CP violation and baryon asymmetry

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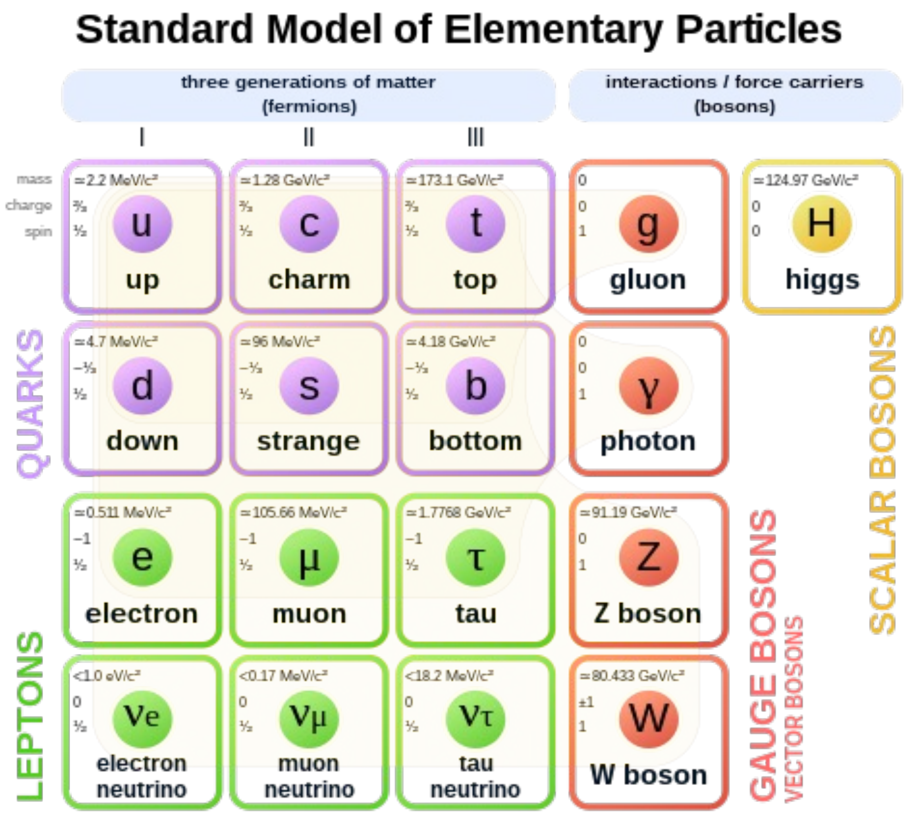
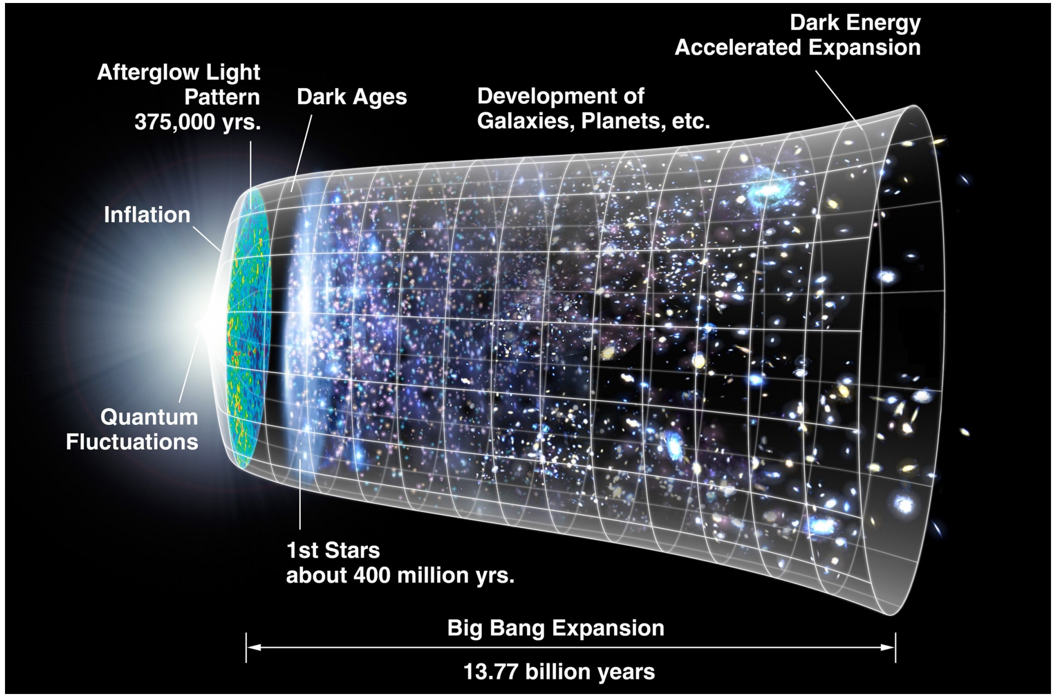
研究背景

粒子物理标准模型/宇宙学标准模型



物质的基本组成及其相互作用

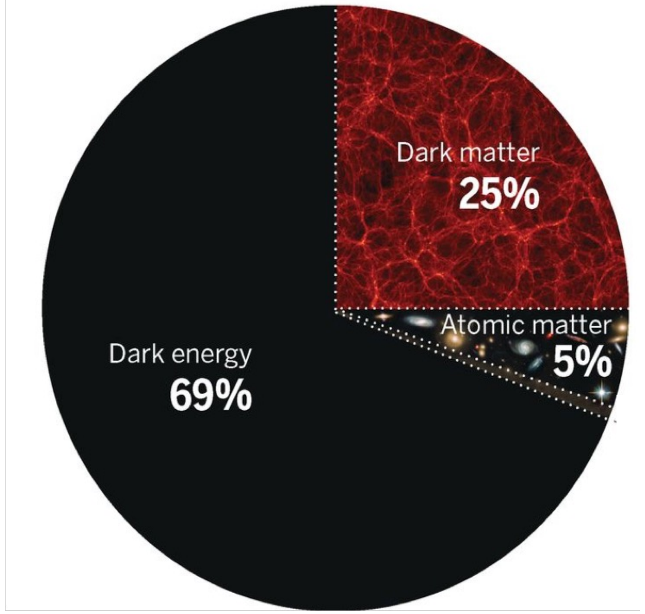
ΛCDM+Inflation



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？

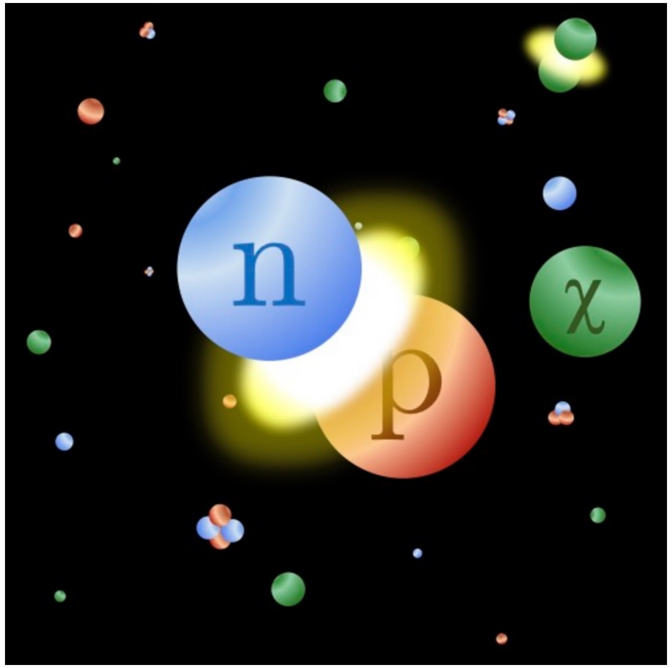
(重子不对称性 or 正反物质不对称性)

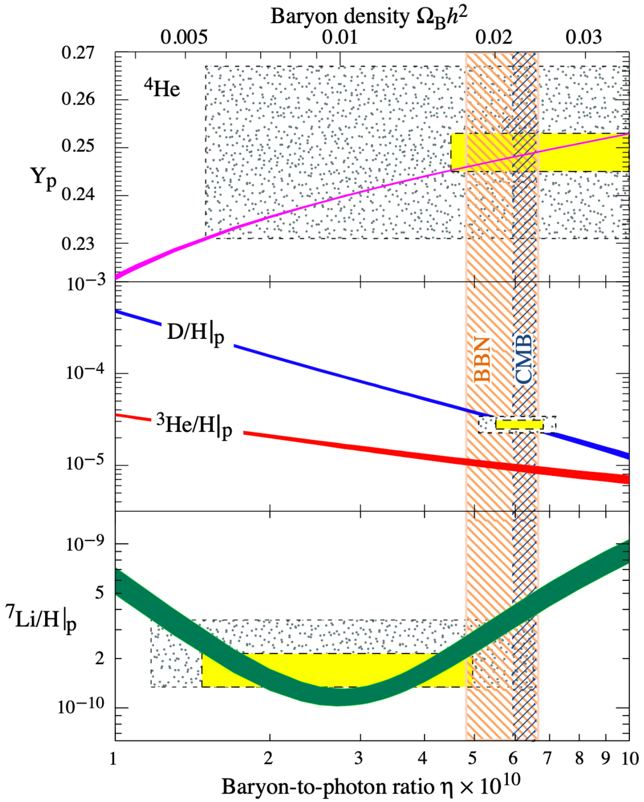
粒子物理和宇宙学面临的共同问题！

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

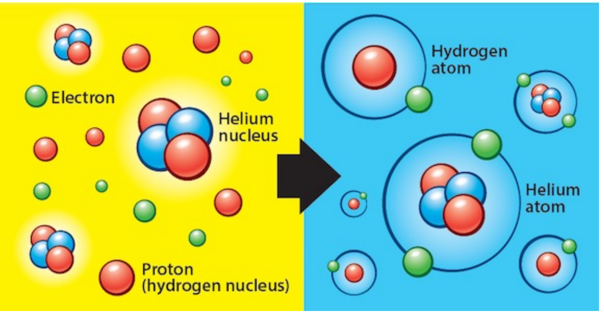
$$\eta = \frac{n_b - n_{\bar{b}}}{n_\gamma} \sim 10^{-10}$$

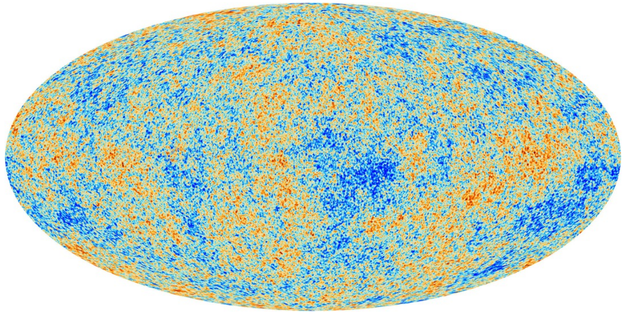


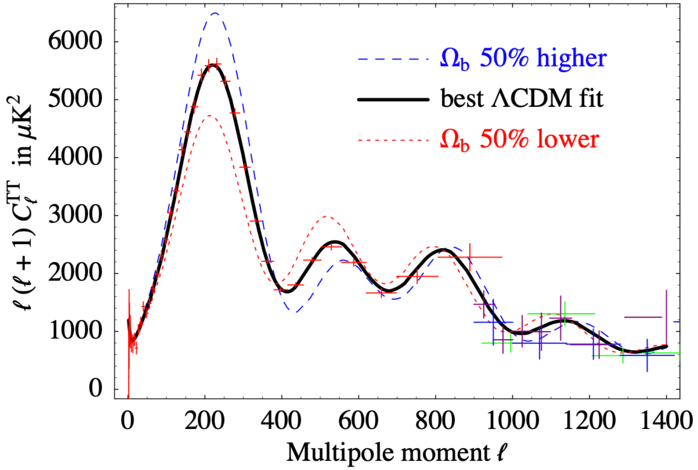


宇宙微波背景辐射

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]	$([2]-[1])/\sigma_1$	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

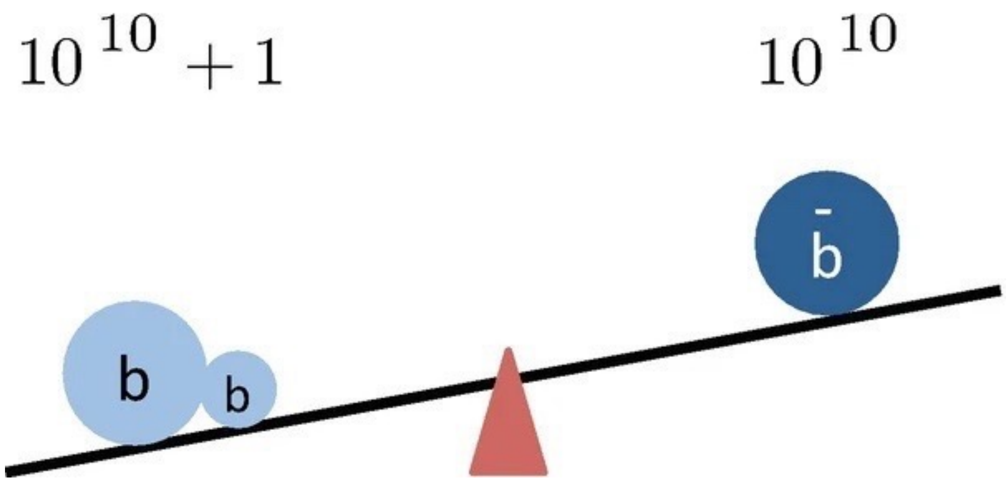
$$\eta = \frac{n_b - n_{\bar{b}}}{n_\gamma} \sim 10^{-10}$$

重子不对称性

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

在宇宙年龄10^{-5} s- 3min 之间，大部分正反物质互相湮灭只留下十亿分之一

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



- **为什么会有这个差别?**
- **为什么这个差别这么小?**

如何产生重子不对称性?

