Type II Seesaw leptogenesis

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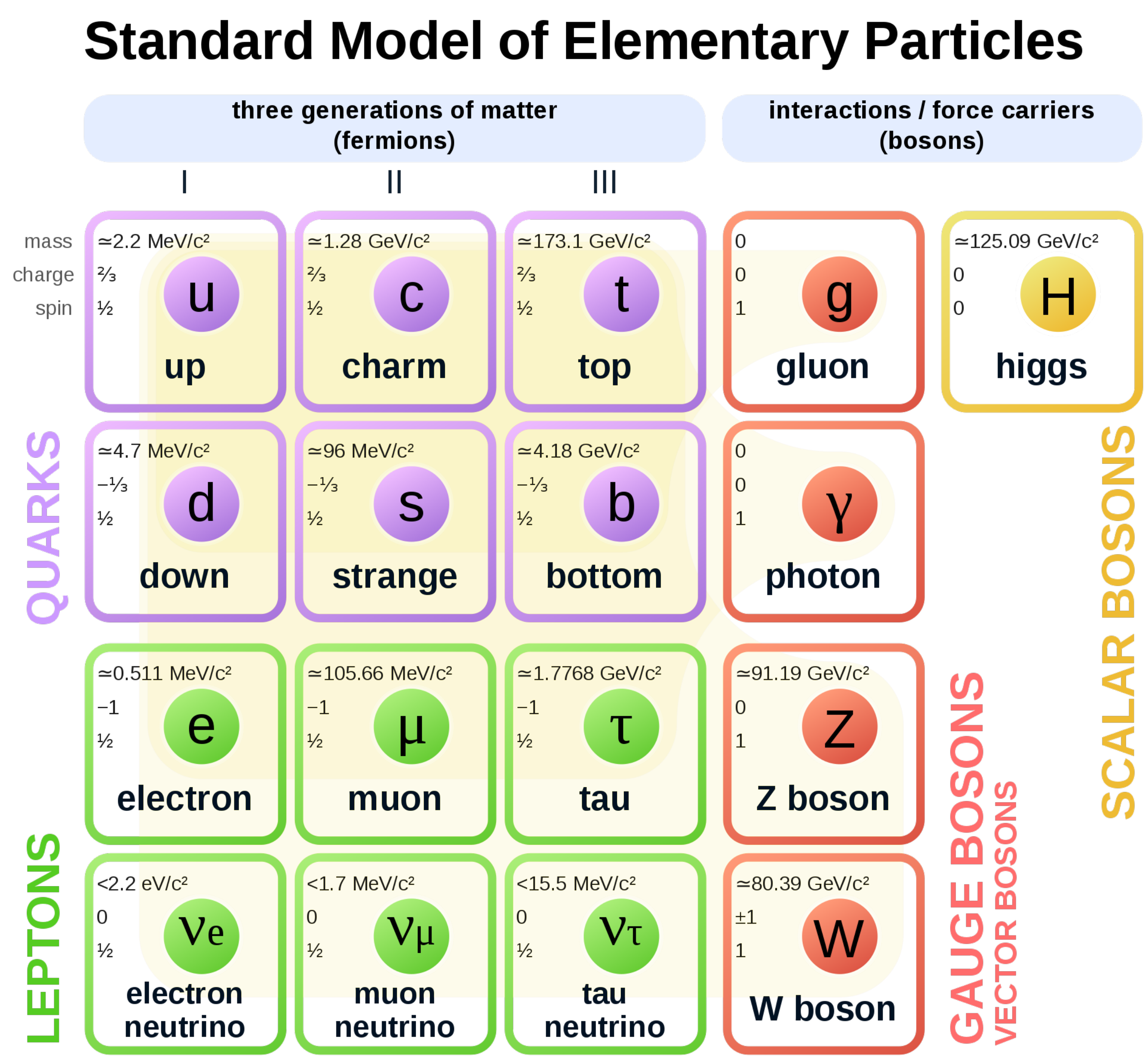
arXiv:2106.03381(Phys. Rev. Lett. 128, 141801) and

arXiv:2204.08202(JHEP 05 (2022) 160)

华中师范大学

2023.4.24

Standard model



Very successful describing low energy scale physics

Observation requiring new physics

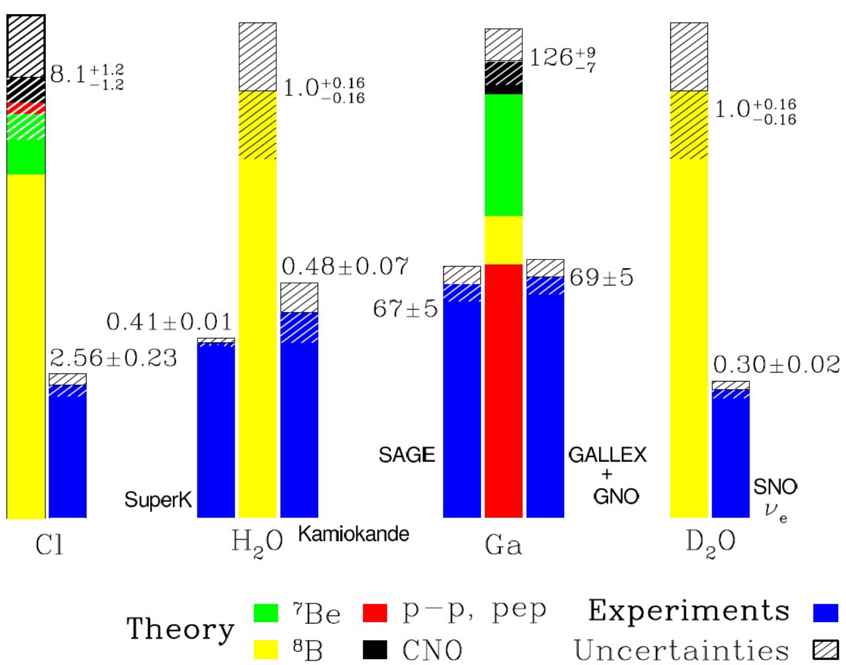
- Neutrino masses
- Baryon asymmetry of our universe
- Inflation

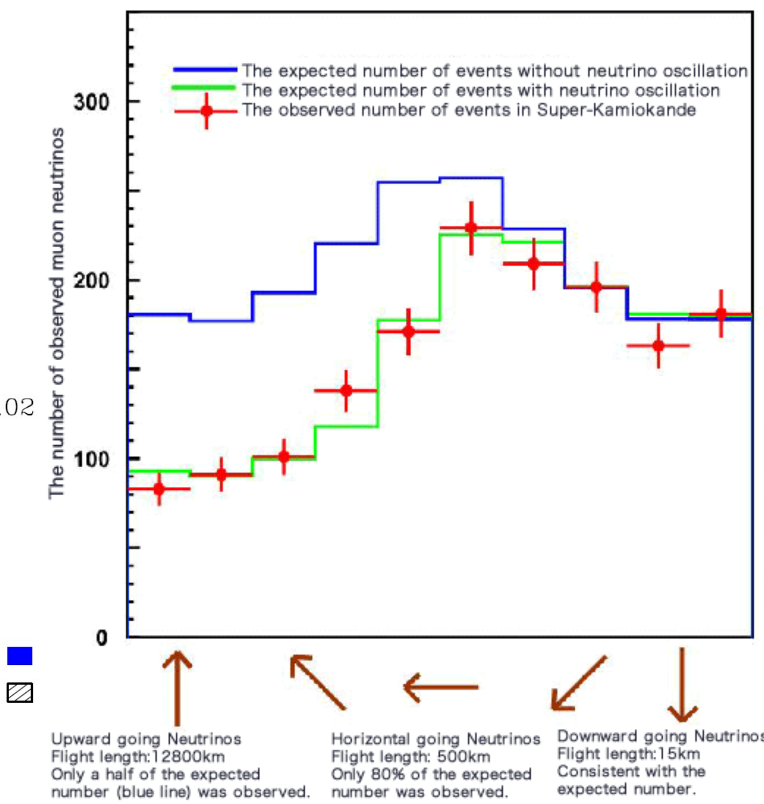
today's talk

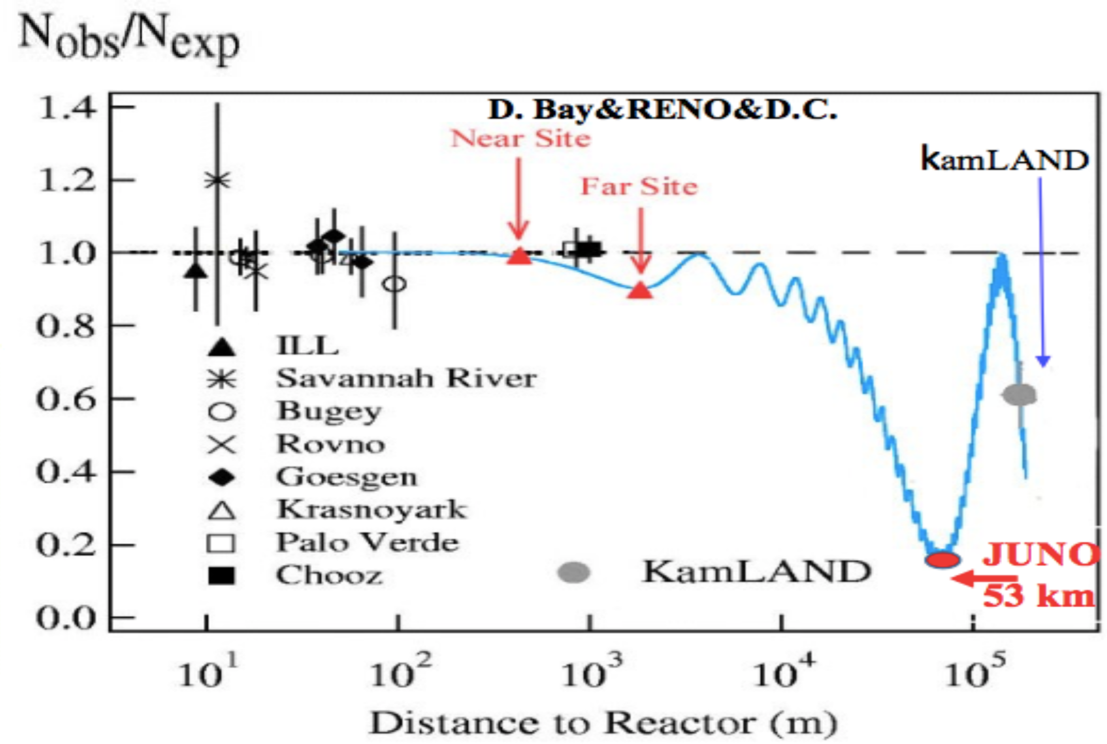
- Dark matter
- Others(muon g-2? W mass?)

Neutrino masses

Neutrino oscillation requiring massive neutrinos







Solar Neutrino oscillations θ_{12}

Atmospheric Neutrino Oscillations θ_{23}

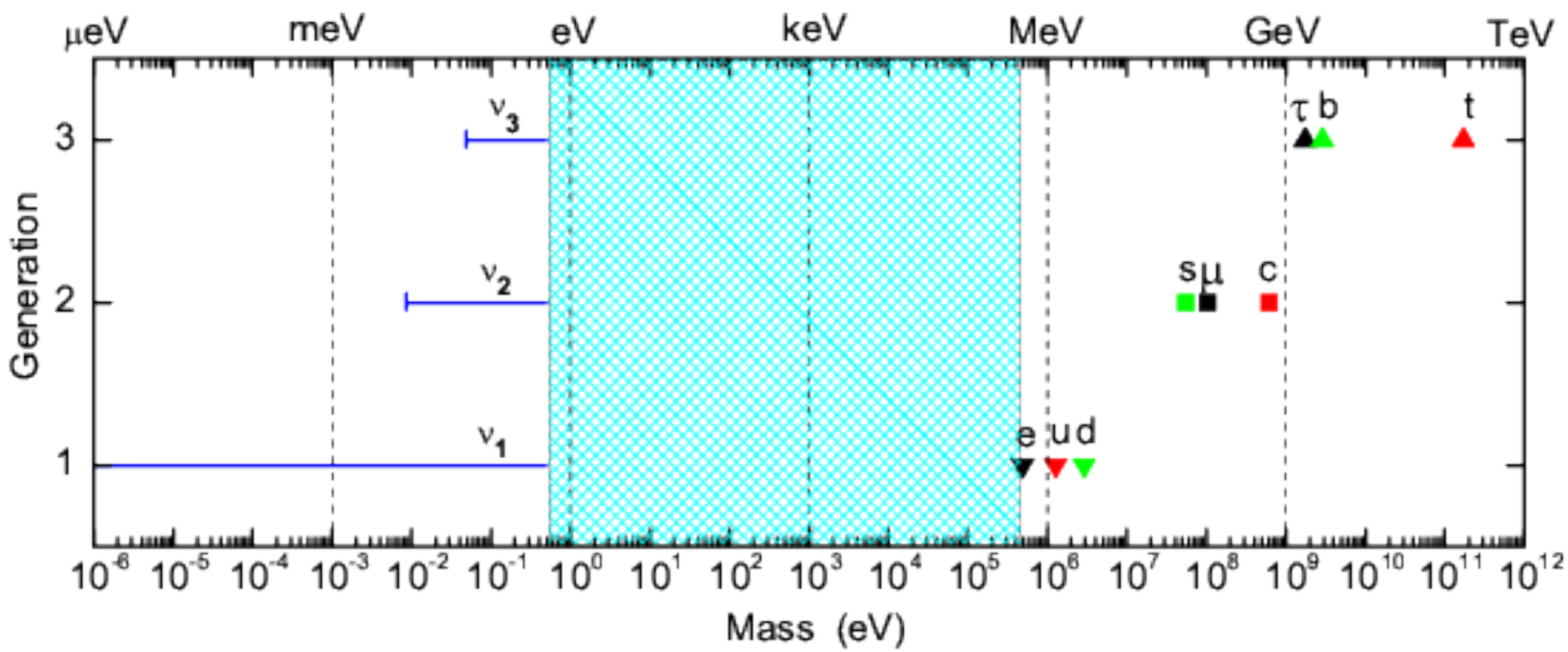
Reactor Neutrino Oscillations θ_{13}

$$\Delta m^2_{21} \simeq 7.42 \times 10^{-5}\ \mathrm{eV}^2 \qquad |\Delta m^2_{13}| \approx |\Delta m^2_{23}| \simeq 2.5 \times 10^{-3}\ \mathrm{eV}^2$$

