# Dirac neutrinos and the matter asymmetry of our universe

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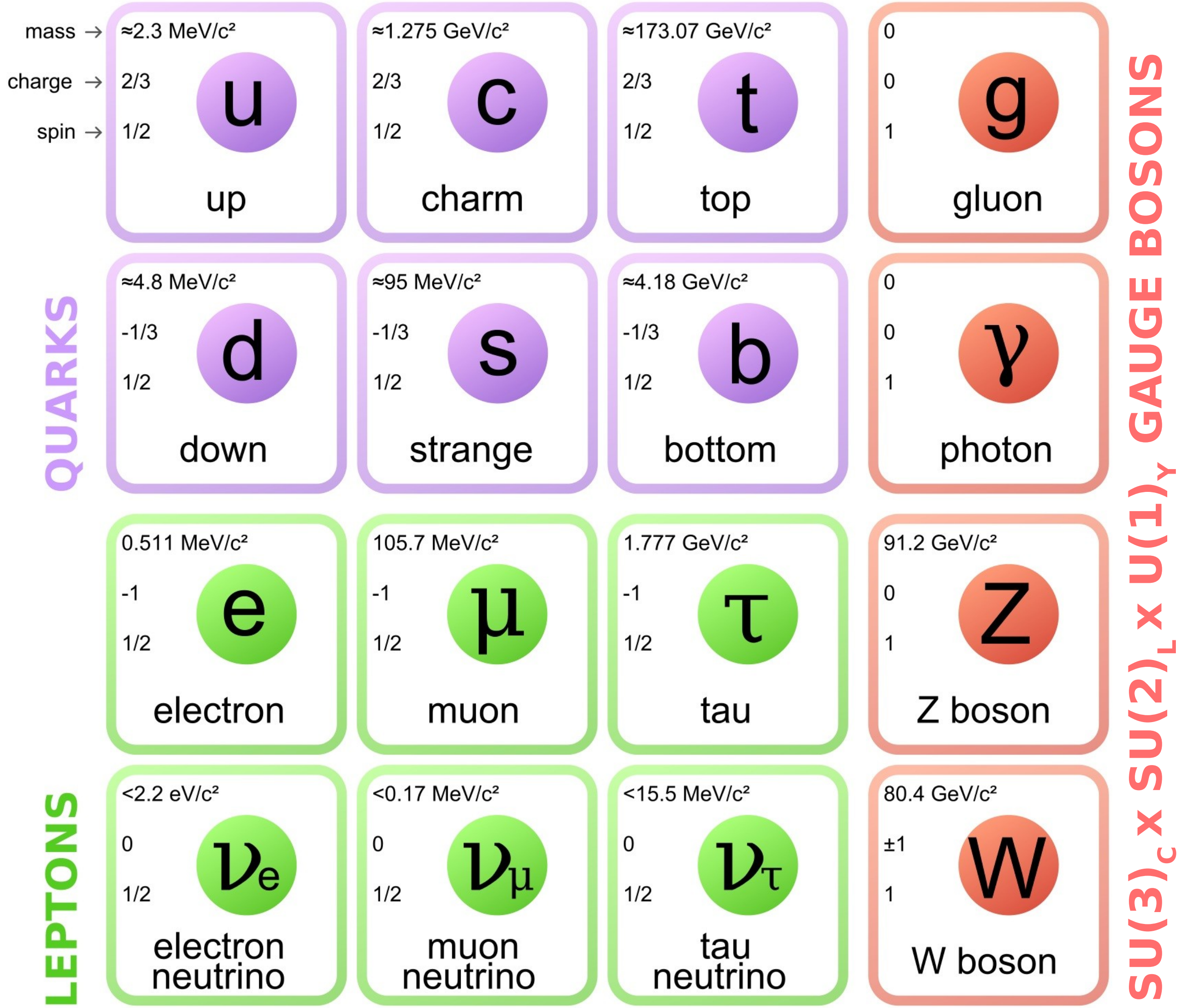
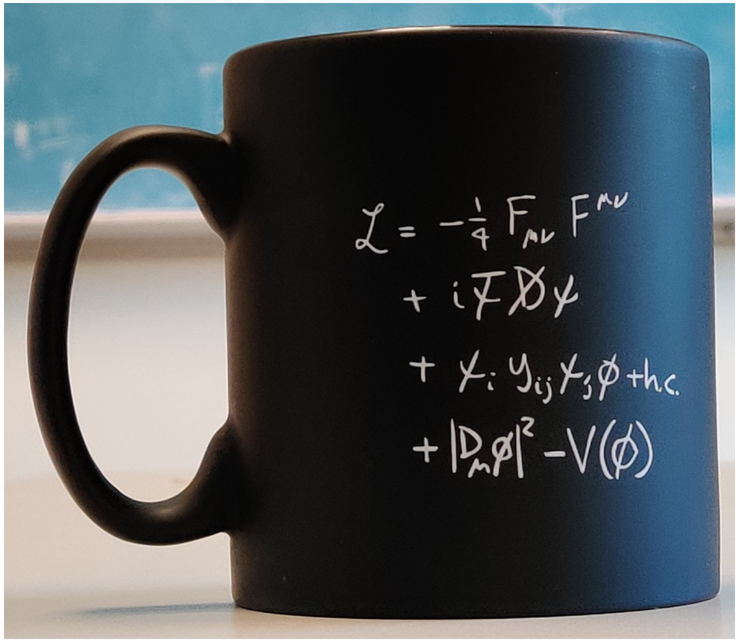
# Standard Model of Particle Physics





