The quest for the mechanism behind the matter-antimatter asymmetry

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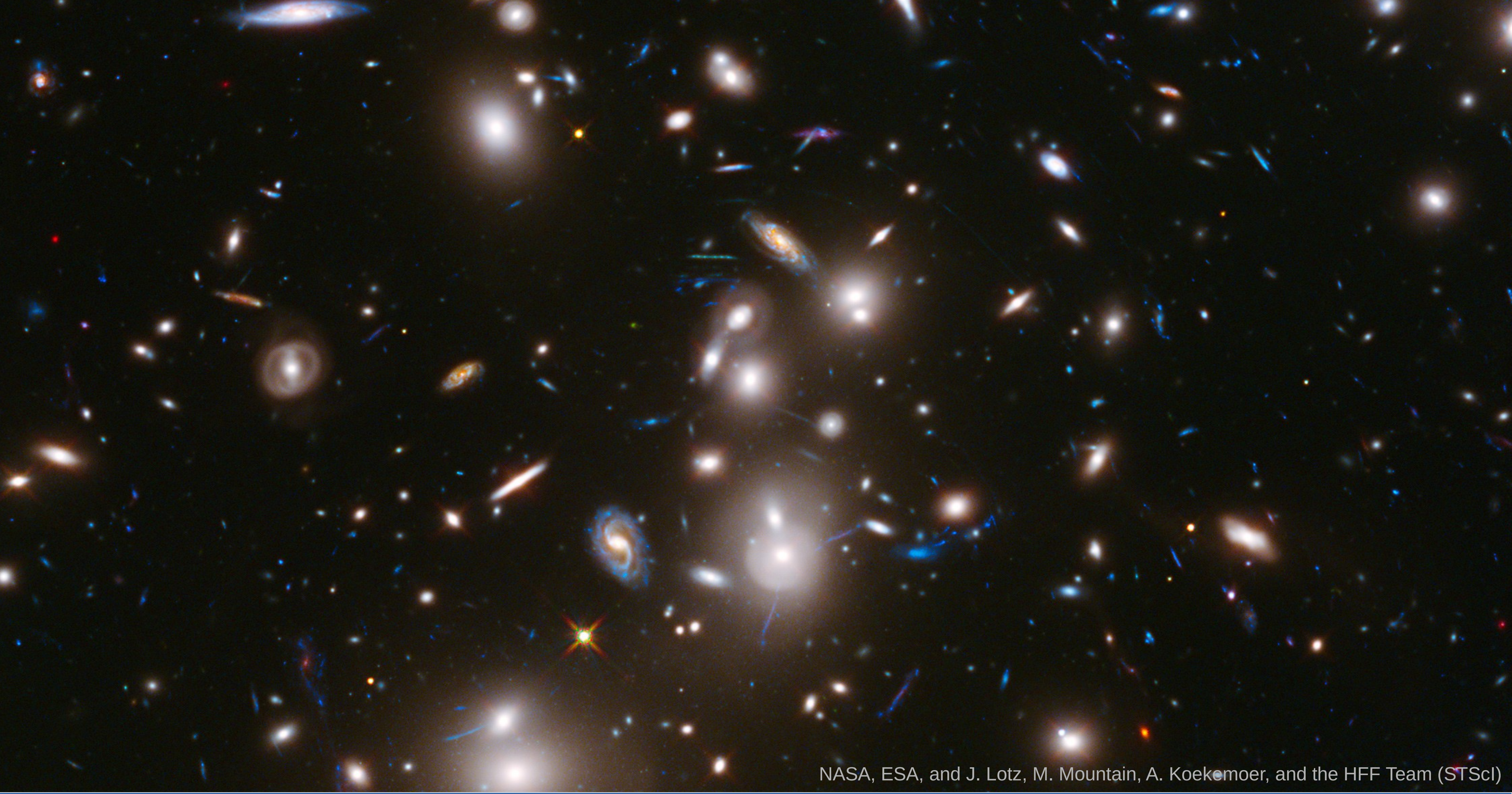
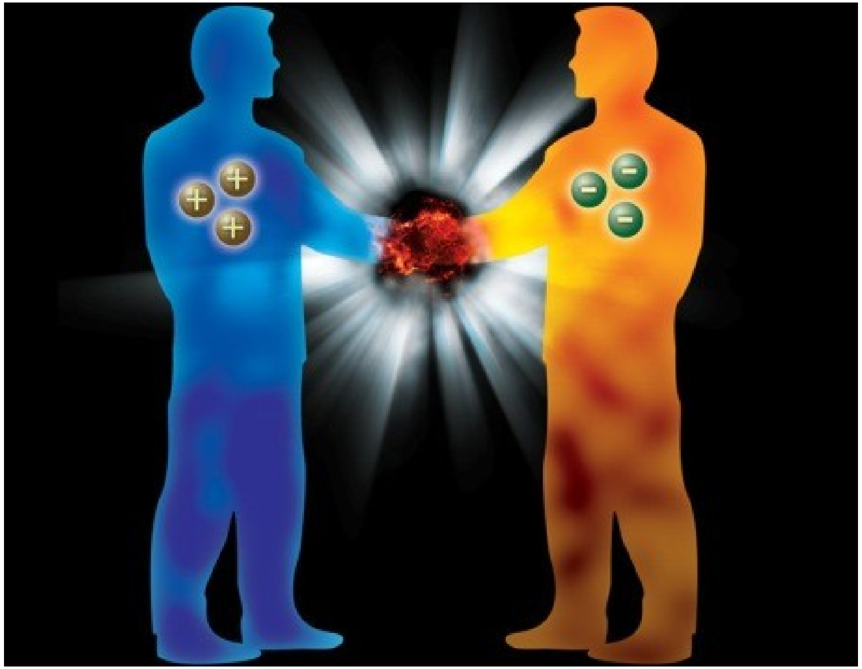
DFG Deutsche Forschungsgemeinschaft


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

What is our Universe made of?

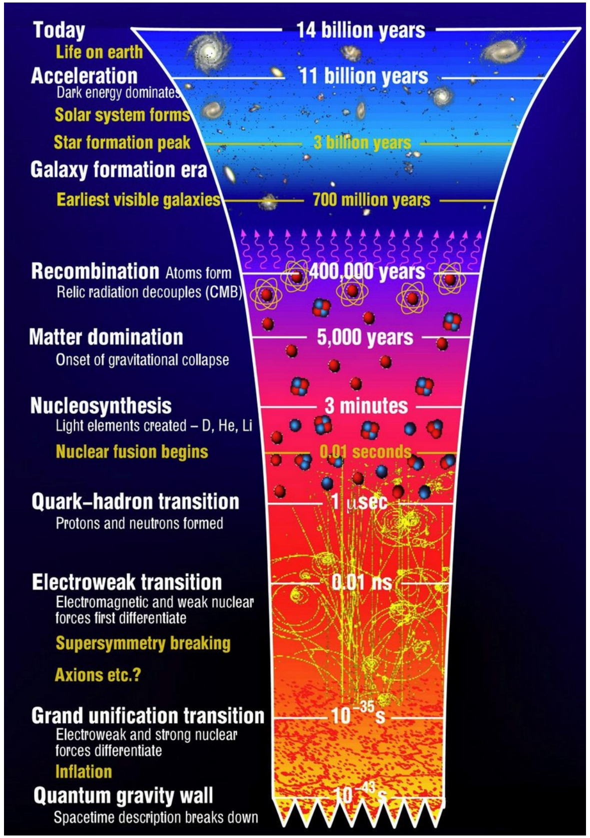
NASA, ESA, and J. Lotz, M. Mountain, A. Koekemoer, and the HFF Team (STScI)

Why do we exist?



Why is there more matter than antimatter?

Traveling back in time...



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

Our Universe consists mainly out of baryonic matter, quantified by the baryon-to-photon ratio:

$$\eta_B = \frac{n_B}{n_\gamma} = \frac{n_b - n_{\bar{b}}}{n_\gamma}$$

Big Bang Nucleosynthesis

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

Deuterium Bottleneck

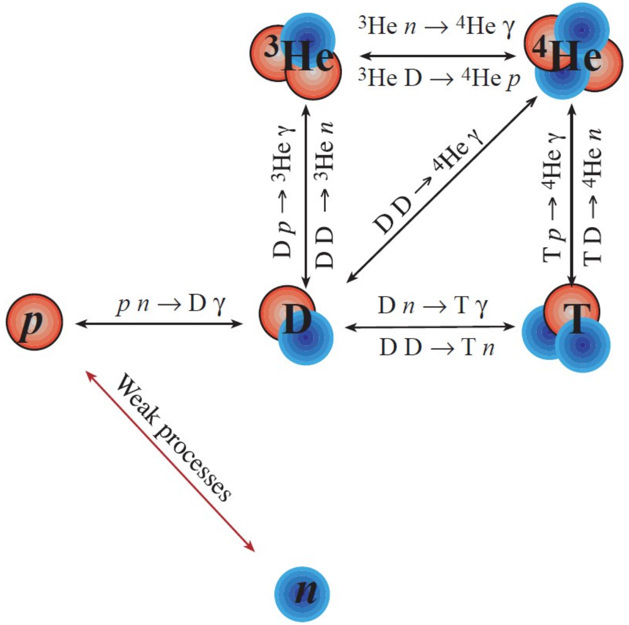
Nucleosynthesis starts with formation of Deuterium (D)

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

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

$$T_{\rm nuc}^{D} \approx \frac{B_D}{\log {\eta_B}^{-1}}$$

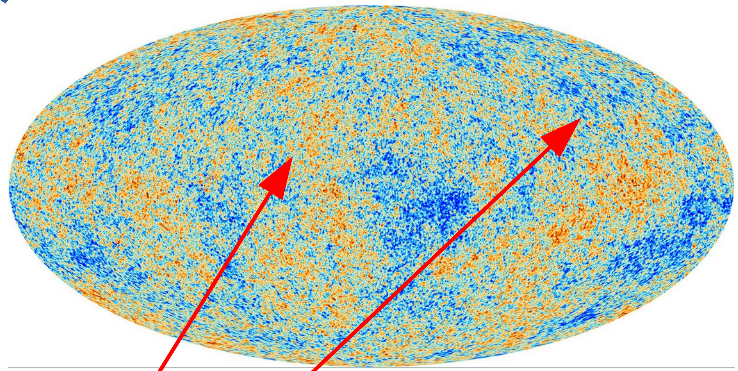
$$\eta_B^{\rm obs} = (6.143 \pm 0.190) \times 10^{-10}$$

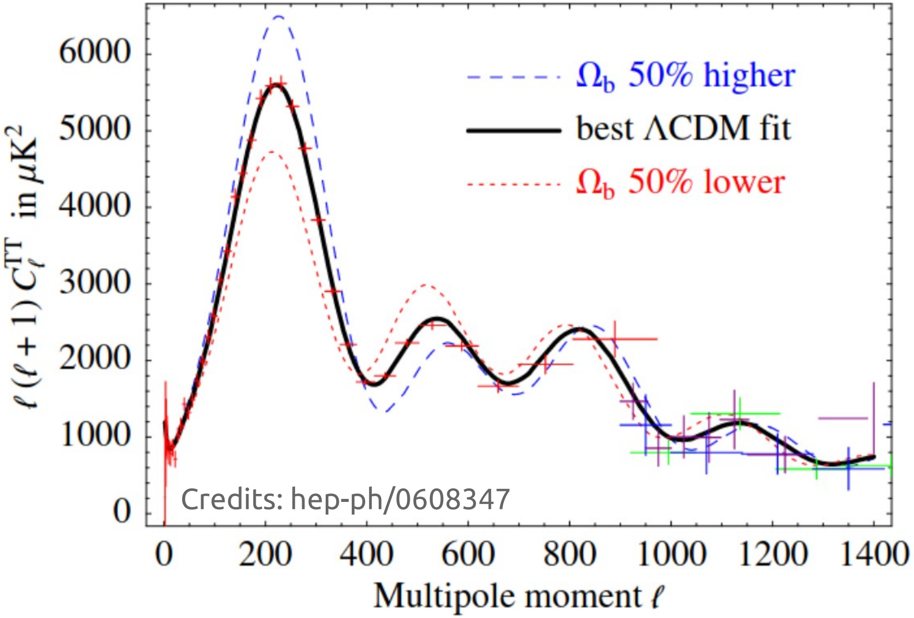


Credits: hep-ph/0608347

Cosmic Microwave Background (CMB)

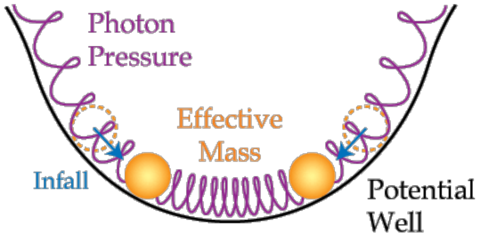
- **400.000 years after Big Bang**
- **measures temperature fluctuations from recombination**



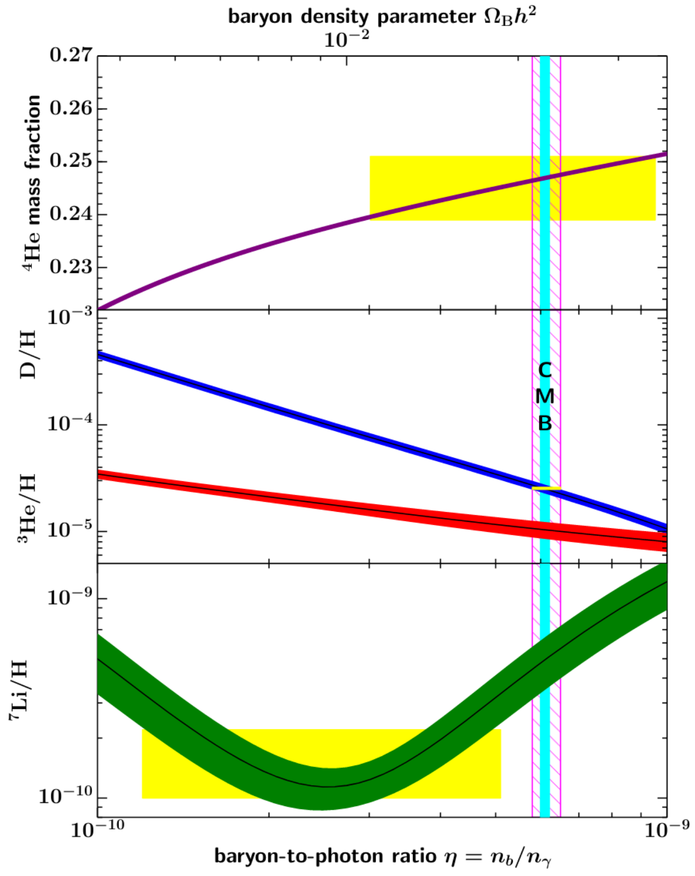


Credits: hep-ph/0608347

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



Combination of BBN & CMB

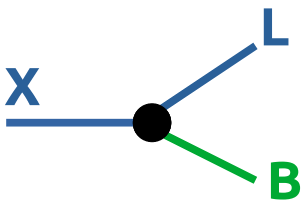


Excellent agreement even though measurements originate from two different epochs!

Why do we need new physics?

Theoretically, we know the conditions on interactions that have to be fulfilled (Sakharov conditions).

☐ baryon number violation



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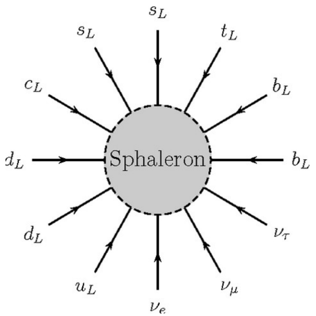
SM?

☐ baryon number violation

SM sphaleron interactions

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

highly active above T_{EW}



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

$\frac{\Gamma^b_{\rm SM}}{V} \sim \exp\left(-\frac{4\pi}{g_w}\frac{v_c}{T}\right)$	**in broken phase suppressed**
$\frac{\Gamma^s_{\rm SM}}{V} \sim \alpha_w^5 T^4$	**in symmetric phase active**

Why do we need new physics?

Theoretically, we know the conditions on interactions that have to be fulfilled (Sakharov conditions).

