Implications of CP violation for new physics beyond SM

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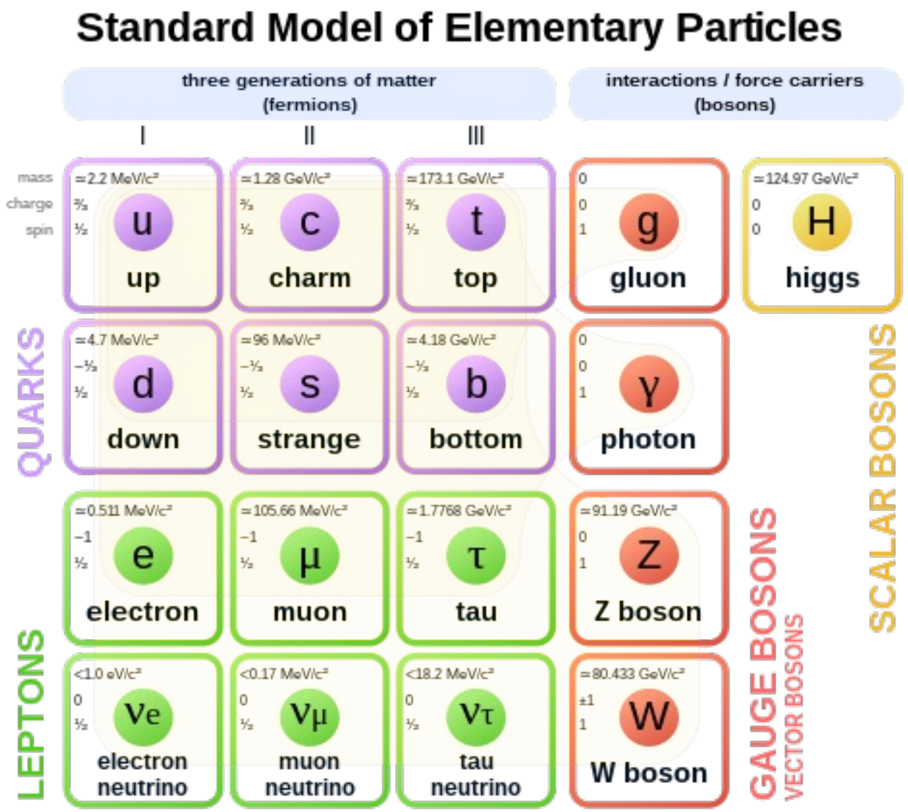
第六届重味物理和量子色动力学研讨会

山东大学 青岛

2024.4.22

标准模型



Very successful at low energy scale

标准模型中CP破坏

夸克有三代，弱相互作用中存在CP破坏

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

$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{bmatrix}$$

$\theta_{12} = 13.04° \pm 0.05°$, $\theta_{13} = 0.201° \pm 0.011°$, $\theta_{23} = 2.38° \pm 0.06°$

$\delta_{13} = 1.20 \pm 0.08$ radians $= 68.8° \pm 4.5°$

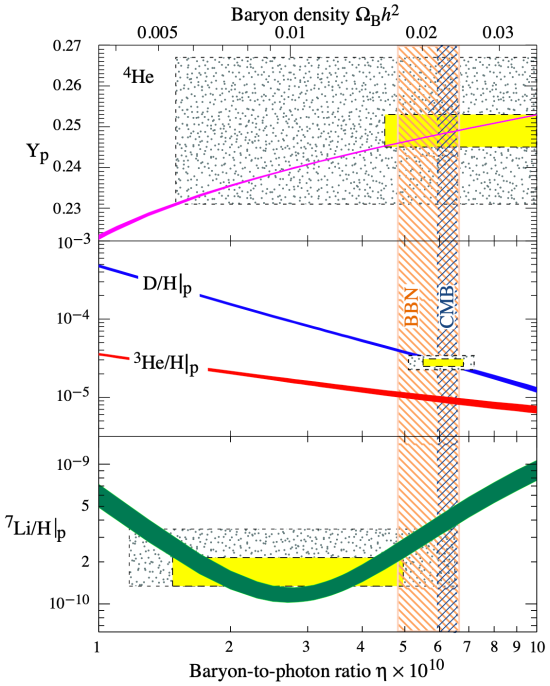
已知的唯一的CP破坏源

CP破坏相关理论问题

- 解释正反物质不对称的CP破坏起源来自于哪里?
- 轻子部分是否存在CP破坏?
- 为什么强相互作用中CP破坏很小(强CP问题)?
- CP破坏是否由自发破缺产生的?

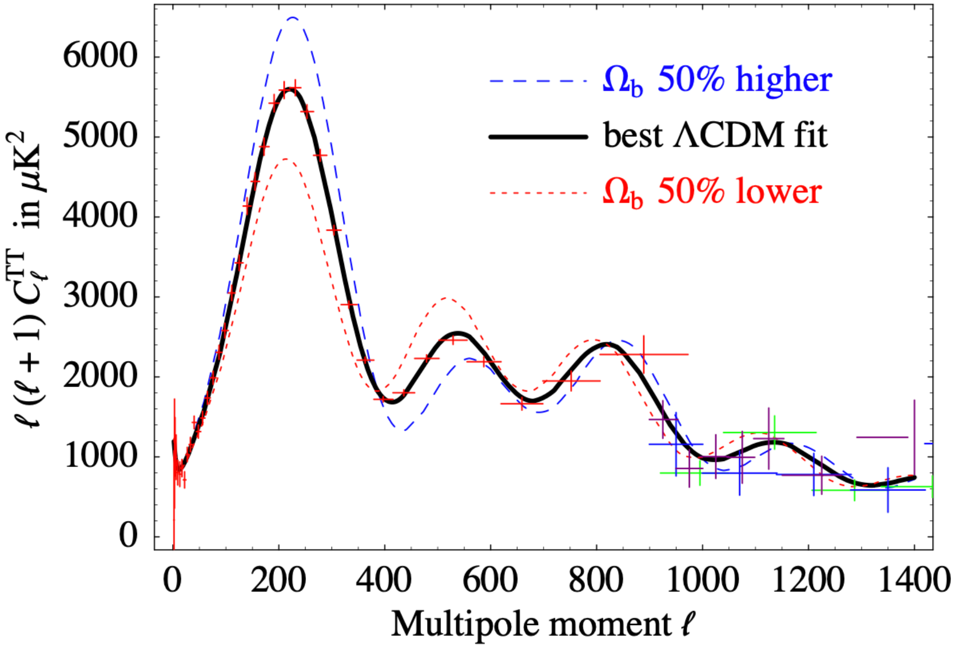
正反物质不对称性

原初核合成(BBN)（t~3 分钟)

