BARYOGENESIS THROUGH NEUTRINO OSCILLATIONS

A Unified Perspective

Brian Shuve

Perimeter Institute for Theoretical Physics

BS, Itay Yavin, arXiv:1401.2459

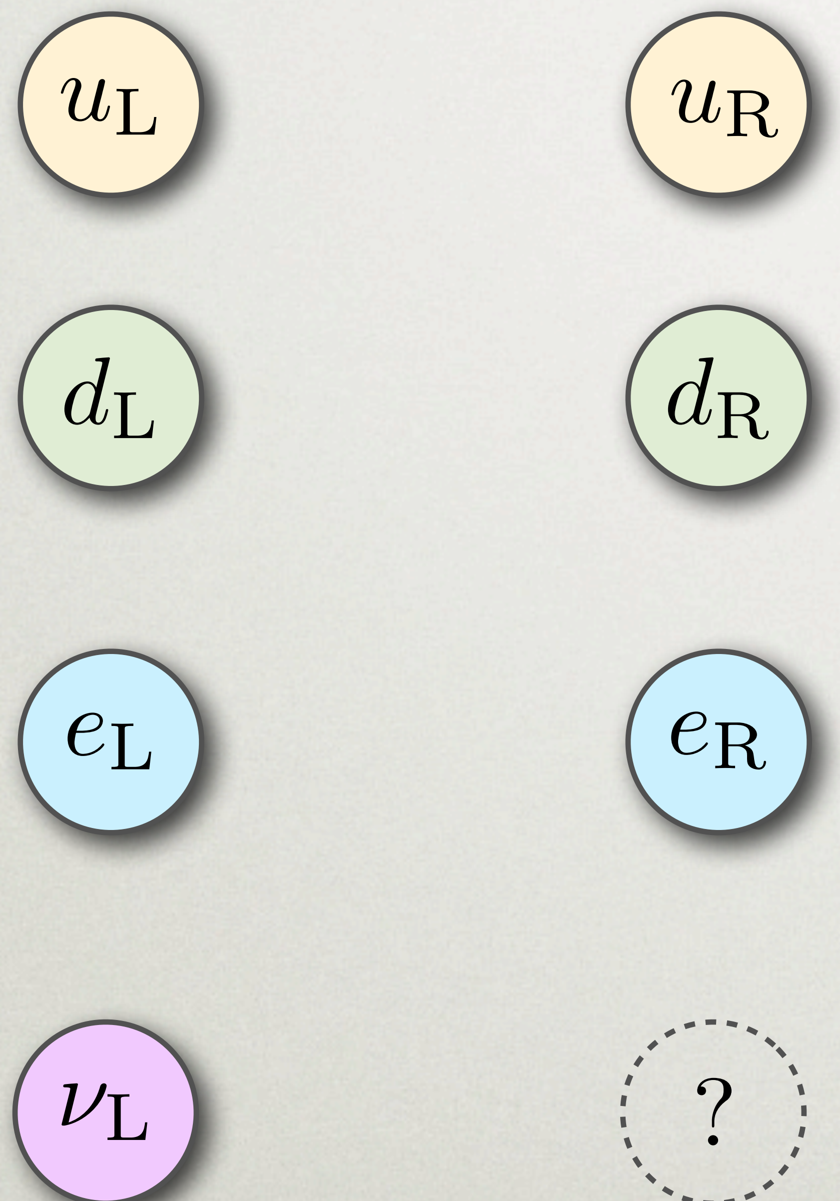
and work in progress

Invisibles Webinar

16 December 2014

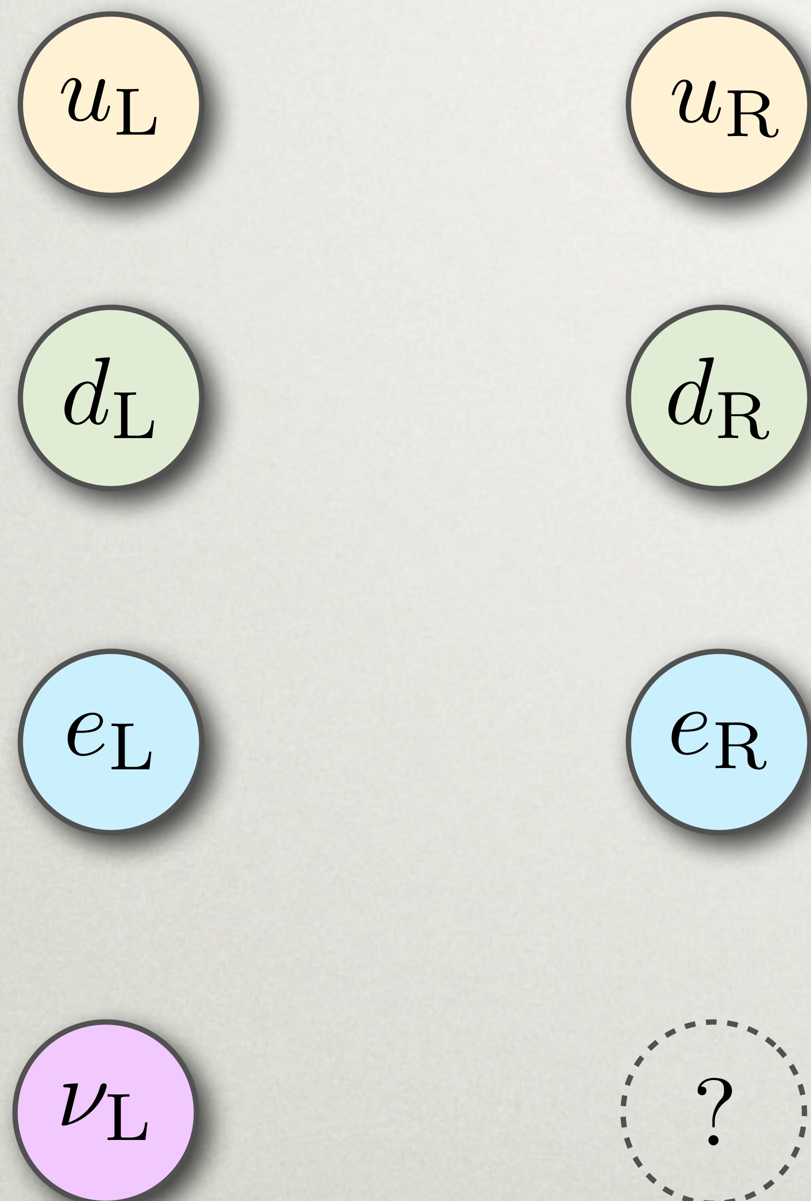
Why sterile neutrinos?

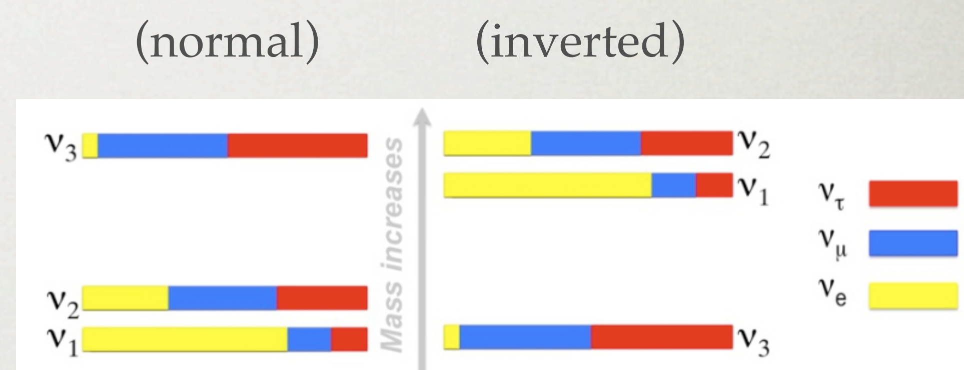
- The Standard Model has missing pieces:



Why sterile neutrinos?

- The Standard Model has missing pieces:

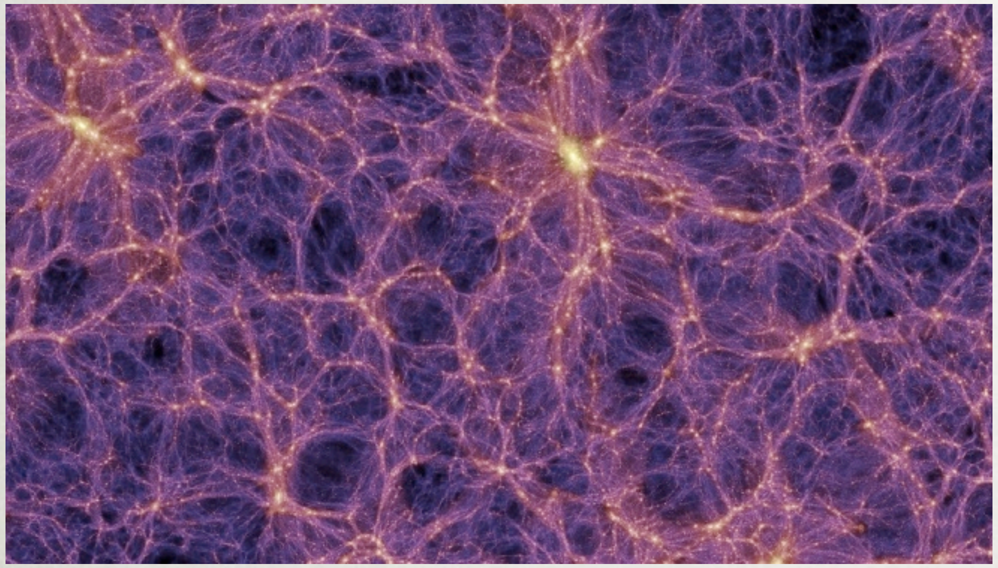




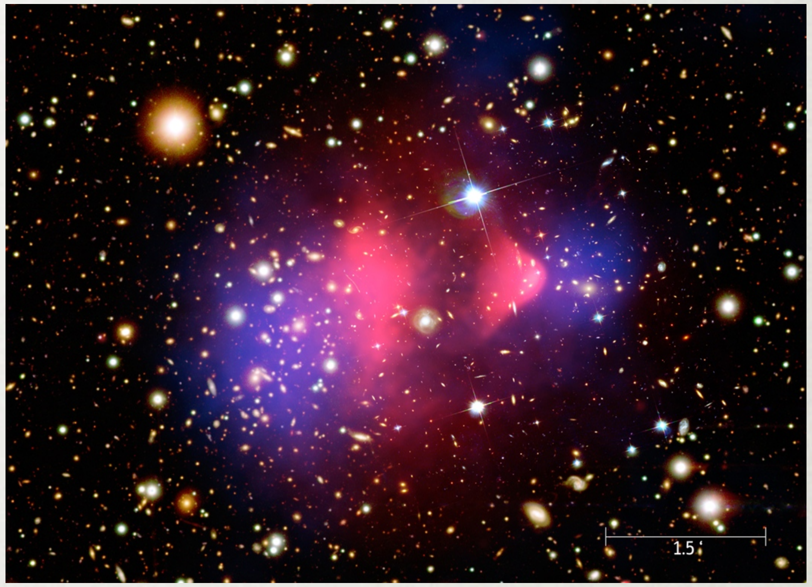
Lujan-Peschard *et al.*, 2013

Why sterile neutrinos?

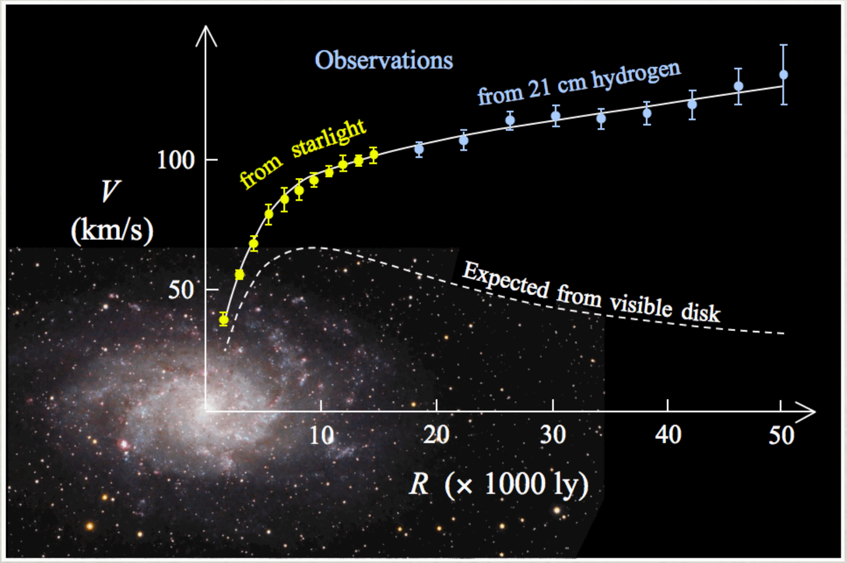
- The Standard Model has missing pieces:



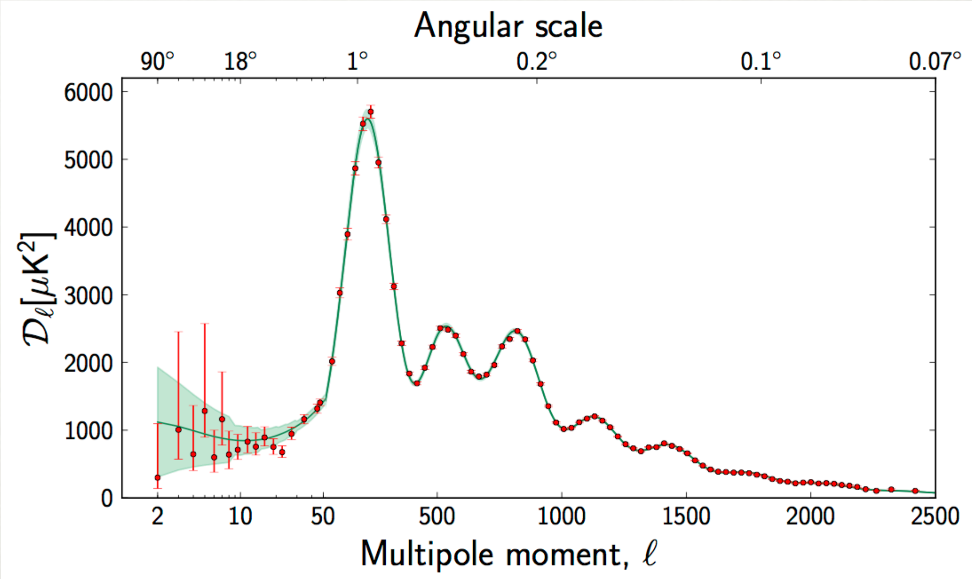
Springel *et al.*, 2005



Clowe *et al.*, 2006; Markevitch *et al.*, 2005



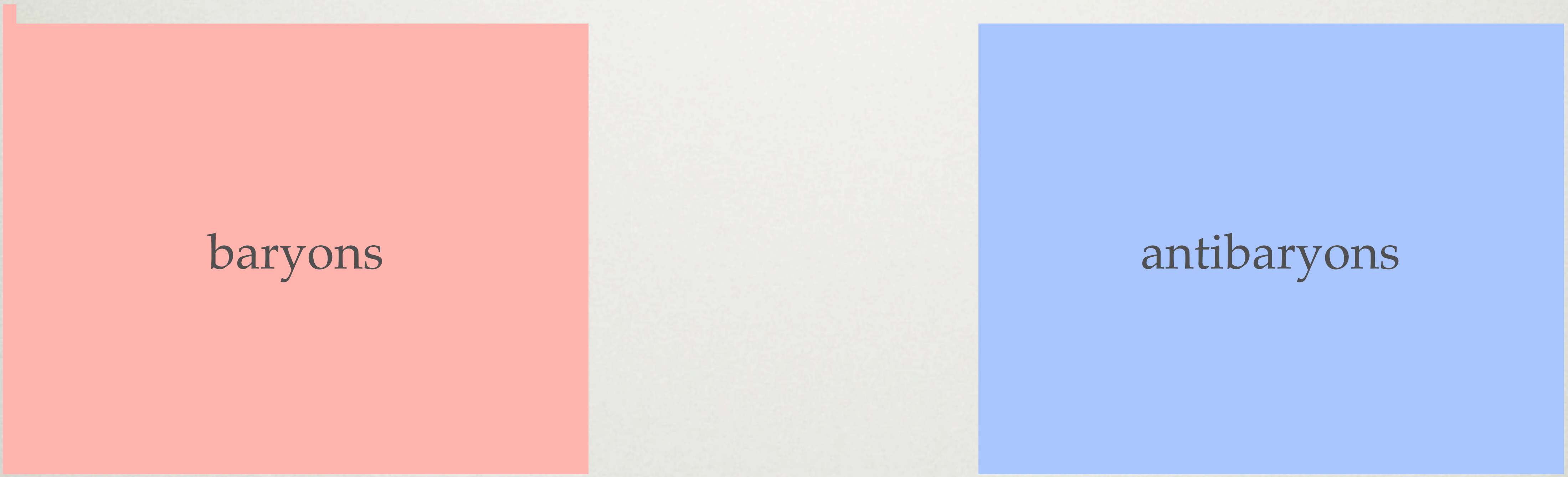
Corbelli, Salucci, 2000



Planck, 2013

Why sterile neutrinos?

- The Standard Model has missing pieces:



$$\frac{n_{\Delta B}}{s} \approx 8 \times 10^{-11}$$

Neutrino Minimal SM

- Remarkably, a minimal extension of the SM with only **three sterile neutrinos** (*N*) can fill in all of these missing pieces!

Neutrino Minimal SM

- Remarkably, a minimal extension of the SM with only **three sterile neutrinos** (*N*) can fill in all of these missing pieces!

$$\mathcal{L}_{\mathrm{see-saw}} = F\, L\Phi N + \frac{M_N}{2} N^2$$

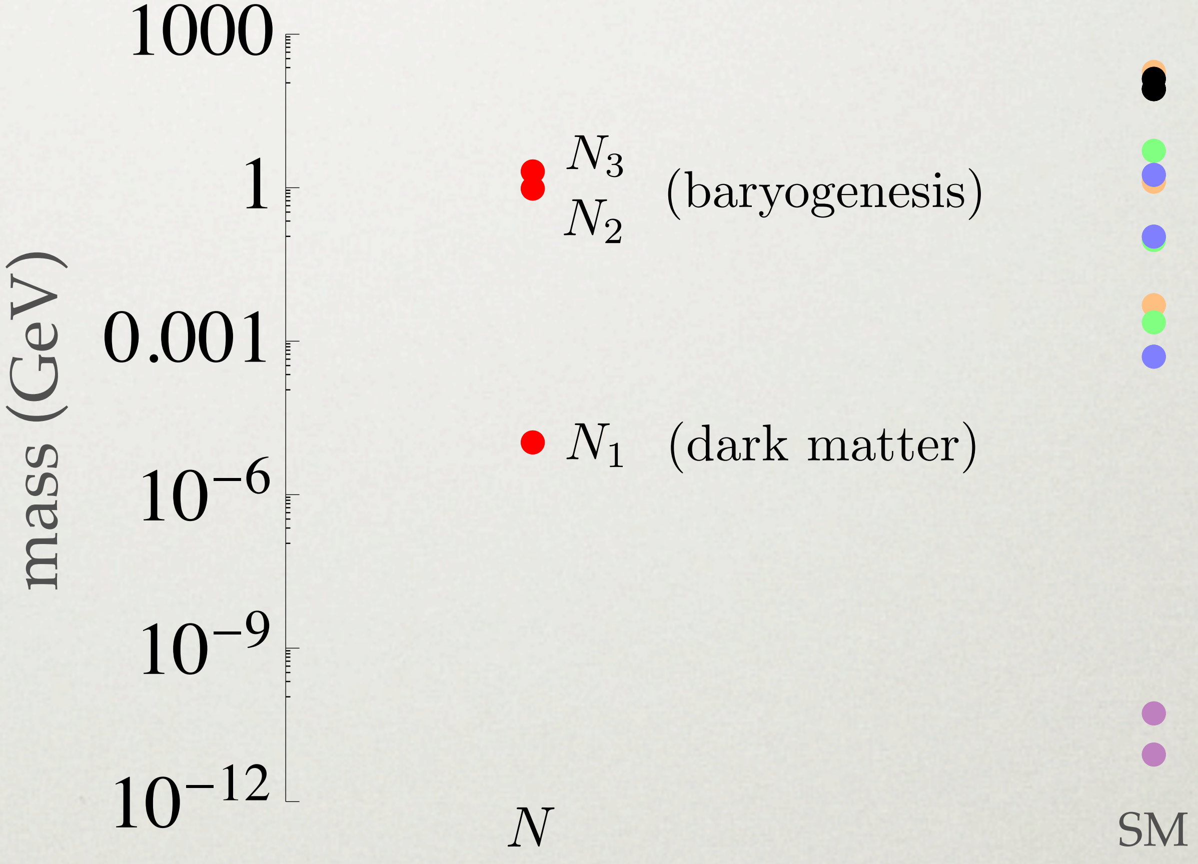
$$m_\nu \sim \frac{F^2 \langle\Phi\rangle^2}{M_N}$$

Neutrino Minimal SM

- Remarkably, a minimal extension of the SM with only **three sterile neutrinos** (*N*) can fill in all of these missing pieces!
    - The masses of all three sterile neutrinos are **below the weak scale**, and kinematically accessible in current experiments

$$\mathcal{L}_{\text{see-saw}} = F\, L \Phi N + \frac{M_N}{2} N^2$$

$$m_\nu \sim \frac{F^2 \langle \Phi \rangle^2}{M_N}$$

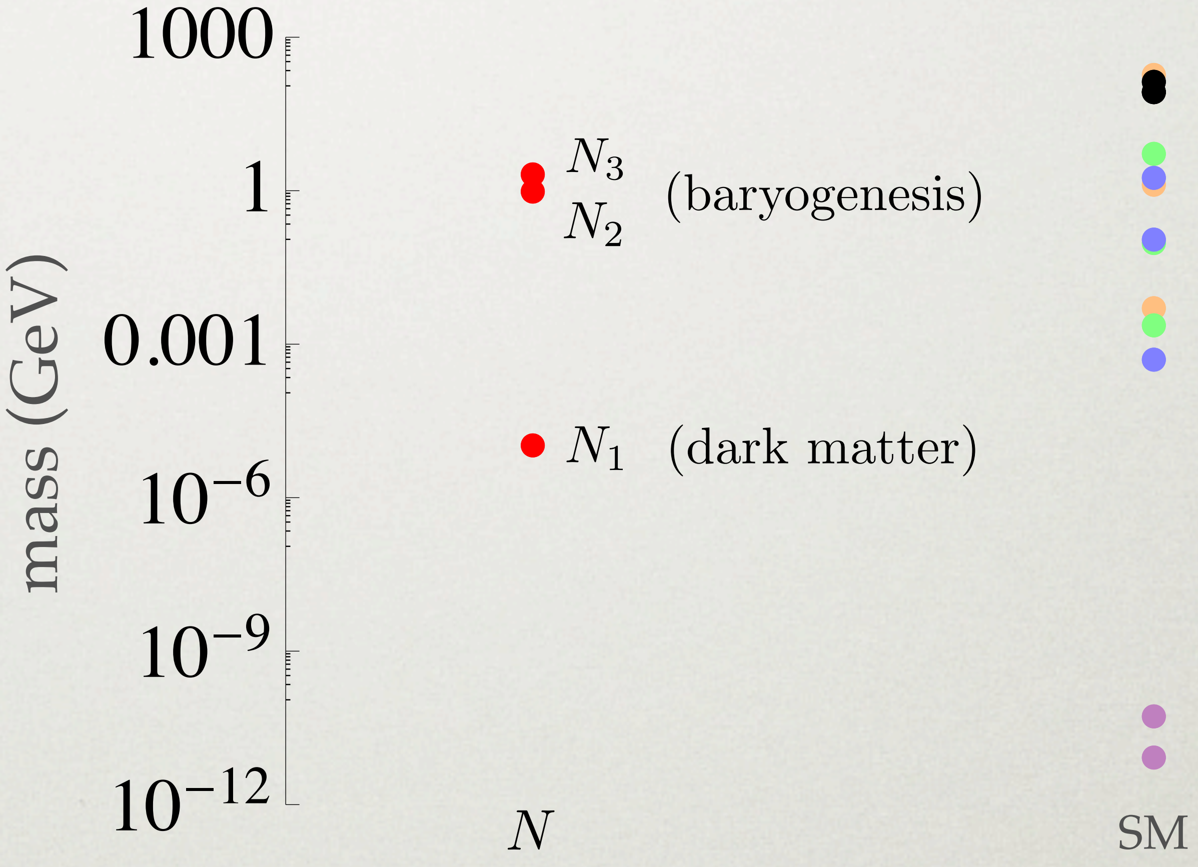


Neutrino Minimal SM

- Remarkably, a minimal extension of the SM with only **three sterile neutrinos** (N) can fill in all of these missing pieces!
    - The masses of all three sterile neutrinos are **below the weak scale**, and kinematically accessible in current experiments

$$\mathcal{L}_{\mathrm{see-saw}} = F\, L\Phi N + \frac{M_N}{2} N^2$$

$$m_\nu \sim \frac{F^2 \langle \Phi \rangle^2}{M_N}$$



- Called the **neutrino minimal SM** (νMSM)
    - Asaka, Shaposhnikov 2005; Asaka, Blanchet, Shaposhnikov 2005; Canetti, Drewes, Frossard, Shaposhnikov 2012; ...