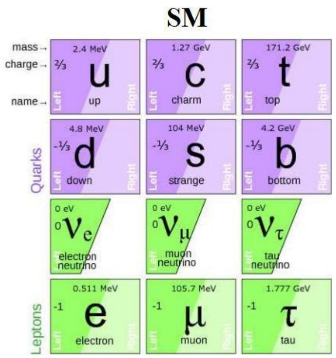
SM?

☑ baryon number violation

☐ C and CP violation

Charge conservation:

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



Requirement of charge violation:

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

Why do we need new physics?

Theoretically, we know the conditions on interactions that have to be fulfilled (Sakharov conditions).

SM?

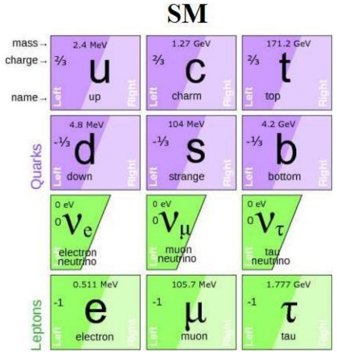
☑ baryon number violation

☐ C and CP violation

Charge and parity conservation:

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

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



Requirement of charge and parity violation:

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

Why do we need new physics?

Theoretically, we know the conditions on interactions that have to be fulfilled (Sakharov conditions).

SM?

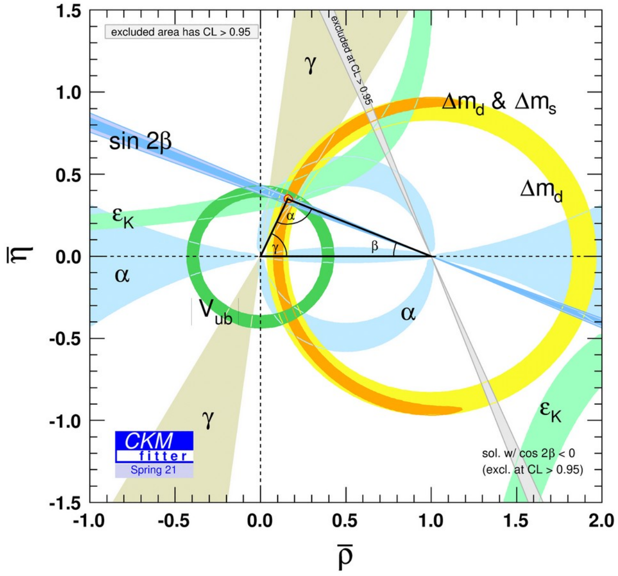
☑ baryon number violation

☒ C and CP violation

Quark sector exhibits CP violation (CPV)

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

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



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

not enough CP violation within SM!

Why do we need new physics?

Theoretically, we know the conditions on interactions that have to be fulfilled (Sakharov conditions).

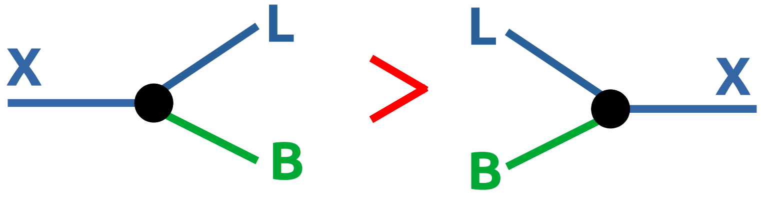
SM?

- baryon number violation
- C and CP violation
- 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

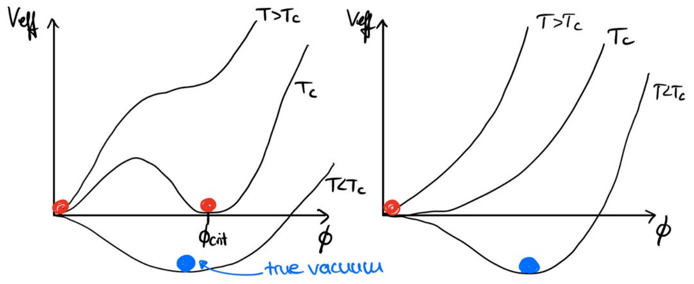


Why do we need new physics?

Theoretically, we know the conditions on interactions that have to be fulfilled (Sakharov conditions).

SM?

- ✓ baryon number violation
- ✗ C and CP violation
- ✗ departure from thermal equilibrium



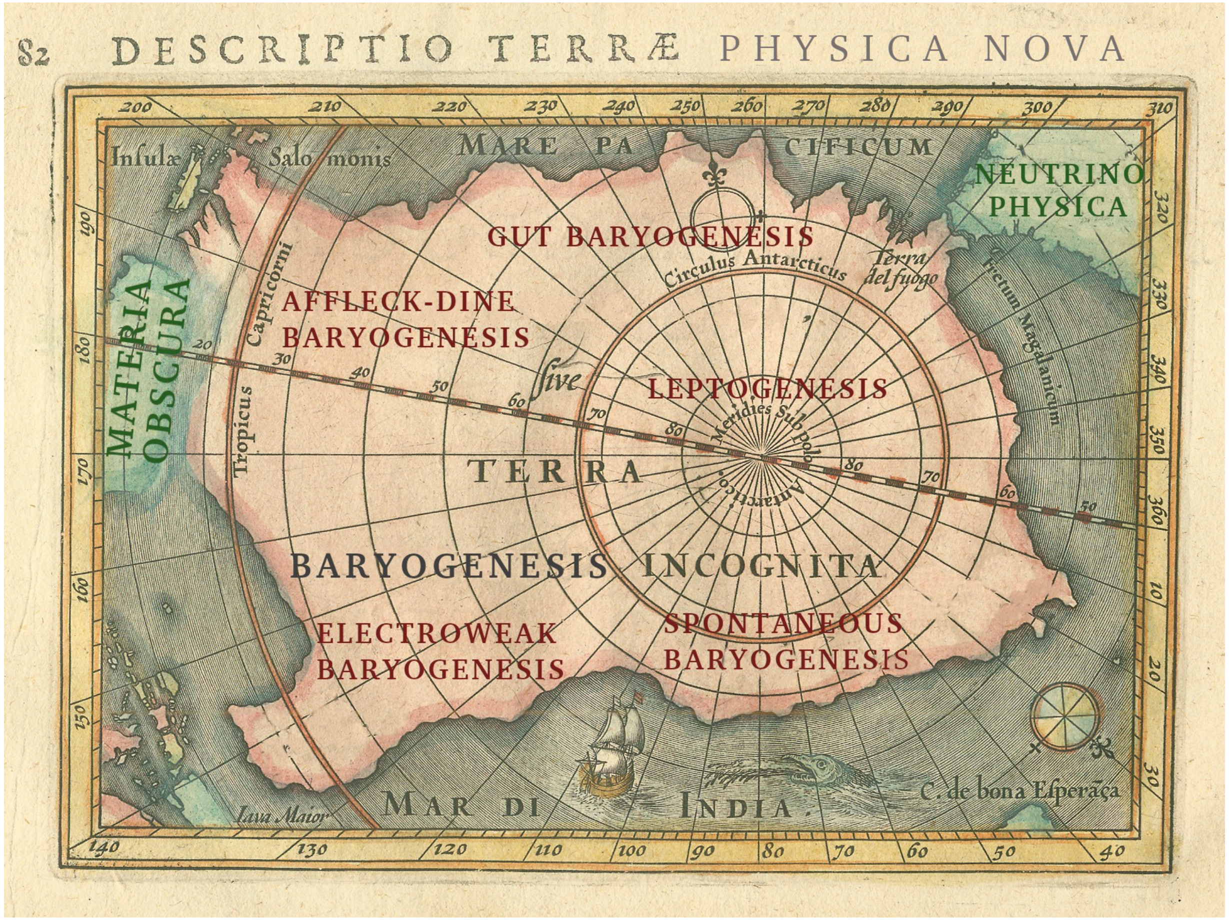
Strong FOPT during EWSB:

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

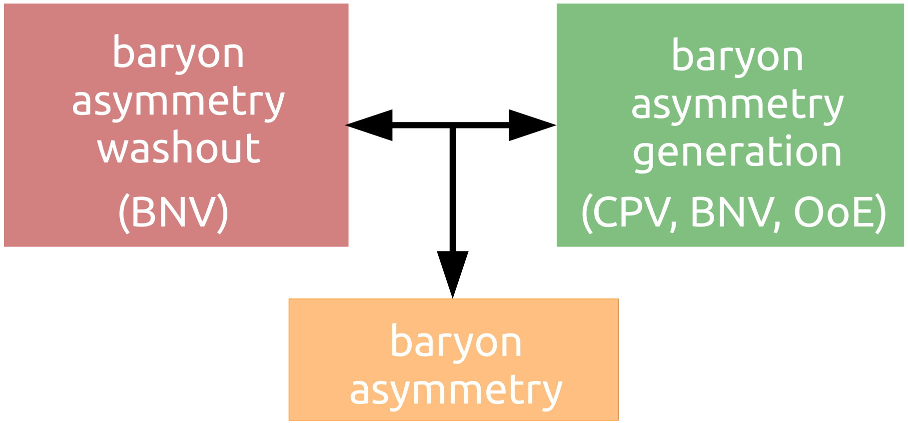
$$m_h \leq 32\mathrm{GeV}$$

→ Higgs too heavy for first order phase transition

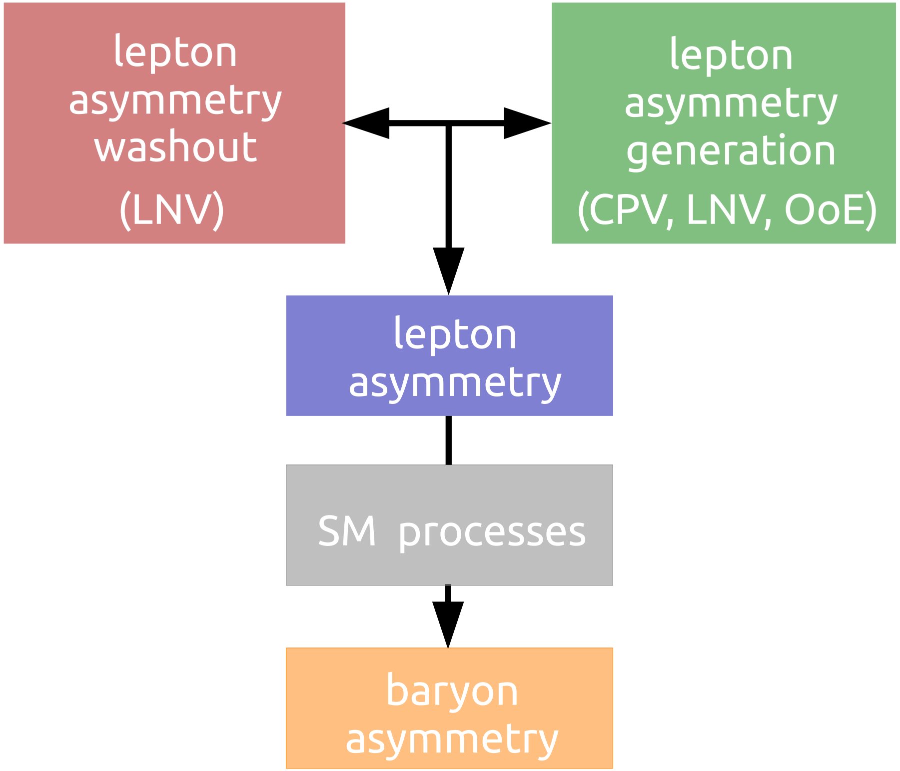
Where do we stand?



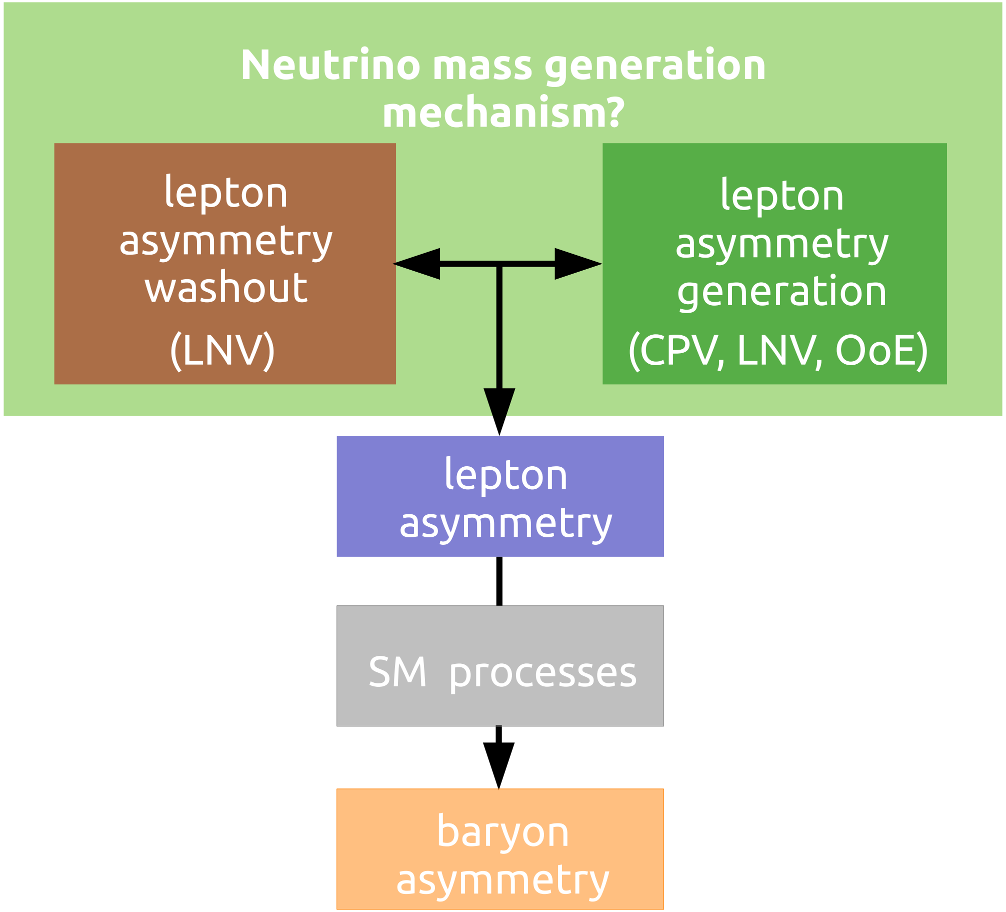
Basic principle of baryogenesis



Basic principle of standard leptogenesis



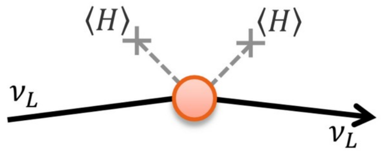
Basic principle of standard leptogenesis



Neutrino mass mechanism

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

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



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

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

Low-scale leptogenesis

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

High-scale leptogenesis

Overview of leptogenesis models

gravitational waves

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

gravitational leptogenesis

freeze-in leptogenesis

wash-in leptogenesis

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

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 via oscillations

With low masses of right-handed neutrinos (RHNs) and small couplings, successful leptogenesis can proceed via the **ARS mechanism**.