At least a neutrino mass larger or similar to 0.05 eV

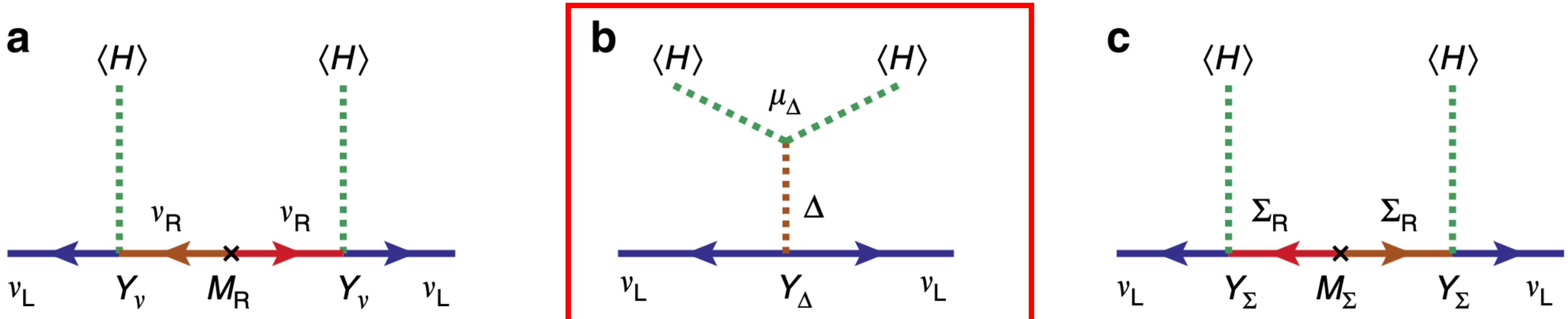
Neutrino masses vs other fermion masses

A large hierarchy comparing with other fermion masses



Three types of seesaw model(tree level)

Tommy Ohlsson, Shun Zhou, Nature Commun. 5 (2014) 5153



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

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

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

SM + 3 singlets fermions

SM + 1 triplet Higgs

SM + 3 triplet fermions

scalar

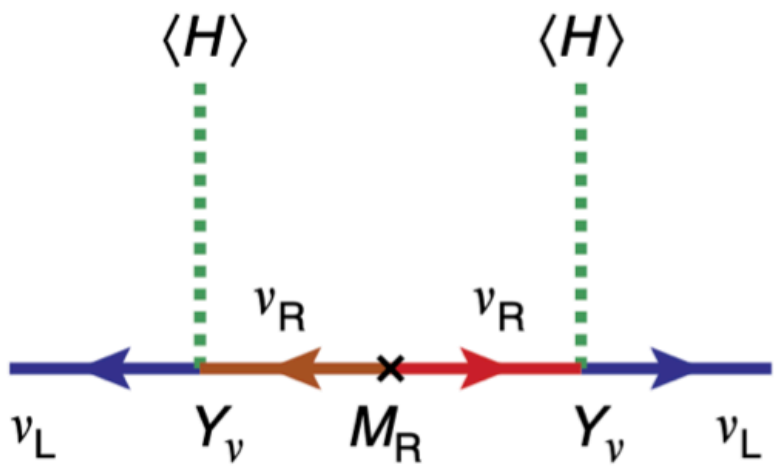
Origin of neutrino masses: type I seesaw

加入三个单态中性右手中微子 N(1, 1, 0)

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

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

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



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

中微子质量被压低!

Origin of neutrino masses: type II seesaw

引入一个希格斯三重态跟中微子直接耦合

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

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

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

$$\downarrow$$

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

- Giving neutrino mass matrix with vev of Delta
- at the same time Delta get a lepton number -2

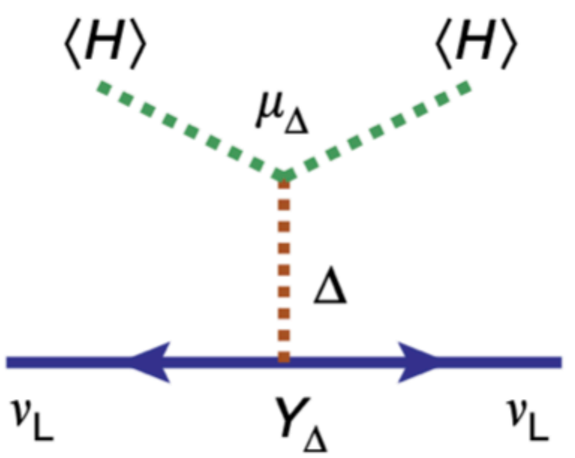
Origin of neutrino masses: type II seesaw

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

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

U(1)L breaking term

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



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

电弱精确测量限制

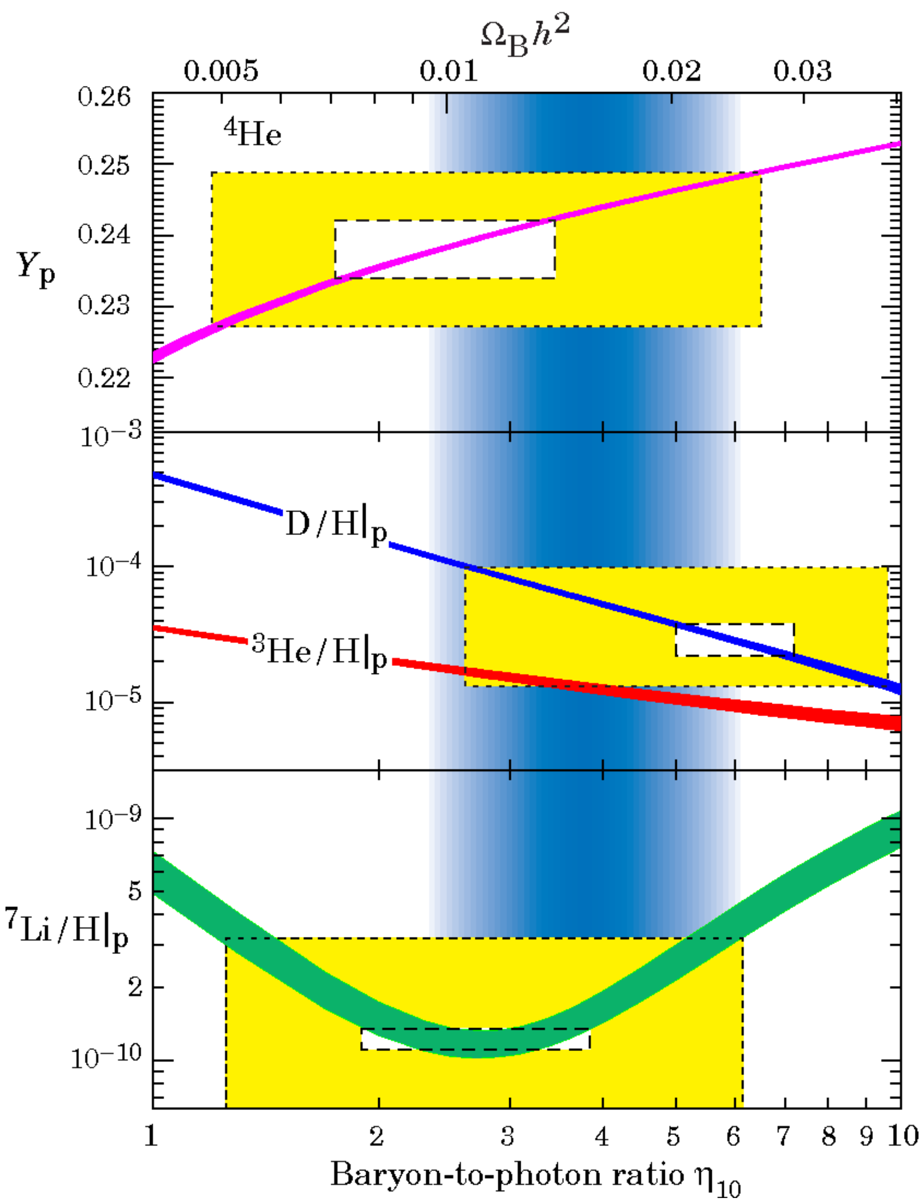
$$\mathcal{O}(1)\ \mathrm{GeV} > |\langle \Delta^0 \rangle| \gtrsim 0.05\ \mathrm{eV}$$

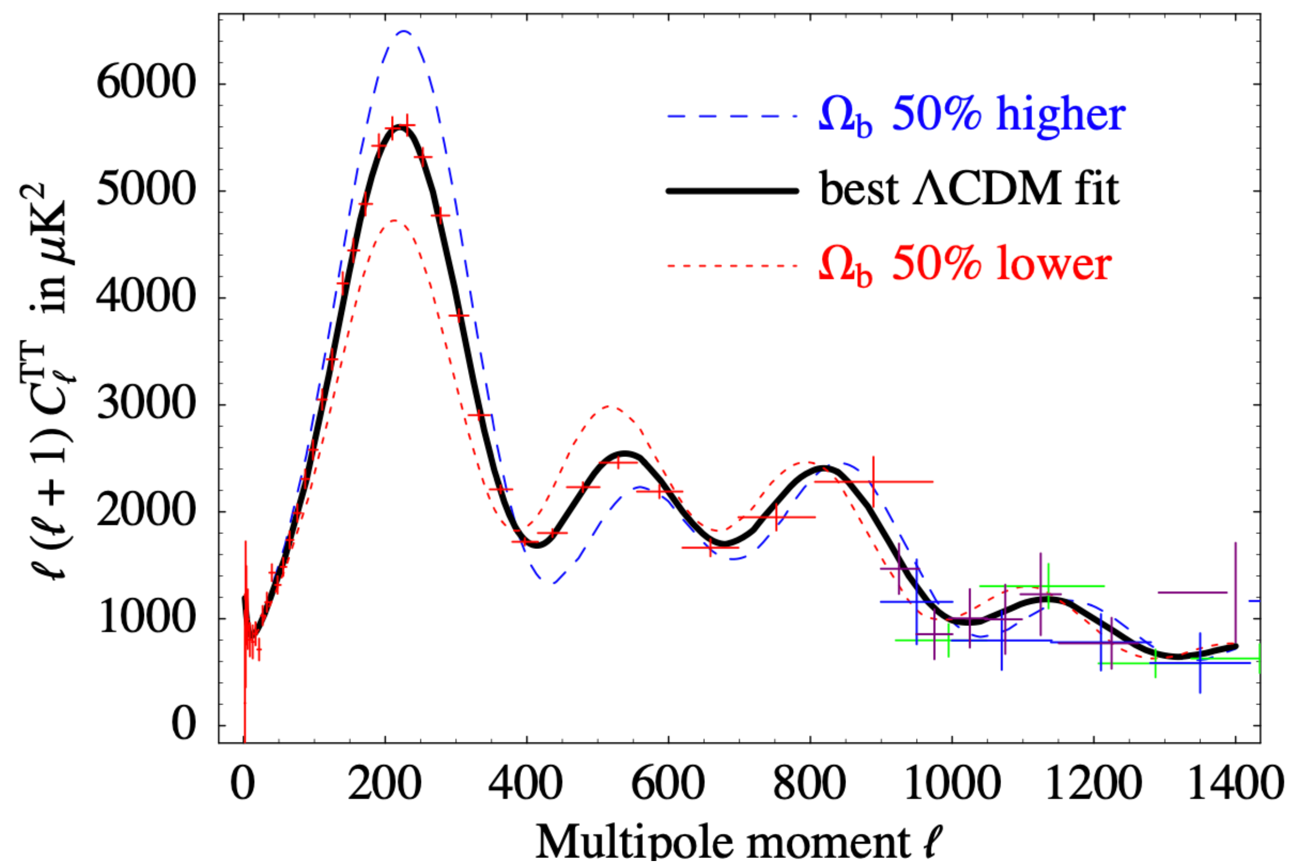
中微子质量要求

Neutrino masses connecting another important problem:

Baryon asymmetry of our universe

Baryon asymmetry of our universe





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 ± 0.0001
$\Omega_c h^2$	0.12011	0.1200 ± 0.0012	0.1197 ± 0.0012	−0.3	0.1198 ± 0.0012

BBN

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

Without baryon asymmetry: too less matter

$$\frac{n_b}{s} = \frac{n_{\bar{b}}}{s} \sim 10^{-20}$$

How to generate baryon asymmetry?

