Baryon Asymmetry of the Universe

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Sun Yat-sen university

INPAC/TDLI Joint Seminar

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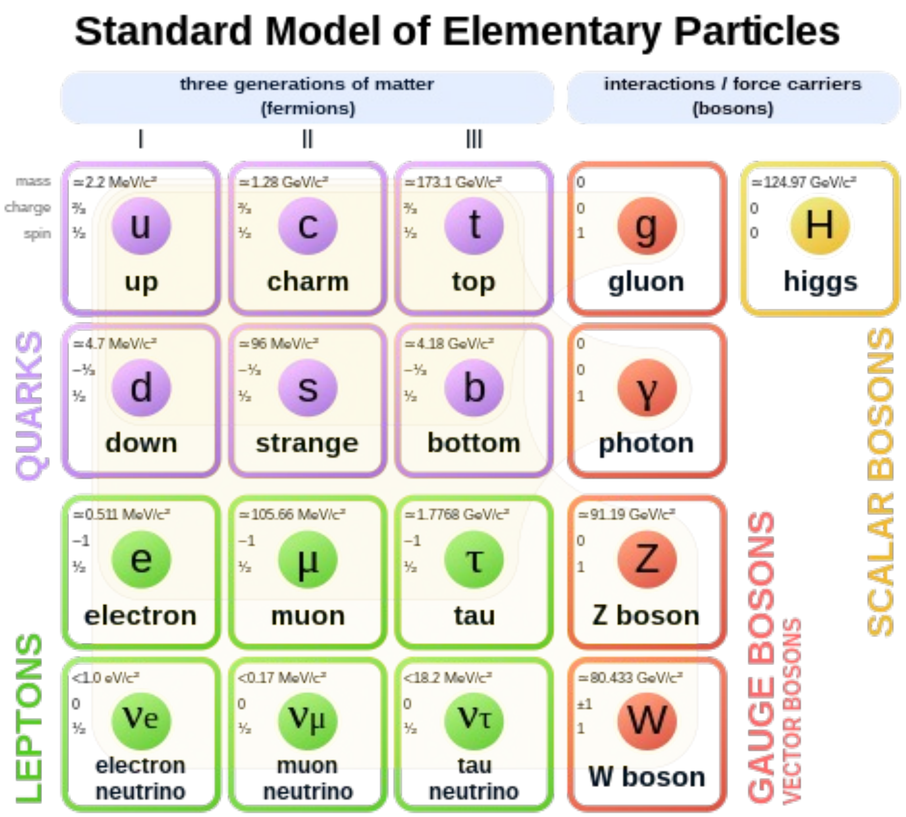
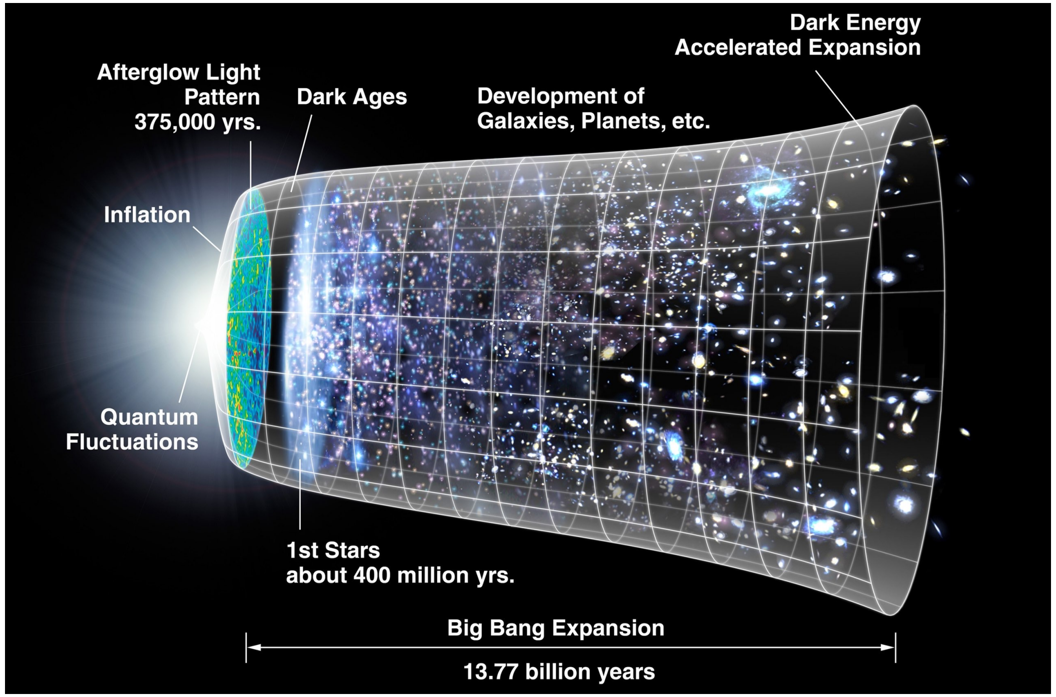
2024.04.24

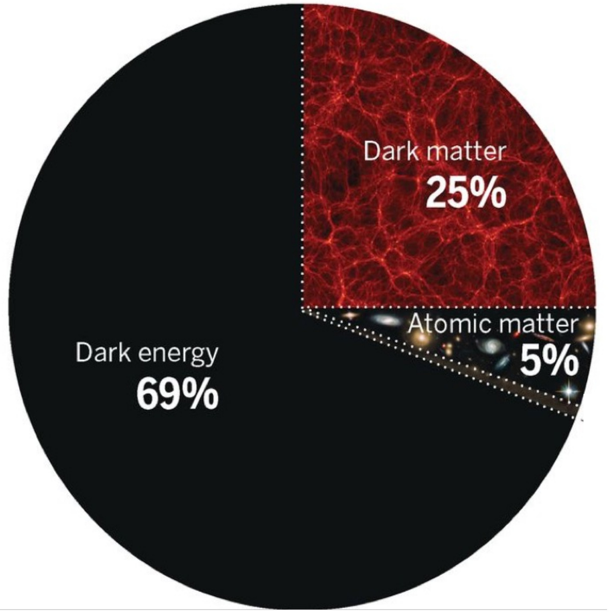
Standard model



ΛCDM+Inflation



What is the Universe made of?



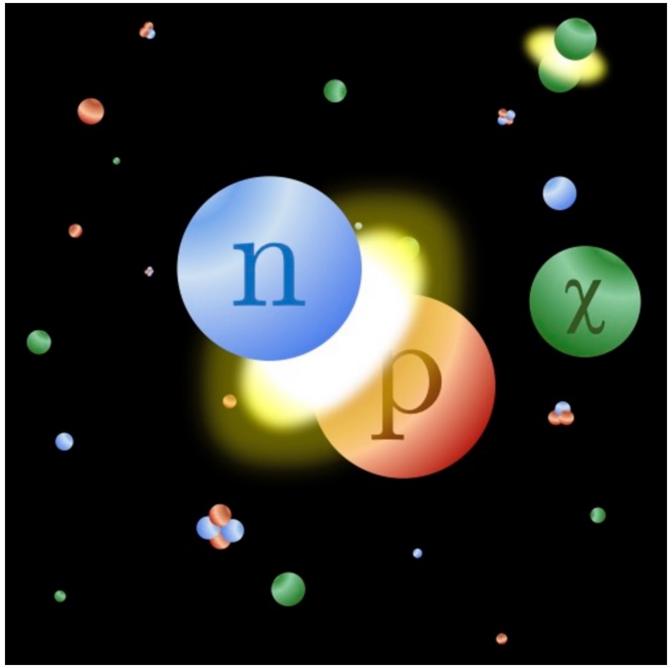
- What is dark energy?
- What is dark matter?
- Why is there baryon asymmetry?

