Baryon asymmetry of the Universe

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2024理论物理前沿与交叉科学研讨会

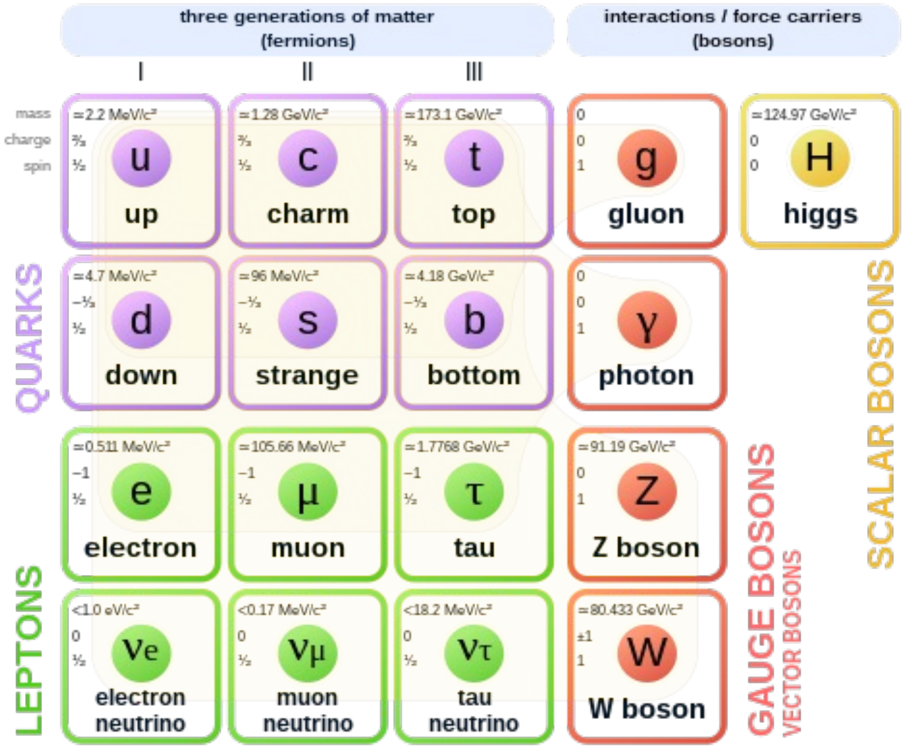
南京师范大学

2024.4.27

研究背景

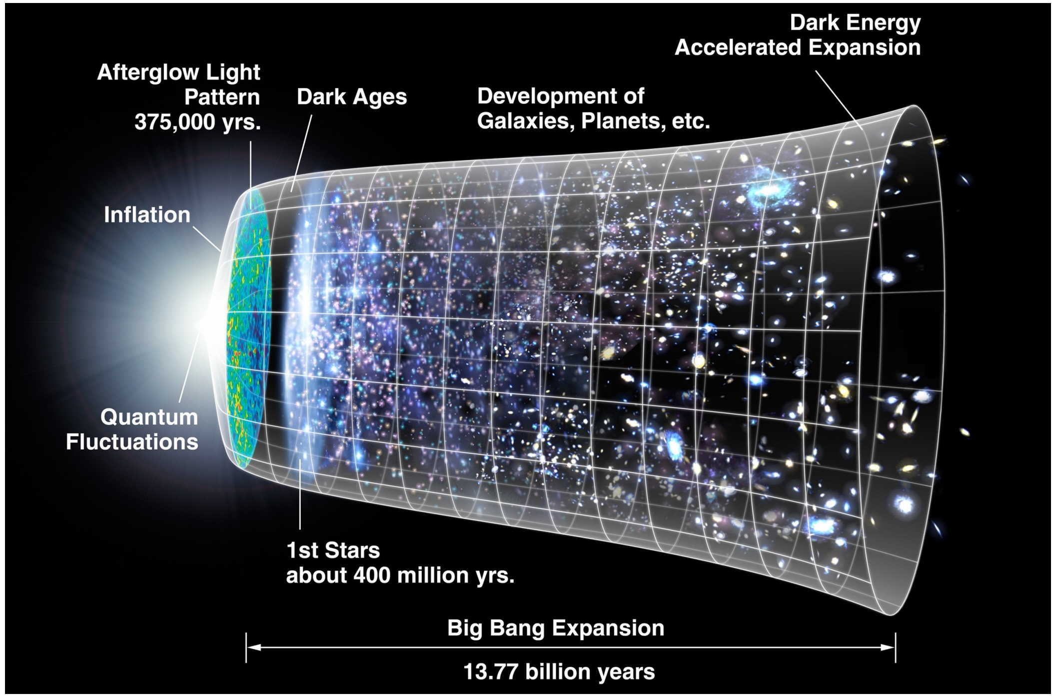
粒子物理标准模型/宇宙学标准模型

Standard Model of Elementary Particles