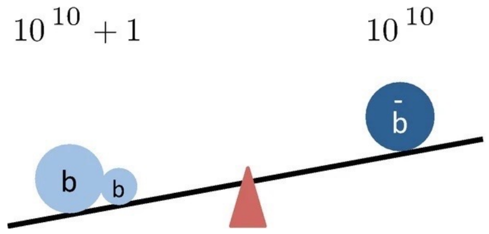


$$\eta = \frac{n_b - n_{\bar{b}}}{n_\gamma} \sim 10^{-10}$$

宇宙微波背景辐射(CMB)(t~38万年)



在宇宙极早期(t <10^{-5} s 时) $n_b \approx n_{\bar{b}} \sim n_\gamma$



正反物质不对称性

如何产生正反物质不对称性?

如果宇宙创生初期就有这个差别，这个差别会在暴涨时期抹平掉

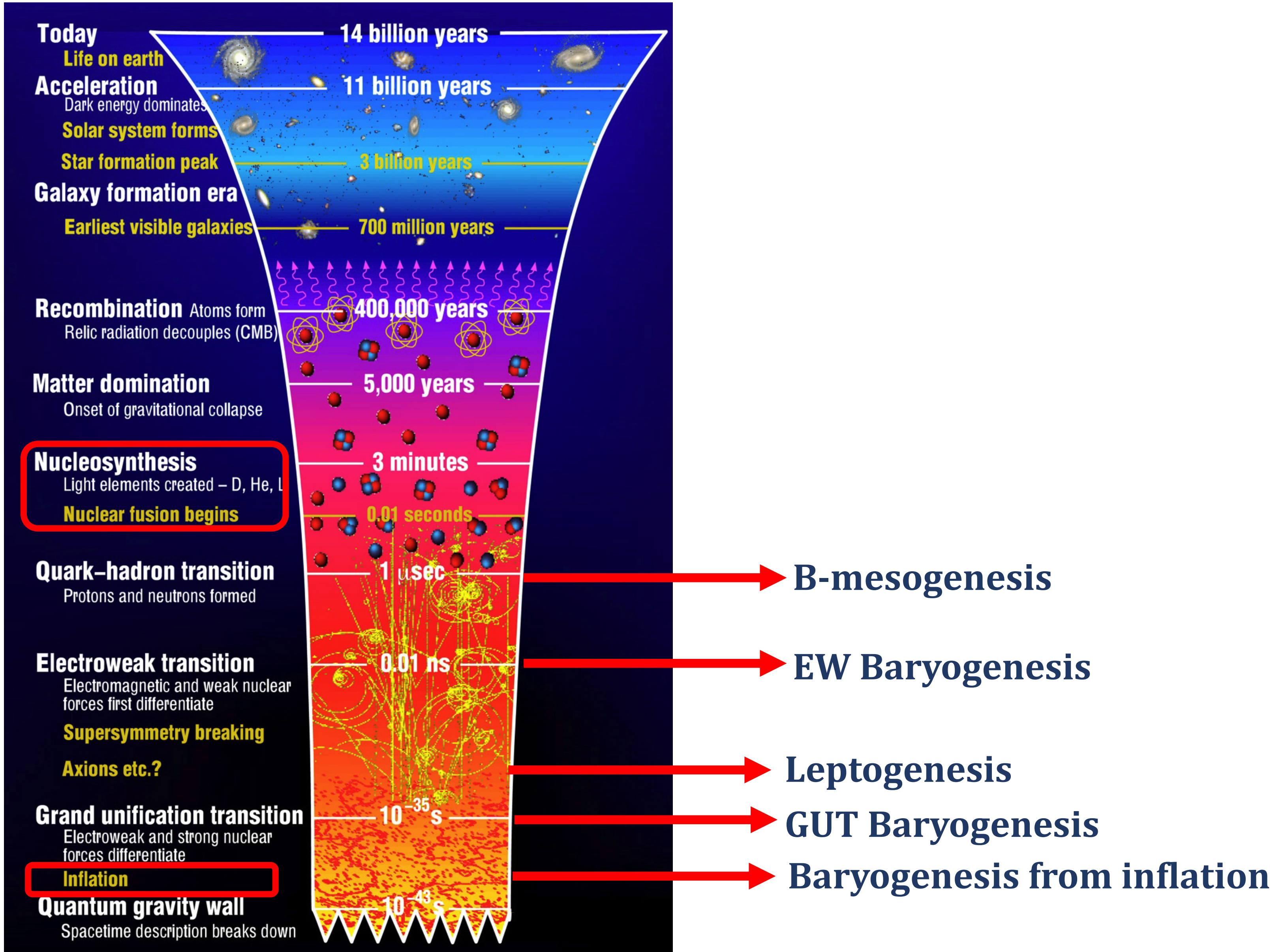
如何从正反物质对称的宇宙演化到正反物质不对称的宇宙？

Sakharov 三条件	标准模型
● 重子数破坏过程	✓
● C 和 CP 破坏	✓✗
● 脱离热平衡	✗

- 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，相变过程中夸克部分提供CP破坏太小，不足以解释现在的观测

寻找新的CP破坏源(味物理实验的重要目标之一)+脱离热平衡条件!

重子不对称性何时产生?