production

$L_A + L_B + L_C = 0$

$h \to l + N_{RA}$, N_{RB}, N_{RC}

$L_A = 0$

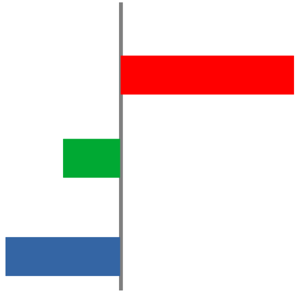
$L_B = 0$

$L_c = 0$

$Y_X \sim 10^{-8} - 10^{-6}$
not in equilibrium

oscillation, CPV

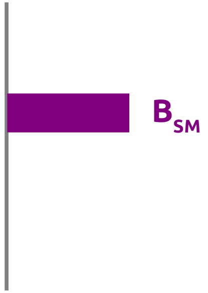
$L_A + L_B + L_C = 0$



$Y_{A,B} > Y_C$
$N_{RA,B}$ reach equilibrium before T_{EW}

sphaleron shut-off

$L_A + L_B \to B_{SM}$

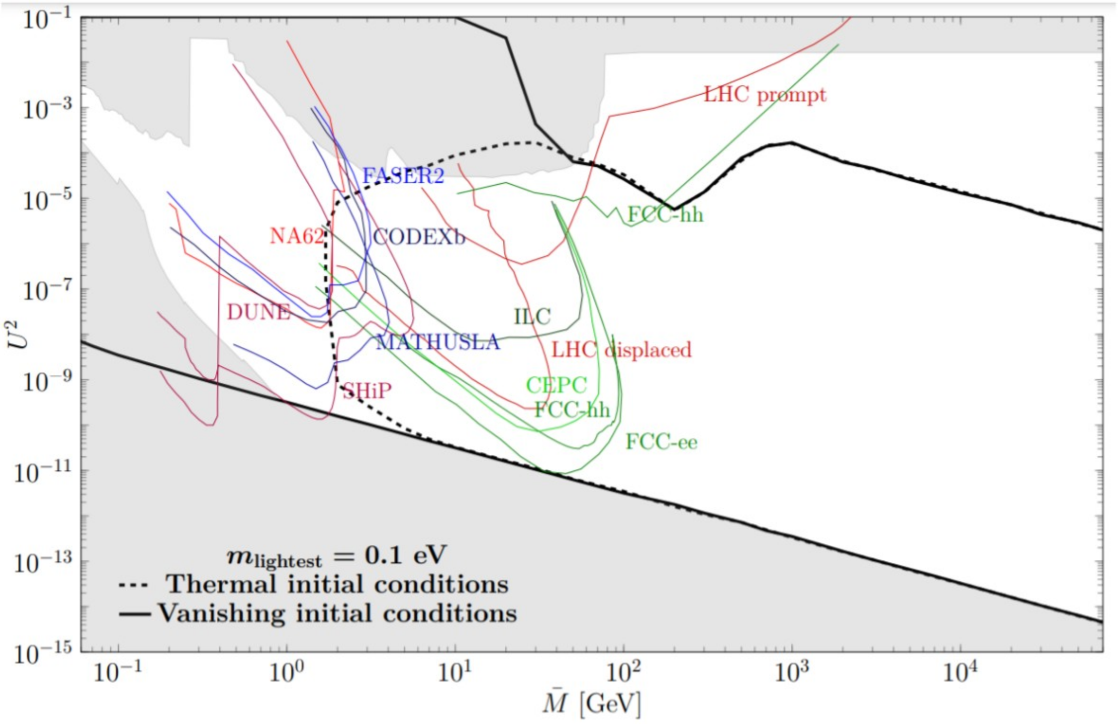


lepton number gets transferred into baryon number

Akhmedov et al. (1998)

Leptogenesis via oscillations

For **N=3** RHNs, parameter space allows for successful leptogenesis via the ARS mechanism:



Drewes et al. 2021

High-scale leptogenesis

- **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

Guidice et al. (2004)

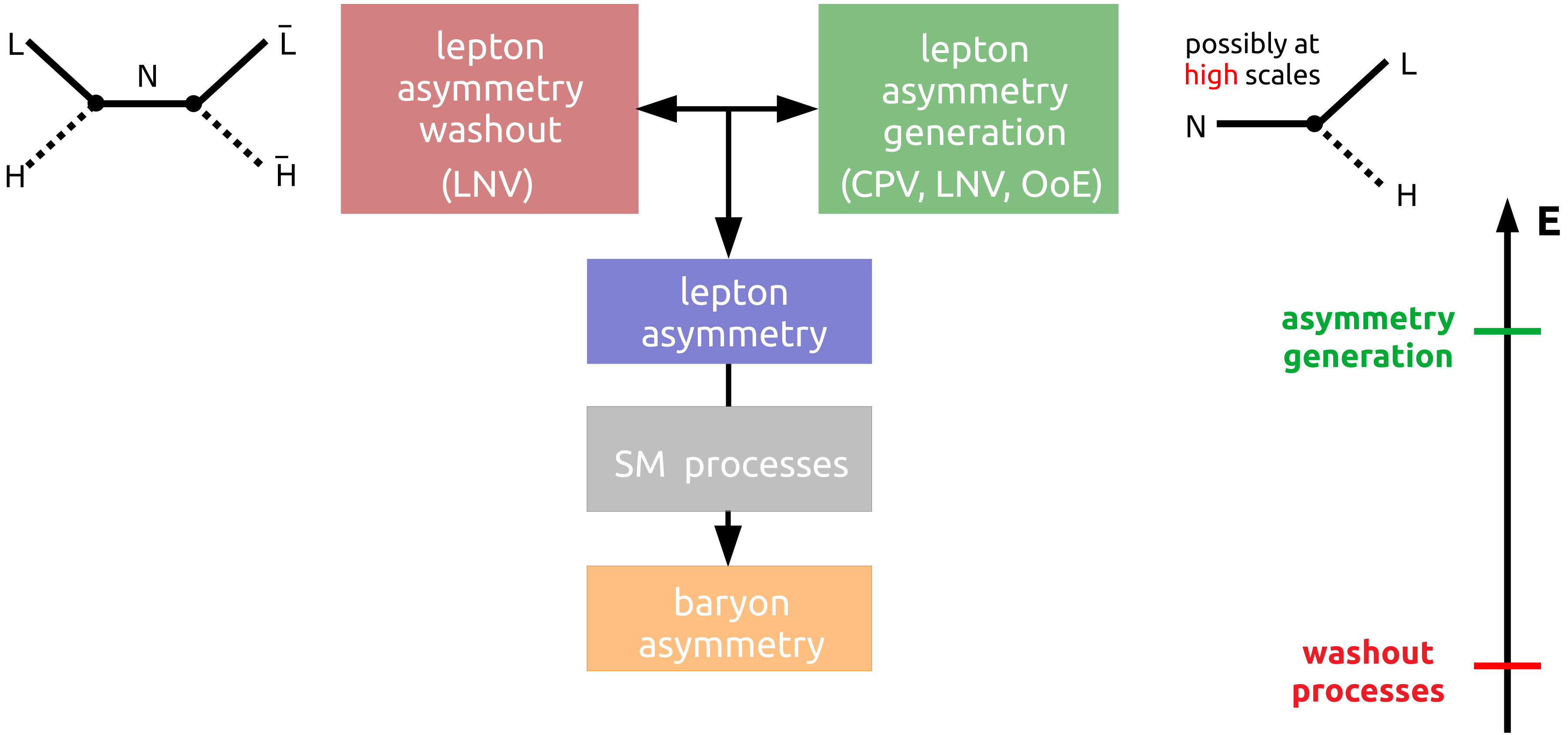
Fukugita, Yanagida (1986)
and many more afterwards...

High-scale leptogenesis

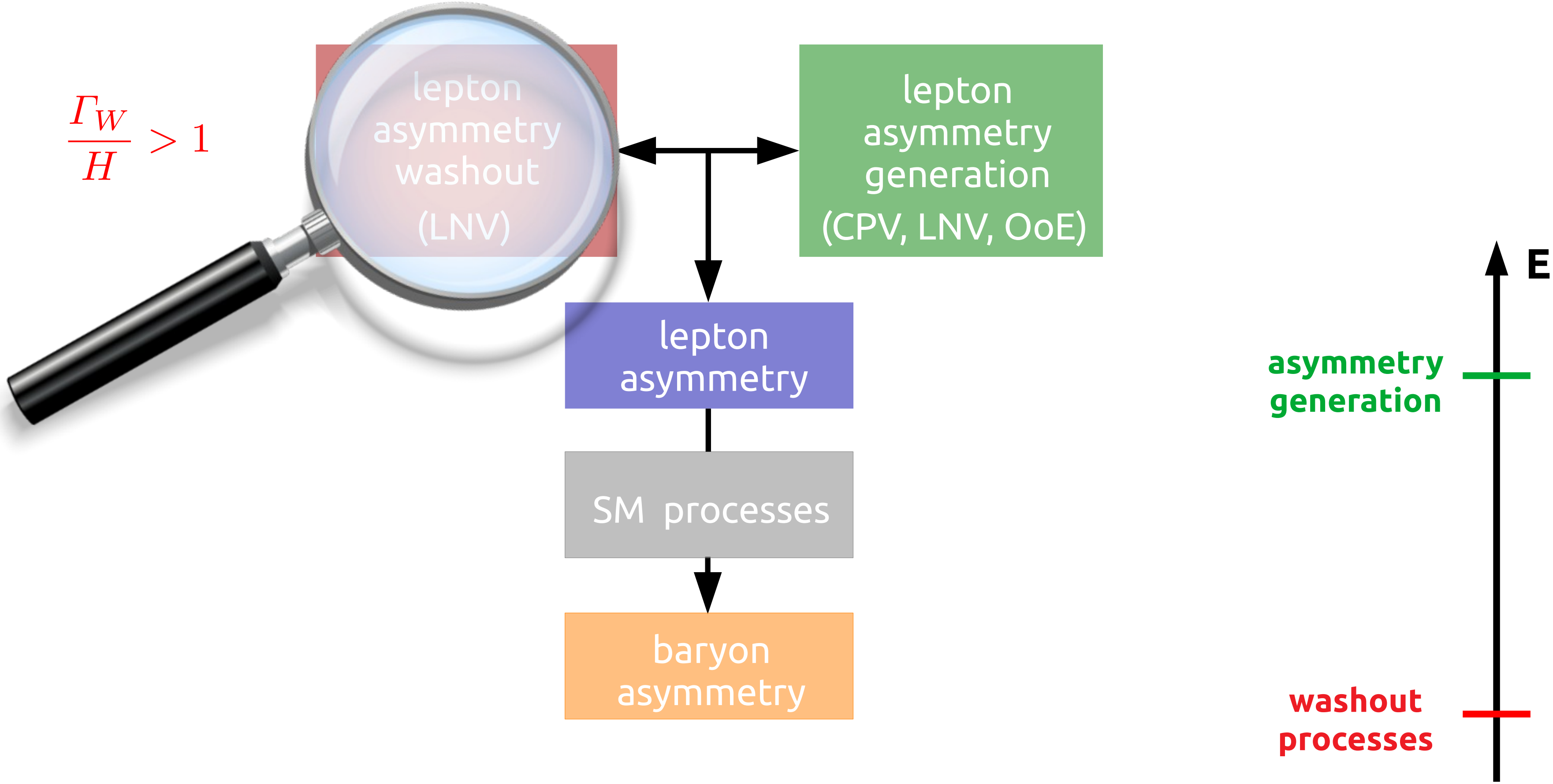
- Extension of **seesaw type-I** by **new scalars**
  → e.g. long-lived scalars, R-hadrons, heavy sterile neutrinos e.g. Fong et al. (2013)
- **Z' models** → same-sign di-lepton final states e.g. Chun (2005)
- **Left-right symmetric models** → falsification by low mass W_R e.g. Dev. et al. (2015)
- **Soft 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" (arxiv:hep-ph/1711.02865)

Basic principle of standard high-scale leptogenesis



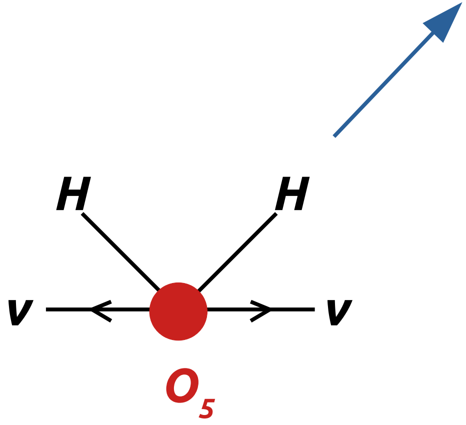
Basic principle of standard high-scale leptogenesis

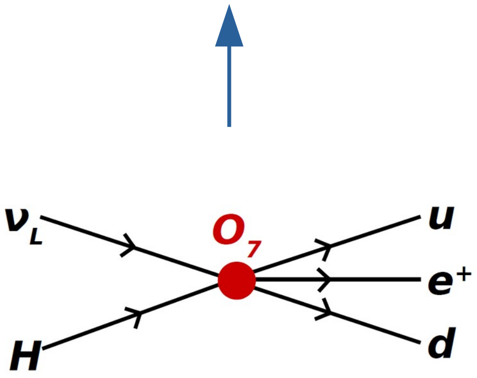


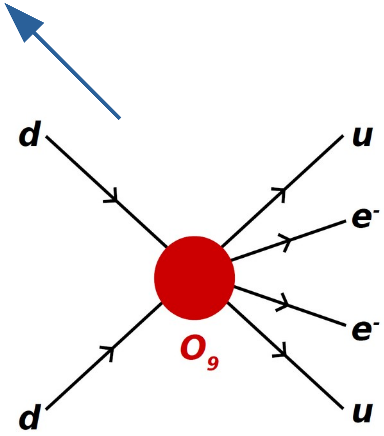
Lepton number violation

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

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



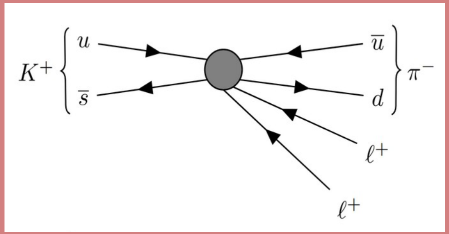




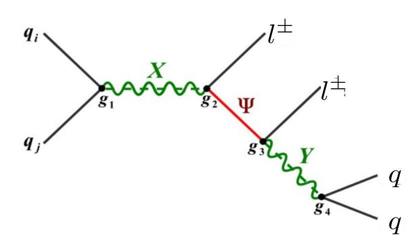
See surveys of all LNV operators up to dim-11 e.g. in Babu, Leung (2001), Gouvea, Jenkins (2008), Graf, JH, Deppisch, Huang (2018)

Probing lepton-number violating processes

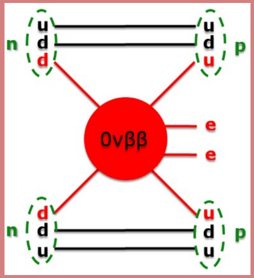
Meson decays



LHC searches

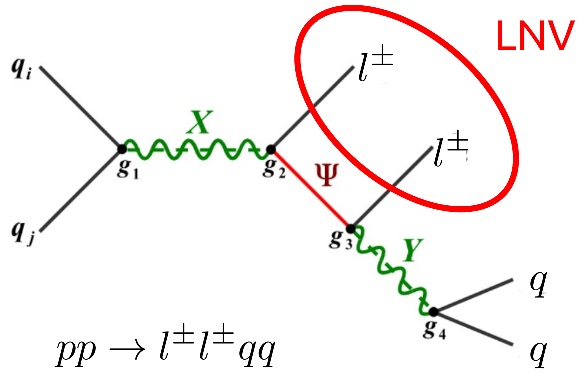


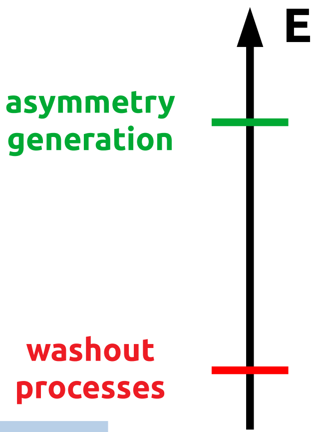
Neutrinoless double beta decay

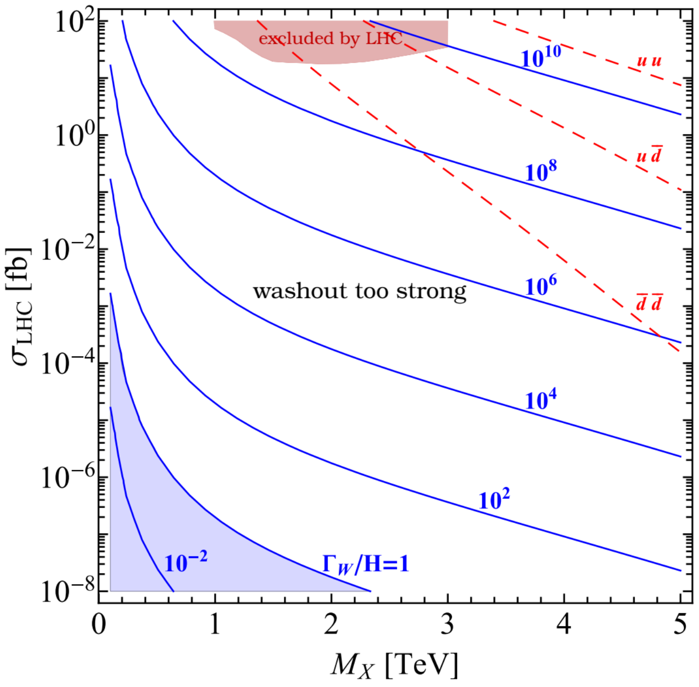


Probing Leptogenesis at the LHC

Washout processes could be observable at the LHC







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

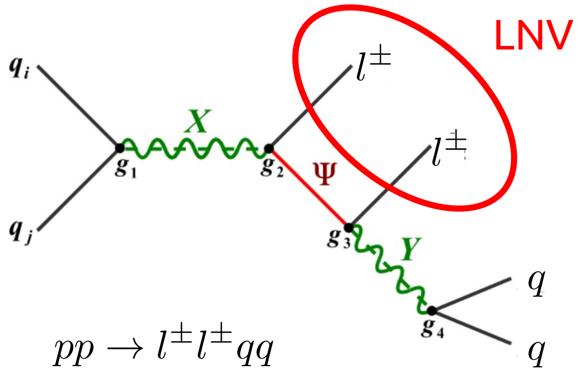
Observation of any washout process at LHC would put high-scale baryogenesis under tension!

