The quest for the mechanism behind the matter-antimatter asymmetry

Julia Harz

29th June 2022, Kitzbühel
Humboldt Kolleg conference on the interface of particle, gravity and quantum physics

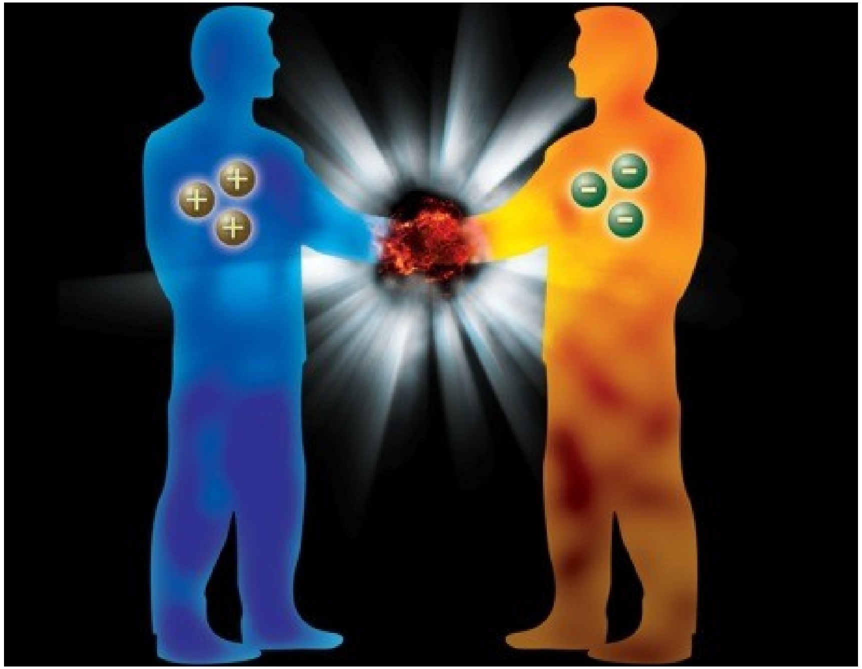
Technische Universität München

Emmy Noether-Programm
DFG Deutsche Forschungsgemeinschaft

Clues to our mysterious Universe?

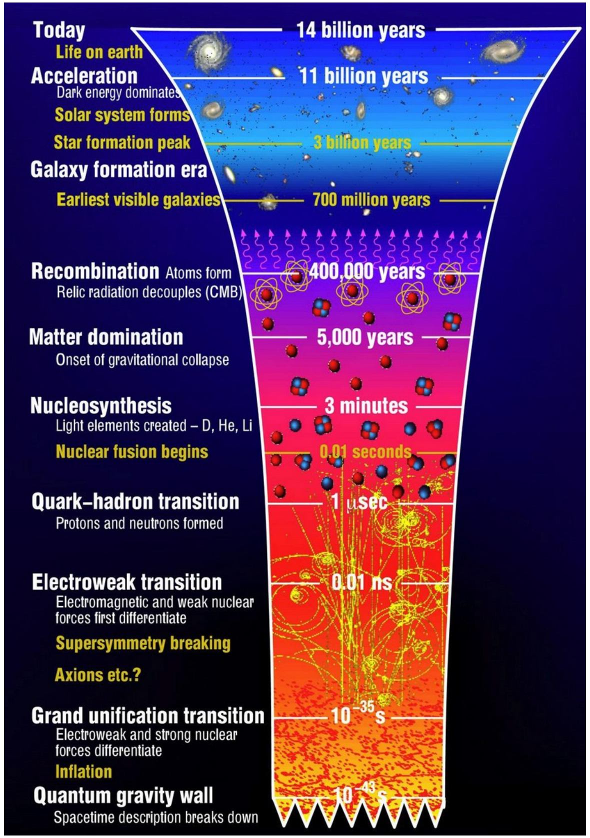
NASA, ESA, and J. Lotz, M. Mountain, A. Koekemoer, and the HFF Team (STScI)

A mystery - why do we exist?



Why is there more matter than antimatter?

The baryon asymmetry

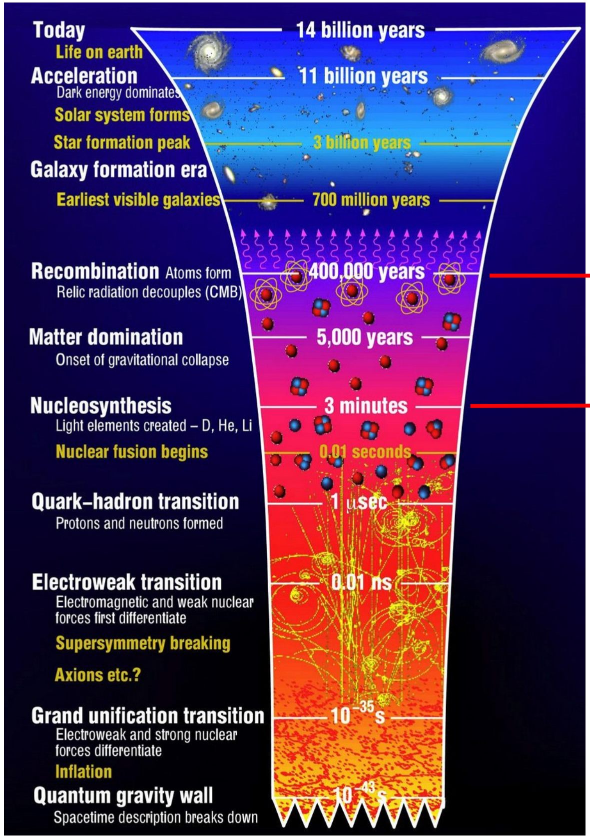


Our Universe consists mainly out of baryonic matter, quantified by the baryon-to-photon ratio:

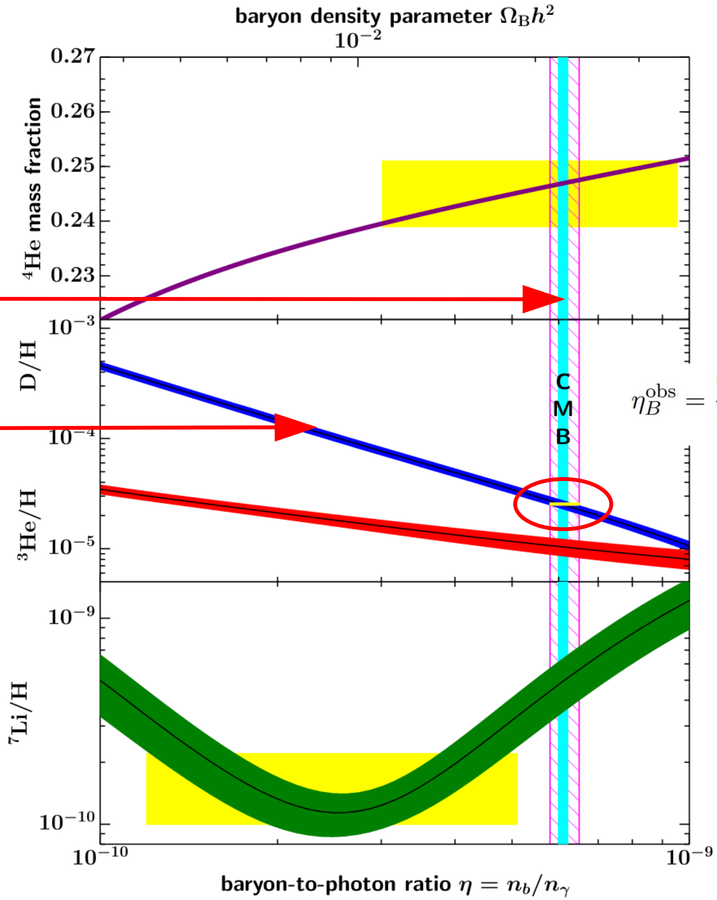
$$\eta_B = \frac{n_B}{n_\gamma} = \frac{n_b - n_{\bar{b}}}{n_\gamma}$$

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

The baryon asymmetry



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



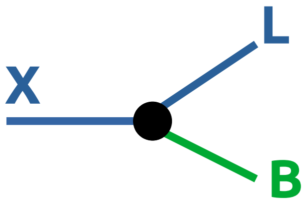
$$\eta_B^{\rm obs} = \frac{n_B}{n_\gamma} = (6.12 \pm 0.04) \times 10^{-10}$$

Excellent agreement !

Why do we need new physics?

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

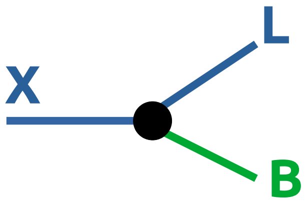
☐ baryon number violation



Why do we need new physics?

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

☐ baryon number violation

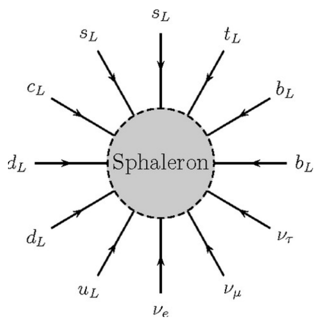


Standard model:

- **At classical level: no B or L violation**
- **At quantum level: SM sphaleron interactions**

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

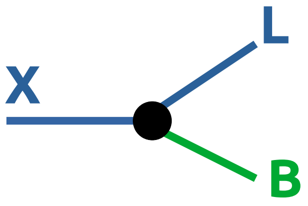
highly active above T_{EW}



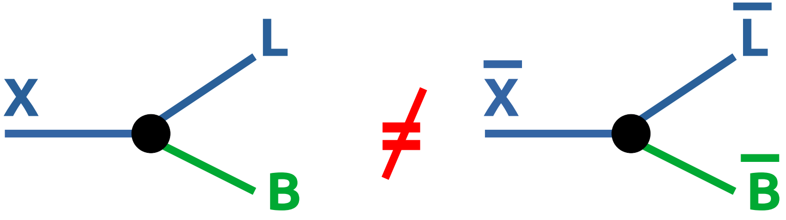
Why do we need new physics?

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

- ☐ baryon number violation



- ☐ C and CP violation

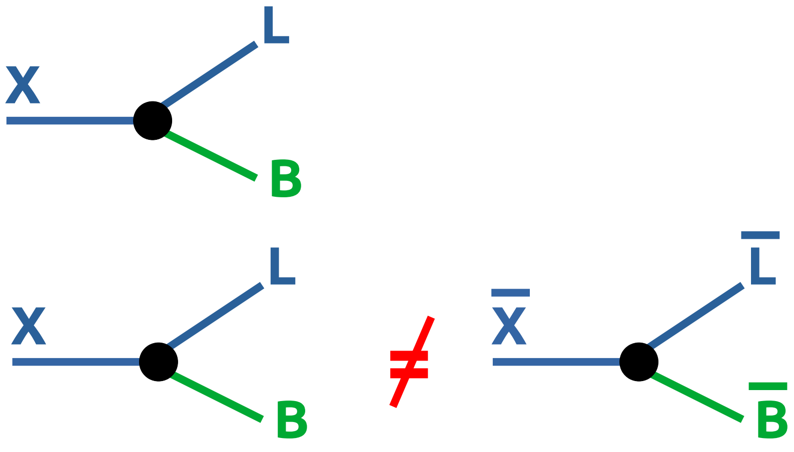


Why do we need new physics?

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

☐ baryon number violation

☐ C and CP violation



Standard model:

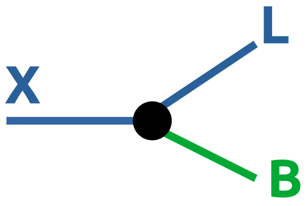
$$\frac{J_{CP}}{T_C^{12}} \approx 10^{-20} \quad \longleftrightarrow \quad \mathcal{O}(10^{-10})$$

not enough CP violation within SM!

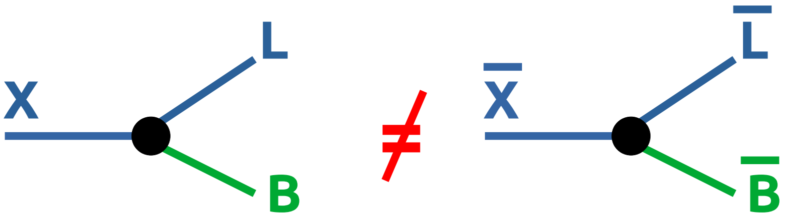
Why do we need new physics?

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

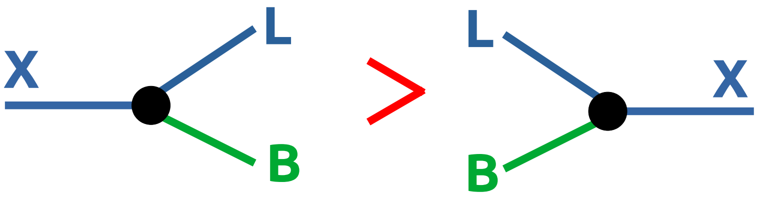
- ☐ baryon number violation



- ☐ C and CP violation



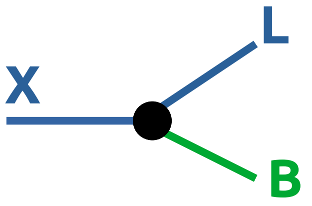
- ☐ departure from thermal equilibrium



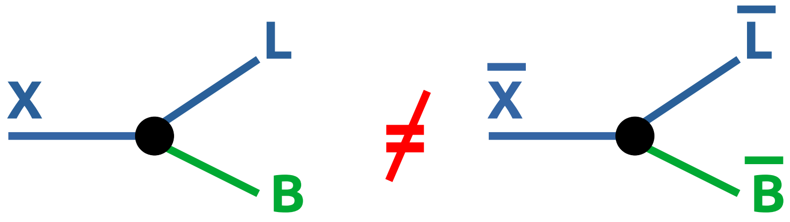
Why do we need new physics?

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

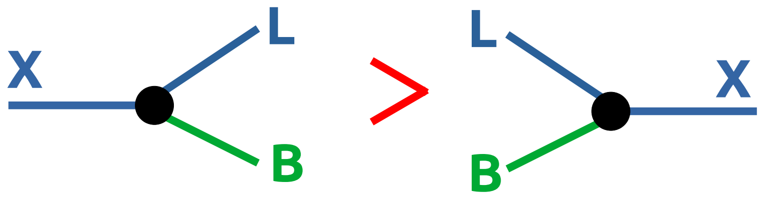
☐ baryon number violation



☐ C and CP violation



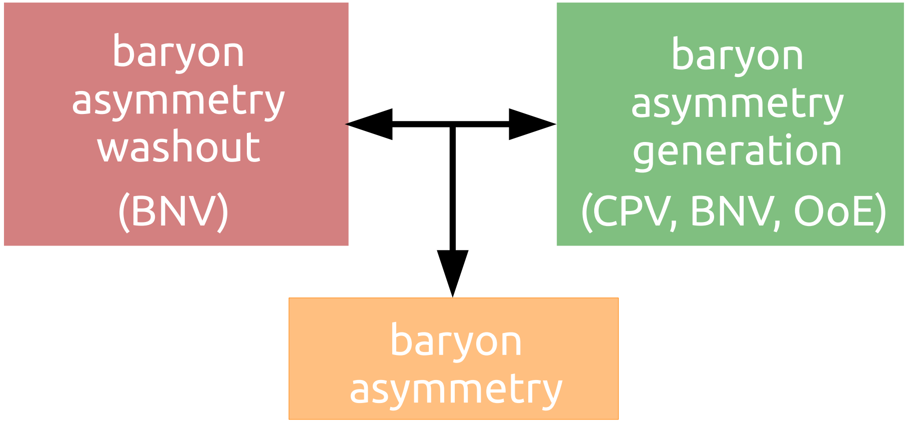
☐ departure from thermal equilibrium



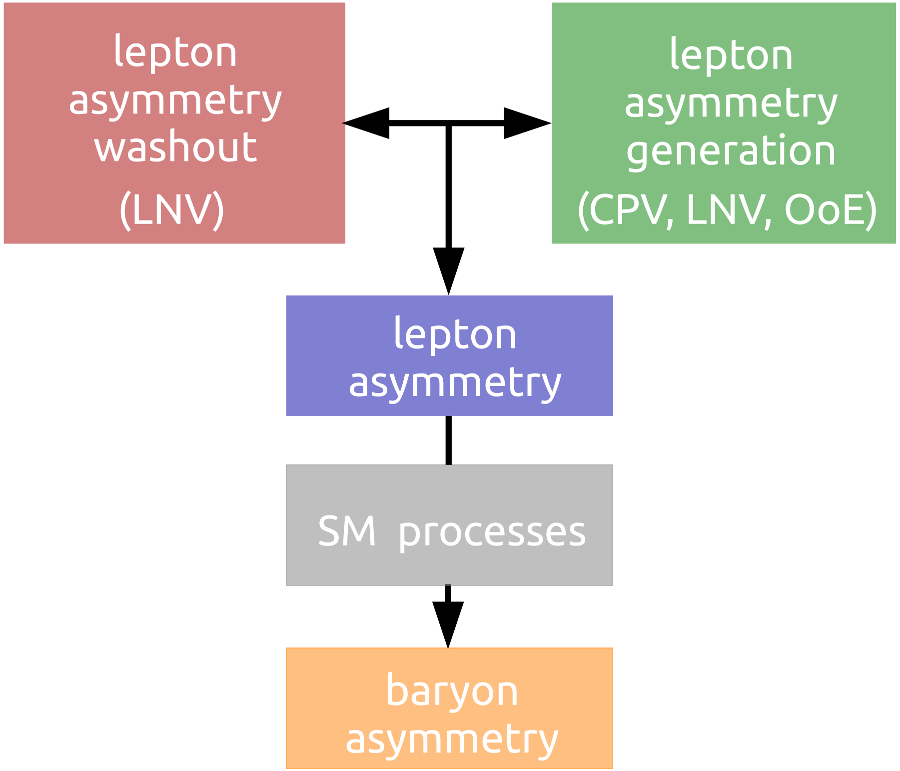
Standard model:

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

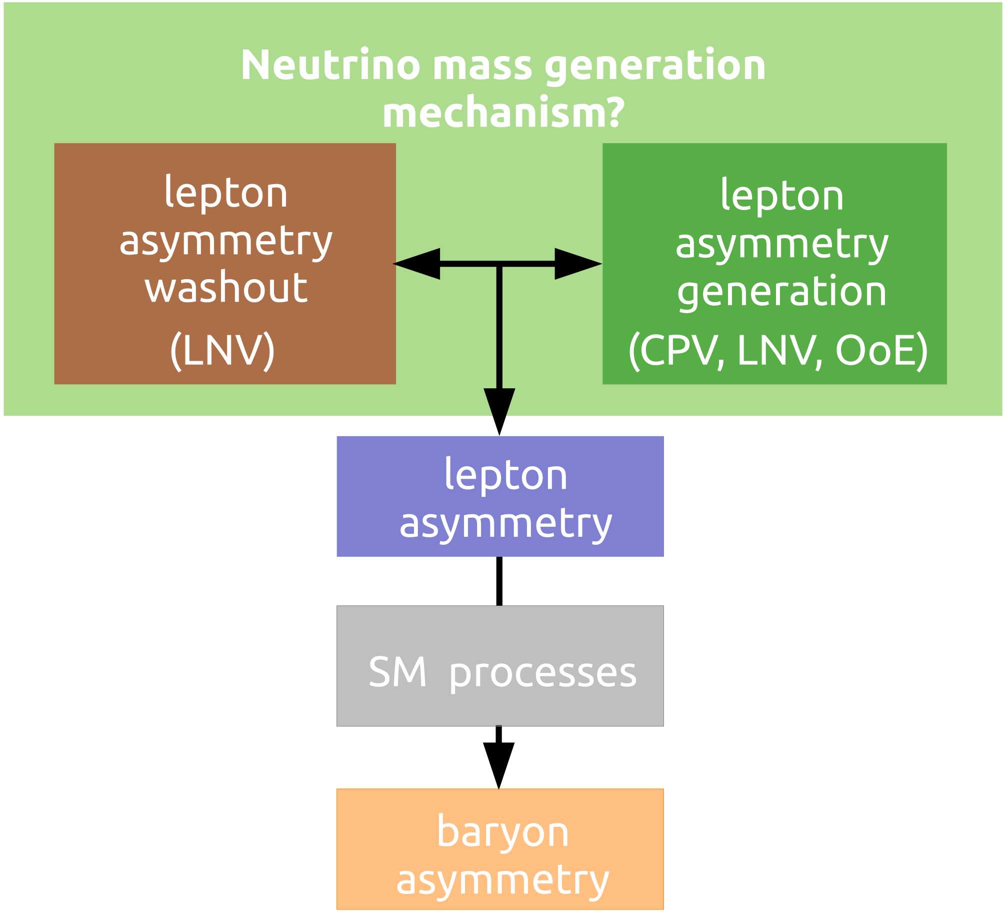
Basic principle of standard baryogenesis



Basic principle of standard leptogenesis



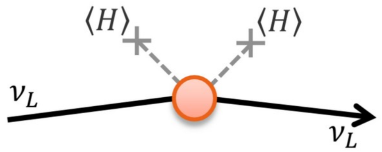
Basic principle of standard leptogenesis



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)**

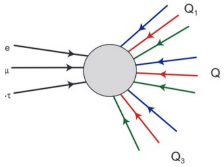
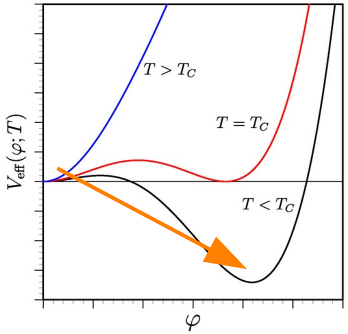
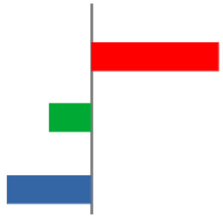
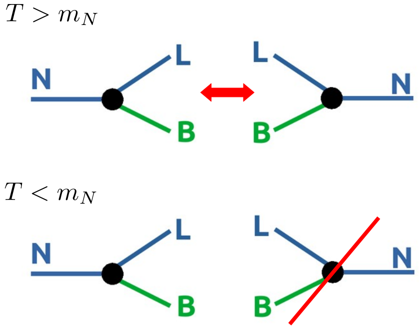
$$\mathrm{M}_\nu \simeq 0.3 \left(\frac{\mathrm{GeV}}{M_N}\right)\left(\frac{\lambda^2}{10^{-14}}\right) \mathrm{eV}$$

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

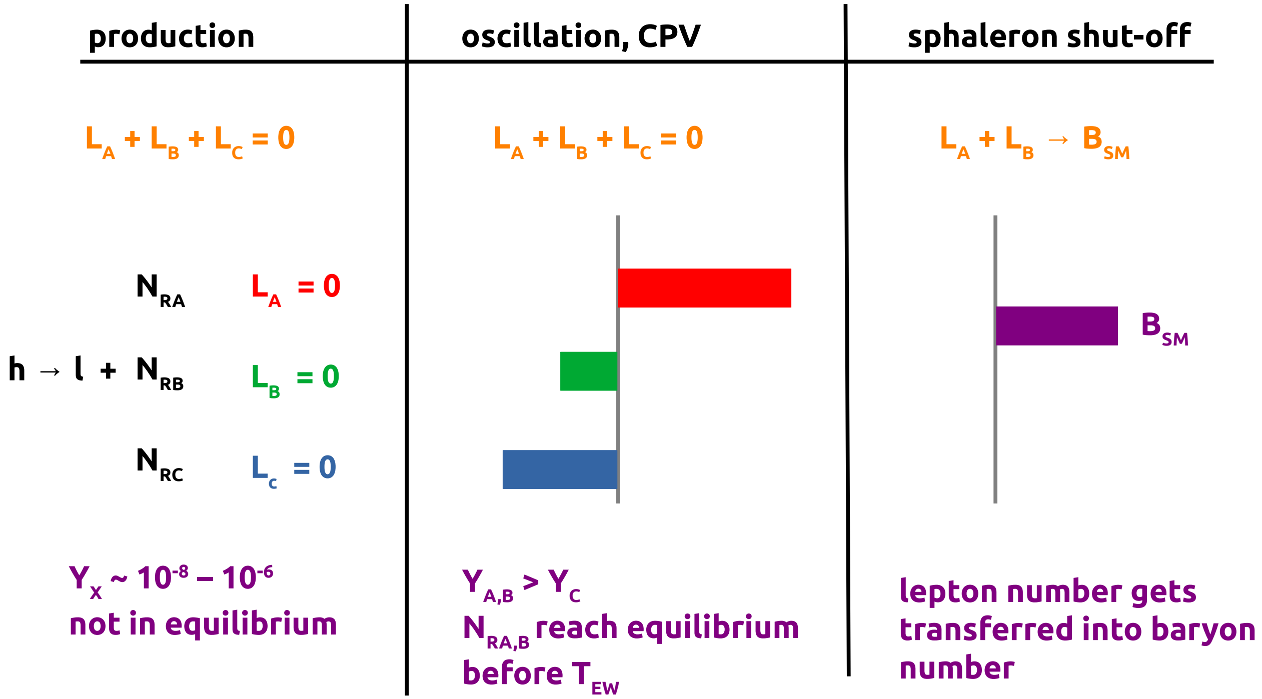
Possible realisations of Sakharov's conditions

Sakharov condition	realisation I	realisation II	realisation III
1. C and CP violation	**+ a new source of CPV**		
2. B violation	**SM sphalerons** active above T_{EW} > 175 GeV  $\Delta B = \Delta L = 3$ B+L violation, B-L conservation	**new B-L violating source** • baryogenesis • baryogensis via leptogenesis	
3. Out of equilibrium	**Strong first order phase transition** 	**oscillations** 	**Out-of-equilibrium decay** 

Leptogenesis.

Leptogenesis via oscillations

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

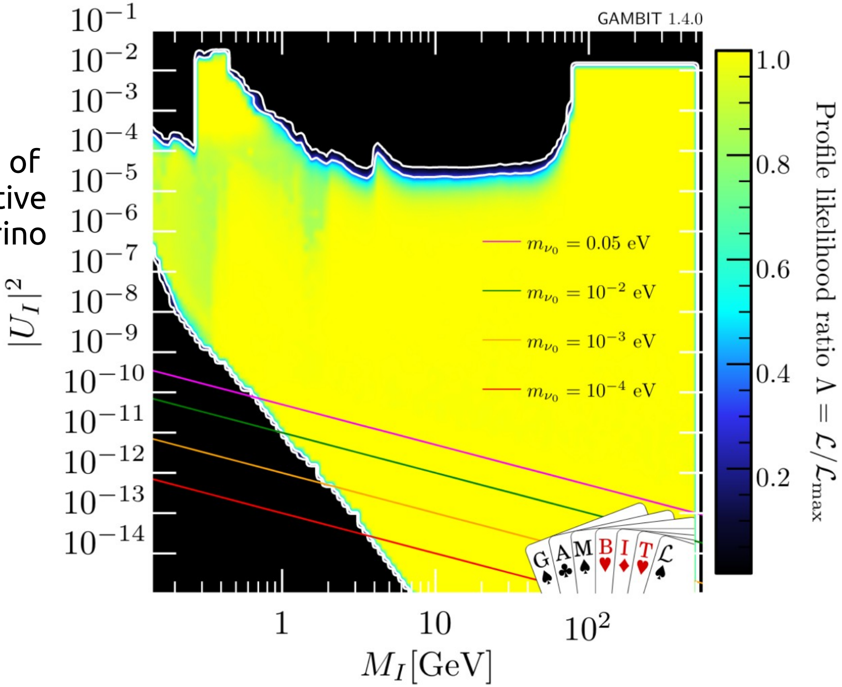


Akhmedov, Rubahkov, Shaposnikov (1998)

Searching for right-handed neutrinos

Most comprehensive global fit of see-saw I with three right-handed neutrinos with GAMBIT

mixing of sterile to active neutrino



mass of sterile neutrino

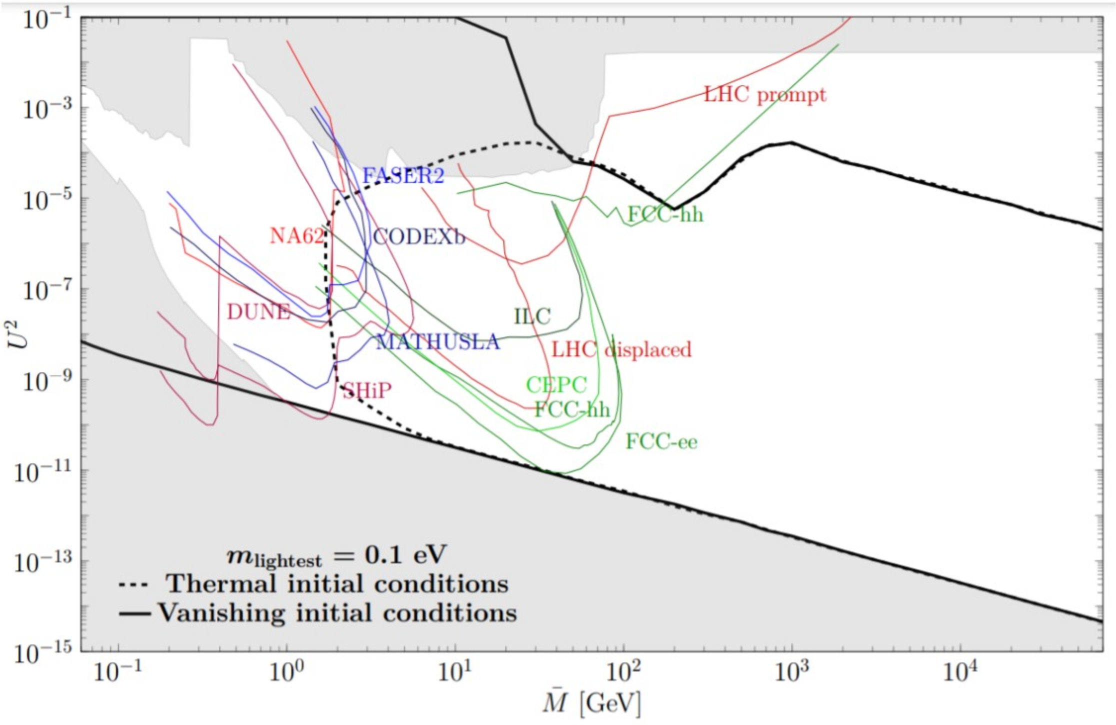
Combining in a rigorous statistic manner:

- electroweak precision data
- active neutrino mixing
- direct and indirect searches
- neutrinoless double beta decay

Chrzaszcz, Drewes, Gonzalo, JH, Krishnamurthy, Weniger (2020)

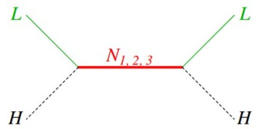
Leptogenesis via oscillations

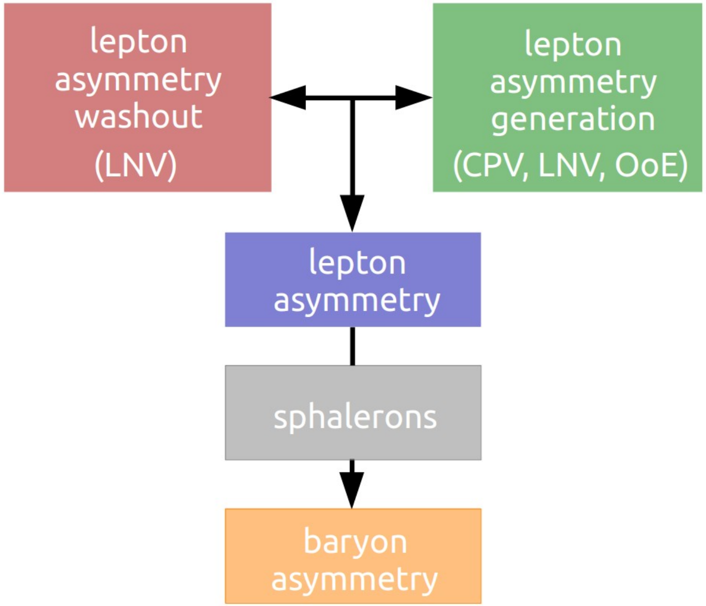
For **N=3** RHNs, parameter space allows for successful leptogenesis via the ARS mechanism:

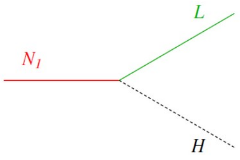


Drewes, Georis, Klaric 2021

High-scale leptogenesis

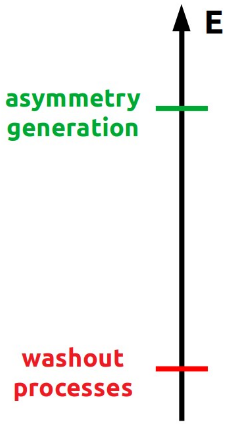






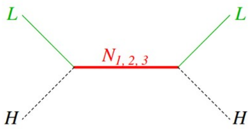
expected at high scales in order to comply with neutrino masses

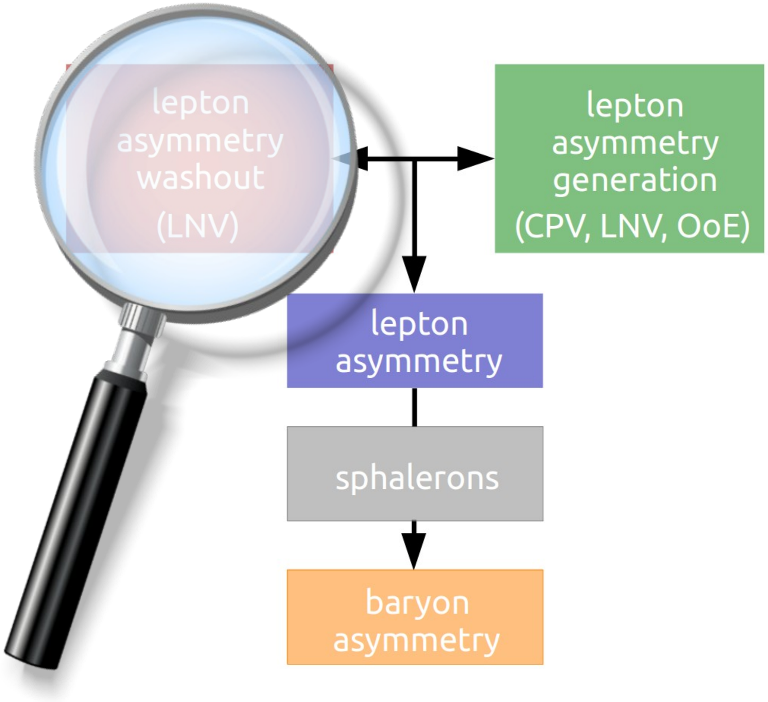
(**Davidson-Ibarra bound**)

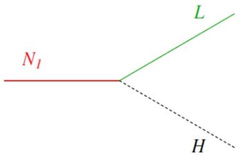


Fukugita, Yanagida (1986)
and many more afterwards...

