Probing the mechanism behind the matter-antimatter asymmetry

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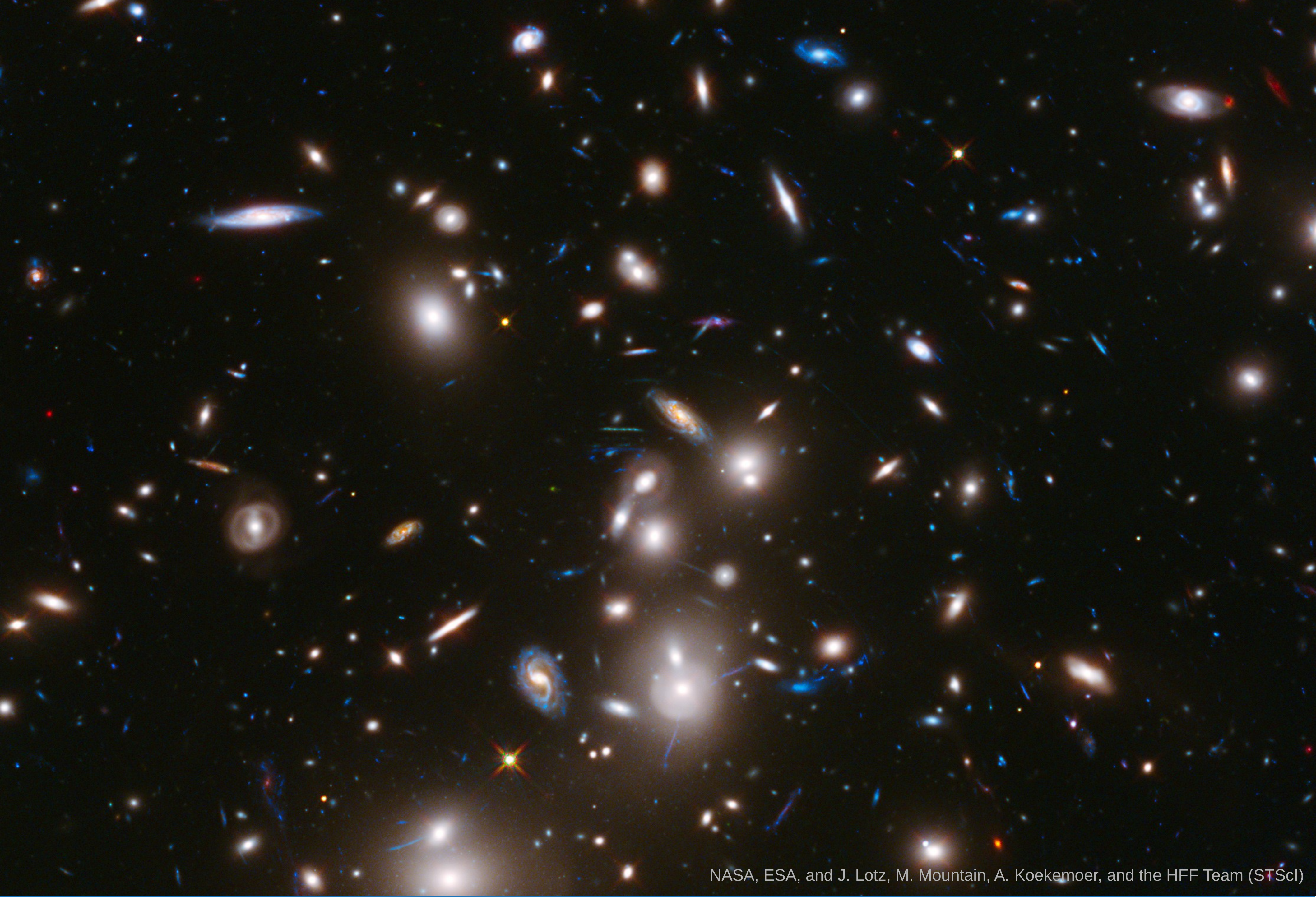
DFG Deutsche Forschungsgemeinschaft



NASA, ESA, and J. Lotz, M. Mountain, A. Koekemoer, and the HFF Team (STScI)

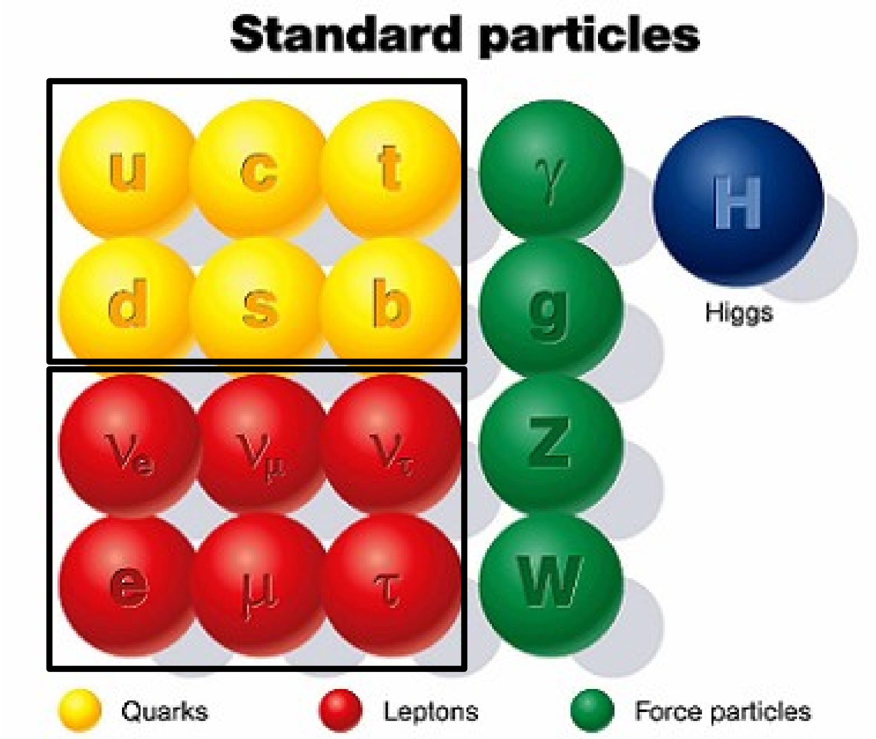
What is our Universe made of?

NASA, ESA, and J. Lotz, M. Mountain, A. Koekemoer, and the HFF Team (STScI)

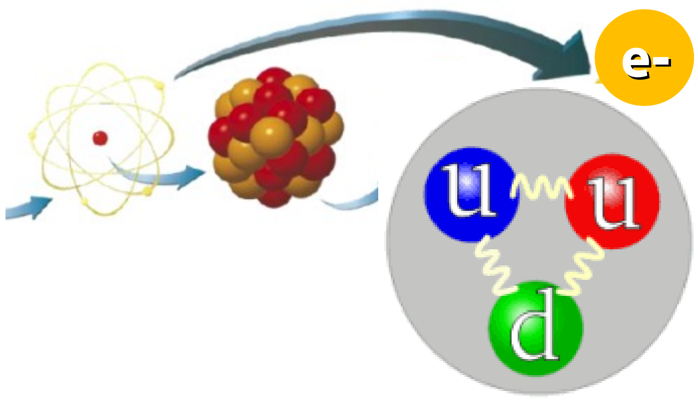
The Standard Model of Particle Physics

quarks

leptons



fermions bosons



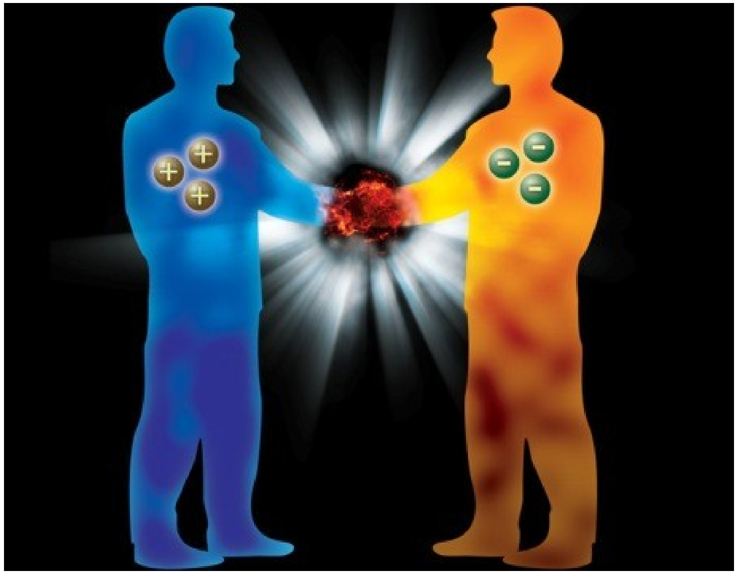
baryon

+ their anti-particles

However, this is cannot be the final word yet …

Why do we exist?

NASA, ESA, and J. Lotz, M. Mountain, A. Koekemoer, and the HFF Team (STScI)



Why is there more matter than anti-matter?

The baryon asymmetry

Equal amounts of matter and antimatter would have annihilated into radiation

As our Universe consists out of matter, a mechanism had to create the asymmetry

$$n_B = n_b - n_{\bar{b}}$$

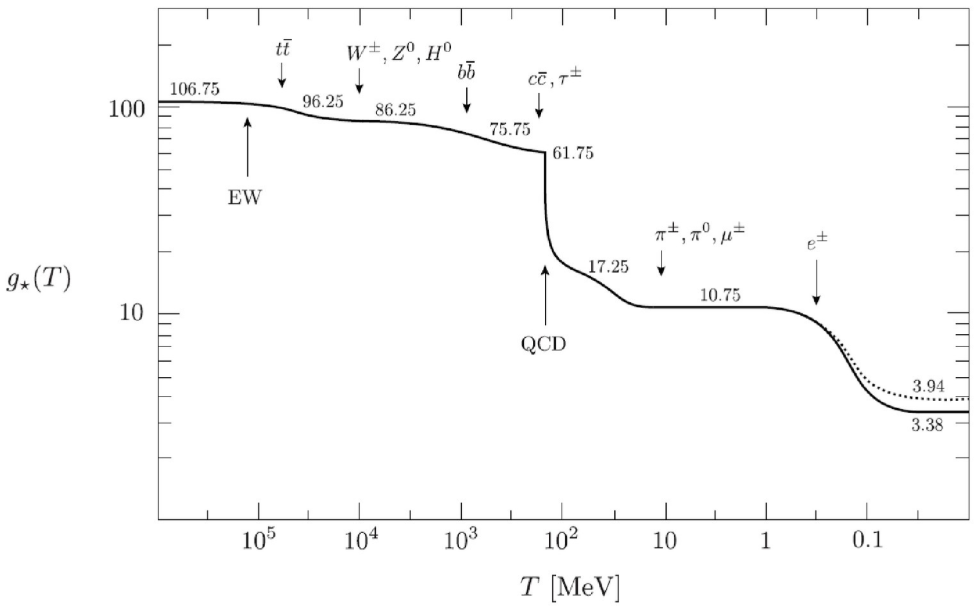
baryon number density

antibaryon number density

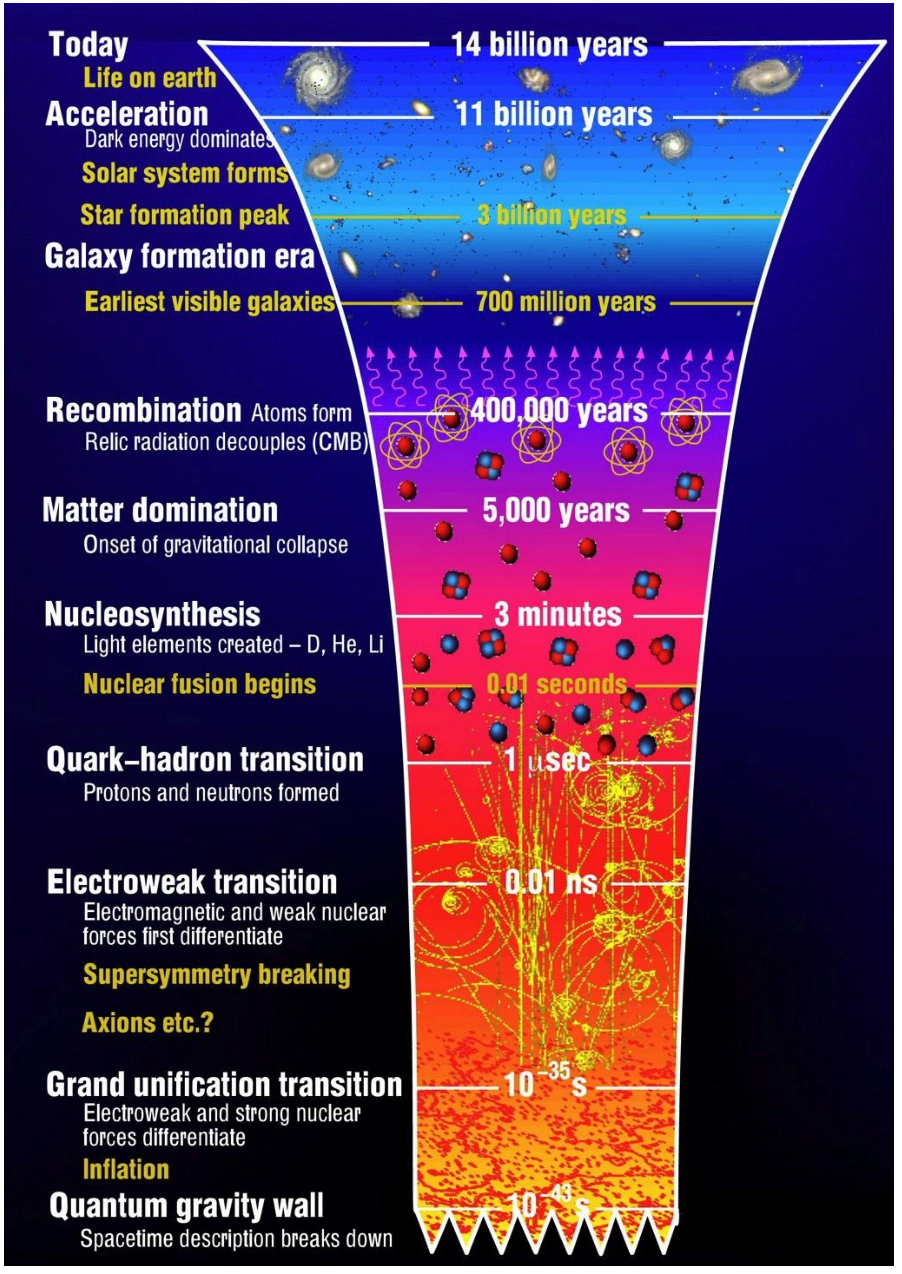
$$n_B = \frac{\rho_N}{m_N} = 1.13 \cdot 10^{-5} (\Omega_B h^2) \mathrm{cm}^{-3}$$

$$Y_B \equiv \frac{n_B}{s} = 3.81 \cdot 10^{-9} (\Omega_B h^2)$$

$$\eta_B \equiv \frac{n_B}{n_\gamma} = 1.8 \cdot g_s^\star \cdot \frac{n_B}{s}$$



From the Big Bang to Today…



Credits: University of Cambridge / The Stephen Hawking Centre for Theoretical Cosmology

Big Bang Nucleosynthesis (BBN)

- 3 min after Big Bang
- BBN creates first light elements (D, He)

Deuterium Bottleneck

→ Nucleosynthesis starts with formation of D

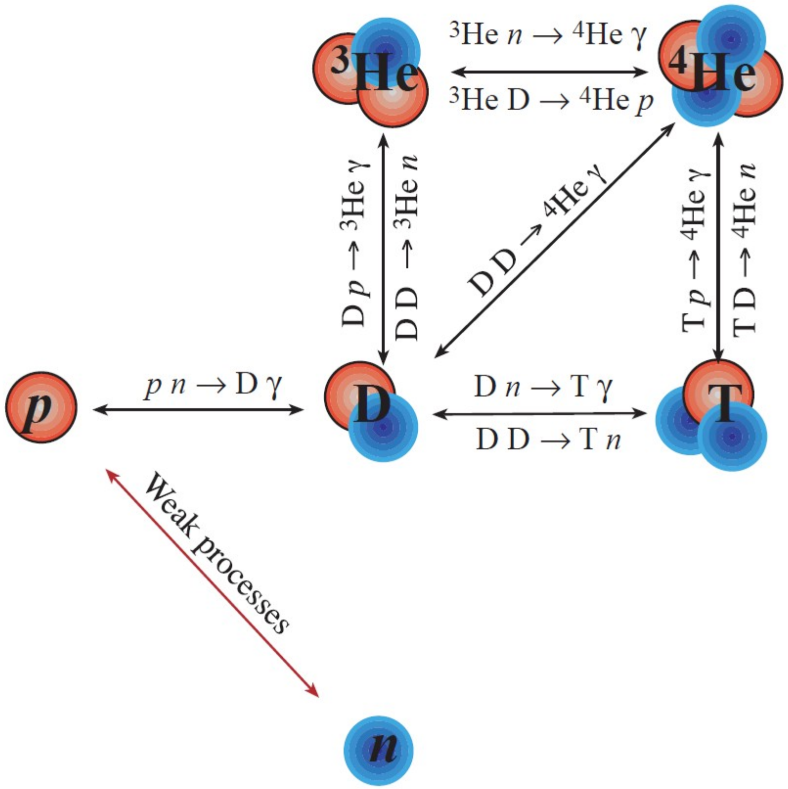
$$p + n \to D + \gamma$$

Only if photo-dissociation ceases to be effective, chain of light elements can be formed

$$\eta_B{}^{-1} e^{-B_D/T} < 1 \qquad B_D = 2.3\text{MeV}$$

$$T^D_{\text{nuc}} \approx \frac{B_D}{\log \eta_B{}^{-1}}$$

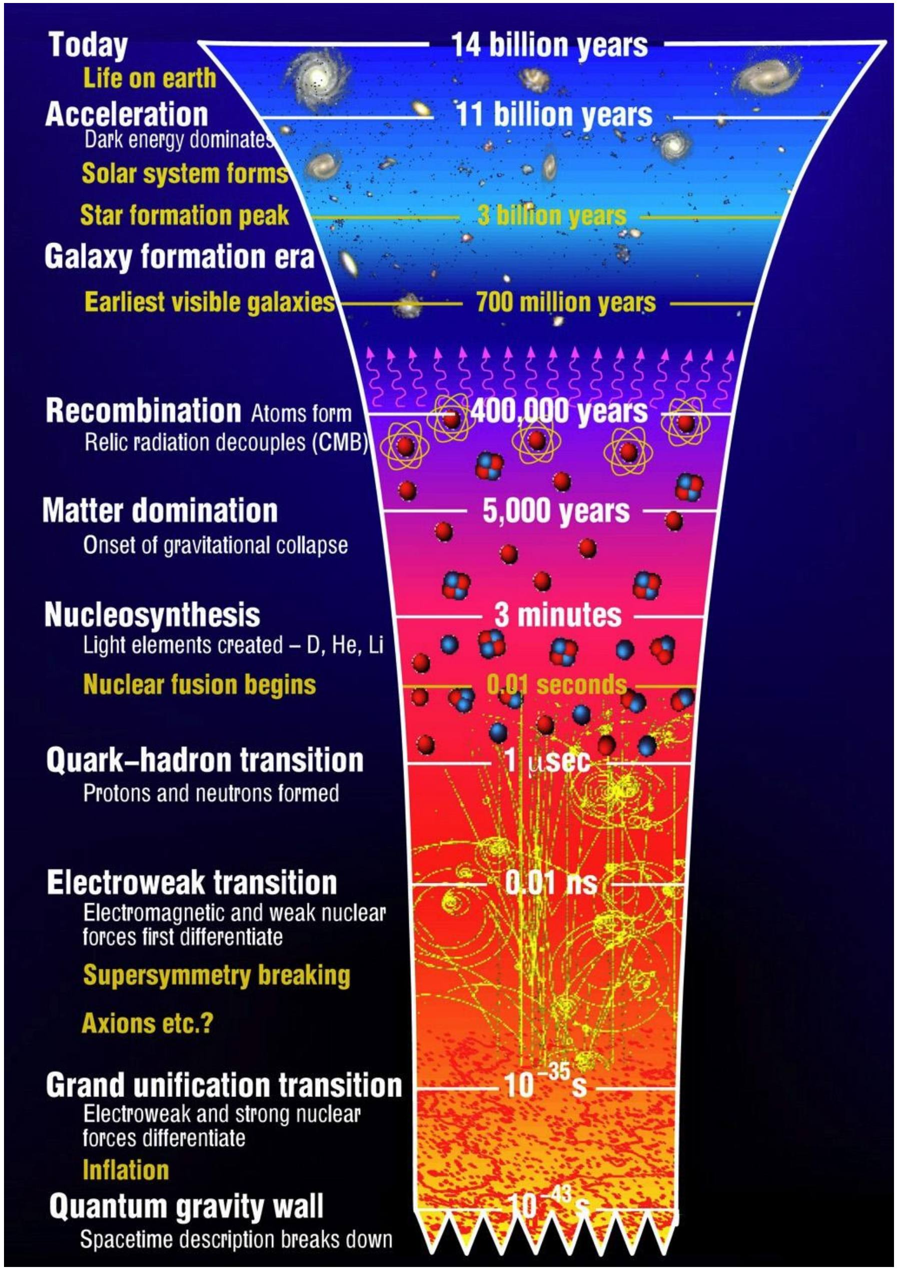
$$T \approx 0.1\text{MeV}$$



Credits: hep-ph/0608347

$$\eta_B^{\text{obs}} = (6.143 \pm 0.190) \times 10^{-10}$$

From the Big Bang to Today...



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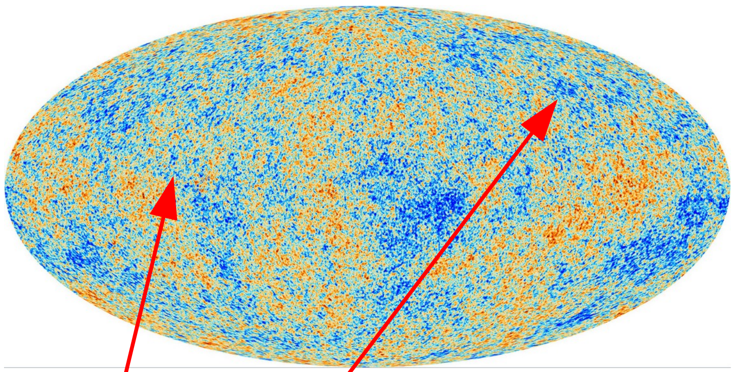
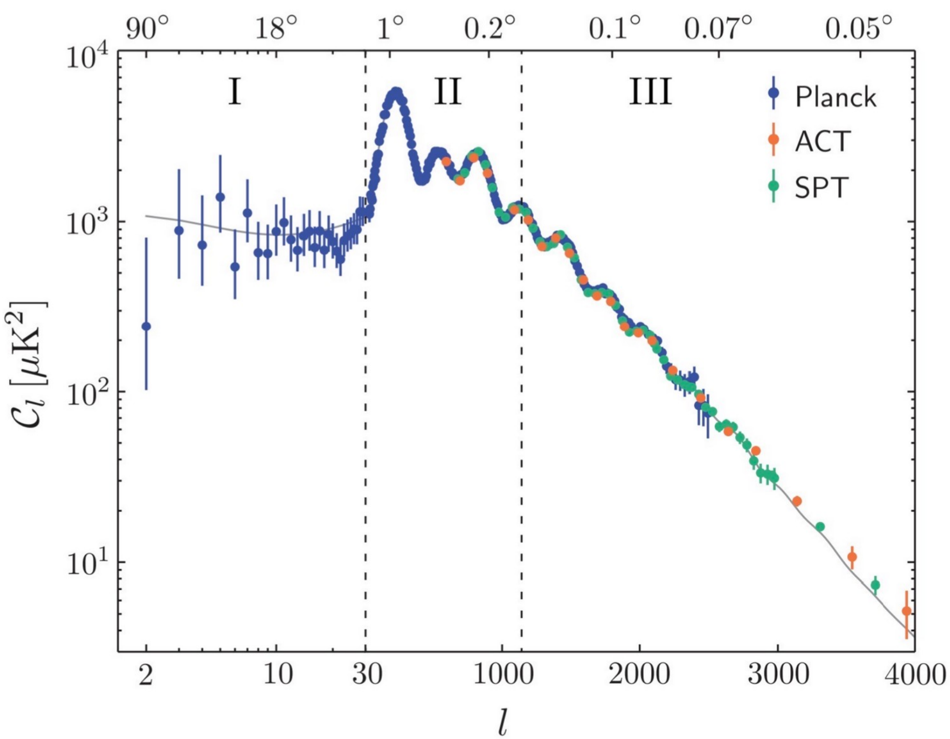
The Cosmic Microwave Background (CMB)

- 400.000 years after Big Bang
- measures temperature fluctuations from recombination

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





$$\langle \theta(\hat{n}), \theta(\hat{n}') \rangle = \sum_{\ell} \frac{2\ell+1}{4\pi} C_\ell P_\ell(\cos\theta)$$

$$\theta(\hat{n}) = \frac{\delta T}{T}$$

The Cosmic Microwave Background (CMB)

