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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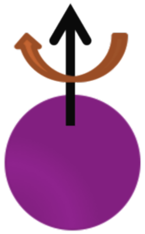
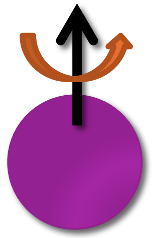
Outline

- 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:  Right-handed : 

- Mass term in SM

electron:

$$-\mathcal{L}_{mass} = y\overline{L_L}\Phi e_R + h.c.$$

$$\Rightarrow m(\overline{e_L}e_R + \overline{e_R}e_L)$$

$$L_L \equiv \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \qquad \langle\Phi\rangle = \begin{pmatrix} 0 \\ v \end{pmatrix}$$

neutrino:

$$-\mathcal{L}_{mass} = y\overline{L_L}\tilde{\Phi}\nu_R + h.c. \quad \times$$

ν_R is not in SM, so neutrino mass = 0

Motivation

ν mass by experiment:

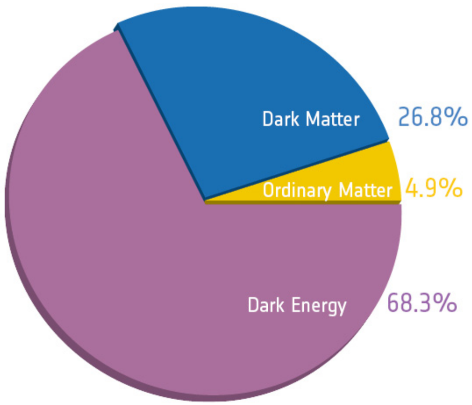
('13 Cappozi et. al.)

$$m_2^2 - m_1^2 = (0.00868\mathrm{eV})^2$$

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

ν_R can explain neutrino mass

ESA/Planck



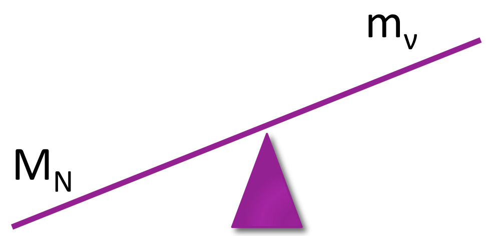
Problem in cosmology:

- Dark matter
- Matter-anti-matter asymmetry

Q. All solved by ν_R ?

A. YES (Conclusion)

Neutrino mass



General mass term

$$-\mathcal{L}_{mass} = \frac{1}{2}\begin{pmatrix}\overline{\nu_L} & \overline{\nu_R^c}\end{pmatrix}\begin{pmatrix}M_L & yv \\ y^T v & M_R\end{pmatrix}\begin{pmatrix}\nu_L^c \\ \nu_R\end{pmatrix} + \text{h.c.}$$

Block diagonalization (M_L,yv<<M_R)

$$\begin{pmatrix}m_\nu & 0 \\ 0 & M_N\end{pmatrix} \qquad \begin{aligned} m_\nu &= M_L - v^2 y M_R^{-1} y^{\mathrm{T}} \quad (0) \quad \text{:light} \\ M_N &\simeq M_R \quad \text{:heavy} \end{aligned}$$

m_ν 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 ν_R

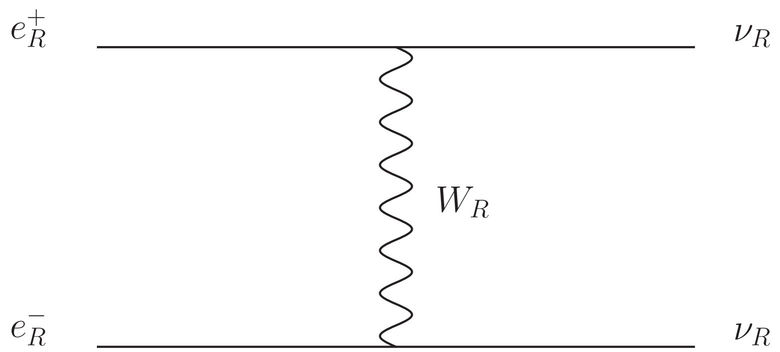
	Weak interaction	Electromagnetic interaction
e_L	○	○
e_R	×	○
ν_L	○	×
ν_R	×	×

