CP violation and Baryon asymmetry

从重味CP破坏到两类seesaw轻子生成机制

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中山大学

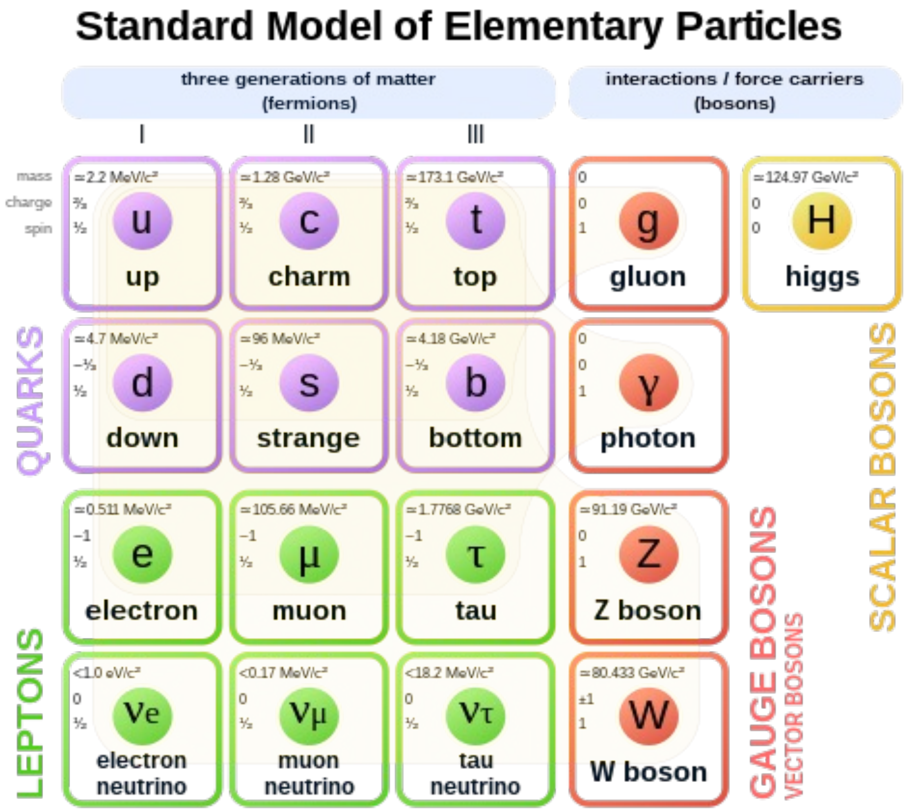
第八届全国重味物理与量子色动力学研讨会

重庆

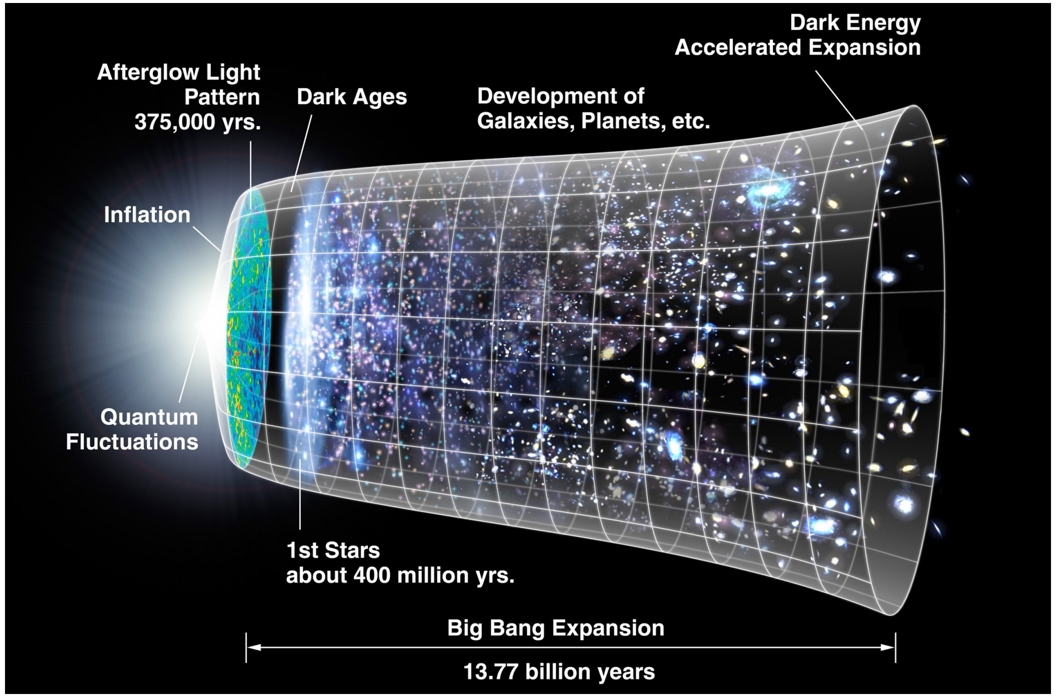
2026.4.26

研究背景

粒子物理标准模型/宇宙学标准模型



ΛCDM+Inflation

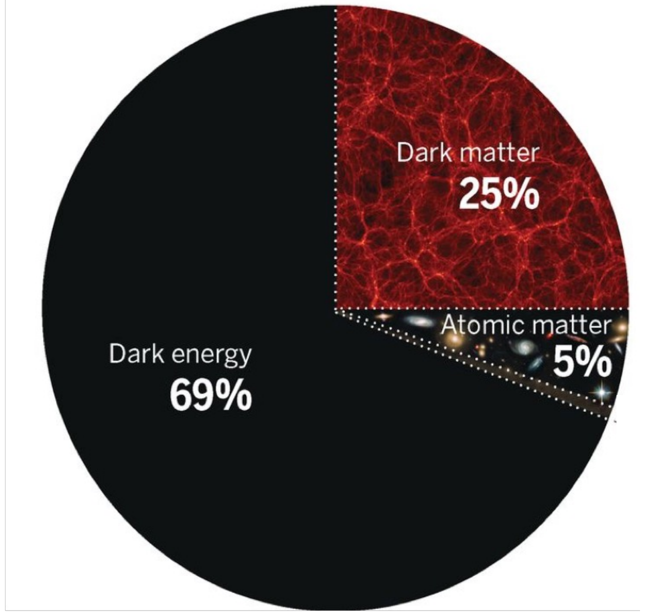


物质的基本组成及其相互作用

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！

如何产生重子不对称性?

如果宇宙创生初期就有这个不对称性，这个不对称性会在暴胀时期抹平掉(宇宙膨胀了至少e^{60})

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!

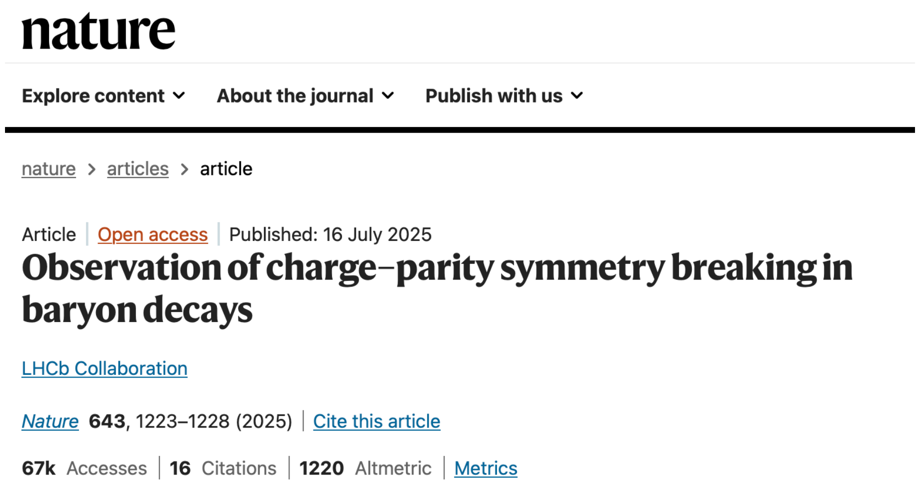
本报告涉及的重子产生机制与检验

- 重味CP破坏与B-mesogenesis　　低能窗口
- Type-I seesaw：高标度轻子生成机制的宇宙学检验　　高标度途径
- Type-II seesaw：低标度可检验的轻子生成机制　　低标度途径

重味CP破坏与B-mesogenesis

Heavy-flavor probes of baryogenesis

CP violation in baryon decay



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Observation of charge–parity symmetry breaking in baryon decays