High-scale leptogenesis

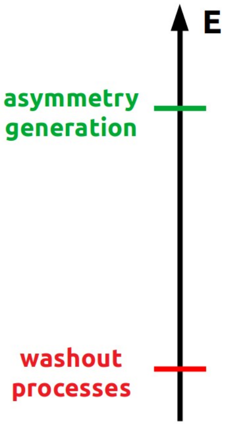






expected at high scales in order to comply with neutrino masses

(**Davidson-Ibarra bound**)



Strong washout:

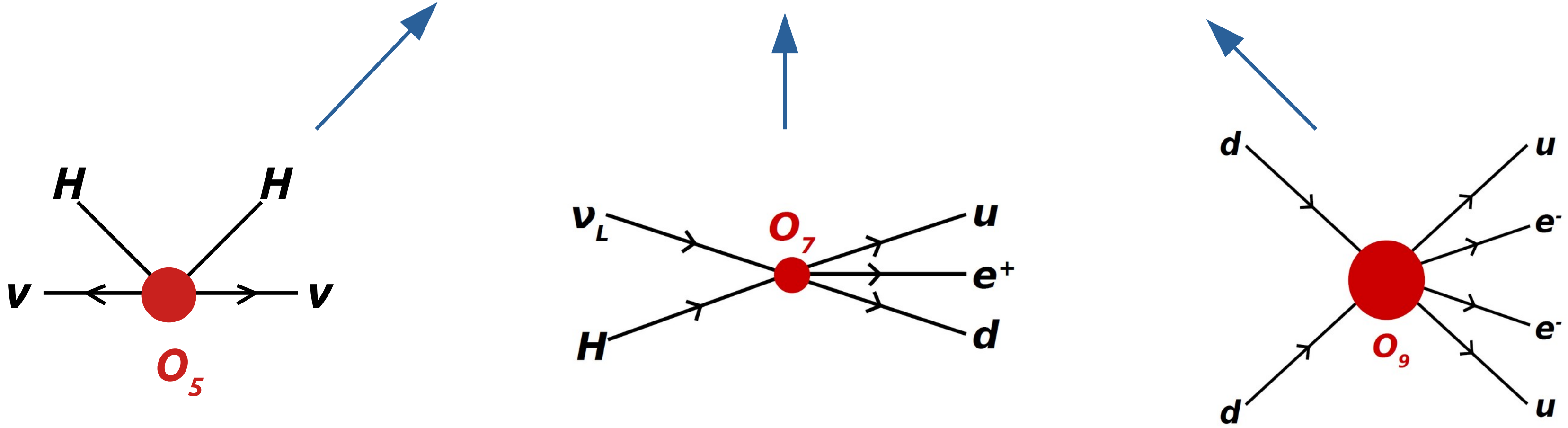
$$\frac{\Gamma_W}{H} > 1$$

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

Lepton number violation

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

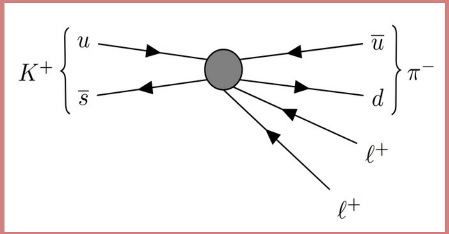
$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda_1}\mathcal{O}_1^{(5)} + \sum_i \frac{1}{\Lambda_i^3}\mathcal{O}_i^{(7)} + \sum_i \frac{1}{\Lambda_i^5}\mathcal{O}_i^{(9)} + \cdots$$



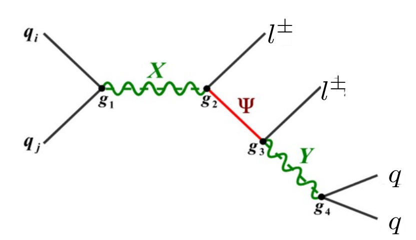
See surveys of all LNV operators up to dim-11 e.g. in Babu, Leung (2001), Gouvea, Jenkins (2008), Graf, JH, Deppisch, Huang (2018)

Probing lepton-number violating processes

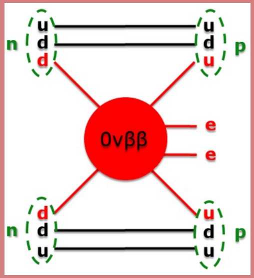
Meson decays



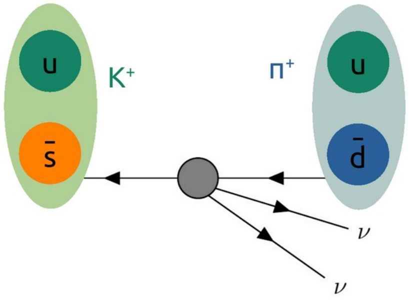
LHC searches



Neutrinoless double beta decay



Constraining lepton number violation with meson decays



Golden Channel

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu})_{\mathrm{SM}} = \left(8.5^{+1.0}_{-1.2}\right) \times 10^{-11}$$

Buras, Buttazzo, Girrbach-Noe, Knegjens (2015)

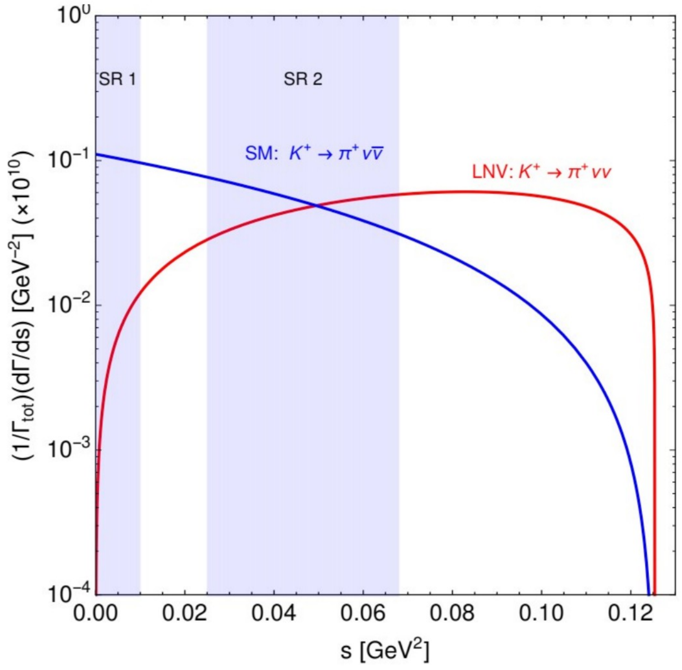
NA62 aims for SM precision!

- **SM**, lepton number **conserving vector** current

$$\mathcal{L}_{\mathrm{SM}}^{K\to\pi\nu\bar{\nu}} = \frac{1}{\Lambda_{\mathrm{SM}}^2} \left(\bar{\nu}_i \gamma^\mu \nu_i\right) \left(\bar{d}\gamma_\mu s\right)$$

- **BSM**, lepton number **violating scalar** current

$$\mathcal{L}_{\mathrm{BSM}}^{K\to\pi\nu\nu} = \frac{v}{\Lambda_{\mathrm{BSM}}^3} \left(\nu_i \nu_j\right) \left(\bar{d}s\right)$$



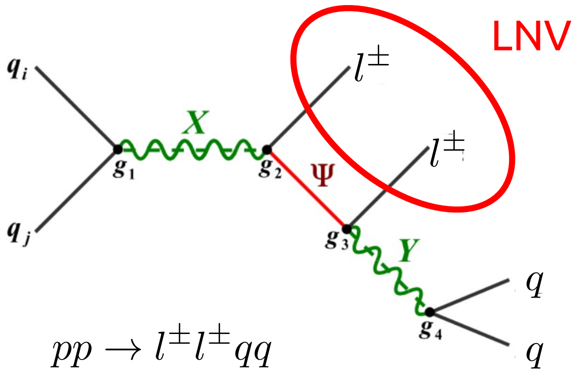
$$s = (E_K - E_\pi)^2$$

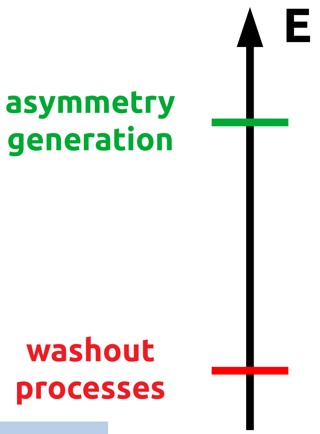
Potential to disentangle LNV and LNC due to kinematics at NA62!

Deppisch, Fridell, JH (2020)

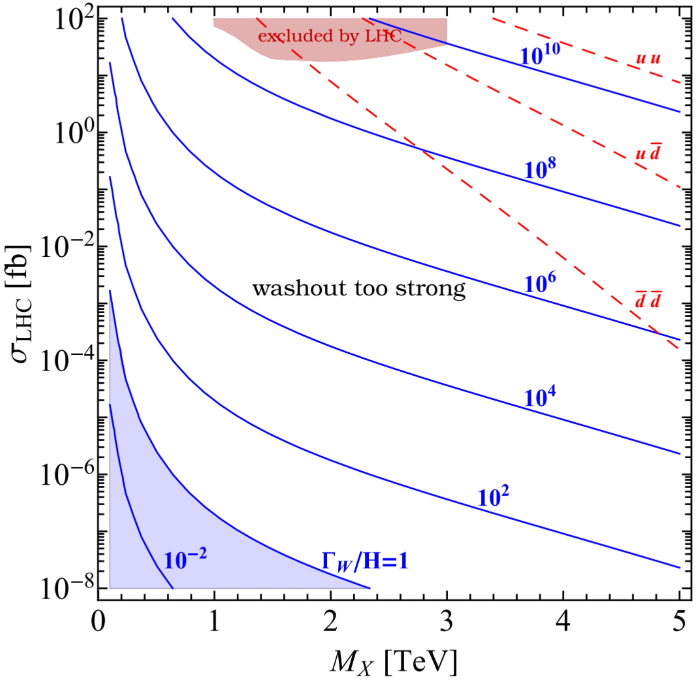
Probing leptogenesis at the LHC

Washout processes could be observable at the LHC





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

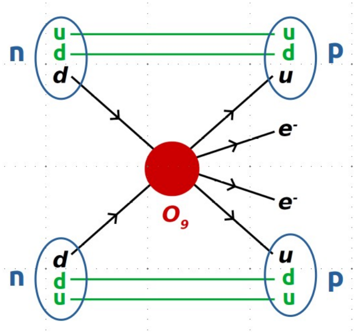


Observation of any washout process at LHC would put high-scale baryogenesis under tension!

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

Deppisch, JH, Hirsch (2014)

Probing leptogenesis with 0νββ decay



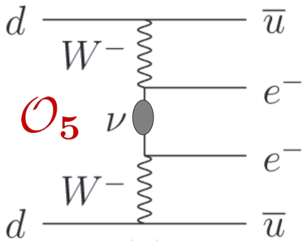
$$T_{1/2}^{-1} = |\,\epsilon_\alpha^\beta\,|^2 G^{0\nu}\,|\,M^{0\nu}\,|^2$$

particle physics phase-space factor nuclear physics

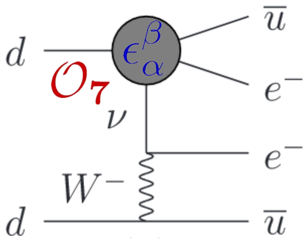
Experimental constraints: $T_{1/2}^{0\nu} > 1.07 \times 10^{26}\text{yr}\ 90\%\text{C.L.}$ KamLAND-Zen (2016)

Possible contributions:

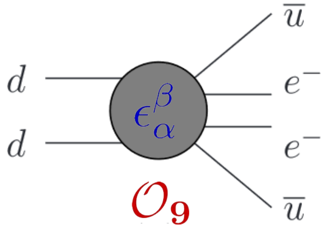
standard mass mechanism



long range contribution



short range contribution



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)

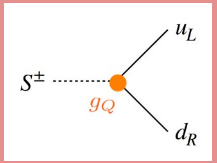
Probing leptogenesis with TeV-scale LNV

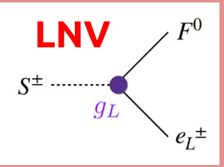
Right-handed neutrino interactions ("standard thermal LG"):

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

Additional TeV-scale interactions

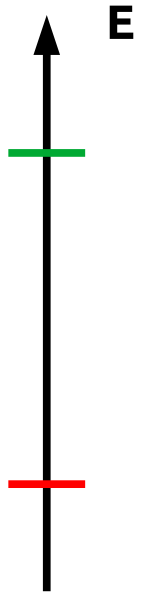
$$\tilde{\mathcal{L}} \supset g_Q \overline{Q} S d_R + g_L \overline{L}(i\tau^2) S^* F - m_S^2 S^\dagger S - \frac{m_F}{2} \overline{F^c} F + \lambda_{HS} (S^\dagger H)^2 + \text{h.c.}$$





high-scale source of lepton asymmetry

TeV-scale LNV "washout" interactions

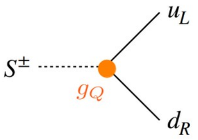


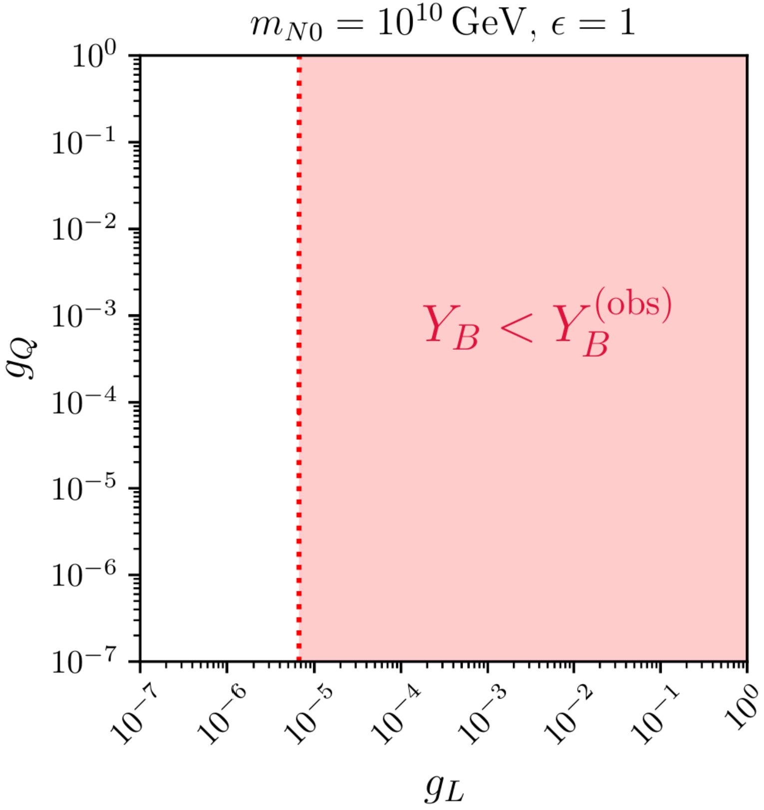
Can TeV-scale LNV destroy the generated asymmetry from standard thermal LG?

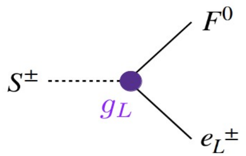
JH, Ramsey-Musolf, Shen, Urrutia-Quiroga (2021)

Implications on leptogenesis

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



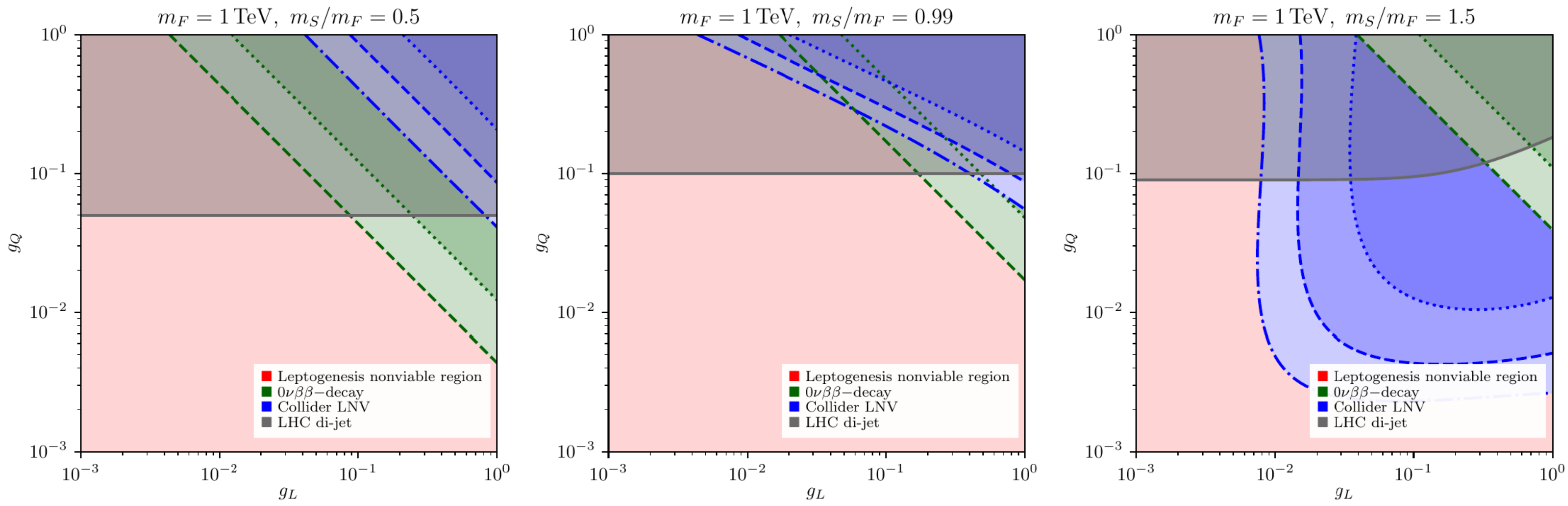




Low-scale LNV destroys lepton asymmetry previously generated by standard LG scenario.

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

Impact & interplay of LHC & 0νββ decay on leptogenesis



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

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

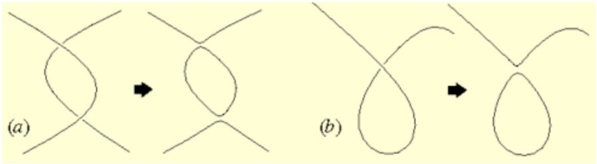
JH, Ramsey-Musolf, Shen, Urrutia-Quiroga (2021)

Probing leptogenesis with gravitational waves

NanoGrav – pulsar timing array:

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

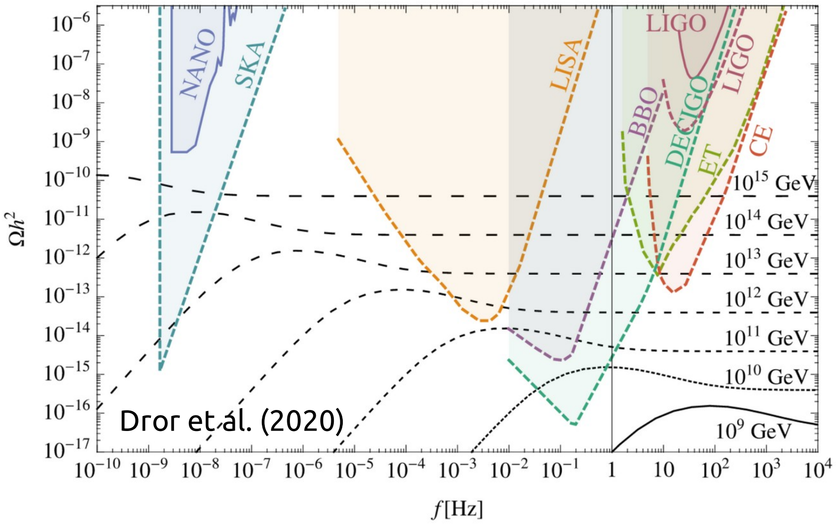
Hints for a cosmic string network in the early Universe emitting a stochastic gravitational wave background?