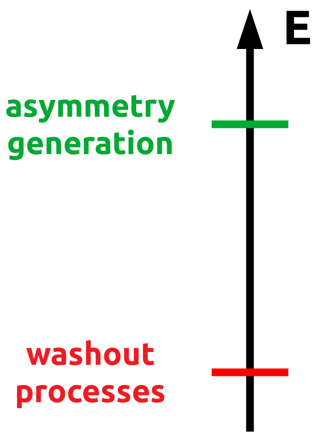
Asymmetry stored in another flavour sector?
→ measurement in all flavours
→ low-scale LFV leading to equilibration

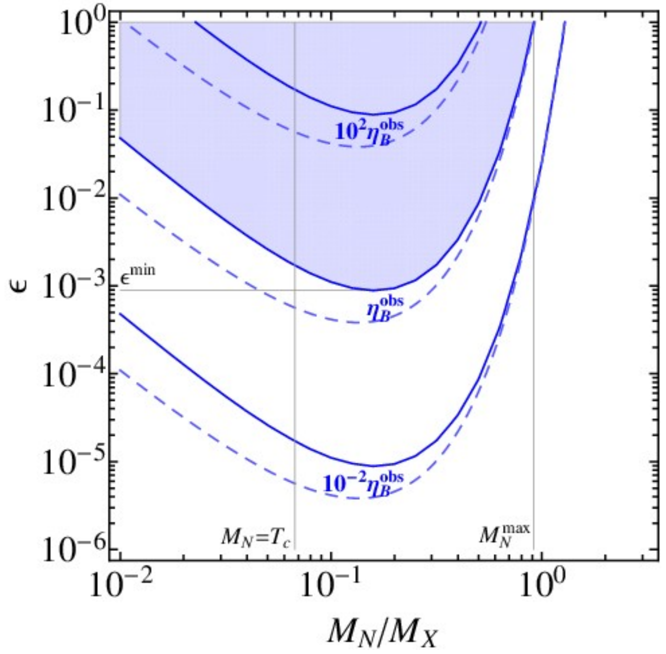
Deppisch, JH, Hirsch (2014)

Probing Leptogenesis at the LHC

Washout processes could be observable at the LHC





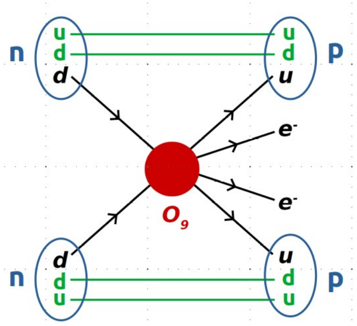


$$\log_{10}\left|\frac{\eta_B}{\eta_B^{\rm obs}}\right| < 2.4\,\frac{M_X}{\rm TeV}\left(1-\frac{4}{3}\frac{M_N}{M_X}\right) + \log_{10}\left[|\epsilon|\left(\frac{\sigma_{\rm LHC}}{\rm fb}\right)^{-1}\left(\frac{4}{3}\frac{M_N}{M_X}\right)^2\right]$$

For similar hierarchies, LNV observation implies lower limit on CP asymmetry!

Deppisch, JH, Hirsch (2014)

Probing leptogenesis with 0νββ decay



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

particle physics

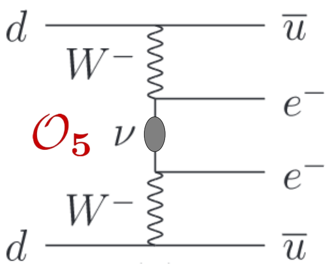
phase-space factors

nuclear physics

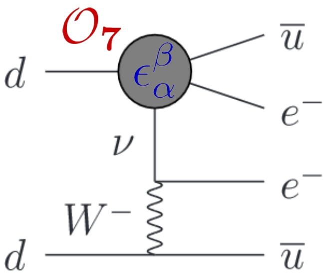
Experimental constraints: $T^{0\nu}_{1/2} > 1.07 \times 10^{26}\mathrm{yr}\ 90\%\mathrm{C.L.}$ KamLAND-Zen (2016)

Possible contributions:

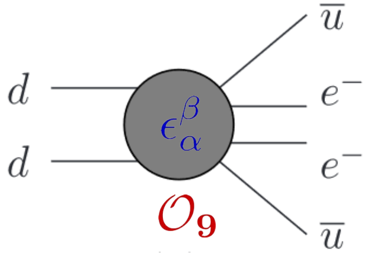
standard mass mechanism



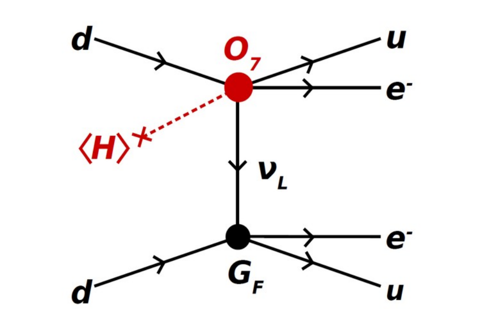
long range contribution



short range contribution



Probing leptogenesis with 0νββ decay



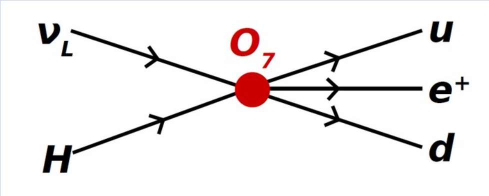
$$T_{1/2}^{-1} = |\,\epsilon_\alpha^\beta\,|^2 G^{0\nu}\,|\,M^{0\nu}\,|^2$$

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	$L^iL^j\overline{Q}_i\overline{u}^cH^k\epsilon_{jk}$
$4_b^\dagger$	$L^iL^j\overline{Q}_k\overline{u}^cH^k\epsilon_{ij}$
8	$L^i\overline{e}^c\overline{u}^cd^cH^j\epsilon_{ij}$

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

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



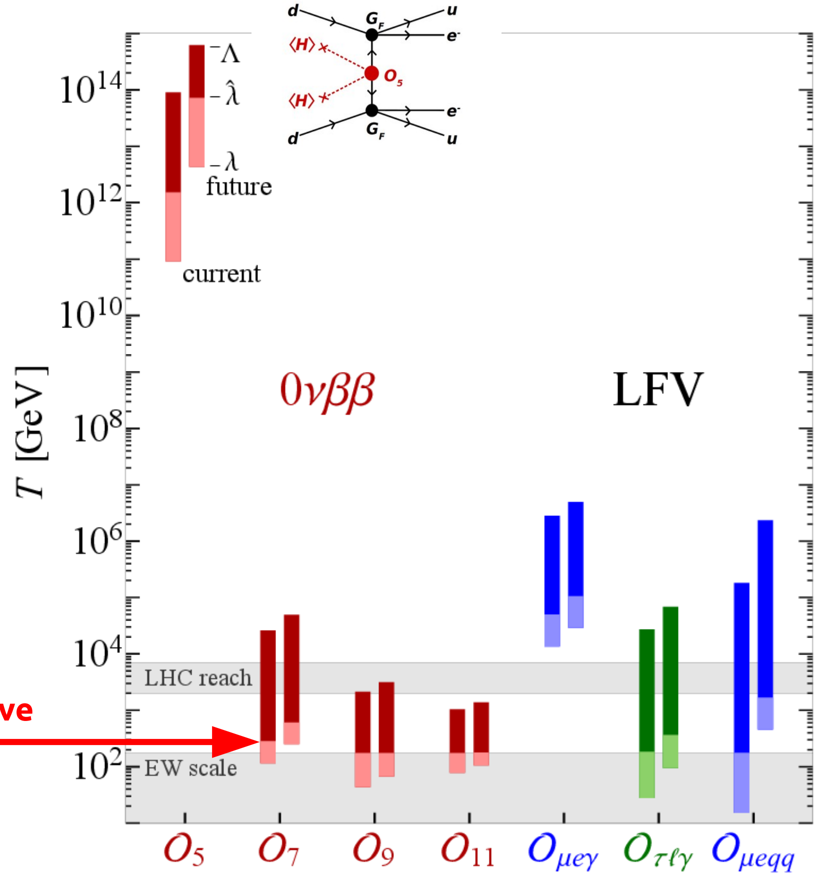
$$\Lambda_7\left(\frac{\Lambda_7}{c_7'\Lambda_{Pl}}\right)^{\frac{1}{5}}\lambda_7 < T < \Lambda_7$$

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

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

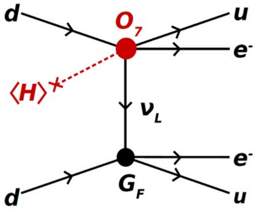
Deppisch, Graf, JH, Huang (2018)
Deppisch, JH, Huang, Hirsch, Päs (2015)
JH, Huang, Päs (2015)

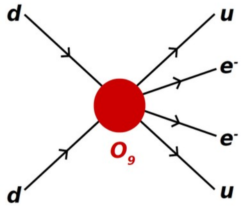
Probing leptogenesis with 0νββ decay

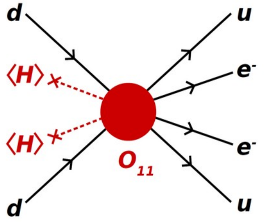


limit above which the washout is highly effective

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







Observation of 0νββ decay with new physics from non-standard mechanism would put high-scale baryogenesis under tension!

Asymmetry stored in another flavour sector?

→ measurement in all flavours
→ low-scale LFV leading to equilibration

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

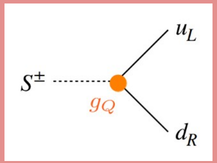
Probing leptogenesis with TeV-scale LNV

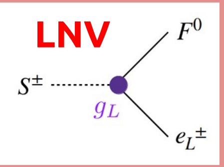
Right-handed neutrino interactions (“standard thermal LG”):

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

Additional TeV-scale interactions

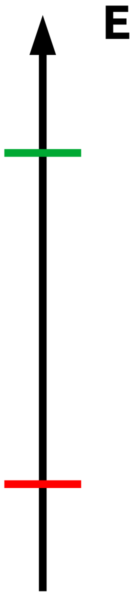
$$\tilde{\mathcal{L}} \supset g_Q \overline{Q} S d_R + g_L \overline{L}(i\tau^2) S^* F - m_S^2 S^\dagger S - \frac{m_F}{2} \overline{F^c} F + \lambda_{HS} (S^\dagger H)^2 + \text{h.c.}$$





high-scale source of lepton asymmetry

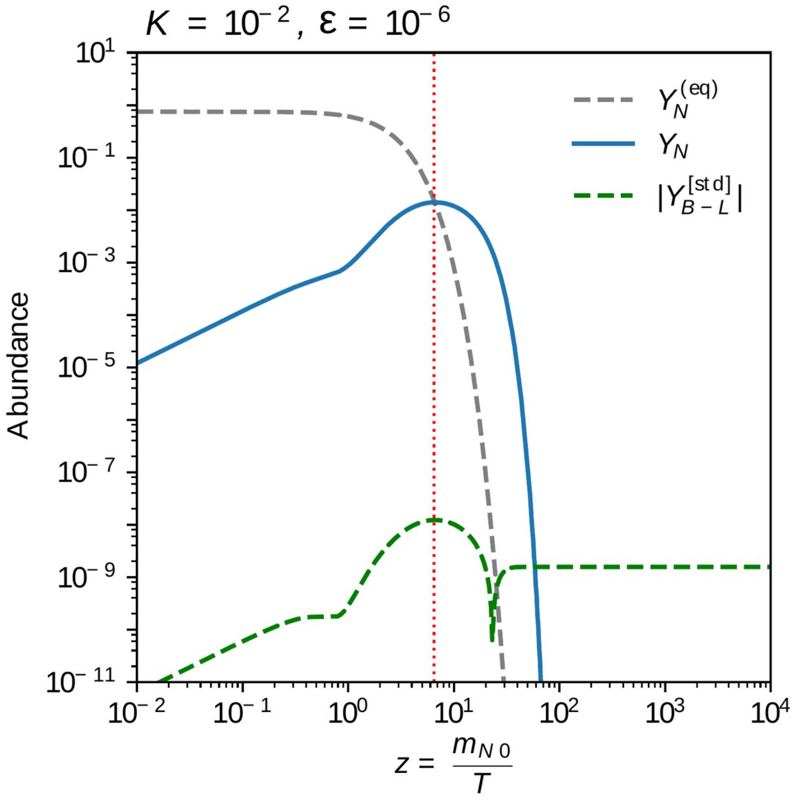
TeV-scale LNV “washout” interactions



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

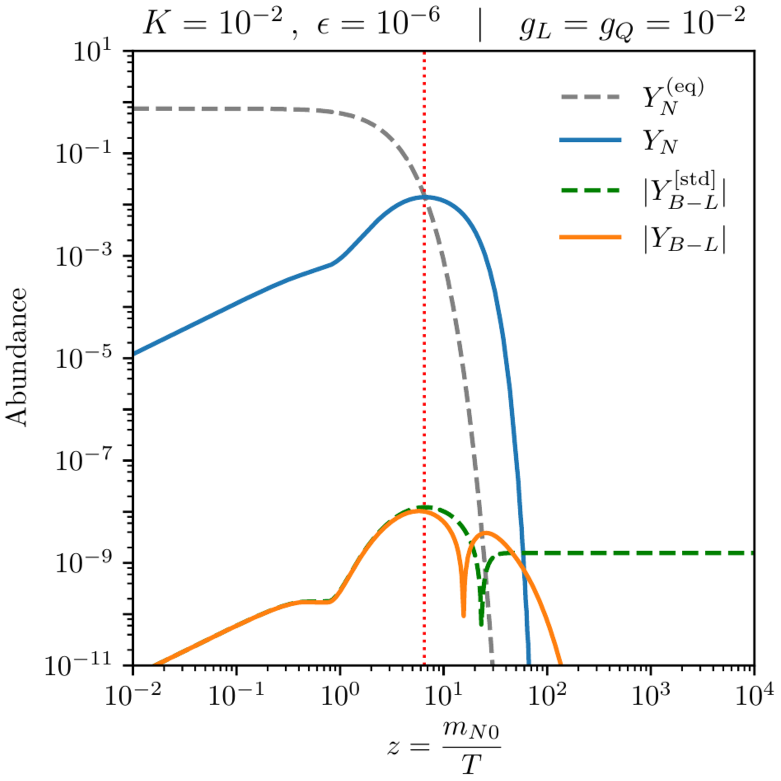
JH, Ramsey-Musolf, Shen, Urrutia-Quiroga (2021)