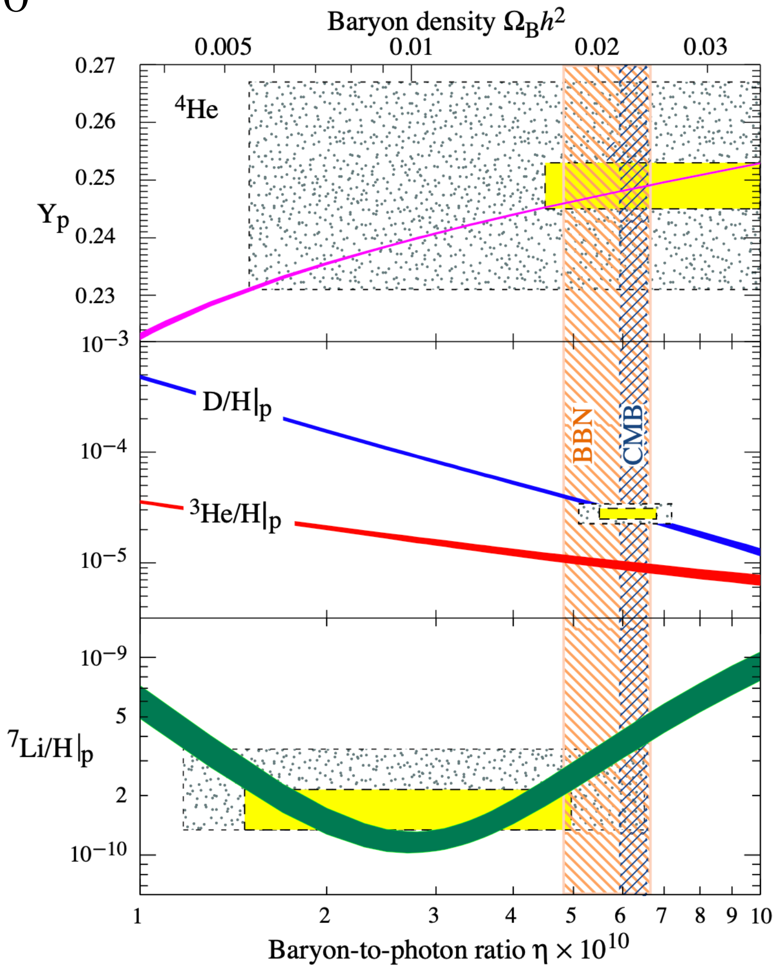
Common problems for particle physics and cosmology

Big bang nucleosynthesis(BBN)

T~1 MeV, t~3 min , production of light nuclei

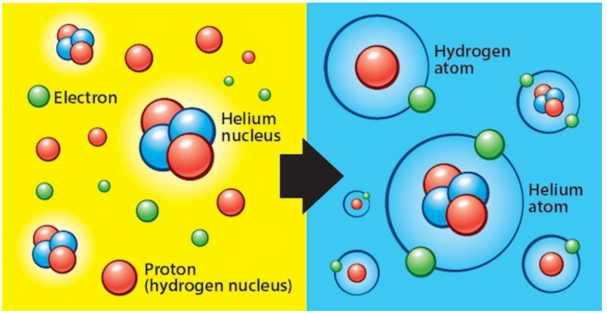
$$\eta = \frac{n_b - n_{\bar{b}}}{n_\gamma} \sim 10^{-10}$$

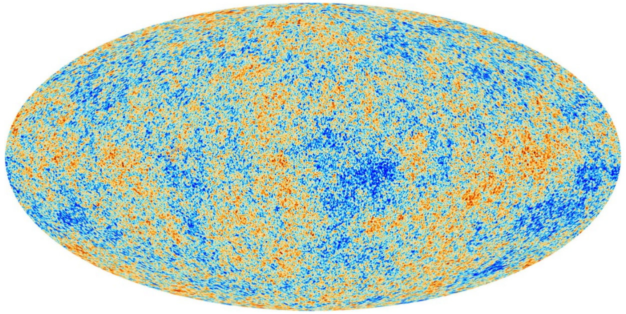


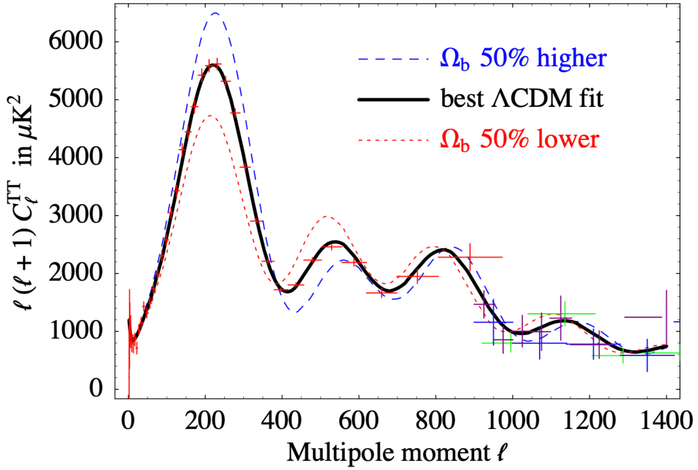


Cosmic microwave background

Cosmic microwave background(CMB)(T~0.1 eV t~380,000 year)







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

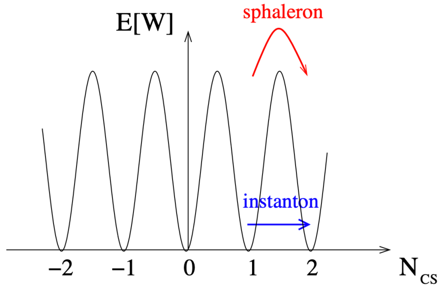
$$\eta = \frac{n_b - n_{\bar{b}}}{n_\gamma} \sim 10^{-10}$$

How to generate BAU?

If the universe is baryon asymmetric in the beginning, inflation dilutes all the asymmetry

Baryon asymmetry evolves from late universe

	Sakharov conditions	Standard model
●	Baryon number breaking process	✓
●	C and CP violation	✓✗
●	Decoupling from thermal equilibrium	✗



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

SU(2) vacuum

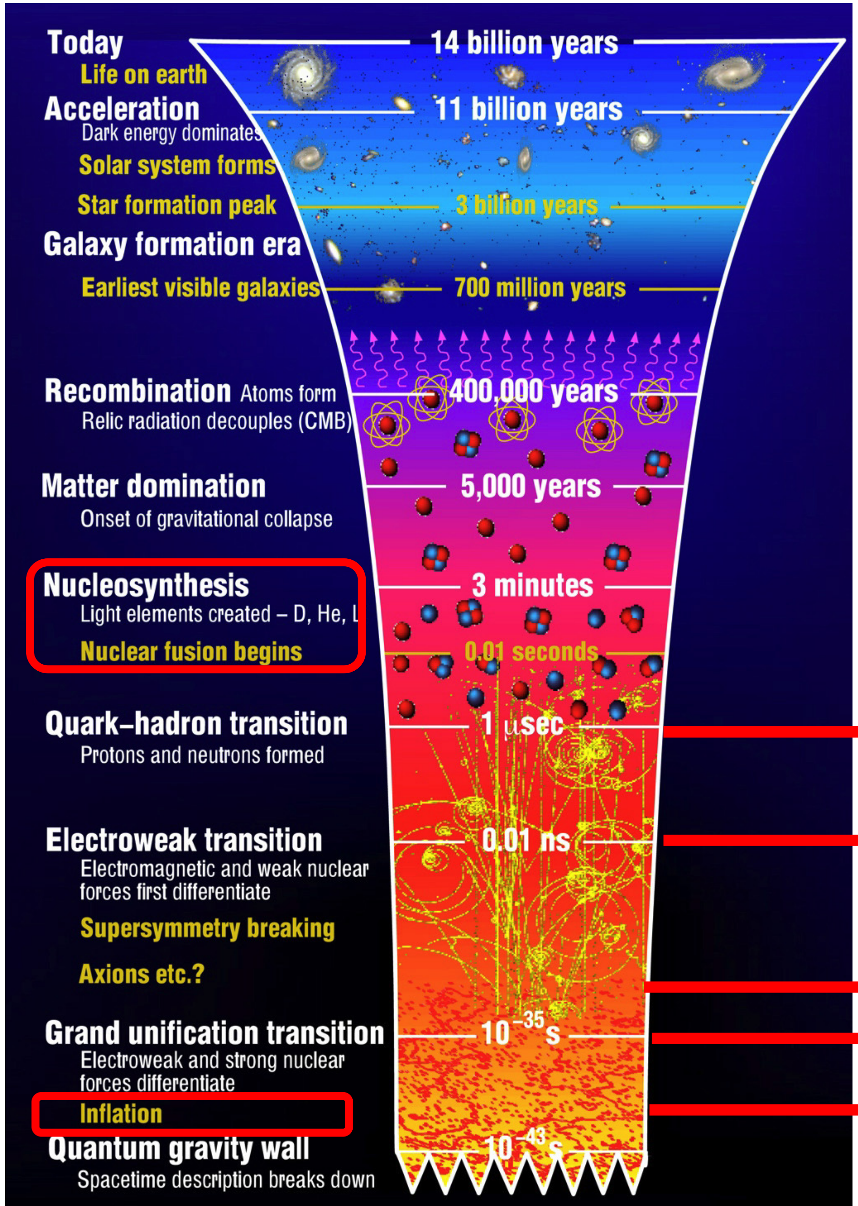
- Non-decoupling from thermal equilibrium, QCD and electroweak phase transition are cross over
- Even if first order phase transition is strong first order, CP violation in quark sector too small

