Charting the Baryogenesis Landscape

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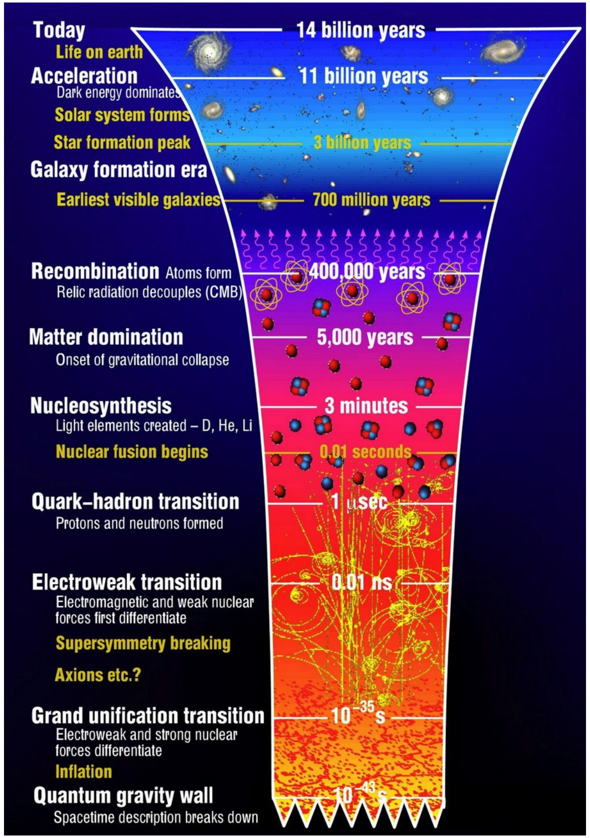
JOHANNES GUTENBERG UNIVERSITÄT MAINZ
JG|U

From the Big Bang to Today



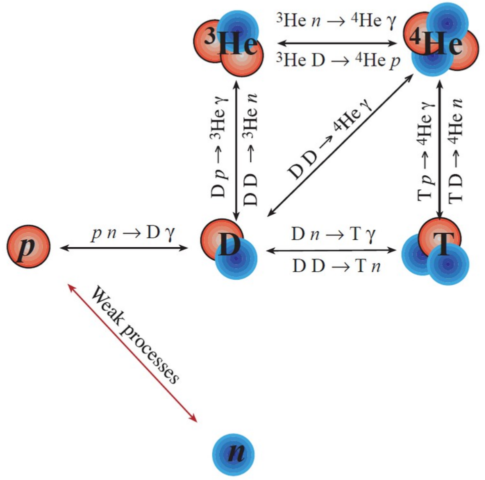
Our Universe consists mainly out of baryonic matter, quantified by the baryon-to-photon ratio:

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

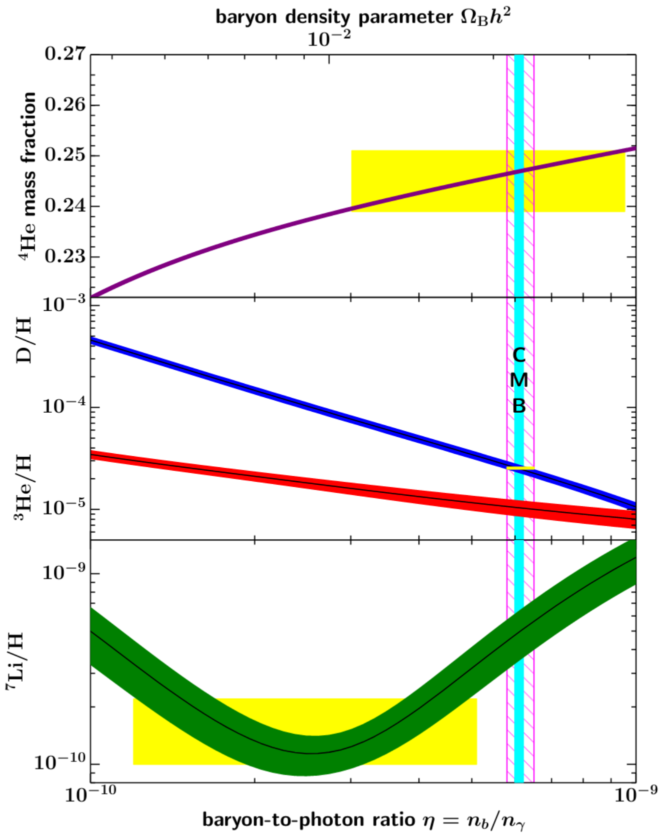
Credits: University of Cambridge / The Stephen Hawking Centre for Theoretical Cosmology

The Baryon Asymmetry of the Universe (BAU)

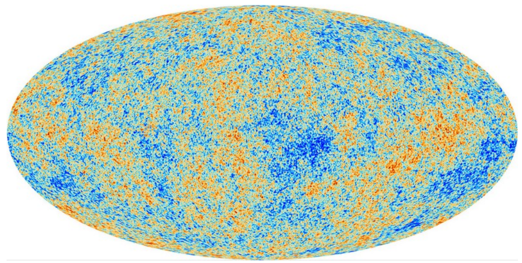
Big Bang Nucleosynthesis



3 min after Big Bang



Cosmic Microwave Background

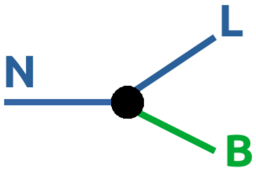


400.000 years after Big Bang

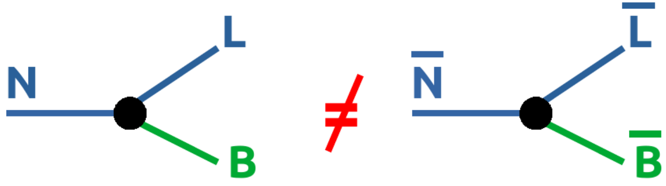
Why do we need new physics?

Theoretically, we know the conditions on interactions that have to be fulfilled (Sakharov conditions 1961)