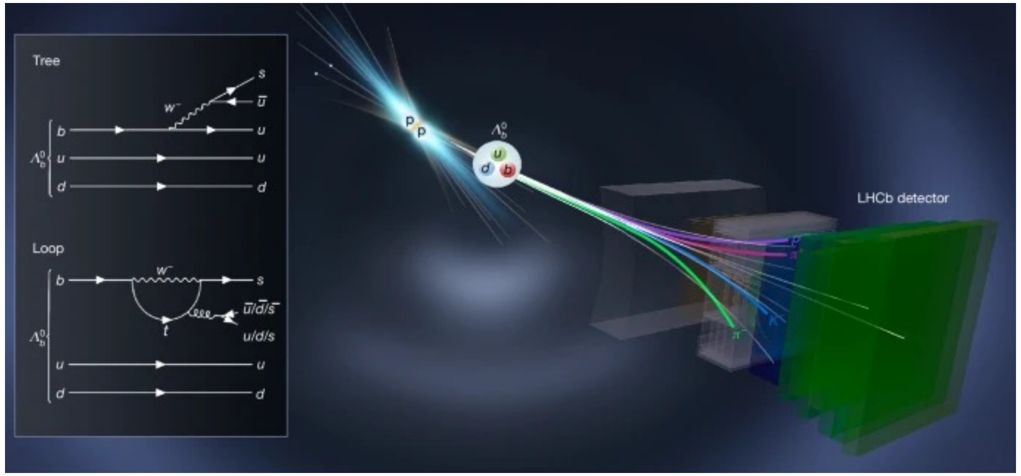
LHCb Collaboration

Nature **643**, 1223–1228 (2025) | Cite this article

67k Accesses | **16** Citations | **1220** Altmetric | Metrics

$$\mathcal{A}_{\mathrm{CP}} \equiv \frac{\Gamma(\Lambda_b^0 \to pK^-\pi^+\pi^-) - \Gamma(\overline{\Lambda}_b^0 \to \overline{p}K^+\pi^-\pi^+)}{\Gamma(\Lambda_b^0 \to pK^-\pi^+\pi^-) + \Gamma(\overline{\Lambda}_b^0 \to \overline{p}K^+\pi^-\pi^+)}$$

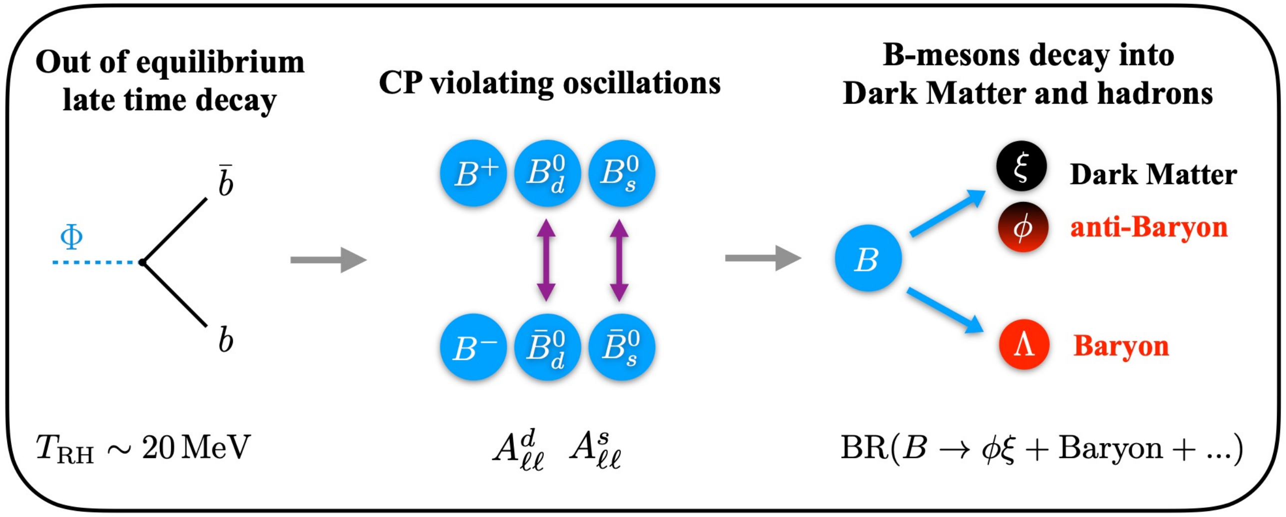
$$\mathcal{A}_{\mathrm{CP}} = (2.45 \pm 0.46 \pm 0.10)\%$$



- CP破坏不只存在于介子系统，也可出现在重子衰变
- 它验证了Sakharov条件中的CP破坏要素
- 结果与CKM一致，加强了标准模型CP破坏不足以解释重子不对称的结论

B-mesogenesis

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



$T_{\mathrm{RH}} \sim 20\,\mathrm{MeV}$ $A^d_{\ell\ell}$ $A^s_{\ell\ell}$ $\mathrm{BR}(B \to \phi\xi + \mathrm{Baryon} + ...)$

$\Rightarrow$

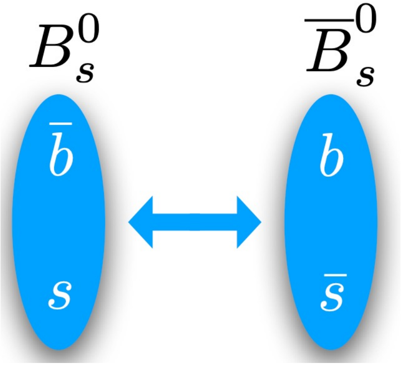
Baryogenesis

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

&

Dark Matter

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



- A long-lived particle decays and produce B-mesons and anti-mesons out of equilibrium
- CP violation from $B^0 - \bar{B}^0$ oscillations generates a matter-antimatter asymmetry
- B meson (5.3 GeV) decays into baryon + anti-baryon(dark matter)+ dark matter
- Yields net excess of baryons in the visible sector and excess anti-baryons in the dark sector
- Baryon number in the whole universe is conserved

B-mesogenesis

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

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

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

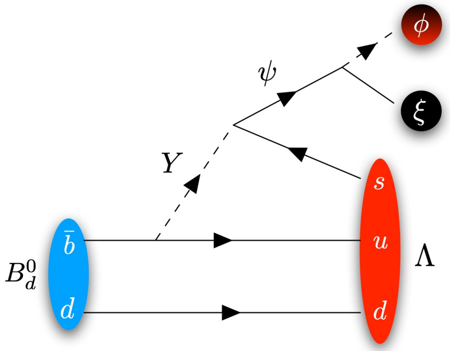
SM prediction:

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

EXP:

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

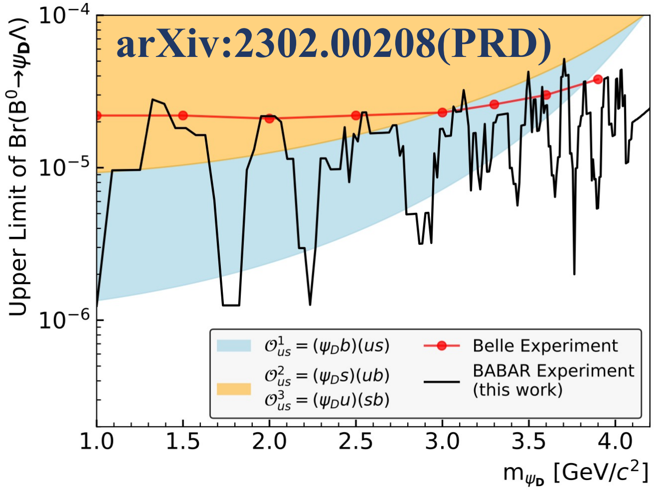
- **SM CKM is enough to provide the CP violation，but**
- **B meson decay into baryon+invisible (BaBar，Belle，LHCb)**
- **Measurement of the CP violation of B meson is important**

