Mapping the viable parameter space for testable leptogenesis

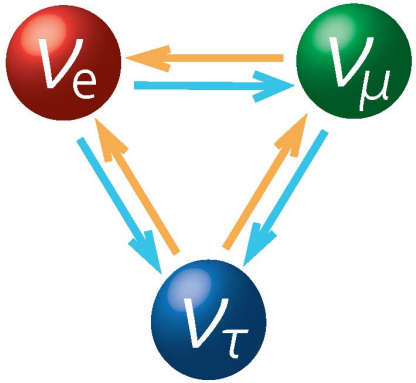
Yannis Georis
based on work in collaboration with M. Drewes and J. Klarić
[Phys. Rev. Lett. **128**, 051801 (2022)]

BLV2022
September 5, 2022

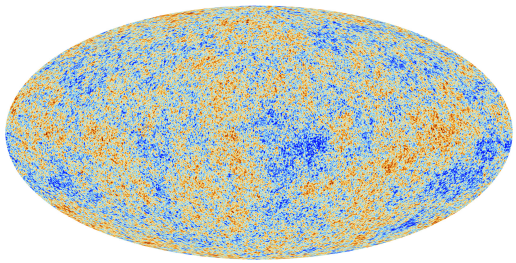
UCLouvain

fnrs
FREEDOM TO RESEARCH

Beyond the Standard Model



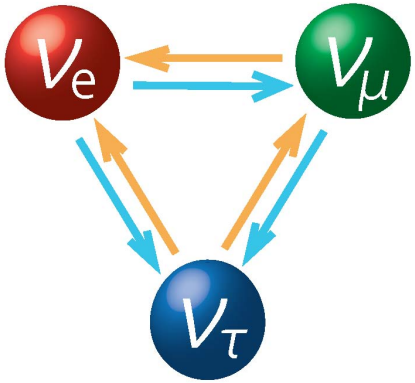
Neutrino masses



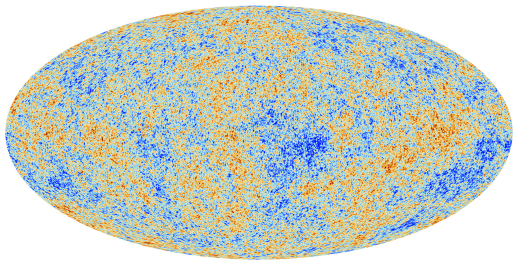
[Planck]

Baryon asymmetry

Beyond the Standard Model

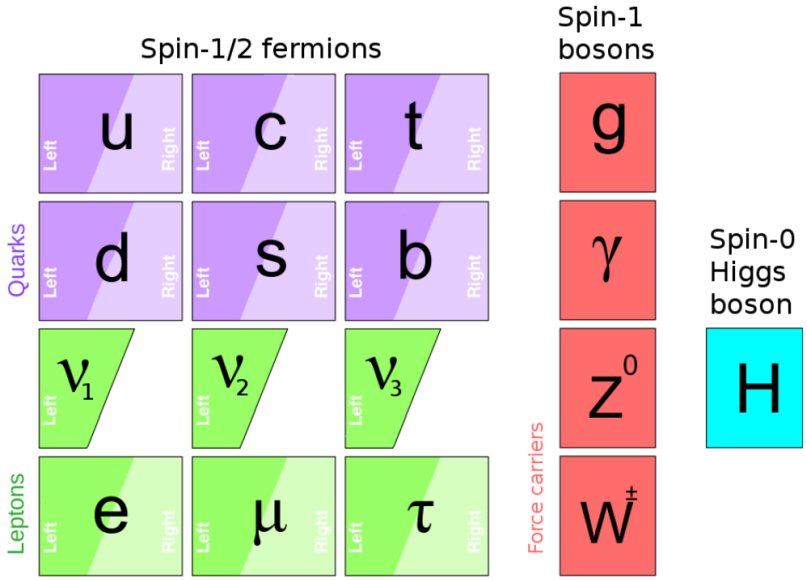


Neutrino masses

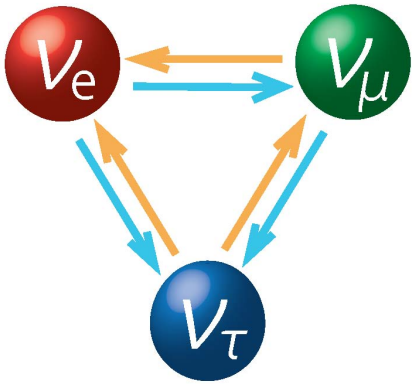


[Planck]

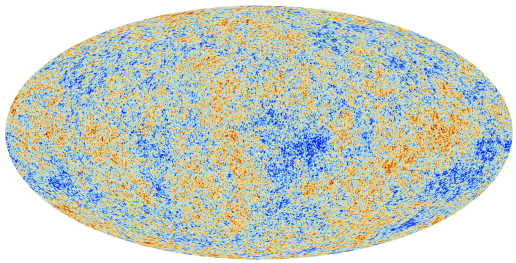
Baryon asymmetry



Right-handed neutrinos (RHN)

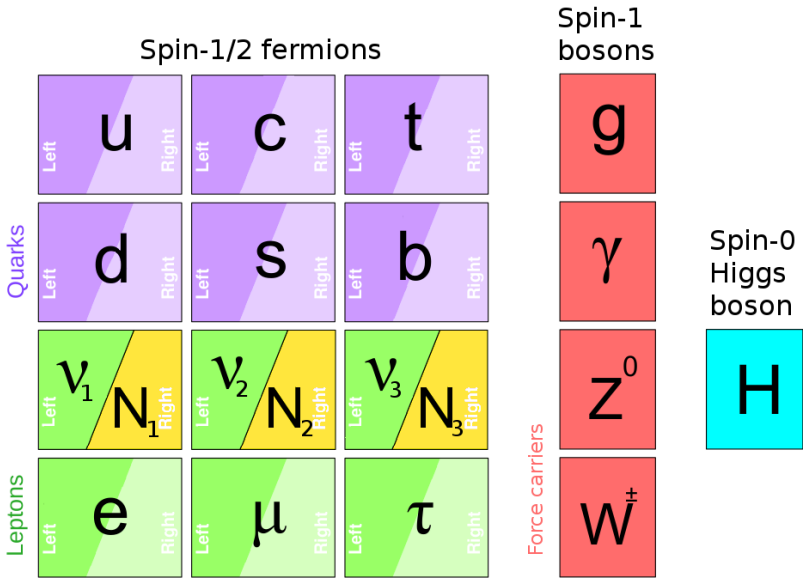


Type-I seesaw mechanism

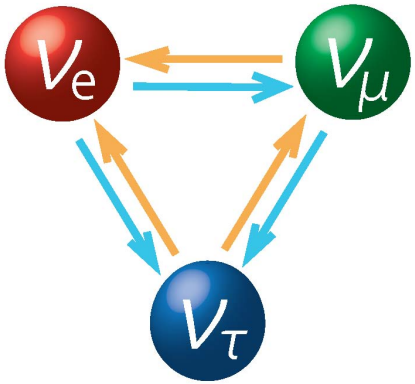


[Planck]

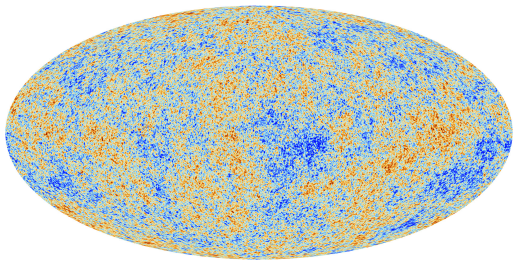
Leptogenesis



Right-handed neutrinos (RHN)

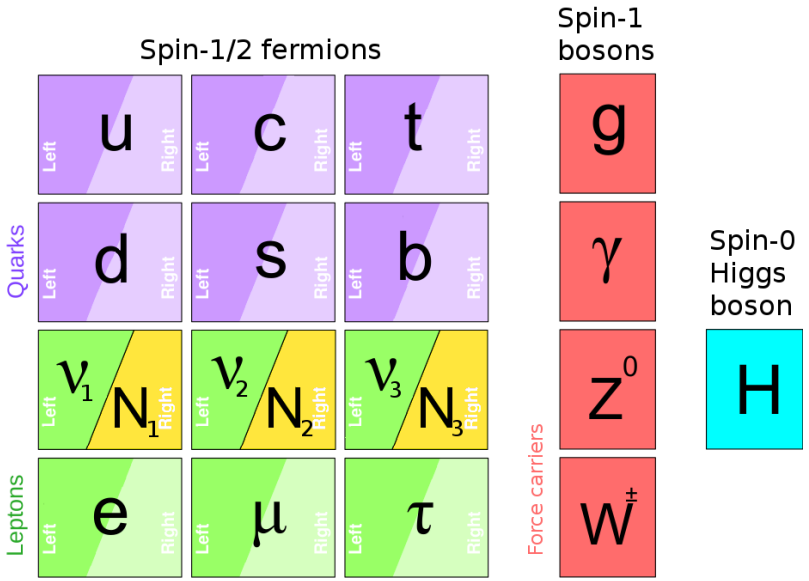


Type-I seesaw mechanism



[Planck]

Leptogenesis



In this work: 3 RHN generations

Leptogenesis

Sakharov conditions:

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

Leptogenesis

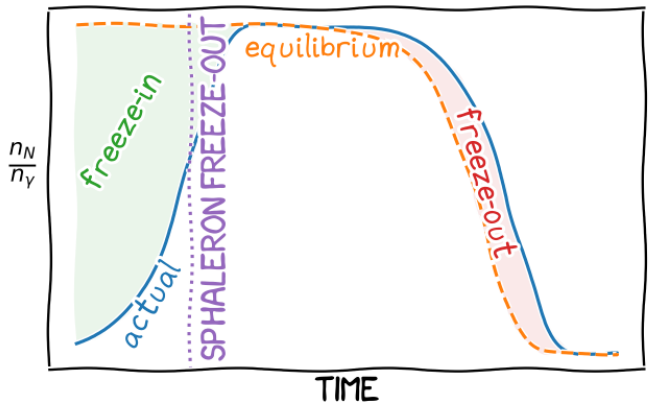
Sakharov conditions:

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

Leptogenesis

Sakharov conditions:

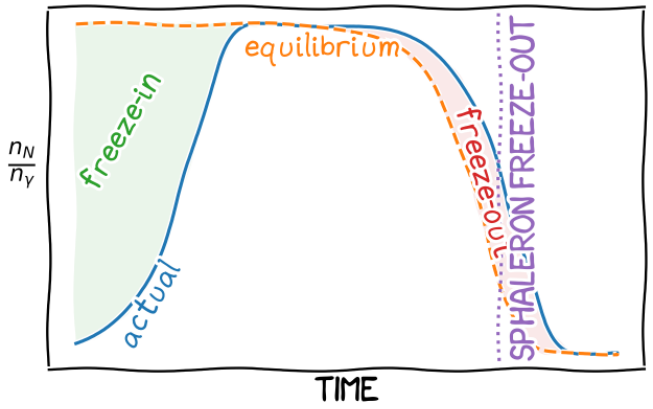
- C- and CP-violation
  - ⋆ RHN oscillations and decay
- Deviation from thermal equilibrium
  - ⋆ Freeze-in and freeze-out of the RHN
- Baryon number violation



