河南師範大學
HENAN NORMAL UNIVERSITY

中微子与暗物质相关的新物理唯象研究

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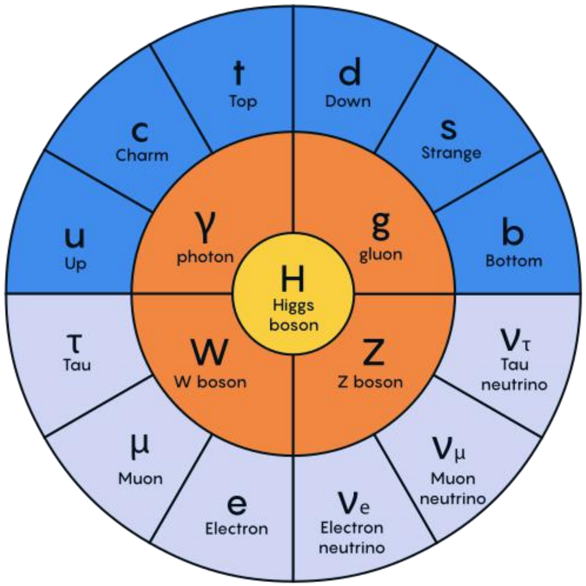
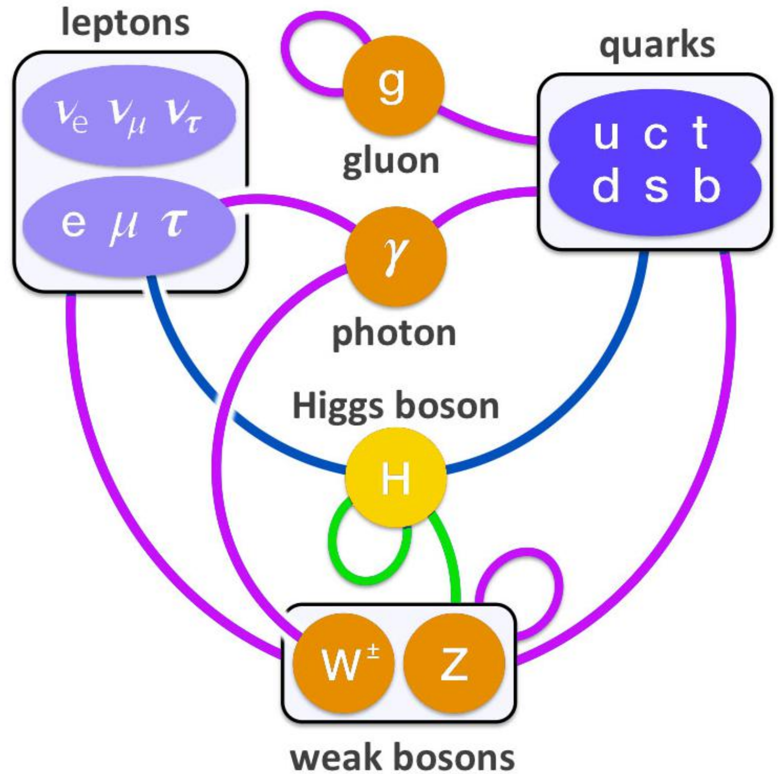
粒子物理标准模型



基本粒子

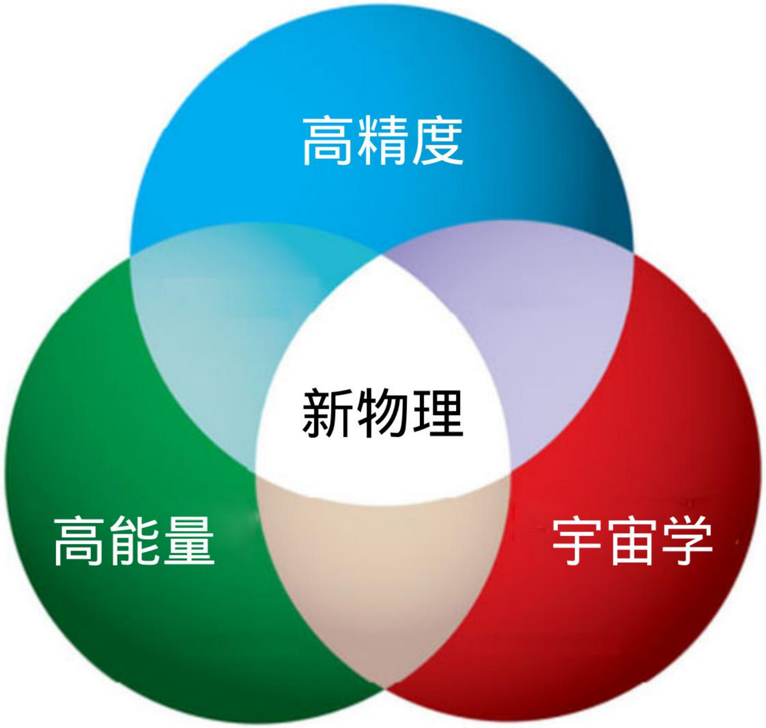
规范群 $\mathrm{SU(3)_C \times SU(2)_L \times U(1)_Y}$



$$\mathcal{L} = (\bar{\psi} i \gamma^\mu D_\mu \psi + \text{h.c.}) - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + |D_\mu \Phi|^2 - V(\Phi) + \left(Y \bar{\psi} \Phi \psi + \text{h.c.}\right)$$

Gauge Higgs Yukawa

超出标准模型的新物理



- 中微子质量
- 带电轻子反常磁矩
- B 物理
- 暗物质的本质
- 正反物质不对称
- ……

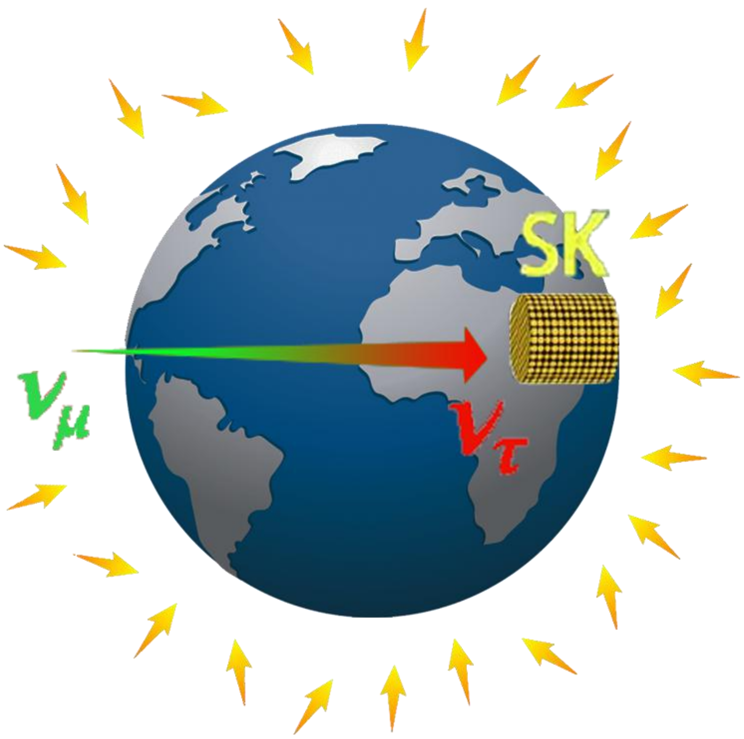
物理场　　相互作用　　群

标准模型中的中微子

标准模型

$$\mathcal{L}_{\text{Yukawa}} = \overline{q_L^i} Y_u u_R \widetilde{H}^i + \overline{q_L^i} Y_d d_R H^i + \overline{\ell_L^i} Y_e e_R H^i + \text{h.c.} \qquad \boxed{\nu_R}$$

中微子振荡



$$P_{\alpha\beta}(t) = |\langle \nu_\beta | \nu_\alpha \rangle|^2$$

$$= U_{\alpha i}^* U_{\beta i} U_{\beta j}^* U_{\alpha j} e^{-i\frac{\Delta m_{ij}^2}{2E}L}$$

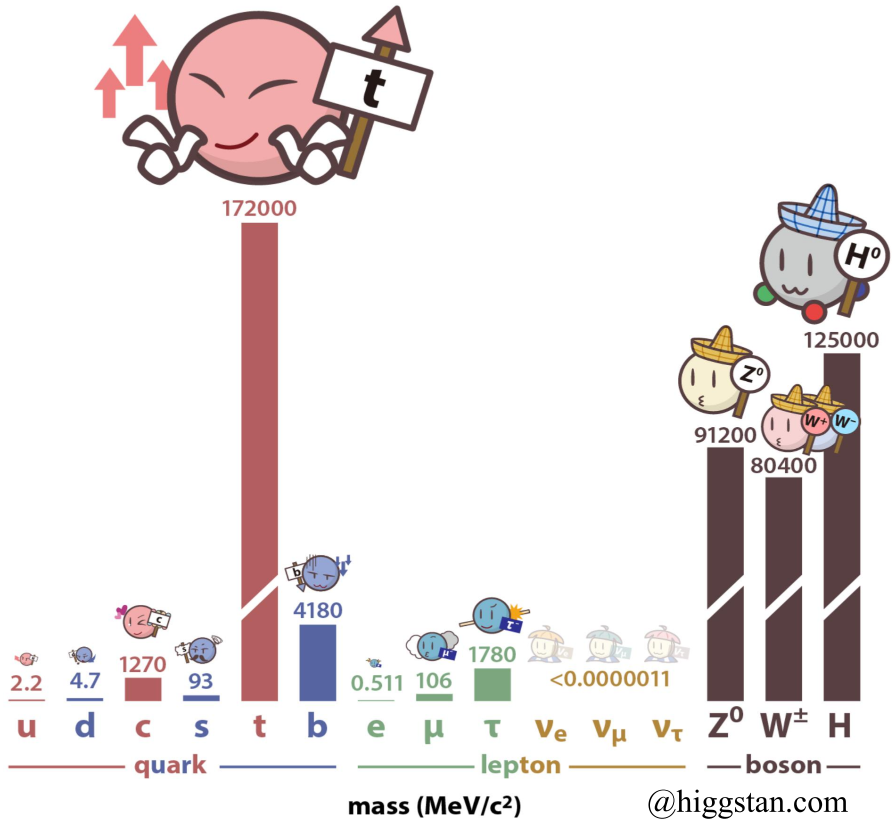
$$\text{Flavor} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\text{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \text{Mass}$$

标准模型中的中微子

Dirac 或 Majorana 质量

$$m\,\overline{\psi}\psi = m\,(\overline{\psi}_L\psi_R + \overline{\psi}_R\psi_L)$$

$$m\,\overline{\psi}_L(\psi_L)^c + m\overline{(\psi_L)^c}\psi_L$$



$\sum m_i \le 0.12$ eV (Planck data)

正序: $m_1 < m_2 < m_3$

逆序: $m_3 < m_1 < m_2$

简并: $m_1 \simeq m_2 \simeq m_3$

Seesaw 机制

中微子获得质量项最直接的方法

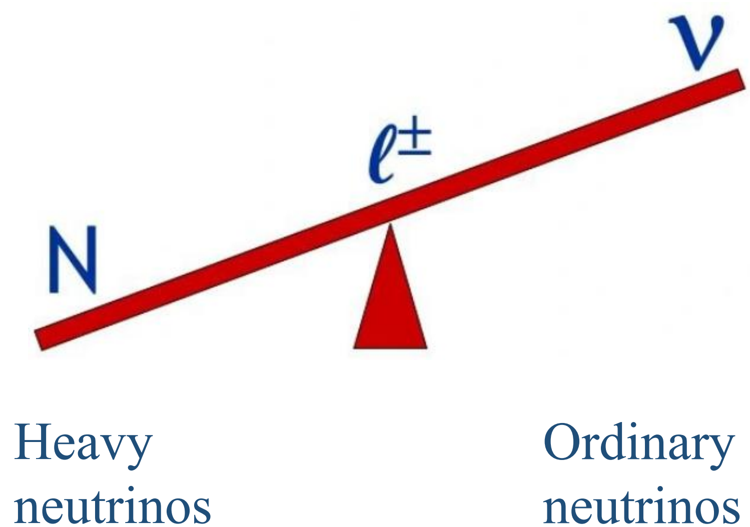
$$y_\nu \bar{L}\tilde{H}\nu_R + \text{h.c.} \longrightarrow \mathcal{M}_\nu = y_\nu\langle H^0\rangle = y_\nu \frac{v}{\sqrt{2}} \qquad y_\nu \sim 10^{-13}$$

加入单态的右手中性场 N_R

$$\mathcal{L}_{\text{Type-I}} = -\overline{L}_L Y_L H e_R - \overline{L}_L Y_N \tilde{H} N_R - \frac{1}{2}\overline{N_R^C} M_R N_R + \text{h.c.}$$

中微子质量矩阵 $(\overline{\nu}_L\ \overline{N_R^C})$

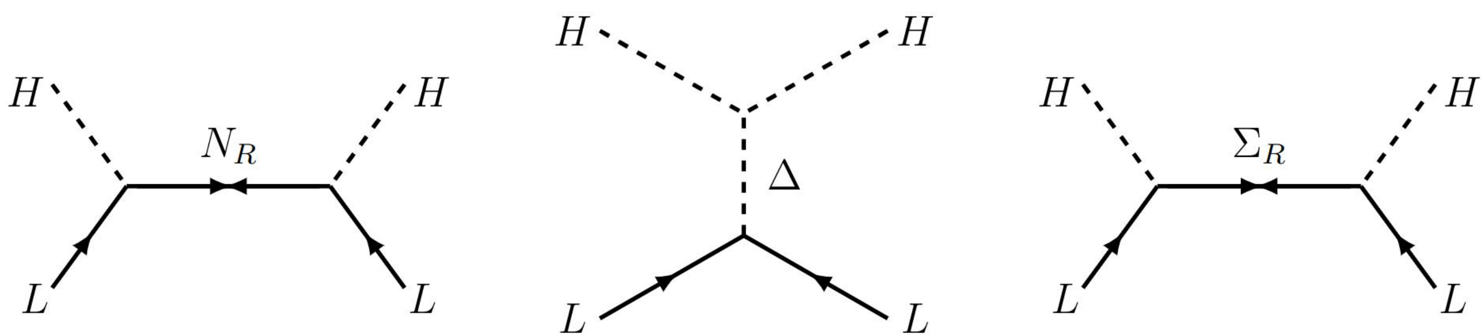
$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \simeq \begin{pmatrix} -m_D M_R^{-1} m_D^T & 0 \\ 0 & M_R \end{pmatrix}$$



$$m_D = Y_N v/\sqrt{2} \qquad m_N \sim 10^{14}\text{GeV}$$

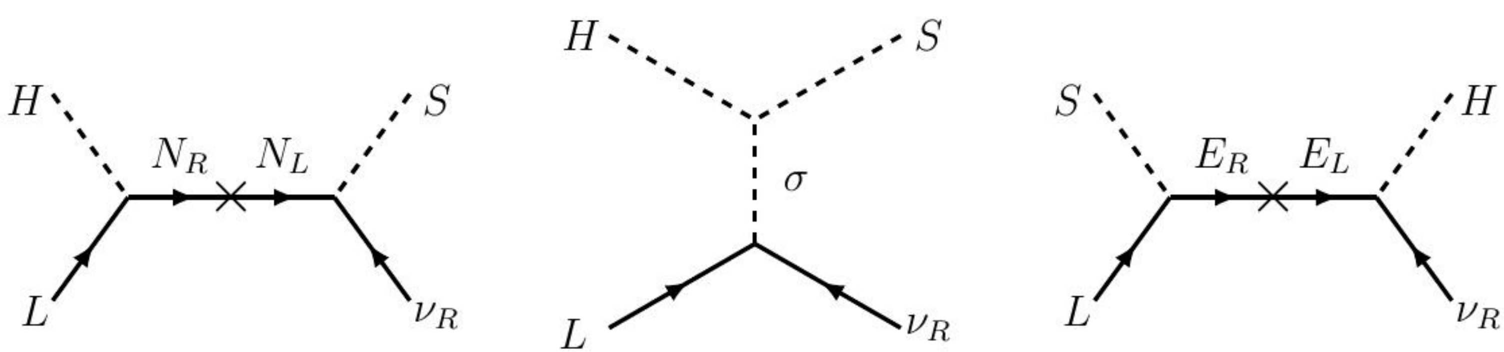
中微子质量模型

常见的 Seesaw 机制



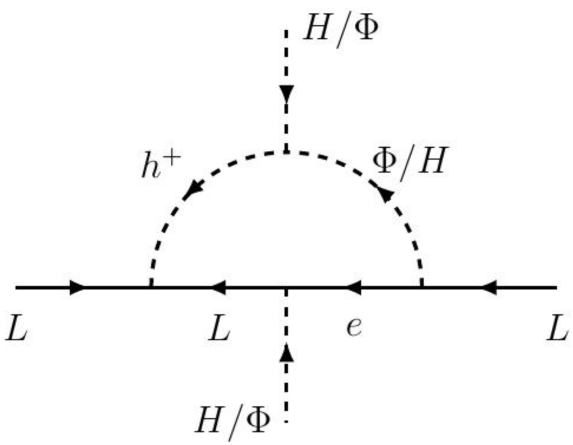
(a) Type-I seesaw (b) Type-II seesaw (c) Type-III seesaw

