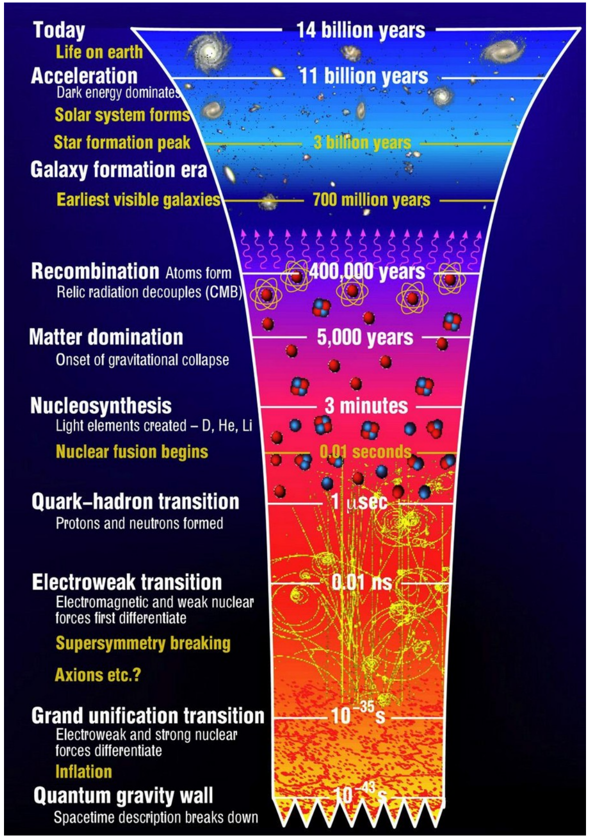
Charting the Landscape of Leptogenesis

Julia Harz

December 7th 2022
Dark Side of the Universe Workshop, UNSW Sydney

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

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

Big Bang Nucleosynthesis

3 min after Big Bang

Deuterium Bottleneck

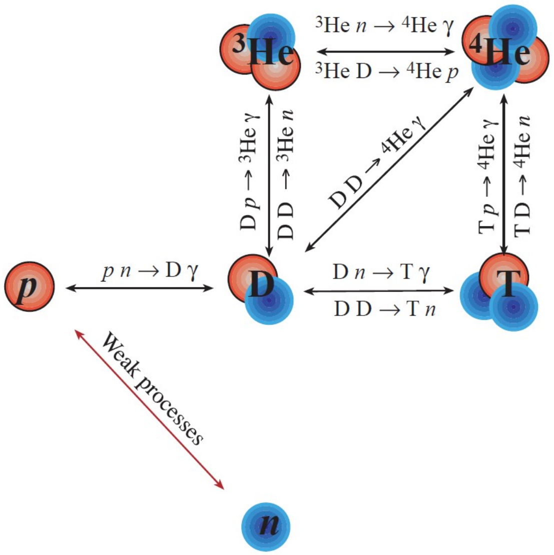
Nucleosynthesis starts with formation of Deuterium (D)

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

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

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

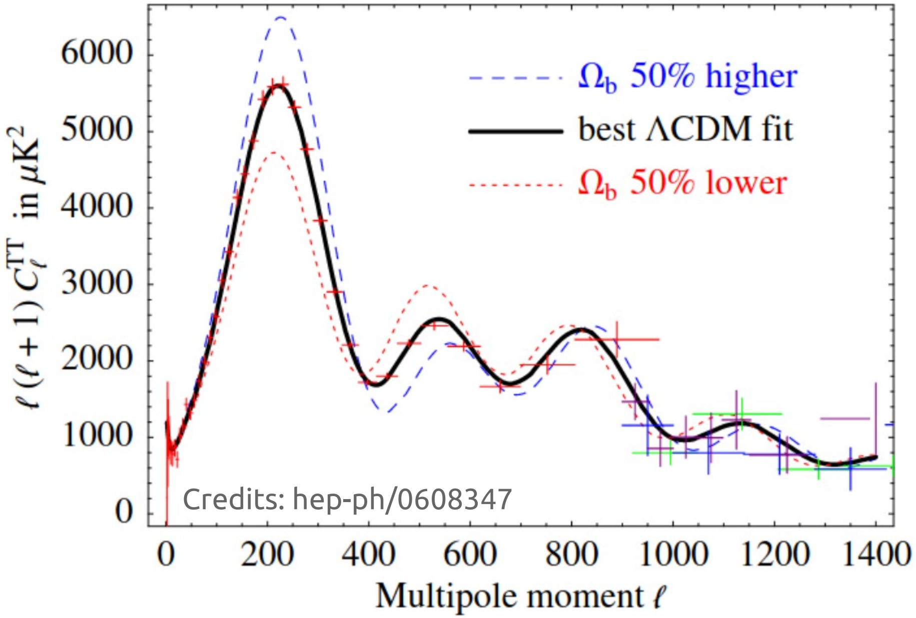
$$\eta_B^{\text{obs}} = (6.14 \pm 0.19) \times 10^{-10}$$



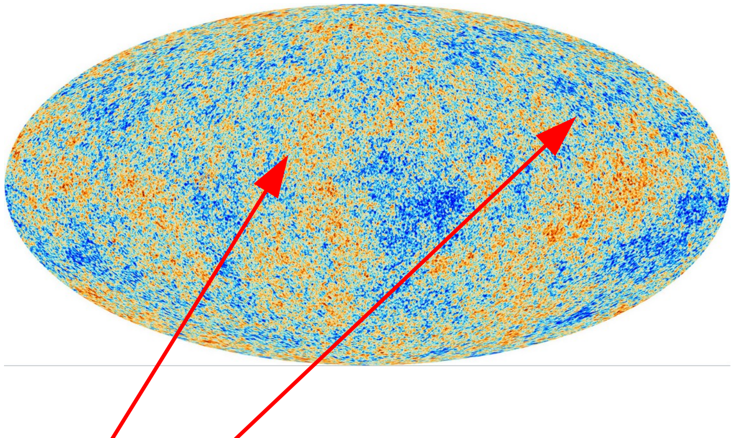
Credits: hep-ph/0608347

Cosmic Microwave Background (CMB)

400.000 years after Big Bang

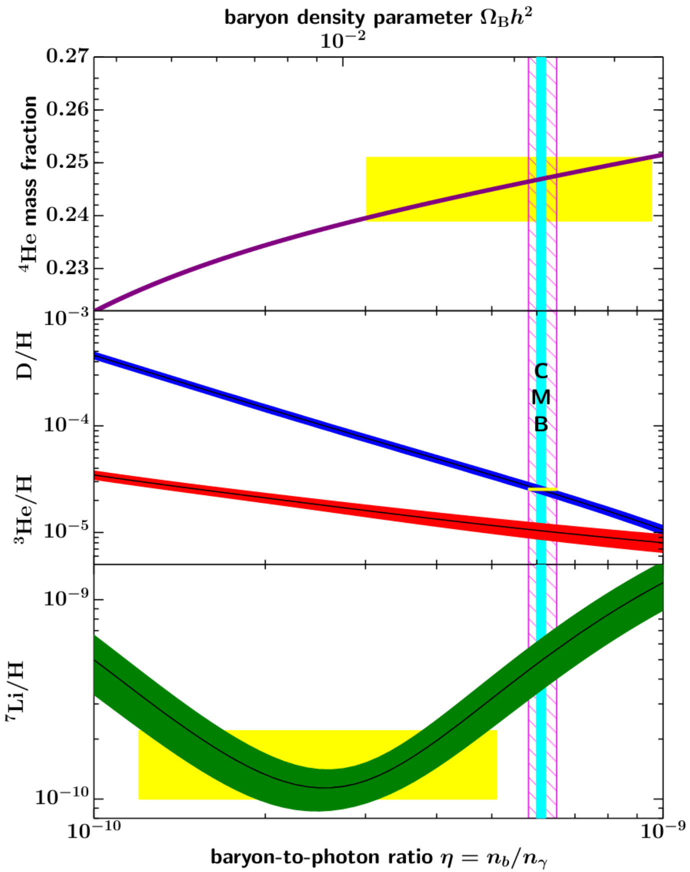


Credits: hep-ph/0608347



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

Combination of BBN & CMB

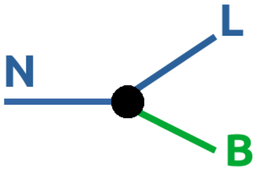


Excellent agreement even though measurements originate from two different epochs!

Why do we need new physics?

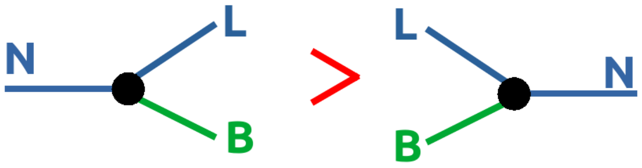
Theoretically, we know the conditions on interactions that have to be fulfilled (Sakharov conditions).

- ☐ B-L violation

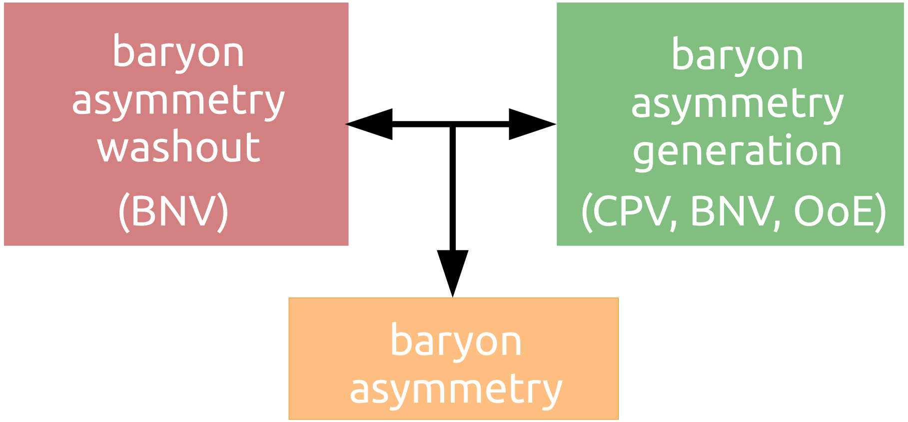


- ☐ C and CP violation

- ☐ departure from thermal equilibrium



Basic principle of baryogenesis



baryon asymmetry washout

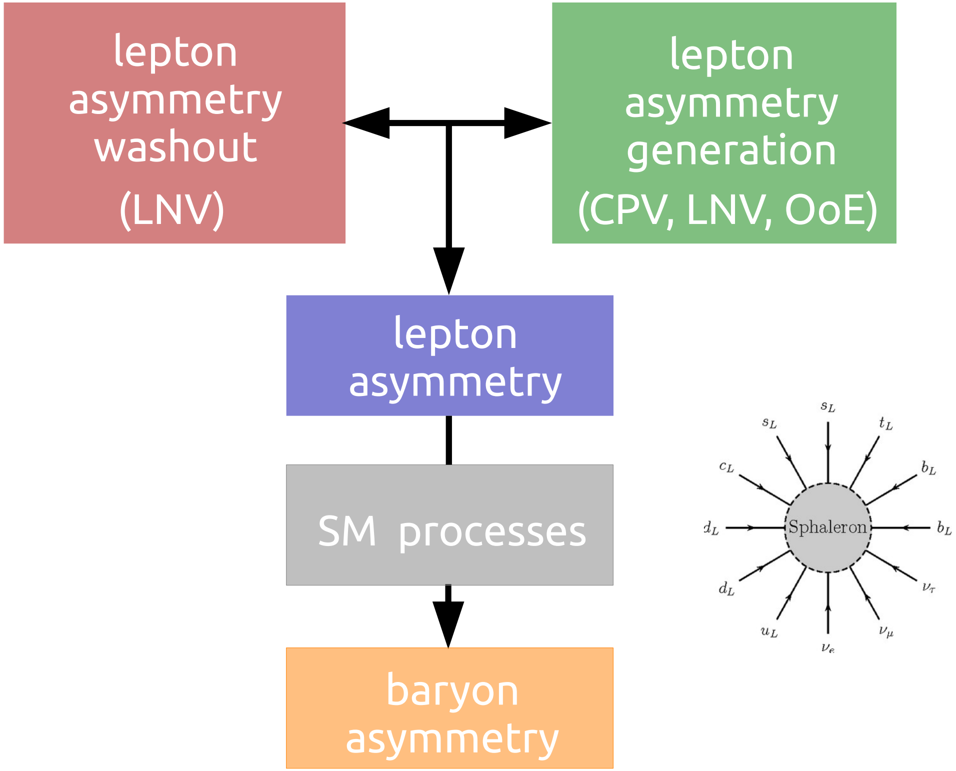
(BNV)

baryon asymmetry generation

(CPV, BNV, OoE)

baryon asymmetry

Basic principle of leptogenesis



lepton asymmetry washout
(LNV)