New source of CP violation + decoupling condition

When BAU happens?

Not later than BBN(T~ MeV)

Not earlier than inflation



B-mesogenesis

EW Baryogenesis

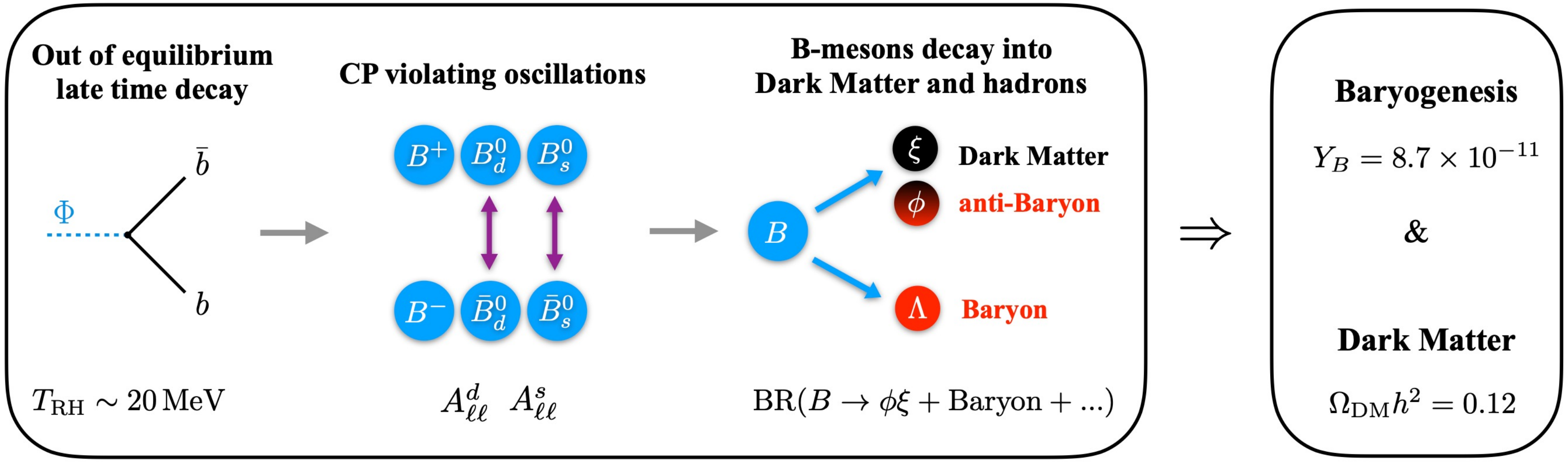
Leptogenesis

GUT Baryogenesis

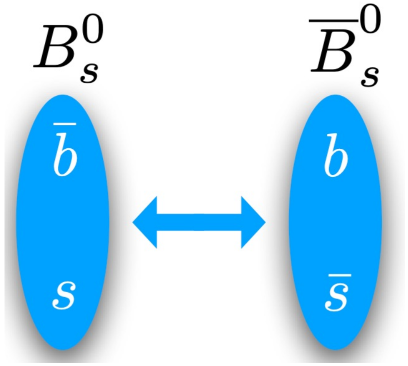
Baryogenesis during inflation

B-mesogenesis

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



- B meson heavy enough(5.3 GeV) to decay into baryon
- CP violation appears during oscillations
- 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_{SL}

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

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

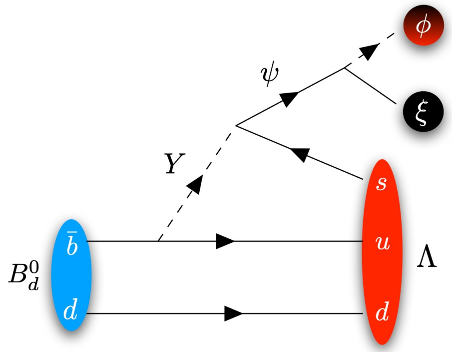
SM prediction:

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

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**

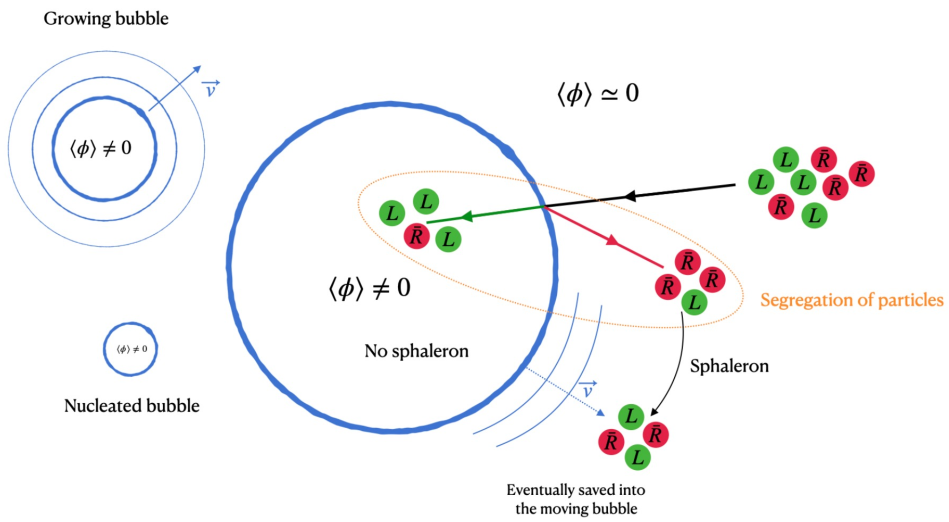


Electroweak baryogenesis

- Adding new scalars(strong first order EW phase transition)
- Adding additional CP violation

Collider searches

Electron edm (< $4.1*10^{-30}$ e.cm)



Associated gravitational wave

Is electroweak baryogenesis dead?