Too-sterile neutrinos

- The model is highly predictive because sterile neutrinos only interact with the SM through the Yukawa couplings

Too-sterile neutrinos

- The model is highly predictive because sterile neutrinos only interact with the SM through the Yukawa couplings

- However, it turns out that sterile neutrinos are **too sterile** if they interact only through the see-saw coupling
    - With just the νMSM, you generically predict **insufficient abundances of DM and baryons**

Too-sterile neutrinos

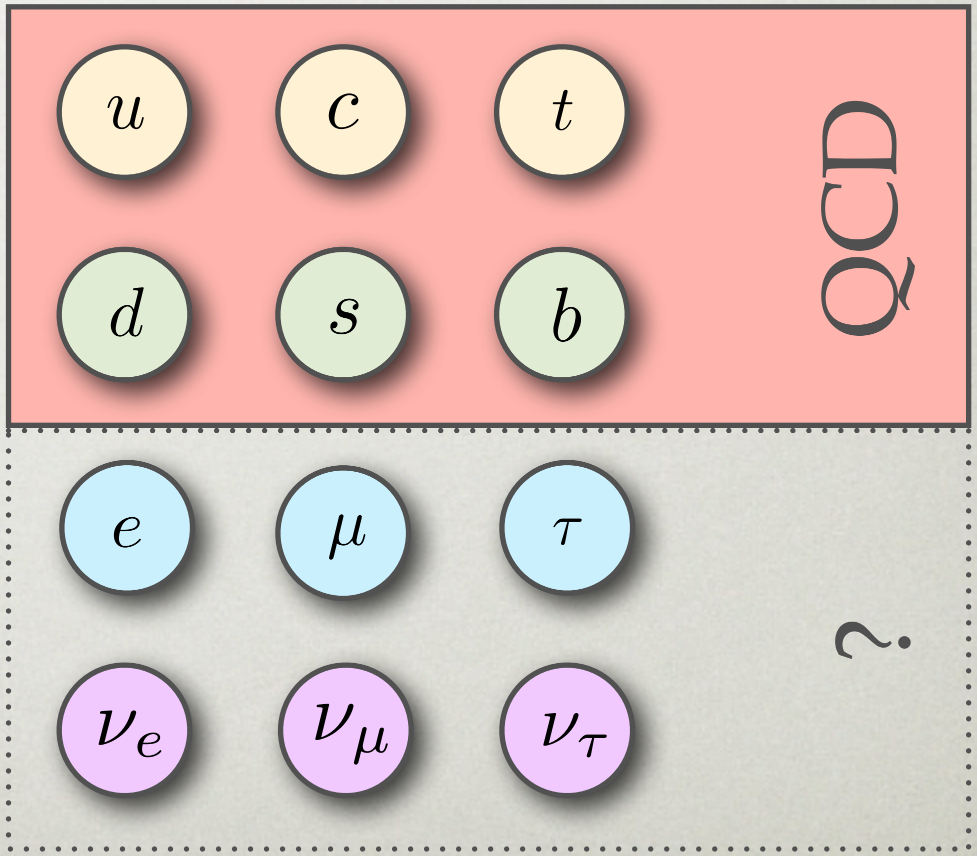
- The model is highly predictive because sterile neutrinos only interact with the SM through the Yukawa couplings

- However, it turns out that sterile neutrinos are **too sterile** if they interact only through the see-saw coupling
    - With just the νMSM, you generically predict **insufficient abundances of DM and baryons**

- For sterile neutrinos to be viable, we need them to be **not-so-sterile**

- For both baryogenesis & dark matter, we expect new leptonic interactions at the weak scale (or below)

- I will focus on the mechanism of **baryogenesis** (N_2, N_3)



Outline

- Mechanism of baryogenesis via neutrino oscillations
- Baryogenesis and tuning in the minimal model
- Enhanced asymmetry with an extended Higgs sector + phenomenology
- Phenomenology of sterile neutrino production

Baryogenesis overview

$$\mathcal{L}_{\nu\mathrm{MSM}} = F_{\alpha I} L_\alpha \Phi N_I + \frac{M_I}{2} N_I^2 \qquad\qquad (m_\nu)_{\alpha\beta} = \langle\Phi\rangle^2 (F\, M_N^{-1} F^{\mathrm{T}})_{\alpha\beta}$$

- Assume no primordial abundance of *N*

Baryogenesis overview

$$\mathcal{L}_{\nu\mathrm{MSM}} = F_{\alpha I} L_\alpha \Phi N_I + \frac{M_I}{2} N_I^2 \qquad (m_\nu)_{\alpha\beta} = \langle\Phi\rangle^2 (F\,M_N^{-1} F^{\mathrm{T}})_{\alpha\beta}$$

- Assume no primordial abundance of *N*
- Baryogenesis occurs through the (slow) production, oscillation, and re-scattering of the heavy sterile neutrino states, N_2 and N_3
  - Akhmedov, Rubakov, Smirnov 1998; Asaka, Shaposhnikov 2005;... Drewes, Garbrecht 2012

Baryogenesis overview

$$\mathcal{L}_{\nu\mathrm{MSM}} = F_{\alpha I} L_\alpha \Phi N_I + \frac{M_I}{2} N_I^2 \qquad (m_\nu)_{\alpha\beta} = \langle\Phi\rangle^2 (F\, M_N^{-1} F^{\mathrm{T}})_{\alpha\beta}$$

- Assume no primordial abundance of *N*
- Baryogenesis occurs through the (slow) production, oscillation, and re-scattering of the heavy sterile neutrino states, N_2 and N_3
    - Akhmedov, Rubakov, Smirnov 1998; Asaka, Shaposhnikov 2005;... Drewes, Garbrecht 2012
- There are three Sakharov conditions for baryogenesis:
    1. **(SM) Baryon number violation:** Need to allow for an excess of baryons to evolve from zero asymmetry

Baryogenesis overview

$$\mathcal{L}_{\nu\mathrm{MSM}} = F_{\alpha I} L_\alpha \Phi N_I + \frac{M_I}{2} N_I^2 \qquad\qquad (m_\nu)_{\alpha\beta} = \langle\Phi\rangle^2 (F\, M_N^{-1} F^{\mathrm{T}})_{\alpha\beta}$$

- Assume no primordial abundance of *N*
- Baryogenesis occurs through the (slow) production, oscillation, and re-scattering of the heavy sterile neutrino states, N_2 and N_3
  - Akhmedov, Rubakov, Smirnov 1998; Asaka, Shaposhnikov 2005;... Drewes, Garbrecht 2012
- There are three Sakharov conditions for baryogenesis:
  1. **(SM) Baryon number violation:** Need to allow for an excess of baryons to evolve from zero asymmetry
  2. **CP violation:** Need to favour matter vs. antimatter

Baryogenesis overview

$$\mathcal{L}_{\nu\mathrm{MSM}} = F_{\alpha I} L_\alpha \Phi N_I + \frac{M_I}{2} N_I^2 \qquad\qquad (m_\nu)_{\alpha\beta} = \langle\Phi\rangle^2 (F\, M_N^{-1} F^{\mathrm{T}})_{\alpha\beta}$$

- Assume no primordial abundance of N
- Baryogenesis occurs through the (slow) production, oscillation, and re-scattering of the heavy sterile neutrino states, N_2 and N_3
  - Akhmedov, Rubakov, Smirnov 1998; Asaka, Shaposhnikov 2005;... Drewes, Garbrecht 2012
- There are three Sakharov conditions for baryogenesis:
  1. **(SM) Baryon number violation:** Need to allow for an excess of baryons to evolve from zero asymmetry
  2. **CP violation:** Need to favour matter vs. antimatter
  3. **Departure from thermal equilibrium:** In equilibrium, inverse *B*-violating processes wipe out any accumulated asymmetry. Out-of-equilibrium condition preserves generated asymmetry

Baryogenesis overview

$$\mathcal{L}_{\nu\mathrm{MSM}} = F_{\alpha I} L_\alpha \Phi N_I + \frac{M_I}{2} N_I^2 \qquad (m_\nu)_{\alpha\beta} = \langle \Phi \rangle^2 (F\, M_N^{-1} F^{\mathrm{T}})_{\alpha\beta}$$

- The νMSM satisfies the three Sakharov conditions for baryogenesis:

Baryogenesis overview

$$\mathcal{L}_{\nu\mathrm{MSM}} = F_{\alpha I} L_\alpha \Phi N_I + \frac{M_I}{2} N_I^2 \qquad\qquad (m_\nu)_{\alpha\beta} = \langle\Phi\rangle^2 (F\, M_N^{-1} F^{\mathrm{T}})_{\alpha\beta}$$

- The νMSM satisfies the three Sakharov conditions for baryogenesis:

  1. **Baryon number violation:** SM lepton number is broken by *N* mass and couplings; lepton asymmetry is transferred to a baryons via the *B* + *L* anomaly (sphalerons)

Baryogenesis overview

$$\mathcal{L}_{\nu\mathrm{MSM}} = F_{\alpha I} L_\alpha \Phi N_I + \frac{M_I}{2} N_I^2 \qquad (m_\nu)_{\alpha\beta} = \langle\Phi\rangle^2 (F\, M_N^{-1} F^{\mathrm{T}})_{\alpha\beta}$$

- The νMSM satisfies the three Sakharov conditions for baryogenesis:

1. **Baryon number violation:** SM lepton number is broken by N mass and couplings; lepton asymmetry is transferred to a baryons via the $B + L$ anomaly (sphalerons)

2. **CP violation:** Three new CP phases in the Yukawa matrix F

Baryogenesis overview

$$\mathcal{L}_{\nu\mathrm{MSM}} = F_{\alpha I} L_\alpha \Phi N_I + \frac{M_I}{2} N_I^2 \qquad\qquad (m_\nu)_{\alpha\beta} = \langle \Phi \rangle^2 (F\, M_N^{-1} F^{\mathrm{T}})_{\alpha\beta}$$

- The νMSM satisfies the three Sakharov conditions for baryogenesis:

1. **Baryon number violation:** SM lepton number is broken by *N* mass and couplings; lepton asymmetry is transferred to a baryons via the *B* + *L* anomaly (sphalerons)

2. **CP violation:** Three new CP phases in the Yukawa matrix *F*

3. **Departure from thermal equilibrium:** For small Yukawa couplings, *N* scattering is out of equilibrium for all *T* above the weak scale

$$\Gamma_N \propto |F|^2 T \lesssim H(T) \qquad\qquad |F|^2 \sim 10^{-14} \left(\frac{m_\nu}{0.1 \text{ eV}}\right) \left(\frac{m_N}{\text{GeV}}\right) \left(\frac{100 \text{ GeV}}{\langle \Phi \rangle}\right)^2$$

Baryogenesis overview

$$\mathcal{L}_{\nu\mathrm{MSM}} = F_{\alpha I} L_\alpha \Phi N_I + \frac{M_I}{2} N_I^2 \qquad\qquad (m_\nu)_{\alpha\beta} = \langle\Phi\rangle^2 (F\, M_N^{-1} F^{\mathrm{T}})_{\alpha\beta}$$

- The νMSM satisfies the three Sakharov conditions for baryogenesis:

1. **Baryon number violation:** SM lepton number is broken by *N* mass and couplings; lepton asymmetry is transferred to a baryons via the *B* + *L* anomaly (sphalerons)

2. **CP violation:** Three new CP phases in the Yukawa matrix *F*

3. **Departure from thermal equilibrium:** For small Yukawa couplings, *N* scattering is out of equilibrium for all *T* above the weak scale

$$\Gamma_N \propto |F|^2 T \lesssim H(T) \qquad\qquad |F|^2 \sim 10^{-14} \left(\frac{m_\nu}{0.1\ \mathrm{eV}}\right)\left(\frac{m_N}{\mathrm{GeV}}\right)\left(\frac{100\ \mathrm{GeV}}{\langle\Phi\rangle}\right)^2$$

- Timing of leptogenesis depends sensitively on CP-violation, so I will briefly review this now

Lightning Review of CPV

$$\mathcal{M}(a \to b) = x\, e^{i\phi} \qquad \longrightarrow \qquad |\mathcal{M}(a \to b)|^2 = x^2$$

$$\mathcal{M}(\bar{a} \to \bar{b}) = x\, e^{-i\phi} \qquad\qquad |\mathcal{M}(\bar{a} \to \bar{b})|^2 = x^2$$

$$\Delta|\mathcal{M}|^2 = 0$$

Lightning Review of CPV

$$\mathcal{M}(a \to b) = x\, e^{i\phi} \qquad\longrightarrow\qquad |\mathcal{M}(a \to b)|^2 = x^2$$

$$\mathcal{M}(\bar{a} \to \bar{b}) = x\, e^{-i\phi} \qquad\qquad |\mathcal{M}(\bar{a} \to \bar{b})|^2 = x^2$$

$$\Delta|\mathcal{M}|^2 = 0$$

$$\mathcal{M}(a \to b) = x_1\, e^{i\phi} + x_2 \qquad\longrightarrow\qquad |\mathcal{M}(a \to b)|^2 = x_1^2 + x_2^2 + 2x_1x_2\cos\phi$$

$$\mathcal{M}(\bar{a} \to \bar{b}) = x_1\, e^{-i\phi} + x_2 \qquad\qquad |\mathcal{M}(\bar{a} \to \bar{b})|^2 = x_1^2 + x_2^2 + 2x_1x_2\cos\phi$$

$$\Delta|\mathcal{M}|^2 = 0$$

Lightning Review of CPV

$$\mathcal{M}(a \to b) = x\, e^{i\phi} \qquad \longrightarrow \qquad |\mathcal{M}(a \to b)|^2 = x^2$$

$$\mathcal{M}(\bar{a} \to \bar{b}) = x\, e^{-i\phi} \qquad\qquad |\mathcal{M}(\bar{a} \to \bar{b})|^2 = x^2$$

$$\Delta|\mathcal{M}|^2 = 0$$

$$\mathcal{M}(a \to b) = x_1\, e^{i\phi} + x_2 \qquad \longrightarrow \qquad |\mathcal{M}(a \to b)|^2 = x_1^2 + x_2^2 + 2x_1x_2\cos\phi$$

$$\mathcal{M}(\bar{a} \to \bar{b}) = x_1\, e^{-i\phi} + x_2 \qquad\qquad |\mathcal{M}(\bar{a} \to \bar{b})|^2 = x_1^2 + x_2^2 + 2x_1x_2\cos\phi$$

$$\Delta|\mathcal{M}|^2 = 0$$

$$\mathcal{M}(a \to b) = x_1\, e^{i\phi+i\theta} + x_2 \qquad \longrightarrow \qquad |\mathcal{M}(a \to b)|^2 = x_1^2 + x_2^2 + 2x_1x_2\cos(\theta+\phi)$$

$$\mathcal{M}(\bar{a} \to \bar{b}) = x_1\, e^{-i\phi+i\theta} + x_2 \qquad\qquad |\mathcal{M}(\bar{a} \to \bar{b})|^2 = x_1^2 + x_2^2 + 2x_1x_2\cos(\theta-\phi)$$

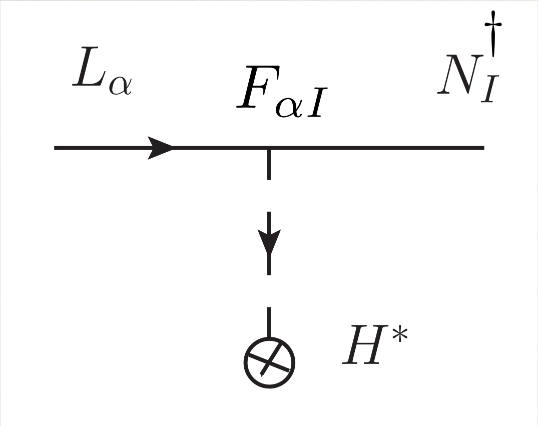
$$\Delta|\mathcal{M}|^2 = -4x_1x_2\sin\phi\sin\theta$$

Asymmetry Generation

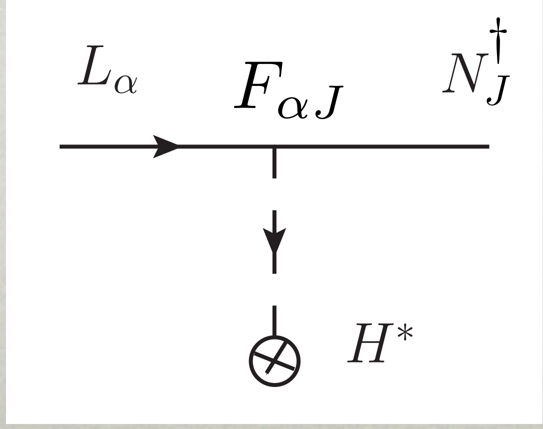
- The physical mechanism for baryogenesis:
  - No primordial abundance of N_2, N_3

Asymmetry Generation

- The physical mechanism for baryogenesis:
  - No primordial abundance of N_2, N_3
  - N_2, N_3 slowly populated by L_α scattering (approximately thermal spectrum)

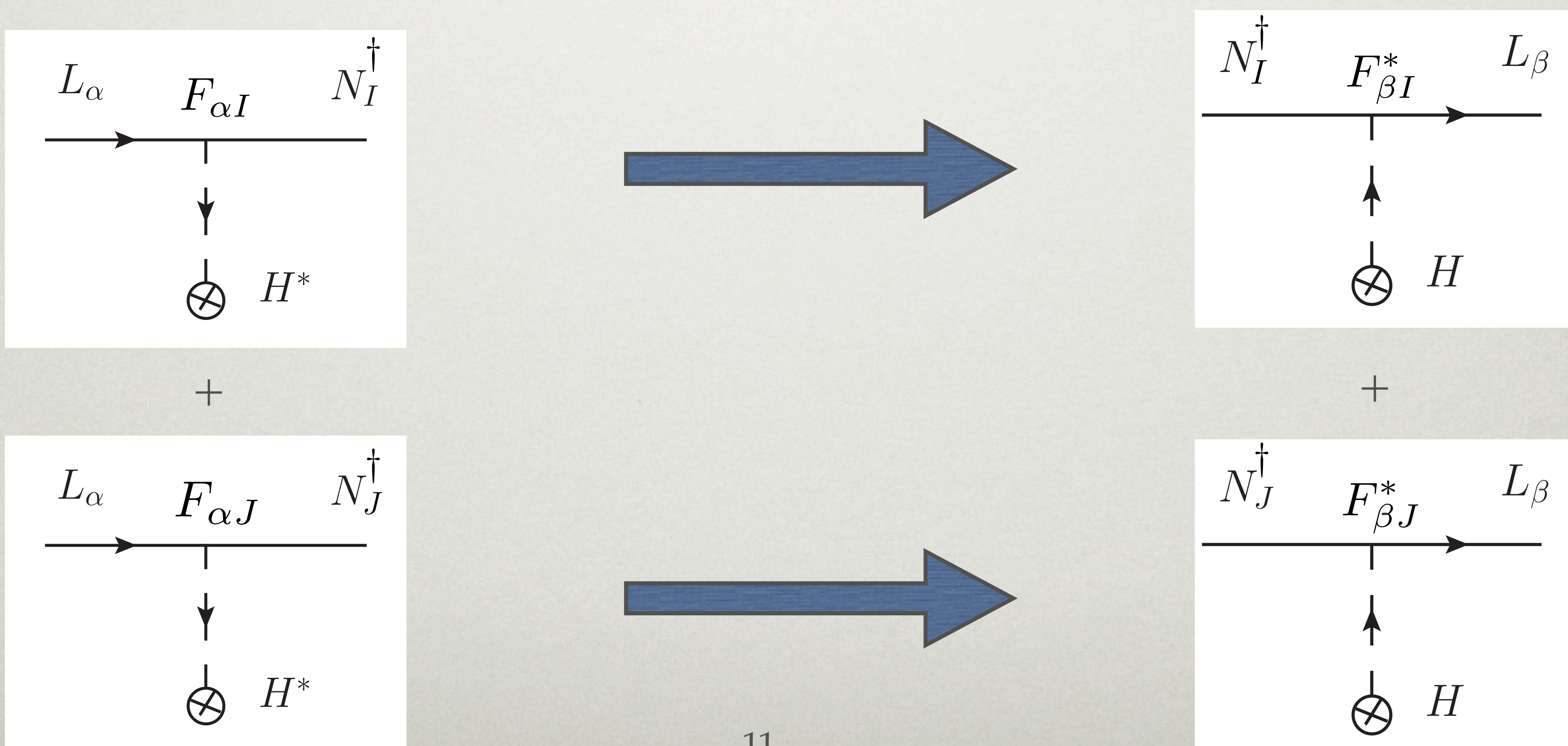


$+$



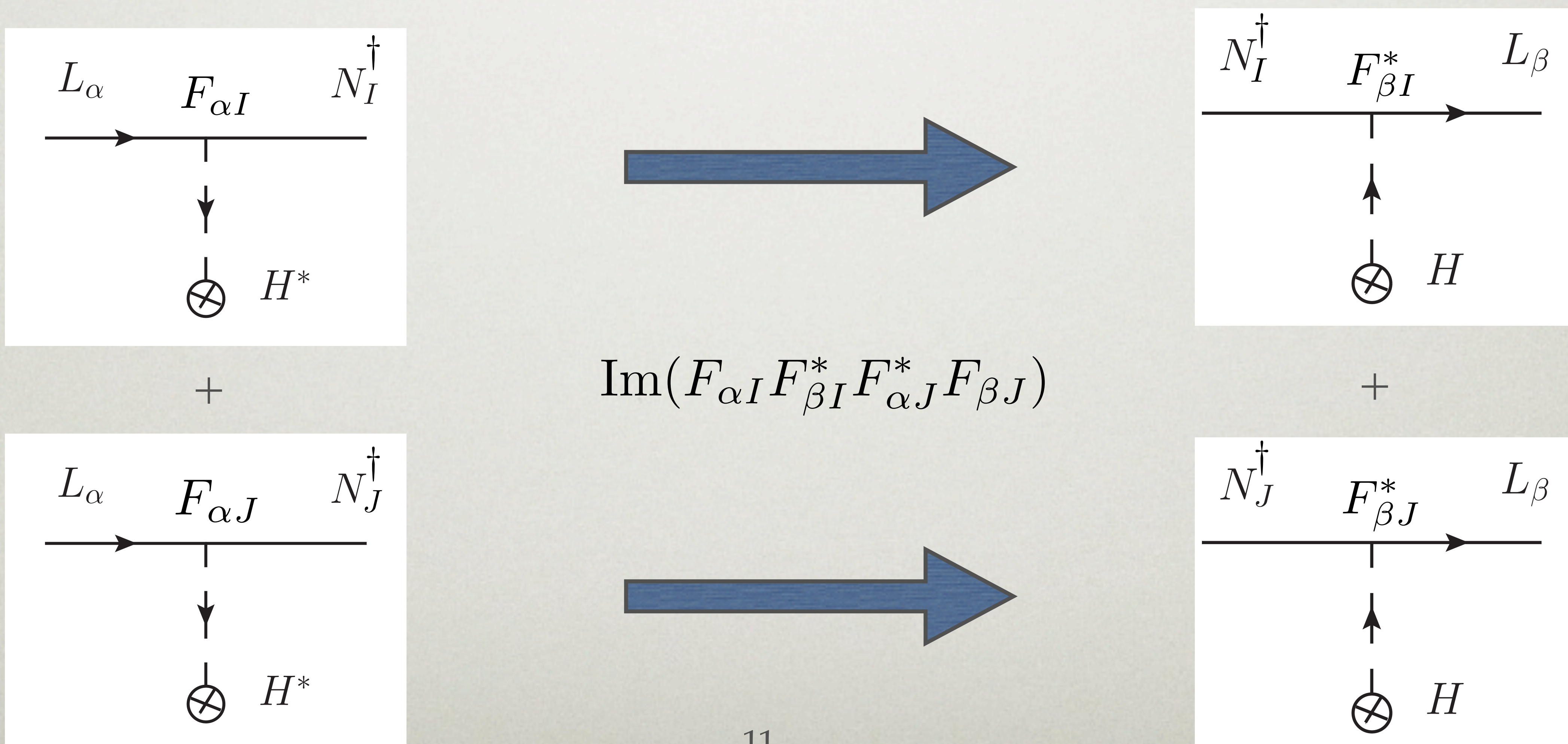
Asymmetry Generation

- The physical mechanism for baryogenesis:
  - No primordial abundance of N_2, N_3
  - N_2, N_3 slowly populated by L_α scattering (approximately thermal spectrum)
  - Some N subsequently scatter back into SM leptons (possibly of a different flavour)



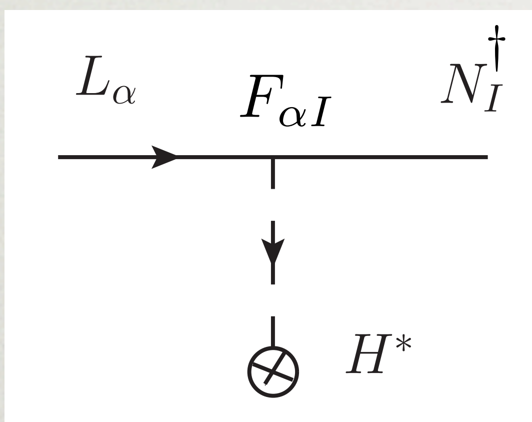
Asymmetry Generation

- The physical mechanism for baryogenesis:
    - No primordial abundance of N_2, N_3
    - N_2, N_3 slowly populated by L_α scattering (approximately thermal spectrum)
    - Some N subsequently scatter back into SM leptons (possibly of a different flavour)
    - We have a CP-odd phase, but **where is the CP-even phase?**

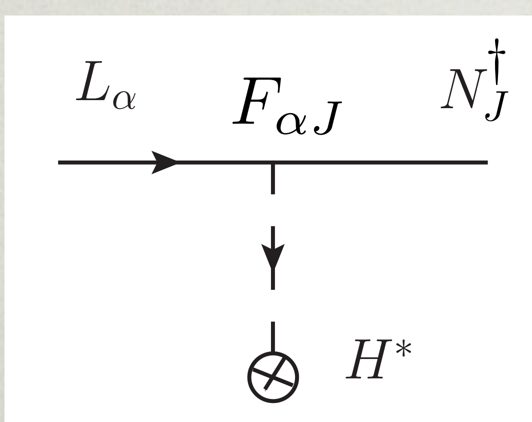


Asymmetry Generation

- N is produced in a **coherent superposition** of mass eigenstates

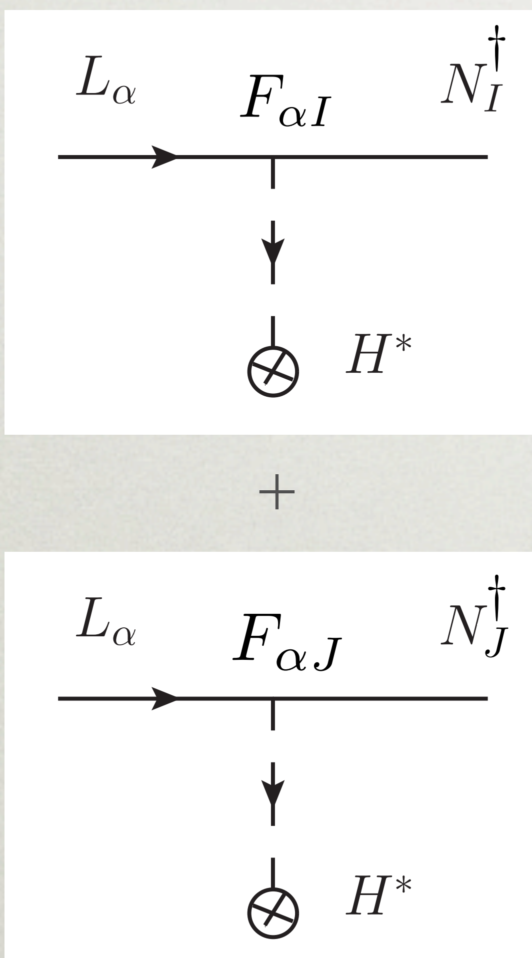


$+$



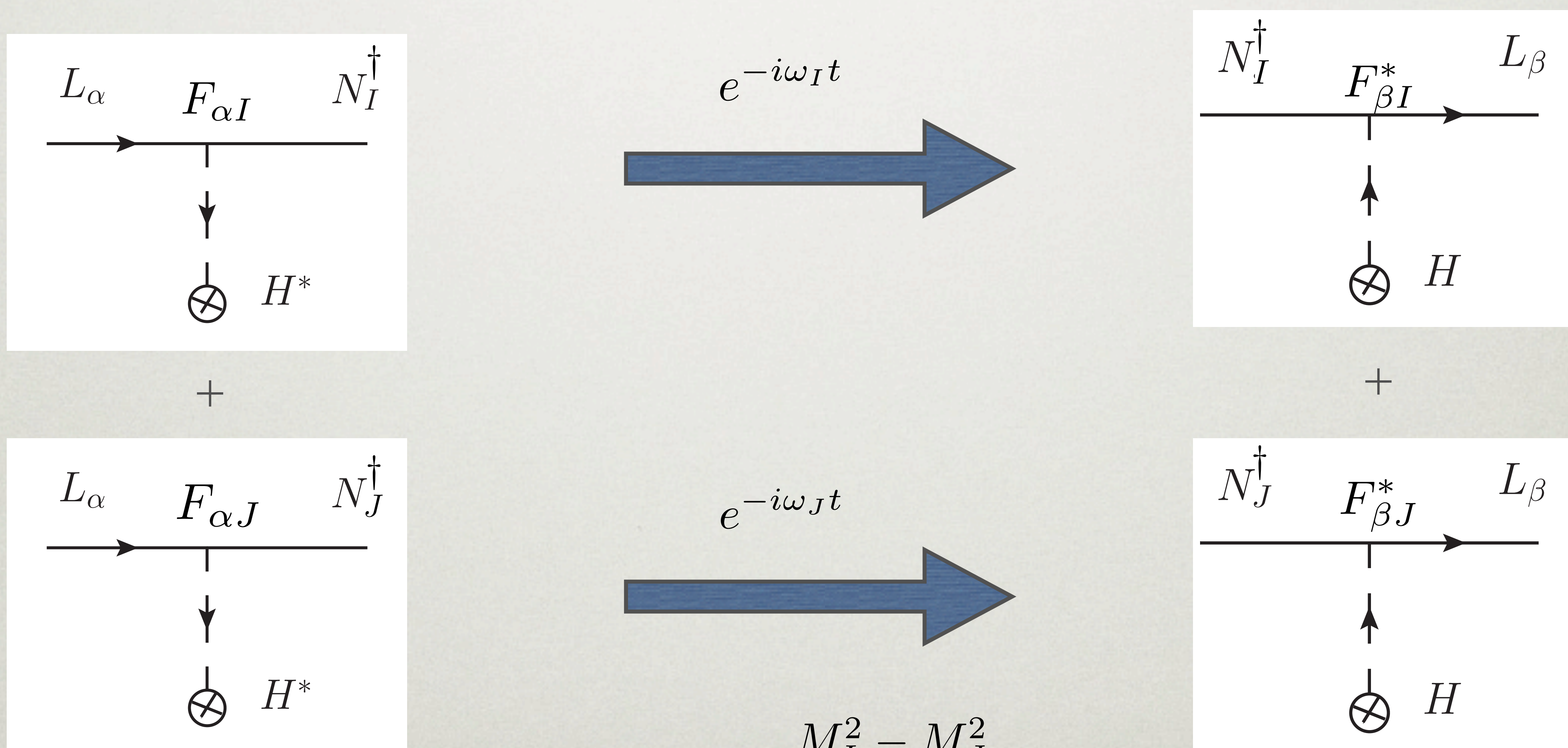
Asymmetry Generation

- N is produced in a **coherent superposition** of mass eigenstates
- Because N scattering is out of equilibrium, **there is no decoherence** between scattering**!**