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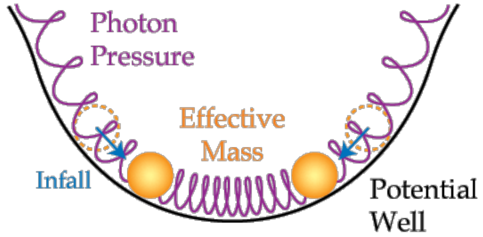
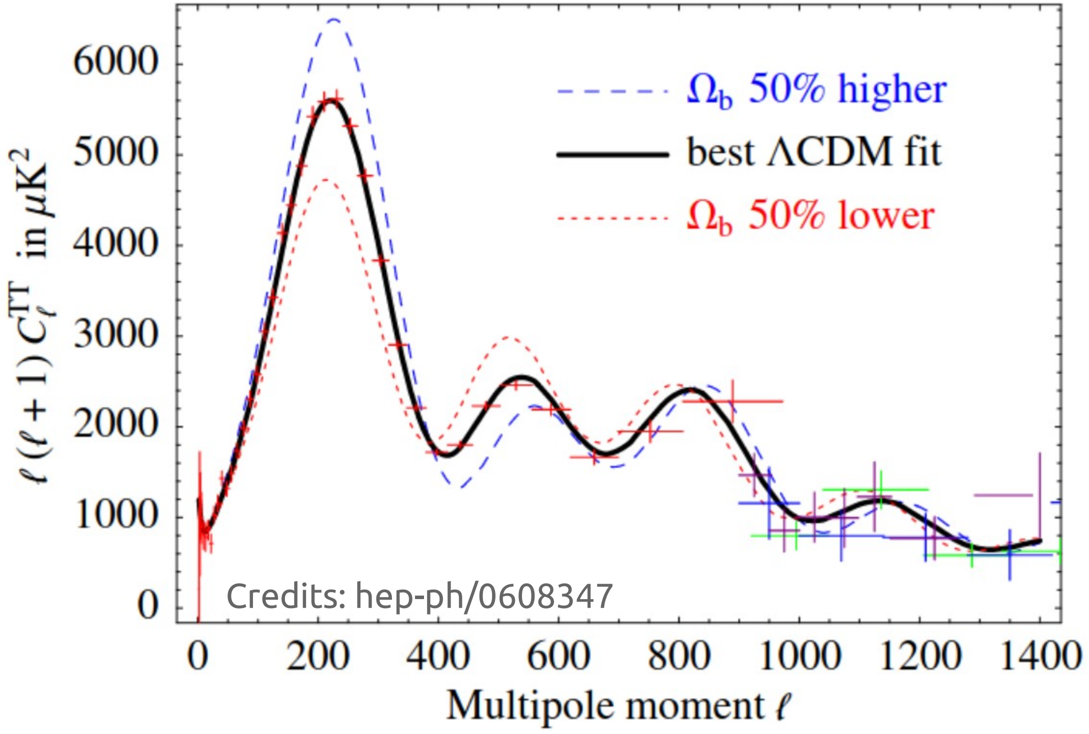
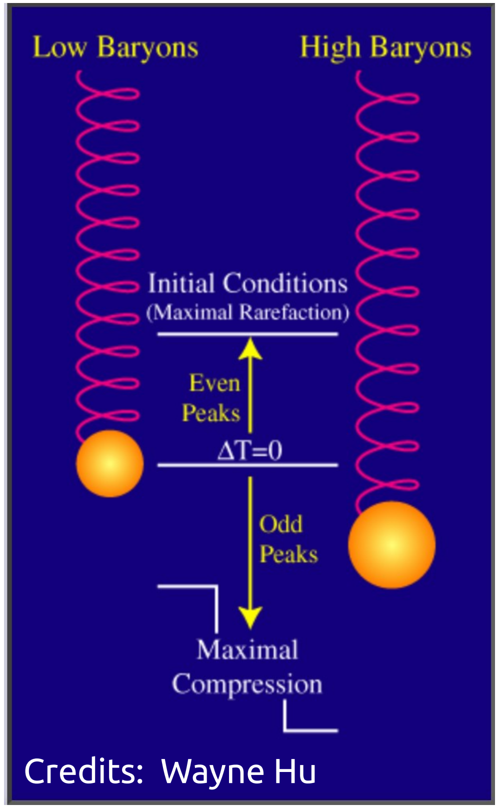
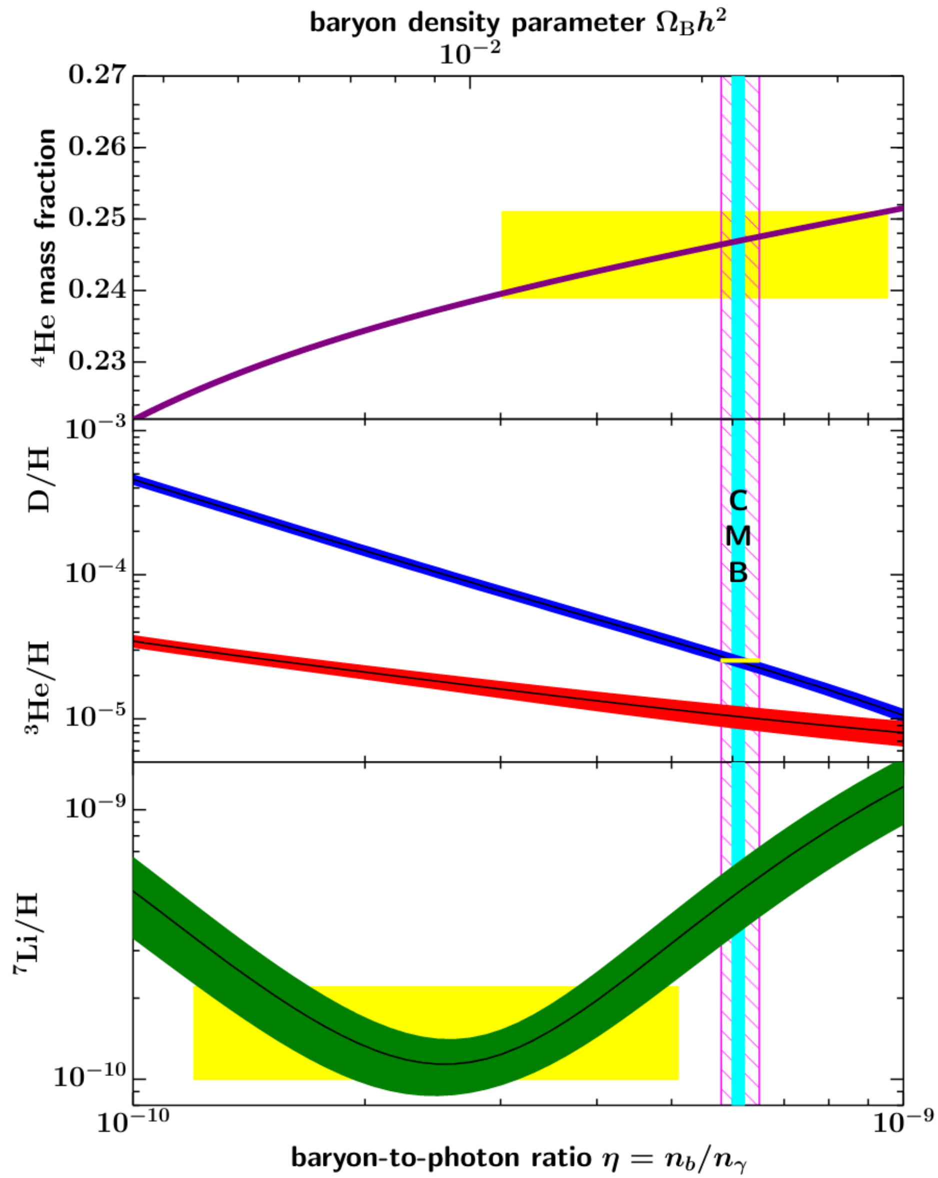






$$\Omega_b^{\rm obs} h^2 = 0.0224 \pm 0.0001$$

Combination: BBN & CMB

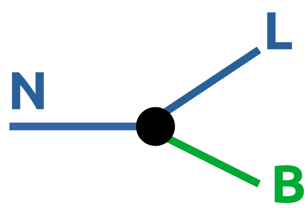


Excellent agreement even though measurements originate from two different epochs!

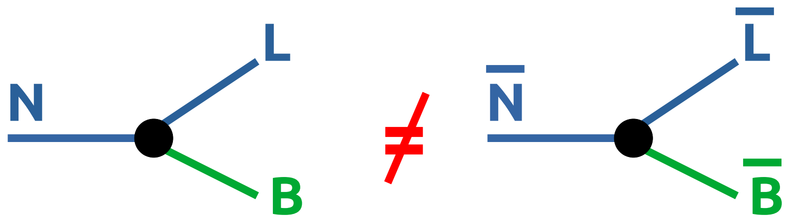
Ingredients for a baryon asymmetry

Theoretical conditions that have to be fulfilled (Sakharov conditions):

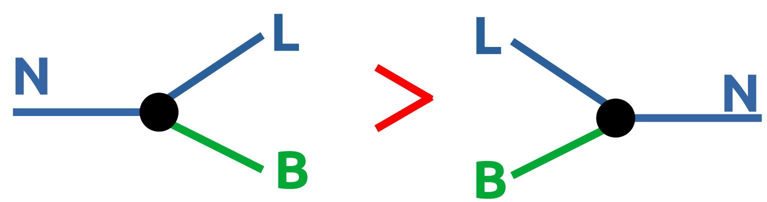
- ☐ B-L violation



- ☐ C and CP violation



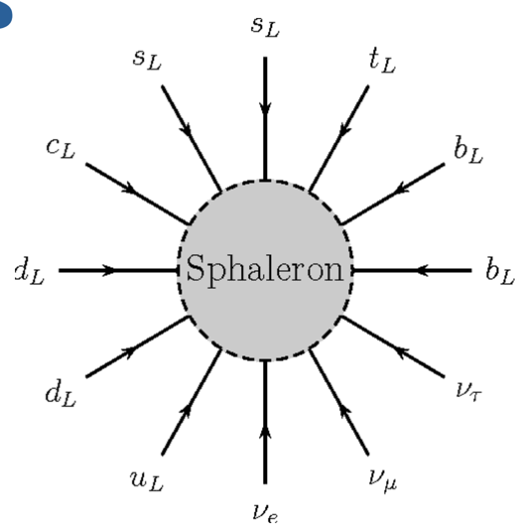
- ☐ departure from thermal equilibrium



B-L violation & Sphaleron Processes

$$J^B_\mu = \frac{1}{3}\sum_i \left(\overline{q}_{Li}\gamma_\mu q_{Li} - \overline{u}^c_i\gamma_\mu u^c_i - \overline{d}^c_i\gamma_\mu d^c_i\right)$$

$$J^L_\mu = \sum_i \left(\overline{\ell}_{Li}\gamma_\mu \ell_{Li} - \overline{e}^c_i\gamma_\mu e^c_i\right)$$



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

Naively expected on classical level: $\partial^\mu J^B_\mu = \partial^\mu J^L_\mu = 0$

Charge operators:

$$\hat{L} = \int d^3x J^L_0(x) \qquad \hat{B} = \int d^3x J^B_0(x)$$

Anomalies on quantum level due to chiral structure of SM:

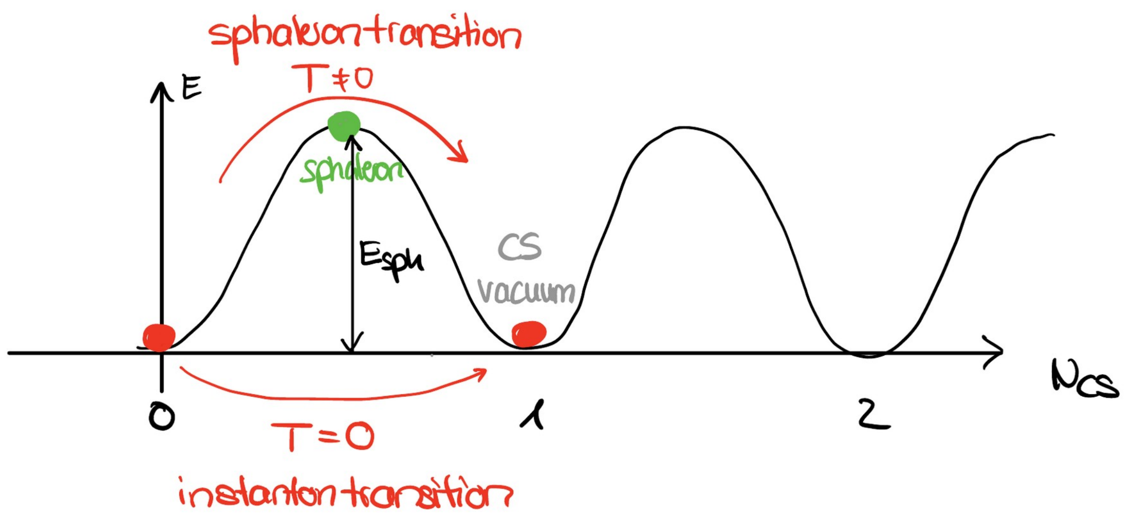
$$\partial_\mu J^{B\mu} = \partial_\mu J^{L\mu} = \frac{N_f}{32\pi}(g^2 W^a_{\mu\nu}\tilde{W}^{a\mu\nu} - g'^2 B_{\mu\nu}\tilde{B}_{\mu\nu}) = N_f \partial_\mu K^\mu$$

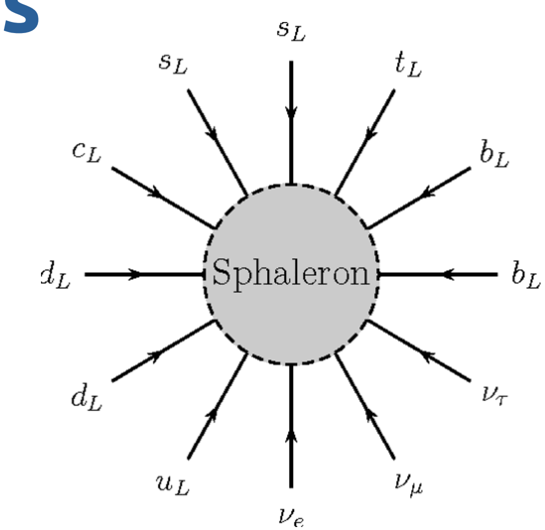
$$\Delta B = \Delta L = N_f \int d^4x \partial_\mu K^\mu = N_f n_{\text{top}}$$

$\partial_\mu(J^{B\mu} - J^{L\mu}) = 0$ **B-L conserved**

$\partial_\mu(J^{B\mu} + J^{L\mu}) \neq 0$ **B+L violated**

B-L violation & Sphaleron Processes





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

$$\Delta B = \Delta L = N_f \int d^4x \partial_\mu K^\mu = N_f n_{\text{top}}$$

→ Sphalerons are active at temperatures above EWSB!

(around 170 GeV)

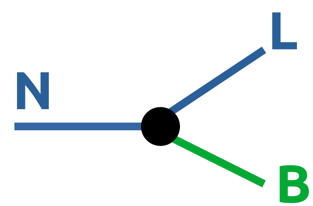
$$\frac{\Gamma^b_{\text{SM}}}{V} \sim \exp\left(-\frac{4\pi}{g_w}\frac{v_c}{T}\right)$$ **in broken phase suppressed**

$$\frac{\Gamma^s_{\text{SM}}}{V} \sim \alpha_w^5 T^4$$ **in symmetric phase active**

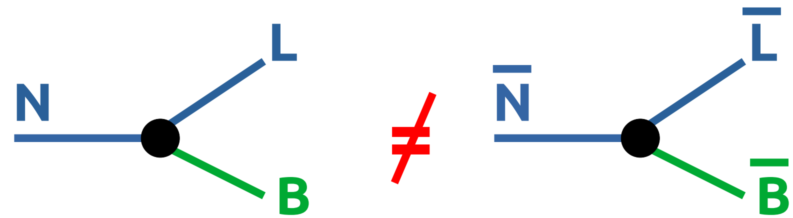
Ingredients for a baryon asymmetry

Theoretical conditions that have to be fulfilled (Sakharov conditions):

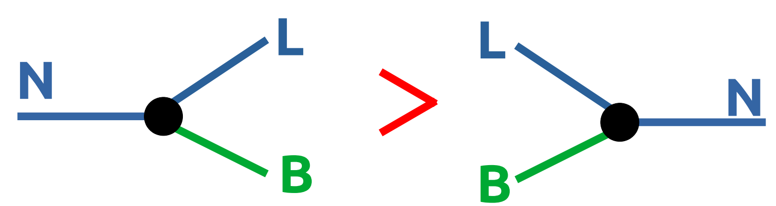
- [x] B-L violation



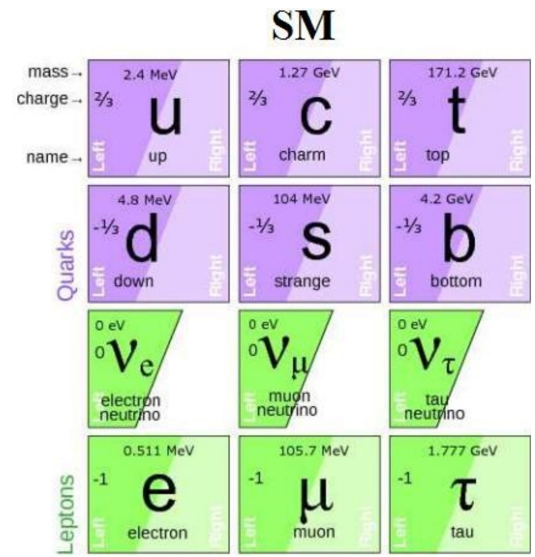
- [ ] C and CP violation



- [ ] departure from thermal equilibrium



C and CP violation



Charge conservation implies:

$$\Gamma(X \to AB) = \Gamma(\overline{X} \to \overline{A}\,\overline{B})$$

Requirement of charge violation:

$$\frac{dY_B}{dt} \approx \Gamma(X \to AB) - \Gamma(\overline{X} \to \overline{A}\,\overline{B})$$

Charge and parity conservation implies:

$$\Gamma(X \to q_L q_L) = \Gamma(\overline{X} \to \overline{q}_R\,\overline{q}_R)$$

$$\Gamma(X \to q_R q_R) = \Gamma(\overline{X} \to \overline{q}_L\,\overline{q}_L)$$

Requirement of charge and parity violation:

$$\frac{dY_B}{dt} \approx \left[(\Gamma(\overline{X} \to \overline{q}_R\,\overline{q}_R) + \Gamma(\overline{X} \to \overline{q}_L\,\overline{q}_L)) - (\Gamma(X \to q_R q_R) + \Gamma(X \to q_L q_L))\right]$$

C and CP violation – Status of the SM?

$$CP\,|K^0\rangle = -\,|\bar{K}^0\rangle = -\,|s\bar{d}\rangle$$

$$CP\,|\bar{K}^0\rangle = -\,|K^0\rangle = -\,|d\bar{s}\rangle$$

Neutral mesons can mix

$$CP\,|K_1^0\rangle = CP\left(\frac{1}{\sqrt{2}}\left(|K^0\rangle - |\bar{K}^0\rangle\right)\right) = +\,|K_1^0\rangle$$

$$CP\,|K_2^0\rangle = CP\left(\frac{1}{\sqrt{2}}\left(|K^0\rangle + |\bar{K}^0\rangle\right)\right) = -\,|K_2^0\rangle$$

Expected decays:

$K_1^0 \to 2\pi$ fast

$K_2^0 \to 3\pi$ slow

BUT: **In 1964, Cronin and Fitch realised that physical states are no pure CP eigenstates!**

$$|K_S^0\rangle = \frac{1}{\sqrt{1+|\epsilon|^2}}\left(|K_1^0\rangle + \epsilon\,|\bar{K}_2^0\rangle\right) \qquad |K_L^0\rangle = \frac{1}{\sqrt{1+|\epsilon|^2}}\left(|K_2^0\rangle + \epsilon\,|\bar{K}_1^0\rangle\right)$$

Indirect CP violation!

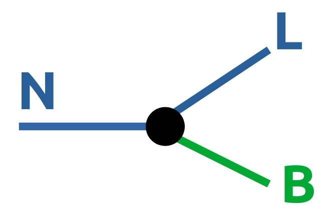
$$\frac{J_{CP}}{T_C^{12}} \approx 10^{-20} \longleftrightarrow \mathcal{O}(10^{-10})$$

not enough CP violation within SM!

Ingredients for a baryon asymmetry

Theoretical conditions that have to be fulfilled (Sakharov conditions):

- B-L violation



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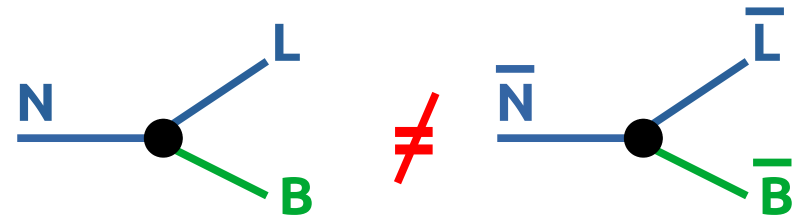
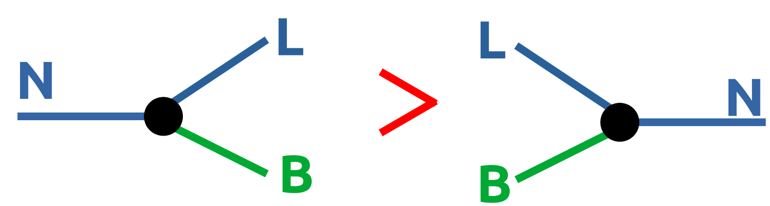


- departure from thermal equilibrium



Departure from thermal equilibrium

$$\langle B \rangle_T = \mathrm{Tr}[e^{-\beta H} B] = \mathrm{Tr}[(CPT)(CPT)^{-1} e^{-\beta H} B]$$
$$= \mathrm{Tr}[e^{-\beta H} (CPT)^{-1} B (CPT)] = -\langle B \rangle_T$$

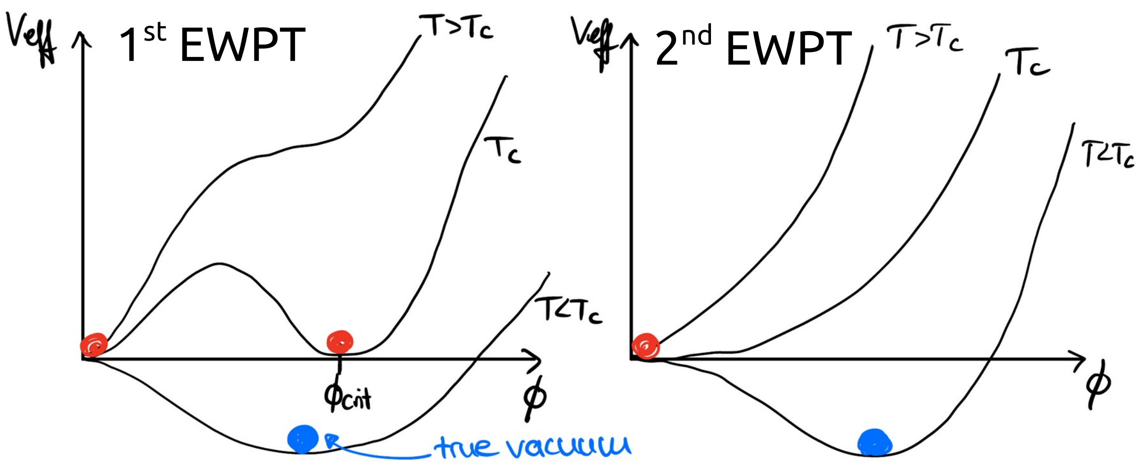
Departure from thermal equilibrium:

- First order phase transition (FOPT)
- Out-of-equilibrium decays

Strong FOPT during EWSB:

$$\frac{v_c}{T_c} \simeq \frac{3 g^3 v^2}{32 \pi^2 m_h^2} \geq 1$$

$$m_h \leq 32 \mathrm{GeV}$$



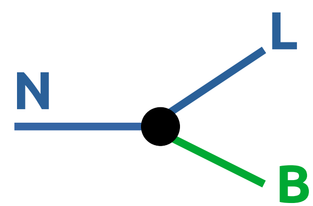
→ **Higgs too heavy for first order phase transition**

Why do we need new physics?

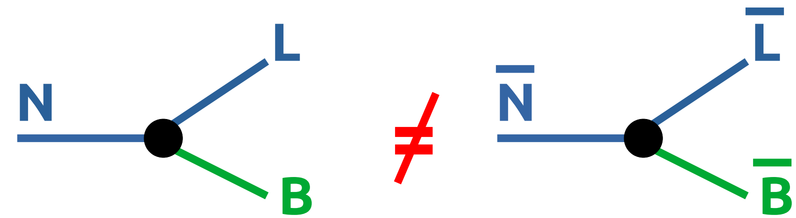
Theoretical conditions that have to be fulfilled (Sakharov conditions):

Standard Model?

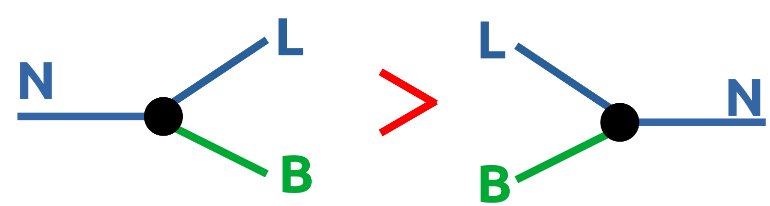
B-L violation



C and CP violation



departure from thermal equilibrium



There has to be new physics in order to explain our own existence!

Do we understand all known matter?