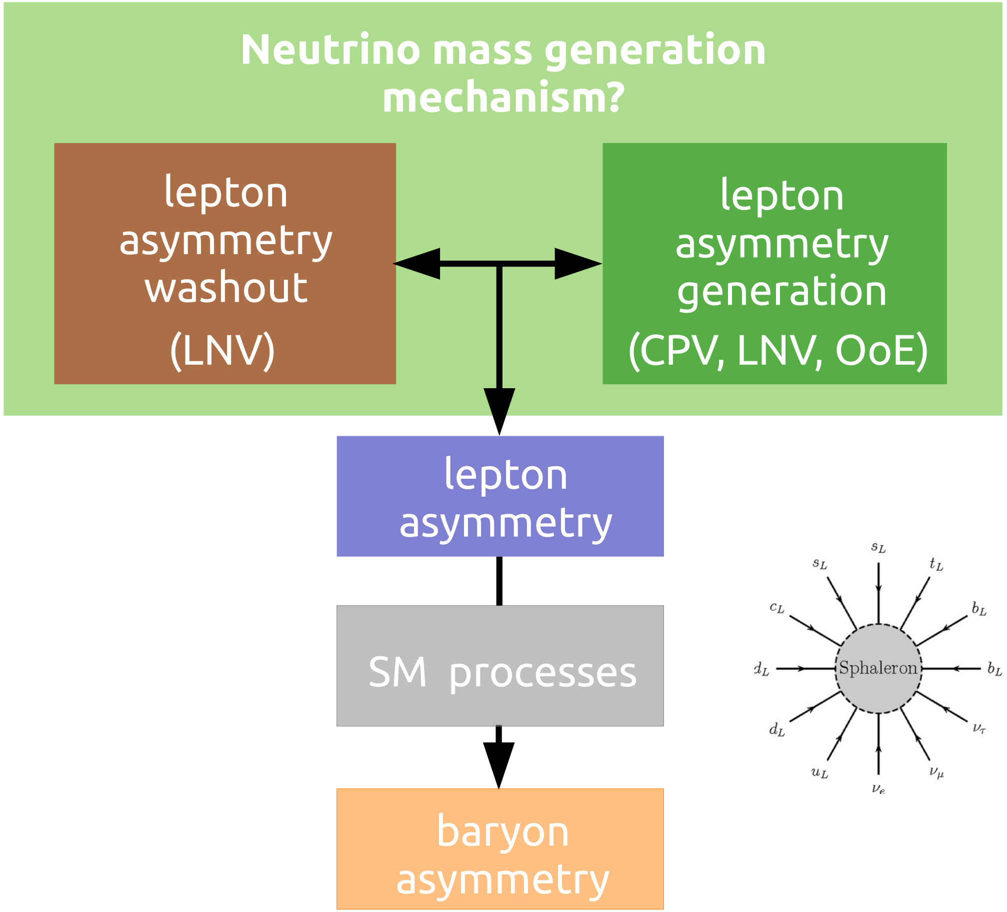
lepton asymmetry generation
(CPV, LNV, OoE)

lepton asymmetry

SM processes

baryon asymmetry

Basic principle of leptogenesis



Neutrino mass generation mechanism?

lepton asymmetry washout

(LNV)

lepton asymmetry generation

(CPV, LNV, OoE)

lepton asymmetry

SM processes

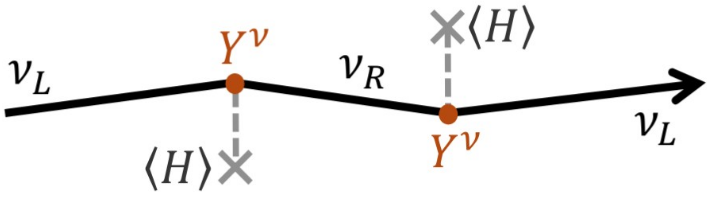
baryon asymmetry

Neutrino mass mechanism - Dirac or Majorana?

Dirac mass

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

→ **lepton number no accidental symmetry anymore**



Majorana mass

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

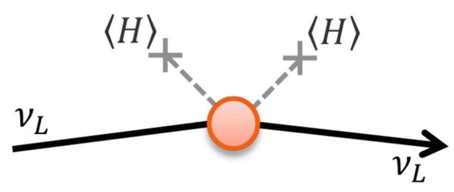
$m_M \overline{\nu}_L \nu_L^c$

not at tree-level within the SM possible

$LLHH$

dim-5 Weinberg-operator

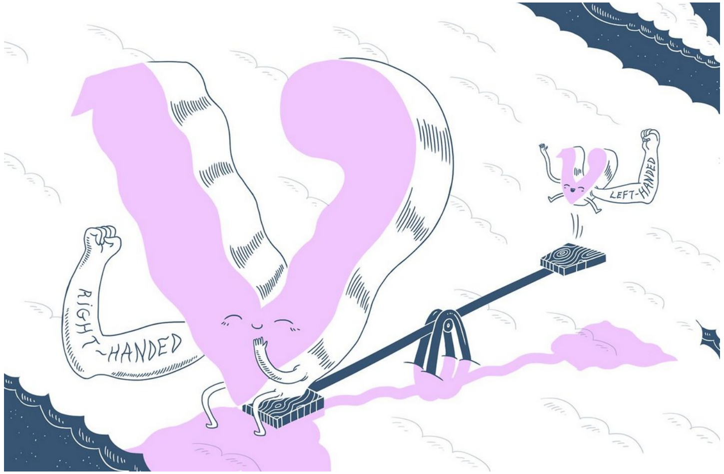
→ **Lepton number violation (LNV)**



See-saw I neutrino mass mechanism

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

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



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

Low-scale leptogenesis

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

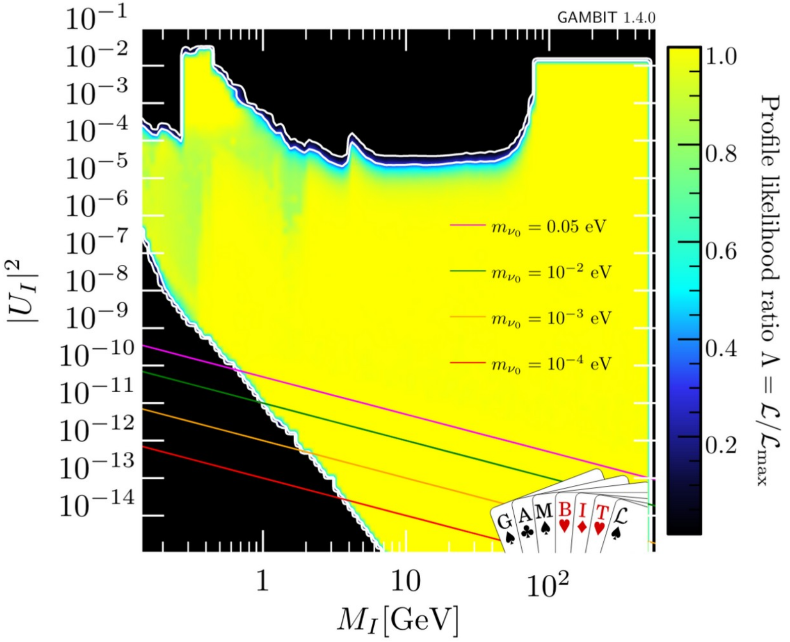
High-scale leptogenesis

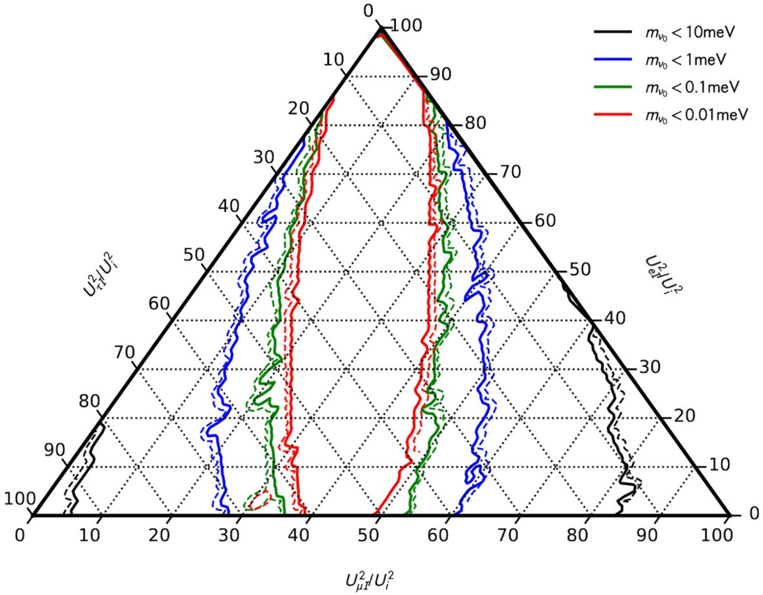
Constraints on right-handed neutrinos

Most comprehensive 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

Combining in a rigorous statistic manner:

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

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…

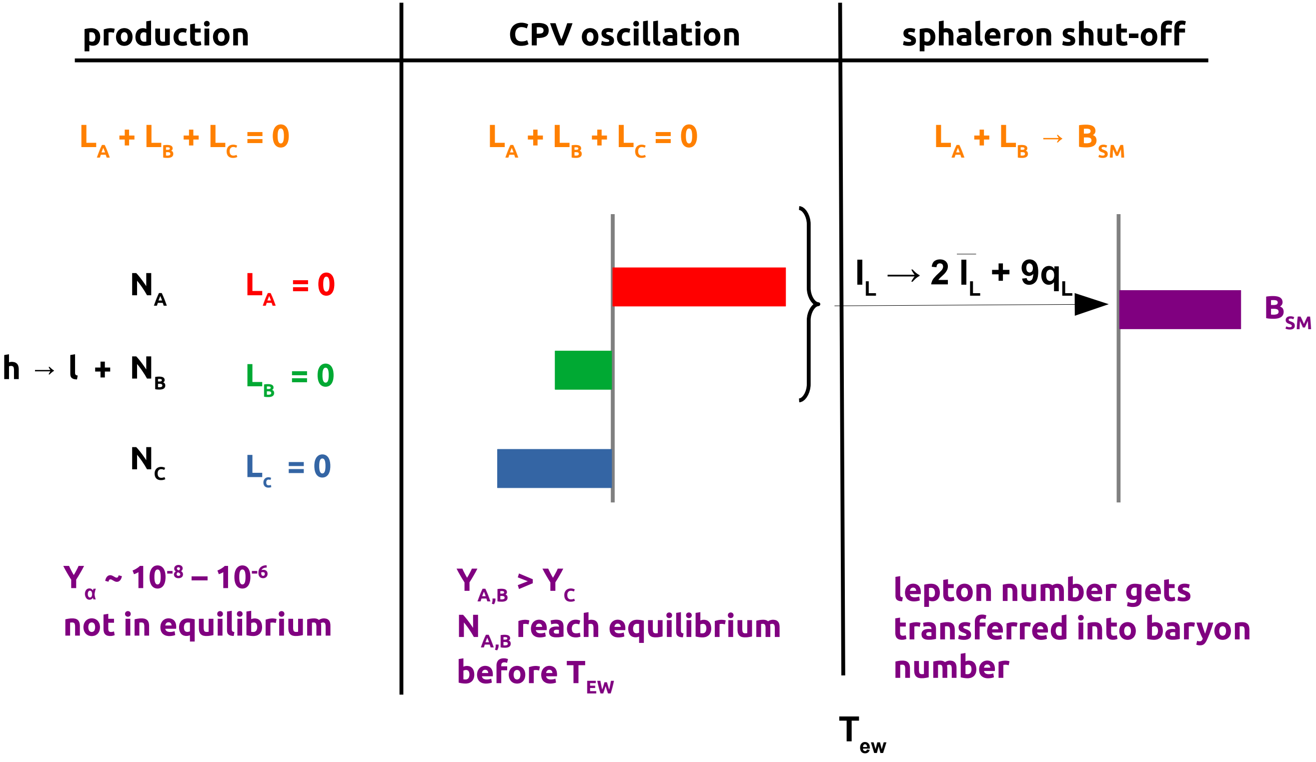
High-scale leptogenesis

- 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)