Assuming no baryon asymmetry in the beginning
(if any, diluted by inflation)

Sakharov conditions

1. B number violation
2. C and CP violation
3. Out of thermal equilibrium

SM has (1) (2) but not enough CP violation, (3) does not

CP violation in neutrino sector → Baryogenesis via leptogenes

Three popular ways to generate baryon asymmetry

- **Electroweak baryogenesis**

Rubakov and Shaposhnikov, 1996'
D. E. Morrissey and M. J. Ramsey-Musolf, 2012'

First order phase transition (adding scalars) + additional $\not{C}P$

Electroweak baryon number nonconservation in the early universe and in high-energy collisions
V.A. Rubakov (Moscow, INR), M.E. Shaposhnikov (CERN and Moscow, INR) (Mar, 1996)
Published in: *Usp.Fiz.Nauk* 166 (1996) 493-537, *Phys.Usp.* 39 (1996) 461-502, Phys. Usp. 39 (1996) 1276. (Erratum)
• e-Print: hep-ph/9603208 [hep-ph]
pdf DOI cite 833 citations

- **Baryogenesis via thermal leptogenesis**

Fukugita and Yanagida, 1986'

Connection to neutrino masses

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

Baryogenesis Without Grand Unification
M. Fukugita (Kyoto U., Yukawa Inst., Kyoto), T. Yanagida (Tohoku U.) (Jan, 1986)
Published in: *Phys.Lett.B* 174 (1986) 45-47
pdf DOI cite 3,675 citations

- **Baryogenesis from Affleck-Dine mechanism**

Affleck and Dine, 1985'

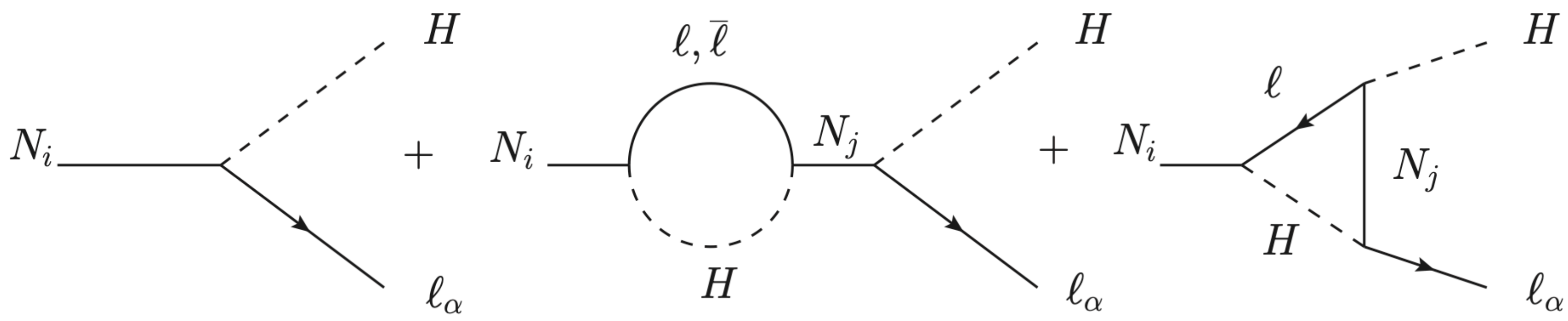
A New Mechanism for Baryogenesis
Ian Affleck (Princeton U.), Michael Dine (Princeton, Inst. Advanced Study) (Jun, 1984)
Published in: *Nucl.Phys.B* 249 (1985) 361-380
DOI cite 1,253 citations

A well-known mechanism for high energy physics society

Baryogenesis via leptogenesis from Type I seesaw

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

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



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

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

Generally N mass > 10^7 GeV, difficult to probe

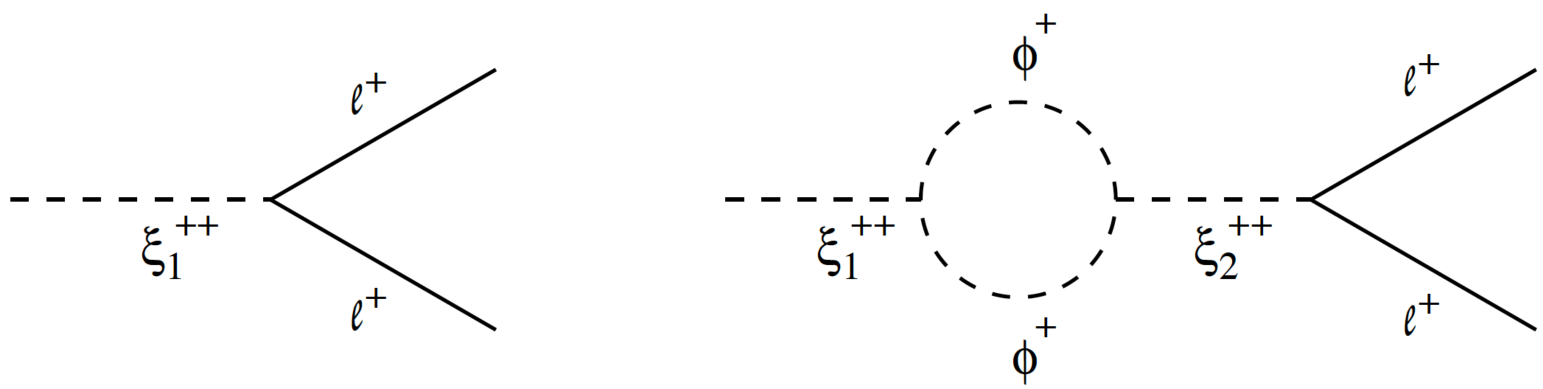
How about type II seesaw leptogenesis?

Leptogenesis from type II seesaw?

Type II seesaw

Neutrino Masses and Leptogenesis with Heavy Higgs Triplets (**500+ citations**)
E. Ma, U. Sarkar, Phys.Rev.Lett. 80 (1998) 5716-5719

$M \sim 10^{13}$ GeV



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

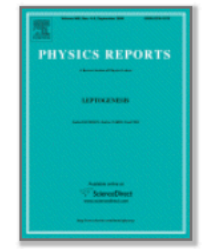
$$\delta_i = \frac{Im\left[\mu_1 \mu_2^* \sum_{k,l} y_{1kl} y_{2kl}^*\right]}{8\pi^2(M_1^2 - M_2^2)} \left[\frac{M_i}{\Gamma_i}\right]$$

At least two triplet Higgs are needed to generate the baryon asymmetry

But one triplet Higgs is enough to give neutrino masses

Leptogenesis from type II seesaw?

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



Leptogenesis **(1,000+ 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

One triplet Higgs can not generate leptogenesis!
but it is enough to give neutrino masses!

Leptogenesis from type II seesaw

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

Affleck-Dine Leptogenesis from Higgs Inflation

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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 vacuum expectation value for the triplet $v_\Delta < 10$ keV. This requires that the triplet Higgs must decay dominantly into the leptonic channel. Additionally, this model will be probed at the future 100 TeV collider, upcoming lepton flavor violation experiments such as Mu3e, and neutrinoless double beta decay experiments. Thus, this simple framework provides a unified solution to the three major unknowns of modern physics—inflation, the neutrino masses, and the observed baryon asymmetry—while simultaneously providing unique phenomenological predictions that will be probed terrestrially at upcoming experiments.

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 violation)

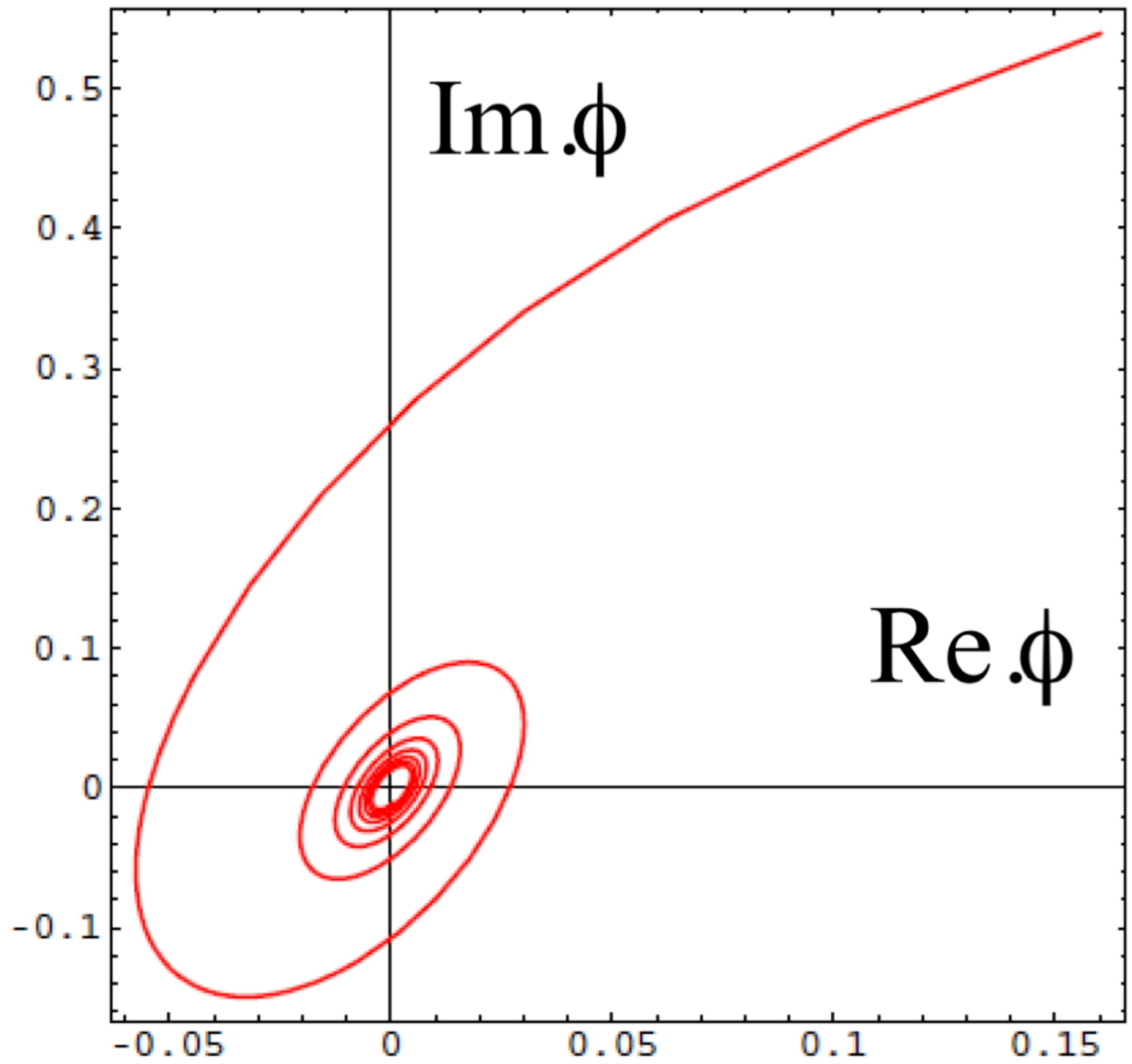
$$j_B^\mu = i(\phi^*\partial^\mu\phi - \phi\partial^\mu\phi^*)$$

ϕ is spatially constant

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

A motion of theta will generate baryon number

Affleck-Dine mechanism



CP is spontaneously broken by <phi>

Affleck-Dine mechanism

Three conditions for Affleck-Dine mechanism

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

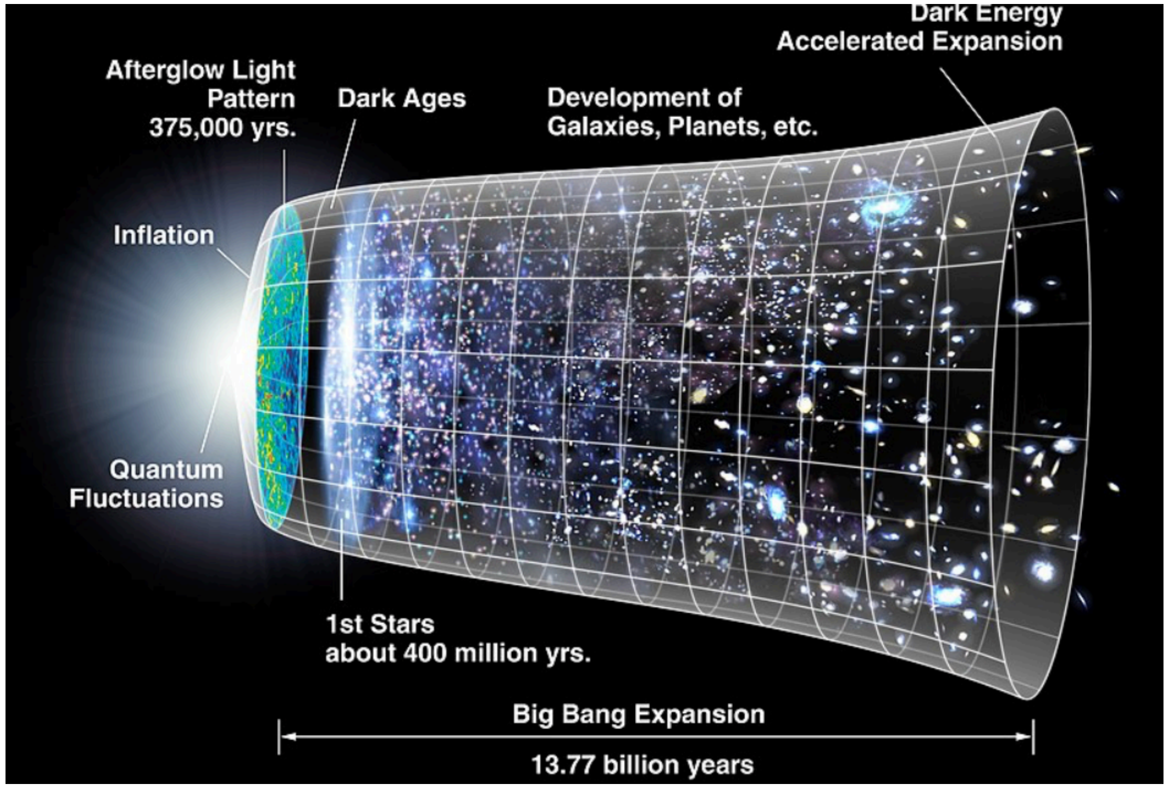
Combing the idea of inflation with A-D mechanism