Leptogenesis

Sakharov conditions:

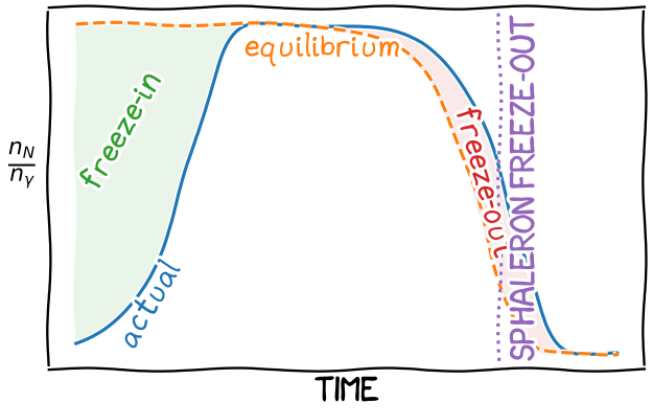
- C- and CP-violation
  - ⋆ RHN oscillations and decay
- Deviation from thermal equilibrium
  - ⋆ Freeze-in and freeze-out of the RHN
- Baryon number violation

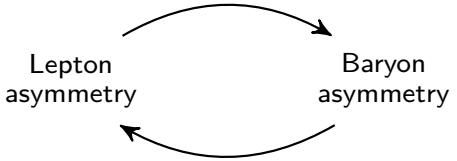


Leptogenesis

Sakharov conditions:

- 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

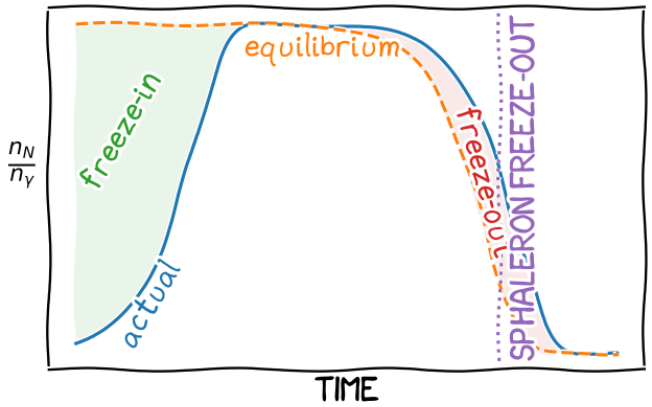


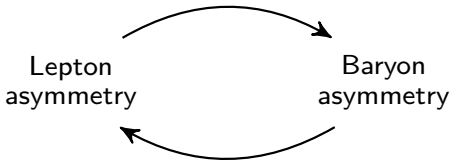


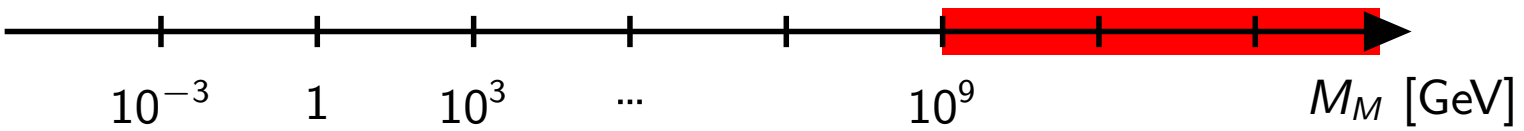
Leptogenesis

Sakharov conditions:

- 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







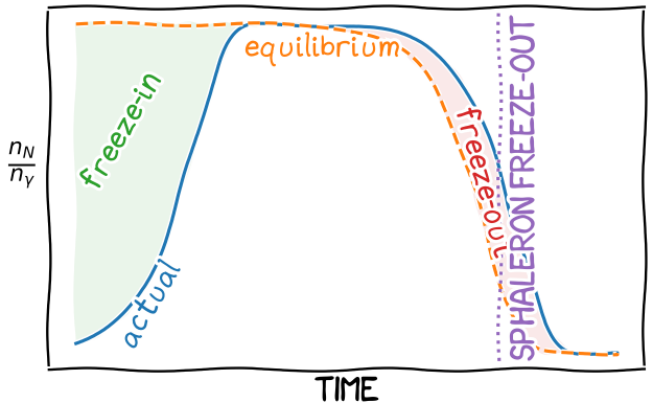
Thermal leptogenesis

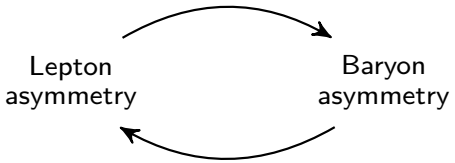
[Fukugita/Yanagida '86]

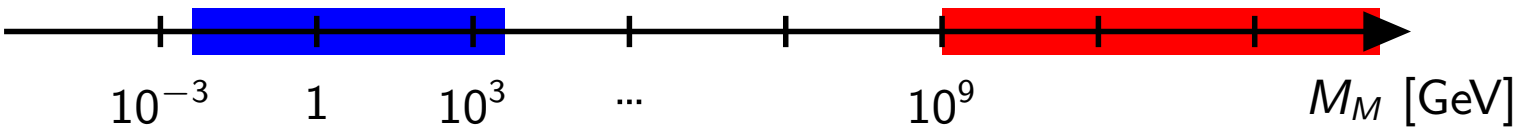
Leptogenesis

Sakharov conditions:

- 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
[Akhmedov/Rubakov/Smirnov '98, Asaka/Shaposhnikov '05]

Thermal leptogenesis
[Fukugita/Yanagida '86]

Quantum kinetic equations

$$i\frac{\mathrm{d}\rho}{\mathrm{d}t} = [\mathbf{H}, \delta\rho] - \frac{i}{2}\{\Gamma, \delta\rho\} - i\sum_{a\in\{e,\mu,\tau\}} \tilde{\Gamma}_a \frac{\mu_a}{T} f_F(1-f_F),$$

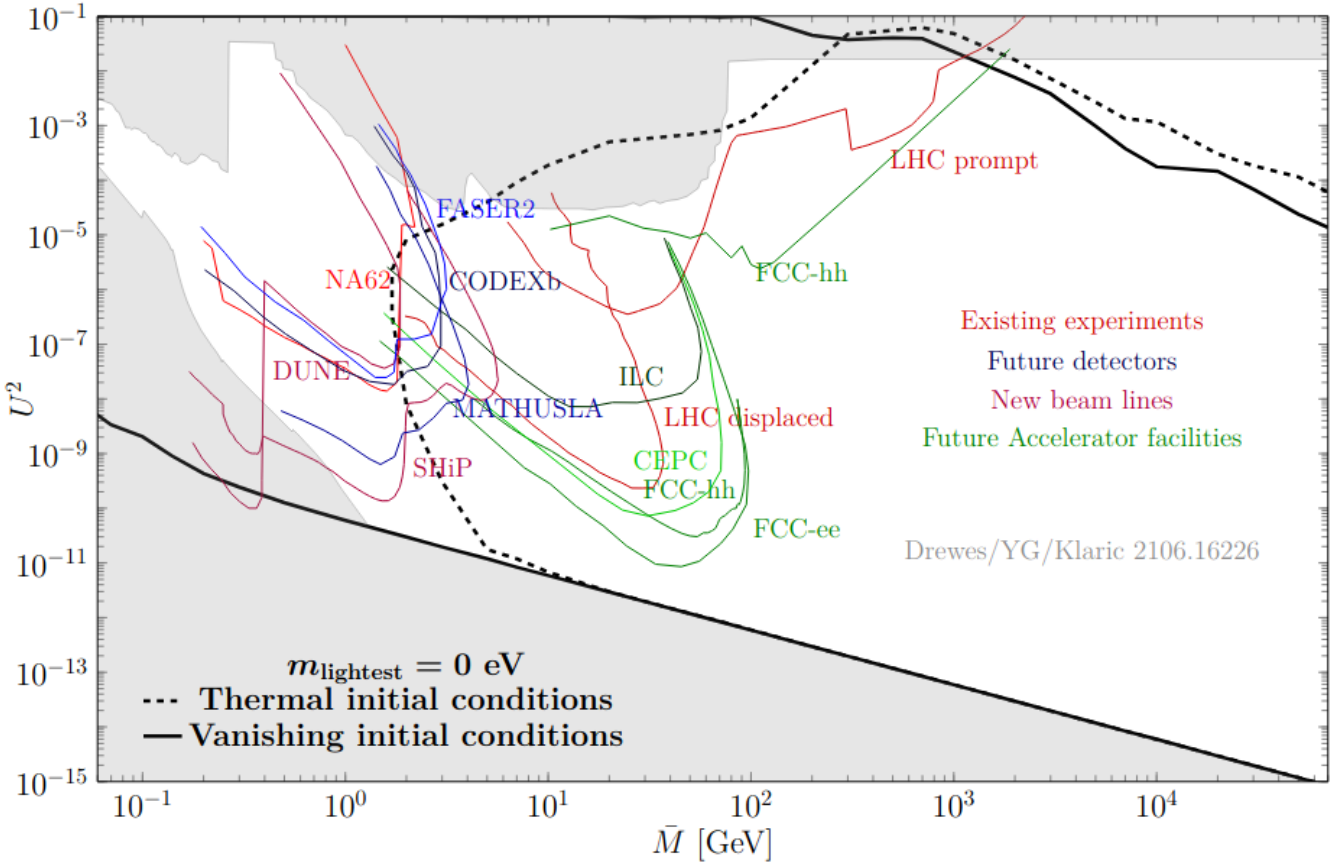
$$i\frac{\mathrm{d}\bar{\rho}}{\mathrm{d}t} = -[\mathbf{H}, \delta\bar{\rho}] - \frac{i}{2}\{\Gamma, \delta\bar{\rho}\} + i\sum_{a\in\{e,\mu,\tau\}} \tilde{\Gamma}_a \frac{\mu_a}{T} f_F(1-f_F),$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\mathbf{n}_{\Delta_a} = -\frac{2i\mu_a}{T}\int \frac{\mathrm{d}^3\vec{k}}{(2\pi)^3}\mathrm{Tr}[\Gamma_a] f_F(1-f_F) + i\int \frac{\mathrm{d}^3\vec{k}}{(2\pi)^3}\mathrm{Tr}[\tilde{\Gamma}_a(\delta\bar{\rho}-\delta\rho)].$$