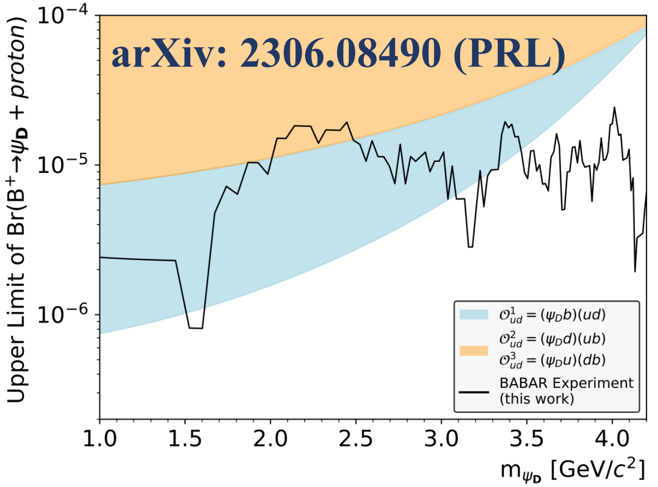


B-mesogenesis

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



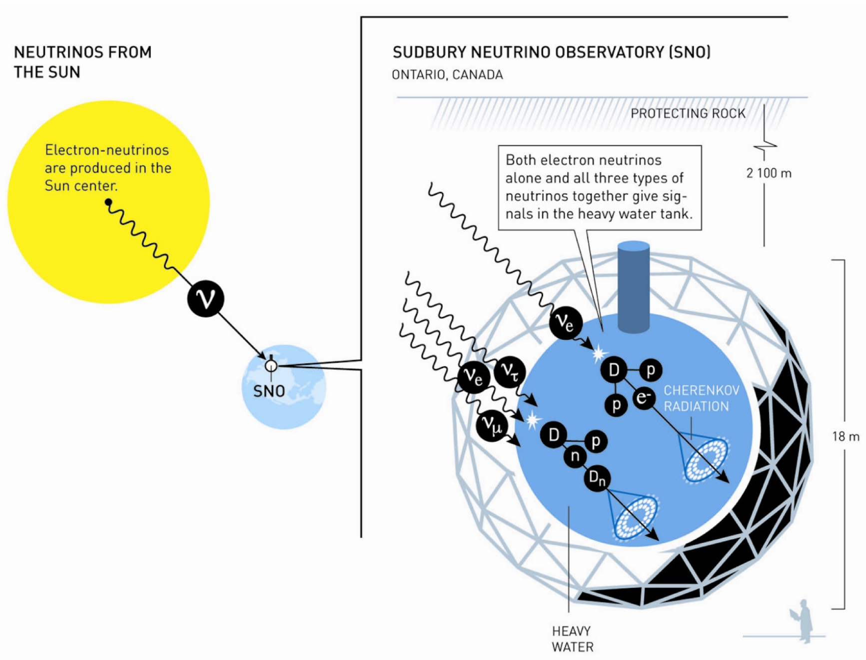


Type-I seesaw：高标度轻子生成机制的宇宙学检验

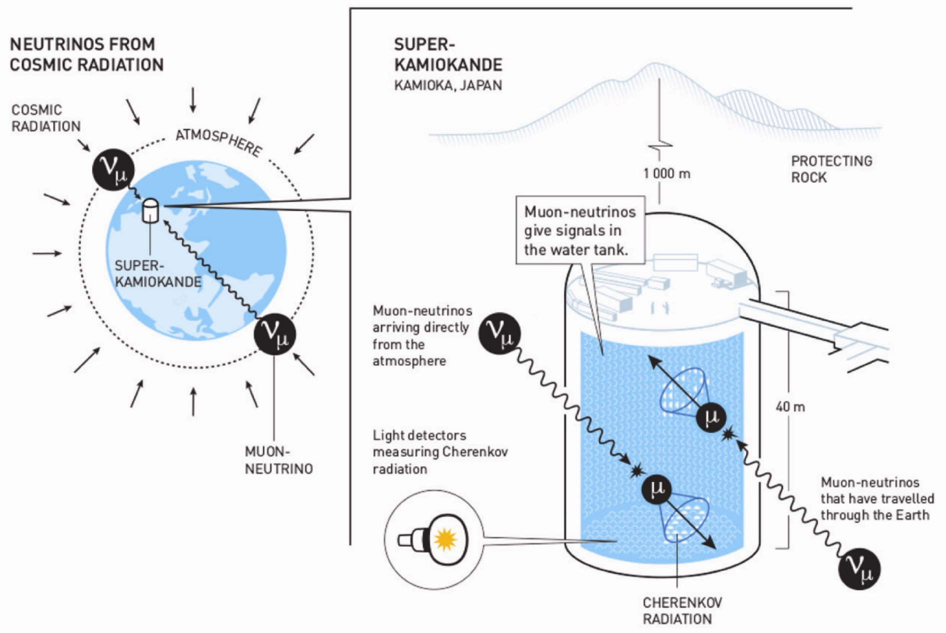
High-scale seesaw and cosmological signatures

中微子质量

太阳中微子之谜

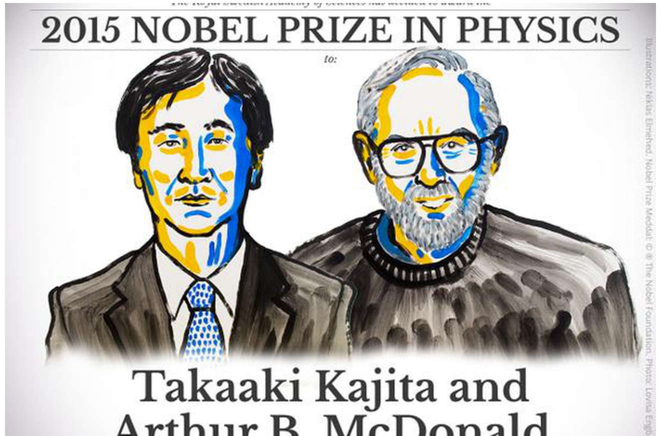


大气中微子反常



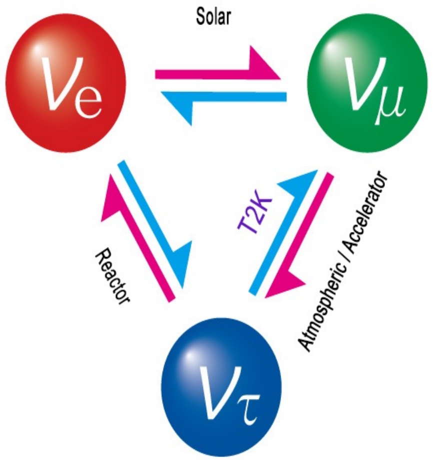
三代中微子之间会互相振荡转化

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



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

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）

Seesaw mechanism

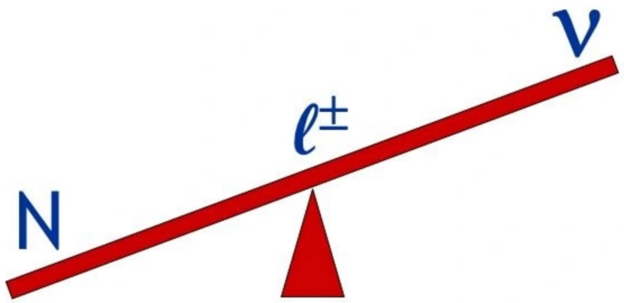
Origin of neutrino masses: seesaw mechanism

$$\mathcal{L} = \mathcal{L}_{\rm SM} + y_\nu \tilde{H}\bar{L}N_R - \frac{1}{2}M_R\bar{N}_R^c N_R + h.c.$$

P. Minkowski ; T. Yanagida; S. L. Glashow;
M. Gell-Mann, P. Ramond and R. Slansky

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

$$m_\nu \sim \frac{m_D^2}{M_R} = \frac{y_\nu^2 \langle h \rangle^2}{2M_R}$$



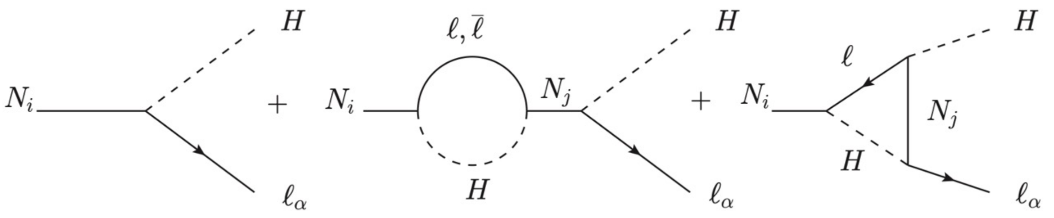
- **Natural prediction of small neutrino masses**
- **Explain the baryon asymmetry of the universe: leptogenesis**

Baryogenesis Without Grand Unification, Fukugita and Yanagida, 1986′

Leptogenesis

Baryogenesis Without Grand Unification, Fukugita and Yanagida, 1986′

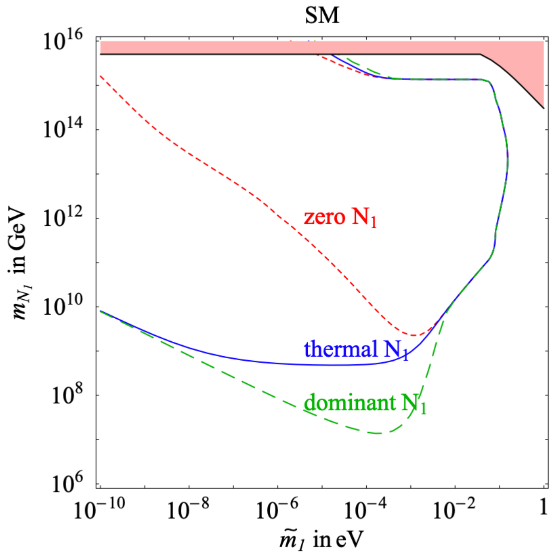
$$\mathcal{L}_I = \mathcal{L}_{SM} + i\overline{N_{R_i}}\partial\!\!\!/ N_{R_i} - \left(\frac{1}{2}M_i\overline{N^c_{R_i}}N_{R_i} + \epsilon_{ab}Y_{\alpha i}\overline{N_{R_i}}\ell^a_\alpha H^b + h.c.\right)$$



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

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

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



Mass of the right-handed neutrino should heavier than 10^9 GeV

Seesaw mechanism

$$m_\nu \sim \frac{m_D^2}{M_R} = \frac{y_\nu^2 \langle h \rangle^2}{2M_R}$$

If the Yukawa coupling is O(1)(as predicted by the GUT), the seesaw scale M_R should be around $10^{13\text{-}14}$ GeV, which is much beyond the reach of particle experiments.

How to test such high scale seesaw?