… and many more …

Leptogenesis via oscillations

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



production

$L_A + L_B + L_C = 0$

N_A $L_A = 0$

$h \to l + N_B$ $L_B = 0$

N_C $L_c = 0$

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

CPV oscillation

$L_A + L_B + L_C = 0$

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

sphaleron shut-off

$L_A + L_B \to B_{SM}$

$l_L \to 2\,\bar{l}_L + 9q_L$

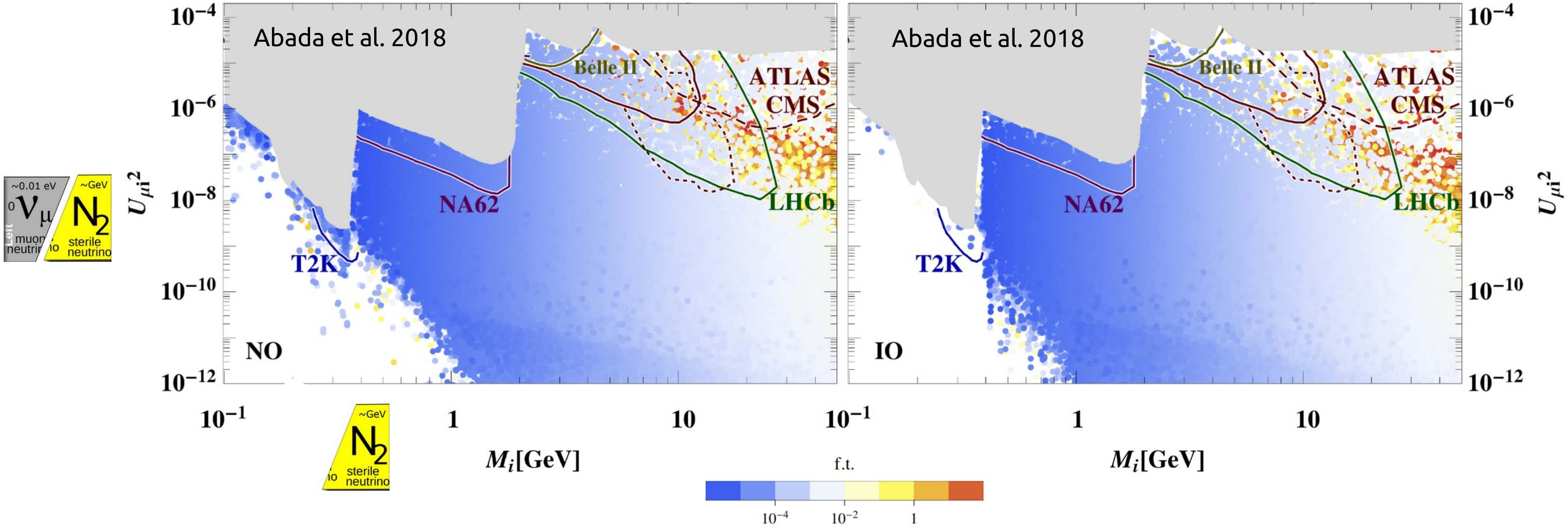
B_{SM}

lepton number gets transferred into baryon number

T_{ew}

Probing leptogenesis via oscillations

Seesaw type I with *three* right-handed neutrinos: the parameter space allows for successful leptogenesis:



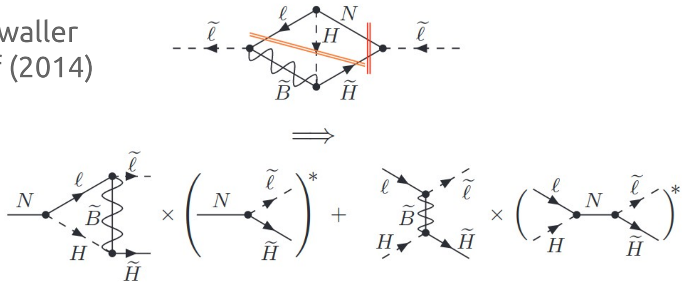
For N=2 see also: Hernandez et al. 2015, Abada et al. 2015, Drewes et al. 2016

Leptogenesis via oscillations opens up a window to many experimental tests!

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)
- Investigations of IR convergence behaviour Beneke, Garbrecht, Herranen, Schwaller (2010), Garbrecht, Ramsey-Musolf (2014)
- Investigations spectator effects Garbrecht, Schwaller (2014), Garbrecht, Klose, Tamarit (2020)



Low-scale Leptogenesis:

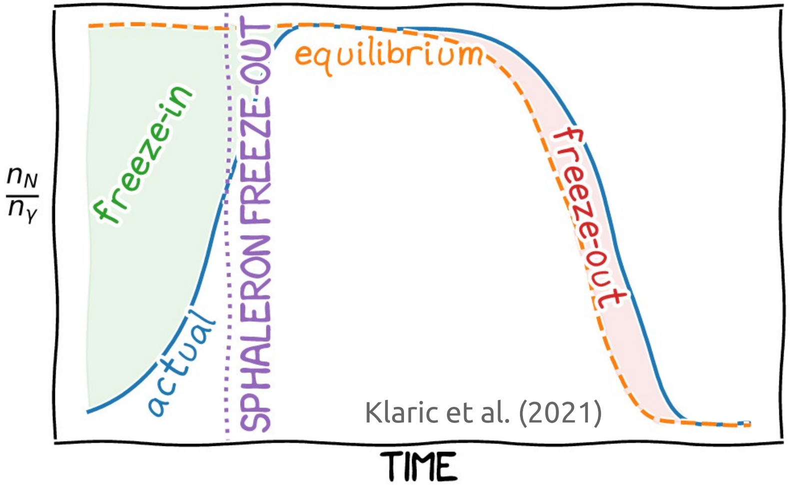
- Generalization of Sigl+Raffelt treatment of relativistic mixed neutrinos with additional heavy states

Sigl, Raffelt (1993), Akhmedov, Rubakov, Smirnov (1998), Asaka, Shaposnikov (2005), Shaposnikov (2007, 2008), Shuve, Yavin (2014), Drewes, Garbrecht, Gueter, Klaric (2016), Ghiglieri, Laine (2016, 2019, 2020)

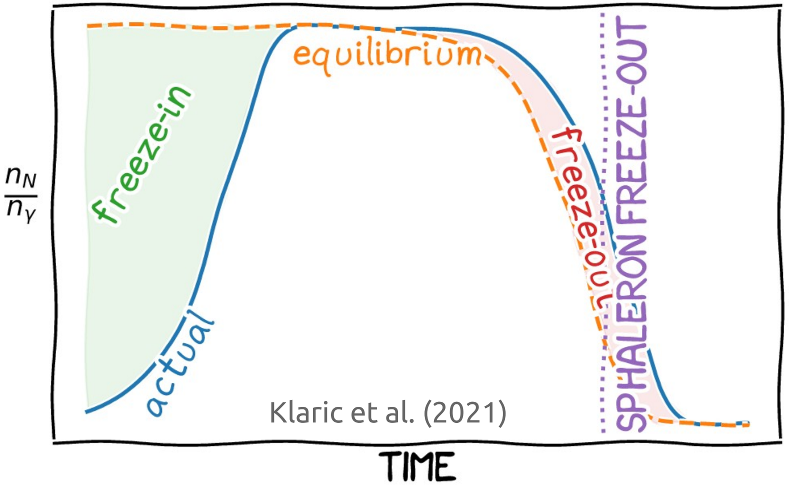
How to bridge both regimes? How accurate is the regime in between with respect to experimental constraints?

Mind the gap?

- **Importance of non-relativistic corrections** Hambye, Teresi (2016), Eijima, Shaposhnikov (2017), Ghiglieri, Laine (2017)
- **Generalization of quantum kinetic equations to include non-relativistic case** Klaric, Shaposnikov, Timiryasov (2020, 2021)



Klaric et al. (2021)



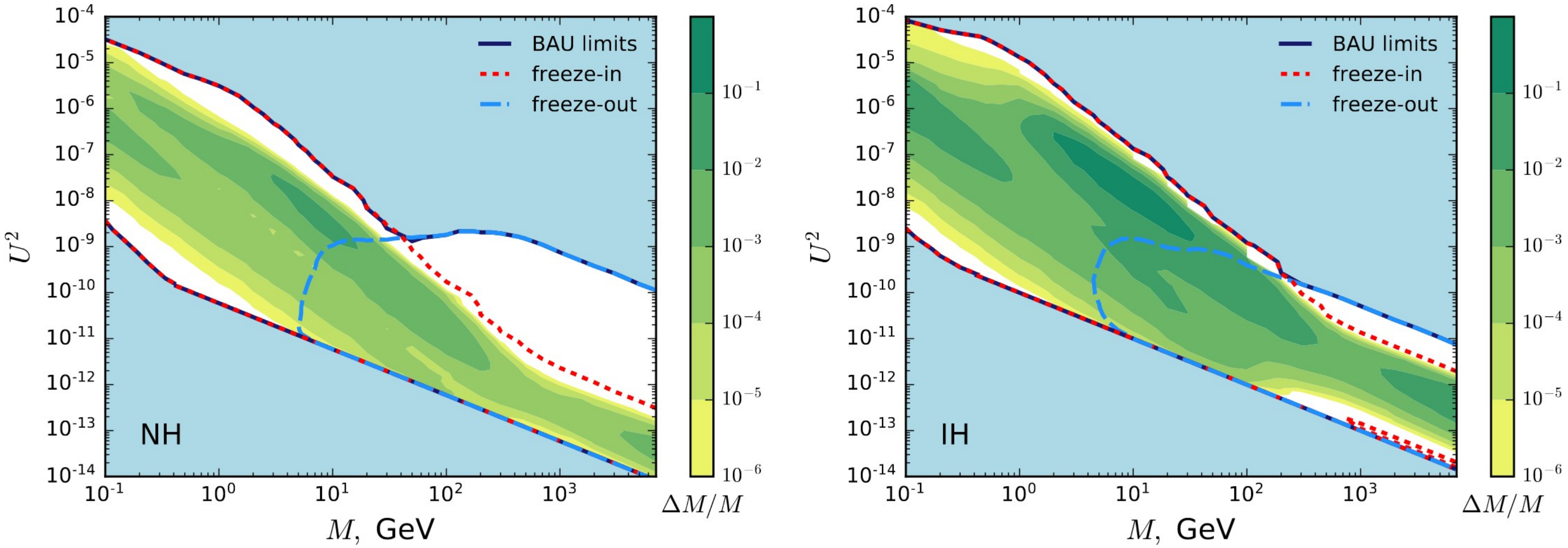
Klaric et al. (2021)

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

Links to previous works by Hernandez, Kekic, Lopez-Pavon, Racker, Salvado (2016), Antusch, Cazzato, Drewes, Fischer, Garbrecht, Gueter, Klaric (2018), Hambye, Teresi (2016, 2017), Granelli, Moffat, Petcov (2020)

Mind the gap?

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

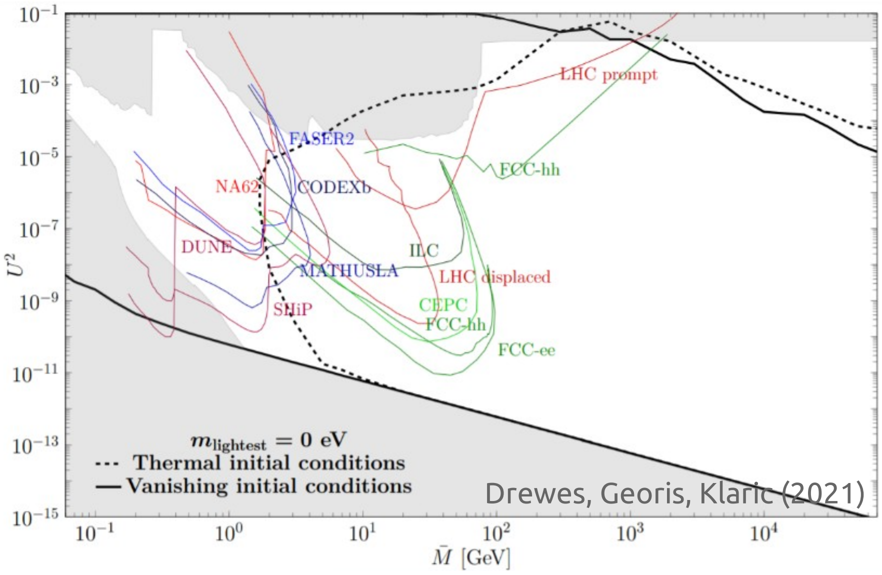


Both regimes overlap!
→ freeze-in relevant up to TeV range
→ freeze-out down to 5 GeV

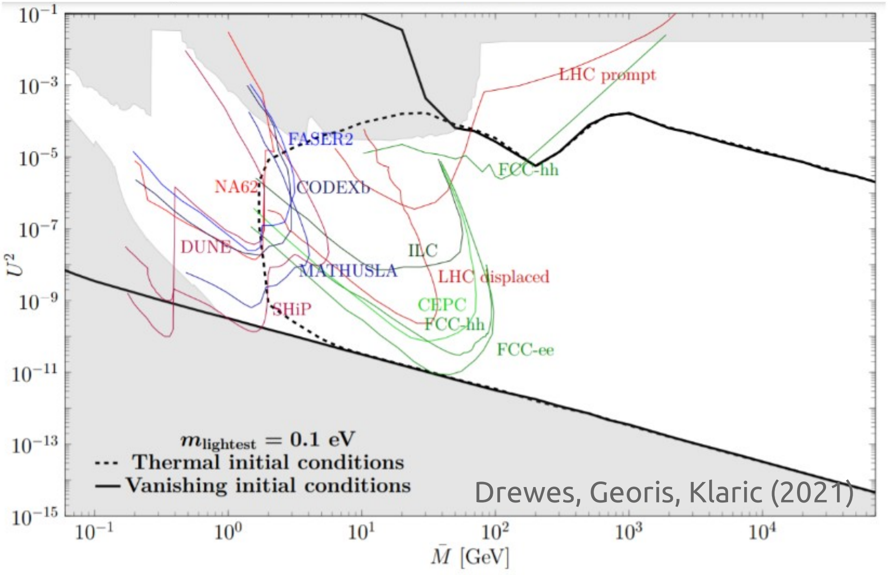
Mapping the viable parameter space of testable LG