物质的基本组成及其相互作用

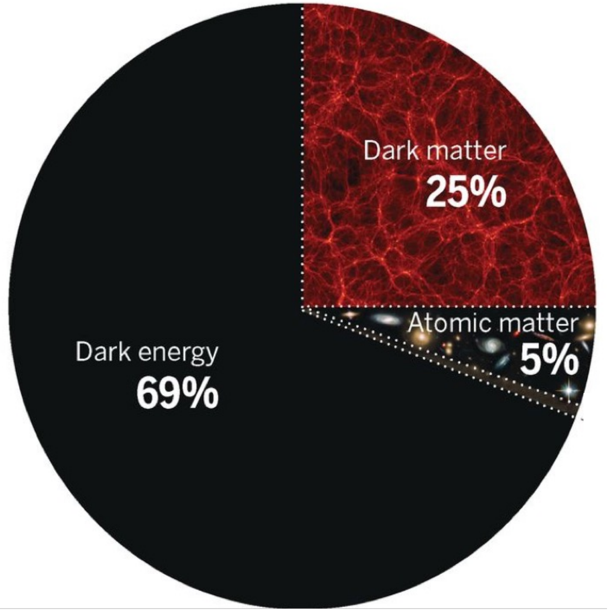
ΛCDM+Inflation



物质的起源与演化

研究背景

What is the Universe made of?



- 暗能量是什么？与粒子物理标准模型有何关联？
- 暗物质是什么？它是不是一种基本粒子？
- 为什么可见物质都是重子，反重子去哪了？

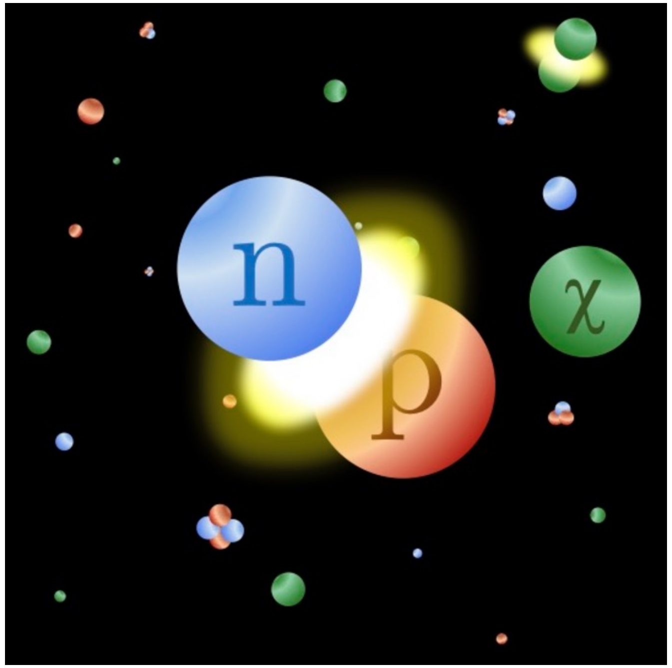
(重子不对称性 or 正反物质不对称性)