Asymmetry Generation

- N is produced in a **coherent superposition** of mass eigenstates
- Because N scattering is out of equilibrium, **there is no decoherence** between scattering**!**
- Each diagram acquires a **CP-even propagation phase** (Schrödinger equation)



$$\omega_I - \omega_J \approx \frac{M_I^2 - M_J^2}{2T}$$

Asymmetry Generation

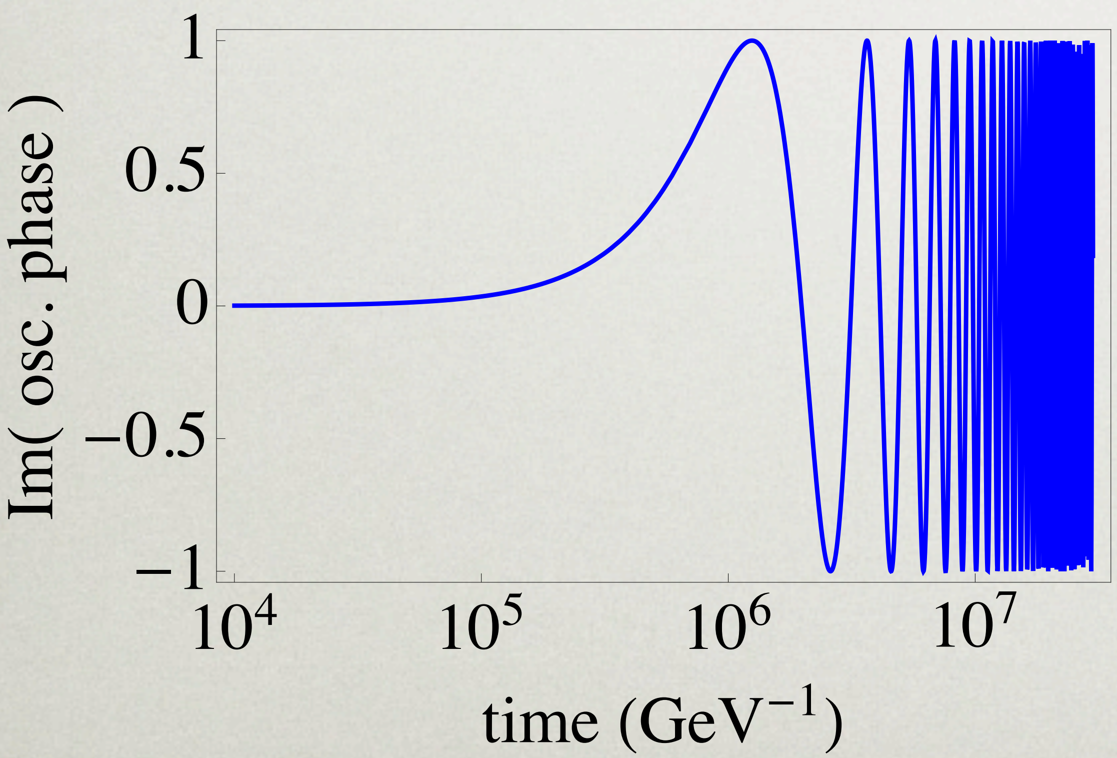
- The CP-violating rate comes from the interference of the diagrams

$$\Gamma(L_\alpha \to L_\beta) - \Gamma(\bar{L}_\alpha - \bar{L}_\beta) \propto \mathrm{Im}\left[\exp\left(-i\int_0^t dt'\,\frac{M_3^2 - M_2^2}{2T(t')}\right)\right]\mathrm{Im}\left[F_{\alpha 3}F_{\beta 3}^{*}F_{\alpha 2}^{*}F_{\beta 2}\right]$$

Asymmetry Generation

- The CP-violating rate comes from the interference of the diagrams

$$\Gamma(L_\alpha \to L_\beta) - \Gamma(\bar{L}_\alpha - \bar{L}_\beta) \propto \mathrm{Im}\left[\exp\left(-i\int_0^t dt' \, \frac{M_3^2 - M_2^2}{2T(t')}\right)\right] \mathrm{Im}\left[F_{\alpha 3}F^*_{\beta 3}F^*_{\alpha 2}F_{\beta 2}\right]$$

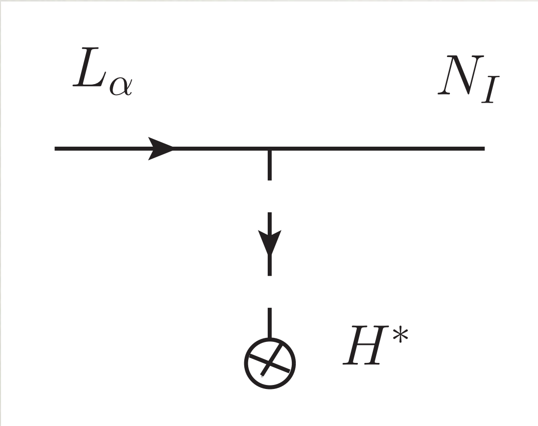


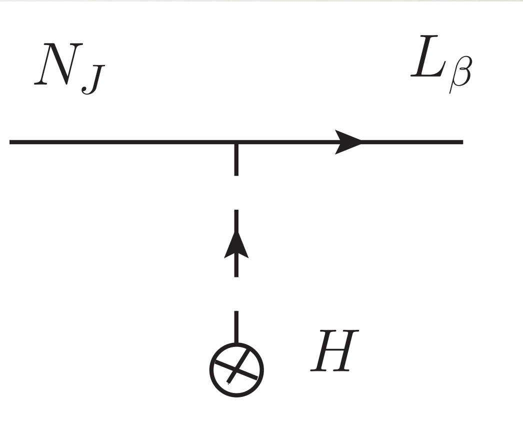
Asymmetry generation **mostly occurs** when

$$\frac{M_3^2 - M_2^2}{T} \sim H(T)$$

$$(T \gg M_N)$$

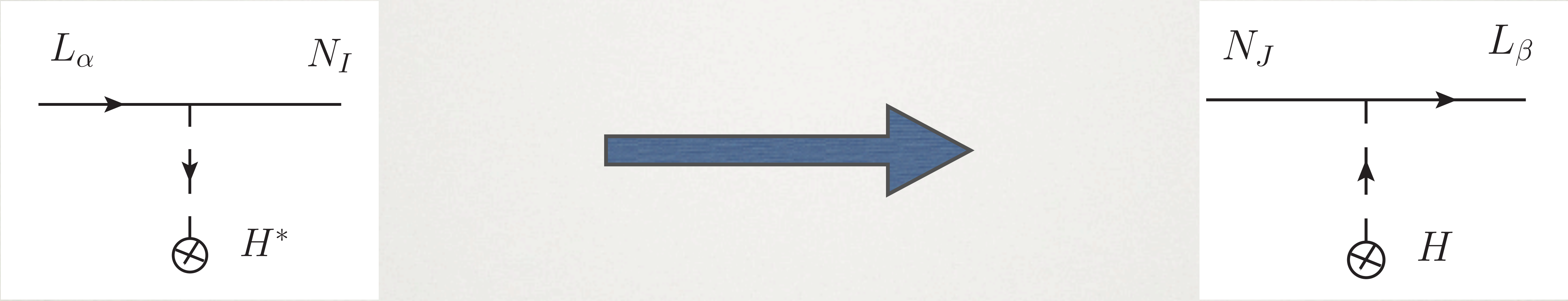
Asymmetry Generation





$$\Gamma(L_\alpha \to L_\beta) \neq \Gamma(\bar{L}_\alpha \to \bar{L}_\beta) \quad \to \quad n_{L_\alpha} \neq n_{\bar{L}_\alpha}$$

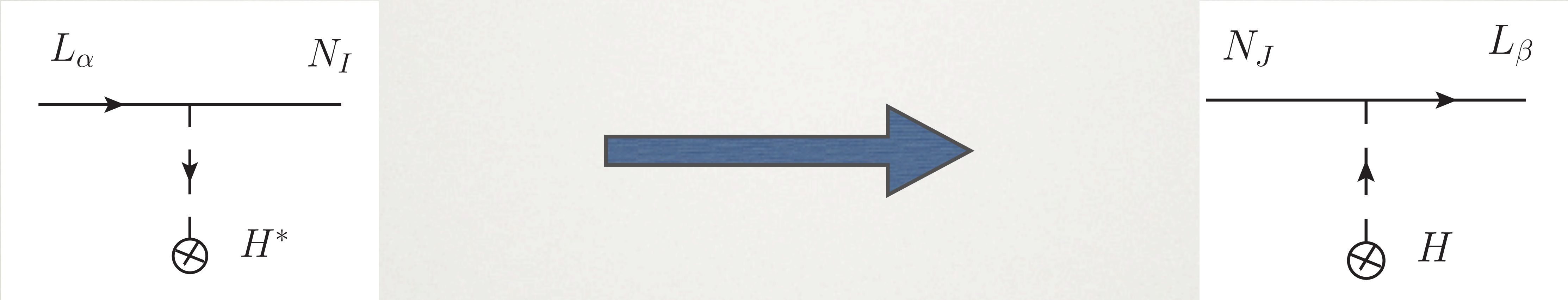
Asymmetry Generation



$$\Gamma(L_\alpha \to L_\beta) \neq \Gamma(\bar{L}_\alpha \to \bar{L}_\beta) \quad \to \quad n_{L_\alpha} \neq n_{\bar{L}_\alpha}$$

- ...but we don't have an asymmetry in **total lepton number** $\sum_\alpha n_{\Delta L_\alpha} = 0$
  - Asymmetries in individual flavours
  - Sphalerons couple to total lepton number

Asymmetry Generation

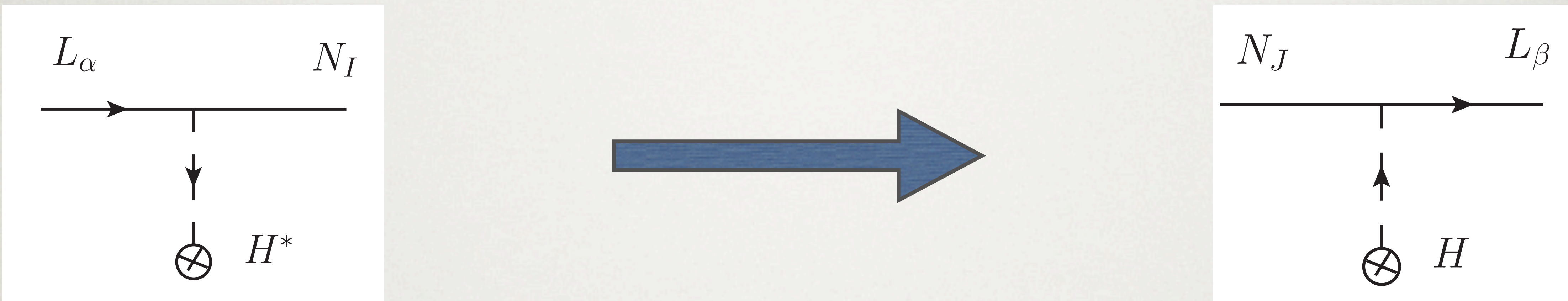


$$\Gamma(L_\alpha \to L_\beta) \neq \Gamma(\bar{L}_\alpha \to \bar{L}_\beta) \quad \to \quad n_{L_\alpha} \neq n_{\bar{L}_\alpha}$$

- ...but we don’t have an asymmetry in **total lepton number** $\sum_\alpha n_{\Delta L_\alpha} = 0$
  - Asymmetries in individual flavours
  - Sphalerons couple to total lepton number

$$\Gamma(L_{\text{tot}} \to \bar{N}) \propto \sum_\alpha n_{L_\alpha} \Gamma(L_\alpha \to \bar{N}) \qquad \Gamma(\bar{L}_{\text{tot}} \to N) \propto \sum_\alpha n_{\bar{L}_\alpha} \Gamma(\bar{L}_\alpha \to N)$$

Asymmetry Generation



$$\Gamma(L_\alpha \to L_\beta) \neq \Gamma(\bar{L}_\alpha \to \bar{L}_\beta) \quad \to \quad n_{L_\alpha} \neq n_{\bar{L}_\alpha}$$

- ...but we don't have an asymmetry in **total lepton number** $\sum_\alpha n_{\Delta L_\alpha} = 0$
  - Asymmetries in individual flavours
  - Sphalerons couple to total lepton number

$$\Gamma(L_{\rm tot} \to \bar{N}) \propto \sum_\alpha n_{L_\alpha} \Gamma(L_\alpha \to \bar{N}) \qquad \Gamma(\bar{L}_{\rm tot} \to N) \propto \sum_\alpha n_{\bar{L}_\alpha} \Gamma(\bar{L}_\alpha \to N)$$

$$\Gamma(L_{\rm tot} \to \bar{N}) - \Gamma(\bar{L}_{\rm tot} \to N) \propto \sum_\alpha n_{\Delta L_\alpha} \Gamma(L_\alpha \to \bar{N})$$

Asymmetry Generation

- Recap:
  - Out-of-equilibrium *N* production and scattering lead to **lepton flavour** asymmetries at $O(F^4)$
  - Subsequent scatterings convert the flavour asymmetries into a **total lepton** asymmetry at $O(F^6)$

$$\Gamma(L_\alpha \to L_\beta) - \Gamma(\bar{L}_\alpha - \bar{L}_\beta) \propto \mathrm{Im}\left[\exp\left(-i\int_0^t dt'\,\frac{M_3^2 - M_2^2}{2T(t')}\right)\right]\mathrm{Im}\left[F_{\alpha 3}F^*_{\beta 3}F^*_{\alpha 2}F_{\beta 2}\right]$$

$$\Gamma(L_{\mathrm{tot}} \to \bar{N}) - \Gamma(\bar{L}_{\mathrm{tot}} \to N) \propto \sum_\alpha n_{\Delta L_\alpha}\Gamma(L_\alpha \to \bar{N})$$

Asymmetry Generation

- Recap:
  - Out-of-equilibrium *N* production and scattering lead to **lepton flavour** asymmetries at $O(F^4)$
  - Subsequent scatterings convert the flavour asymmetries into a **total lepton** asymmetry at $O(F^6)$

$$\Gamma(L_\alpha \to L_\beta) - \Gamma(\bar{L}_\alpha - \bar{L}_\beta) \propto \mathrm{Im}\left[\exp\left(-i\int_0^t dt'\, \frac{M_3^2 - M_2^2}{2T(t')}\right)\right] \mathrm{Im}\left[F_{\alpha 3}F^*_{\beta 3}F^*_{\alpha 2}F_{\beta 2}\right]$$

$$\Gamma(L_{\mathrm{tot}} \to \bar{N}) - \Gamma(\bar{L}_{\mathrm{tot}} \to N) \propto \sum_\alpha n_{\Delta L_\alpha}\Gamma(L_\alpha \to \bar{N})$$

- Comments:
  - No **explicit** violation of total *L*+*N* symmetry (this is suppressed by $(M_N/T)^2$)

Asymmetry Generation

- Recap:
  - Out-of-equilibrium N production and scattering lead to **lepton flavour** asymmetries at $O(F^4)$
  - Subsequent scatterings convert the flavour asymmetries into a **total lepton** asymmetry at $O(F^6)$

$$\Gamma(L_\alpha \to L_\beta) - \Gamma(\bar{L}_\alpha - \bar{L}_\beta) \propto \mathrm{Im}\left[\exp\left(-i\int_0^t dt'\, \frac{M_3^2 - M_2^2}{2T(t')}\right)\right] \mathrm{Im}\left[F_{\alpha 3}F^*_{\beta 3}F^*_{\alpha 2}F_{\beta 2}\right]$$

$$\Gamma(L_{\mathrm{tot}} \to \bar{N}) - \Gamma(\bar{L}_{\mathrm{tot}} \to N) \propto \sum_\alpha n_{\Delta L_\alpha}\Gamma(L_\alpha \to \bar{N})$$

- Comments:
  - No **explicit** violation of total $L+N$ symmetry (this is suppressed by $(M_N/T)^2$)
  - This means that if N equilibrate, the baryon asymmetry is completely destroyed

Asymmetry Generation

- Recap:
  - Out-of-equilibrium N production and scattering lead to **lepton flavour** asymmetries at $O(F^4)$
  - Subsequent scatterings convert the flavour asymmetries into a **total lepton** asymmetry at $O(F^6)$

$$\Gamma(L_\alpha \to L_\beta) - \Gamma(\bar{L}_\alpha - \bar{L}_\beta) \propto \mathrm{Im}\left[\exp\left(-i\int_0^t dt' \, \frac{M_3^2 - M_2^2}{2T(t')}\right)\right] \mathrm{Im}\left[F_{\alpha 3} F^*_{\beta 3} F^*_{\alpha 2} F_{\beta 2}\right]$$

$$\Gamma(L_{\mathrm{tot}} \to \bar{N}) - \Gamma(\bar{L}_{\mathrm{tot}} \to N) \propto \sum_\alpha n_{\Delta L_\alpha} \Gamma(L_\alpha \to \bar{N})$$

- Comments:
  - No **explicit** violation of total $L+N$ symmetry (this is suppressed by $(M_N/T)^2$)
  - This means that if N equilibrate, the baryon asymmetry is completely destroyed
  - Baryon asymmetry **frozen in** when sphalerons decouple at T_{EW} (must be before equilibration time)

Baryogenesis and tuning in the minimal model

Parametric Dependence

- What drives the size of the final baryon asymmetry?

Parametric Dependence

- What drives the size of the final baryon asymmetry?
- **Yukawa couplings:**
  - Normalize number densities to entropy density

$$\Gamma(L_\alpha \to L_\beta) - \Gamma(\bar{L}_\alpha - \bar{L}_\beta) \propto \mathrm{Im}\left[\exp\left(-i\int_0^t dt'\,\frac{M_3^2 - M_2^2}{2T(t')}\right)\right]\mathrm{Im}\left[F_{\alpha 3}F^*_{\beta 3}F^*_{\alpha 2}F_{\beta 2}\right]$$

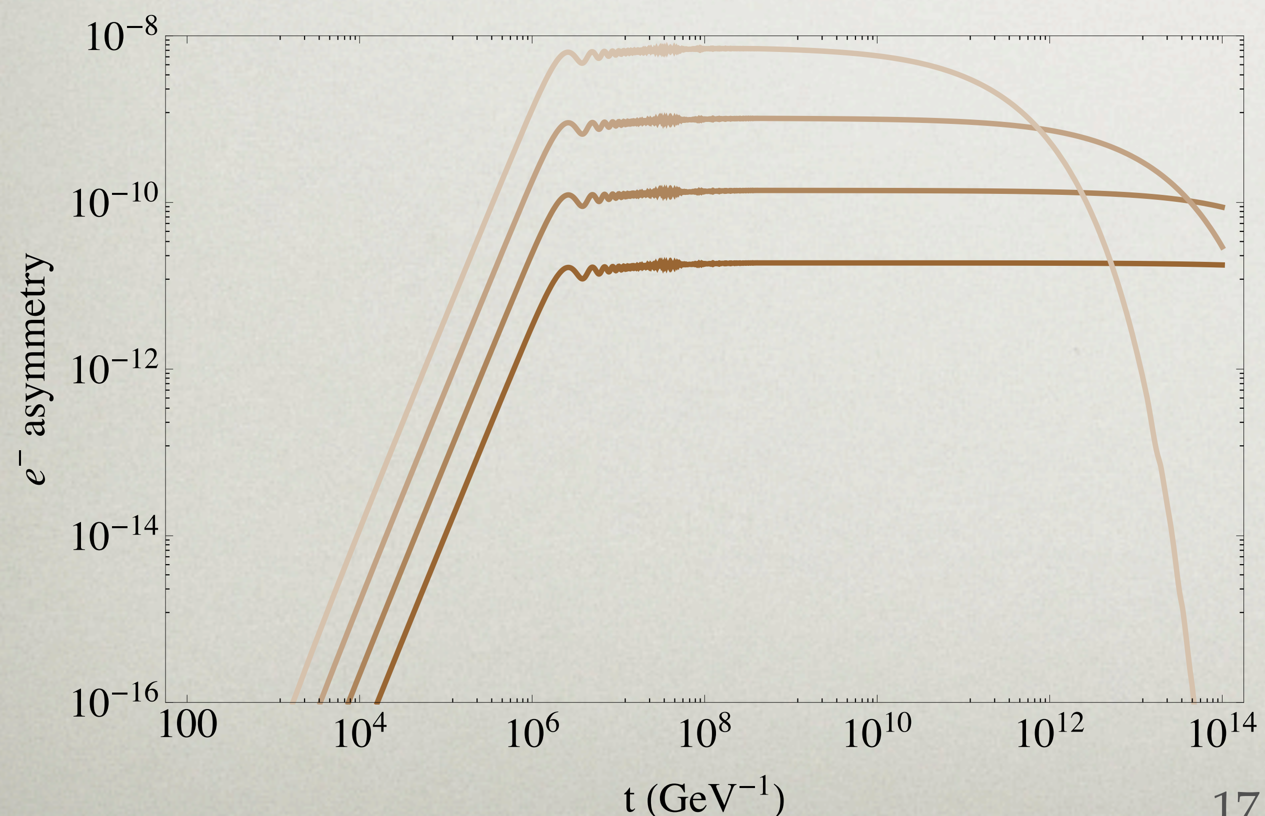
$$\frac{n_{\Delta L,\alpha}}{s} \sim \frac{M_{\mathrm{Pl}}^{4/3}}{(M_3^2 - M_2^2)^{2/3}}\mathrm{Im}\left[(FF^\dagger)^2\right]_{\alpha\alpha}$$

Parametric Dependence

- What drives the size of the final baryon asymmetry?
- **Yukawa couplings:**
  - Normalize number densities to entropy density

$$\Gamma(L_\alpha \to L_\beta) - \Gamma(\bar{L}_\alpha - \bar{L}_\beta) \propto \mathrm{Im}\left[\exp\left(-i\int_0^t dt'\,\frac{M_3^2 - M_2^2}{2T(t')}\right)\right]\mathrm{Im}\left[F_{\alpha 3}F^*_{\beta 3}F^*_{\alpha 2}F_{\beta 2}\right]$$

$$\frac{n_{\Delta L,\alpha}}{s} \sim \frac{M_{\mathrm{Pl}}^{4/3}}{(M_3^2 - M_2^2)^{2/3}}\mathrm{Im}\left[(FF^\dagger)^2\right]_{\alpha\alpha}$$



lighter colour =
larger Yukawa coupling

Parametric Dependence

- **Mass splitting:**
  - Asymmetry is predominantly generated over the first oscillation
  - Asymmetry is **larger** at **later time** due to the slower Hubble expansion

$$\Gamma(L_\alpha \to L_\beta) - \Gamma(\bar{L}_\alpha - \bar{L}_\beta) \propto \mathrm{Im}\left[\exp\left(-i\int_0^t dt'\,\frac{M_3^2 - M_2^2}{2T(t')}\right)\right]\mathrm{Im}\left[F_{\alpha 3}F^*_{\beta 3}F^*_{\alpha 2}F_{\beta 2}\right]$$

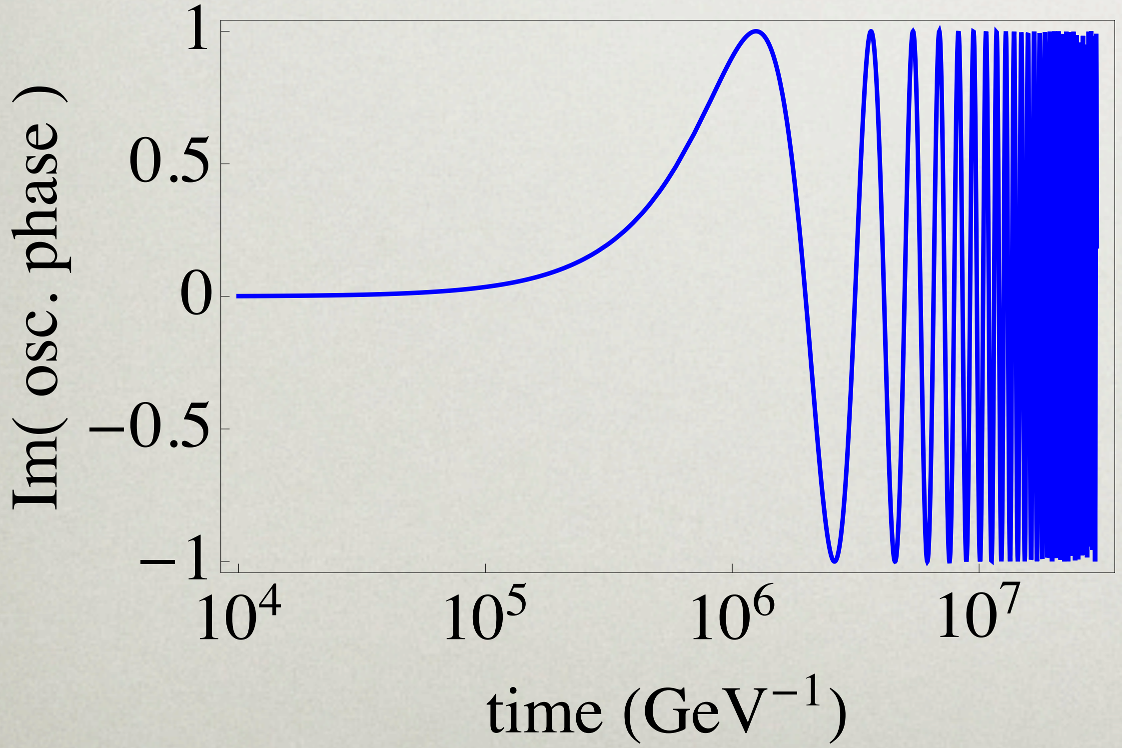
$$\frac{n_{\Delta L,\alpha}}{s} \sim \frac{M_{\mathrm{Pl}}^{4/3}}{(M_3^2 - M_2^2)^{2/3}}\mathrm{Im}\left[(FF^\dagger)^2\right]_{\alpha\alpha}$$