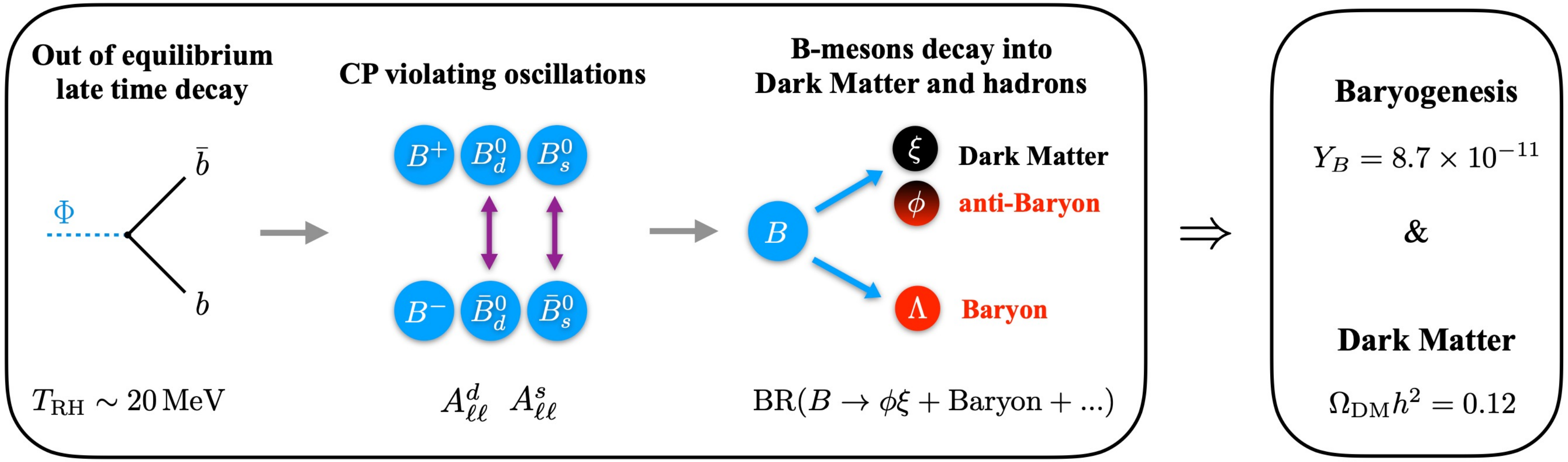


不能晚于原初核合成，否则元素丰度不一致

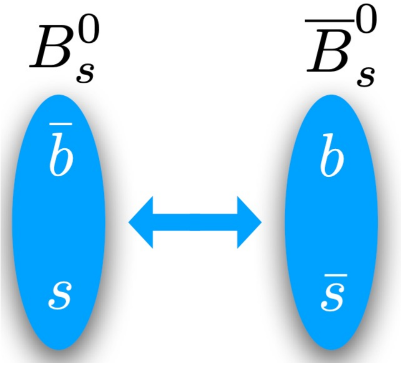
不能早于暴胀，因为宇宙在很短时间内膨胀了 e^{60} 倍，任何早期的不对称性都变的极小

B-mesogenesis

G. Elor, M. Escudero, A. E. Nelson, Phys. Rev. D 99, 035031 (2019)



- B 介子比较重(5.3 GeV)，容易实现重子道衰变
- CP破坏体现在B介子振荡
- 同时解释暗物质的起源



B-mesogenesis

最终的重子数密度跟B介子的重子-暗物质衰变分支比和B介子CP破坏测量A_{SL}有关

$$Y_B \simeq 8.7 \times 10^{-11} \frac{\mathrm{Br}(B \to \psi + \mathcal{B} + \mathcal{M})}{10^{-2}} \sum_q \alpha_q \frac{A_{\mathrm{SL}}^q}{10^{-4}}$$

$$A_{\mathrm{SL}}^q = \mathrm{Im}\left(\frac{\Gamma_{12}^q}{M_{12}^q}\right) = \frac{\Gamma(\overline{B}_q^0 \to B_q^0 \to f) - \Gamma(B_q^0 \to \overline{B}_q^0 \to \bar{f})}{\Gamma(\overline{B}_q^0 \to B_q^0 \to f) + \Gamma(B_q^0 \to \overline{B}_q^0 \to \bar{f})}$$

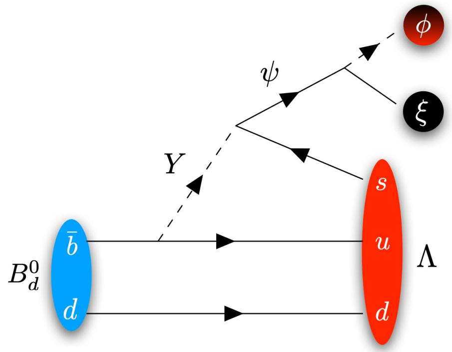
标准模型预言

$$A_{\mathrm{SL}}^d|_{\mathrm{SM}} = (-4.7 \pm 0.4) \times 10^{-4}$$
$$A_{\mathrm{SL}}^s|_{\mathrm{SM}} = (2.1 \pm 0.2) \times 10^{-5}$$

实验测量

$$A_{\mathrm{SL}}^d = (-2.1 \pm 1.7) \times 10^{-3}$$
$$A_{\mathrm{SL}}^s = (-0.6 \pm 2.8) \times 10^{-3}$$

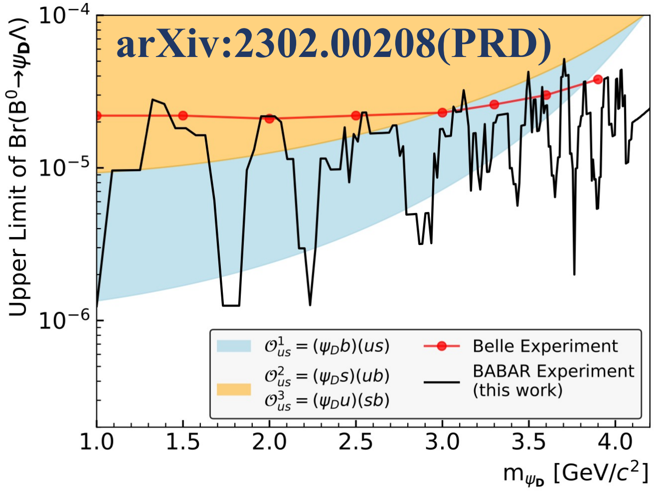
- **标准模型CKM理论上可以提供足够的CP破坏，但是**
- **B介子衰变到重子-invisible (BaBar，Belle，LHCb)**
- **对B介子的CPV测量可以进一步检验正反物质不对称CP破坏的起源**

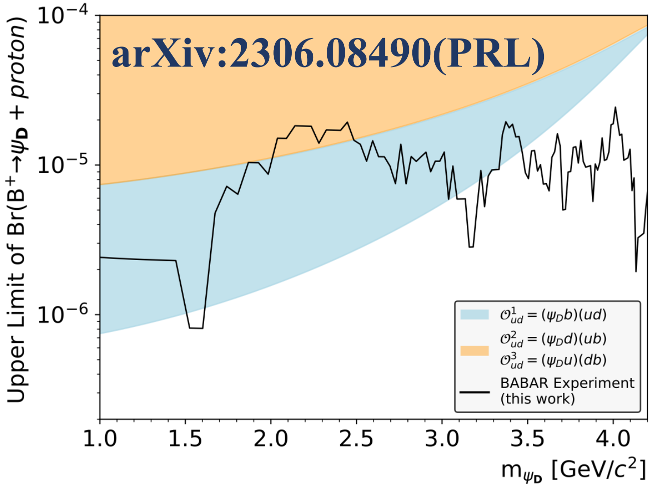


B-mesogenesis

Collider Signals of Baryogenesis and Dark Matter from B Mesons: A Roadmap to Discovery, G. Alonso-Álvarez, G. Elor, M. Escudero, Phys. Rev. D 104, 035028 (2021)