Englert & Higgs ‘13



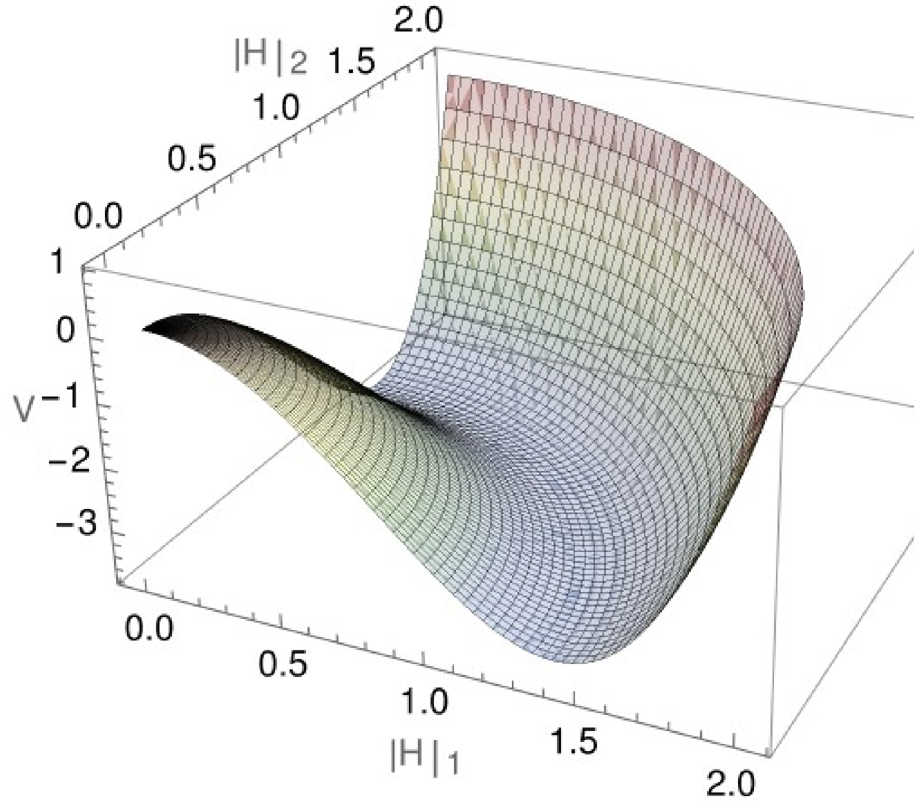

[wikipedia]

# Masses in the Standard Model

- $\mathrm{SU}(2)_{\mathrm{L}} \times \mathrm{U}(1)_{\mathrm{Y}}$ gauge symmetry forbids mass terms.
- Masses via spontaneous symmetry breaking $\rightarrow \mathrm{U}(1)_{\mathrm{EM}}$.
- Higgs-fermion couplings:

$$\mathcal{L}_{\mathrm{SM}} \supset y_f \, \bar{f}_L \, H \, f_R + \text{h.c.}$$

$$\rightarrow \underbrace{y_f \, \langle H \rangle}_{m_f \,=\, y_f \,\times\, 174\,\mathrm{GeV}} \bar{f}_L \, f_R + \text{h.c.}$$




- For neutrinos: no $\nu_R$!

The 3 neutrinos $\nu_{e,\mu,\tau}$ in the SM are massless.

# Neutrinos oscillate!

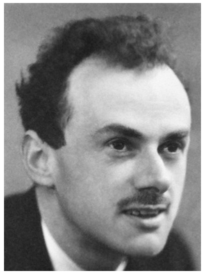
Kajita & McDonald ‘15

- Neutrino oscillations are evidence for neutrino masses and mixing!
- $\nu_{e,\mu,\tau}$ are not the mass eigenstates.
- Mass splittings are tiny:

$$|m_3^2 - m_1^2| \simeq 2 \times 10^{-3}\,\mathrm{eV}^2\,, \qquad m_2^2 - m_1^2 \simeq 8 \times 10^{-5}\,\mathrm{eV}^2\,.$$

- Absolute masses unknown but below 0.8 eV. [KATRIN ‘22]
- Experimental program continues to pin down parameters (phases, mass scale, ordering).

Implications for theory?

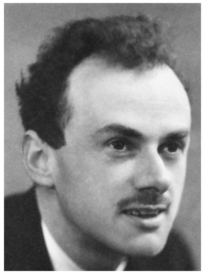


# Neutrino mass = new particles

- Dirac neutrinos:
  - $\nu = \nu_\text{L} + \nu_\text{R} \neq \bar{\nu}$.
  - $U(1)_L$ conserved.
  - $\nu_\text{R}$ - $\nu_\text{L}$ -Higgs coupling:

$$\text{m}_\nu = \text{y}_\nu \langle \text{H} \rangle$$
$$= 1\,\text{eV}\left(\frac{\text{y}_\nu}{10^{-11}}\right).$$

  - Tiny Yukawa couplings.
  - $\nu_\text{R}$ is gauge singlet
    → difficult to see.



# How to see Dirac neutrinos?

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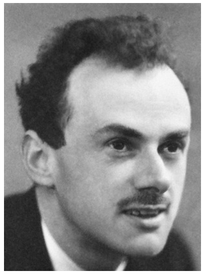
- $\nu_R$ are ultra-light new particles.
  - Contribute to early-universe radiation density $N_{eff} \propto \rho_{radiation}/\rho_\gamma$?
  - Not via tiny Higgs couplings. [Shapiro+, '80; recent: Luo+, '21]
  - Maybe via Hawking radiation. [Hooper+, '19; Lunardini+, '19; Das+, '23]
- $\nu_R$ has additional interactions in many models → $\Delta N_{eff}$! [Steigman+, '79; Olive+, '81; Barger+, '03]

Dirac neutrinos = extra radiation?



# Only option? No!

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- Majorana neutrinos:
  - $\nu = \nu_L + \nu_L^c = \bar{\nu}$.
  - $U(1)_L$ broken.
  - Add $m_M \overline{\nu}_R^c \nu_R$?
  - Or scalar SU(2) triplet Δ:

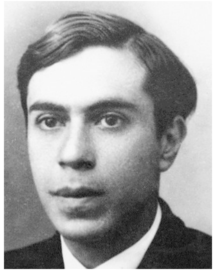
$$\mathcal{L} \supset y_{\alpha\beta} \overline{L}_\alpha^c \Delta L_\beta - \mu H \Delta H$$

$$\rightarrow m_\nu \simeq y \langle \Delta \rangle \sim y \frac{\mu \langle H \rangle^2}{M_\Delta^2}.$$

  - New particles often weakly coupled or heavy...

