

# Mapping the viable parameter space for testable leptogenesis

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based on work in collaboration with M. Drewes and J. Klarić  
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BLV2022

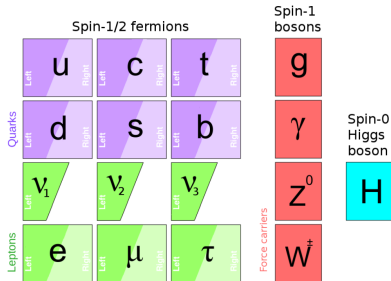
September 5, 2022

## Neutrino masses

[Planck]

## Baryon asymmetry

## Neutrino masses



[Planck]

## Baryon asymmetry

## Type-I seesaw mechanism

[Planck]

**Leptogenesis**

**Type-I seesaw mechanism**

[Planck]

**Leptogenesis**

**In this work: 3 RHN  
generations**

$r = \frac{1}{2} \frac{d \ln \rho}{d \ln s}$

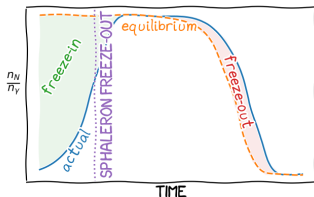
- | C- and CP-violation
- | Deviation from thermal equilibrium
- | Baryon number violation

$r - \frac{V_P - \phi_f}{\langle \sigma \bar{\sigma} \rangle} =$

- | C- and CP-violation
- ? RHN oscillations and decay
  
- | Deviation from thermal equilibrium
- ? Freeze-in and freeze-out of the RHN
  
- | Baryon number violation

$r - \nu p - \phi f \langle b \rangle \langle s \rangle =$

- | C- and CP-violation
- ? RHN oscillations and decay
- | Deviation from thermal equilibrium
- ? Freeze-in and freeze-out of the RHN
- | Baryon number violation





$r - \frac{V_P - \phi_f}{\langle \sigma \rangle} \approx \frac{b^2}{s} =$

- | C- and CP-violation
- ? RHN oscillations and **decay**
  
- | Deviation from thermal equilibrium
- ? Freeze-in and **freeze-out** of the RHN
  
- | Baryon number violation

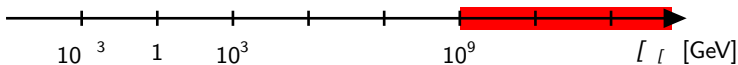
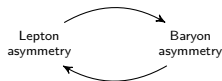
r-VP-df <math>\hat{b}^{\hat{s}}\hat{s}^{\hat{s}}</math>=

- | C- and CP-violation
- ? RHN oscillations and decay
  
- | Deviation from thermal equilibrium
- ? Freeze-in and freeze-out of the RHN
  
- | Baryon number violation
- ? Sphaleron process



$r = \frac{V_P}{V} \ll 1$

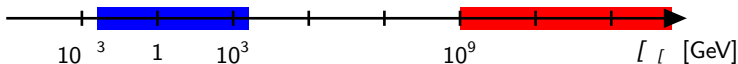
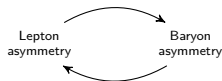
- | C- and CP-violation
- ? RHN oscillations and decay
  
- | Deviation from thermal equilibrium
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Thermal leptogenesis  
[Fukugita/Yanagida '86]

$$r - \frac{V-P}{\rho f} \langle b^{\otimes 2} \rangle^s =$$

- | C- and CP-violation
- ? RHN oscillations and decay
  
- | Deviation from thermal equilibrium
- ? Freeze-in and freeze-out of the RHN
  
- | Baryon number violation
- ? Sphaleron process



Low-scale leptogenesis

[Akshmedov/Rubakov/Smirnov '98, Asaka/Shaposhnikov '05]