NASA, ESA, and J. Lotz, M. Mountain, A. Koekemoer, and the HFF Team (STScI)

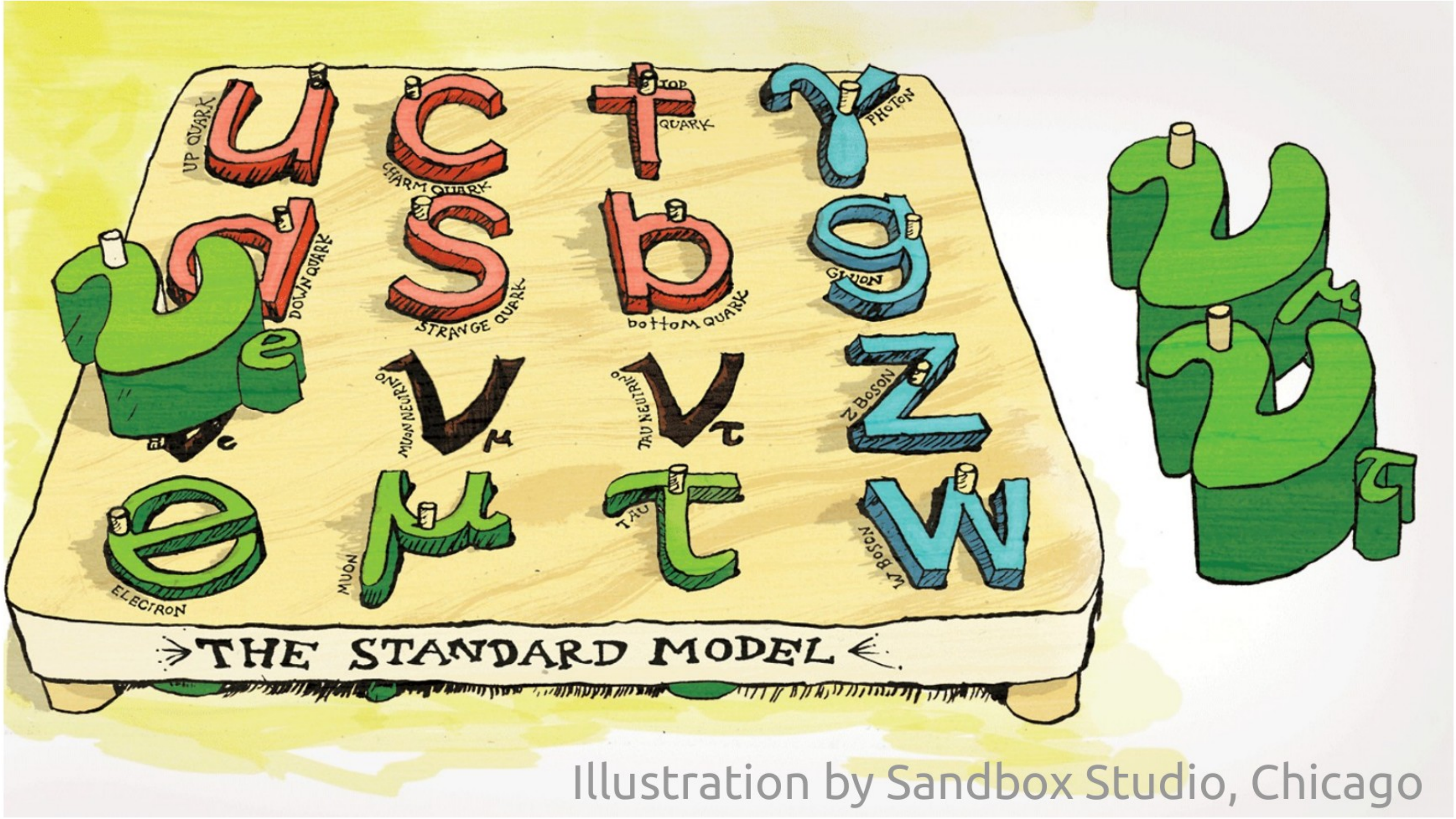
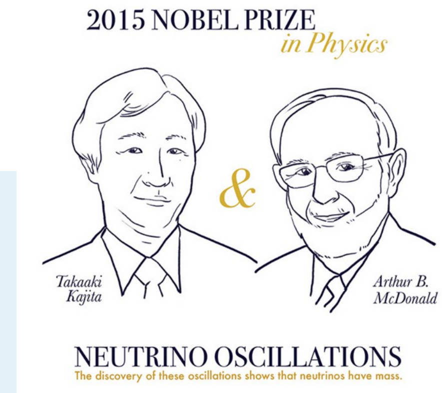
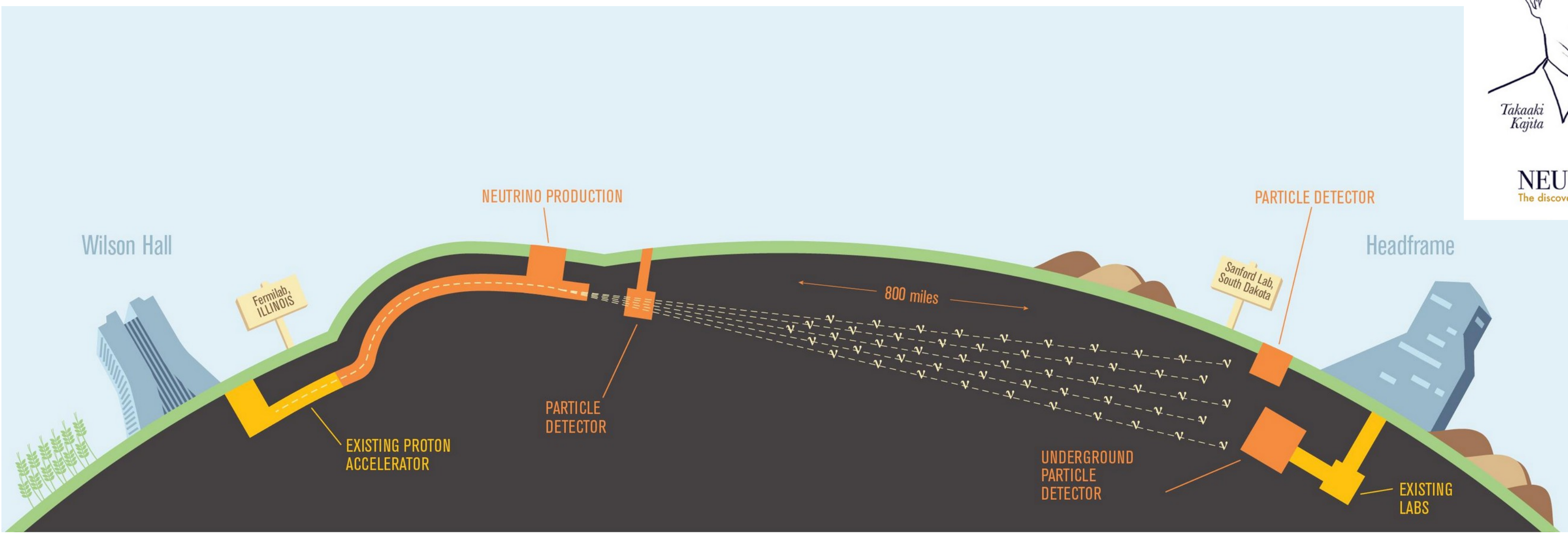


Illustration by Sandbox Studio, Chicago

What is the nature of neutrinos?

What is the nature of neutrinos?





ν_μ ν_e

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2}{4E} L\right)$$

Neutrino **oscillations** require **massive** neutrinos, forbidden in the Standard Model.

How do neutrinos get their masses?

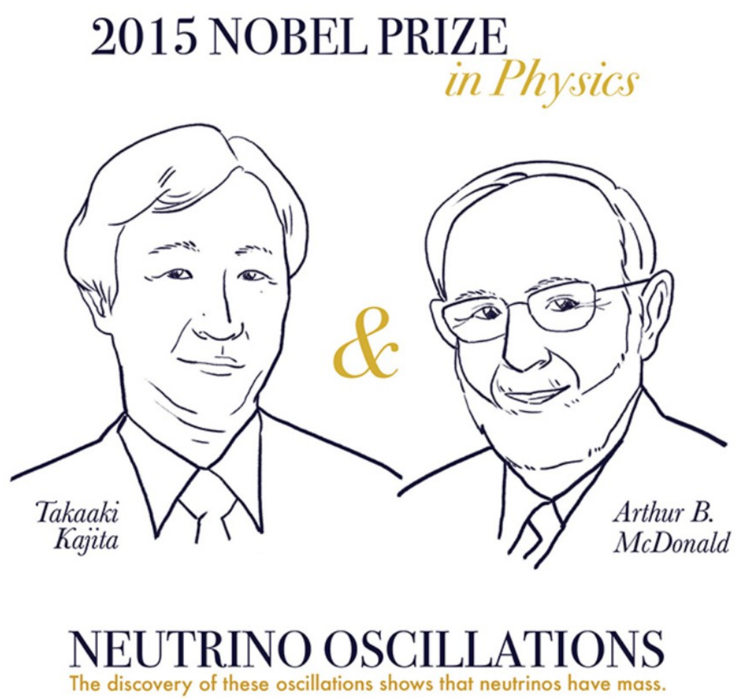
Neutrinos – what do we know?

- Neutrinos in the Standard Model are **massless**

$$L_i \to \begin{pmatrix} \nu_i \\ \ell_i \end{pmatrix} \qquad\qquad m_\nu = 0$$

- Neutrino **mixing**

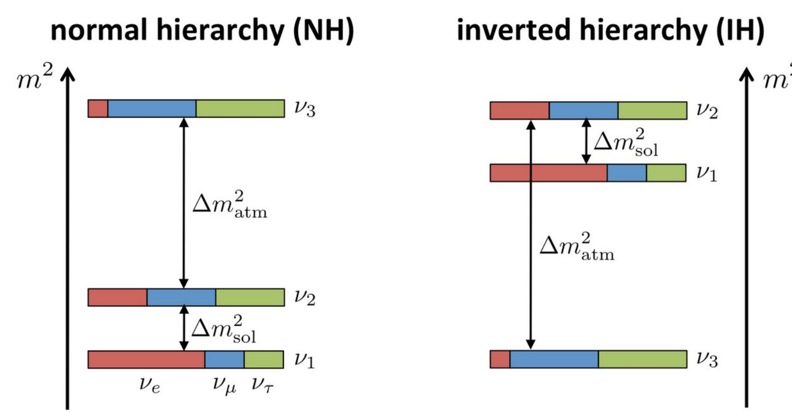
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



- Neutrino **oscillations** require **massive** neutrinos

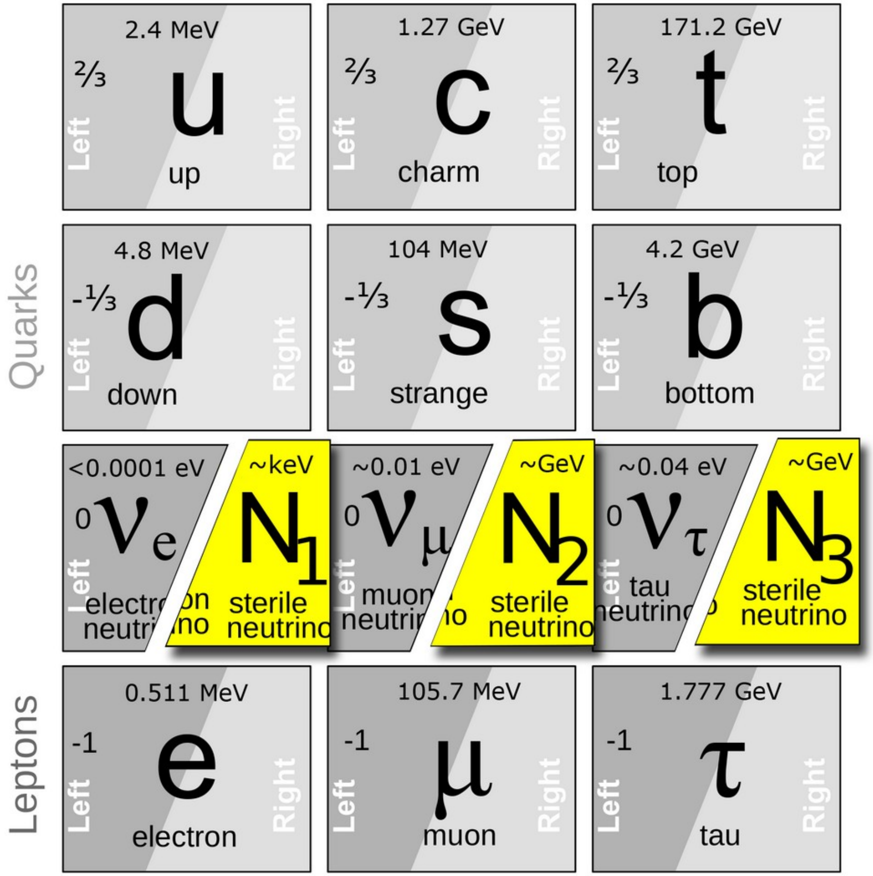
$$P(\nu_i \to \nu_j) \propto \Delta m_{ij}^2 \qquad \begin{aligned} \Delta m_{12}^2 &\sim 7.59 \times 10^{-5} \mathrm{eV}^2 \\ \Delta m_{23}^2 \sim \Delta m_{31}^2 &\sim 2.3 \times 10^{-3} \mathrm{eV}^2 \end{aligned}$$

- **Normal** vs. **inverted** hierarchy



How do neutrinos get their masses?
What nature do neutrinos have? Are they their own anti-particles?

Right-handed Neutrinos as New Physics



Right-handed neutrinos could explain the neutrino masses

Neutrino mass mechanism

Dirac mass

1/2

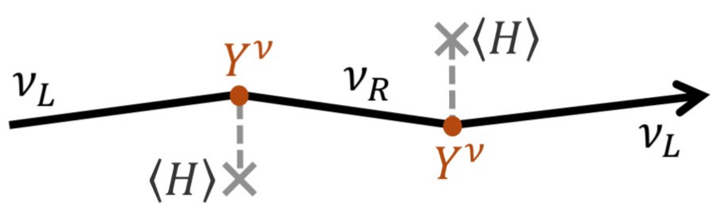
$$y_\nu L\epsilon H\overline{\nu}_R \supset m_D\nu_L\overline{\nu}_R$$

-1/2 0

- tiny Yukawa couplings

$$m_\nu/\Lambda_{EW} \leq 10^{-12}$$

→ lepton number no accidental symmetry anymore



$$m_\nu = \frac{m_D^2}{m_M}$$

hypercharge

Majorana mass

$$m_M\overline{\nu}_R\nu_R^c$$

0 0

→ higher dimensional operator

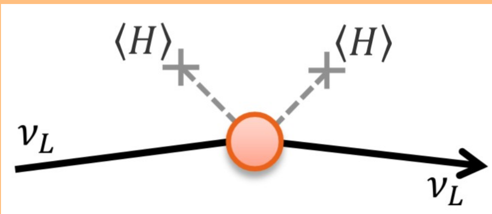
1/2 1/2 -1/2 1/2

$$m_M\overline{\nu}_L\nu_L^c \qquad LLHH$$

-1/2 1/2

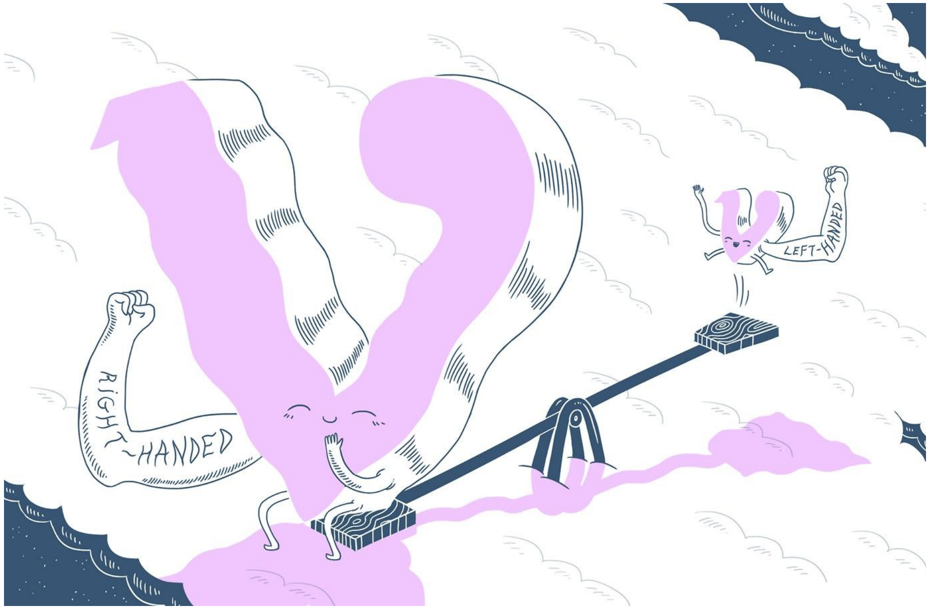
not at tree-level within the SM possible

→ Lepton number violation (LNV)



SeeSaw mechanism

$$\mathcal{L} \supset Y_\nu L \overline{\nu}_R \phi + M_M \overline{\nu}_R \nu_R^c$$
$$= M_D \nu_L \overline{\nu}_R + M_M \overline{\nu}_R \nu_R^c$$



$$\mathrm{M}_\nu = \begin{pmatrix} \delta m_\nu^{1loop} & M_D \\ M_D^T & M_M \end{pmatrix}$$

Diagonalisation with M_M >> M_D:

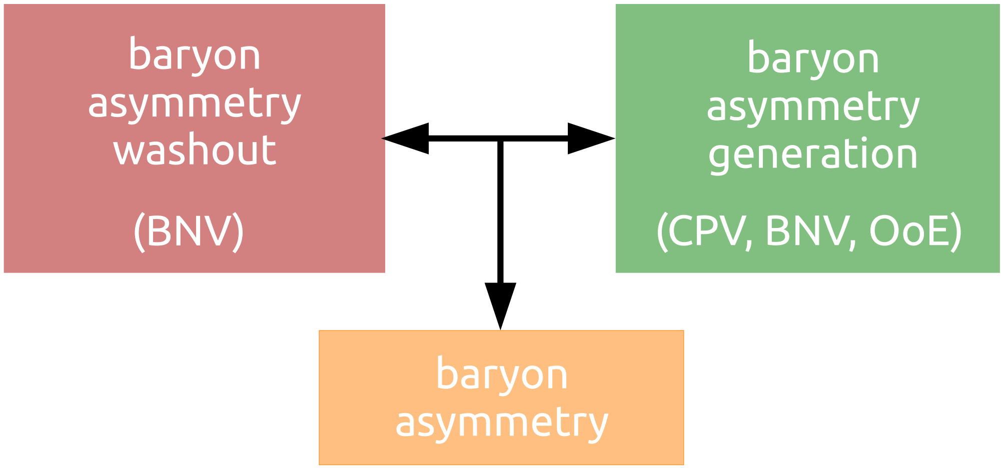
$\nu \simeq \nu_L + \theta \nu_R^c$	$m_\nu \simeq \dfrac{M_D^2}{M_M}$	mainly **active** $SU(2)_L$ doublet states with **light** masses
$N \simeq \nu_R + \theta^T \nu_L^c$	$m_N \simeq M_M$	mainly **sterile** singlet states with **heavy** masses

Seesaw type I

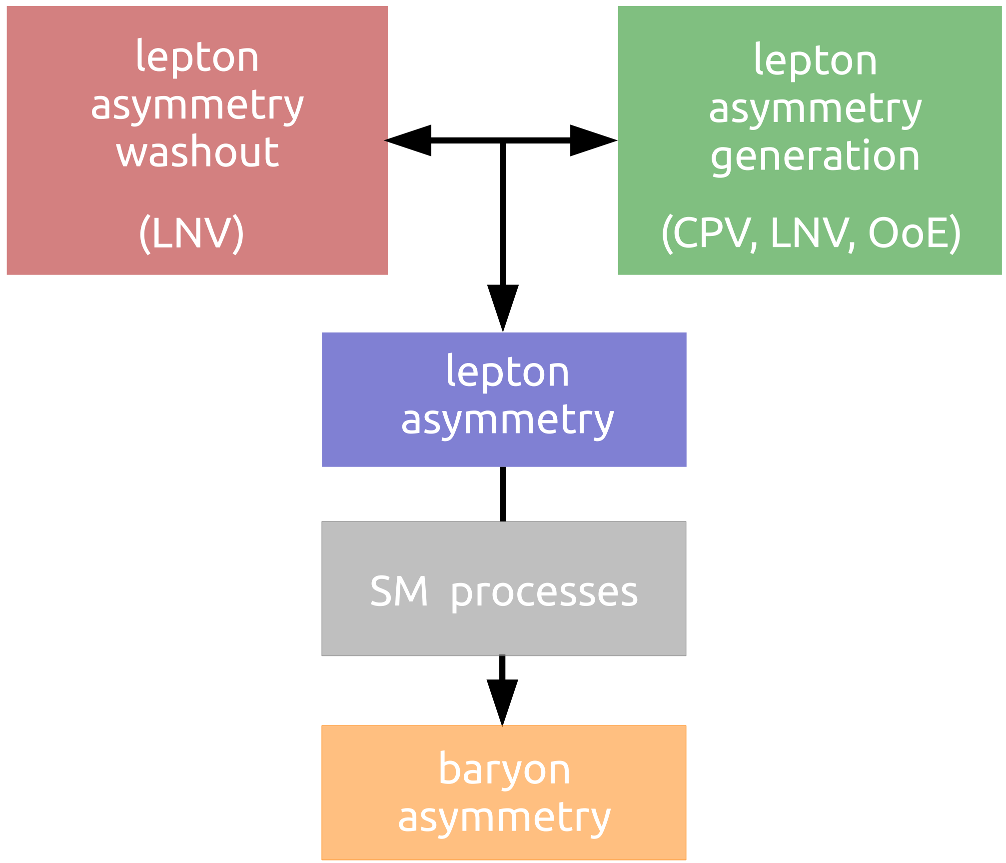
"*naturally*" small neutrino masses

Baryogenesis / Leptogenesis.

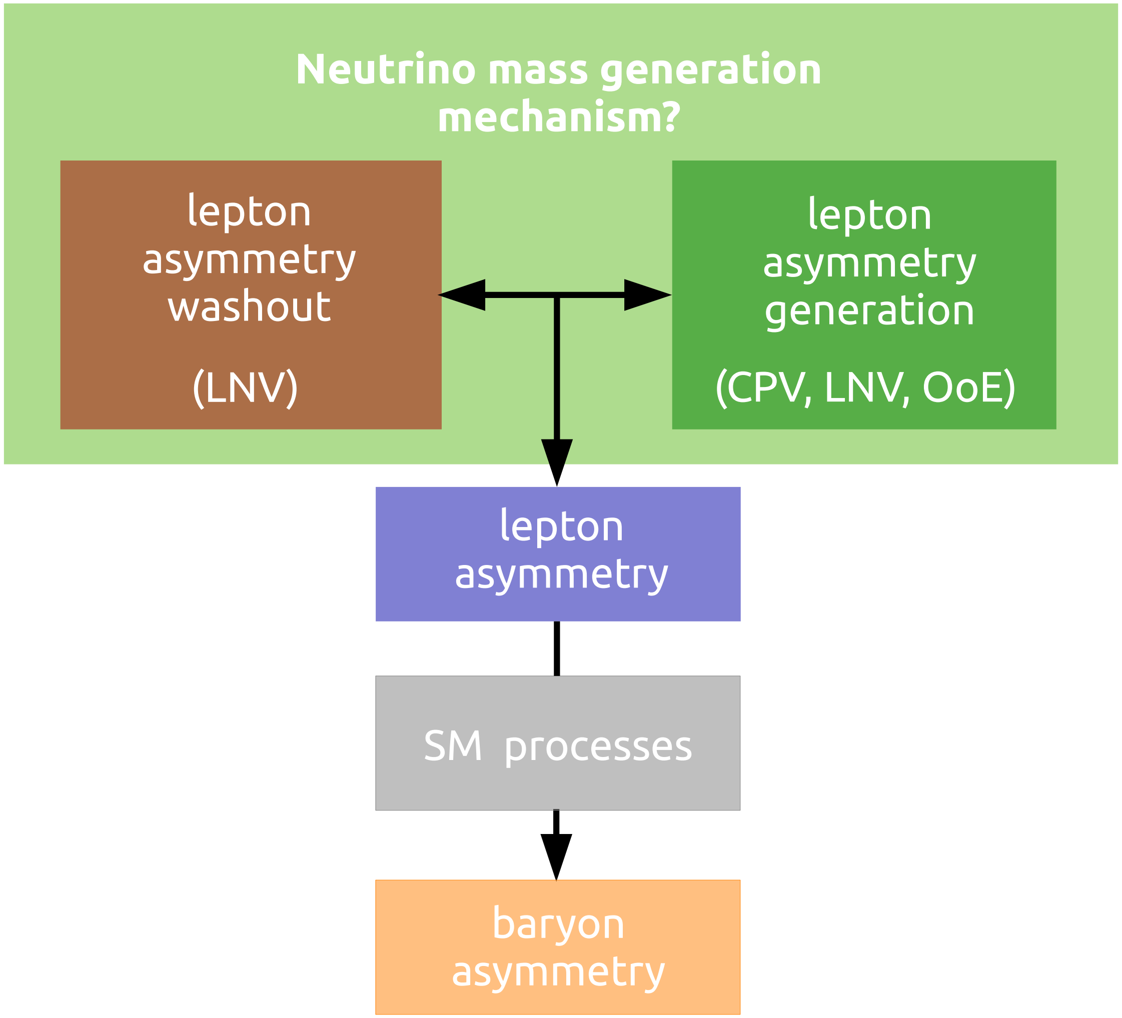
Basic principle of standard baryogenesis



Basic principle of standard leptogenesis



Basic principle of standard leptogenesis



Leptogenesis.