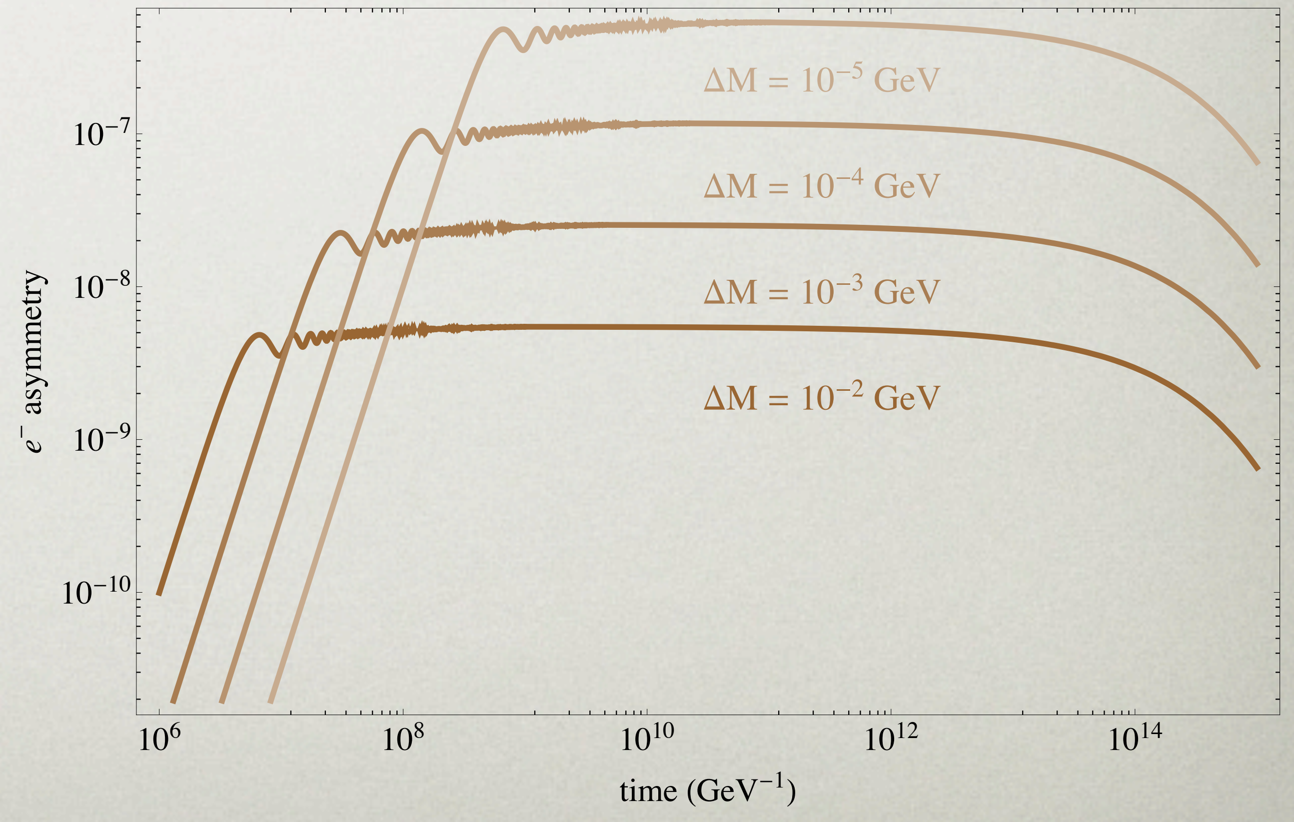
Parametric Dependence

- **Mass splitting:**
  - Asymmetry is predominantly generated over the first oscillation
  - Asymmetry is **larger** at **later time** due to the slower Hubble expansion

$$\Gamma(L_\alpha \to L_\beta) - \Gamma(\bar{L}_\alpha - \bar{L}_\beta) \propto \mathrm{Im}\left[\exp\left(-i\int_0^t dt' \, \frac{M_3^2 - M_2^2}{2T(t')}\right)\right] \mathrm{Im}\left[F_{\alpha 3} F^*_{\beta 3} F^*_{\alpha 2} F_{\beta 2}\right]$$

$$\frac{n_{\Delta L,\alpha}}{s} \sim \frac{M_{\mathrm{Pl}}^{4/3}}{(M_3^2 - M_2^2)^{2/3}} \mathrm{Im}\left[(FF^\dagger)^2\right]_{\alpha\alpha}$$





Parametric Dependence

- **Generation-dependence of scattering rates:**

$$\Gamma(L_{\rm tot} \to \bar{N}) - \Gamma(\bar{L}_{\rm tot} \to N) \propto \sum_\alpha n_{\Delta L_\alpha} \Gamma(L_\alpha \to \bar{N})$$

$$\sum_\alpha n_{\Delta L_\alpha} = 0 \text{ at } \mathcal{O}(|F|^4)$$

Parametric Dependence

- **Generation-dependence of scattering rates:**

$$\Gamma(L_{\text{tot}} \to \bar{N}) - \Gamma(\bar{L}_{\text{tot}} \to N) \propto \sum_\alpha n_{\Delta L_\alpha} \Gamma(L_\alpha \to \bar{N})$$

$$\sum_\alpha n_{\Delta L_\alpha} = 0 \text{ at } \mathcal{O}(|F|^4)$$

  - If $\Gamma(L_\alpha \to \bar{N})$ is the same for all α, then **no baryon asymmetry accumulates**

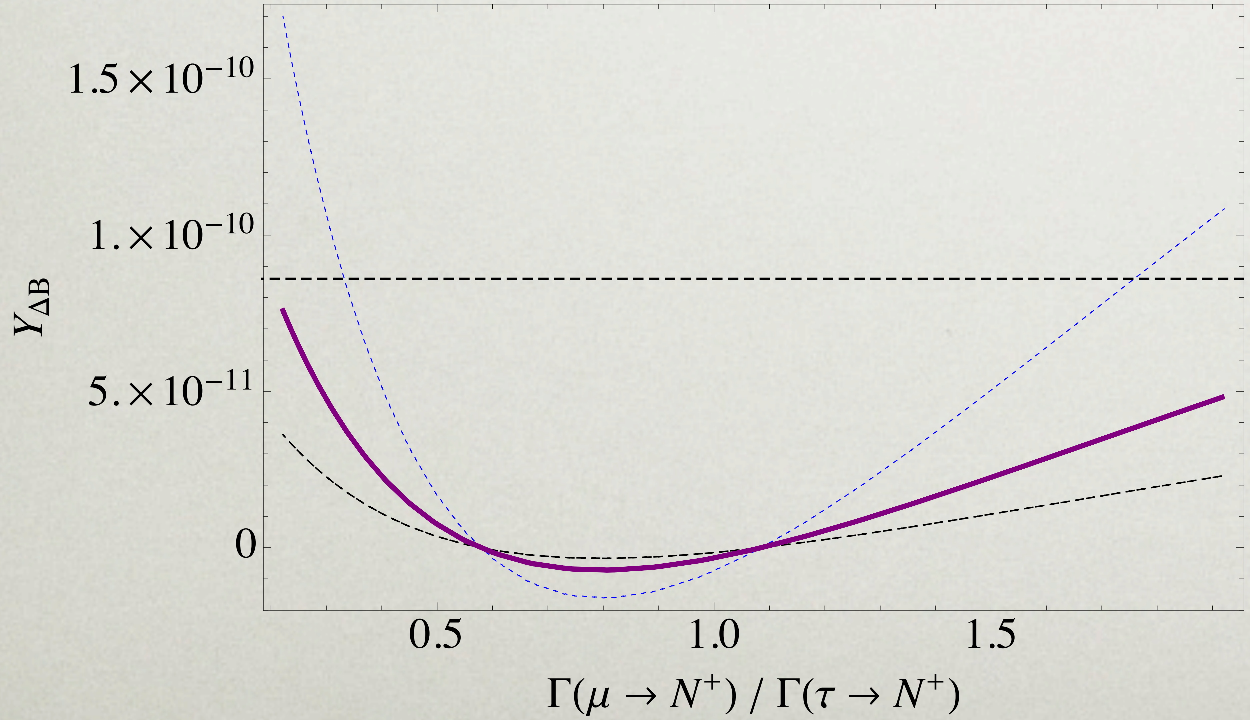
Parametric Dependence

- **Generation-dependence of scattering rates:**

$$\Gamma(L_{\rm tot} \to \bar{N}) - \Gamma(\bar{L}_{\rm tot} \to N) \propto \sum_\alpha n_{\Delta L_\alpha} \Gamma(L_\alpha \to \bar{N})$$

$$\sum_\alpha n_{\Delta L_\alpha} = 0 \text{ at } \mathcal{O}(|F|^4)$$

  - If $\Gamma(L_\alpha \to \bar{N})$ is the same for all α, then **no baryon asymmetry accumulates**

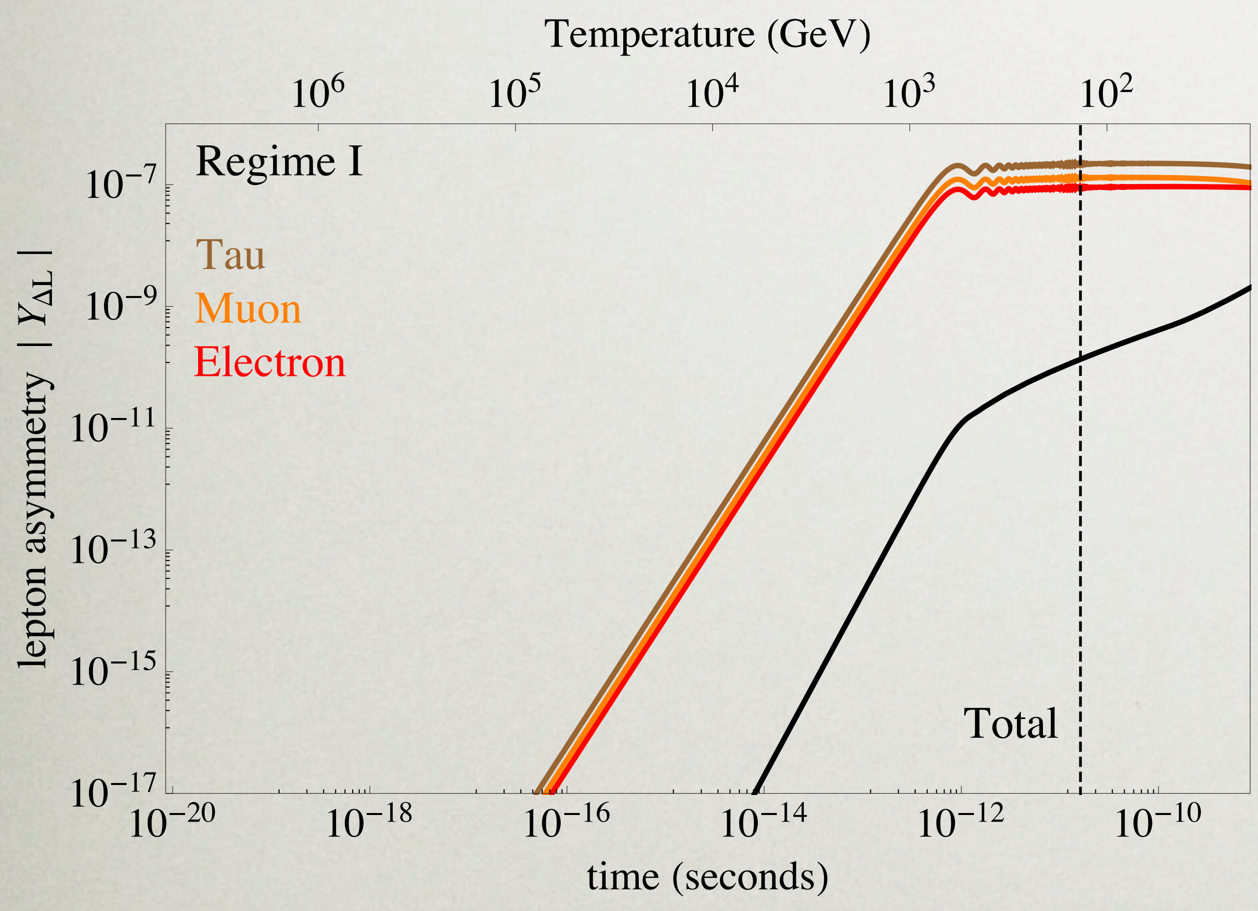


- This condition is generically satisfied due to large mixing in MNS matrix

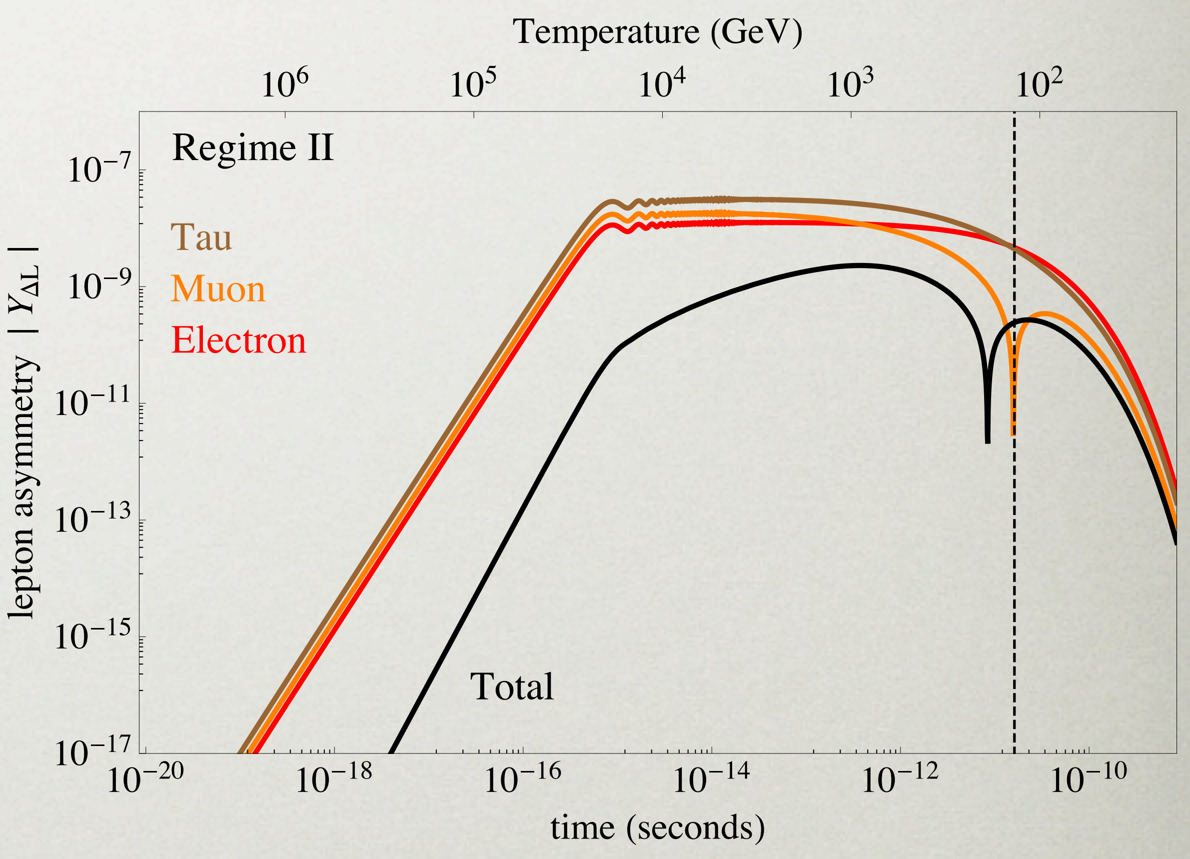
Asymmetry Generation

- Putting this all together, can get correct baryon asymmetry with either mass degeneracy (Regime I) and/or large Yukawa couplings (Regime II)

Regime I: $t_{\rm osc} \sim t_{\rm w} < t_{\rm eq}$



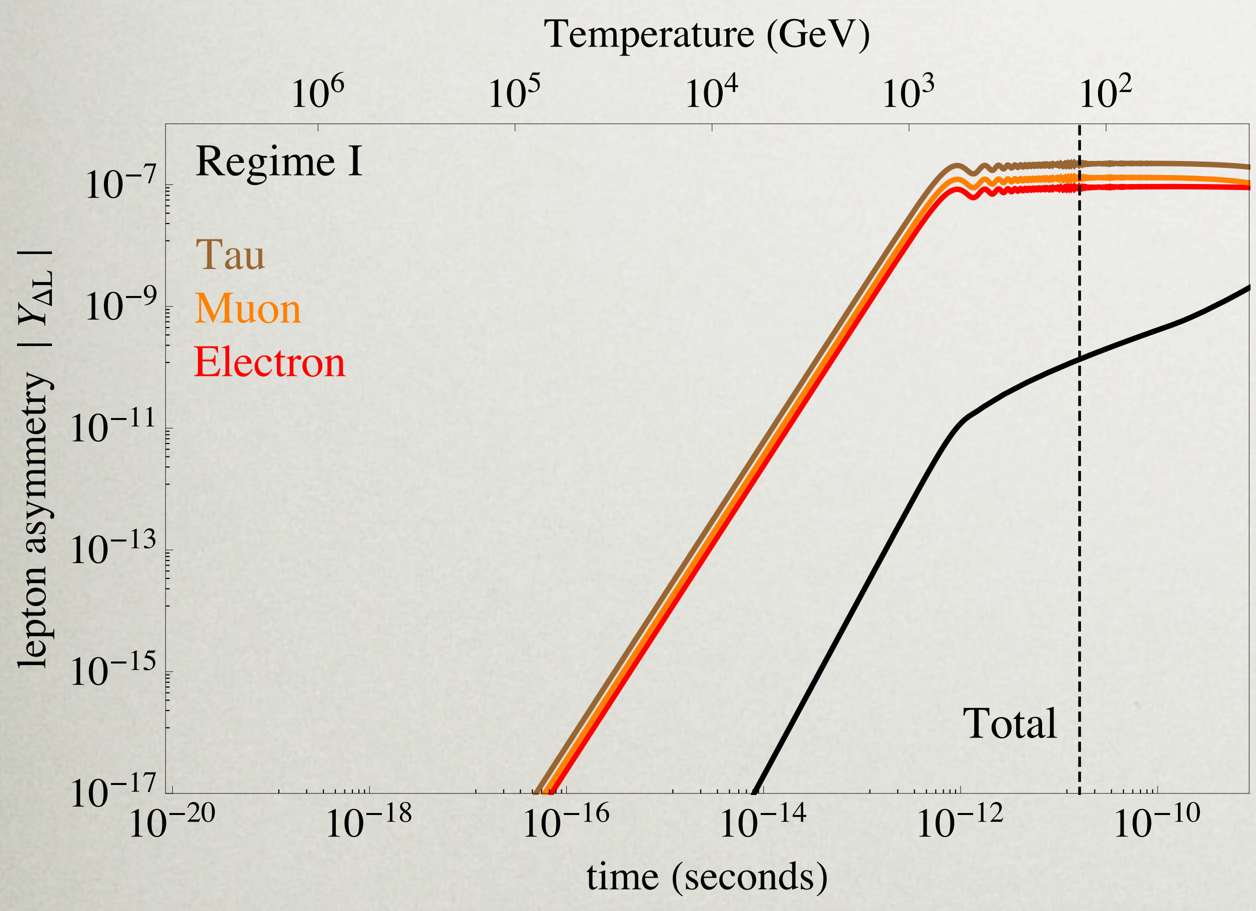
Regime II: $t_{\rm osc} < t_{\rm eq} \sim t_{\rm w}$



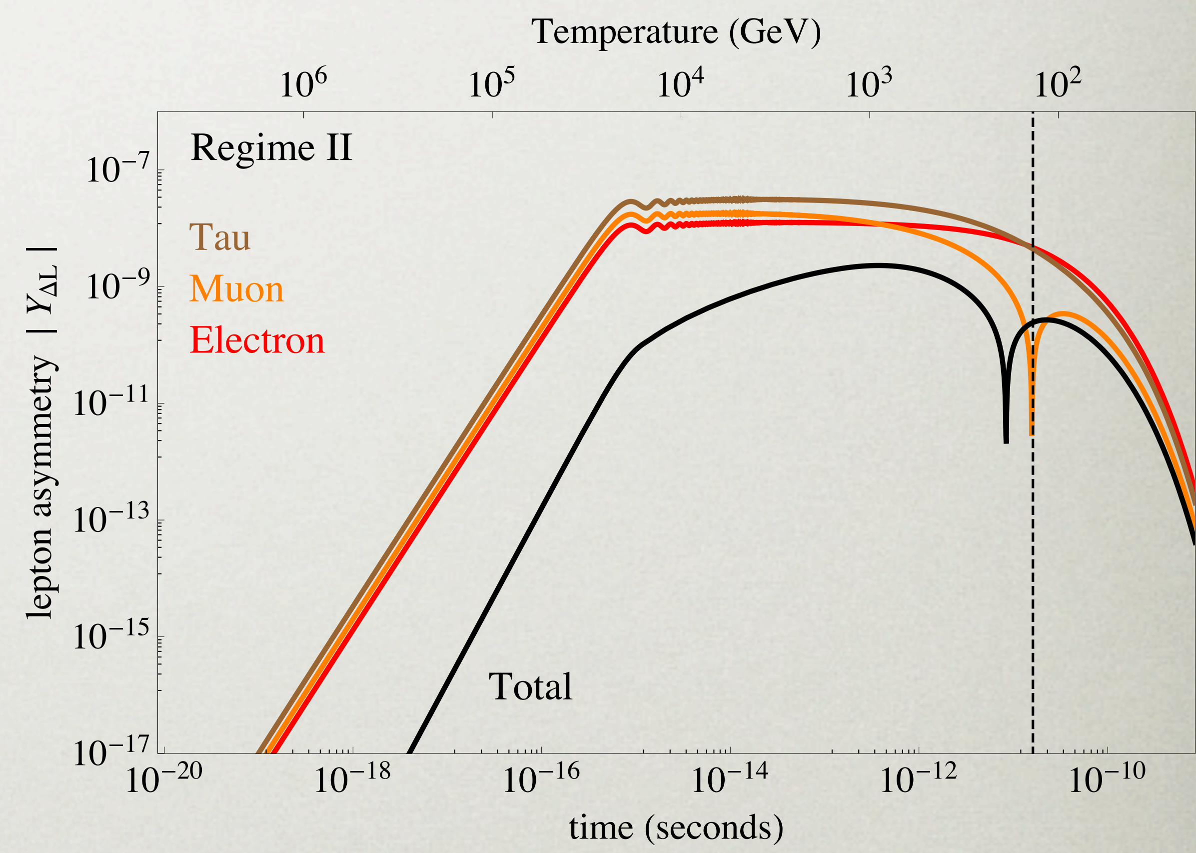
Asymmetry Generation

- Putting this all together, can get correct baryon asymmetry with either mass degeneracy (Regime I) and/or large Yukawa couplings (Regime II)

Regime I: $t_{\mathrm{osc}} \sim t_{\mathrm{w}} < t_{\mathrm{eq}}$



Regime II: $t_{\mathrm{osc}} < t_{\mathrm{eq}} \sim t_{\mathrm{w}}$



- Condition: at least one N does not equilibrate until t_{W}

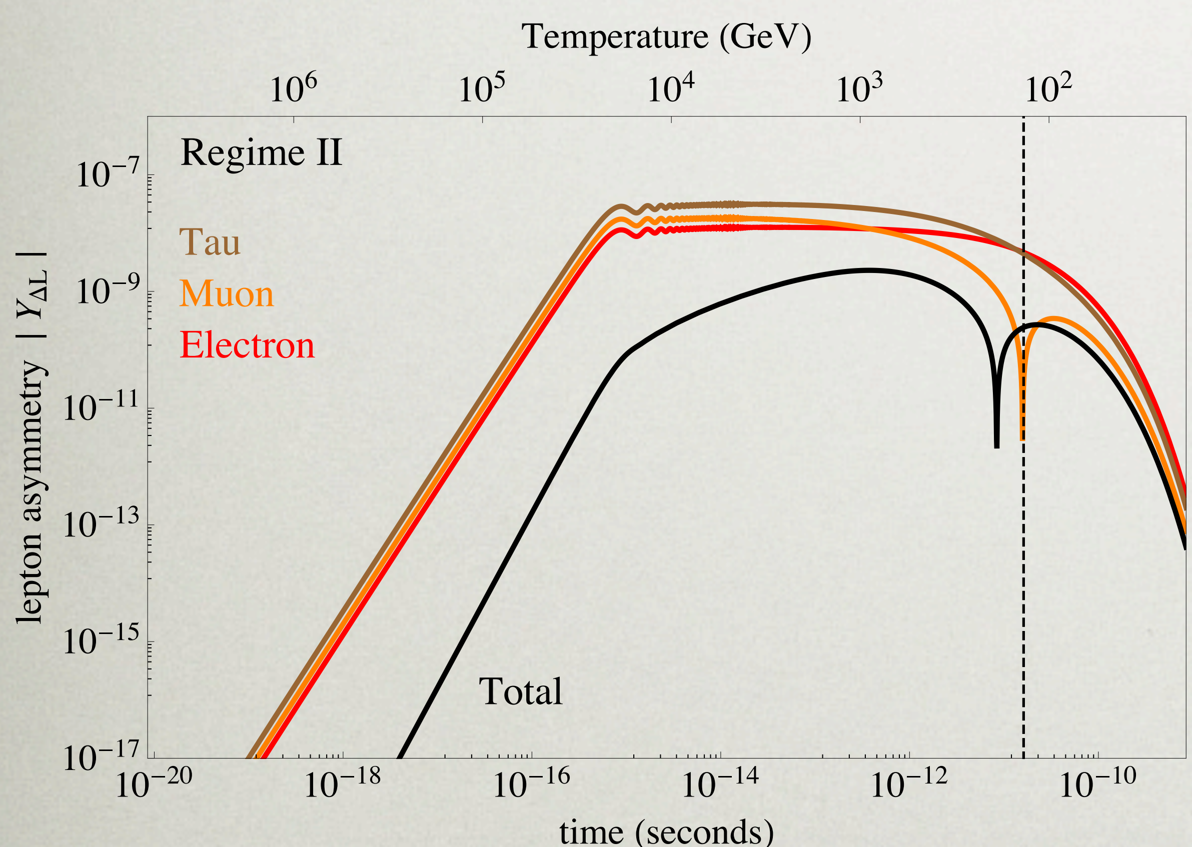
Asymmetry Generation

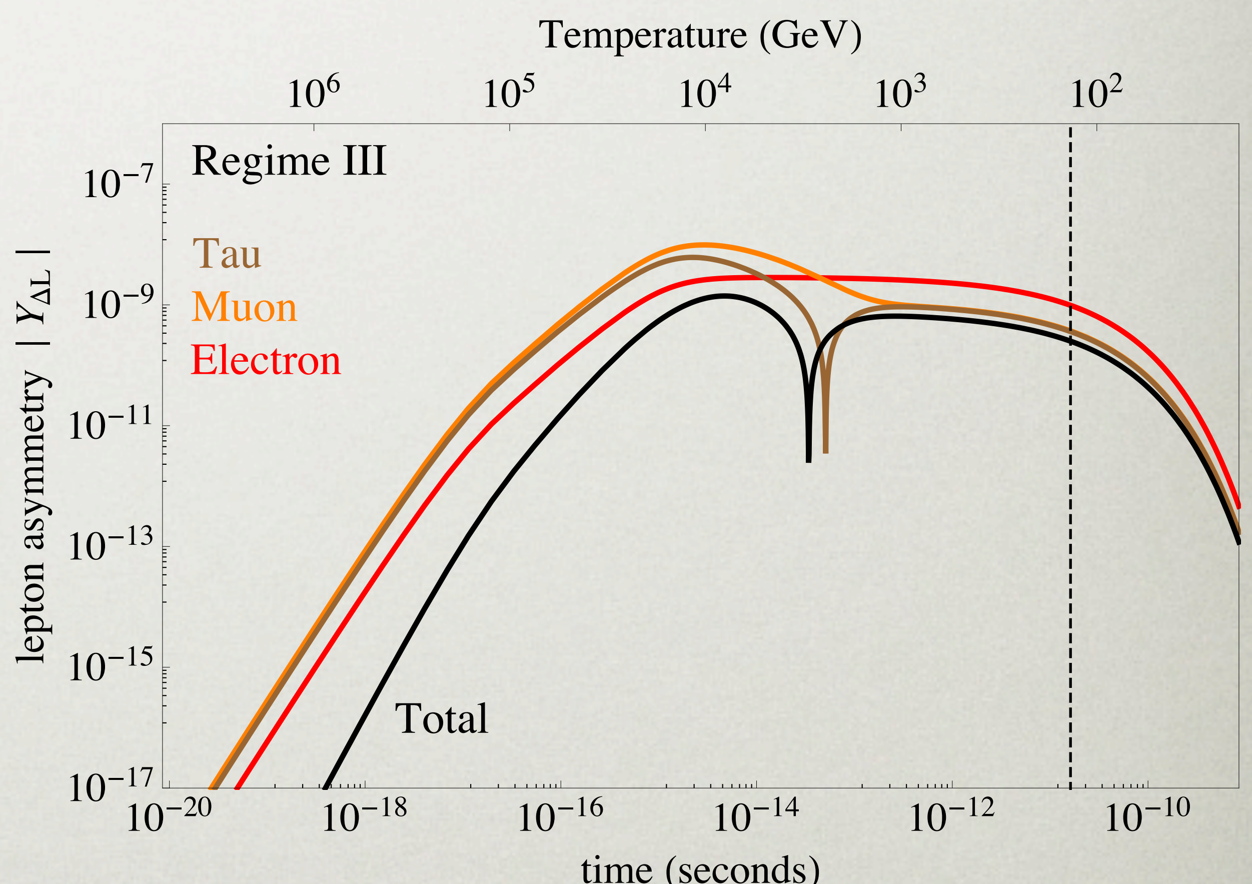
- The **largest** possible Yukawa couplings are when **one** of the Yukawa couplings is much smaller than the others (Regime III)

(Regime I: $t_{\mathrm{osc}} \sim t_{\mathrm{w}} < t_{\mathrm{eq}}$**)**

Regime II: $t_{\mathrm{osc}} < t_{\mathrm{eq}} \sim t_{\mathrm{w}}$

Regime III: $t_{\mathrm{osc}} < t_{\mathrm{eq},\alpha} \ll t_{\mathrm{eq},\beta} \sim t_{\mathrm{w}}$





Third regime found in Drewes, Garbrecht 2012

$$\Gamma_e \ll \Gamma_\mu, \Gamma_\tau$$

See also Garbrecht 2014 for very large Yukawa regime

Realization in minimal model

- How are these regimes populated in the minimal model parameter space?