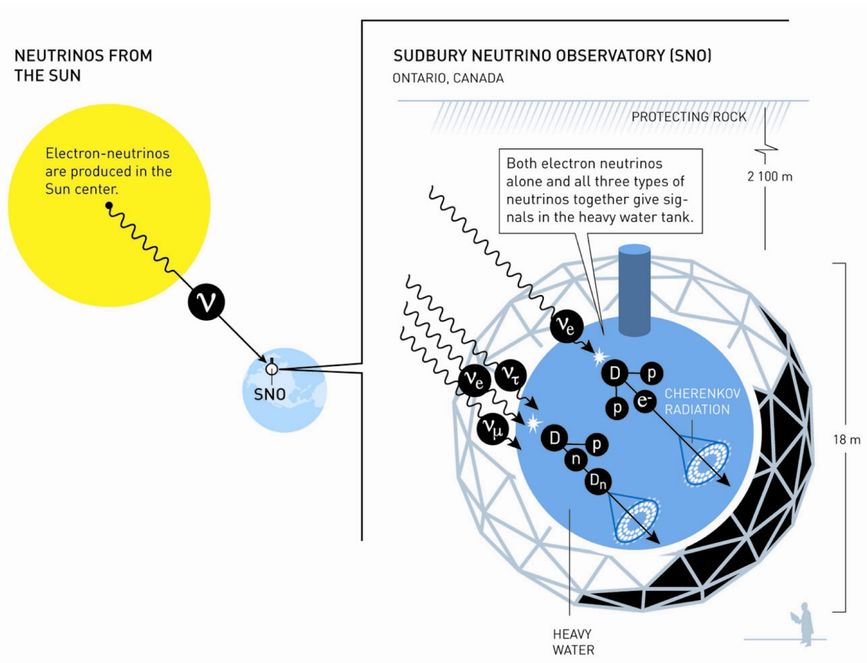
James M. Cline[1,2]

[1]CERN, Theoretical Physics Department, Geneva, Switzerland
[2]Department of Physics, McGill University, 3600 Rue University, Montréal, Québec, Canada H3A 2T8

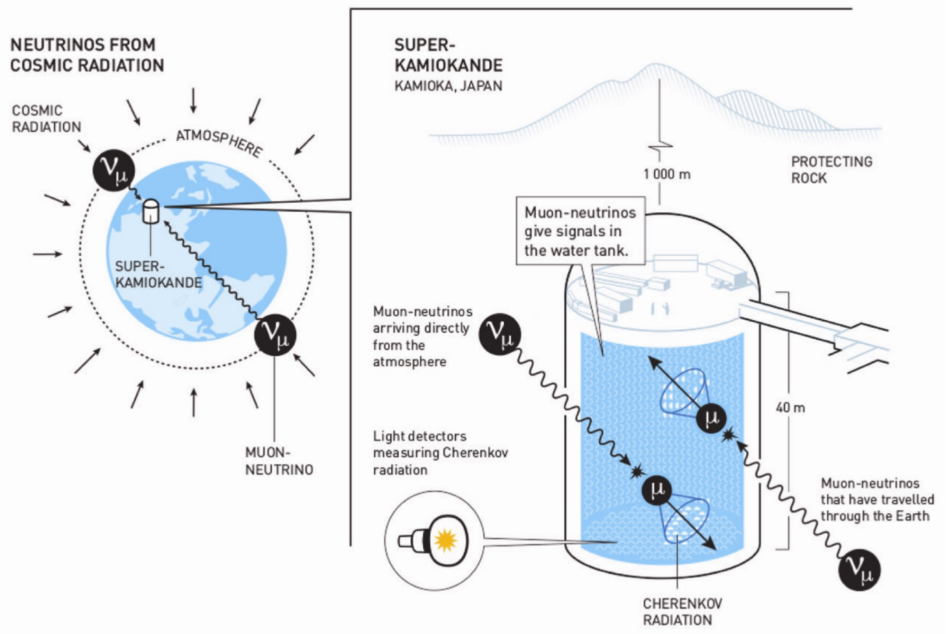
Challenge in model building

Neutrino mass

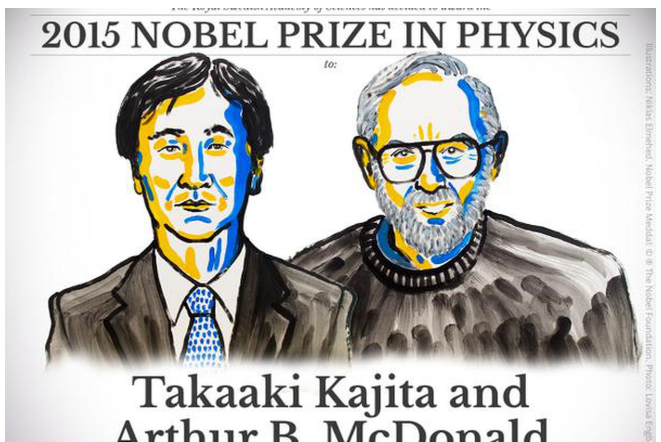
Solar neutrino



Atmospheric neutrinos



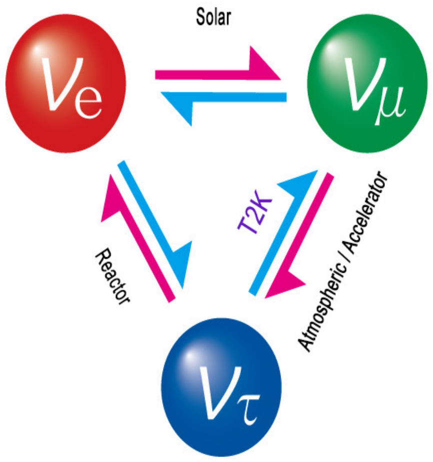
Neutrino oscillation



Neutrinos are massive

Neutrino mass

Kobayashi and Maskawa(2008 Nobel prize) mechanism tells us, there would be CP violation if neutrino massive, the CP violation appears in PMNS matrix which is similar to the CKM matrix in quark sector



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

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

NO

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

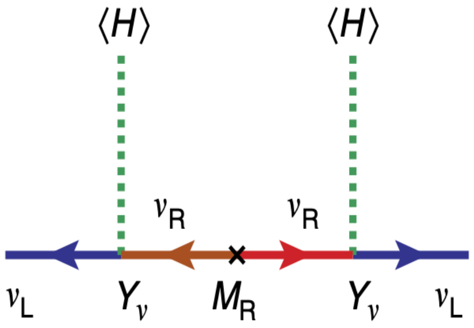
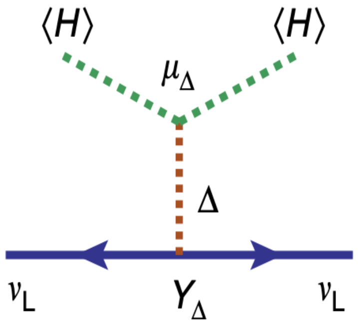
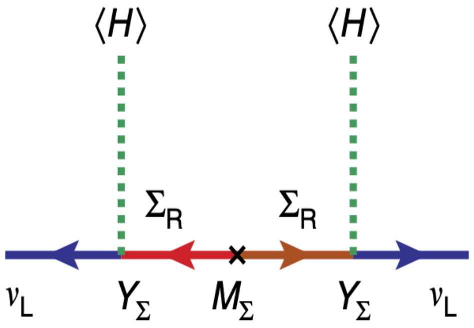
IO

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

Lepton sector provides new source of CP violation(T2K indication), matter asymmetry may be firstly generated from lepton sector, transfer into baryon sector via sphaleron process——leptogenesis

Seesaw mechanism

To explain the neutrino mass, new particle must be introduced

Type I	Type II	Type III
		
$M_\nu = -\langle H\rangle^2 Y_\nu M_R^{-1} Y_\nu^T$	$M_\nu = \langle H\rangle^2 Y_\Delta \mu_\Delta / M_\Delta^2$	$M_\nu = -\langle H\rangle^2 Y_\Sigma M_\Sigma^{-1} Y_\Sigma^T$
SM+3 singlets fermions	**SM+1 triplet Higgs**	**SM+3 triplet fermions**
Minkowski, Gell-Mann, Glashow, Yanagida	Magg, Wetterich	Foot, Lew, He, Joshi

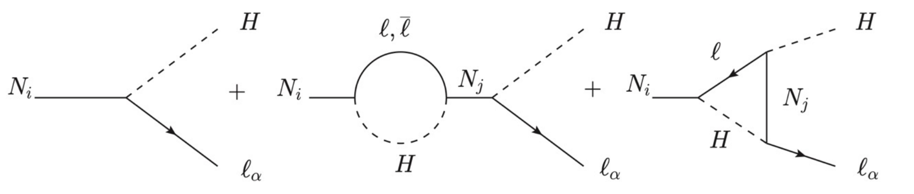
New heavy particle could decouple in the early universe!