∞ models give the same neutrino oscillation formula!

# How to see Majorana neutrinos?



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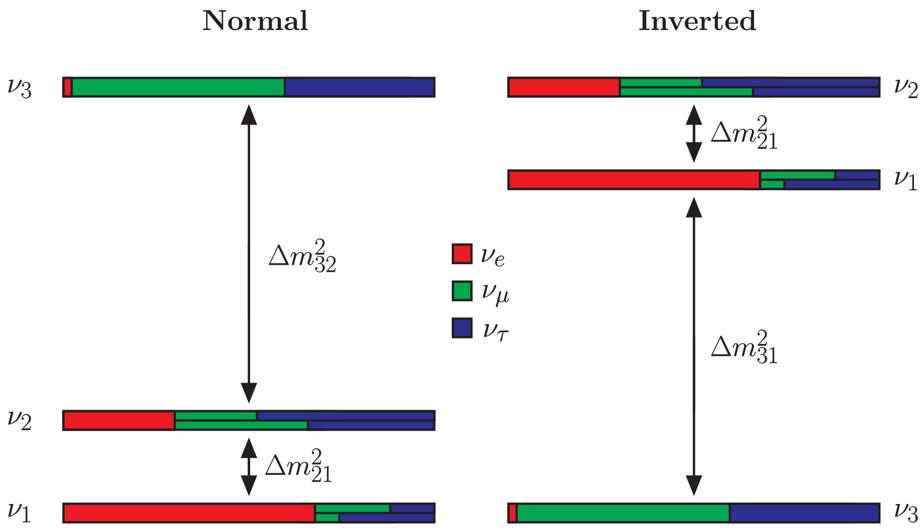
# ΔL = 2:

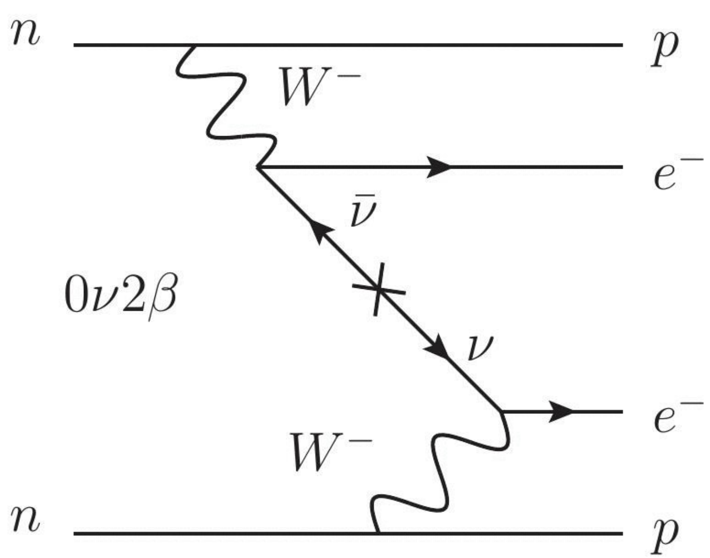
- Neutrinoless double-β decay:

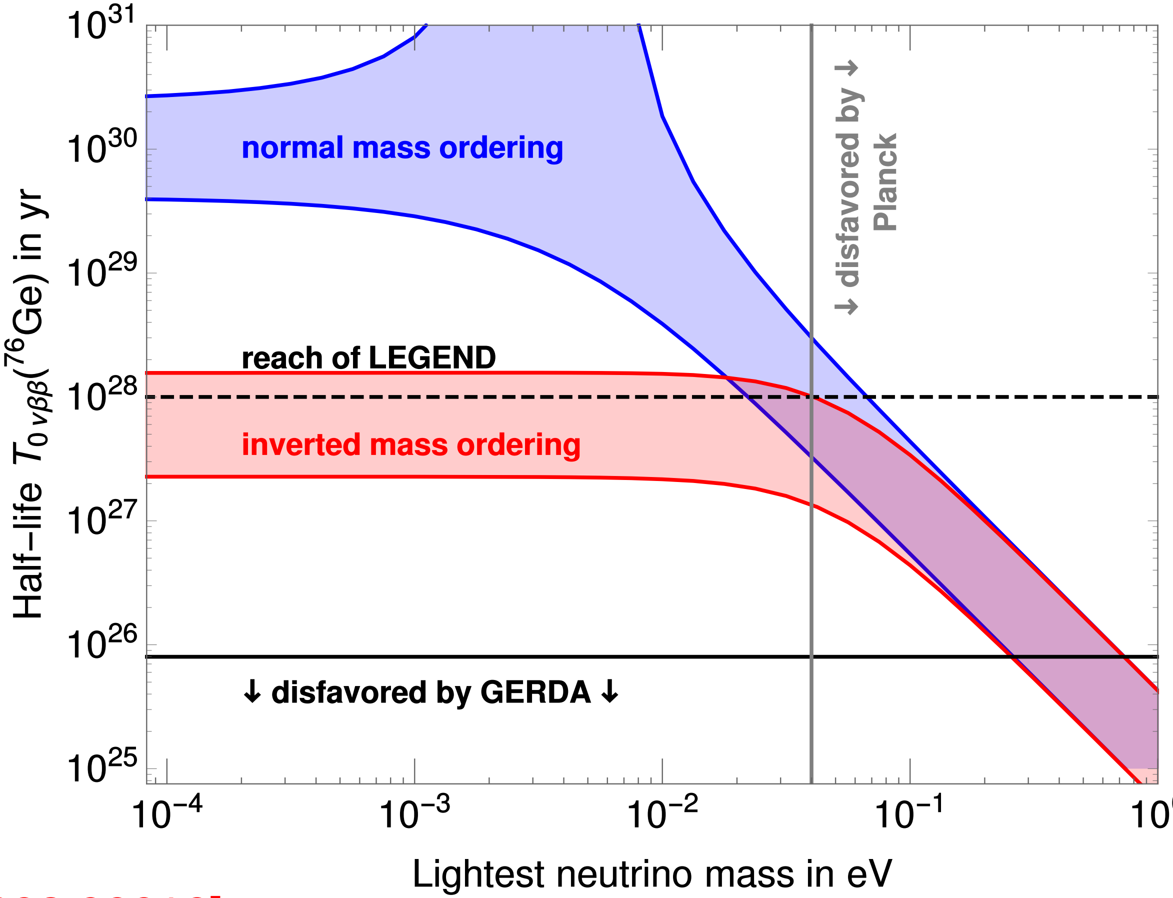
  (A,Z) → (A,Z+2) + 2 e$^-$

  in β stable isotopes.