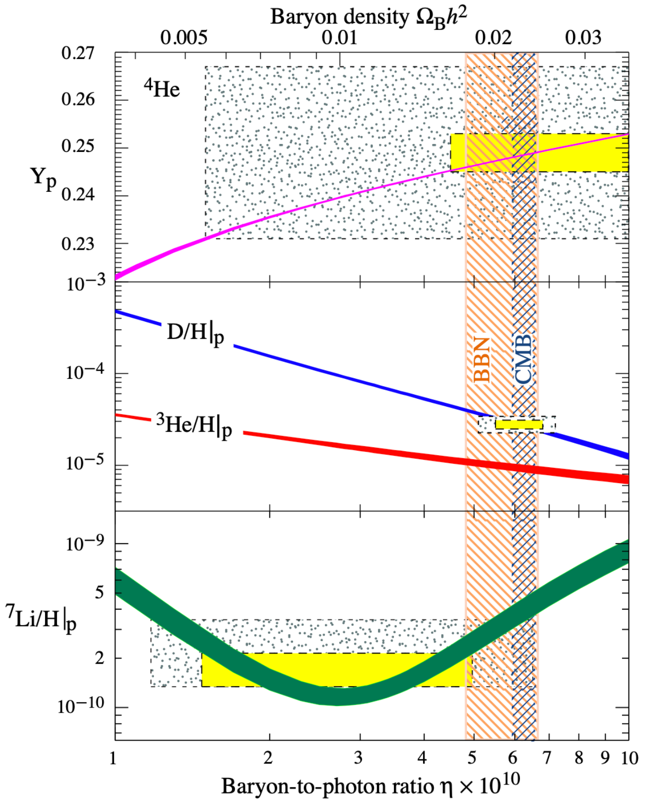
粒子物理和宇宙学面临的共同问题！

原初核合成

原初核合成(BBN)（T~1 MeV, t~3 分钟)，轻核元素的形成，宇宙大爆炸的直接证据

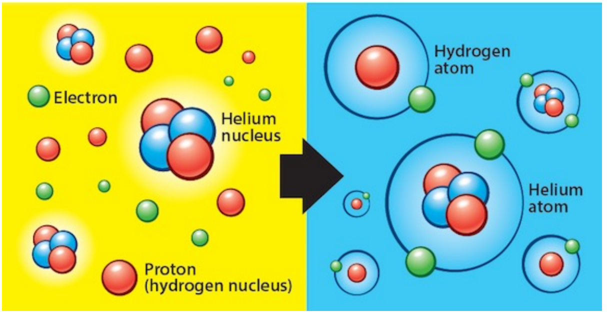
$$\eta = \frac{n_b - n_{\bar{b}}}{n_\gamma} \sim 10^{-10}$$

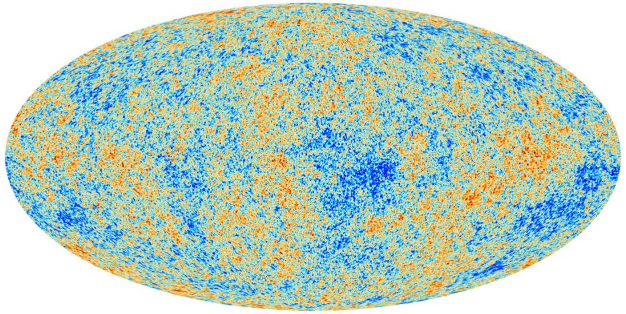


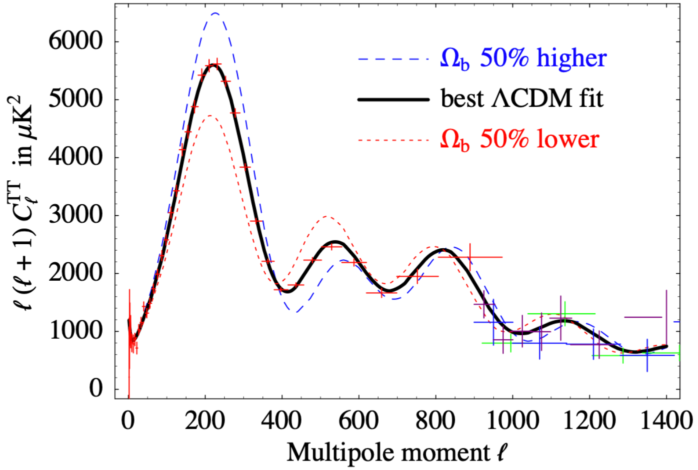


宇宙微波背景辐射

宇宙大爆炸的遗迹：宇宙微波背景辐射(CMB)(T~0.1 eV 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

