CP violation and leptogenesis

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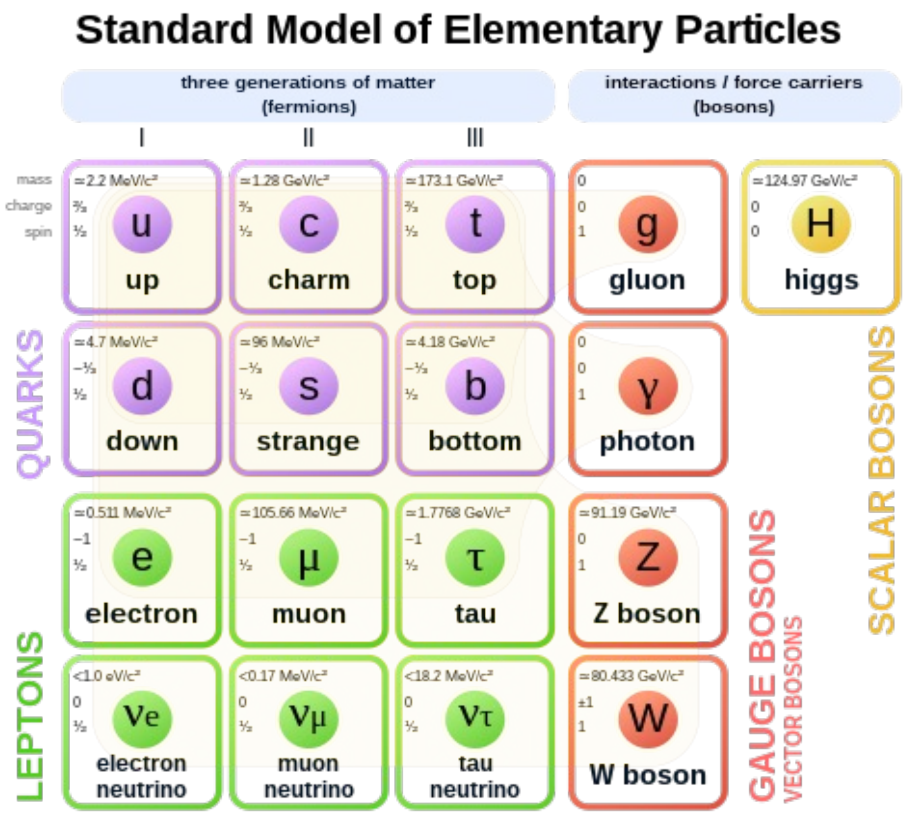
中山大学

第二十届重味物理和CP破坏研讨会

复旦大学

2023.12.17

粒子物理标准模型



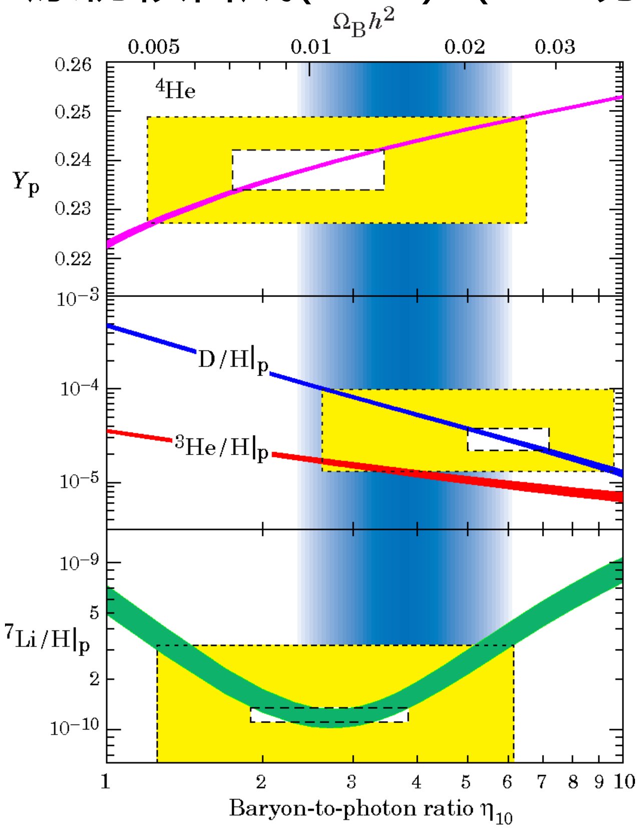
物质的基本组成及其相互作用

仍然存在一些观测结果，标准模型无法解释

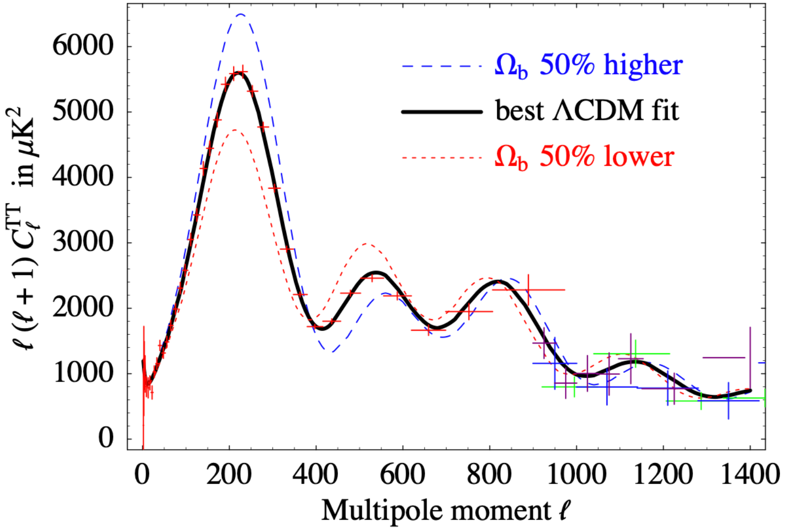
- 正反物质不对称性
- 中微子质量
- 暗物质

正反物质不对称性(重子不对称性)

原初核合成(BBN) (t~3 分钟)



宇宙微波背景辐射(CMB)(t~38万年)



Parameter	Plik best fit	Plik [1]	CamSpec [2]	([2] − [1])/σ_1	Combined
$\Omega_b h^2$	0.022383	0.02237 ± 0.00015	0.02229 ± 0.00015	−0.5	0.02233 ± 0.00015
$\Omega_c h^2$	0.12011	0.1200 ± 0.0012	0.1197 ± 0.0012	−0.3	0.1198 ± 0.0012