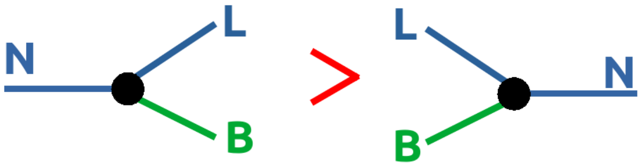
- ☐ B violation



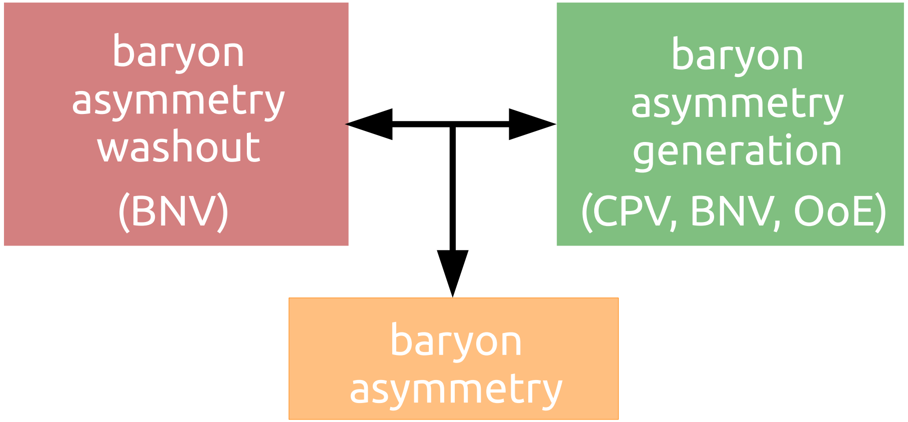
- ☐ C and CP violation



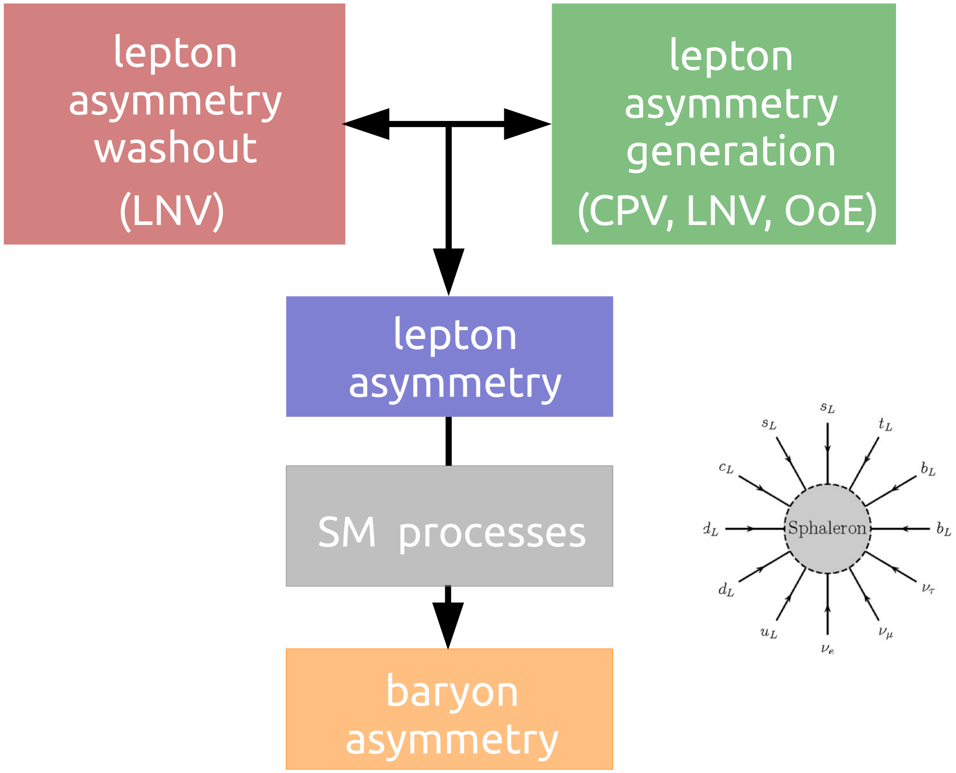
- ☐ departure from thermal equilibrium



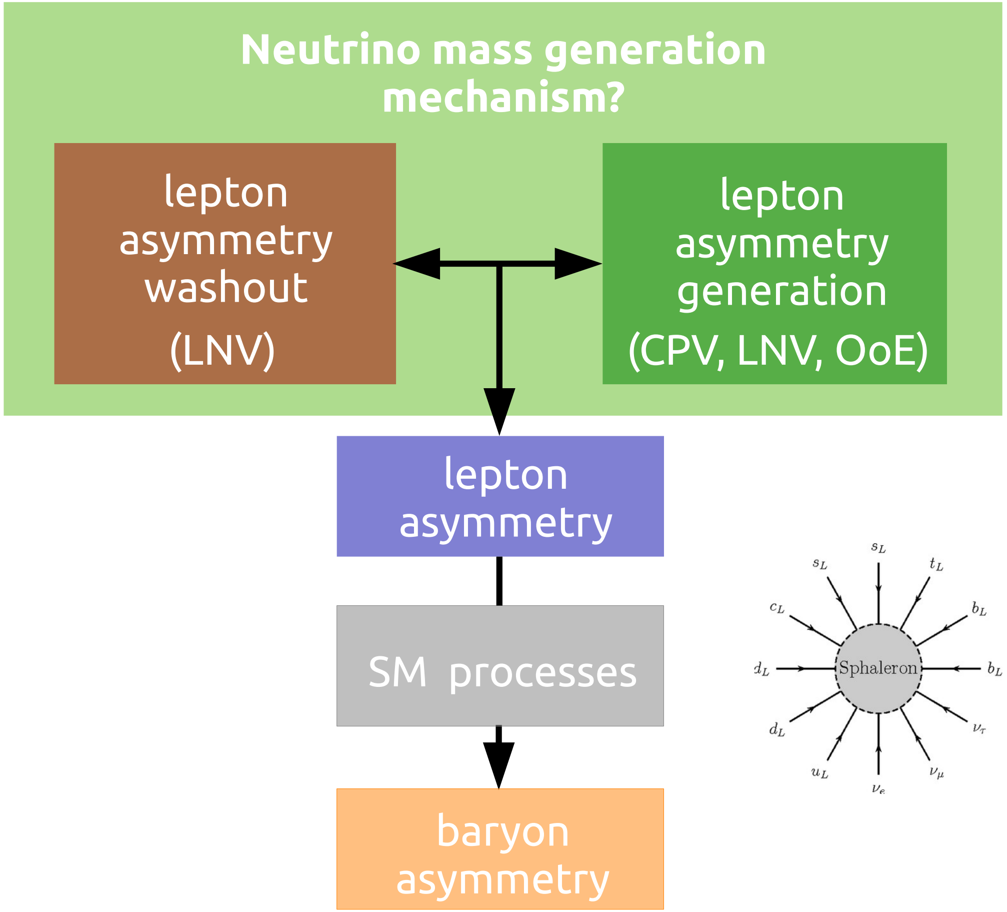
Basic principle of baryogenesis



Basic principle of leptogenesis



Basic principle of leptogenesis



Neutrino mass mechanism - Dirac or Majorana?

Dirac mass

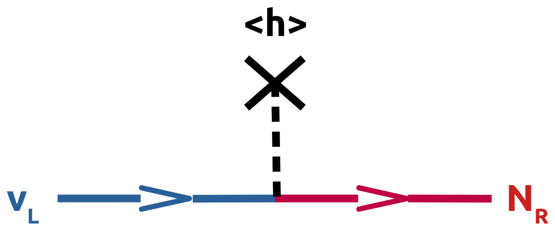
$$y_\nu L \epsilon H \overline{\nu}_R \supset m_D \nu_L \overline{\nu}_R$$

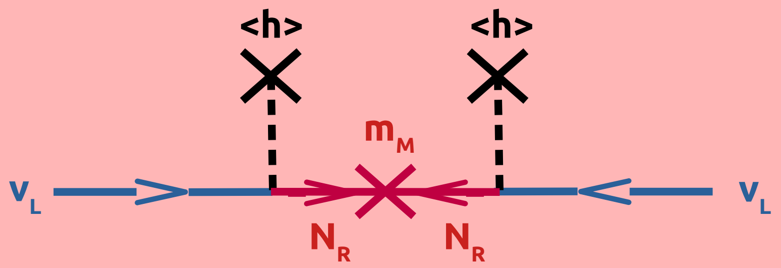
Majorana mass

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

→ **lepton number no accidental symmetry anymore**

$LLHH$ dim-5 Weinberg-operator

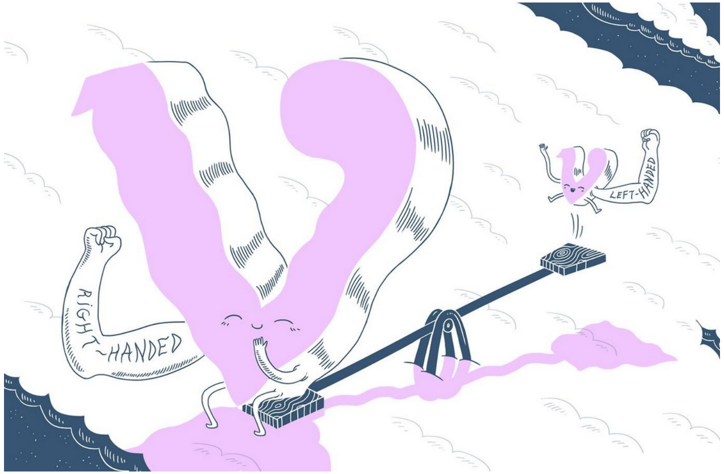




→ **Lepton number violation (LNV)**

See-saw I neutrino mass mechanism

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



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

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

Low-scale leptogenesis

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

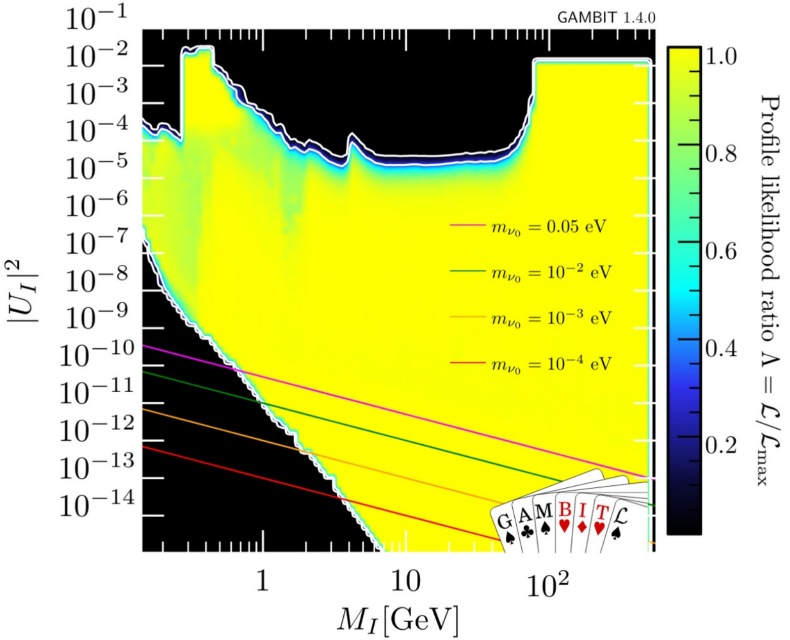
High-scale leptogenesis

Constraints on right-handed neutrinos

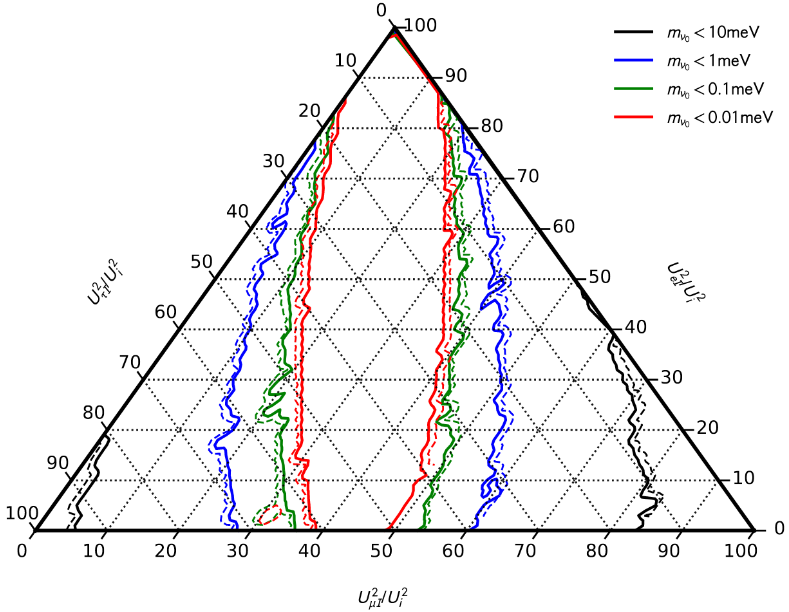
Analysis of see-saw I with *three* right-handed neutrinos using GAMBIT

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

mixing of sterile to active neutrino



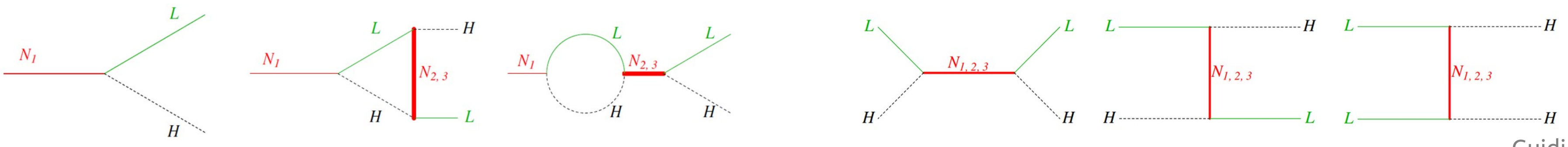
mass of sterile neutrino



For $M_I\, U_I^2 > 10^{-10}$ GeV,
motivated by experimental sensitivity

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



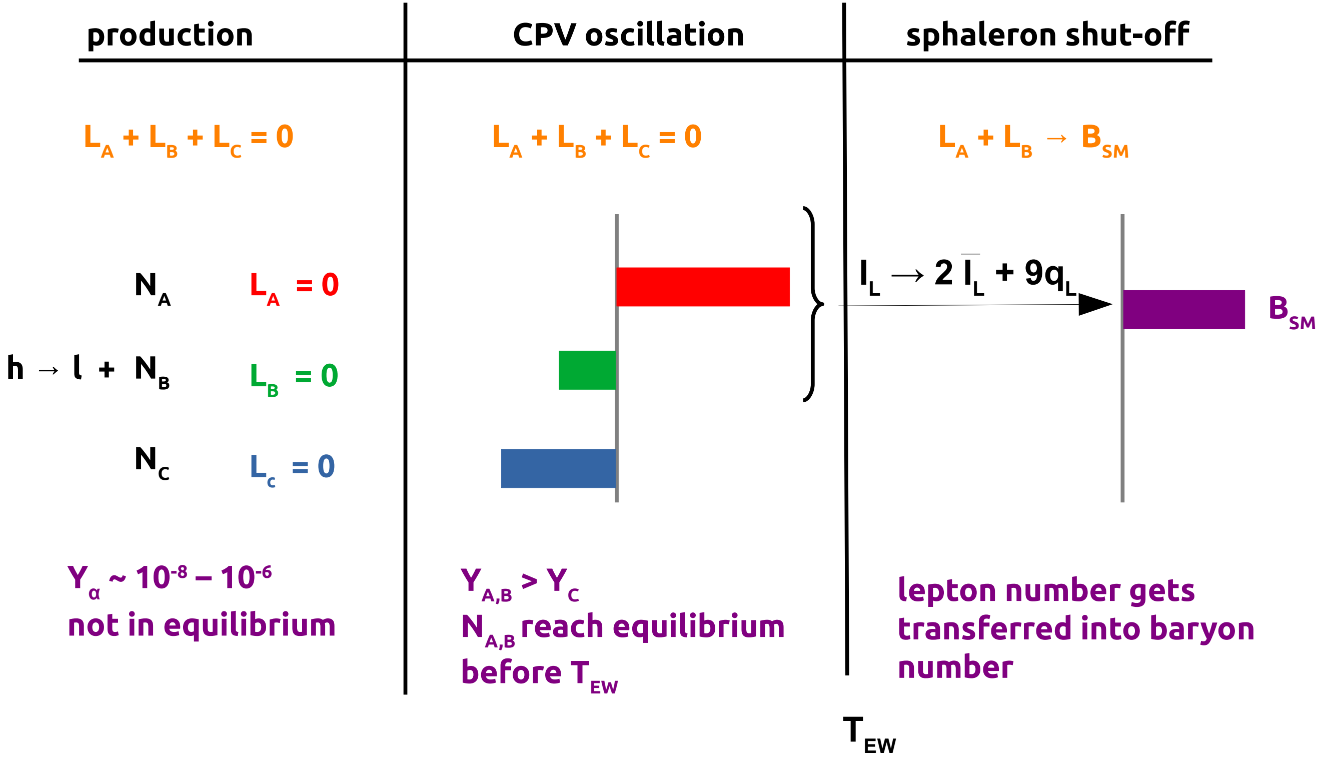
Guidice et al. (2004)