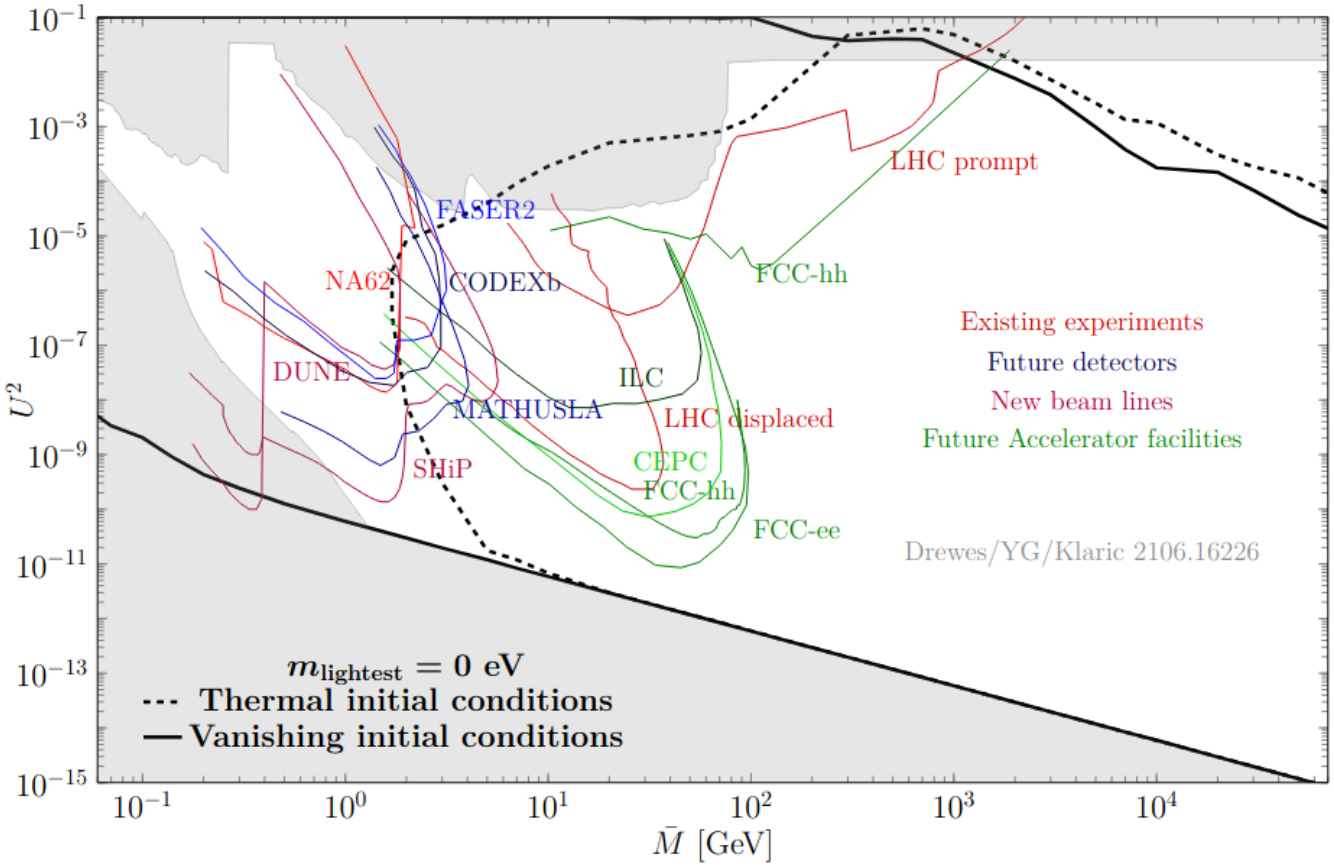
Density matrix/**Matter-antimatter asymmetry**
Effective Hamiltonian/**Interaction rates**

- Momentum-averaged rates from Klaric/Shaposhnikov/Timiryasov [2103.165451]
- Cover a mass range from 50 MeV to 70 TeV.

Viable parameter space

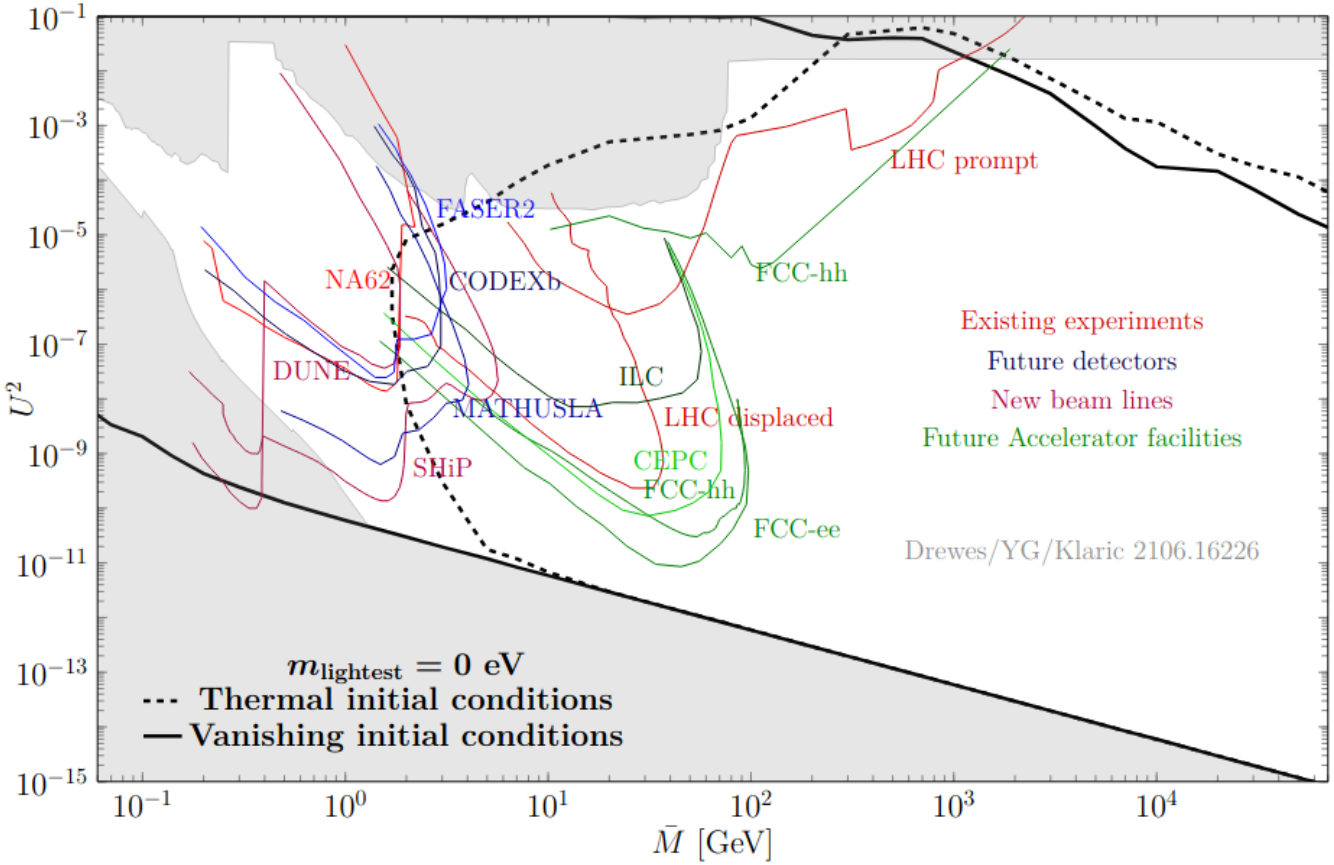


Viable parameter space



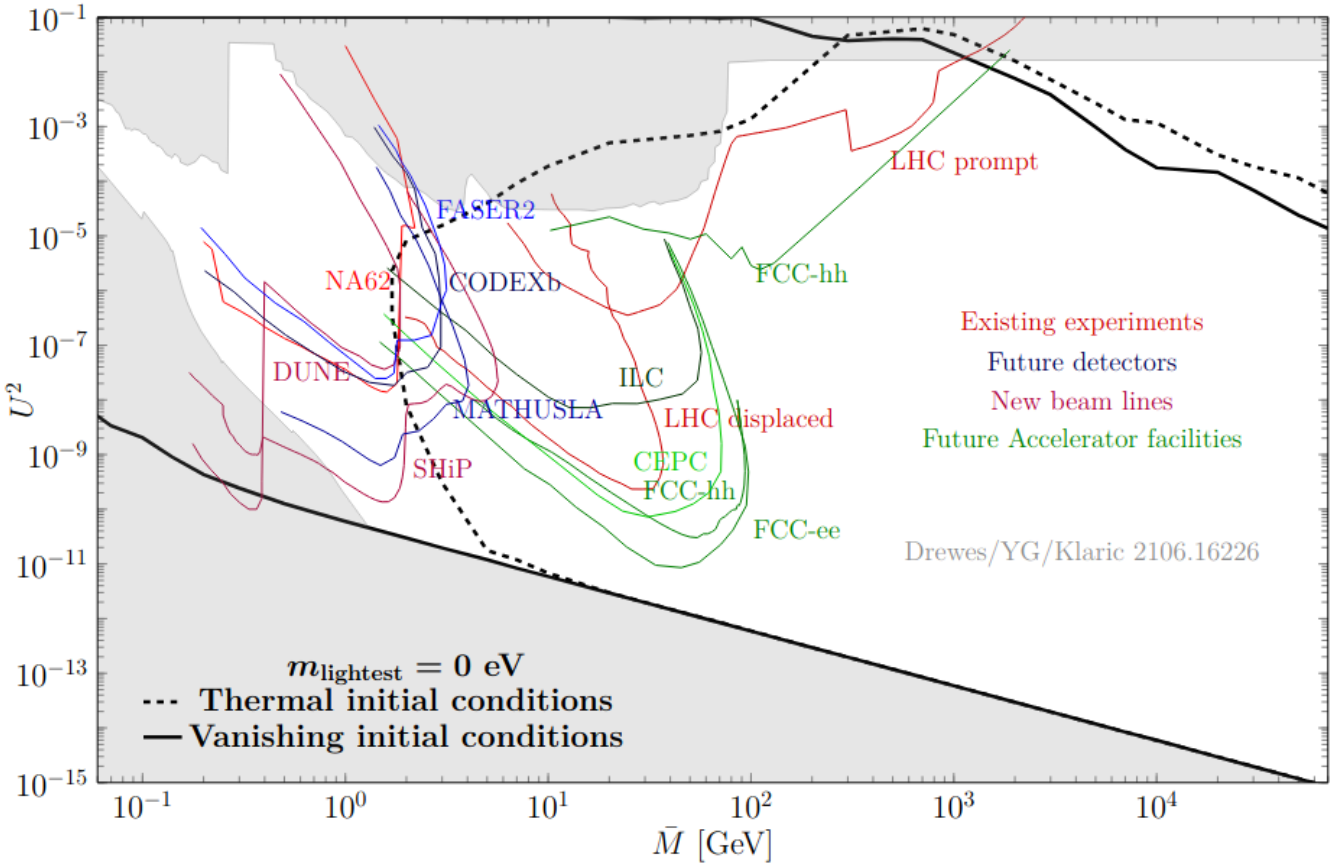
- Experiments will cut deep into $n = 3$ parameter space.

Viable parameter space



- Experiments will cut deep into $n = 3$ parameter space.
- Can expect to produce thousands of displaced vertices at HL-LHC: Testability !