Operator and Decay	Initial State	Final State	ΔM (MeV)
$\mathcal{O}_{ud} = \psi\, b\, u\, d$ $\bar{b} \to \psi\, u\, d$	B_d	$\psi + n\,(udd)$	4340.1
	B_s	$\psi + \Lambda\,(uds)$	4251.2
	B^+	$\psi + p\,(duu)$	4341.0
	Λ_b	$\bar{\psi} + \pi^0$	5484.5
$\mathcal{O}_{us} = \psi\, b\, u\, s$ $\bar{b} \to \psi\, u\, s$	B_d	$\psi + \Lambda\,(usd)$	4164.0
	B_s	$\psi + \Xi^0\,(uss)$	4025.0
	B^+	$\psi + \Sigma^+\,(uus)$	4090.0
	Λ_b	$\bar{\psi} + K^0$	5121.9
$\mathcal{O}_{cd} = \psi\, b\, c\, d$ $\bar{b} \to \psi\, c\, d$	B_d	$\psi + \Lambda_c + \pi^-\,(cdd)$	2853.6
	B_s	$\psi + \Xi_c^0\,(cds)$	2895.0
	B^+	$\psi + \Lambda_c^+\,(dcu)$	2992.9
	Λ_b	$\bar{\psi} + \overline{D}^0$	3754.7
$\mathcal{O}_{cs} = \psi\, b\, c\, s$ $\bar{b} \to \psi\, c\, s$	B_d	$\psi + \Xi_c^0\,(csd)$	2807.8
	B_s	$\psi + \Omega_c\,(css)$	2671.7
	B^+	$\psi + \Xi_c^+\,(csu)$	2810.4
	Λ_b	$\bar{\psi} + D^- + K^+$	3256.2



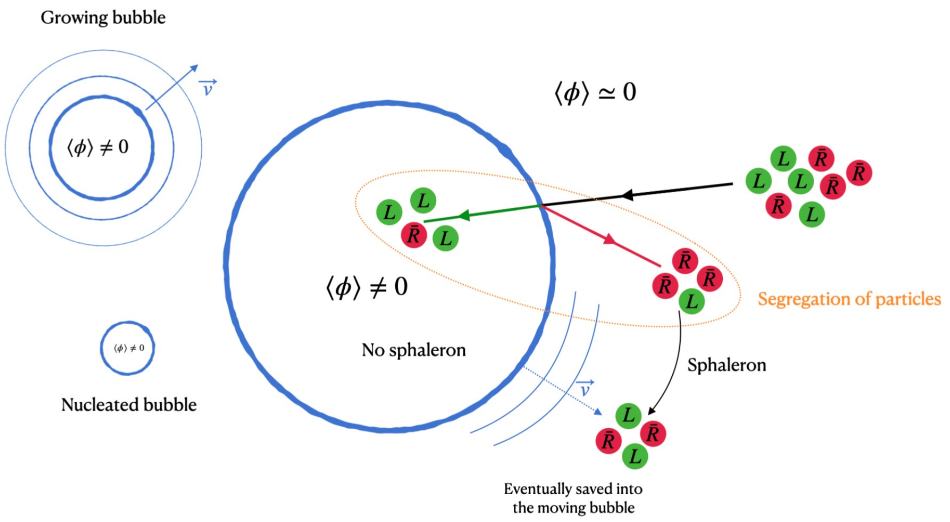


电弱重子生成

- 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)



伴随的引力波信号

Is electroweak baryogenesis dead?

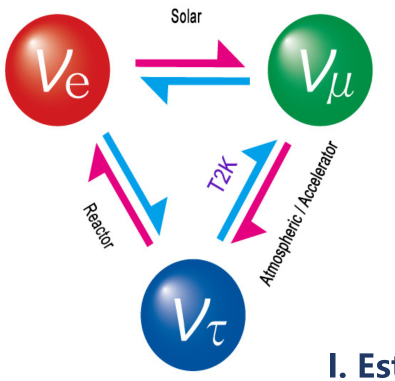
James M. Cline[1,2]

[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存在非零的质量，Kobayashi and Maskawa机制告诉我们，如果中微子有质量，类似于CKM矩阵，轻子部分可能有CP破坏(PMNS矩阵)



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

I. Esteban, M.C. Gonzalez-Garcia, M. Maltoni, T. Schwetz, A. Zhou，JHEP 09 (2020) 178

NO

$$\theta_{12} = 33.44^{\circ}{}^{+0.77^{\circ}}_{-0.74^{\circ}}$$
$$\theta_{23} = 49.2^{\circ}{}^{+0.9^{\circ}}_{-1.2^{\circ}}$$
$$\theta_{13} = 8.57^{\circ}{}^{+0.12^{\circ}}_{-0.12^{\circ}}$$
$$\delta_{\mathrm{CP}} = 197^{\circ}{}^{+27^{\circ}}_{-24^{\circ}}$$

IO

$$\theta_{12} = 33.45^{\circ}{}^{+0.78^{\circ}}_{-0.75^{\circ}}$$
$$\theta_{23} = 49.3^{\circ}{}^{+0.9^{\circ}}_{-1.1^{\circ}}$$
$$\theta_{13} = 8.60^{\circ}{}^{+0.12^{\circ}}_{-0.12^{\circ}}$$
$$\delta_{\mathrm{CP}} = 282^{\circ}{}^{+26^{\circ}}_{-30^{\circ}}$$

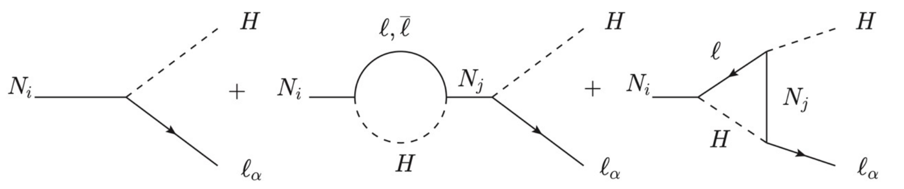
轻子部分提供了新的CP破坏源(T2K实验暗示中微子部分可能存在CP破坏)，正反物质不对称性可能从轻子部分开始，再由sphaleron过程传递给重子——轻子生成机制（leptogenesis）