Davidson-Ibarra bound: $M_N > 10^9$ GeV (except resonant leptogenesis) Davidson, Ibarra (2002)

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

Leptogenesis via oscillations

Akhmedov-Rubakov-Smirnov (ARS) mechanism Akhmedov, Rubakov, Smirnov (1998)

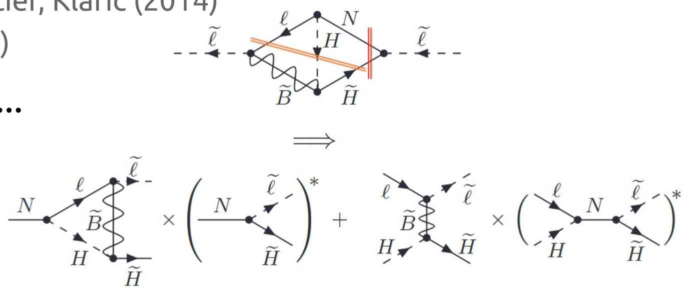


+ Asaka, Shaposhnikov (2005)

Methodological advancements

High-scale Leptogenesis:

- "normal" BEQ treatment breaks down in the limit of degenerate neutrinos Covi, Roulet (1997), Pilaftis (1997), Covi, Rius, Roulet, Vissani (1998)
- Numerous investigations in closed-time-path (CTP) and density matrix formalism
  - → solving directly Schwinger-Dyson equations Garny, Kartavtsev, Hohenegger (2013), Iso, Shimada, Yamanaka (2014)
  - → performing Wigner transform Garbrecht, Herranen (2012), Garbrecht, Gautier, Klaric (2014)
  - → two-momentum picture Millington, Pilaftsis (2013), Bödeker, Schröder (2020)
- Further investigations incl. IR convergence behaviour, spectator effects, ...
  Beneke, Garbrecht, Herranen, Schwaller (2010), Garbrecht, Ramsey-Musolf (2014)
  Garbrecht, Schwaller (2014), Garbrecht, Klose, Tamarit (2020)



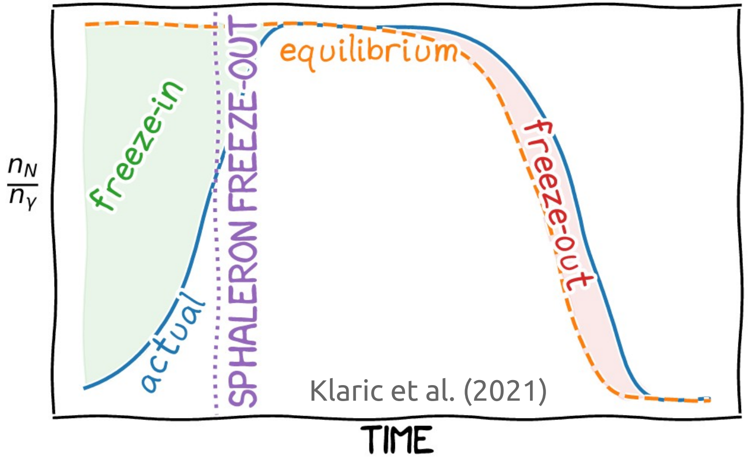
Low-scale Leptogenesis:

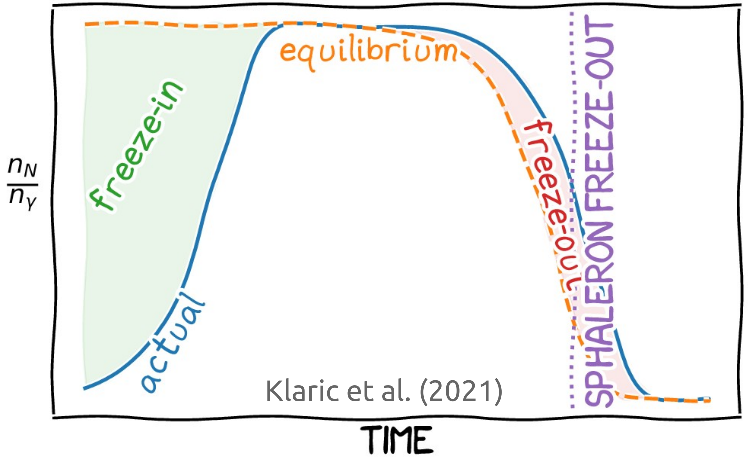
- Generalization of Sigl+Raffelt treatment of relativistic mixed neutrinos with additional heavy states
  Sigl, Raffelt (1993), Akhmedov, Rubakov, Smirnov (1998), Asaka, Shaposhnikov (2005)
- Application to CTP formalism Garbrecht, Herranen (2012), Drewes, Garbrecht, Gueter, Klaric (2016)
- Further refinements incl. susceptibility matrices, fermion number violating effects, EWSB, non-instantaneous sphaleron freeze-out Shuve, Yavin (2014), Ghiglieri, Laine (2016, 2019, 2020), Shaposhnikov et al. (2008, 2017)

Can both mechanisms related? How to bridge both regimes? How accurately covered is the intermediate regime?

Mind the gap?

- **Importance of non-relativistic corrections to ARS leptogenesis** Hambye, Teresi (2016), Eijima, Shaposhnikov (2017), Ghiglieri, Laine (2017)
- **Indications that freeze-out (in) can happen at lower (higher) RHN masses** Garbrecht (2014), Hernandez, Kekic, Lopez-Pavon, Racker, Salvado (2016), Hambye, Teresi (2016, 2017), Granelli, Moffat, Petcov (2020)
- **Generalization of quantum kinetic equations to cover non-relativistic case** Klaric, Shaposnikov, Timiryasov (2020, 2021)

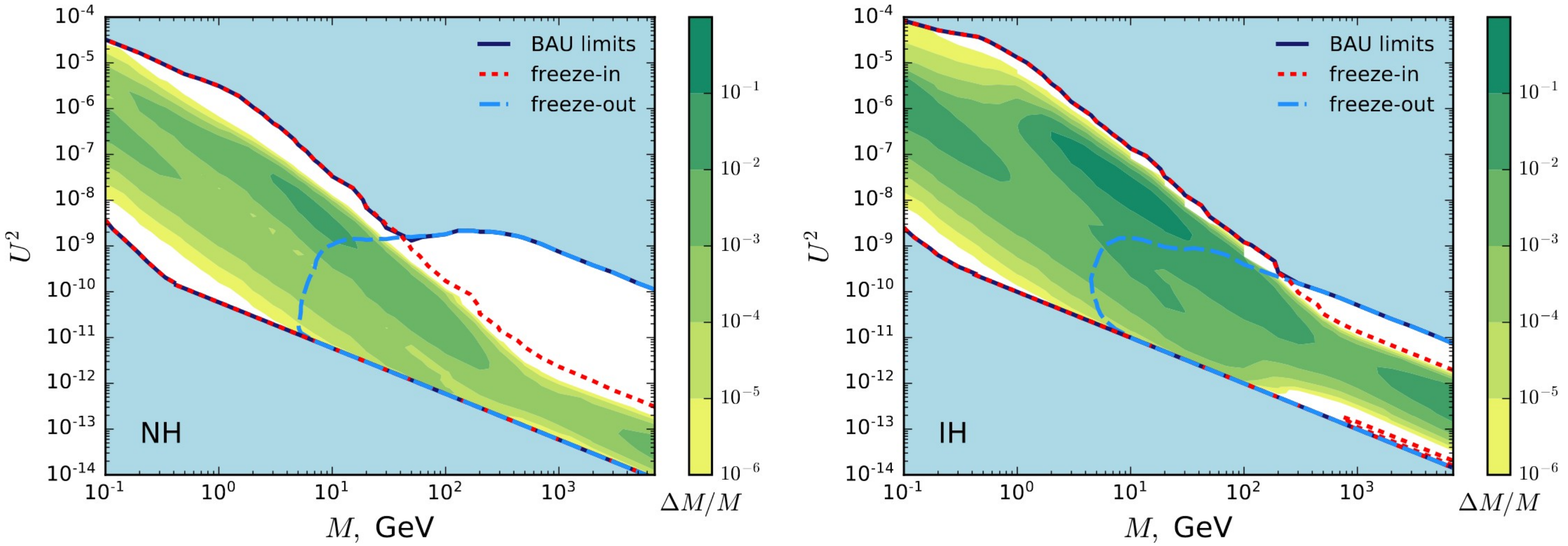




- **Thermal initial conditions → only freeze-out contributes**
- **Vanishing initial conditions → both freeze-in and freeze-out possible**

Mind the gap?