Probing leptogenesis with gravitational waves

NanoGrav: Sign of cosmic strings?

$$\Delta\mathcal{L} = -\left[y^{\rm D}_{i\alpha}\,\overline{N^{\rm R}_i}\,\tilde{H}^\dagger L_\alpha + \frac{1}{2}\,y^{\rm M}_i\,\Phi\,\overline{N^{\rm R}_i}\,\left(N^{\rm R}_i\right)^{\rm C} + {\rm H.c.}\right] - \left[\lambda_\phi\left(|\Phi|^2 - \frac{1}{2}\,v^2_{B-L}\right)^2 + \lambda_{\phi h}\,|\Phi|^2\,|H|^2\right].\ \ (\text{:}$$



Stochastic gravitational wave spectrum depends on

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

$$\mu \sim v^2$$

cosmic string tension

$U_{B\text{-}L}$-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

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

freeze-in / wash-in leptogenesis

gravitational waves

gravitational leptogenesis

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

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)

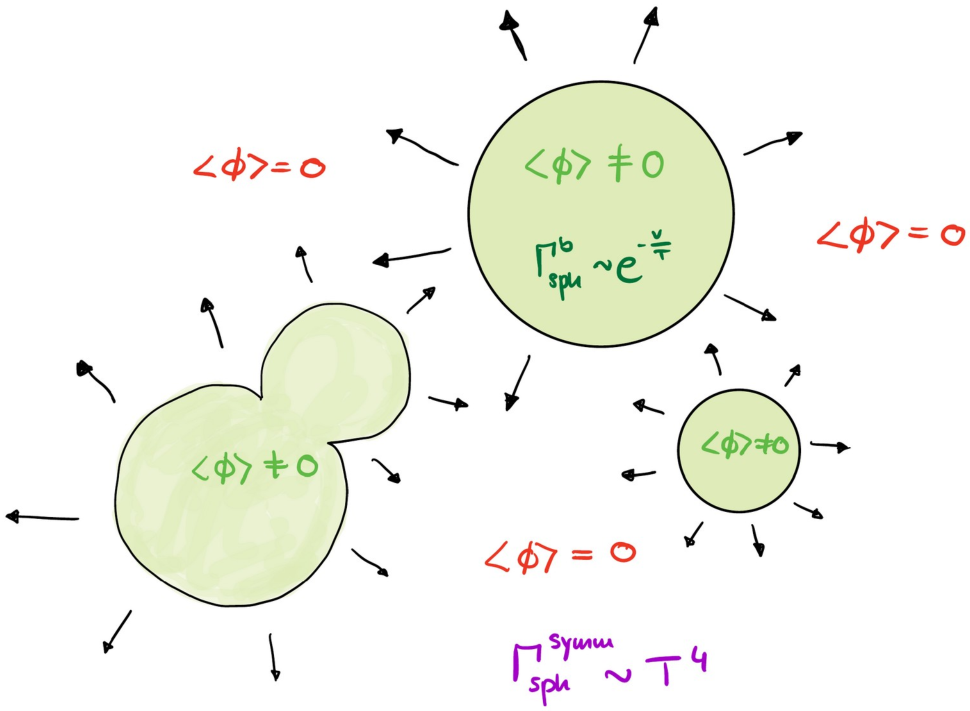
light RHNs → ShiP, meson decays, LHC

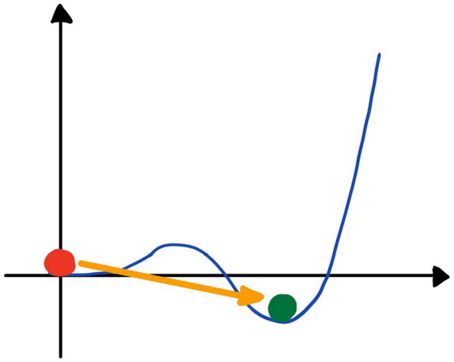
→ See review "Probing leptogenesis" (arxiv:hep-ph/1711.02865)

Baryogenesis.

Concept of electroweak baryogenesis

Asymmetry generation via strong first order phase transition (SFOPT).





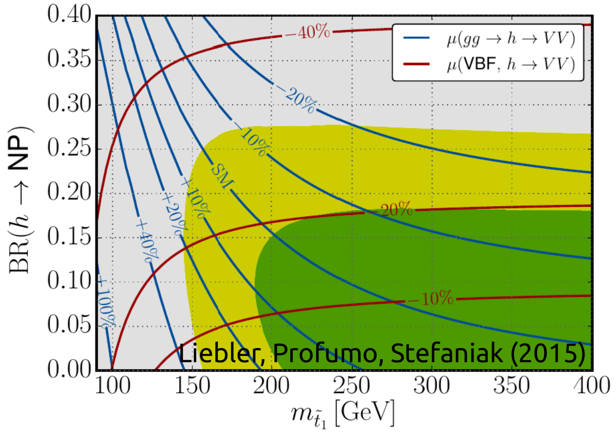
Unfortunately, Higgs boson is too heavy for EWBG.

Electroweak baryogenesis due to 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….

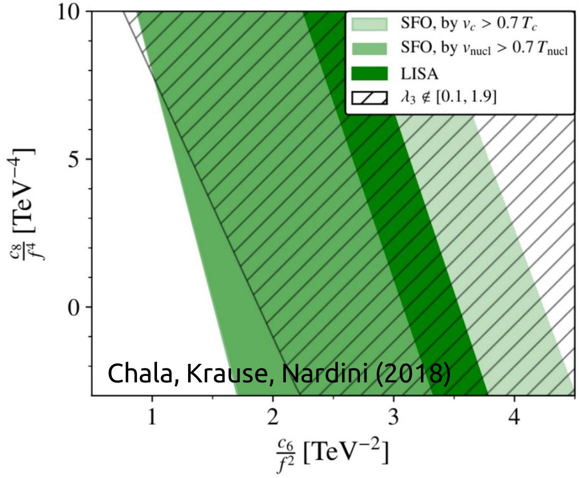


- **Now: going beyond with general extended scalar sectors**

- **General difficulties:**
  - Constraints from EDMs
  - Higgs physics sets stringent constraints

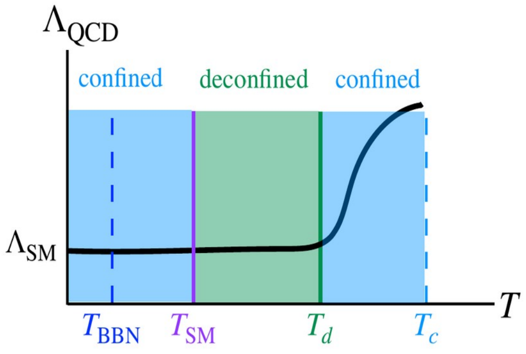
→ Interplay between colliders and gravitational wave frontier

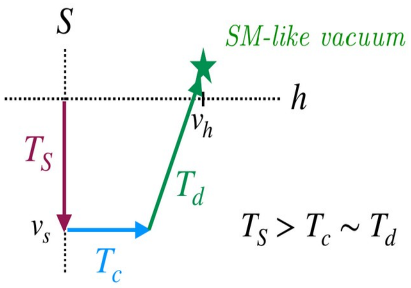
$$L = L_{\text{SM}} + \frac{c_6}{f^2}(\phi^\dagger\phi)^3 + \frac{c_8}{f^4}(\phi^\dagger\phi)^4$$

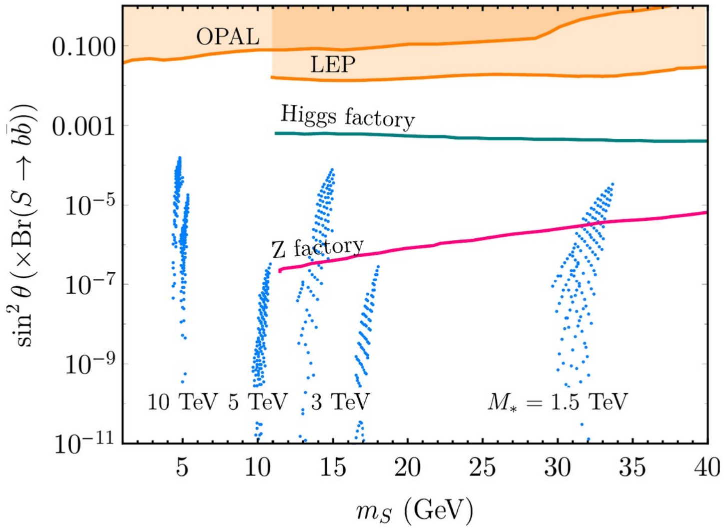


Baryogenesis via strong QCD phase transition

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.

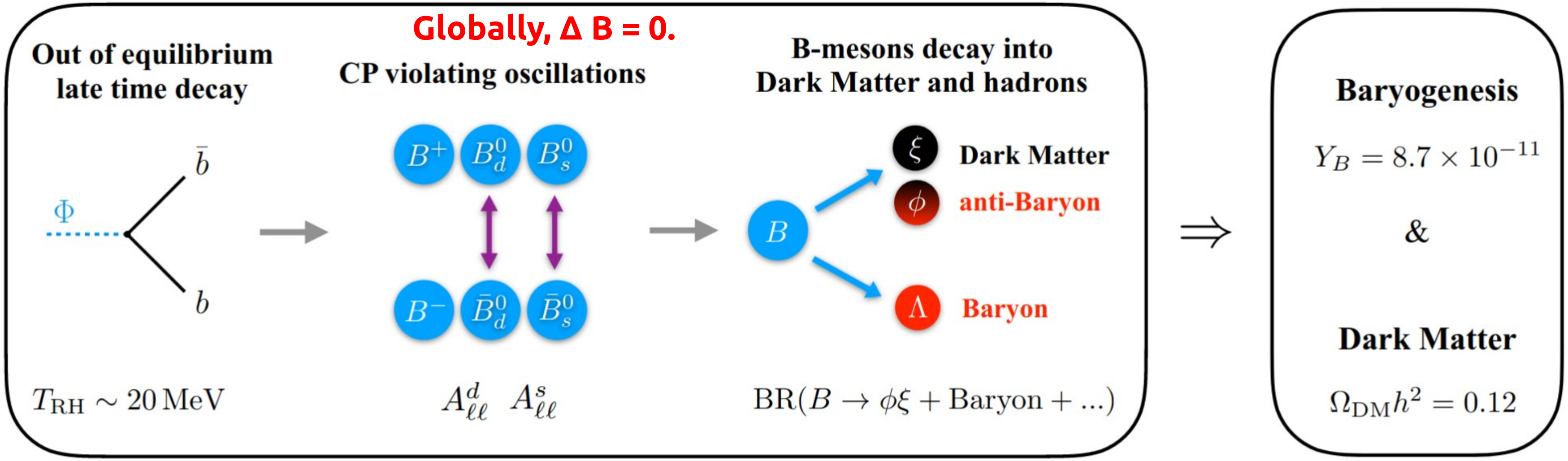
Introduce new scalar field S that perturbs the potential.

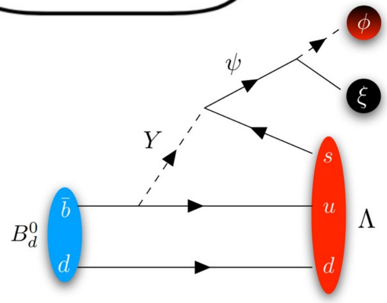
Testable light states predicted.

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

Baryogenesis via meson oscillations

Asymmetry generation via oscillations – a testable low-scale mechanism.





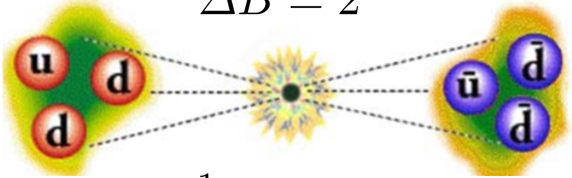
Testable scenario at Belle-II and BarBar!

Elor, Escudero, Nelson (2019+)
and several follow-up works

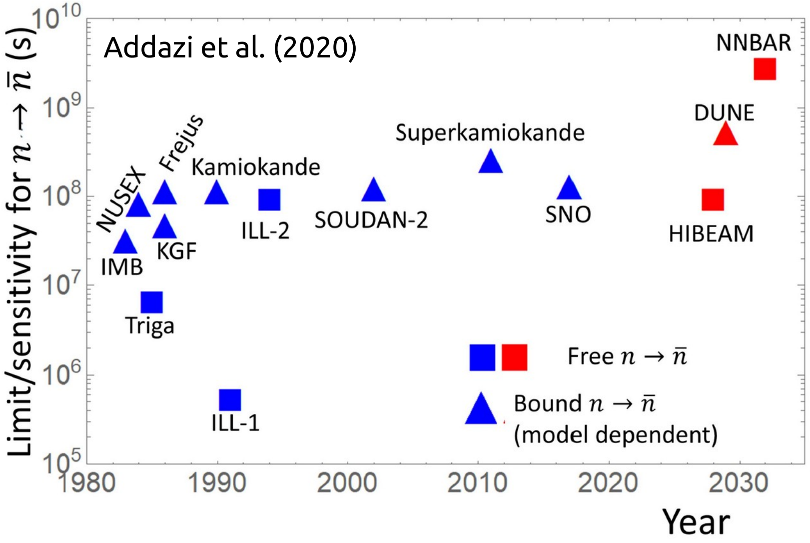
Promising interface to $n\bar{n}$ oscillations

Unambiguous test for baryon number violation.

$$\Delta B = 2$$



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

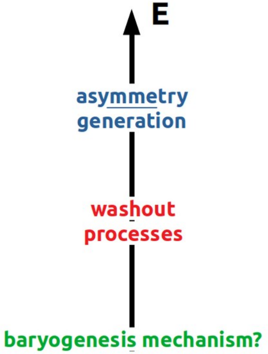


Future sensitivity to new physics: $\Lambda_{\rm NP} > 10^6\,{\rm GeV}$

In case of observation:

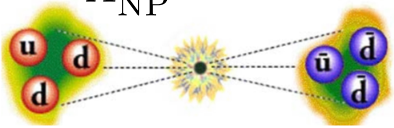
Case 1: Possible low-scale washout process (BNV, no CPV)

Case 2: Possible connection to asymmetry generation mechanism (BNV, CPV, OoE)



CPC effective $n\bar{n}$ operator

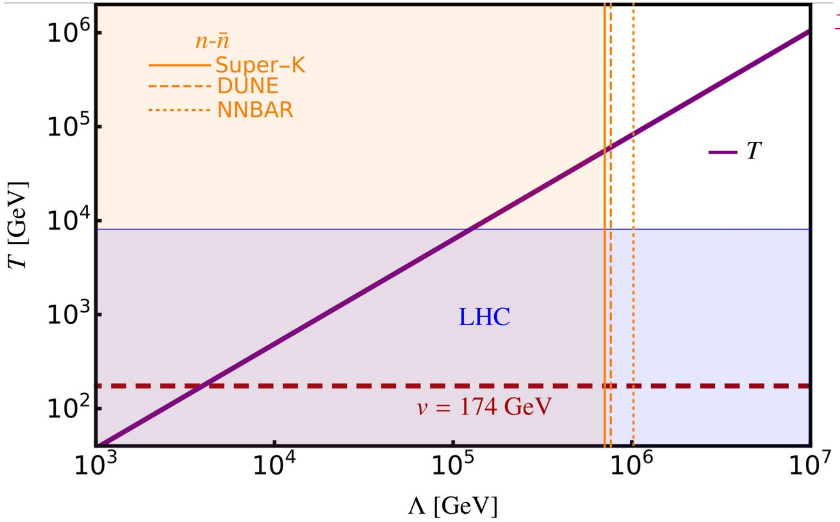
$$\frac{1}{\Lambda_{\rm NP}^5} uddudd$$



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.



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

E

asymmetry generation

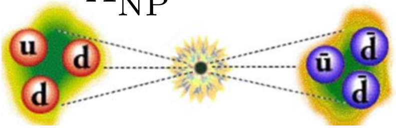
washout processes

baryogenesis mechanism?