轻子生成机制

第一类跷跷板机制中的轻子生成机制(Type I seesaw leptogenesis)

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

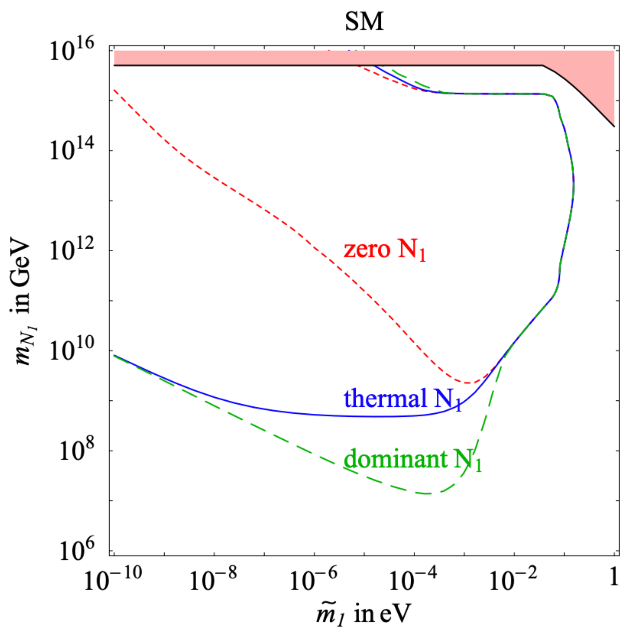
$$\mathcal{L}_I = \mathcal{L}_{SM} + i\overline{N_{R_i}}\partial\!\!\!/ N_{R_i} - \left(\frac{1}{2}M_i\overline{N^c_{R_i}}N_{R_i} + \epsilon_{ab}Y_{\alpha i}\overline{N_{R_i}}\ell^a_\alpha H^b + h.c.\right)$$



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

$$Y_{\mathcal{L}_i} = Y_{N_1} \times \epsilon \times \eta \qquad n_B = \frac{28}{79}(\mathcal{B} - \mathcal{L})_i$$

G.F. Giudice, et al, Nucl.Phys.B 685 (2004) 89-149



一般要求右手中微子质量超过10^8GeV, 很难进行检验

Type III seesaw情形与Type I 类似

第二类跷跷板机制

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

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

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

EW precision measurement

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

required by neutrino masses

轻子生成机制

第二类跷跷板机制中的轻子生成机制(Type II seesaw leptogenesis)

VOLUME 80, NUMBER 26 PHYSICAL REVIEW LETTERS 29 JUNE 1998

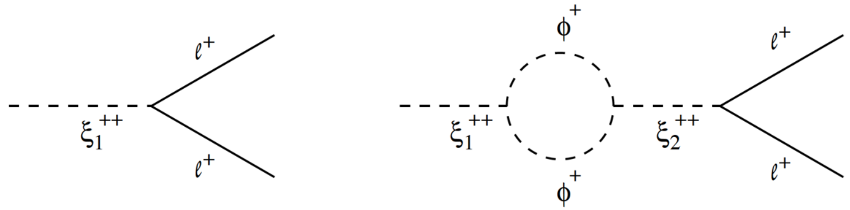
500+ citations

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

希格斯三重态质量需要超过10^{10} GeV



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

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

一个希格斯三重态无法传递CP破坏，单纯第二类跷跷板机制不能实现轻子生成机制

轻子生成机制

Physics Reports
Volume 466, Issues 4–5, September 2008, Pages 105-177

Leptogenesis

1000+ citations

Sacha Davidson [a], Enrico Nardi [b, c], Yosef Nir [d, 1]

To calculate ϵ_T, one should use the Lagrangian terms given in eqn (2.15). While a single triplet is enough to produce three light massive neutrinos, there is a problem in leptogenesis if indeed this is the only source of neutrinos masses: The asymmetry is generated only at higher loops and in unacceptably small.

It is still possible to produce the required lepton asymmetry from a single triplet scalar decays if there are additional sources for the neutrino masses, such as type I, type III, or type II contributions from

“一个希格斯三重态可以解释中微子质量，但是实现轻子生成机制却是有问题的”

轻子生成机制

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(可以提供暴胀)，满足脱离热平衡条件，从而实现轻子生成机制(通过AD机制)

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

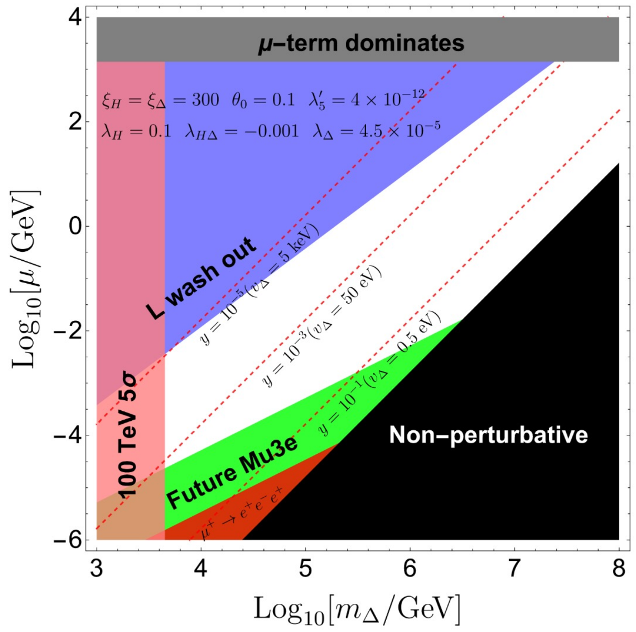
Affleck-Dine Leptogenesis from Higgs Inflation

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

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



轻子生成机制

“Leptogenesis”综述Phys. Rept.作者之一Sacha Davidson在她最新的文章JHEP 11 (2023) 101阐述TeV的希格斯三重态是可以实现轻子生成机制

Ref. [64]). While, in the type II seesaw case, thermal leptogenesis requires a triplet mass above 10^{10} GeV or so [65–67], a TeV-scale scalar triplet with non-minimal coupling to gravity can lead to successful leptogenesis [68] through the Affleck-Dine mechanism [69]. The