Overview of leptogenesis models

Flood et al. (2021)
Domcke et al. (2021)

freeze-in leptogenesis

wash-in leptogenesis

gravitational waves

McDonald et al. (2014, 2015, 2017, 2020)
Samanta et al. (2020)

gravitational leptogenesis

high-scale out-of-equilibrium decay

Fukugita, Yanagida (1986)

model specific new d.o.f. possibly at lower scale

Pilaftsis et al. (2005)
Nardi et al. (2006)
Abada et al. (2006)
Petcov et al. (2018, 2020)
Moffat et al. (2019)
Granelli et al. (2021)
Mukaida et al. (2021)

flavoured leptogenesis

**low-energy rare decays (LFV),
neutrino oscillations,
neutrino mass spectrum
etc.**

resonant leptogenesis

Pilaftsis,
Underwood (2003)

**medium range RHNs
→ LHC**

leptogenesis via oscillations

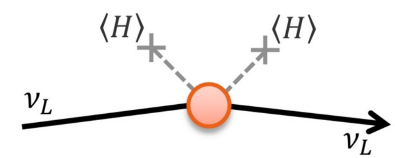
Akhmedov et al. (1998)

**light RHNs
→ ShiP, meson decays, LHC**

Leptogenesis & the neutrino mass mechanism

$$\mathcal{L} \supset y_\nu L\epsilon H \overline{\nu}_R + \frac{1}{2} m_M \overline{\nu}_R \nu_R^c + h.c.$$

$$m_\nu \approx -\frac{v^2}{2} y_\nu m_N^{-1} y_\nu^T$$



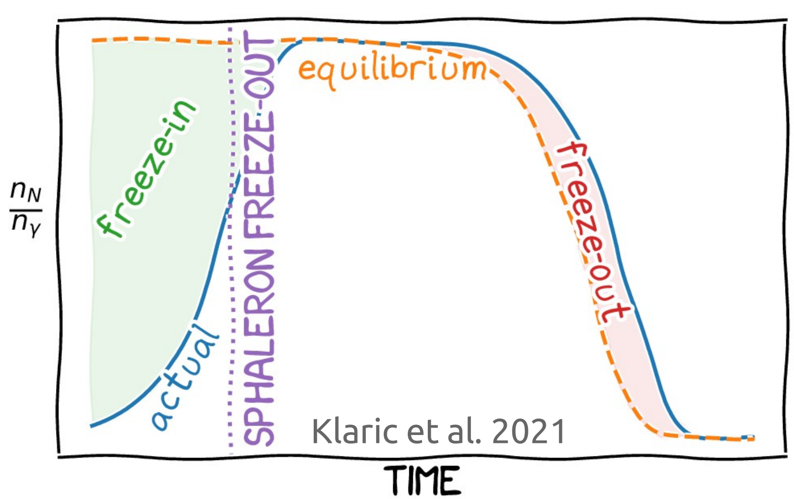
- Majorana neutrino mass
- Higher dimensional operator
- **Lepton number violation (LNV)**

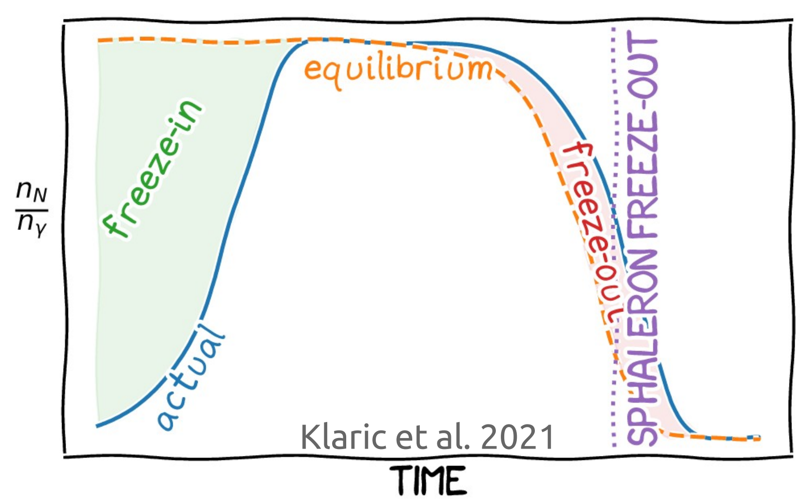
$$\mathrm{M}_\nu \simeq 0.3 \left(\frac{\mathrm{GeV}}{M_N}\right)\left(\frac{\lambda^2}{10^{-14}}\right) \mathrm{eV}$$

Leptogenesis via oscillations

$$\mathrm{M}_\nu \simeq 0.3 \left(\frac{10^8\mathrm{GeV}}{M_N}\right)\left(\frac{\lambda^2}{10^{-6}}\right) \mathrm{eV}$$

High-scale Leptogenesis

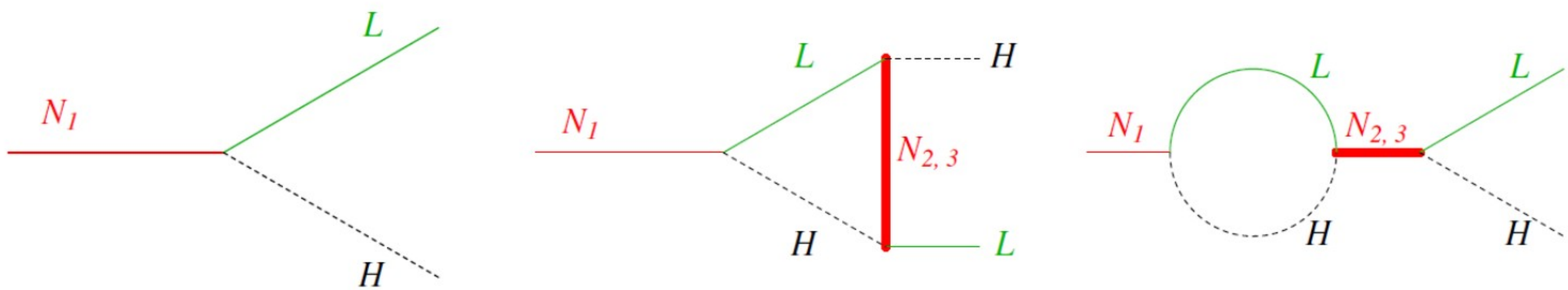




Combined analysis of both regimes and comparison with existing literature (Klaric et al. 2021)

High-scale leptogenesis I

- **Generation** of lepton asymmetry via **heavy neutrino decays** with sources of **CP violation**
- **Competition** with lepton number violating (LNV) **washout** processes
- **Conversion** to a baryon asymmetry via **sphaleron** processes



$$\varepsilon_1 \equiv \frac{\Gamma(N_1 \to LH) - \Gamma(N_1 \to \overline{L}\,\overline{H})}{\Gamma(N_1 \to LH) + \Gamma(N_1 \to \overline{L}\,\overline{H})} \approx -\frac{3}{8\pi}\frac{1}{(hh^\dagger)_{11}}\sum_{i=2,3}\mathrm{Im}(hh^\dagger)^2_{li}\frac{M_1}{M_i}$$

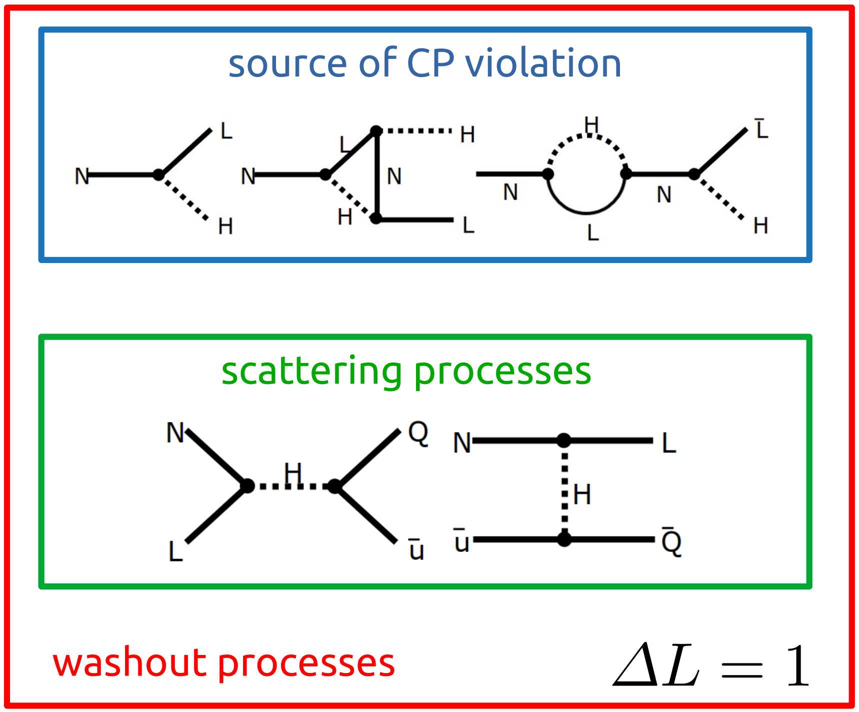
Fukugita et al. (1986)

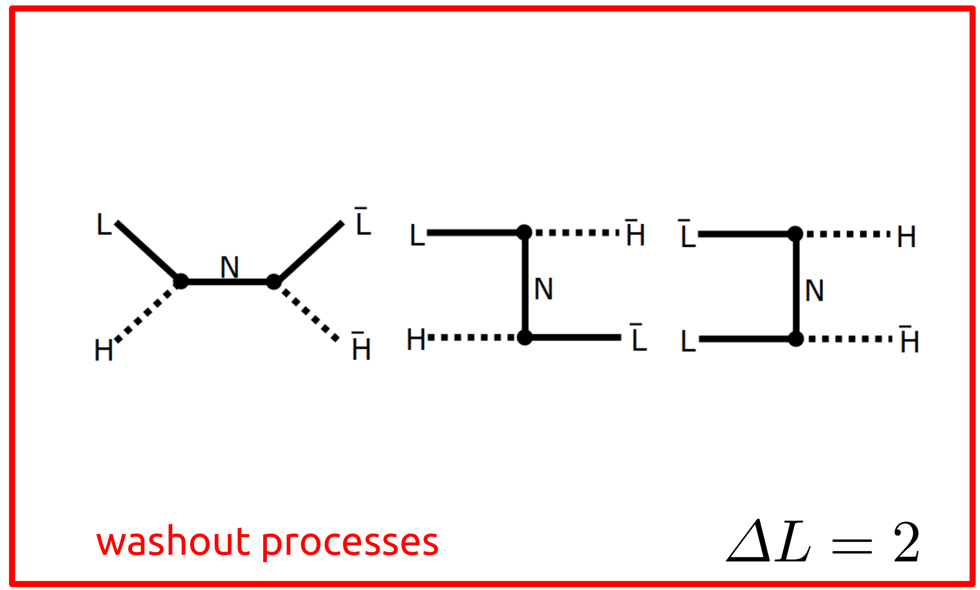
High-scale leptogenesis II

- **Generation** of lepton asymmetry via **heavy neutrino decays** with sources of **CP violation**
- **Competition** with lepton number violating (LNV) **washout** processes
- **Conversion** to a baryon asymmetry via **sphaleron** processes

$$\frac{dY_N}{dz} = -\left(D + S\right)\left(Y_N - Y_N^{\mathrm{eq}}\right)$$

$$\frac{dY_{B-L}}{dz} = -\epsilon\, D \left(Y_N - Y_N^{\mathrm{eq}}\right) - W\, Y_{B-L}$$





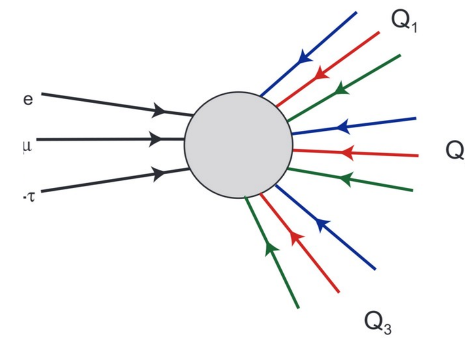
Fukugita et al. (1986)

High-scale leptogenesis III

- **Generation** of lepton asymmetry via **heavy neutrino decays** with sources of **CP violation**
- **Competition** with lepton number violating (LNV) **washout** processes
- **Conversion** to a baryon asymmetry via **sphaleron** processes

$$B = \sum_i (2\mu_{q_i} + \mu_{u_i} + \mu_{d_i}) \qquad L = \sum_i (2\mu_{\ell_i} + \mu_{e_i})$$

- ELH Yukawa: $0 = \mu_E + \mu_L + \mu_H$
- DQH Yukawa: $0 = \mu_D + \mu_Q + \mu_H$
- UQH Yukawa: $0 = \mu_U + \mu_Q - \mu_H$
- QQQL sphalerons: $0 = 3\mu_Q + \mu_L$
- No electric charge: $0 = N_{\text{gen}}(\mu_Q - 2\mu_U + \mu_D - \mu_L + \mu_E) - 2N_{\text{Higgs}}\mu_H$

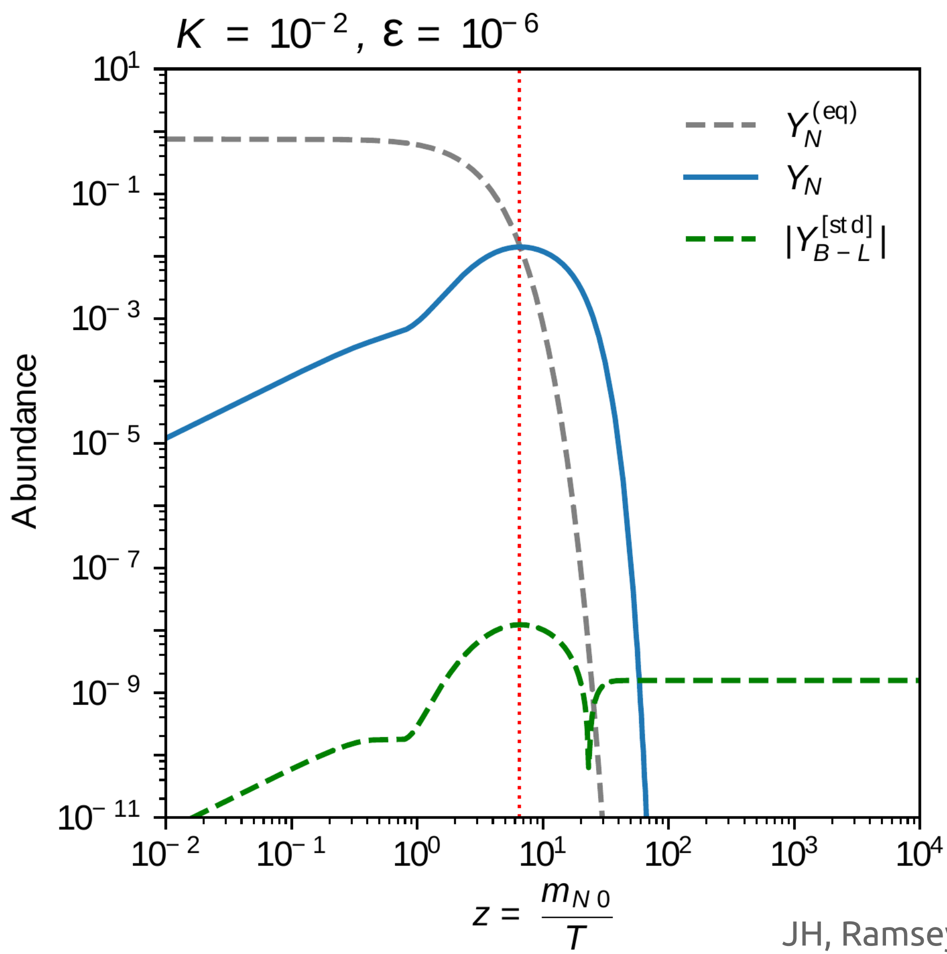


$$\boxed{B = \frac{8N_f + 4m}{22N_f + 13m}(B - L)}$$

Fukugita et al. (1986)

High-scale leptogenesis IV

- **Generation** of lepton asymmetry via **heavy neutrino decays** with sources of **CP violation**
- **Competition** with lepton number violating (LNV) **washout** processes
- **Conversion** to a baryon asymmetry via **sphaleron** processes



JH, Ramsey-Musolf, Shen, Urrutia-Quiroga (2021)

High-scale leptogenesis – models

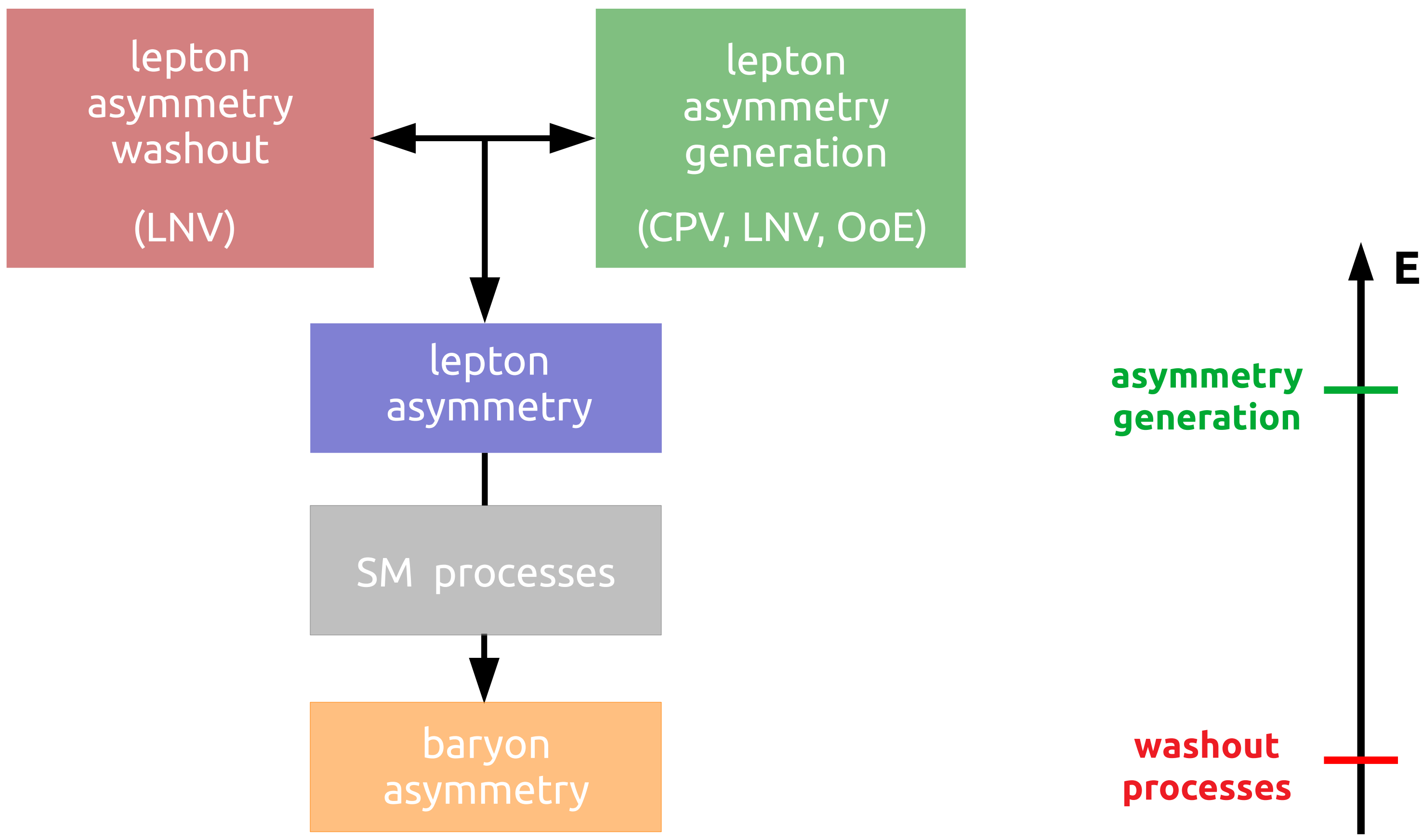
Plethora of examples:

- Extension of seesaw type-I by **new scalars** with same quantum numbers as SM fermions → e.g. long-lived scalars, R-hadrons, heavy sterile neutrinos e.g. Fong et al. (2013)
- **Z' models** → same-sign di-lepton final states e.g. Chun (2005)
- **Left-right symmetric models** → falsification by low mass W_R e.g. Dev. et al. (2015)
- **Soft leptogenesis** → type-I: charged LFV e.g. Adhikari et al. (2015)
  → type-II: same-sign di-lepton resonance, same-sign tetra-leptons e.g. Chun et al. (2006)

See review "Probing Leptogenesis", JH, Chun et al. (arxiv:hep-ph/1711.02865)

Generic problem: new physics at high scales

Basic principle of leptogenesis



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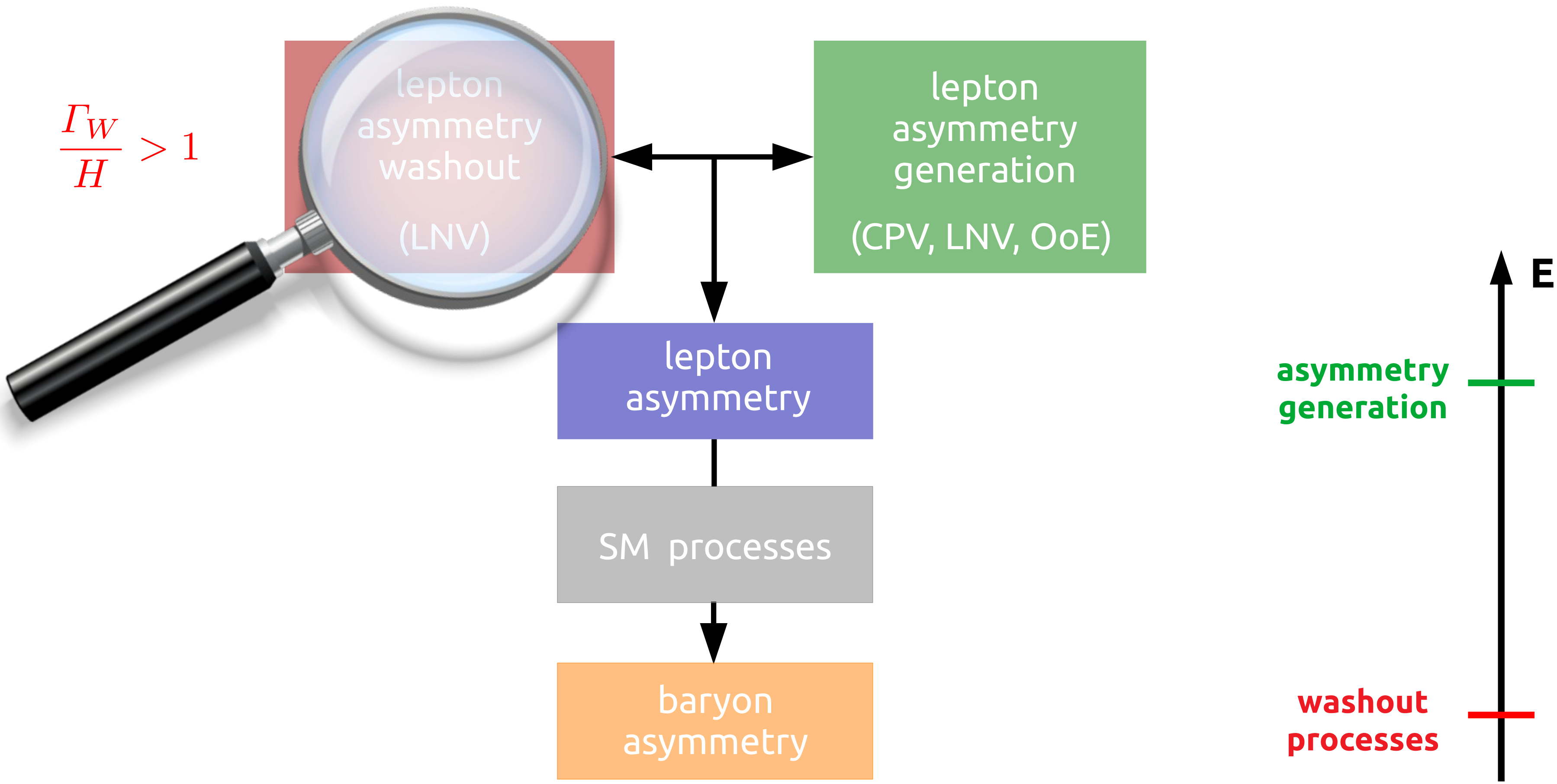
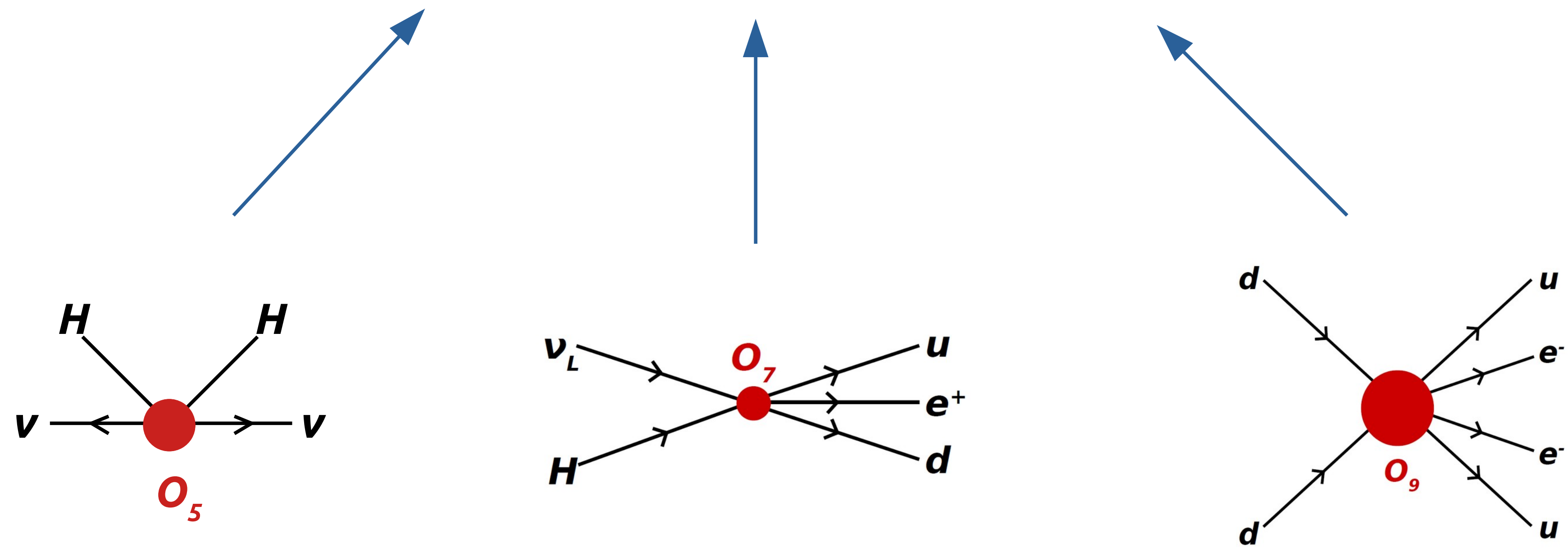


Strategy: Search for washout processes with the potential to falsify models!