Realization in minimal model

- How are these regimes populated in the minimal model parameter space?
- The Yukawa matrices can be fully decomposed as: Casas, Ibarra 2001
  - 2 RH neutrino masses (can have **arbitrary** mass splitting)
  - 3 LH neutrino masses (essentially fixed by neutrino osc. experiments)
  - Three LH (real) mixing angles (fixed) and two LH CP phases δ, η (arbitrary)
  - One **complex** RH mixing angle, ω

Realization in minimal model

- How are these regimes populated in the minimal model parameter space?
- The Yukawa matrices can be fully decomposed as: Casas, Ibarra 2001
  - 2 RH neutrino masses (can have **arbitrary** mass splitting)
  - 3 LH neutrino masses (essentially fixed by neutrino osc. experiments)
  - Three LH (real) mixing angles (fixed) and two LH CP phases δ, η (arbitrary)
  - One **complex** RH mixing angle, ω
- The angle ω **does not appear** in the neutrino mass formula!

$$(m_\nu)_{\alpha\beta} = \langle\Phi\rangle^2 (F\, M_N^{-1} F^{\mathrm{T}})_{\alpha\beta}$$

$$F F^\dagger \sim \frac{M_N\, m_\nu}{\langle\Phi\rangle^2} \cosh(2\mathrm{Im}\,\omega)$$

Realization in minimal model

- How are these regimes populated in the minimal model parameter space?
- The Yukawa matrices can be fully decomposed as: Casas, Ibarra 2001
  - 2 RH neutrino masses (can have **arbitrary** mass splitting)
  - 3 LH neutrino masses (essentially fixed by neutrino osc. experiments)
  - Three LH (real) mixing angles (fixed) and two LH CP phases δ, η (arbitrary)
  - One **complex** RH mixing angle, ω
- The angle ω **does not appear** in the neutrino mass formula!

$$(m_\nu)_{\alpha\beta} = \langle\Phi\rangle^2 (F\, M_N^{-1} F^{\mathrm{T}})_{\alpha\beta}$$

$$F F^\dagger \sim \frac{M_N\, m_\nu}{\langle\Phi\rangle^2} \cosh(2\mathrm{Im}\,\omega)$$

- Yukawa couplings can be arbitrarily large!
  - Cancellation among Yukawa entries gives **same** LH neutrino masses $(F F^{\mathrm{T}} \ll F F^\dagger)$

Large Yukawas?

- Yukawa couplings can be arbitrarily large!
  - But at what cost?
  - Look at how physical quantities vary with theory parameters (Giudice, Barbieri, 1988)

$$\frac{d\log m_\nu}{dF} \sim \cosh(2\mathrm{Im}\,\omega)$$

Large Yukawas?

- Yukawa couplings can be arbitrarily large!
  - But at what cost?
  - Look at how physical quantities vary with theory parameters (Giudice, Barbieri, 1988)

$$\frac{d\log m_\nu}{dF} \sim \cosh(2\mathrm{Im}\,\omega)$$

- Large ω can be associated with an approximate lepton number symmetry, but the establishment/breaking of this symmetry not understood in minimal model

Shaposhnikov, 2006

Large Yukawas?

- Yukawa couplings can be arbitrarily large!
  - But at what cost?
  - Look at how physical quantities vary with theory parameters (Giudice, Barbieri, 1988)

$$\frac{d \log m_\nu}{dF} \sim \cosh(2\mathrm{Im}\,\omega)$$

- Large ω can be associated with an approximate lepton number symmetry, but the establishment/breaking of this symmetry not understood in minimal model

Shaposhnikov, 2006

- Whether the minimal model requires degenerate masses, tuned Yukawas, or both depends on numerology

Numerical results

- Use **density matrix** formalism for computing asymmetry:
  - Simpler, gives same answer as more correct closed-time-path formalism (up to $O(1)$)

Drewes, Garbrecht 2012

Numerical results

- Use **density matrix** formalism for computing asymmetry:
    - Simpler, gives same answer as more correct closed-time-path formalism (up to $O(1)$)

Drewes, Garbrecht 2012

- Density matrices for sterile neutrinos ρ_N, for SM leptons ρ_L
    - On-diagonal entries are the **abundances**
    - Off-diagonal entries are the **coherences** between different states (i.e. oscillation phase)

Akhmedov, Rubakov, Smirnov 1998; Asaka, Shaposhnikov 2005

Numerical results

- Use **density matrix** formalism for computing asymmetry:
  - Simpler, gives same answer as more correct closed-time-path formalism (up to $O(1)$)

Drewes, Garbrecht 2012

- Density matrices for sterile neutrinos ρ_N, for SM leptons ρ_L
  - On-diagonal entries are the **abundances**
  - Off-diagonal entries are the **coherences** between different states (i.e. oscillation phase)

Akhmedov, Rubakov, Smirnov 1998; Asaka, Shaposhnikov 2005

$$\frac{d\rho_N}{dt} = -i[H,\rho_N] - \frac{1}{2}\left\{\Gamma(L^\dagger \to N)_{2\times 2}, \rho_N - \rho_{\bar{L}}^{\mathrm{eq}}\mathbb{I}_{2\times 2}\right\} - \frac{1}{2}\gamma^{\mathrm{av}} T F^\dagger \rho_{L-L} F$$

$$\frac{d\rho_{L-\bar{L}}}{dt} = -\frac{1}{4}\left\{\Gamma(L \to N^\dagger)_{3\times 3}, \rho_{L-\bar{L}}\right\} + \frac{1}{2}\gamma^{\mathrm{av}} T \left(F\rho_{\bar{N}}F^\dagger - F^*\rho_N F^{\mathrm{T}}\right)$$

$$\Gamma(L \to N^\dagger) \equiv \gamma^{\mathrm{av}}(T)\, T\, F F^\dagger$$

Numerical results

- Use **density matrix** formalism for computing asymmetry:
  - Simpler, gives same answer as more correct closed-time-path formalism (up to $O(1)$)

Drewes, Garbrecht 2012

- Density matrices for sterile neutrinos ρ_N, for SM leptons ρ_L
  - On-diagonal entries are the **abundances**
  - Off-diagonal entries are the **coherences** between different states (i.e. oscillation phase)

Akhmedov, Rubakov, Smirnov 1998; Asaka, Shaposhnikov 2005

oscillation

$$\frac{d\rho_N}{dt} = -i[H, \rho_N] - \frac{1}{2}\left\{\Gamma(L^\dagger \to N)_{2\times 2}, \rho_N - \rho_{\bar{L}}^{\rm eq}\mathbb{I}_{2\times 2}\right\} - \frac{1}{2}\gamma^{\rm av} T F^\dagger \rho_{L-L} F$$

$$\frac{d\rho_{L-\bar{L}}}{dt} = -\frac{1}{4}\left\{\Gamma(L \to N^\dagger)_{3\times 3}, \rho_{L-\bar{L}}\right\} + \frac{1}{2}\gamma^{\rm av} T\left(F\rho_{\bar{N}}F^\dagger - F^*\rho_N F^{\rm T}\right)$$

$$\Gamma(L \to N^\dagger) \equiv \gamma^{\rm av}(T)\, T\, F F^\dagger$$

Numerical results

- Use **density matrix** formalism for computing asymmetry:
  - Simpler, gives same answer as more correct closed-time-path formalism (up to $O(1)$)

Drewes, Garbrecht 2012

- Density matrices for sterile neutrinos ρ_N, for SM leptons ρ_L
  - On-diagonal entries are the **abundances**
  - Off-diagonal entries are the **coherences** between different states (i.e. oscillation phase)

Akhmedov, Rubakov, Smirnov 1998; Asaka, Shaposhnikov 2005

$$\frac{d\rho_N}{dt} = \underbrace{-i[H,\rho_N]}_{\text{oscillation}} - \frac{1}{2}\underbrace{\{\Gamma(L^\dagger \to N)_{2\times 2}, \rho_N - \rho_{\bar{L}}^{\mathrm{eq}}\mathbb{I}_{2\times 2}\}}_{\text{scattering}} - \frac{1}{2}\gamma^{\mathrm{av}} T F^\dagger \rho_{L-L} F$$

$$\frac{d\rho_{L-\bar{L}}}{dt} = -\frac{1}{4}\{\Gamma(L \to N^\dagger)_{3\times 3}, \rho_{L-\bar{L}}\} + \frac{1}{2}\gamma^{\mathrm{av}} T \left(F\rho_{\bar{N}}F^\dagger - F^*\rho_N F^{\mathrm{T}}\right)$$

$$\Gamma(L \to N^\dagger) \equiv \gamma^{\mathrm{av}}(T)\, T\, F F^\dagger$$

Numerical results

- Use **density matrix** formalism for computing asymmetry:
  - Simpler, gives same answer as more correct closed-time-path formalism (up to $O(1)$)

Drewes, Garbrecht 2012

- Density matrices for sterile neutrinos ρ_N, for SM leptons ρ_L
  - On-diagonal entries are the **abundances**
  - Off-diagonal entries are the **coherences** between different states (i.e. oscillation phase)

Akhmedov, Rubakov, Smirnov 1998; Asaka, Shaposhnikov 2005

$$\frac{d\rho_N}{dt} = \overbrace{-i[H,\rho_N]}^{\text{oscillation}} - \frac{1}{2}\overbrace{\left\{\Gamma(L^\dagger \to N)_{2\times 2}, \rho_N - \rho^{\mathrm{eq}}_{\bar{L}}\mathbb{I}_{2\times 2}\right\}}^{\text{scattering}} - \overbrace{\frac{1}{2}\gamma^{\mathrm{av}} T F^\dagger \rho_{L-L} F}^{\text{asym. transfer}}$$

$$\frac{d\rho_{L-\bar{L}}}{dt} = -\frac{1}{4}\left\{\Gamma(L \to N^\dagger)_{3\times 3}, \rho_{L-\bar{L}}\right\} + \frac{1}{2}\gamma^{\mathrm{av}} T \left(F\rho_{\bar{N}}F^\dagger - F^*\rho_N F^{\mathrm{T}}\right)$$

$$\Gamma(L \to N^\dagger) \equiv \gamma^{\mathrm{av}}(T)\, T\, F F^\dagger$$

Numerical results

- Use **density matrix** formalism for computing asymmetry:
  - Simpler, gives same answer as more correct closed-time-path formalism (up to $O(1)$)

Drewes, Garbrecht 2012

- Density matrices for sterile neutrinos ρ_N, for SM leptons ρ_L
  - On-diagonal entries are the **abundances**
  - Off-diagonal entries are the **coherences** between different states (i.e. oscillation phase)

Akhmedov, Rubakov, Smirnov 1998; Asaka, Shaposhnikov 2005

oscillation scattering asym. transfer

$$\frac{d\rho_N}{dt} = -i[H,\rho_N] - \frac{1}{2}\{\Gamma(L^\dagger \to N)_{2\times 2}, \rho_N - \rho_{\bar{L}}^{\text{eq}}\mathbb{I}_{2\times 2}\} - \frac{1}{2}\gamma^{\text{av}} T F^\dagger \rho_{L-L} F$$

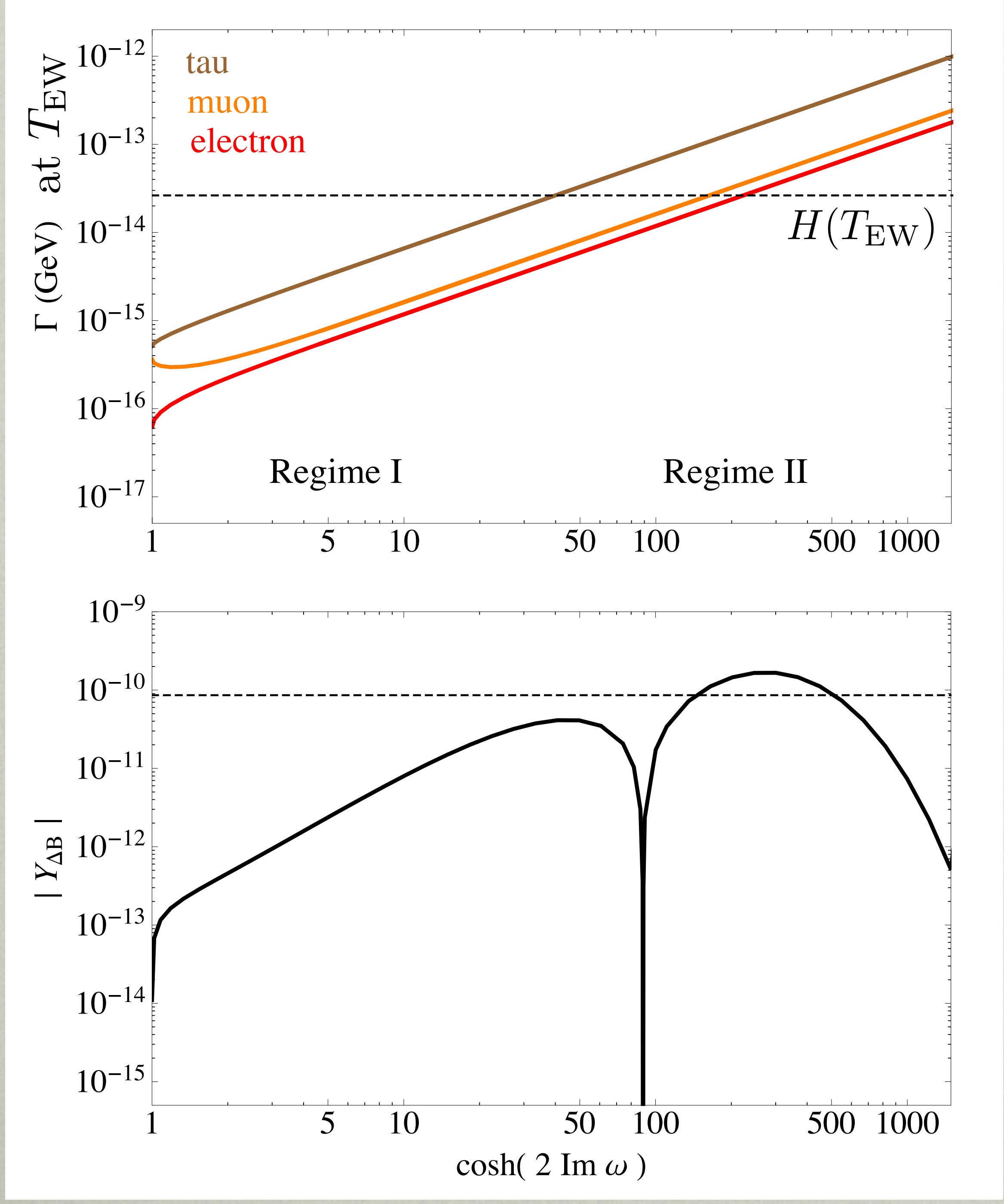
$$\frac{d\rho_{L-\bar{L}}}{dt} = -\frac{1}{4}\{\Gamma(L\to N^\dagger)_{3\times 3}, \rho_{L-\bar{L}}\} + \frac{1}{2}\gamma^{\text{av}} T \left(F\rho_{\bar{N}}F^\dagger - F^* \rho_N F^{\text{T}}\right)$$

$$\Gamma(L\to N^\dagger) \equiv \gamma^{\text{av}}(T)\, T\, F F^\dagger$$

- We include various corrections, including **spectator effects**

Numerical results

- Regimes I-II (choose normal hierarchy for concreteness)



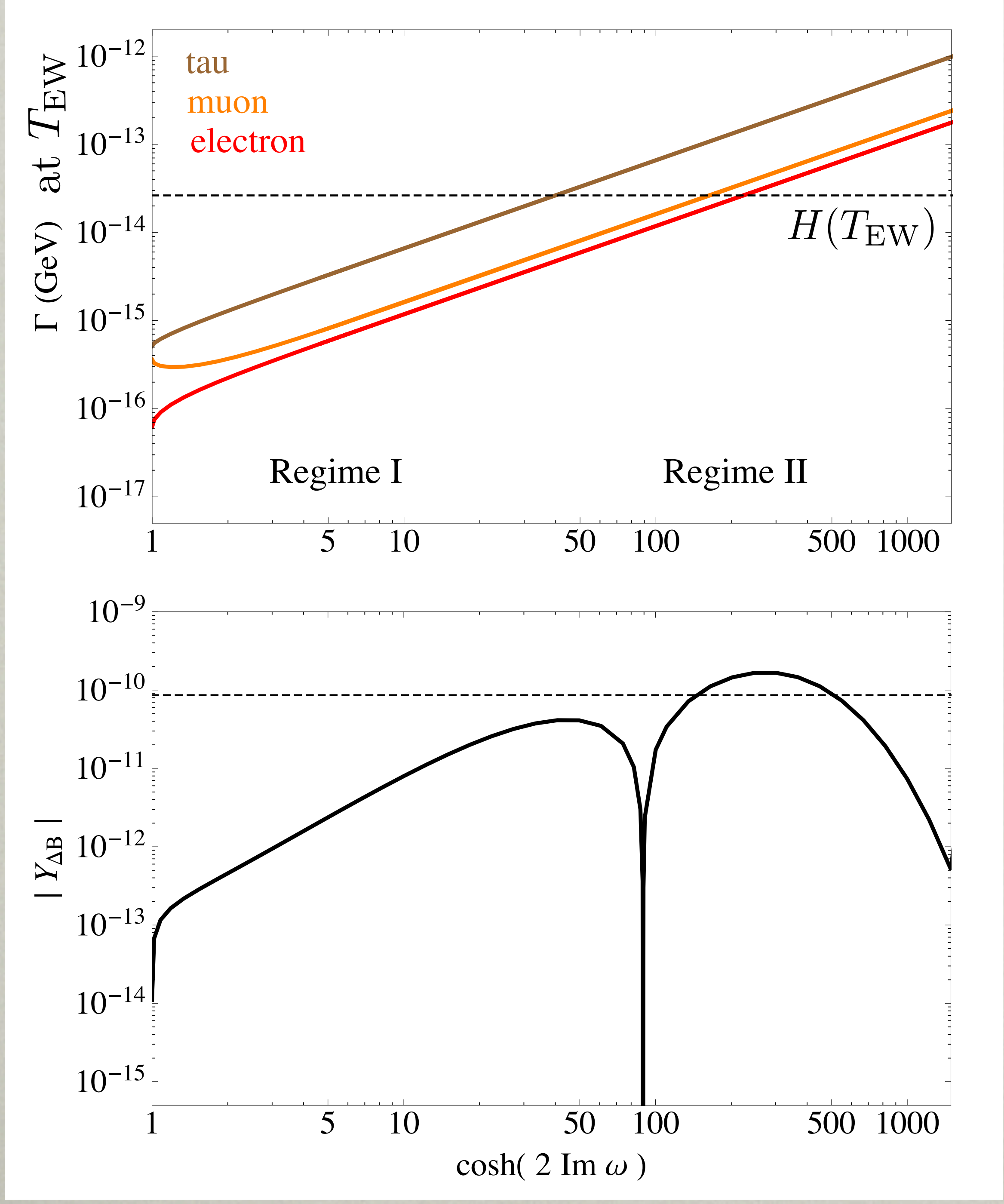
$$\Gamma_e \sim \Gamma_\mu \sim \Gamma_\tau$$

$M_N = 1$ GeV
$\Delta M_N = 10^{-5}$ GeV
$\eta = -\pi/4$
$\delta = 3\pi/4$
$\mathrm{Re}\,\omega = \pi/4$

- Need either **degenerate masses** or **tuned Yukawas**

Numerical results

- Regimes I-II-III

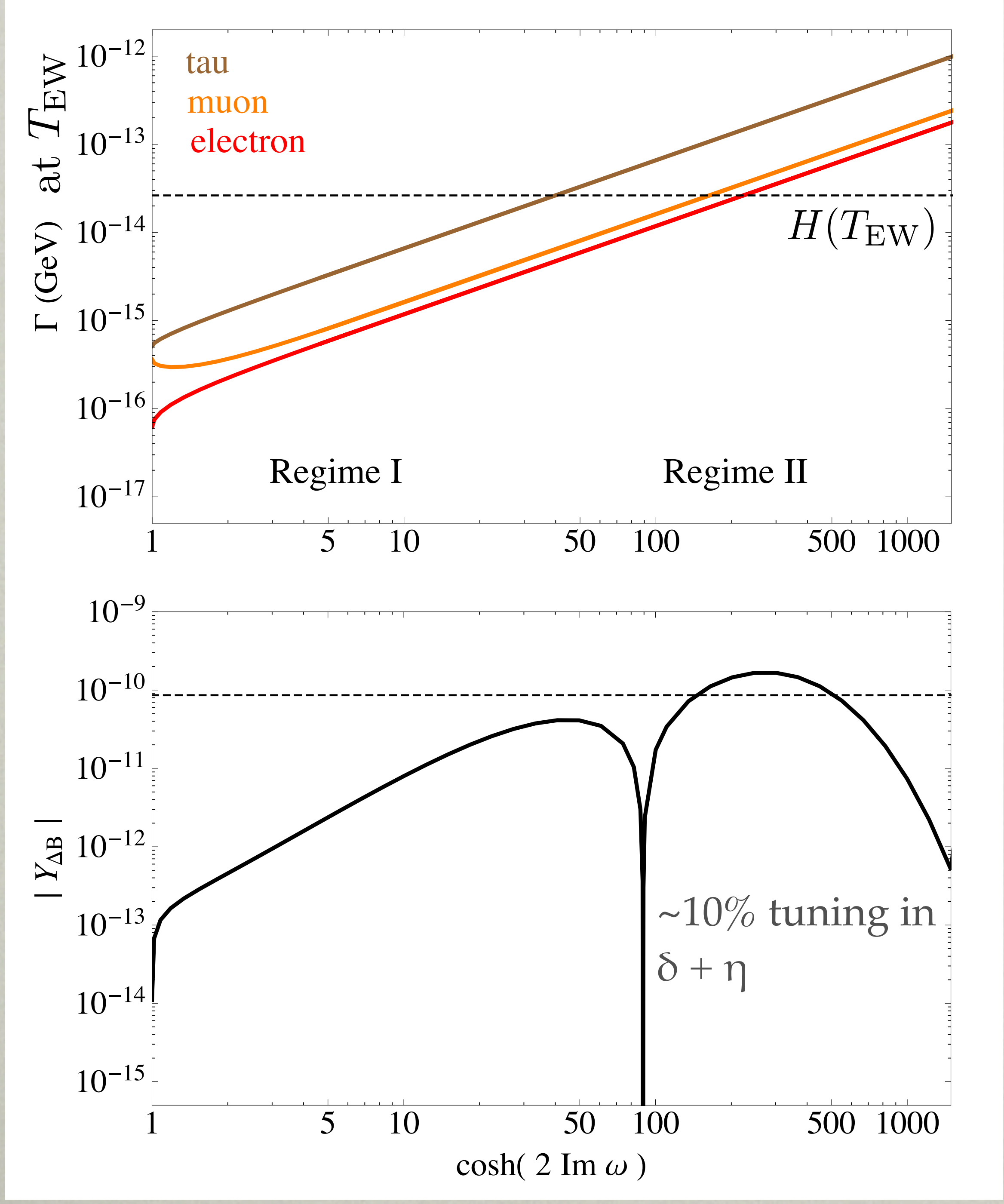


$$\Gamma_e \ll \Gamma_\mu \sim \Gamma_\tau$$

$M_N = 1$ GeV
$\Delta M_N = 10^{-3}$ GeV
$\eta = -\pi/4$
$\delta = -\pi/4$
$\mathrm{Re}\omega = \pi/4$