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

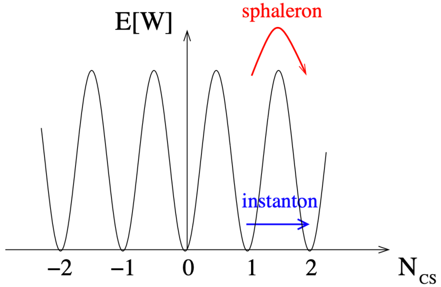
正反物质不对称性

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，这个差别会在暴胀时期抹平掉

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	✗



SU(2) vacuum

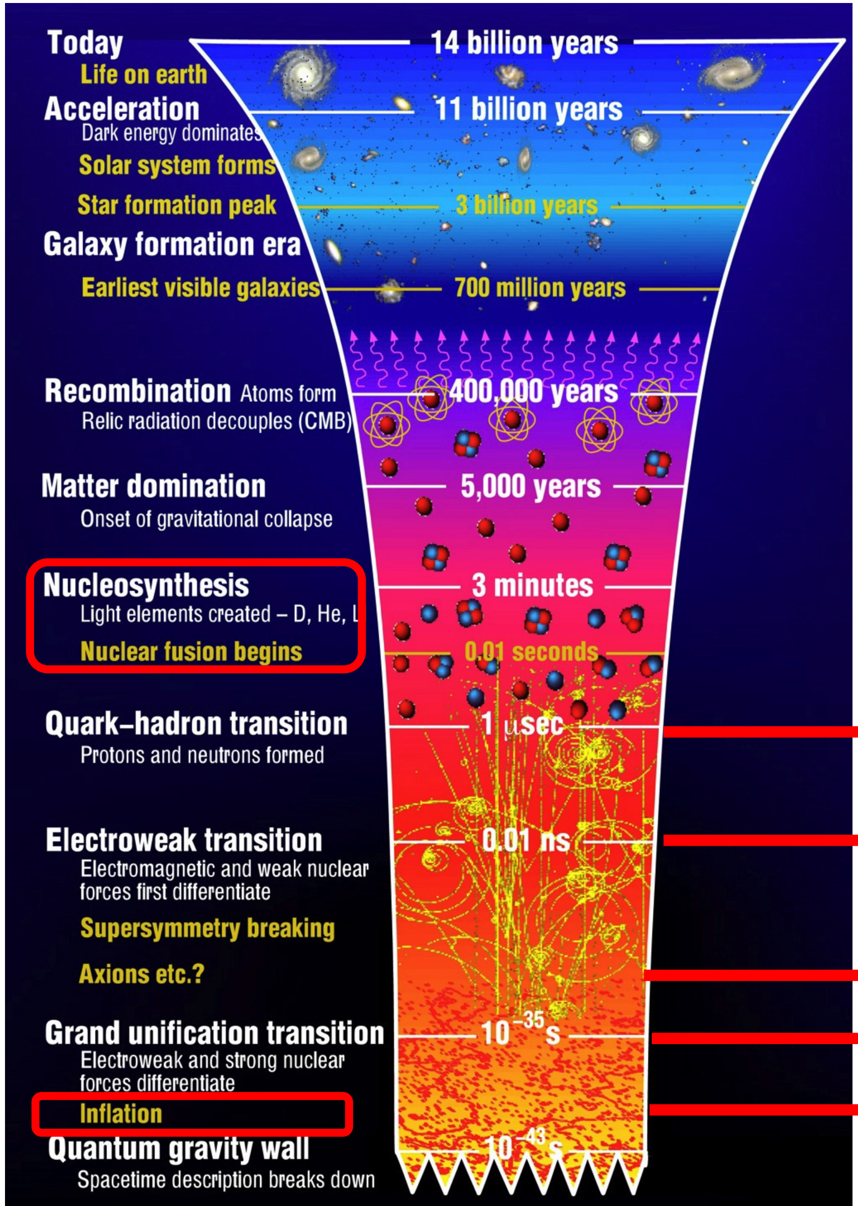
$$\Delta B = \Delta L = -3$$

- 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



B-mesogenesis

EW Baryogenesis

Leptogenesis

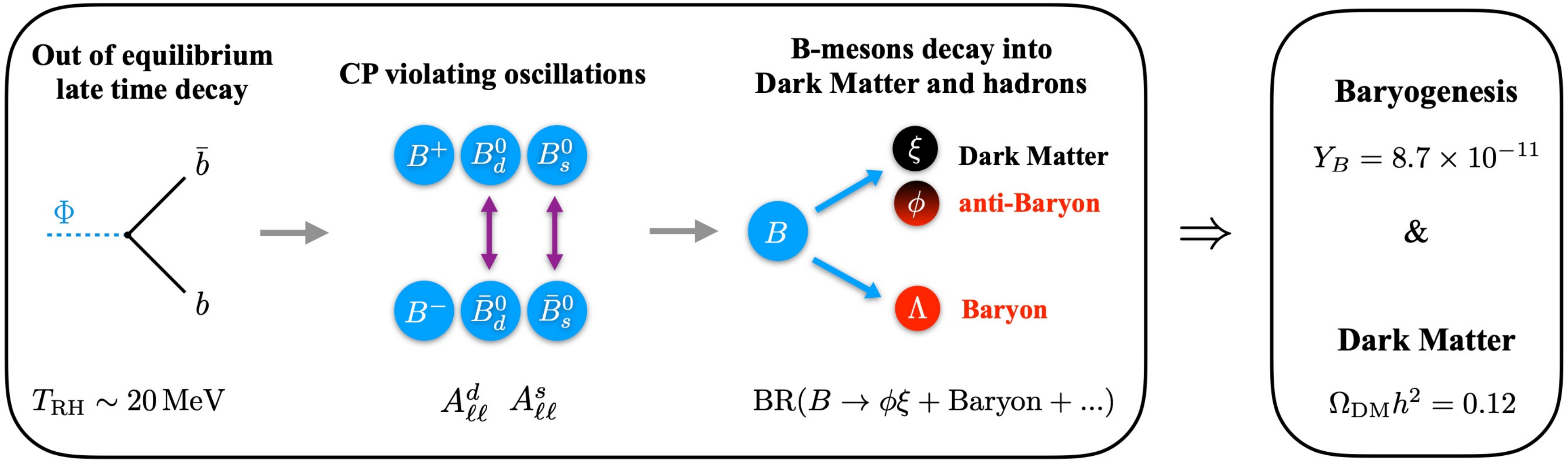
GUT Baryogenesis

Baryogenesis from inflation

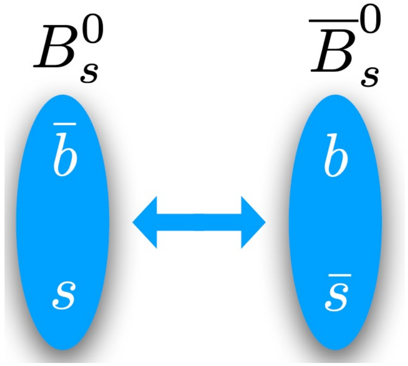
不能早于暴胀，因为宇宙在很短时间内膨胀了 e^{60} 倍，任何早期的不对称性都变的极小

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