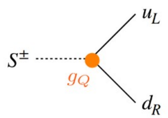
Implications on leptogenesis

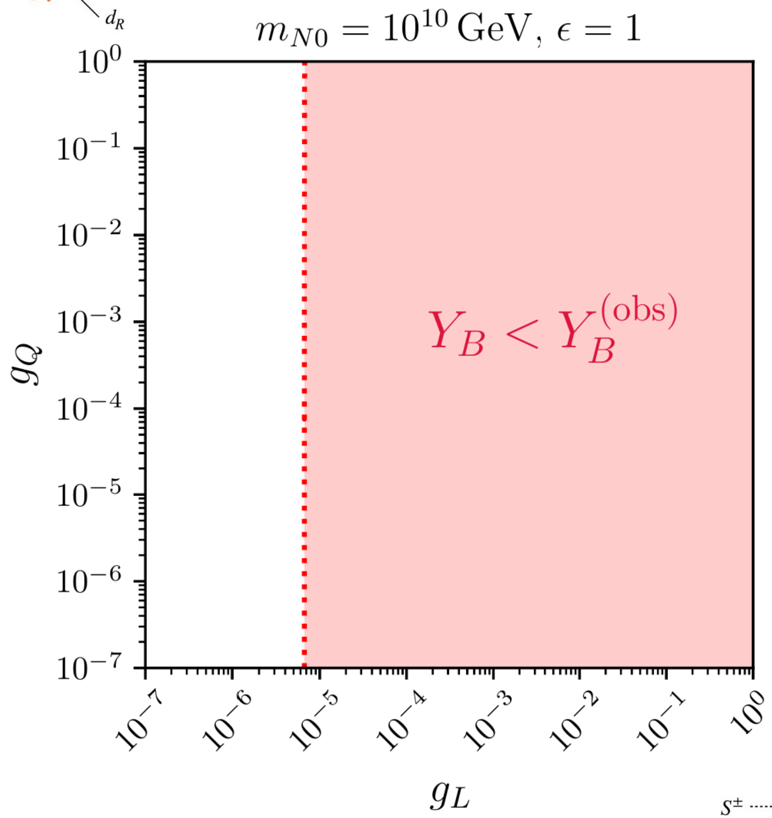


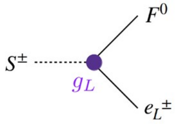
Implications on leptogenesis

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







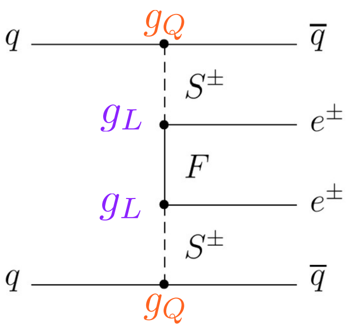


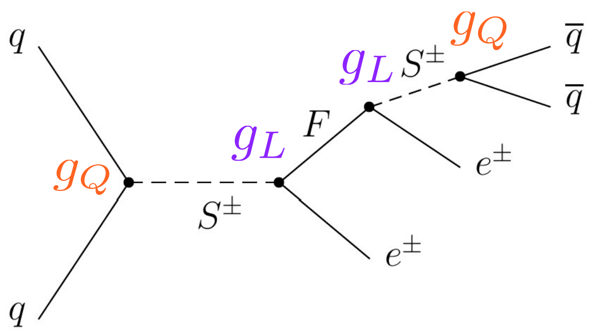
Low-scale LNV destroys lepton asymmetry previously generated by standard LG scenario.

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

Probing leptogenesis at LHC

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





Signal generation: Madgraph + Pythia 8 + Delphes

Background:

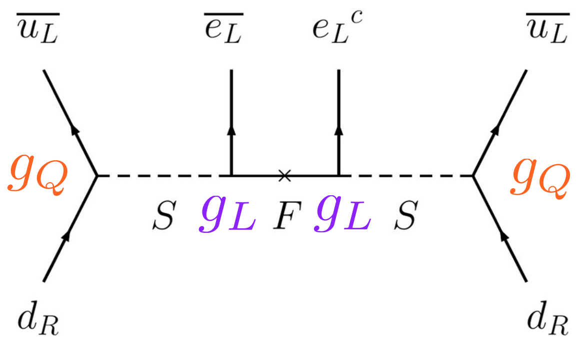
- SM processes with same-sign leptons (e.g. jjWW)
- Charge misidentification
- Jet-fake leptons from heavy flavour decays

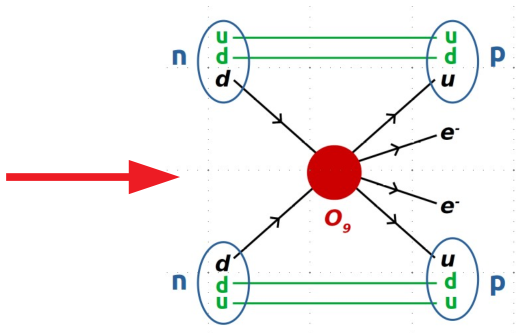
Case	Mass hierarchy	Process
C1	$m_S < m_F$	$pp \to e^\pm F, \quad F \to e^\pm S^\mp, \quad S^\mp \to jj$
C2	$m_S = m_F$	$pp \to e^\pm F, \quad F \to e^\pm jj$
C3	$m_S > m_F$	$pp \to S^\pm, \quad S^\pm \to e^\pm F, \quad F \to e^\pm jj$

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

Probing leptogenesis with 0νββ decay

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

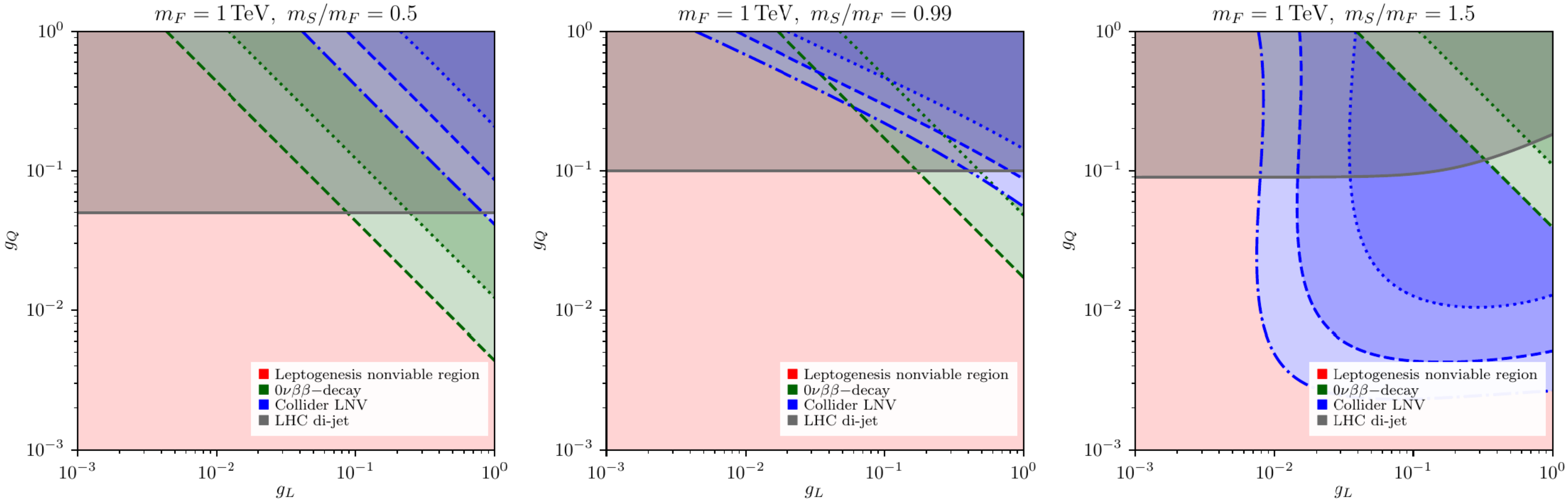




$T^{0\nu}_{1/2} > 1.07 \times 10^{26}\text{yr } 90\%\text{C.L.}$ KamLAND-Zen (2016)

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

Impact & interplay of LHC & 0νββ decay on leptogenesis



→ **Comprehensive analysis demonstrates interesting interplay between collider and 0νββ reach**

→ **TeV-scale LNV renders standard high-scale leptogenesis invalid**

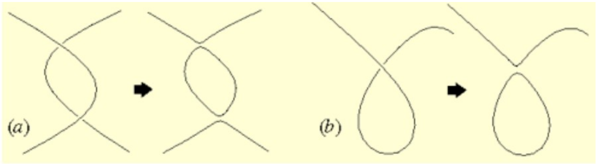
JH, Ramsey-Musolf, Shen, Urrutia-Quiroga (2021)

Probing leptogenesis with gravitational waves

NanoGrav – pulsar timing array:

→ evidence for a stochastic common-spectrum process in the 12.5 y data

Hints for a cosmic string network in the early Universe emitting a stochastic gravitational wave background?



Probing leptogenesis with gravitational waves

NanoGrav: Sign of cosmic strings?

$$\Delta\mathcal{L} = -\left[y_{i\alpha}^{\mathrm{D}}\,\overline{N_i^{\mathrm{R}}}\,\tilde{H}^\dagger L_\alpha + \frac{1}{2}\,y_i^{\mathrm{M}}\,\Phi\,\overline{N_i^{\mathrm{R}}}\left(N_i^{\mathrm{R}}\right)^{\mathrm{C}} + \mathrm{H.c.}\right] - \left[\lambda_\phi\left(|\Phi|^2 - \frac{1}{2}\,v_{B-L}^2\right)^2 + \lambda_{\phi h}\,|\Phi|^2\,|H|^2\right].\ (\,$$

Stochastic gravitational wave spectrum depends on

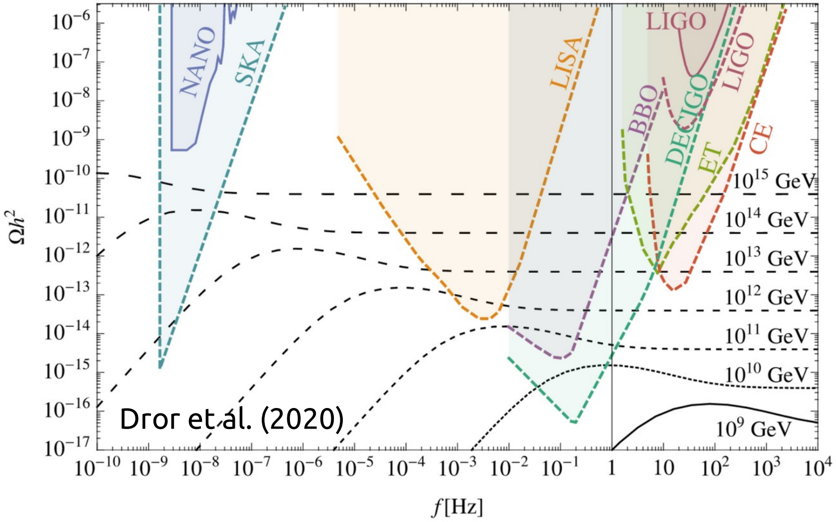
$$\Omega_{\mathrm{GW}} h^2 \propto G\mu^2$$

$$\mu \sim v^2$$

cosmic string tension

U_{B-L}-breaking scale

Hindmarsh (2011)
Buchmueller et al. (2013)



Vibrant field, many recent exciting works:

Gouttenoire et al. (2019+)
Dror et al. (2020)
Ellis et al. (2020)
Blasi et al. (2020+)
Buchmüller et al. (2021+)

Overview of leptogenesis models

gravitational waves

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

gravitational leptogenesis

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

freeze-in leptogenesis

wash-in leptogenesis

high-scale out-of-equilibrium decay

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

Fukugita, Yanagida (1986)

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)

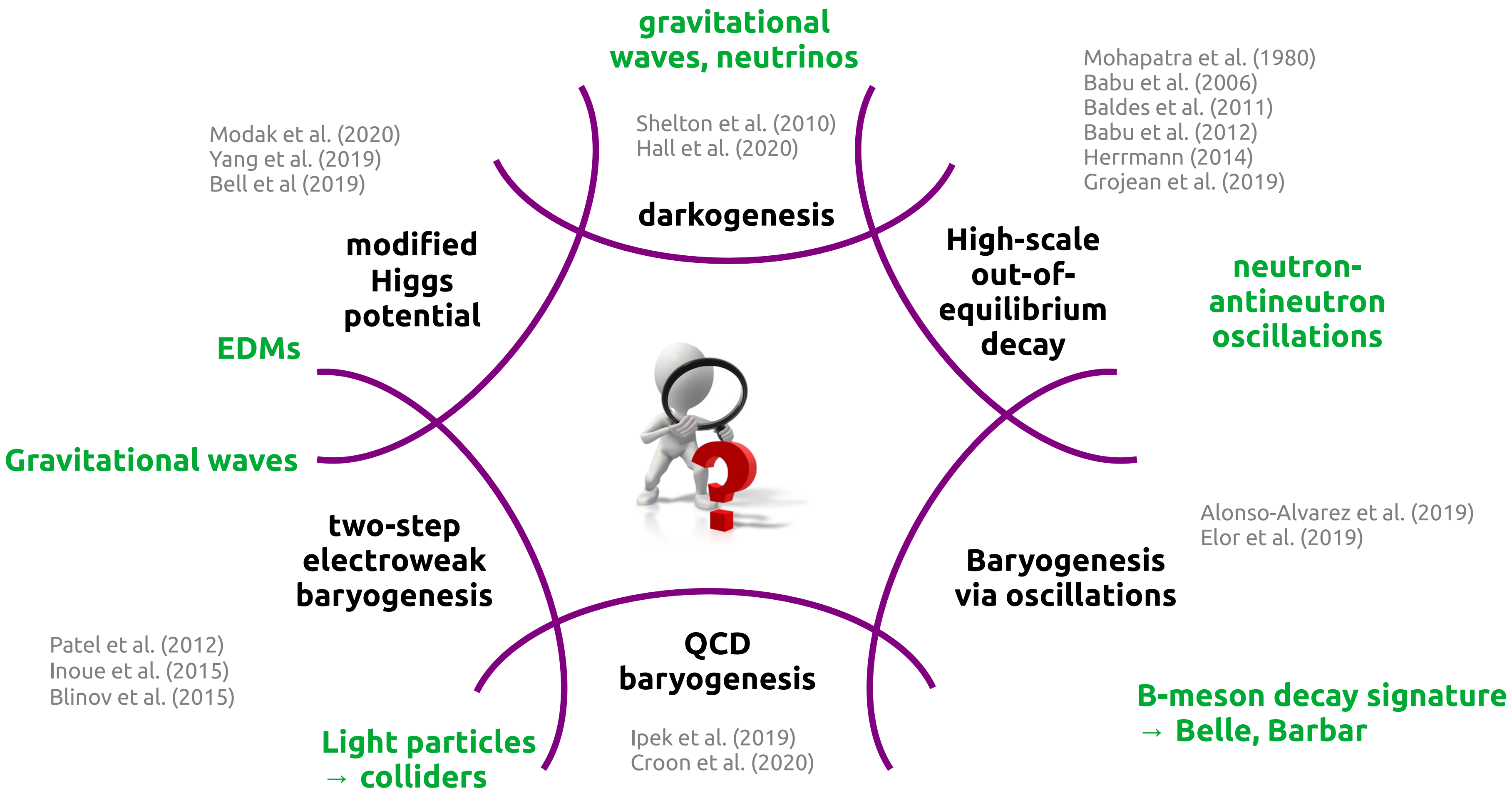
medium range RHNs → LHC

leptogenesis via oscillations

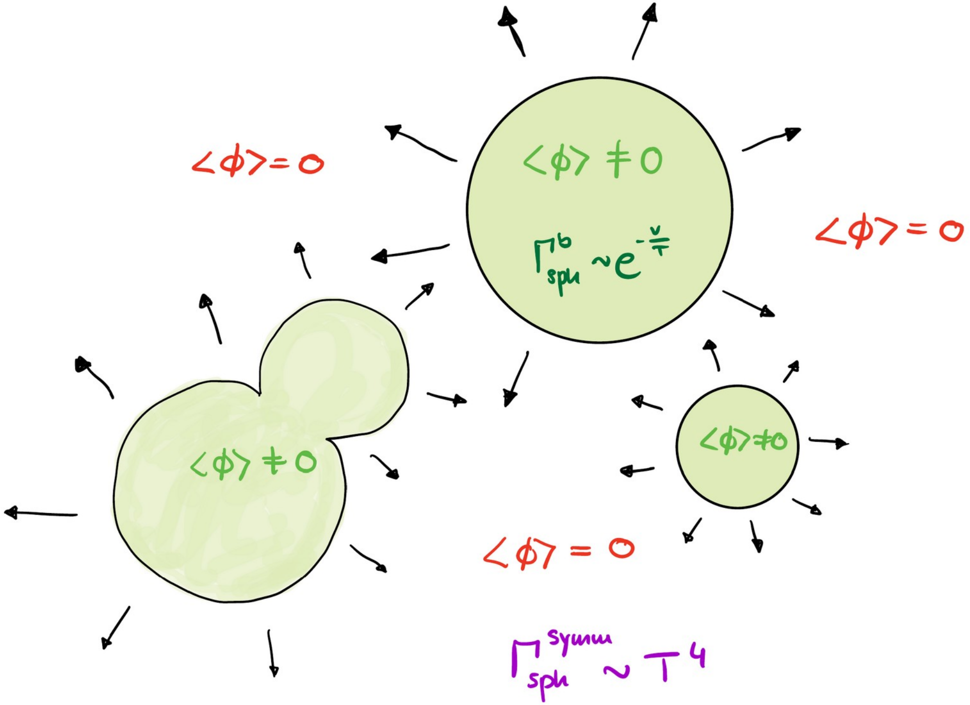
Akhmedov et al. (1998)