Numerical results

- Regimes I-II-III



$$\Gamma_e \ll \Gamma_\mu \sim \Gamma_\tau$$

$M_N = 1$ GeV
$\Delta M_N = 10^{-3}$ GeV
$\eta = -\pi/4$
$\delta = -\pi/4$
$\mathrm{Re}\,\omega = \pi/4$

- This can be accomplished with **destructive interference** in Γ_e

$$\tan\theta_{13} = \frac{m_{\nu 2}}{m_{\nu 3}} \sin\theta_{12} \quad \text{and} \quad \cos(\delta + \eta) = -1$$

Asaka, Eijima, Ishida 2011
Drewes, Garbrecht 2012

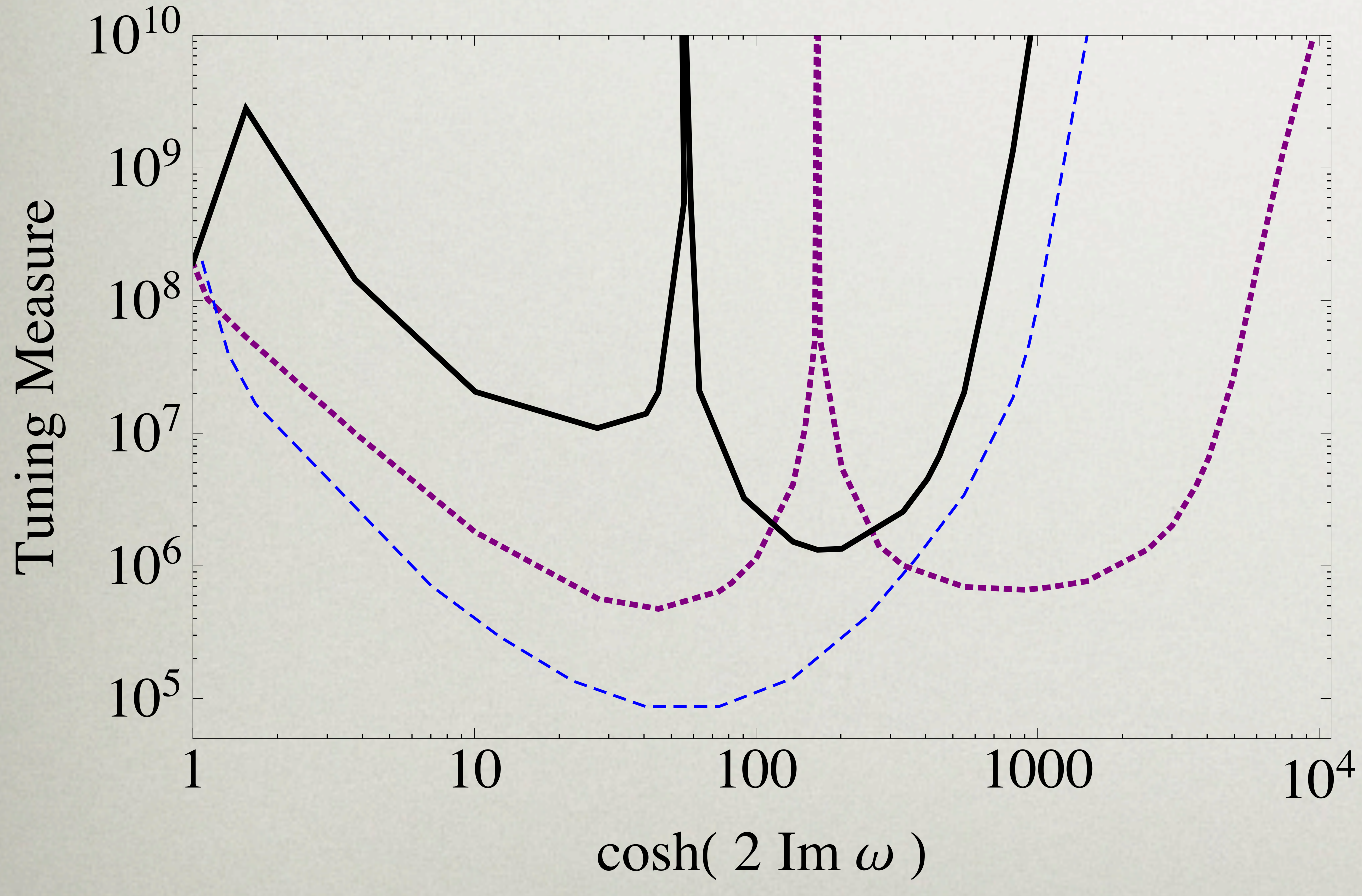
Numerical results

- When considering all different possible combinations, there is a **minimum** tuning of the parameter space ~ 10^5
  - Yukawa couplings are generically **too small** to account for baryon asymmetry
  - For each point, determine mass degeneracy needed to obtain baryon asymmetry

Numerical results

- When considering all different possible combinations, there is a **minimum** tuning of the parameter space ~ 10^5
  - Yukawa couplings are generically **too small** to account for baryon asymmetry
  - For each point, determine mass degeneracy needed to obtain baryon asymmetry

$$\text{tuning/alignment} = \frac{M}{\Delta M}\cosh(2\mathrm{Im}\,\omega)$$



$M_N = 1$ GeV

Black	Purple	Blue
$\eta = \pi/4$	$\eta = -\pi/4$	$\eta = 2.42$
$\delta = \pi/4$	$\delta = -\pi/4$	$\delta = 0.5$
$\mathrm{Re}\omega = \pi/4$	$\mathrm{Re}\omega = \pi/4$	$\mathrm{Re}\omega = \pi/2$

Numerical results

$$FF^\dagger \sim \frac{M_N\, m_\nu}{\langle\Phi\rangle^2}\cosh(2\mathrm{Im}\,\omega)$$

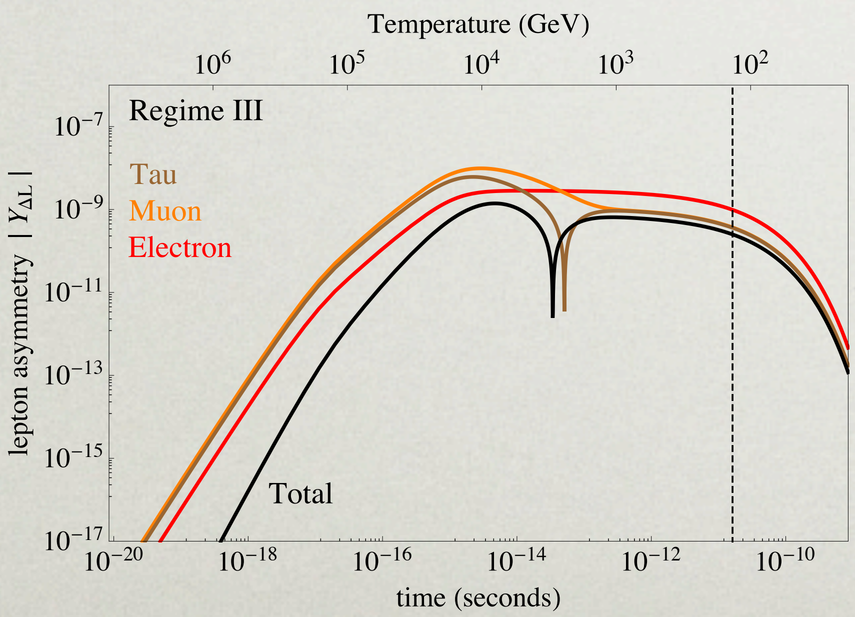
- The general conclusion still holds if we have....
    - **Heavier M_N:** Naturally get larger Yukawa couplings, **but** ΔM_N / M_N gets smaller

Numerical results

$$FF^\dagger \sim \frac{M_N\, m_\nu}{\langle \Phi \rangle^2} \cosh(2\mathrm{Im}\,\omega)$$

- The general conclusion still holds if we have....
  - **Heavier M_N**: Naturally get larger Yukawa couplings, **but** ΔM_N / M_N gets smaller
  - **More sterile neutrinos:** With 3+ sterile neutrinos, there is viable parameter space in Regime III **without** degenerate sterile neutrinos

Drewes, Garbrecht 2012



$$\Gamma_e \ll \Gamma_\mu, \Gamma_\tau$$

- Tuning all shifted into Yukawa couplings (large Im(ω))
- Relies on large cancellations in electron rate

Baryon asymmetry with an extended Higgs sector

Yukawas in a 2HDM

$$F^\dagger F \sim \frac{M_N\, m_\nu}{\langle\Phi\rangle^2} \cosh(2\mathrm{Im}\,\omega)$$

- Up until now, we have taken $\Phi = \Phi_{\mathrm{SM}}$
- If $\langle\Phi\rangle < \langle\Phi\rangle_{\mathrm{SM}}$, the Yukawa couplings are naturally larger than in the conventional see-saw

Yukawas in a 2HDM

$$F^\dagger F \sim \frac{M_N\, m_\nu}{\langle\Phi\rangle^2}\cosh(2\mathrm{Im}\,\omega)$$

- Up until now, we have taken $\Phi = \Phi_{\rm SM}$
- If $\langle\Phi\rangle < \langle\Phi\rangle_{\rm SM}$, the Yukawa couplings are naturally larger than in the conventional see-saw
- **Our proposal:** a leptophilic two Higgs doublet model
  - "Leptophilic": SM-like Higgs doublet couples to quarks, new Higgs doublet couples to leptons (avoids FCNCs)
  - Smallness of charged lepton masses can be a consequence of small VEV for leptophilic Higgs

Possibility of 2HDM in νMSM also mentioned in Drewes, Garbrecht 2012

$$\mathcal{L}_{\rm Yuk} = -\lambda_u Q H_q u^{\rm c} - \lambda_d Q H_q^* d^{\rm c} - \lambda_\ell L H_\ell^* E^{\rm c} - F\, L H_\ell N$$

$$\tan\beta = \frac{\langle H_q\rangle}{\langle H_\ell\rangle} \gg 1 \qquad\qquad \lambda_\ell = \tan\beta\,\frac{m_\ell}{\langle H_q\rangle} \gg \frac{m_\ell}{v_{\rm SM}}$$

Yukawas in a 2HDM

- The size of the Yukawa coupling is limited by the fact that N cannot equilibrate before the electroweak phase transition

$$\text{asymmetry equilibration rate} \sim FF^\dagger \sim \frac{m_\nu M_N}{\langle \Phi \rangle^2} \cosh(2\mathrm{Im}\,\omega)$$

Yukawas in a 2HDM

- The size of the Yukawa coupling is limited by the fact that N cannot equilibrate before the electroweak phase transition

$$\text{asymmetry equilibration rate} \sim FF^\dagger \sim \frac{m_\nu M_N}{\langle\Phi\rangle^2}\cosh(2\mathrm{Im}\,\omega)$$

- Asymmetry creation goes like $\mathrm{Im}[(FF^*)^2]$, so naïvely the asymmetry creation rate goes like $\cosh(2\mathrm{Im}\omega)^2$. But....

$$\text{asymmetry creation rate} \sim \mathrm{Im}\left[F_{\alpha 3}F^*_{\beta 3}F^*_{\alpha 2}F_{\beta 2}\right] \sim \frac{m_\nu^2 M_N^2}{\langle\Phi\rangle^4}\cosh(2\mathrm{Im}\,\omega)$$

Yukawas in a 2HDM

- The size of the Yukawa coupling is limited by the fact that N cannot equilibrate before the electroweak phase transition

$$\text{asymmetry equilibration rate} \sim FF^\dagger \sim \frac{m_\nu M_N}{\langle\Phi\rangle^2}\cosh(2\mathrm{Im}\,\omega)$$

- Asymmetry creation goes like Im[(FF*)^2], so naïvely the asymmetry creation rate goes like cosh(2Imω)^2 . But....

$$\text{asymmetry creation rate} \sim \mathrm{Im}\left[F_{\alpha 3}F^*_{\beta 3}F^*_{\alpha 2}F_{\beta 2}\right] \sim \frac{m_\nu^2 M_N^2}{\langle\Phi\rangle^4}\cosh(2\mathrm{Im}\,\omega)$$

- In the asymmetry creation rate, there is a **partial cancellation of the Yukawa couplings** when the couplings are tuned to be large

Yukawas in a 2HDM

- The size of the Yukawa coupling is limited by the fact that N cannot equilibrate before the electroweak phase transition

$$\text{asymmetry equilibration rate} \sim FF^\dagger \sim \frac{m_\nu M_N}{\langle \Phi \rangle^2} \cosh(2\mathrm{Im}\,\omega)$$

- Asymmetry creation goes like Im[(FF*)^2], so naïvely the asymmetry creation rate goes like cosh(2Imω)^2 . But....

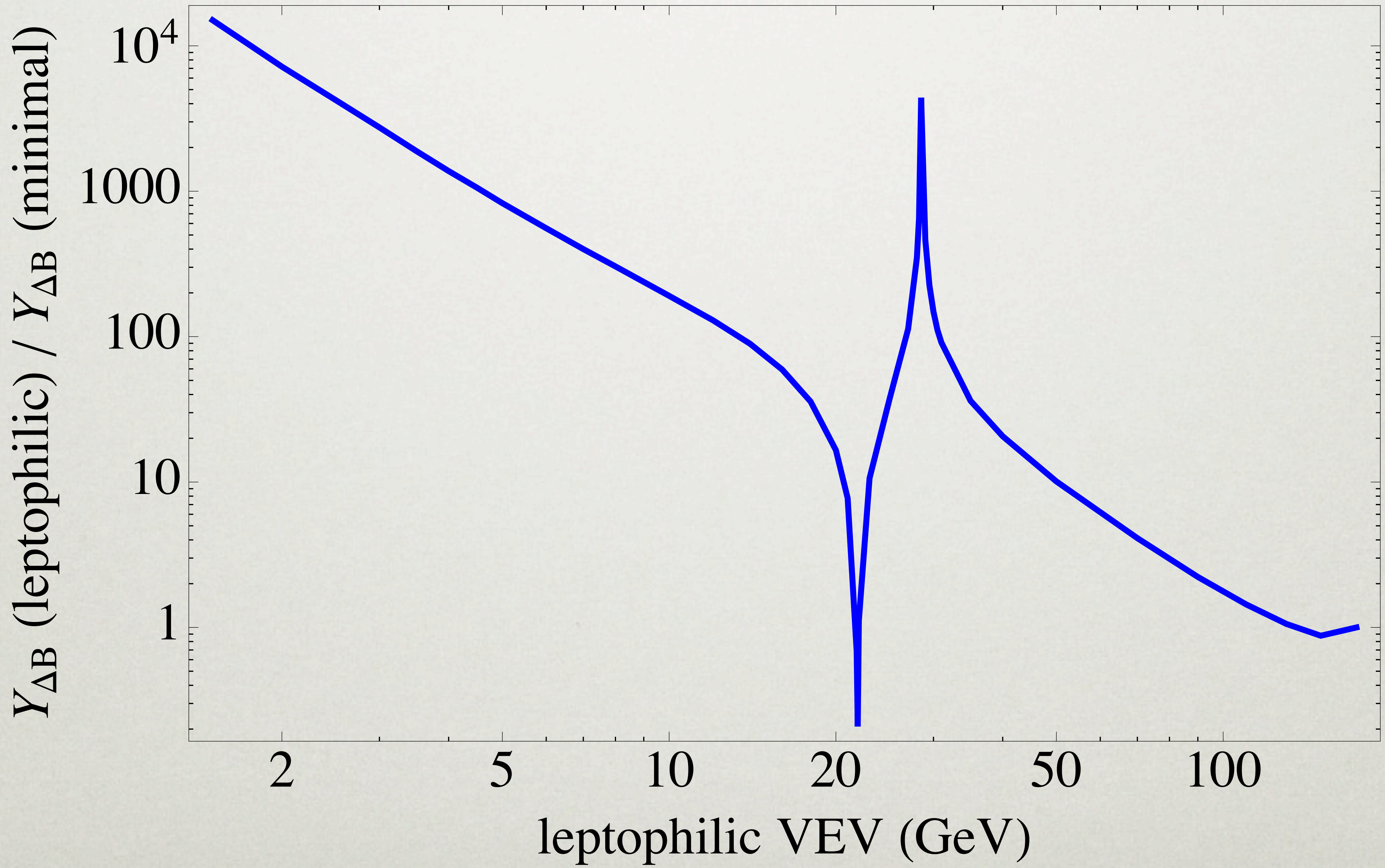
$$\text{asymmetry creation rate} \sim \mathrm{Im}\left[F_{\alpha 3} F^*_{\beta 3} F^*_{\alpha 2} F_{\beta 2}\right] \sim \frac{m_\nu^2 M_N^2}{\langle \Phi \rangle^4} \cosh(2\mathrm{Im}\,\omega)$$

- In the asymmetry creation rate, there is a **partial cancellation of the Yukawa couplings** when the couplings are tuned to be large

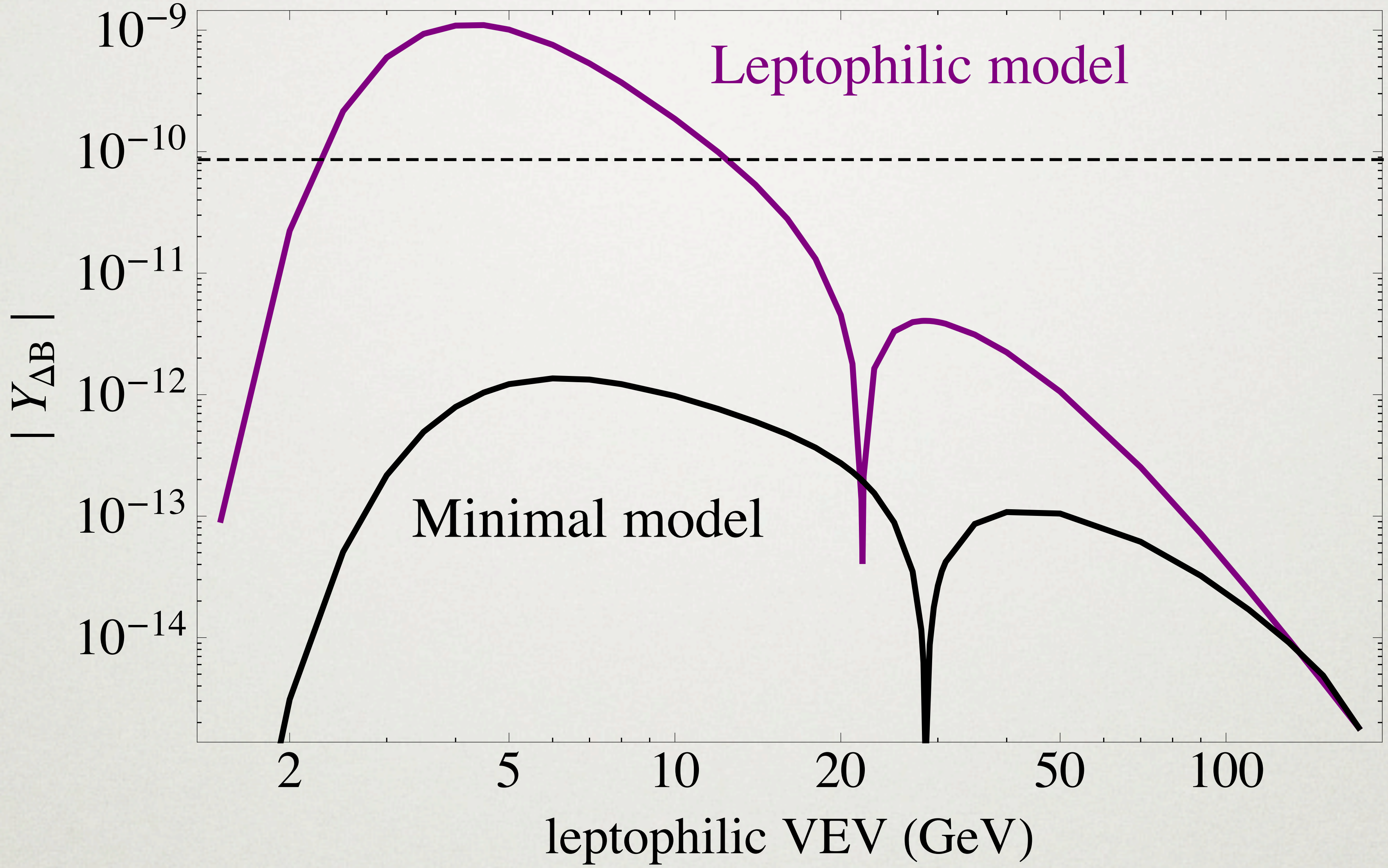
- A smaller Higgs VEV gives a quadratic enhancement of the baryon asymmetry over the tuned model

Baryogenesis and a 2HDM

- Compare leptophilic 2HDM with VEV v to the minimal model where the Yukawa couplings are tuned to be the same magnitude

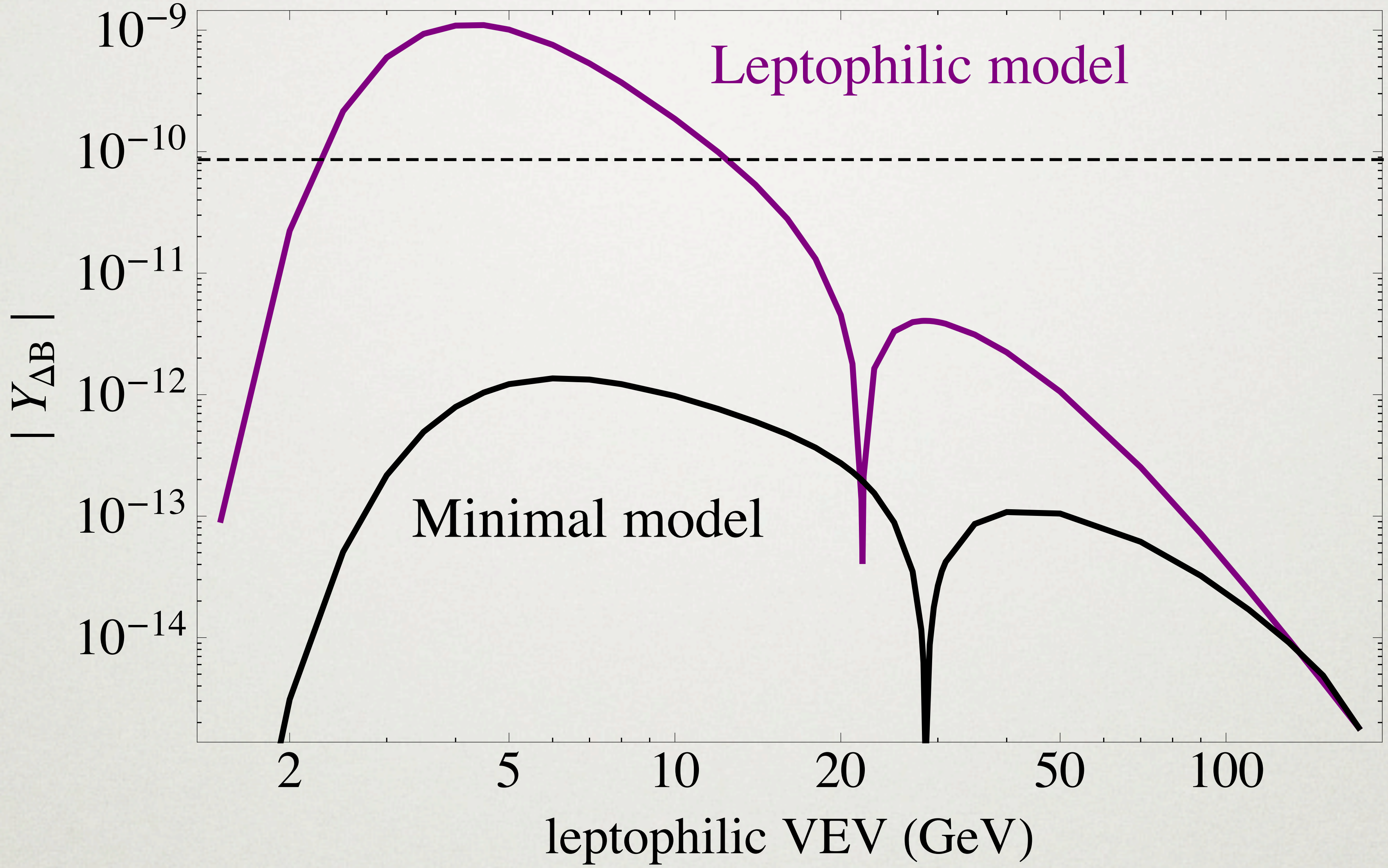


Baryogenesis and a 2HDM



$M_2 = 0.5$ GeV
$M_3 = 1.5$ GeV
$\omega = \pi/4 + i$
$\eta = \delta = -\pi/4$

Baryogenesis and a 2HDM



- Depending on leptophilic VEV, can get observed baryon asymmetry with:
  - Non-degenerate spectrum
  - No tuning of the Yukawa couplings needed
  - Generic phases OK (1/2 - 1/3 of total parameter space)

$M_2 = 0.5$ GeV
$M_3 = 1.5$ GeV
$\omega = \pi/4 + i$
$\eta = \delta = -\pi/4$

2HDM Phenomenology

- Generic connection between enhanced baryon asymmetry and extended Higgs sector

2HDM Phenomenology

- Generic connection between enhanced baryon asymmetry and extended Higgs sector

- Explore the Higgs phenomenology:

$$V(H_q, H_\ell) = -\mu_1^2|H_q|^2 + \mu_2^2|H_\ell|^2 + \frac{\lambda_1}{4}|H_q|^4 + \frac{\lambda_2}{4}|H_\ell|^4 + \lambda_{12}|H_q|^2|H_\ell|^2$$

$$V_{\text{mix}} = \mu_{\text{mix}}^2 H_\ell H_q^*$$

2HDM Phenomenology

- Generic connection between enhanced baryon asymmetry and extended Higgs sector

- Explore the Higgs phenomenology:

$$V(H_q, H_\ell) = -\mu_1^2 |H_q|^2 + \mu_2^2 |H_\ell|^2 + \frac{\lambda_1}{4}|H_q|^4 + \frac{\lambda_2}{4}|H_\ell|^4 + \lambda_{12}|H_q|^2|H_\ell|^2$$

$$V_{\rm mix} = \mu_{\rm mix}^2 H_\ell H_q^*$$

- Z_2 symmetry means that naturally $\mu_{\rm mix}^2 \ll \mu_1^2,\, \mu_2^2$

2HDM Phenomenology

- Generic connection between enhanced baryon asymmetry and extended Higgs sector

- Explore the Higgs phenomenology:

$$V(H_q, H_\ell) = -\mu_1^2|H_q|^2 + \mu_2^2|H_\ell|^2 + \frac{\lambda_1}{4}|H_q|^4 + \frac{\lambda_2}{4}|H_\ell|^4 + \lambda_{12}|H_q|^2|H_\ell|^2$$

$$V_{\rm mix} = \mu_{\rm mix}^2 H_\ell H_q^*$$

- Z_2 symmetry means that naturally $\mu_{\rm mix}^2 \ll \mu_1^2,\ \mu_2^2$

- This gives induces a VEV for the leptophilic Higgs, relates $\tan\beta$ to mixing angle $\sin\alpha$