Leptogenesis

Leptogenesis in Type I seesaw

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

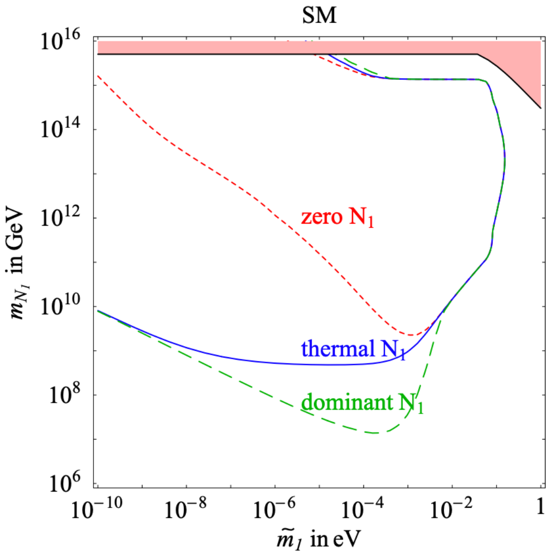
$$\mathcal{L}_I = \mathcal{L}_{SM} + i\overline{N_{R_i}}\partial\!\!\!/ N_{R_i} - \left(\frac{1}{2}M_i\overline{N^c_{R_i}}N_{R_i} + \epsilon_{ab}Y_{\alpha i}\overline{N_{R_i}}\ell^a_\alpha H^b + h.c.\right)$$



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

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

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



Requiring a heavy right-handed neutrino >10^7 GeV, difficult to test

Type III seesaw is similar to Type I seesaw, even heavier mass

Type II seesaw

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

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

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

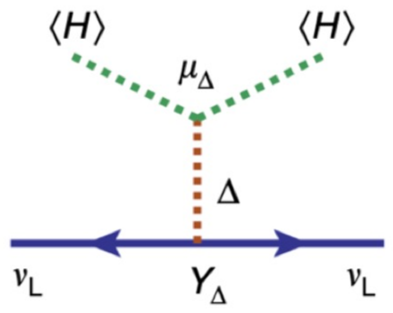
- Giving neutrino mass matrix with vev of Delta
- Delta get a lepton number -2

Type II seesaw

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

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

Leptogenesis

Leptogenesis in Type II seesaw ?

VOLUME 80, NUMBER 26 PHYSICAL REVIEW LETTERS 29 JUNE 1998

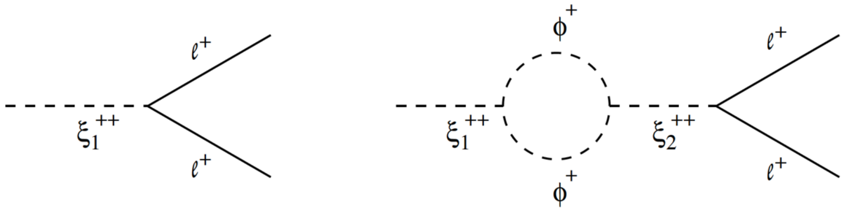
500+ citations

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

Higgs triplet mass should heavy (10^{10} GeV)



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

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

A triplet Higgs can not generate the lepton asymmetry!

Leptogenesis

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

Leptogenesis

Type II seesaw leptogenesis via Affleck-Dine mechanism

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]

Affleck-Dine mechanism

Assuming phi is a complex scalar with B charge

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

(B/L violation)

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

ϕ is spatially constant

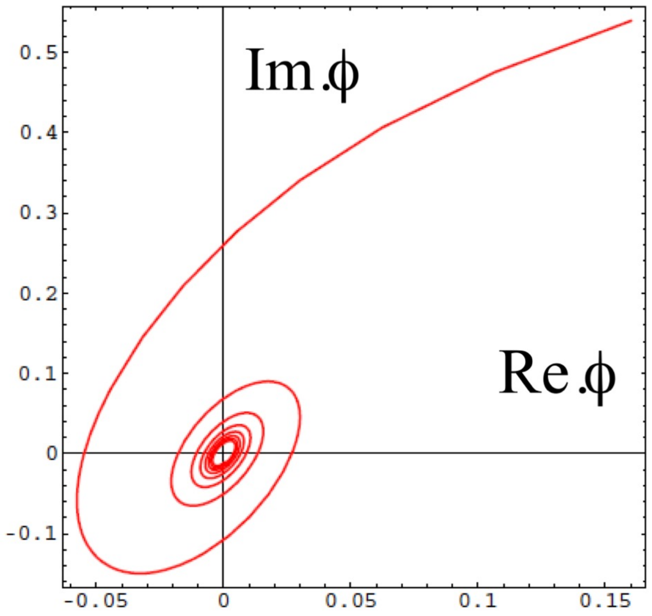
$$n_B = i(\phi^*\dot{\phi} - \phi\dot{\phi}^*) = \rho^2\dot{\theta} \qquad \phi = \frac{1}{\sqrt{2}}\rho_\phi e^{i\theta}$$

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

Only from U(1) breaking term

A motion of theta will generate baryon number

Affleck-Dine mechanism



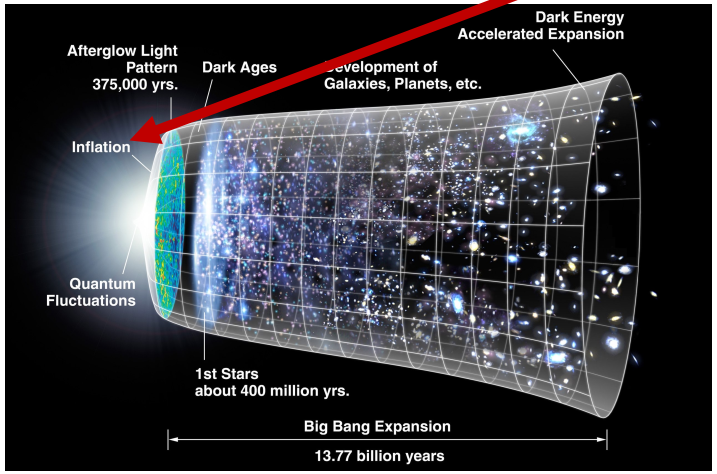
- **Scalar particle taking B/L charge**
- **Small B/L violation term in the potential(charge neutral)**
- **Scalar particle with initial displaced vacuum**

Affleck-Dine mechanism

	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

(Similar to Higgs inflation)



Type II seesaw leptogenesis

To be consistent with inflation, we add non-minimal couplings(similar to Higgs inflation)

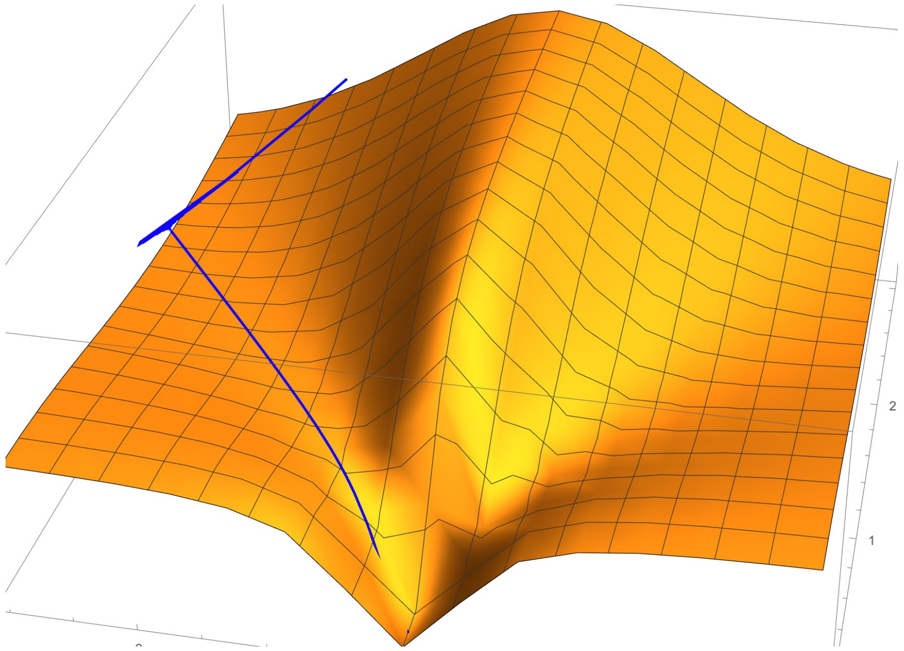
$$\frac{\mathcal{L}}{\sqrt{-g}} = -\frac{1}{2}M_P^2 R - f(H,\Delta)R - g^{\mu\nu}(D_\mu H)^\dagger(D_\nu H)$$
$$-g^{\mu\nu}(D_\mu \Delta)^\dagger(D_\nu \Delta) - V(H,\Delta) + \mathcal{L}_{\text{Yukawa}}$$

$$h \equiv \frac{1}{\sqrt{2}}\rho_H e^{i\eta} \qquad \Delta^0 \equiv \frac{1}{\sqrt{2}}\rho_\Delta e^{i\theta}$$

$$F(H,\Delta) = \xi_H |h|^2 + \xi_\Delta |\Delta^0|^2 = \frac{1}{2}\xi_H \rho_H^2 + \frac{1}{2}\xi_\Delta \rho_\Delta^2$$