Dirac 中微子质量模型

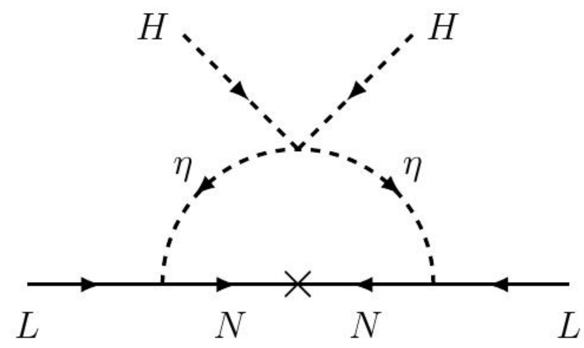


(a) Type-I seesaw (b) Type-II seesaw (c) Type-III seesaw

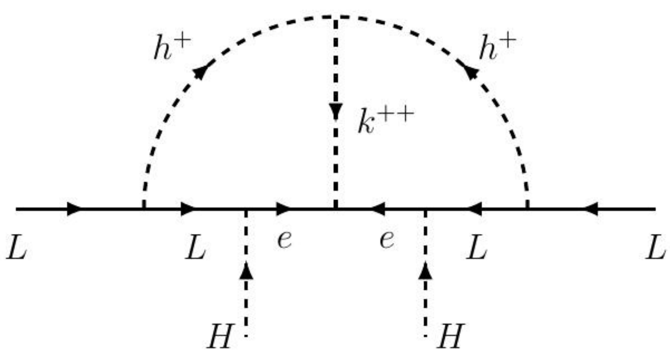
中微子质量辐射模型



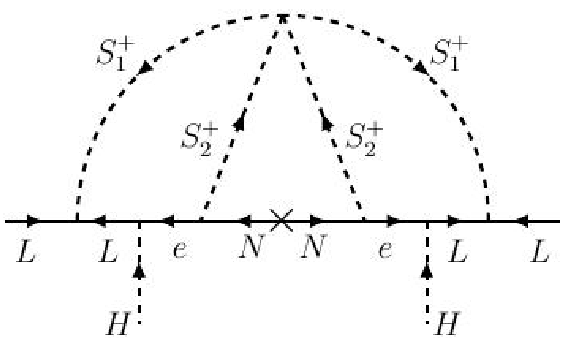
Zee 模型



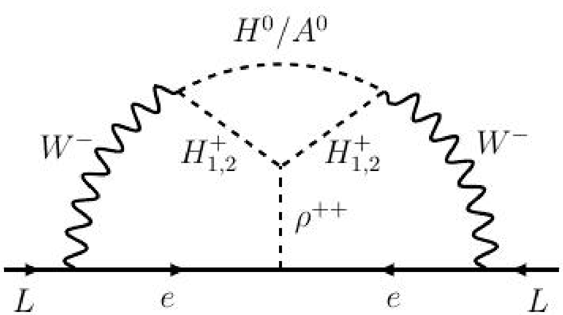
Scotogenic 模型



Zee-Babu 模型

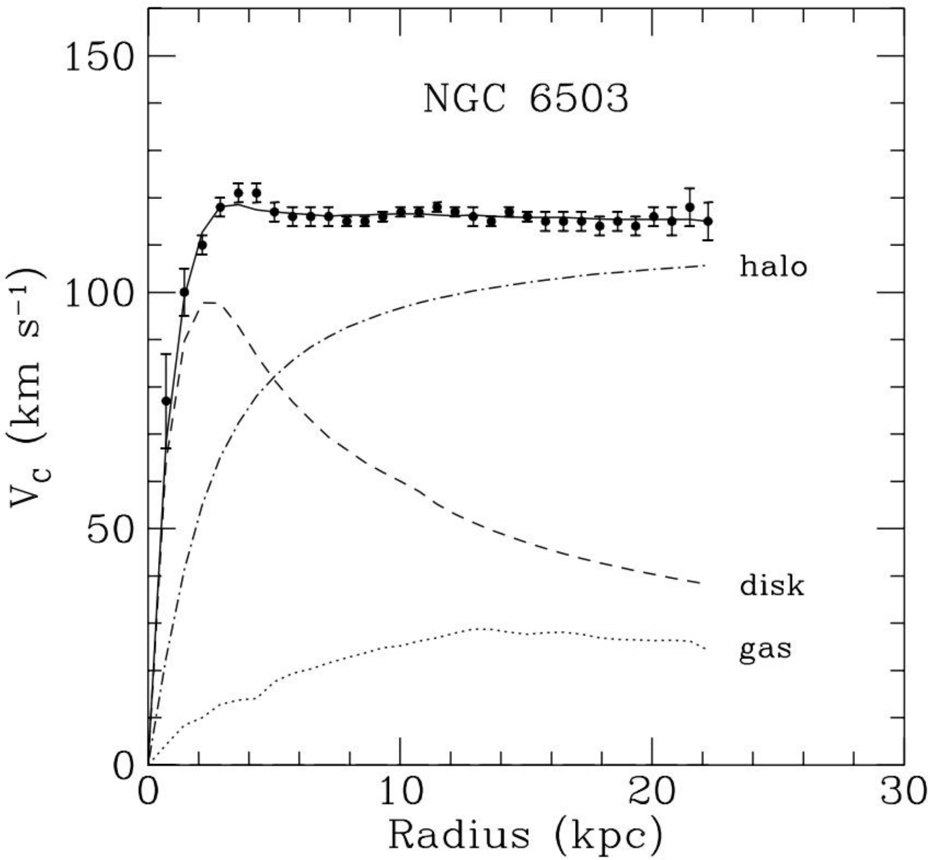


KNT 模型



Cocktail 模型

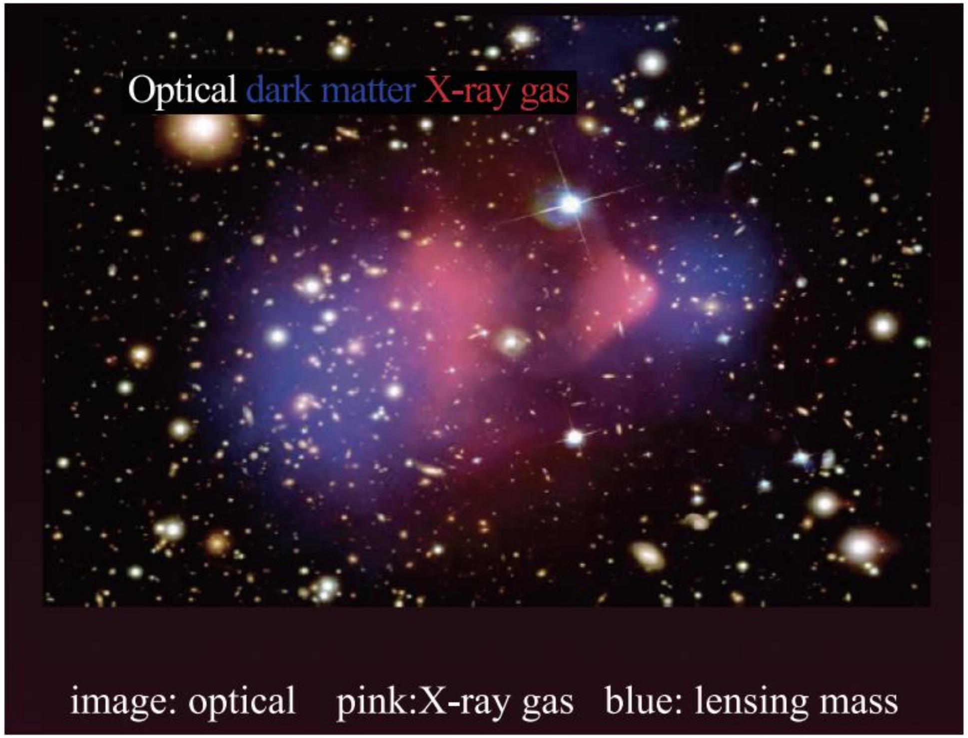
暗物质存在证据

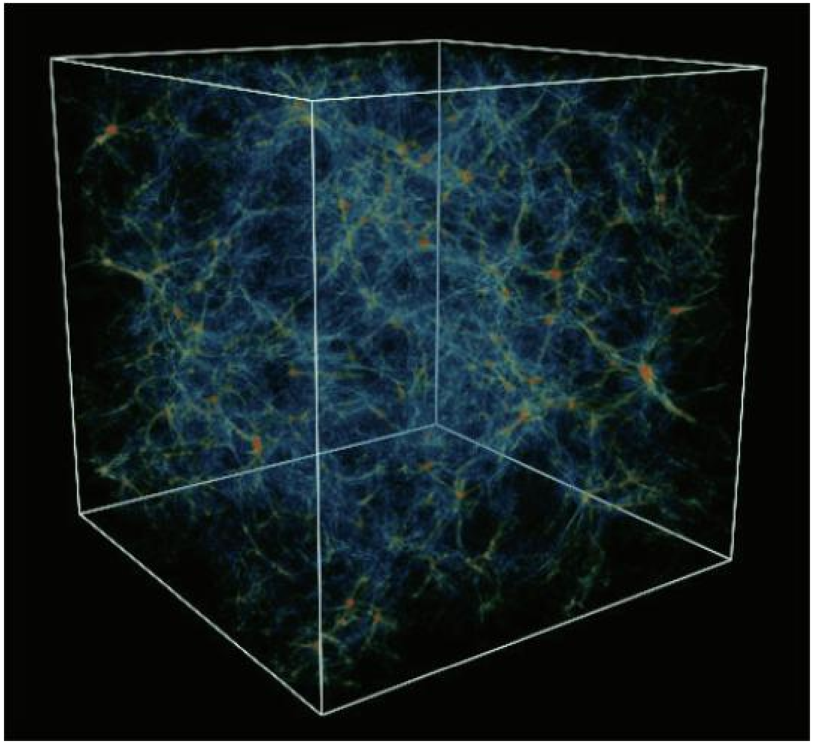


螺旋星系 NGC 6530 旋转曲线

引力透镜效应

暗物质存在证据





星系团碰撞

宇宙大尺度结构

暗物质粒子性质

- 稳定性

  暗物质粒子应该是高度稳定的或者其寿命要远大于宇宙的寿命

- 电中性

  暗物质粒子不发光也几乎不参与电磁相互作用

- “冷”暗物质

  暗物质在退耦时的速度不能太大

- 质量范围

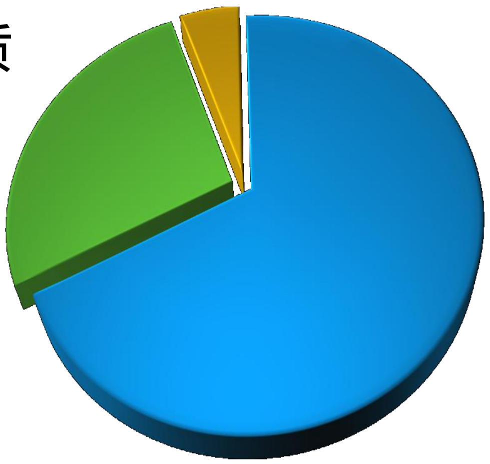
  暗物质可允许的质量范围非常大：$10^{-22}\,\mathrm{eV} \lesssim m_{\mathrm{DM}} \lesssim 10^{48}\,\mathrm{GeV}$

- …

暗物质候选者与 WIMP 奇迹

目前暗物质在宇宙中的残留丰度

$$\Omega_\chi h^2 = 0.120 \pm 0.001$$



Boltzmann 输运方程

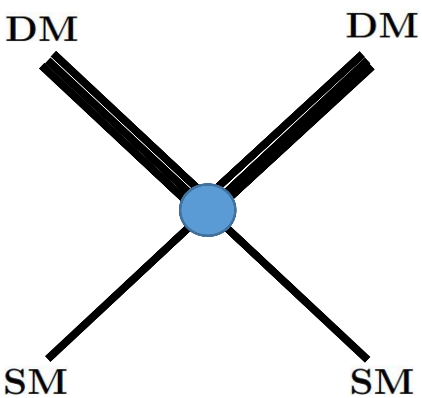
$$\frac{dn}{dt} = -3Hn - \langle \sigma_{\text{ann}} v \rangle (n^2 - n_{\text{EQ}}^2)$$

估算结果

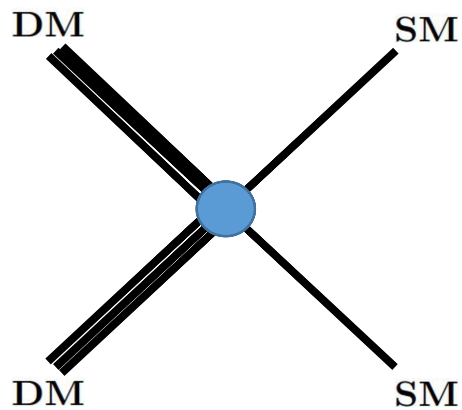
$$\Omega_\chi h^2 = \frac{m_\chi n_0}{\rho_c} h^2 \simeq \frac{10^{-27}\,\text{cm}^3 \cdot \text{s}^{-1}}{\langle \sigma_{\text{ann}} v \rangle}$$

暗物质粒子很可能是目前一些超出标准模型新物理模型中的某种粒子，这类可能为暗物质的粒子被称为 WIMPs (Weakly Interacting Massive Particles)，这种理论上的巧合被称为 WIMP 奇迹。