Thermal leptogenesis

[Fukugita/Yanagida '86]

$$S_{@Z}^@ = [H; ] \frac{S}{|} f; g S^X \sim -\frac{H(c H)}{y};$$

$$S_{@Z}^@ = [H; ] \frac{S}{|} f; g + S^X \sim -\frac{H(c H)}{y};$$

$$\frac{@}{@Z} n = \frac{|S}{y} \frac{@^3 W}{(|)^3} y d \cdot ] H(c H) + S \frac{@^3 W}{(|)^3} y d \cdot - ( ) ]:$$

**Density matrix** **Matter-antimatter asymmetry**  
**Effective Hamiltonian** **Interaction rates**

| [ b \ C^z \ Q f C q L C @ q z C S H p \ Klaric/Shaposhnikov/Timiryasov  
 [2103.165451]

| ; b f C q - \ - s s q ^ L C H p \ I C E [ C z b u C E y C i



| BteCpA C^zs ..SY <~z @00e S^zb ^ = { e-q \ CzCq se- <D

- | BteCp, C^zs ..SY <-z @Ce S^zb ^ = { e-q \ CzCq se-<D
- | ; - ^ CteCz zb ep@-<CzPb~s- ^@s bH@SeY <@fCqS-Cs -z OXOXO; =  
yCsz-4SS%f



- | BteCpA C^zs ..SY <~z @00e S'zb ^ = { e-q \ CzCq se-<D
- | ; - ^ CteCz zb ep@<C zPb~s ^@s bH@SeY <@fCqS-Cs -z OXOXO; =  
yCsz-4SS%F
- | XGezblC^CsS ..zP zPq\ -YS^SS Y<b^@zS^s ..bq\ Hbq\ -ssCs -s Yb...  
-s O(c.u) KC =zCsz-4C -z dLi ] , v|i

# Backup slides

| d-q \ Cq se- <C s\ -Y Cq Hbq \ yL Pz Csz = CFC C i

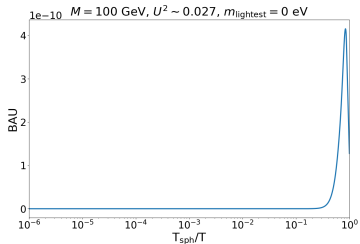
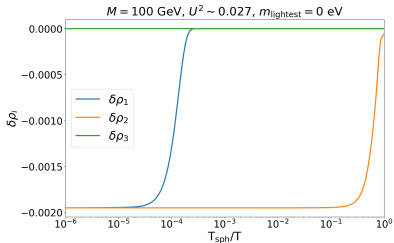
| d-q \ CzCq se- <C s\ -YCq Hbq \ ySLPzCsz = CFC C i

$$G = \frac{S}{f} \left\{ \begin{array}{l} q \text{---} \\ | \text{ @SL } p \text{---} \\ \text{---} \\ \text{---} \end{array} \right. \frac{p}{[ l }$$

n=2 lines from Klaric/Shaposhnikov/Timiryasov [2008.13771]

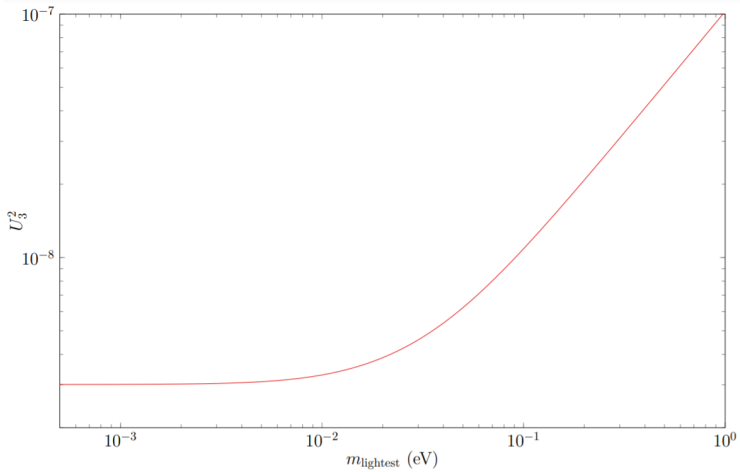
n=2 lines from Klaric/Shaposhnikov/Timiryasov [2008.13771]