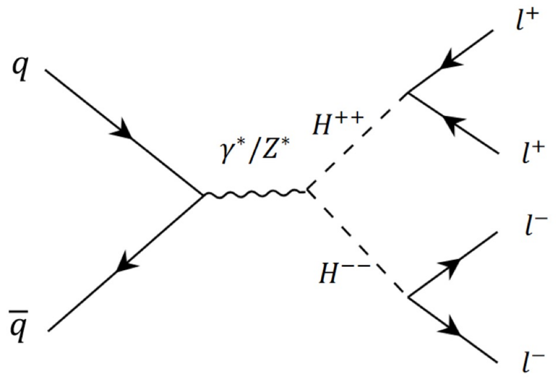
“TeV标度的标量三重态可以成功实现轻子生成机制通过AD机制”

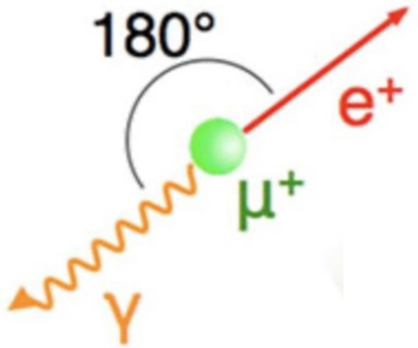
中微子Pontecorvo奖获得者，诺贝尔奖提名专家 S. T. Petcov在(JHEP 01 (2023) 001)对我们工作进行评述

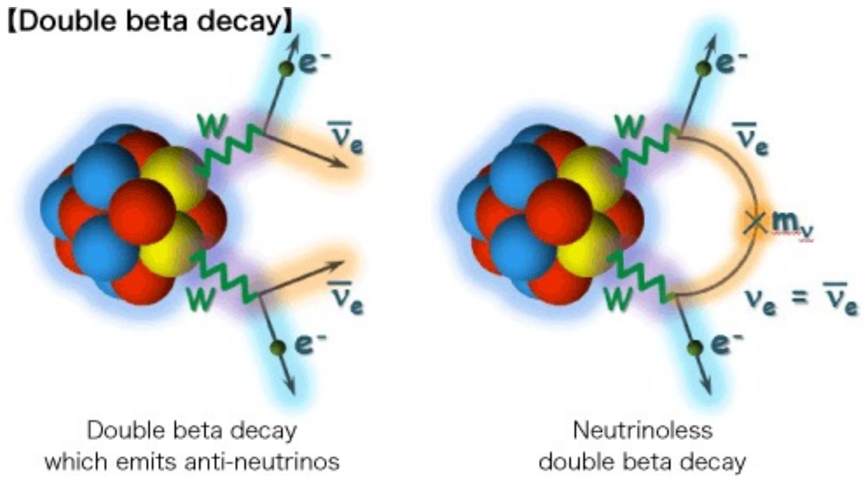
The Type II Seesaw mechanism is known to be unable to successfully lead to standard thermal Leptogenesis, in contrast to the Type I and III Seesaw mechanisms. Thermal Leptogenesis can only be achieved in this mechanism through the inclusion of additional particles, an extra triplet Higgs or a right-handed neutrino [16], undoing the minimal nature of the model. However, in recent work, it was found that it is possible to achieve successful Leptogenesis within the minimal Type II Seesaw framework, through the ADM [17, 20–22].

“与第一类和第三类跷跷板机制不同，第二类跷跷板机制被认为不能实现轻子生成机制...然而，在最近的研究中发现，在第二类跷跷板机制框架内，是可以通过AD机制成功实现轻子生成机制的”

实验检验







- 希格斯三重态质量可以轻至 TeV，可以在对撞机直接寻找
- 与轻子有相当的耦合, 轻子味破坏测量实验例如Mu2e、BESIII等实验对其进行寻找
- 中微子为Majorana粒子: 无中微子双beta衰变

实验检验

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

- CP破坏跟正反物质不对称性起源直接相关
- 如果正反物质不对称起源中的CP破坏由CKM提供，未来对撞机上直接进行检验
- 轻子部分可能存在CP破坏，可以提供了正反物质不对称起源(type I/II/III跷跷板机制)

强CP问题

强相互作用中允许一个CP破坏项： $\mathcal{L} \supset \theta \frac{g^2}{32\pi^2} G_a^{\mu\nu} \tilde{G}_{a\mu\nu}$

$$\bar{\theta} = \theta + \text{Arg}\{\text{Det}(M_u M_d)\}$$

Neutron eDM → $\bar{\theta} < 10^{-10}$

强CP问题：为什么这个参数这么小

- u夸克是无质量的(格点QCD排除这种可能性)
- CP对称性自发破缺
- Pecci-Quinn对称性(预言axion存在)

CP对称性自发破缺

假设CP是一种对称性，theta项被禁戒，可以解释theta为什么这么小

但是弱相互作用中CP是破坏的，CP需要自发破缺

最早CP自发破缺的理论是由李先生提出来

CP NONCONSERVATION AND SPONTANEOUS SYMMETRY BREAKING*

T.D. LEE
Columbia University, New York, N.Y. 10027, USA

Received 4 October 1973

问题：如何把CP破坏传递到弱相互作用中，同时不影响theta?

Nelson-Barr机制

A. E. Nelson, 1984'，S. M. Barr, 1984'

$$\mathcal{L} = Y_{\alpha,i}\eta_\alpha D\bar{d}_i + M_D D\bar{D} + y_{ij} H_d Q_i \bar{d}_j$$

$$\mathcal{M} = \begin{pmatrix} m_d & B \\ 0 & M_D \end{pmatrix}, \; m_d \equiv y v_d; B_i = Y_{\alpha,i}\eta_\alpha$$

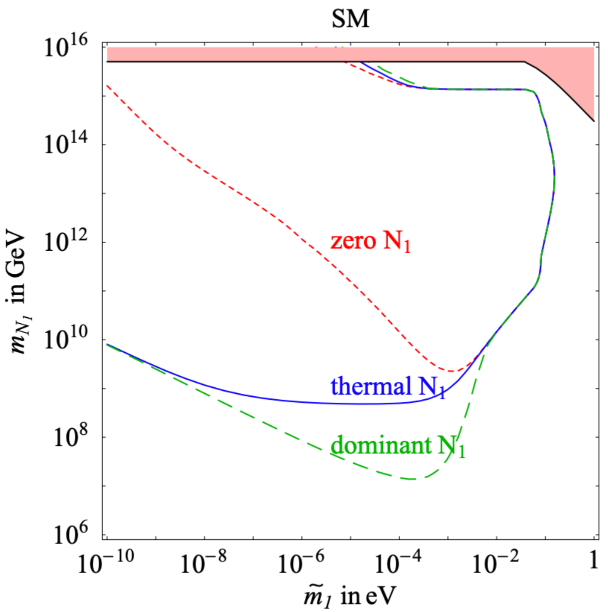
$$\mathrm{Arg}[\det\mathcal{M}] = 0$$ → 不产生额外theta