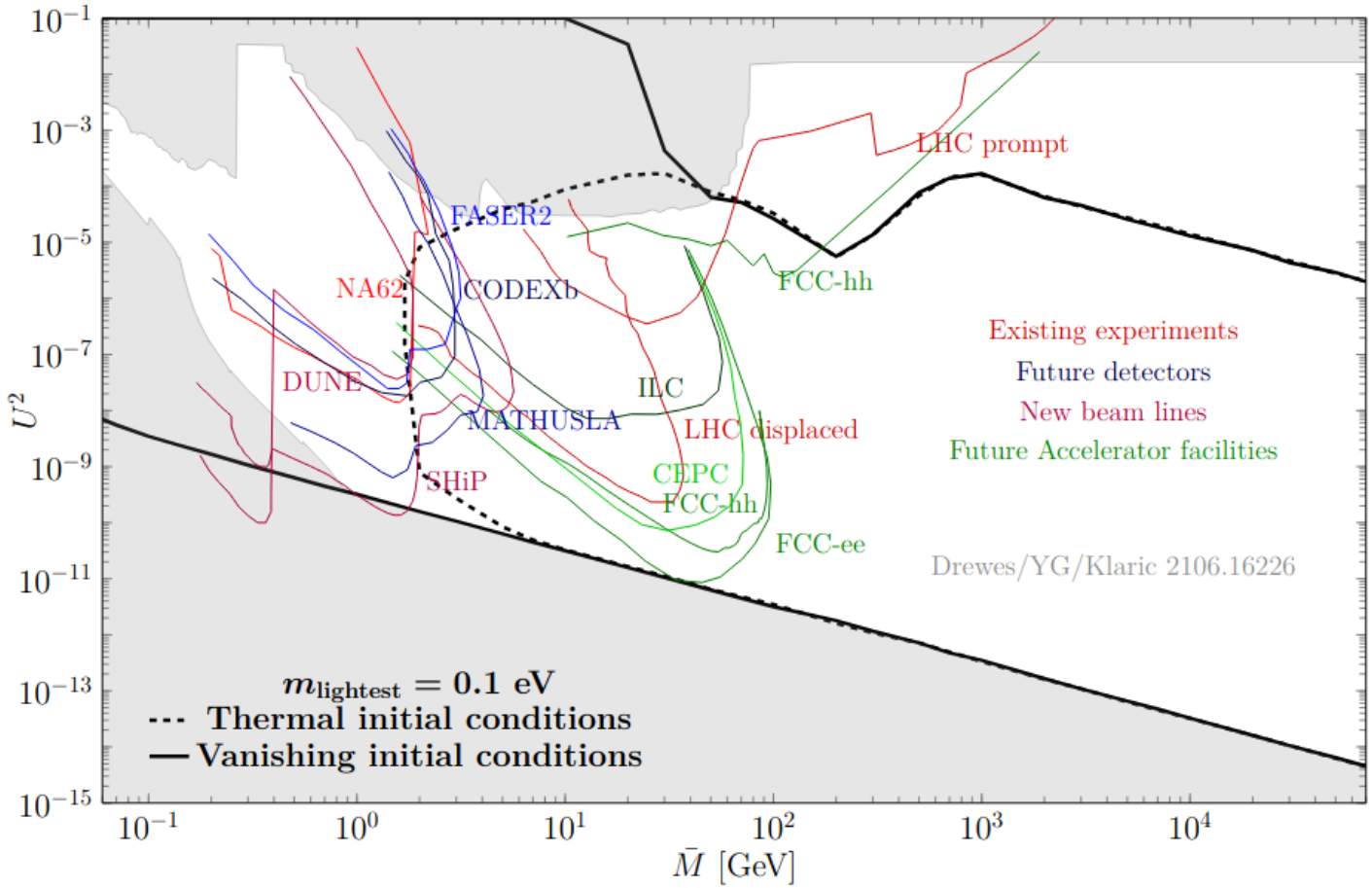
Viable parameter space



- Experiments will cut deep into $n = 3$ parameter space.
- Can expect to produce thousands of displaced vertices at HL-LHC: Testability !
- Leptogenesis with thermal initial conditions works for masses as low as $\mathcal{O}(1.7)$ GeV: testable at *e.g.* NA62.

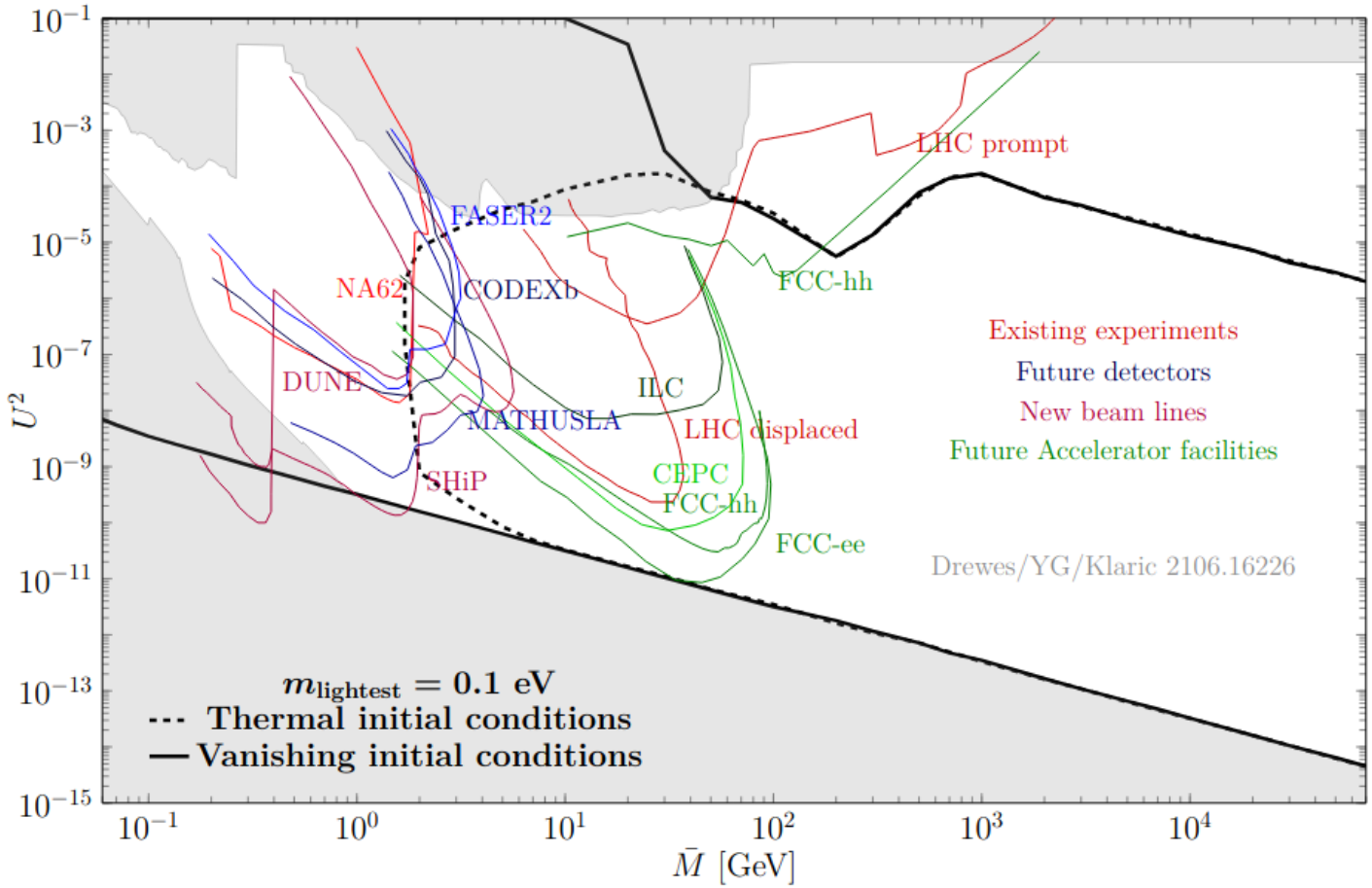
Backup slides

Results for $m_{\text{lightest}} = 0.1$ eV



- Parameter space smaller for $m_{\text{lightest}} = 0.1$ eV.

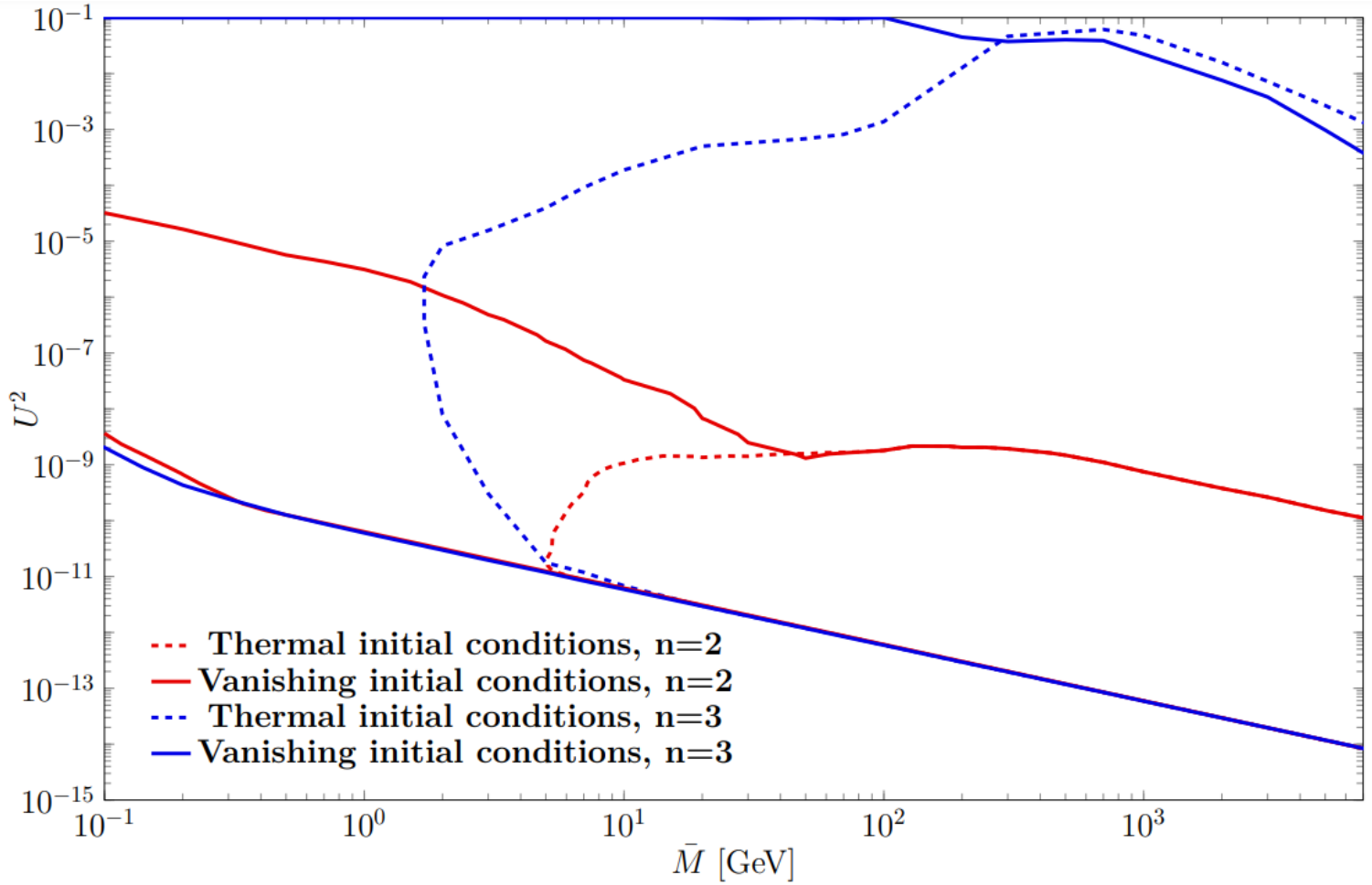
Results for $m_{\text{lightest}} = 0.1$ eV



- Parameter space smaller for $m_{\text{lightest}} = 0.1$ eV.