Three conditions for Affleck-Dine mechanism

If the scalar plays the role of inflation	Type II seesaw
● Scalar particle with initial displaced vacuum	✓
● Scalar particle taking B/L charge	✓
● Small B/L violation term in the potential	✓

Inflation

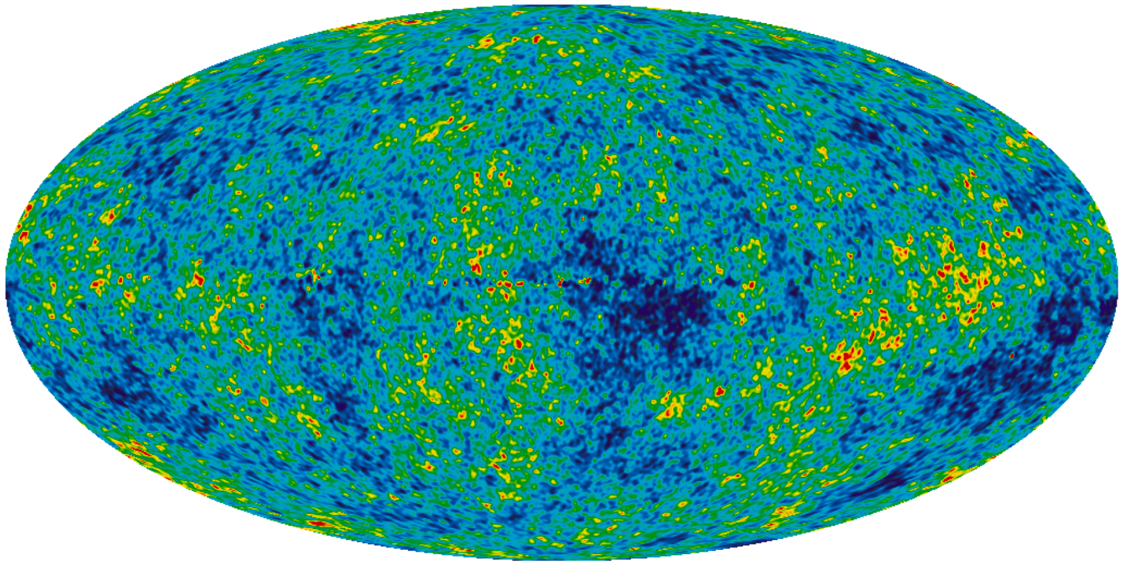
Rapid expansion of the universe in the early time

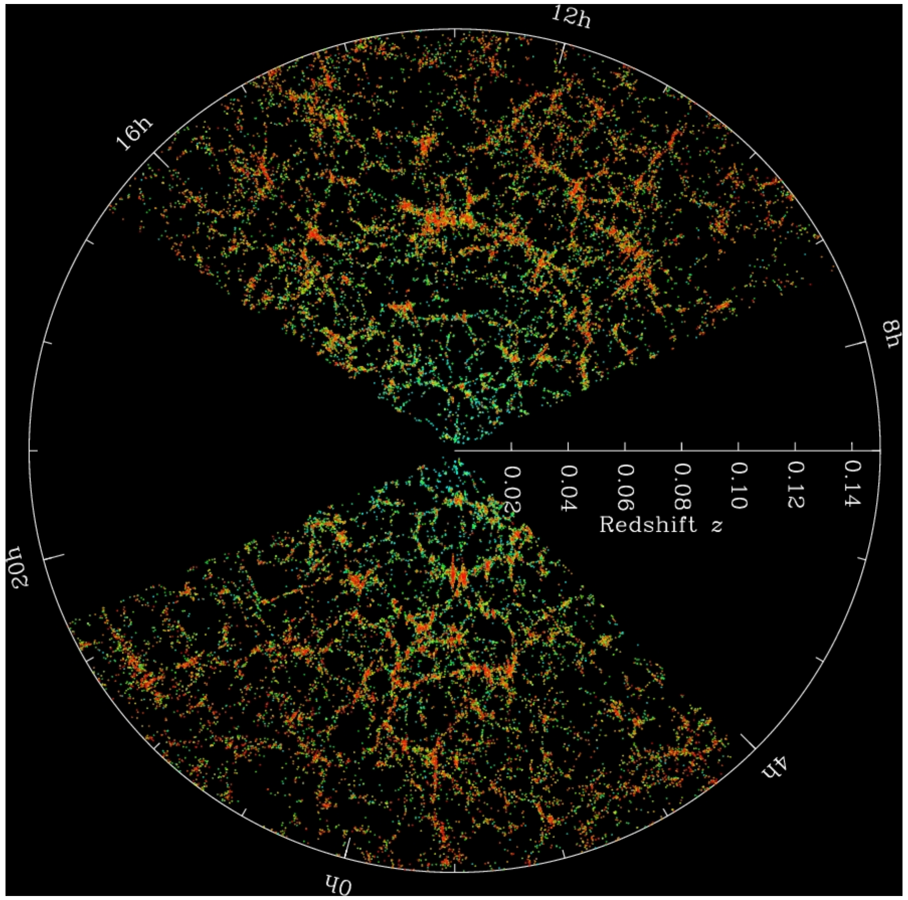


- Flatness problem
- Horizon problem
- Seeding the primordial anisotropies in CMB

Inflation

Generating quantum fluctuations(anisotropies in CMB)





$$\frac{\delta T}{T} \sim 10^{-5}$$

Such small fluctuations finally develops the large structure of our universe

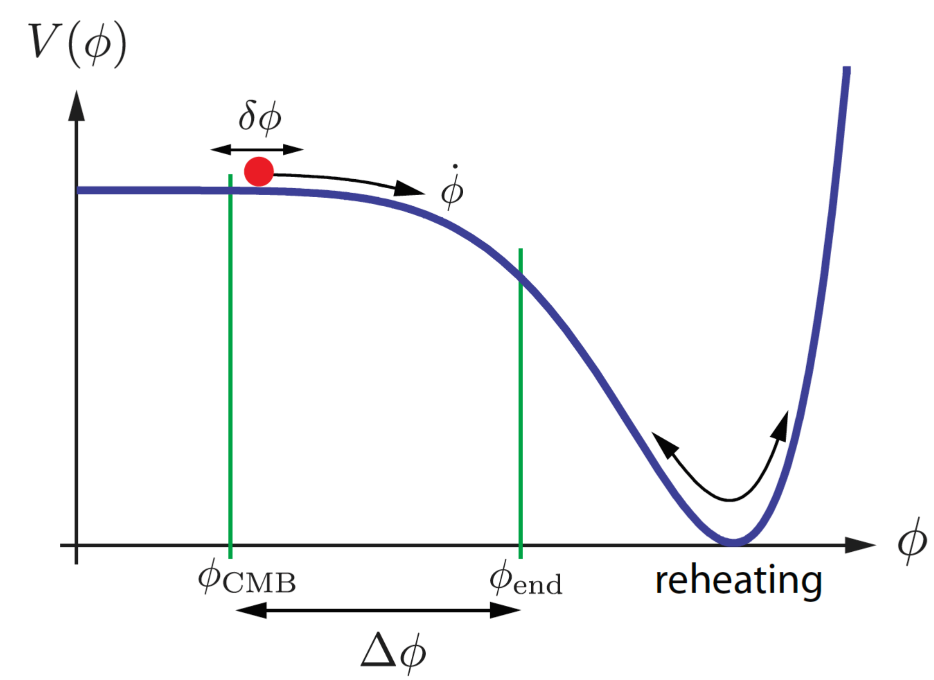
Slow-roll inflation

Assume a scalar field, with equation of motion

$$\ddot{\phi} + 3H\dot{\phi} + \frac{\partial V}{\partial \phi} = 0$$

$$H^2 = \frac{1}{3}\left(\frac{1}{2}\dot{\phi}^2 + V(\phi)\right)$$

Slow roll condition



$$\epsilon_{\rm v}(\phi) \equiv \frac{M_{\rm pl}^2}{2}\left(\frac{V_{,\phi}}{V}\right)^2 \qquad \eta_{\rm v}(\phi) \equiv M_{\rm pl}^2 \frac{V_{,\phi\phi}}{V}$$

$$\epsilon_{\rm v}, |\eta_{\rm v}| \ll 1$$

$$H^2 \approx \frac{1}{3}V(\phi) \approx \text{const.}$$

$$\dot{\phi} \approx -\frac{V_{,\phi}}{3H},$$

$\longrightarrow$ $a(t) \sim e^{Ht}$

Daniel Baumann, TASI Lectures on Inflation

SM+Type II seesaw

To be consistent with inflation, we need add non-minimal couplings

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

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

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

SM+Type II seesaw

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

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

$$\rho_H = \varphi \sin\alpha, \ \ \rho_\Delta = \varphi \cos\alpha$$
$$\xi \equiv \xi_H \sin^2\alpha + \xi_\Delta \cos^2\alpha$$

