neutrino mass** explained by heavy $\nu_R$
• $\nu_{R1}$ DM produced as thermal relic (over production)
• Decay of $\nu_{R2}$ dilute $\nu_{R1}$ and produce matter-anti-matter asymmetry

Conclusion:
• $m_\nu$, DM, asymmetry of matter can be explained simultaneously
ニュートリノの混合

弱い相互作用の固有状態

\[ \nu_{L\alpha} = U_{\alpha i} \nu'_{Li} + \theta_{\alpha I} \nu'_R \]

\[ \theta_{\alpha I} \equiv (m_D M^{-1})_{\alpha I} \]

重いニュートリノは、混合により弱い相互作用をする強さ:

\[ \sim g \theta_I \]

\[ \theta^2_I \equiv \sum_{\alpha=e, \mu, \tau} |\theta_{\alpha I}|^2 \]

重いニュートリノの反応性を決定する変数:
• $g(x)$

図 3.2: $g(x)$（実線）およびその漸近式 $-\frac{3}{2\sqrt{x}}$（点線）。

$$g\left(\frac{M_3^2}{M_2^2}\right) \simeq -\frac{3}{2} \frac{M_2}{M_3} \quad (M_3/M_2 \gtrsim 3)$$
Tremaine-Gunn境界

\[ Q \equiv \frac{\rho}{\langle v^2/3 \rangle^{3/2}} \]

\[ = 3^{3/2} m_{DM}^4 \frac{n}{\langle p^2 \rangle^{3/2}} \]

\[ < \max f(p) = \frac{g_{DM}}{(2\pi)^3} \]

dSph(Coma Berenices等)の観測:

\[ q = 5 \times 10^{-3} \sim 2 \times 10^{-2}, \]

\[ Q = q \frac{M/pc^3}{(km/s)^3} \]

\[ m > 1.0 \text{ keV} \left( \frac{q}{5 \times 10^{-3}} \right)^{1/4} \]
X-ray bound

\[ \Gamma_{\nu_s \rightarrow \gamma \nu_a} = \frac{9}{256\pi^4} \alpha_{EM} G_F^2 \sin^2 \theta m_s^5 \]

\[ = \frac{1}{1.8 \times 10^{21}} \sin^2 \theta \left( \frac{m_s}{\text{keV}} \right)^5 \]
バリオン数生成

・CP: $v_R$ の湯川相互作用
・熱平衡からのずれ:
熱浴の外にいる $v_R$ の崩壊

作られるレプトン数:

$$Y_{L\alpha} \mid \text{崩壊後} \propto \epsilon_{I\alpha} Y_I \mid \text{崩壊前}$$

CPの破れ:

$$\epsilon_{I\alpha} \equiv \frac{\langle \Gamma(N_I \rightarrow L_\alpha \Phi) \rangle - \langle \Gamma(N_I \rightarrow \overline{L_\alpha} \Phi^*) \rangle}{\sum_\alpha \{ \langle \Gamma(N_I \rightarrow L_\alpha \Phi) \rangle + \langle \Gamma(N_I \rightarrow \overline{L_\alpha} \Phi^*) \rangle \}}$$

量子異常によりレプトン数はバリオン数に変換

$$Y_B = \frac{28}{79} Y_L$$
非等方性

\[ E \sim 3 \times 10^{53} \text{erg}, \]

\[ p_{\nu,\text{total}} \sim 1 \times 10^{43} \text{g cm/s}. \]

\[ p_* = (1.4M_\odot)v \sim 3 \times 10^{41} \left(\frac{v}{1000 \text{km/s}}\right) \text{g cm/s} \]

\[ \approx 0.03 \left(\frac{v}{1000 \text{km/s}}\right) p_{\nu,\text{total}}. \]

1%〜5%くらいの非等方性で説明できる
An active neutrino is converted into a sterile neutrino, it no longer interacts with matter and comes out of the star. Some of the sterile neutrinos:

\[
\begin{align*}
n + e^+ & \rightleftharpoons p + \bar{\nu}_e, \\
p + e^- & \rightleftharpoons n + \nu_e, \\
\sigma(\uparrow e^-, \uparrow \nu) & \neq \sigma(\uparrow e^-, \downarrow \nu)
\end{align*}
\]