Lepton Number Violation

LNV occurs only at odd mass dimension beyond dim-4:

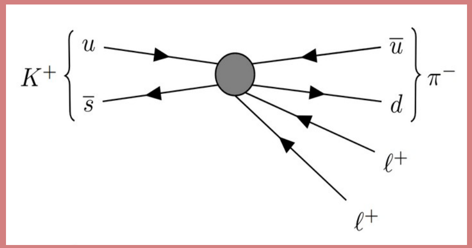
$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda_1}\mathcal{O}_1^{(5)} + \sum_i \frac{1}{\Lambda_i^3}\mathcal{O}_i^{(7)} + \sum_i \frac{1}{\Lambda_i^5}\mathcal{O}_i^{(9)} + \cdots$$



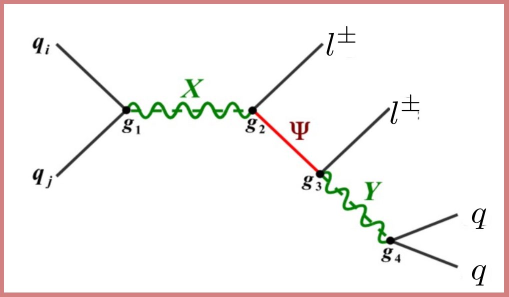
See surveys of all LNV operators up to dim-11 e.g. in
Babu, Leung (2001), Gouvea, Jenkins (2008), Graf, JH, Deppisch, Huang (2018)

Probing LNV washout interactions

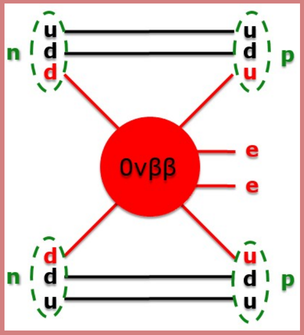
Meson decays



LHC searches



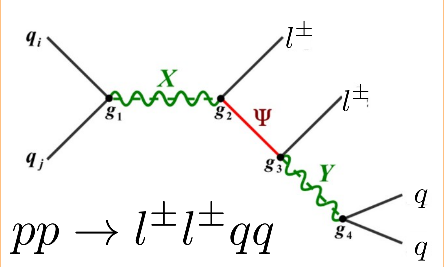
Neutrinoless double beta decay



Falsifying baryogenesis with LHC & 0νββ decay

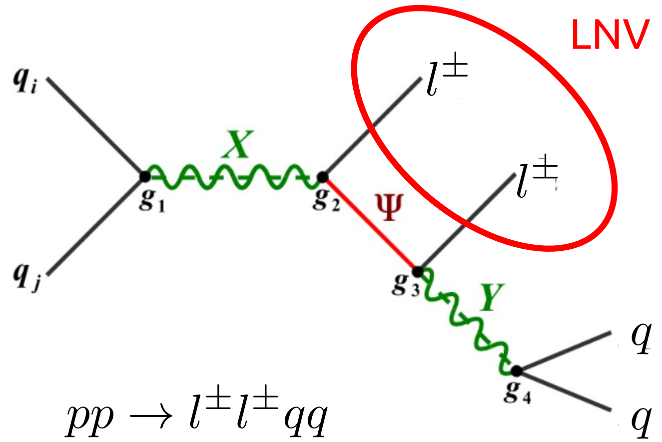
Observation of any LNV washout process at the LHC would falsify high-scale baryogenesis

Deppisch, JH, Hirsch (2014)



Probing Leptogenesis at the LHC

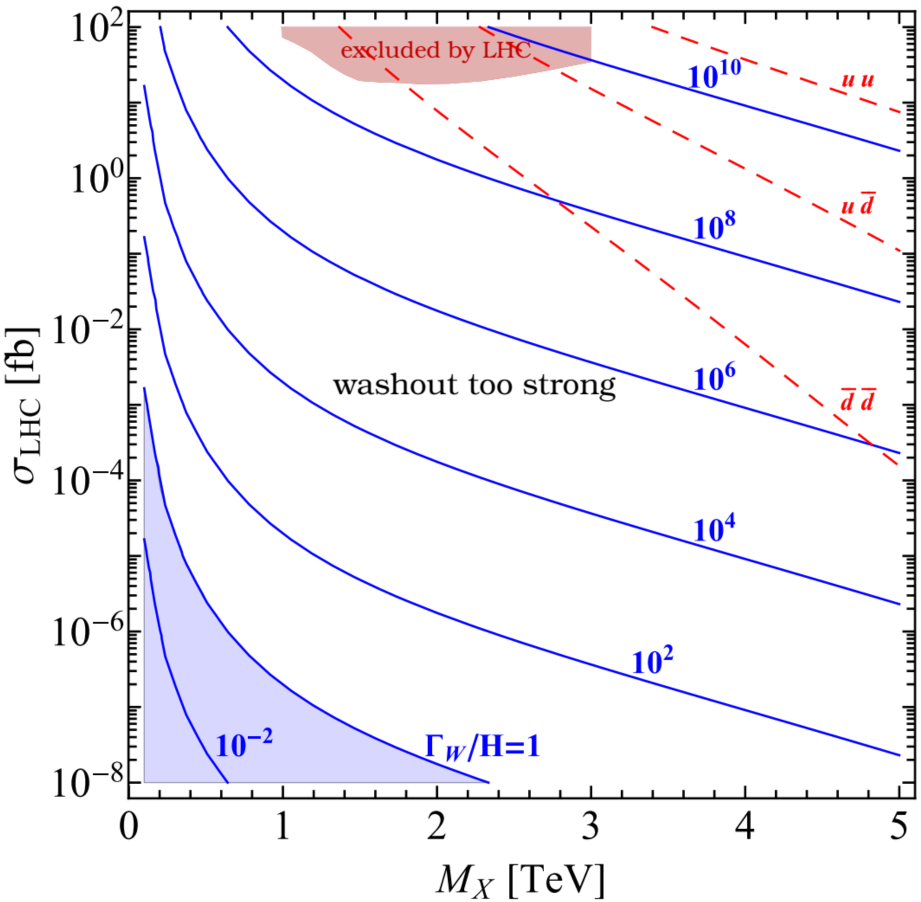
Washout processes could be observable at the LHC



$$\log_{10}\frac{\Gamma_W}{H} > 6.9 + 0.6\left(\frac{M_X}{\mathrm{TeV}} - 1\right) + \log_{10}\frac{\sigma_{\mathrm{LHC}}}{\mathrm{fb}}$$

Observation of any washout process at LHC would falsify high scale baryogenesis!

(scale of asymmetry generation *above* M_X)



Deppisch, JH, Hirsch, Phys. Rev. Lett. (2014)
Deppisch, JH, Hirsch, Päs, Int. J. Mod. Phys. A (2015)

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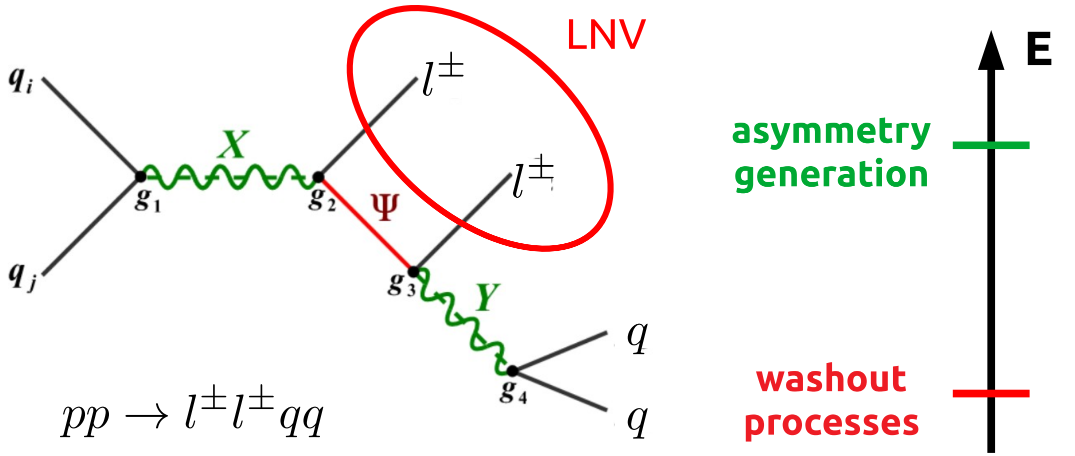
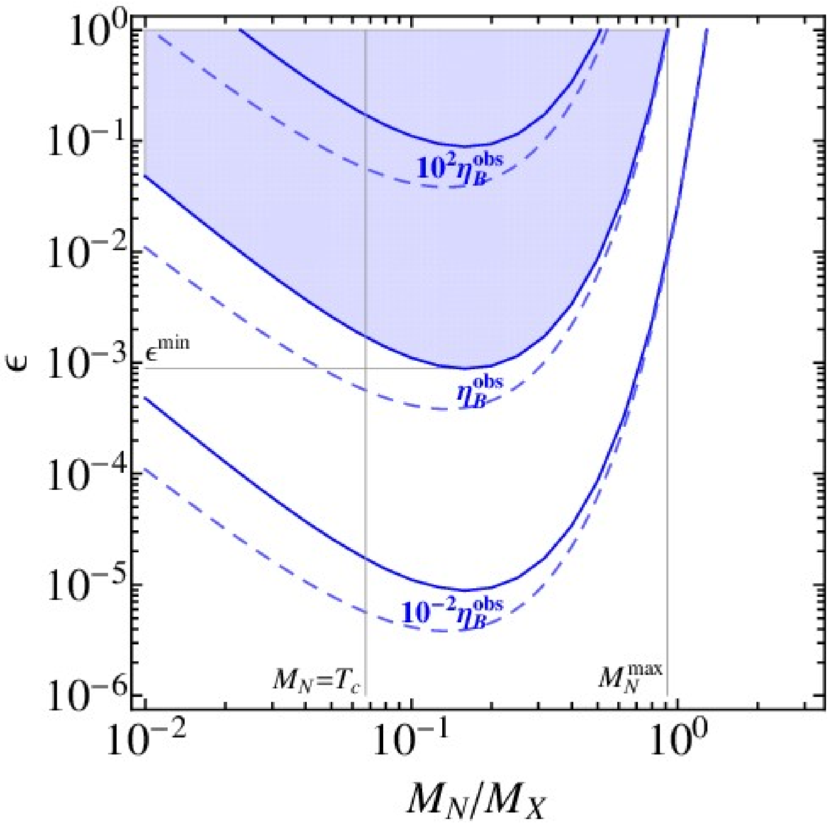


$pp \to l^\pm l^\pm qq$

$$\log_{10}\left|\frac{\eta_B}{\eta_B^{\rm obs}}\right| < 2.4\,\frac{M_X}{\rm TeV}\left(1-\frac{4}{3}\frac{M_N}{M_X}\right) + \log_{10}\left[|\epsilon|\left(\frac{\sigma_{\rm LHC}}{\rm fb}\right)^{-1}\left(\frac{4}{3}\frac{M_N}{M_X}\right)^2\right]$$



And indicate a minimal CP asymmetry!

Deppisch, JH, Hirsch, Phys. Rev. Lett. (2014)
Deppisch, JH, Hirsch, Päs, Int. J. Mod. Phys. A (2015)

Falsifying baryogenesis with LHC & 0νββ decay

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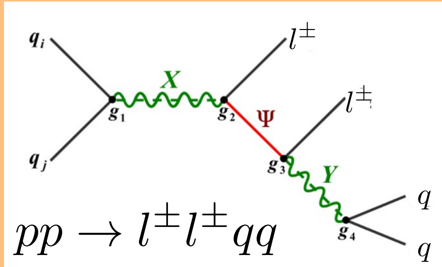
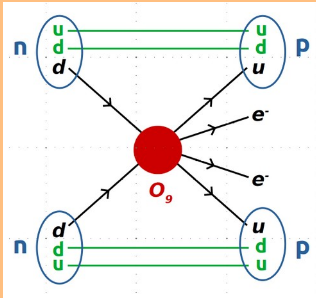


Observation of neutrinoless double beta decay with new physics from > dim-5 LNV operators would falsify high-scale baryogenesis

Deppisch, Graf, JH, Huang (2018)
Deppisch, JH, Huang, Hirsch, Päs (2015)



Half life of Neutrinoless Double Beta Decay

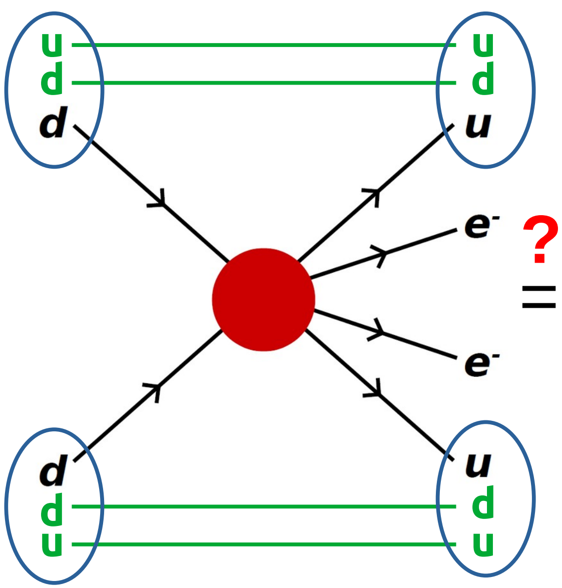
$$T_{1/2}^{-1} = |\,\epsilon_\alpha^\beta\,|^2 G^{0\nu}\,|\,M^{0\nu}\,|^2$$

particle physics

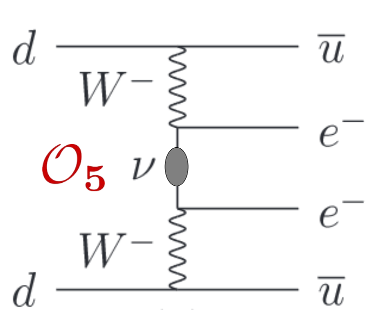
phase-space factors

nuclear physics

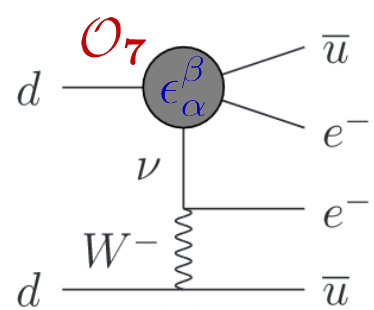
Experimental constraints: $T_{1/2}^{0\nu} > 1.07 \times 10^{26}\text{yr}\ 90\%\text{C.L.}$ KamLAND-Zen (2016)



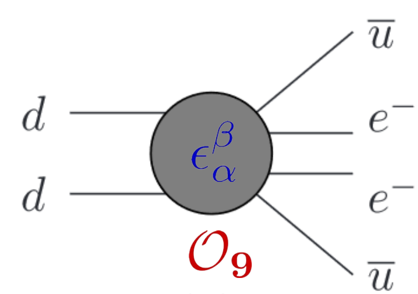
standard mass mechanism



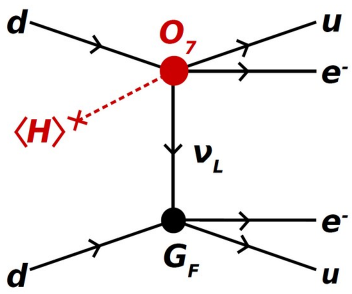
long range contribution



short range contribution



Probing Leptogenesis with 0νββ



$$T_{1/2}^{-1} = G_{0\nu} |\mathcal{M}|^2 |\epsilon_\alpha^\beta|^2$$

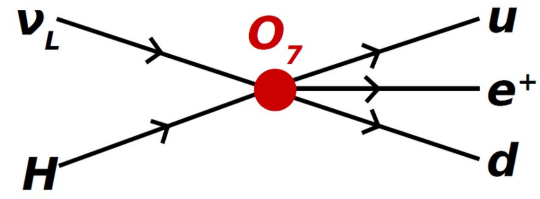
Observation would fix the **effective coupling** for one operator

$\mathcal{O}$	Operator
1^{H^2}	$L^iL^jH^kH^l\overline{H}^tH_t\epsilon_{ik}\epsilon_{jl}$
2	$L^iL^jL^ke^cH^l\epsilon_{ij}\epsilon_{kl}$
3_a	$L^iL^jQ^kd^cH^l\epsilon_{ij}\epsilon_{kl}$
3_b	$L^iL^jQ^kd^cH^l\epsilon_{ik}\epsilon_{jl}$
4_a	$L^iL^j\overline{Q}_i\bar{u}^cH^k\epsilon_{jk}$
$4_b^\dagger$	$L^iL^j\overline{Q}_k\bar{u}^cH^k\epsilon_{ij}$
8	$L^i\bar{e}^c\bar{u}^cd^cH^j\epsilon_{ij}$

$$\frac{G_F\epsilon_7}{\sqrt{2}} = \frac{g^3 v}{2\Lambda_7{}^3}$$

effective coupling can be related to the **scale of the operator**

$\mathcal{O}_D$	Λ_D^0 [GeV]
$\mathcal{O}_5$	9.1×10^{13}
$\mathcal{O}_7$	2.6×10^4
$\mathcal{O}_9$	2.1×10^3
$\mathcal{O}_{11}$	1.0×10^3



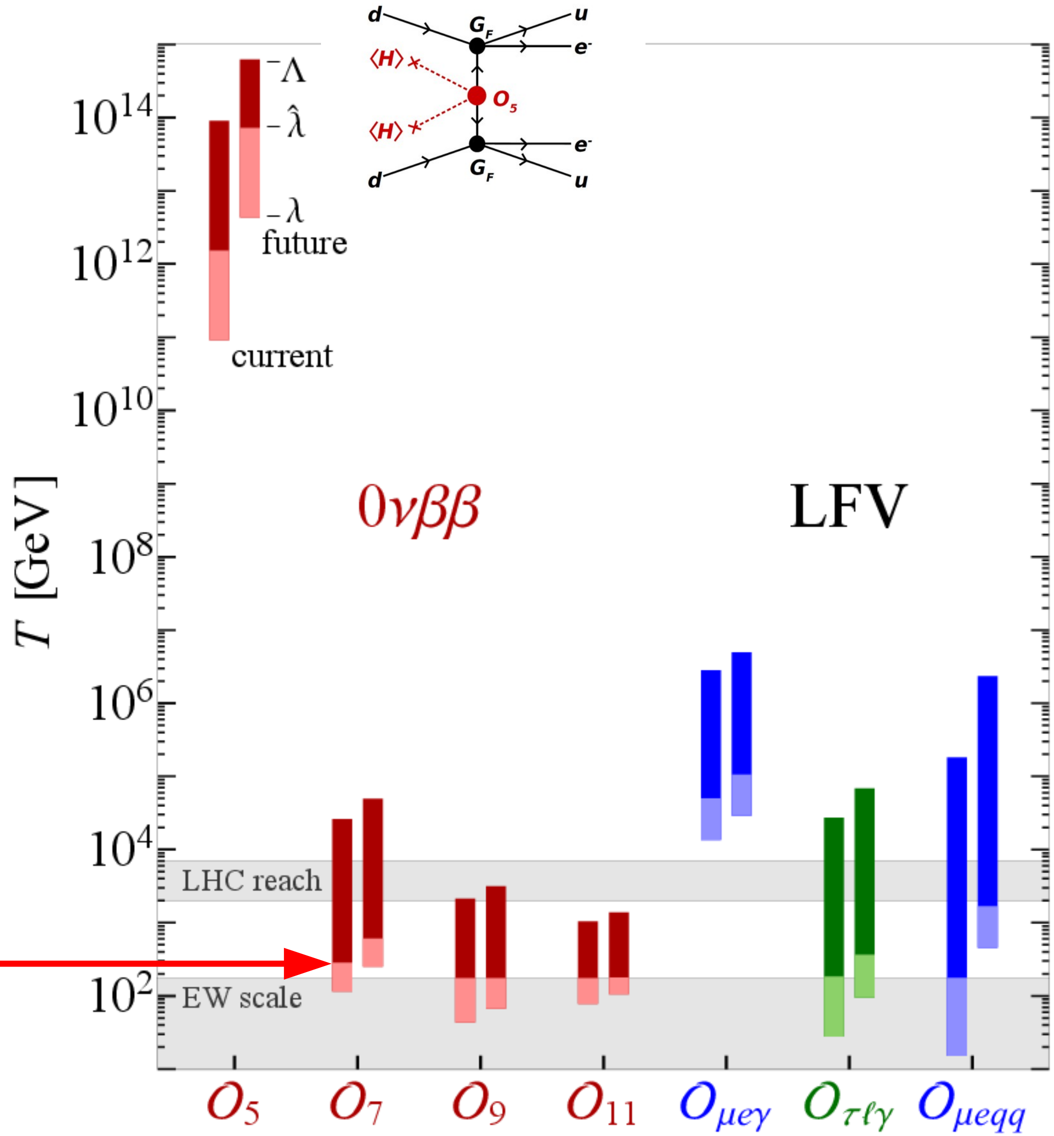
$$\Lambda_7 \left(\frac{\Lambda_7}{c_7' \Lambda_{Pl}}\right)^{\frac{1}{5}} \lambda_7 < T < \Lambda_7$$

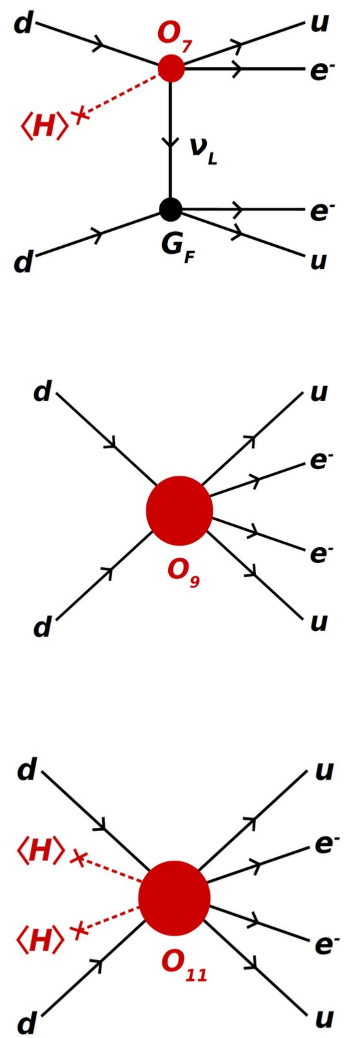
Limit above which the washout is highly effective can be calculated in dependence of the **operator scale**

$$\frac{\Gamma_W}{H} > 1$$

Deppisch, Graf, JH, Huang (2018)
Deppisch, JH, Huang, Hirsch, Päs (2015)

Probing Leptogenesis with 0νββ





limit above which the washout is highly effective

$$\frac{\Gamma_W}{H} > 1$$

Potential to falsify baryogenesis models!

Deppisch, Graf, JH, Huang (2018)
Deppisch, JH, Huang, Hirsch, Päs (2015)

Falsifying baryogenesis with LHC & 0νββ decay

Observation of any LNV washout process at the LHC would falsify high-scale baryogenesis

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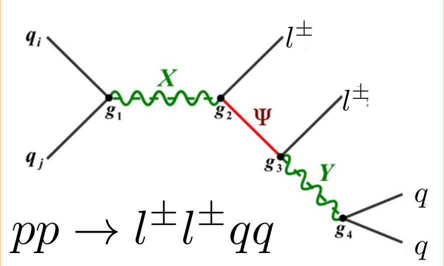

Observation of neutrinoless double beta decay with new physics from > dim-5 LNV operators would falsify high-scale baryogenesis

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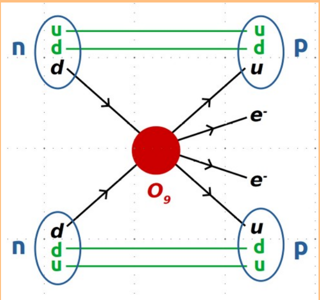


Caveats might apply, e.g.:

- **Flavor specific leptogenesis**
- **Dark U(1) symmetries**

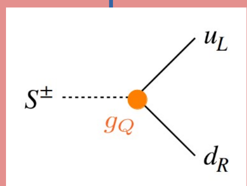
Aristizabal Sierra, Fong, Nardi, Peinado (2014)
Frandsen, Hagedorn, Huang, Molinaro, Päs (2018)

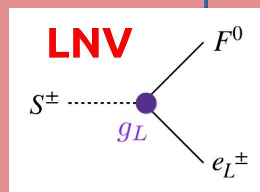
How do LHC and 0νββ decay compare wrt their strength to falsify leptogenesis?
Does TeV-scale LNV really render standard thermal leptogenesis invalid?