Two cosmological signatures in this talk

- **Local-type non-Gaussianity from Higgs-modulated reheating**
- **Cosmological-collider signal from RH-neutrino loops**

Testing high scale seesaw

CH, H. He, L. Song, J. You, arXiv: 2412.21045(PRDL)， 2412.16033(PRD)

Minimal model incorporates inflation and seesaw

$$\Delta\mathcal{L} = \sqrt{-g}\Big[-\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) + \overline{N}_{\rm R}\,\mathrm{i}\not{\partial} N_{\rm R} + \frac{1}{\Lambda}\partial_\mu\phi\,\overline{N}_{\rm R}\gamma^\mu\gamma^5 N_{\rm R} + \Big(-\frac{1}{2}M\overline{N^{\rm c}_{\rm R}}N_{\rm R} - y_\nu\,\overline{L}_{\rm L}\tilde{\mathbb{H}}N_{\rm R} + \mathrm{H.c.}\Big)\Big]$$

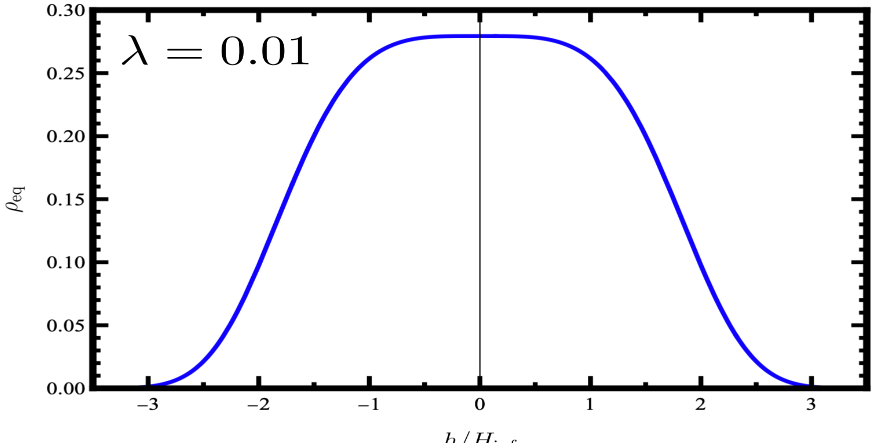
Consequence of the seesaw mechanism

$$\mathcal{L} \supset \frac{1}{2}\bar{\psi}_L\mathbf{M}_\nu\psi_R + \mathrm{h.c.}, \qquad \mathbf{M}_\nu = \begin{pmatrix} 0 & \frac{y_\nu h}{\sqrt{2}} \\ \frac{y_\nu h}{\sqrt{2}} & M \end{pmatrix}$$

$$m_\nu \simeq -\frac{y_\nu^2 h^2}{2M}, \qquad M_N \simeq M + \frac{y_\nu^2 h^2}{2M} \qquad\qquad \Gamma \simeq \frac{m_\phi M^2}{4\pi\Lambda^2}\left[1 + \frac{1}{4}\left(\frac{y_\nu h}{M}\right)^2\right]$$

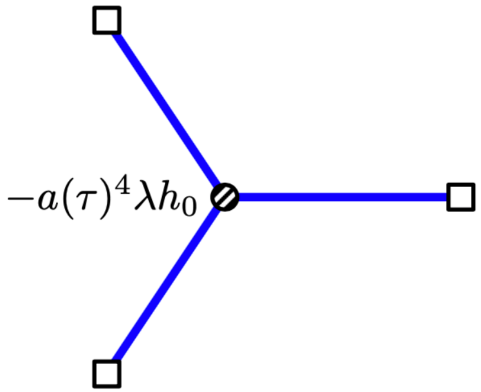
Testing high scale seesaw

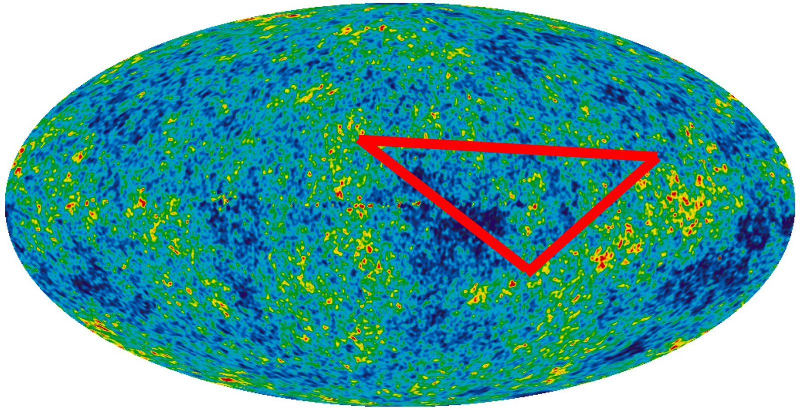
CH, H. He, L. Song, J. You, arXiv: 2412.21045(PRDL)， 2412.16033(PRD

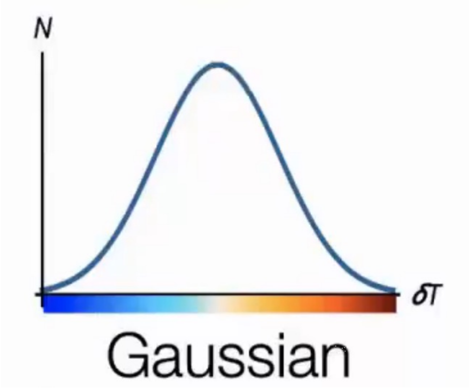


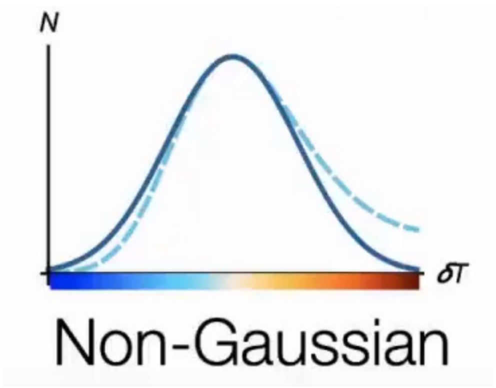
$$\rho_{eq}(h) = \frac{2\lambda^{1/4}}{\Gamma(1/4)}\left(\frac{2\pi^2}{3}\right)^{1/4}\exp\left(\frac{-2\pi^2\lambda h^4}{3H_{inf}^4}\right)$$

Due to the Higgs self-coupling

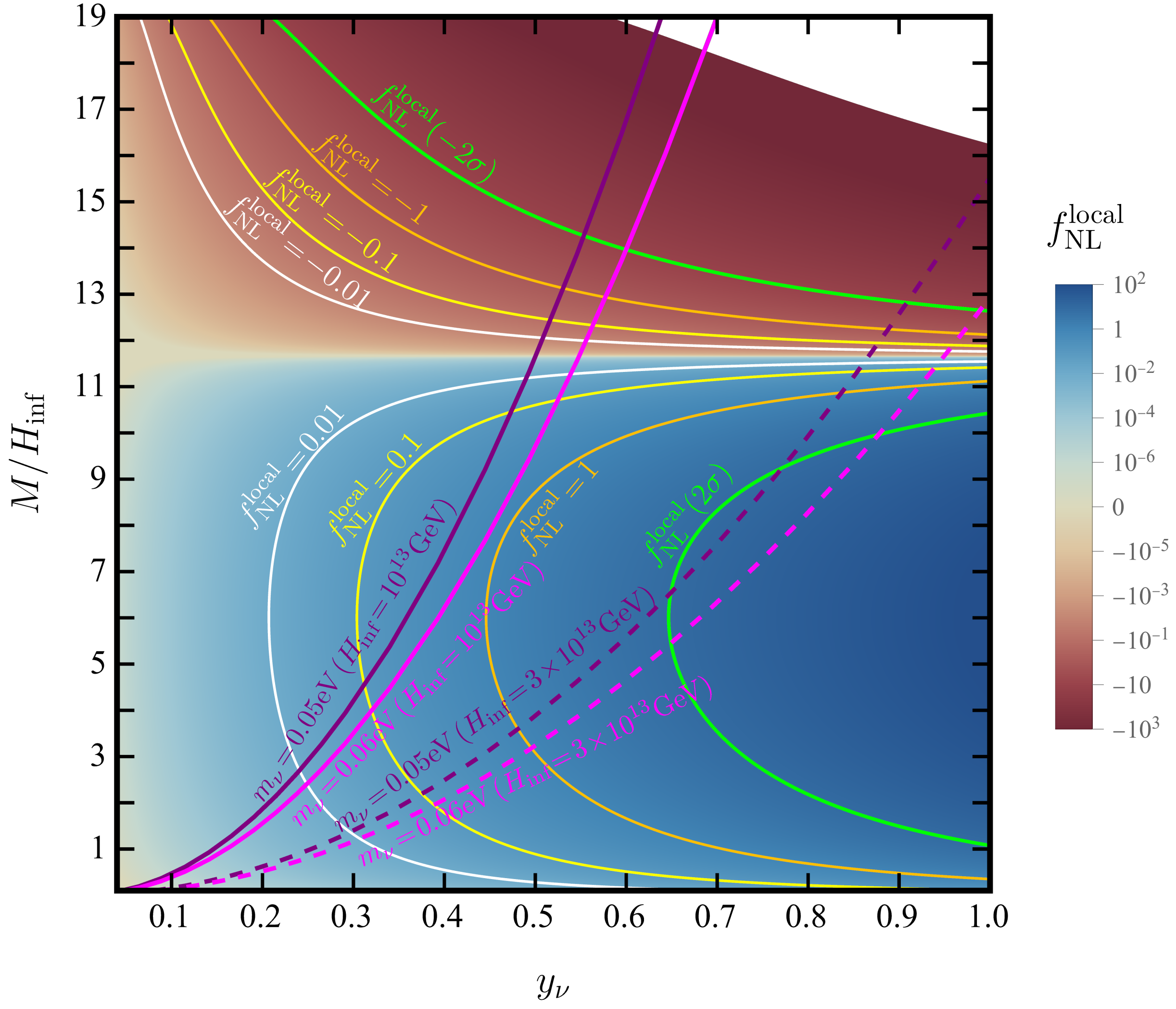








Testing high scale seesaw

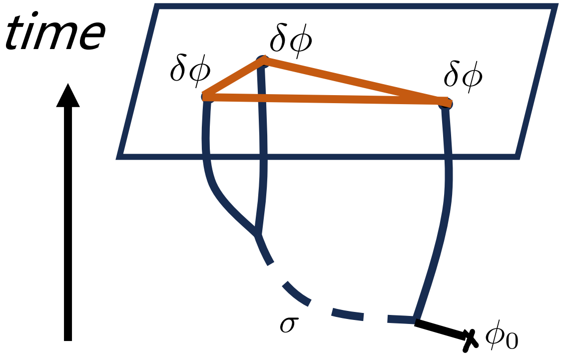


- **Colored curves indicating future searches**
- **Parameter space with Yukawa O(1) could be probed by future observations**
- **Interplaying with neutrino experiments(JUNO, DUNE for neutrino ordering)**