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	✗

- 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，不足以解释现在的观测

新的CP破坏源+脱离热平衡条件!

宇宙早期热平衡

处于热平衡的粒子满足玻色-爱因斯坦或Fermi-Dirac(费米子)统计分布

$$f_i(\vec{p};T,\mu_i) = \left[e^{(E_i-\mu_i)/T} \mp 1\right]^{-1}$$

处于热平衡的粒子数密度

$$n_i(T,\mu) = g_i \int \frac{d^3p}{(2\pi)^3} f_i(\vec{p}) \simeq \begin{cases} g_i \xi_i^{(n)} \frac{\zeta(3)}{\pi^2} T^3 & ; \qquad T \gg m_i,\, \mu_i \\ g_i \left(\frac{m_i T}{2\pi}\right)^{3/2} e^{-(m_i-\mu_i)/T} & ; \qquad T \ll (m_i - \mu_i) \end{cases}$$

$$\xi_i^{(n)} = 1 \ (3/4) \text{ for } i \text{ a boson (fermion)}$$

宇宙早期热平衡

正反粒子不对称性跟化学势有关

$\xi_i^{(\Delta)} = 2\ (1)$ for ψ a boson (fermion)

$$n_\psi - n_{\bar\psi} = g_\psi \int \frac{d^3p}{(2\pi)^3}\left[f_\psi(\vec p; T, \mu_\psi) - f_\psi(\vec p; T, -\mu_\psi)\right]$$

$$\simeq \begin{cases} \xi_\psi^{(\Delta)} \frac{g_\psi}{6} T^3 \left[\left(\frac{\mu_\psi}{T}\right) + \frac{1}{\pi^2}\left(\frac{\mu_\psi}{T}\right)^3 + \ldots\right] & ;\ T \gg m_\psi \\ 2\sinh\left(\frac{\mu_\psi}{T}\right)\ g_\psi \left(\frac{m_\psi T}{2\pi}\right) e^{-m_\psi/T} & ;\ T \ll m_\psi \end{cases}$$

温度比较高时，正反粒子的不对称性正比于化学势

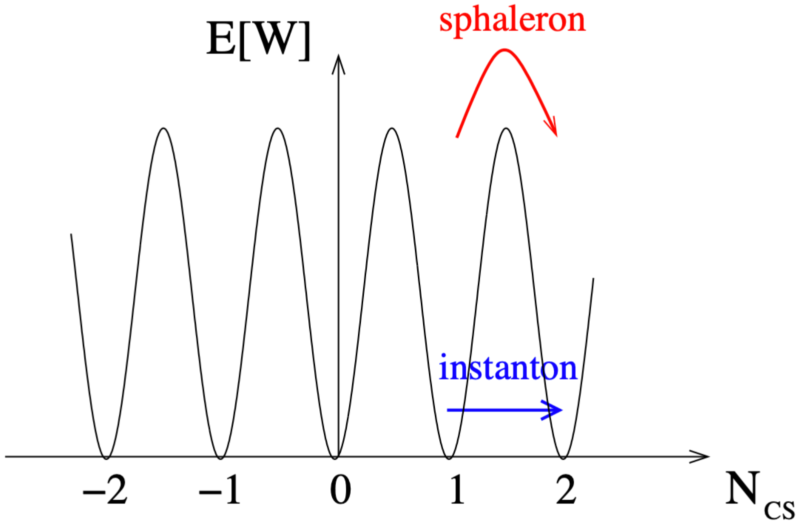
$$A + B \leftrightarrow C + D$$

$$\mu_A + \mu_B = \mu_C + \mu_D$$

光子、胶子等化学势为0，因此粒子与反粒子化学势反号

标准模型重子数破坏过程

SU(2) 真空



Instanton 贡献

$$\Gamma \propto e^{-S_E} \leq e^{-8\pi^2/g^2} \simeq 10^{-160}$$

Sphaleron 贡献

$$E_{sp}(T) \simeq \frac{8\pi\, v(T)}{g} f(m_h/m_W)$$

$$\Gamma_{sp} \simeq A\,(\alpha_W T)^4 \left[\frac{E_{sp}(T)}{T}\right]^7 e^{-E_{sp}(T)/T}$$

高温时速率很快（T >100 GeV） $\Gamma_{sp} = (18 \pm 3)\,\alpha_W^5 T^4$

低温时指数压低

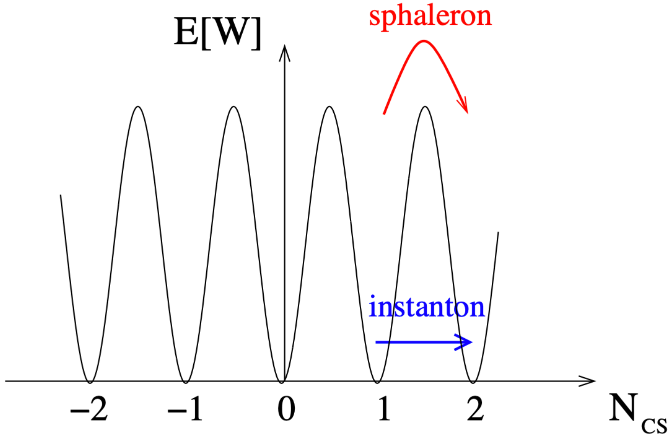
标准模型重子数破坏过程

标准模型中的重子流和轻子流存在反常

$$\partial_\mu j_B^\mu = \partial_\mu j_L^\mu = \frac{n_g}{32\pi^2}\left(g^2 W^a_{\mu\nu}\widetilde{W}^{a\,\mu\nu} - g'^2 B_{\mu\nu}\widetilde{B}^{\mu\nu}\right)$$

$$B = \int d^3x\, j_B^0$$

$$\Delta B = n_g \Delta N_{CS}$$



不同真空的跃迁会产生或减少重子数，但是不影响B−L

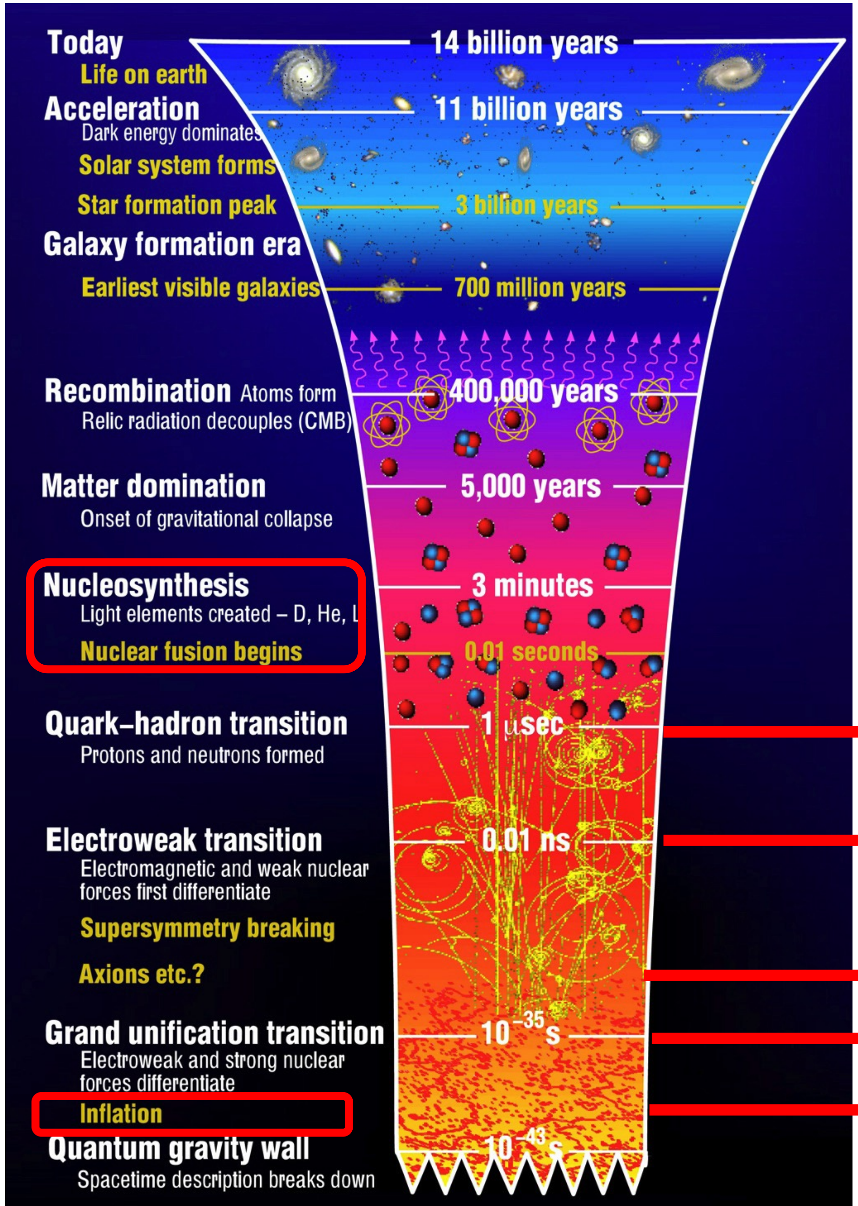
标准模型重子数破坏过程

重子数破坏过程对化学势的影响 $P = \{L, E, Q, U, D, H\}$

$$\begin{aligned}\mathcal{B} &= N_{\text{gen}}(2\mu_Q - \mu_U - \mu_D) = \frac{28}{79}(\mathcal{B}-\mathcal{L})_0\\ \mathcal{L} &= \mathcal{B} - (\mathcal{B}-\mathcal{L}) = -\frac{51}{79}(\mathcal{B}-\mathcal{L})_0\end{aligned}$$

- Sphaleron过程是有效(T> 100 GeV)
- 宇宙初期B=0，L=0，因此B需要在某个特定过程中产生
- 如果产生的B=L，最终产生的重子不对称性将会是零(除非关闭sphaleron过程)
- Sphaleron过程不破坏B-L，一旦产生反轻子数就会转化为重子数（轻子生成机制）

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

EW Baryogenesis

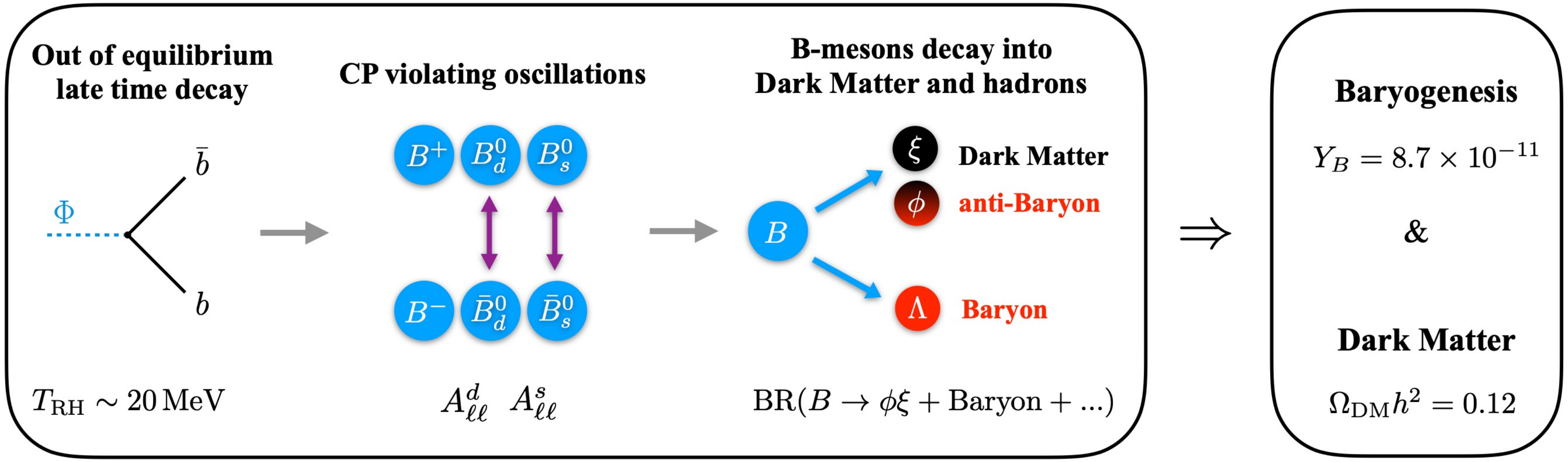
Leptogenesis

GUT Baryogenesis

Baryogenesis from inflation

B-mesogenesis

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



Out of equilibrium late time decay

Φ $\bar{b}$ b

$T_{\mathrm{RH}} \sim 20\,\mathrm{MeV}$

CP violating oscillations

B^+ B_d^0 B_s^0

B^- $\bar{B}_d^0$ $\bar{B}_s^0$

$A_{\ell\ell}^d \quad A_{\ell\ell}^s$

B-mesons decay into Dark Matter and hadrons

B ξ **Dark Matter**

ϕ **anti-Baryon**

Λ **Baryon**

$\mathrm{BR}(B \to \phi\xi + \mathrm{Baryon} + ...)$

$\Rightarrow$

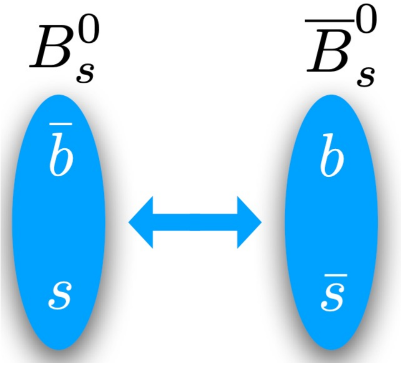
Baryogenesis

$Y_B = 8.7 \times 10^{-11}$

&

Dark Matter

$\Omega_{\mathrm{DM}} h^2 = 0.12$



- B meson heavy enough(5.3 GeV) to decay into baryon
- CP violation appears during oscillations, then B-> Bbar and Bbar -> B rate different, difference B and Bbar
- Explain the origin of the dark matter