2HDM Phenomenology

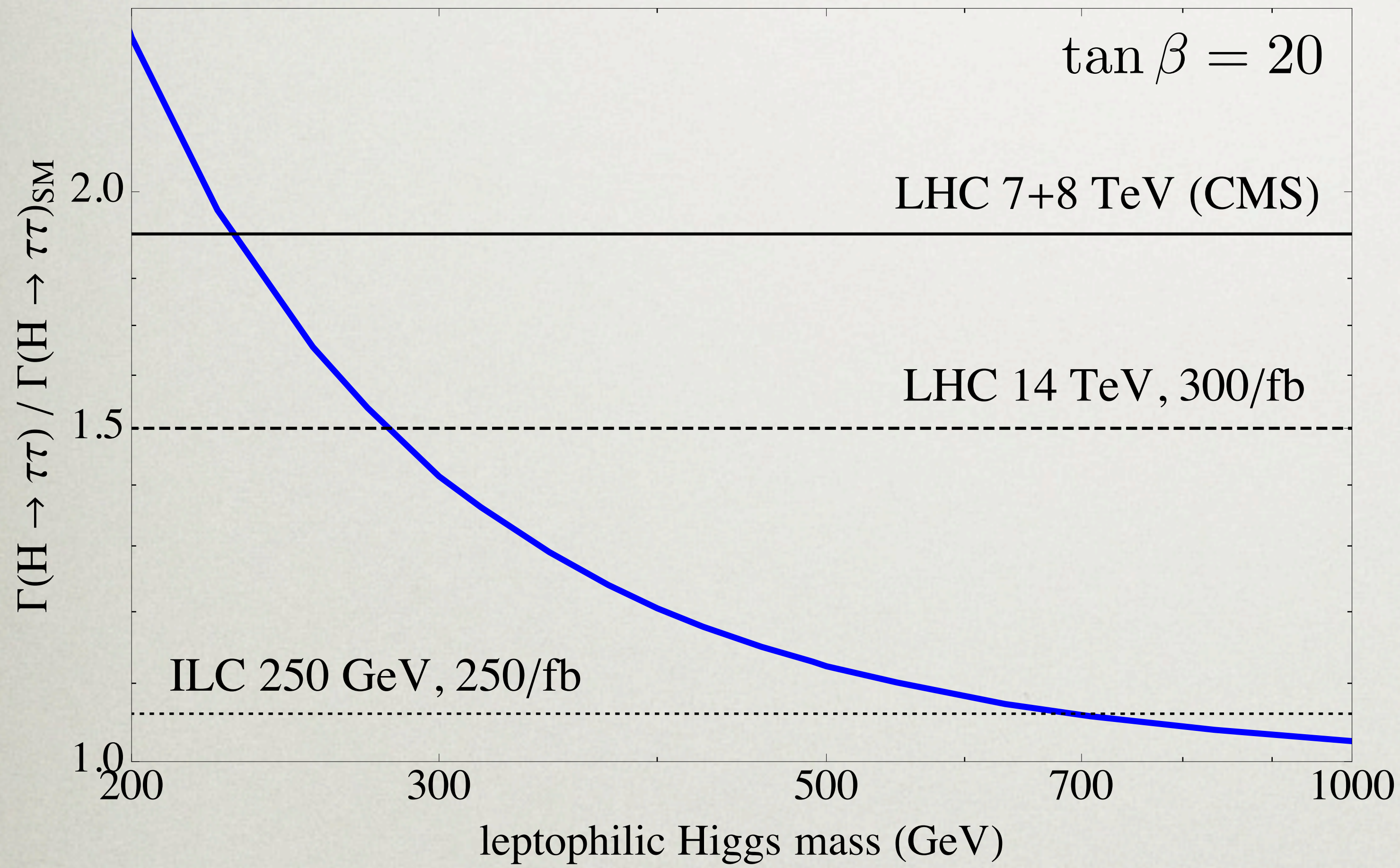
- Modifies SM Higgs coupling to leptons

$$\lambda_\tau \to \lambda_\tau \tan\beta \sin\alpha$$

2HDM Phenomenology

- Modifies SM Higgs coupling to leptons

$$\lambda_\tau \to \lambda_\tau \tan\beta \sin\alpha$$



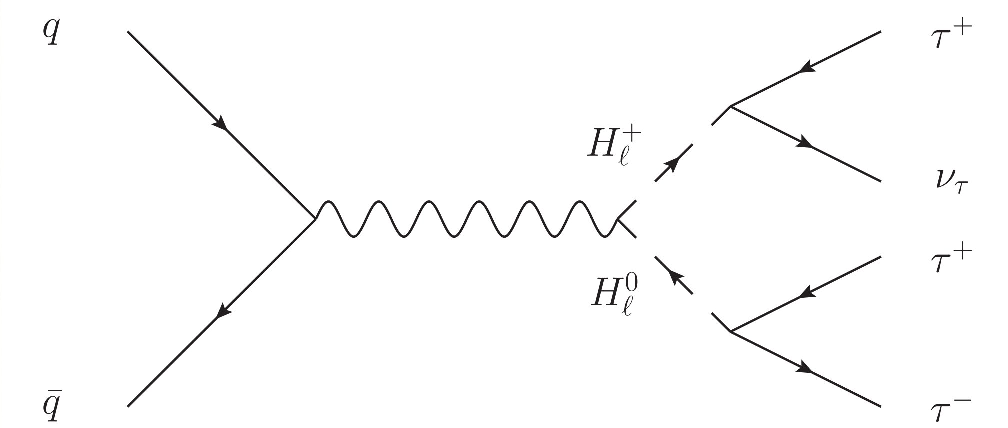
Calculated with 2HDMC

Future projections derived from Peskin, 2012

Recent 8 TeV scan:
ex. Ferreira *et al.*, 2014

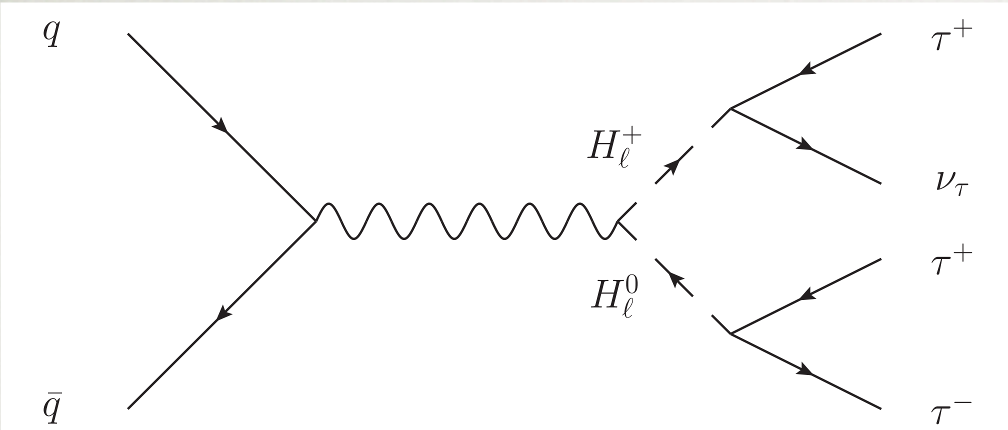
2HDM Phenomenology

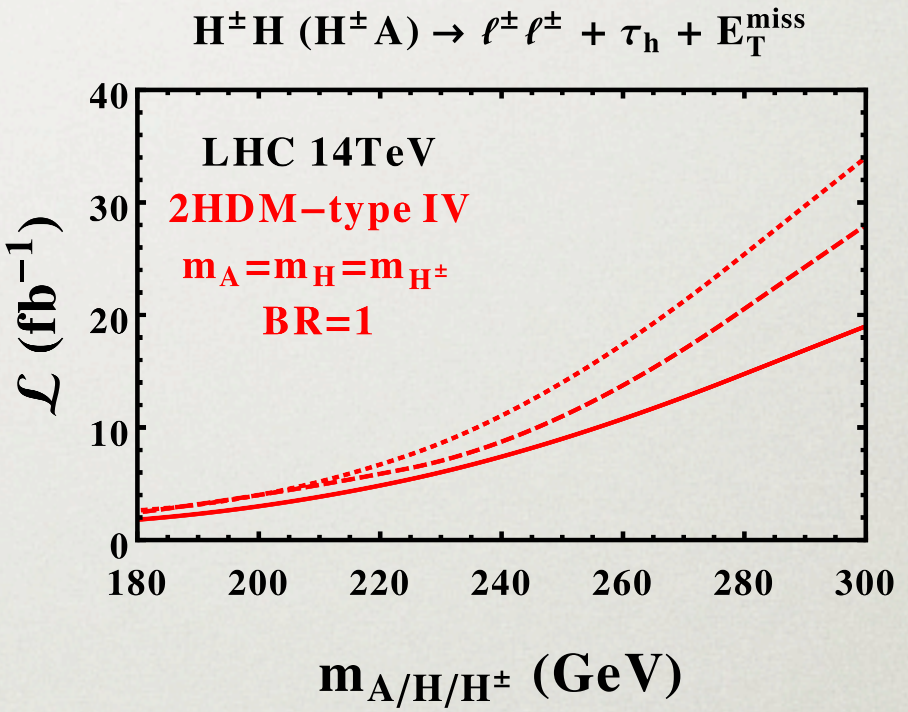
- At large $\tan\beta$, can also study in a **model-independent** fashion via direct pair-production of the new states



2HDM Phenomenology

- At large $\tan\beta$, can also study in a **model-independent** fashion via direct pair-production of the new states





- A promising search channel is same-sign dileptons + hadronic tau (current bound = 150 GeV)
- See Liu, BS, Weiner, Yavin, 2013 for more details of search possibilities

2HDM Phenomenology

- There are other, more exotic possibilities
    - Suppose H_ℓ gives mass **only** to neutrinos
    - Constraints from Higgs to $\tau\tau$ go away

2HDM Phenomenology

- There are other, more exotic possibilities
  - Suppose H_ℓ gives mass **only** to neutrinos
  - Constraints from Higgs to ττ go away

- Can have very large $\tan\beta$, and very light N

$$(m_\nu)_{\alpha\beta} = \langle\Phi\rangle^2 (F\, M_N^{-1} F^{\mathrm{T}})_{\alpha\beta}$$

2HDM Phenomenology

- There are other, more exotic possibilities
  - Suppose H_ℓ gives mass **only** to neutrinos
  - Constraints from Higgs to ττ go away
- Can have very large $\tan\beta$, and very light N $\quad (m_\nu)_{\alpha\beta} = \langle\Phi\rangle^2 (F\, M_N^{-1} F^{\mathrm{T}})_{\alpha\beta}$
- Can look at decays via the operator that gives rise to neutrino masses!

$$F_{\alpha I} L_\alpha H_\ell N_I \qquad\qquad H_\ell^\pm \to \ell^\pm N$$

2HDM Phenomenology

- There are other, more exotic possibilities
  - Suppose H_ℓ gives mass **only** to neutrinos
  - Constraints from Higgs to ττ go away

- Can have very large $\tan\beta$, and very light N $\quad (m_\nu)_{\alpha\beta} = \langle\Phi\rangle^2 (F\, M_N^{-1} F^{\mathrm{T}})_{\alpha\beta}$

- Can look at decays via the operator that gives rise to neutrino masses!

$$F_{\alpha I} L_\alpha H_\ell N_I \qquad\qquad H_\ell^\pm \to \ell^\pm N$$

- This looks exactly like a **slepton** (lepton + missing energy), but with non-universal couplings
  - Bounds are approx. 300 GeV for decay to muon/electron, 100 GeV for decay to tau

2HDM Phenomenology

- There are other, more exotic possibilities
  - Suppose H_ℓ gives mass **only** to neutrinos
  - Constraints from Higgs to ττ go away

- Can have very large $\tan\beta$, and very light N

$$(m_\nu)_{\alpha\beta} = \langle\Phi\rangle^2 (F\, M_N^{-1} F^{\mathrm{T}})_{\alpha\beta}$$

- Can look at decays via the operator that gives rise to neutrino masses!

$$F_{\alpha I} L_\alpha H_\ell N_I \qquad\qquad H_\ell^\pm \to \ell^\pm N$$

- This looks exactly like a **slepton** (lepton + missing energy), but with non-universal couplings
  - Bounds are approx. 300 GeV for decay to muon/electron, 100 GeV for decay to tau

- Also the possibility for **displaced vertices** over some part of the parameter space
  - Ongoing work

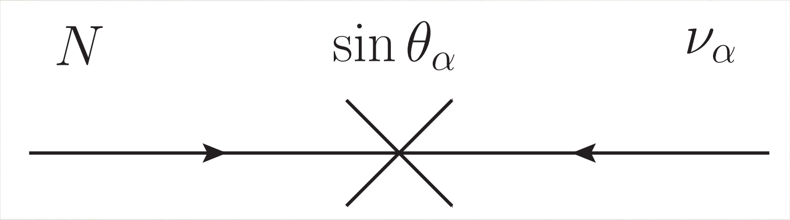
Sterile Neutrino Phenomenology

Sterile neutrino pheno

- There are two main avenues we can use to constrain the **sterile neutrinos** directly
    - Cosmology (consistency of Big Bang Nucleosynthesis)

Sterile neutrino pheno

- There are two main avenues we can use to constrain the **sterile neutrinos** directly
    - Cosmology (consistency of Big Bang Nucleosynthesis)
    - Direct searches

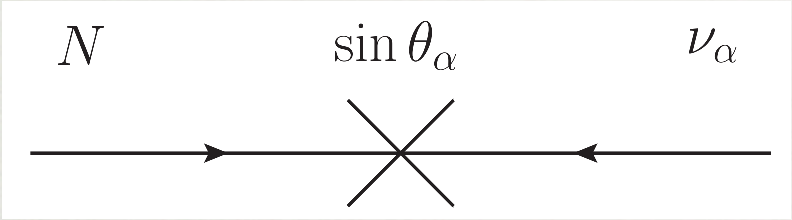


$$\sin\theta_{\alpha I} \approx \frac{F_{\alpha I}\langle H\rangle}{M_N}$$

Shrock 1981; Gorbunov, Shaposhnikov 2007

Sterile neutrino pheno

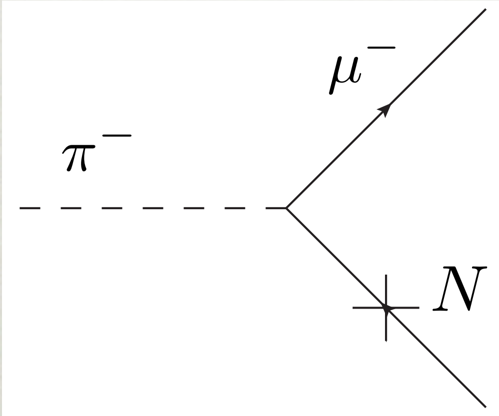
- There are two main avenues we can use to constrain the **sterile neutrinos** directly
    - Cosmology (consistency of Big Bang Nucleosynthesis)
    - Direct searches

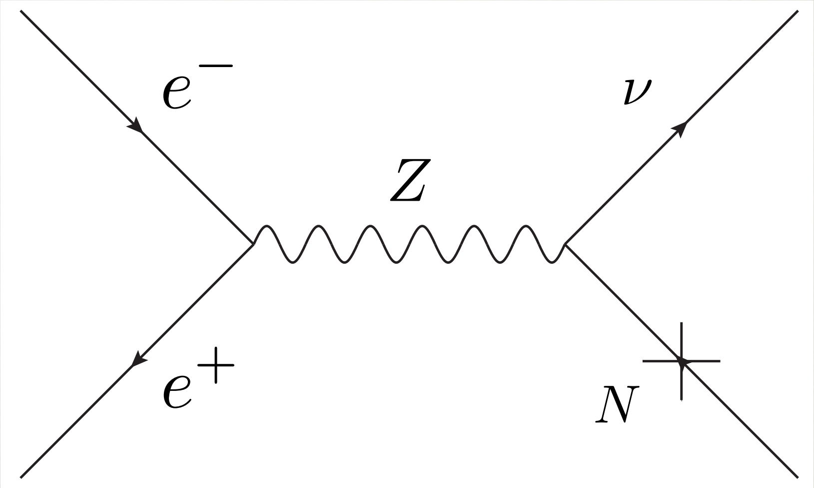


$$\sin\theta_{\alpha I} \approx \frac{F_{\alpha I}\langle H\rangle}{M_N}$$

Shrock 1981; Gorbunov, Shaposhnikov 2007

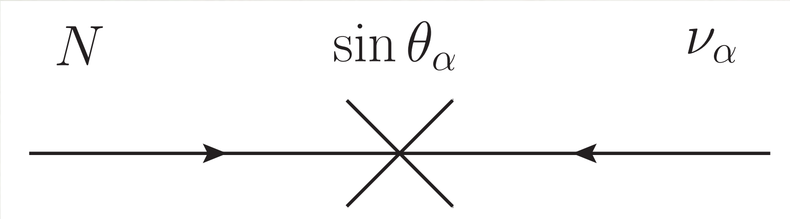
- Can get N everywhere we have ν at the price of $\sin\theta$ in the amplitude





Sterile neutrino pheno

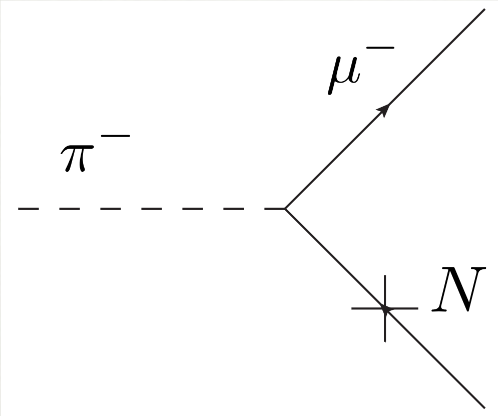
- There are two main avenues we can use to constrain the **sterile neutrinos** directly
  - Cosmology (consistency of Big Bang Nucleosynthesis)
  - Direct searches

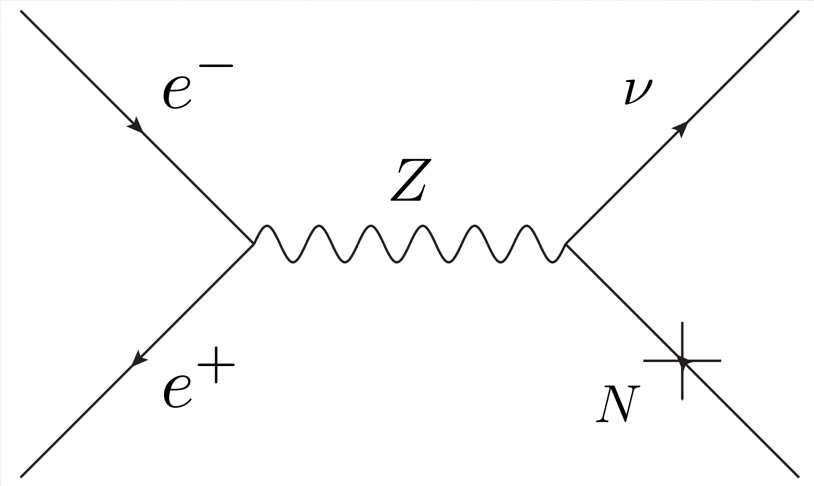


$$\sin\theta_{\alpha I} \approx \frac{F_{\alpha I}\langle H\rangle}{M_N}$$

Shrock 1981; Gorbunov, Shaposhnikov 2007

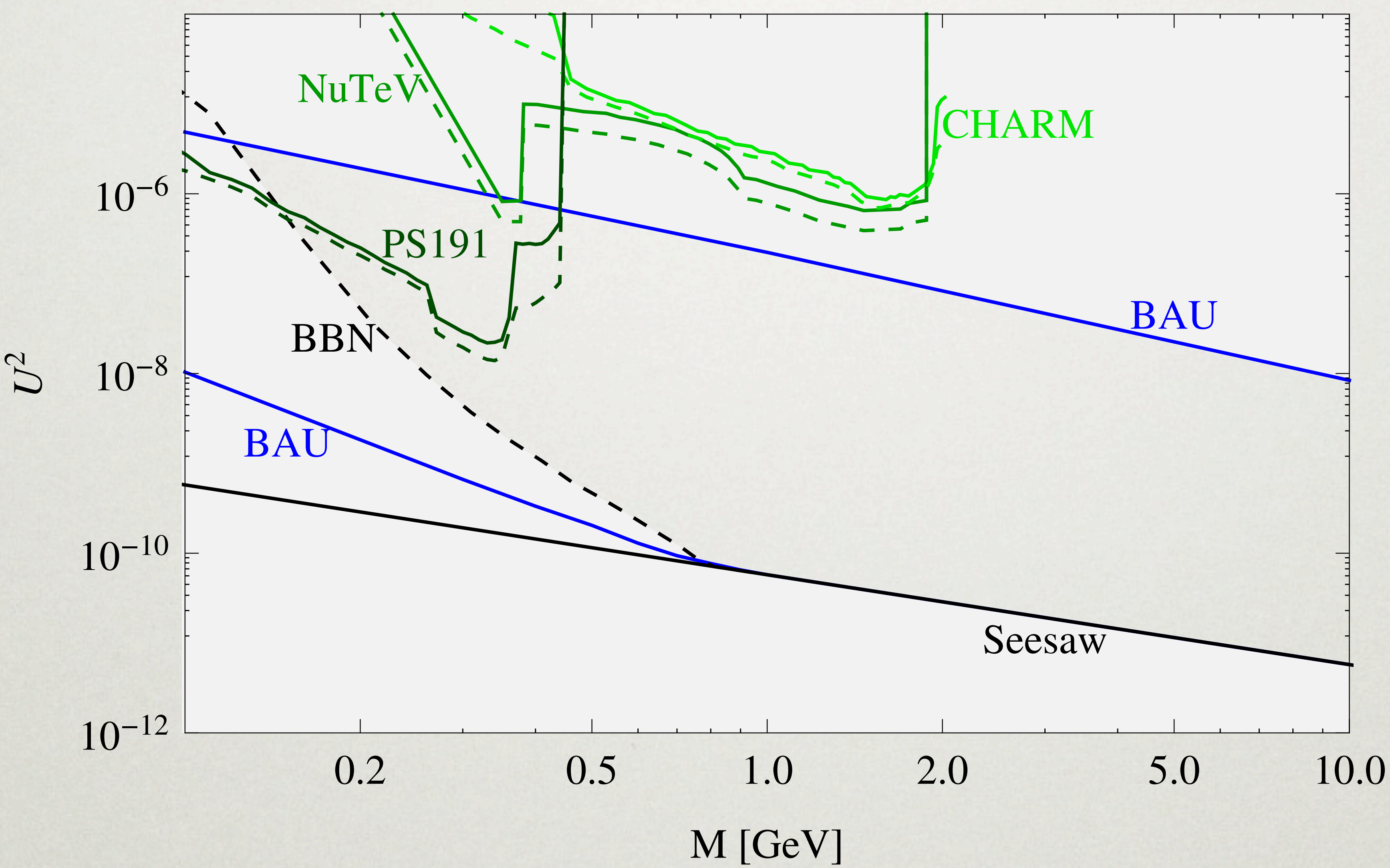
  - Can get N everywhere we have ν at the price of $\sin\theta$ in the amplitude