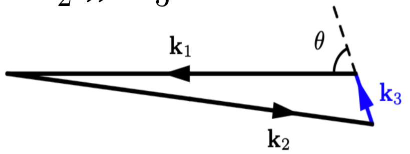
Cosmological collider signals

X. Chen and Y. Wang, JCAP 04 (2010)027
N. Arkani-Hamed and J. Maldacena, arXiv:1503.08043

- **Inflation can act as a high-energy collider sensitive to particles with mass ~ H**
- **Their mass and spin are encoded in non-analytic features of the squeezed bispectrum**
- **Particles with $m{\sim}H$ produce oscillatory signals, whereas heavier states are increasingly suppressed**



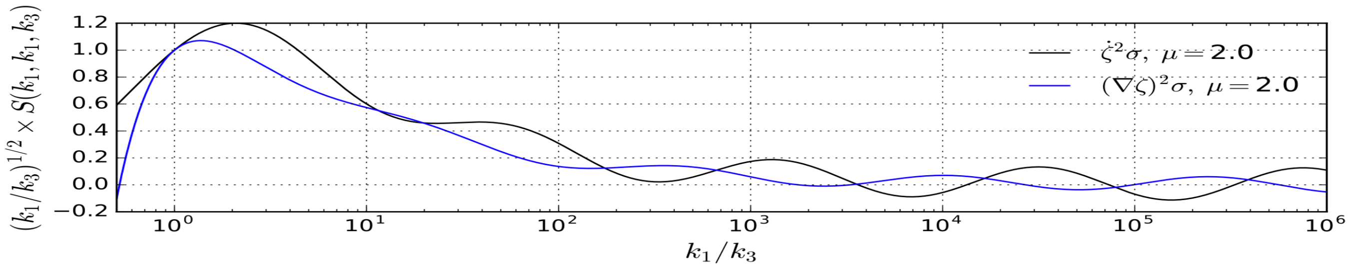
$k_1 \sim k_2 \gg k_3$



$$\mu = \sqrt{\frac{m^2}{H^2} - \frac{9}{4}}$$

$$\langle \delta\phi_{\mathbf{k_1}} \delta\phi_{\mathbf{k_2}} \delta\phi_{\mathbf{k_2}} \rangle \sim e^{-\pi\mu} \cos\left(\mu \log \frac{k_3}{k_1} + \delta\right) P_s(\cos\theta)$$

P. Daniel Meerburg, M. Münchmeyer, J. B. Muñoz, X. Chen, JCAP 03 (2017) 050



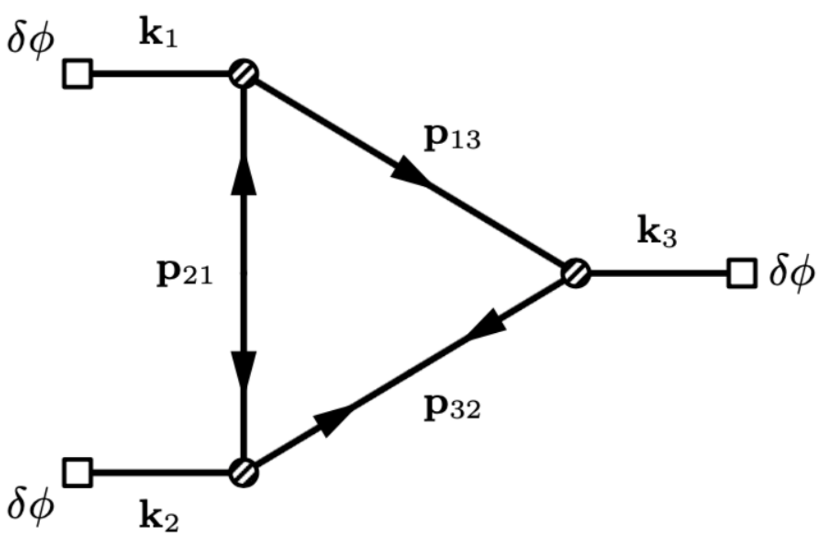
$$\langle \zeta^3 \rangle \equiv (2\pi)^3 \delta_D(\mathbf{k}_{123}) \frac{A^2}{(k_1 k_2 k_3)^2} S(k_1, k_2, k_3)$$

$$P_\zeta(k) = A/k^3 \qquad \zeta = \frac{H}{\dot\phi}\delta\phi$$

Cosmological collider signals

X. Chen and Y. Wang, JCAP 04 (2010)027
N. Arkani-Hamed and J. Maldacena, arXiv:1503.08043

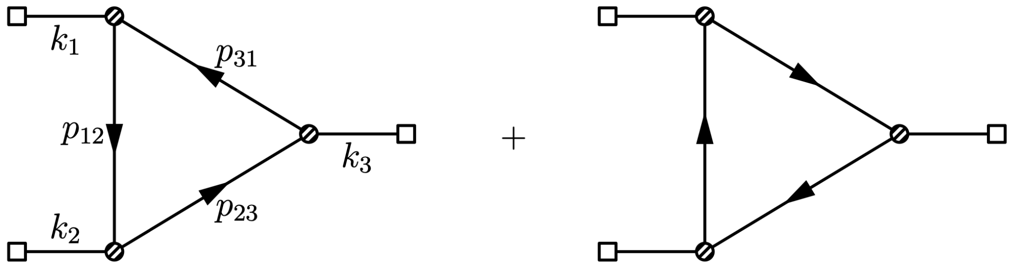
Prediction of cosmological collider signal: help to identify the mass of the right-handed neutrino



Fermion-Loop Calculation Is Challenging

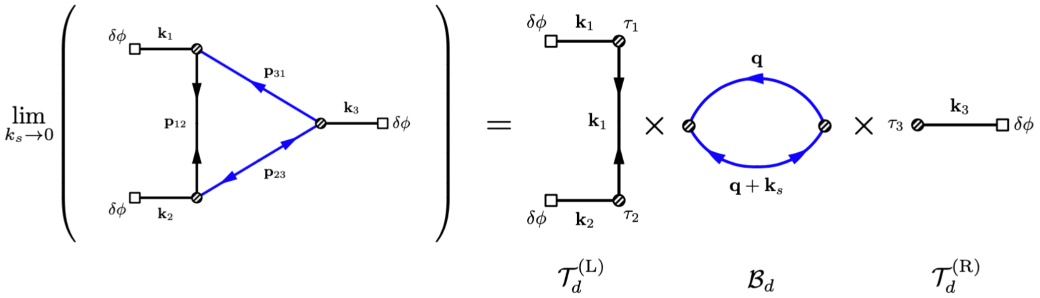
- The fermion mode functions in de Sitter space are nontrivial
- The loop-momentum integration must be handled carefully to isolate the nonlocal signal
- A controlled calculation therefore requires more than a simple benchmark estimate

What Earlier Work Assumed

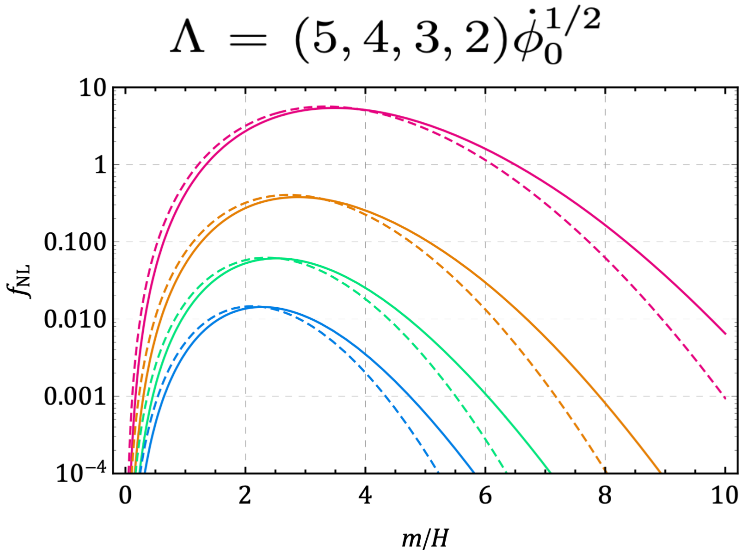


X. Chen, Y. Wang, and Z.-Z. Xianyu, JHEP 09 (2018) 022
A. Hook, J. Huang, and D. Racco, JHEP 01 (2020) 105

The cosmological collider signal only emerges in specific soft limits, which can be factorized.