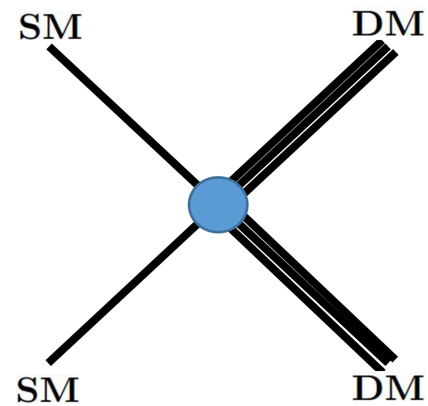
暗物质探测



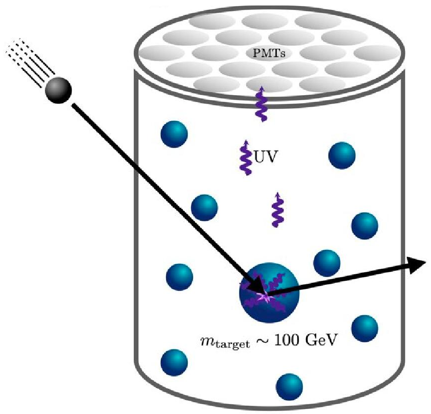
直接探测

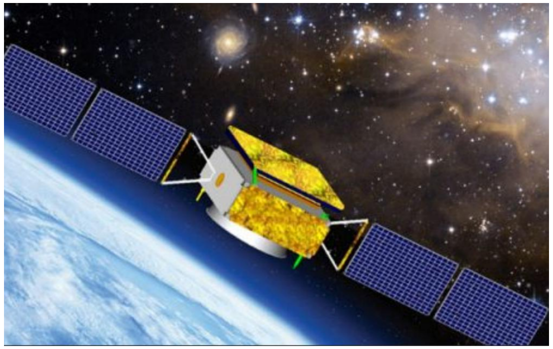


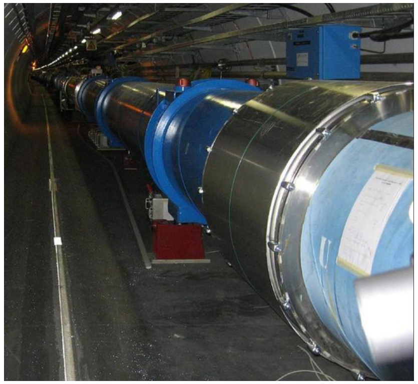
间接探测



对撞机探测

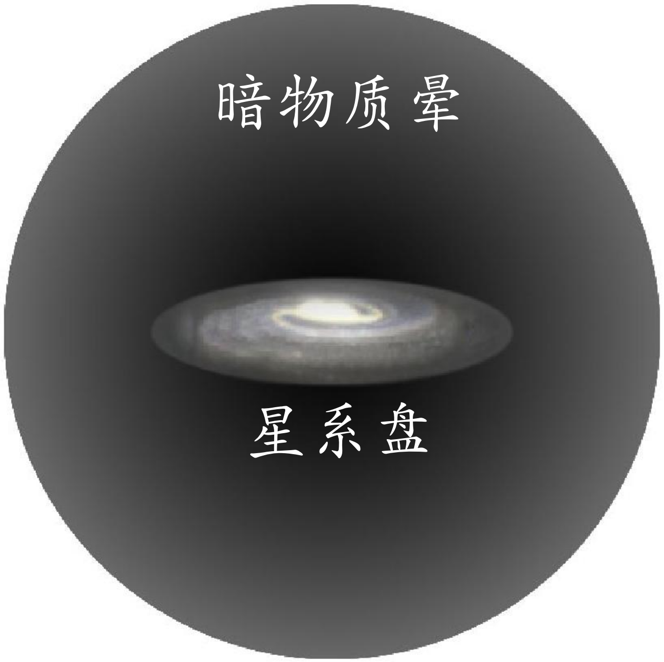




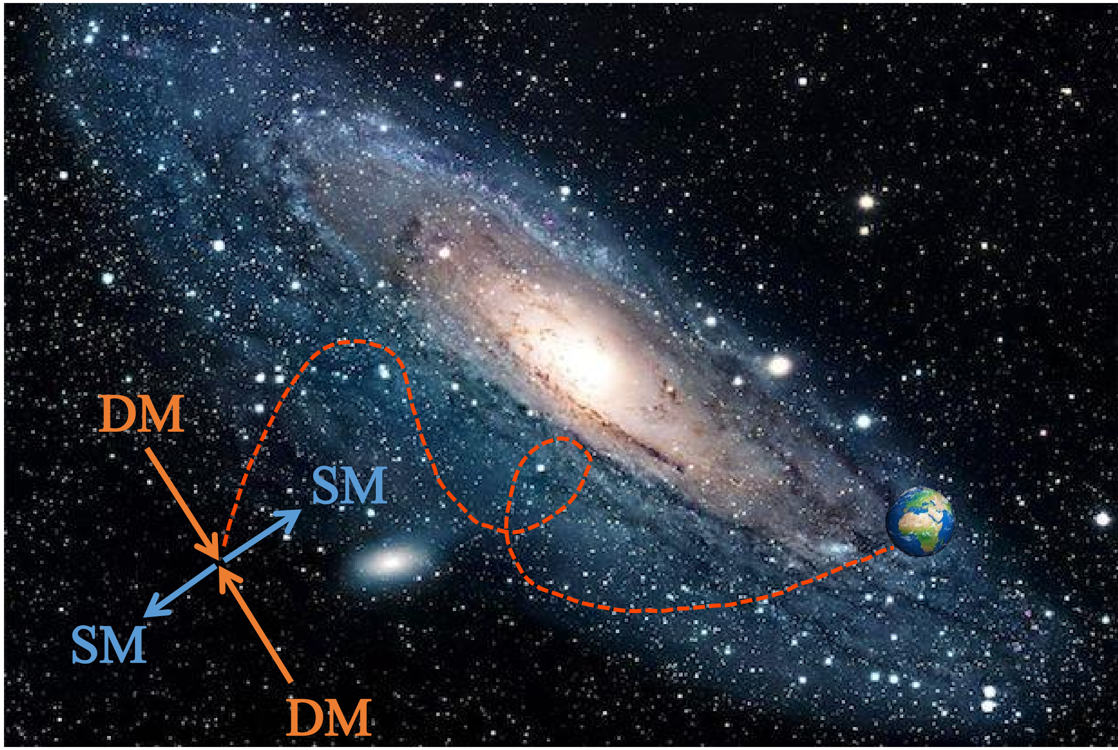


1，利用双三重态 Higgs 门户暗物质模型解释宇宙射线中正负电子超出

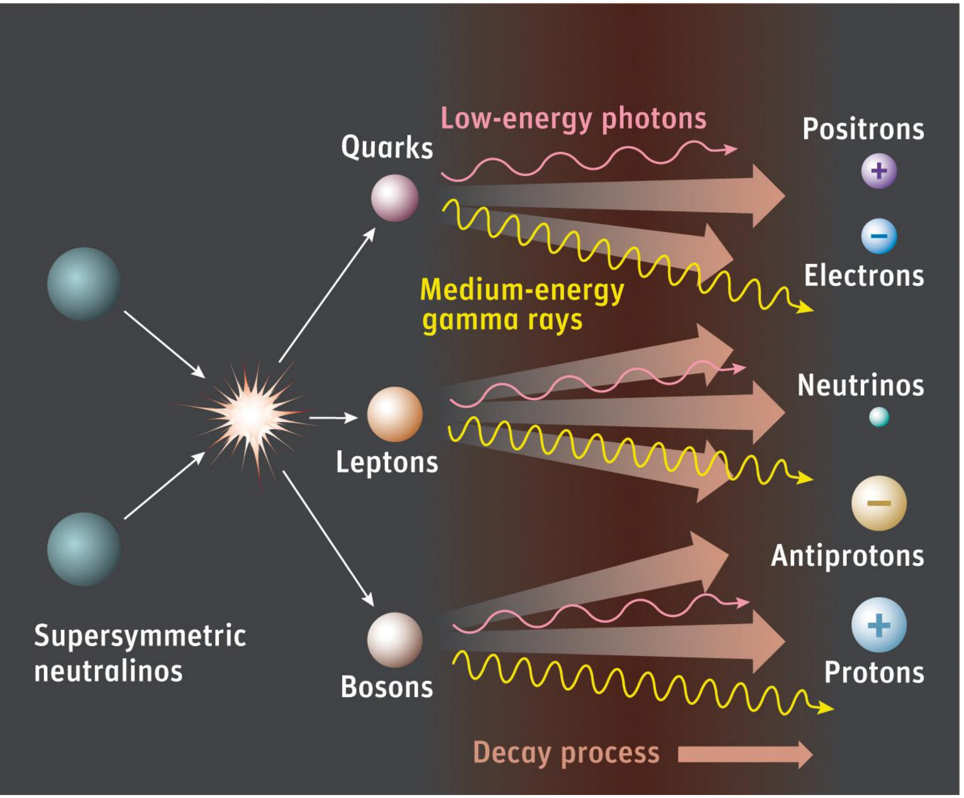
暗物质间接探测



银河系结构



暗物质间接探测



带电粒子:

PAMELA, AMS-02, DAMPE, *etc.*.

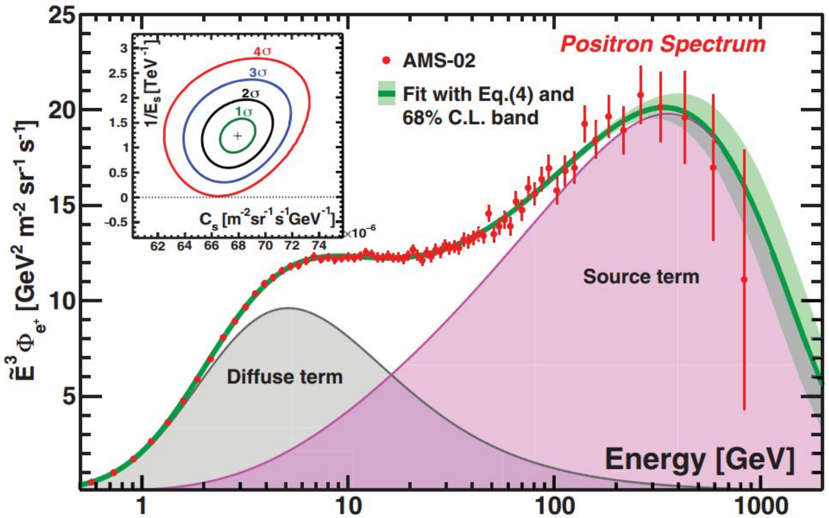
中微子:

ANTARES, SuperKamiokande, IceCube, *etc.*.

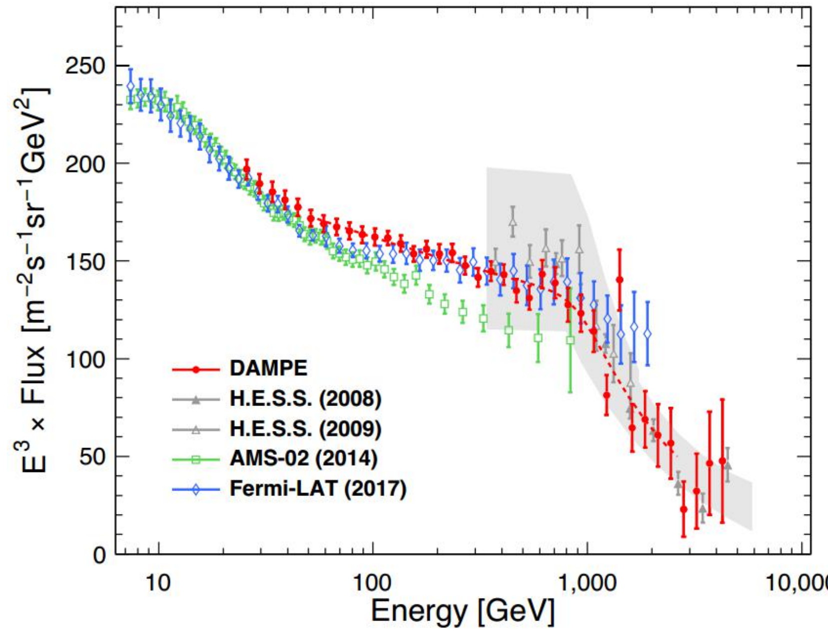
光子:

Fermi, H.E.S.S., VERITAS, HAWC, LHAASO, *etc.*.

暗物质间接探测



M. Aguilar, 2019, AMS Collaboration



G. Ambrosi, 2017, DAMPE Collaboration

S.-F. Ge *et al.*, 1712.02744 PLB, 2004.10683 NPB; S. Ghosh *et al.*, 2003.07675 PRD.

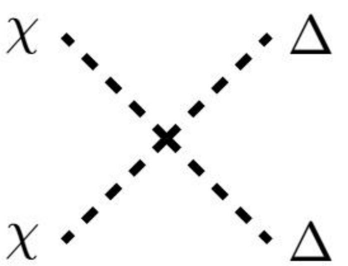
T. Li *et al.*, 1712.00869 PLB, 1804.09835 PRD;

三重态 Higgs 门户暗物质模型

标量场:

$$\Delta(3,+2) = \begin{pmatrix} \frac{1}{\sqrt{2}}\Delta^+ & \Delta^{++} \\ \Delta^0 & -\frac{1}{\sqrt{2}}\Delta^+ \end{pmatrix} \qquad \chi(1,0)$$

势能项:



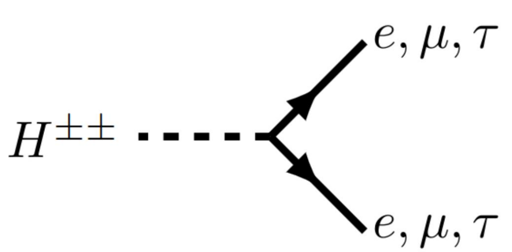
$$V_{\mathrm{DM}} = m_\chi^2\chi^2 + \rho_\chi\chi^4 + \lambda_{ij}\chi^2\mathrm{Tr}(\Delta_i^\dagger\Delta_j) + \ldots$$

物理场:

$$h, \quad H, \quad A, \quad H^\pm, \quad H^{\pm\pm}$$

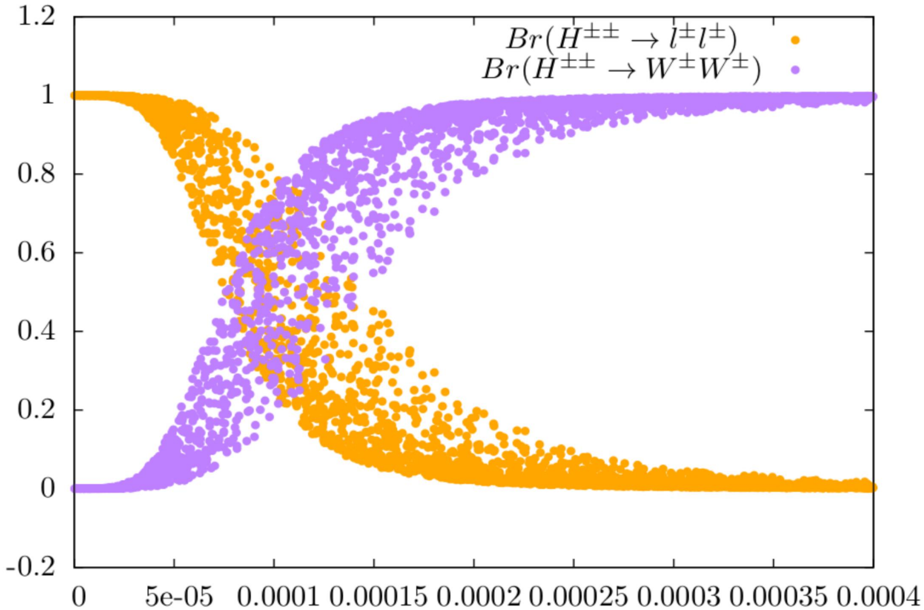
Yukawa 项:

$$\mathcal{L}'_{\mathrm{Yukawa}}(\Delta,\ L) = \frac{1}{\sqrt{2}}(Y_\Delta)_{ij}\overline{(L_L^i)^C}\, i\tau_2\Delta L_L^j + \mathrm{h.c.}$$



三重态 Higgs 门户暗物质模型

$$H^{\pm\pm} \to \ell^{\pm}\ell^{\pm},\ W^{\pm}H^{\pm},\ W^{\pm}W^{\pm}$$



2001.09349 [JHEP]

质量简并条件

$$m_{H^{\pm\pm}} \simeq m_{H^{\pm}}$$

三重态 Higgs 真空期望值

$$v_{\Delta} \sim \mathrm{keV}$$

中微子质量项

$$(M_{\nu})_{ij} = (Y_{\Delta})_{ij} v_{\Delta}$$

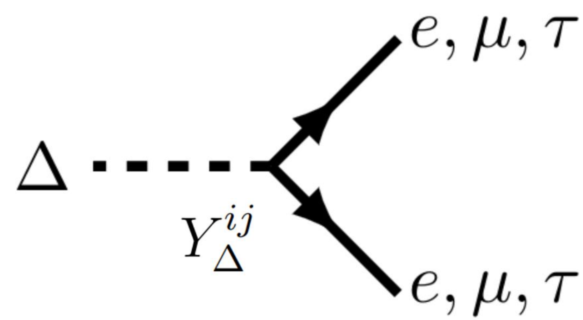
耦合参数矩阵

$$Y_{\Delta} = \frac{1}{v_{\Delta}} U^{*}_{\mathrm{PMNS}} M_{\nu}^{\mathrm{diag}} U^{\dagger}_{\mathrm{PMNS}}$$

正序 逆序 简并

三重态 Higgs 门户暗物质模型

$$Y_\Delta = \frac{1}{v_\Delta} U^*_{\mathrm{PMNS}} \begin{pmatrix} m_1 & & \\ & m_2 & \\ & & m_3 \end{pmatrix} U^\dagger_{\mathrm{PMNS}}$$