Fridell, JH, Hati (2021)

CPC effective $n\bar{n}$ operator

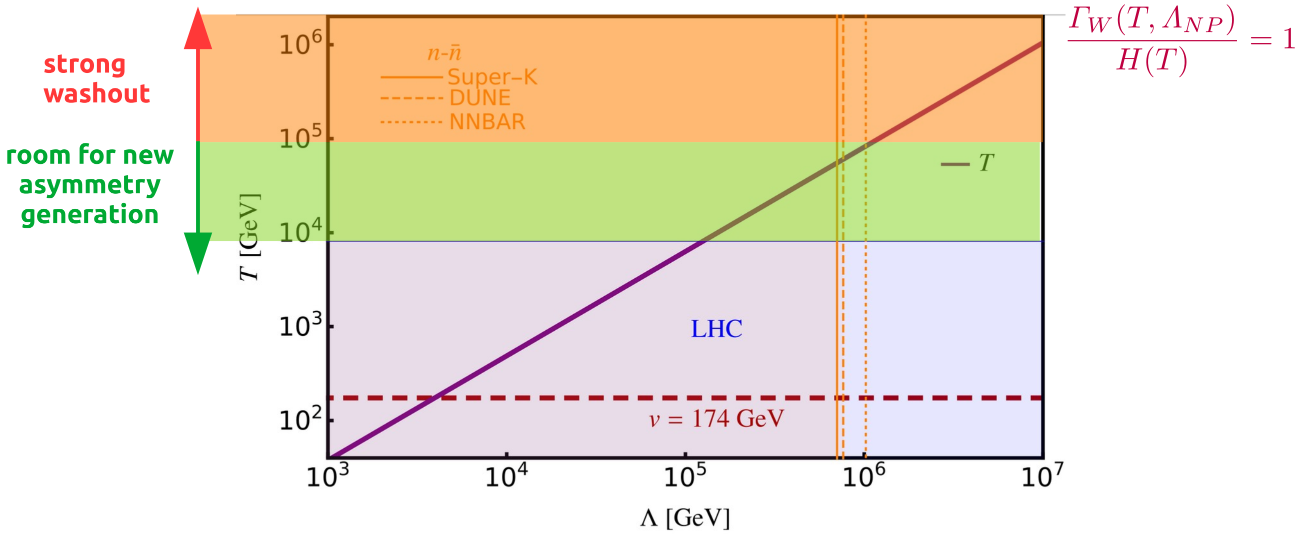
$$\frac{1}{\Lambda_{\rm NP}^5}\,uddudd$$

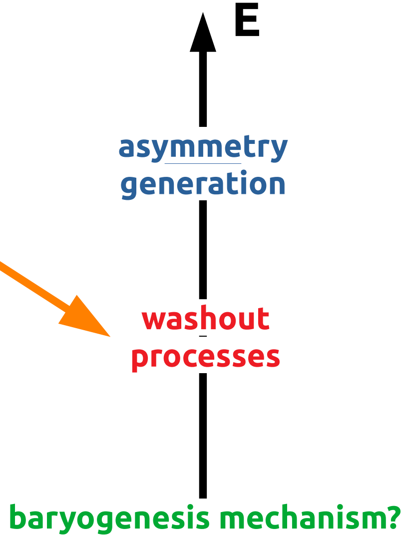


Observation of neutron-antineutron oscillations at $\Lambda_{\rm NP}$

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

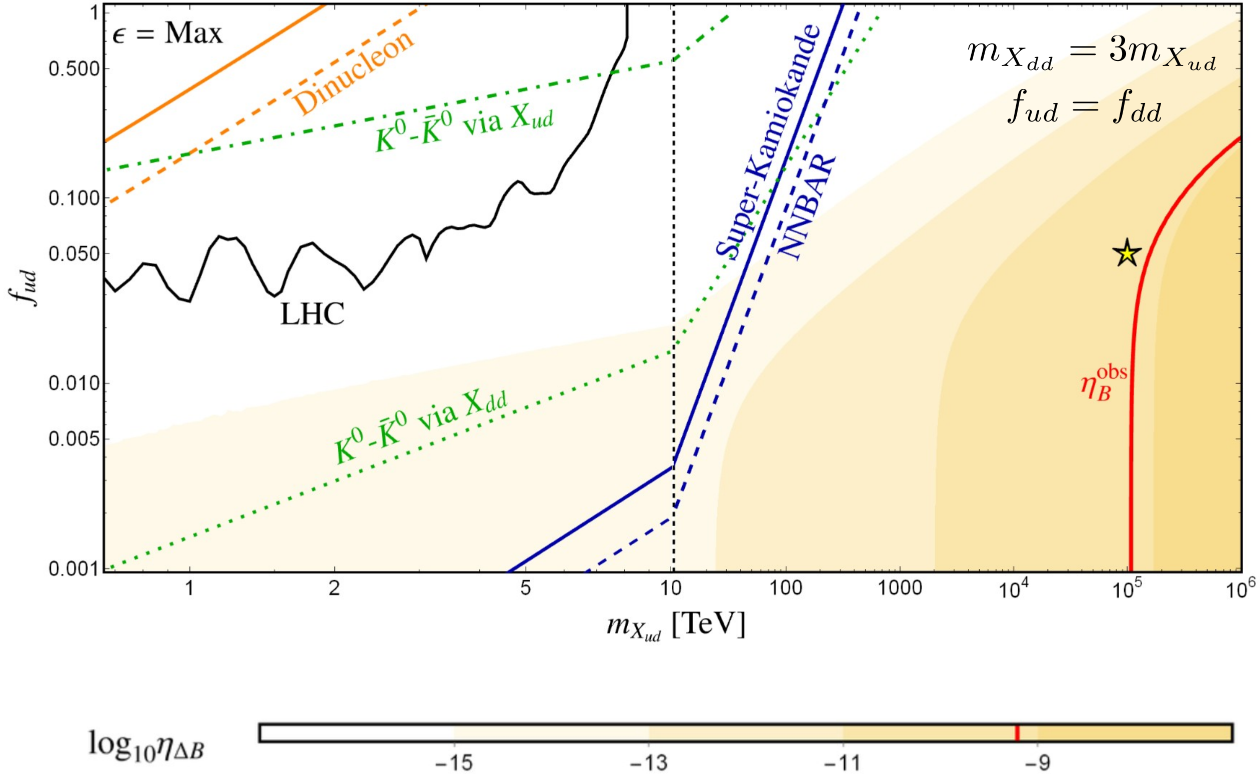
Identify scale T above which the washout rate is large enough to wipe out a previously generated asymmetry.

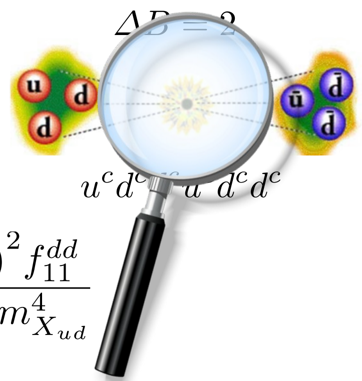




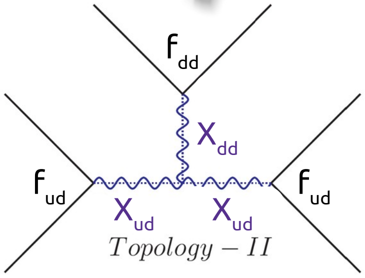
Fridell, JH, Hati (2021)

CPV effective $n\bar{n}$ operator





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



For studies on topology I see

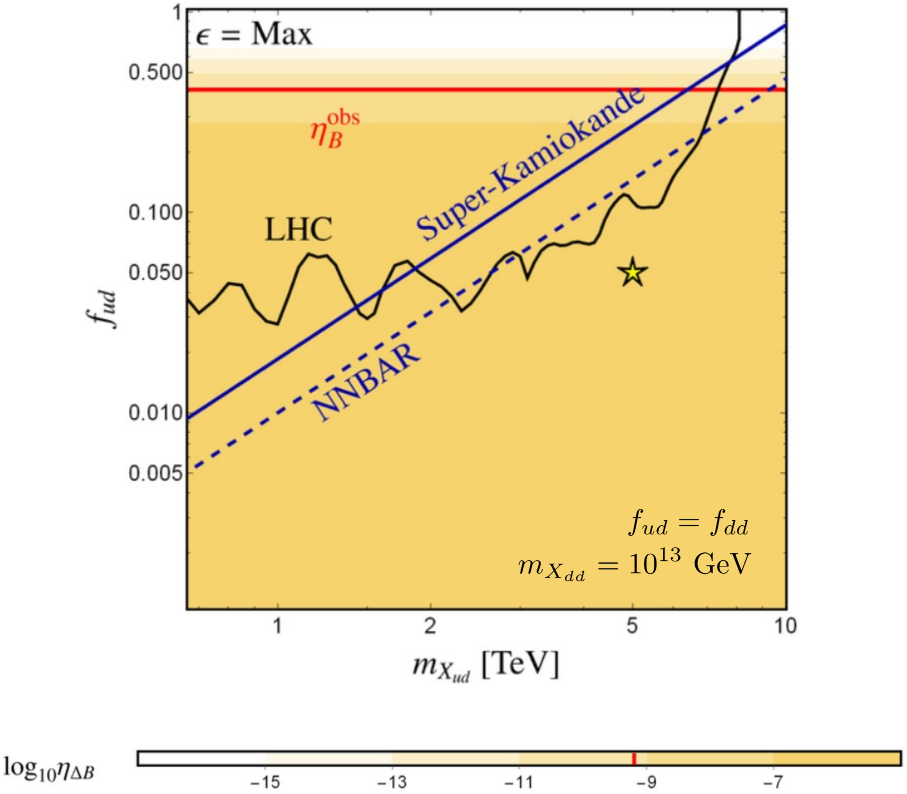
Grojean et al. (2019)

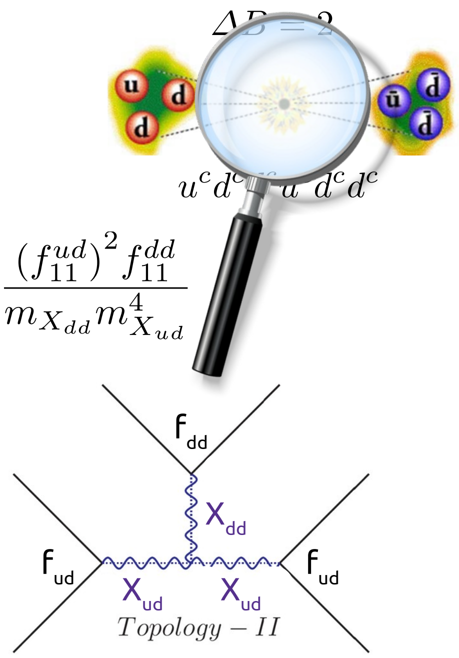
For related studies on topology II see

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

Fridell, JH, Hati (2021)

CPV effective $n\bar{n}$ operator



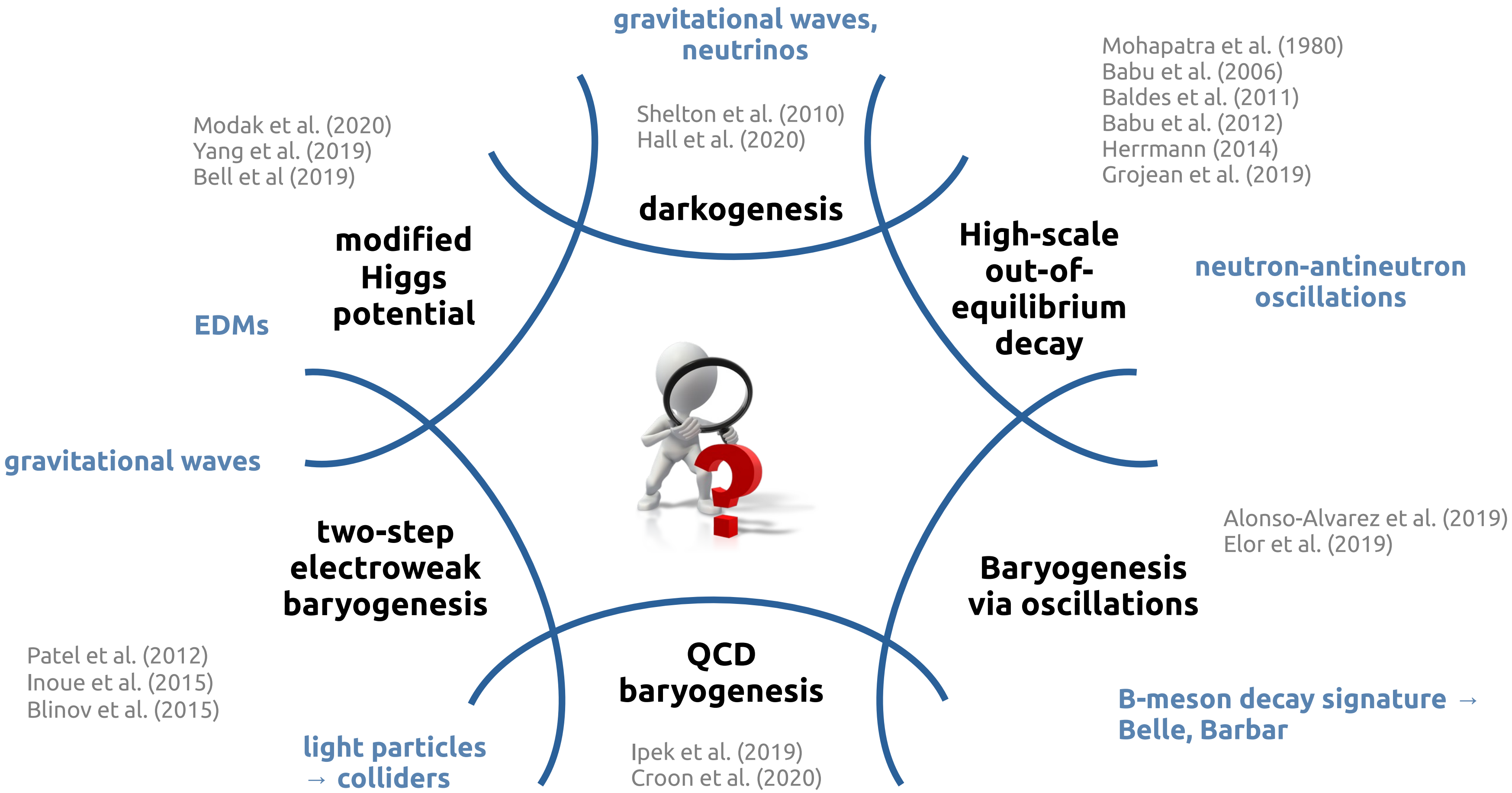


$$C_1 \approx \frac{(f_{11}^{ud})^2 f_{11}^{dd}}{m_{X_{dd}} m_{X_{ud}}^4}$$

In case of observation, the combination of different experiments will help us to pin down the potential NP.

Fridell, JH, Hati (2021)

Overview of baryogenesis models



Example: FIMPs and their implications on baryogenesis

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

(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

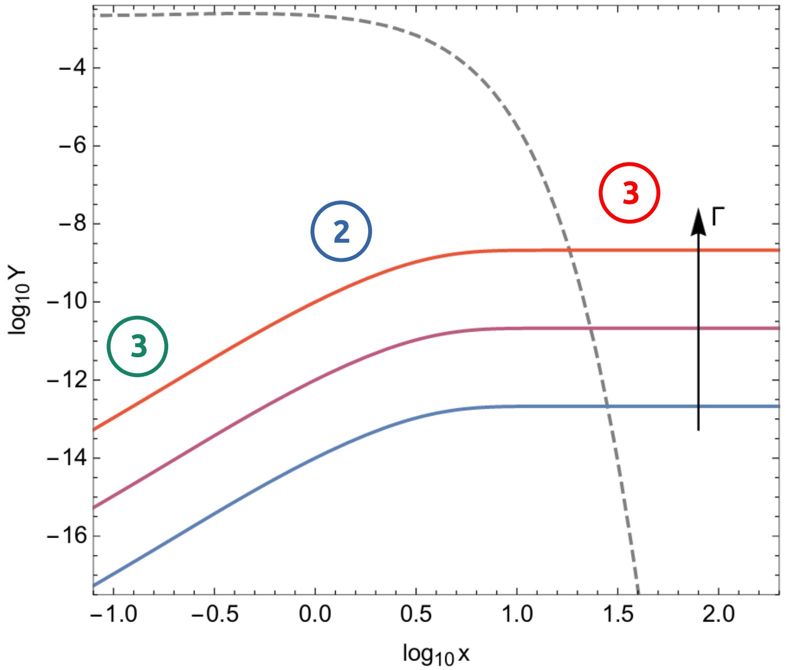
DM gets produced via decay of a heavier particle Y
that is in equilibrium with the SM bath $Y \to \mathrm{SM}\ \chi$

(3) Freeze-in

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

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

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

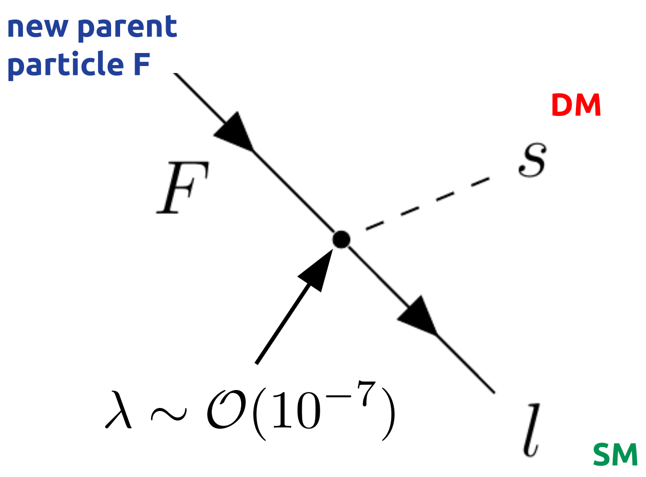


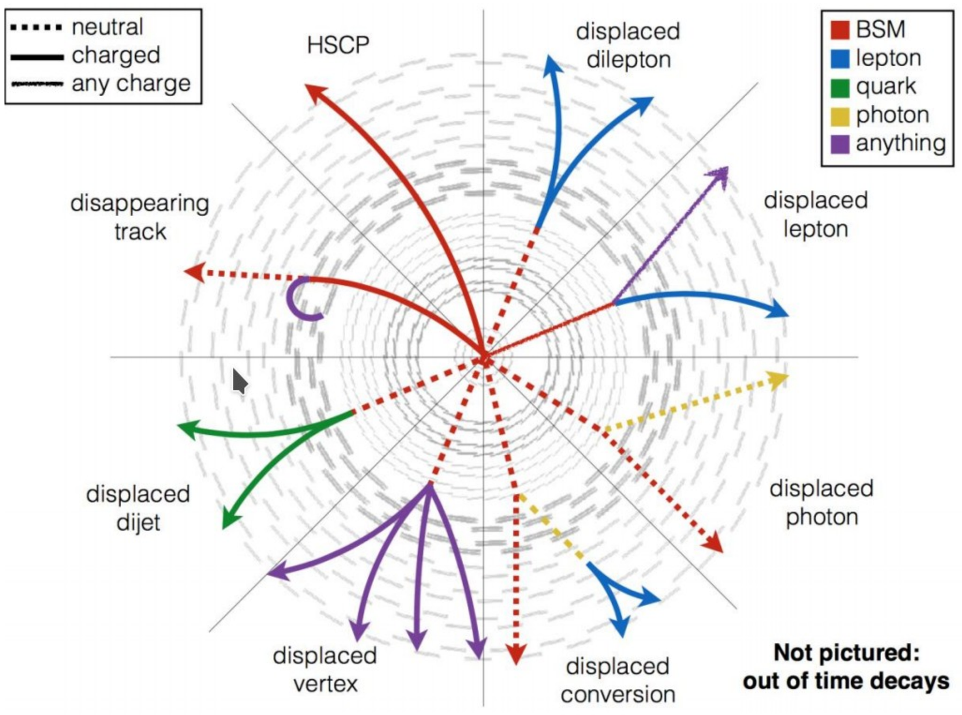
cooling down

$x = m_Y/T$

Example: FIMPs and their implications on baryogenesis

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



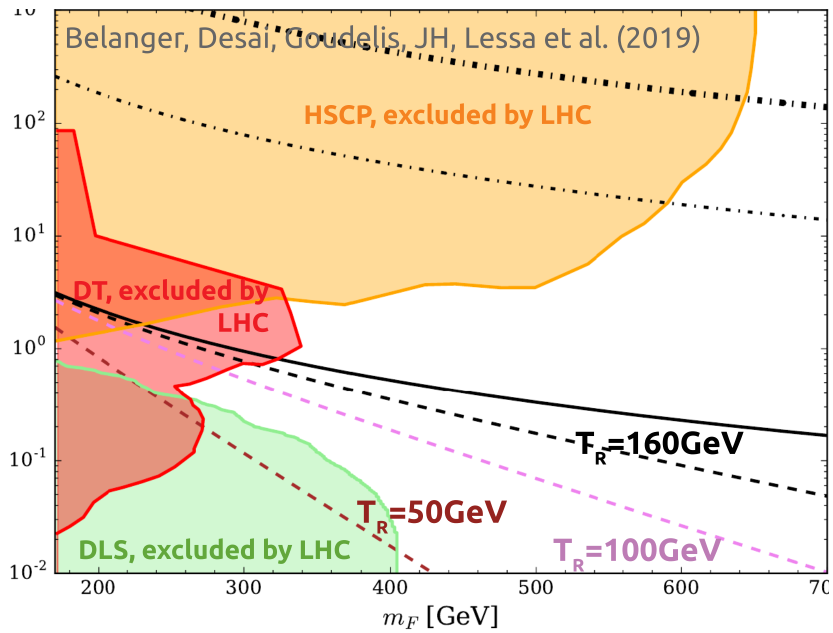


Example: FIMPs and their implications on baryogenesis

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 a small reheating temperature

Belanger, Desai, Goudelis, JH, Lessa et al. (2019)
also Calibbi, D'Eramo, Junius, Lopez-Honorez, Mariotti (2021)

Conclusions

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

- **Strong complementarity of different probes**
  LNV: LHC, 0νββ 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 comprehensive overview see SNOWMASS white papers:
→ arxiv:2203.05010 [hep-ph]
→ arxiv:2203.07059 [hep-ph]

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

Thank you for your attention!