Seesaw type-I with *two* heavy neutrinos between 100 MeV and 10 TeV



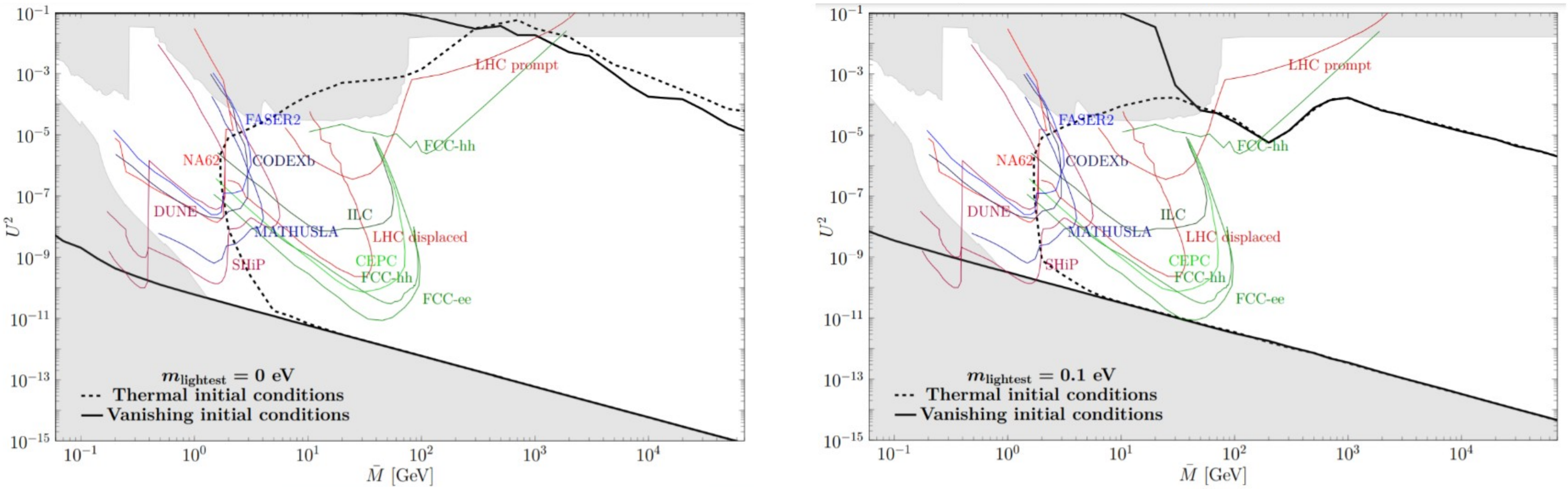
Both regimes can be smoothly described and overlap!
→ freeze-in relevant up to TeV range
→ freeze-out down to 5 GeV

Klaric, Shaposhnikov, Timiryasov (2020, 2021)

Mapping the viable parameter space of testable LG

Study of whole parameter space of seesaw type-I with *three* heavy neutrinos between 50 MeV and 70 TeV

Drewes, Georis, Klaric (2021)

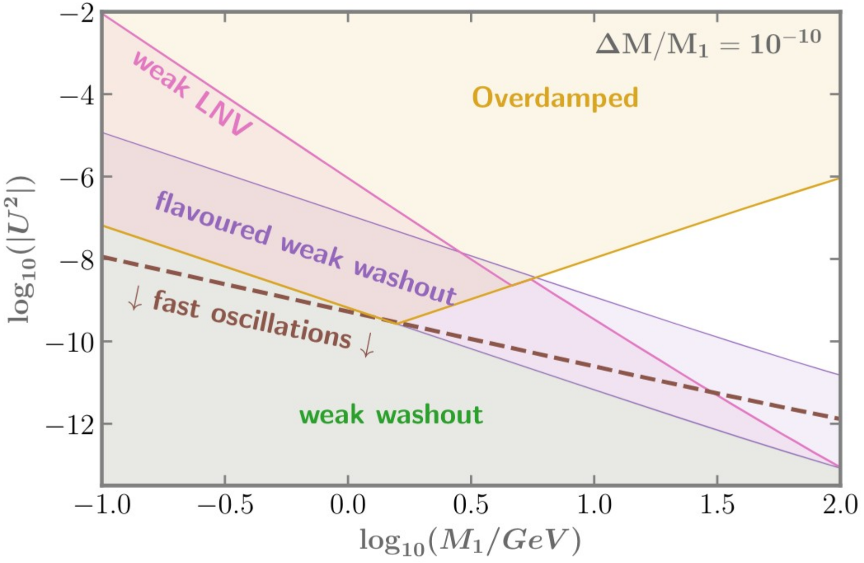


→ with *three* RHNs range of couplings much larger than with *two* RHNs

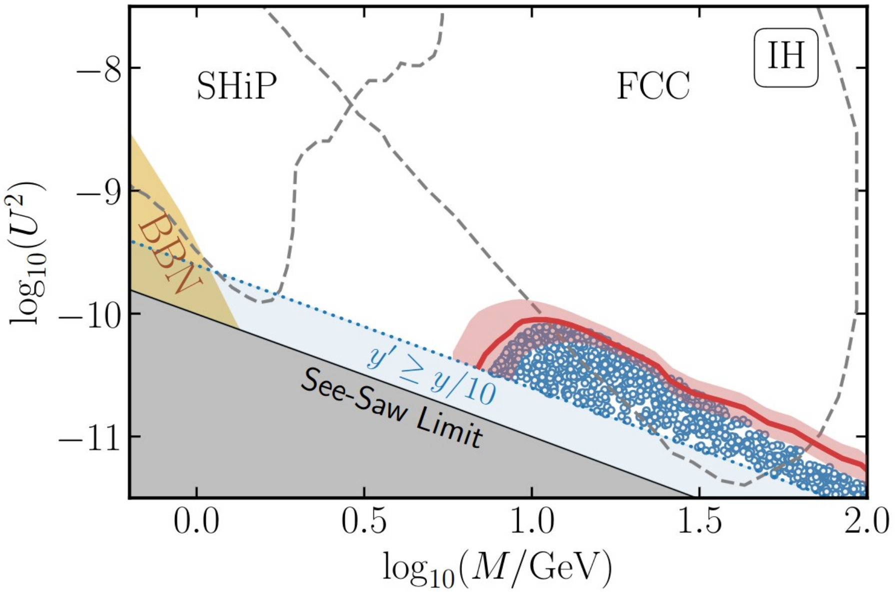
Analytic understanding via CP flavour invariants

Seesaw type-I with *two* right handed neutrinos with large HNL mixings

Hernandez, Pavon, Rius, Sandner (2022)



Hernandez, Pavon, Rius, Sandner (2023)



→ derivation of analytic approximations in inverse see-saw limit
→ expressed in measurable quantities

→ in case of two *exactly* degenerate RHNs in MFV see-saw limit, BAU can be predicted by measuring their mass, mixing, and CP violation

Leptogenesis & Flavour

- Flavoured soft leptogenesis Fong, Gonzalez-Garcia (2010), Fong Gonzalez-Garcia, Nardi, Racker (2010)
- Three-flavoured non-resonant leptogenesis at intermediate scales Moffat, Pascoli, Petcov, Schulz, Turner (2018)
- Flavoured resonant leptogenesis at sub-TeV scales Granelli, Moffat, Petcov (2020)
- Wash-in leptogenesis Domcke, Kamada, Mukaida, Schmitz, Yamada (2020)
- Leptoflavorgenesis Mukaida, Schmitz, Yamada (2022)

Non-minimal chemical background where conserved charges can take arbitrary values at LG:

$$\mu_{\ell_\alpha} + \mu_\phi = \mu_\alpha^0 - \sum_\beta C_{\alpha\beta}\mu_{\Delta_\beta}$$

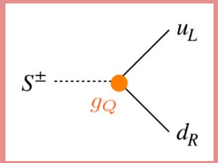
Falsifying leptogenesis with TeV-scale LNV

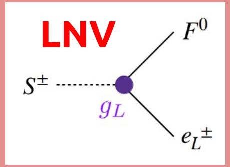
Right-handed neutrino interactions ("standard thermal LG"):

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

Additional TeV-scale interactions

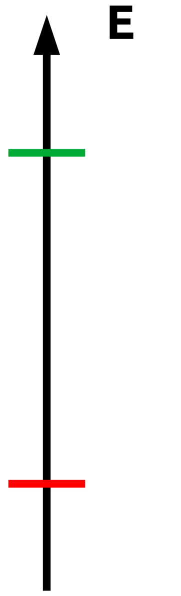
$$\tilde{\mathcal{L}} \supset g_Q \overline{Q} S d_R + g_L \overline{L}(i\tau^2) S^* F - m_S^2 S^\dagger S - \frac{m_F}{2} \overline{F^c} F + \lambda_{HS} (S^\dagger H)^2 + \text{h.c.}$$





high-scale source of lepton asymmetry

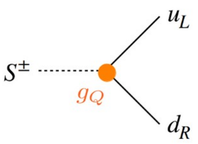
TeV-scale LNV "washout" interactions

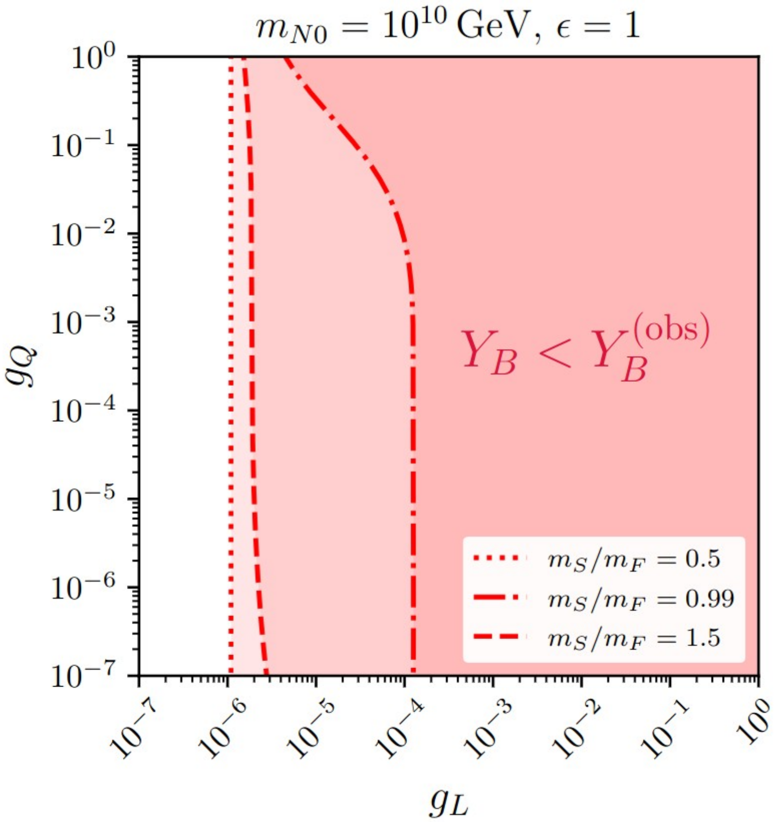


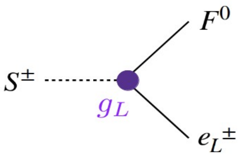
Can TeV-scale LNV destroy the generated asymmetry from standard thermal LG?

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

Falsifying leptogenesis with TeV-scale LNV





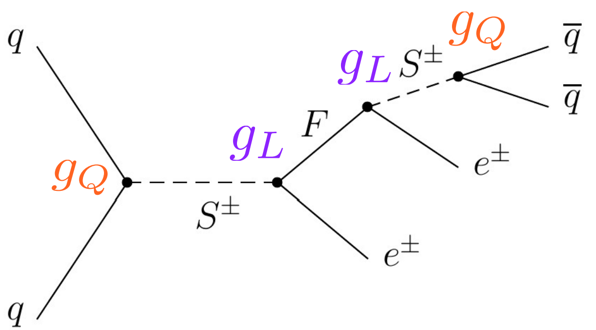


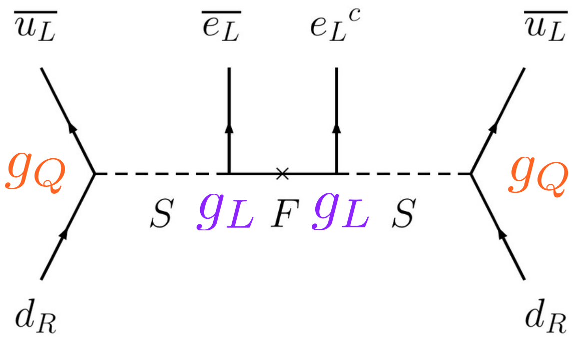
TeV-scale LNV washes-out lepton asymmetry previously generated by standard LG scenario.