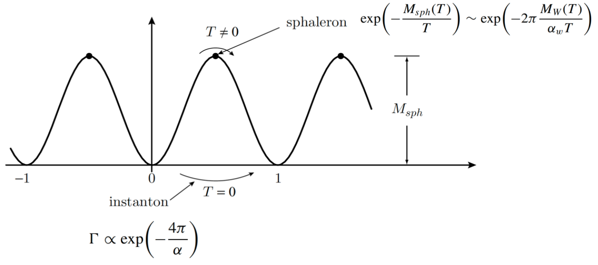
$$\eta = \frac{n_b - n_{\bar{b}}}{n_\gamma} \sim 10^{-10}$$

- Why is there baryon asymmetry? If not $n_b/n_\gamma = n_{\bar{b}}/n_\gamma \sim 10^{-20}$
- Why the asymmetry is so small? In the early universe (T > 1 GeV) $n_b, n_{\bar{b}} \sim n_\gamma$

如何产生正反物质不对称性?

Sakharov 三条件 | 标准模型

- 重子数破坏(Sphaleron过程) ✓
- C和CP破坏 ✓✗
- 脱离热平衡 ✗



$$\Delta B = \Delta L = -3$$

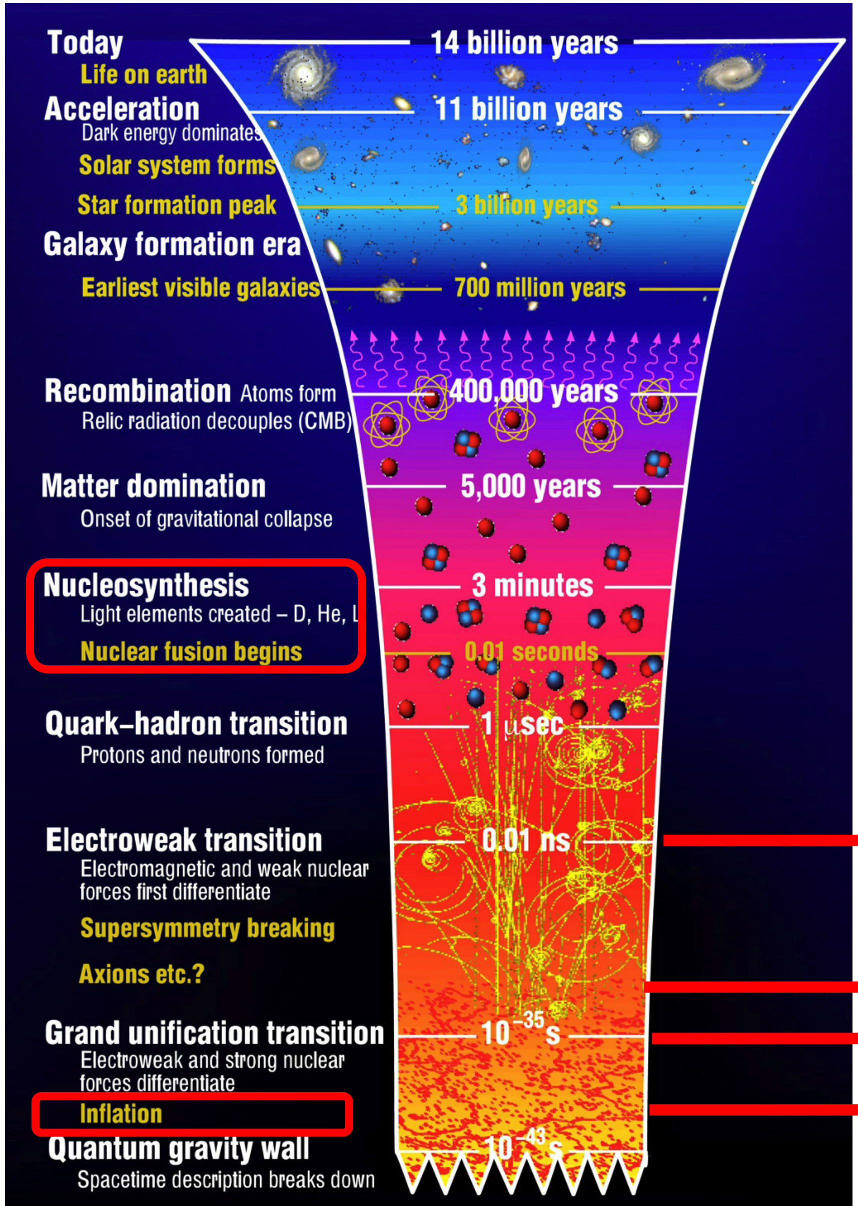
标准模型面临的问题

- 无法提供脱离热平衡条件(QCD相变和电弱相变均为 cross over)
- 即使有强一阶相变，夸克部分提供CP破坏太小(10^{-19})

1. 需要新的CP破坏源(重味物理实验的一个重要目标)
2. 新粒子实现脱离热平衡条件

正反物质不对称什么时候产生?

不能晚于原初核合成，否则元素丰度不一致



EW Baryogenesis

Leptogenesis

GUT Baryogenesis

Baryogenesis from inflation

不能早于暴胀，因为宇宙在很短时间内膨胀了 e^{60} 倍，任何早期的不对称性都变的极小

电弱重子生成(EW baryogenesis)

Rubakov and Shaposhnikov, 1996, D. E. Morrissey and M. J. Ramsey-Musolf, 2012'

电弱重子生成

- 在电弱标度增加新的标量粒子(电弱强一阶相变)
- 额外的CP破坏

- 对撞机限制
- 电子EDM测量(< 4.1*10^{-30} e.cm)

Is electroweak baryogenesis dead?