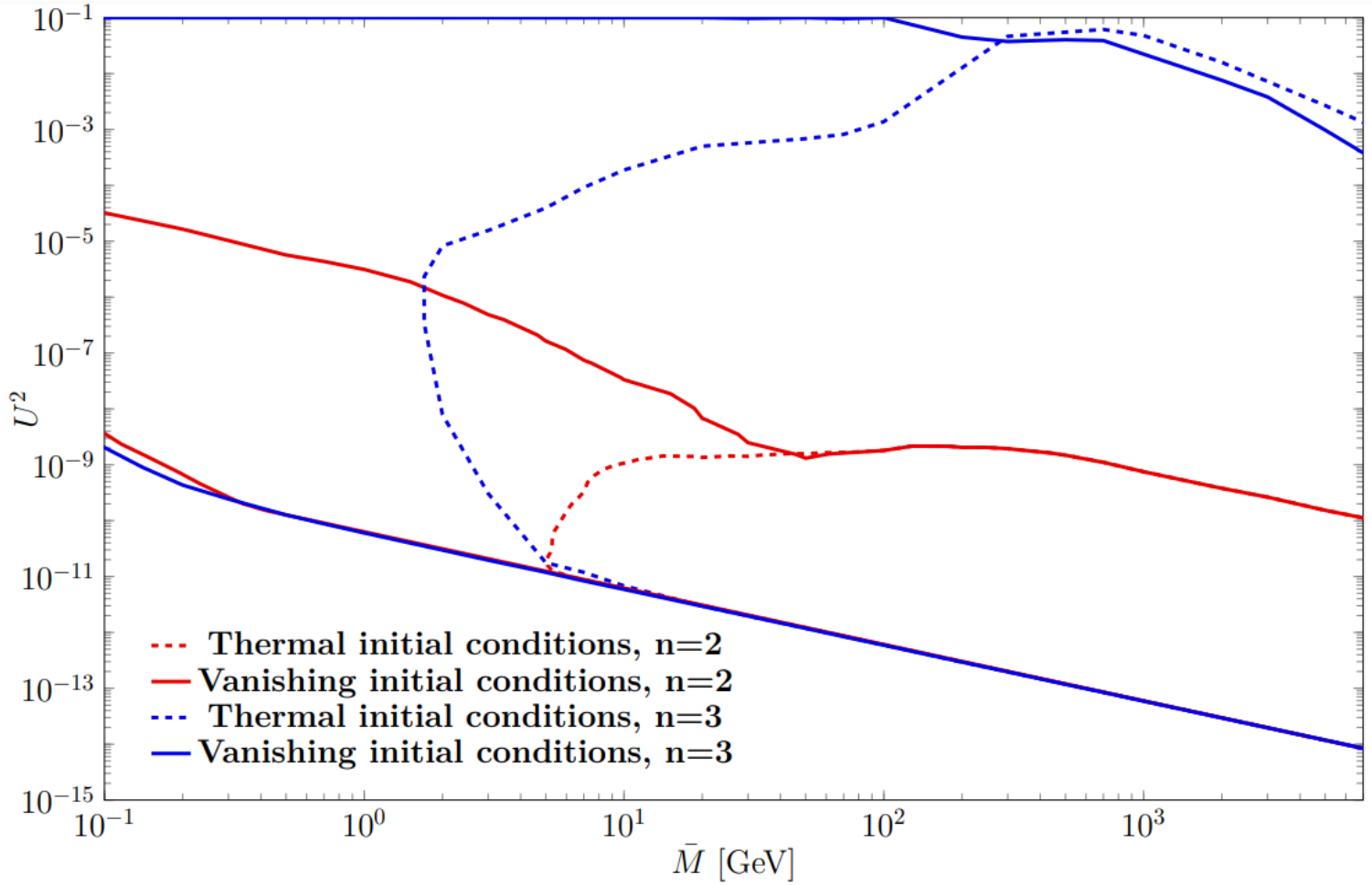
$$F = \frac{i}{v} U_\nu \sqrt{m_\nu^{diag}} R \sqrt{M_M}$$

Comparing $n = 2$ and $n = 3$.



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

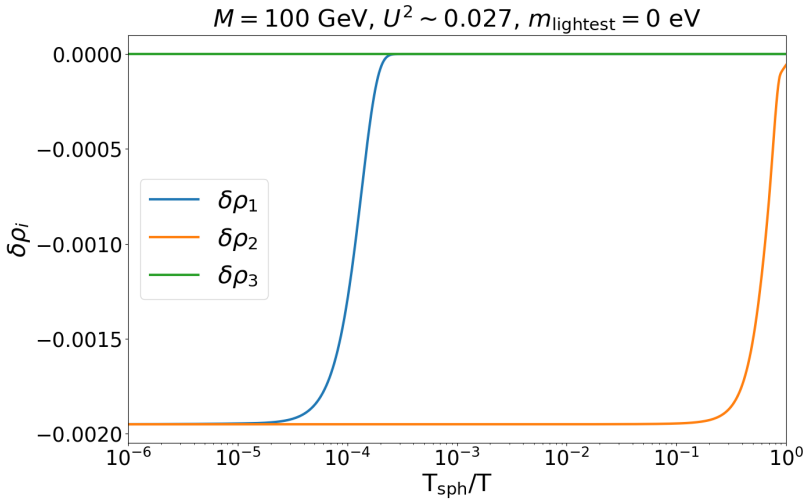
Comparing $n = 2$ and $n = 3$.

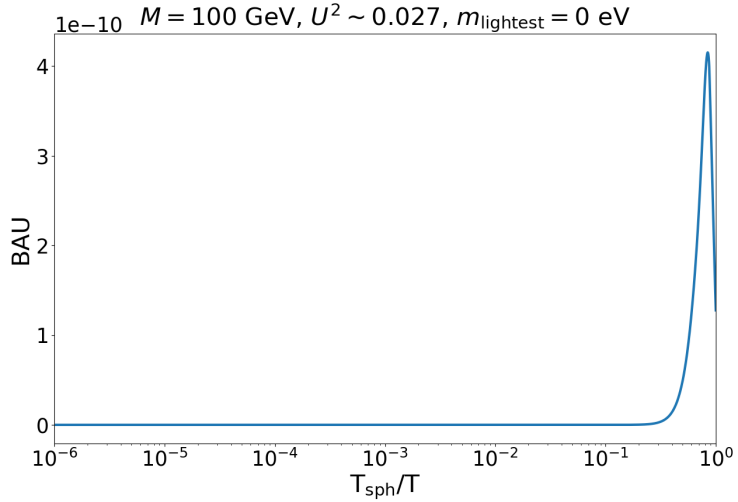


n=2 lines from Klaric/Shaposhnikov/Timiryasov [2008.13771]

- Parameter space way larger than in the $n = 2$ scenario: Late BAU production.

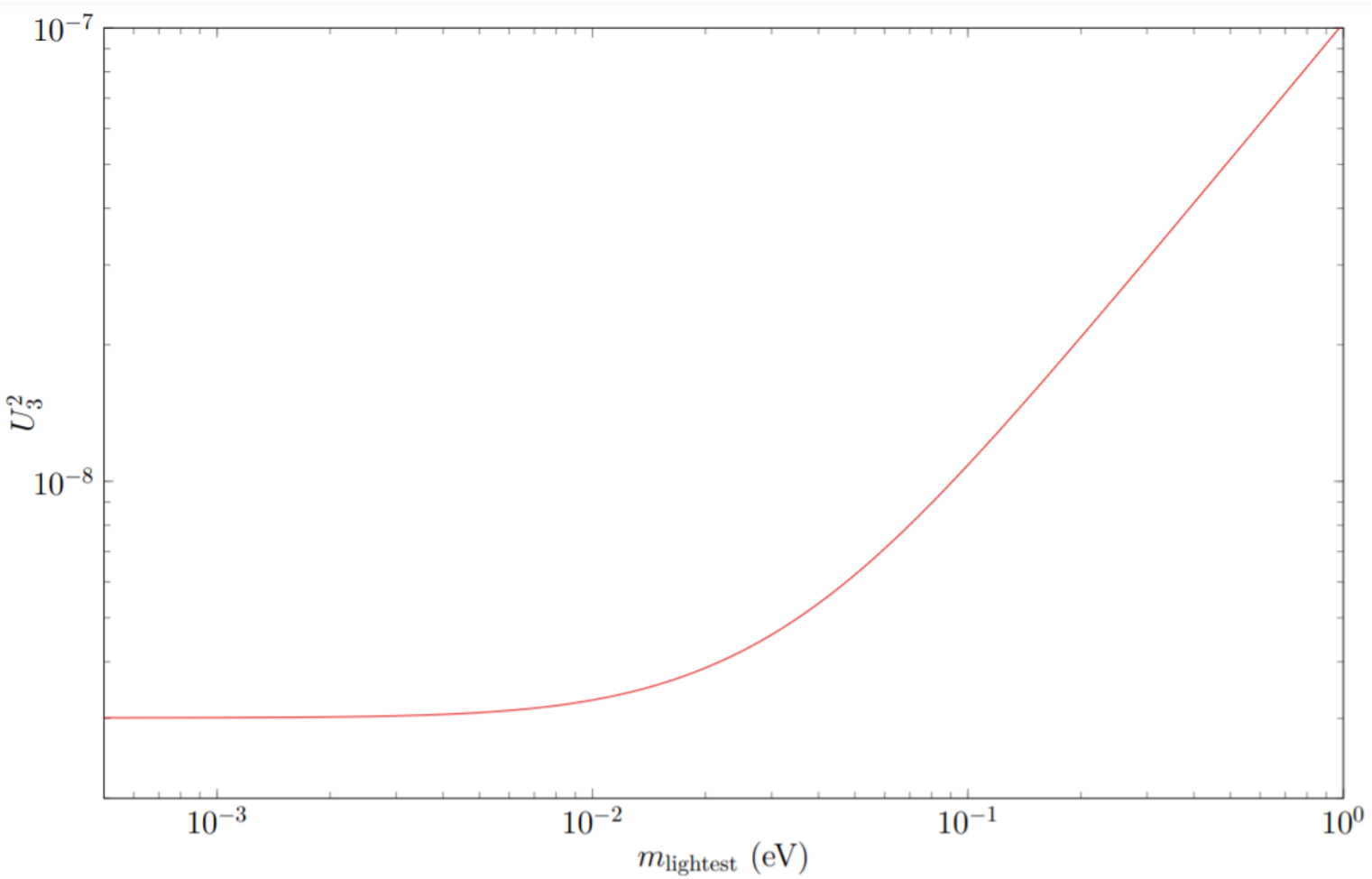
Late equilibration



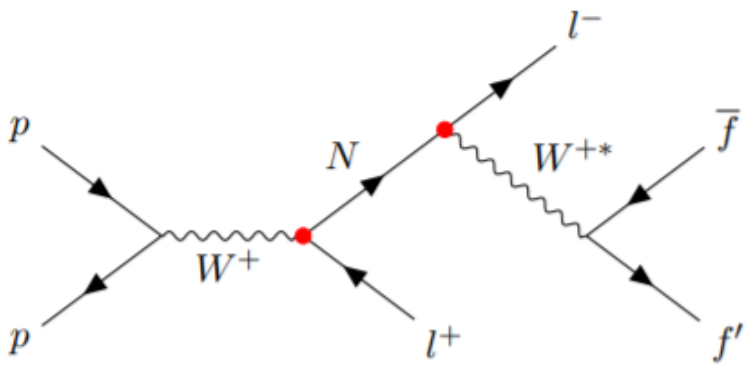


- Large mixing angles allow late equilibration of one heavy neutrino $U_i^2 \propto \epsilon'^2$.
- Implies late BAU production.