- ν_R interact weakly by mixing with ν_L -> Dark matter

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

Production of ν_{R1} DM

Assumption 1: ν_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 ν_R
2. Simple calculation of abundance today
3. Colder than other mechanism ('94 Dodelson, Widrow)
   ->weaker constraint from Ly-α

Production of ν_{R1} DM

- Problem of thermal relic: Over production

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

$$\Rightarrow \quad \Omega_{N_1} \gtrsim 10\Omega_{DM}$$
$$\gg \Omega_{DM} \sim 0.3$$

- Solution: Diluted by Entropy production $s \to \frac{S_{after}}{S_{before}} s$

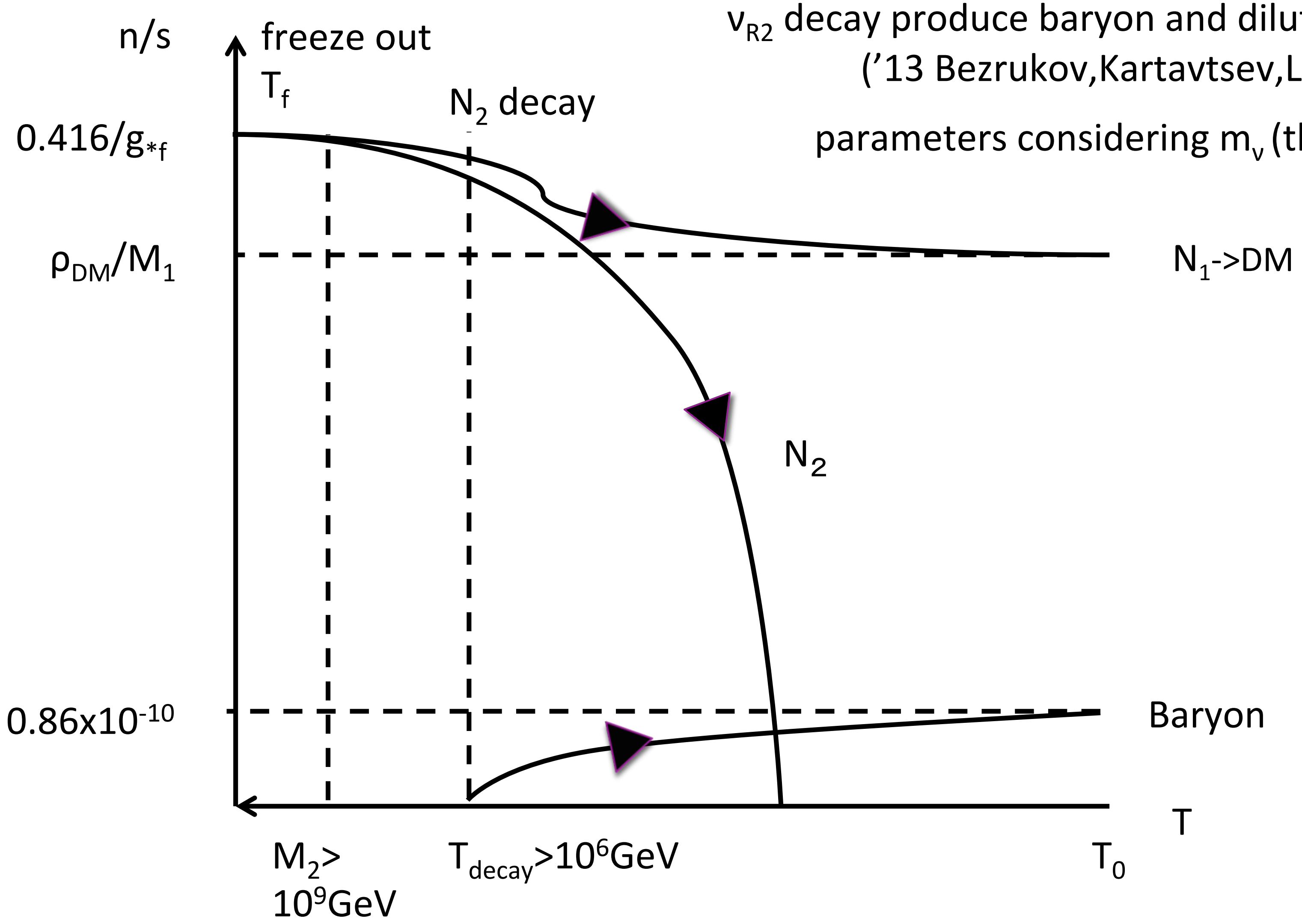
Assumption 2: ν_{R2} decay produce entropy $\frac{S_{after}}{S_{before}} \sim 10$