Similar to SUSY case, but mixing with a general angle

SM+Type II seesaw

Finally the model can be simplified as

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

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

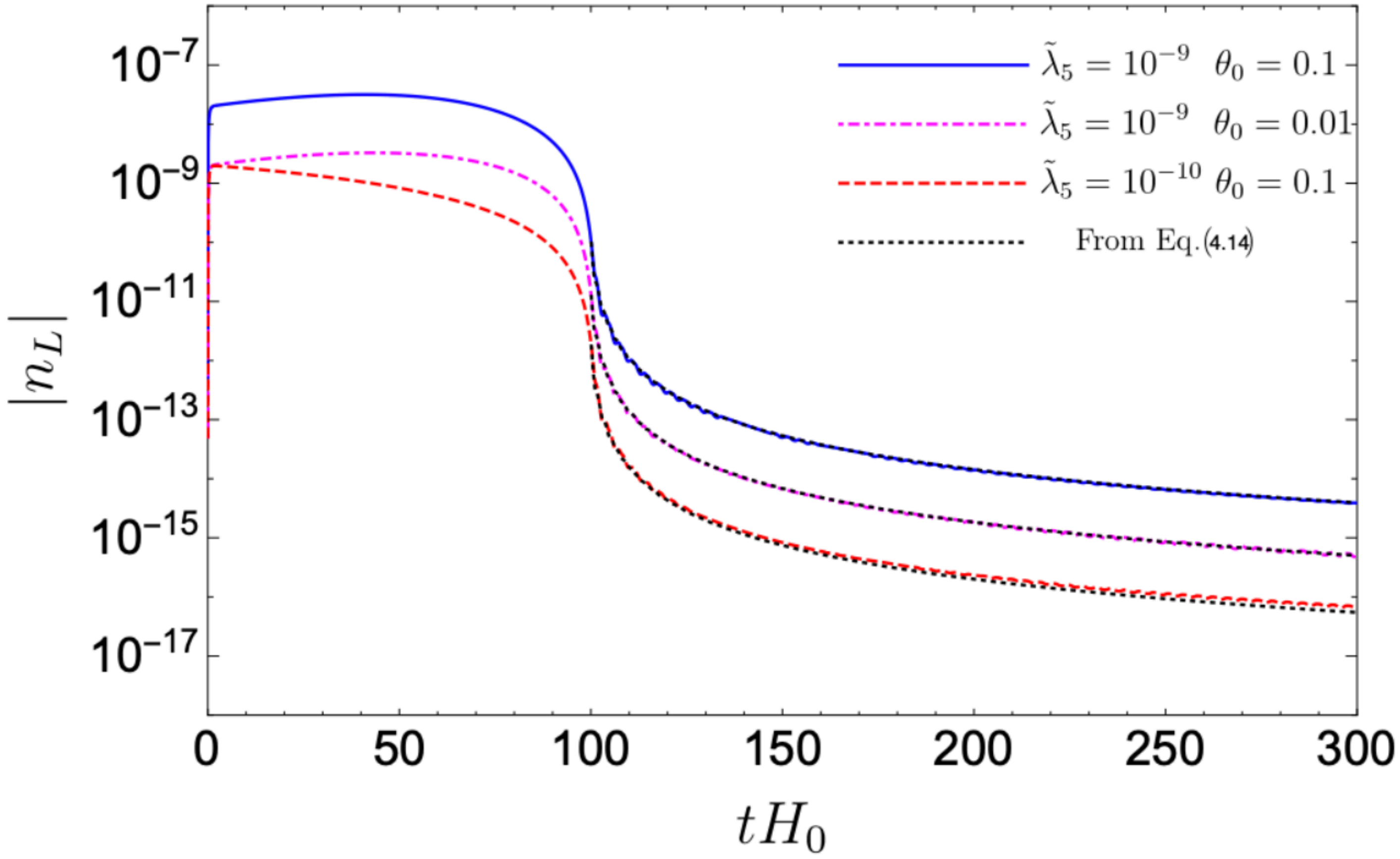
We need keep the theta term, because

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

Lepton number generation

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

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



- 暴胀开始轻子数为0
- 轻子数在暴胀过程中产生
- 暴胀结束后轻子数守恒

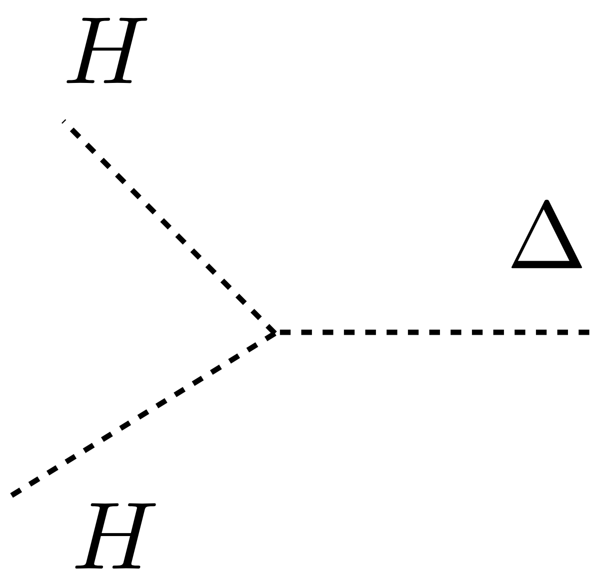
SM+Type II seesaw

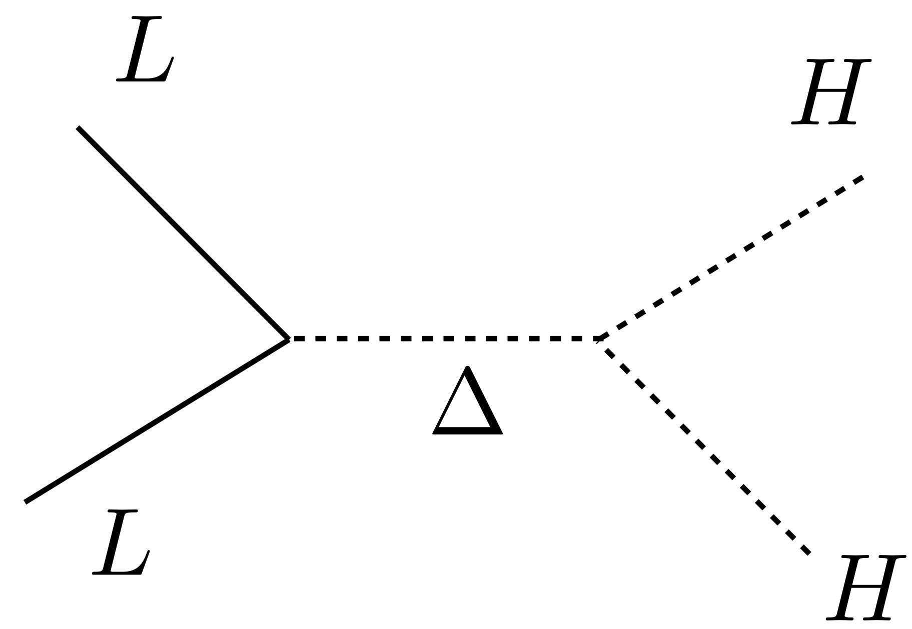
$$T_{\rm reh} \approx 2.2 \cdot 10^{14}\ {\rm GeV}$$

$$\eta_B = \frac{n_B}{s}\bigg|_{\rm reh} = \eta_B^{\rm obs} \left(\frac{|n_{L{\rm end}}|/M_p^3}{1.3 \cdot 10^{-16}} \right) \left(\frac{g_*}{112.75} \right)^{-\frac{1}{4}}$$

$$\tilde{\lambda}_5 = 7 \cdot 10^{-15}\ {\rm for}\ \theta_0 = 0.1$$

Wash out process



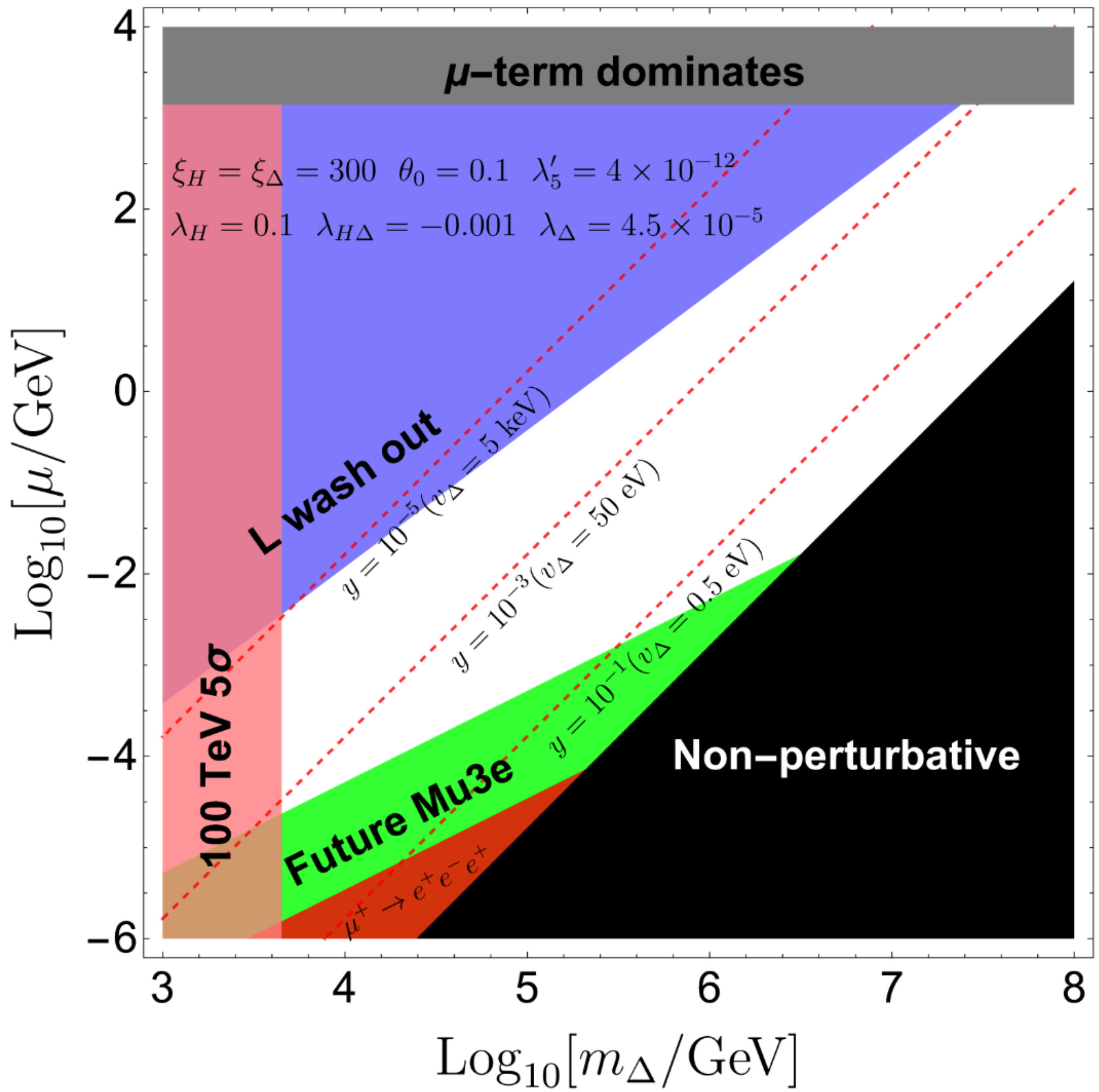


$$\frac{\mu^2}{8\pi m_\Delta} < H(m) = \frac{m_\Delta^2}{M_P}$$

$$m_\Delta < 10^{12}\ \mathrm{GeV}$$

A small mu term is preferred

SM+Type II seesaw

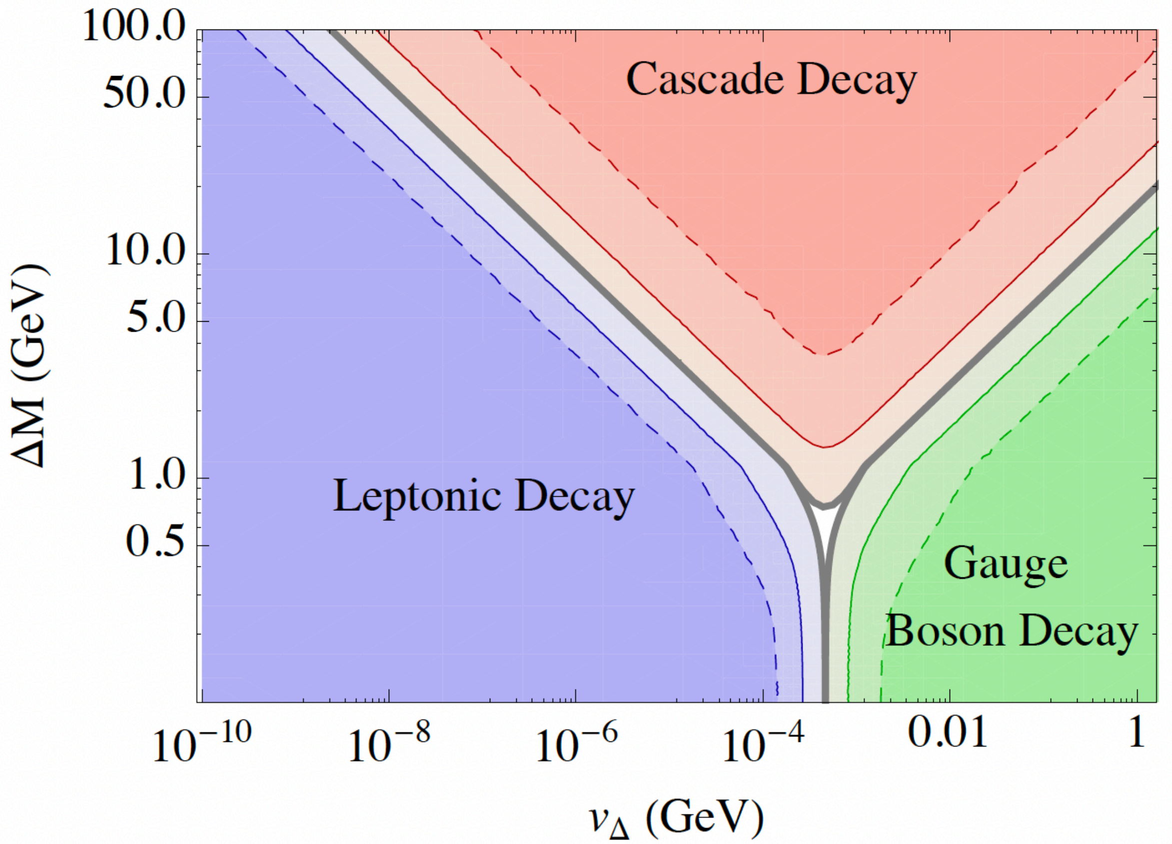


- Triplet Higgs could be as light as TeV
- Vacuum value < 10 keV, traditional type II seesaw < 1 GeV