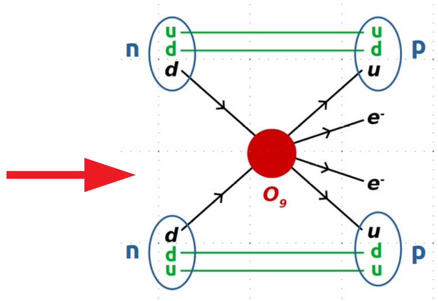
JH, Ramsey-Musolf, Shen, Urrutia-Quiroga (2021)

Falsifying leptogenesis with LHC and 0νββ decay

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







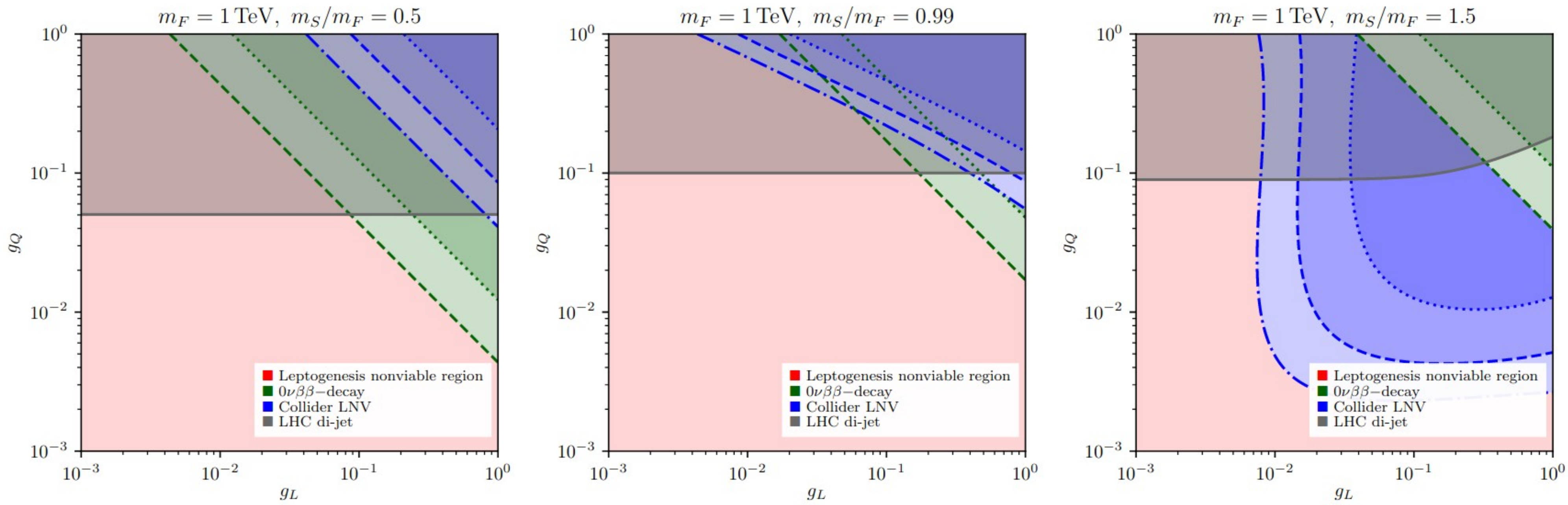
Observation of any LNV washout process at the LHC would falsify high-scale leptogenesis.

JH, Ramsey-Musolf, Shen, Urrutia-Quiroga (2021)
Deppisch, JH, Hirsch (2014)
Frère, Hambye, Vertongen (2008)

Observation of 0νββ decay via non-standard mechanism would falsify high-scale leptogenesis.

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

Falsifying leptogenesis with LHC and 0νββ decay



→ **interplay of collider searches and 0νββ decay can give insights into underlying UV physics**

→ **TeV-scale LNV can falsify high-scale leptogenesis**

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

Probing leptogenesis with GWs from cosmic strings

Right-handed neutrino masses – breaking of a higher symmetry?

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

Stochastic gravitational wave spectrum depends on

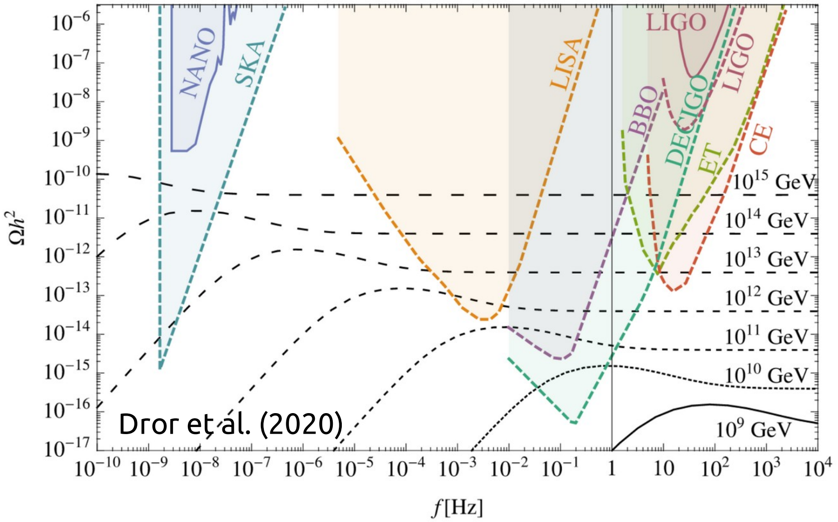
$$\Omega_{\mathrm{GW}}h^2 \propto G\mu^2$$

$$\mu \sim v^2$$

cosmic string tension → μ

$U_{B\text{-}L}$-breaking scale → v

Hindmarsh (2011)
Buchmueller et al. (2013)



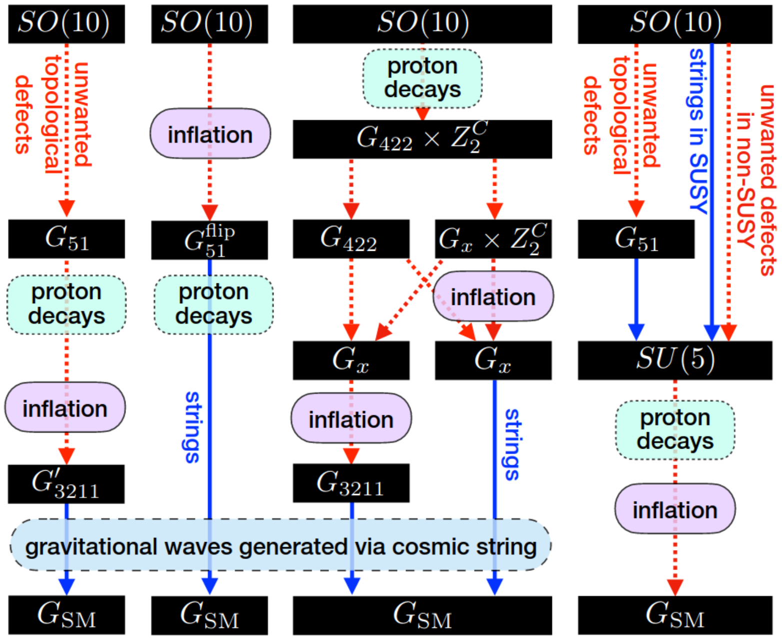
Vibrant field, many recent exciting works:

Gouttenoire et al. (2019+)
Dror et al. (2020)
Ellis et al. (2020)
Blasi et al. (2020+)
Buchmüller et al. (2021+)
Fridell, JH, Hati, Heger, Mojahed (to appear)

Confronting SO(10) GUTs with proton decay and GWs

Exploring GUT models with potential of successful leptogenesis

King, Pascoli, Turner, Zhou (2021+), Fu, King, Marsili, Pascoli, Turner, Zhou (2022)

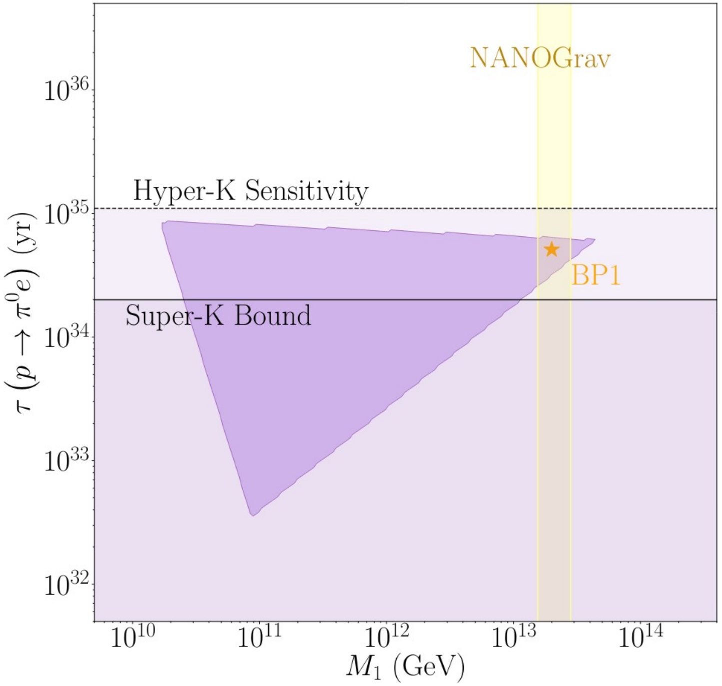


$$SO(10)$$
$$\mathbf{54} \downarrow \text{ broken at } M_X$$ ← **Proton decay**
$$G_3 \equiv SU(4) \times SU(2)_L \times SU(2)_R \times Z_2^C$$
$$\mathbf{210} \downarrow \text{ broken at } M_3$$
$$G_2 \equiv SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_X \times Z_2^C$$
$$\mathbf{45} \downarrow \text{ broken at } M_2$$
$$G_1 \equiv SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_X$$
$$\overline{\mathbf{126}} \downarrow \text{ broken at } M_1$$ ← **$U(1)_{B-L}$ breaking → cosmic strings**
$$G_{SM} \equiv SU(3)_c \times SU(2)_L \times U(1)_Y \, .$$

Confronting SO(10) GUTs with proton decay and GWs

Exploring GUT models with potential of successful leptogenesis

King, Pascoli, Turner, Zhou (2021+), Fu, King, Marsili, Pascoli, Turner, Zhou (2022)