James M. Cline[1,2] 2017'

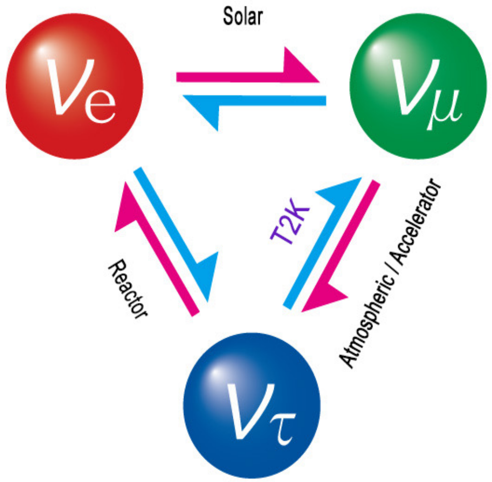
[1]CERN, Theoretical Physics Department, Geneva, Switzerland

[2]Department of Physics, McGill University, 3600 Rue University, Montréal, Québec, Canada H3A 2T8

Challenge in model building

中微子的启示

中微子振荡实验表明，中微子有微小的质量(质量和大于0.05eV)，味道本征态和质量本征态不一致



类似夸克部分的CKM矩阵，轻子部分存在一个PMNS矩阵

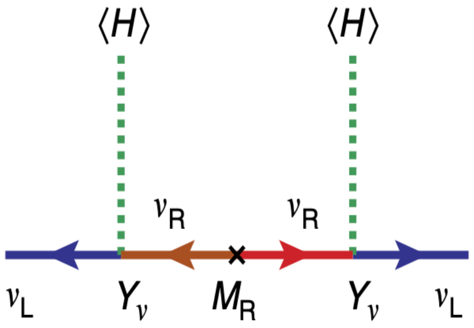
$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\begin{aligned} \theta_{12} &= 33.41^{\circ}{}^{+0.75^{\circ}}_{-0.72^{\circ}} \\ \theta_{23} &= 49.1^{\circ}{}^{+1.0^{\circ}}_{-1.3^{\circ}} \\ \theta_{13} &= 8.54^{\circ}{}^{+0.11^{\circ}}_{-0.12^{\circ}} \\ \delta_{\mathrm{CP}} &= 197^{\circ}{}^{+42^{\circ}}_{-25^{\circ}} \end{aligned}$$

轻子部分提供了新的CP破坏源, 正反物质不对称性从轻子部分开始——轻子生成机制（leptogenesis）(由sphaleron过程传递给重子)

中微子质量起源——跷跷板机制

Type I

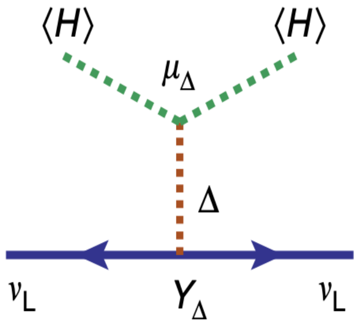


$$M_\nu = -\langle H\rangle^2 Y_\nu M_R^{-1} Y_\nu^T$$

SM+3 singlets fermions

Minkowski, Gell-Mann,
Glashow, Yanagida

Type II



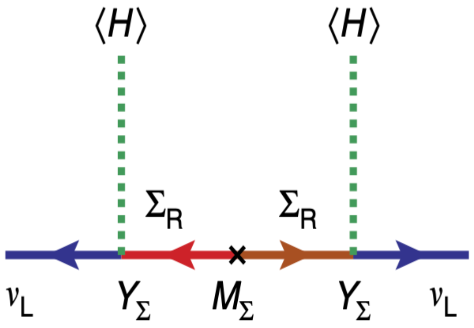
$$M_\nu = \langle H\rangle^2 Y_\Delta \mu_\Delta / M_\Delta^2$$

SM+1 triplet Higgs

Magg, Wetterich

Scalar boson

Type III



$$M_\nu = -\langle H\rangle^2 Y_\Sigma M_\Sigma^{-1} Y_\Sigma^T$$

SM+3 triplet fermions

Foot, Lew, He, Joshi

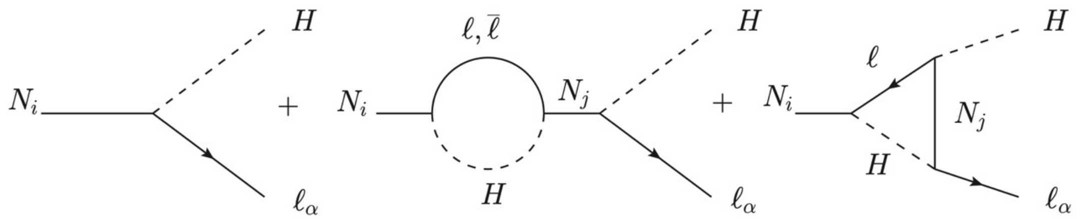
Simplest extension, not found yet, all possible

Type I seesaw leptogenesis

Baryogenesis Without Grand Unification (4000+ citations), Fukugita and Yanagida, 1986'

脱离热平衡条件由右手中微子在宇宙早期热退耦来实现

$$\mathcal{L}_I = \mathcal{L}_{SM} + i\overline{N_{R_i}}\partial\!\!\!/ N_{R_i} - \left(\frac{1}{2}M_i\overline{N^c_{R_i}}N_{R_i} + \epsilon_{ab}Y_{\alpha i}\overline{N_{R_i}}\ell^a_\alpha H^b + h.c.\right)$$



$$\epsilon_{i\alpha} = \frac{\gamma\left(N_i \to \ell_\alpha H\right) - \gamma\left(N_i \to \overline{\ell_\alpha} H^*\right)}{\sum_\alpha \gamma\left(N_i \to \ell_\alpha H\right) + \gamma\left(N_i \to \overline{\ell_\alpha} H^*\right)}$$

$$n_B = \frac{28}{79}(\mathcal{B} - \mathcal{L})_i$$

一般要求右手中微子质量超过10^7GeV, 很难进行检验

Type II seesaw

$$H(2,1/2),\ \ \Delta(3,1),\ \ L(2,-1/2)$$

$$H = \begin{pmatrix} h^+ \\ h \end{pmatrix},\quad \Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}$$

$$\mathcal{L}_{Yukawa} = \mathcal{L}^{\rm SM}_{\rm Yukawa} - \frac{1}{2} y_{ij} \bar{L}^c_i \Delta L_j + h.c. \longrightarrow \frac{1}{2} y_{ij} \Delta^0 \bar{\nu}^c \nu + h.c.$$

EW precision measurement

$$\mathcal{O}(1)\ {\rm GeV} > |\langle \Delta^0 \rangle| \gtrsim 0.05\ {\rm eV}$$

required by neutrino masses

Type II seesaw leptogenesis?