  - Look for different 2-body kinematics and/or displaced decays

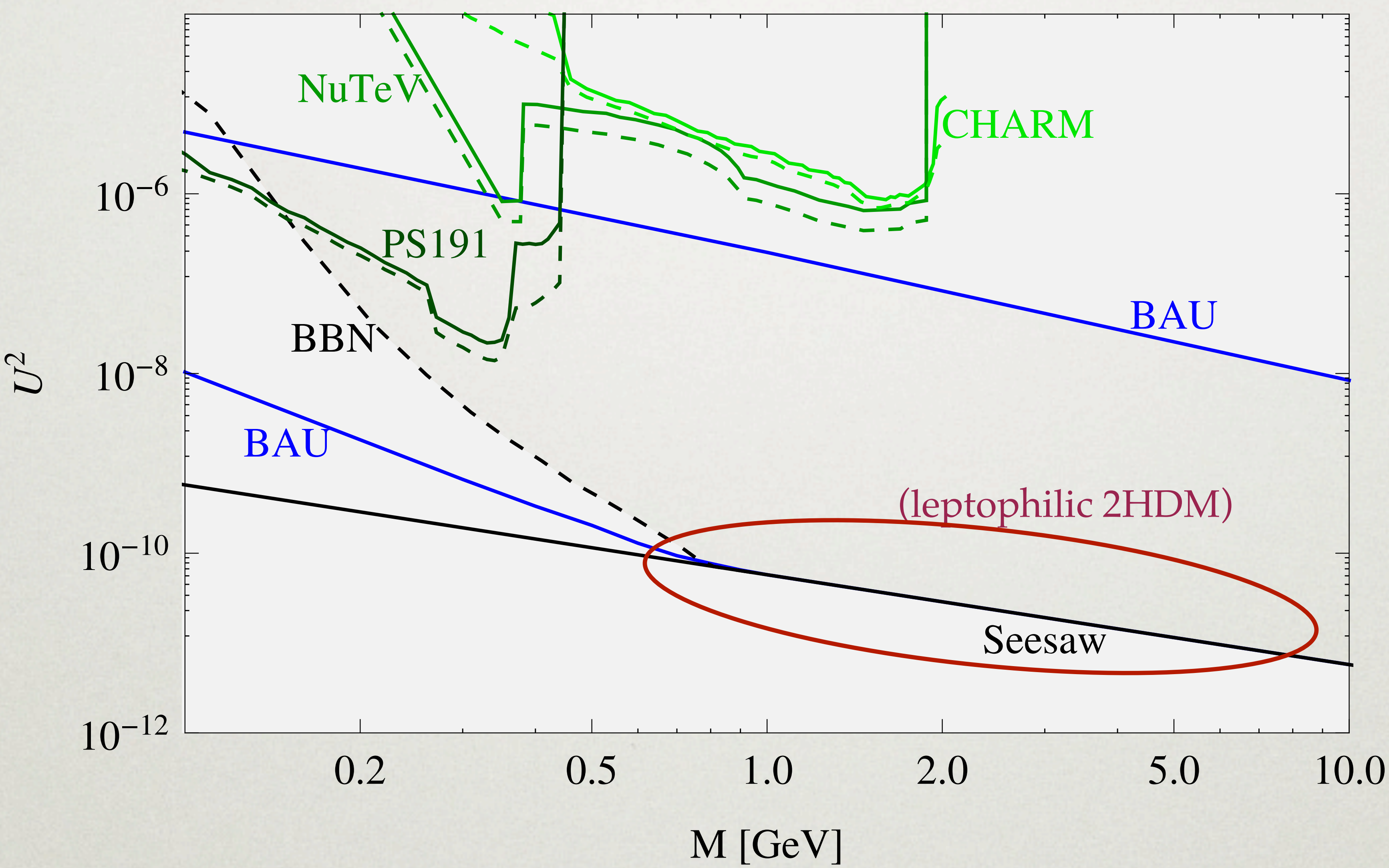
Sterile neutrino bounds



$$U^2 \sim \sum_\alpha \theta_\alpha^2$$

Canetti, Drewes, Frossard, Shaposhnikov, 2012

Sterile neutrino bounds

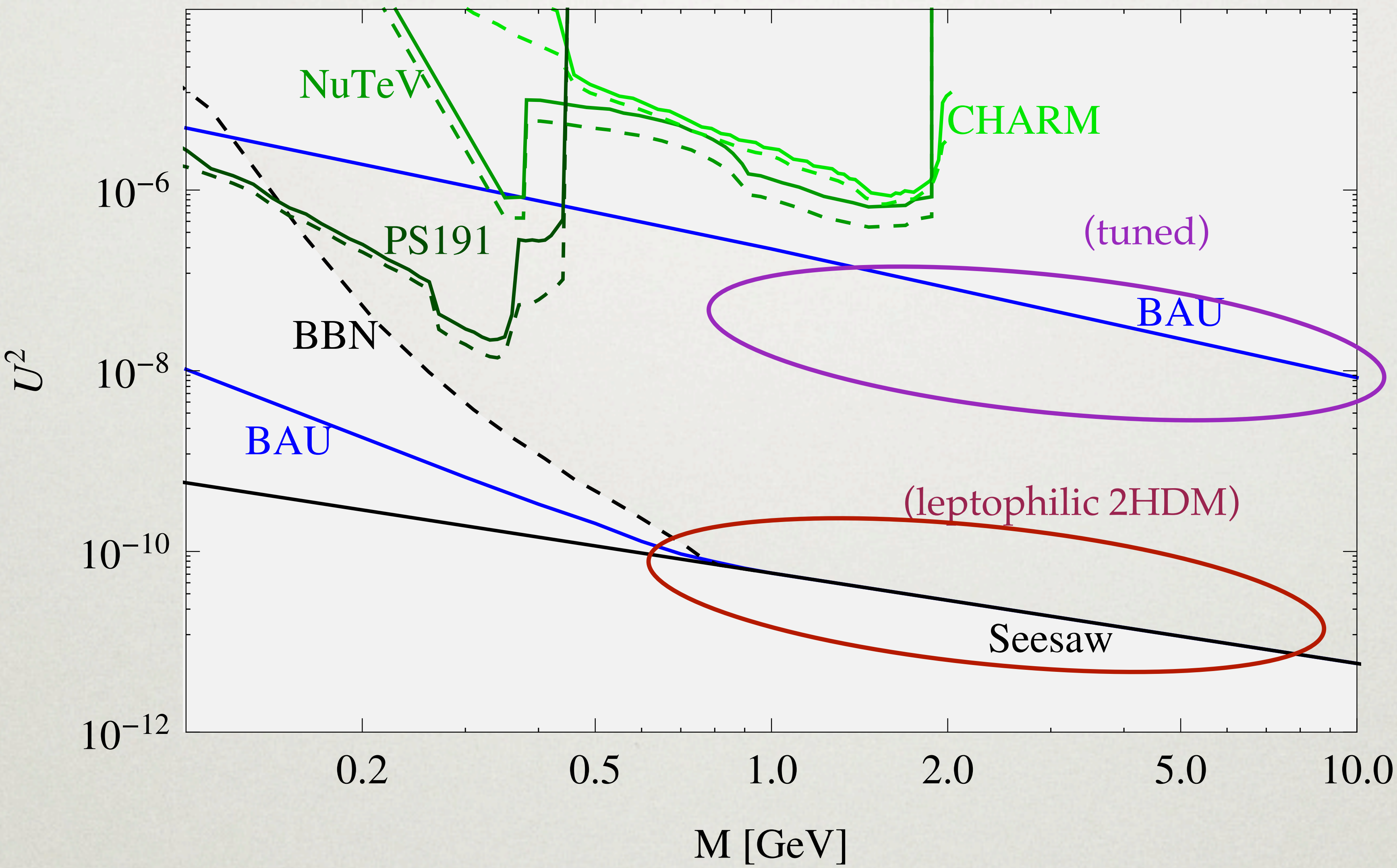


$$\theta \sim \frac{F_{\rm SM} v_{\rm SM}}{M_N} = \frac{F_\ell v_\ell}{M_N}$$

$$U^2 \sim \sum_\alpha \theta_\alpha^2$$

Canetti, Drewes, Frossard, Shaposhnikov, 2012

Sterile neutrino bounds



$\mathrm{Im}\,\omega \gg 1$

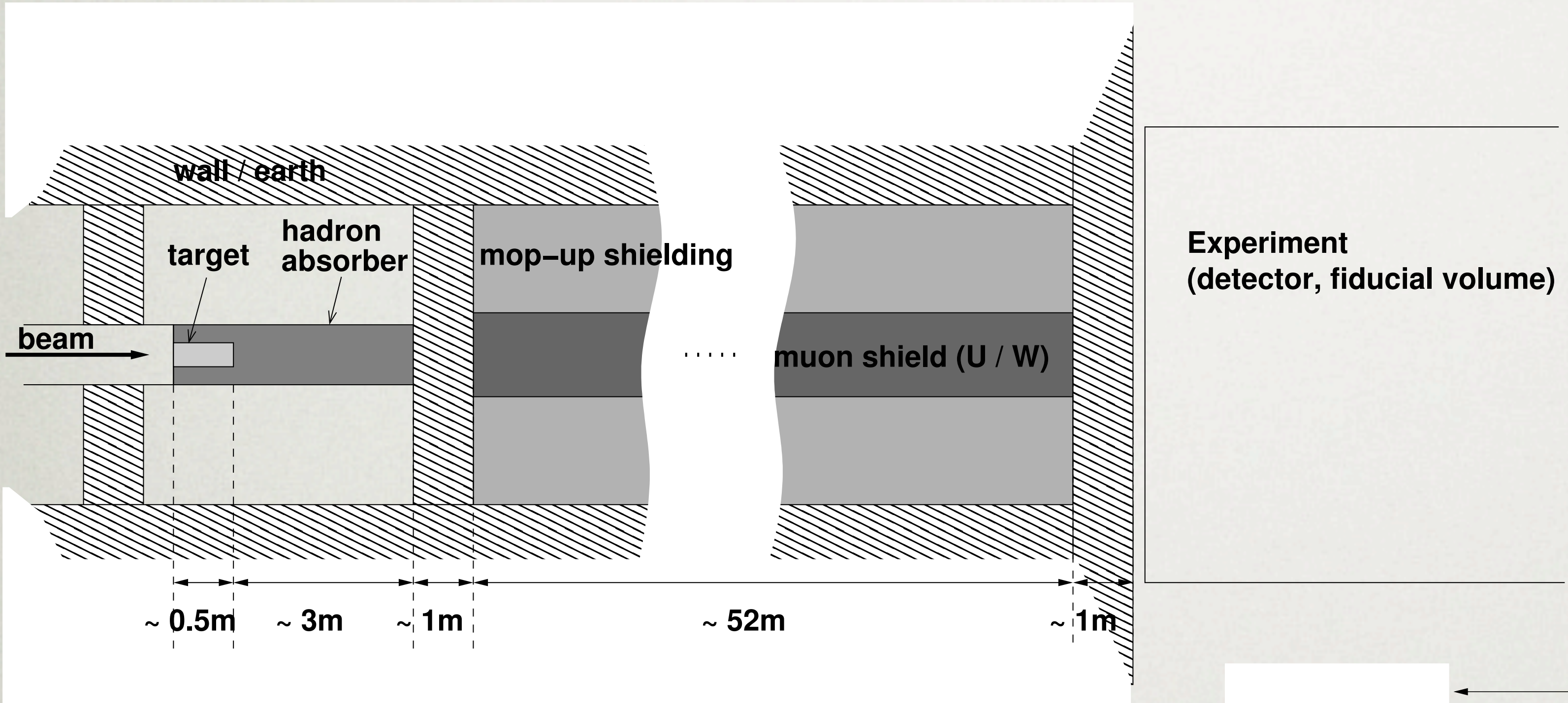
$$\theta \sim \frac{F_{\mathrm{SM}} v_{\mathrm{SM}}}{M_N} = \frac{F_\ell v_\ell}{M_N}$$

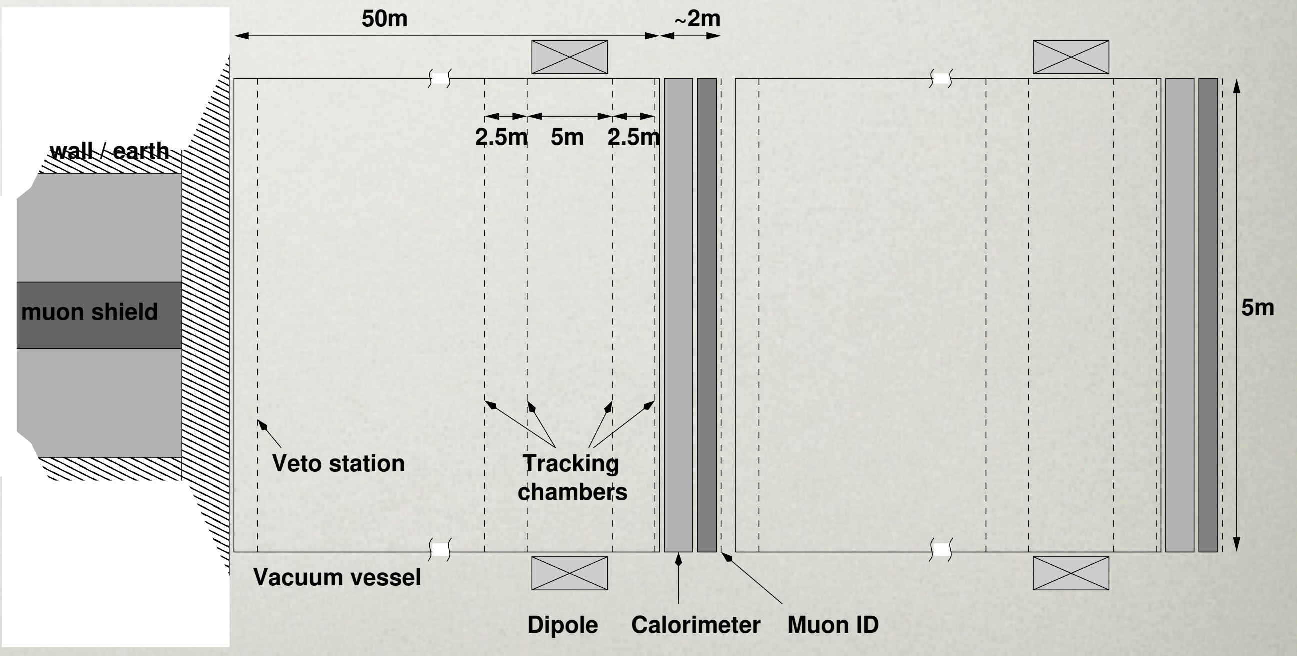
$$U^2 \sim \sum_\alpha \theta_\alpha^2$$

Canetti, Drewes, Frossard, Shaposhnikov, 2012

SHIP Proposal

- Proposal for the CERN SPS



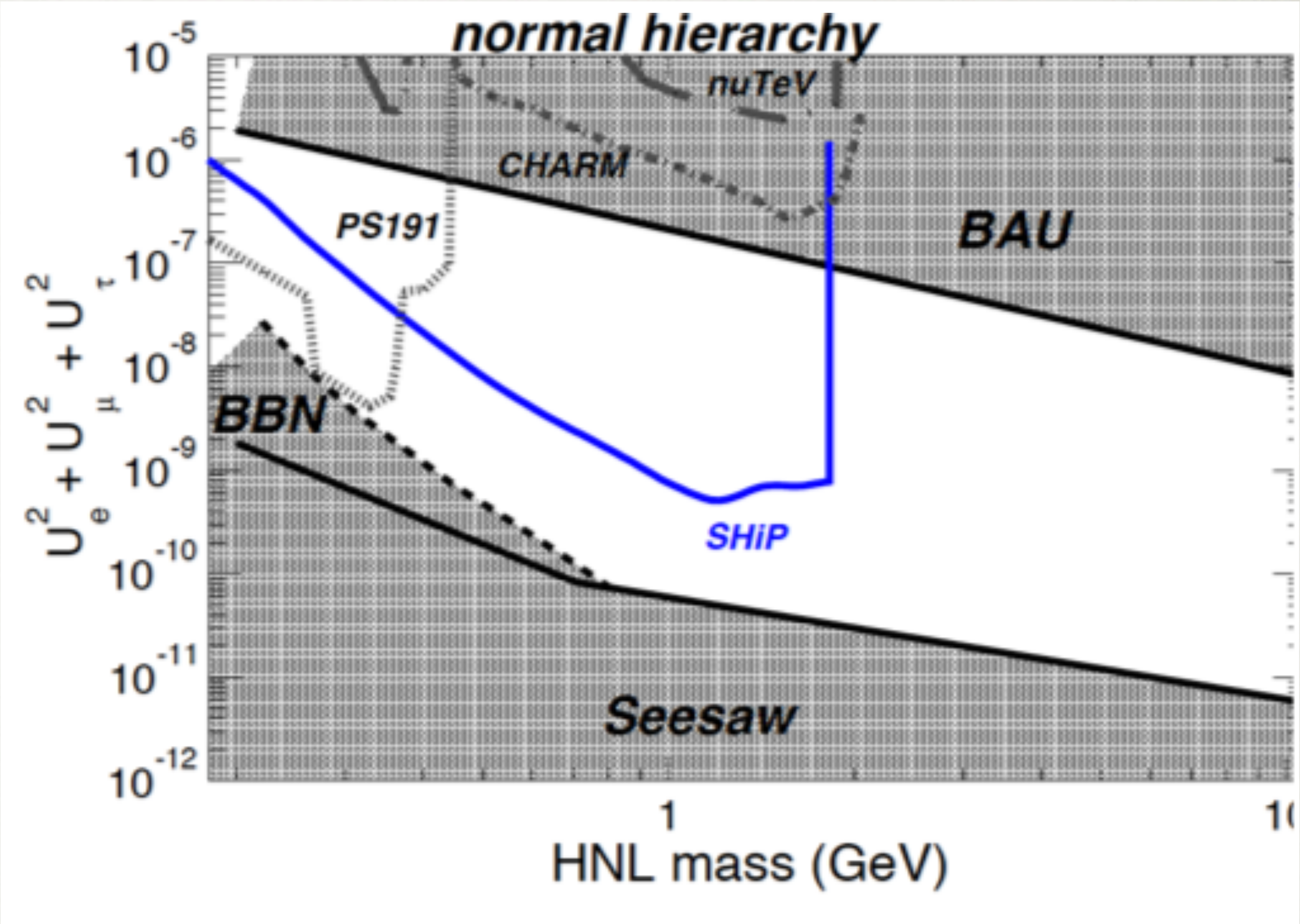


SHIP proposal, 2013

SHIP Proposal

- Proposal for the CERN SPS

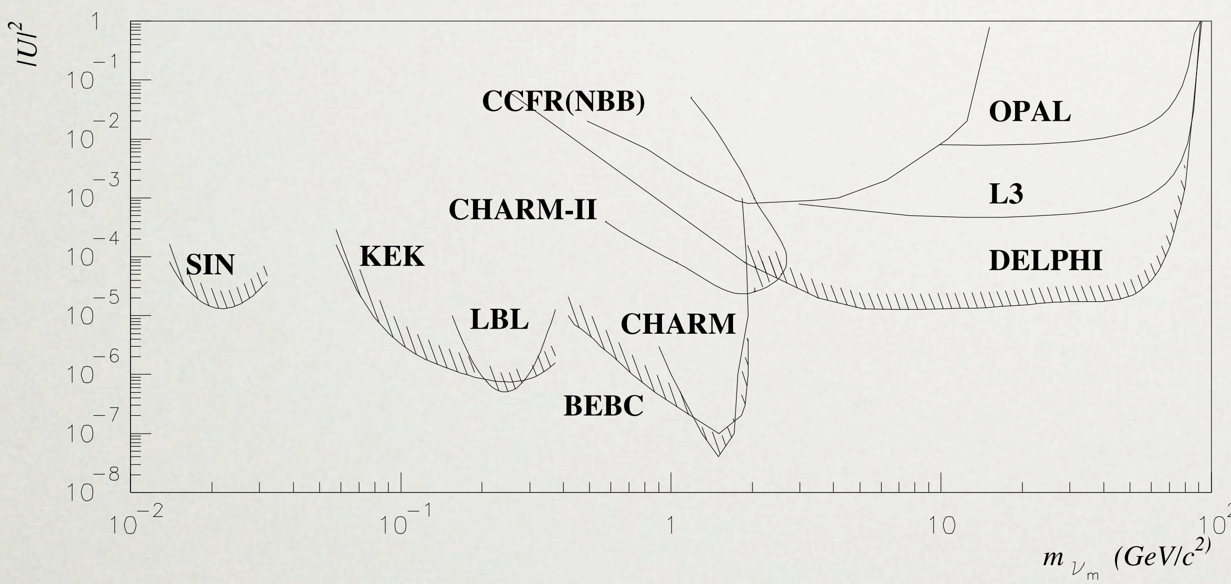
W. Bonivento, SHIP talk, 2014



- Can probe much of parameter space, but what about > charm mass?

SHIP Proposal

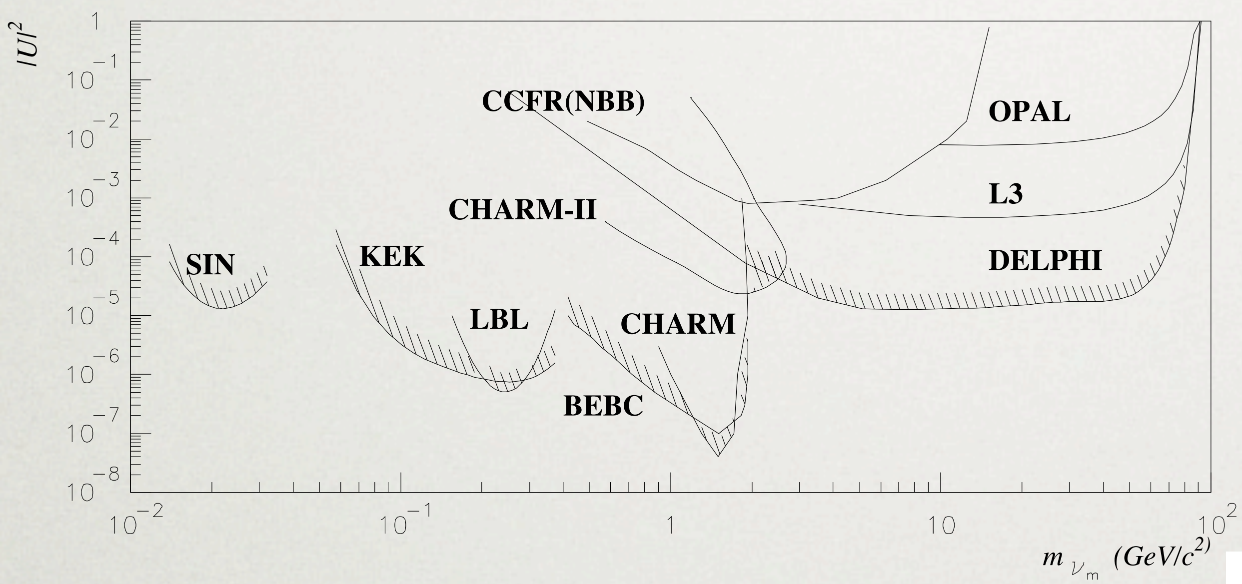
- Above c/b threshold, can only produce *N* at **high-energy, high-luminosity colliders**



DELPHI (LEP), 1997

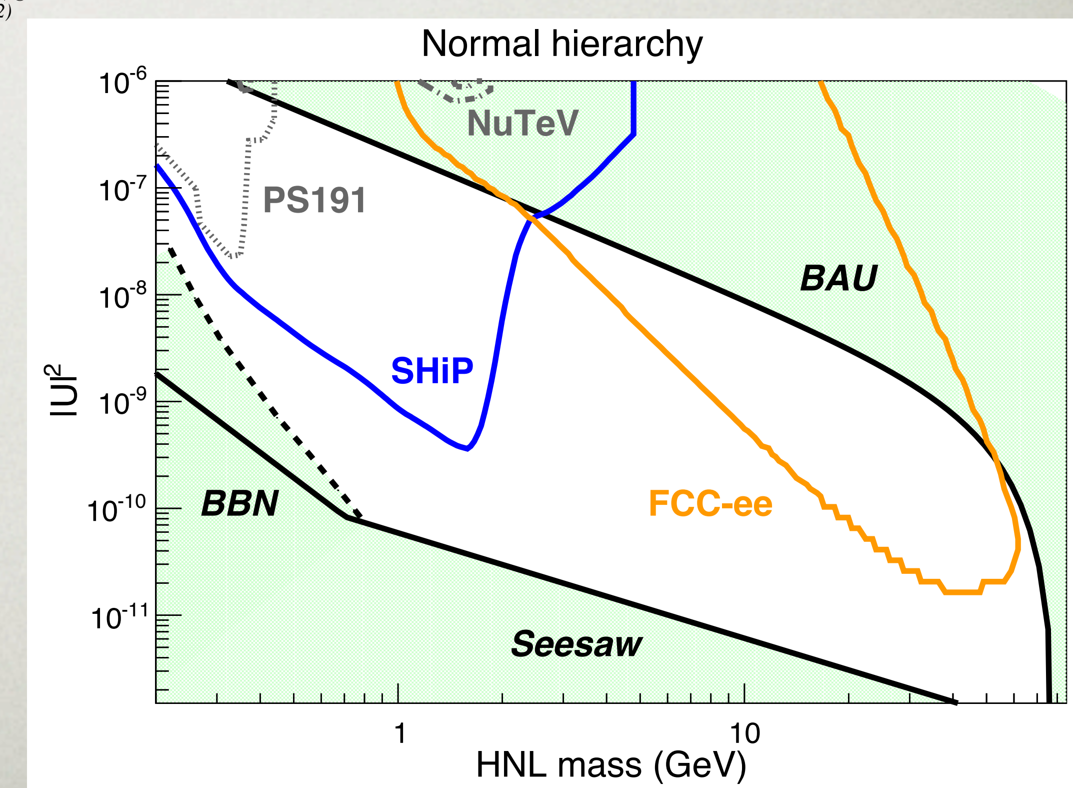
SHIP Proposal

- Above c/b threshold, can only produce N at **high-energy, high-luminosity colliders**



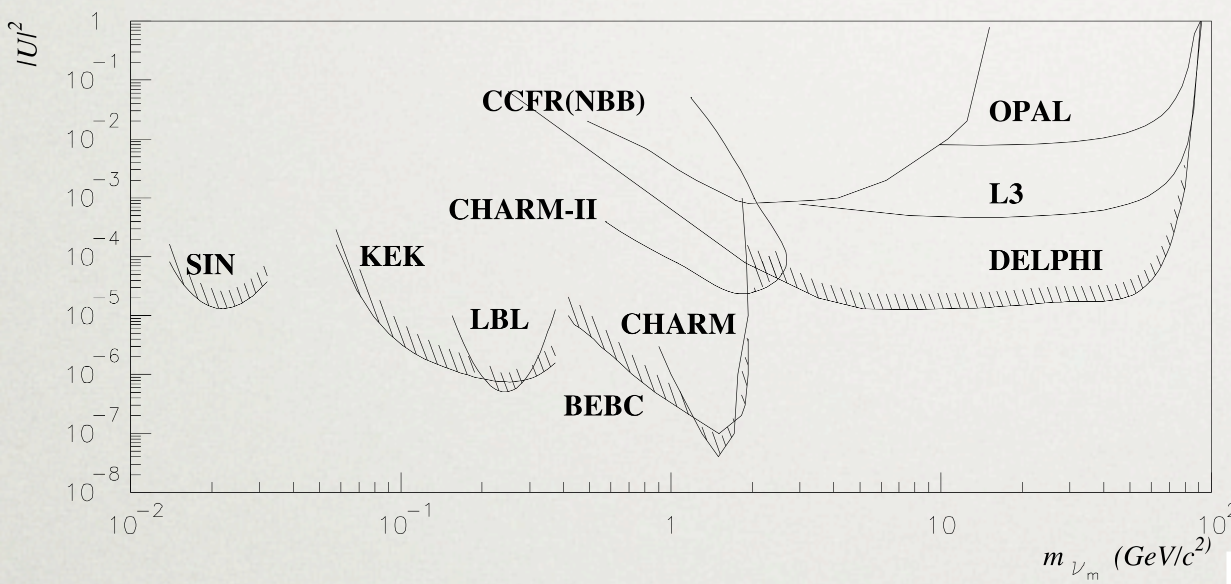
DELPHI (LEP), 1997

TLEP (tera-Z)
Blondel, Graverini, Serra, Shaposhnikov 2014

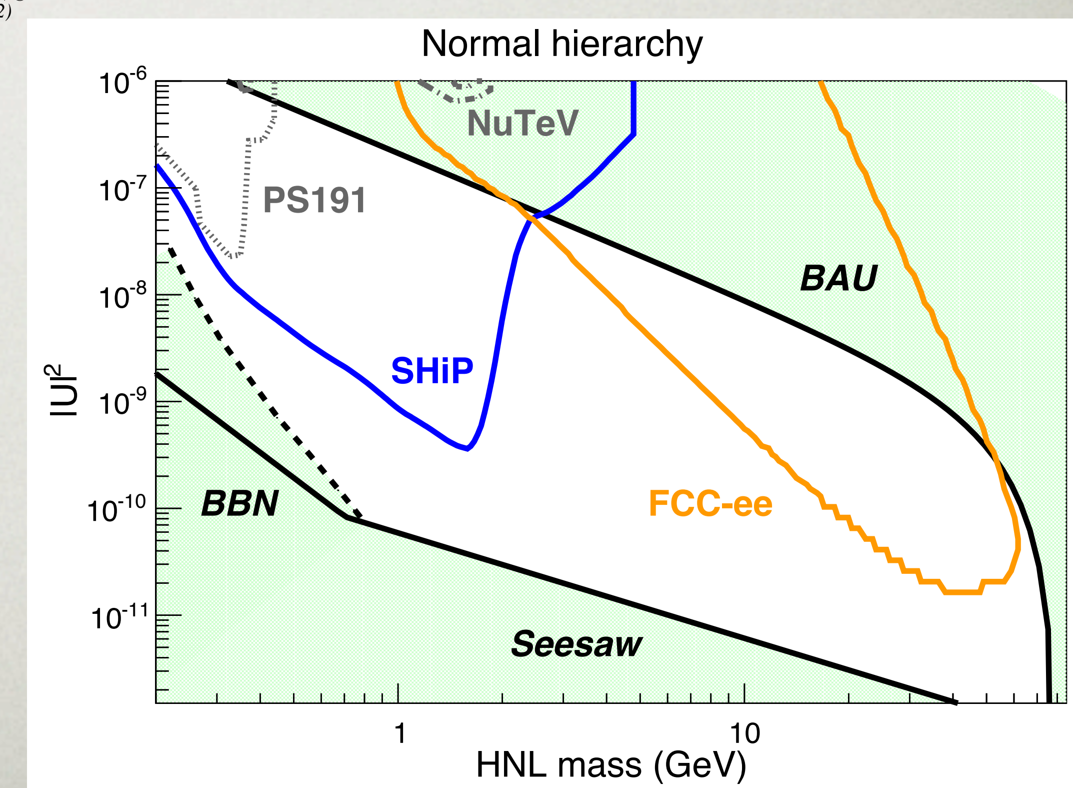


SHIP Proposal

- Above c/b threshold, can only produce *N* at **high-energy, high-luminosity colliders**



DELPHI (LEP), 1997



TLEP (tera-Z)
Blondel, Graverini, Serra, Shaposhnikov 2014

- What about the LHC?
  Optimized analyses needed (ongoing work)

Conclusions

- The missing pieces of the SM can be filled in with new sterile neutrino states at **phenomenologically accessible scales**

- The simplest model can explain all of dark matter, baryogenesis, neutrino masses, but with a high degree of parameter alignment/tuning

- Models with **a leptophilic Higgs** at and below the weak scale can substantially enhance the baryon asymmetry
    - Robust prediction for interesting new physics with leptons at energy and intensity frontiers
    - Act as independent probes of sterile neutrino cosmology
    - See BS, I. Yavin, arXiv:1403.2727 for similar work on sterile neutrino DM

- Searches for leptophilic Higgs/direct searches for N complementary
    - Best way to fill in gaps? Other uses for SHIP experiment?