Thermal history

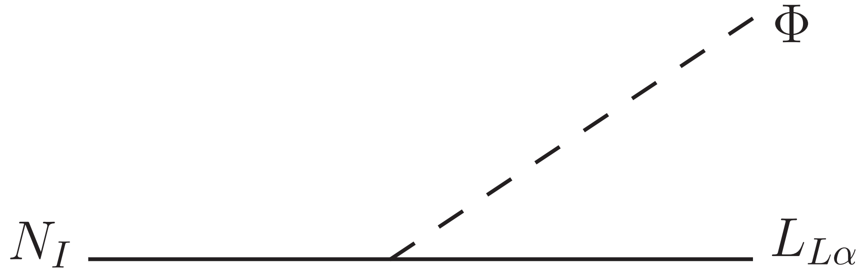
ν_{R1},ν_{R2} was in equilibrium

ν_{R2} decay produce baryon and dilute ν_{R1}
('13 Bezrukov,Kartavtsev,Lindner)

parameters considering m_ν (this work)



Entropy production



$$\tilde{y}_{\alpha I} \equiv (yV^*)_{\alpha I}$$

Ratio of entropy
before and after ν_{R2} decay :

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

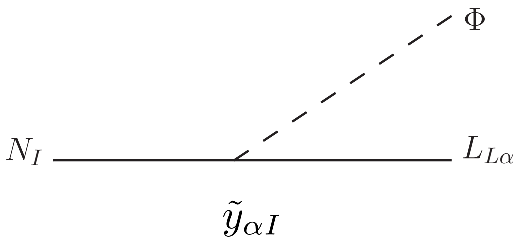
$$\Gamma_{N_2} = \frac{(\tilde{y}^\dagger \tilde{y})_{22}}{8\pi} M_2$$

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

Matter-antimatter asymmetry

N_2 decays into lepton and anti-lepton

$\epsilon \propto$



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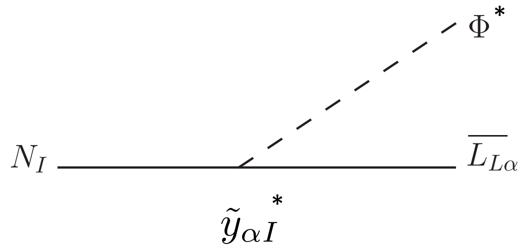


Ratio: 1,000,000,000 : 1,000,000,001

Baryon number:

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

By 1-loop calculation of ε,

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

(2)

Parameter

$$-\mathcal{L}_{mass} = \frac{1}{2}\begin{pmatrix}\overline{\nu_L} & \overline{\nu_R^c}\end{pmatrix}\begin{pmatrix}M_L & yv \\ y^T v & M_R\end{pmatrix}\begin{pmatrix}\nu_L^c \\ \nu_R\end{pmatrix} + \mathrm{h.c.}$$

Condition:

1. Neutrino mass

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

2. Dark matter

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

3. Matter asymmetry

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

Result

Masses of ν_R:

$$M_1 \sim \mathrm{keV},\ M_2 \gtrsim 10^9 \mathrm{GeV}$$

Yukawa coupling:

$$\tilde{y} v = i V_\nu (X_\nu^{\mathrm{diag}})^{1/2} R (M_R^{\mathrm{diag}})^{1/2}$$