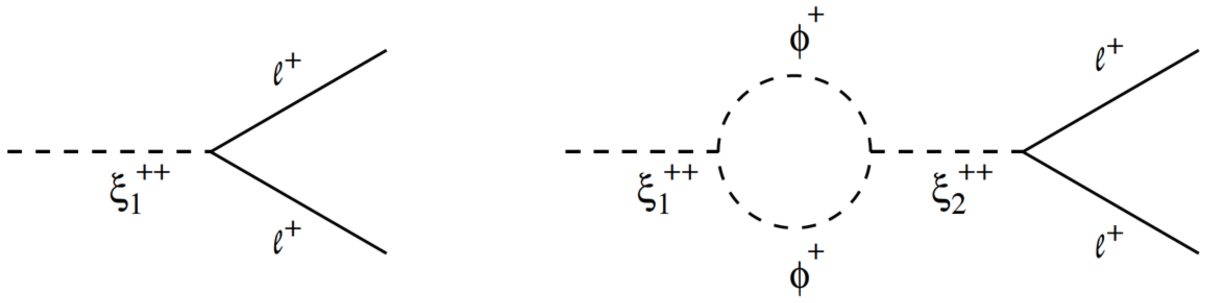
VOLUME 80, NUMBER 26 PHYSICAL REVIEW LETTERS 29 JUNE 1998

500+ citations

Neutrino Masses and Leptogenesis with Heavy Higgs Triplets

Ernest Ma
Department of Physics, University of California, Riverside, California 92521
Utpal Sarkar
Physical Research Laboratory, Ahmedabad 380 009, India

类似，脱离热平衡条件由希格斯三重态在宇宙早期热退耦来实现



但是一个希格斯三重态无法传递轻子部分的CP破坏

$$\delta_i = 2\left[B\left(\psi_i^- \to ll\right) - B\left(\psi_i^+ \to l^c l^c\right)\right]$$

$$\delta_i = \frac{Im\left[\mu_1 \mu_2^* \sum_{k,l} y_{1kl} y_{2kl}^*\right]}{8\pi^2 (M_1^2 - M_2^2)} \left[\frac{M_i}{\Gamma_i}\right]$$

单纯第二类跷跷板机制不能产生轻子生成机制，需要至少2个triplet Higgs

Type II seesaw leptogenesis

希格斯三重态是标量粒子，在宇宙早期拥有大的真空期望值(提供暴胀)，满足脱离热平衡条件，从而实现轻子生成机制

PHYSICAL REVIEW LETTERS **128,** 141801 (2022)

Affleck-Dine Leptogenesis from Higgs Inflation

Neil D. Barrie,[1,*] Chengcheng Han,[2,†] and Hitoshi Murayama[3,4,5,‡]

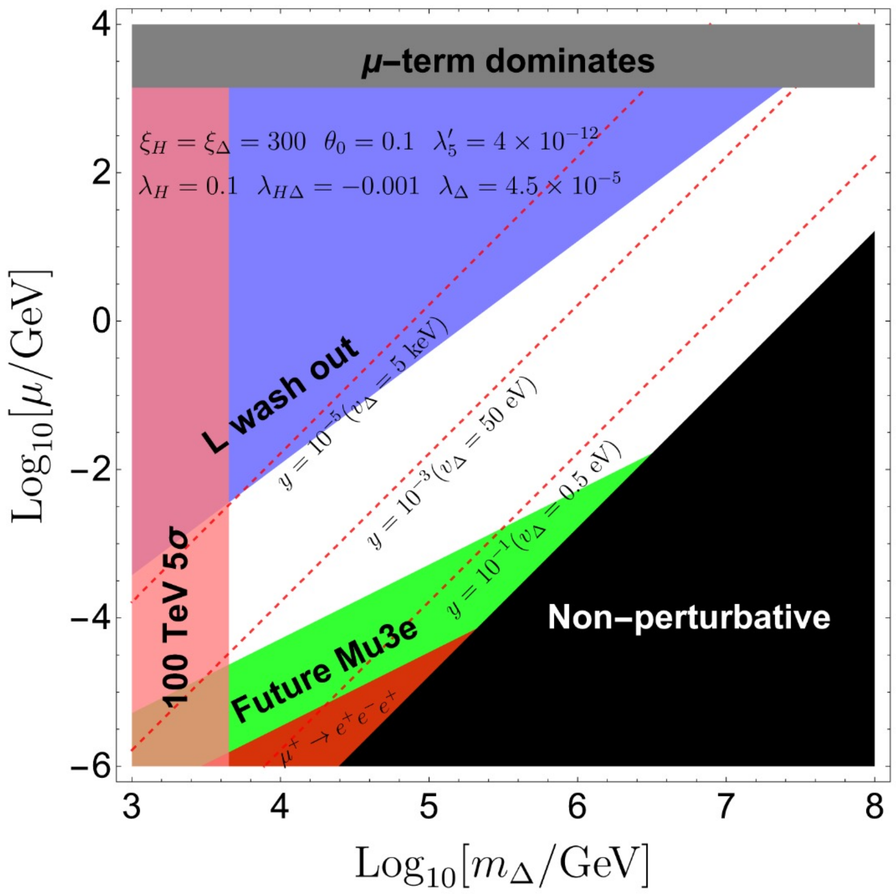
We find that the triplet Higgs of the type-II seesaw mechanism can simultaneously generate the neutrino masses and observed baryon asymmetry while playing a role in inflation. We survey the allowed parameter space and determine that this is possible for triplet masses as low as a TeV, with a preference for a small