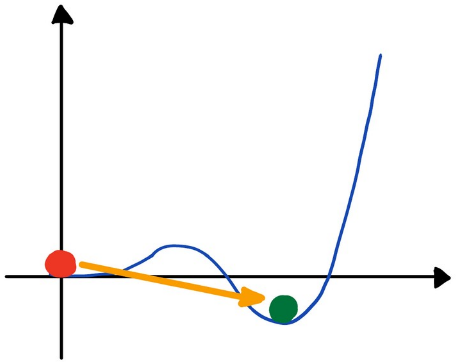
light RHNs → ShiP, meson decays, LHC

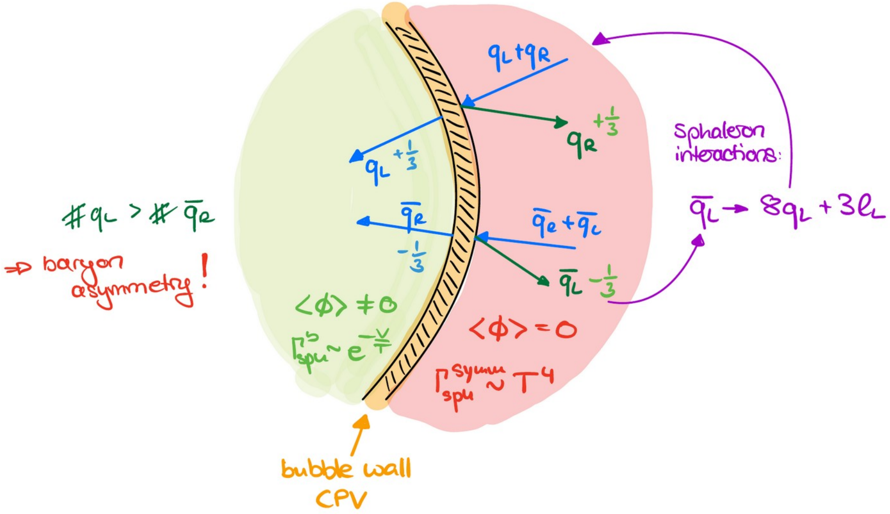
Overview of baryogenesis models



Electroweak baryogenesis







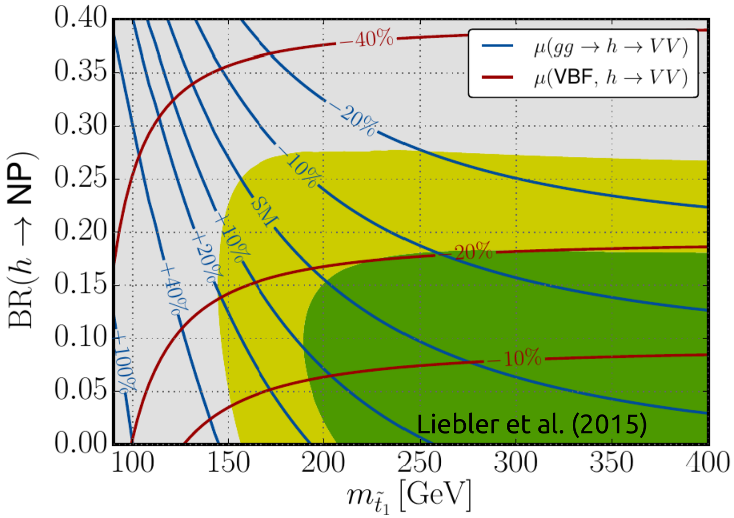
Unfortunately, Higgs boson is too heavy for EWBG!

Electroweak baryogenesis including 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….



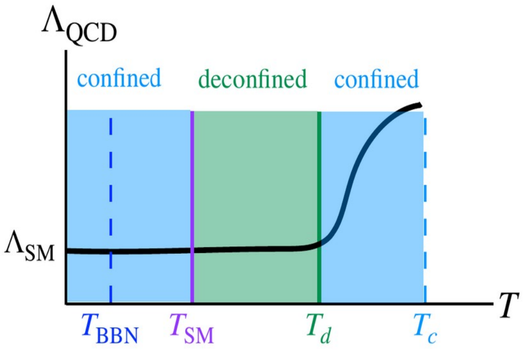
- **General extended scalar sectors, e.g.**
  - 2HDM with extra bottom Yukawa coupling Modak et al. (2020)
  - B-LSSM (B-L symmetric MSSM) Yang et al. (2019)
  - New gauge singlets and vector-like leptons Bell et al. (2019)

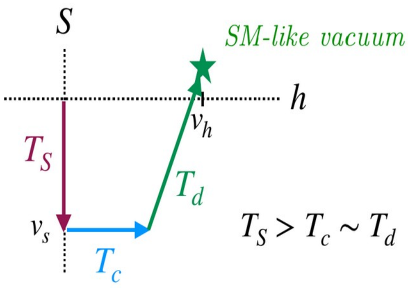
General difficulties:

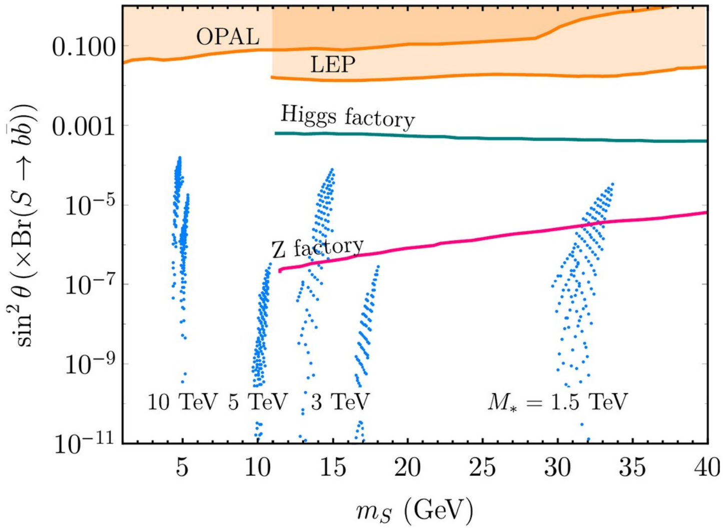
- Constraints from EDMs
- Higgs physics sets stringent constraints

QCD baryogenesis

If # of massless fermions > 3, QCD confinement proceeds via SFOFT Pisarski (1984)







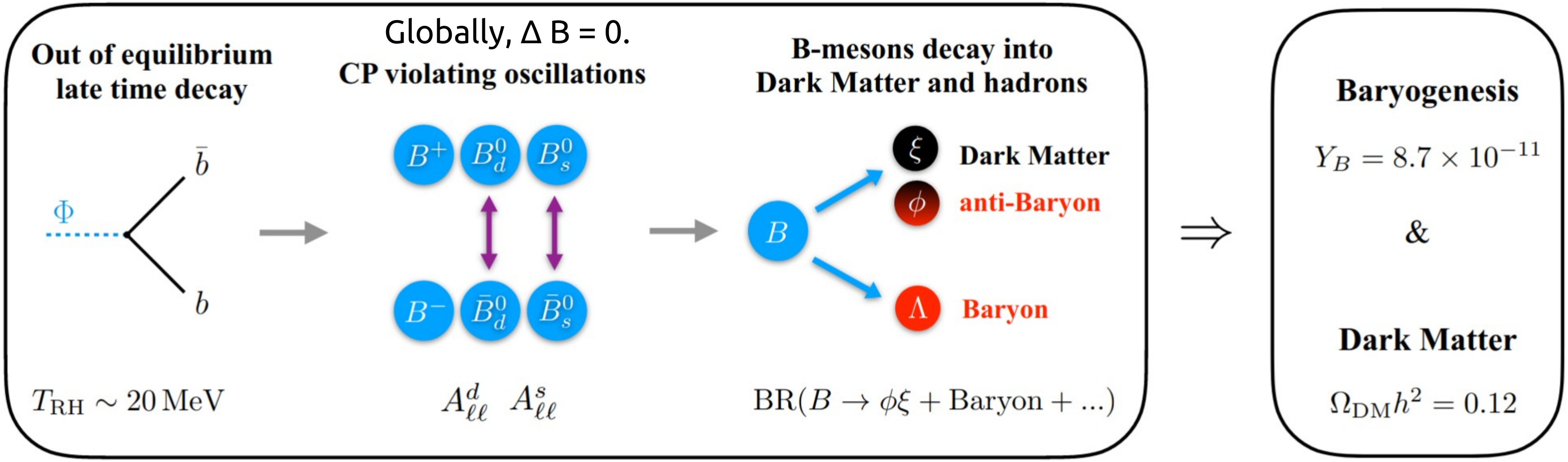
If QCD confines when the Higgs vev is zero (fermions massless), phase transition is first order.

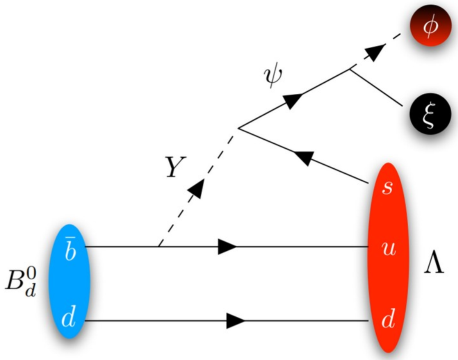
Introduce new scalar field S that perturbs the potential.

Testable light states predicted.

Ipek et al. (2019)
Croon et al. (2020)

Low-scale baryogenesis: mesogenesis



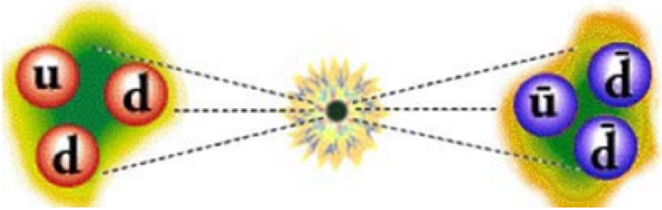


Testable scenario at Belle-II and BarBar!

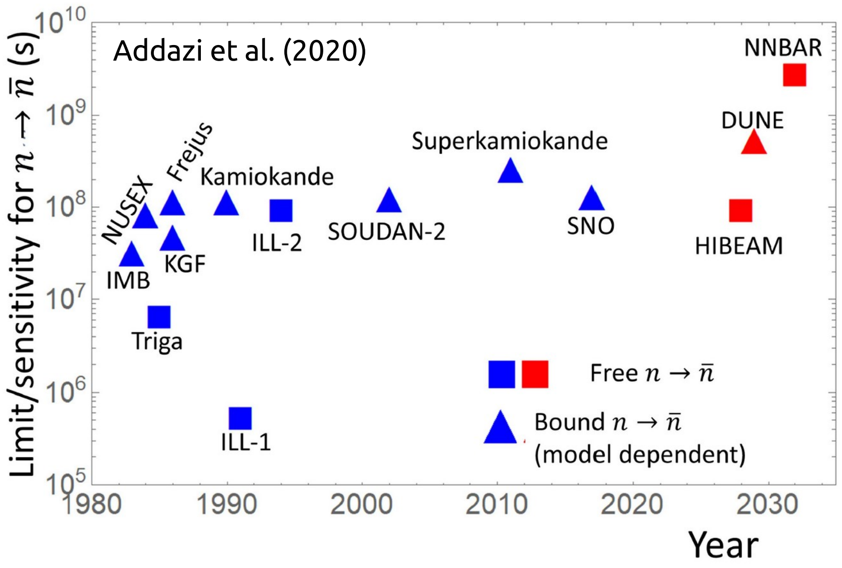
Alonso-Alvarez et al. (2019)
Elor et al. (2019+)

Probing high-scale baryogenesis with $n\bar{n}$ 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: $\tau_{n\bar{n}} \geq 10^{10} s$

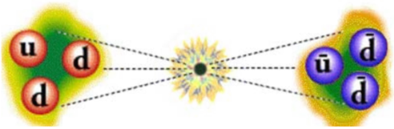
Naive estimate: $$\tau_{n-\bar{n}} \approx \frac{\Lambda_{\rm NP}^5}{\Lambda_{\rm QCD}^6}$$

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

What can we learn from nn̄ oscillations?

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

$$\Delta B = 2$$

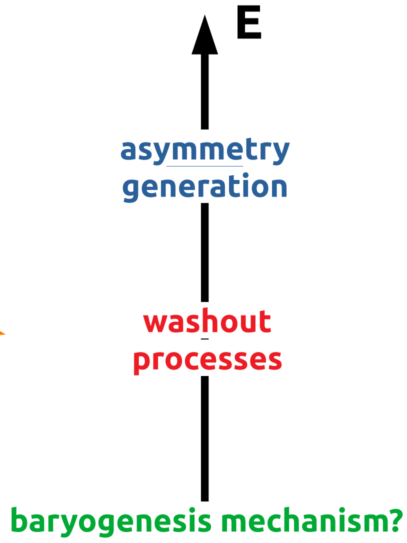


$$\frac{1}{\Lambda_{\mathrm{NP}}^5} uddudd$$

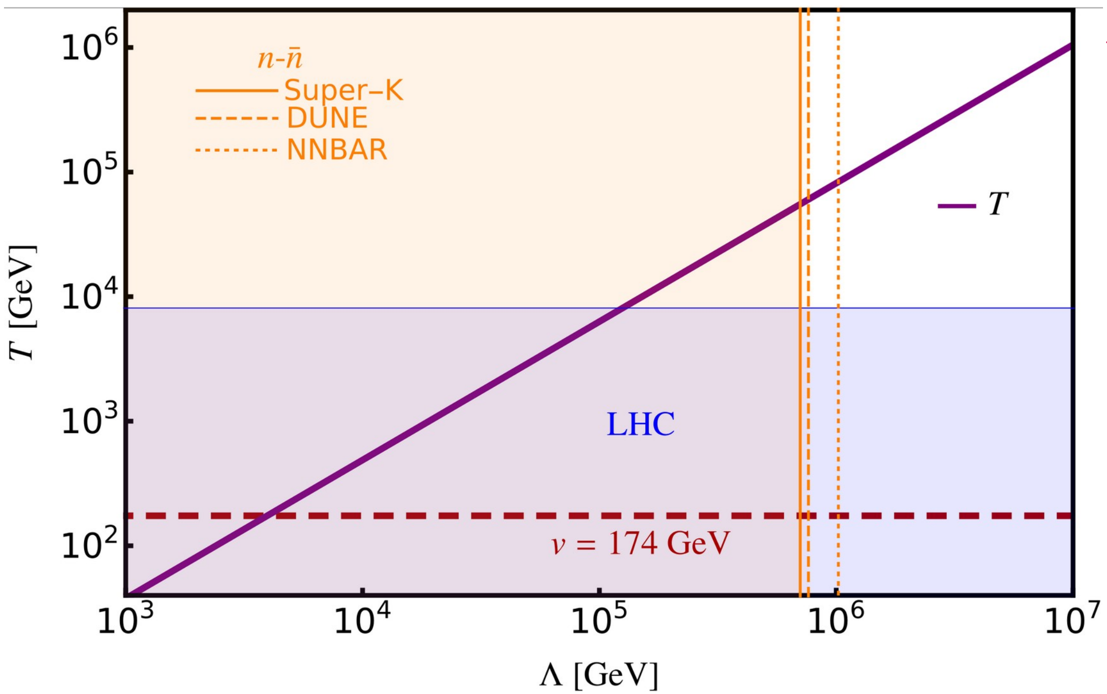
Observation of neutron-antineutron oscillations at Λ_{NP}

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

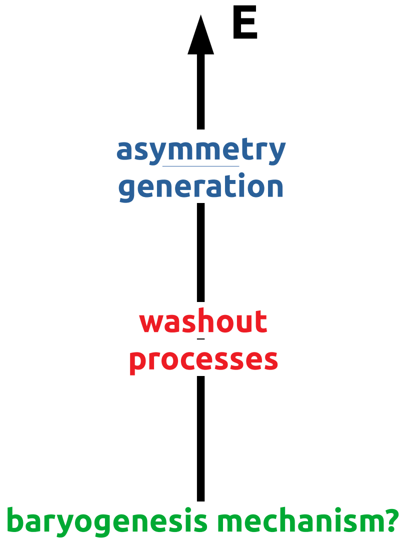
Identify scale T above which the washout rate is large enough to wipe out a previously generated asymmetry.