\(V(\nu_s) = 0,\)
\(V(\nu_e) = -V(\bar{\nu}_e) = V_0(3 Y_e - 1 + 4 Y_{\bar{\nu}_e}),\)
\(V(\nu_{\mu,\tau}) = -V(\bar{\nu}_{\mu,\tau}) = V_0(Y_e - 1 + 2 Y_{\bar{\nu}_e}) + \frac{eG_F}{\sqrt{2}} \left( \frac{3N_e}{\pi^4} \right)^{1/3} \frac{\vec{k} \cdot \vec{B}}{|k|},\)

\[
\frac{\Delta k_s}{k} = \frac{1}{6} \frac{\Delta k_s}{k_s} = \frac{4e\sqrt{2}}{3\pi^2} \frac{\mu_e \mu_n^{1/2}}{m_n^{3/2} T^2} B
\]

\[
= 0.01 \left( \frac{\mu_e}{100 \text{ MeV}} \right) \left( \frac{\mu_n}{80 \text{ MeV}} \right)^{1/2} \left( \frac{20 \text{ MeV}}{T} \right)^2 \left( \frac{B}{3 \times 10^{16} \text{ G}} \right).
\]
excluded region

excluded above if 100% of dark matter

delayed pulsar kick (no MSW)

Fig. 7. The allowed regions for delayed kicks with delays from 1 through 5 s (assuming the other parameters are fixed) are shown by black solid lines marked by the numbers representing the delay time in seconds [18].

There is no reason to believe that it has the same direction or magnitude as the surface field at the end of the neutrino cooling phase. This, however, is only one of several stages in the evolution of the magnetic field. Next, at some temperature below 0 (5 MeV, the nuclear matter becomes a type-II superconductor. The magnetic field lines form the flux tubes, reconnect, and migrate. Next, over some millions of years, the pulsar rotation converts the magnetic field energy into radio waves and causes the field to evolve even further. The end result of this evolution is, of course, a configuration of magnetic fields that is very different from what it was five seconds after the onset of the supernova.

Clearly, the magnetic field inside a hot young neutron star is not expected to have much correlation with the surface field of a present-day pulsar.

5.11. Spin-kick from neutrinos

Spruit and Phinney [204] pointed out that the pulsar rotational velocities may also be explained by the kick received by the neutron stars at birth. The core of the progenitor star is likely to co-rotate with the whole star until about 10 years before the collapse. This is because the core should be tied to the rest of the star by the magnetic field. However, then the angular momentum of the core at the time of collapse is $10^3$ times smaller than the angular momentum of a typical pulsar.

Spruit and Phinney [204] have pointed out that the kick that accelerates the pulsar can also spin it up, unless the kick force is exerted exactly head-on.

The neutrino kick can be strongly off-centered, depending on the configuration of the magnetic field. If the magnetic field of a pulsar is offset from the center, so is the force exerted on the pulsar by the anisotropic emission of neutrinos. This mechanism may explain simultaneously the high spatial velocities and the unusually high rotation speeds of nascent neutron stars. [200] It was suggested by Phinney (private communication) that a highly off-centered magnetic field could be generated by a thin-shell dynamo in a hot neutron star. Since the neutron star is cooled from the outside, a convective zone forms near the surface and, at later times, extends to the interior. While convection takes place in the spherical shell, the dynamo effect can cause a growth in the magnetic field. Thin-shell dynamos are believed to be responsible for generating magnetic fields of Uranus and Neptune [247–249]. According to the Voyager 2 measurements [250], the magnetic fields of both Uranus and Neptune are off-centered dipoles, tilted with respect to the axis of rotation. Unlike other planets, which have convection in the deep interior and end up with a well-centered dipole field, Uranus and Neptune have thin spherical convective zones near the surface, which explains the peculiarity of their dynamos. During the first few seconds after the supernova collapse, convection in a neutron star also takes place in a spherical layer near the surface. The thin-shell dynamo can, in principle, generate an off-center magnetic field in a neutron star, just like it does in Uranus and Neptune. As a result, the anisotropic neutrino emission can give the pulsar the kick, and also spin it up.

5.12. $\vec{B} - \vec{v}$ correlation

While the $\vec{B} - \vec{v}$ correlation is not expected from a neutrino-driven mechanism, one does expect the correlation between the direction of the pulsar motion and the axis of rotation. This is because the neutrino anisotropy axis is associated with the dipole magnetic field, which is rotating with the star. If the pulsar is accelerated by anisotropic emission of neutrinos over the time period of several seconds, the components of the thrust orthogonal to the axis of rotation would average to zero, while the component along the axis would not be affected by rotation (see Fig. 8). As a result, one expects the pulsar to receive a non-vanishing kick along its rotational axis. To probe this correlation, one needs to perform accurate measurements of the polarization of the radio signal from the pulsar. The recent observations confirm the $\vec{B} - \vec{v}$ correlation [211, 215, 216].