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

Drewes, Georis, Klaric (2021)



Drewes, Georis, Klaric (2021)



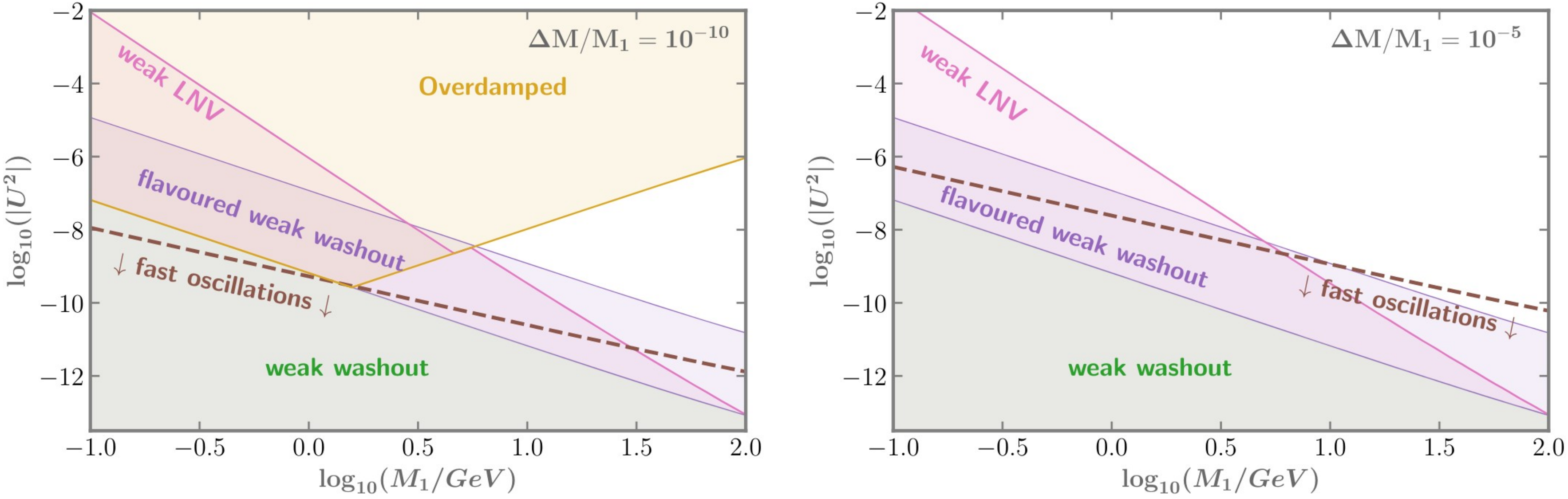
Drewes, Georis, Klaric (2021)

→ **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

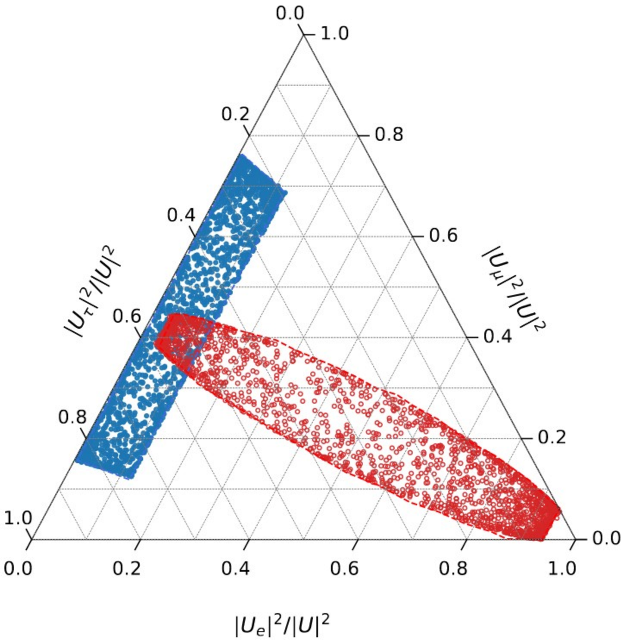
Hernandez, Pavon, Rius, Sandner (2022)



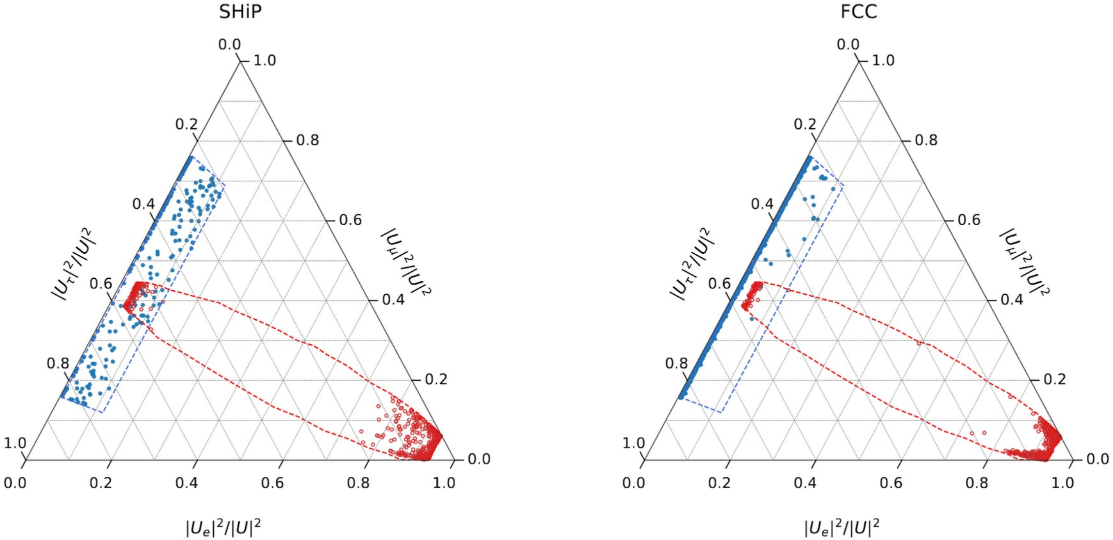
Analytic understanding via CP flavour invariants

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

Hernandez, Pavon, Rius, Sandner (2022)



$\Delta M/M = \text{free}$



$\Delta M/M = 10^{-2}$

→ **for large mass splittings successful BAU requires weak flavour washout**

Flavoured leptogenesis

- 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-trivial chemical background with conserved charges that can take arbitrary values at LG:

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

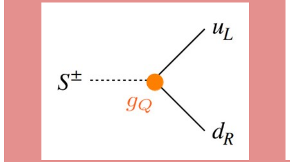
Falsifying leptogenesis with TeV-scale LNV

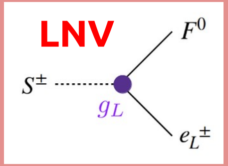
Right-handed neutrino interactions (“standard thermal LG”):

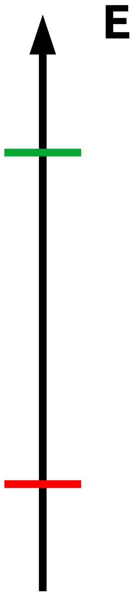
$$\mathcal{L} \supset y_\nu \bar{L} H N - \frac{m_N}{2}\bar{N}^c N + \text{h.c.}$$

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

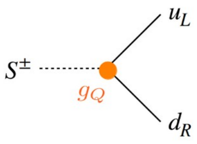
TeV-scale LNV “washout” interactions

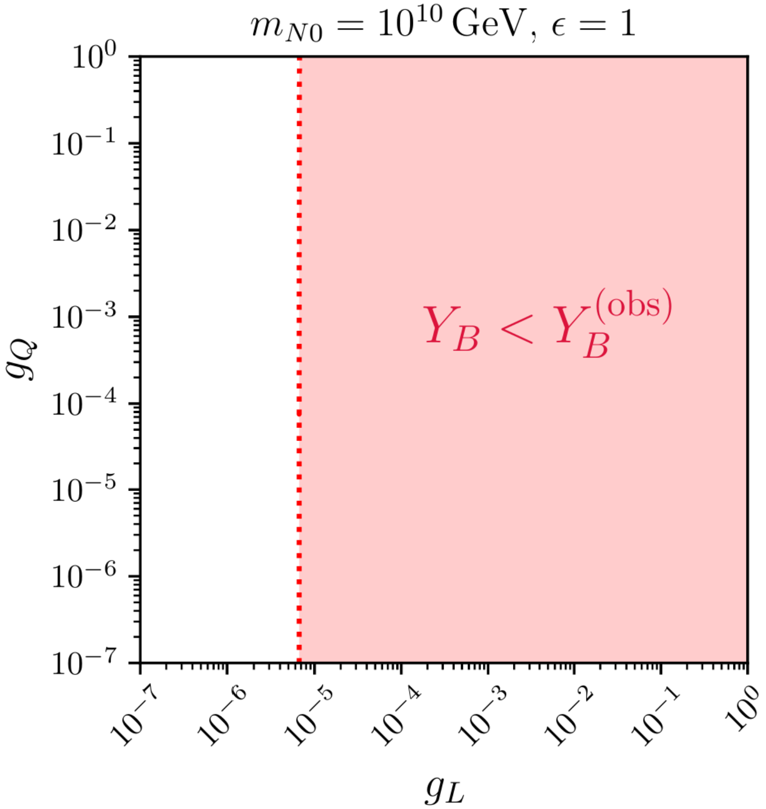
Can TeV-scale LNV destroy the generated asymmetry from standard thermal LG?

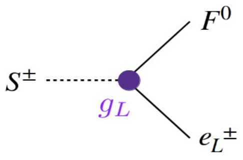
JH, Ramsey-Musolf, Shen, Urrutia-Quiroga (2021)

Falsifying leptogenesis with TeV-scale LNV

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





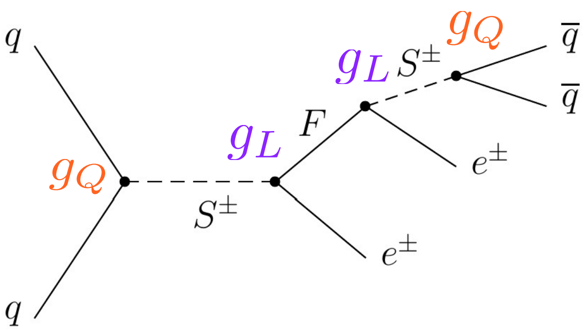


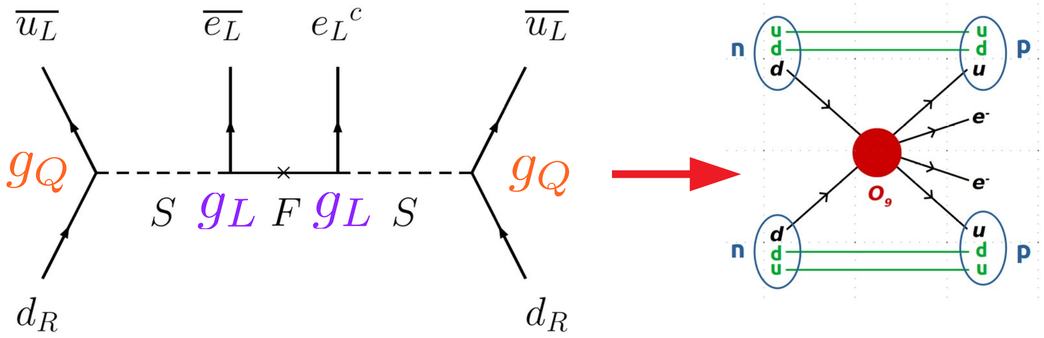
TeV-scale LNV washes-out lepton asymmetry previously generated by standard LG scenario.