Phenomenology implications I: collider physics

Decay of the doubly-charged Higgs

$$\Delta M = m_{\Delta^{++}} - m_{\Delta^{+}}$$



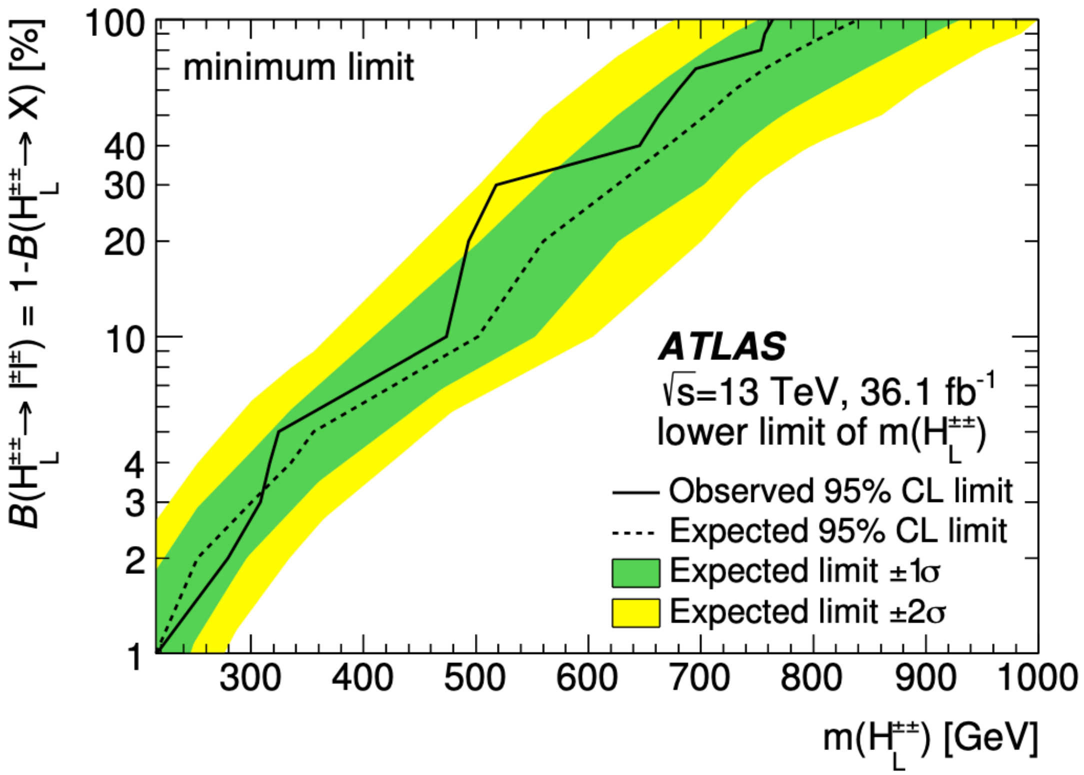
For v > 1 MeV, mainly decay gauge bosons

For v < 0.1 MeV, mainly decay leptons

Phenomenology implications I: collider physics

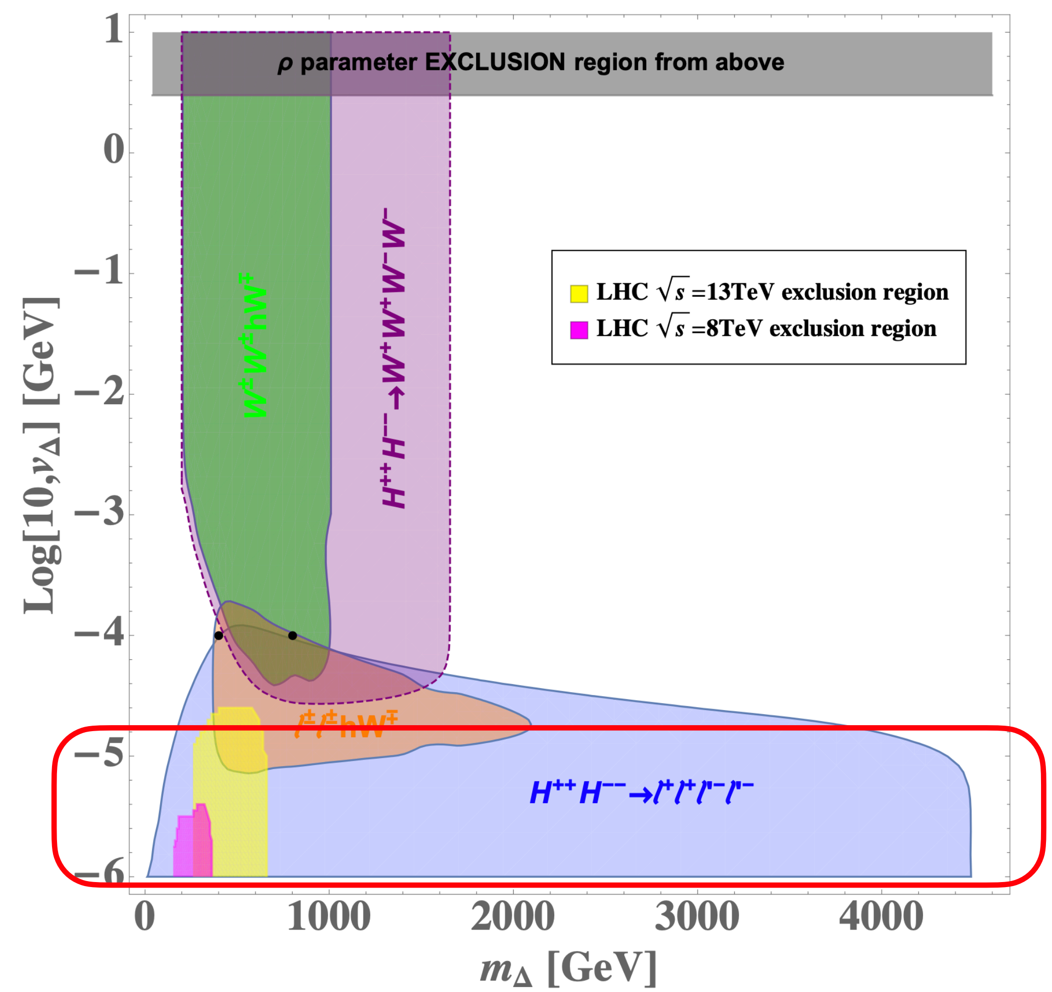
Current limit from LHC

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



Future reach

Y. Du, A. Dunbrack, M. J. Ramsey-Musolf, J. Yu, JHEP01(2019)101

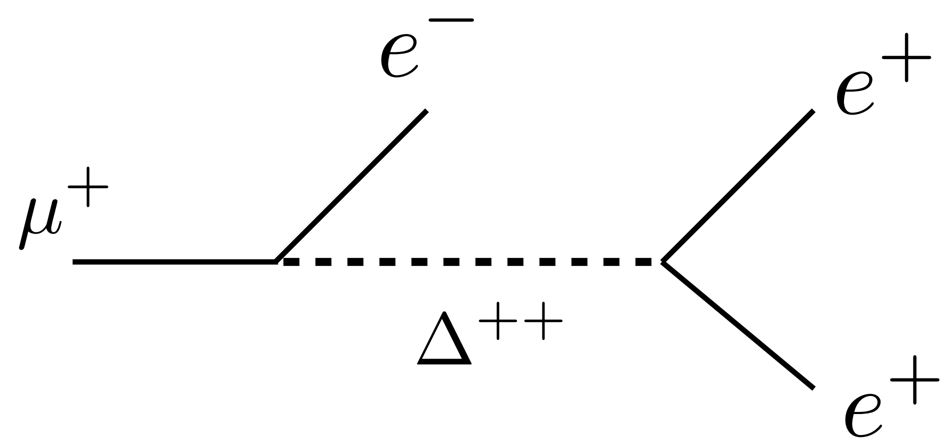


5 sigma discover region @100 TeV collider

Smoking gun: observing doubly-charged Higgs from leptonic channel

Phenomenology implications II: flavor physics

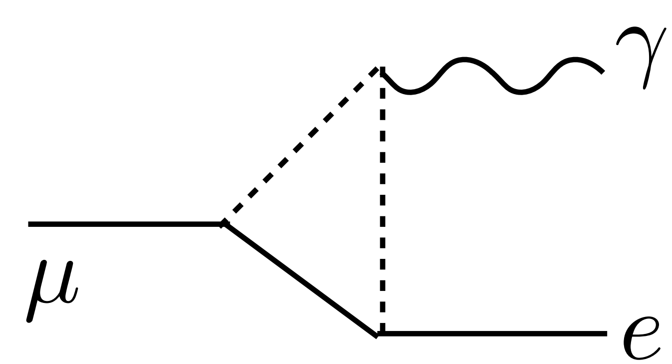
$$\mathcal{B}(\mu^+ \to e^+ e^- e^+) = \frac{|y_{\mu e} y^\dagger_{ee}|^2}{16 G_F^2 m^4_{\Delta^{++}}}$$



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

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

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



Phenomenology implications II: flavor physics

2201.04646, Y. Du, X. Li, J. Yu

Type: $\psi_L\psi_L\psi_R\psi_R$

Operator	Type-I	Type-II	Type-III
$\mathcal{O}_{le,prst}$	$\frac{1}{8M^2}(3+2L)(Y_\nu Y_\nu^\dagger)^{pr}(Y_e^\dagger Y_e)^{st}$ $-\frac{1}{6M^2}\mathrm{tr}(Y_\nu Y_\nu^\dagger)Y_e^{pt}Y_e^{*rs}$ $+\frac{1}{4M^2}(Y_\nu Y_\nu^\dagger Y_e)^{pt}Y_e^{*rs}$ $+\frac{1}{4M^2}Y_e^{pt}(Y_e^\dagger Y_\nu Y_\nu^\dagger)^{sr}$ $-\frac{g_1^2}{72M^2}(11+6L)(Y_\nu Y_\nu^\dagger)^{pr}\delta^{st}$	$-\frac{3}{8M^2}(3+2L)(Y_\nu^\dagger Y_e^*)^{ps}(Y_e^T Y_\nu)^{tr}$ $-\frac{\mu^2}{4M^2}Y_e^{pt}Y_e^{*rs}-\frac{g_1^4}{20M^2}\delta^{pr}\delta^{st}$ $+\frac{g_1^2}{6M^2}(5+3L)(Y_\nu^\dagger Y_\nu)^{pr}\delta^{st}$	$\frac{3}{8M^2}(3+2L)(Y_\Sigma^\dagger Y_\Sigma)^{pr}(Y_e^\dagger Y_e)^{st}$ $-\frac{1}{2M^2}\mathrm{tr}(Y_\Sigma^\dagger Y_\Sigma)Y_e^{pt}Y_e^{*rs}$ $-\frac{3}{4M^2}(Y_\Sigma^\dagger Y_\Sigma Y_e)^{pt}Y_e^{*rs}$ $-\frac{3}{4M^2}Y_e^{pt}(Y_e^\dagger Y_\Sigma^\dagger Y_\Sigma)^{sr}$ $-\frac{g_1^2}{24M^2}(11+6L)(Y_\Sigma^\dagger Y_\Sigma)^{pr}\delta^{st}$
$\mathcal{O}_{lu,prst}$	$-\frac{1}{8M^2}(3+2L)(Y_\nu Y_\nu^\dagger)^{pr}(Y_u^\dagger Y_u)^{st}$ $+\frac{g_1^2}{108M^2}(11+6L)(Y_\nu Y_\nu^\dagger)^{pr}\delta^{st}$	$\frac{g_1^4}{30M^2}\delta^{pr}\delta^{st}-\frac{g_1^2}{9M^2}(5+3L)(Y_\nu^\dagger Y_\nu)^{pr}\delta^{st}$	$-\frac{3}{8M^2}(3+2L)(Y_\Sigma^\dagger Y_\Sigma)^{pr}(Y_u^\dagger Y_u)^{st}$ $+\frac{g_1^2}{36M^2}(11+6L)(Y_\Sigma^\dagger Y_\Sigma)^{pr}\delta^{st}$
$\mathcal{O}_{ld,prst}$	$\frac{1}{8M^2}(3+2L)(Y_\nu Y_\nu^\dagger)^{pr}(Y_d^\dagger Y_d)^{st}$ $-\frac{g_1^2}{216M^2}(11+6L)(Y_\nu Y_\nu^\dagger)^{pr}\delta^{st}$	$-\frac{g_1^4}{60M^2}\delta^{pr}\delta^{st}+\frac{g_1^2}{18M^2}(5+3L)(Y_\nu^\dagger Y_\nu)^{pr}\delta^{st}$	$\frac{3}{8M^2}(3+2L)(Y_\Sigma^\dagger Y_\Sigma)^{pr}(Y_d^\dagger Y_d)^{st}$ $-\frac{g_1^2}{72M^2}(11+6L)(Y_\Sigma^\dagger Y_\Sigma)^{pr}\delta^{st}$
$\mathcal{O}_{qe,prst}$		$\frac{g_1^4}{60M^2}\delta^{pr}\delta^{st}$	
$\mathcal{O}^{(1)}_{qu,prst}$	$-\frac{1}{18M^2}\mathrm{tr}(Y_\nu Y_\nu^\dagger)Y_u^{pt}Y_u^{*rs}$	$-\frac{\mu^2}{12M^4}Y_u^{pt}Y_u^{*rs}-\frac{g_1^4}{90M^2}\delta^{pr}\delta^{st}$	$-\frac{1}{6M^2}\mathrm{tr}(Y_\Sigma^\dagger Y_\Sigma)Y_u^{pt}Y_u^{*rs}$
$\mathcal{O}^{(8)}_{qu,prst}$	$-\frac{1}{3M^2}\mathrm{tr}(Y_\nu Y_\nu^\dagger)Y_u^{pt}Y_u^{*rs}$	$-\frac{\mu^2}{2M^4}Y_u^{pt}Y_u^{*rs}$	$-\frac{1}{M^2}\mathrm{tr}(Y_\Sigma^\dagger Y_\Sigma)Y_u^{pt}Y_u^{*rs}$
$\mathcal{O}^{(1)}_{qd,prst}$	$-\frac{1}{18M^2}\mathrm{tr}(Y_\nu Y_\nu^\dagger)Y_d^{pt}Y_d^{*rs}$	$-\frac{\mu^2}{12M^4}Y_d^{pt}Y_d^{*rs}+\frac{g_1^4}{180M^2}\delta^{pr}\delta^{st}$	$-\frac{1}{6M^2}\mathrm{tr}(Y_\Sigma^\dagger Y_\Sigma)Y_d^{pt}Y_d^{*rs}$
$\mathcal{O}^{(8)}_{qd,prst}$	$-\frac{1}{3M^2}\mathrm{tr}(Y_\nu Y_\nu^\dagger)Y_d^{pt}Y_d^{*rs}$	$-\frac{\mu^2}{2M^4}Y_d^{pt}Y_d^{*rs}$	$-\frac{1}{M^2}\mathrm{tr}(Y_\Sigma^\dagger Y_\Sigma)Y_d^{pt}Y_d^{*rs}$