| d-q \ CzQ se- <C...%YdCqzP- ^ S^ zPC ^ = | s<C^ - qb = X-zC 3, }  
edp@~<S^i

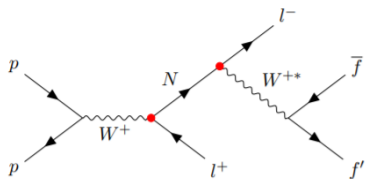


| X-q.C \ \$S^L - ^LYCs - Yb... YzC  
 D ~SS1q zS^ bHb^C PG f%o  
 ^C-zoP^b } S / ^2i

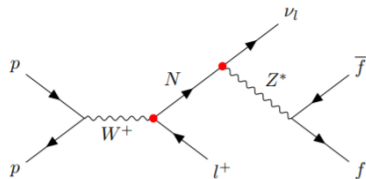
| R eYCs YzC 3, } ep@ <S^i





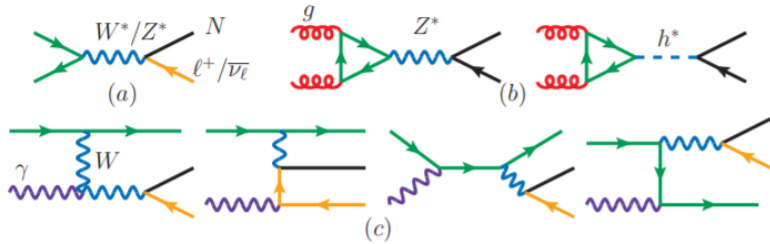


(a) Charged current decay.

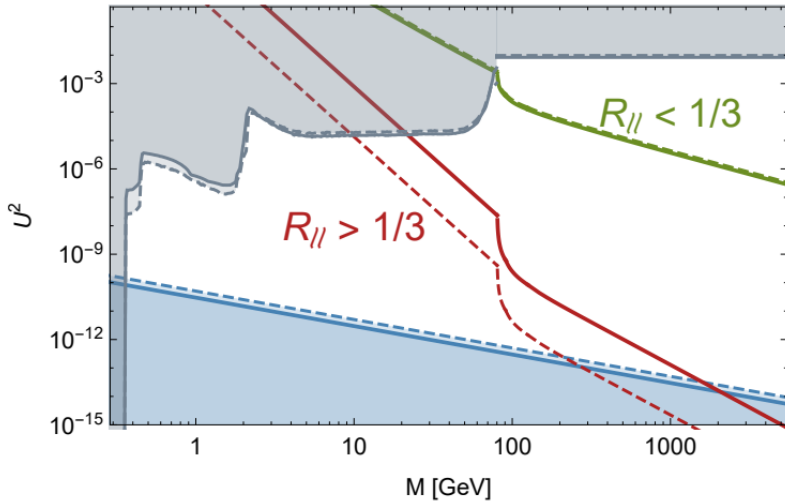


(b) Neutral current decay.

Drewes/Hajer 1903.06100



Pascoli/Ruiz/weiland 1812.08750



L B p 2 b 2 2 b r # Q m M /

$$I_B^k \frac{q \frac{K_{iK}^k + K_{HB}^k}{J} \cdot R y^{Ry} \frac{20}{J_B}}{J}$$