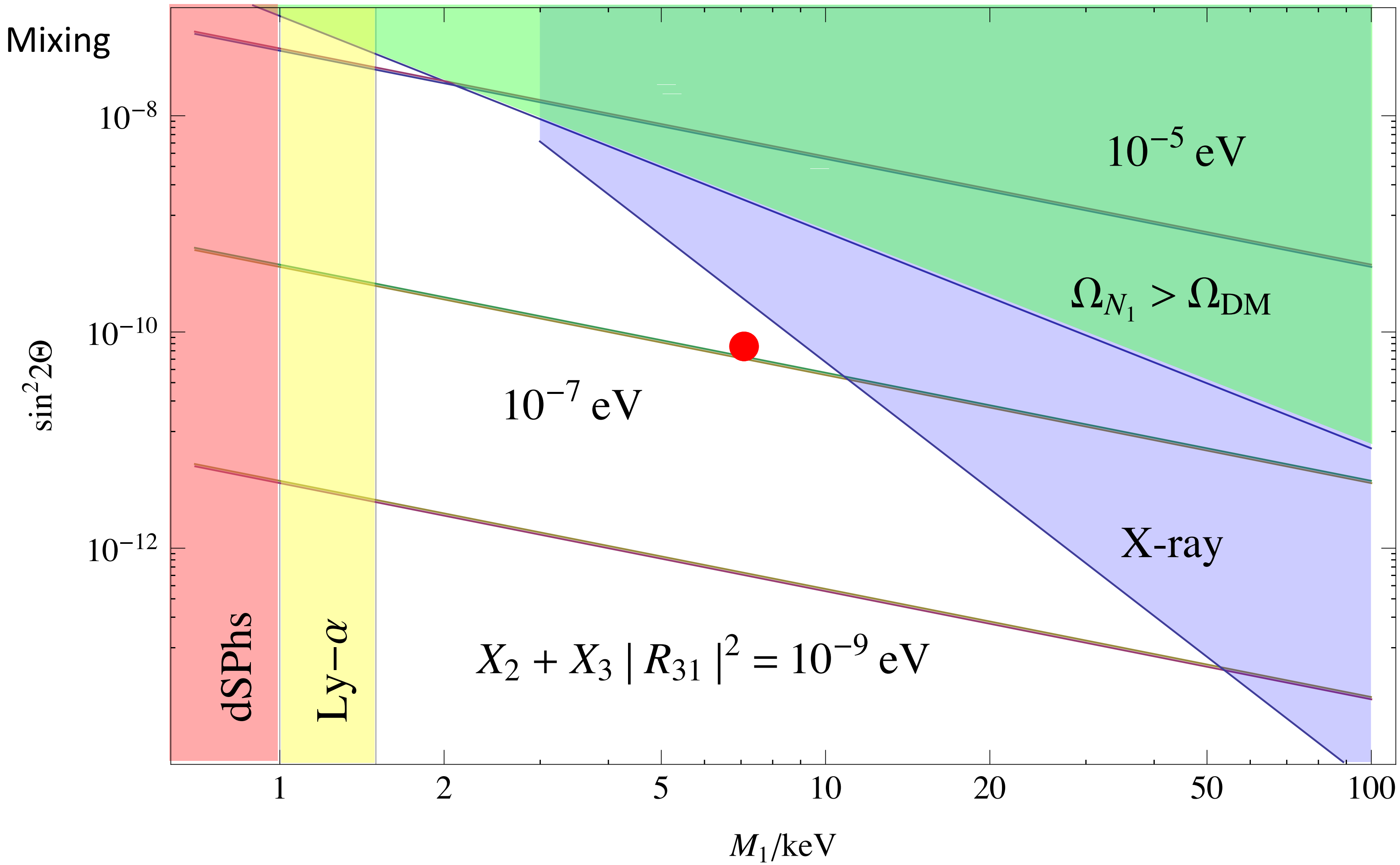
$$X_\nu \equiv m_\nu - M_L, \quad X_\nu^{\mathrm{diag}} = V_\nu^\dagger X_\nu V_\nu^* \quad R \sim \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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 ν_{R1} DM

Detection?@7keV
(arXiv: 1402.2301, 1402.4119)



Summary

Model:

- neutrino mass explained by heavy ν_R
- ν_{R1} DM produced as thermal relic (over production)
- Decay of ν_{R2} dilute ν_{R1} and produce matter-anti-matter asymmetry

Conclusion:

- m_ν, 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

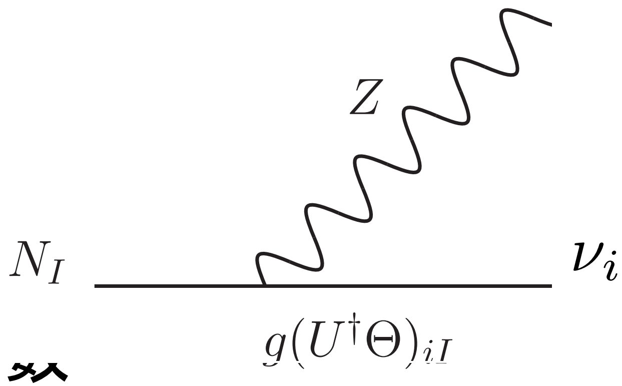
$$\nu_{L\alpha} = U_{\alpha i}\nu'_{Li} + \theta_{\alpha I}\nu'^{c}_{RI}$$

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

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: $\sim g\theta_I$

$$\theta_I^2 \equiv \sum_{\alpha=e,\mu,\tau} |\theta_{\alpha I}|^2$$



重いニュートリノの反応性を決定する変

- g(x)

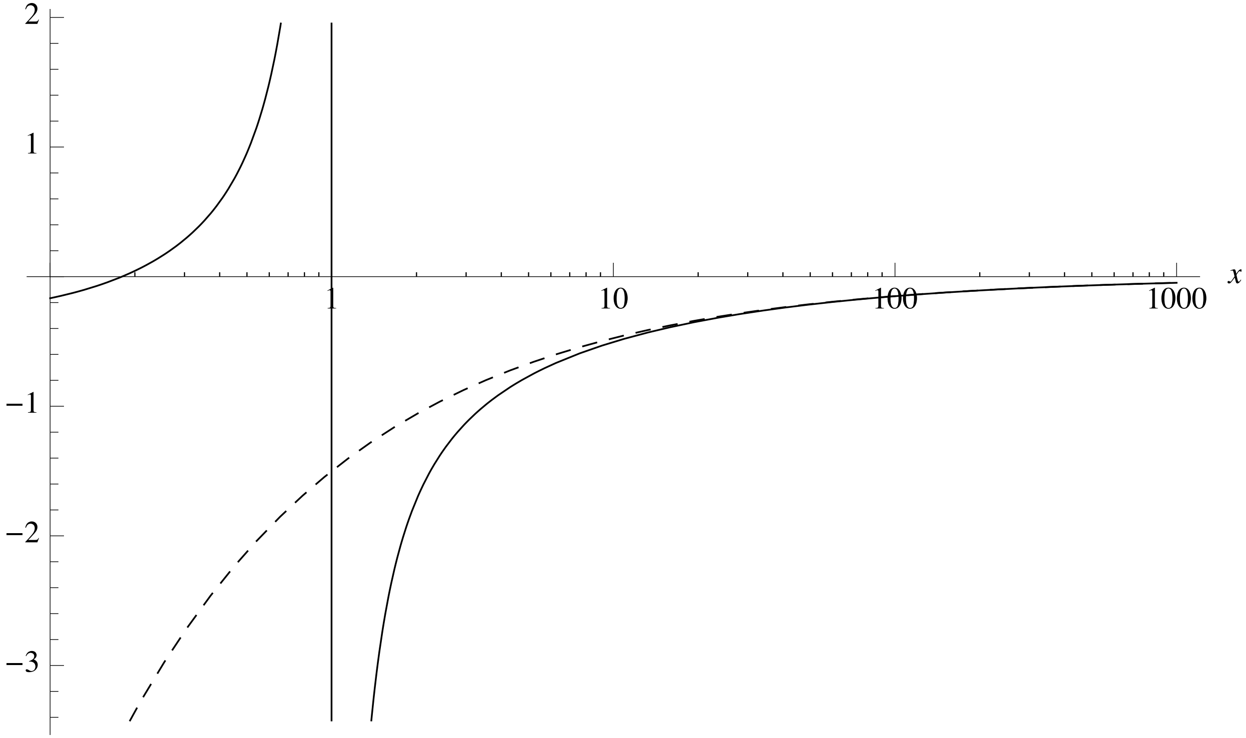


図 3.2: $g(x)$（実線）およびその漸近式 $-\frac{3}{2\sqrt{x}}$（点線）。

$$g(M_3^2/M_2^2) \simeq -\frac{3}{2}\frac{M_2}{M_3} \quad (M_3/M_2 \gtrsim 3)$$

Tremaine-Gunn境界

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