中微子质量为正序时 $m_1 < m_2 < m_3$

$$Y_\Delta = \frac{10^{-2}\,\mathrm{eV}}{v_\Delta} \begin{pmatrix} 0.35 + 0.06\,i & -0.25 - 0.14\,i & -0.74 - 0.12\,i \\ -0.25 - 0.14\,i & 3.11 + 0.02\,i & 2.13 - 0\,i \\ -0.74 - 0.12\,i & 2.13 - 0\,i & 2.40 - 0.01\,i \end{pmatrix}$$

质量顺序	$H^{\pm\pm}$ decays						$H^{\pm}$ decays		
	ee	$e\mu$	$e\tau$	$\mu\mu$	$\mu\tau$	$\tau\tau$	$e\nu$	$\mu\nu$	$\tau\nu$
正序	0.49%	0.67%	4.36%	37.37%	34.90%	22.21%	3.00%	55.14%	41.86%
逆序	47.53%	1.32%	0.84%	9.84%	23.74%	16.73%	49.27%	50.72%	0%
简并	25.26%	0.32%	0.28%	37.83%	1.88%	34.43%	24.79%	25.51%	49.70%

正负电子束流在银河系中的扩散

扩散损失方程

$$\frac{\partial f}{\partial t} = \nabla \left[\mathcal{K}(E,\vec{x})\nabla f\right] + \frac{\partial}{\partial E}\left[b(E,\vec{x})f\right] + Q(E,\vec{x})$$

扩散系数: $\mathcal{K}(E) = K_0(E/\mathrm{GeV})^{\delta}$　　能量损失系数: $b(E,\vec{x}) = b_0(E/\mathrm{GeV})^2$

准静态系统

$$\mathcal{K}_0 E^{\delta}\,\nabla^2 f + \frac{\partial}{\partial E}(b_0 E^2 f) + Q(E,\vec{x}) = 0$$

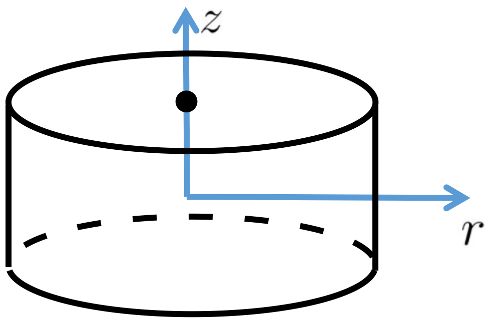
格林函数法

$$f(E,x) = \int_E^{E_{\max}} dE_s \int_V d\vec{x}_s\, G(E,\vec{x};E_s,\vec{x}_s)Q(E_s,\vec{x}_s)$$

$$I(E,E_s,\vec{x}) \equiv \int_V d\vec{x}_s\, G(E,\vec{x};E_s,\vec{x}_s)\left(\frac{\rho(\vec{x}_s)}{\rho_\odot}\right)^2 \qquad \mathcal{I}\left(\lambda_D(E,E_S),\vec{x}\right) = b(E)I(E,E_s,\vec{x})$$

$$\nabla^2\mathcal{I}(\lambda_D,r,z) - \frac{2}{\lambda_D}\frac{\partial}{\partial\lambda_D}\mathcal{I}(\lambda_D,r,z) = 0 \qquad \lambda_D = \theta(E_s - E)\sqrt{\frac{4\mathcal{K}_0(E^{\delta-1} - E_s^{\delta-1})}{b_0(1-\delta)}}$$

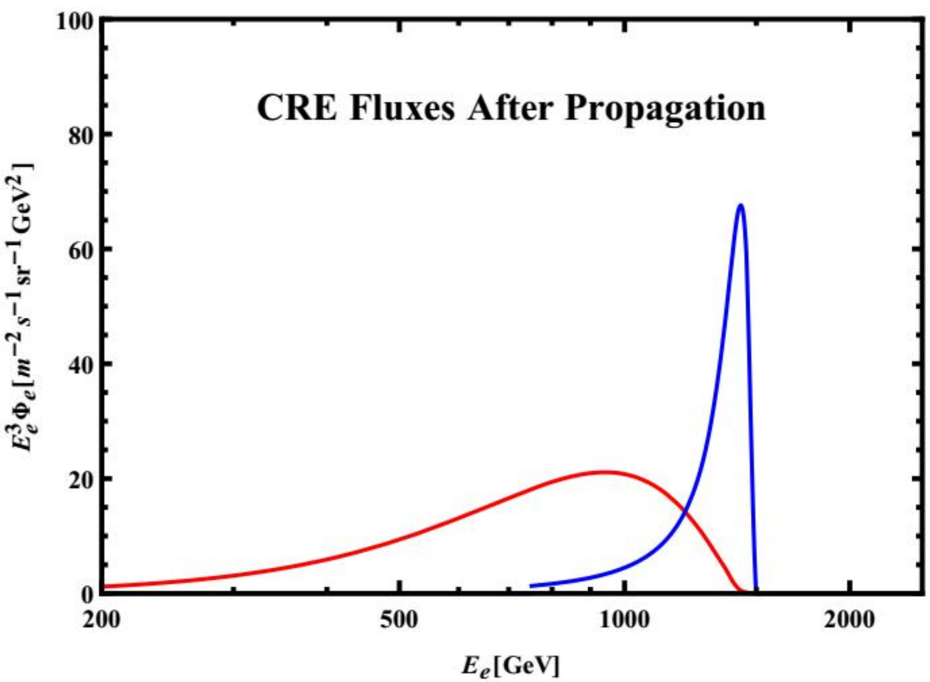
$$\mathcal{I}(0,r,z) = \left(\frac{\rho(r,z)}{\rho_\odot}\right)^2, \quad \mathcal{I}(\lambda_D,R_{\mathrm{gal}},z) = 0, \quad \mathcal{I}(\lambda_D,r,\pm z) = 0$$

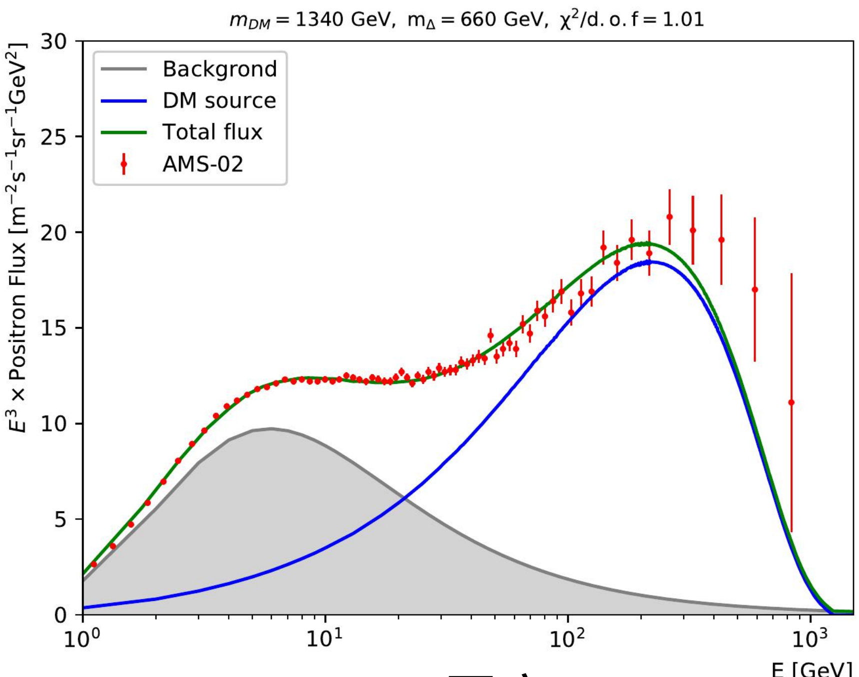


AMS-02 数据拟合

直接衰变 $\Delta \to ee$

次级衰变 $\Delta \to \mu\mu(\tau\tau) \to ee$



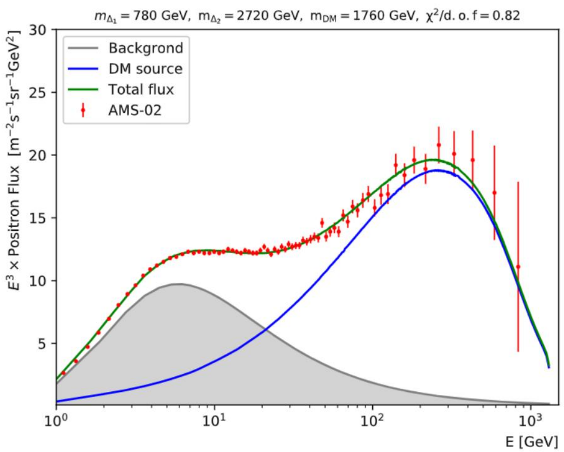


正序

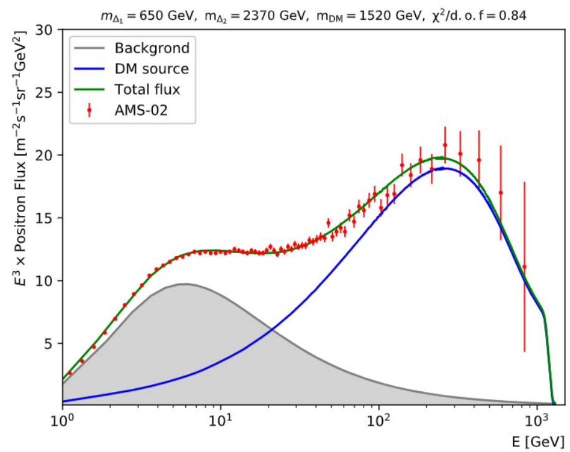
AMS-02 数据拟合

双三重态 Higgs 门户暗物质模型

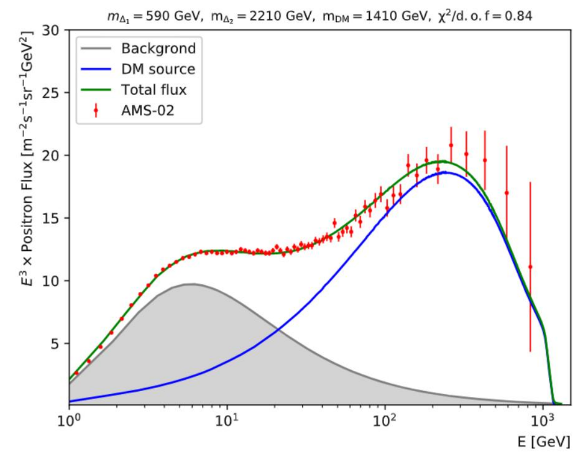
$$(M_\nu)_{ij} = (Y_{\Delta_1})_{ij} v_1 + (Y_{\Delta_2})_{ij} v_2$$



正序



逆序

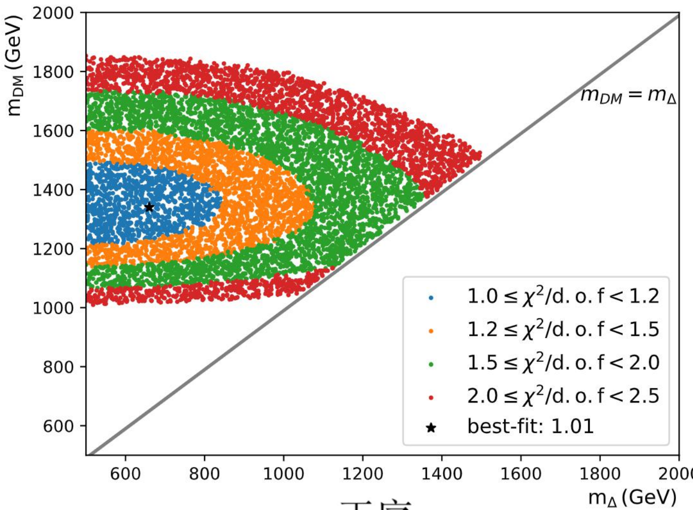


简并

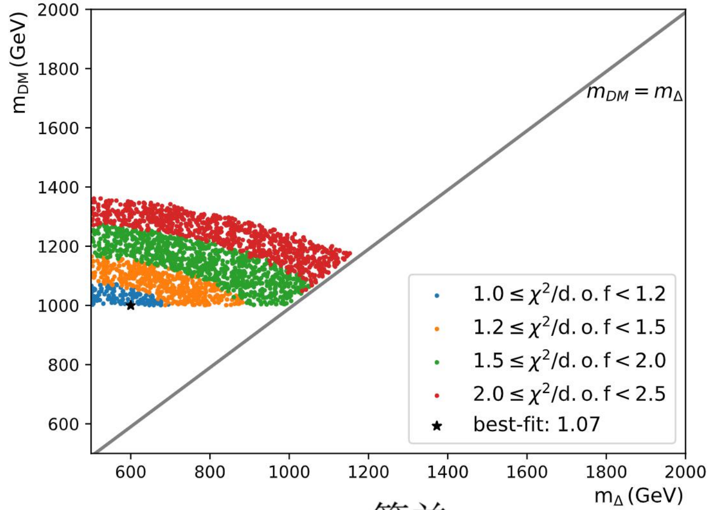
	正序质量	逆序质量	简并质量
单三重态 Higgs 模型	1.01	8.12	1.07
双三重态 Higgs 模型	0.82	0.84	0.82