A simplified model study of TeV scale LNV

UV realization of dim-9 operator:

$$\tilde{\mathcal{L}} \supset g_Q \overline{Q} S d_R + g_L \overline{L}(i\tau^2) S^* F - m_S^2 S^\dagger S - \frac{m_F}{2} \overline{F^c} F + \lambda_{HS} (S^\dagger H)^2 + \text{h.c.}$$



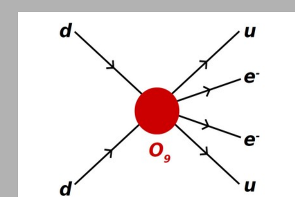


TeV-scale LNV "washout" interactions

$$\Lambda = (m_S^4 m_F)^{1/5}$$
$$C_1 = g_L^2 g_Q^2$$

Integrating out heavy d.o.f. leads to dim-9 LNV operator:

$$L_{LNV}^{eff} = \frac{C_1}{\Lambda^5} \bar{Q}\tau^+ d \bar{Q}\tau^+ d \bar{L} L^C + \text{h.c.}$$



JH, Ramsey-Musolf, Shen, Urrutia-Quiroga (2021)

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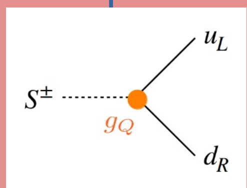

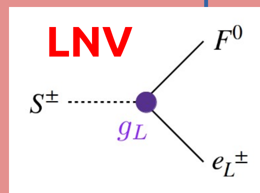

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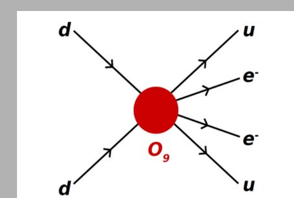

Right-handed neutrino interactions ("standard thermal LG"):

$$\mathcal{L} \supset y_\nu \bar{L} H N - \frac{m_N}{2} \bar{N}^c N + \text{h.c.}$$

high-scale source of lepton asymmetry

JH, Ramsey-Musolf, Shen, Urrutia-Quiroga (2021)

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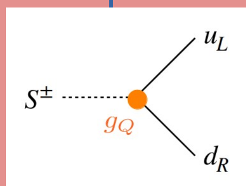

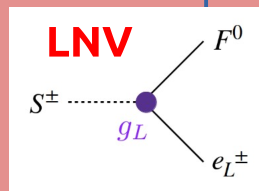

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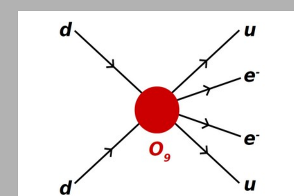


Right-handed neutrino interactions ("standard thermal LG"):

$$\mathcal{L} \supset y_\nu \bar{L} H N - \frac{m_N}{2} \bar{N}^c N + \text{h.c.}$$

high-scale source of lepton asymmetry

Can TeV-scale LNV destroy the generated asymmetry from standard thermal LG?

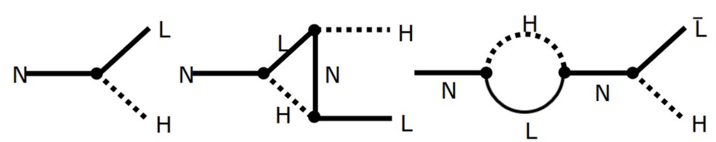
JH, Ramsey-Musolf, Shen, Urrutia-Quiroga (2021)

Implications for Leptogenesis

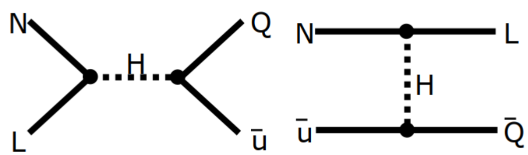
$$\frac{dY_N}{dz} = -\left(D + S\right)\left(Y_N - Y_N^{\mathrm{eq}}\right)$$
$$\frac{dY_{B-L}}{dz} = -\epsilon\, D\left(Y_N - Y_N^{\mathrm{eq}}\right) - W\, Y_{B-L}$$

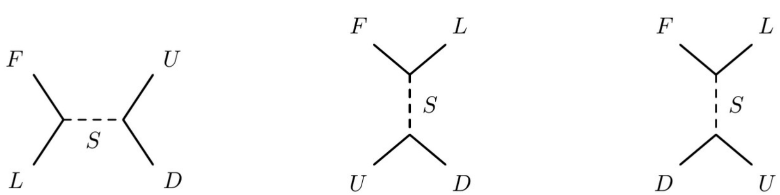
$\Delta L = 1$

source of CP violation



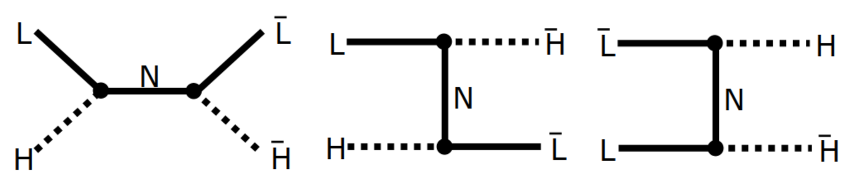
scattering processes

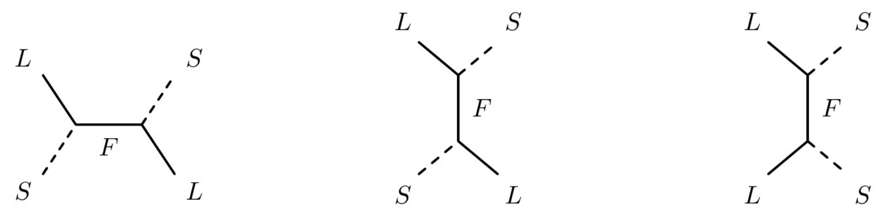




washout processes

$\Delta L = 2$



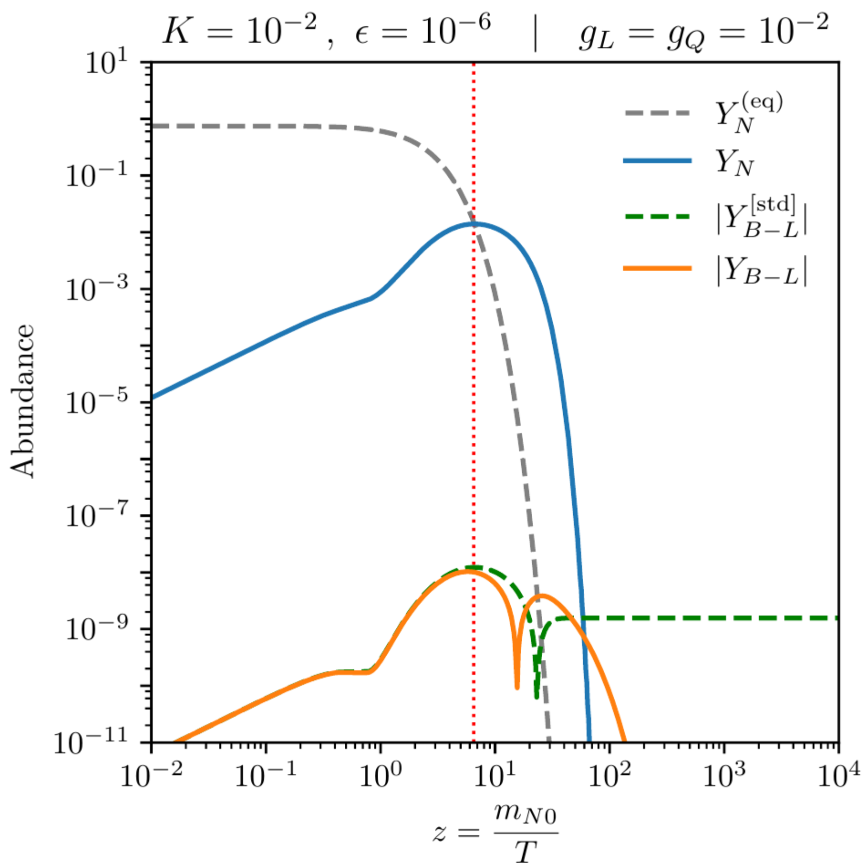


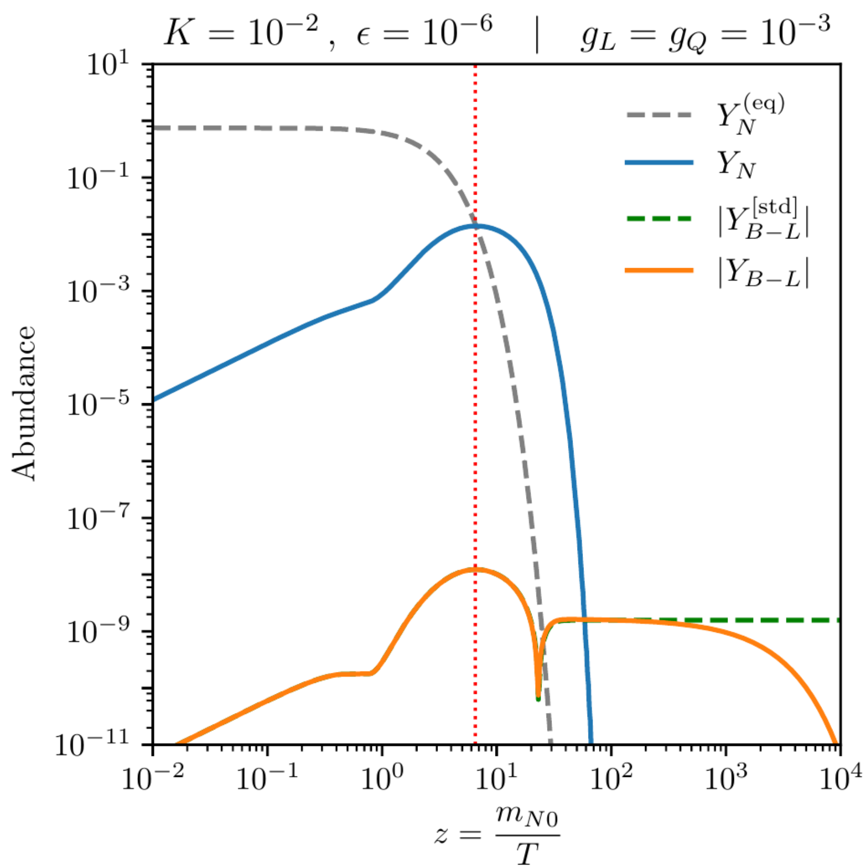
washout processes

JH, Ramsey-Musolf, Shen, Urrutia-Quiroga (2021)

Implications for Leptogenesis

$$\mathcal{O}(m_S) \approx \mathcal{O}(m_F) \approx \mathcal{O}(\text{TeV})$$

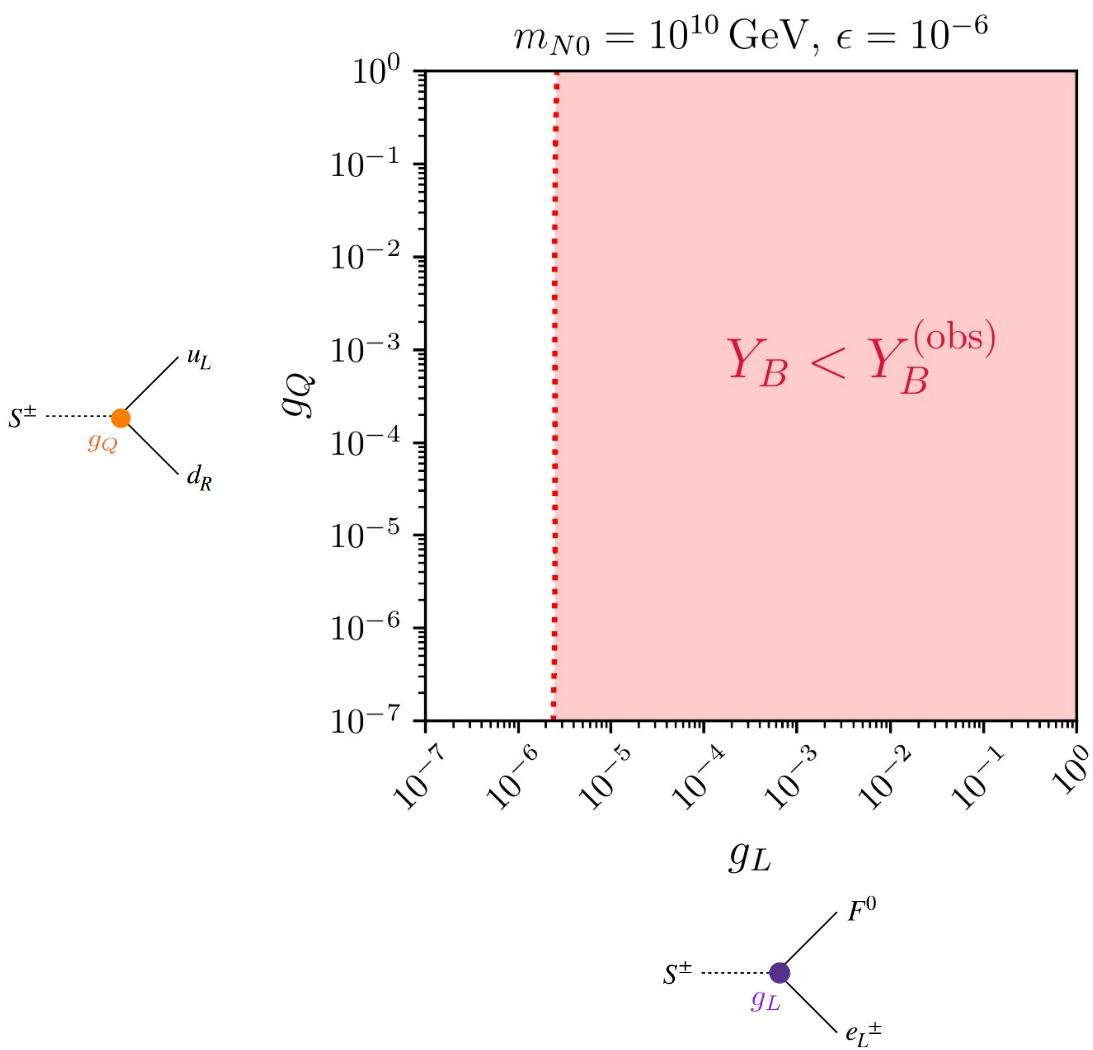




Low-scale LNV destroys lepton asymmetry previously generated by standard LG scenario.

JH, Ramsey-Musolf, Shen, Urrutia-Quiroga (2021)

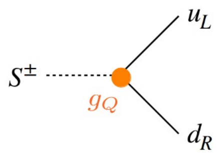
Implications for Leptogenesis

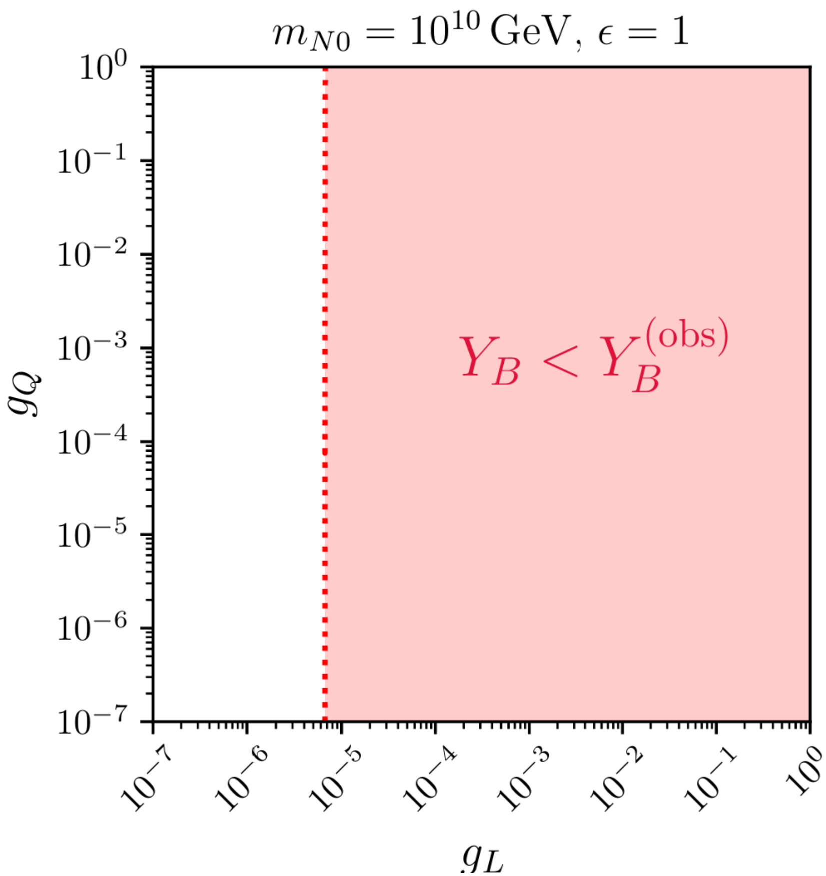


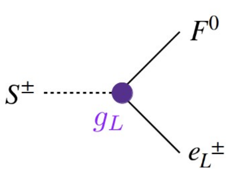
Lepton asymmetry from standard thermal LG is washed out below observable value.

JH, Ramsey-Musolf, Shen, Urrutia-Quiroga (2021)

Implications for Leptogenesis



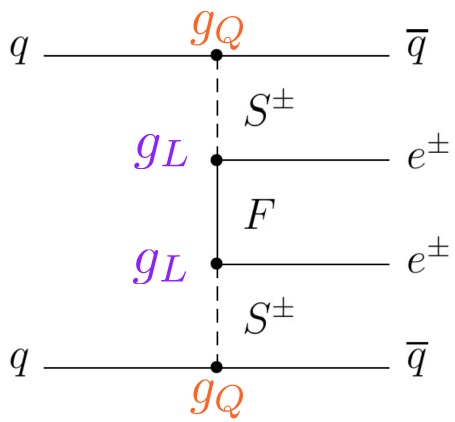


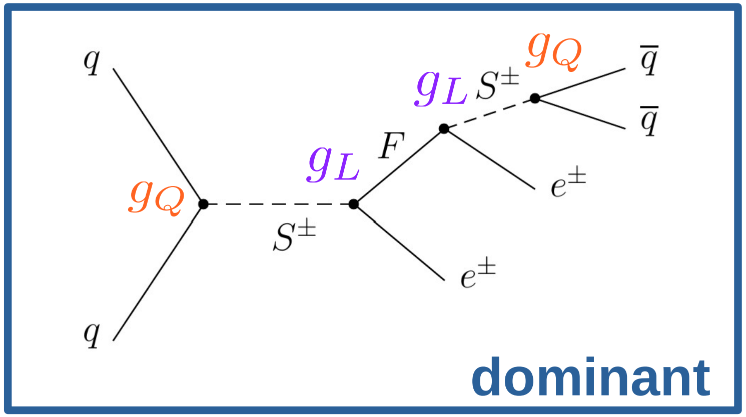


Lepton asymmetry from standard thermal LG is washed out below observable value.

JH, Ramsey-Musolf, Shen, Urrutia-Quiroga (2021)

Reach at colliders





Case	Mass hierarchy	Process
C1	$m_S < m_F$	$pp \to e^{\pm}F, \quad F \to e^{\pm}S^{\mp}, \quad S^{\mp} \to jj$
C2	$m_S = m_F$	$pp \to e^{\pm}F, \quad F \to e^{\pm}jj$
C3	$m_S > m_F$	$pp \to S^{\pm}, \quad S^{\pm} \to e^{\pm}F, \quad F \to e^{\pm}jj$

Signal generation: Madgraph + Pythia 8 + Delphes

Background:

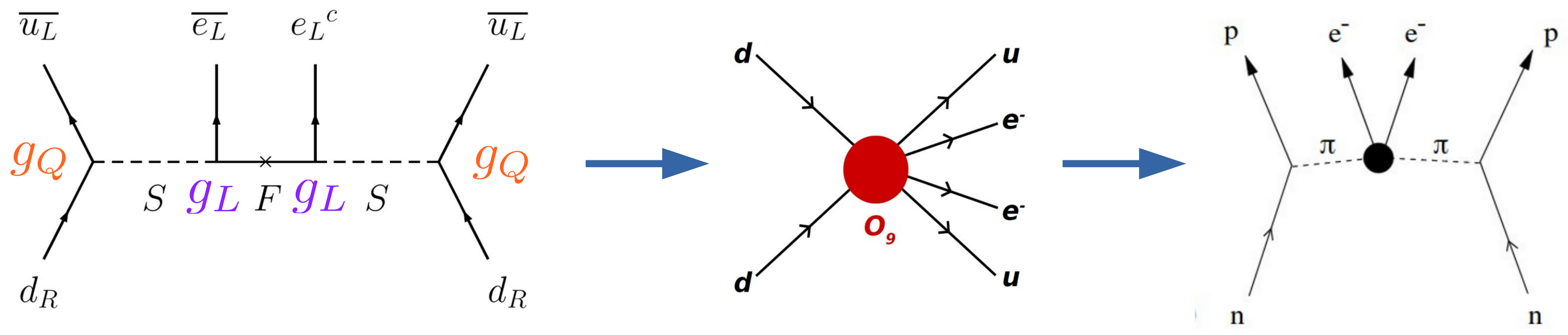
- SM processes with same-sign leptons (e.g. jjWW)
- Charge misidentification
- Jet-fake leptons from heavy flavour decays

S/B discrimination:

neural network

JH, Ramsey-Musolf, Shen, Urrutia-Quiroga (2021)

Reach at 0νββ decay experiments



$$\frac{C_{\rm eff}}{2\Lambda^5}\left(\bar q_L\tau^+q_R\ \bar q_L\tau^+q_R+\bar q_R\tau^+q_L\ \bar q_R\tau^+q_L\right)\bar e_L e_R^c+\text{h.c.}$$

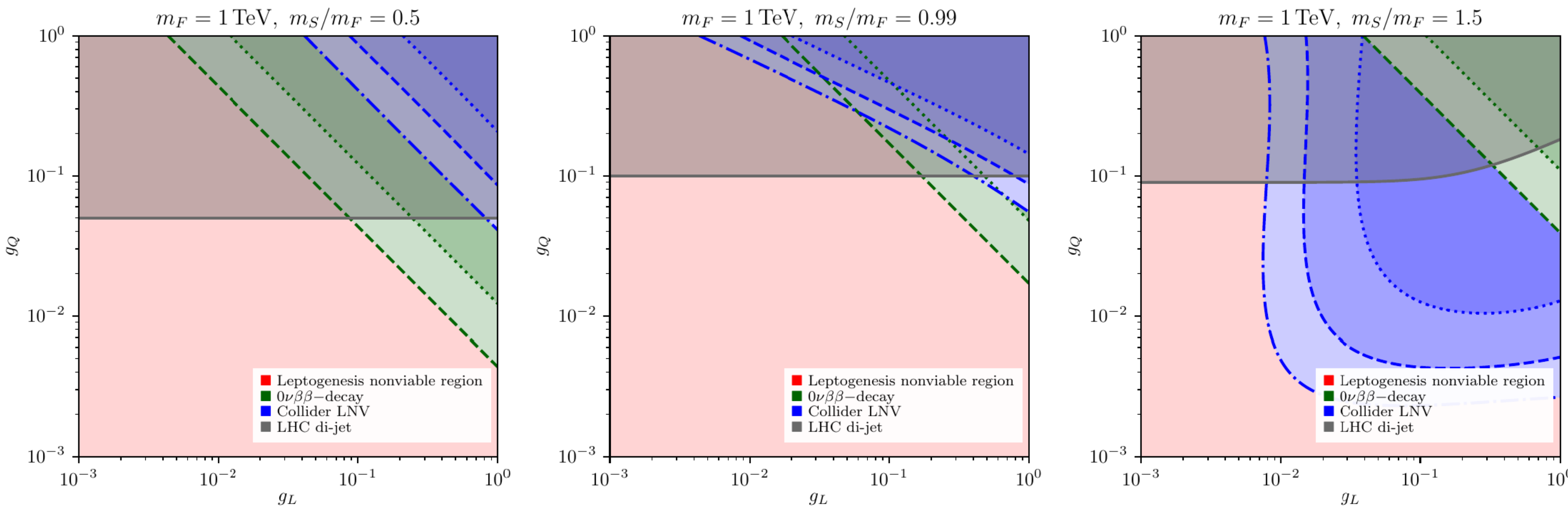
$$\downarrow$$

$$\frac{C_{\rm eff}\Lambda_H^2F_\pi^2}{2\Lambda^5}\pi^-\pi^-\bar e_L e_R^c+\text{h.c.}$$

$$\frac{1}{T_{1/2}}=|M_0|^2\left[G_{0\nu}\times(1\,\text{TeV})^2\right]\left(\frac{\Lambda_H}{\text{TeV}}\right)^4\left(\frac{1}{144}\right)\times\left(\frac{v}{\text{TeV}}\right)^8\left(\frac{1}{\cos\theta_C}\right)^4\left[\frac{C_{\rm eff}^2}{(\Lambda/\text{TeV})^{10}}\right]$$

JH, Ramsey-Musolf, Shen, Urrutia-Quiroga (2021)

Combined results: Leptogenesis, LHC & 0νββ decay

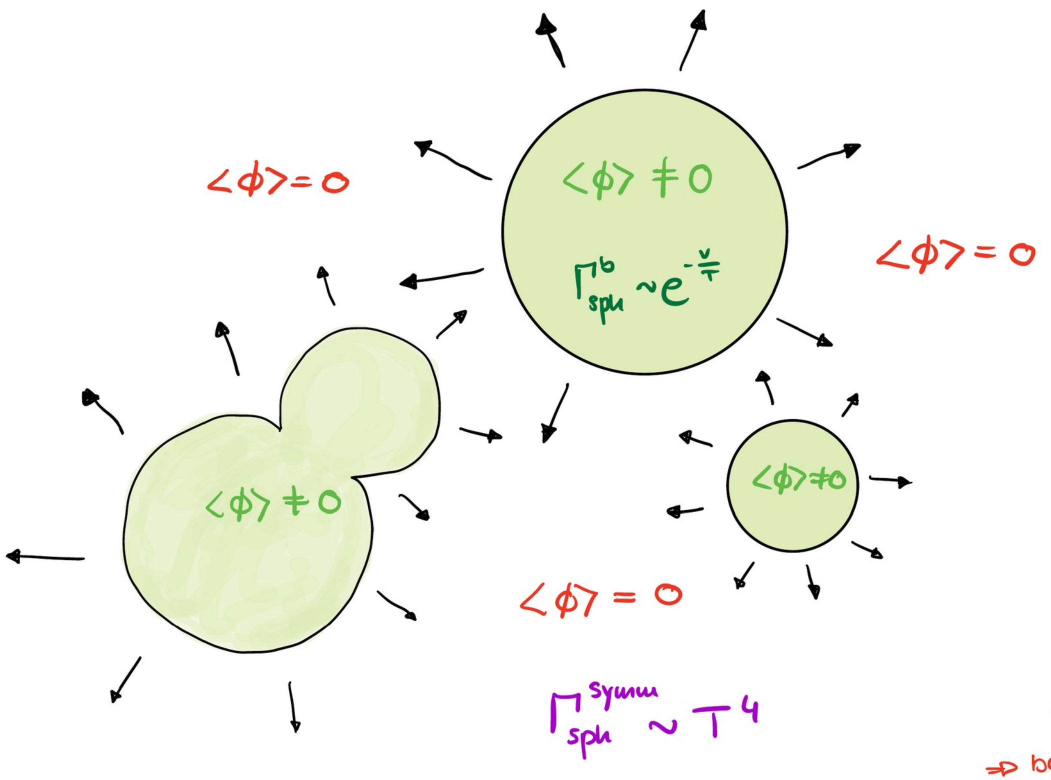


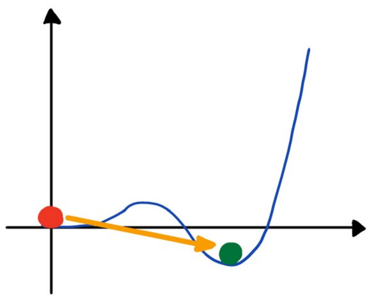
Comprehensive analysis confirms EFT results and demonstrates interesting interplay between collider and 0νββ reach.