- Current limits ~ $10^{26}$ yr.
- 0ν2β ⇔ Majorana ν.




[Review: Perez, Wise, **Heeck** et al, 2208.00010]

# How to see Majorana neutrinos?

Generically 0ν2β, but model-dependent interference.

Everything else model dependent as well: lepton flavor violation, collider signatures, …

- Majorana neutrinos:
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  - New particles often weakly coupled or heavy...

# The seesaw mechanism

- Add $\nu_R$ and allow for Majorana mass term:

$$\mathcal{L} \supset -y\,\overline{\nu}_L\,H\,\nu_R - \tfrac{1}{2} m_M \overline{\nu}_R^c \nu_R + \text{h.c.}$$

- Full mass matrix for $m_M \gg m_D = y\langle H\rangle$ : [Minkowski, PLB '77]

$$\begin{pmatrix} 0 & m_D \\ m_D^T & m_M \end{pmatrix} \simeq V^* \begin{pmatrix} -\,m_D m_M^{-1} m_D^T & 0 \\ 0 & m_M \end{pmatrix} V^\dagger$$

- Majorana neutrino masses suppressed by $m_M$:

$$m_\nu \simeq m_D m_M^{-1} m_D^T = 1\,\text{eV}\,\left(\frac{m_D}{100\,\text{GeV}}\right)^2 \left(\frac{10^{13}\,\text{GeV}}{m_M}\right).$$

- $\nu_R$-$\nu_L$ mixing matrix

$$V \sim m_D m_M^{-1} = \mathcal{O}(\sqrt{m_\nu/m_M})$$

Naive scaling not true with fine-tuning or structure in $m_D$!

[Pilaftsis, hep-ph/9901206]

# Split spectrum

Seesaw neutrinos, Majorana

$N \equiv \nu_{\text{heavy}} \simeq \nu_R + \nu_R^c$

$m_M$

Dirac neutrinos

$\nu_D = \nu_L + \nu_R$

$m_D$

$$\begin{pmatrix} 0 & m_D \\ m_D^T & m_M \end{pmatrix}$$

$\longrightarrow$

$m_M \gg m_D$

$\nu_{\text{light}} \simeq \nu_L + \nu_L^c$

$m_D^2/m_M$

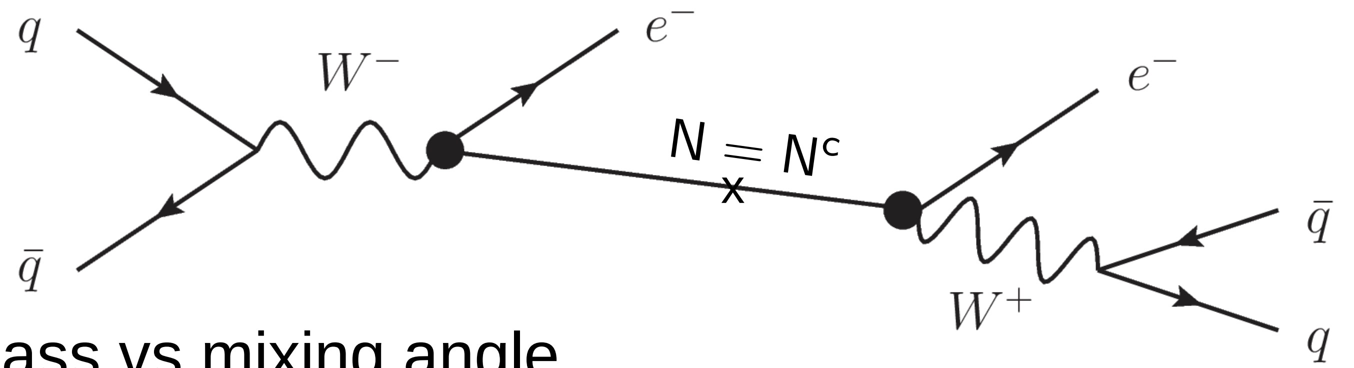
# Detection of heavy steriles

- Lepton flavor violation could be detectable now: [Cheng & Li, '80]

$$\frac{\Gamma(\ell_\alpha \to \ell_\beta \gamma)}{\Gamma(\ell_\alpha \to \ell_\beta \nu_\alpha \overline{\nu}_\beta)} \simeq \frac{3\alpha_{\rm EM}}{8\pi} |(m_D m_M^{-2} m_D^\dagger)_{\alpha\beta}|^2 = \mathcal{O}(m_\nu^2/m_M^2)?$$

Not true with fine-tuning or structure in $m_D$!

- For sub-TeV N: direct production possible! [Keung & Senjanović, PRL '83]