B-mesogenesis

The baryon asymmetry is related to the B meson decay rate into baryon+invi and B meson oscillation CP violation A$_{\mathrm{SL}}$

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

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

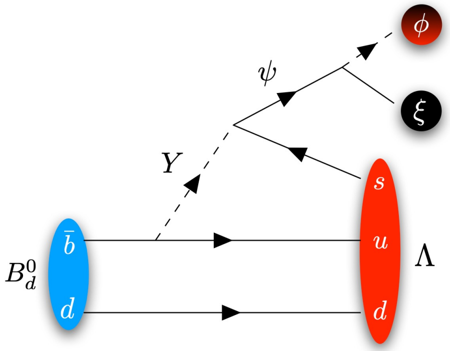
SM prediction:

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

EXP:

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

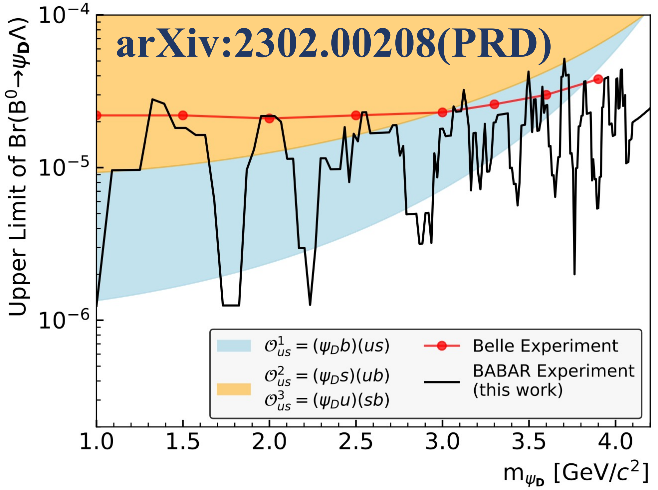
- **SM CKM is enough to provide the CP violation，but**
- **B meson decay into baryon+invisible (BaBar，Belle，LHCb)**
- **Measurement of the CP violation of B meson is important**

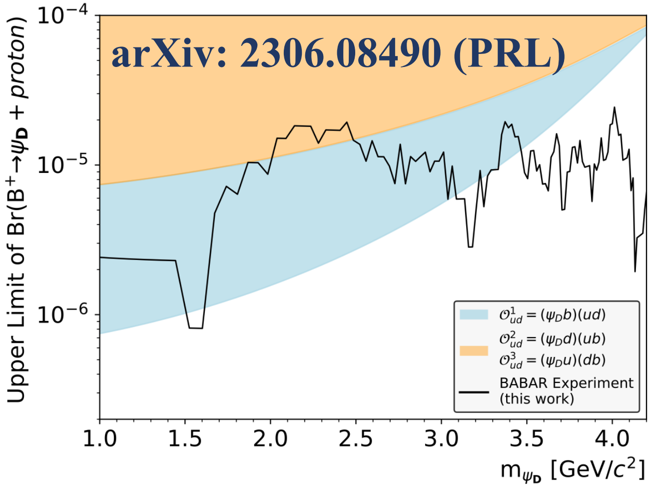


B-mesogenesis

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



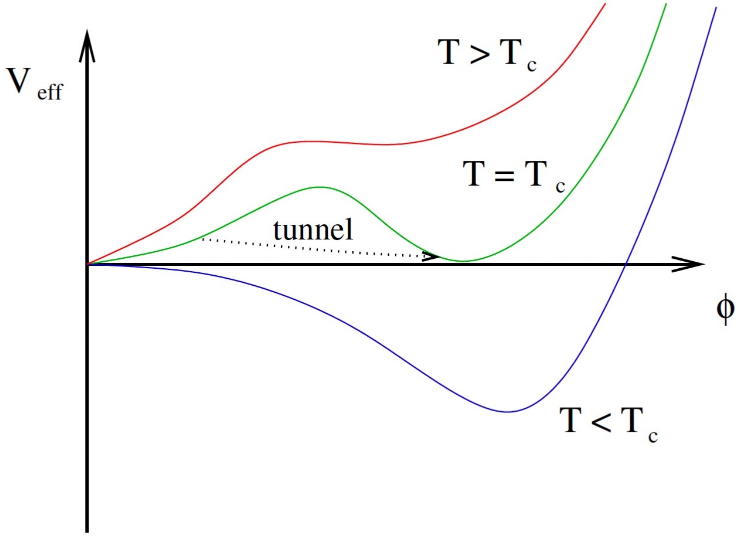


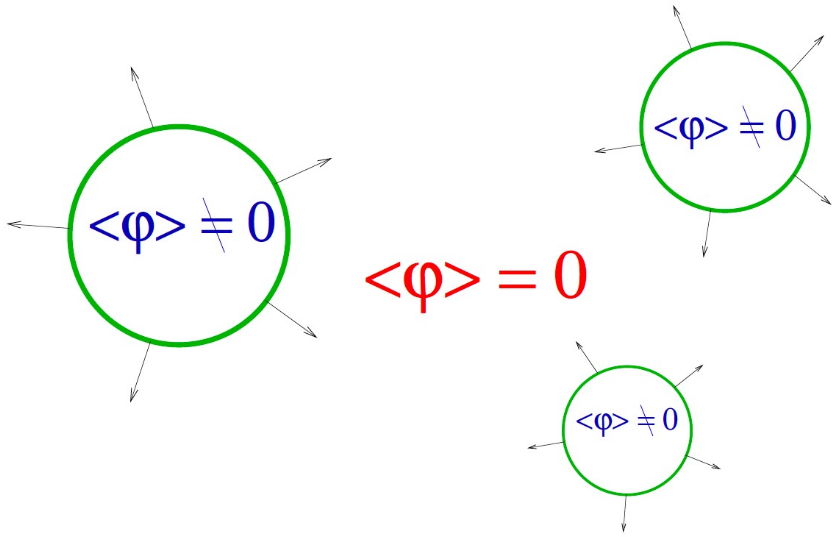
电弱重子生成

Rubakov and Shaposhnikov, 1996′

D. E. Morrissey and M. J. Ramsey-Musolf, 2012′

电弱相变

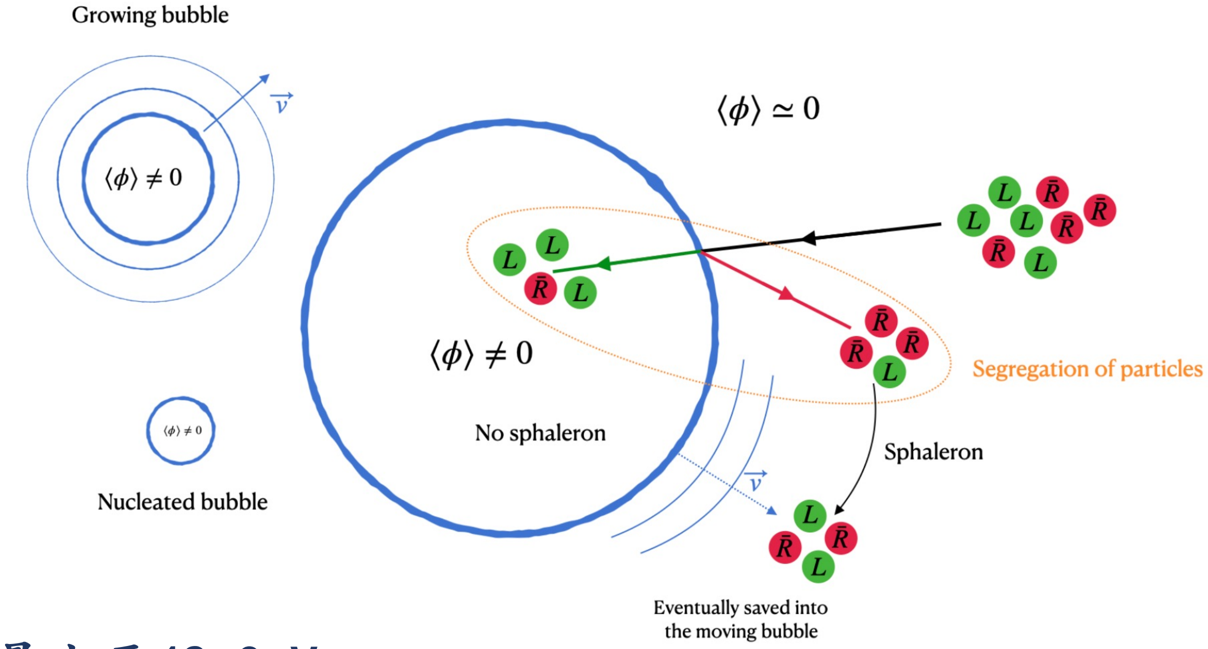




但是Lattice的结果表明，如果希格斯质量小于75 GeV 标准模型才会出现一阶相变

电弱重子生成

实际电弱重子生成机制中，不仅要求一阶相变，这个相变必须是强一阶相变，需要禁戒真空泡里面的sphaleron过程



- 强一阶相变要求希格斯质量小于42 GeV
- 即便如此，标准模型里的夸克部分提供的CP破坏效应太小，不足以产生足够的重子不对称

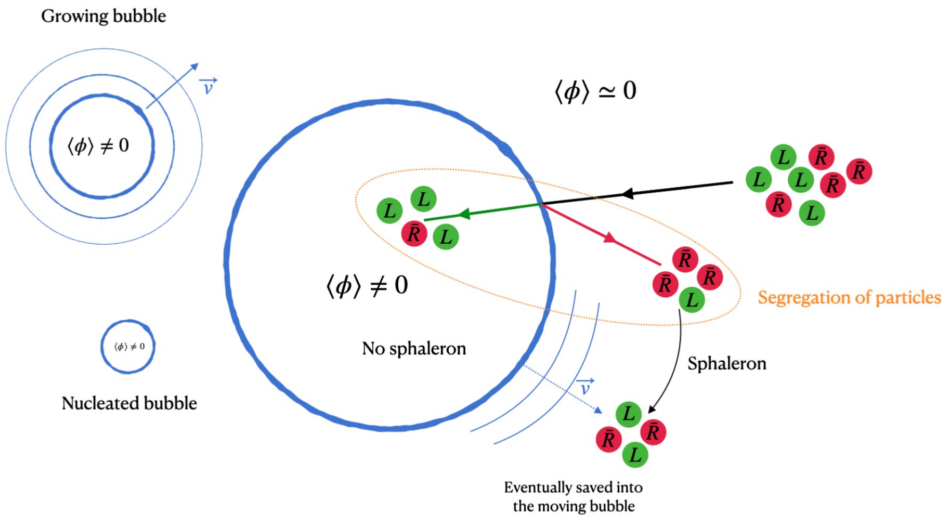
$$\delta_{CP} \approx J\frac{(m_t^2-m_c^2)(m_t^2-m_u^2)(m_c^2-m_u^2)(m_b^2-m_s^2)(m_b^2-m_d^2)(m_s^2-m_d^2)}{m_W^{12}} \sim 10^{-18}$$

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

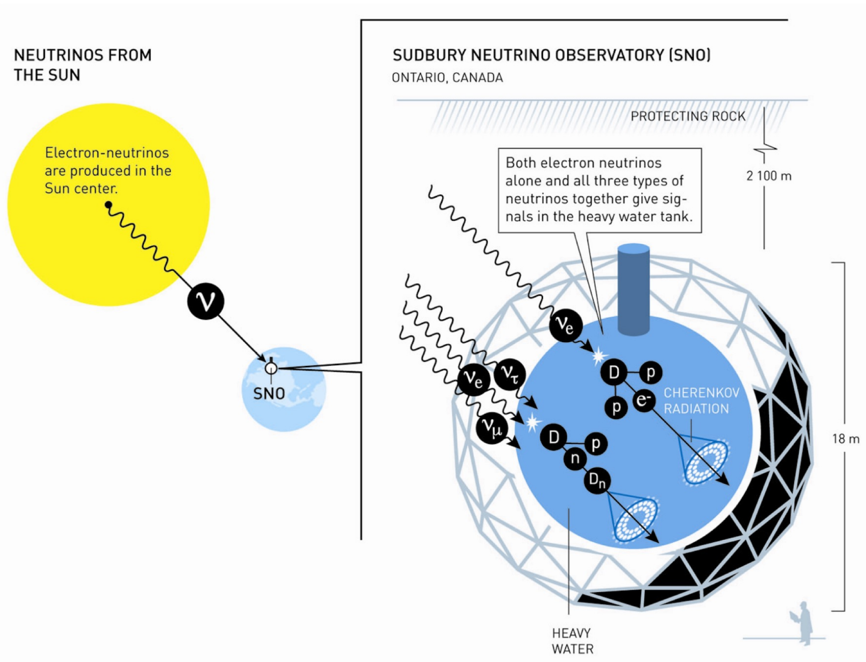
电子EDM测量(< $4.1*10^{-30}$ e.cm)