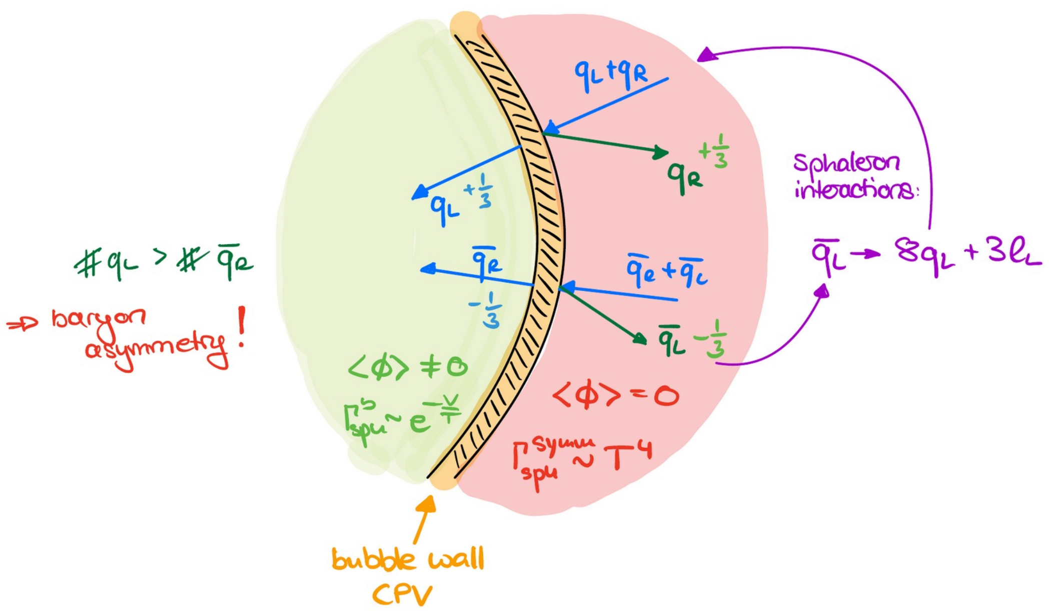
JH, Ramsey-Musolf, Shen, Urrutia-Quiroga (2021)

Baryogenesis.

Electroweak baryogenesis







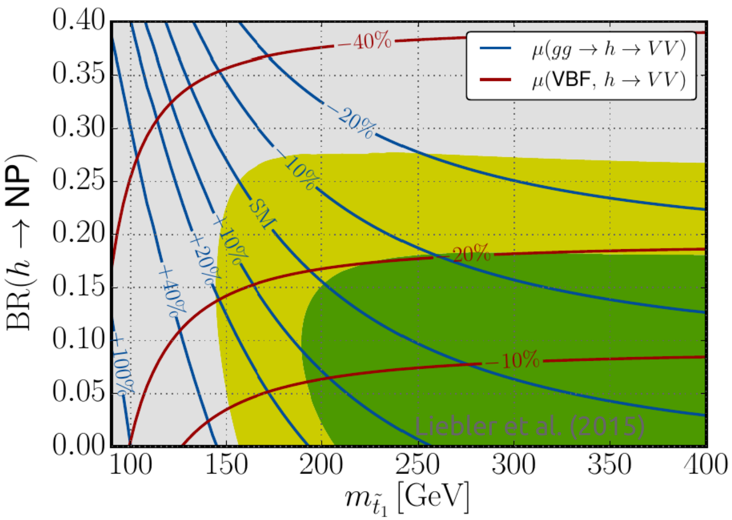
Unfortunately, Higgs boson is too heavy for EWBG!

Electroweak baryogenesis with New Physics

Are there new degrees of freedom that modify the scalar potential and lead to a SFOPT for successful baryogenesis?

- **Prime example: MSSM with a light stop**
  - Lattice calculations set limit of <155 GeV
  - Is the necessary light stop excluded?

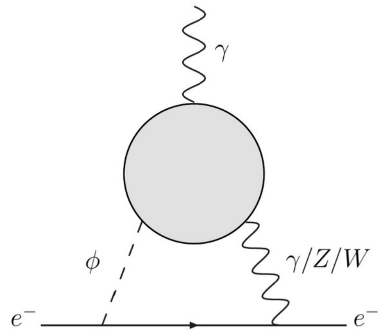
Delphine et al. (1996), Carena et al. (1996, 1998, 2003, 2009), Espinosa et al. (1996), Huber et al. (1999), Profumo (2007), Curtin (2012), Liebler (2015) and more….



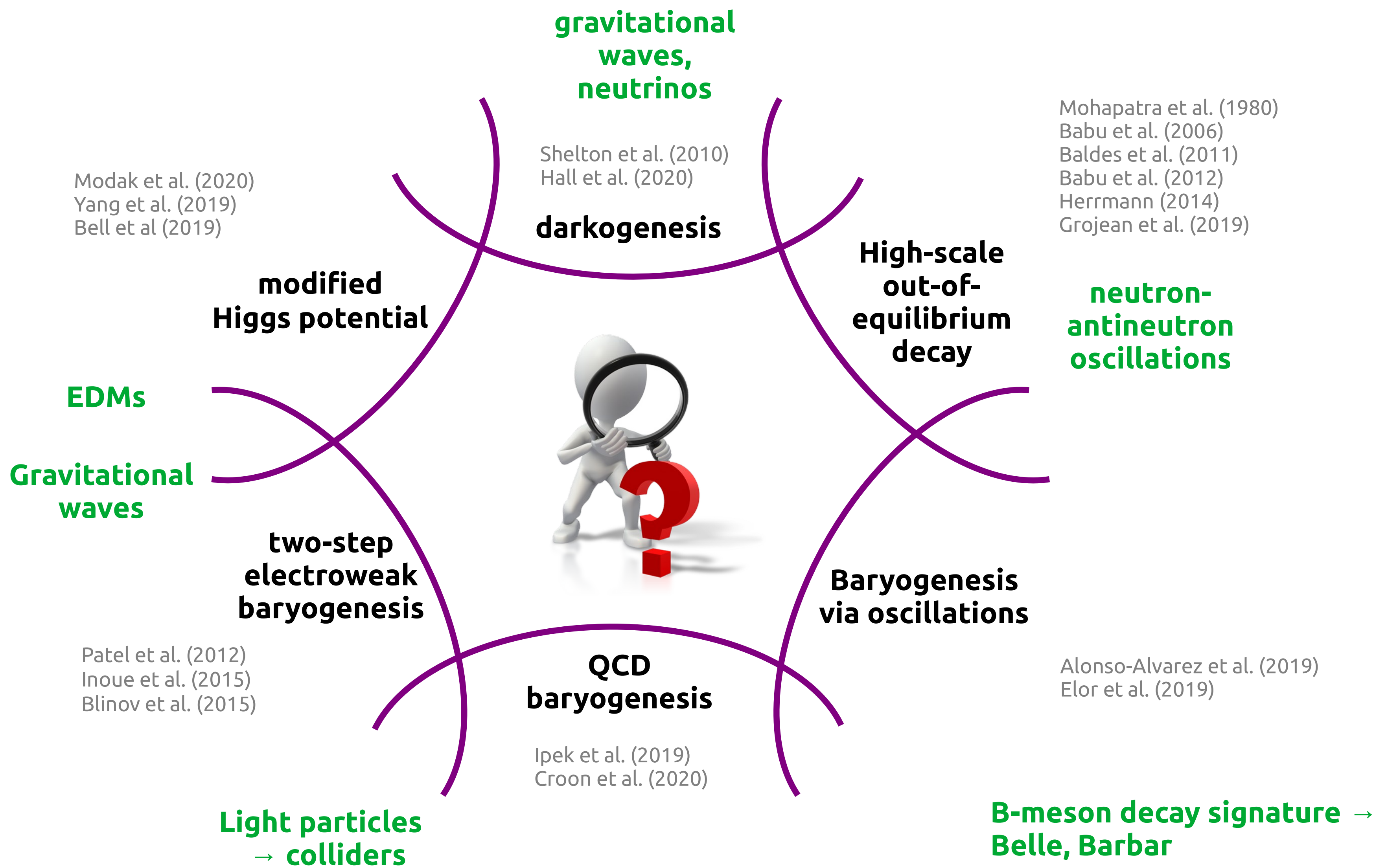
- **General extended scalar sectors, e.g.**
  - 2HDM with extra bottom Yukawa coupling Modak et al. (2020)
  - B-LSSM (B-L symmetric MSSM) Yang et al. (2019)
  - New gauge singlets and vector-like leptons Bell et al. (2019)

General difficulties:

- Constraints from EDMs
- Higgs physics sets stringent constraints

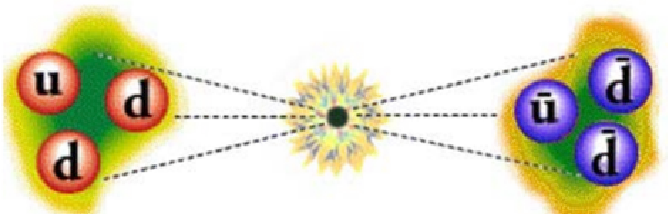


Overview of baryogenesis models

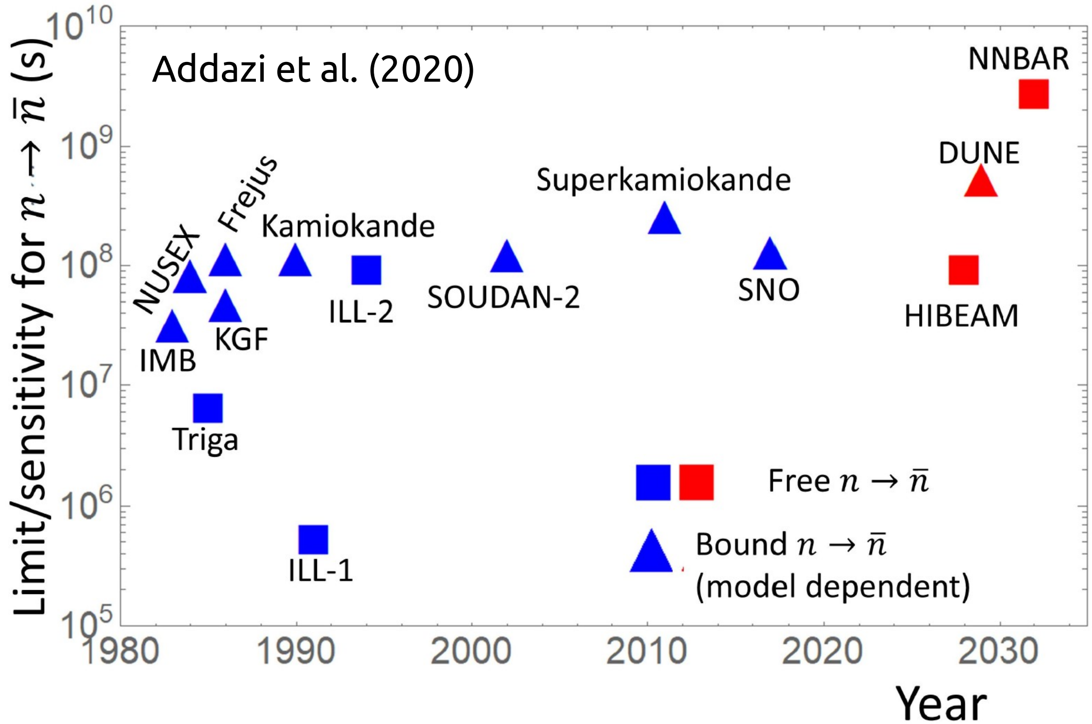


High-scale baryogenesis & $n\bar{n}$ oscillations

$\Delta B = 2$



$u^c d^c d^c u^c d^c d^c$



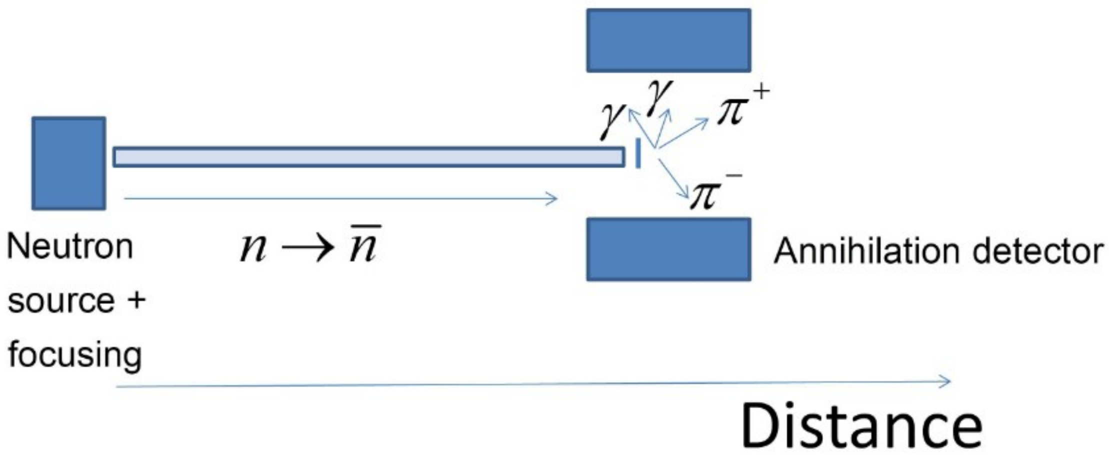
HIBEAM/NNBAR program is a proposed two-stage experiment at the European Spallation Source (ESS) **to search for baryon number violation**.

Future sensitivity at ESS: $\tau_{n\bar{n}} \geq 10^{10} s$

Naive estimate: $\tau_{n-\bar{n}} \approx \frac{\Lambda_{\rm NP}^5}{\Lambda_{\rm QCD}^6}$

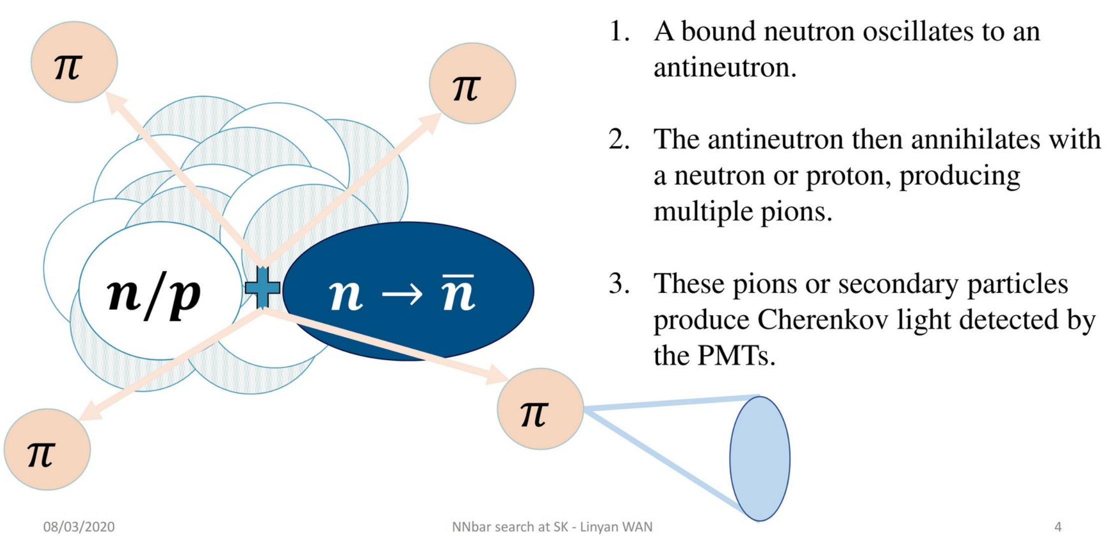
$$\Lambda_{\rm NP} > 10^6 {\rm GeV}$$

Free vs bound neutron-antineutron oscillations



Free oscillation

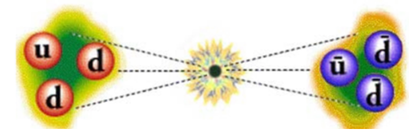
Bound oscillation



What do we learn from $n\bar{n}$ oscillations?

- **Baryon number violating**
- **Possible washout process (BNV)**
- **Possible asymmetry generation mechanism (BNV, CPV, OoE)**

$$\Delta B = 2$$

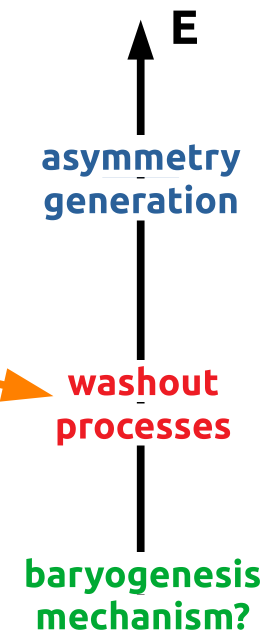


$$\frac{1}{\Lambda_{\rm NP}^5} uddudd$$

Observation of neutron-antineutron oscillations at $\Lambda_{\rm NP}$

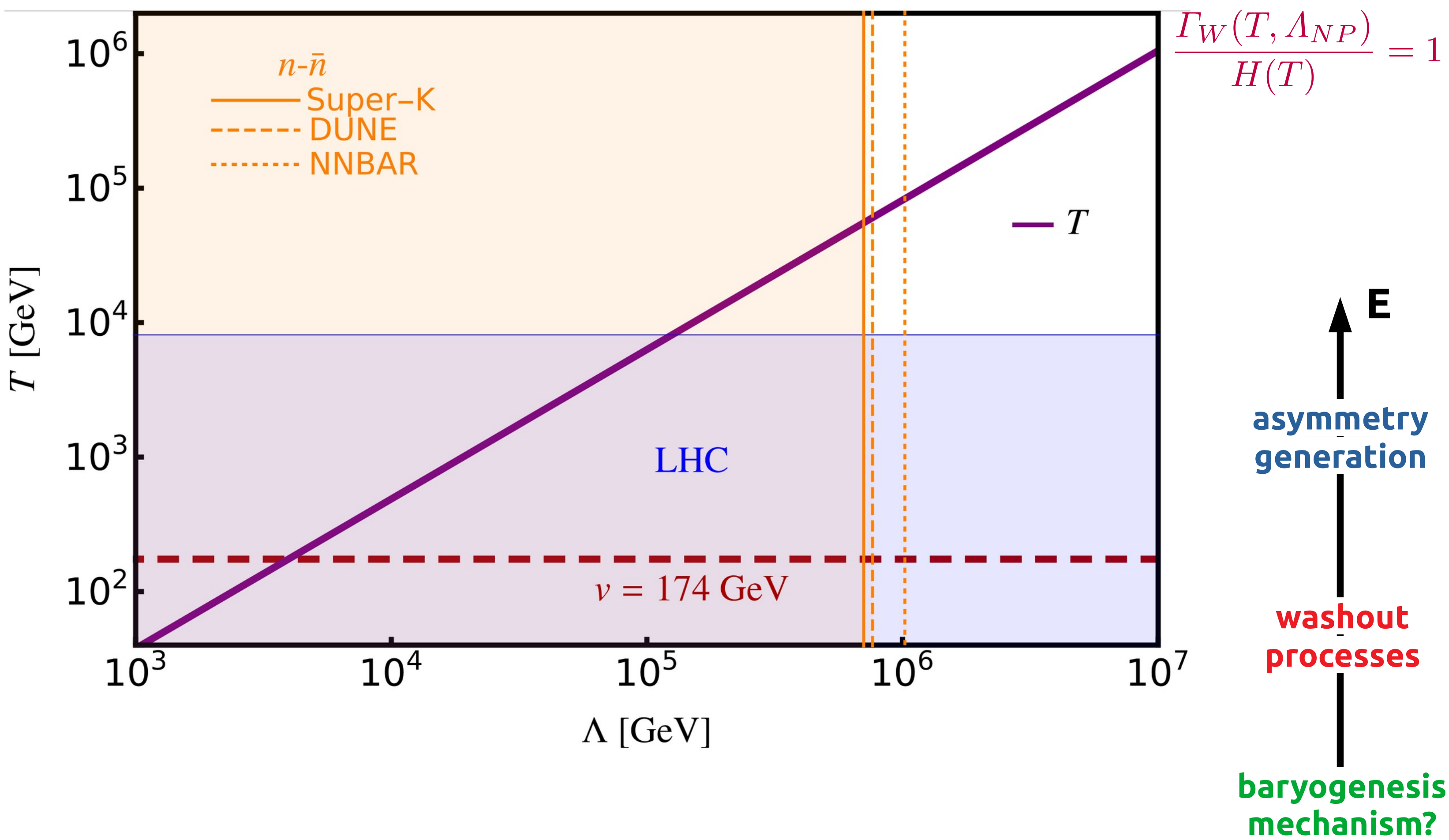
$$\frac{\Gamma_W(T,\Lambda_{NP})}{H(T)} > 1$$

Identify scale T above which the washout rate is large enough to wipe out a previously generated asymmetry.