L Bp2 b22b r #QmM/

q \_\_\_\_\_

$I_B^k$   $\frac{K_{iK}^k + K_{HB;?i}^k}{J}$   $Ry^{Ry} \frac{20}{J_B}$

" @ TT`QtBK i2 bvKK2i`v

J @ R y y y  
y R yA  
y y 0

0  $\frac{7(R+)}{7(R+)} \frac{2)}{2)} \frac{B_2(7R)}{B(7R)} \frac{2)}{2)} \frac{7^0}{7^0} \frac{1}{A}$   
@  $\frac{7(R+)}{7(R+)} \frac{)}{)} \frac{B(7R)}{B(7R)} \frac{)}{)} \frac{7^0}{7^0} \frac{A}{A}$   
 $\frac{7(R+)}{7(R+)} \frac{)}{)} \frac{B(7R)}{B(7R)} \frac{)}{)} \frac{7^0}{7^0}$

aK HHM2bb Q7 HB;?i M2mi`BMQ K bb2b 7`Q  
bvKK2i`v #`2 FBM; ;T; `0K2R2`b

h?2`K H +Q``2+iBQMb + M  
;2M2` i2 bK HH K bb bTH

?  
?  
?  
?  
y

\_2bQM Mi 2M? M+2K2M







| b v K K 2 i ` B 2 b ; 2 M 2 ` i 2 / / m ` B M ; 7 ` 2 2 x 2 @ B M M /  
b B ; M b X

\*QMbBbi2M@QrB+ BHH iBQM / i BM/m+2/ #v \*  
 T ` K2i`Bb iBQM

$$6 = \frac{B}{p} \quad q \frac{\text{---}}{K/B} ; p \frac{\text{---}}{J_J}$$

a22b r ` 2HKiBQM<sup>k</sup>6 J\_J<sup>R</sup> 6<sup>i</sup>:

\*QMbBbi2M@QrB+BBHH iBQM / i BM/m+2/ #v \*  
 T ` K2i`Bb iBQM

$$6 = \frac{B}{p} \cdot \frac{q}{K/B} ; \frac{p}{J_j}$$

M4j

j \*S@pBQH iBM; T? b2b  
 j SJLa M;H2t2/V  
 j HB;?i M2mi`B MUk; t2b2b  
 j +QKTH2t 1mH2` M;H2b  
 j J DQ` M K bb2b

\_ Bb +QKTH2t`Qi iB  
 K i`Bt

Rj 7`22 T ` K2i2`b

\*QMbBbi2M@QrB+BBHH iBQM / i BM/m+2/ #v \*  
 T ` K2i`Bb iBQM

$$6 = \frac{B}{p} \overset{q}{\text{---}} \overset{p}{\text{---}} \frac{K/B}{\text{---}} \frac{J}{J}$$

M4k

k \*S@pBQH iBM; T? b2b  
 j SJLa M;H2t2/V  
 k HB;?i M2mi`BMUqt2/Vb2  
 R +QKTH2t 1mH2` M;H2  
 k J DQ` M K bb2b

e 7`22 T ` K2i2`b

M4j

j \*S@pBQH iBM; T? b2b  
 j SJLa M;H2t2/V  
 j HB;?i M2mi`BMUqt2/Vb2  
 j +QKTH2t 1mH2` M;H2  
 j J DQ` M K bb2b

Rj 7`22 T ` K2i2`b

I LQ`K H Q`/2` B;M;?i20/y y 2oX

- | LQ`K H Q`/2` B;M;?i20/y y R 2oX
- | J b b /2;2M2` i2 bJ+2M RBQ

| LQ`K H Q`/2` B M ; ? i 2 0 / y y R 2 o X

| J b b /2 ; 2 M 2 ` i 2 b j + 2 M R B Q

| h ? 2 Q ` 2 i B + H + Q M b i ` B M i b ,

| LQ`K H Q`/2` B;?i20/y y R 2oX

| J bb /2;2M2` i2 b<sub>j</sub>+2M RBQ

| h?2Q`2iB+ H +QMbi` BMib,  
S2`im`# iBp2 m<sub>k</sub>MBi`Biv



| LQ`K H Q`/2` B;?i20/y y R 2oX

| J bb /2;2M2` i2 b<sub>j</sub>+2M RBQ

| h?2Q`2iB+ H +QMbi` BMib,  
S2`im`# iBp2 m<sub>k</sub>M<sub>k</sub>Bi`Biv  
a22b r 2tT M<sub>k</sub>ByCRM