	$(\bar{L}L)(\bar{R}R)$
Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$

Affecting leptonic decays of mesons

Search for the lepton flavor violating decay $J/\psi \to e\mu$

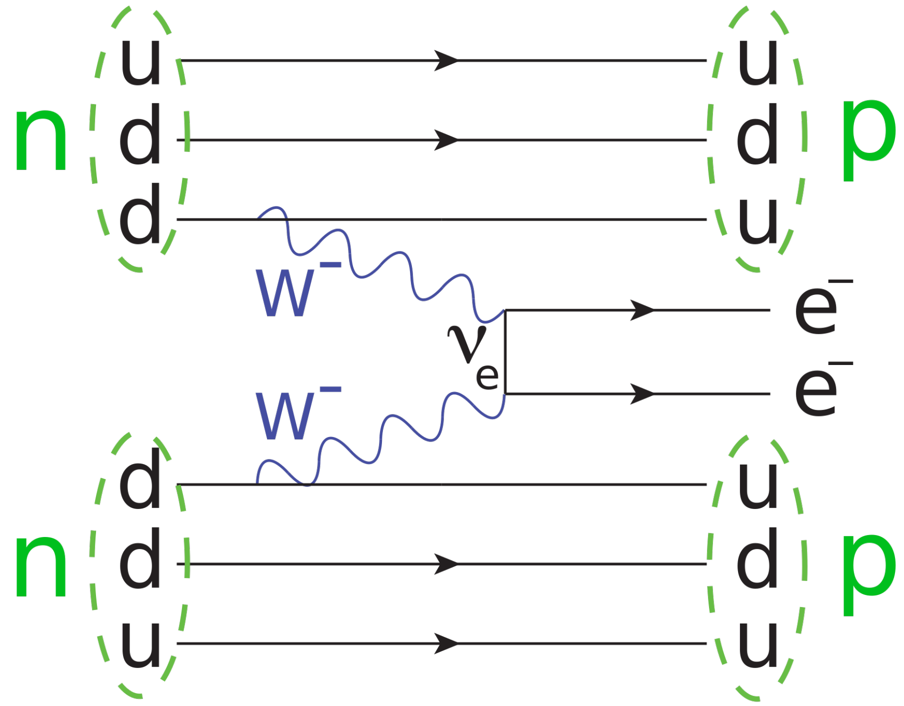
BESIII collaboration[1,*]

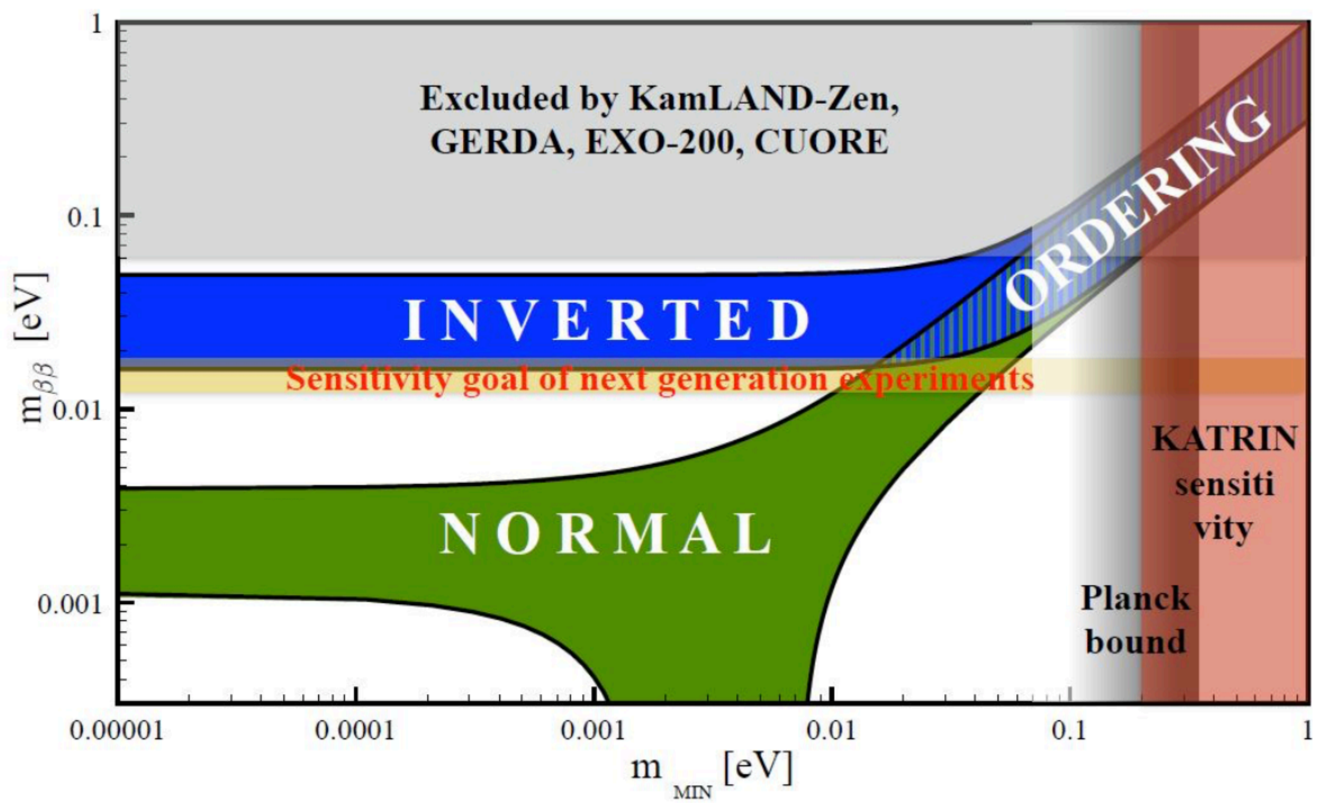
Need to investigate

Phenomenology implications III: neutrino physics

- Neutrino must be majorana type

Neutrinoless double beta decay

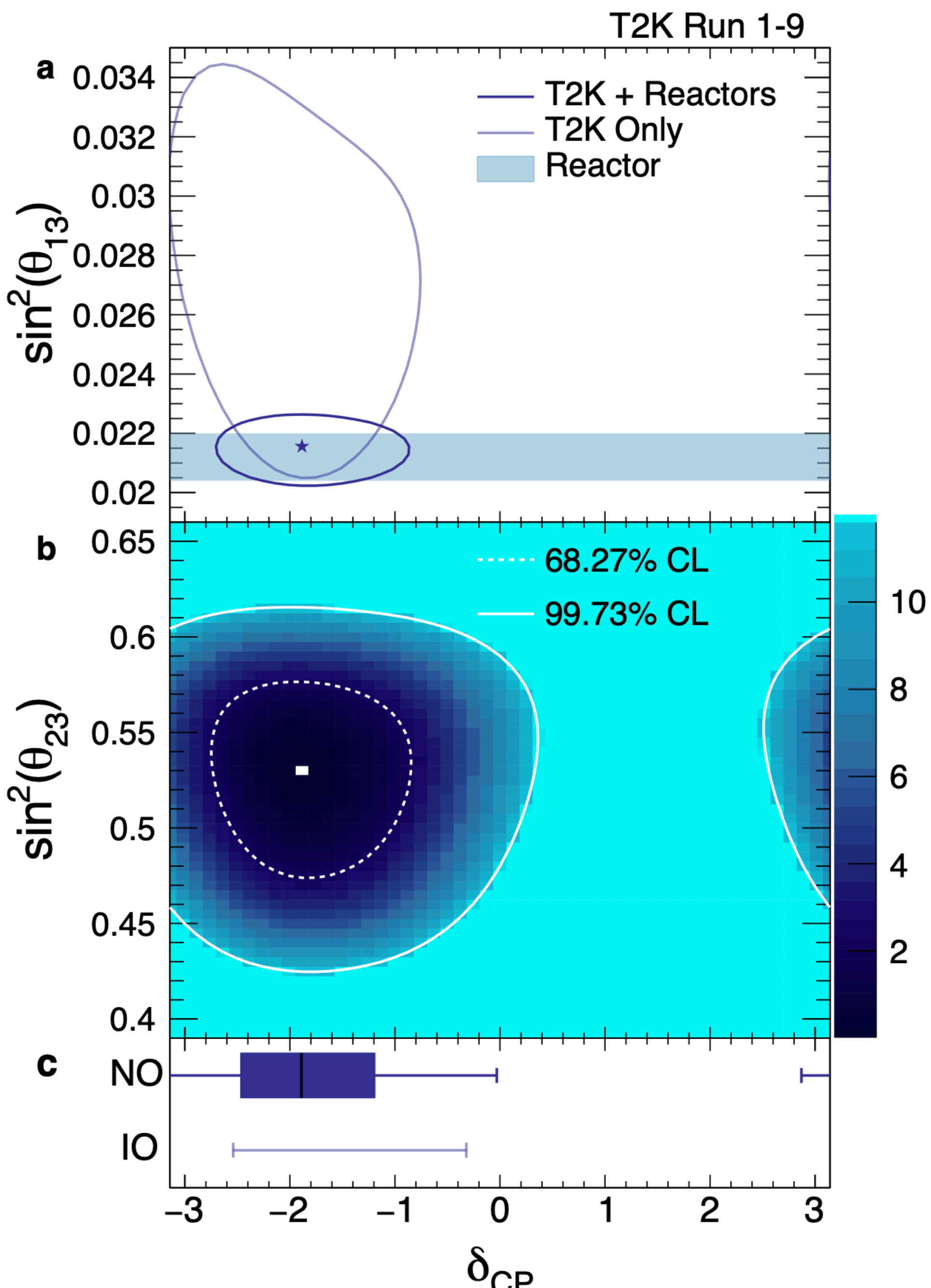




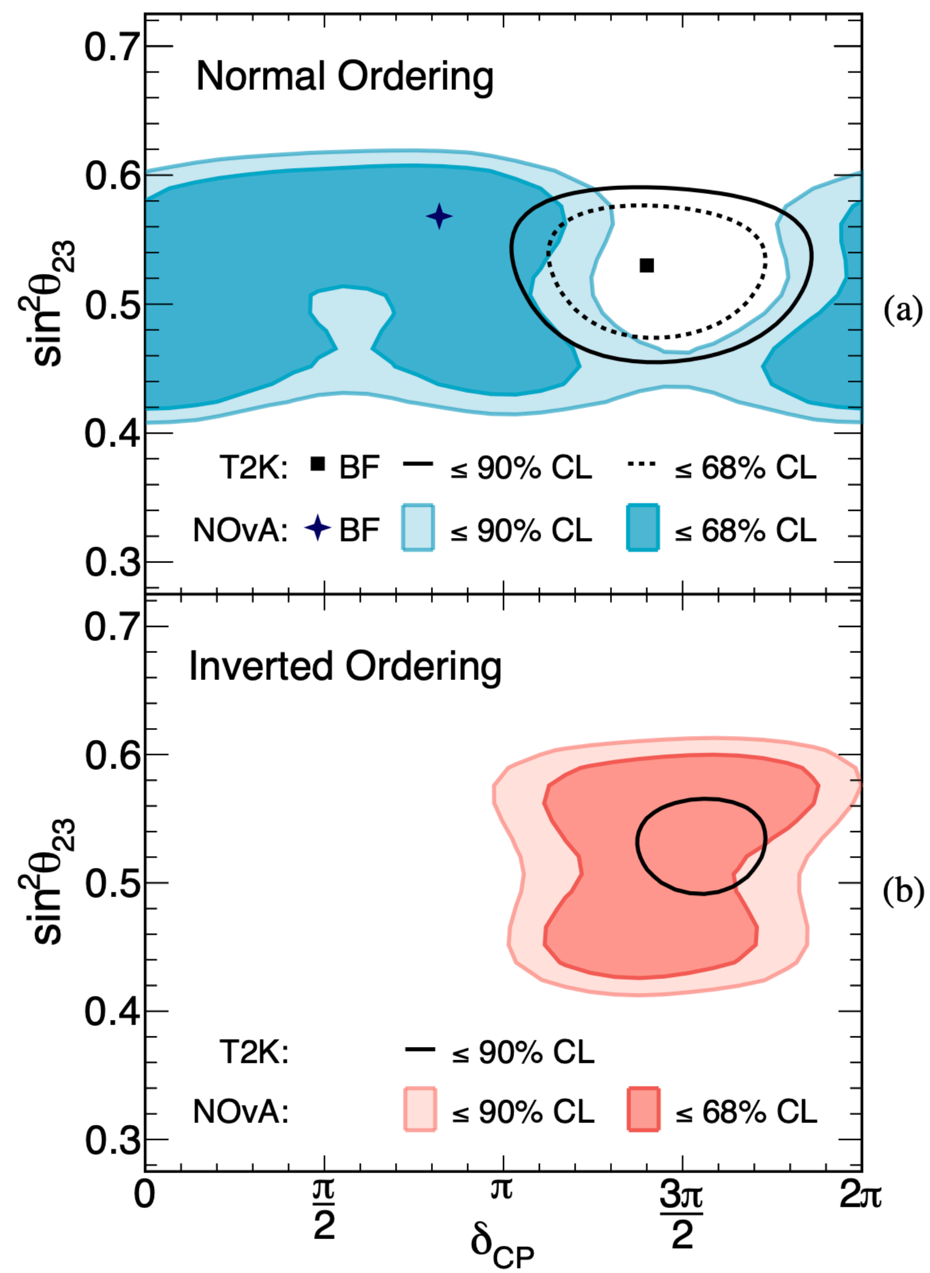
Phenomenology implications III: neutrino physics