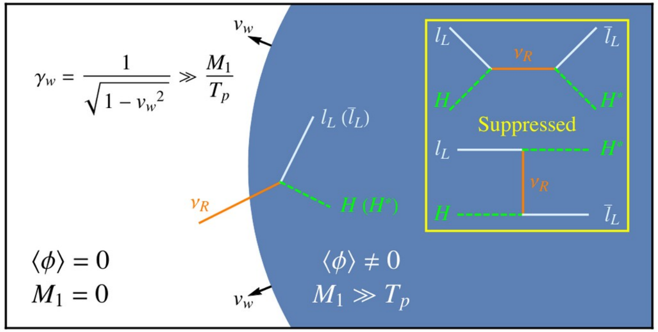


$$
\begin{array}{c}
SO(10) \\
\mathbf{54} \downarrow \text{ broken at } M_X \\
G_3 \equiv SU(4) \times SU(2)_L \times SU(2)_R \times Z_2^C \\
\mathbf{210} \downarrow \text{ broken at } M_3 \\
G_2 \equiv SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_X \times Z_2^C \\
\mathbf{45} \downarrow \text{ broken at } M_2 \\
G_1 \equiv SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_X \\
\overline{\mathbf{126}} \downarrow \text{ broken at } M_1 \\
G_{\rm SM} \equiv SU(3)_c \times SU(2)_L \times U(1)_Y \,.
\end{array}
$$

← **Proton decay** (at M_X)

← **$U(1)_{B-L}$ breaking → cosmic strings** (at M_1)

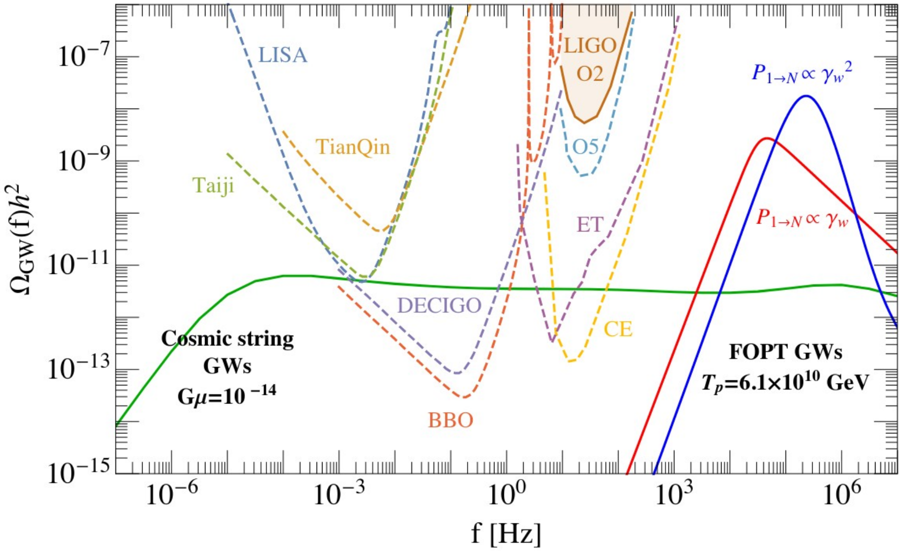
Probing leptogenesis with GWs from FOPT



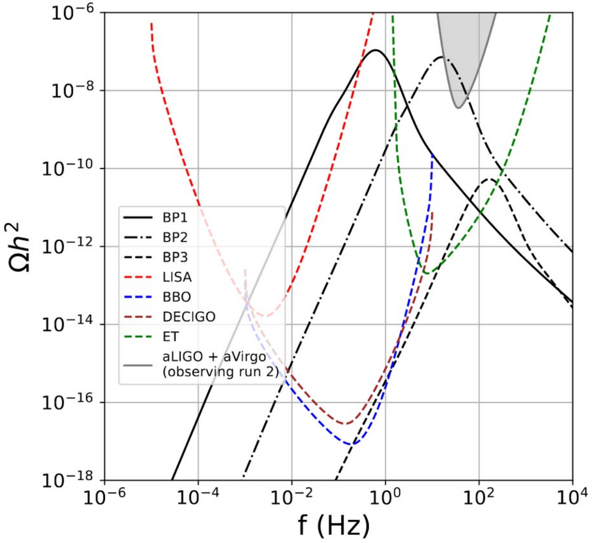
Leptogenesis based on mass gain mechanism with first order phase transition

Azatov, Vanvlasselaer (2020)
Azatov, Vanvlasselaer, Yin (2021), Baldes, Blasi, Mariotti, Severin, Turbang (2021)
Dasgupta, Dev, Ghoshal, Mazumdar (2022), Huang, Xie (2022)
Fridell, JH, Hati, Heger, Mojahed (to appear)

High-scale leptogenesis Huang, Xie (2022)



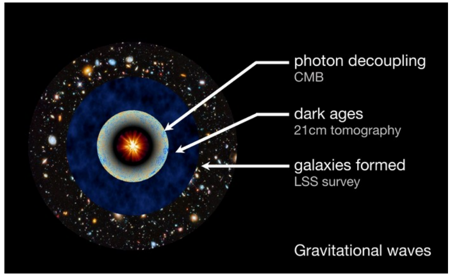
Resonant leptogenesis Dasgupta, Dev, Ghoshal, Mazumdar (2022)

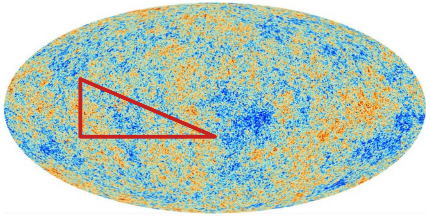


Cosmological (higgs) collider as novel probe for LG

Idea: Use the Universe as gigantic "cosmic collider"

Chen, Wang (2009), Baumann, Green (2011), Arkani-Hamed, Maldacena (2015)

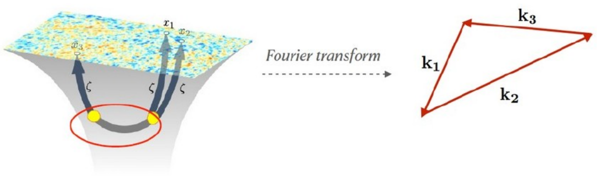




3-point function = higher order correlations
→ non-Gaussianities

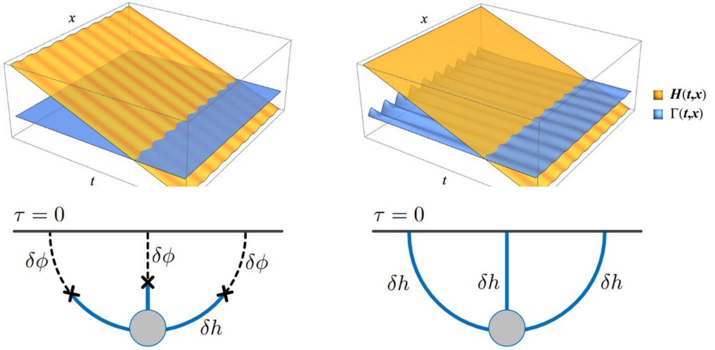
→ **info about particle interaction with inflaton**

In squeezed limit, $k_1, k_2 \gg k_3$, **"mass measurement"** at cosmic collider



$$\langle \zeta_{\mathbf{k}_1} \zeta_{\mathbf{k}_2} \zeta_{\mathbf{k}_3} \rangle' \equiv (2\pi)^4 P_\zeta^2 \frac{1}{(k_1 k_2 k_3)^2} S(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3)$$

Specific set-up: Cosmic Higgs collider

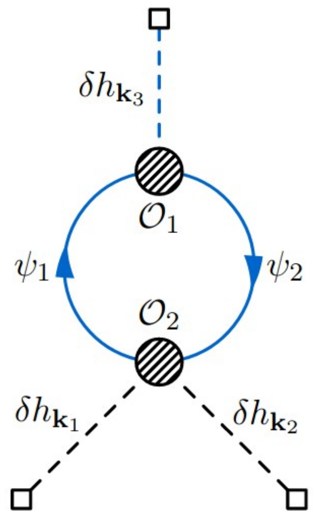


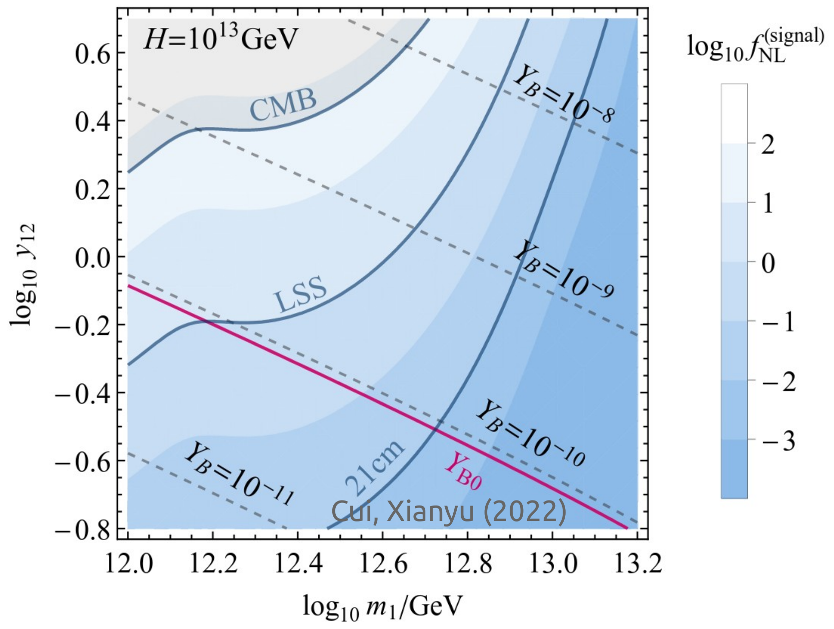
Liu, Wang, Xianyu (2019)

Cosmological (higgs) collider as novel probe for LG

Heavy RHN (~ H) can be probed via the "cosmic collider"

Cui, Xianyu (2022)