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

Falsifying leptogenesis with LHC and 0νββ decay

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





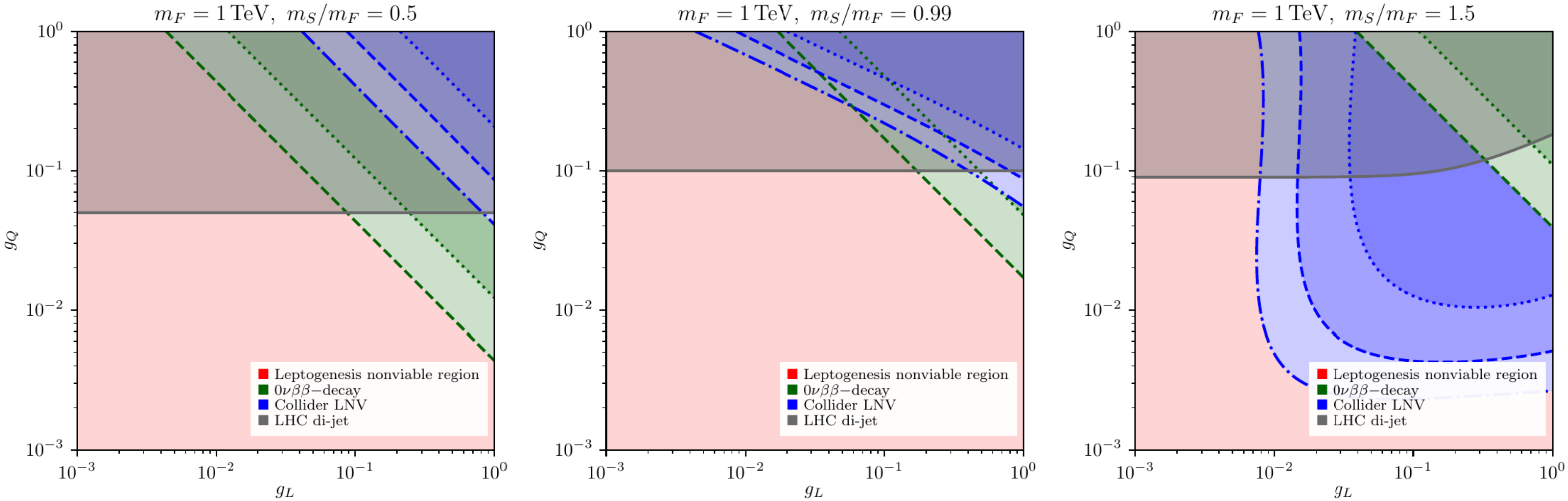
Observation of any LNV washout process at the LHC would falsify high-scale leptogenesis.

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

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

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**

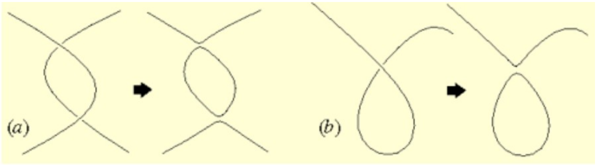
JH, Ramsey-Musolf, Shen, Urrutia-Quiroga (2021)

Probing leptogenesis with GWs from cosmic strings

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 GWs from cosmic strings

Right-handed neutrinos require a mass – 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

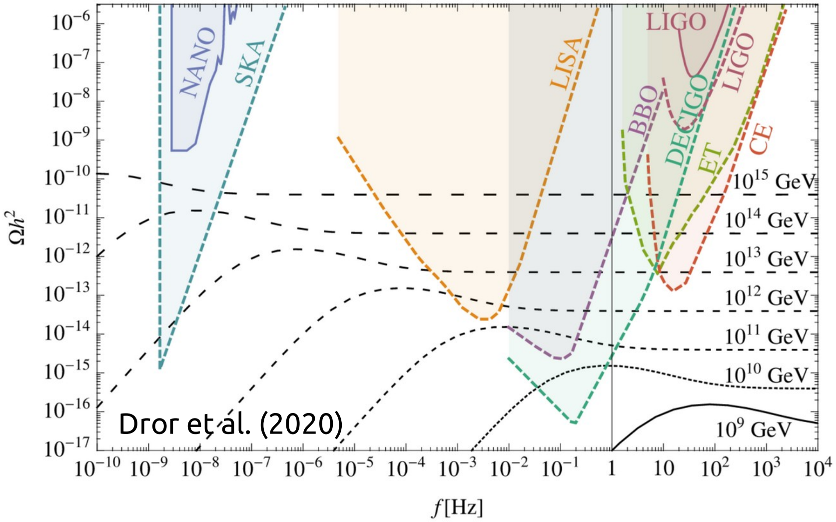
$$\Omega_{\mathrm{GW}}h^2 \propto G\mu^2$$

$$\mu \sim v^2$$

cosmic string tension

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

Hindmarsh (2011)
Buchmueller et al. (2013)



Dror et al. (2020)

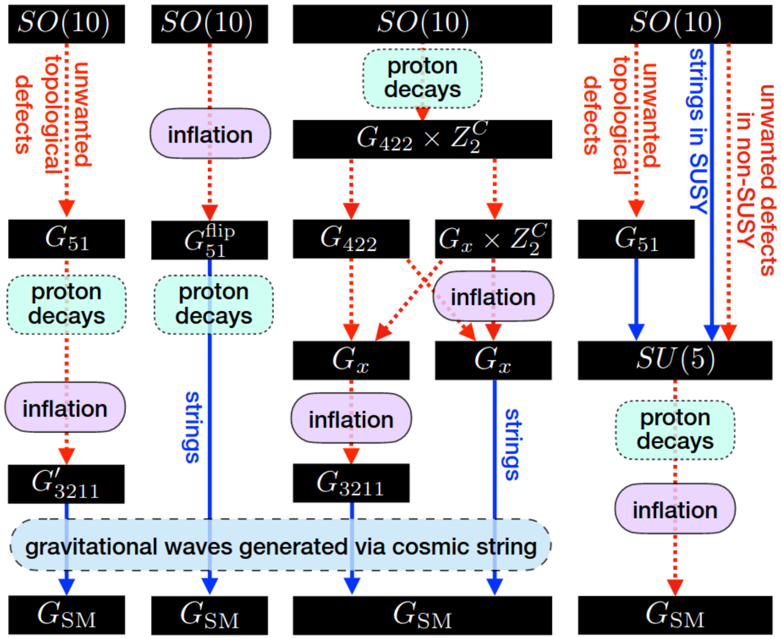
Vibrant field, many recent exciting works:

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

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)



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

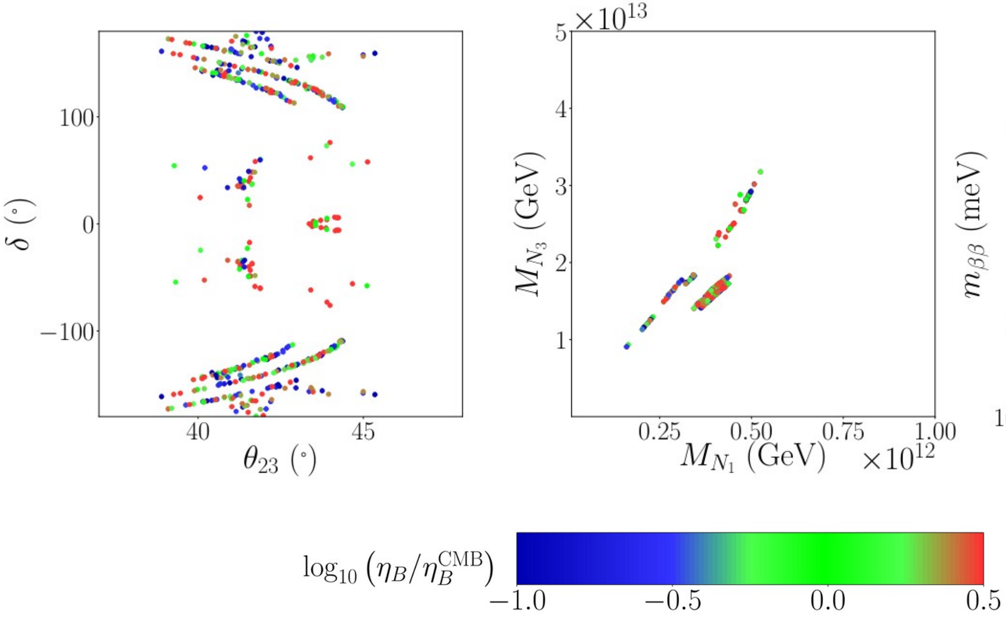
Proton decay (at M_X)

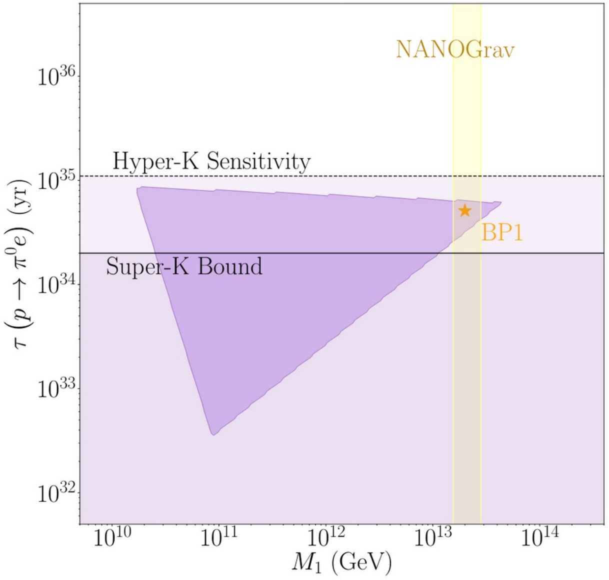
$U(1)_{B\text{-}L}$ breaking (at M_1)
→ cosmic strings, N mass generation via seesaw type I

Confronting SO(10) GUTs with proton decay and GWs

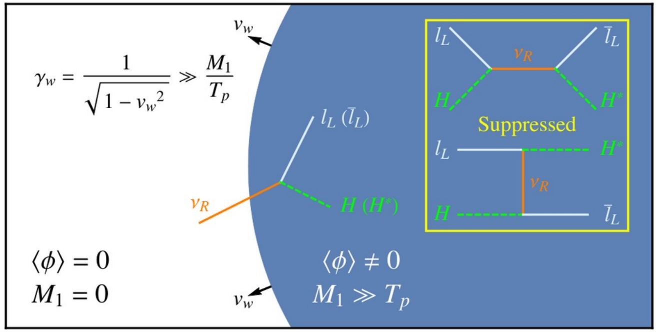
Exploring GUT models with potential of successful leptogenesis

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





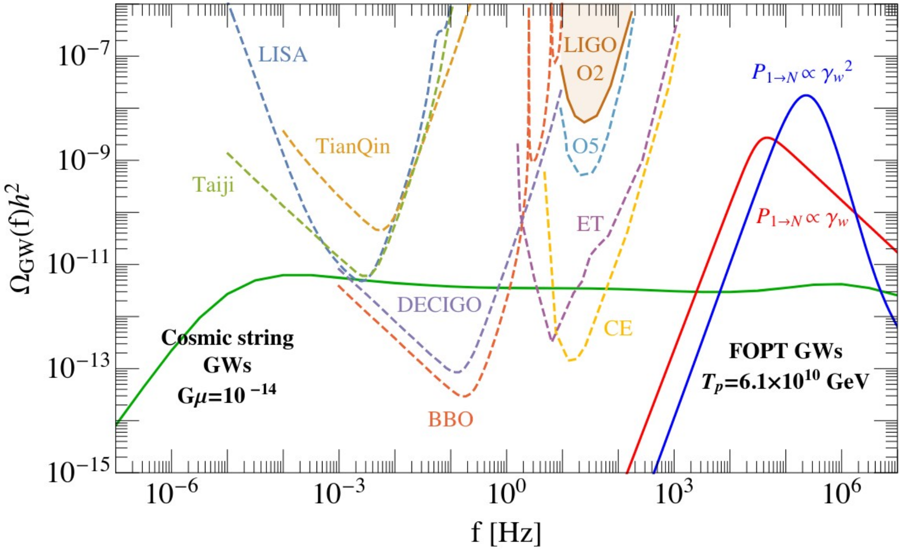
Probing leptogenesis with GWs from FOPT



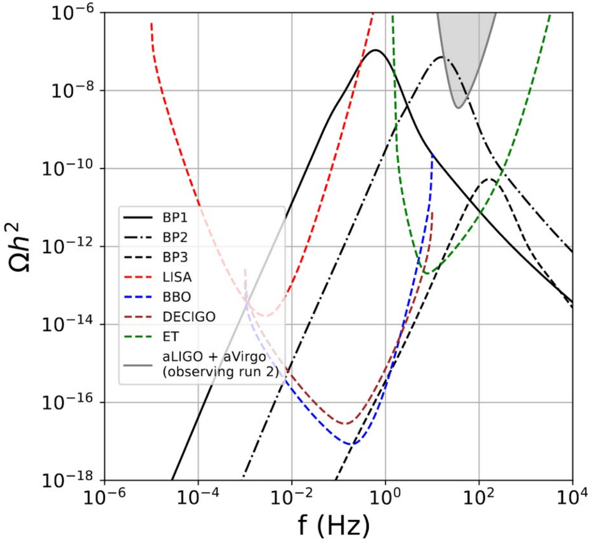
Leptogenesis based on mass gain mechanism with first order phase transition

Azatov, Vanvlasselaer (2020)
Azatov, Vanvlasselaer, Yin (2020), Baldes, Blasi, Mariotti, Sevrin, Trubang (2021)
Dasgupta, Dev, Ghoshal, Mazumdar (2022), Huang, Xie (2022)

High-scale leptogenesis Huang, Xie (2022)