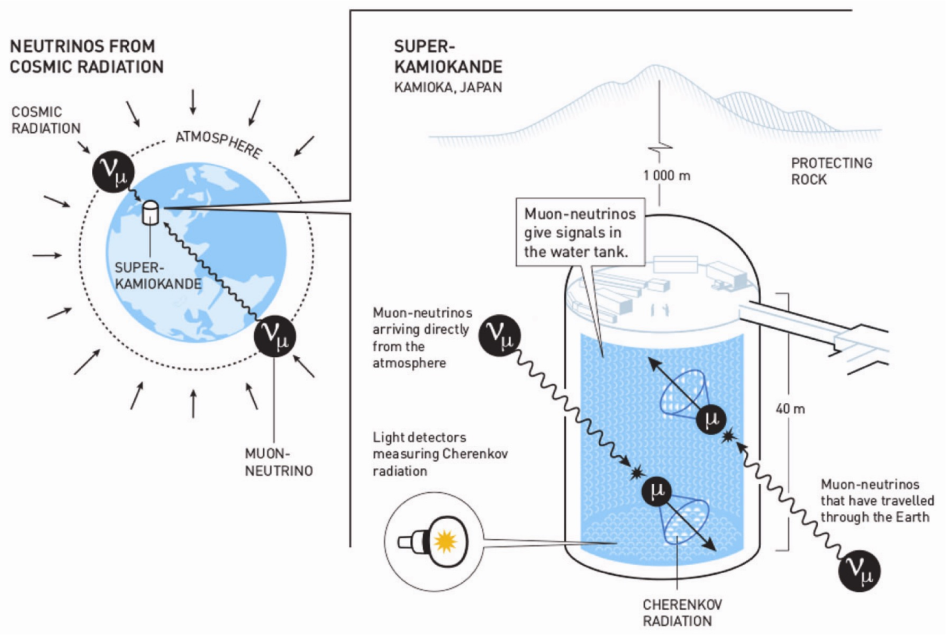
伴随的引力波信号，热门研究之一

中微子质量

太阳中微子之谜

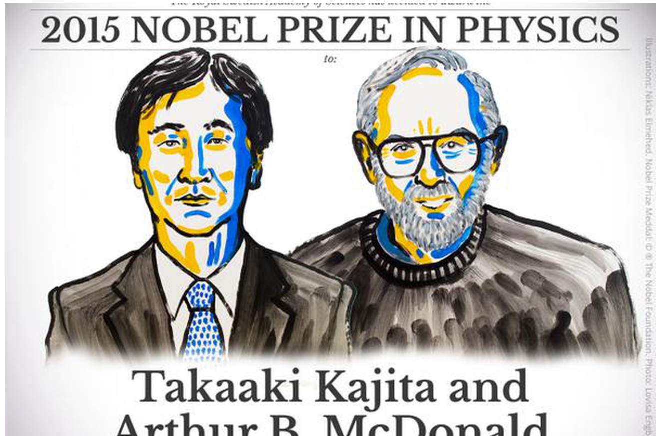


大气中微子反常



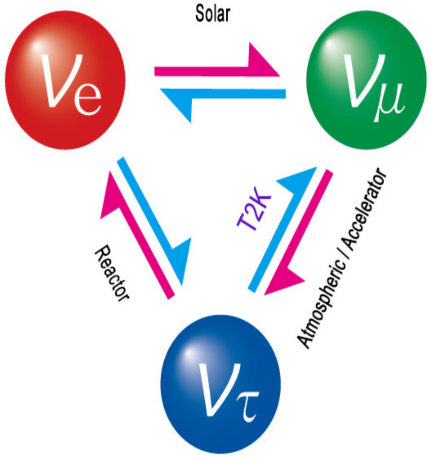
三代中微子之间会互相振荡转化

中微子存在质量！(~0.05 eV)



中微子质量

Kobayashi and Maskawa(2008 Nobel prize) 机制告诉我们，如果中微子有质量，轻子部分可能有CP破坏



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

NO

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

IO

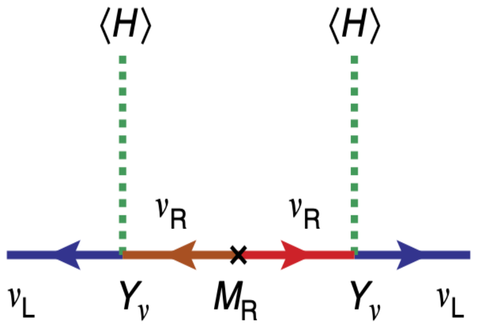
$$\theta_{12} = 33.45^{\circ}{}^{+0.78^{\circ}}_{-0.75^{\circ}}$$
$$\theta_{23} = 49.3^{\circ}{}^{+0.9^{\circ}}_{-1.1^{\circ}}$$
$$\theta_{13} = 8.60^{\circ}{}^{+0.12^{\circ}}_{-0.12^{\circ}}$$
$$\delta_{\rm CP} = 282^{\circ}{}^{+26^{\circ}}_{-30^{\circ}}$$

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）

跷跷板机制

为了解释中微子质量，必然引入新的粒子

Type I

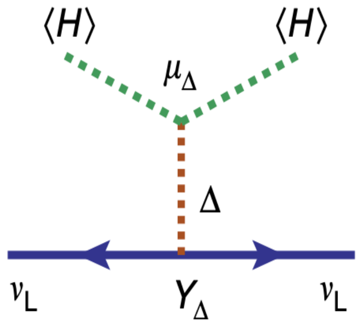


$$M_\nu = -\langle H\rangle^2 Y_\nu M_R^{-1} Y_\nu^T$$

SM+3 singlets fermions

Minkowski, Gell-Mann,
Glashow, Yanagida

Type II

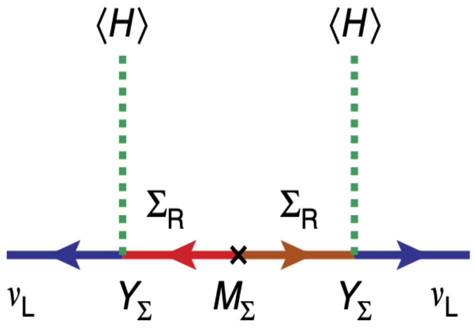


$$M_\nu = \langle H\rangle^2 Y_\Delta \mu_\Delta / M_\Delta^2$$

SM+1 triplet Higgs

Magg, Wetterich

Type III



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

SM+3 triplet fermions

Foot, Lew, He, Joshi

引入的新粒子可以在宇宙早期会热退耦——脱离热平衡条件

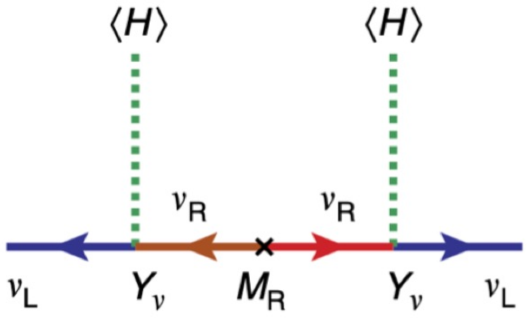
第一类跷跷板机制

加入三个单态中性右手中微子 N(1，1，0)

$$\mathcal{L} = \mathcal{L}_{SM} + y_\nu \tilde{H}\bar{L}N - M_R\bar{N}^cN$$

$$M = \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix}$$

$$m_\nu \sim \frac{m_D^2}{M_R} = \frac{1}{2}\frac{y_\nu^2 < H >^2}{M_R}$$



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

中微子质量被压低!

第二类跷跷板机制

$$H(2,1/2), \boxed{\Delta(3,1)}, \; L(2,-1/2) \qquad H = \begin{pmatrix} h^+ \\ h \end{pmatrix}, \quad \Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}$$

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

$$\Big\downarrow$$

$$\frac{1}{2} y_{ij} \Delta^0 \bar{\nu}^c \nu + h.c.$$

- **Giving neutrino mass matrix with vev of Delta**
- **Delta get a lepton number -2**

第二类跷跷板机制

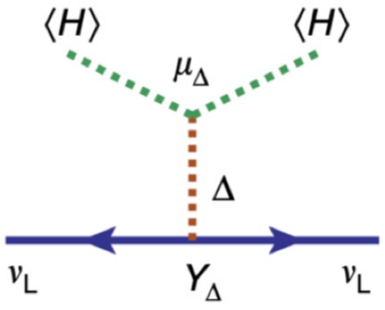
$$
\begin{aligned}
V(H,\Delta) \;=\; & -m_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 + m_\Delta^2 \mathrm{Tr}(\Delta^\dagger \Delta) + \lambda_1 (H^\dagger H)\mathrm{Tr}(\Delta^\dagger \Delta) \\
& + \lambda_2 (\mathrm{Tr}(\Delta^\dagger \Delta))^2 + \lambda_3 \mathrm{Tr}(\Delta^\dagger \Delta)^2 + \lambda_4 H^\dagger \Delta \Delta^\dagger H \\
& \boxed{+ \left[\mu (H^T i\sigma^2 \Delta^\dagger H) + h.c.\right] + \ldots}
\end{aligned}
$$

U(1)L breaking term

$$\langle \Delta^0 \rangle \simeq \frac{\mu v_{\mathrm{EW}}^2}{2 m_\Delta^2}$$

EW precision measurement

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



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

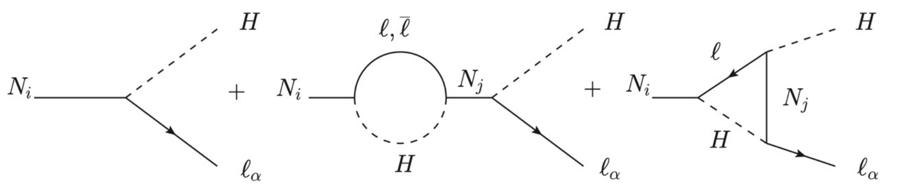
required by neutrino masses

轻子生成机制

Leptogenesis in Type I seesaw

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

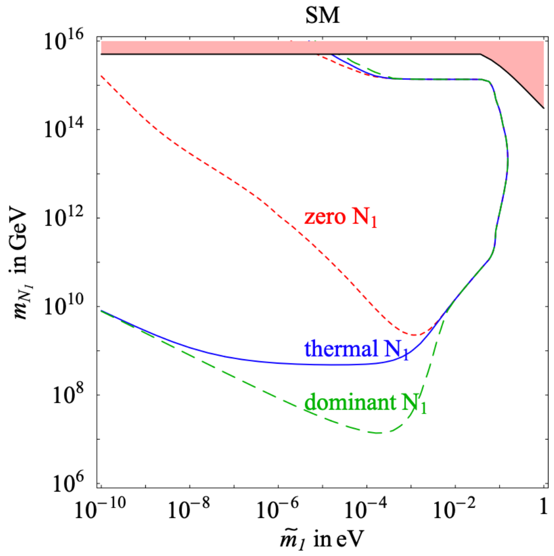
$$\mathcal{L}_I = \mathcal{L}_{SM} + i\overline{N_{R_i}}\partial\!\!\!/ N_{R_i} - \left(\frac{1}{2}M_i\overline{N^c_{R_i}}N_{R_i} + \epsilon_{ab}Y_{\alpha i}\overline{N_{R_i}}\ell^a_\alpha H^b + h.c.\right)$$



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

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

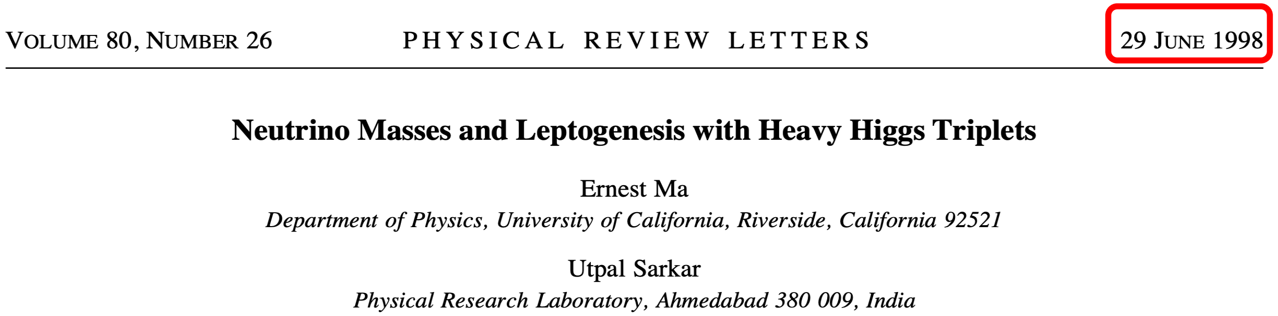
G.F. Giudice, et al,
Nucl.Phys.B 685 (2004) 89-149



一般要求右手中微子质量超过10^7GeV　　Type III seesaw情形与Type I 类似

轻子生成机制

Leptogenesis in Type II seesaw ?