Type II seesaw leptogenesis

During inflation(Oleg Lebedev and Hyun Min Lee, arXiv:1105.2284)



$$\frac{\rho_H}{\rho_\Delta} \equiv \tan\alpha = \sqrt{\frac{2\lambda_\Delta \xi_H - \lambda_{H\Delta}\xi_\Delta}{2\lambda_H \xi_\Delta - \lambda_{H\Delta}\xi_H}}$$

$$\rho_H = \varphi \sin\alpha, \;\; \rho_\Delta = \varphi\cos\alpha$$

$$\xi \equiv \xi_H \sin^2\alpha + \xi_\Delta \cos^2\alpha$$

Effective a single field inflation

Type II seesaw leptogenesis

The model can be simplified as

$$\frac{\mathcal{L}}{\sqrt{-g}} = -\frac{M_p^2}{2}R - \frac{\xi}{2}\varphi^2 R - \frac{1}{2}g^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi - \frac{1}{2}\varphi^2\cos^2\alpha\; g^{\mu\nu}\partial_\mu\theta\partial_\nu\theta - V(\varphi,\theta)$$

$$V(\varphi,\theta) = \frac{1}{2}m^2\varphi^2 + \frac{\lambda}{4}\varphi^4 + 2\varphi^3\left(\tilde{\mu} + \frac{\tilde{\lambda}_5}{M_p}\varphi^2\right)\cos\theta$$

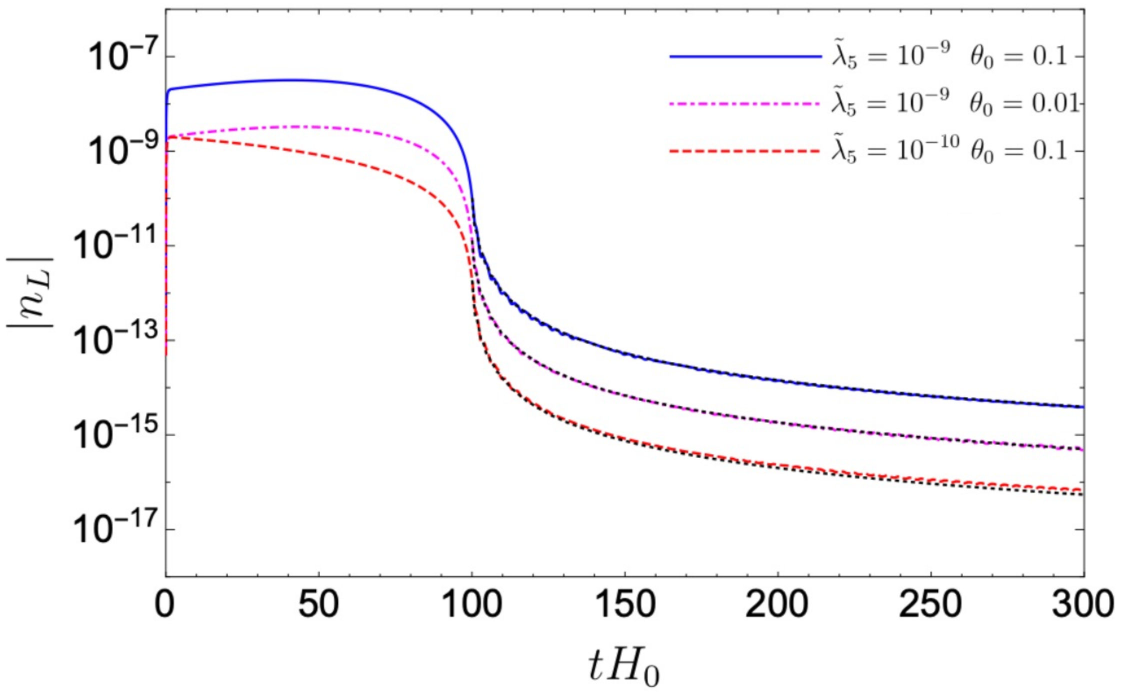
We need keep the theta term, because

$$n_L = Q_L\varphi^2\dot{\theta}\cos^2\alpha$$

Type II seesaw leptogenesis

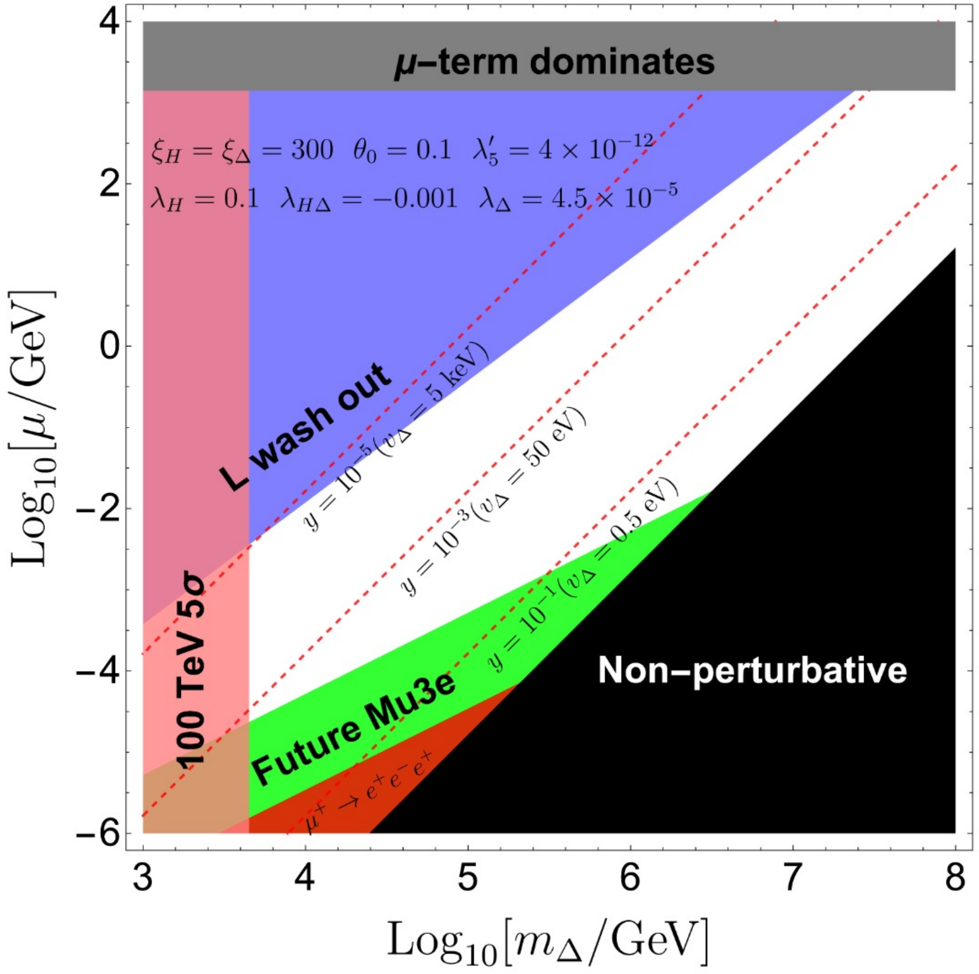
$\xi = 300,\ \lambda = 4.5 \cdot 10^{-5}$