但是Planck压低的算符会贡献额外的相位

$$\frac{1}{M_P}\eta_\alpha\eta_\beta D\bar{D}$$ → CP自发破缺的标度<eta>小于10^8GeV

Nelson-Barr机制

但是CP破坏又跟正反物质不对称相关，例如第一类跷跷板机制中的轻子生成机制



要求右手中微子质量超过10^8GeV，与CP自发破缺机制不相容

PHYSICAL REVIEW D **103**, L111701 (2021)

Letter

Complete solution to the strong *CP* problem: Supersymmetric extension of the Nelson-Barr model

Jason L. Evans,[1,*] Chengcheng Han,[2,3] Tsutomu T. Yanagida,[1,4] and Norimi Yokozaki[5]

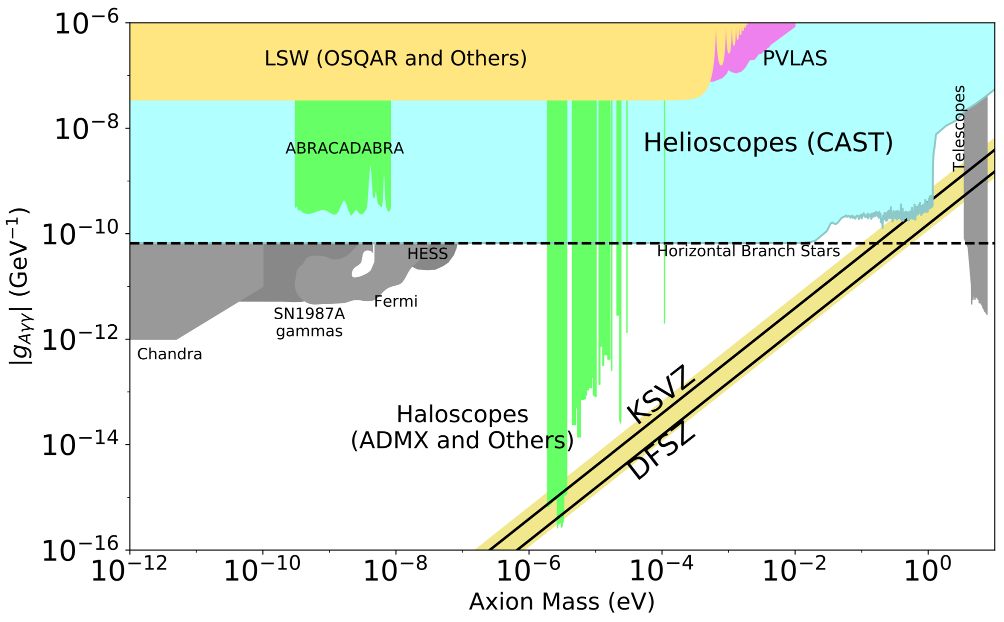
- CP对称性自发破缺
- 禁戒高维算符，使其与轻子生成机制兼容
- 避免圈图的贡献

Pecci-Quinn对称性

如果存在PQ对称性，存在axion，移除对theta的依赖

$$\mathcal{L} \supset \theta \frac{g^2}{32\pi^2} G_a^{\mu\nu} \tilde{G}_{a\mu\nu} \longrightarrow (\theta + \frac{a}{f}) \frac{g^2}{32\pi^2} G_a^{\mu\nu} \tilde{G}_{a\mu\nu}$$