VOLUME 80, NUMBER 26 PHYSICAL REVIEW LETTERS 29 JUNE 1998

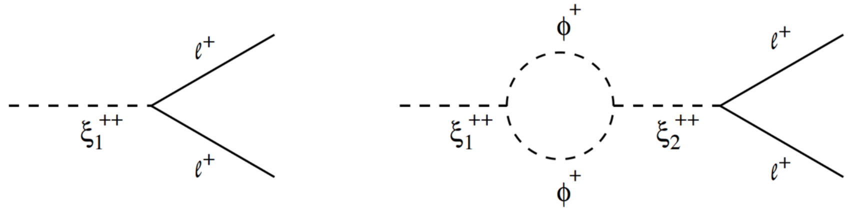
Neutrino Masses and Leptogenesis with Heavy Higgs Triplets

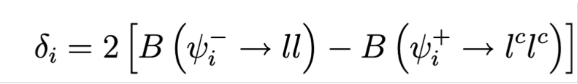
Ernest Ma
Department of Physics, University of California, Riverside, California 92521

Utpal Sarkar
Physical Research Laboratory, Ahmedabad 380 009, India

500+ citations

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

Affleck-Dine 机制

Assuming phi is a complex scalar with B charge

$$V(\phi) = \frac{1}{2}m^2|\phi|^2 + \underbrace{[c_{n,m}\phi^n(\phi^*)^m + h.c]}_{\downarrow} \quad m \neq n$$

(B/L violation)

$$j_B^\mu = i(\phi^*\partial^\mu\phi - \phi\partial^\mu\phi^*)$$

ϕ is spatially constant

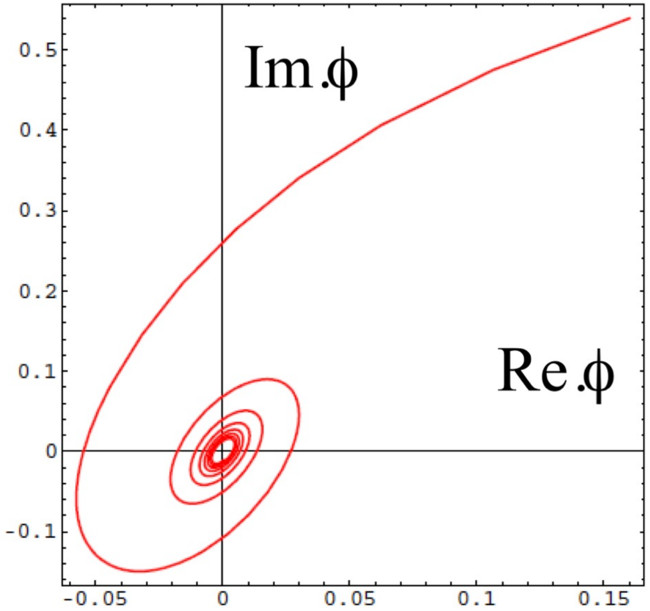
$$n_B = i(\phi^*\dot{\phi} - \phi\dot{\phi}^*) = \rho^2\dot{\theta} \qquad \phi = \frac{1}{\sqrt{2}}\rho_\phi e^{i\theta}$$

$$\dot{n}_B + 3Hn_B = \mathrm{Im}\left(\phi\frac{\partial V}{\partial\phi}\right)$$

Only from U(1) breaking term

A motion of theta will generate baryon number

Affleck-Dine 机制



- **Scalar particle taking B/L charge**
- **Small B/L violation term in the potential(charge neutral)**
- **Scalar particle with initial displaced vacuum**

Affleck-Dine 机制

- **Scalar**
- **Taking baryon(lepton) charge**
- **Charge neutral, otherwise no breaking team**

First two conditions seem easy

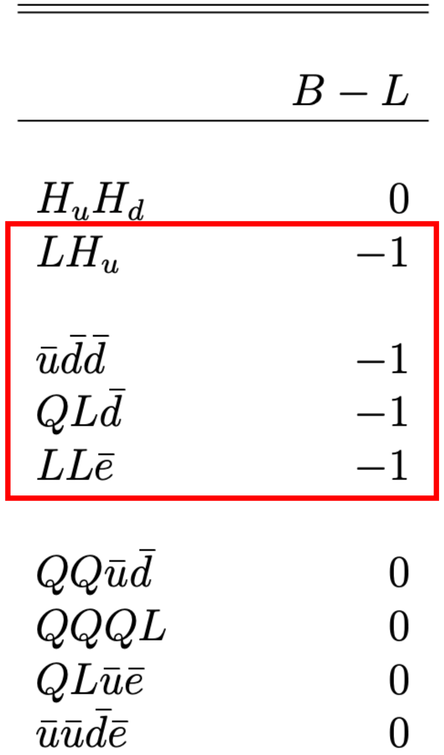
- **Leptoquarks** $y\phi\overline{u_R^c}e_R$
  - color triplet, charge 1/3
- **Diquarks** $y\phi\overline{u_R^c}d_R$
  - charge -1/3
- **Double charged scalar** $y\phi^{++}\overline{e_R^c}e_R$
  - charge 2

None of above works!

Affleck-Dine 机制

超对称中有很多例子

- **Many scalars take B/L charge**
- **Flat directions(quartic coupling vanish, no charge)**



	$B-L$
H_uH_d	0
LH_u	-1
$\bar{u}\bar{d}\bar{d}$	-1
$QL\bar{d}$	-1
$LL\bar{e}$	-1
$QQ\bar{u}\bar{d}$	0
$QQQL$	0
$QL\bar{u}\bar{e}$	0
$\bar{u}\bar{u}\bar{d}\bar{e}$	0

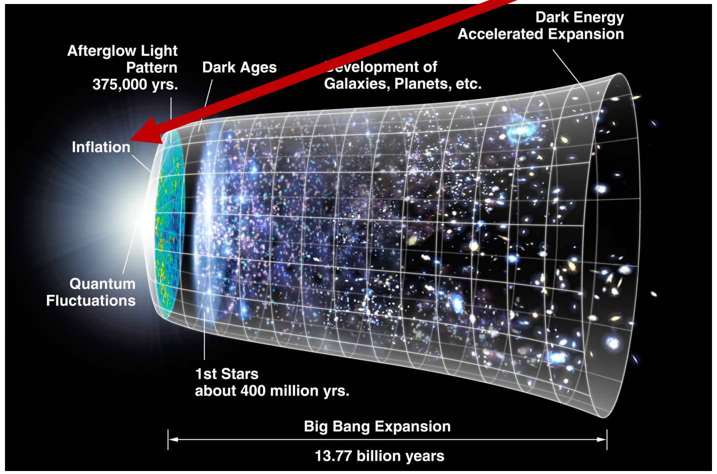
$$H_u = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ \phi \end{pmatrix}, \quad L = \frac{1}{\sqrt{2}}\begin{pmatrix} \phi \\ 0 \end{pmatrix}$$

$$V = m^2|\phi|^2 + \left[\frac{A}{M^{n-3}}\phi^n + h.c\right]$$

Affleck-Dine 机制

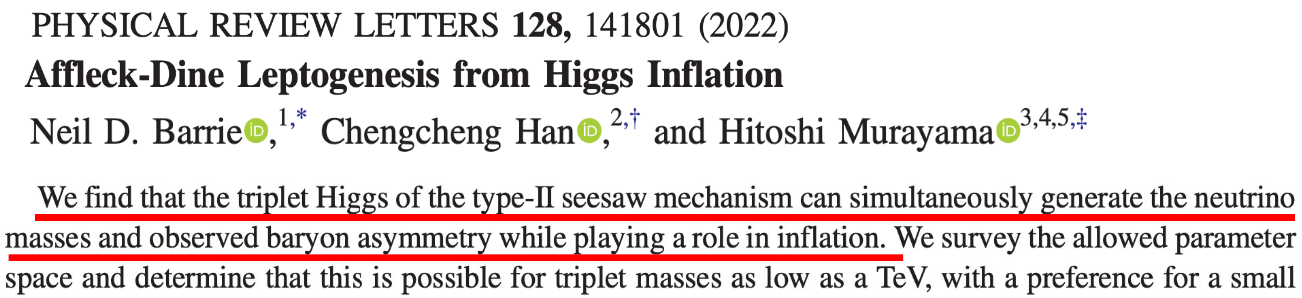
	Type II seesaw
● Scalar particle taking B/L charge	✓
● Small B/L violation term in the potential(charge neutral)	✓
● Scalar particle with initial displaced vacuum	?

If the scalar plays the role of inflaton



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(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)

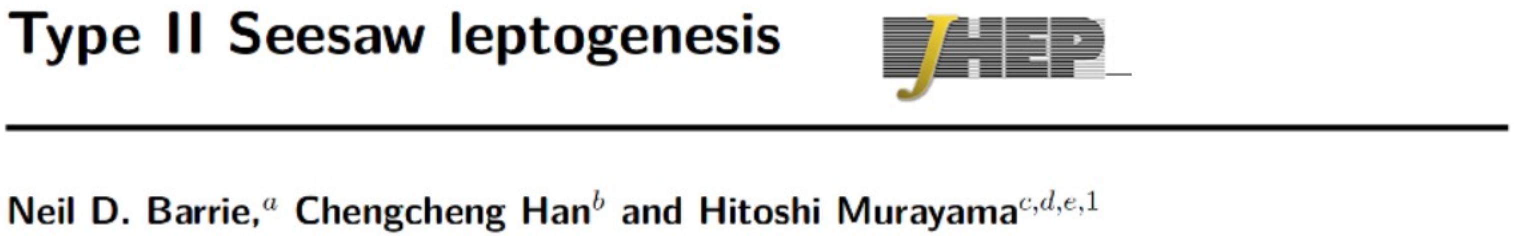


PHYSICAL REVIEW LETTERS **128,** 141801 (2022)

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

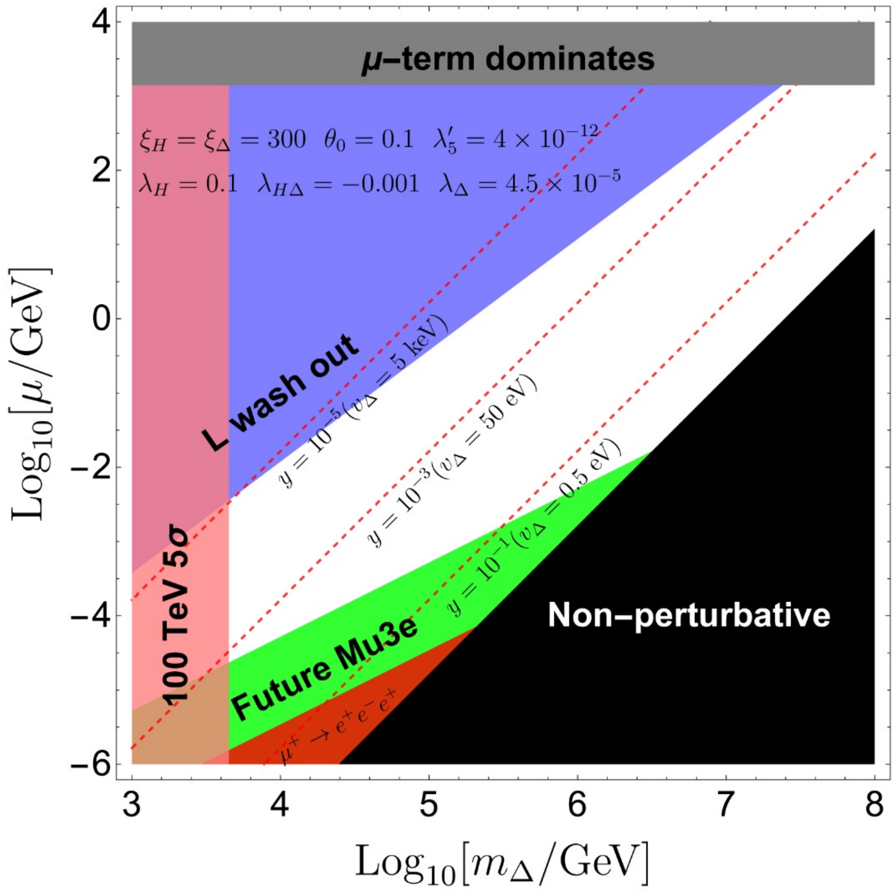


Type II Seesaw leptogenesis

JHEP

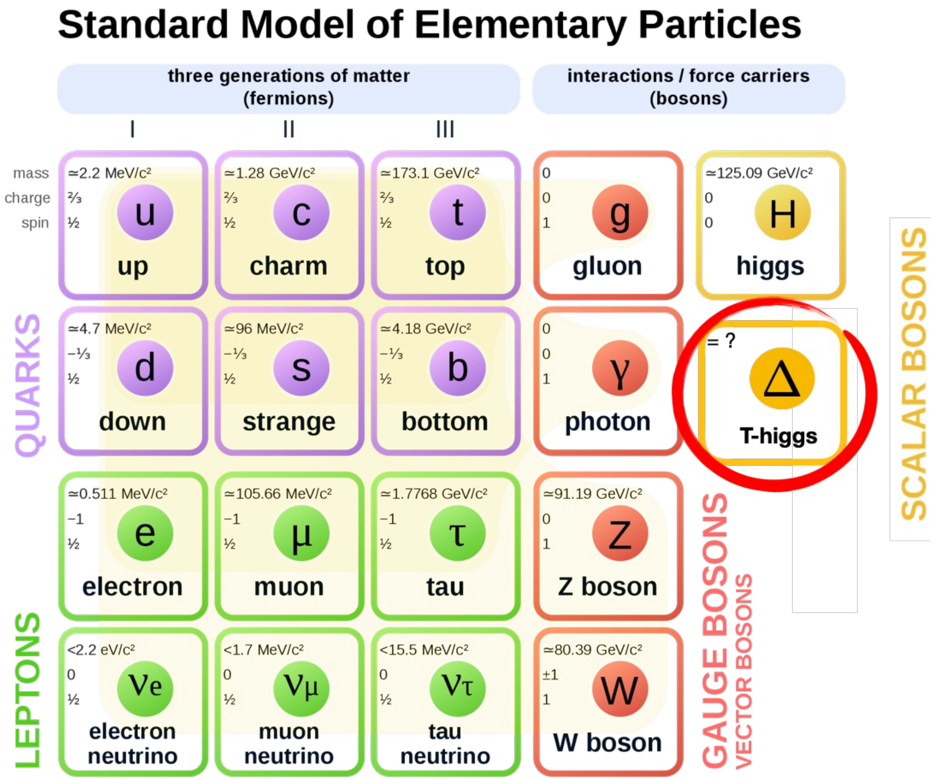
Neil D. Barrie,[a] Chengcheng Han[b] and Hitoshi Murayama[c,d,e,1]