Probing high-scale baryogenesis with $n\bar{n}$ oscillations

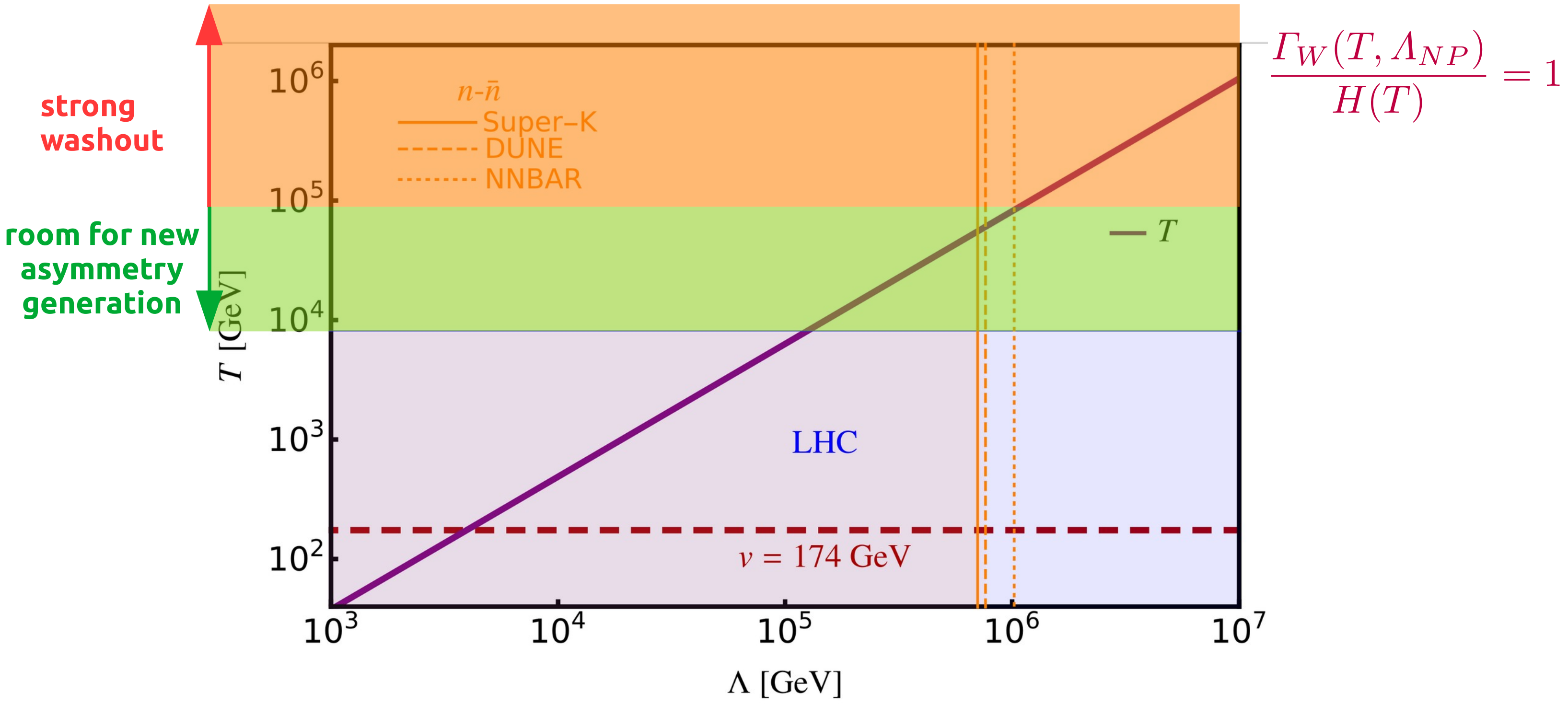


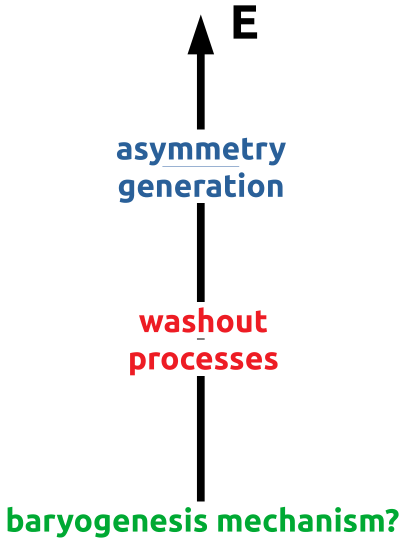
$$\frac{\Gamma_W(T, \Lambda_{NP})}{H(T)} = 1$$



Fridell, JH, Hati (2021)

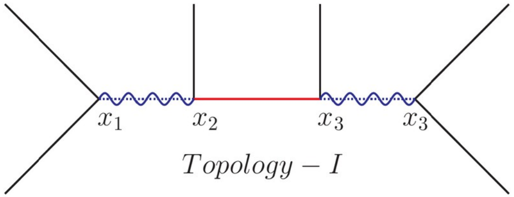
Probing high-scale baryogenesis with $n\bar{n}$ oscillations

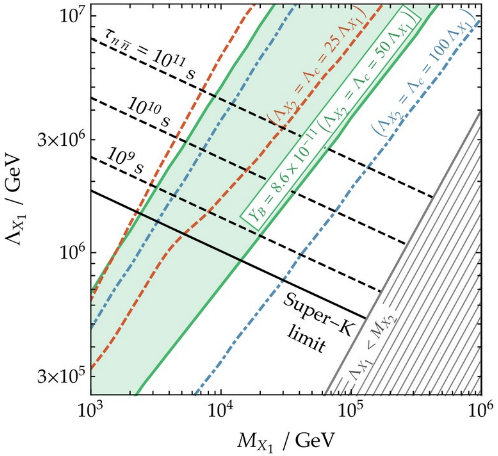




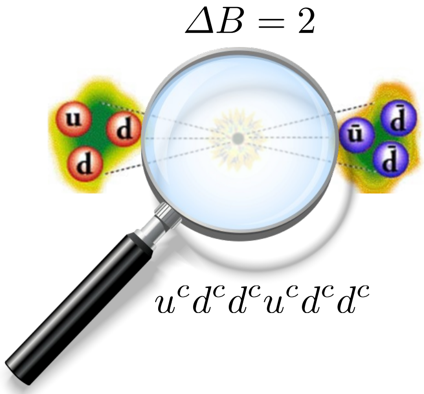
Fridell, JH, Hati (2021)

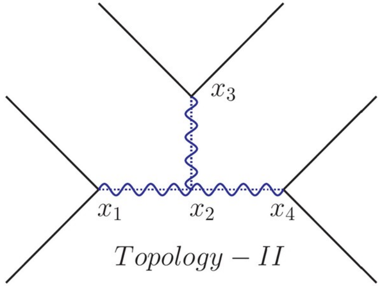
Possible UV topologies





Grojean et al. (2019)





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

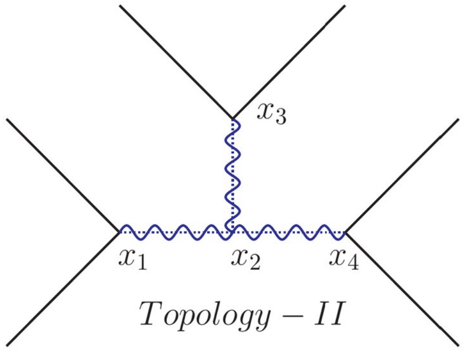
NOW:

- **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)

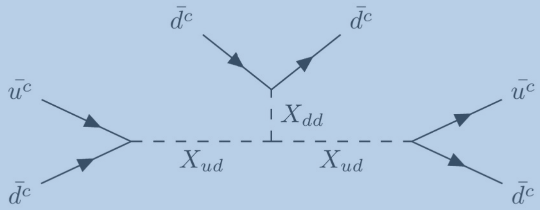
Simplified model of toplogy II

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

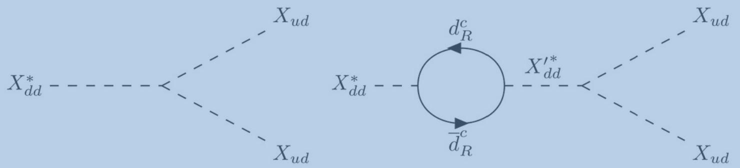


- Diquarks motivated by GUT embedding into SO(10)
- Non-SUSY SO(10) unification requires TeV-scale X_{ud} and GUT-scale X_{dd} / v_{B-L}

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



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

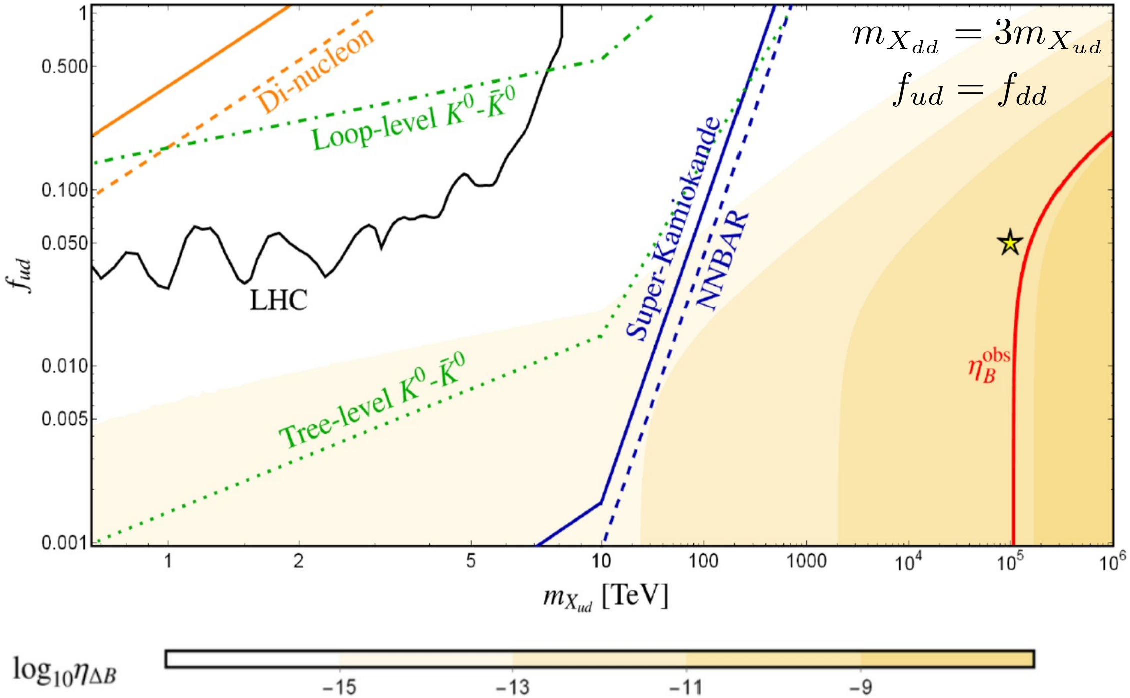


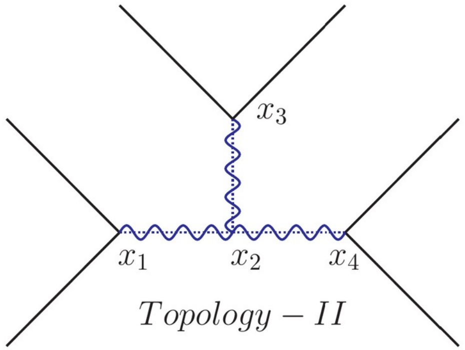
$$\epsilon = \frac{\Gamma_{X_{dd}\to X^*_{ud} X^*_{ud}} - \Gamma^*_{X_{dd}\to X_{ud} X_{ud}}}{\Gamma_{X_{dd}\to X^*_{ud} X^*_{ud}} + \Gamma^*_{X_{dd}\to X_{ud} X_{ud}}}$$

Source of CP violation

Fridell, JH, Hati (2021)

Low-scale scenario

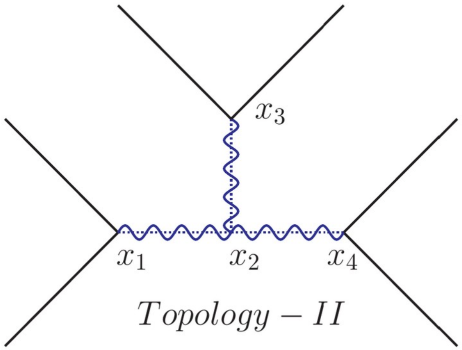


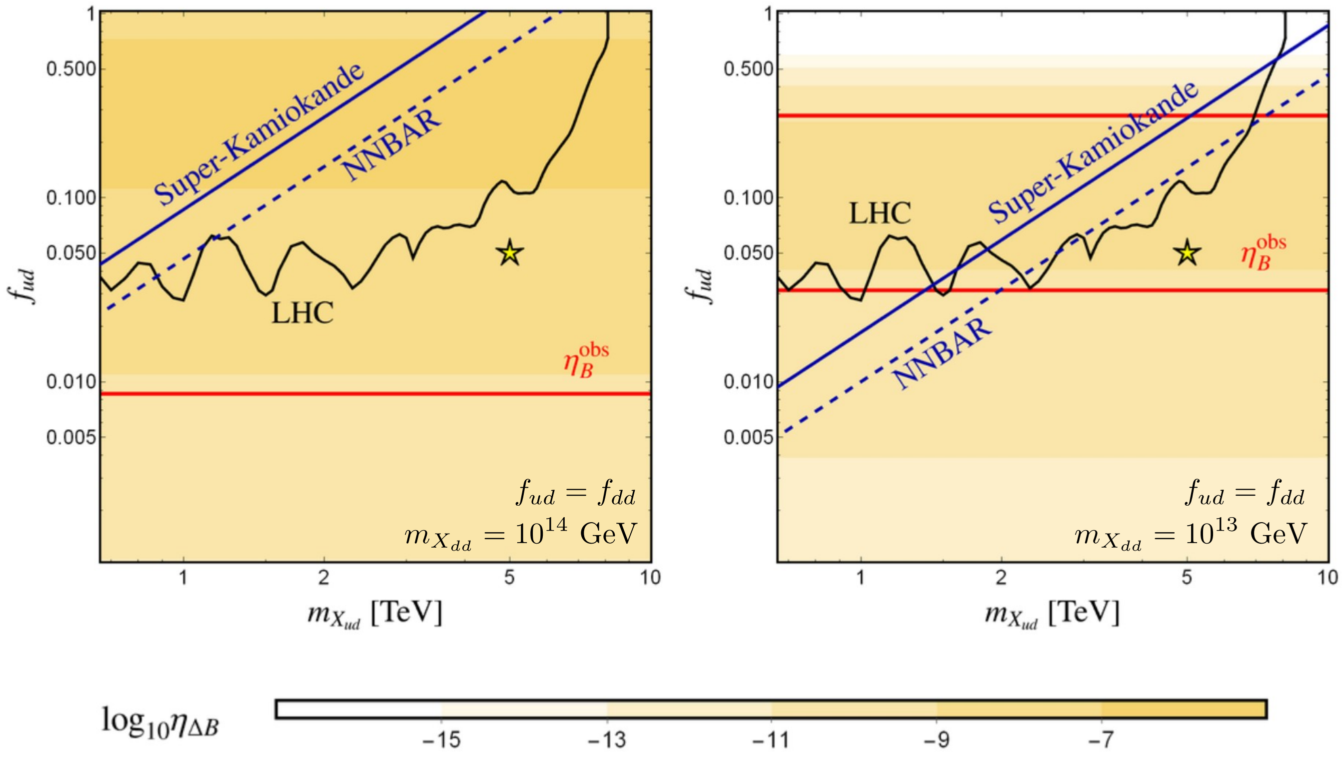


$$C_1 \approx \frac{(f_{11}^{ud})^2 f_{11}^{dd}}{m_{X_{dd}} m_{X_{ud}}^4}$$

Fridell, JH, Hati (2021)