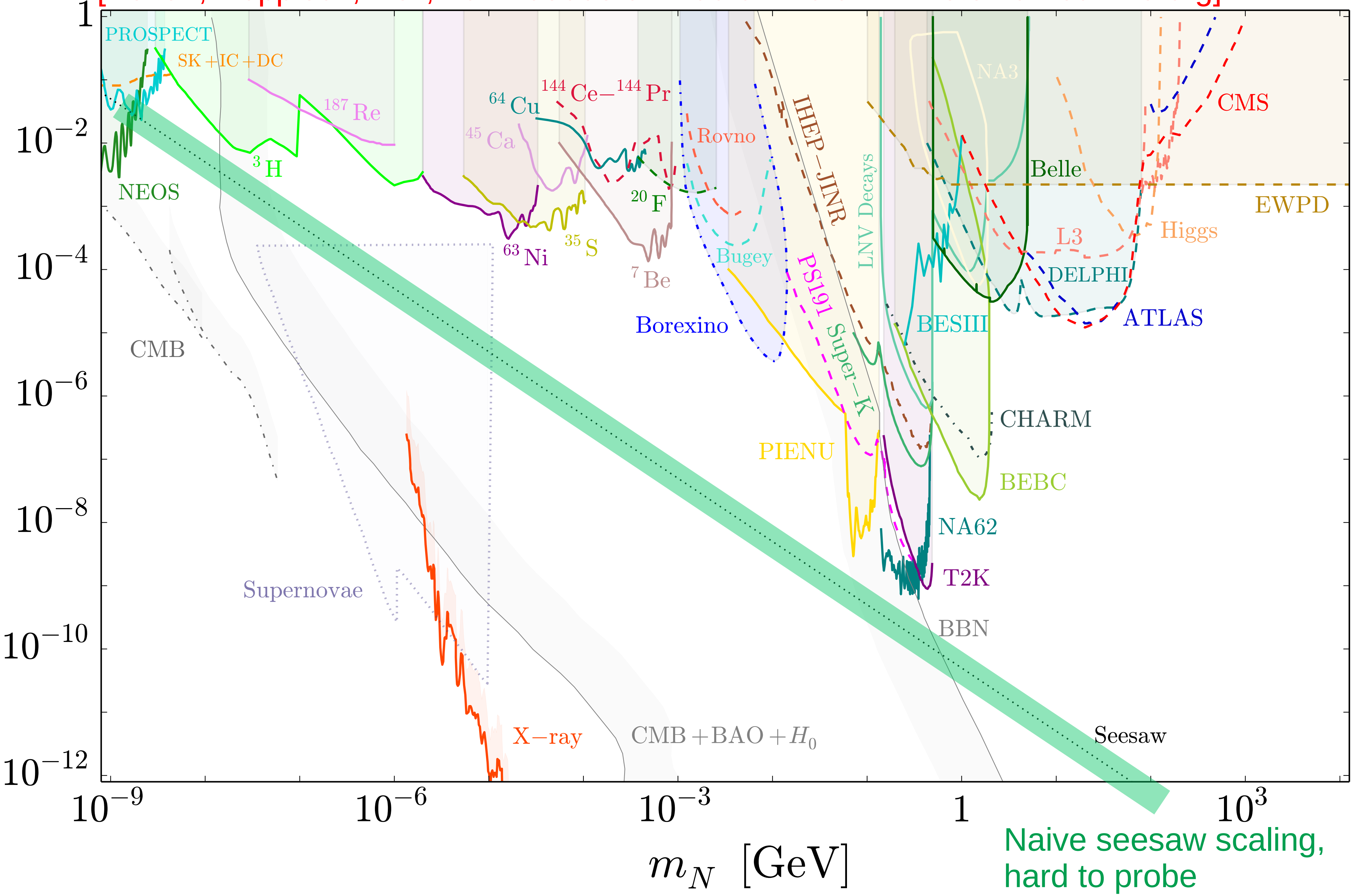

- N mass vs mixing angle

$$V \sim m_D m_M^{-1} = \mathcal{O}(\sqrt{m_\nu/m_M})$$

spans huge parameter space.

# Current constraints on $\nu_e$ mixing angle

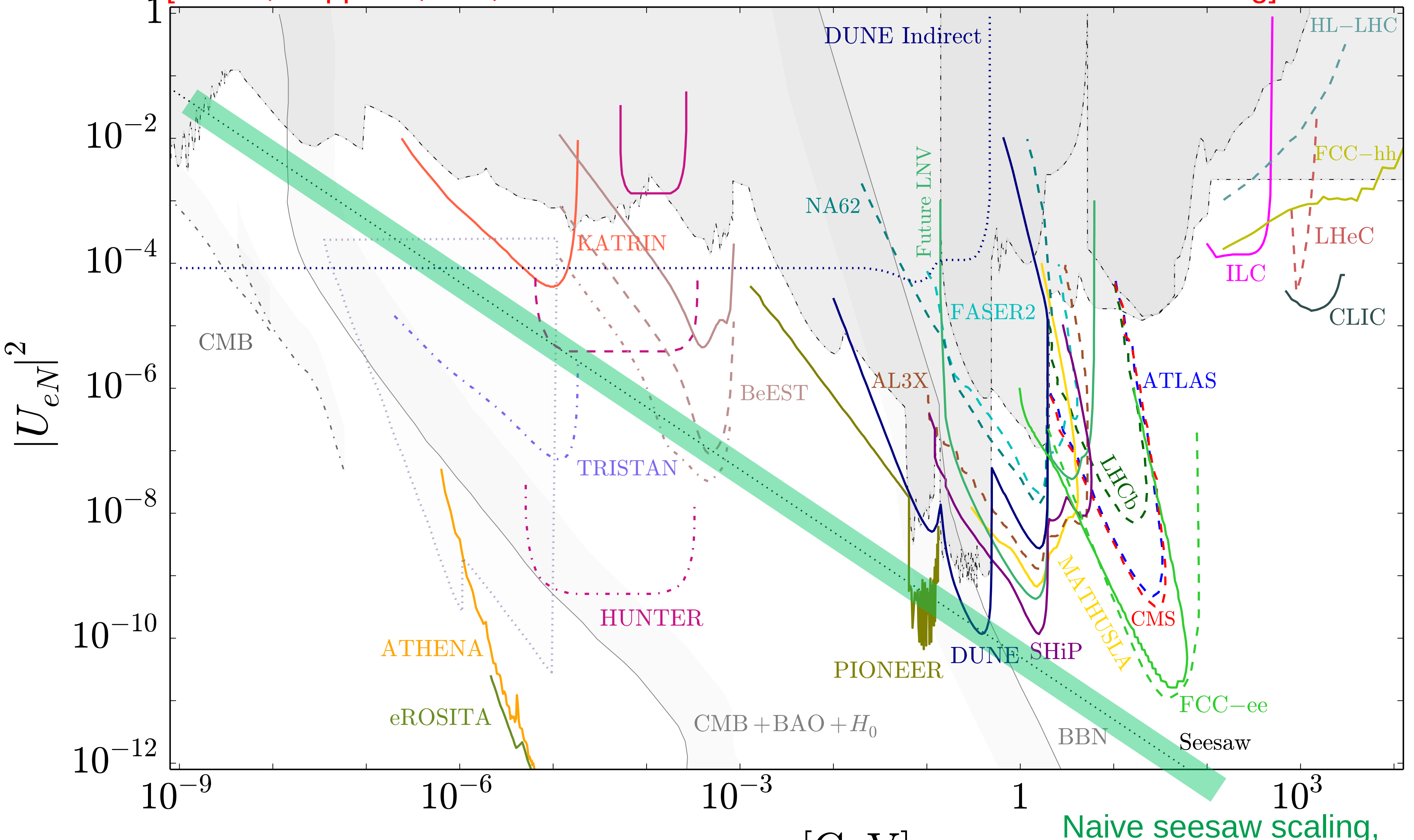
[Bolton, Deppisch, Dev, 1912.03058 & 2206.01140 & www.sterile-neutrino.org]