Type II Seesaw leptogenesis

JHEP

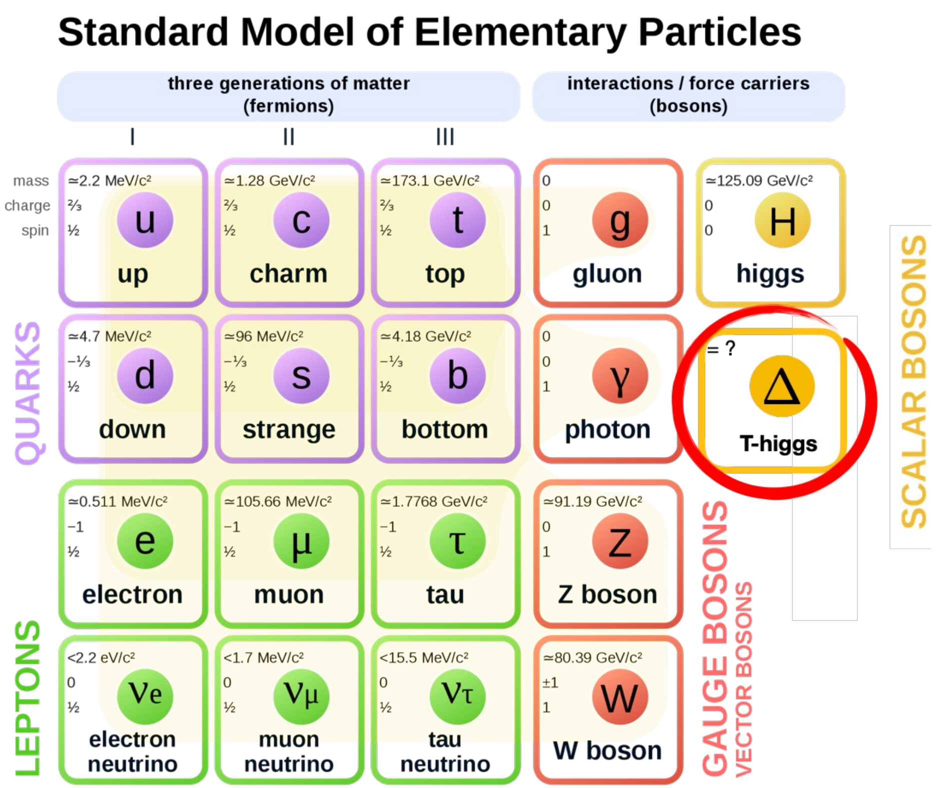
Neil D. Barrie,[a] Chengcheng Han[b] and Hitoshi Murayama[c,d,e,1]

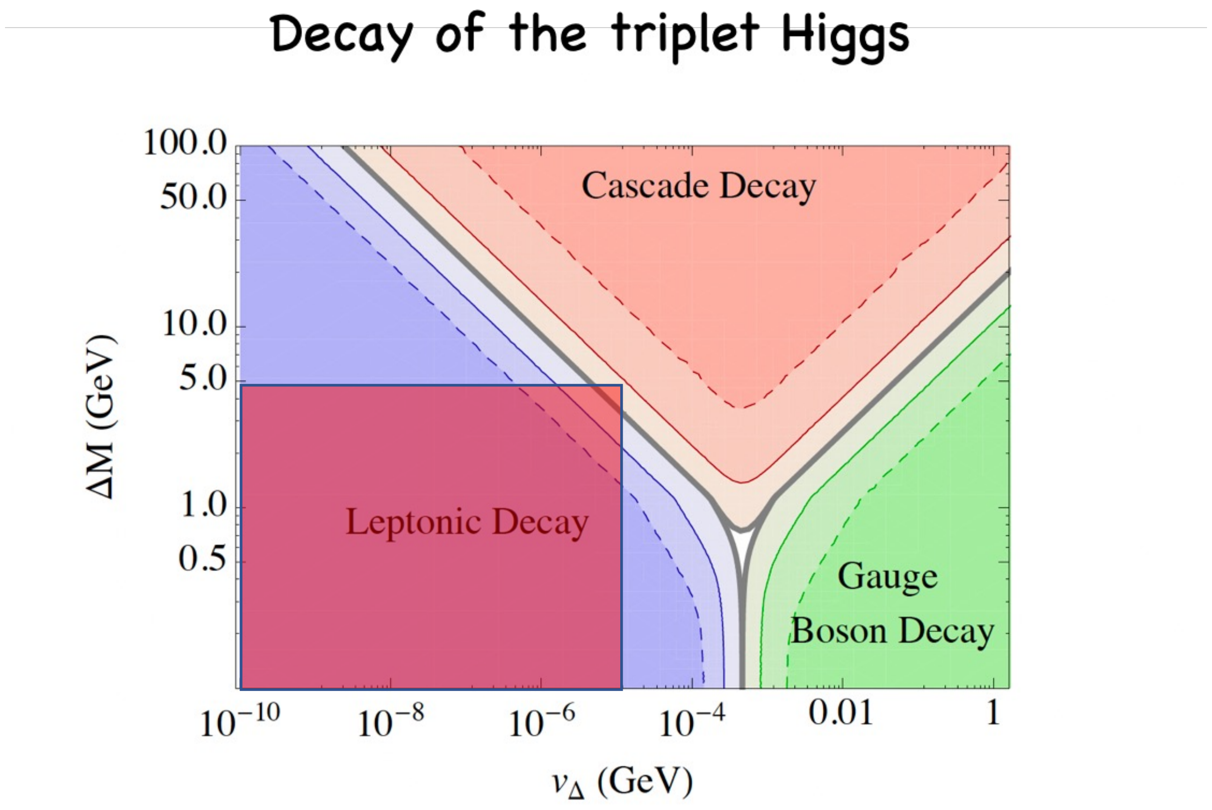
Type II seesaw leptogenesis



- 三重态质量可以轻至 TeV，适合对撞机探测
- 轻子味改变的耦合 $y > 10^{-5}$, 轻子味改变信号
- 真空期望值 < 10 keV（对比传统type II seesaw < 1 GeV）
- 中微子为Majorana粒子