High-scale scenario





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

Fridell, JH, Hati (2021)

Darkogenesis

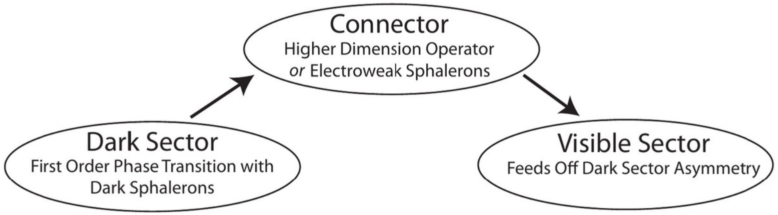
First order phase transition in dark sector transmitts the asymmetry into visible sector

Connector: Neutrino portal Hall et al. (2020)

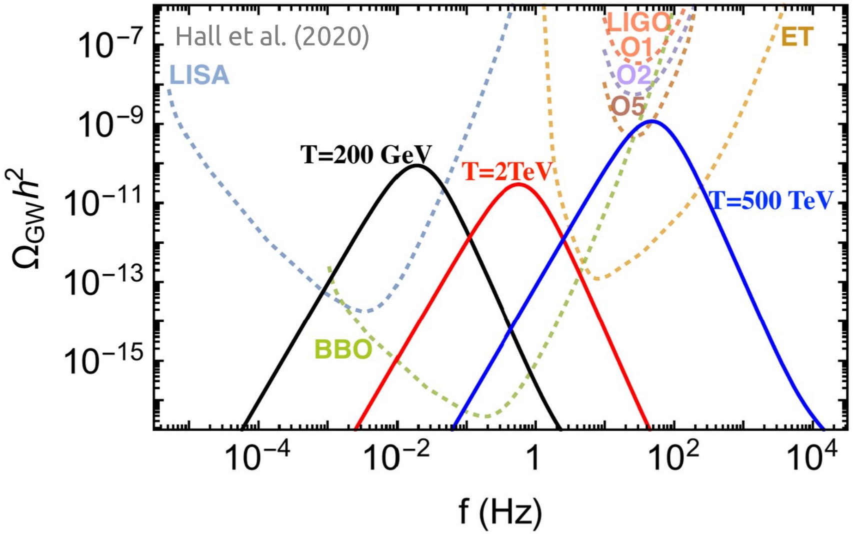
$$\mathcal{L}_Y = -\,Y_{a\alpha}\bar{L}_1\Phi_a N_\alpha - \tilde{Y}_{a\alpha}\bar{L}_1\tilde{\Phi}_a N_\alpha + c.c.$$

$$\Delta\mathcal{L}_Y = -y_{i\alpha}\bar{\ell}_i N_\alpha \tilde{H} + c.c.$$

field	$SU(2)_D$	γ_5	Q_1	Q_2	$\mathbb{Z}_2$
$\Phi_{1,2}$	**2**	0	0	0	+
L_1	**2**	−1	+1	0	+
$N_{u,d}$	**1**	+1	+1	0	+
L_2	**2**	−1	0	+1	−



Shelton et al. (2010)



Not subject to strong constraints from EDMs!

FIMPs and their implications on baryogenesis

Feebly interacting particles (FIMPS) can be DM candidate via another mechanism (freeze-in)

(1) DM *not* in thermal equilibrium with SM bath

DM is feebly interacting with the SM bath;
abundance negligible $\lambda \sim \mathcal{O}(10^{-7})$

(2) DM production

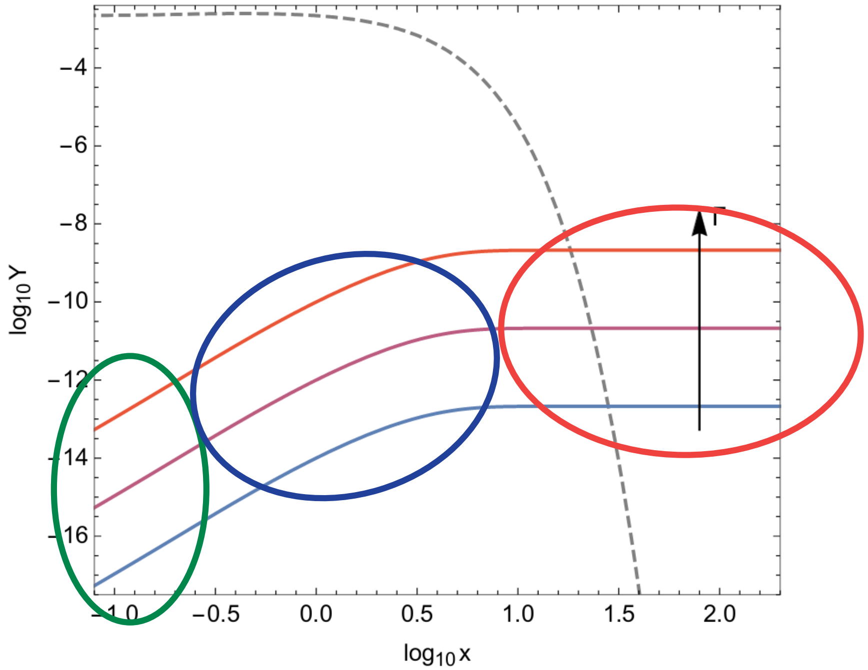
DM gets produced via decay of a heavier particle Y
that is in equilibrium with the SM bath $Y \to \mathrm{SM}\ \chi$

(3) Freeze-in

when T falls below mass of parent particle Y,
production gets Boltzmann suppressed

$$n_Y \approx \exp(-m_Y/T)$$

$$\Omega_\chi h^2 \sim 4.48 \times 10^8 \frac{g_Y}{g_*^S \sqrt{g_*}} \frac{m_\chi}{\mathrm{GeV}} \frac{M_{\mathrm{Pl}} \Gamma_Y}{m_Y^2}$$

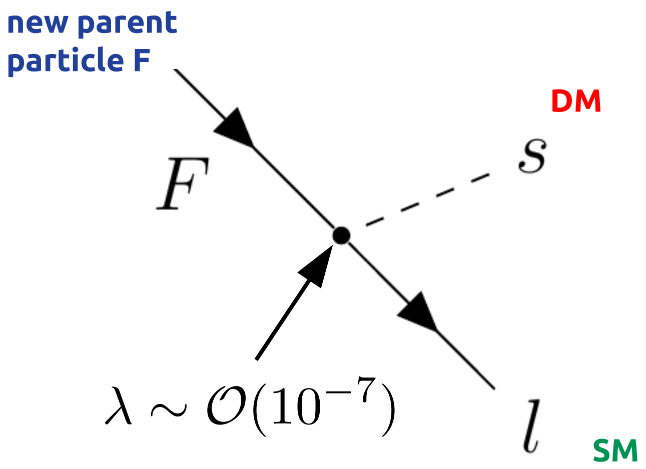


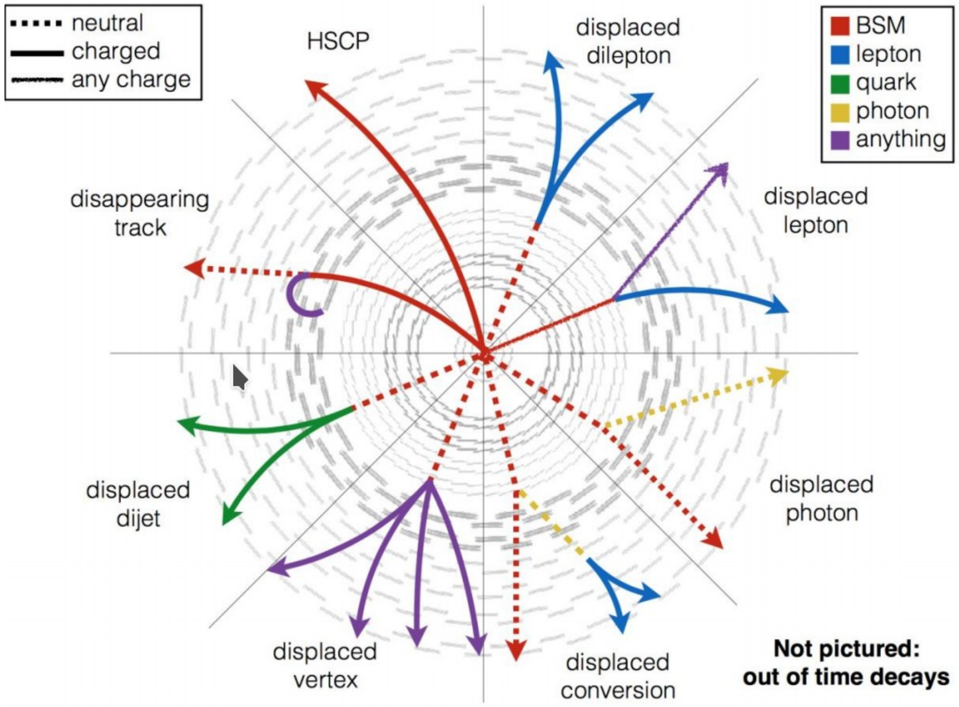
cooling down

$x = m_Y/T$

FIMPs and their implications on baryogenesis

Feebly interacting particles (FIMPS) can lead to interesting Long Lived Particle (LLP) signatures at the LHC



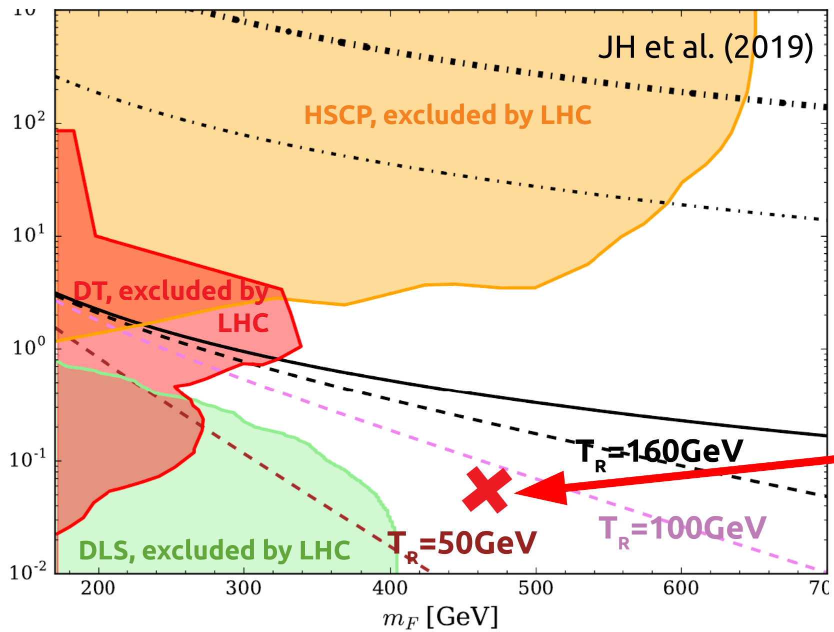


FIMPs and their implications on baryogenesis

The relic abundance can be related with the parent particle life time and its mass m_F

$$c\tau \approx 4.5\ \mathrm{m}\ \xi g_F \left(\frac{0.12}{\Omega_s h^2}\right)\left(\frac{m_s}{100\mathrm{keV}}\right)\left(\frac{200\mathrm{GeV}}{m_F}\right)^2\left(\frac{102}{g_*(m_F/3)}\right)^{3/2}\left[\frac{\int_{m_F/T_R}^{m_F/T_0} dx\ x^3 K_1(x)}{3\pi/2}\right]$$

Decay length of parent particle



mass of parent particle

exclusion of specific baryogenesis models in case of an observation indicating too small reheating temperature

→ **supercooled scenario?**

Belanger, Desai, Goudelis, JH, Lessa et al. (2019)

Conclusions

- Discovery potential and complementarity of new physics connected to Sakharov's conditions

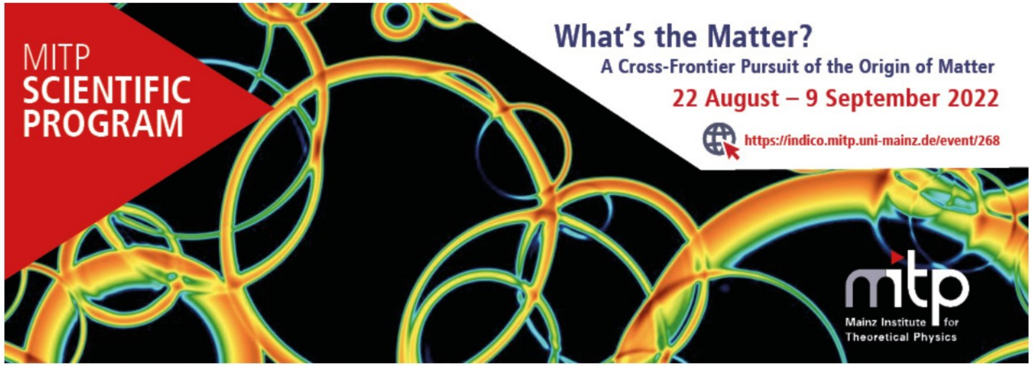
- Strong complementary of different probes
  LNV: LHC, $0\nu\beta\beta$ decay, meson decays
  BNV: LHC, nnbar oscillations, meson oscillations, dinucleon decay

- Exploration of the energy, intensity, long-life time and gravitational wave frontiers for baryogenesis

- Baryogenesis and its connection to QCD phase transition, dark matter and in particular neutrino physics

For a great overview check out SNOWMASS white papers: arxiv:2203.05010 [hep-ph], arxiv:2203.07059 [hep-ph]

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



What's the Matter? A Cross-Frontier Pursuit of the Origin of Matter

August 22, 2022 to September 9, 2022
Mainz Institute for Theoretical Physics, Johannes Gutenberg University
Europe/Berlin timezone

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Contact @ MITP : Sibylle & Kerstin

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Despite tremendous progress in particle physics in the last decades, the origin of matter remains an open mystery. At the heart of this mystery is the baryon asymmetry, produced during an unknown but consequential epoch of our cosmic history.

"What's the matter?" brings together global experts from all subfields united by this problem to explore common and complementary opportunities for discovering the origin of matter. Topics include

- *Theory frontier:* improving computational techniques required to understand baryogenesis
- *High-energy frontier:* how can we test models of baryogenesis at current and future colliders, for instance by probing the physics leading to first-order phase transitions
- *High-intensity and long-lifetime frontier:* connections between baryogenesis and long-lived particles, and searches for the latter
- *Precision and low-energy frontier:* how can low-energy precision tests, in particular probes of CP violation, elucidate the physics of baryogenesis?
- *Cosmology frontier:* what traces can baryogenesis have left in the CMB, in gravitational waves, and in other cosmological observables?
- *Neutrino frontier:* the deep connections between neutrinos and baryogenesis – for instance in the context of leptogenesis – and experimental ways to probe it
- *Dark matter frontier:* what can dark matter tell us about the origin of baryons?

Application deadline: May 15th!

COSMOLOGY MARCHES ON

Thank you for your attention!