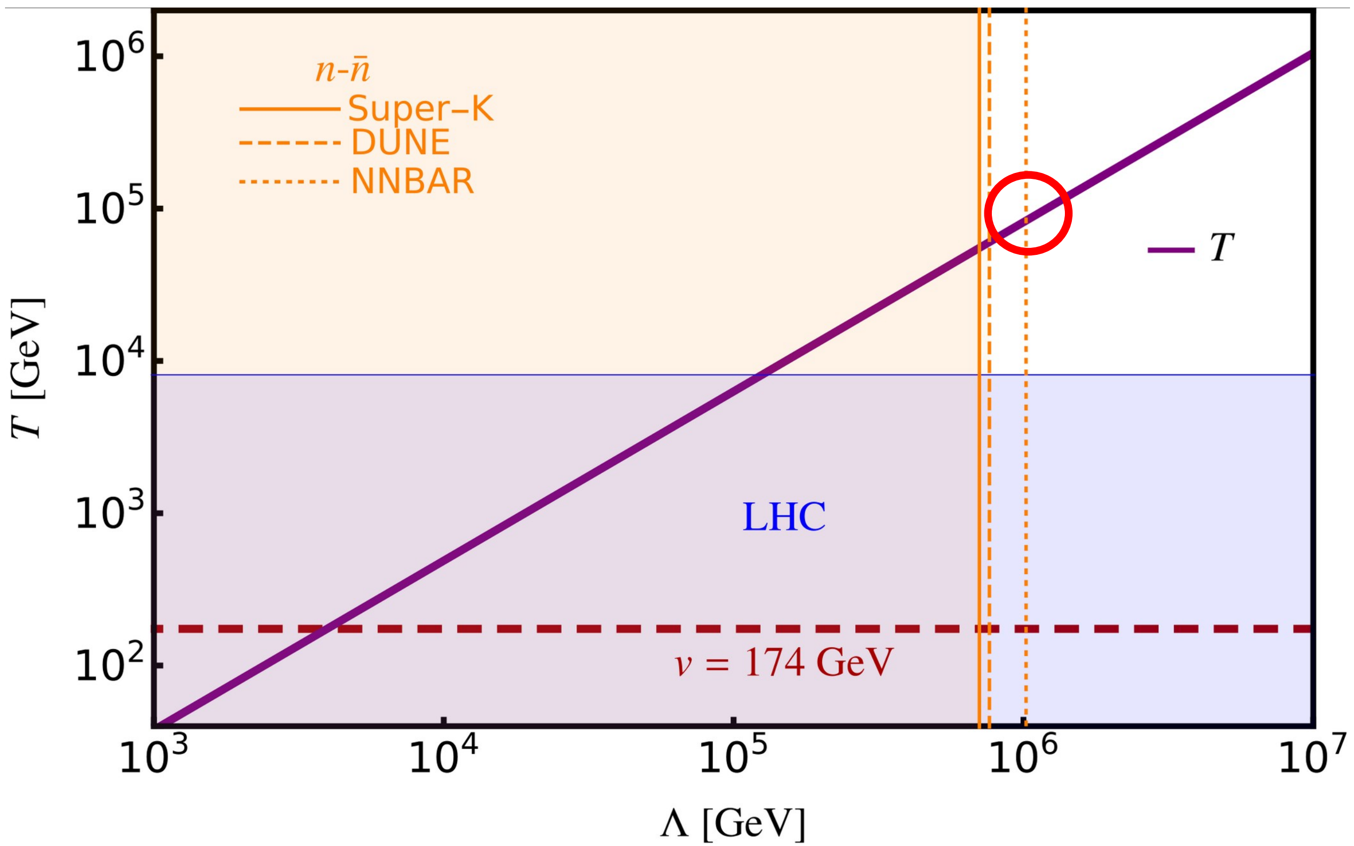
Fridell, JH, Hati (2021)

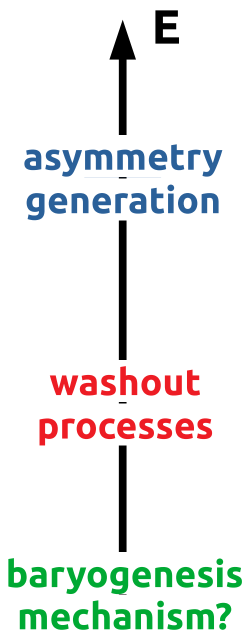
Probing baryogenesis with $n\bar{n}$ oscillations



Fridell, JH, Hati (2021)

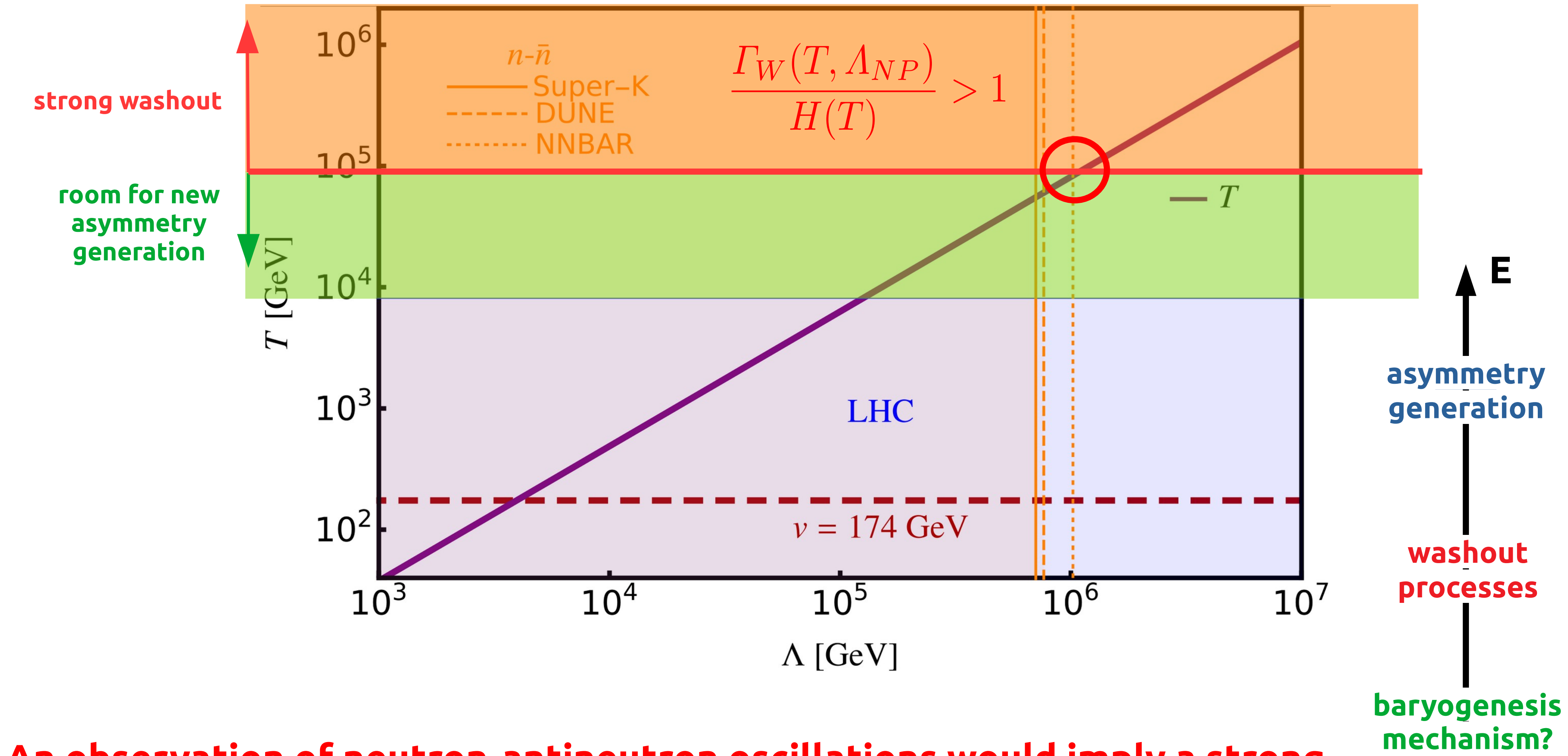
Probing baryogenesis with $n\bar{n}$ oscillations





Fridell, JH, Hati (2021)

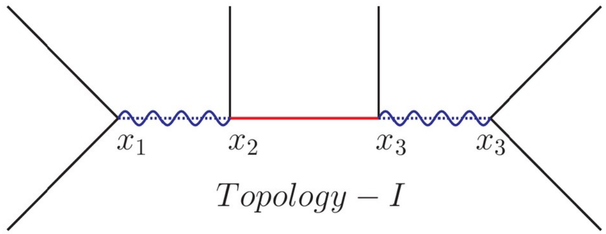
Probing baryogenesis with $n\bar{n}$ oscillations

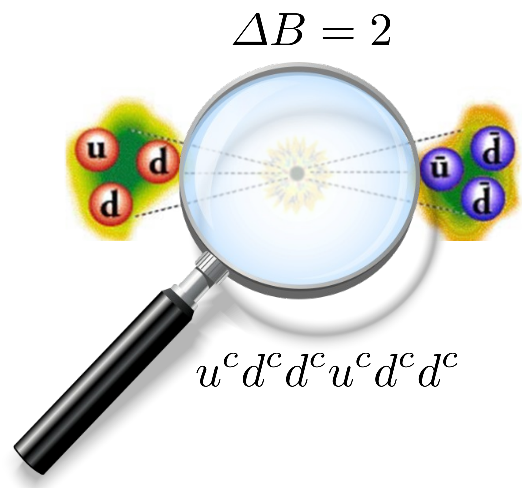


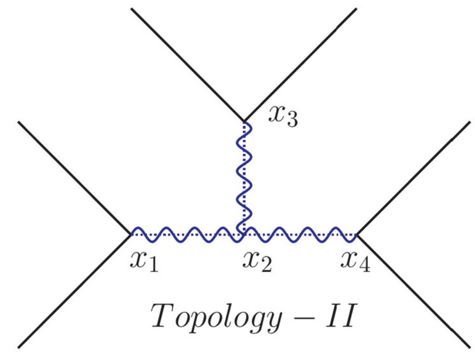
An observation of neutron-antineutron oscillations would imply a strong asymmetry washout until a scale reachable at (future) colliders!

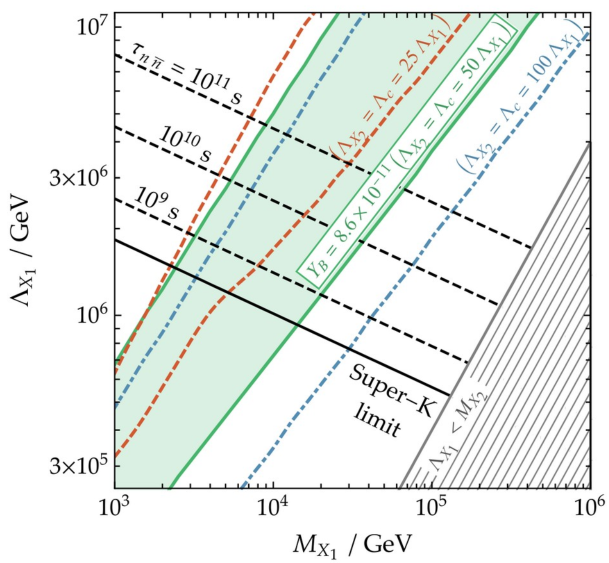
Fridell, JH, Hati (2021)

Possible topologies









Grojean et al. (2019)

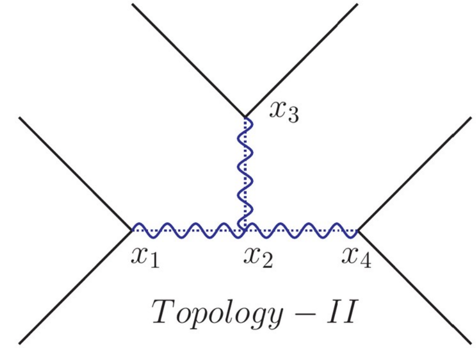
- Left-right symmetric model
- SO(10) GUT
- Post-sphaleron set-up

NOW:

- **simplified model set-up considering asymmetry generation (CPV source!)**
- **confronting with current and future experimental results**

Mohapatra, Marshak (1980)
Babu, Mohapatra, Nasri (2006)
Baldes, Bell, Volkas (2011)
Babu, Mohapatra (2012)
E. Herrmann (2014)

Simplified model of Topology II

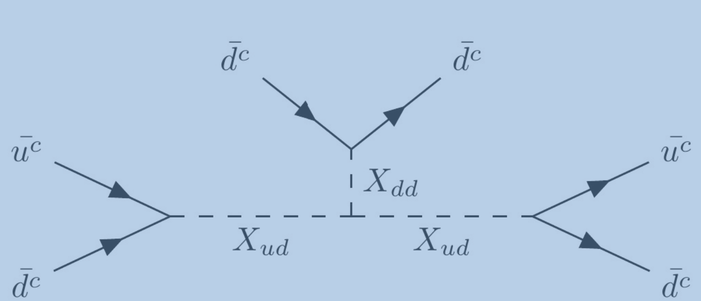


$$\mathcal{L}_{II}^{\text{eff}} \supset f_{ij}^{dd} X_{dd} \bar{d}_i^c \bar{d}_j^c + \frac{f_{ij}^{ud}}{\sqrt{2}} X_{ud} (\bar{u}_i^c \bar{d}_j^c + \bar{u}_j^c \bar{d}_i^c) + \lambda \xi X_{dd} X_{ud} X_{ud} + \text{h.c.}$$

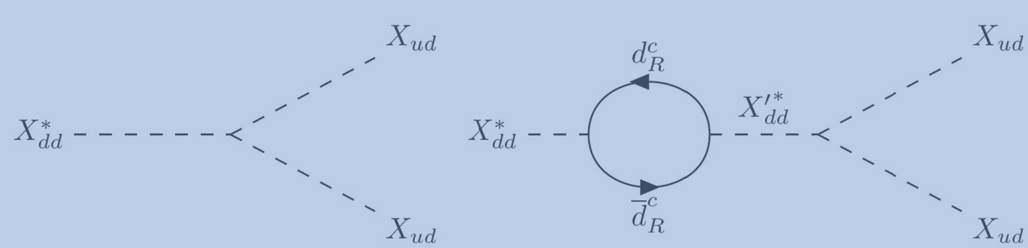
- Diquarks motivated by GUT embedding into SO(10)
- Non-SUSY SO(10) unification requires TeV-scale X_{ud} and GUT-scale X_{dd} / v_{B-L}

$$m_{X_{dd}} > m_{X_{ud}} > m_d$$

Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$Q = T_{3L} + Y$	B
X_{dd}	$\bar{6}$ or 3	1	$+\frac{2}{3}$	$+\frac{2}{3}$	$-\frac{2}{3}$
X_{ud}	$\bar{6}$ or 3	1	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{2}{3}$



Neutron-antineutron oscillations (for 1st generation at tree-level)



$$\epsilon = \frac{\Gamma_{X_{dd} \to X^*_{ud} X^*_{ud}} - \Gamma^*_{X_{dd} \to X_{ud} X_{ud}}}{\Gamma_{X_{dd} \to X^*_{ud} X^*_{ud}} + \Gamma^*_{X_{dd} \to X_{ud} X_{ud}}}$$

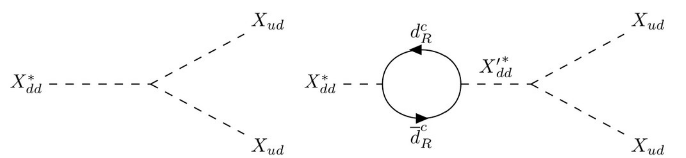
Source of CP violation

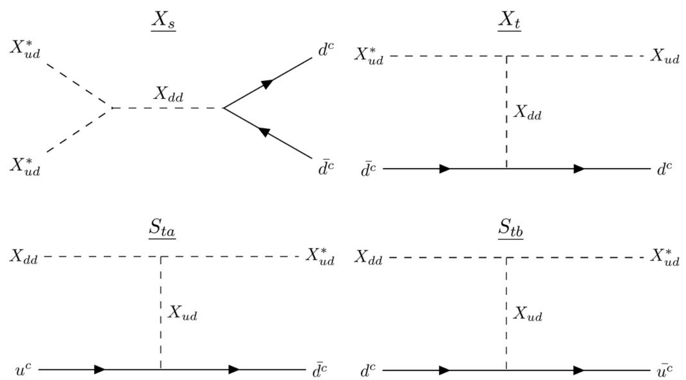
Fridell, JH, Hati (2021)

Baryogenesis

$$\frac{dY_{X_{dd}}}{dz} = -\left(D + S\right)\left(Y_{X_{dd}} - {}^{\mathrm{eq}}_{X_{dd}}\right)$$
$$\frac{dY_B}{dz} = -\epsilon\, D\left(Y_{X_{dd}} - Y^{\mathrm{eq}}_{X_{dd}}\right) - W\, Y_B$$

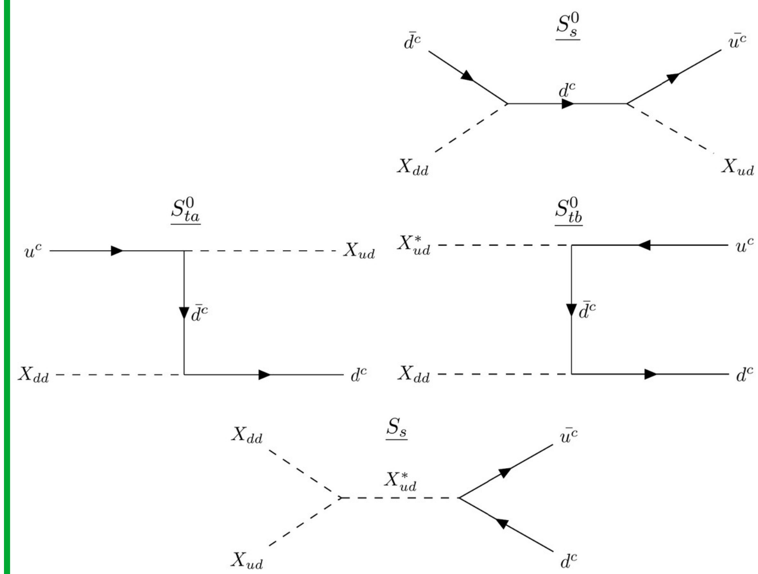
source of CP violation



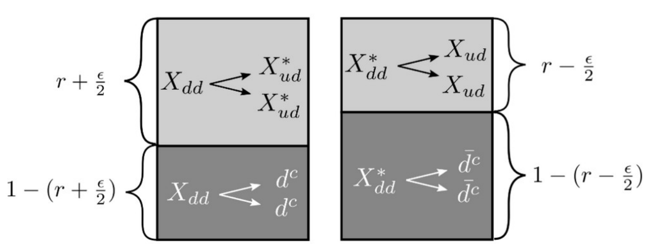


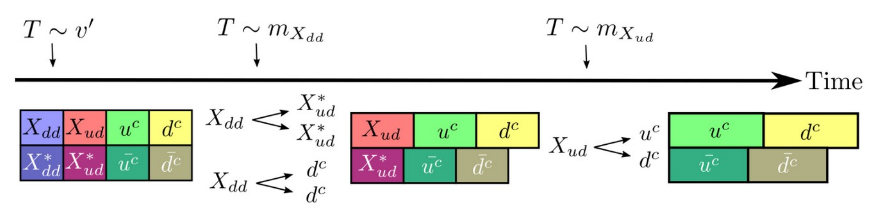
washout processes

scattering processes



washout processes

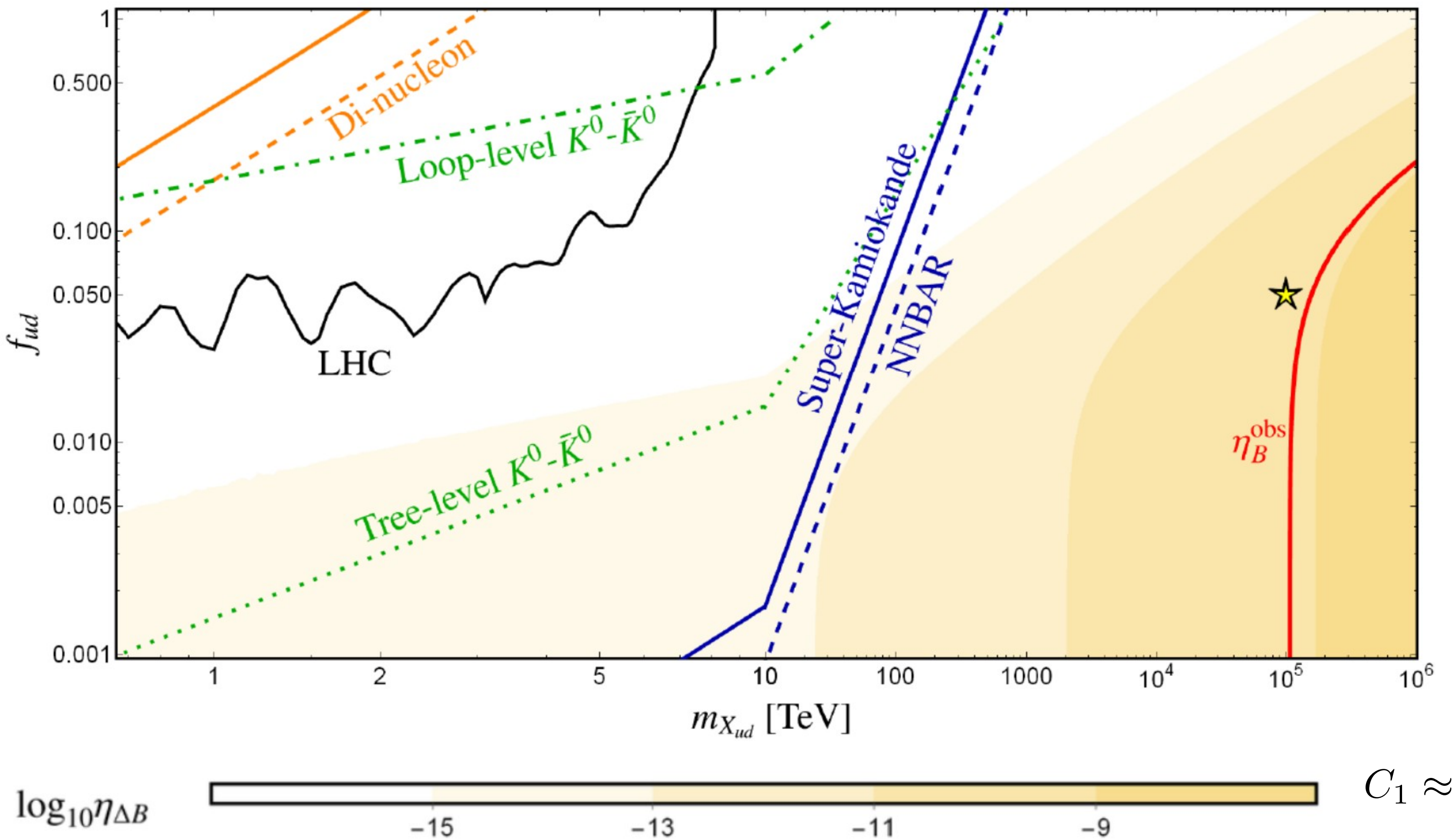




Fridell, JH, Hati (2021)

Results: low-scale scenario

$$f_{ud} = f_{dd}$$
$$m_{X_{dd}} = 3 m_{X_{ud}}$$



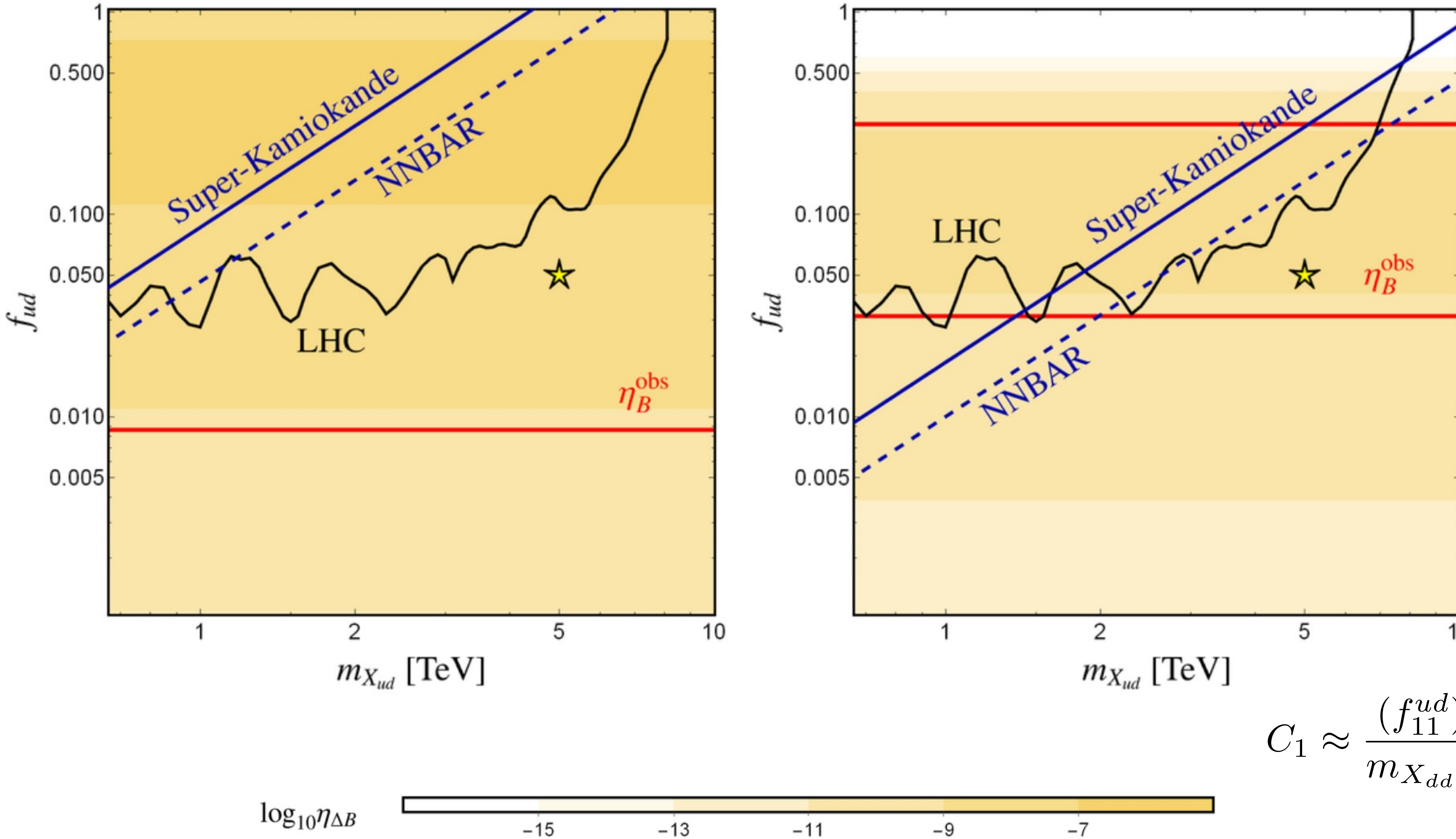
$$C_1 \approx \frac{\left(f_{11}^{ud}\right)^2 f_{11}^{dd}}{m_{X_{dd}} m_{X_{ud}}^4}$$

Fridell, JH, Hati (2021)

Results: high-scale scenario

$$f_{ud} = f_{dd}$$

$$m_{X_{dd}} = 10^{14}\ \mathrm{GeV} \qquad m_{X_{dd}} = 10^{13}\ \mathrm{GeV}$$



$$C_1 \approx \frac{\left(f_{11}^{ud}\right)^2 f_{11}^{dd}}{m_{X_{dd}} m_{X_{ud}}^4}$$

Fridell, JH, Hati (2021)

Conclusions

- **Matter-antimatter asymmetry is one of the most pressing open questions of (astro)particle physics**

- Many models, many ideas – **how** can we **identify** the one that is realised in nature?

- Some models connected to **light** new physics → **testable**!

- Some models connected to new physics at **high-scale** → **difficult to test**!

- **"Falsification" of high-scale models instead:**

- Observation of **LNV** can imply **strong lepton (and baryon!) asymmetry washout**

- Observation of **neutron-antineutron oscillations** directly constrain **BNV** interactions; generally imply a strong washout down to LHC scales (first generation)

Great future ahead to (hopefully) nail down the mechanism behind BAU!

Thank you for your attention!