AMS-02 数据拟合

单三重态 Higgs 模型

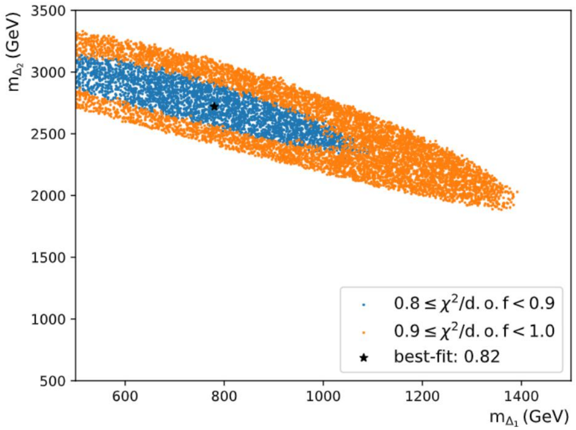


正序

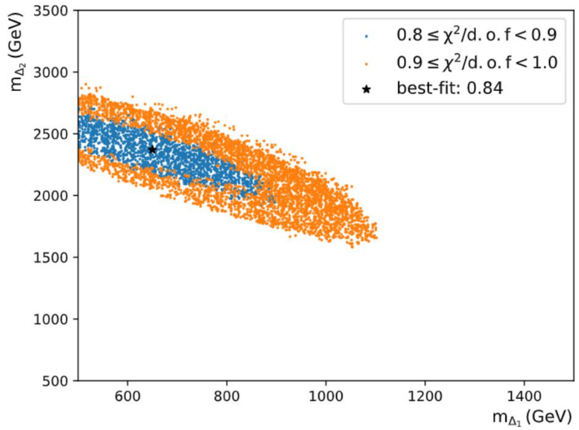


简并

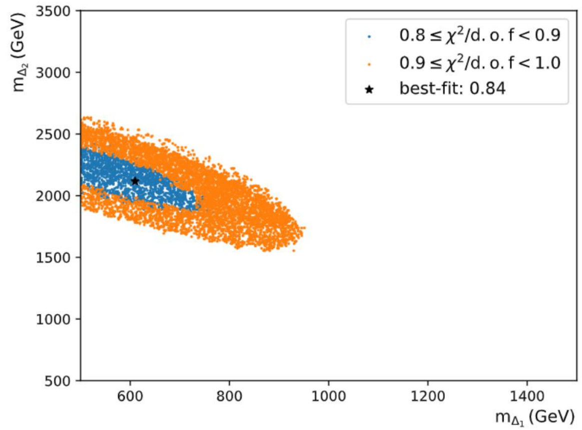
双三重态 Higgs 模型



正序

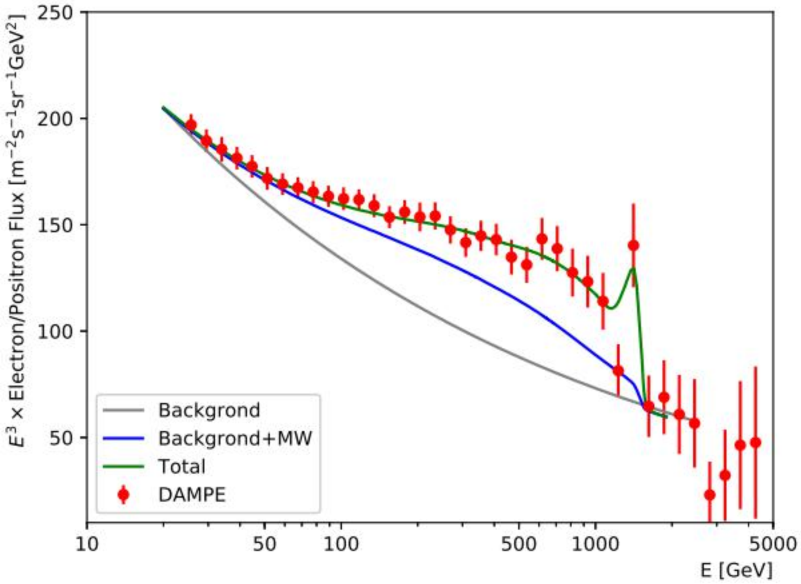


逆序

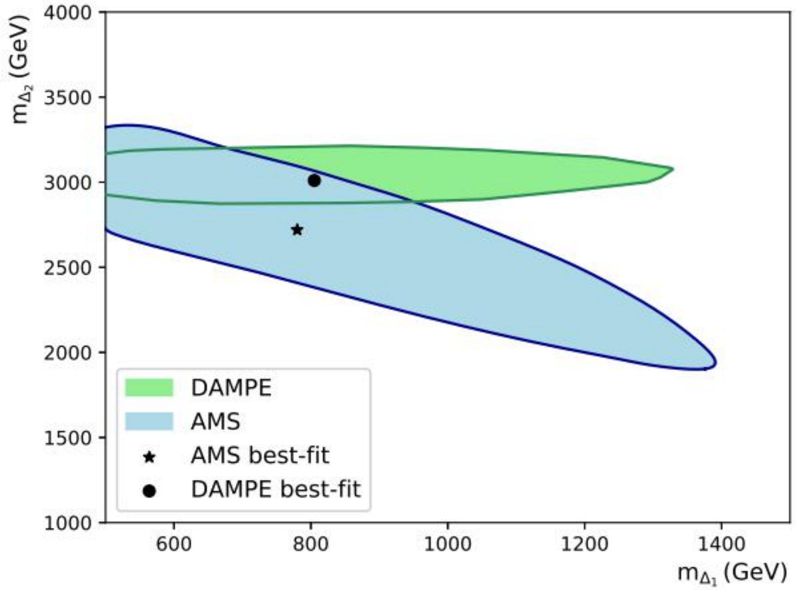


简并

DAMPE 数据拟合



$E^3 \times$ Electron/Positron Flux [$m^{-2}s^{-1}sr^{-1}GeV^2$]
250
200
150
100
50
10
50
100
500
1000
5000
E [GeV]
Backgrond
Backgrond+MW
Total
DAMPE



m_{Δ_2} (GeV)
4000
3500
3000
2500
2000
1500
1000
600
800
1000
1200
1400
m_{Δ_1} (GeV)
DAMPE
AMS
AMS best-fit
DAMPE best-fit

小结

- 考察了三重态 Higgs 门户暗物质模型，其中三重态 Higgs 场通过 Type-II seesaw 来提供中微子质量项，同时又作为暗物质媒介粒子

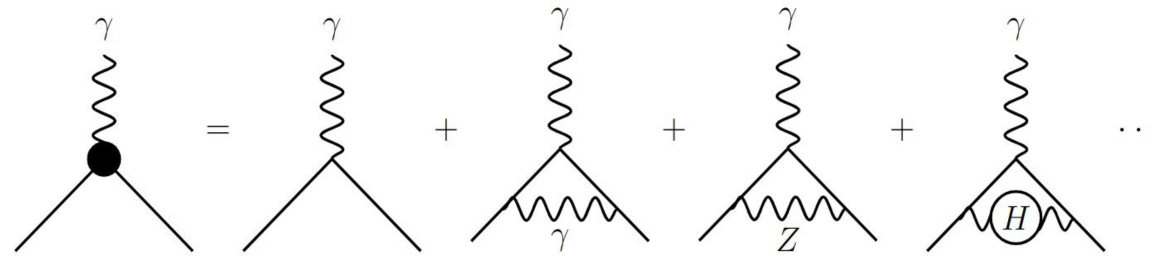
- 解释了暗物质间接探测实验 AMS-02 和 DAMPE 实验中的电子超出现象

- 比较了单三重态 Higgs 模型和双三重态 Higgs 模型在中微子质量不同次序情况下，模型对 AMS-02 实验和 DAMPE 实验的拟合，并给出了可以同时拟合两个实验的参数空间

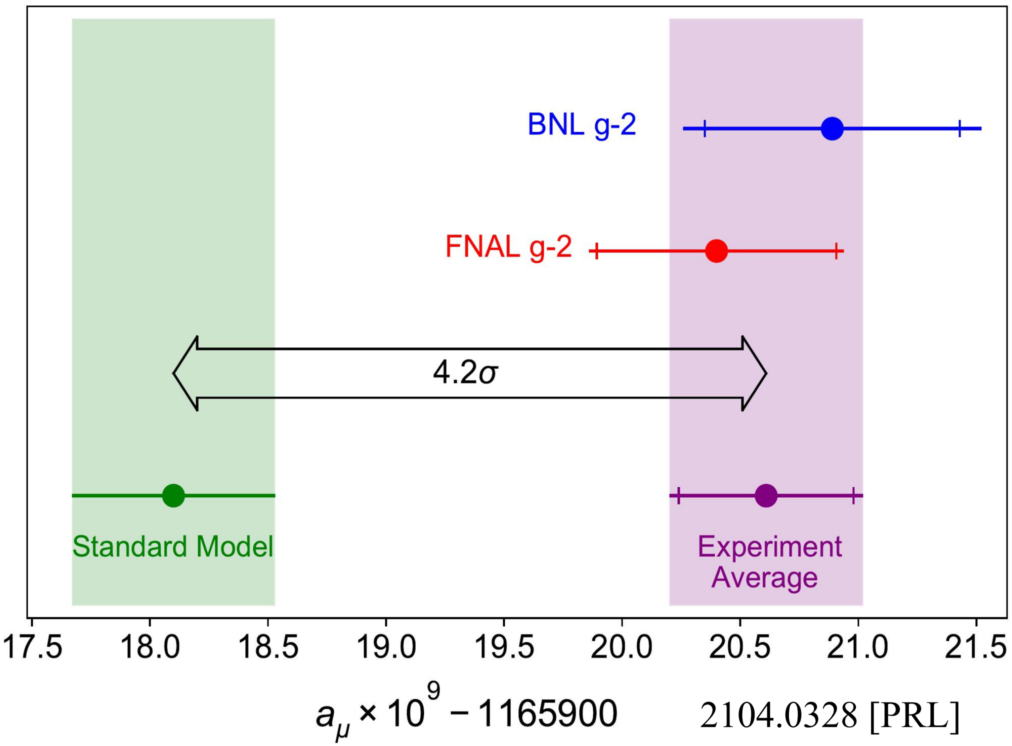
2，利用 Leptoquark 模型解释带电轻子反常磁矩、B 介子衰变过程中轻子味普适性破坏和中微子质量

带电轻子的反常磁矩

$$a_\ell \equiv \frac{(g_\ell - 2)}{2}$$



$$a_\ell = a_\ell(\text{QED}) + a_\ell(\text{Weak}) + a_\ell(\text{Hadron})$$



$$a_e^{\text{SM}} = 1\,159\,652\,181.61\,(23) \times 10^{-12}$$

$$a_\mu^{\text{SM}} = 116\,591\,810\,(43) \times 10^{-11}$$

$$\Delta a_e = a_e^{\text{exp}} - a_e^{\text{SM}} = -(8.7 \pm 3.6) \times 10^{-13}$$

$2.4\ \sigma$

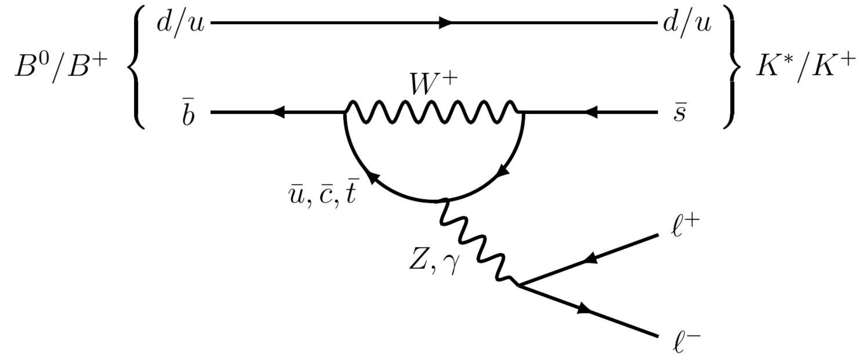
$$\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (2.51 \pm 0.59) \times 10^{-9}$$

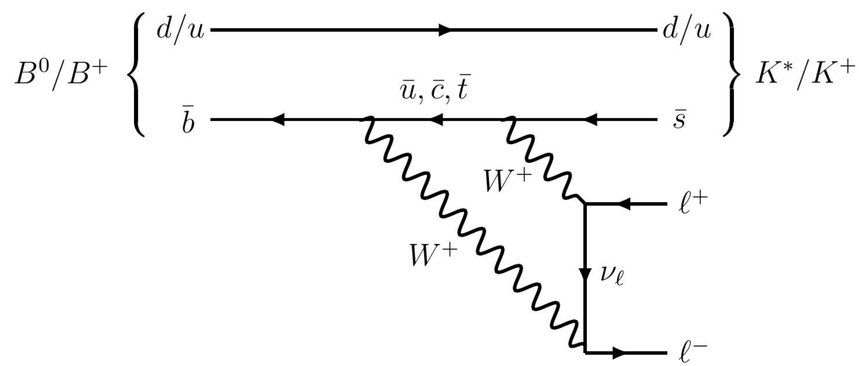
$4.2\ \sigma$

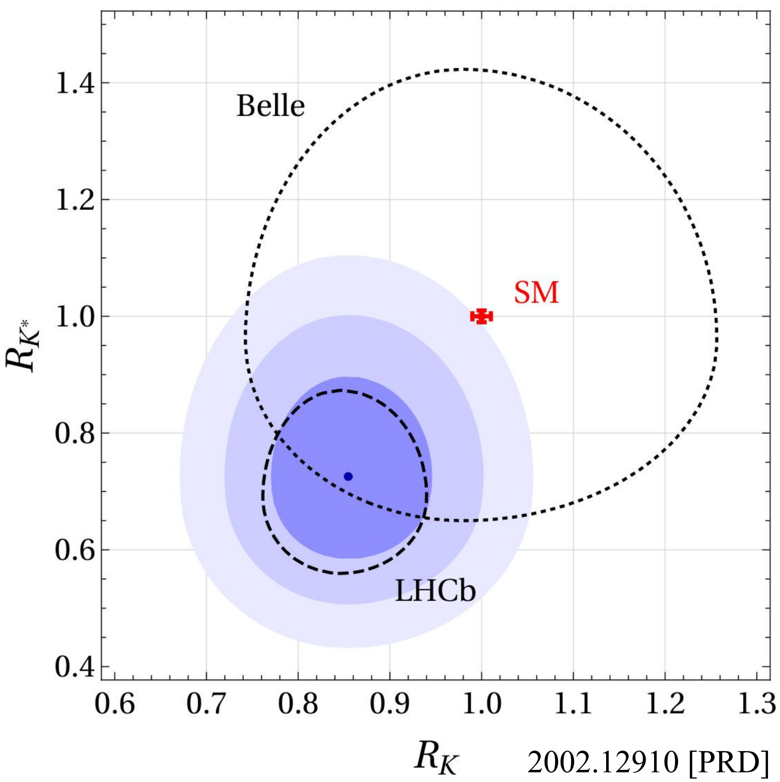
B 介子衰变中轻子味普适性破坏

$$R_K = \frac{\mathrm{Br}(B^+ \to K^+\mu^+\mu^-)}{\mathrm{Br}(B^+ \to K^+e^+e^-)}$$

$$R_{K^*} = \frac{\mathrm{Br}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathrm{Br}(B^0 \to K^{*0}e^+e^-)}$$







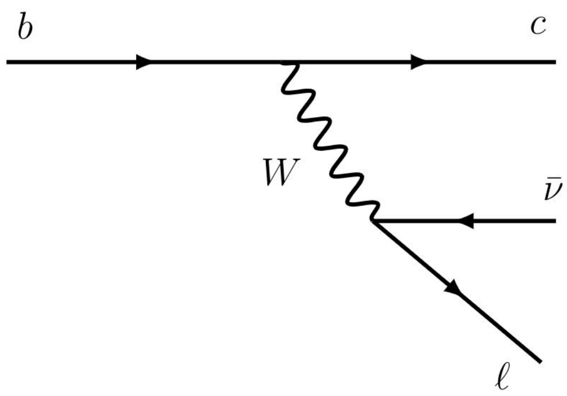
$$R_K^{\mathrm{SM}} = 1.0003 \pm 0.0001\,, \quad R_{K^*}^{\mathrm{SM}} = 1.00 \pm 0.01$$

$$R_K^{\mathrm{LHCb}} = 0.846^{+0.042\,+0.013}_{-0.039\,-0.012} \quad R_{K^*}^{\mathrm{LHCb}} = 0.685^{+0.113}_{-0.069} \pm 0.047$$

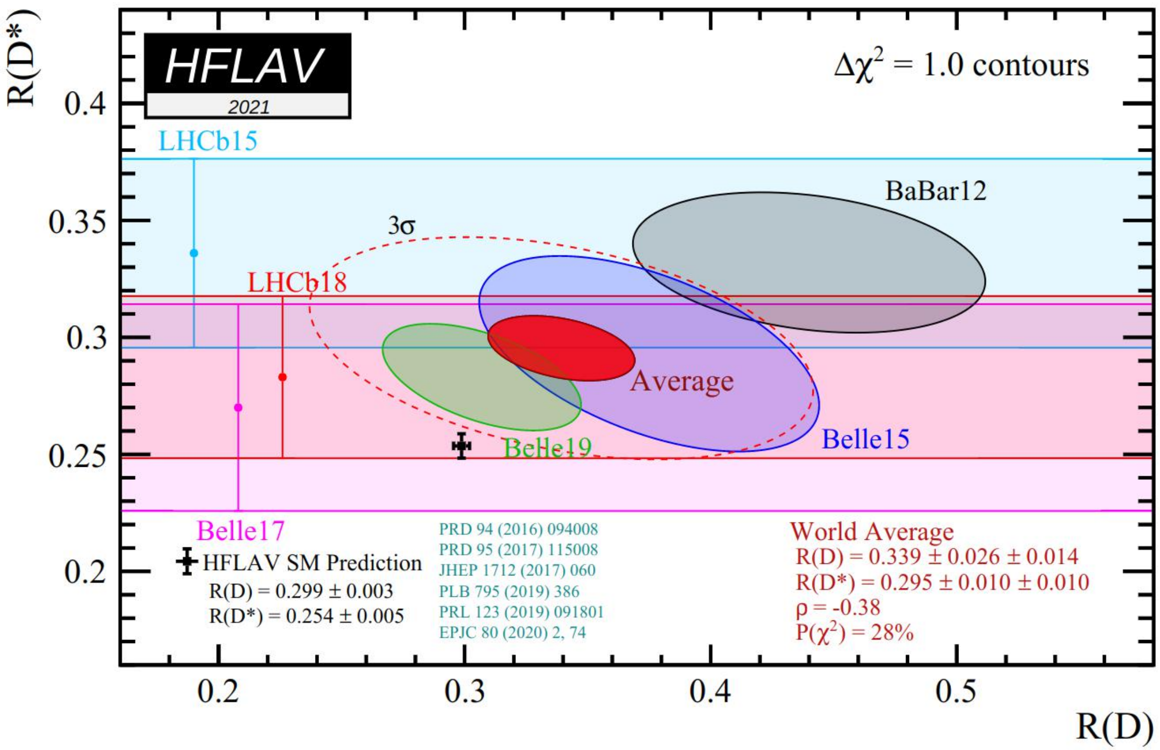
3 σ

B 介子衰变中轻子味普适性破坏

$$R_D = \frac{\mathrm{Br}(B \to D\tau\bar{\nu})}{\mathrm{Br}(B \to D\ell\bar{\nu})} \qquad R_{D^*} = \frac{\mathrm{Br}(B \to D^*\tau\bar{\nu})}{\mathrm{Br}(B \to D^*\ell\bar{\nu})} \qquad \ell = e, \mu$$