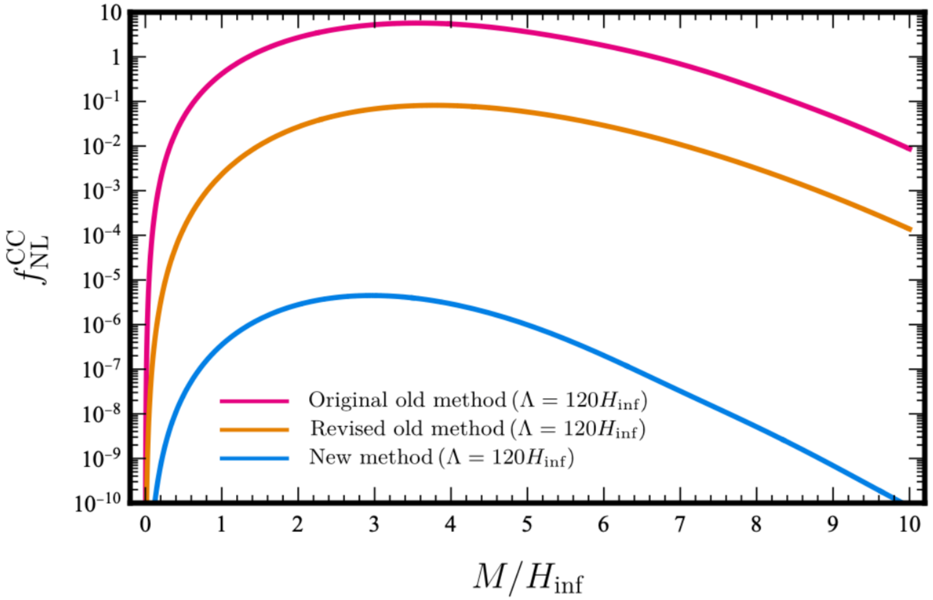
- **The TL was estimated with a saddle-point approximation**
- **The bubble subdiagram was approximated using a typical loop momentum ks instead of the full integration**
- **Under those assumptions, the loop signal looked potentially observable.**


$\Lambda = (5,4,3,2)\dot{\phi}_0^{1/2}$

Our Controlled Reanalysis

CH, H. He, L. Song, J. You, arXiv: 2604.XXXXX

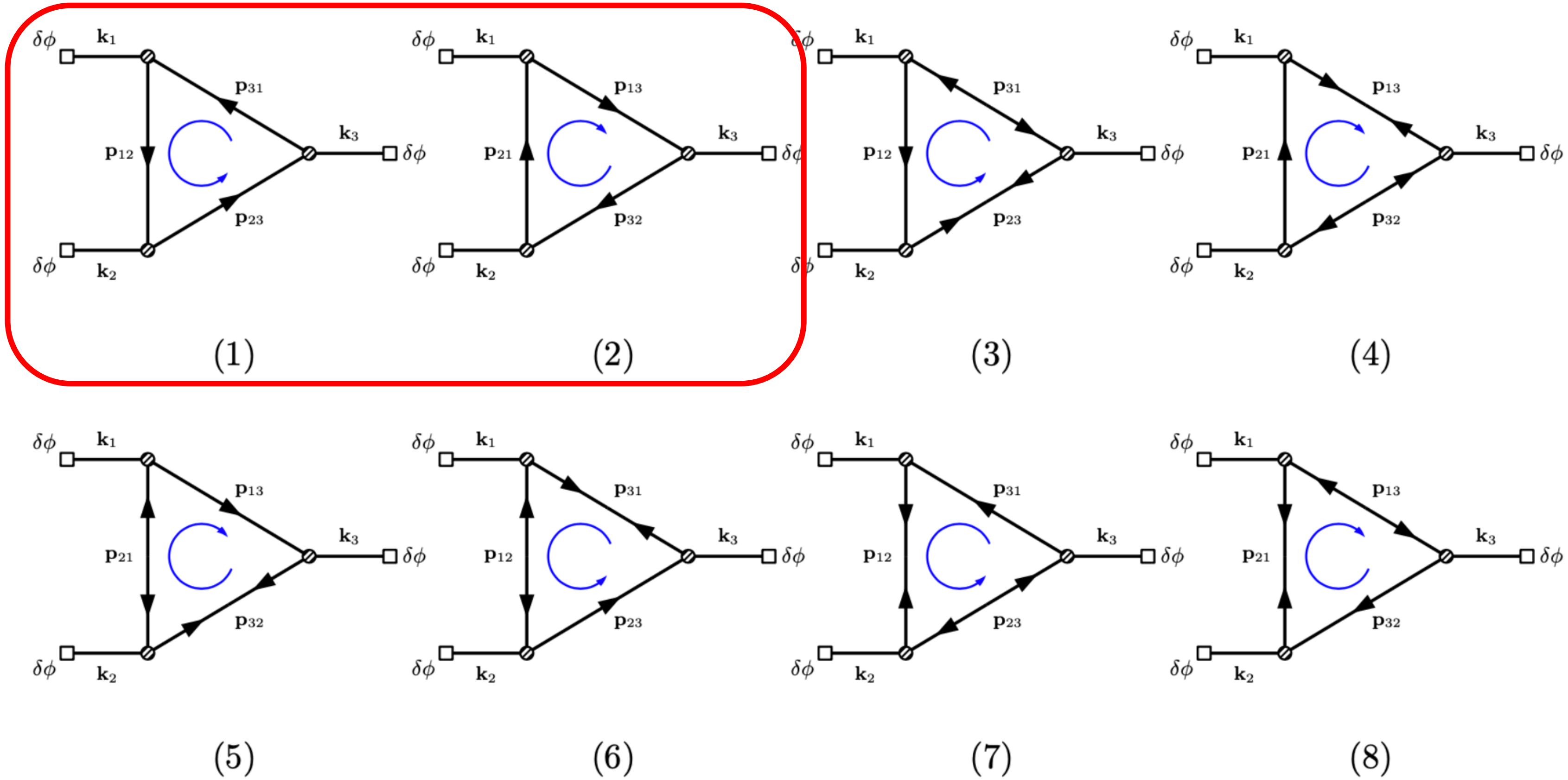
- **We compute TL analytically rather than using a saddle-point approximation**
- **We evaluate the bubble contribution through the full loop-momentum integration**
- **With these improvements, the old benchmark is reduced by roughly six orders of magnitude**



If one corrects only the old benchmark contribution, the cc signal appears hopelessly small

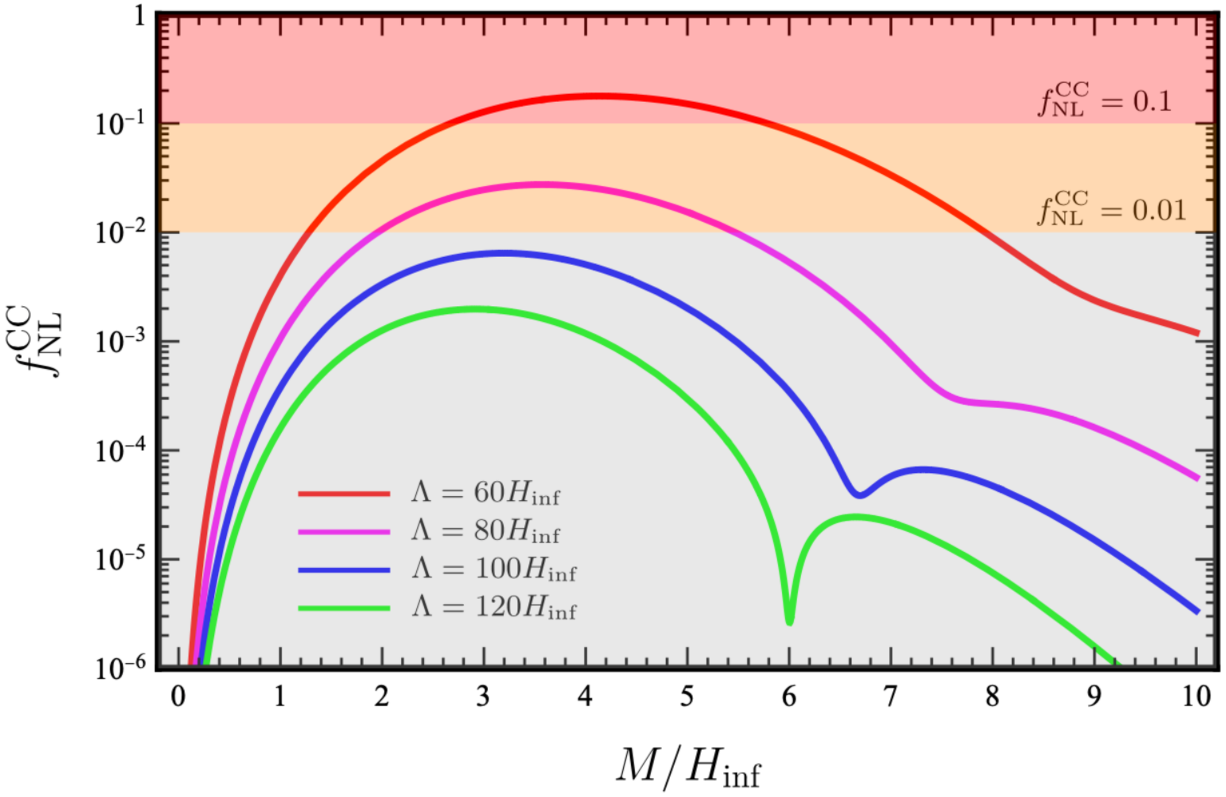
Missing Diagrams Matter

The old literature evaluated only a subset of diagrams



Result of Cosmological-Collider Signal

- **New diagrams can dominate over the old benchmark contribution**
- **In part of parameter space, the total RH-neutrino loop signal reaches an observable level**