Why do we need new physics?

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

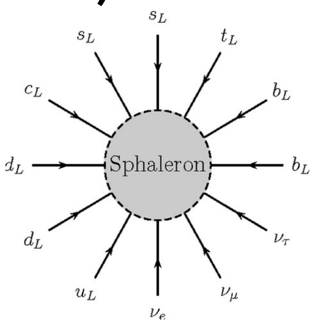
SM?

baryon number violation

SM sphaleron interactions

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

highly active above T_{EW}



$$J_\mu^B = \frac{1}{3}\sum_i \left(\overline{q}_{Li}\gamma_\mu q_{Li} - \overline{u}_i^c\gamma_\mu u_i^c - \overline{d}_i^c\gamma_\mu d_i^c\right)$$

$$J_\mu^L = \sum_i \left(\overline{\ell}_{Li}\gamma_\mu \ell_{Li} - \overline{e}_i^c\gamma_\mu e_i^c\right)$$

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

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

Big Bang Nucleosynthesis

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

Deuterium Bottleneck

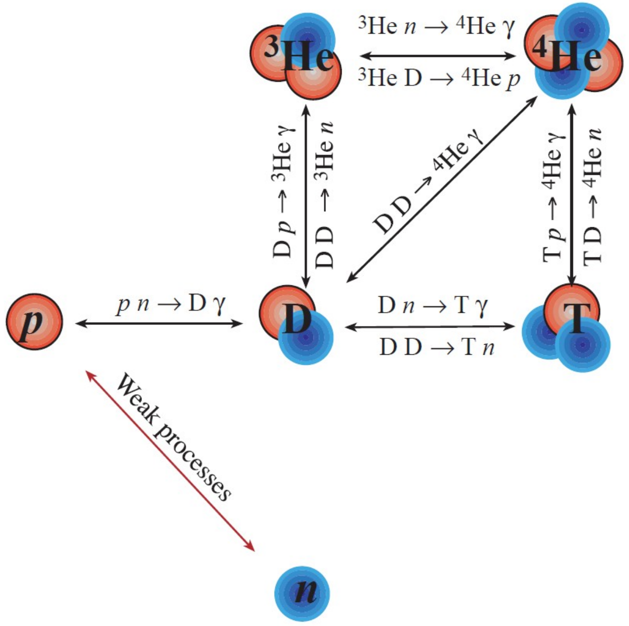
Nucleosynthesis starts with formation of Deuterium (D)

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

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

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

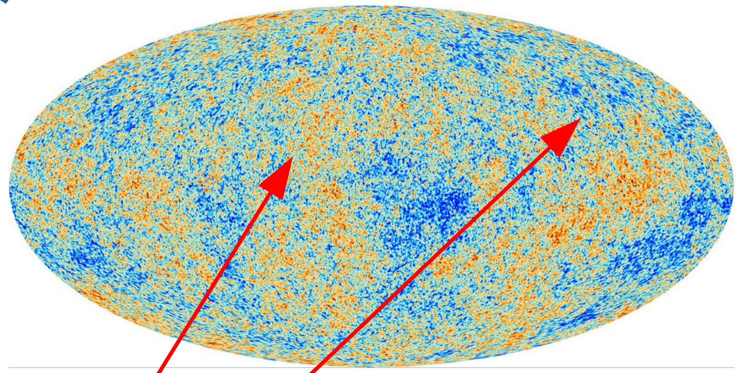
$$\eta_B^{\rm obs} = (6.143 \pm 0.190) \times 10^{-10}$$

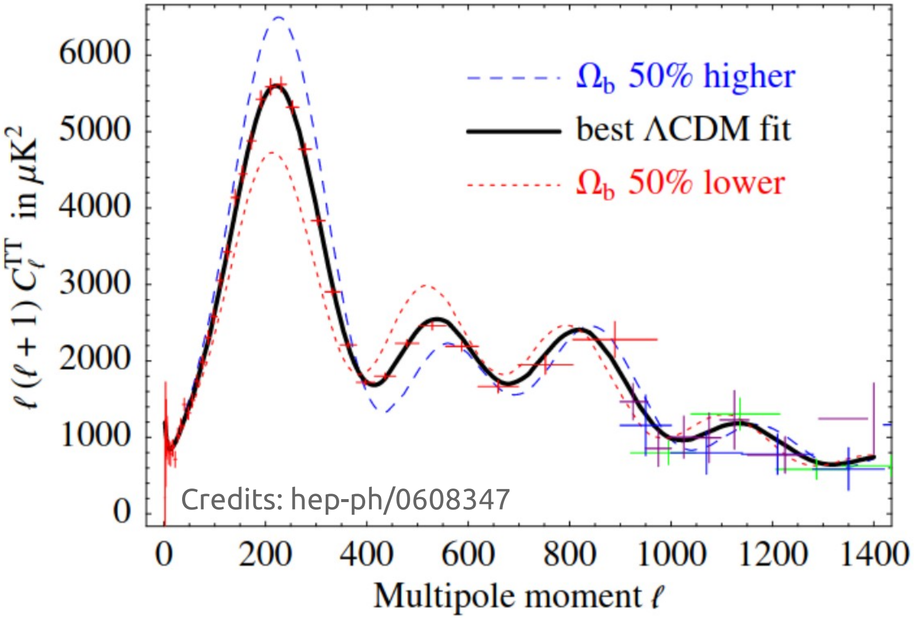


Credits: hep-ph/0608347

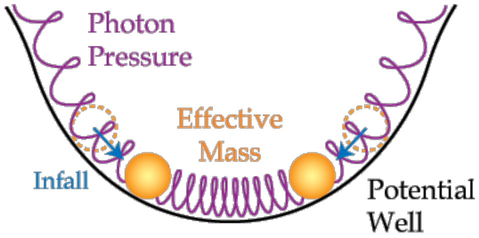
Cosmic Microwave Background (CMB)

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





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



Interface to the mystery of neutrino masses

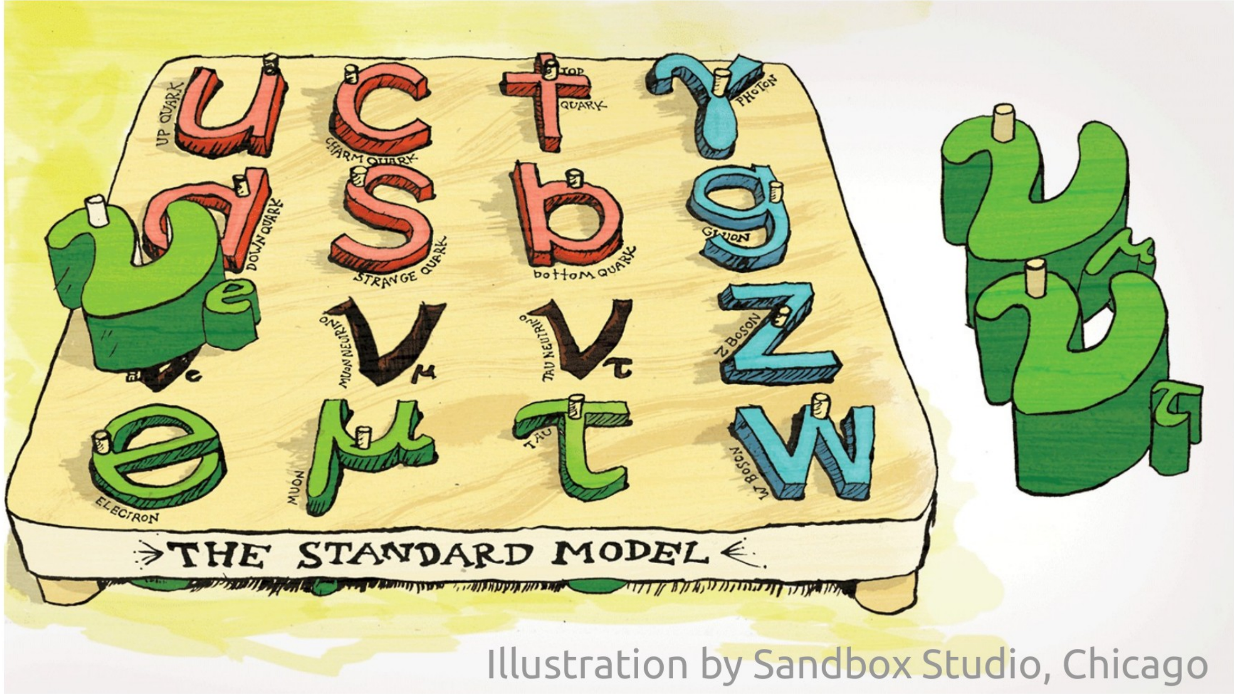
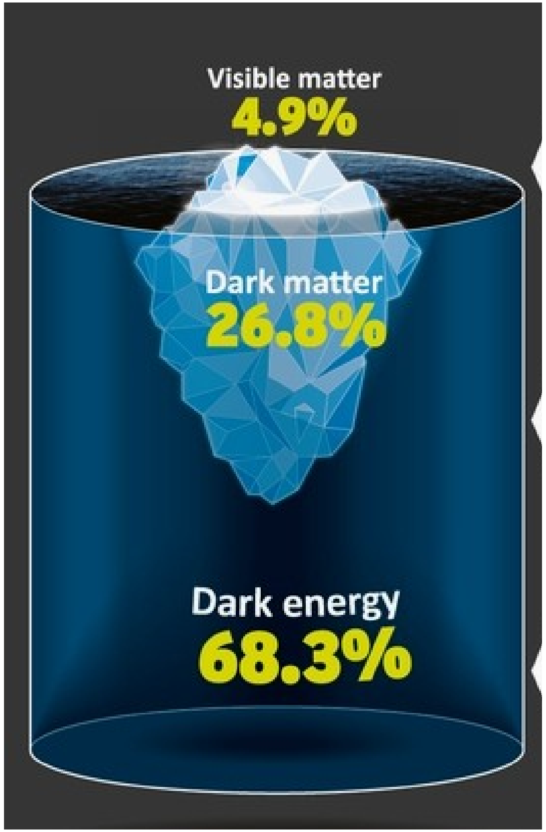
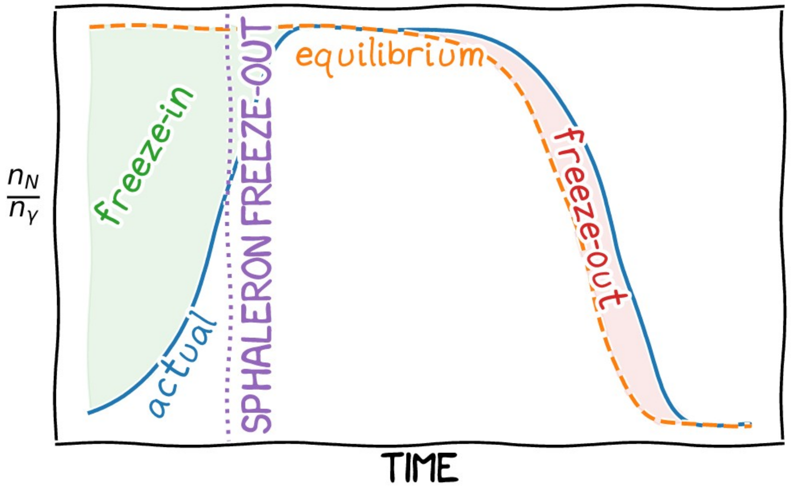


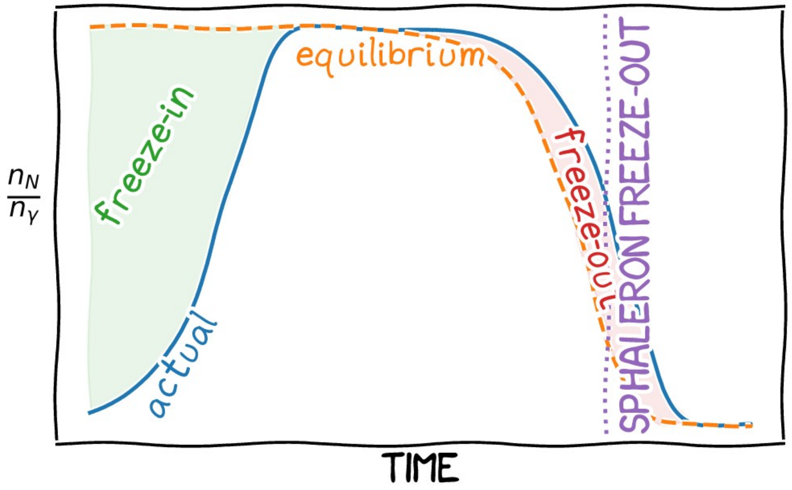
Illustration by Sandbox Studio, Chicago

Interface to the mystery of dark matter



Freeze-in vs freeze-out leptogenesis

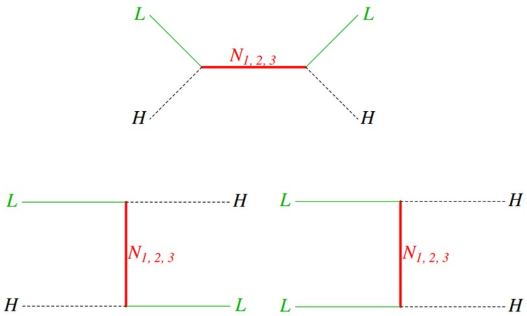


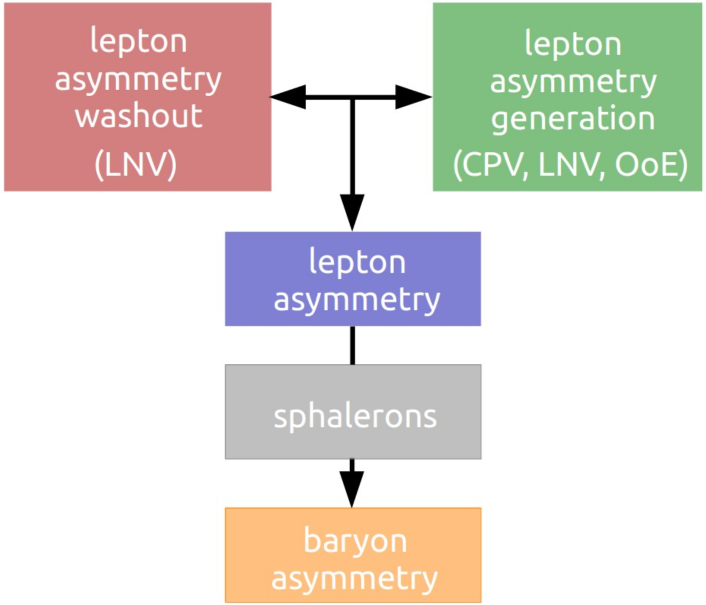


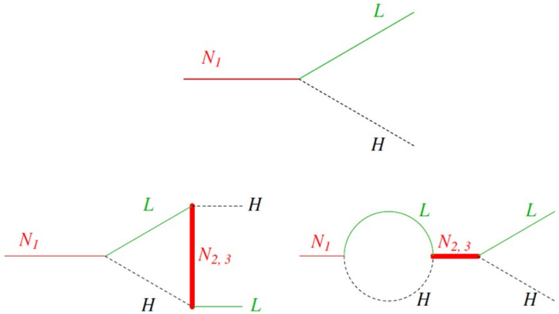
Combined analysis of both regimes and comparison with existing literature.