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

$$A^q_{\mathrm{SL}} = \mathrm{Im}\left(\frac{\Gamma^q_{12}}{M^q_{12}}\right) = \frac{\Gamma(\overline{B}^0_q \to B^0_q \to f) - \Gamma(B^0_q \to \overline{B}^0_q \to \bar{f})}{\Gamma(\overline{B}^0_q \to B^0_q \to f) + \Gamma(B^0_q \to \overline{B}^0_q \to \bar{f})}$$

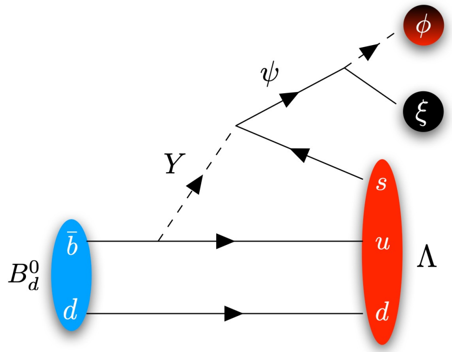
标准模型预言

$$A^d_{\mathrm{SL}}|_{\mathrm{SM}} = (-4.7 \pm 0.4) \times 10^{-4}$$
$$A^s_{\mathrm{SL}}|_{\mathrm{SM}} = (2.1 \pm 0.2) \times 10^{-5}$$

实验测量

$$A^d_{\mathrm{SL}} = (-2.1 \pm 1.7) \times 10^{-3}$$
$$A^s_{\mathrm{SL}} = (-0.6 \pm 2.8) \times 10^{-3}$$