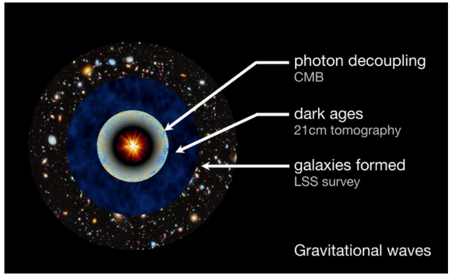
Resonant leptogenesis Dasgupta, Dev, Ghoshal, Mazumdar (2022)

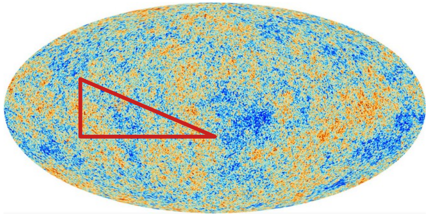


Cosmological (higgs) collider as novel probe for LG

Idea: Use the Universe as gigantic "cosmic collider"

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

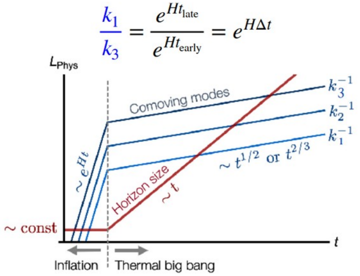




3-point function = higher order correlations
→ non-Gaussianities

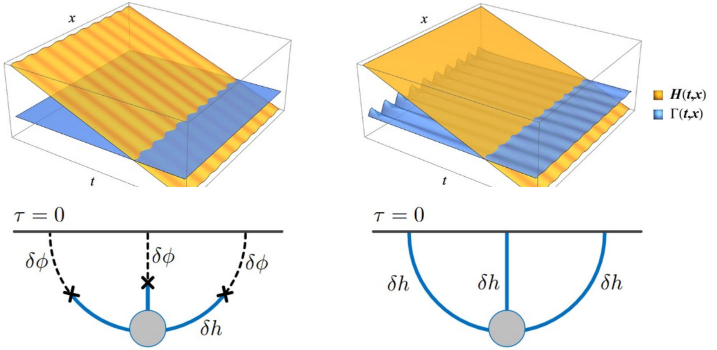
→ **info about particle interaction with inflaton**

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



$$S(k_1, k_3) \propto e^{-\pi m/H} e^{im\Delta t}$$
$$\sim e^{-\pi m/H} (k_1/k_3)^{im/H}$$

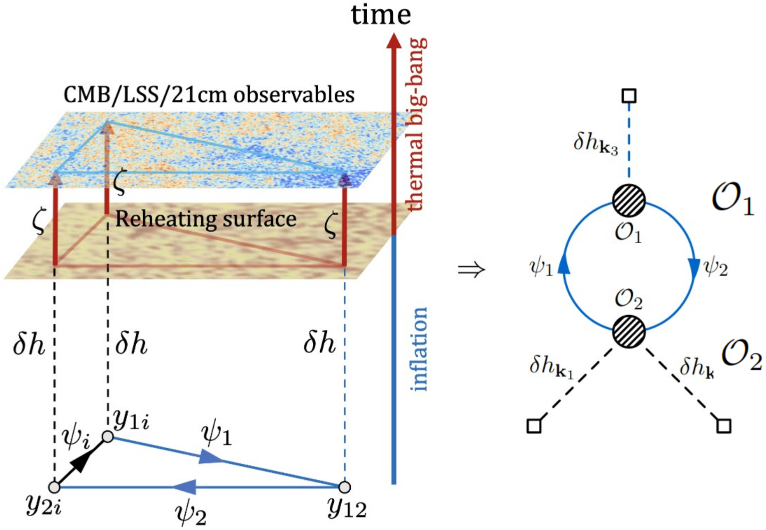
Specfic set-up: Cosmic Higgs collider



Liu, Wang, Xianyu (2019)

Cosmological (higgs) collider as novel probe for LG

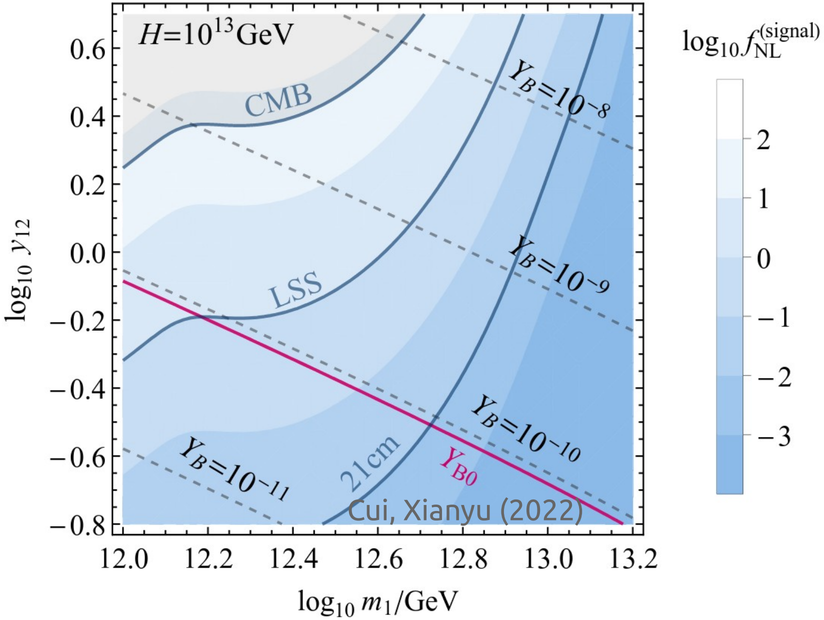
Heavy RHN (~ H) that couple to Higgs as heavy particle to probe at a CHC Cui, Xianyu (2022)



$$\mathcal{O}_1 \equiv y_{12}(e^{i\varphi_{12}}\psi_1\psi_2 + \text{c.c.})$$

$$\mathcal{O}_2 \equiv \frac{1}{\Lambda}(e^{i\varphi_5}\psi_1\psi_2 + \text{c.c.})$$

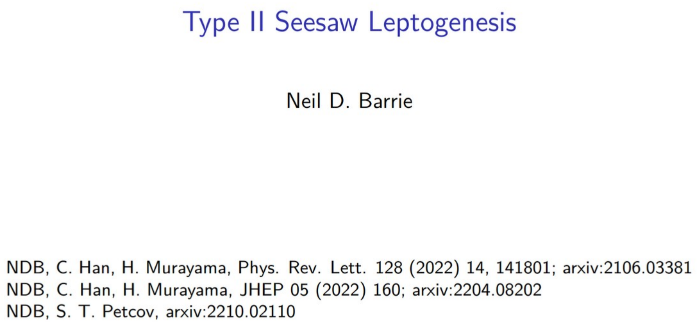
$$\langle \mathcal{O}_1(x)\mathcal{O}_2(y)\rangle = -\frac{4y_{12}}{\Lambda}\Big[\cos(\varphi_{12}+\varphi_5)g_{m_1}(x,y)g_{m_2}(x,y) + \cos(\varphi_{12}-\varphi_5)f_{m_1}(x,y)f_{m_2}(x,y)\Big] \xrightarrow{\quad} \textbf{Signal strength } f_{NL}$$



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

… not the end …

Leptogenesis via Affleck-Dine mechanism



Type II Seesaw Leptogenesis

Neil D. Barrie

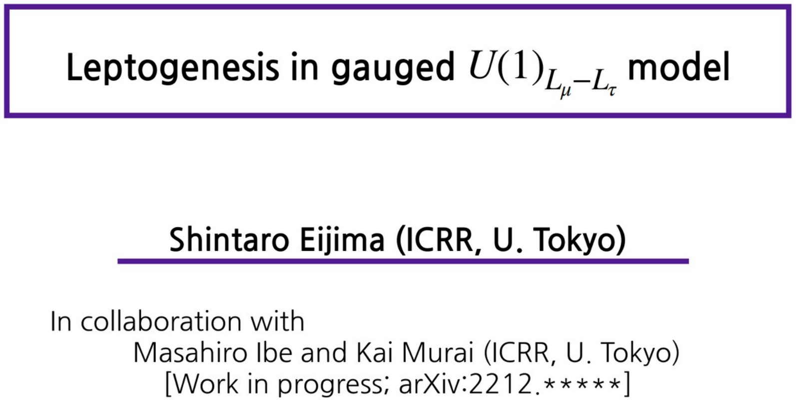
NDB, C. Han, H. Murayama, Phys. Rev. Lett. 128 (2022) 14, 141801; arxiv:2106.03381
NDB, C. Han, H. Murayama, JHEP 05 (2022) 160; arxiv:2204.08202
NDB, S. T. Petcov, arxiv:2210.02110

Universe with a large lepton asymmetry

Masahiro Kawasaki
(ICRR, University of Tokyo)

Refs. MK, Murai arXiv:2203.09713
Kasuya, MK, Murai in preparation

Non-thermal Leptogenesis and g-2



Leptogenesis in gauged $U(1)_{L_\mu - L_\tau}$ model

Shintaro Eijima (ICRR, U. Tokyo)

In collaboration with
Masahiro Ibe and Kai Murai (ICRR, U. Tokyo)
[Work in progress; arXiv:2212.*****]

… and many more

Outlook: Baryogenesis

gravitational waves, neutrinos

Shelton et al. (2010)
Hall et al. (2020)

darkogenesis

Mohapatra et al. (1980)
Babu et al. (2006)
Baldes et al. (2011)
Babu et al. (2012)
Herrmann (2014)
Grojean et al. (2019)

High-scale out-of-equilibrium decay

neutron-antineutron oscillations

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

Baryogenesis via oscillations

QCD baryogenesis

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

two-step electroweak baryogenesis

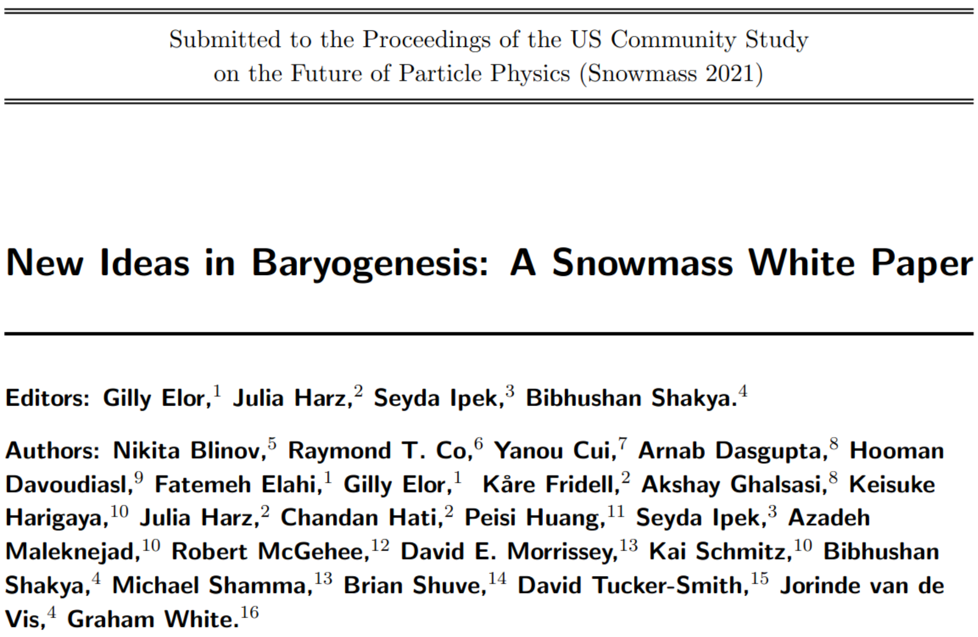
Patel et al. (2012)
Inoue et al. (2015)
Blinov et al. (2015)

Gravitational waves

EDMs

modified Higgs potential

Modak et al. (2020)
Yang et al. (2019)
Bell et al (2019)