Type-II seesaw:低标度可检验的轻子生成机制

Triplet scalar dynamics and testable leptogenesis

第二类跷跷板机制

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

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

$$\Big\downarrow$$

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

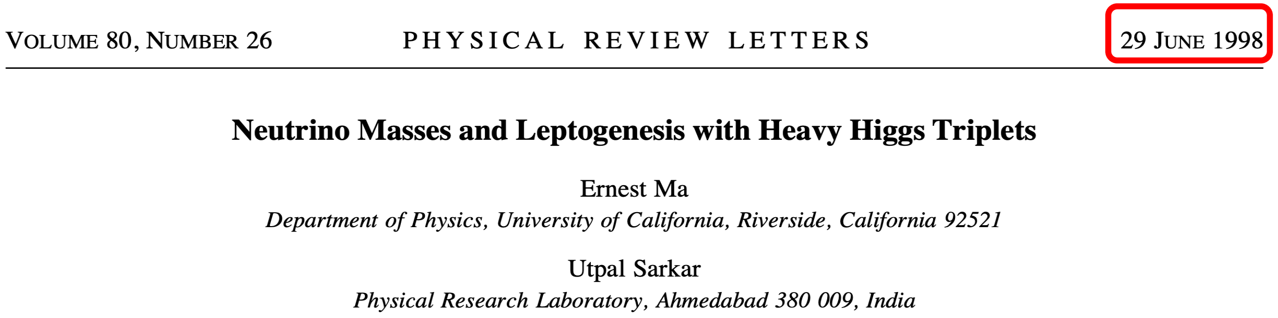
EW precision measurement

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

required by neutrino masses

第二类跷跷板机制与轻子生成机制

Leptogenesis in Type II seesaw ?



VOLUME 80, NUMBER 26 PHYSICAL REVIEW LETTERS 29 JUNE 1998

Neutrino Masses and Leptogenesis with Heavy Higgs Triplets

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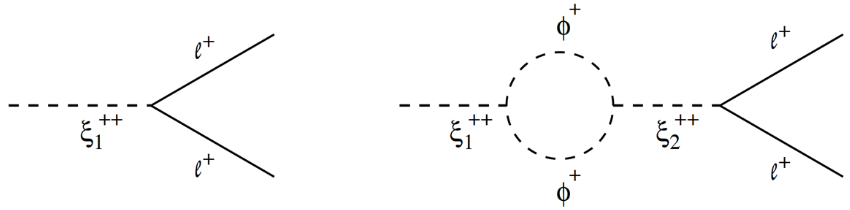
500+ citations

希格斯三重态质量需要超过10^{10} GeV



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

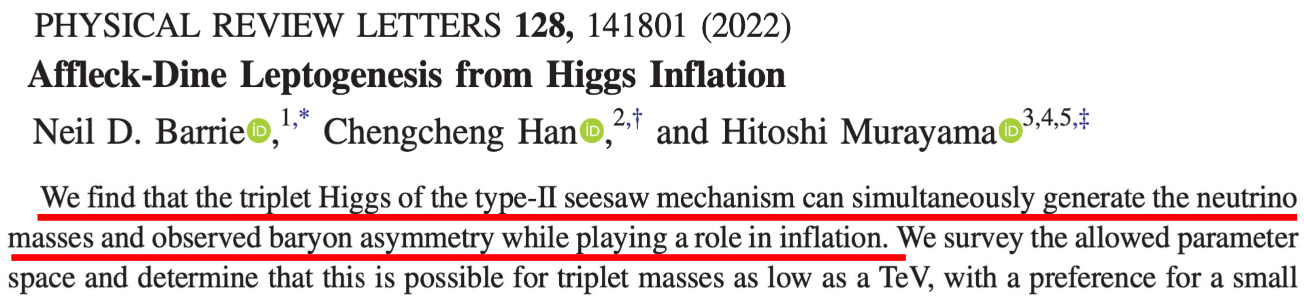
$$\delta_i = \frac{Im\left[\mu_1\mu_2^*\sum_{k,l} y_{1kl}y_{2kl}^*\right]}{8\pi^2(M_1^2 - M_2^2)}\left[\frac{M_i}{\Gamma_i}\right]$$

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(热)轻子生成机制

第二类轻子生成机制

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)

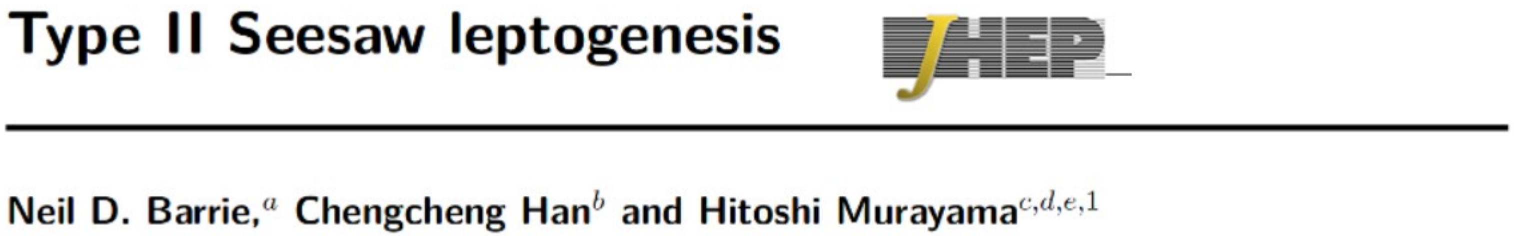


PHYSICAL REVIEW LETTERS **128,** 141801 (2022)

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

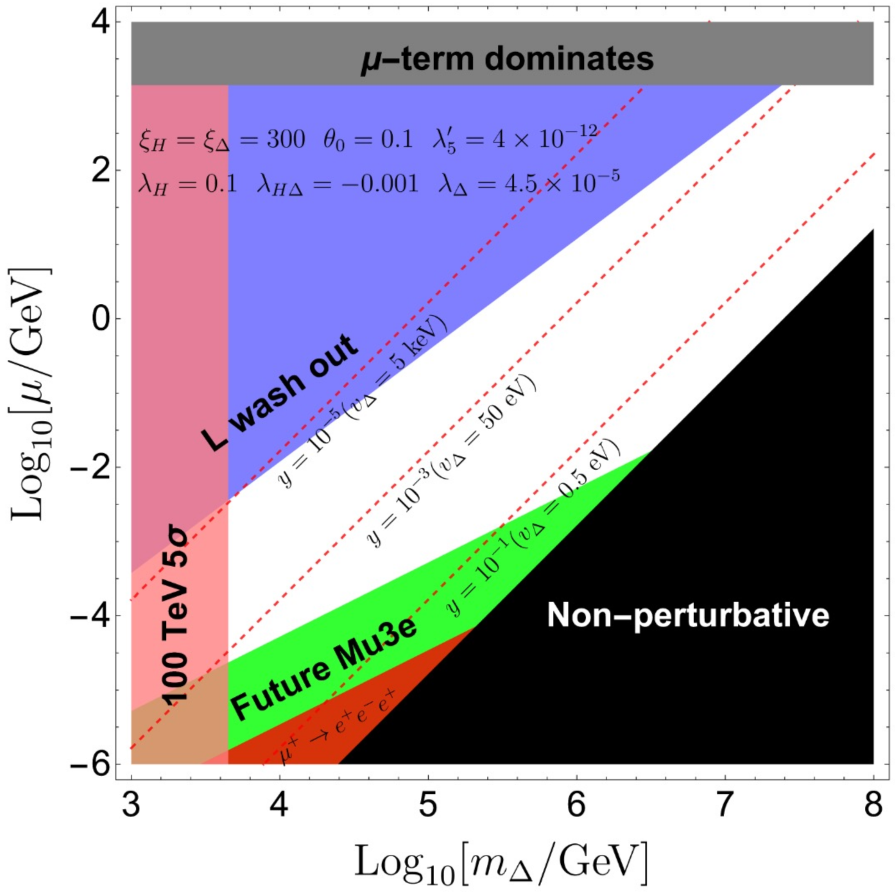


Type II Seesaw leptogenesis

JHEP

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

第二类轻子生成机制



- 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, 轻子味破坏过程对其进行检验
- 中微子为Majorana粒子: 无中微子双beta衰变