- **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**

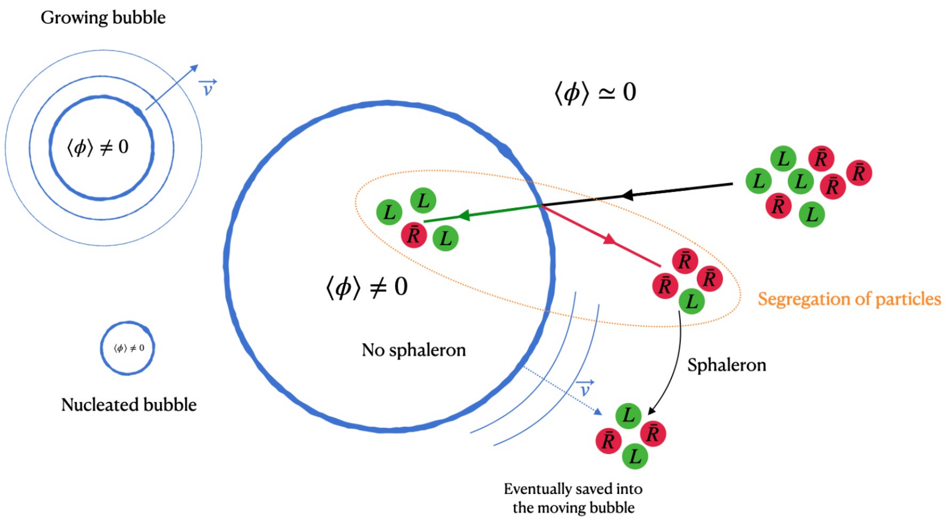


电弱重子生成

- 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]

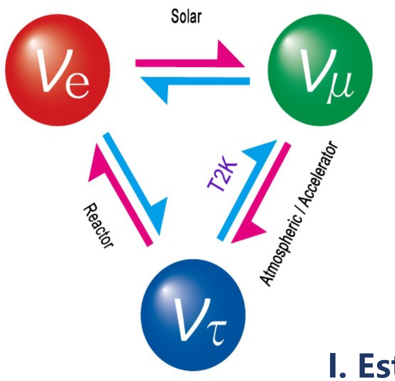
[1]CERN, Theoretical Physics Department, Geneva, Switzerland

[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)



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

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

NO

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

IO

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

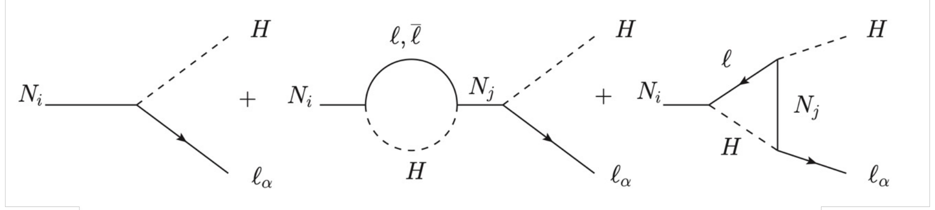
轻子部分提供了新的CP破坏源(T2K实验暗示中微子部分可能存在CP破坏)，正反物质不对称性可能从轻子部分开始，再由sphaleron过程传递给重子——轻子生成机制（leptogenesis）

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’

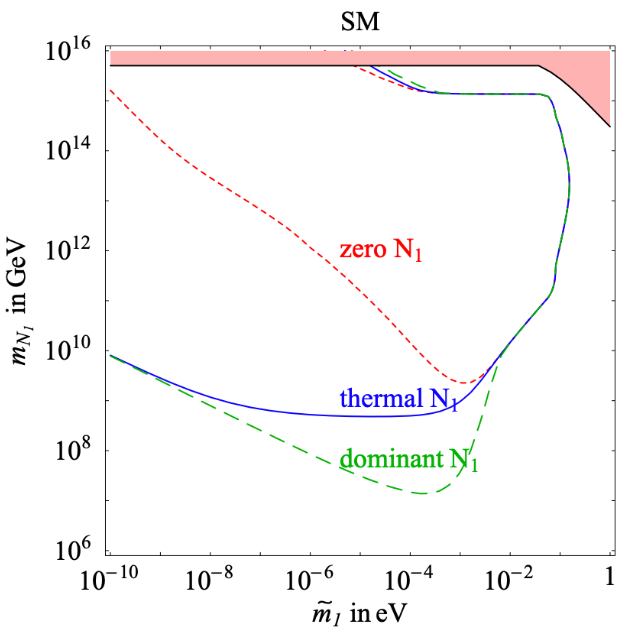
$$\mathcal{L}_I = \mathcal{L}_{SM} + i\overline{N_{R_i}}\partial\!\!\!/ N_{R_i} - \left(\frac{1}{2}M_i\overline{N^c_{R_i}}N_{R_i} + \epsilon_{ab}Y_{\alpha i}\overline{N_{R_i}}\ell^a_\alpha H^b + h.c.\right)$$