Type II seesaw leptogenesis

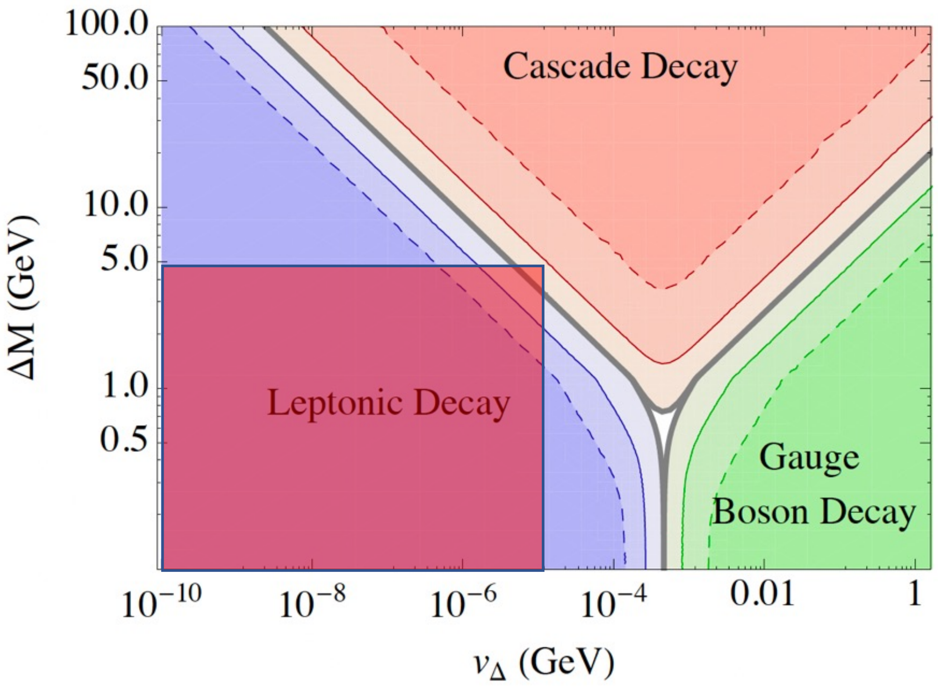


- 三重态质量可以轻至 TeV，适合对撞机探测
- 轻子味改变的耦合 y > 10-5, 轻子味改变信号
- 真空期望值 < 10 keV（对比传统type II seesaw < 1 GeV）
- 中微子为Majorana粒子

对撞机寻找



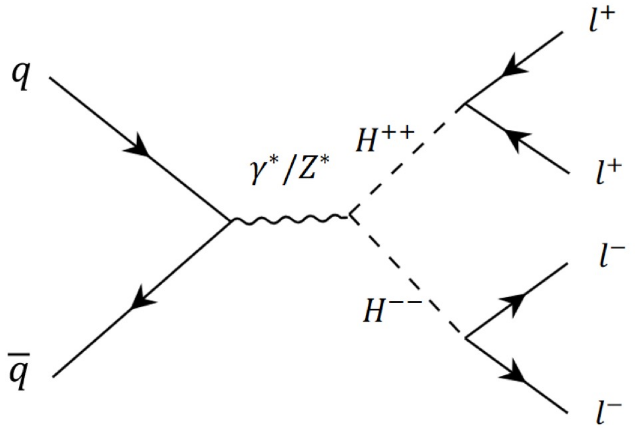
Decay of the triplet Higgs



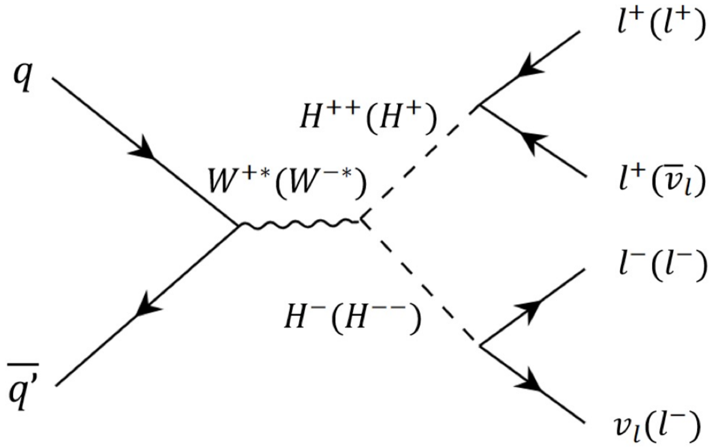
模型预言希格斯三重态主要轻子道衰变

希格斯三重态质量可以低至TeV, 可以通过对撞机进行验证

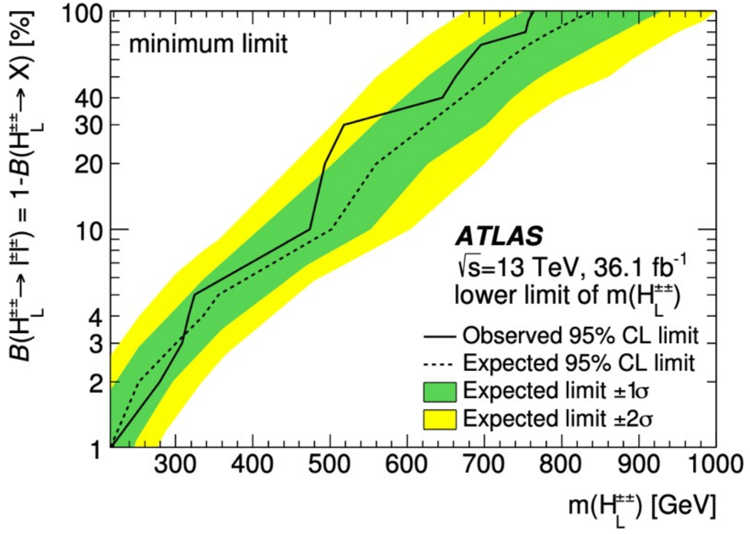
对撞机寻找



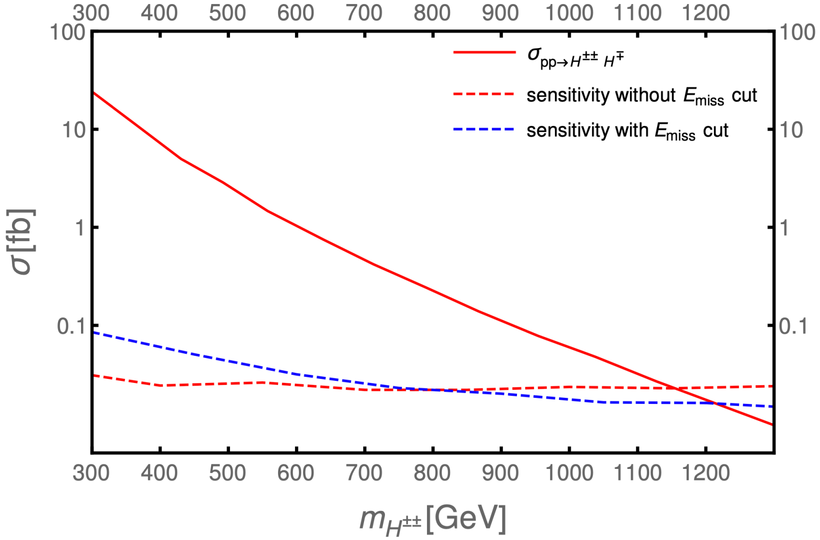
CCH, Z. Lei, W. Liao, hep-ph>arXiv:2303.15709