- CP violation in neutrino sector

T2K, 19'



Nova, 21'



Leptogenesis even without CP violation

Summary

- One simple extension of SM, three problems can be solved: inflation, baryogenesis and neutrino masses

- Unique signatures at collider, LFV violation, neutrino experiments and astronomy observations

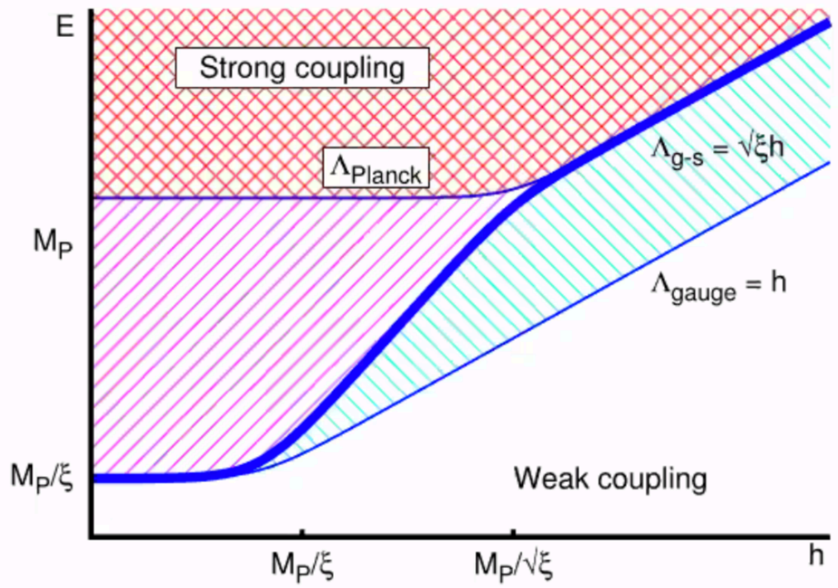
Thanks

Back up

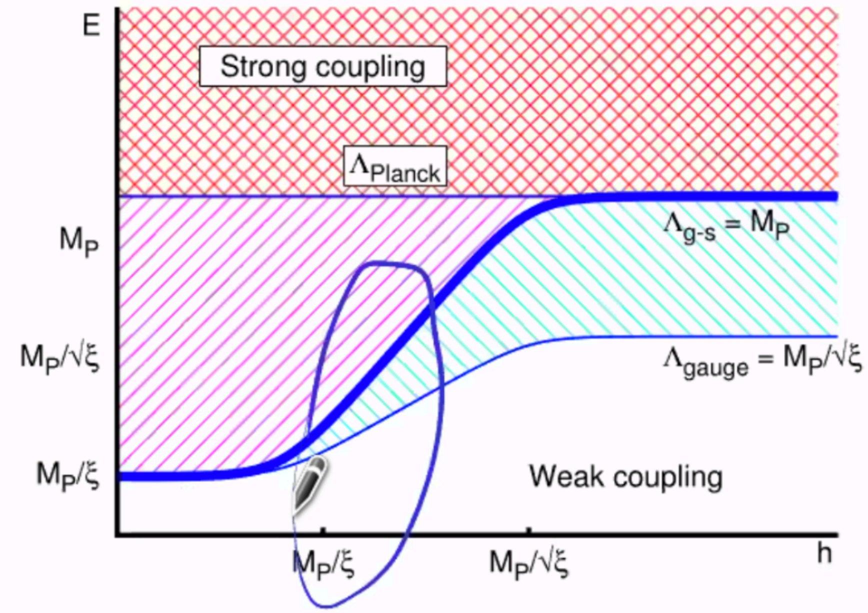
Unitary problem for Higgs inflation

Cut-off grows with the field background

Jordan frame



Einstein frame



Relation between cut-offs in different frames:

$$\Lambda_{\text{Jordan}} = \Lambda_{\text{Einstein}}\Omega$$

Relevant scales at inflation

Hubble scale $H \sim \lambda^{1/2}\frac{M_P}{\xi}$

Energy density at inflation

$$V^{1/4} \sim \lambda^{1/4}\frac{M_P}{\sqrt{\xi}}$$

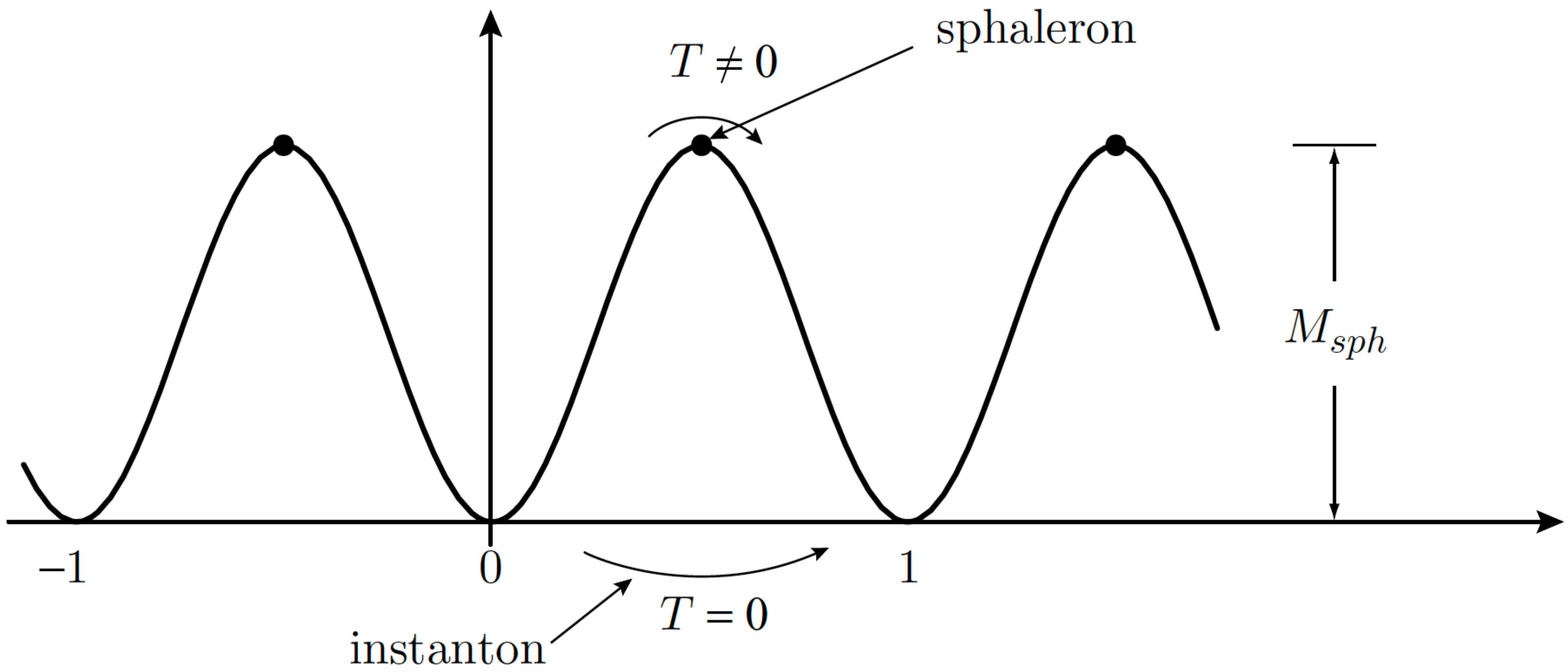
Reheating temperature $M_P/\xi < T_{\text{reheating}} < M_P/\sqrt{\xi}$

Problems during reheating

Instanton, sphaleron process

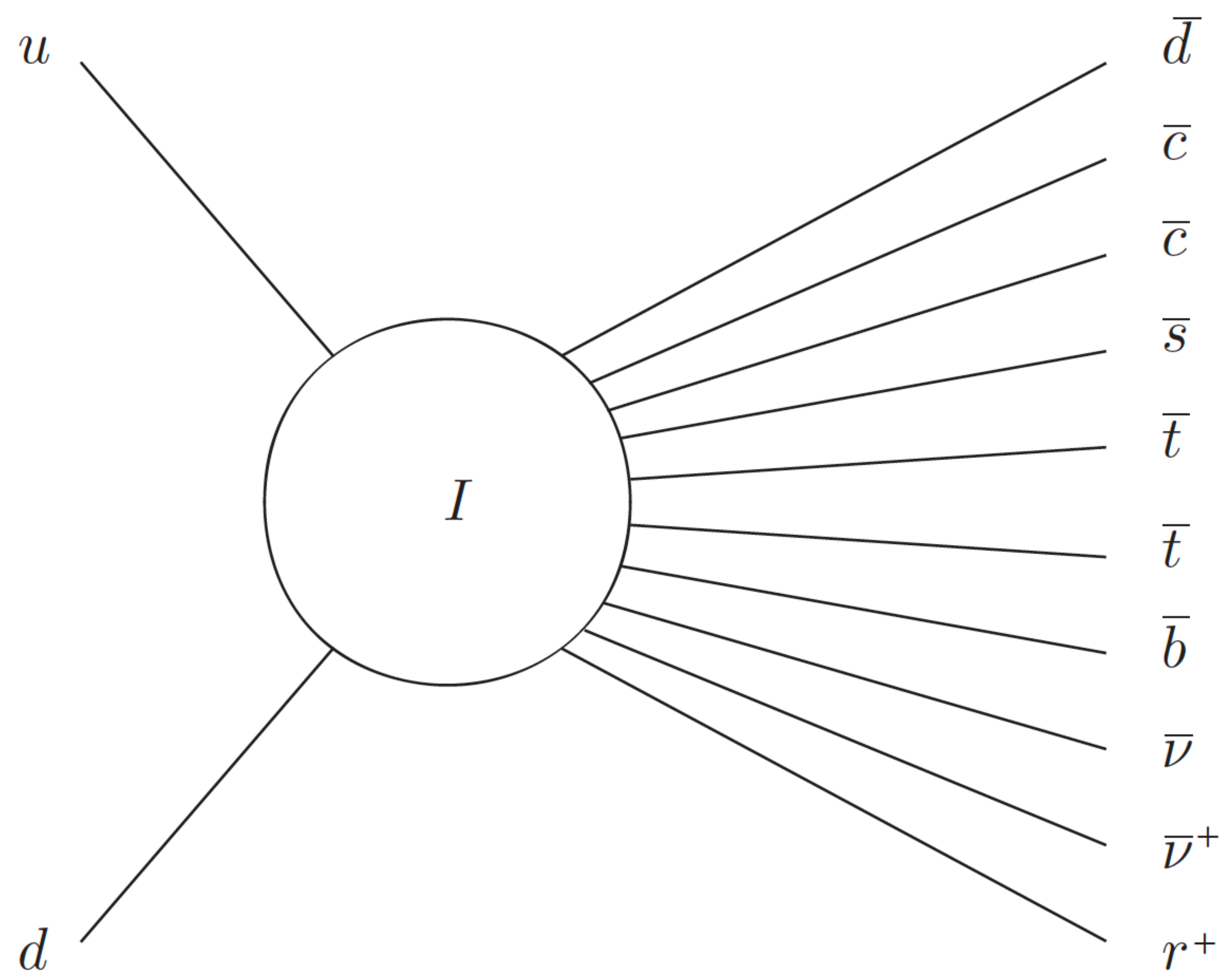
Effective for T> 100 GeV

$$\exp\left(-\frac{M_{sph}(T)}{T}\right) \sim \exp\left(-2\pi\frac{M_W(T)}{\alpha_w T}\right)$$



$$\Gamma \propto \exp\left(-\frac{4\pi}{\alpha}\right)$$

Instanton, sphaleron



Baryon asymmetry via leptogenesis

1. the sphaleron interactions themselves:

$$\sum_i (3\mu_{q_i} + \mu_{\ell_i}) = 0$$

2. a similar relation for QCD sphalerons:

$$\sum_i (2\mu_{q_i} - \mu_{u_i} - \mu_{d_i}) = 0.$$

3. vanishing of the total hypercharge of the universe:

$$\sum_i \left(\mu_{q_i} - 2\mu_{\bar{u}_i} + \mu_{\bar{d}_i} - \mu_{\ell_i} + \mu_{\bar{e}_i}\right) + \frac{2}{N}\mu_H = 0$$

4. the quark and lepton Yukawa couplings give relations:

$$\mu_{q_i} - \mu_\phi - \mu_{d_j} = 0, \quad \mu_{q_i} - \mu_\phi - \mu_{u_j} = 0, \quad \mu_{\ell_i} - \mu_\phi - \mu_{e_j} = 0.$$

$$B = \frac{8N+4}{22N+13}(\mathcal{B} - \mathcal{L})_i$$