对撞机寻找



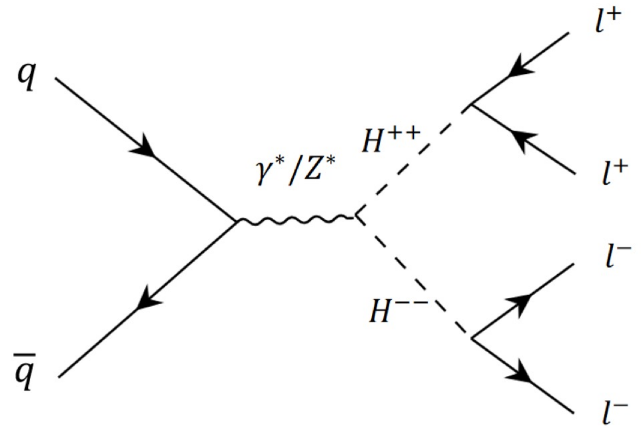


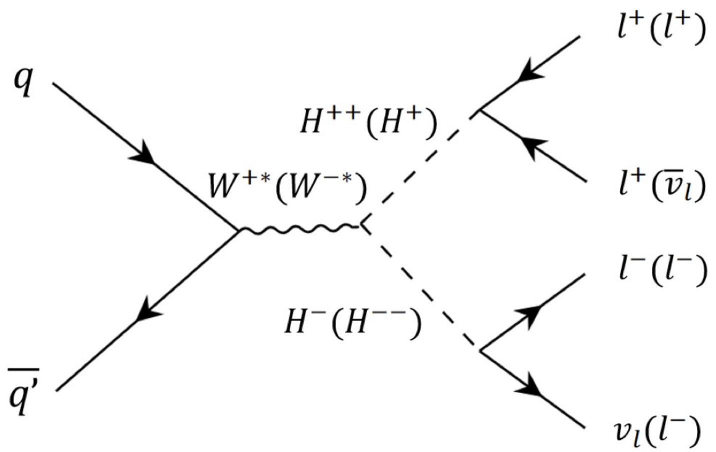
模型预言希格斯三重态主要轻子道衰变

希格斯三重态质量可以低至TeV, 可以通过对撞机进行验证

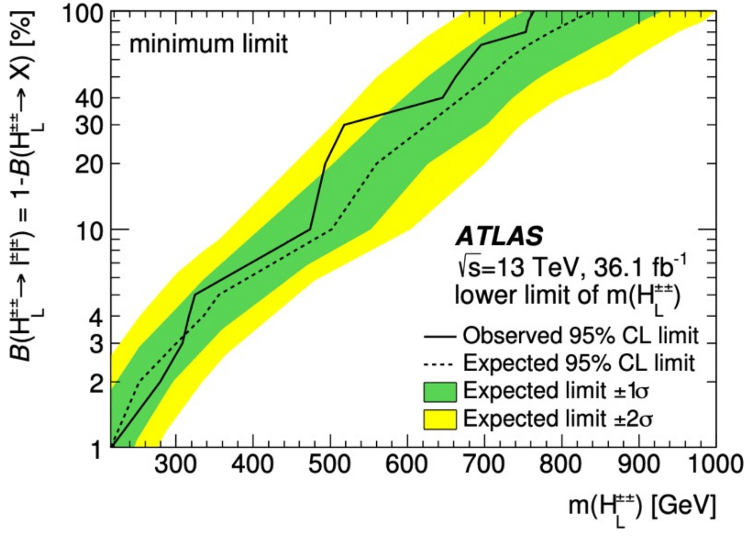
对撞机寻找

CCH, Z. Lei, W. Liao, hep-ph>arXiv:2303.15709

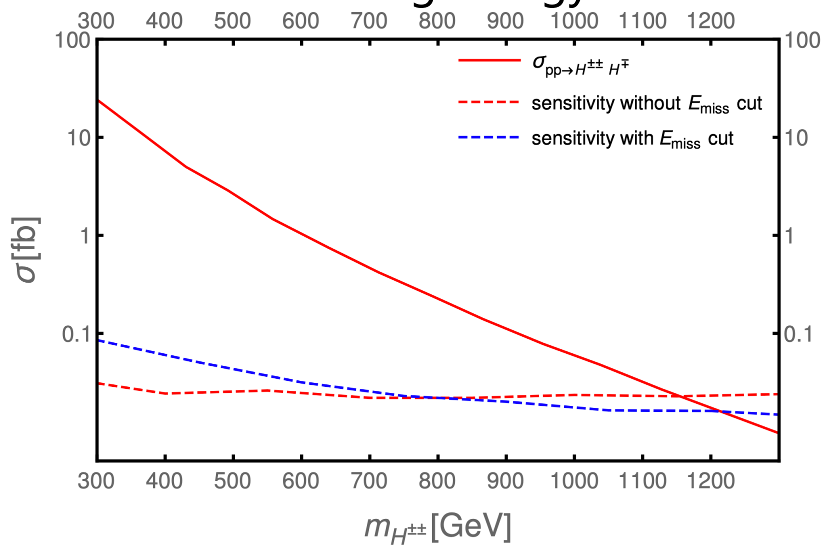




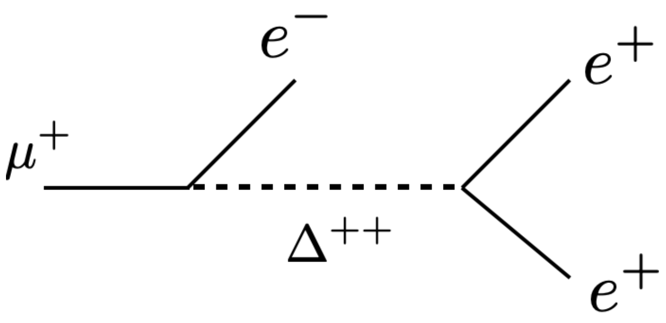
ATLAS, Eur. Phys. J. C 78 (2018) 199

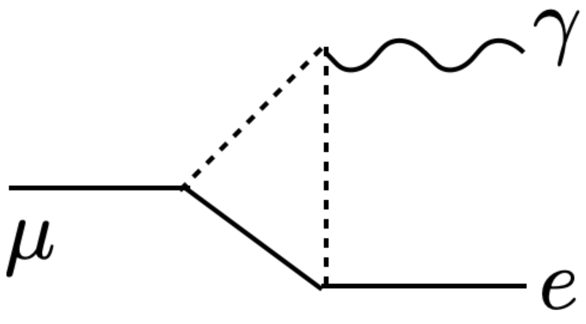


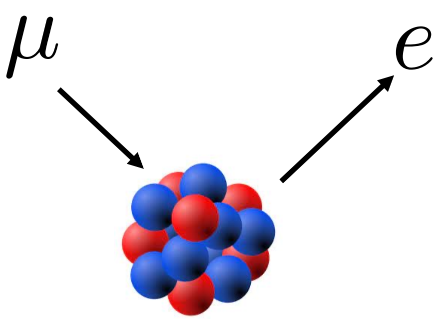
3l+missing energy



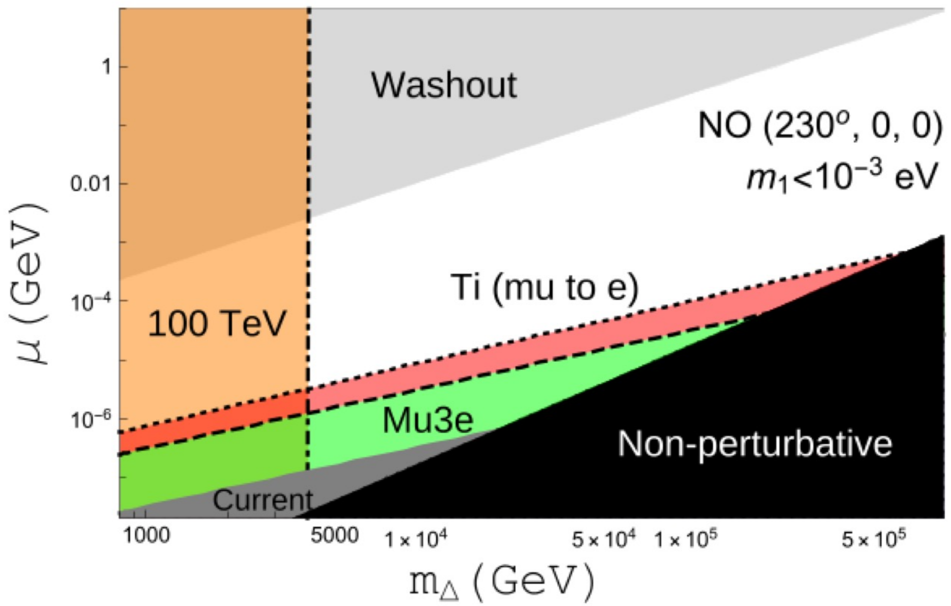
轻子味破坏过程







N.D. Barrie, S.T. Petcov, JHEP 01 (2023) 001



LFV operators from type II seesaw

LFV operators between quark and lepton, potential target at flavor physics

Xu Li, Di Zhang, Shun Zhou, JHEP 04 (2022) 038,
Yong Du, Xu-Xiang Li, Jiang-Hao Yu, JHEP 09 (2022) 207

$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	$\mathcal{O}^{(1)}_{lq,prst}$	$\frac{g_1^4}{120M^2}\delta^{pr}\delta^{st} - \frac{g_1^2}{36M^2}(5+3L)(Y_\nu^\dagger Y_\nu)^{pr}\delta^{st}$
$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	$\mathcal{O}^{(3)}_{lq,prst}$	$-\frac{g_2^4}{60M^2}\delta^{pr}\delta^{st} + \frac{g_2^2}{12M^2}(2+L)(Y_\nu^\dagger Y_\nu)^{pr}\delta^{st}$
$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$	$\mathcal{O}_{lu,prst}$	$\frac{g_1^4}{30M^2}\delta^{pr}\delta^{st} - \frac{g_1^2}{9M^2}(5+3L)(Y_\nu^\dagger Y_\nu)^{pr}\delta^{st}$
$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}_{ld,prst}$	$-\frac{g_1^4}{60M^2}\delta^{pr}\delta^{st} + \frac{g_1^2}{18M^2}(5+3L)(Y_\nu^\dagger Y_\nu)^{pr}\delta^{st}$