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

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

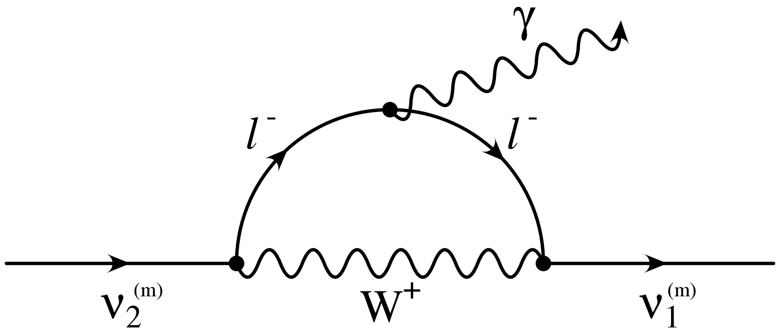
dSph(Coma Berenices等)の観測:

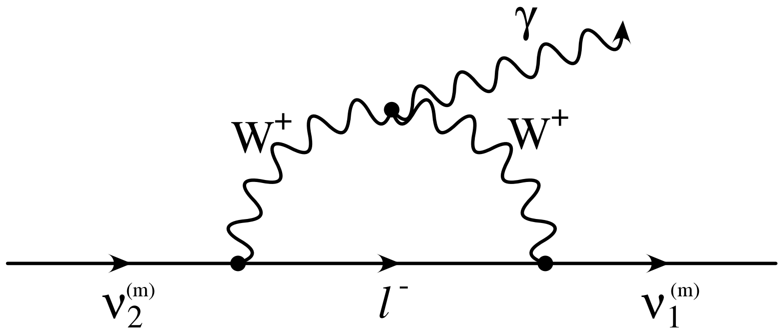
$$q = 5 \times 10^{-3} \sim 2 \times 10^{-2},$$

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

$$m > 1.0 \ {\rm keV} \left(\frac{q}{5 \times 10^{-3}} \right)^{1/4}$$

X-ray bound



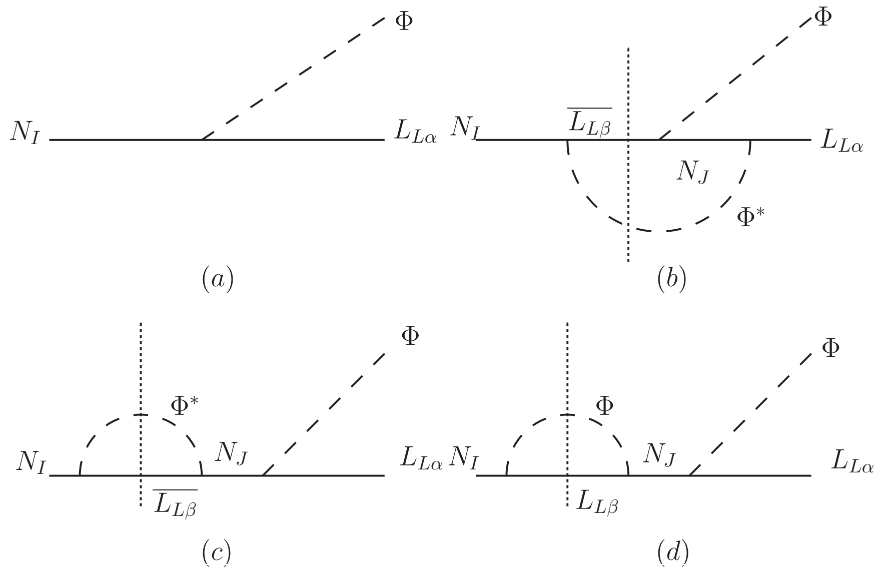


$$\Gamma_{\nu_s \to \gamma \nu_a} = \frac{9}{256\pi^4} \alpha_{\mathrm{EM}} \mathrm{G}_{\mathrm{F}}^2 \sin^2\theta\, m_{\mathrm{s}}^5$$
$$= \frac{1}{1.8 \times 10^{21}\ \mathrm{s}} \sin^2\theta \left(\frac{m_{\mathrm{s}}}{\mathrm{keV}}\right)^5$$