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

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

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

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

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

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

EW precision measurement

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

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

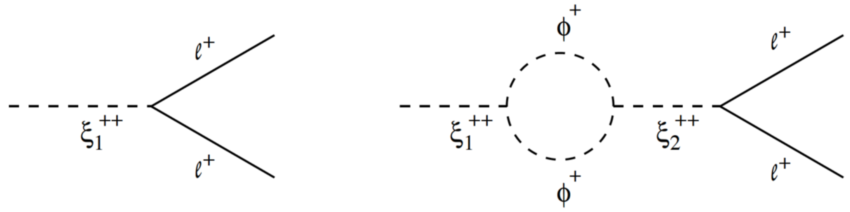
500+ citations

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

ELSEVIER

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)

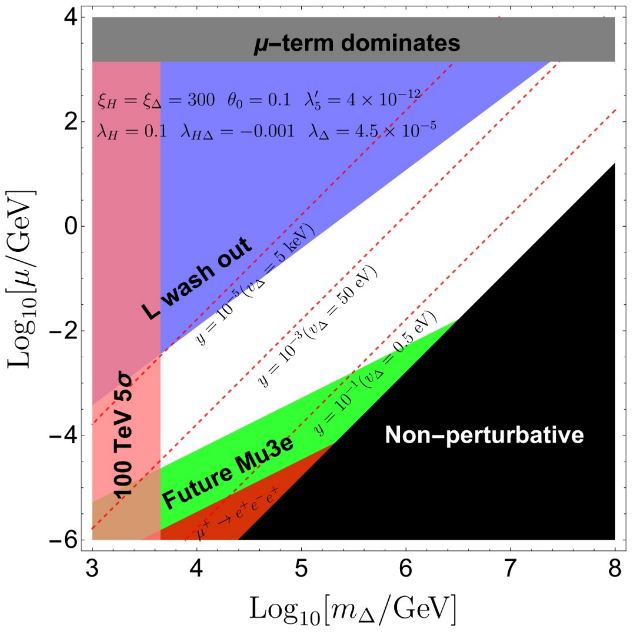
Affleck-Dine Leptogenesis from Higgs Inflation

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

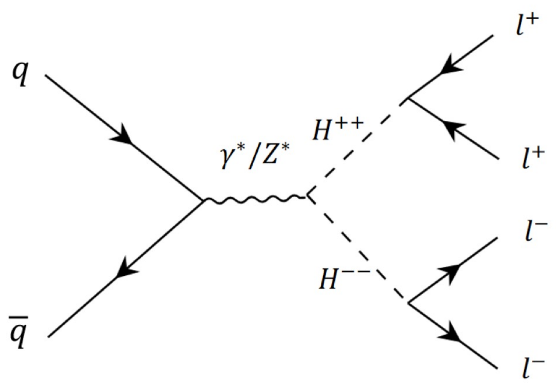
We find that the triplet Higgs of the type-II seesaw mechanism can simultaneously generate the neutrino masses and observed baryon asymmetry while playing a role in inflation. We survey the allowed parameter space and determine that this is possible for triplet masses as low as a TeV, with a preference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

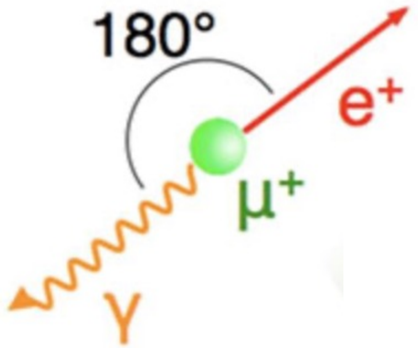
Type II Seesaw leptogenesis

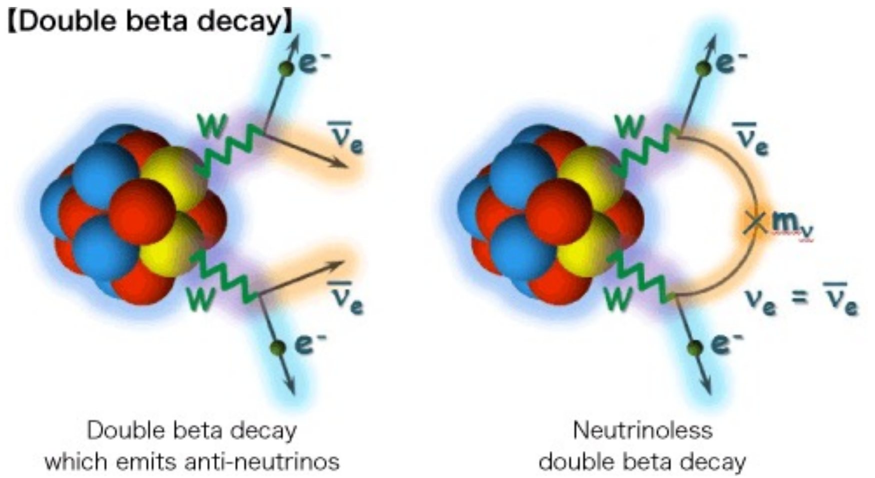
Neil D. Barrie,[a] Chengcheng Han[b] and Hitoshi Murayama[c,d,e,1]