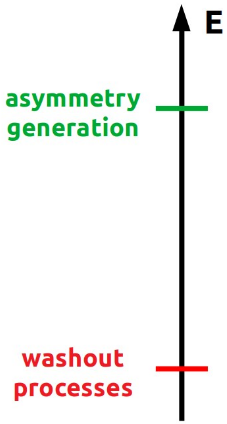
Klaric et al. 2021

High-scale leptogenesis







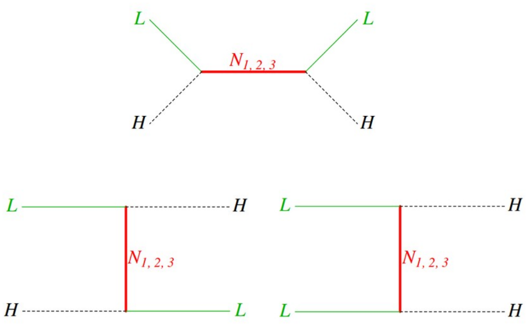


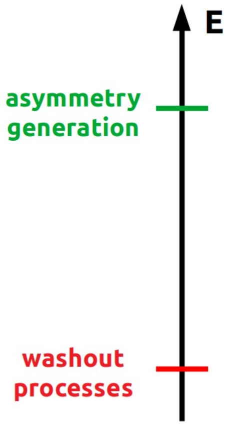
expected at high scales in order to comply with neutrino masses

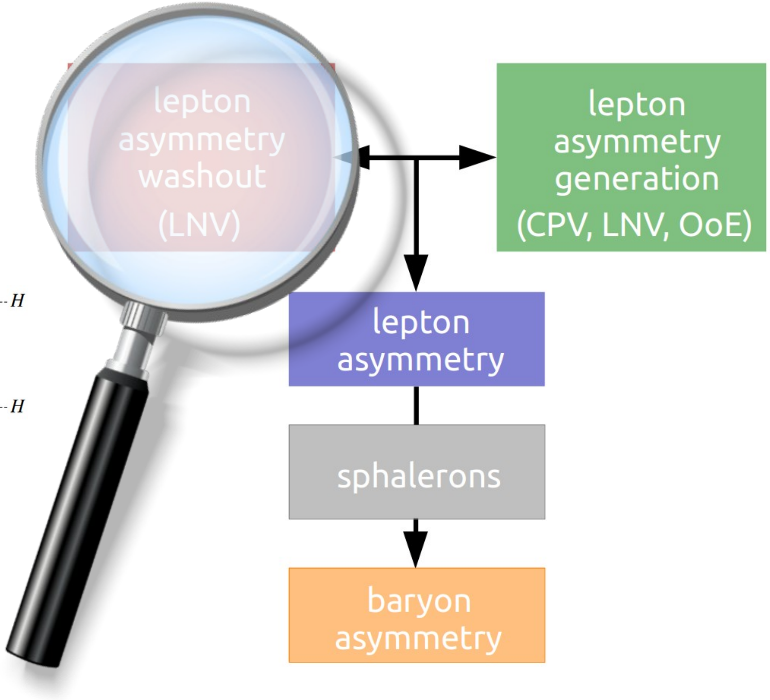
(**Davidson-Ibarra bound**)

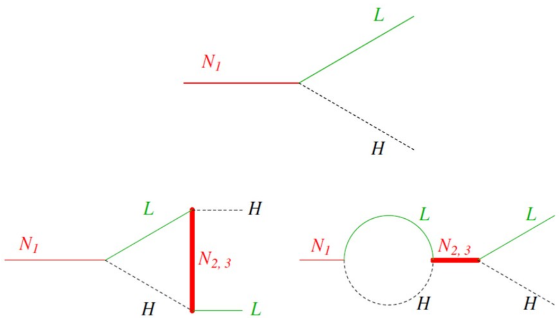
Fukugita, Yanagida (1986)
and many more afterwards...

High-scale leptogenesis









expected at high scales in order to comply with neutrino masses

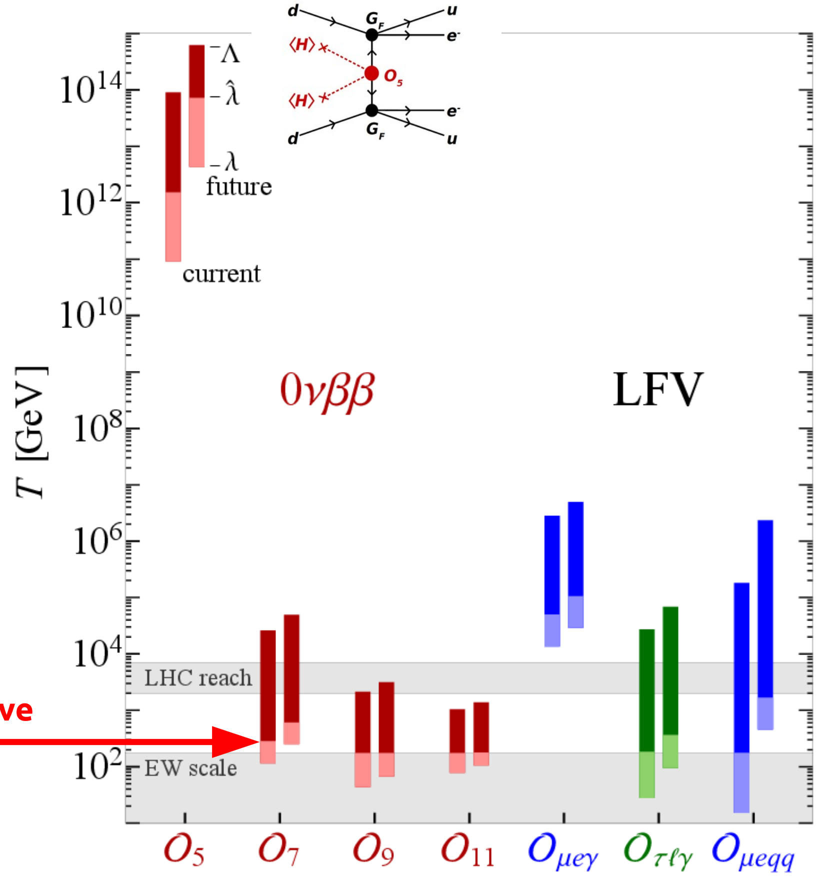
(**Davidson-Ibarra bound**)

Strong washout:

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

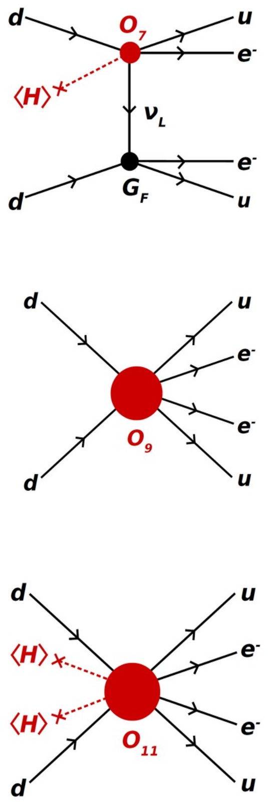
Fukugita, Yanagida (1986)
and many more afterwards...

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!

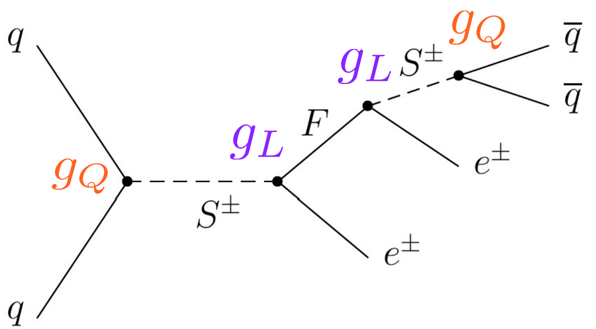
Asymmetry stored in another flavour sector?

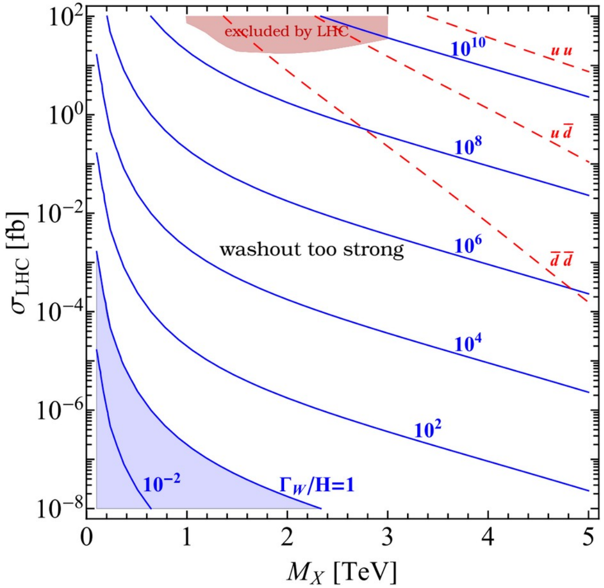
→ measurement in all flavours
→ low-scale LFV leading to equilibration

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

Probing leptogenesis 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:

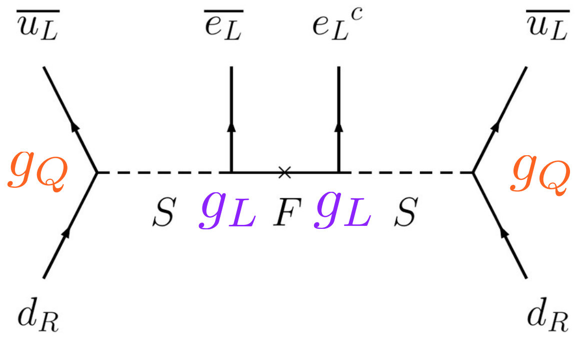
- SM processes with same-sign leptons (e.g. jjWW)
- Charge misidentification
- Jet-fake leptons from heavy flavour decays

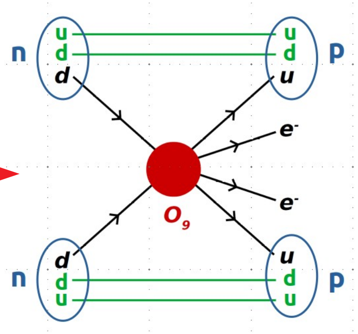
Observation of any LNV washout process at the LHC would falsify high-scale baryogenesis

Deppisch, JH, Hirsch (2014)
JH, Ramsey-Musolf, Shen, Urrutia-Quiroga (2021)

Probing leptogenesis with 0νββ decay

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

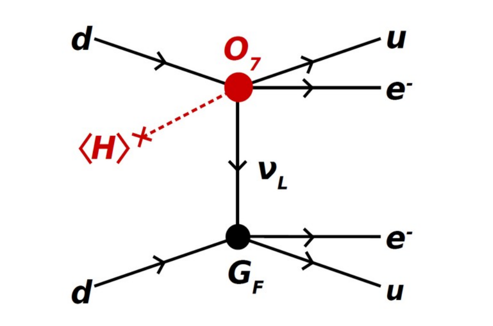




$T_{1/2}^{0\nu} > 1.07 \times 10^{26}\text{yr } 90\%\text{C.L.}$ KamLAND-Zen (2016)

JH, Ramsey-Musolf, Shen, Urrutia-Quiroga (2021)
Deppisch, Graf, JH, Huang (2018)
Deppisch, JH, Huang, Hirsch, Päs (2015)

Probing leptogenesis with 0νββ decay



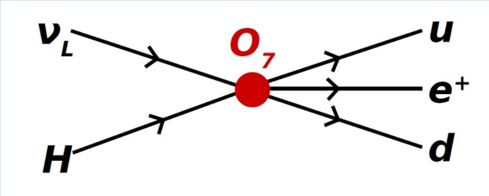
$$T_{1/2}^{-1} = |\ \epsilon_\alpha^\beta\ |^2 G^{0\nu}\ |\ M^{0\nu}\ |^2$$

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	$L^i\overline{e}^c\overline{u}^cd^cH^j\epsilon_{ij}$

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

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



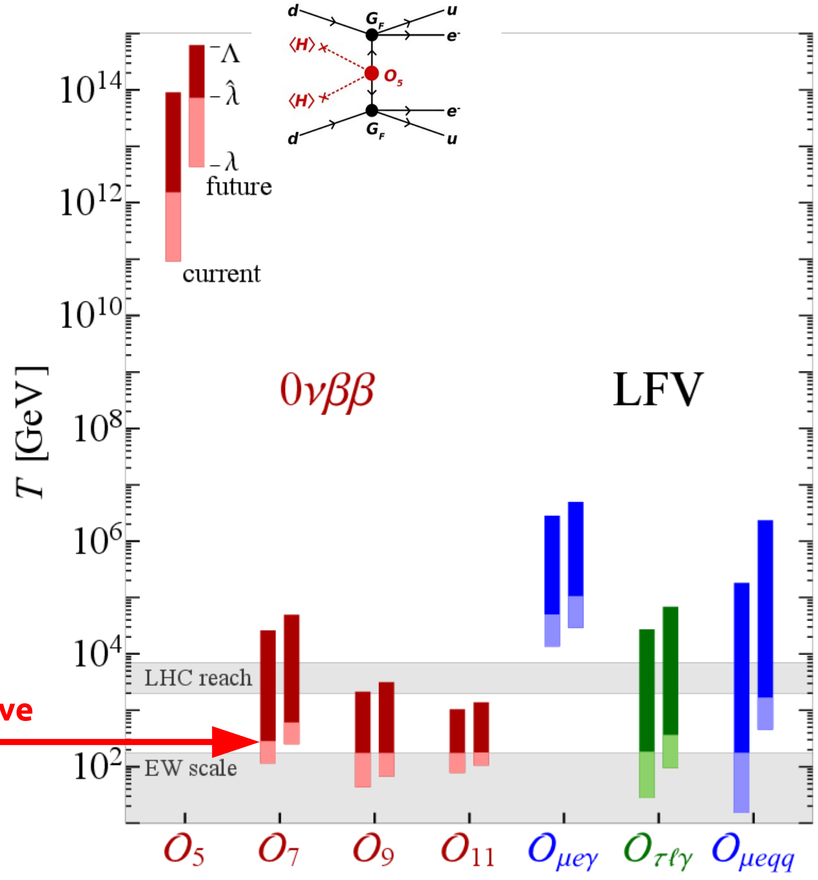
$$\Lambda_7\left(\frac{\Lambda_7}{c_7'\Lambda_{Pl}}\right)^{\frac{1}{5}}\lambda_7 < T < \Lambda_7$$

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

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

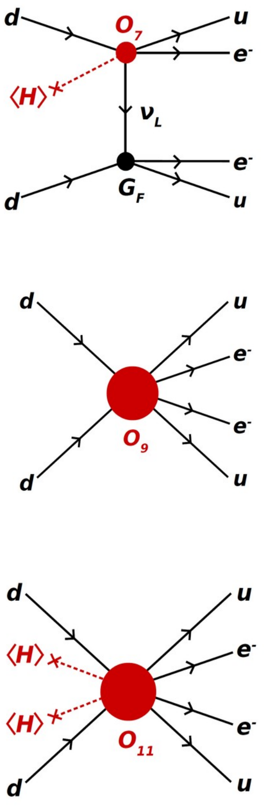
Deppisch, Graf, JH, Huang (2018)
Deppisch, JH, Huang, Hirsch, Päs (2015)
JH, Huang, Päs (2015)

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!

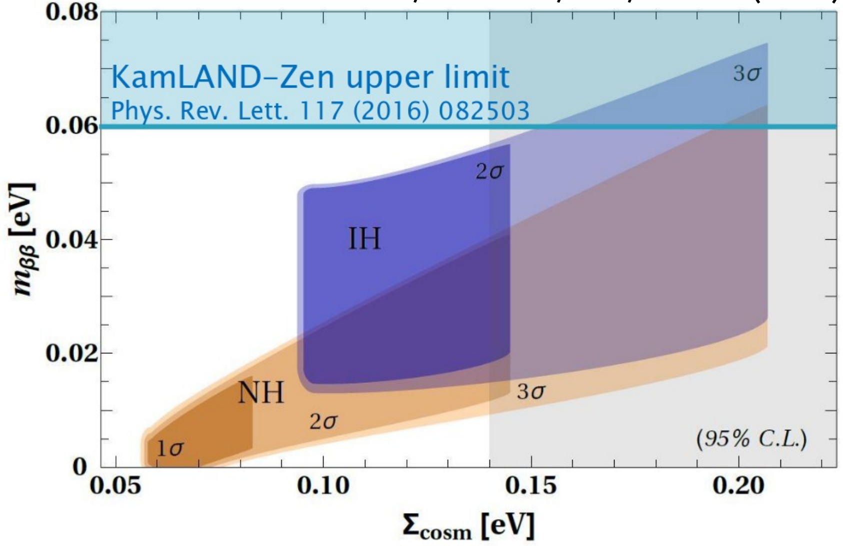
Asymmetry stored in another flavour sector?

→ 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)

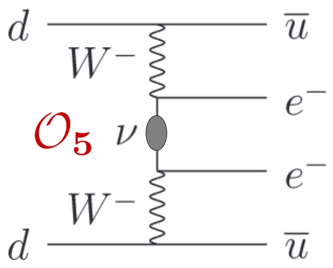
Interplay with cosmology

Dell'Oro, Marcocci, Viel, Vissani (2016)



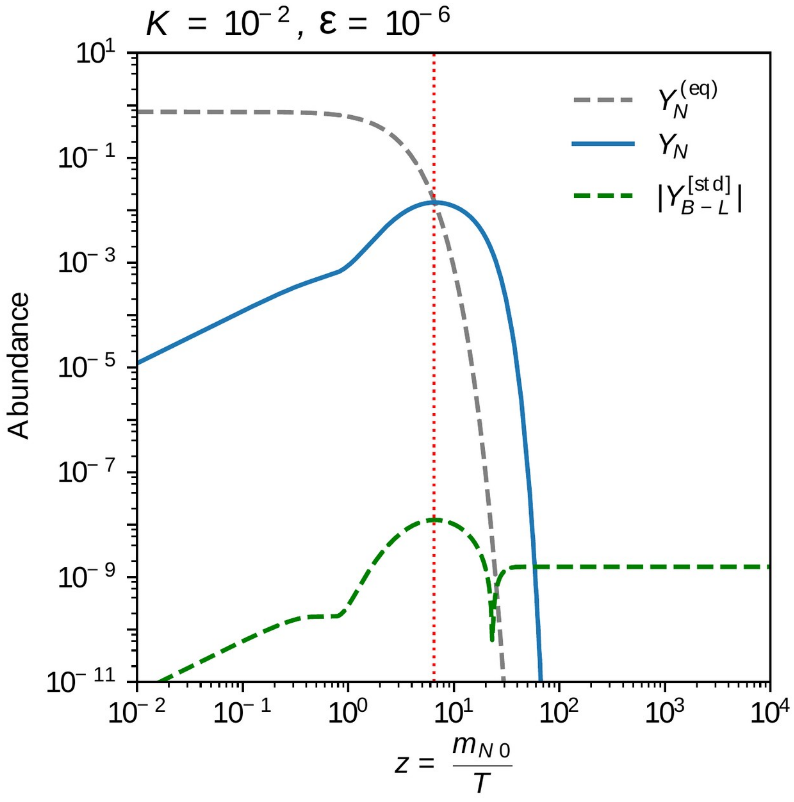
Plot assumes standard mass mechanism.