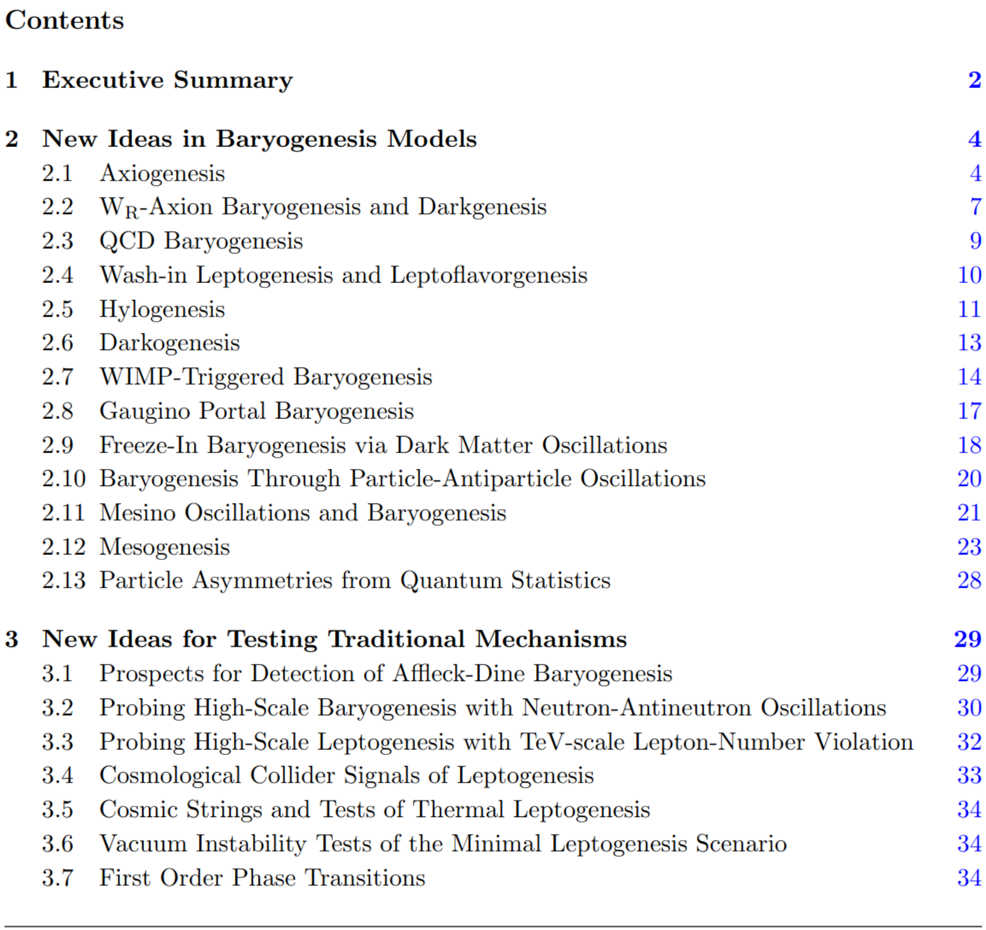
Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

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

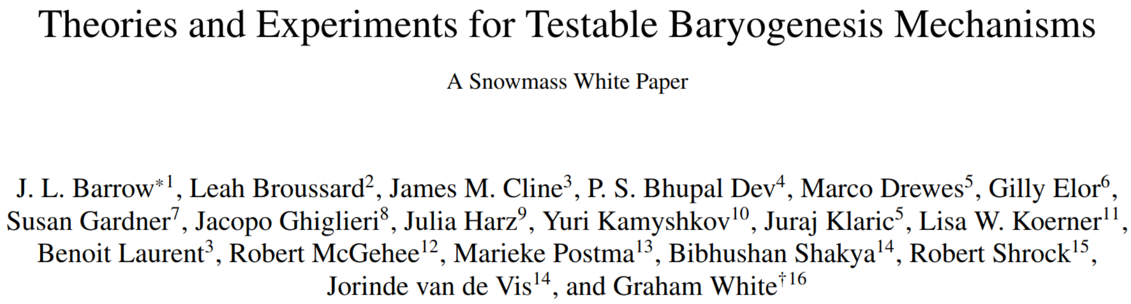


Contents

1 Executive Summary 2

2 New Ideas in Baryogenesis Models 4
- 2.1 Axiogenesis 4
- 2.2 W_R-Axion Baryogenesis and Darkgenesis 7
- 2.3 QCD Baryogenesis 9
- 2.4 Wash-in Leptogenesis and Leptoflavorgenesis 10
- 2.5 Hylogenesis 11
- 2.6 Darkogenesis 13
- 2.7 WIMP-Triggered Baryogenesis 14
- 2.8 Gaugino Portal Baryogenesis 17
- 2.9 Freeze-In Baryogenesis via Dark Matter Oscillations 18
- 2.10 Baryogenesis Through Particle-Antiparticle Oscillations 20
- 2.11 Mesino Oscillations and Baryogenesis 21
- 2.12 Mesogenesis 23
- 2.13 Particle Asymmetries from Quantum Statistics 28

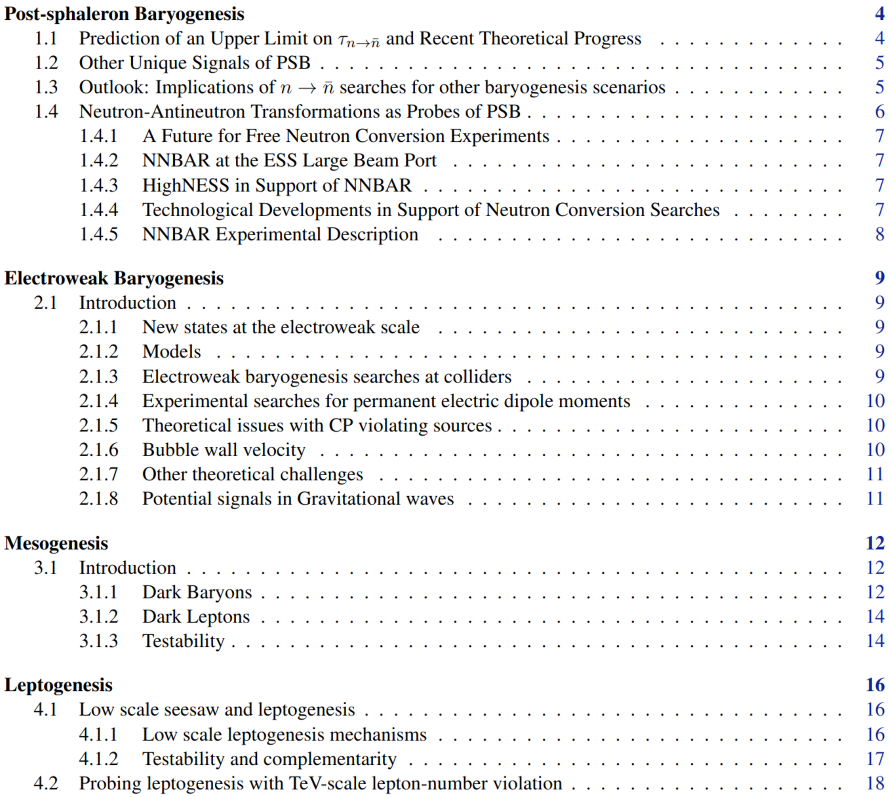
3 New Ideas for Testing Traditional Mechanisms 29
- 3.1 Prospects for Detection of Affleck-Dine Baryogenesis 29
- 3.2 Probing High-Scale Baryogenesis with Neutron-Antineutron Oscillations 30
- 3.3 Probing High-Scale Leptogenesis with TeV-scale Lepton-Number Violation 32
- 3.4 Cosmological Collider Signals of Leptogenesis 33
- 3.5 Cosmic Strings and Tests of Thermal Leptogenesis 34
- 3.6 Vacuum Instability Tests of the Minimal Leptogenesis Scenario 34
- 3.7 First Order Phase Transitions 34



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]



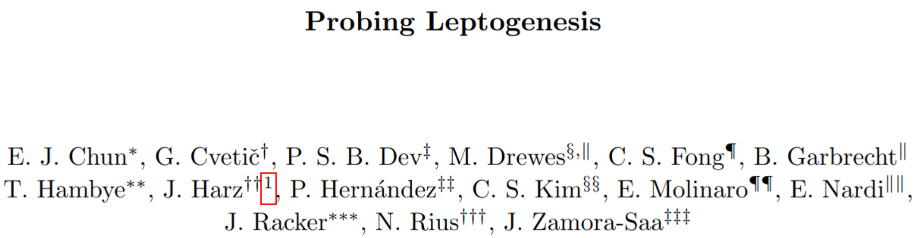
Post-sphaleron Baryogenesis 4
- 1.1 Prediction of an Upper Limit on $\tau_{n\to\bar{n}}$ and Recent Theoretical Progress . . . 4
- 1.2 Other Unique Signals of PSB . . . 5
- 1.3 Outlook: Implications of $n \to \bar{n}$ searches for other baryogenesis scenarios . . . 5
- 1.4 Neutron-Antineutron Transformations as Probes of PSB . . . 6
  - 1.4.1 A Future for Free Neutron Conversion Experiments . . . 7
  - 1.4.2 NNBAR at the ESS Large Beam Port . . . 7
  - 1.4.3 HighNESS in Support of NNBAR . . . 7
  - 1.4.4 Technological Developments in Support of Neutron Conversion Searches . . . 7
  - 1.4.5 NNBAR Experimental Description . . . 8

Electroweak Baryogenesis 9
- 2.1 Introduction . . . 9
  - 2.1.1 New states at the electroweak scale . . . 9
  - 2.1.2 Models . . . 9
  - 2.1.3 Electroweak baryogenesis searches at colliders . . . 9
  - 2.1.4 Experimental searches for permanent electric dipole moments . . . 10
  - 2.1.5 Theoretical issues with CP violating sources . . . 10
  - 2.1.6 Bubble wall velocity . . . 10
  - 2.1.7 Other theoretical challenges . . . 11
  - 2.1.8 Potential signals in Gravitational waves . . . 11

Mesogenesis 12
- 3.1 Introduction . . . 12
  - 3.1.1 Dark Baryons . . . 12
  - 3.1.2 Dark Leptons . . . 14
  - 3.1.3 Testability . . . 14

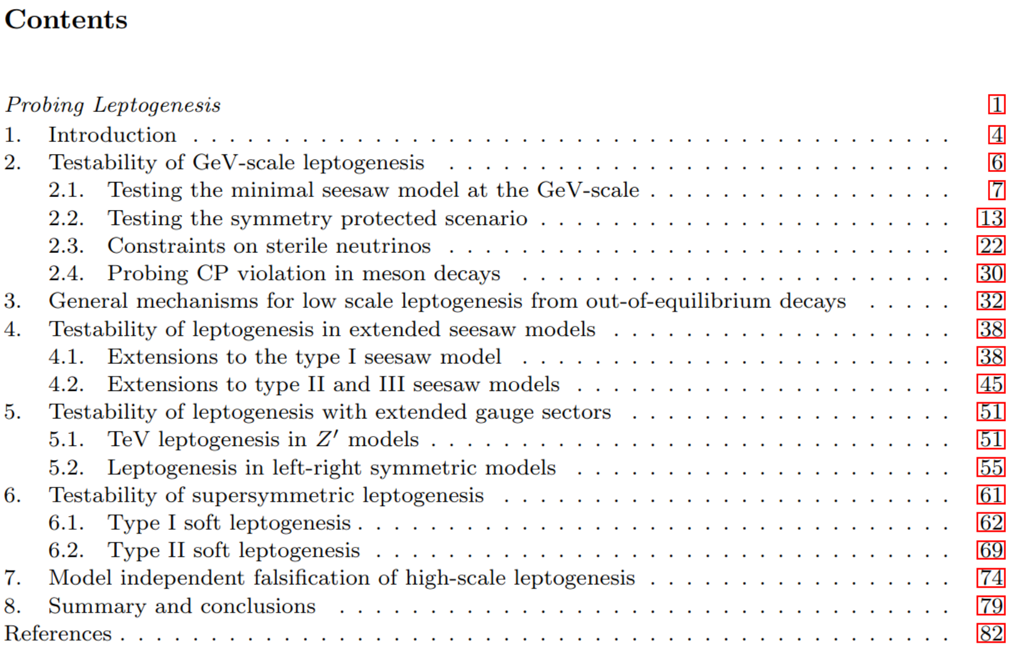
Leptogenesis 16
- 4.1 Low scale seesaw and leptogenesis . . . 16
  - 4.1.1 Low scale leptogenesis mechanisms . . . 16
  - 4.1.2 Testability and complementarity . . . 17
- 4.2 Probing leptogenesis with TeV-scale lepton-number violation . . . 18

arxiv:hep-ph/2203.07059



Probing Leptogenesis

E. J. Chun[*], G. Cvetič[†], P. S. B. Dev[‡], M. Drewes[§,‖], C. S. Fong[¶], B. Garbrecht[‖]
T. Hambye[**], J. Harz[††][1], P. Hernández[‡‡], C. S. Kim[§§], E. Molinaro[¶¶], E. Nardi[‖‖],
J. Racker[***], N. Rius[†††], J. Zamora-Saa[‡‡‡]