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

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

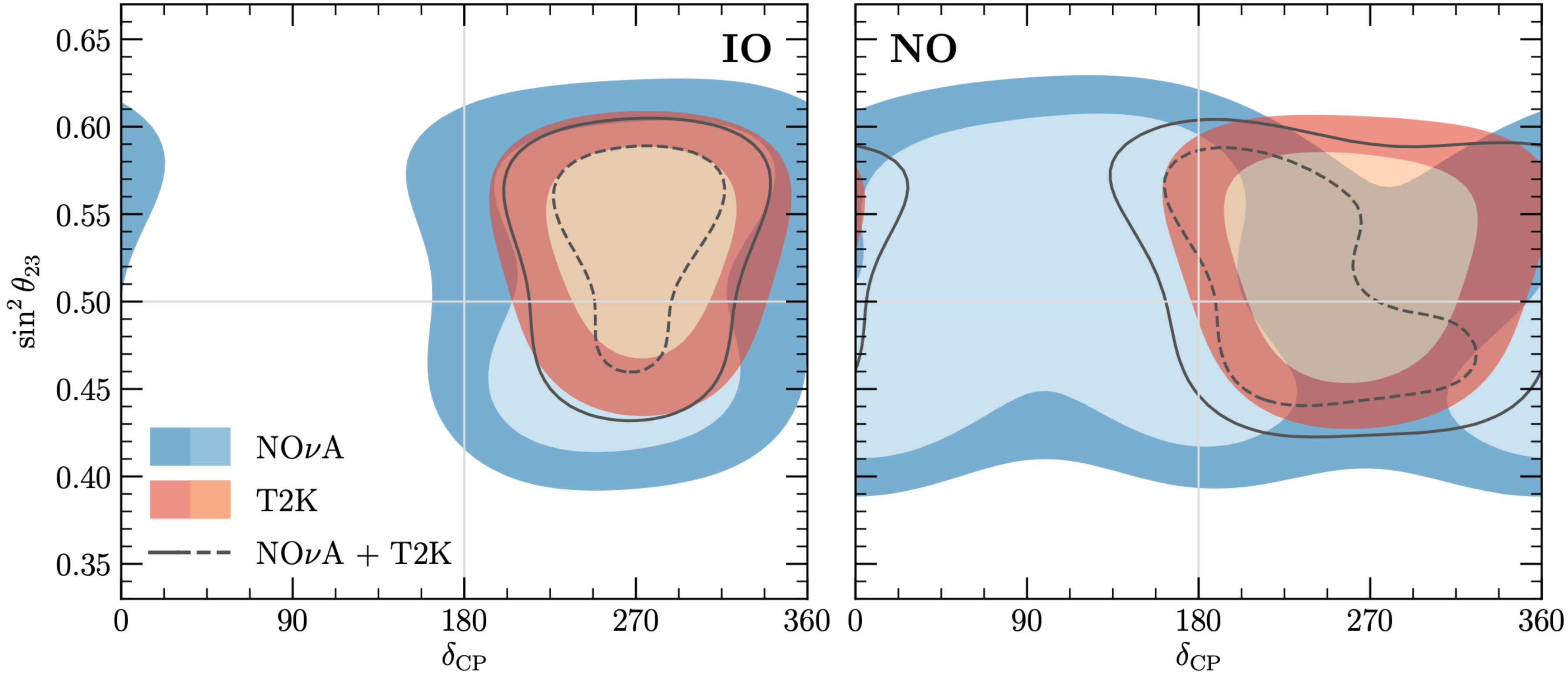
The Type II Seesaw mechanism is known to be unable to successfully lead to standard thermal Leptogenesis, in contrast to the Type I and III Seesaw mechanisms. Thermal Leptogenesis can only be achieved in this mechanism through the inclusion of additional particles, an extra triplet Higgs or a right-handed 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”

总结

- 正反物质不对称性起源仍然是粒子物理和宇宙学中面临的重要问题
- 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)
- 未来实验将对各类重子生成机制进行检验

THANK YOU



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