standard mass mechanism



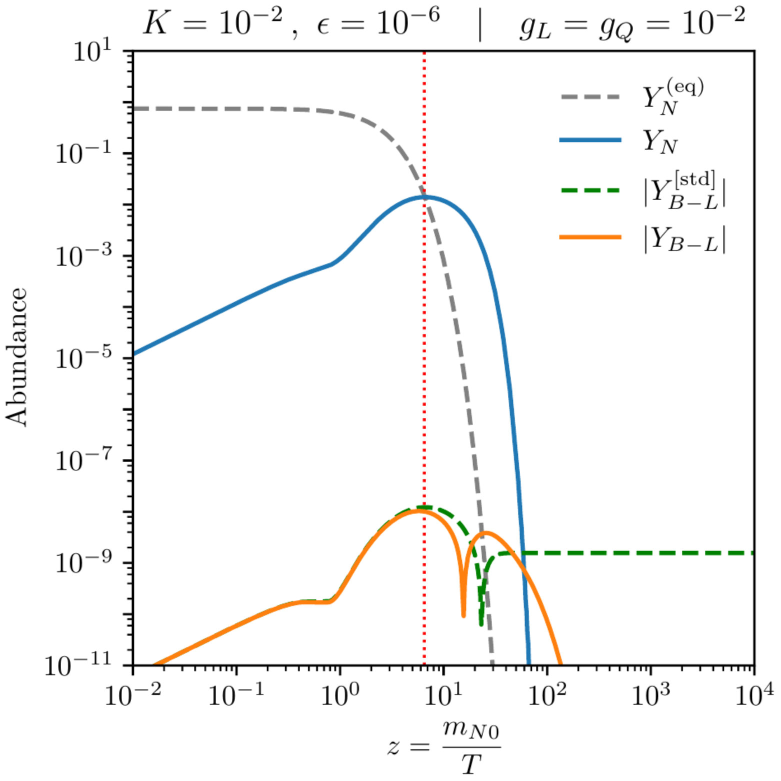
→ discrepancy between sum of neutrino masses from cosmology and 0νββ half life measurements could indicate non-standard mechanism

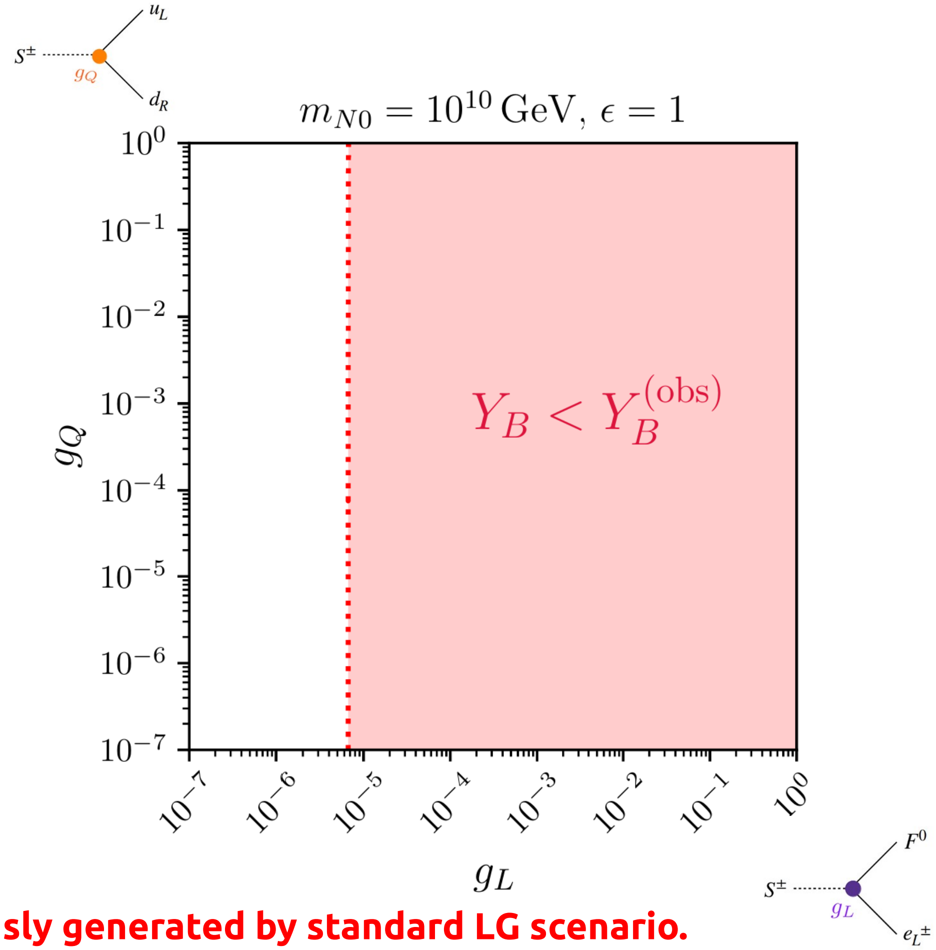
Implications on leptogenesis



Implications on leptogenesis

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



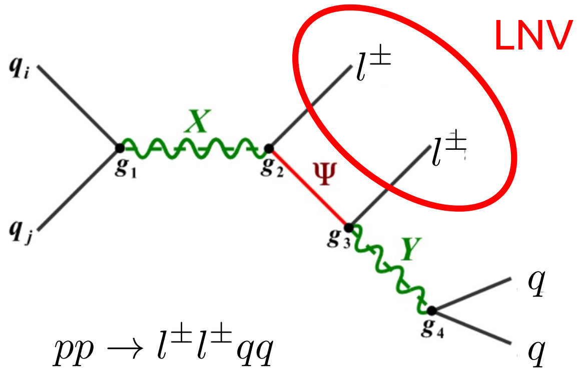


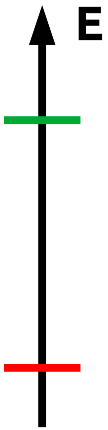
Low-scale LNV destroys lepton asymmetry previously generated by standard LG scenario.

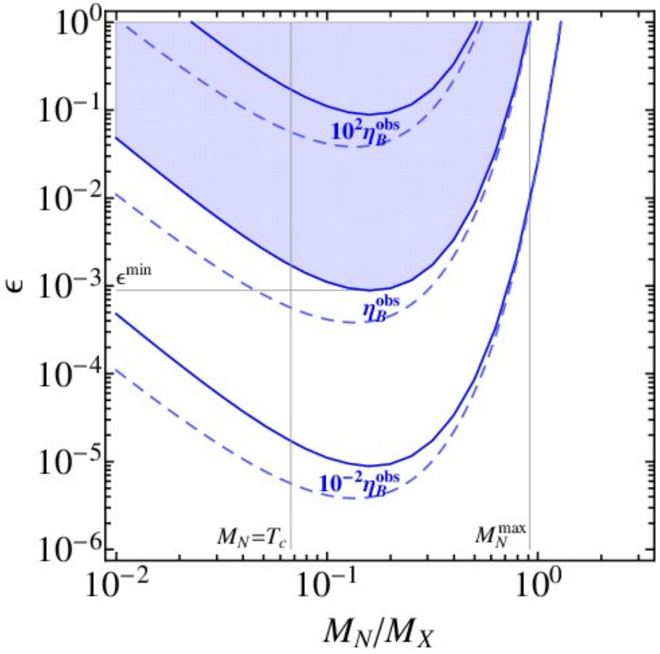
JH, Ramsey-Musolf, Shen, Urrutia-Quiroga (2021)

Probing Leptogenesis at the LHC

Washout processes could be observable at the LHC





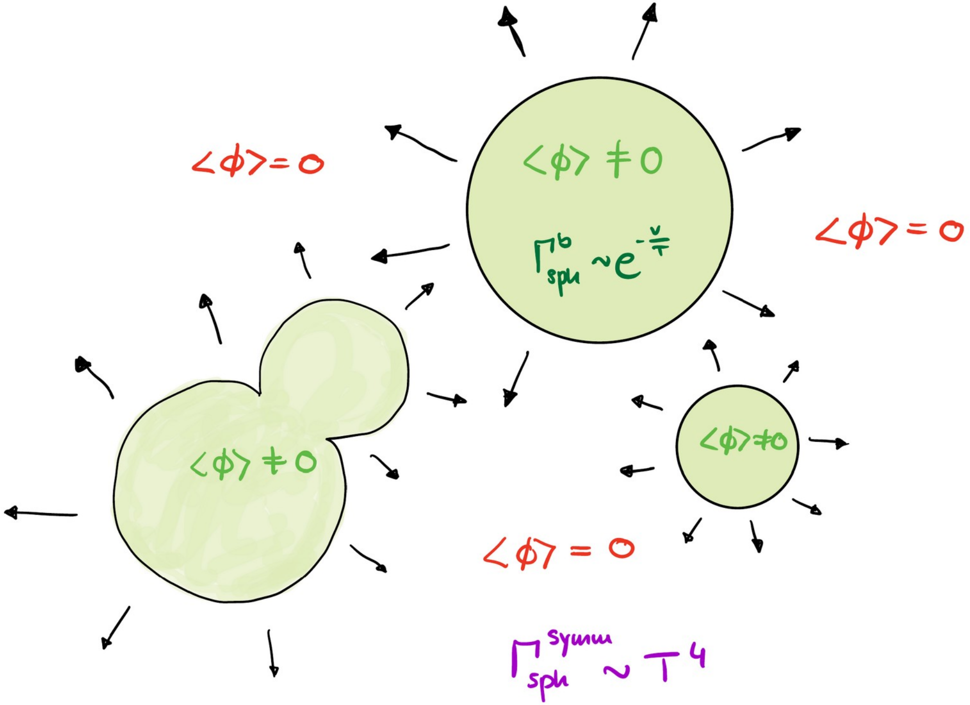


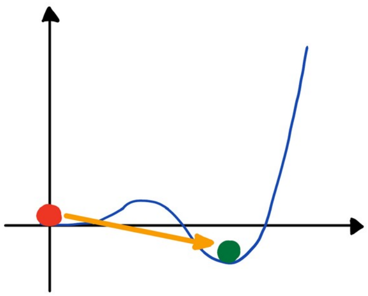
$$\log_{10}\left|\frac{\eta_B}{\eta_B^{obs}}\right| < 2.4\,\frac{M_X}{\text{TeV}}\left(1 - \frac{4}{3}\frac{M_N}{M_X}\right) + \log_{10}\left[|\epsilon|\left(\frac{\sigma_{\text{LHC}}}{\text{fb}}\right)^{-1}\left(\frac{4}{3}\frac{M_N}{M_X}\right)^2\right]$$

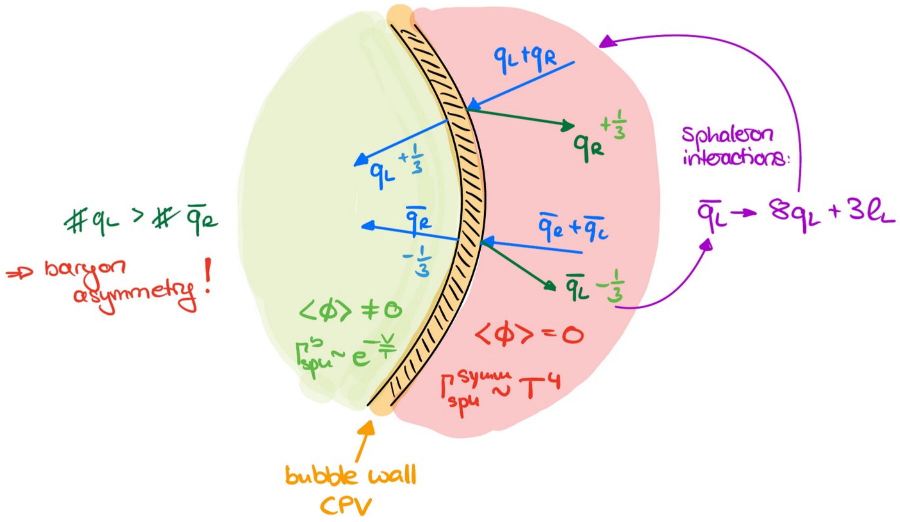
For similar hierarchies, LNV observation implies lower limit on CP asymmetry!

Deppisch, JH, Hirsch (2014)

Electroweak baryogenesis







Unfortunately, Higgs boson is too heavy for EWBG!

Darkogenesis

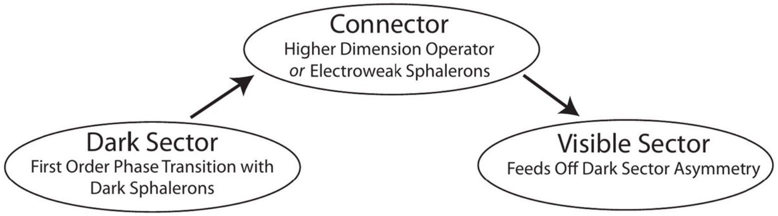
First order phase transition in dark sector transmitts the asymmetry into visible sector

Connector: Neutrino portal Hall et al. (2020)

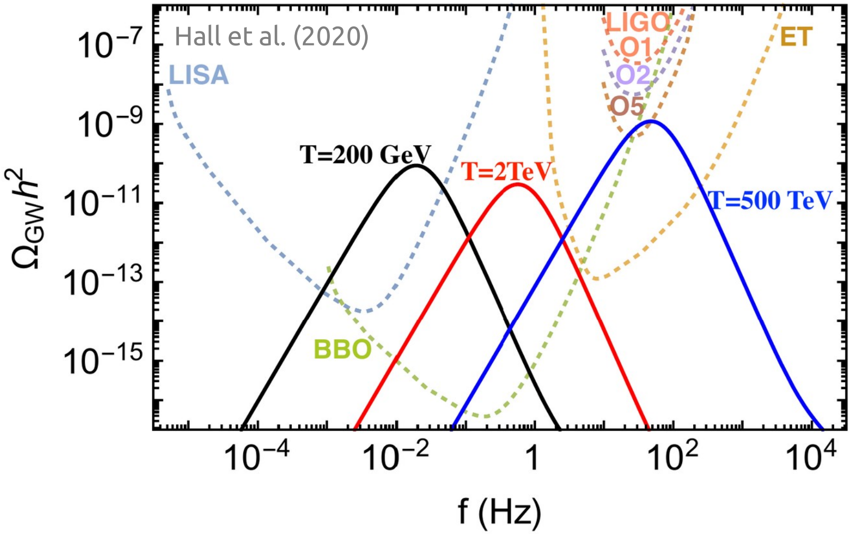
$$\mathcal{L}_Y = -Y_{a\alpha}\bar{L}_1\Phi_a N_\alpha - \tilde{Y}_{a\alpha}\bar{L}_1\tilde{\Phi}_a N_\alpha + c.c.$$

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

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	−

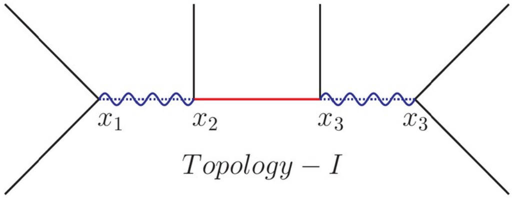


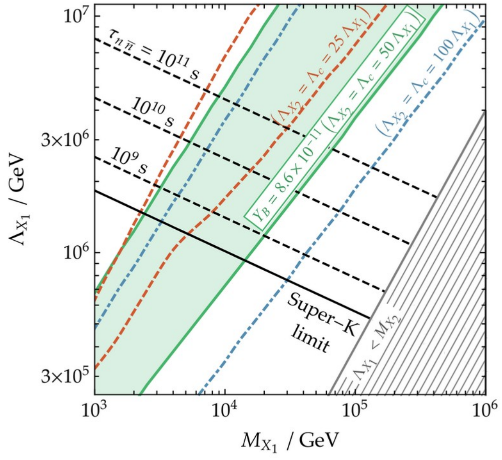
Shelton et al. (2010)



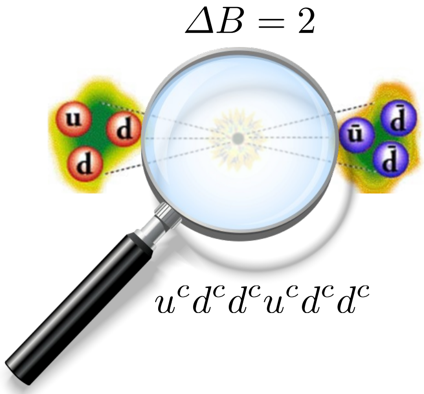
Not subject to strong constraints from EDMs!

Possible UV topologies



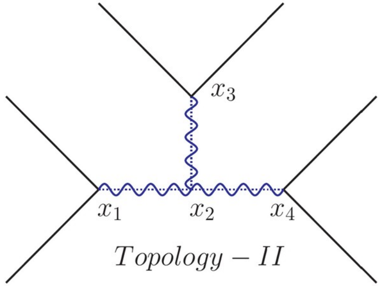


Grojean et al. (2019)



NOW:

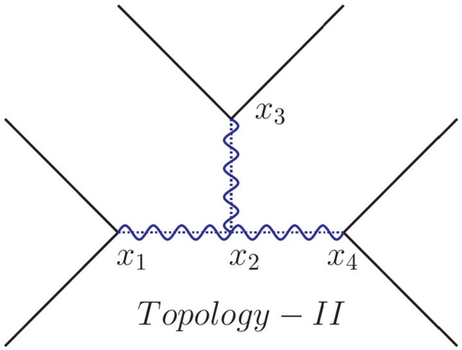
- **simplified model set-up considering asymmetry generation (CPV source!)**
- **confronting with current and future experimental results**



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

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

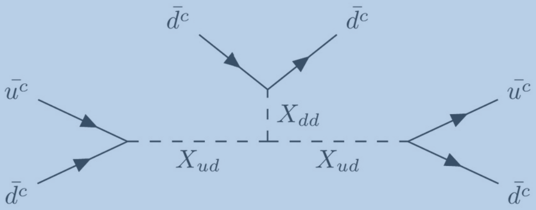
Case 2: CPV in effective nn operator



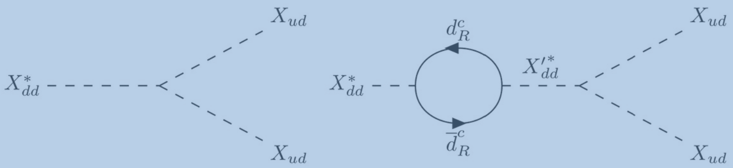
$$\mathcal{L}_{II}^{\text{eff}} \supset f_{ij}^{dd} X_{dd} \bar{d}_i^c \bar{d}_j^c + \frac{f_{ij}^{ud}}{\sqrt{2}} X_{ud} (\bar{u}_i^c \bar{d}_j^c + \bar{u}_j^c \bar{d}_i^c) + \lambda \xi X_{dd} X_{ud} X_{ud} + \text{h.c.}$$

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

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



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)