$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	$\mathcal{O}_{ledq,prst}$	$\frac{\mu^2}{2M^4}Y_e^{pr}Y_d^{*ts}$
$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	$\mathcal{O}^{(1)}_{lequ,prst}$	$-\frac{\mu^2}{2M^4}Y_e^{pr}Y_u^{st}$

Inducing meson LFV decays,   for example J/psi -> l_i l_j

总结

- 在标准模型基础上只增加一个希格斯三重态，可以解释中微子质量和正反物质不对称

- 在对撞机，味物理实验都相应的信号，需要实验和理论共同合作

THANK YOU

真空稳定性

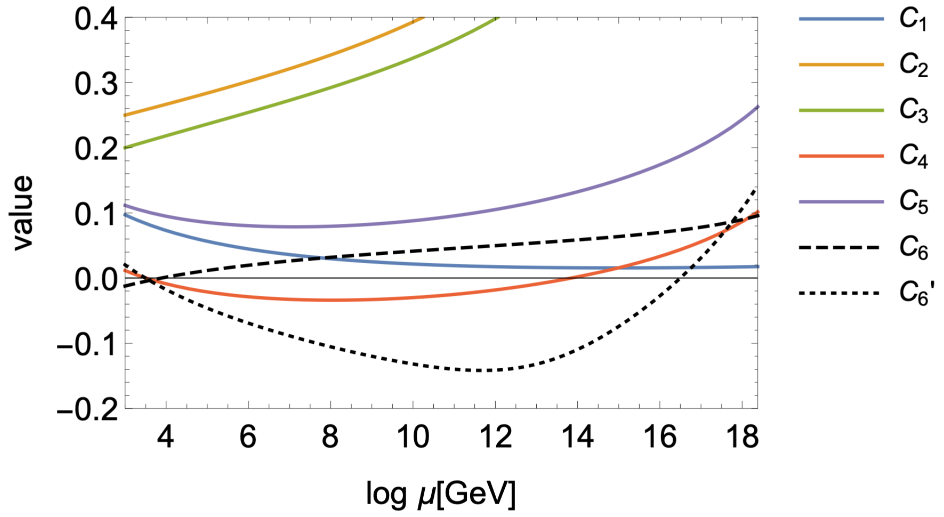
CCH, S. Huang, Z. Lei, Phys.Rev.D 107 (2023) 1, 015021

$$V(H,\Delta) = -m_H^2 H^\dagger H + m_\Delta^2 \mathrm{Tr}(\Delta^\dagger \Delta) + \lambda_H (H^\dagger H)^2 + \lambda_1 (H^\dagger H)\mathrm{Tr}(\Delta^\dagger\Delta) + \lambda_2(\mathrm{Tr}(\Delta^\dagger\Delta))^2 + \lambda_3 \mathrm{Tr}(\Delta^\dagger\Delta)^2 + \lambda_4 H^\dagger \Delta\Delta^\dagger H + [\mu(H^T i\sigma^2 \Delta^\dagger H)$$

真空稳定性条件

$$C_1, C_2, C_3, C_4, C_5 > 0 \text{ and } [C_6 > 0 \text{ or } C_6' > 0]$$

$$\begin{aligned}
C_1 &= \lambda_H \,, \\
C_2 &= \lambda_2 + \lambda_3 \,, \\
C_3 &= \lambda_2 + \frac{1}{2}\lambda_3 \,, \\
C_4 &= \lambda_1 + 2\sqrt{\lambda_H(\lambda_2+\lambda_3)} \,, \\
C_5 &= \lambda_1 + \lambda_4 + 2\sqrt{\lambda_H(\lambda_2+\lambda_3)} \,, \\
C_6 &= |\lambda_4|\sqrt{\lambda_2+\lambda_3} - 2\lambda_3\sqrt{\lambda_H} \,, \\
C_6' &= 2\lambda_1 + \lambda_4 + \sqrt{(8\lambda_H\lambda_3 - \lambda_4^2)(2\lambda_2/\lambda_3 + 1)}
\end{aligned}$$