实验上正在积极寻找axion粒子，暂时未发现axion迹象

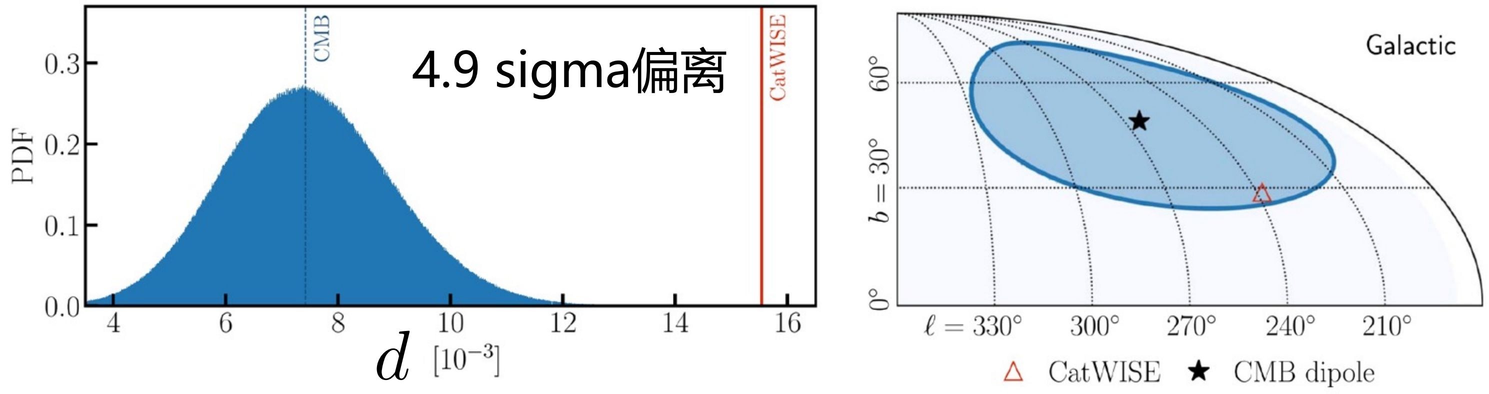


Axion暗物质与宇宙偶极子

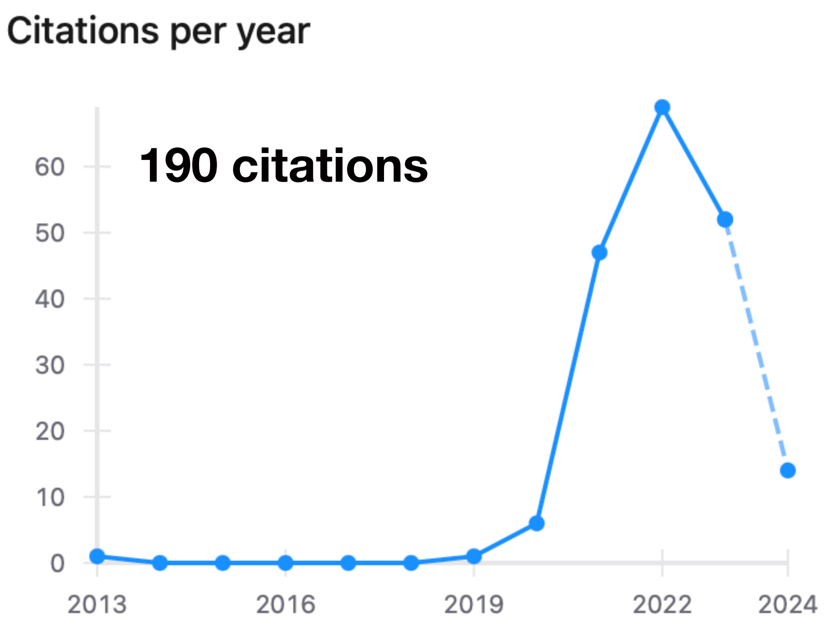
The Astrophysical Journal Letters, 908:L51 (6pp), 2021 February 20 https://doi.org/10.3847/2041-8213/abdd40

A Test of the Cosmological Principle with Quasars

Nathan J. Secrest[1], Sebastian von Hausegger[2,3,4], Mohamed Rameez[5], Roya Mohayaee[3], Subir Sarkar[4], and Jacques Colin[3]



天文观测到跟宇宙学标准模型不一致，存在一个偶极子问题



引起学术界广泛关注

Axion暗物质与宇宙偶极子

宇宙偶极子可能暗示着轴子的存在

PHYSICAL REVIEW D **108,** 015026 (2023)

QCD axion dark matter and the cosmic dipole problem

Chengcheng Han*
School of Physics, Sun Yat-Sen University, Guangzhou 510275, China

被该天文组邀请去讲报告

Request to give a webinar over zoom on your recent work 2211.06912
Rameez 发送给 韩成成

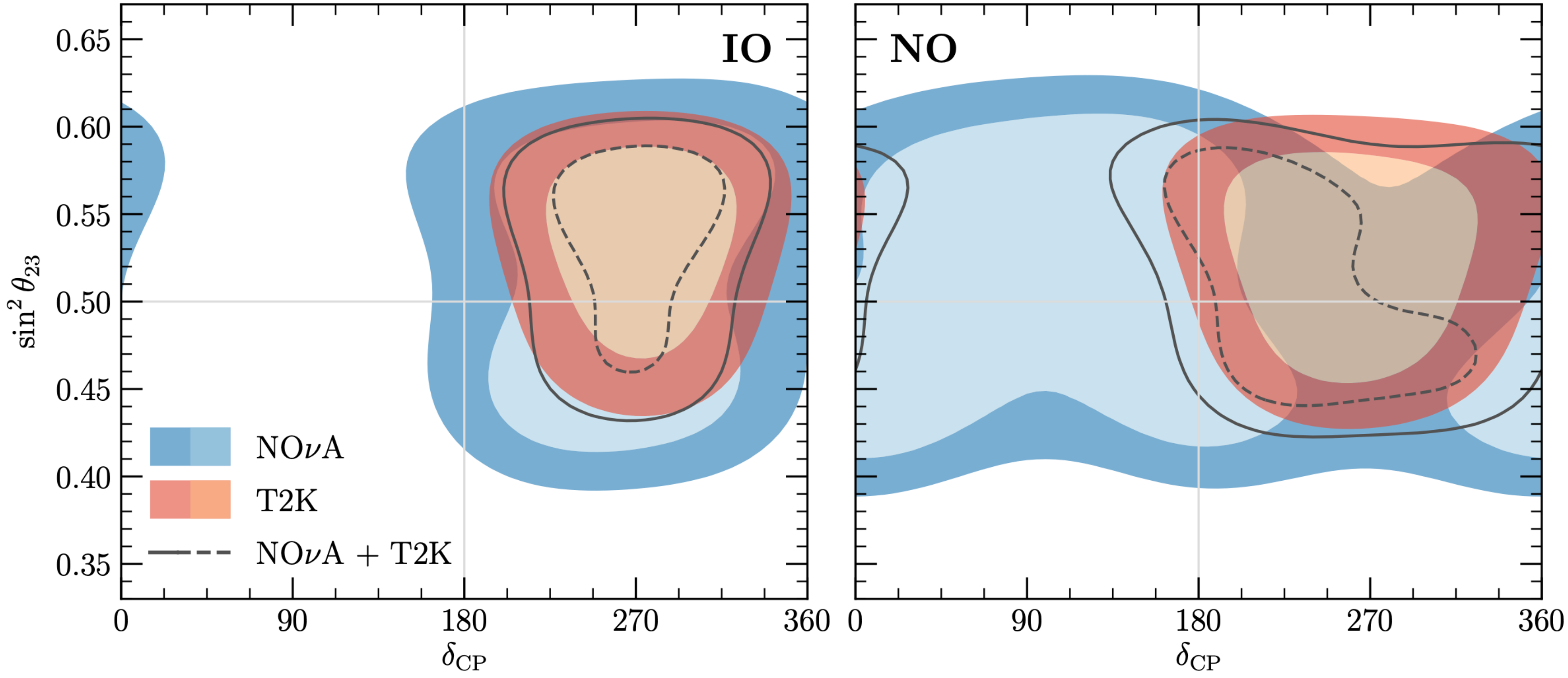
Dear Prof Chengcheng Han

Your recent paper on “QCD axion dark matter and the cosmic dipole anomaly” is very interesting. I would be very grateful if you could spare some time to tell us about it over a zoom webinar.

总结

- CP破坏跟很多重要的物理问题相关，例如物质不对称性，强CP问题等
- 轻子部分可能存在CP破坏，可以提供了正反物质不对称起源(type I/II/III跷跷板机制)
- 强CP问题仍然是长期以来未解决的重要问题之一，自发CP破坏或者axion?

THANK YOU



IO
NO
NOνA
T2K
NOνA + T2K
$\sin^2\theta_{23}$
δ_{CP}
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0
90
180
270
360