[2206.07501]



$$R_D^{\mathrm{SM}} = 0.299 \pm 0.003$$

$$R_{D^*}^{\mathrm{SM}} = 0.258 \pm 0.003$$

$$R_D^{\mathrm{exp}} = 0.339 \pm 0.026 \pm 0.014$$

$$R_{D^*}^{\mathrm{exp}} = 0.295 \pm 0.010 \pm 0.010$$

3.4 σ

Leptoquark 模型

- Leptoquarks 是一类玻色子

  SU(5) GUT 模型, SU(4) Pati-Salam 模型等

- 直接与轻子和夸克耦合

  携带有颜色量子数, 分数电荷, 重子数 (B) 和 轻子数 (L)

- 自旋为 0 或 1

  标量 Leptoquarks 和矢量 Leptoquarks

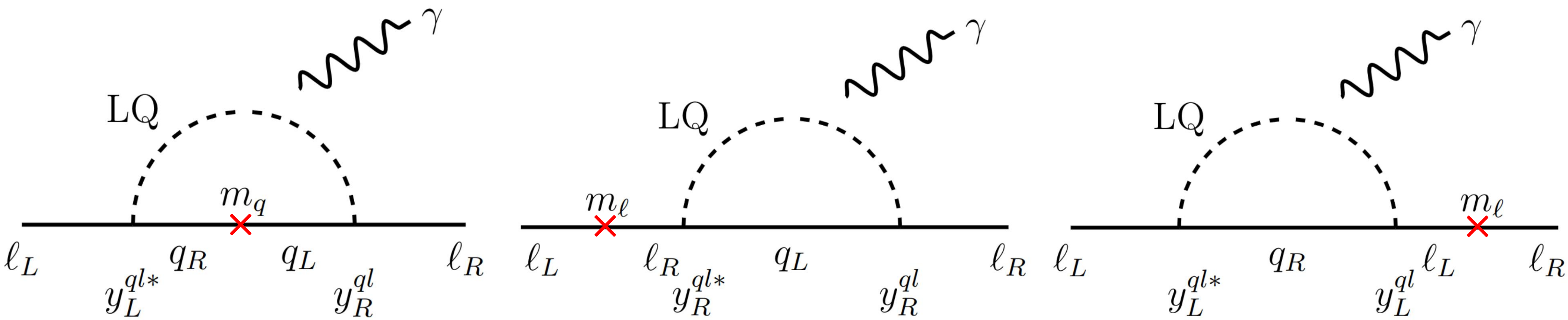
Leptoquark	自旋	(SU(3),SU(2),U(1))	电荷
S_1	0	$(\bar{3}, 1, 1/3)$	$+1/3$
$\tilde{S}_1$	0	$(\bar{3}, 1, 4/3)$	$+4/3$
R_2	0	$(3, 2, 7/6)$	$+2/3, +5/3$
$\tilde{R}_2$	0	$(3, 2, 1/6)$	$-1/3, +2/3$
S_3	0	$(\bar{3}, 3, 1/3)$	$-2/3, +1/3, +4/3$

带电轻子的反常磁矩

标量 Leptoquark 相互作用一般形式:

$$\mathcal{L} = \overline{q^{(C)}}_i (y_R^{ij} P_R + y_L^{ij} P_L) \ell_j S + \text{h.c.}$$

手征性压低：



$$\Delta a_\ell = -\frac{3m_\ell}{8\pi^2 m_S^2} \sum_q \Big[m_\ell (|y_R^{q\ell}|^2 + |y_L^{q\ell}|^2) F(x) + m_q \mathrm{Re}(y_L^{*q\ell} y_R^{q\ell}) G(x) \Big]$$

Leptoquark	chirality	$(g-2)_{e,\mu}$ at one-loop
S_1	no-chiral	✓
$\tilde{S}_1$	chiral	✗
R_2	no-chiral	✓
$\tilde{R}_2$	chiral	✗
S_3	chiral	✗

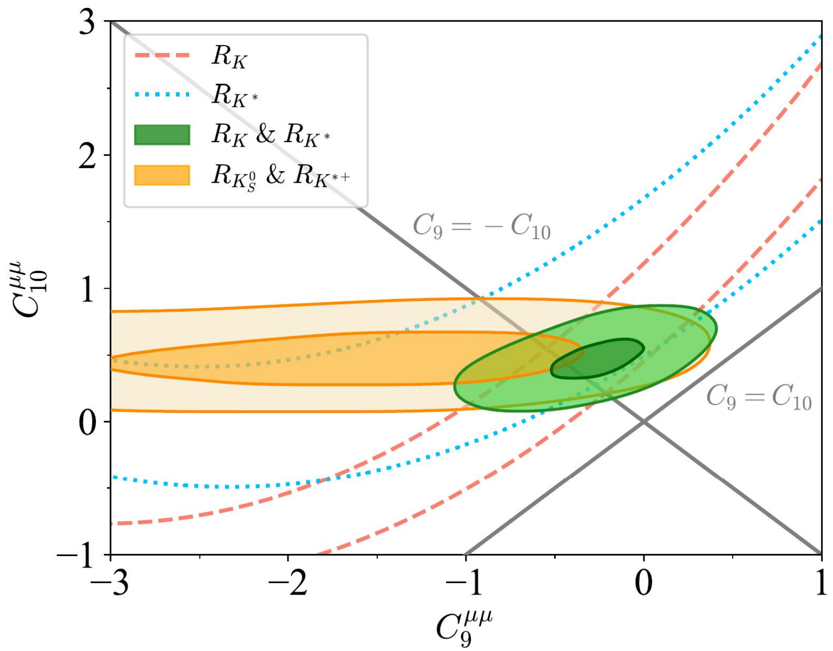
B 介子衰变中轻子味普适性反常

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \Big[\sum_{X=9,10} (C_X^{\ell\ell}\mathcal{O}_X^{\ell\ell} + C_{X'}^{\ell\ell}\mathcal{O}_{X'}^{\ell\ell}) \Big] + \text{h.c.}$$

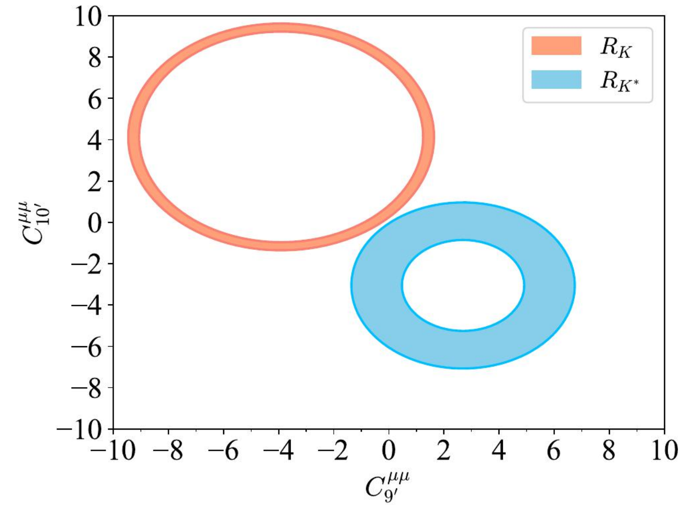
$$\mathcal{O}_9^{\ell\ell} = \frac{e^2}{(4\pi)^2}(\bar{s}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu \ell)\,, \quad \mathcal{O}_{10}^{\ell\ell} = \frac{e^2}{(4\pi)^2}(\bar{s}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu\gamma_5 \ell)\,,$$

$$\mathcal{O}_{9'}^{\ell\ell} = \frac{e^2}{(4\pi)^2}(\bar{s}\gamma^\mu P_R b)(\bar{\ell}\gamma_\mu \ell)\,, \quad \mathcal{O}_{10'}^{\ell\ell} = \frac{e^2}{(4\pi)^2}(\bar{s}\gamma^\mu P_R b)(\bar{\ell}\gamma_\mu\gamma_5 \ell)$$

最佳拟合: $C_9^{\mu\mu} = -C_{10}^{\mu\mu} = -0.45$

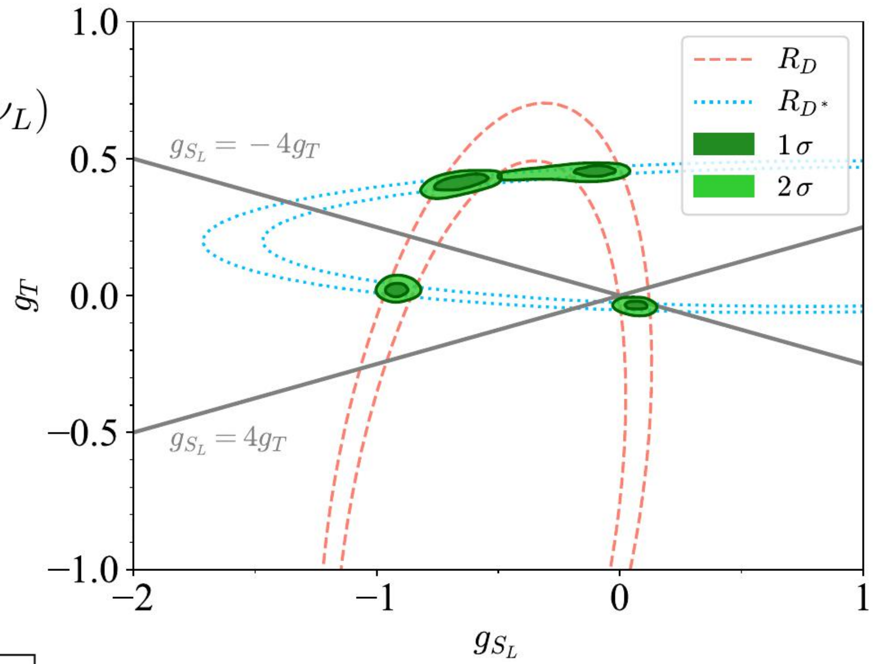


Leptoquark	树图阶	$R_{K^{(*)}}$
S_1	✗	✗
$\tilde{S}_1$	✗	✗
R_2	$C_{9'} = -C_{10'}$	✗
$\tilde{R}_2$	$C_9 = C_{10}$	✗
S_3	$C_9 = -C_{10}$	✓



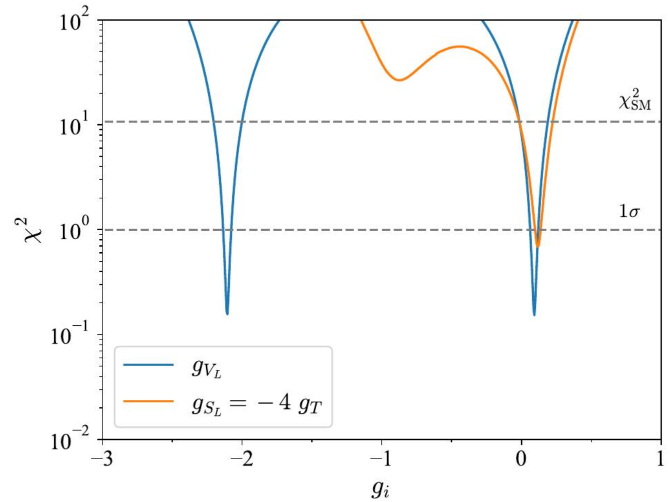
B 介子衰变中轻子味普适性反常

$$\mathcal{H}_{\rm eff} = \frac{4G_F}{\sqrt{2}} V_{cb} \Big[g_{V_L} (\bar{c}_L \gamma_\mu b_L)(\bar{\tau}_L \gamma^\mu \nu_L) + g_{S_L} (\bar{c}_R b_L)(\bar{\tau}_R \nu_L) + g_T (\bar{c}_R \sigma_{\mu\nu} b_L)(\bar{\tau}_R \sigma^{\mu\nu} \nu_L) \Big] + \text{h.c.}\,.$$

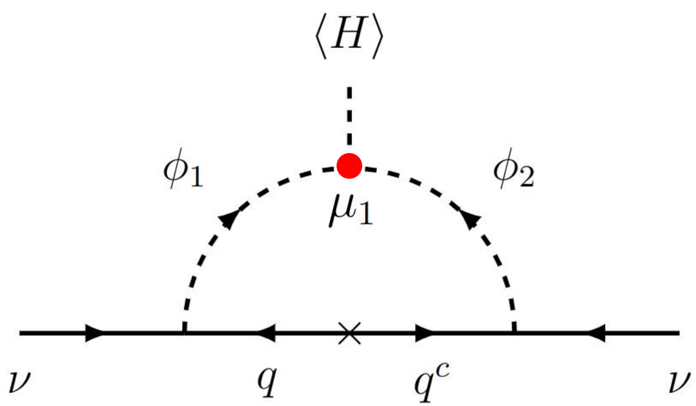


最佳拟合: $g_{S_L} = -4g_T = 0.12$

Leptoquark	树图阶	$R_{D^{(*)}}$
S_1	$g_{S_L} = -4\, g_T, g_{V_L}$	✓
$\tilde{S}_1$	✗	✗
R_2	$g_{S_L} = 4\, g_T$	✓(虚部)
$\tilde{R}_2$	✗	✗
S_3	g_{V_L}	✗



中微子质量起源



Leptoquark	(SU(3),SU(2),U(1))	电荷
S_1	$(\bar{3}, 1, 1/3)$	$+1/3$
$\tilde{S}_1$	$(\bar{3}, 1, 4/3)$	$+4/3$
R_2	$(3, 2, 7/6)$	$+2/3, +5/3$
$\tilde{R}_2$	$(3, 2, 1/6)$	-1/3, +2/3
S_3	$(\bar{3}, 3, 1/3)$	-2/3, +1/3, +4/3

可能的组合：$S_1 - \tilde{R}_2 \quad S_3 - \tilde{R}_2$

中微子质量矩阵：$(\mathcal{M}_\nu)_{\alpha\beta} = \left(y_{1L}^T \Lambda y_{2L} + y_{2L}^T \Lambda^T y_{1L}\right)_{\alpha\beta}$

$$\Lambda \equiv \begin{pmatrix} \Lambda_d & 0 & 0 \\ 0 & \Lambda_s & 0 \\ 0 & 0 & \Lambda_b \end{pmatrix} \qquad \Lambda_k \simeq \frac{3}{32\pi^2} m_k \frac{\sqrt{2}\mu_1 v}{m_{\phi_1}^2 - m_{\phi_2}^2} \log\left(\frac{m_{\phi_1}^2}{m_{\phi_2}^2}\right)$$

混合参数: $\mu_1 \sim 10\,\mathrm{keV}$

对相关物理现象的统一解释

Leptoquark	$(g-2)_{e,\mu}$	$R_{K^{(*)}}$	$R_{D^{(*)}}$	中微子质量
S_1	✓	✗	✓	$S_1 - \widetilde{R}_2$ $S_3 - \widetilde{R}_2$
$\tilde{S}_1$	✗	✗	✗	
R_2	✓	✗	✓	
$\tilde{R}_2$	✗	✗	✗	
S_3	✗	✓	✗	

两种可能组合: ① $S_1 - \widetilde{R}_2 - S_3$ ② $R_2 - \widetilde{R}_2 - S_3$

① 最小 Yukawa 耦合系数:

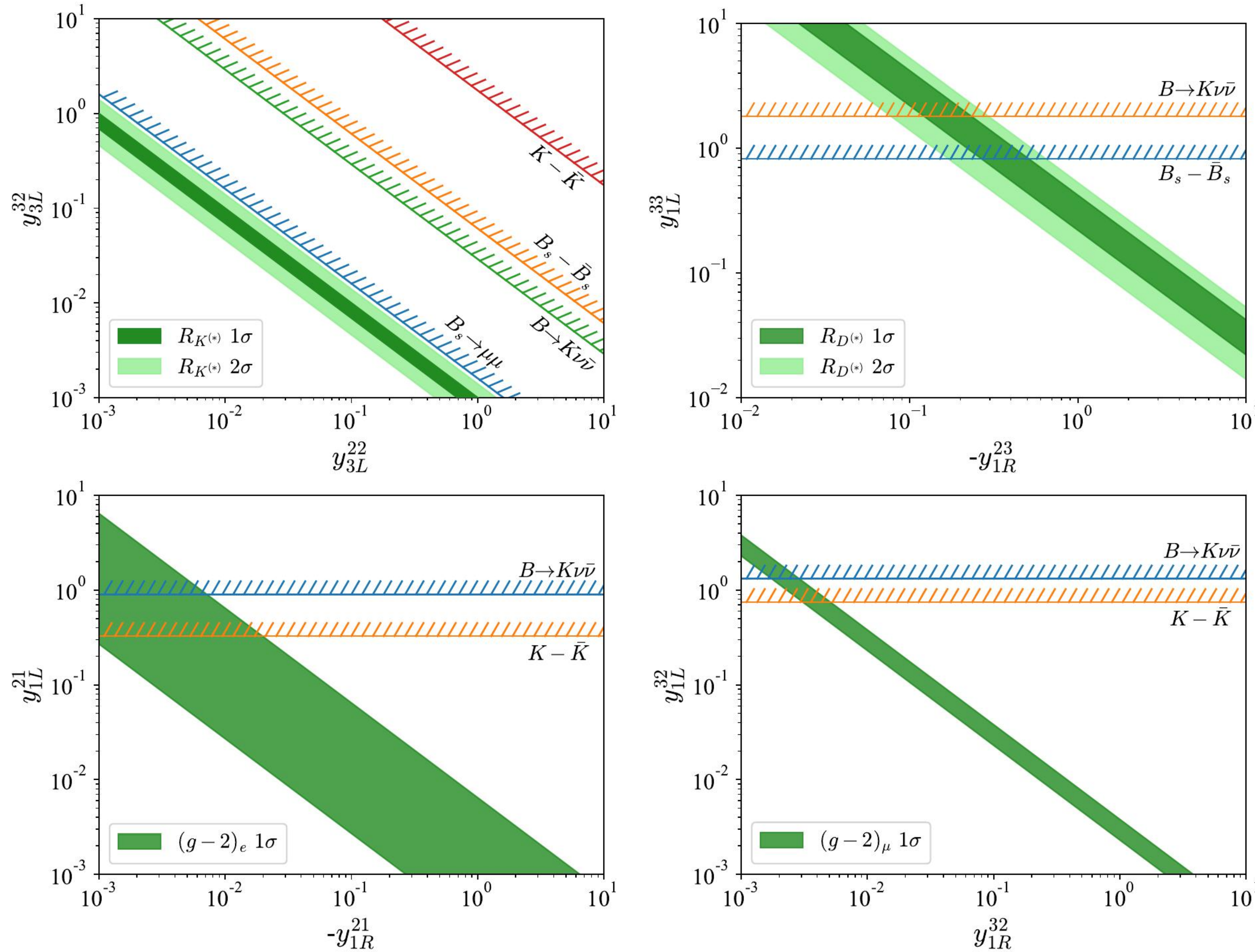
$$y_{1R} = \begin{pmatrix} 0 & 0 & 0 \\ y_{1R}^{21} & 0 & y_{1R}^{23} \\ 0 & y_{1R}^{32} & 0 \end{pmatrix}, \quad y_{1L} = \begin{pmatrix} 0 & 0 & 0 \\ y_{1L}^{21} & 0 & y_{1L}^{23} \\ 0 & y_{1L}^{32} & y_{1L}^{33} \end{pmatrix},$$

$$y_{3L} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_{3L}^{22} & y_{3L}^{23} \\ y_{3L}^{31} & y_{3L}^{32} & 0 \end{pmatrix}, \quad y_{2L} = \begin{pmatrix} 0 & 0 & 0 \\ y_{2L}^{21} & y_{2L}^{22} & y_{2L}^{23} \\ y_{2L}^{31} & y_{2L}^{32} & y_{2L}^{33} \end{pmatrix}$$

- $(g-2)_e$
- $(g-2)_\mu$
- R_D, R_{D^*}
- R_K, R_{K^*}

$y_{1L} - y_{2L}$
$y_{3L} - y_{2L}$ 中微子振荡

可行参数空间



$R_{K^{(*)}}$ 1σ
$R_{K^{(*)}}$ 2σ
$K-\bar{K}$
$B_s-\bar{B}_s$
$B\to K\nu\bar{\nu}$
$B_s\to\mu\mu$
y_{3L}^{32}
y_{3L}^{22}
$R_{D^{(*)}}$ 1σ
$R_{D^{(*)}}$ 2σ
$B\to K\nu\bar{\nu}$
$B_s-\bar{B}_s$
y_{1L}^{33}
$-y_{1R}^{23}$
$(g-2)_e$ 1σ
$B\to K\nu\bar{\nu}$
$K-\bar{K}$
y_{1L}^{21}
$-y_{1R}^{21}$
$(g-2)_\mu$ 1σ
$B\to K\nu\bar{\nu}$
$K-\bar{K}$
y_{1L}^{32}
y_{1R}^{32}

Benchmark Points

Benchmark point 1:

$$y_{1R} = \begin{pmatrix} 0 & 0 & 0 \\ -0.37 & 0 & -0.70 \\ 0 & 0.054 & 0 \end{pmatrix}, \qquad y_{3L} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0.029 & 0 \\ 0 & 0.023 & 0 \end{pmatrix},$$

$$y_{1L} = \begin{pmatrix} 0 & 0 & 0 \\ 0.012 + 0.016i & 0 & -0.049 - 0.0042i \\ 0 & 0.57 + 0.0082i & 0.59 + 0.052i \end{pmatrix},$$

$$y_{2L} = \begin{pmatrix} 0 & 0 & 0 \\ 0.043 - 0.042i & 0.044 & -0.048 \\ -0.00013 & 0.00038 & 0.00027 \end{pmatrix}.$$

Benchmark point 2:

$$y_{1R} = \begin{pmatrix} 0 & 0 & 0 \\ -0.014 & 0 & -0.93 \\ 0 & 0.012 & 0 \end{pmatrix}, \quad y_{1L} = \begin{pmatrix} 0 & 0 & 0 \\ 0.37 & 0 & 0 \\ 0 & 0.21 & 0.38 \end{pmatrix},$$

$$y_{3L} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0.070 & 0.038 \\ 0.0019 & 0.0059 & 0 \end{pmatrix}, \quad y_{2L} = \begin{pmatrix} 0 & 0 & 0 \\ -0.015 & -0.0020 & 0.023 \\ 0.0015 & 0.0031 & -0.00078 \end{pmatrix}.$$

Benchmark Points

观测量	允许范围	BP1	BP2
$\Delta m_{21}^2(10^{-5}\mathrm{eV}^2)$	[6.82, 8.04]	7.44	7.40
$\Delta m_{32}^2(10^{-3}\mathrm{eV}^2)$	[2.435, 2.598]	2.50	2.51
$\sin^2\theta_{12}$	[0.269, 0.343]	0.305	0.301
$\sin^2\theta_{23}$	[0.405, 0.620]	0.569	0.570
$\sin^2\theta_{13}$	[0.02064, 0.02430]	0.0226	0.0225
$\delta_{\mathrm{CP}}/^\circ$	[169, 246]	194	180
R_K	[0.795, 0.901]	0.808	0.812
R_{K^*}	[0.569, 0.845]	0.794	0.817
$R_{K_S^0}$	[0.48, 0.88]	0.808	0.812
$R_{K^{*+}}$	[0.53, 0.91]	0.825	0.844
R_D	[0.310, 0.370]	0.358	0.351
R_{D^*}	[0.281, 0.309]	0.305	0.292
$\Delta a_e\,(10^{-13})$	[-12.3, -5.1]	-8.48	-9.89
$\Delta a_\mu\,(10^{-9})$	[1.93, 3.11]	2.52	2.06

Benchmark Points

$\mathrm{Br}(\mu \to e\gamma)$	$< 4.2 \times 10^{-13}$	6.49×10^{-21}	1.04×10^{-17}
$\mathrm{Br}(\tau \to e\gamma)$	$< 3.3 \times 10^{-8}$	2.98×10^{-18}	6.09×10^{-16}
$\mathrm{Br}(\tau \to \mu\gamma)$	$< 4.4 \times 10^{-8}$	2.99×10^{-18}	7.82×10^{-16}
$\mathrm{Br}(\mu - e)_{\mathrm{Au}}$	$< 7 \times 10^{-13}$	4.84×10^{-19}	2.62×10^{-15}
$\mathrm{Br}(B_s^0 \to \mu\mu)$	$[2.58,\ 3.28]\ \times 10^{-9}$	2.93×10^{-9}	3.42×10^{-9}
$\mathrm{Br}(B_s^0 \to \tau\tau)$	$< 6.8 \times 10^{-3}$	7.82×10^{-7}	7.95×10^{-7}
$\mathrm{Br}(B_s^0 \to \mu\tau)$	$< 1.4 \times 10^{-5}$	2.11×10^{-14}	1.40×10^{-10}
$R_K^{\nu\nu}$	< 3.9	1.3	0.75
$R_{K^*}^{\nu\nu}$	< 2.7	1.4	0.76
$\Delta m_{B_s}^{\mathrm{SM+NP}} / \Delta m_{B_s}^{\mathrm{SM}}$	[0.85,1.15]	1.03	1.01
$\Delta m_K^{\mathrm{NP}} (10^{10}\ s^{-1})$	< 0.95	0.0016	0.52

小结

- 通过 TeV 量级的 Leptoquarks 同时解释了带电轻子反常磁矩、B 介子衰变中轻子味普适性破坏和中微子质量
- 至少需要三个 Leptoquarks 才能给出对相关物理过程的统一解释
- 结合了相关低能物理过程对模型参数的限制，找出了可行的最小参数空间

3，构建 scotogenic Georgi-Machacek 模型，同时实现中微子质量起源、轻子产生机制和提供暗物质候选者

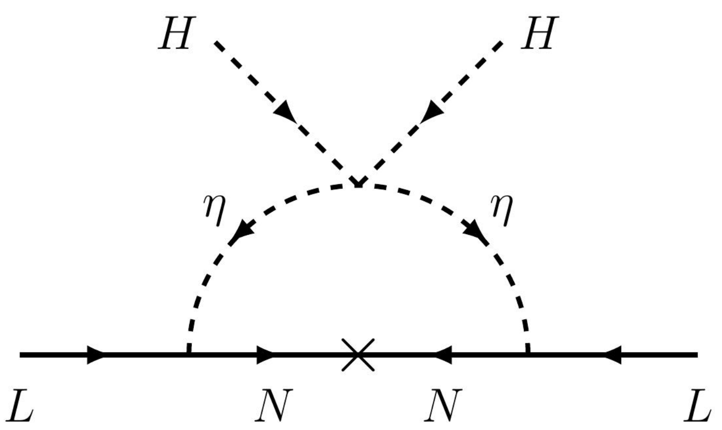
Scotogenic 中微子质量模型

E. Ma, hep-ph/9805219

- 三个单态费米场 $N_i(i = 1, 2, 3)$
- 一个二重态标量场 $\eta = (\eta^+, \eta^0)$
- 引入 Z_2 对称性来禁闭掉树图阶中微子质量项，同时提供暗物质候选者

中微子质量相关的拉氏量

$$\mathcal{L}_{\rm scot} \supset M_{Nk}\overline{N_k^C}N_k - Y_N^{ij}\,\overline{N_i^C}\eta^+ L_j + \frac{\lambda}{2}(H^\dagger\eta)^2 + \text{h.c.}$$



中微子质量矩阵

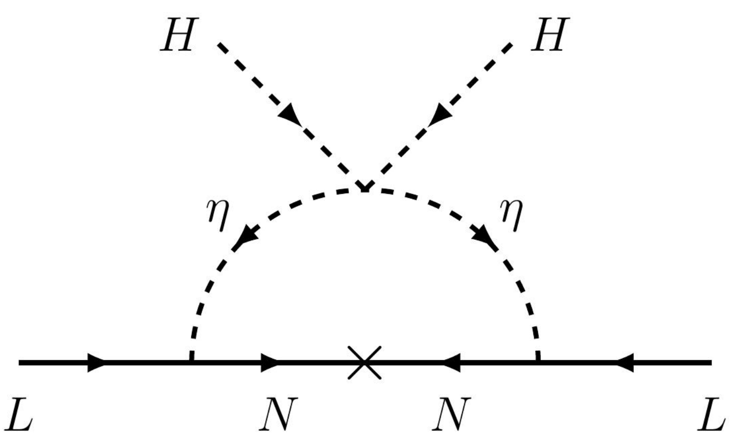
$$(\mathcal{M}_\nu)_{ij} \simeq \frac{1}{16\pi^2}\lambda v^2 \sum_k \frac{(Y_N)_{ik}(Y_N)_{jk}}{M_{Nk}}$$

Scotogenic Georgi-Machacek 模型

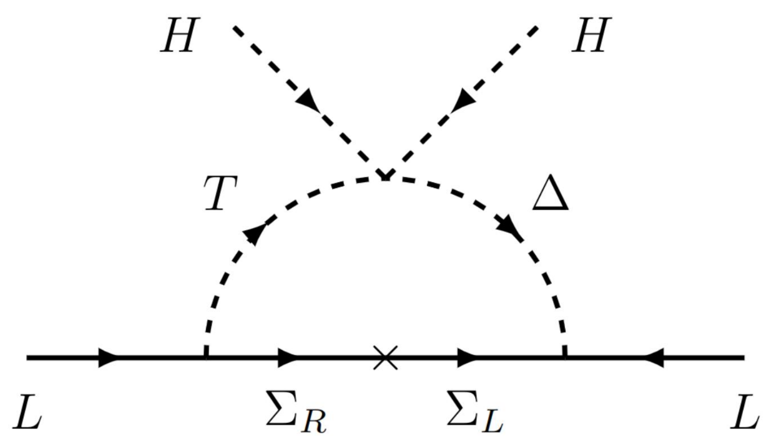
Georgi & Machacek 1985

- $Y=1$ 三重态复标量场 $\Delta(D^0, D^+, D^{++})$
- $Y=0$ 三重态实标量场 $T(T^-, T^0, T^+)$

$$\Delta = \begin{pmatrix} \frac{D^+}{\sqrt{2}} & -D^{++} \\ D^0 & -\frac{D^+}{\sqrt{2}} \end{pmatrix} \qquad T = \begin{pmatrix} \frac{T^0}{\sqrt{2}} & -T^+ \\ -T^- & -\frac{T^0}{\sqrt{2}} \end{pmatrix}$$



Scotogenic 中微子质量模型



Scotogenic GM 模型

Scotogenic Georgi-Machacek 模型

标量场:

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}, \ \Delta = \begin{pmatrix} \frac{D^+}{\sqrt{2}} & -D^{++} \\ D^0 & -\frac{D^+}{\sqrt{2}} \end{pmatrix}, \ T = \begin{pmatrix} \frac{T^0}{\sqrt{2}} & -T^+ \\ -T^- & -\frac{T^0}{\sqrt{2}} \end{pmatrix}$$

类矢量费米场:

$$\Sigma_L \equiv (\Sigma_L^0 \quad \Sigma_L^-)^T, \qquad \Sigma_R \equiv (\Sigma_R^0 \quad \Sigma_R^-)^T$$

引入两个额外的分离对称性:

Fields	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$\mathcal{Z}_4$	$\mathcal{Z}_2$
T	1	3	0	1	-
Δ	1	3	1	1	-
ϕ_1	1	2	1/2	-i	+
ϕ_2	1	2	1/2	i	+
$\Sigma_{L,R}$	1	2	$-1/2$	1	-

Fields	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$\mathcal{Z}_4$	$\mathcal{Z}_2$
Q_L	3	1	1/6	1	+
u_R	3	1	2/3	i	+
d_R	3	1	-1/3	-i	+
L_L	1	2	-1/2	1	+
e_R	1	1	-1	-i	+