$\chi_0 = 6.0 M_p,\ \dot{\chi}_0 = 0$, and $\theta_0 = 0$



- Lepton number is generated during inflation
- After inflation, Lepton number is conserved

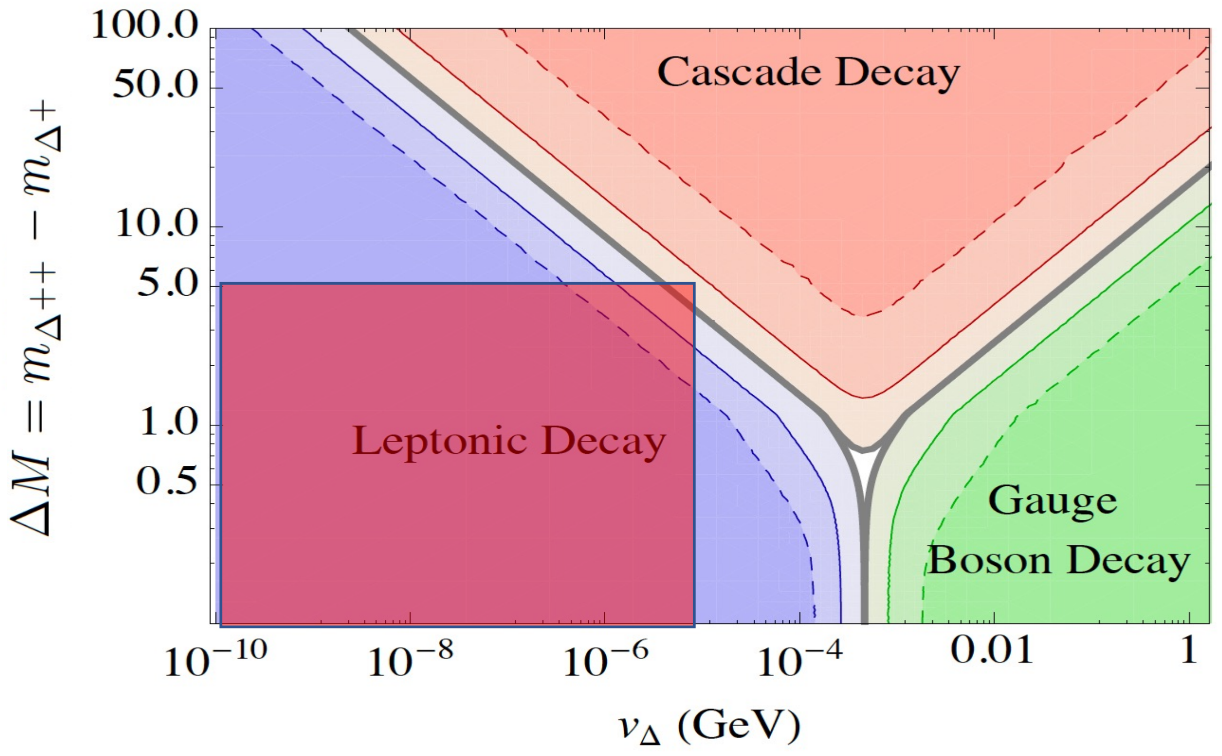
Type II seesaw leptogenesis



Higgs triplet can be as light as TeV

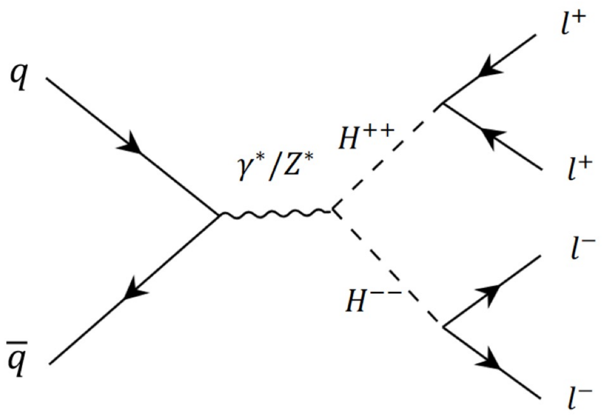
Collider searches

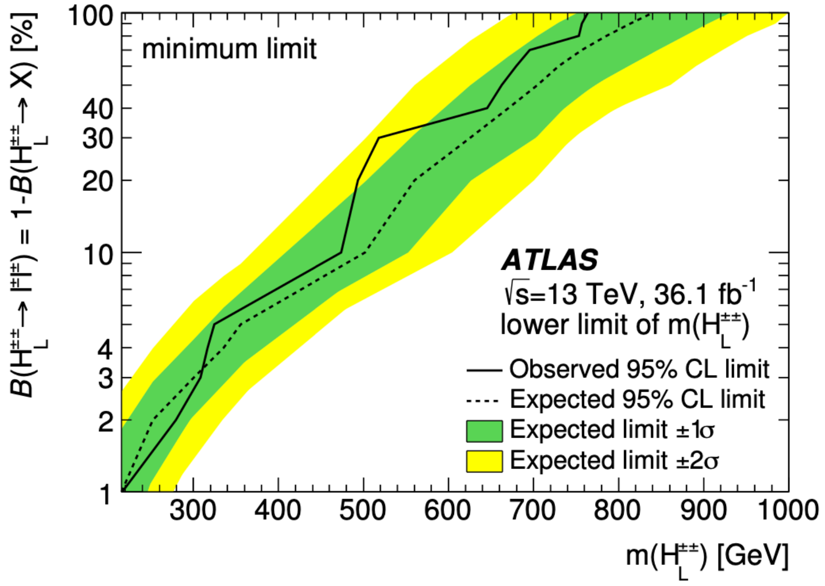
Decay of the doubly-charged Higgs



- For v > 1 MeV, mainly decay gauge bosons
- For v < 0.1 MeV, mainly decay leptons

Collider searches

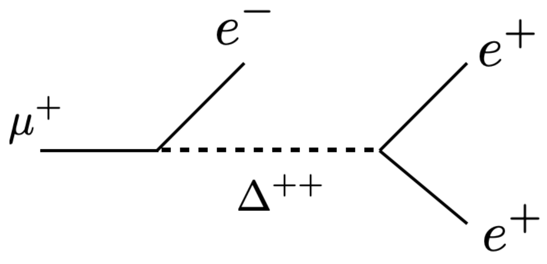




Smoking gun: observing doubly-charged Higgs from leptonic channel

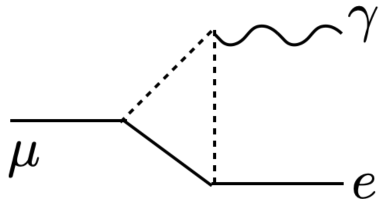
Lepton flavor violation

$$\mathcal{B}(\mu^+ \to e^+e^-e^+) = \frac{|y_{\mu e}y^\dagger_{ee}|^2}{16G_F^2 m^4_{\Delta^{++}}}$$