Naive seesaw scaling, hard to probe

# Future constraints on $\nu_e$ mixing angle

[Bolton, Deppisch, Dev, 1912.03058 & 2206.01140 & www.sterile-neutrino.org]




Naive seesaw scaling, hard to probe

# Early universe

- Add $\nu_R$ and allow for Majorana mass term:

$$\mathcal{L} \supset -y\,\overline{L}\,H\,\nu_R - \tfrac{1}{2} m_M \overline{\nu}^c_R \nu_R + \text{h.c.}$$

- Majorana neutrino masses suppressed by $m_M \gg m_D = y\langle H\rangle$ :

$$m_\nu \simeq m_D m_M^{-1} m_D^T = 1\,\text{eV}\,\left(\frac{m_D}{100\,\text{GeV}}\right)^2 \left(\frac{10^{13}\,\text{GeV}}{m_M}\right).$$

- If universe reached T ~ $m_M$: thermalized N from large y.
  - $\Delta L = 2$ interactions drive any lepton asymmetry to 0.

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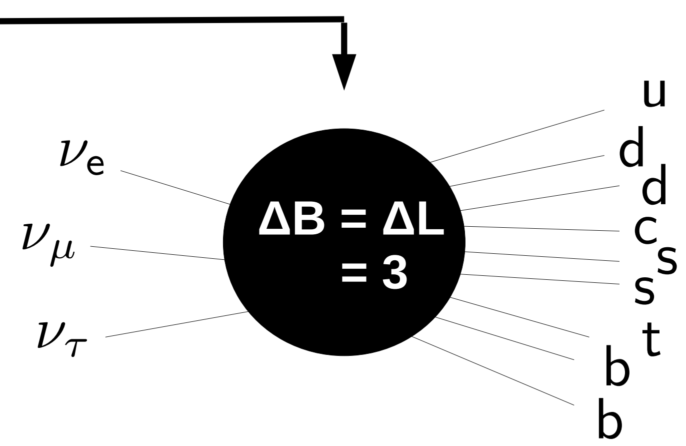
- If universe reached T ~ $m_M$: thermalized N from large y.
  - ΔL = 2 interactions drive any lepton asymmetry to 0.
  - Oh no! Sphalerons convert L ↔ B, so baryon asymmetry is driven to 0! ⚡

    ['t Hooft, '76; Klinkhamer & Manton '84; Kuzmin, Rubakov, Shaposhnikov, '85]



# The baryon asymmetry of our universe

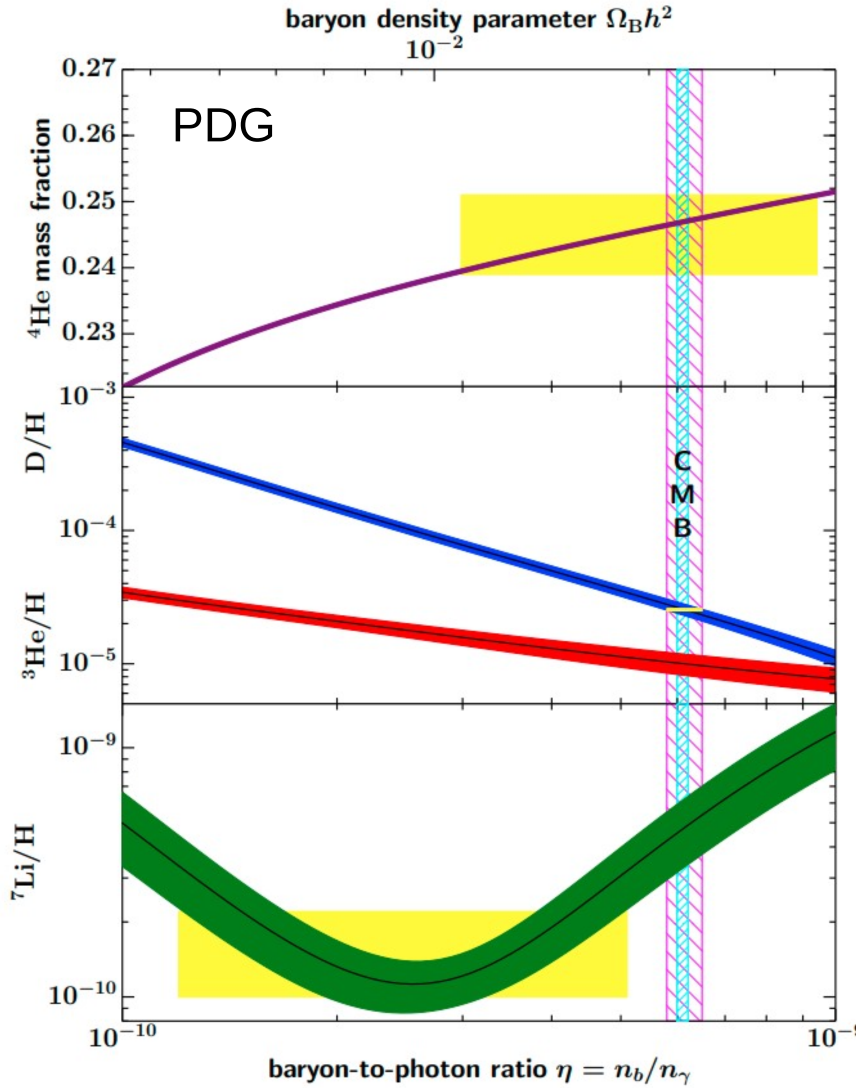
- Visible universe only contains matter, no anti-matter.
  - No signs of annihilation from border regions. [Steigman '76]
- Symmetric universe would have

$$\frac{n_b}{n_\gamma} = \frac{n_{\bar{b}}}{n_\gamma} \sim 10^{-19}.$$

- Nuclear abundances in Big Bang nucleosynthesis (T = MeV):

$$n_b/n_\gamma \simeq 6 \times 10^{-10}$$

- Consistent with cosmic microwave background value at T = eV.