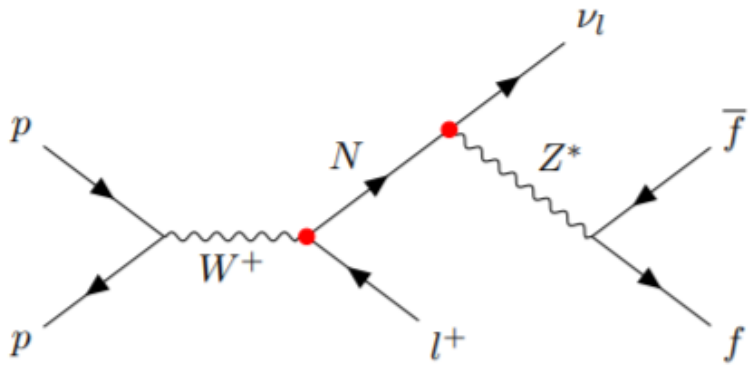
Late equilibration for $m_{\text{lightest}} \neq 0$ eV



Displaced vertices



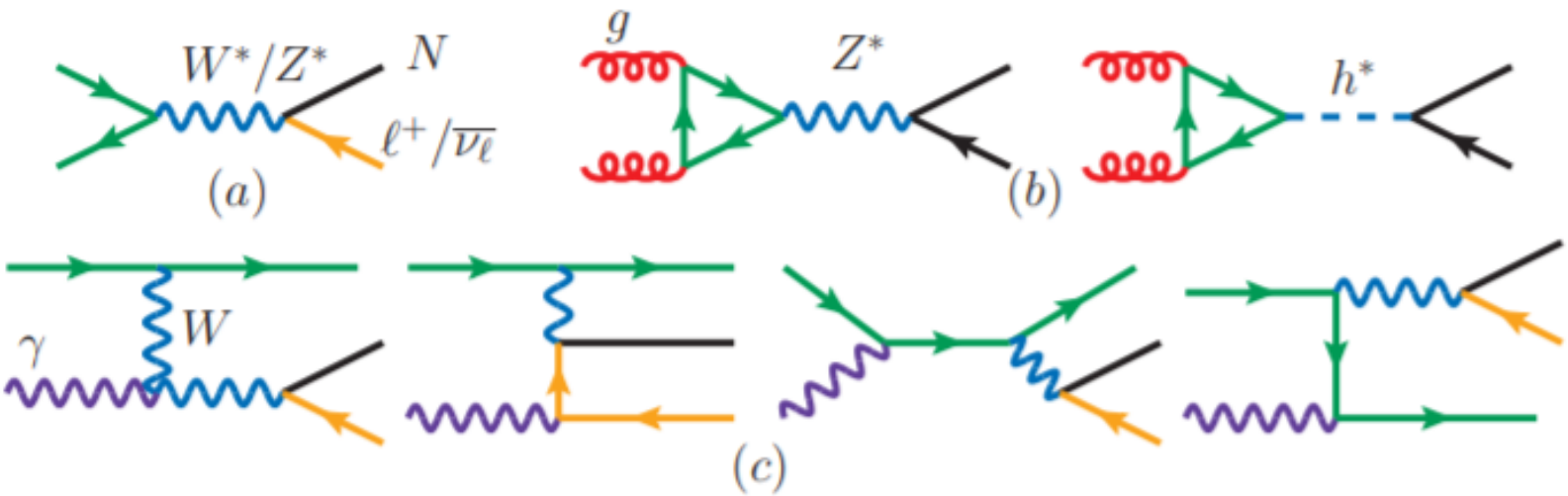
(a) Charged current decay.



(b) Neutral current decay.

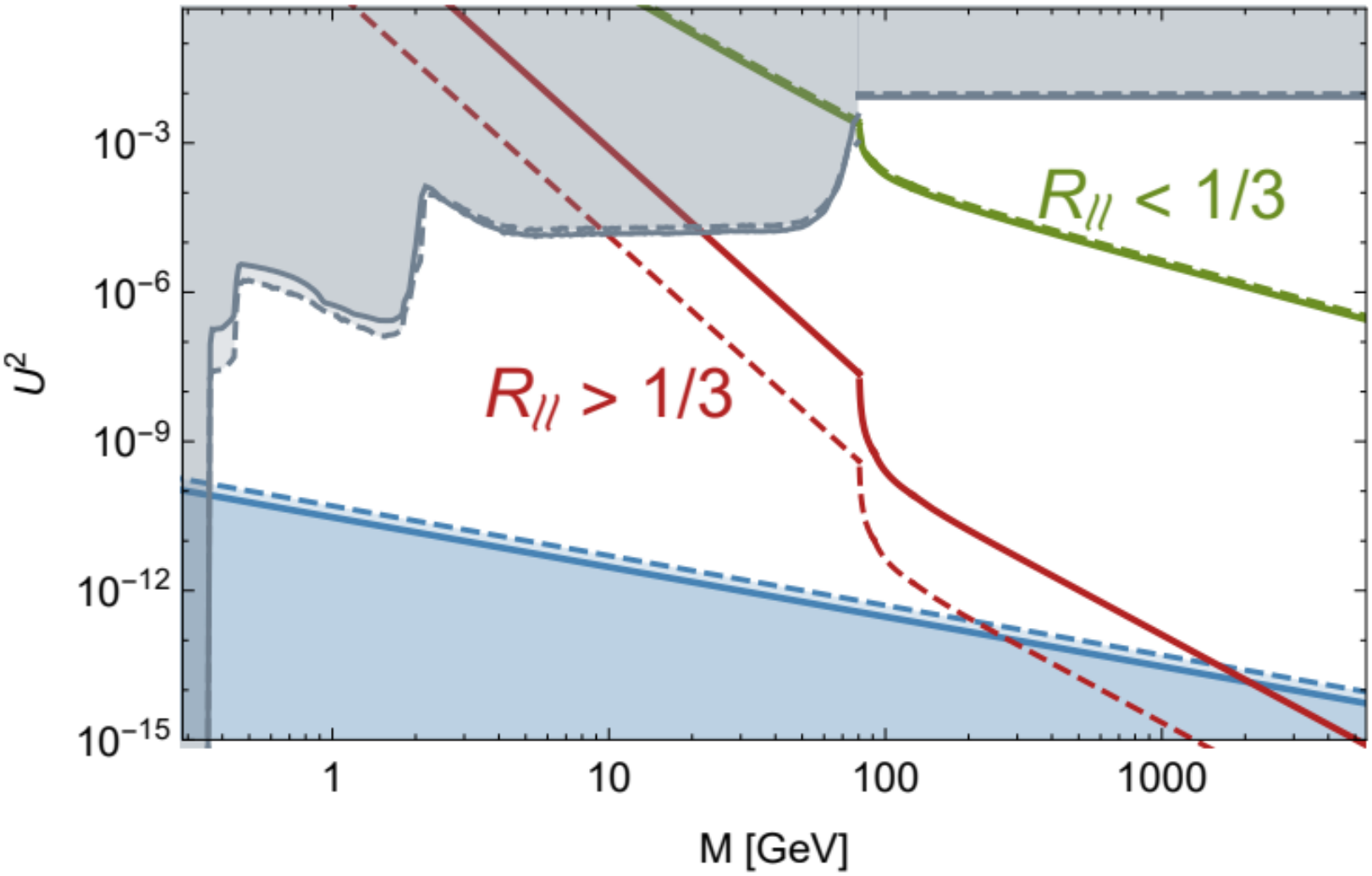
Drewes/Hajer 1903.06100

Production processes



Pascoli/Ruiz/weiland 1812.08750

LNV processes



B-$\bar{\text{L}}$ approximate symmetry

Naive seesaw bound

$$U_i^2 \sim \frac{\sqrt{\Delta m^2_{atm} + m^2_{light}}}{M} \lesssim 10^{-10} \frac{\text{GeV}}{M_i}$$

B-$\bar{\text{L}}$ approximate symmetry

Naive seesaw bound

$$U_i^2 \sim \frac{\sqrt{\Delta m^2_{atm} + m^2_{light}}}{M} \lesssim 10^{-10} \frac{\text{GeV}}{M_i}$$

B-$\bar{\text{L}}$ approximate symmetry

Majorana mass

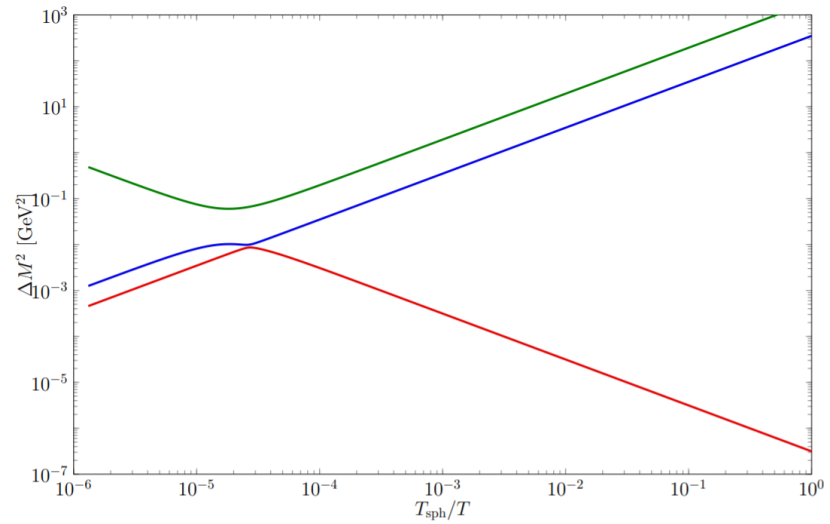
$$\bar{M} \cdot \begin{pmatrix} 1-\mu & 0 & 0 \\ 0 & 1+\mu & 0 \\ 0 & 0 & \mu' \end{pmatrix}$$