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Higgs 势:

$$
\begin{aligned}
V(2\mathrm{HDM},\Delta,T) = & V_{2\mathrm{HDM}} + m_\Delta^2 \mathrm{Tr}(\Delta^\dagger\Delta) + \frac{m_T^2}{2}\mathrm{Tr}(T^2) \\
& + \rho_1[\mathrm{Tr}(\Delta^\dagger\Delta)]^2 + \rho_2\mathrm{Tr}(\Delta^\dagger\Delta\Delta^\dagger\Delta) + \rho_3\mathrm{Tr}(T^4) \\
& + \rho_4\mathrm{Tr}(\Delta^\dagger\Delta)\mathrm{Tr}(T^2) + \rho_5\mathrm{Tr}(\Delta^\dagger T)\mathrm{Tr}(T\Delta) \\
& + \sum_{a=1,2}\left(\kappa_{1a}\mathrm{Tr}(\Delta^\dagger\Delta)\phi_a^\dagger\phi_a + \kappa_{2a}\phi_a^\dagger\Delta\Delta^\dagger\phi_a + \frac{\kappa_{3a}}{2}\mathrm{Tr}(T^2)\phi_a^\dagger\phi_a\right) \\
& + \kappa_{41}(\phi_1^\dagger\Delta T\tilde{\phi}_2 + \mathrm{h.c.}) + \kappa_{42}(\phi_2^\dagger\Delta T\tilde{\phi}_1 + \mathrm{h.c.})
\end{aligned}
$$

物理场:

$h,\ H,\ A,\ H^\pm$ $\qquad$ $S_1,\ S_2,\ S_1^\pm,\ S_2^\pm,\ S^{\pm\pm}$

模型参数空间限制:

- 真空稳定性条件
- 电弱精细观测量
- 轻子味破坏过程
- 对撞机限制

暗物质

暗物质领域自由参数:

$$m_{S_2},\ \sin\gamma,\ \kappa_{1i},\ \kappa_{2i},\ \kappa_{3i},\ \kappa_{4i}\quad (i=1,2)$$

与暗物质遗迹丰度相关的自由参数:

$$m_{S_2},\ \sin\gamma,\ \kappa_{2i},\ \kappa_{4i}\quad (i=1,2)$$

$0\le \sin\gamma \le \frac{1}{\sqrt{2}}$

κ_{41}	κ_{42}	κ_{21}	κ_{22}	暗物质候选者
-	-	+	+	S_1
-	-	-	-	S_1
+	+	-	-	S_2
+	+	+	+	×

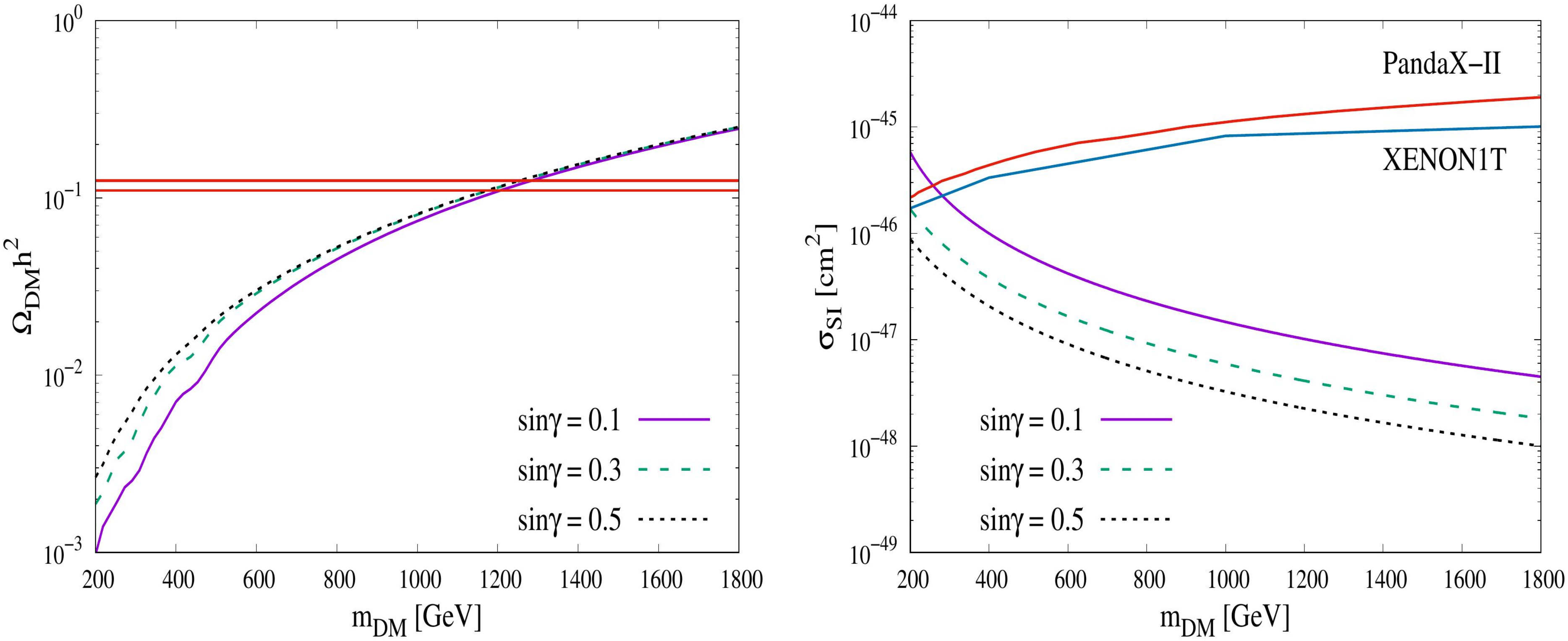
$-\frac{1}{\sqrt{2}}\le \sin\gamma \le 0$

κ_{41}	κ_{42}	κ_{21}	κ_{22}	暗物质候选者
+	+	+	+	S_1
+	+	-	-	S_1
-	-	-	-	S_2
-	-	+	+	×

暗物质候选者为S_1

参数: $\sin\gamma$

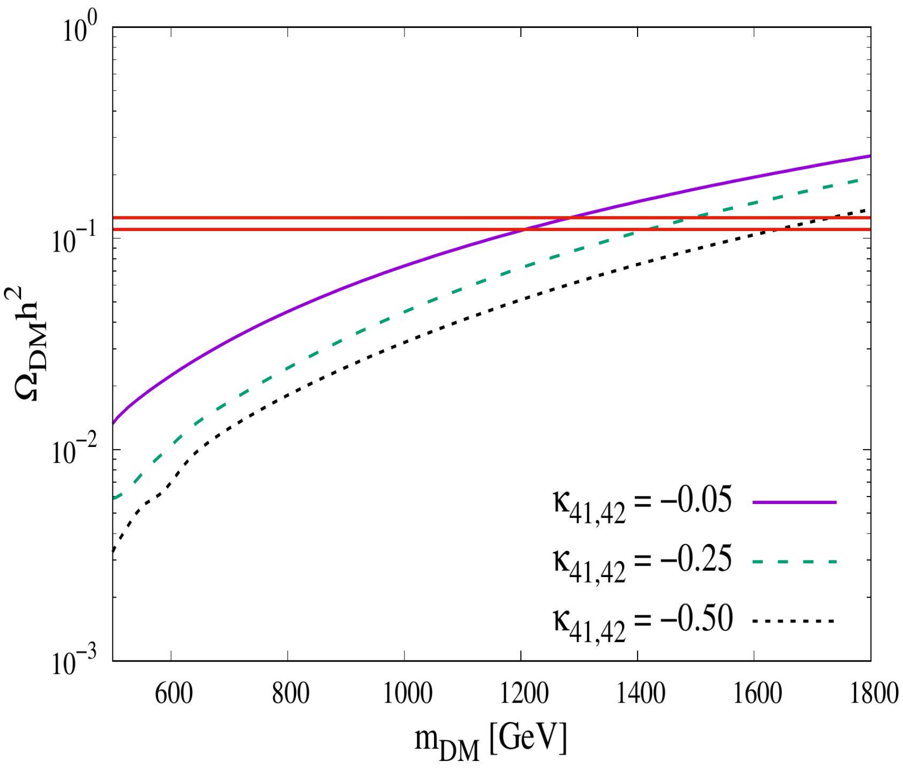
$$\tan\beta = 1,\ \kappa_{1i} = \kappa_{2i} = \kappa_{3i} = 0.05,\ \kappa_{4i} = -0.05$$



暗物质候选者为S_1

参数: $\kappa_{41,42}$

$$\sin\gamma = 0.1,\ \tan\beta = 1,\ \kappa_{1i} = \kappa_{2i} = \kappa_{3i} = 0.05$$



暗物质候选者为S_1

参数: $\tan\beta$

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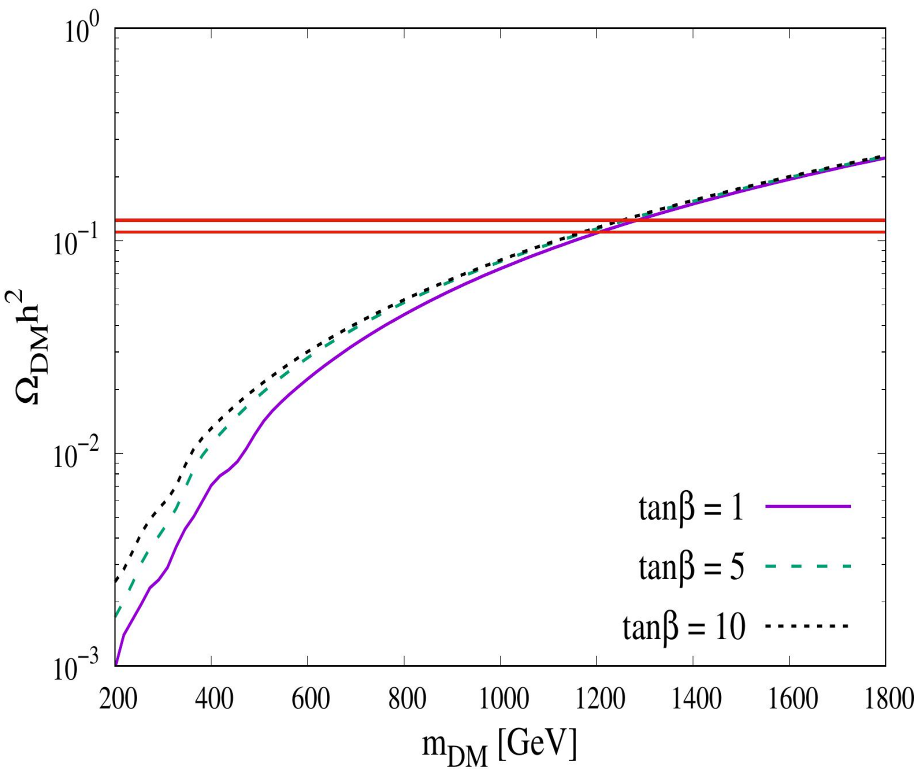

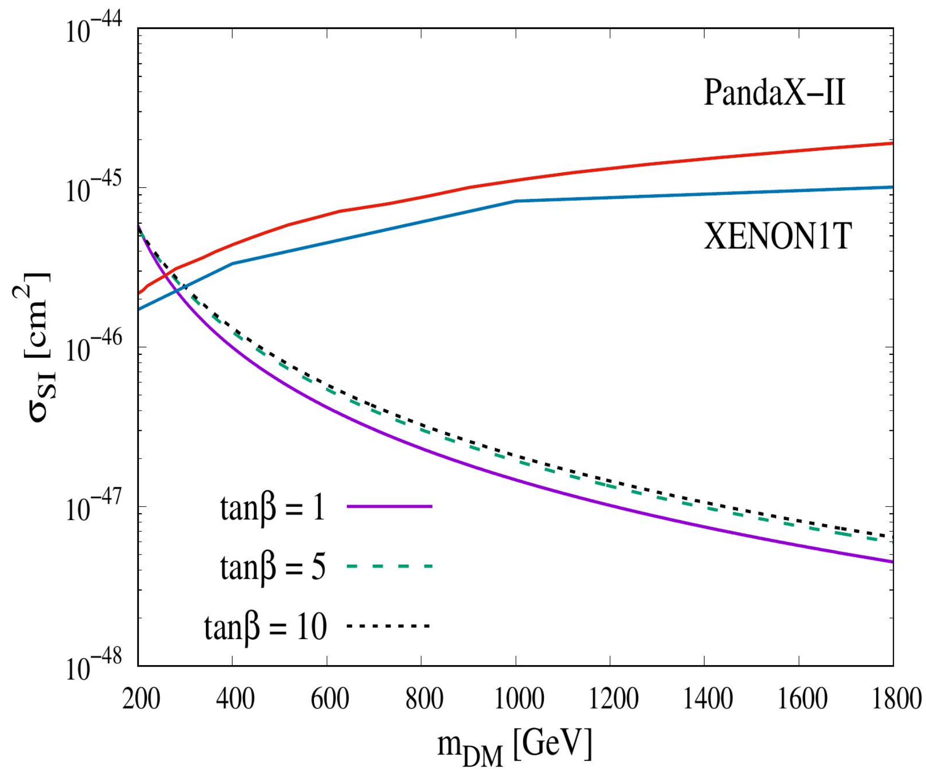

轻子产生机制

类矢量费米子衰变产生的不对称

$$\epsilon_{1\Delta} = \frac{\sum_\alpha [\Gamma(\Sigma \to l_L^c + \Delta) - \Gamma(\Sigma^c \to l_L + \Delta^*)]}{\Gamma_1}$$

$$\epsilon_{1T} = \frac{\sum_\alpha [\Gamma(\Sigma^c \to l_L^c + T^*) - \Gamma(\Sigma \to l_L + T)]}{\Gamma_1}$$

Boltzmann 方程

$$\frac{dY_{\Sigma_1}}{dz} = -z\frac{\Gamma_1}{\mathrm{H}_1}\frac{K_1(z)}{K_2(z)}\left(Y_{\Sigma_1} - Y_{\Sigma_1}^{\mathrm{eq}}\right)$$

$$\frac{dY_L^\Delta}{dz} = -\frac{\Gamma_1}{\mathrm{H}_1}\left(\epsilon_{1\Delta} z\frac{K_1(z)}{K_2(z)}(Y_{\Sigma_1}^{eq} - Y_{\Sigma_1}) + \mathrm{Br}_L^\Delta \frac{z^3 K_1(z)}{4} Y_L^\Delta\right)$$

$$\frac{dY_L^T}{dz} = -\frac{\Gamma_1}{\mathrm{H}_1}\left(\epsilon_{1T} z\frac{K_1(z)}{K_2(z)}(Y_{\Sigma_1}^{eq} - Y_{\Sigma_1}) + \mathrm{Br}_L^T \frac{z^3 K_1(z)}{4} Y_L^T\right)$$

净轻子数 $Y_L(z \to \infty) = 2\left(Y_L^\Delta(z \to \infty) + Y_L^T(z \to \infty)\right)$

宇宙中的重子数 $Y_B = (8 - 9.5) \times 10^{-11}$ $\qquad Y_B(z \to \infty) = \frac{10}{31} Y_L(z \to \infty)$

小结

- 通过拓展双二重态 Higgs 和 Georgi-Machacek 模型构建了 scotogenic Georgi-Machacek 模型

- 新的物理模型中同时实现中微子质量起源、轻子产生机制和提供暗物质候选者

- 结合目前实验和理论对模型参数空间的限制，详细分析了模型的可行的参数空间

总结

- 基于中微子质量产生机制，暗物质本质和宇宙中正反物质不对称，并结合标准模型与目前实验数据间的反常现象，考察了它们在超出标准模型的新物理模型中的统一性

- 利用中微子的 type-II seesaw 模型中的三重态 Higgs 场作为暗物质与标准模型中粒子的媒介，解释 AMS-02 和 DAMPE 实验中关于正负电子的超出

- 采用 Leptoquark 模型同时解释带电轻子反常磁矩、B 介子衰变过程中轻子味普适性破坏和中微子质量，结合目前最新的实验数据寻找模型的可行参数空间

- 构建 scotogenic Georgi-Machacek 模型，同时实现中微子质量起源、轻子产生机制和提供暗物质候选者

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谢谢各位老师和同学