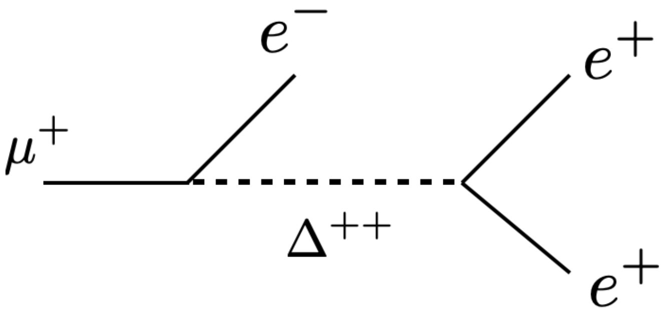
ATLAS, Eur. Phys. J. C 78 (2018) 199

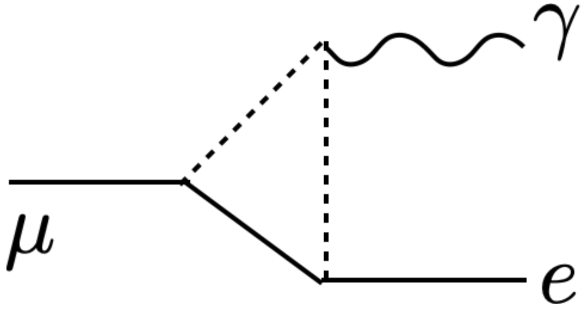


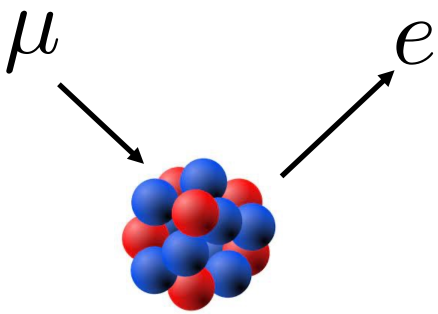
3l+missing energy



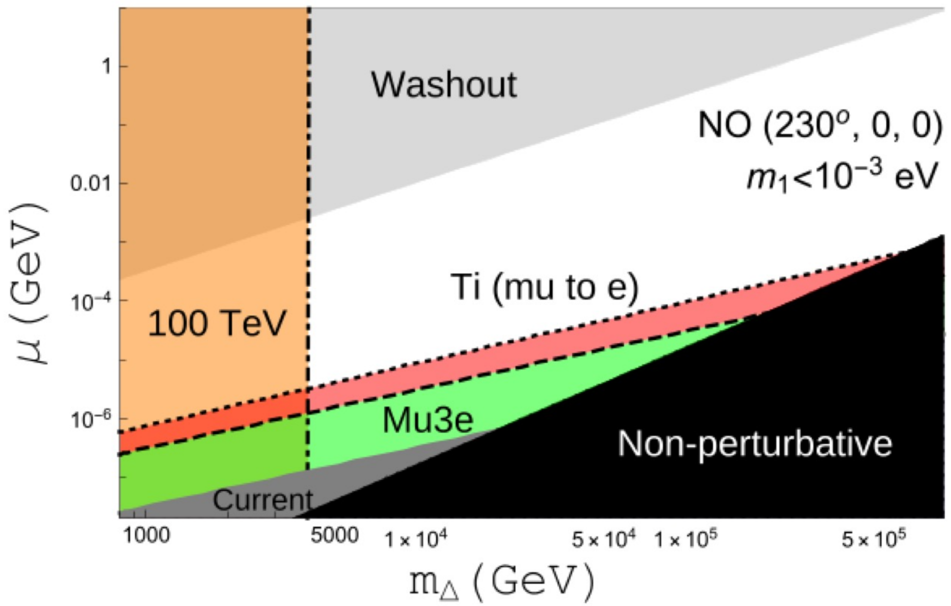
轻子味破坏过程







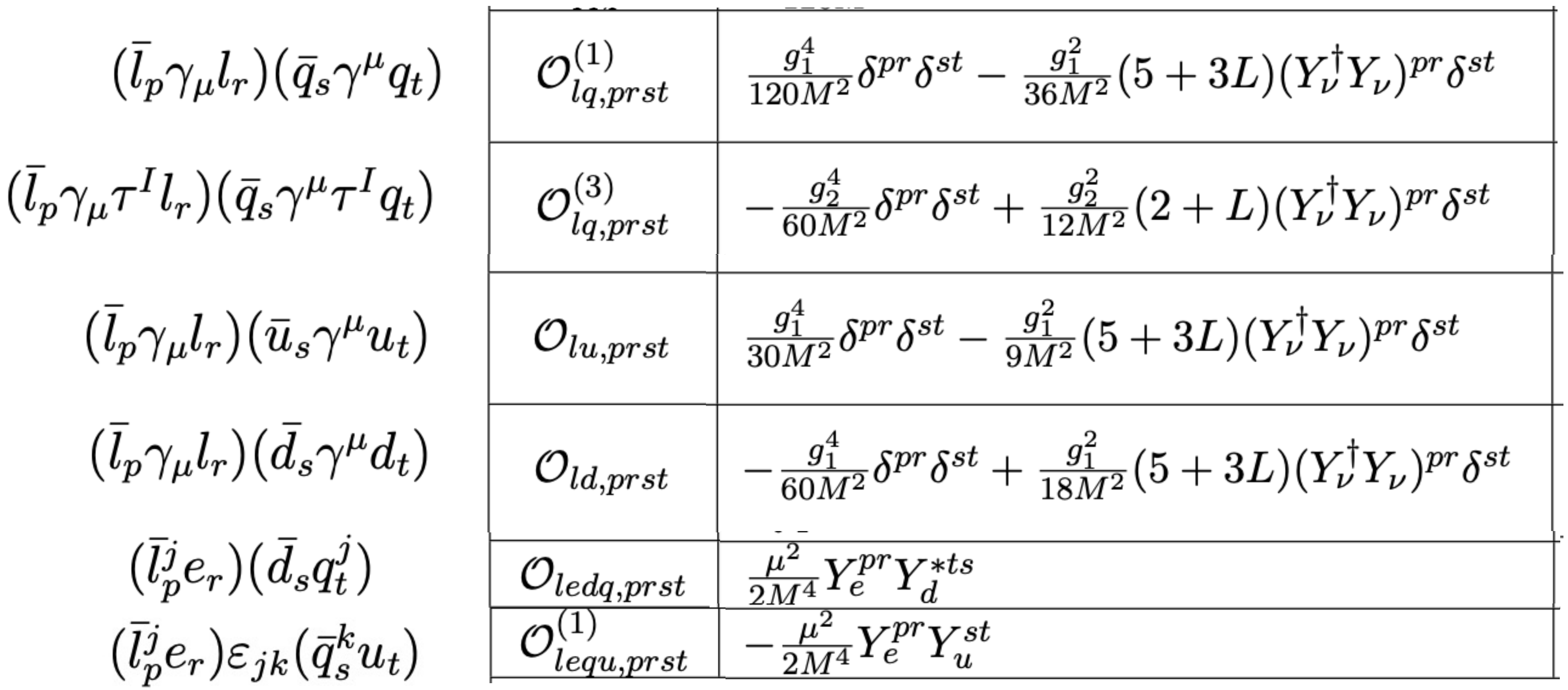
N.D. Barrie, S.T. Petcov, JHEP 01 (2023) 001



LFV operators from type II seesaw

LFV operators between quark and lepton, potential target at BESIII

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



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

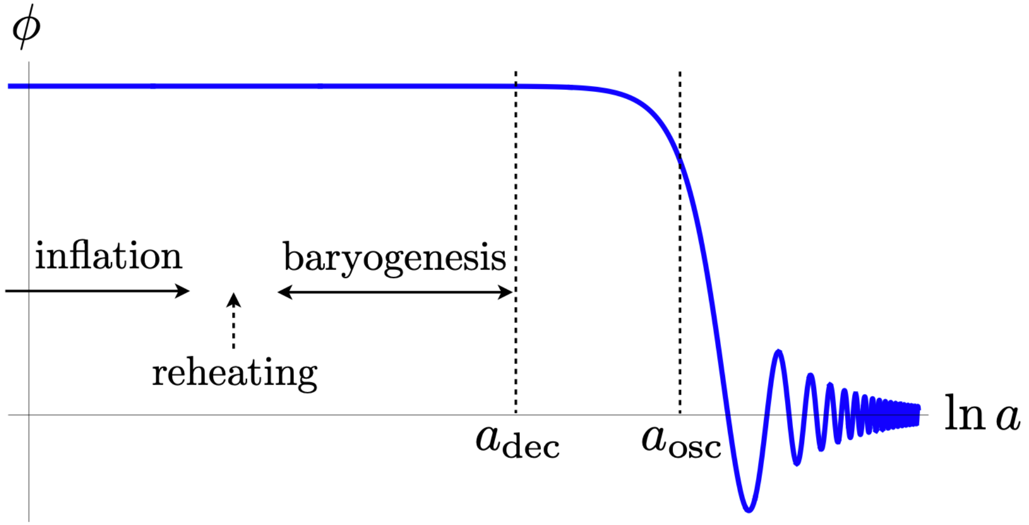
Inducing meson LFV decays, for example J/psi -> l_i l_j

Spontaneous baryogenesis

A. G. Cohen and D. B. Kaplan, Phys. Lett. B 199, 251 (1987)

$$S = \int d^4x\sqrt{-g}\left\{-\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi) - \sum_i c_i\frac{\partial_\mu\phi}{f}j_i^\mu + \cdots\right\}$$

- **phi在暴胀期间获得很大真空期望值**
- **phi跟重子流耦合,运动时提供化学势** $\mu_i = c_i\frac{\dot{\phi}}{f}$
- **存在重子数破坏过程**
- **重子数破坏过程退耦**



根据phi起源的不同，各种变种：Axiogenesis, Majoron-genesis, Lepto-axiogenesis

Keisuke Harigaya, Wei Chao, Eung Jin Chun...

Majoron-genesis

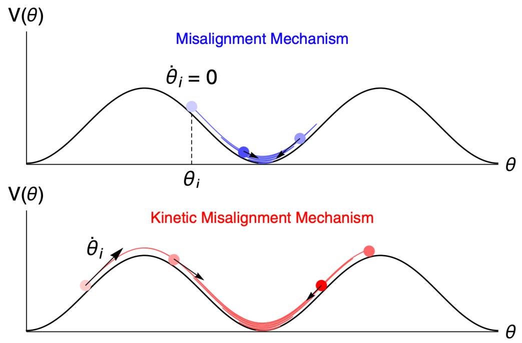
Global U(1)B-L model

Eung Jin Chun, Tae Hyun Jung, 2311.09005
Patrick Barnes, Raymond T. Co, Keisuke Harigaya, Aaron Pierce, 2402.10263

$$-\mathcal{L}_{\rm int} = \frac{1}{2}\sum_{I} y_{N_I}\Phi \bar{N}_I^c N_I + \sum_{\alpha,\, I} Y_{N,\alpha I}\bar{l}_\alpha \tilde{H} N_I + h.c.,$$

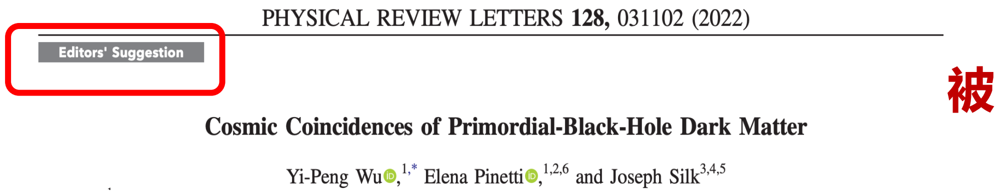
$$\Phi \to \frac{f_J}{\sqrt{2}} e^{iJ/f_J}$$

- **Lepton number wash out process + sphaleron process**
- **When T< 100 GeV, baryon number fixed**
- **Some problem with majoron life time too long**
- **Need kinetic misalignment**



重子不对称性与原初黑洞

鲁伯宇宙学奖得主J. Silk等在2022年提出一个非常具有吸引力的想法


PHYSICAL REVIEW LETTERS **128,** 031102 (2022)

Editors' Suggestion

Cosmic Coincidences of Primordial-Black-Hole Dark Matter

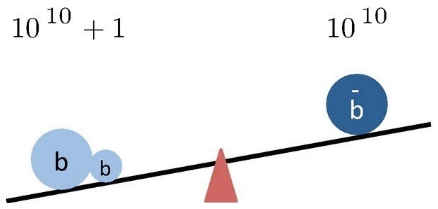
Yi-Peng Wu,[1,*] Elena Pinetti,[1,2,6] and Joseph Silk[3,4,5]

被PRL Editor 推荐发表

如果宇宙早期经历超慢滚暴胀

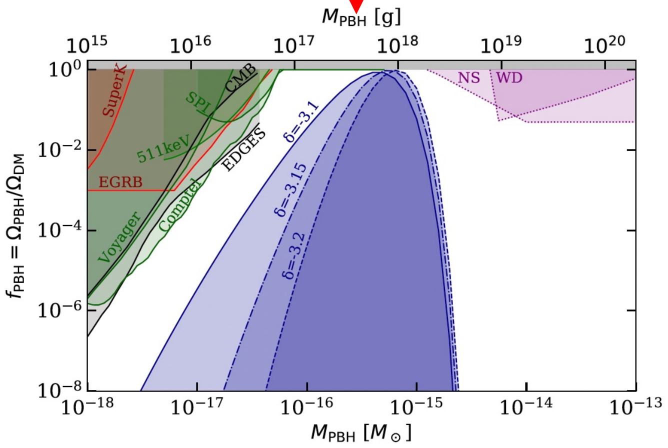
诱导标量场产生非零真空期望值

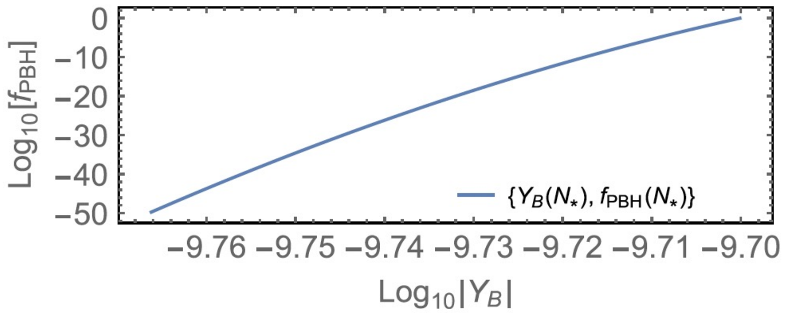
如果带重子数，产生重子不对称性



产生原初黑洞

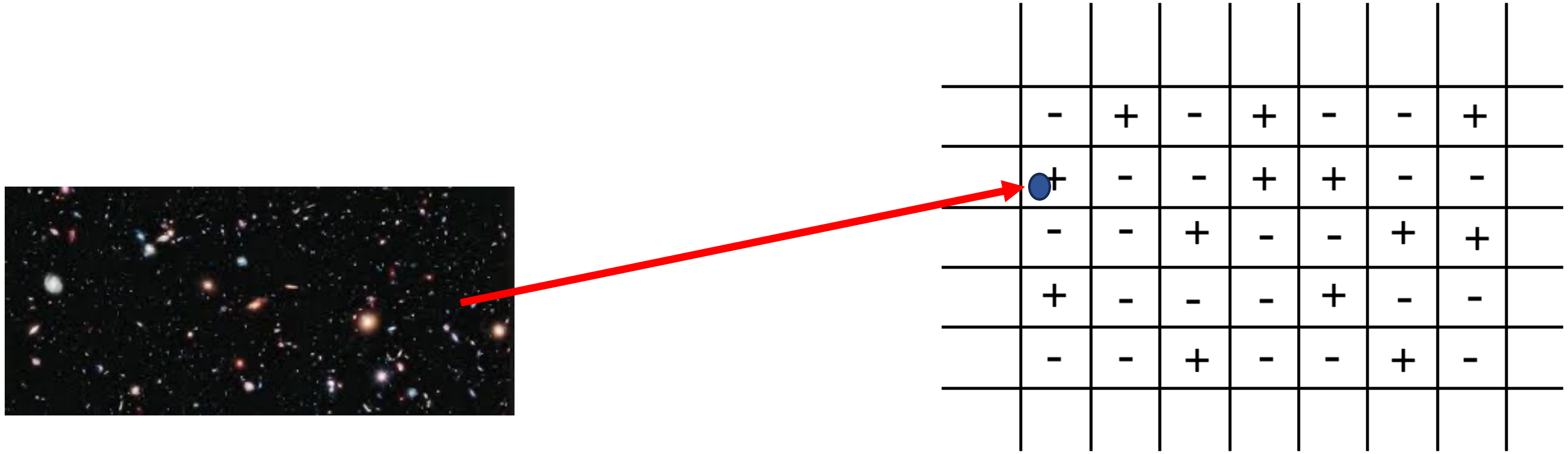
解释暗物质





重子不对称性与原初黑洞

由于诱导出的标量场真空期望值相位随机 → 整个宇宙分为正、反物质部分，整体平均重子数为零



-	+	-	+	-	-	+
+	-	-	+	+	-	-
-	-	+	-	-	+	+
+	-	-	-	+	-	-
-	-	+	-	-	+	-

如果我们的可观测宇宙只是正物质区域的一部分，则理论是自恰的

正反物质对称的宇宙

核心问题是这个区域到底多大(关联长度)?