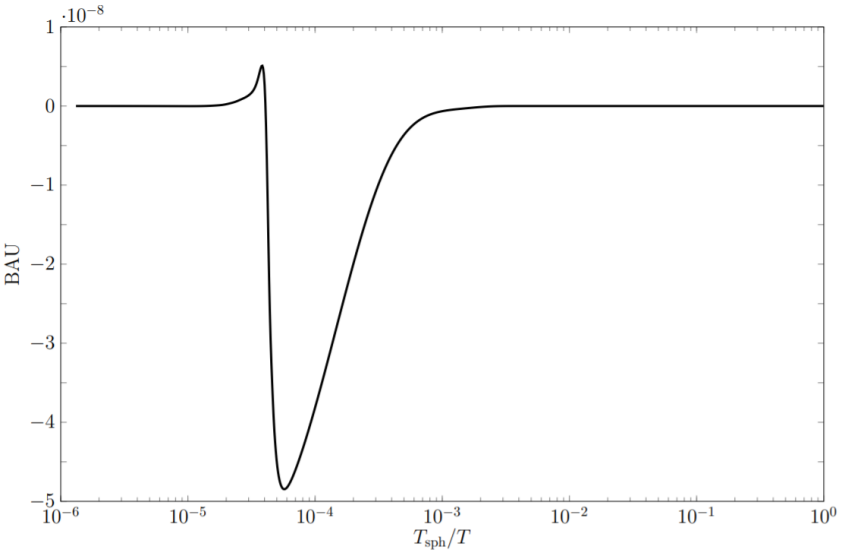
Yukawa coupling

$$\begin{pmatrix} f_e(1+\epsilon_e) & if_e(1-\epsilon_e) & f_e\epsilon'_e \\ f_\mu(1+\epsilon_\mu) & if_\mu(1-\epsilon_\mu) & f_\mu\epsilon'_\mu \\ f_\tau(1+\epsilon_\tau) & if_\tau(1-\epsilon_\tau) & f_\tau\epsilon'_\tau \end{pmatrix}$$

Smallness of light neutrino masses from the smallness of the symmetry breaking parameters $\mu, \epsilon, \epsilon' \ll 1$.