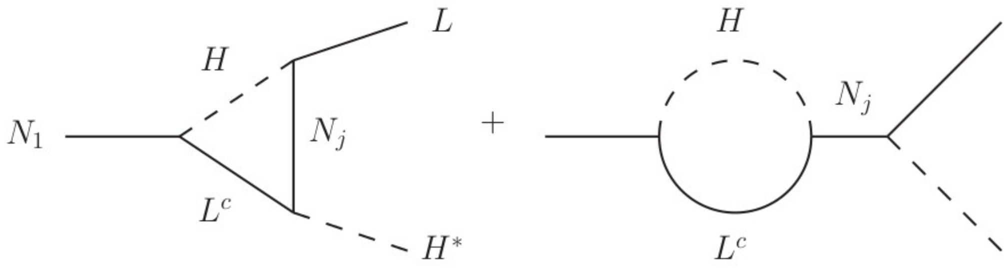

**⇒ baryon asymmetry**

# Bug vs. feature

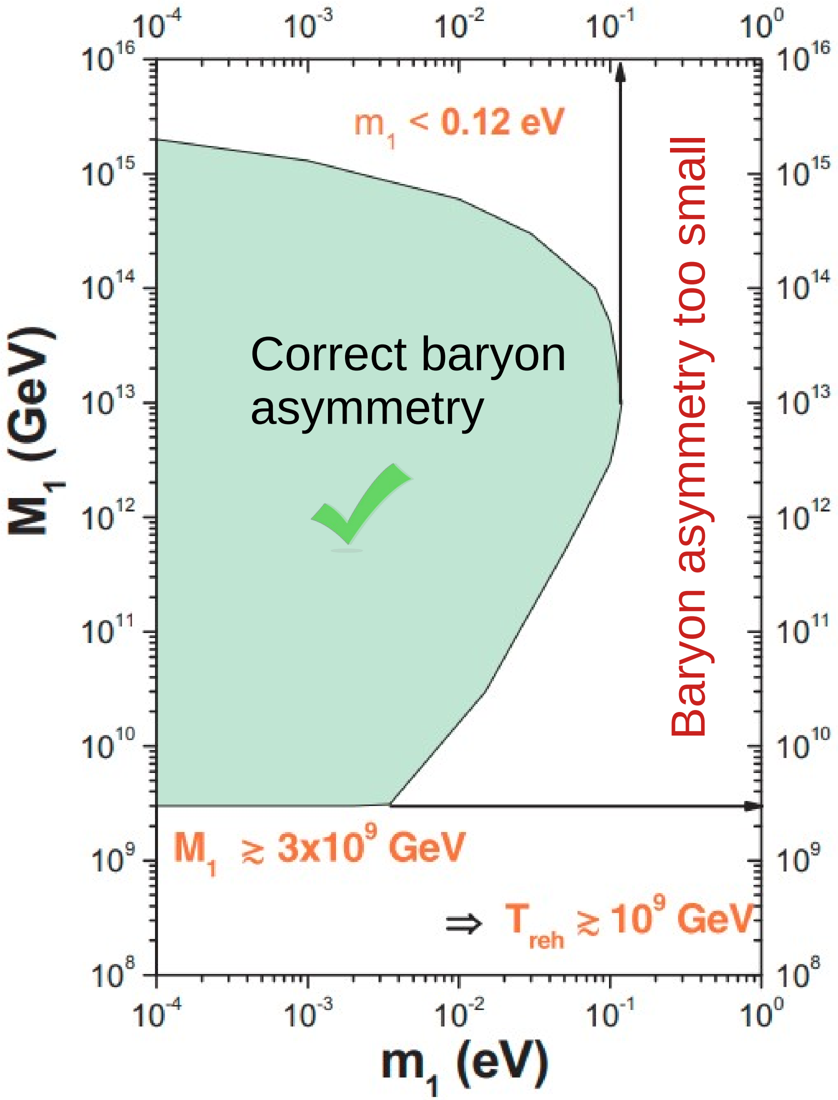
- Thermalized heavy Majorana neutrinos N could **erase** ΔB:
  - Provides limits on parameter space…
- Out-of-equilibrium N could **generate** ΔB! [Fukugita & Yanagida, ‘86]
  - Satisfies Sakharov’s conditions: [Sakharov ‘67]
    - B-L violation
    - C and CP violation
    - Out-of-equilibrium reactions
  - Dynamical baryo-genesis through lepto-genesis even for initial ΔB = 0!
  - Perfect/required for inflationary models.

# Leptogenesis [Fukugita & Yanagida, PLB '86]

- Heavy Majoranas N decay out of equilibrium into LH & $\overline{\text{LH}}$.




- Loop-level CP asymmetry generates lepton asymmetry.
- Sphalerons convert this into baryon asymmetry.
- Works easiest for N mass above $10^9$ GeV, [Davidson & Ibarra, PLB '02] but can be pushed lower.
- Fits very well with seesaw idea and observed mass splittings.




[Blanchet & Di Bari, NJP '12]

# Are Dirac neutrinos useless for BAU?

- Majorana neutrino models can use $\Delta L = 2$ for leptogenesis.
- Can *Dirac neutrinos* do anything for BAU?
- Yes! Two simple ideas:

- **Dirac leptogenesis**
  - $\Delta L$ is fine with Dirac $\nu$, as long as $\Delta L \neq 2$.
  - Use $\Delta L = 4$ for lepton asymmetry.
  - Sphalerons $\rightarrow$ $\Delta B$.