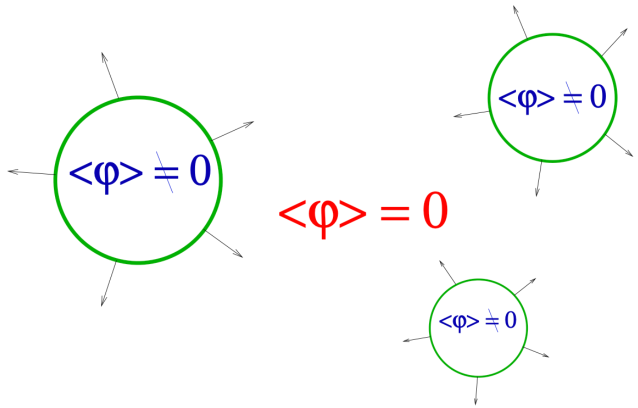


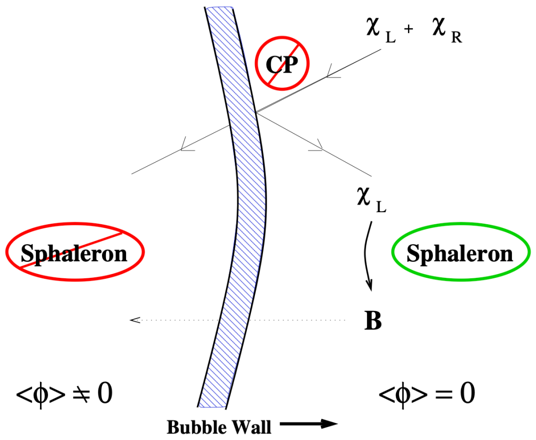
- 修正以往文献真空稳定性的条件
- 解决希格斯真空不稳定的问题
- 只在电弱标度附近要求真空稳定性是不够的

电弱重子生成(Electroweak baryogenesis)

Rubakov and Shaposhnikov, 1996, D. E. Morrissey and M. J. Ramsey-Musolf, 2012'

- Strong first order phase transition (through adding new scalars)
- Additional new CP sources





- New scalars close to electroweak scale, constrained by LHC searches
- New CP violation is highly constrained by electron EDM(< $4.1*10^{-30}$ e.cm)

EW baryogenesis within standard model

Phys.Rev.D 102 (2020) 7, 073003

Sphalerons, baryogenesis and helical magnetogenesis in the electroweak transition of the minimal standard model

Dmitri Kharzeev[1,2], Edward Shuryak[1] and Ismail Zahed[1]

Phys.Rev.D 108 (2023) 6, 063502

Baryogenesis from sphaleron decoupling

Muzi Hong[a,b1], Kohei Kamada[b2] and Jun'ichi Yokoyama[a,b,c,d3]

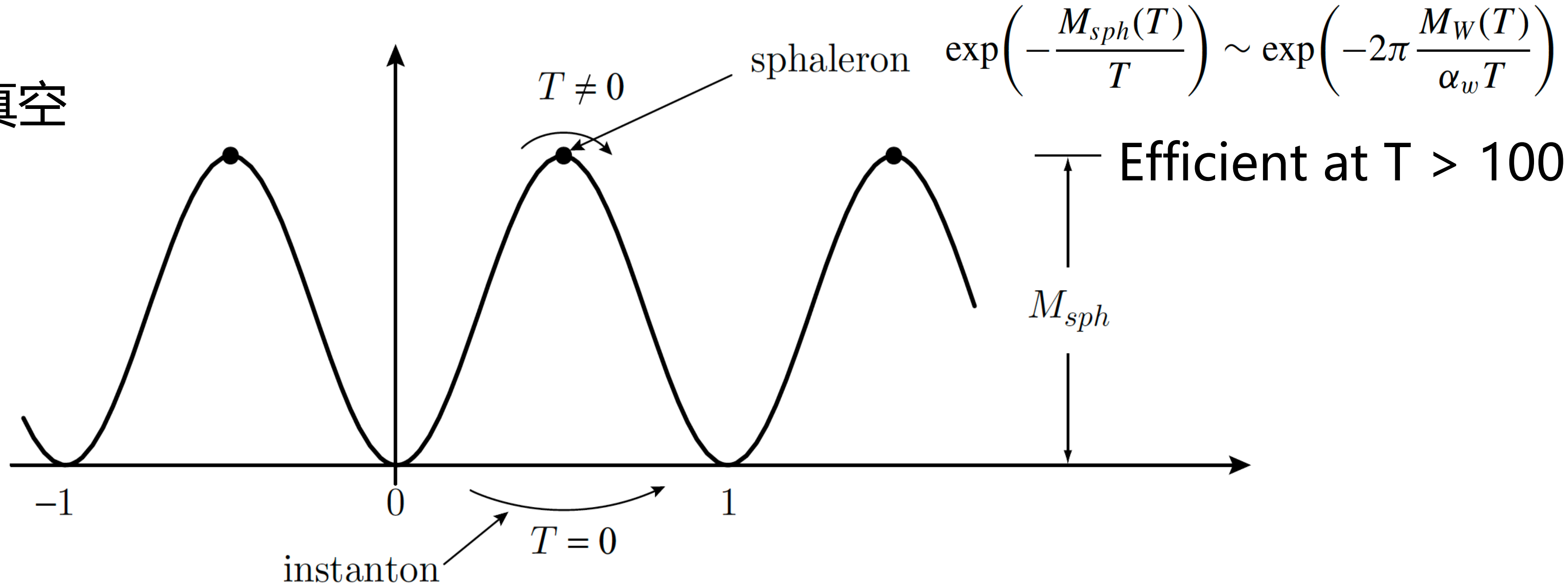
- Large size sphaleron decoupling provides Sakharov third condition
- CP violation can be enhanced at low momentum
- The final baryon asymmetry is 2-3 order smaller than observed one

.

New source of CP violation is necessary!

Instanton and Sphaleron

SU(2) 真空



Efficient at T > 100 GeV

$$\Gamma \propto \exp\left(-\frac{4\pi}{\alpha}\right)$$

- 每次跃迁产生 $\Delta B = \Delta L = -3$ (只有左手粒子参与)
- 为标准模型提供重子数破坏的过程
- 可以把轻子物质的不对称转化为重子物质的不对称性(轻子生成机制)