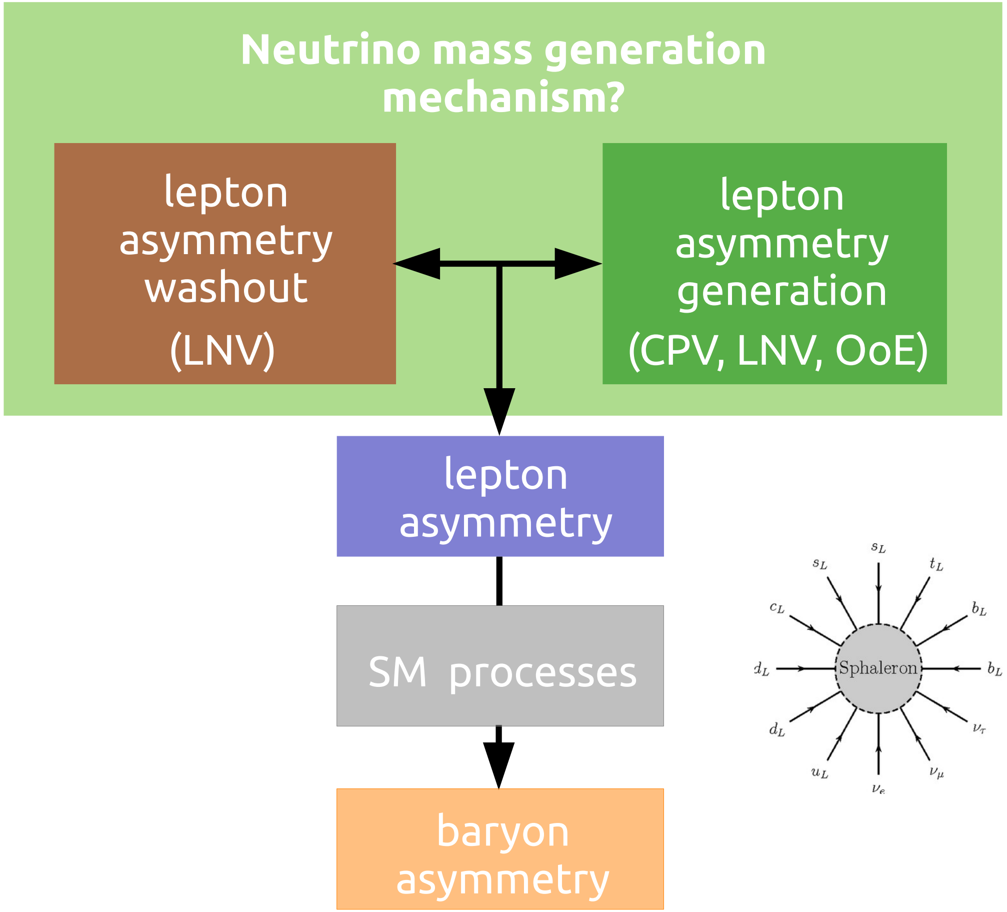




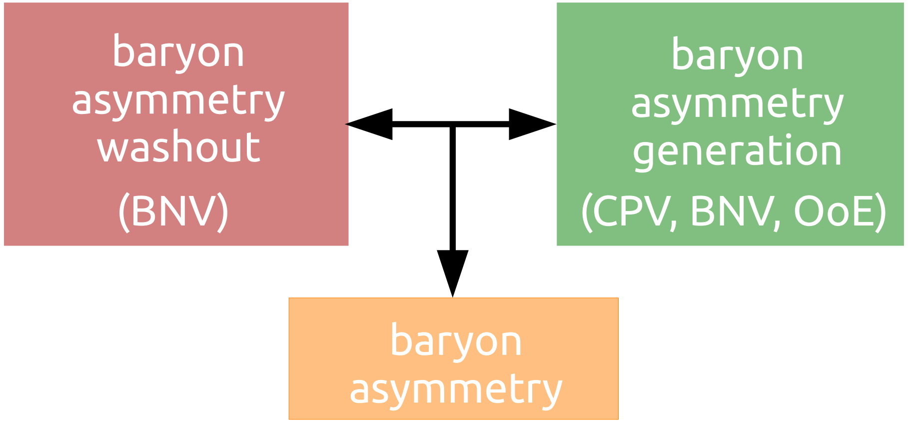
$\langle \mathcal{O}_1(x)\mathcal{O}_2(y)\rangle$ → **f_{NL}, amplitude of $S(k_1,k_3)$**

→ CHC can probe (specific mass range of) high-scale LG

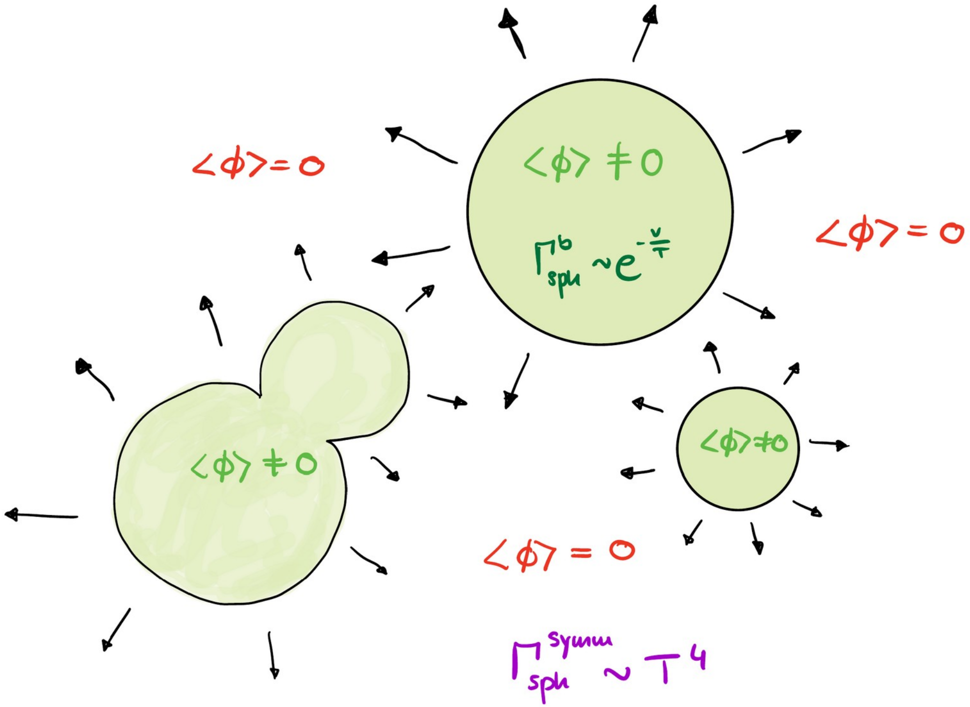
Basic principle of leptogenesis

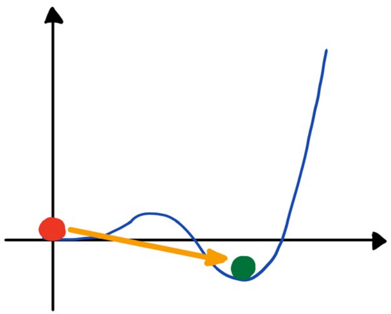


Basic principle of baryogenesis



Electroweak baryogenesis





Unfortunately, Higgs boson is too heavy for EWBG.

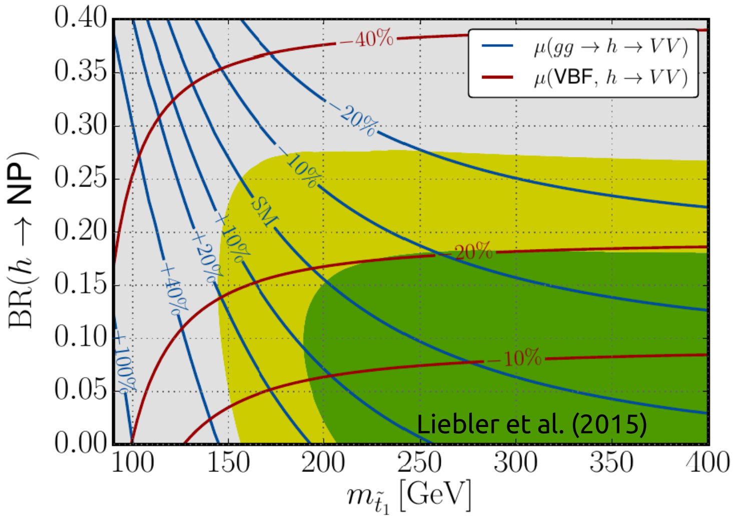
Electroweak baryogenesis including new physics

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….

- **Way out: modified scalar sector, e.g.**
  - vEWBG Fernandez-Martinez, Lopez-Pavon, No, Ota, Rosauro-Alcaraz (2022)
  - EWBG in minimal composite Higgs Bruggisser, von Harling, Matsedonskyi, Servant (2022)
  - 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 challenges:

- Constraints from EDMs
- Higgs physics sets stringent constraints

Beyond electroweak baryogenesis

- **two-step electroweak baryogenesis** — e.g.Patel et al. (2012), Inoue et al. (2015), Blinov et al. (2015)
- **EWBG with modified Higgs potential** — e.g. Modak et al. (2020), Yang et al. (2019), Bell et al (2019)
- **QCD baryogenesis** — e.g. Ipek et al. (2019), Croon et al. (2020)
- **High-scale out-of-equilibrium decay** — e.g. Mohapatra et al. (1980), Babu et al. (2006), Baldes et al. (2011), Babu et al. (2012), Herrmann (2014), Grojean et al. (2019), JH et al (2022)
- **Baryogenesis via oscillations** — e.g. Alonso-Alvarez et al. (2019), Elor et al. (2019)
- **Baryogenesis and Dark Matter** — e.g. Shelton et al. (2010), Hall et al. (2020), Goudelis et al. (2020+), Co et al. (2023)

→ **EDMs**

→ **gravitational waves**

→ **Light particles at colliders**

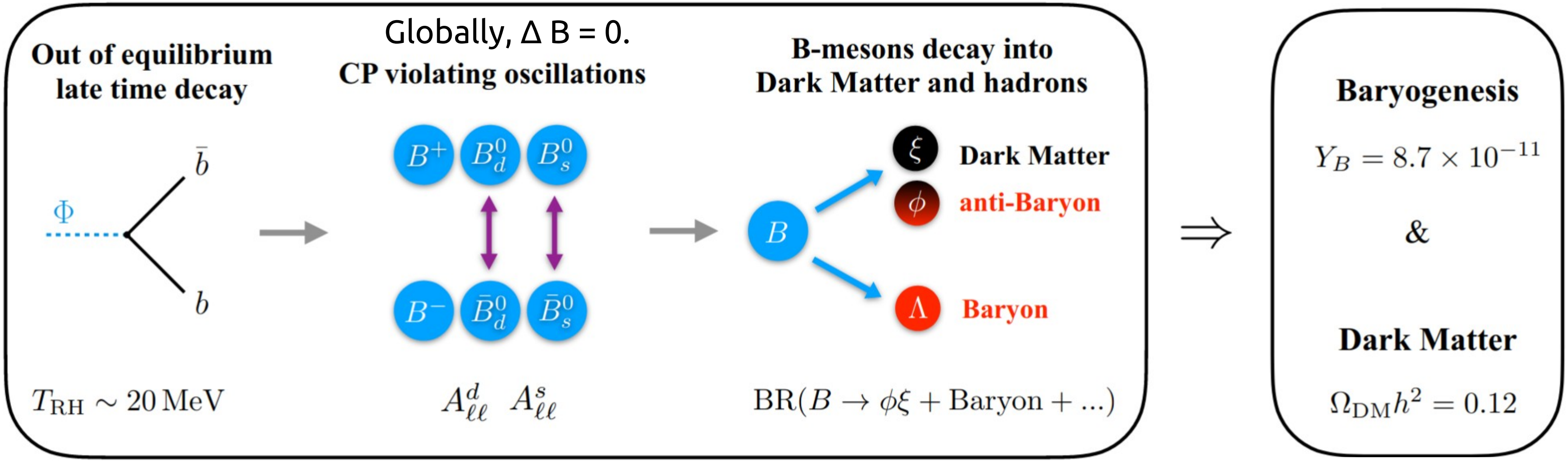
→ **neutron-antineutron oscillations**

→ **Belle, Barbar**

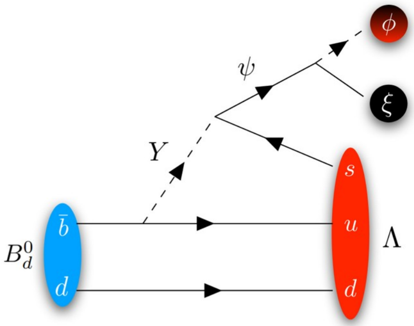
→ **neutrinos**

...and many more

Low-scale baryogenesis: mesogenesis



$$Y_B \propto \sum_{q=s,d} A_{\ell\ell}^q \times \mathrm{Br}(B_q^0 \to \phi\,\xi + \mathrm{Baryon} + X)$$