バリオン数生成

- CP:ν_Rの湯川相互作用
- 熱平衡からのずれ：

熱浴の外にいるν_Rの崩壊



作られるレプトン数：

$$Y_{L_\alpha}\Big|_{\text{崩壊後}} \propto \epsilon_{I\alpha} Y_I\Big|_{\text{崩壊前}}$$

CPの破れ：

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

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

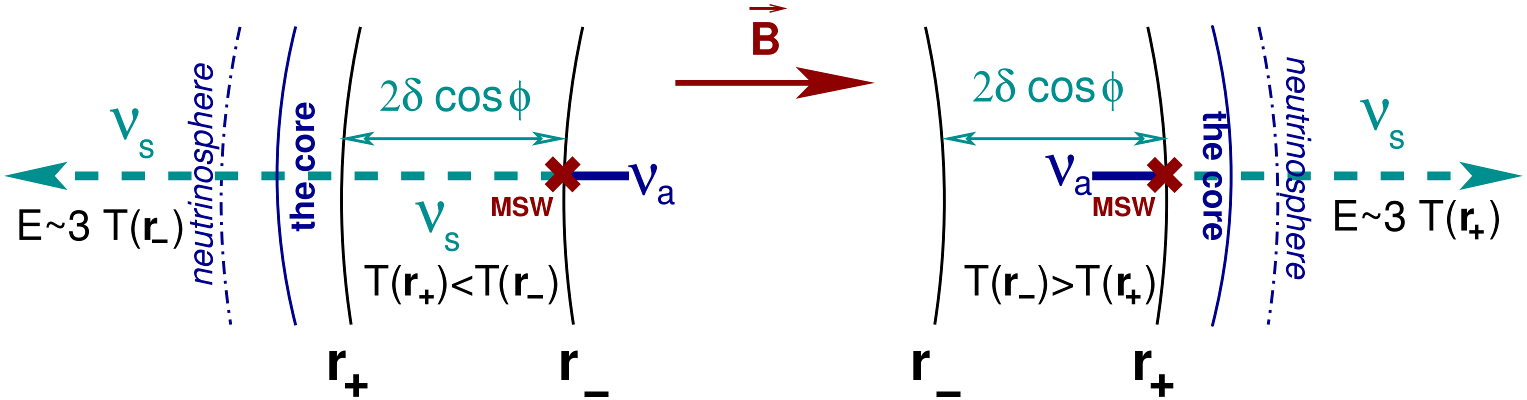
$$E \sim 3 \times 10^{53}\ \mathrm{erg},$$

(09 Kusenko)
1erg=10^-7J
M_sun=2.0*10^30kg

$$p_{\nu,\mathrm{total}} \sim 1 \times 10^{43} \mathrm{g\,cm/s}.$$

$$p_* = (1.4 M_\odot) v \approx 3 \times 10^{41} \left(\frac{v}{1000\ \mathrm{km/s}} \right) \mathrm{g\,cm/s}$$
$$\approx 0.03 \left(\frac{v}{1000\ \mathrm{km/s}} \right) p_{\nu,\mathrm{total}}.$$