Resonant enhancement



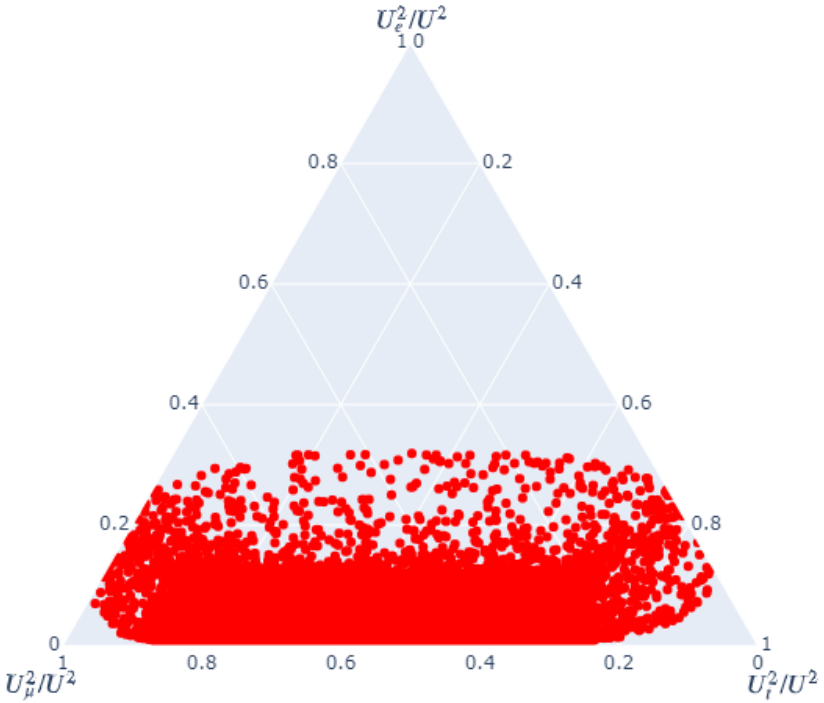


Thermal corrections can dynamically generate small mass splittings

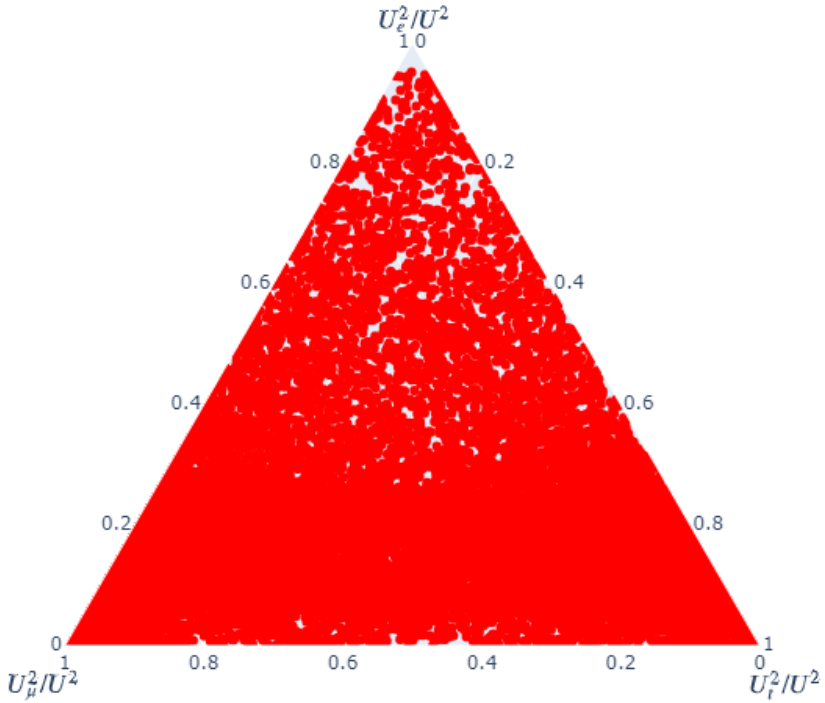
↓

Resonant enhancement

Branching ratios

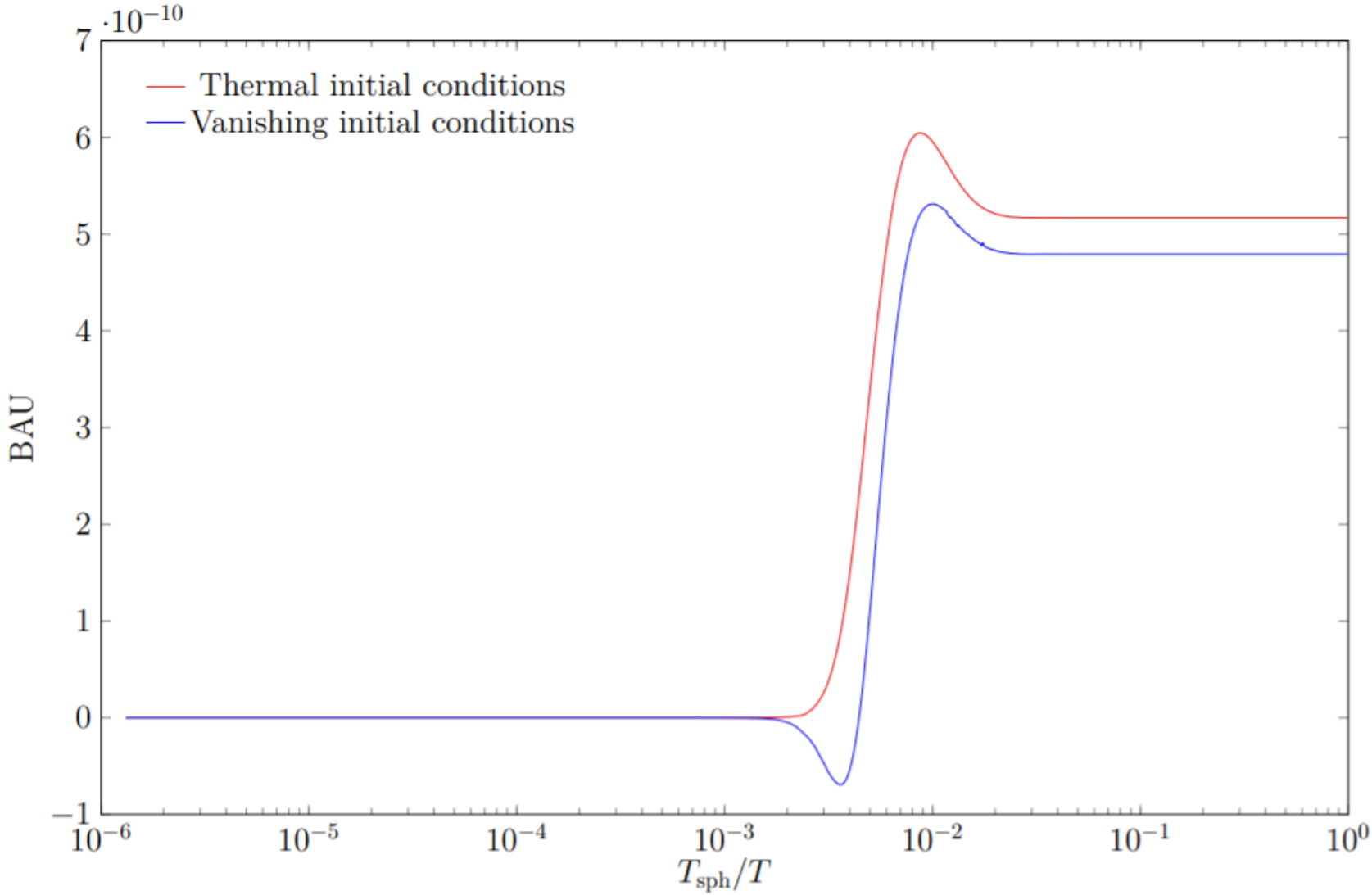


$m_{\text{lightest}} = 0$ eV

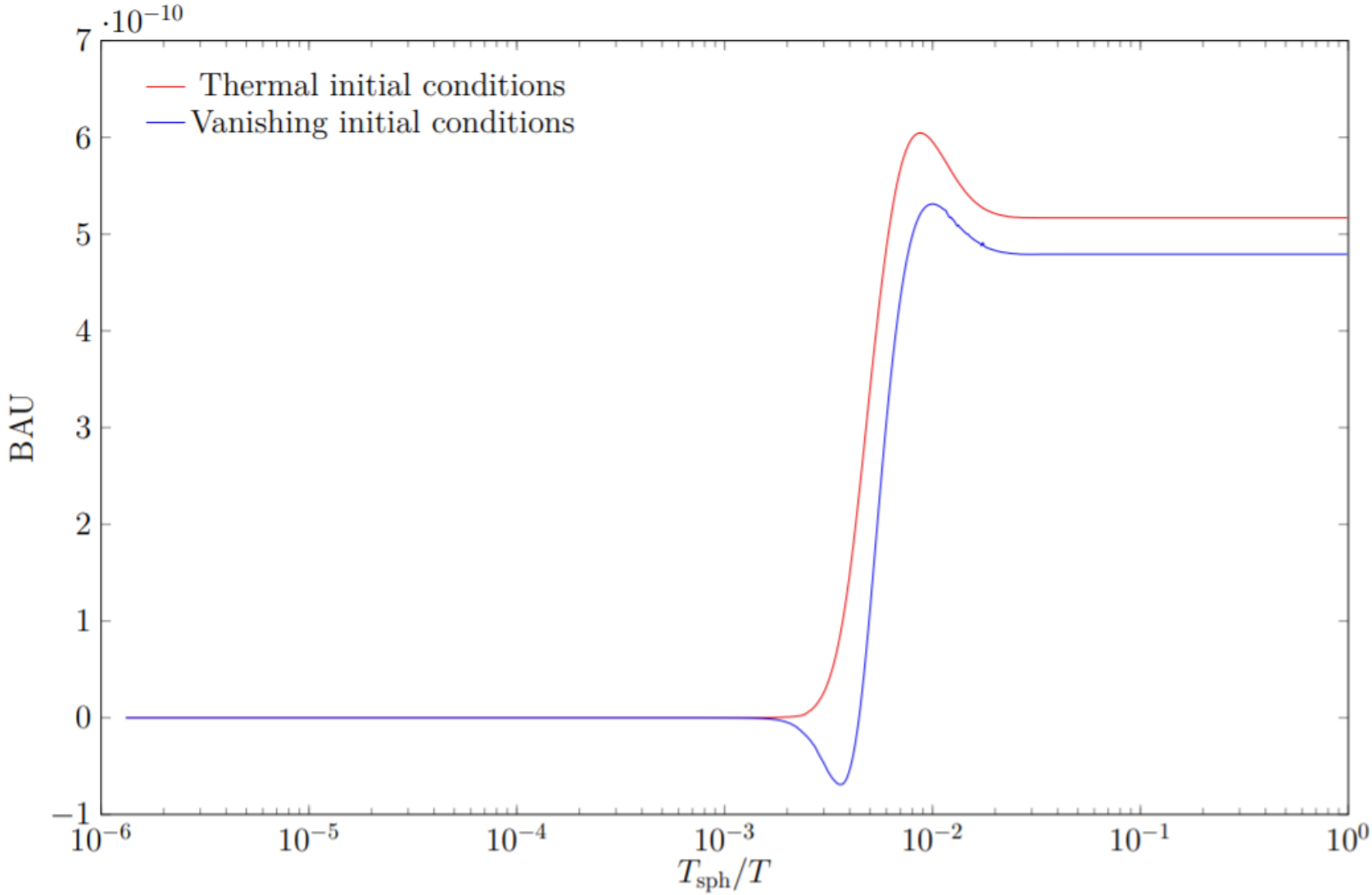


$m_{\text{lightest}} = 0.1$ eV

Thermal vs vanishing initial conditions



Thermal vs vanishing initial conditions



- Asymmetries generated during freeze-in and freeze-out have opposite signs.

Seesaw parameter space

Consistency with ν-oscillation data induced by Casas-Ibarra parametrisation

$$F = \frac{i}{v} U_\nu \sqrt{m_\nu^{diag}}\, \mathbf{R} \sqrt{M_M}$$

Seesaw relation: $m_\nu = -v^2 F \cdot {M_M}^{-1} \cdot F^t$.

Seesaw parameter space

Consistency with ν-oscillation data induced by Casas-Ibarra parametrisation

$$F = \frac{i}{v} U_\nu \sqrt{m_\nu^{diag}}\, \mathbf{R} \sqrt{M_M}$$

R is a complex rotation matrix

n=3

3 CP-violating phases

3 PMNS angles (fixed)

3 light neutrino masses (2 fixed)

3 complex Euler angles

3 Majorana masses

13 free parameters

Seesaw parameter space

Consistency with ν-oscillation data induced by Casas-Ibarra parametrisation

$$F = \frac{i}{v} U_\nu \sqrt{m_\nu^{diag}}\, \mathbf{R} \sqrt{M_M}$$

n=2	**n=3**
2 CP-violating phases	**3 CP-violating phases**
3 PMNS angles (fixed)	**3 PMNS angles** (fixed)
2 light neutrino masses (fixed)	**3 light neutrino masses** (2 fixed)
1 complex Euler angle	**3 complex Euler angles**
2 Majorana masses	**3 Majorana masses**
6 free parameters	13 free parameters

Constraints

- Normal ordering and $m_{\text{lightest}} \in \{0, 0.1\}$ eV.

Constraints

- Normal ordering and $m_{\text{lightest}} \in \{0, 0.1\}$ eV.
- Mass degenerate scenario $\frac{\Delta M}{M} \lesssim 0.1$

Constraints

- Normal ordering and $m_{\text{lightest}} \in \{0, 0.1\}$ eV.
- Mass degenerate scenario $\frac{\Delta M}{M} \lesssim 0.1$

- Theoretical constraints:

Constraints

- Normal ordering and $m_{\text{lightest}} \in \{0, 0.1\}$ eV.
- Mass degenerate scenario $\frac{\Delta M}{M} \lesssim 0.1$

- Theoretical constraints:

1. Perturbative unitarity $\Gamma < \frac{M}{2}$

Constraints

- Normal ordering and $m_{\text{lightest}} \in \{0, 0.1\}$ eV.
- Mass degenerate scenario $\frac{\Delta M}{M} \lesssim 0.1$

- Theoretical constraints:

1. Perturbative unitarity $\Gamma < \frac{M}{2}$
2. Seesaw expansion $U^2 < 0.1$

Constraints

- Normal ordering and $m_{\text{lightest}} \in \{0, 0.1\}$ eV.
- Mass degenerate scenario $\frac{\Delta M}{M} \lesssim 0.1$

- Theoretical constraints:

1. Perturbative unitarity $\Gamma < \frac{M}{2}$
2. Seesaw expansion $U^2 < 0.1$
3. No large radiative corrections $(1 - ||\frac{m_{tree}}{m_{loop}}||)^2 < \frac{1}{4}$.

Initial conditions

We consider 2 types of initial conditions:

Initial conditions

We consider 2 types of initial conditions:

- **Thermal initial conditions :**
  - Resonant leptogenesis dominates.
  - Well-motivated in the context of SM gauge extensions.

Initial conditions

We consider 2 types of initial conditions:

- **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.

Seesaw type-I

- Seesaw Lagrangian

$$\mathcal{L} \supset F_{ai}(\bar{\ell}_a \tilde{\phi})\nu_{Ri} + \frac{1}{2}\bar{\nu}^c_{Ri}(M_M)_{ij}\nu_{Rj} + \text{h.c.}$$

Seesaw type-I

- Seesaw Lagrangian

$$\mathcal{L} \supset \boxed{F_{ai}}(\bar{\ell}_a \tilde{\phi})\nu_{Ri} + \frac{1}{2}\bar{\nu}^c_{Ri}\boxed{(M_M)_{ij}}\nu_{Rj} + \text{h.c.}$$

Yukawa **Majorana**

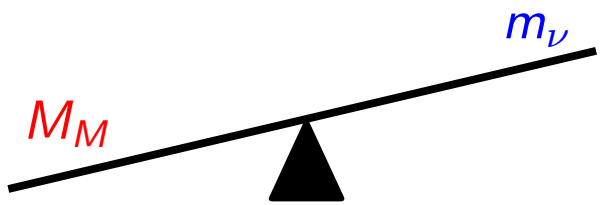
Seesaw type-I

- Seesaw Lagrangian

$$\mathcal{L} \supset F_{ai}(\bar{\ell}_a \tilde{\phi})\nu_{Ri} + \frac{1}{2}\bar{\nu}^c_{Ri}(M_M)_{ij}\nu_{Rj} + \text{h.c.}$$

Seesaw relation

$$m_\nu = -v^2 F \cdot {M_M}^{-1} \cdot F^t.$$



$$\nu \simeq U_\nu^\dagger(\nu_L - \theta\nu_R^c) + \text{h.c.}$$

Light neutrinos

$$N \simeq U_N^\dagger(\nu_R + \theta^t\nu_L^c) + \text{h.c.}$$

Heavy neutrinos

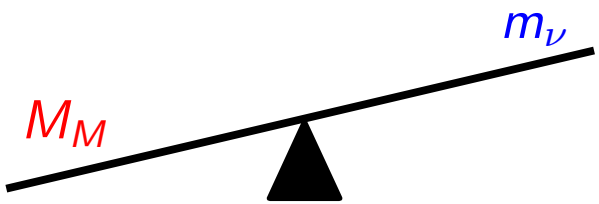
Seesaw type-I

- Seesaw Lagrangian

$$\mathcal{L} \supset F_{ai}(\bar{\ell}_a \tilde{\phi})\nu_{Ri} + \frac{1}{2}\bar{\nu}^c_{Ri}(M_M)_{ij}\nu_{Rj} + \text{h.c.}$$

Seesaw relation

$$m_\nu = -v^2 F \cdot {M_M}^{-1} \cdot F^t.$$



$n \gtrsim 2$ needed to explain light neutrino masses.

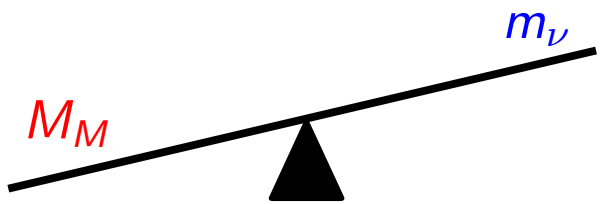
Seesaw type-I

- Seesaw Lagrangian

$$\mathcal{L} \supset F_{ai}(\bar{\ell}_a \tilde{\phi})\nu_{Ri} + \frac{1}{2}\bar{\nu}^c_{Ri}(M_M)_{ij}\nu_{Rj} + \text{h.c.}$$

Seesaw relation

$$m_\nu = -v^2 F \cdot {M_M}^{-1} \cdot F^t.$$



In this work, $n = 3$.

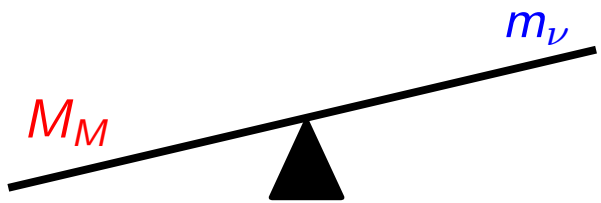
Seesaw type-I

- Seesaw Lagrangian

$$\mathcal{L} \supset F_{ai}(\bar{\ell}_a \tilde{\phi})\nu_{Ri} + \frac{1}{2}\bar{\nu}^c_{Ri}(M_M)_{ij}\nu_{Rj} + \text{h.c.}$$

Seesaw relation

$$m_\nu = -v^2 F \cdot {M_M}^{-1} \cdot F^t.$$



In this work, $n = 3$.

- Interaction strength of the heavy neutrinos

$$U^2 = v^2 \sum_{a,i} |(F \cdot M_M^{-1})_{ai}|^2 \equiv \sum_{a,i} |\theta_{ai}|^2.$$