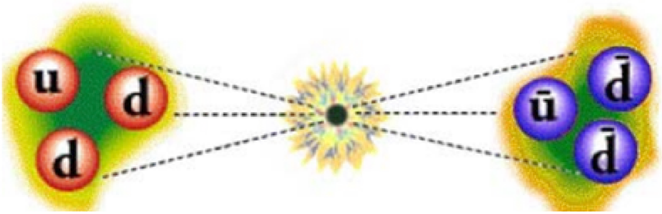


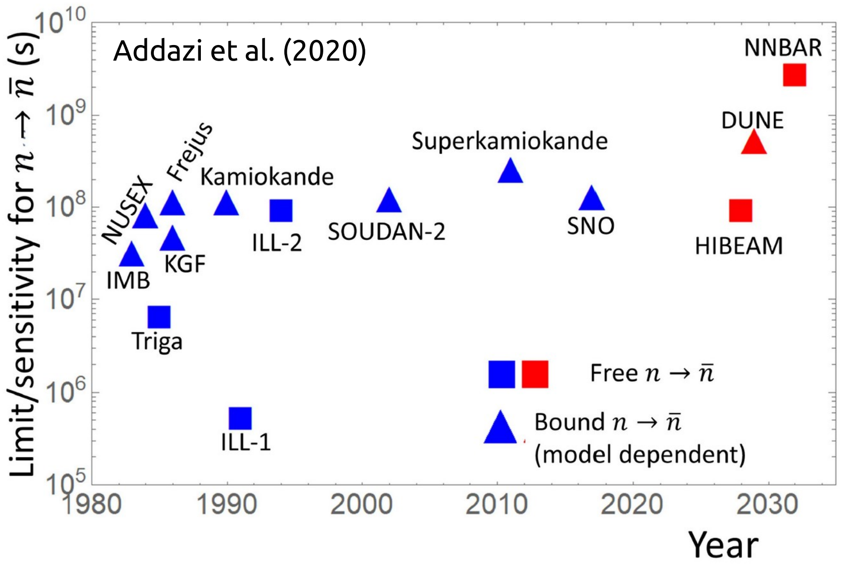
Testable scenario at Belle-II and BarBar!

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

Probing high-scale baryogenesis with nn̄ oscillations

$$\Delta B = 2$$





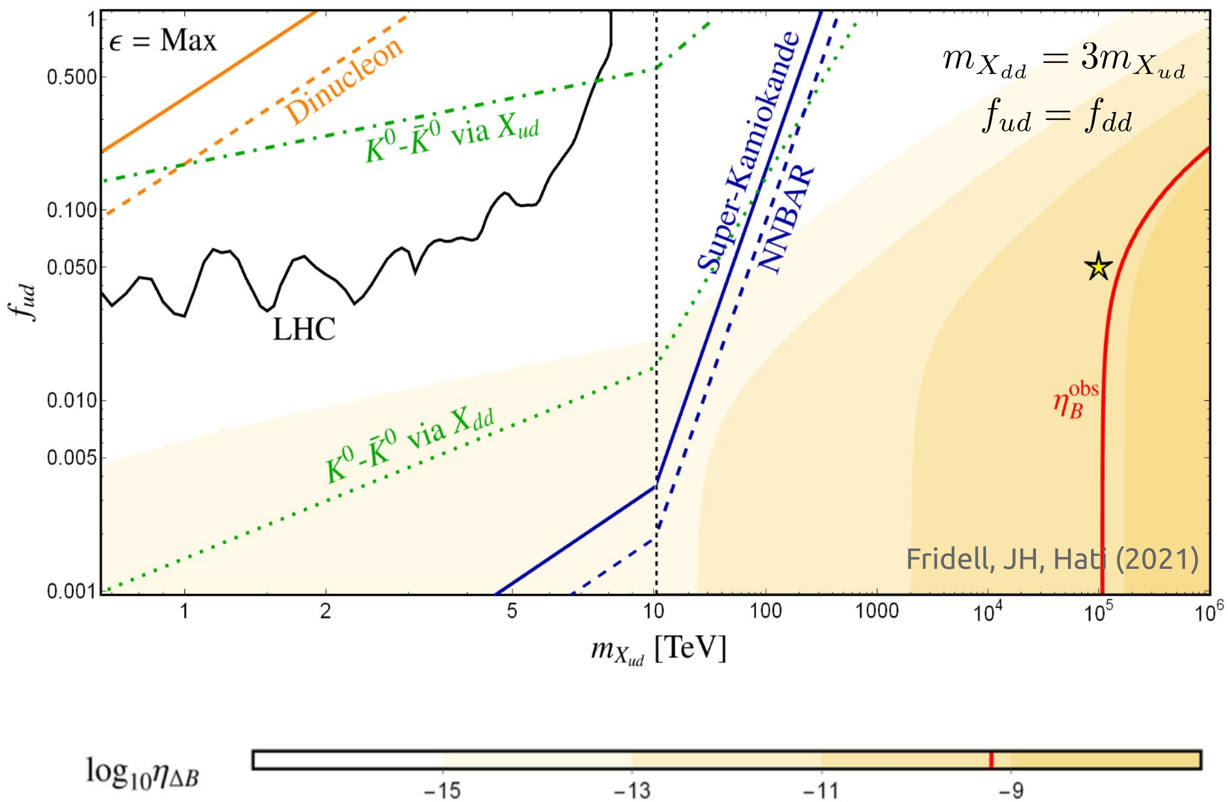
HIBEAM/NNBAR program is a proposed two-stage experiment at the European Spallation Source (ESS) **to search for baryon number violation**.

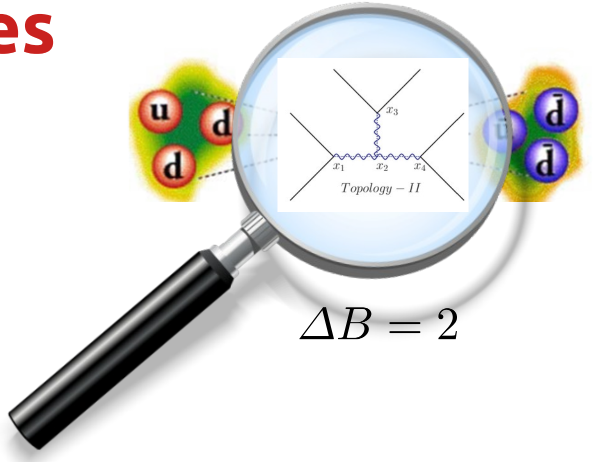
Future sensitivity at ESS: $\tau_{n\bar{n}} \geq 10^{10} s$

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

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

Interplay of different experimental probes





Further relevant high-scale studies:

Fridell, JH, Hati (2021)
Grojean et al. (2019)
Herrmann (2014)
Babu et al. (2012)
Baldes et al. (2011)
Babu et al. (2006)
Mohapatra et al. (1980)

Post-sphaleron studies:

Bell, Corbett, Nee, Ramsey-Musolf (2018)
Babu, Dev, Fortes, Mohapatra (2013)
Babu, Mohapatra (2006)

→ **Interplay between nnbar, meson oscillations and LHC searches.**

Theories and Experiments for Testable Baryogenesis Mechanisms

A Snowmass White Paper

J. L. Barrow*[1], Leah Broussard[2], James M. Cline[3], P. S. Bhupal Dev[4], Marco Drewes[5], Gilly Elor[6], Susan Gardner[7], Jacopo Ghiglieri[8], Julia Harz[9], Yuri Kamyshkov[10], Juraj Klaric[5], Lisa W. Koerner[11], Benoit Laurent[3], Robert McGehee[12], Marieke Postma[13], Bibhushan Shakya[14], Robert Shrock[15], Jorinde van de Vis[14], and Graham White†[16]

arxiv:hep-ph/2203.07059

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

New Ideas in Baryogenesis: A Snowmass White Paper

Editors: Gilly Elor,[1] Julia Harz,[2] Seyda Ipek,[3] Bibhushan Shakya.[4]

Authors: Nikita Blinov,[5] Raymond T. Co,[6] Yanou Cui,[7] Arnab Dasgupta,[8] Hooman Davoudiasl,[9] Fatemeh Elahi,[1] Gilly Elor,[1] Kåre Fridell,[2] Akshay Ghalsasi,[8] Keisuke Harigaya,[10] Julia Harz,[2] Chandan Hati,[2] Peisi Huang,[11] Seyda Ipek,[3] Azadeh Maleknejad,[10] Robert McGehee,[12] David E. Morrissey,[13] Kai Schmitz,[10] Bibhushan Shakya,[4] Michael Shamma,[13] Brian Shuve,[14] David Tucker-Smith,[15] Jorinde van de Vis,[4] Graham White.[16]

arxiv:hep-ph/2203.05010

Contents

Conclusions

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

- Rich probes by combining energy, intensity, long-life time and gravitational wave frontiers

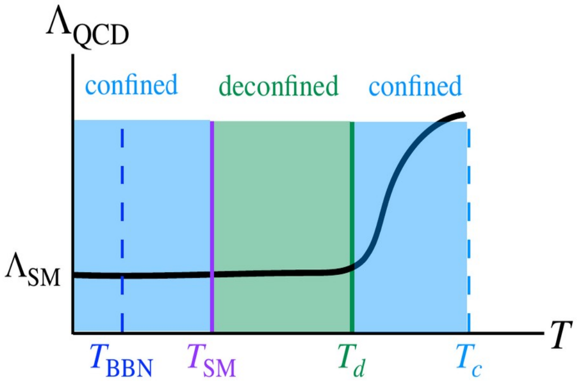
- Tantalizing possible connection to neutrino physics and dark matter

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

Thank you for your attention!

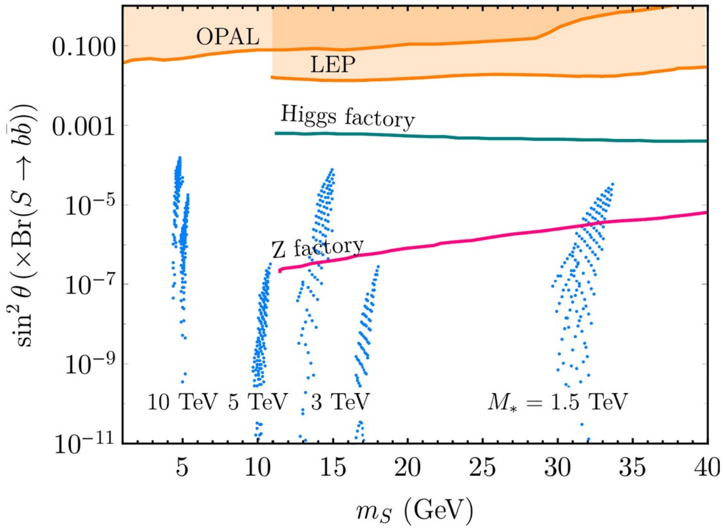
QCD baryogenesis

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)