$$\mathcal{B}(\mu^+ \to e^+e^-e^+) \leqslant 1.0 \times 10^{-12}$$

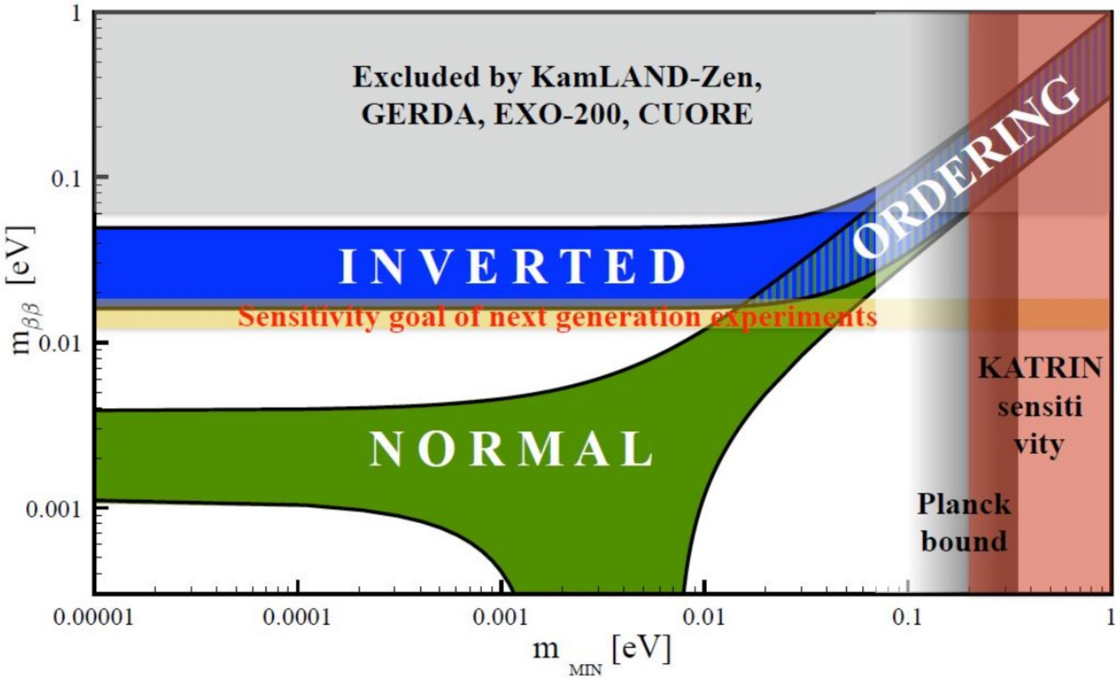
$$\mathcal{B}(\mu \to e\gamma) \simeq \frac{\alpha}{3072\pi} \frac{\left|(y^\dagger y)_{e\mu}\right|^2}{G_F^2} \left(\frac{1}{m^2_{\Delta^+}} + \frac{8}{m^2_{\Delta^{++}}}\right)^2$$

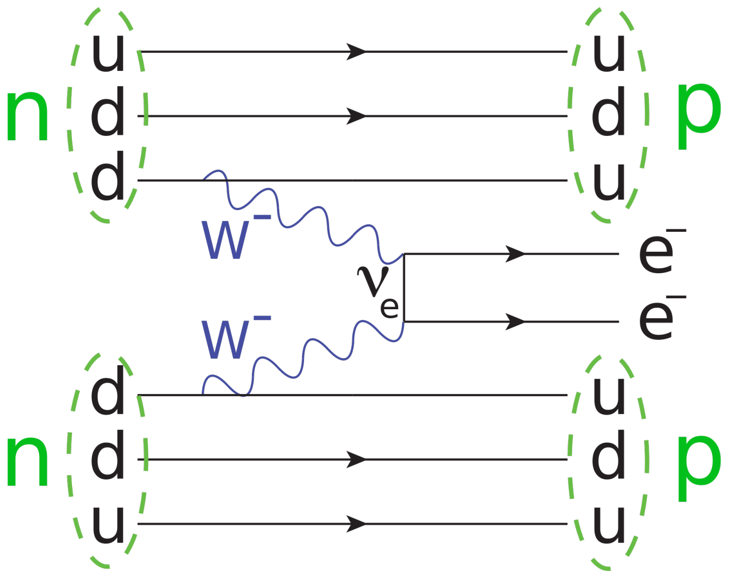


$$\mathcal{B}(\mu \to e\gamma) < 4.2 \times 10^{-13}$$

Neutrino physics

Neutrinos are majorana-type





Comments

"Leptogenesis" (Phys. Rept.) **Sacha Davidson** in their recent paper JHEP 11 (2023) 101 comment that "TeV Type II seesaw can lead successful leptogenesis"

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

Pontecorvo award **S. T. Petcov** in JHEP 01 (2023) 001 comment that

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].

Summary

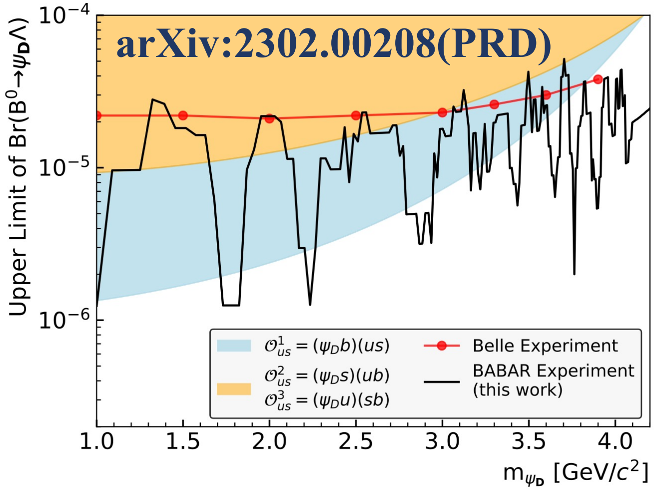
- **Baryon asymmetry remains one of big challenges for particle physics and cosmology**
- **Leptogenesis provide a feasible way to address the origin of neutrino masses as well as baryon asymmetry**
- **Future experiment would provide more clues for the Type I/II/III seesaw leptogenesis**

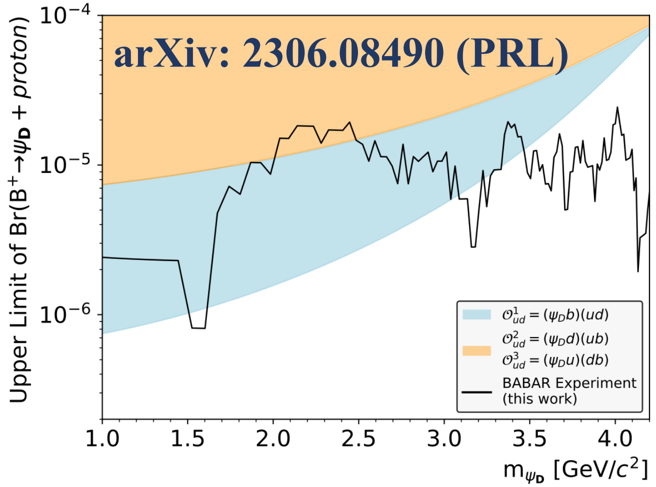
THANK YOU

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



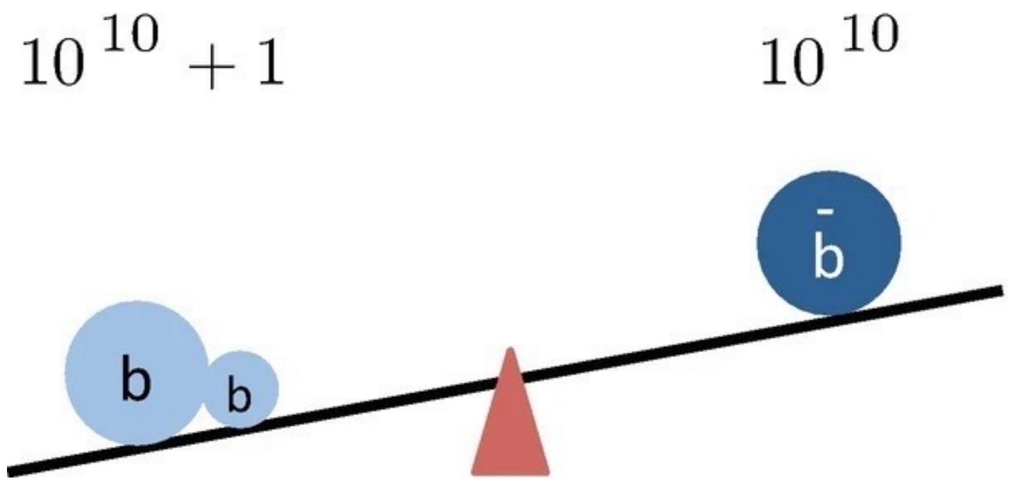


Baryon asymmetry

In very early universe(t <10^{-5} s) $n_b \approx n_{\bar{b}} \sim n_\gamma$

During 10^{-5} s- 3min, most of baryon and ant-baryon annihilate

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



- **Why are there difference?**
- **Why the difference so small?**