Contents

Probing Leptogenesis 1
1. Introduction . . . 4
2. Testability of GeV-scale leptogenesis . . . 6
    2.1. Testing the minimal seesaw model at the GeV-scale . . . 7
    2.2. Testing the symmetry protected scenario . . . 13
    2.3. Constraints on sterile neutrinos . . . 22
    2.4. Probing CP violation in meson decays . . . 30
3. General mechanisms for low scale leptogenesis from out-of-equilibrium decays . . . 32
4. Testability of leptogenesis in extended seesaw models . . . 38
    4.1. Extensions to the type I seesaw model . . . 38
    4.2. Extensions to type II and III seesaw models . . . 45
5. Testability of leptogenesis with extended gauge sectors . . . 51
    5.1. TeV leptogenesis in Z' models . . . 51
    5.2. Leptogenesis in left-right symmetric models . . . 55
6. Testability of supersymmetric leptogenesis . . . 61
    6.1. Type I soft leptogenesis . . . 62
    6.2. Type II soft leptogenesis . . . 69
7. Model independent falsification of high-scale leptogenesis . . . 74
8. Summary and conclusions . . . 79
References . . . 82

arxiv:hep-ph/1711.02865

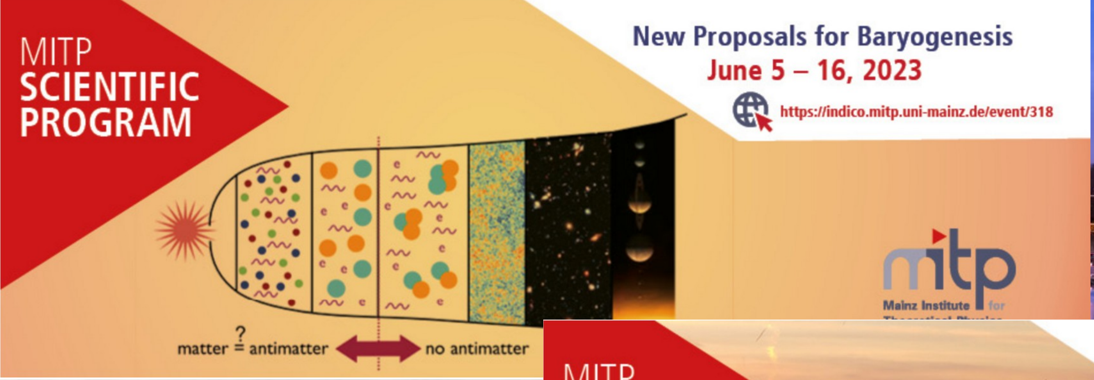
Conclusions

- **Discovery potential and complementarity 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**

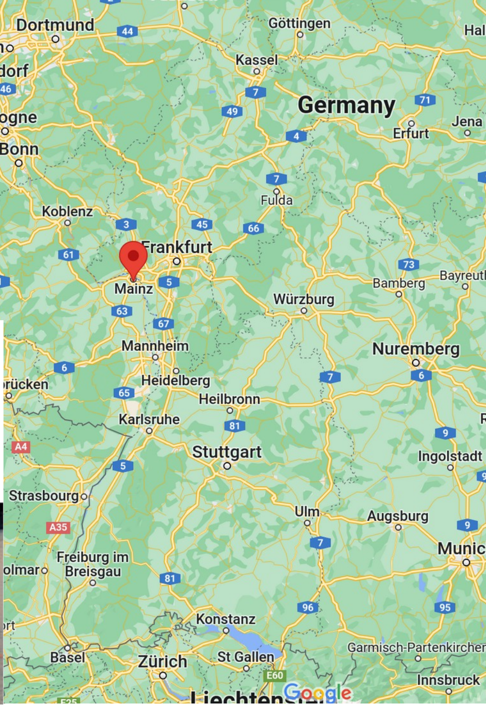
Great future ahead to (hopefully) nail down the mechanism behind BAU!



MITP
SCIENTIFIC
PROGRAM

New Proposals for Baryogenesis
June 5 – 16, 2023
https://indico.mitp.uni-mainz.de/event/318

CC BY 2.0 – salomon10



MITP
TOPICAL
WORKSHOP

Neutrino Scattering at Low and Intermediate Energies
June 26 – 30, 2023
https://indico.mitp.uni-mainz.de/event/324

www.mainz-tourismus.com

MITP
TOPICAL
WORKSHOP

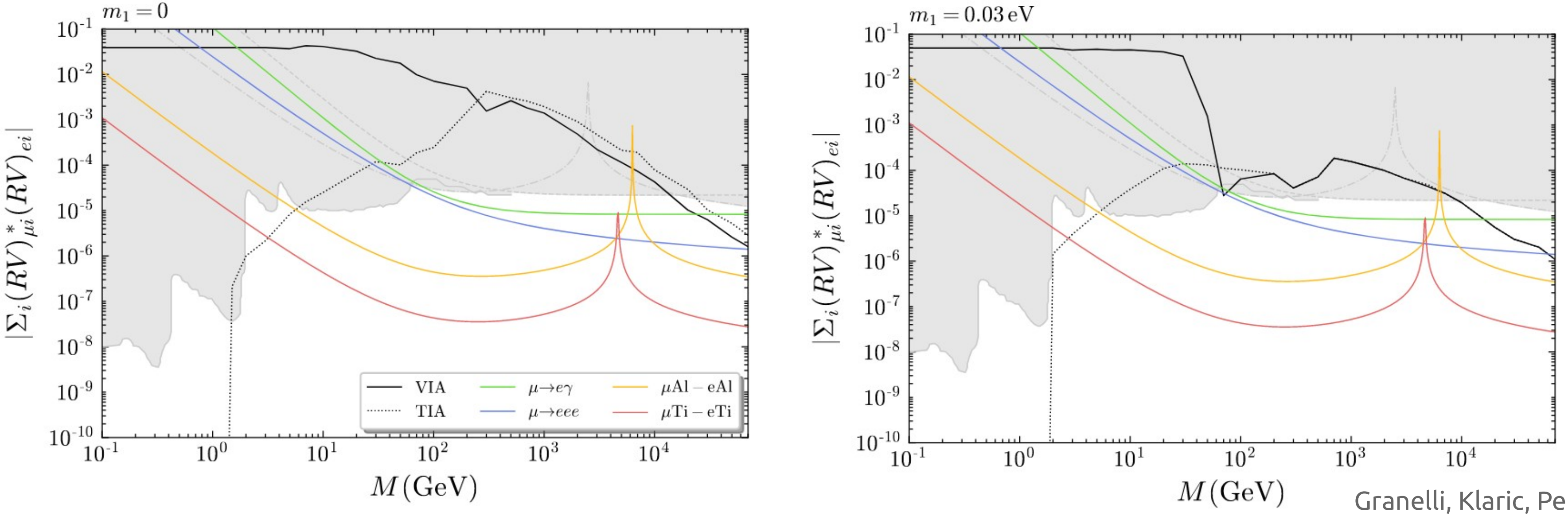
Pulsar Timing Arrays:
A Star-Way to New Physics
August 14 – 18, 2023
https://indico.mitp.uni-mainz.de/event/326

© Pedro Schwaller

Thank you for your attention!

Test of low-scale leptogenesis in charged LFV experiments

Study of parameter space of seesaw type-I with *three almost degenerate* heavy neutrinos



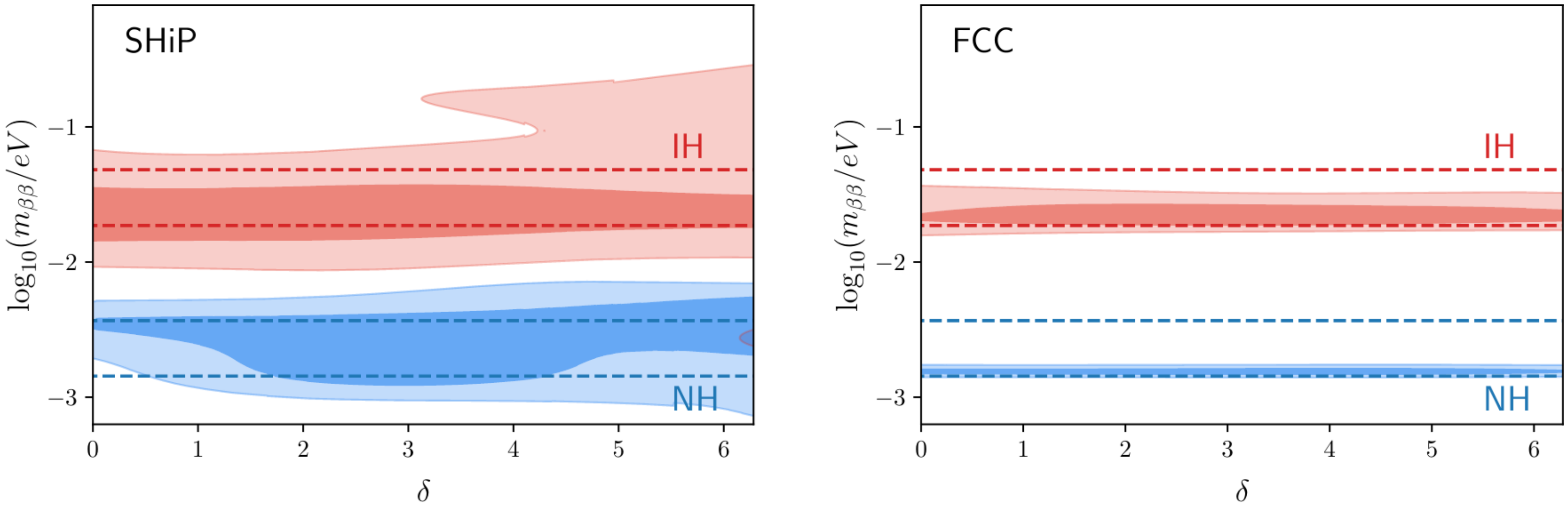
Granelli, Klaric, Petcov (2022)

→ future charged lepton flavour probes can reach further into the parameter space

Analytic understanding via CP flavour invariants

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

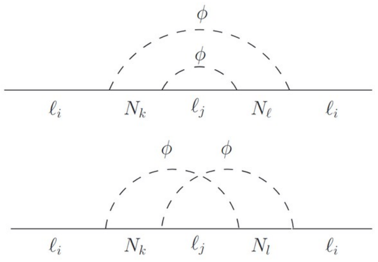
Hernandez, Pavon, Rius, Sandner (2022)



Gravitational Leptogenesis

RH neutrino induced gravitational leptogenesis mechanism (RIGL)

McDonald, Shore (2014, 2015, 2017, 2020)



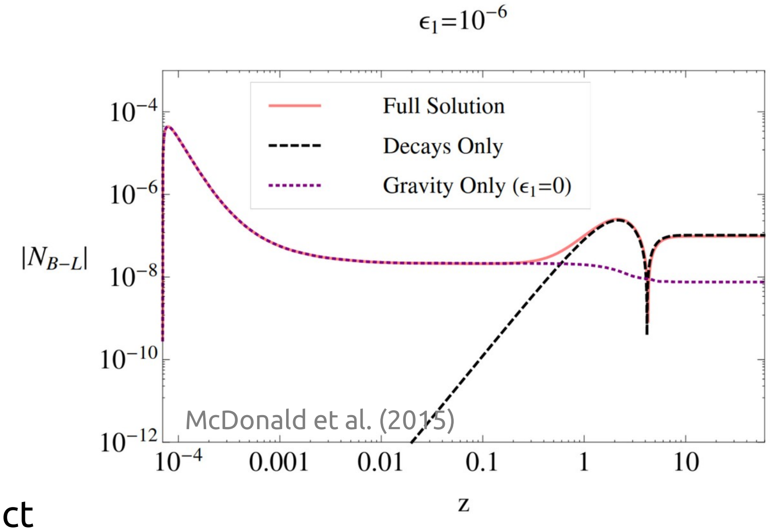
$$\mathcal{L}_i = \partial_\mu R\,\bar{\ell}_i\gamma^\mu\ell_i \sum_{k\,j\,l}\frac{\mathrm{Im}\left[h^\dagger_{ki}h_{il}h^\dagger_{kj}h_{jl}\right]}{3M_kM_l}I_{[kl]}$$

back-ground curvature

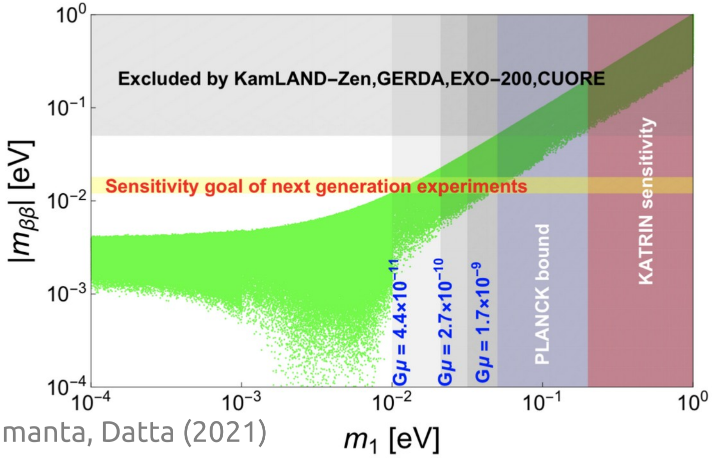
CP phase

loop effect

$$N^{\mathrm{eq}}_{B-L} = \frac{\pi^2\dot{R}}{2\zeta(3)T}\sum_{i,\,j}\frac{\mathrm{Im}\left[K^2_{ij}\right]}{18M_iM_j}I_{[ij]}$$



McDonald et al. (2015)



Samanta, Datta (2021)