1%~5%くらいの非等方性で説明できる



$$n + e^+ \rightleftharpoons p + \bar{\nu}_e,$$

$$p + e^- \rightleftharpoons n + \nu_e,$$

$$\sigma(\uparrow e^-, \uparrow \nu) \neq \sigma(\uparrow e^-, \downarrow \nu)$$

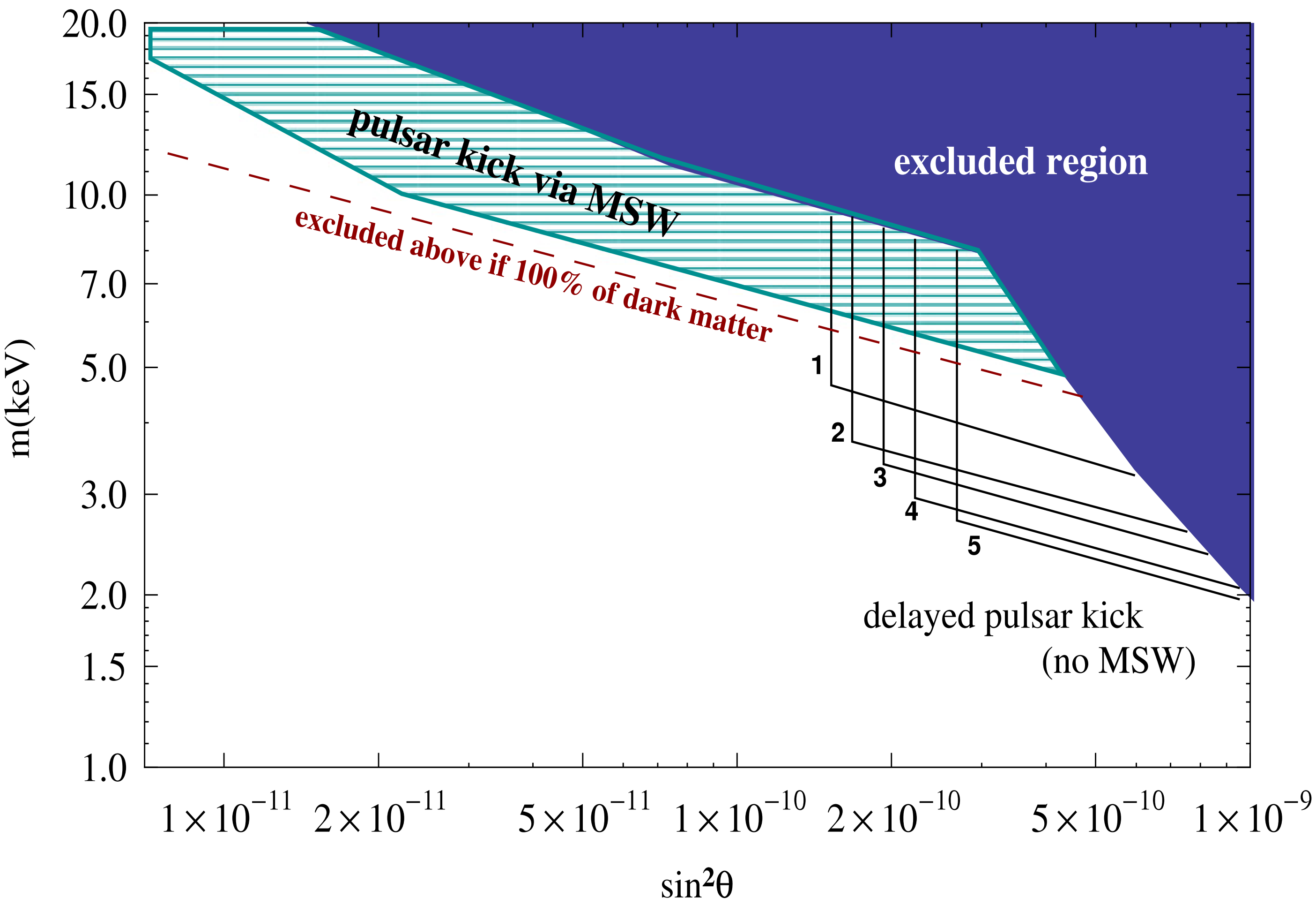
$$V(\nu_s) = 0,$$

$$V(\nu_e) = -V(\bar{\nu}_e) = V_0(3\,Y_e - 1 + 4\,Y_{\nu_e}),$$

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

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

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



20.0
15.0
10.0
7.0
5.0
3.0
2.0
1.5
1.0
m(keV)
1×10^{-11}
2×10^{-11}
5×10^{-11}
1×10^{-10}
2×10^{-10}
5×10^{-10}
1×10^{-9}
$\sin^2\theta$
excluded region
pulsar kick via MSW
excluded above if 100% of dark matter
1
2
3
4
5
delayed pulsar kick
(no MSW)