重子不对称性与原初黑洞

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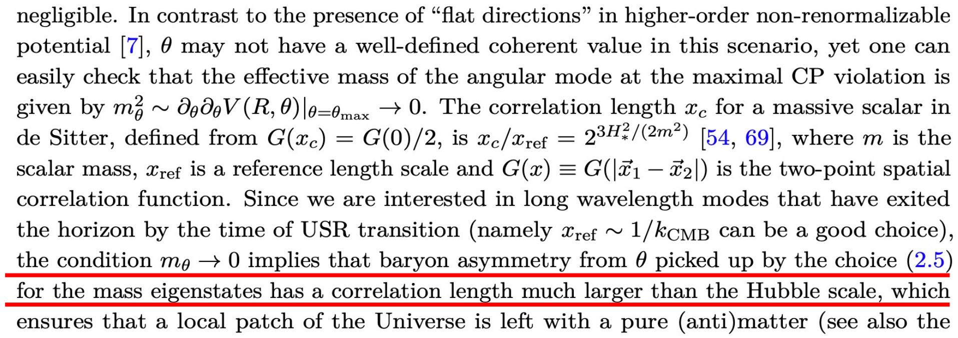
Baryogenesis from ultra-slow-roll inflation

Yi-Peng Wu,[a] **Elena Pinetti,**[a,b,c] **Kalliopi Petraki**[a,d] **and Joseph Silk**[e,f,g]

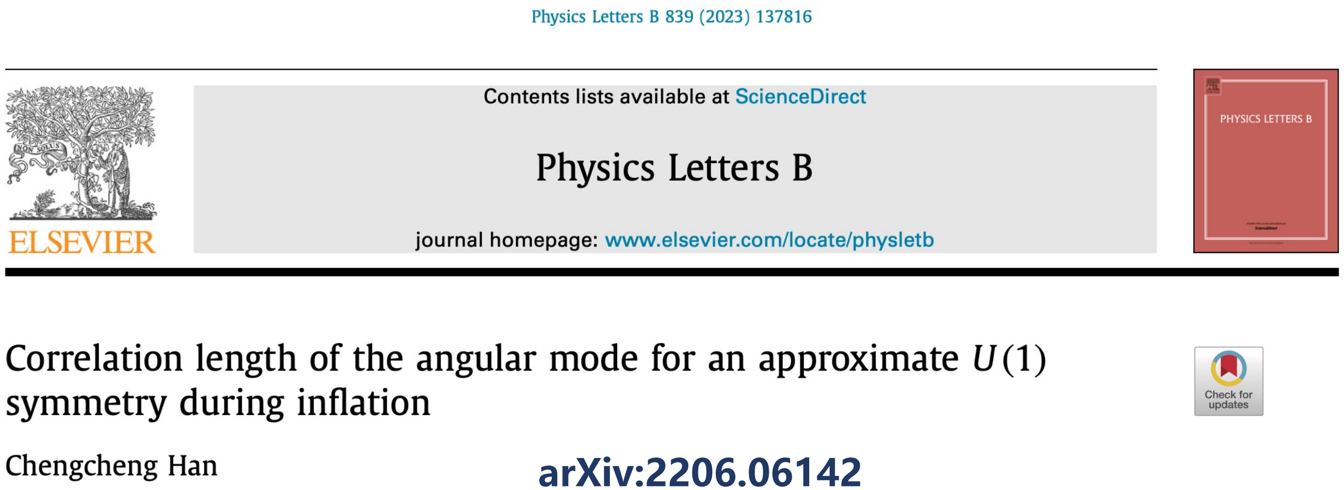
他们的长文中给了一个解释：如果相互作用是近似U(1)对称性，区域大小远比我们的可观测宇宙大



negligible. In contrast to the presence of "flat directions" in higher-order non-renormalizable potential [7], θ may not have a well-defined coherent value in this scenario, yet one can easily check that the effective mass of the angular mode at the maximal CP violation is given by $m_\theta^2 \sim \partial_\theta \partial_\theta V(R,\theta)|_{\theta=\theta_{\max}} \to 0$. The correlation length x_c for a massive scalar in de Sitter, defined from $G(x_c) = G(0)/2$, is $x_c/x_{\rm ref} = 2^{3H_*^2/(2m^2)}$ [54, 69], where m is the scalar mass, $x_{\rm ref}$ is a reference length scale and $G(x) \equiv G(|\vec{x}_1 - \vec{x}_2|)$ is the two-point spatial correlation function. Since we are interested in long wavelength modes that have exited the horizon by the time of USR transition (namely $x_{\rm ref} \sim 1/k_{\rm CMB}$ can be a good choice), the condition $m_\theta \to 0$ implies that baryon asymmetry from θ picked up by the choice (2.5) for the mass eigenstates has a correlation length much larger than the Hubble scale, which ensures that a local patch of the Universe is left with a pure (anti)matter (see also the

关联长度： $R_c \sim H^{-1} \exp(H^2/m^2)$

重子不对称性与原初黑洞



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ELSEVIER

Correlation length of the angular mode for an approximate $U(1)$ symmetry during inflation

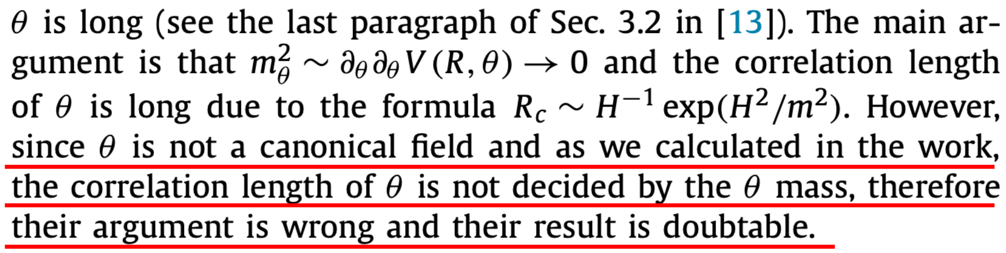
Chengcheng Han

arXiv:2206.06142

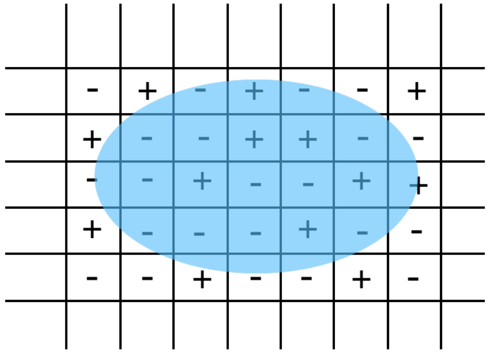
但是theta不是正则的场，不能直接使用公式 $R_c \sim H^{-1}\exp(H^2/m^2)$

完整的计算需要解随机过程中的Fokker-Planck方程

$$\frac{\partial\rho(\varphi,t)}{\partial t}=\frac{1}{3H}\left[\rho(\varphi,t)\nabla^2V(\varphi)+\nabla V(\varphi)\cdot\nabla\rho(\varphi,t)\right]+\frac{H^3}{8\pi^2}\nabla^2\rho(\varphi,t)$$



θ is long (see the last paragraph of Sec. 3.2 in [13]). The main argument is that $m_\theta^2 \sim \partial_\theta\partial_\theta V(R,\theta) \to 0$ and the correlation length of θ is long due to the formula $R_c \sim H^{-1}\exp(H^2/m^2)$. However, since θ is not a canonical field and as we calculated in the work, the correlation length of θ is not decided by the θ mass, therefore their argument is wrong and their result is doubtable.

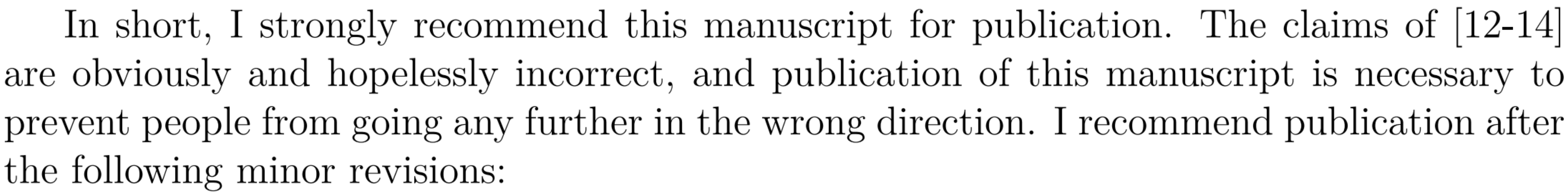


-	+	-	+	-	-	+
+	-	-	+	+	-	-
-	-	+	-	-	+	+
+	-	-	-	+	-	-
-	-	+	-	-	+	-

我们的宇宙是由~e^{100}个这样的区域组成，平均重子数密度几乎为零，因此他们结论是值得怀疑的

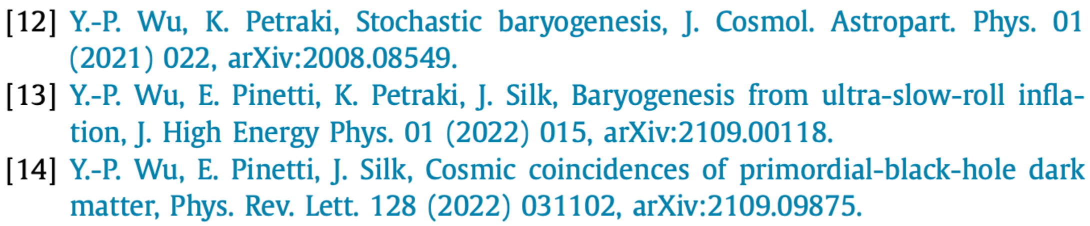
重子不对称性与原初黑洞

Referee意见



In short, I strongly recommend this manuscript for publication. The claims of [12-14] are obviously and hopelessly incorrect, and publication of this manuscript is necessary to prevent people from going any further in the wrong direction. I recommend publication after the following minor revisions:

“我强烈建议此文章发表，文献[12-14]是明显错误和无希望的，这篇文章的发表可以阻止大家在错误的方向上走的更远”



[12] Y.-P. Wu, K. Petraki, Stochastic baryogenesis, J. Cosmol. Astropart. Phys. 01 (2021) 022, arXiv:2008.08549.
[13] Y.-P. Wu, E. Pinetti, K. Petraki, J. Silk, Baryogenesis from ultra-slow-roll inflation, J. High Energy Phys. 01 (2022) 015, arXiv:2109.00118.
[14] Y.-P. Wu, E. Pinetti, J. Silk, Cosmic coincidences of primordial-black-hole dark matter, Phys. Rev. Lett. 128 (2022) 031102, arXiv:2109.09875.

Summary

- 重子不对称性仍然是粒子物理和宇宙学面临的重要问题之一
- 轻子生成机制在解释重子不对称起源问题上是非常有吸引力的
- 各类重子生成机制的实验检验需要进一步探索

THANK YOU

第二类跷跷板机制

$$H(2,1/2),\ \boxed{\Delta(3,1)},\ L(2,-1/2) \qquad H=\begin{pmatrix} h^+ \\ h \end{pmatrix},\quad \Delta=\begin{pmatrix}\Delta^+/\sqrt{2} & \Delta^{++}\\ \Delta^0 & -\Delta^+/\sqrt{2}\end{pmatrix}$$

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

$$\Big\downarrow$$

$$\frac{1}{2}y_{ij}\Delta^0\bar{\nu}^c\nu+h.c.$$

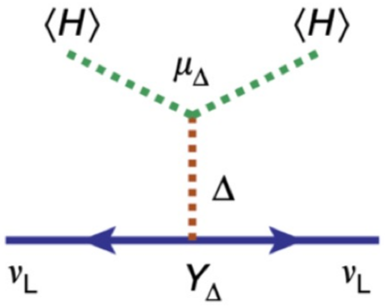
- **Giving neutrino mass matrix with vev of Delta**
- **Delta get a lepton number -2**

第二类跷跷板机制

$$\begin{aligned} V(H,\Delta) \quad = \quad & -m_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 + m_\Delta^2 \mathrm{Tr}(\Delta^\dagger \Delta) + \lambda_1 (H^\dagger H)\mathrm{Tr}(\Delta^\dagger \Delta) \\ & +\lambda_2 (\mathrm{Tr}(\Delta^\dagger \Delta))^2 + \lambda_3 \mathrm{Tr}(\Delta^\dagger \Delta)^2 + \lambda_4 H^\dagger \Delta \Delta^\dagger H \\ & \boxed{+ \left[\mu (H^T i\sigma^2 \Delta^\dagger H) + h.c.\right] + \ldots} \end{aligned}$$

U(1)L breaking term

$$\langle \Delta^0 \rangle \simeq \frac{\mu v_{\mathrm{EW}}^2}{2 m_\Delta^2}$$



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

EW precision measurement

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

required by neutrino masses

标准模型重子数破坏过程

重子数破坏过程对化学势的影响 $P = \{L, E, Q, U, D, H\}$

$$\begin{cases} ELH \text{ Yukawa}: & 0 = \mu_E + \mu_L + \mu_H \\ DQH \text{ Yukawa}: & 0 = \mu_D + \mu_Q + \mu_H \\ UQ\bar{H} \text{ Yukawa}: & 0 = \mu_U + \mu_Q - \mu_H \\ QQQL \text{ sphalerons}: & 0 = 3\mu_Q + \mu_L \\ \text{No electric charge}: & 0 = N_{\text{gen}}(\mu_Q - 2\mu_U + \mu_D - \mu_L + \mu_E) - 2N_{\text{Higgs}}\mu_H \end{cases}$$

$$\begin{aligned} \mathcal{B} &= N_{\text{gen}}(2\mu_Q - \mu_U - \mu_D) = \frac{28}{79}(\mathcal{B} - \mathcal{L})_0 \\ \mathcal{L} &= \mathcal{B} - (\mathcal{B} - \mathcal{L}) = -\frac{51}{79}(\mathcal{B} - \mathcal{L})_0 \end{aligned}$$

- 假设sphaleron过程是有效的(T> 100 GeV)
- 宇宙初期B=0, L=0, 因此B需要在某个特定过程中产生
- 如果产生的B=L, 最终产生的重子不对称性将会是零(除非关闭sphaleron过程)
- Sphaleron过程不破坏B-L, 一旦产生反轻子数就会转化为重子数（轻子生成机制）