总结

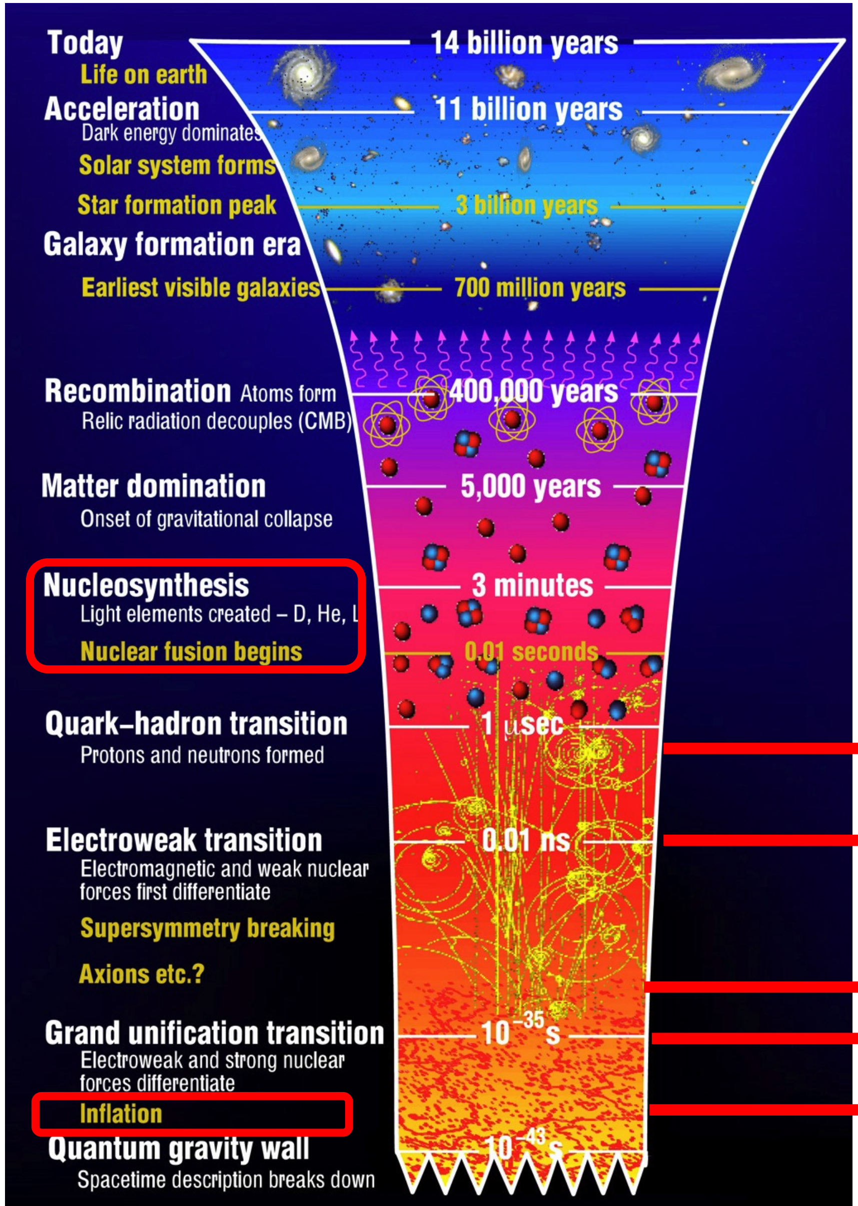
- **B-mesogenesis：B稀有衰变给出重味检验途径**
- **Type-I seesaw：local non-Gaussianity 和cosmological collider信号检验**
- **Type-II seesaw：低标度可检验的轻子生成机制**

THANK YOU

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

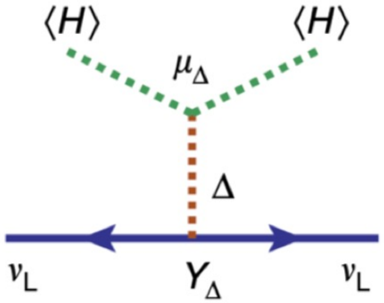
GUT Baryogenesis

Baryogenesis from inflation

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



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

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

EW precision measurement

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

required by neutrino masses

B-mesogenesis

The baryon asymmetry is related to the B meson decay rate into baryon+invi and B meson oscillation CP violation A_{SL}

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

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

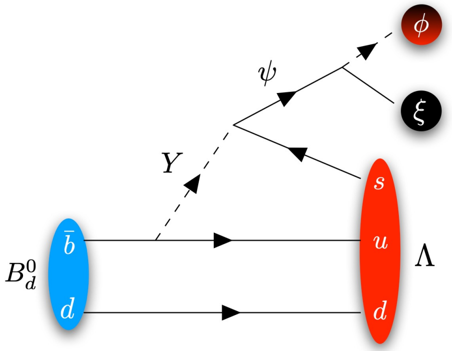
SM prediction:

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

EXP:

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

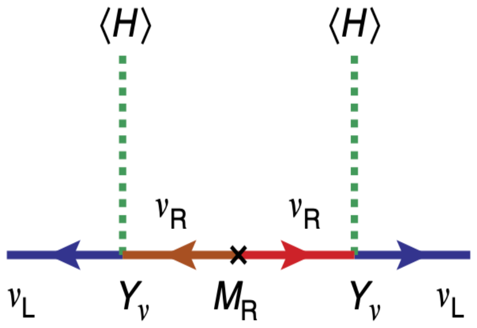
- **SM CKM is enough to provide the CP violation，but**
- **B meson decay into baryon+invisible (BaBar，Belle，LHCb)**
- **Measurement of the CP violation of B meson is important**



跷跷板机制

为了解释中微子质量，必然引入新的粒子

Type I

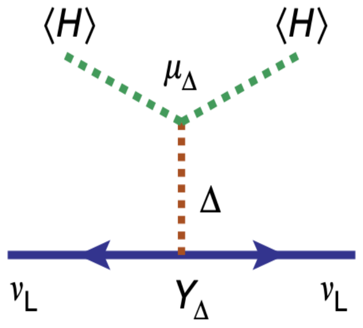


$$M_\nu = -\langle H\rangle^2 Y_\nu M_R^{-1} Y_\nu^T$$

SM+3 singlets fermions

Minkowski, Gell-Mann,
Glashow, Yanagida

Type II

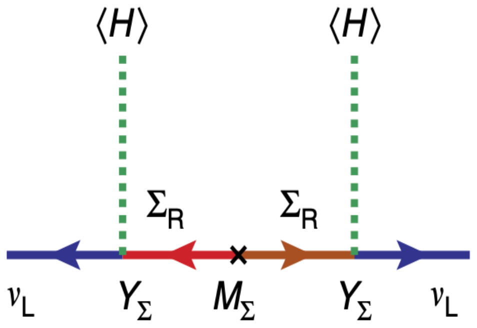


$$M_\nu = \langle H\rangle^2 Y_\Delta \mu_\Delta / M_\Delta^2$$

SM+1 triplet Higgs

Magg, Wetterich

Type III



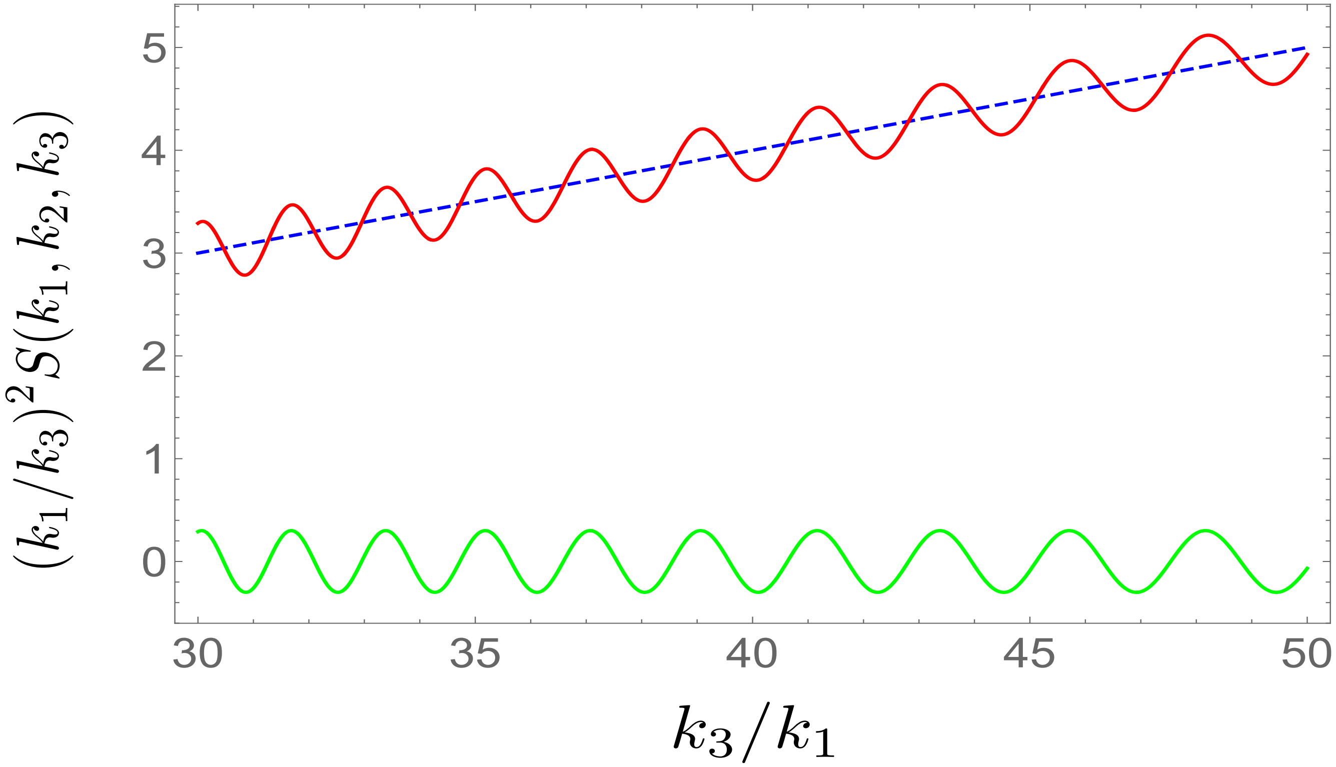
$$M_\nu = -\langle H\rangle^2 Y_\Sigma M_\Sigma^{-1} Y_\Sigma^T$$

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

Complementarity of the Two Signatures



- **Local-type non-Gaussianity probes reheating dynamics induced by the seesaw sector**
- **The cosmological-collider signal probes the heavy RH-neutrino mass more directly**
- **Together, they provide complementary cosmological tests of the seesaw mechanism**