| LQ`K H Q`/2` B;M;?i20/y y R 2oX

| J b b /2;2M2` i2 b<sub>j</sub>+2M RBQ

| h?2Q`2iB+ H +QMbi` BMib,

S2`im`# iBp2 m<sub>k</sub>M<sub>k</sub>Bi`Biv

a22b r 2tT M<sub>k</sub>By<sub>Q</sub>RM

LQ H `;2` /B iBp2(-RQ` $\frac{K_{i2}i}{K_{HQ}i}$ )<sup>k</sup>B<Q<sub>g</sub>M<sub>b</sub>

„ C <b^s@q | z/aCs bHS^SS Y <b^@SS^s=

„ C  $\langle b^{\wedge}SSCq | z\%aCs bHS^SSY \langle b^{\wedge}SS^{\wedge}s=$

| **Thermal initial conditions :**

Resonant leptogenesis dominates.

Well-motivated in the context of SM gauge extensions.

„ C  $\langle b^{\wedge}SSCq | z/aCs bHS^SSY \langle b^{\wedge}SS^{\wedge}s=$

| **Thermal initial conditions :**

Resonant leptogenesis dominates.

Well-motivated in the context of SM gauge extensions.

| **Vanishing initial conditions :**

Both freeze-out and freeze-in processes can contribute.

| rCCs...X-Lq^LS^

$$L \quad G.S(\cdot) \rho S + \frac{C}{I} \rho S(I) \rho U + \rho I$$

| r00s...X-Lq ^LS ^

$$L \quad \boxed{G_S}(\cdot, \cdot)_{pS} + \frac{C}{i} \leq \boxed{([I \ I]_{S})} pU + Pi \triangleleft$$

**Yukawa**

**Majorana**

| rCCs...X-Lq ^LS ^

$$L \quad G_s(\cdot, \cdot)_{pS} + \frac{C}{I} \hat{p}_S([I]_{I})_{\mathcal{M} pU} + \Pi \Delta$$

### Seesaw relation

$$\lambda = f^2 G [I]^{-1} G^Z:$$



$$\lambda = f^2 G [I]^{-1} G^Z:$$

XSLPz ^C-zqf'bs

$$\lambda = f^2 G [I]^{-1} G^Z:$$

OG-f%δC-zqf'bs



| r00s...X-Lq^LS^

$$L \quad G_s(\cdot) \quad p_s + \frac{C}{I} \quad p_s([I]) \quad w_{pU} + P_i \quad \Delta$$

### Seesaw relation

$$\lambda = f^2 G [I]^{-1} G^z$$



^ & | ^00@@zb CteY S^ \ LPz ^C-zo^b \ -ssCi

| r00s...X-Lq^LS^

$$L \quad G_s(\cdot) \quad p_s + \frac{c}{|} \quad \lesssim ([ \ ] ) \quad \text{or } p_u + \text{Pi} \triangleleft$$

### Seesaw relation

$$\lambda = f^2 G [ \ ]^{-1} G^z$$



In this work,  $\lambda = \{.$

| rCCs...X-Lq ^LS ^

$$L \quad G_s(\cdot) \quad p_s + \frac{C}{I} \quad p_s([I]) \quad \text{or } p_U + P_i \Delta$$

### Seesaw relation

$$\lambda = f^2 G [I]^{-1} G^Z$$



**In this work,  $\lambda = \{.$**

| R^zCq <Sb^ szqC^LzP bHzPC PC-f%G-zqS^bs

$$\lambda^2 = f^2 \times_{-;S} j(G [I]^{-1}) \cdot s^2 \times_{-;S} j \cdot s^2$$