  [**Heeck**, 1307.2241]

- **Neutrinogenesis**
  - B-L conserved here.
  - $\nu_R$ decoupled from SM bath, can hide $\Delta L$ in there!
  - Create $\Delta\nu_R$, matched by $\Delta$(B-L) in SM bath.
  - Sphalerons $\rightarrow$ $\Delta B$.

  [Dick, Lindner, Ratz, Wright, PRL ‘00]

# Lepton-number-violating Dirac neutrinos

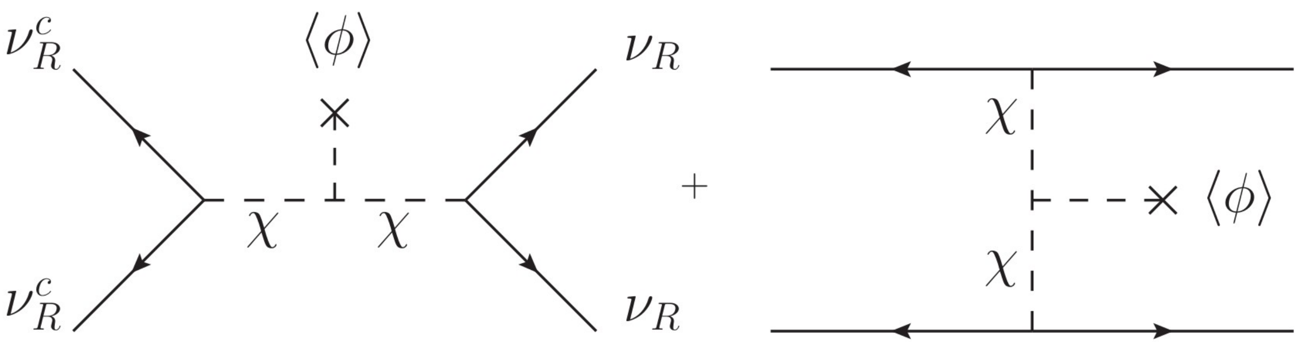
- Simplest realization: gauged $U(1)_{B-L}$, three $\nu_R \sim -1$, one scalar $\phi \sim 4$ to break B-L, one scalar $\chi \sim -2$ as mediator:

$$\mathrm{L} \supset y\overline{L}H\nu_R + \kappa\chi\overline{\nu}_R\nu_R^c + \mu\phi\chi^2 + \mathrm{h.c.}$$

[**Heeck**, 1307.2241]

- $\langle\phi\rangle$ breaks U(1) to a $Z_4$: $\chi \to -\chi$, lepton $\to$ i lepton.
- $\chi$ is split into real and imaginary parts.
- Dirac nature protected and still $\Delta L = 4$ processes:

$$\frac{\mu\langle\phi\rangle}{m_c^4}\ \overline{\nu}_R^c\nu_R\ \overline{\nu}_R^c\nu_R :$$




- Test via *neutrinoless quadruple beta decay*?

[**Heeck** & Rodejohann, 1306.0580; NEMO-3, PRL ‘17; Fonseca & Hirsch, 1804.10545]

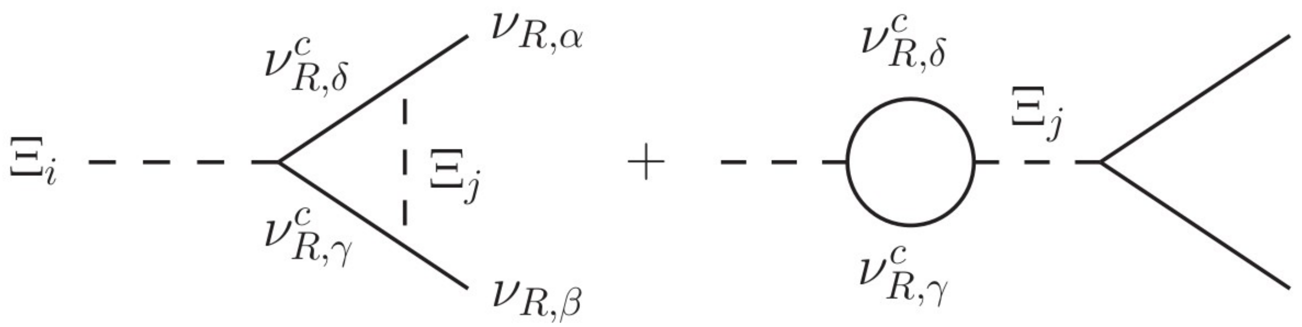
# Lepton-number-violating Dirac neutrinos

- Leptogenesis: add second copy of mediator χ.
  - $\chi_{1,2}$ split into 4 *real* scalars Ξ:

$$\mathcal{L} \supset \frac{1}{2} V^j_{\alpha\beta}\, \Xi_j \overline{\nu}_{R,\alpha} \nu^c_{R,\beta} + \frac{1}{2} \overline{V}^j_{\alpha\beta}\, \Xi_j \overline{\nu}^c_{R,\alpha} \nu_{R,\beta} \,.$$

[**Heeck**, 1307.2241]

  - Lightest Ξ decays (out-of-equilibrium) into $\nu_R \nu_R$ and $\overline{\nu}_R \overline{\nu}_R$:




  - CP asymmetry:

$$Y_{\nu_R} \equiv \frac{n_{\nu_R}}{s} \sim \frac{1}{g_*} \frac{\Gamma\left(\Xi_i \to \nu_R \nu_R\right) - \Gamma\left(\Xi_i \to \nu^c_R \nu^c_R\right)}{\Gamma\left(\Xi_i \to \nu_R \nu_R\right) + \Gamma\left(\Xi_i \to \nu^c_R \nu^c_R\right)}$$

⇒ asymmetry in $\nu_R$ vs $\overline{\nu}_R$

# Lepton-number-violating Dirac neutrinos

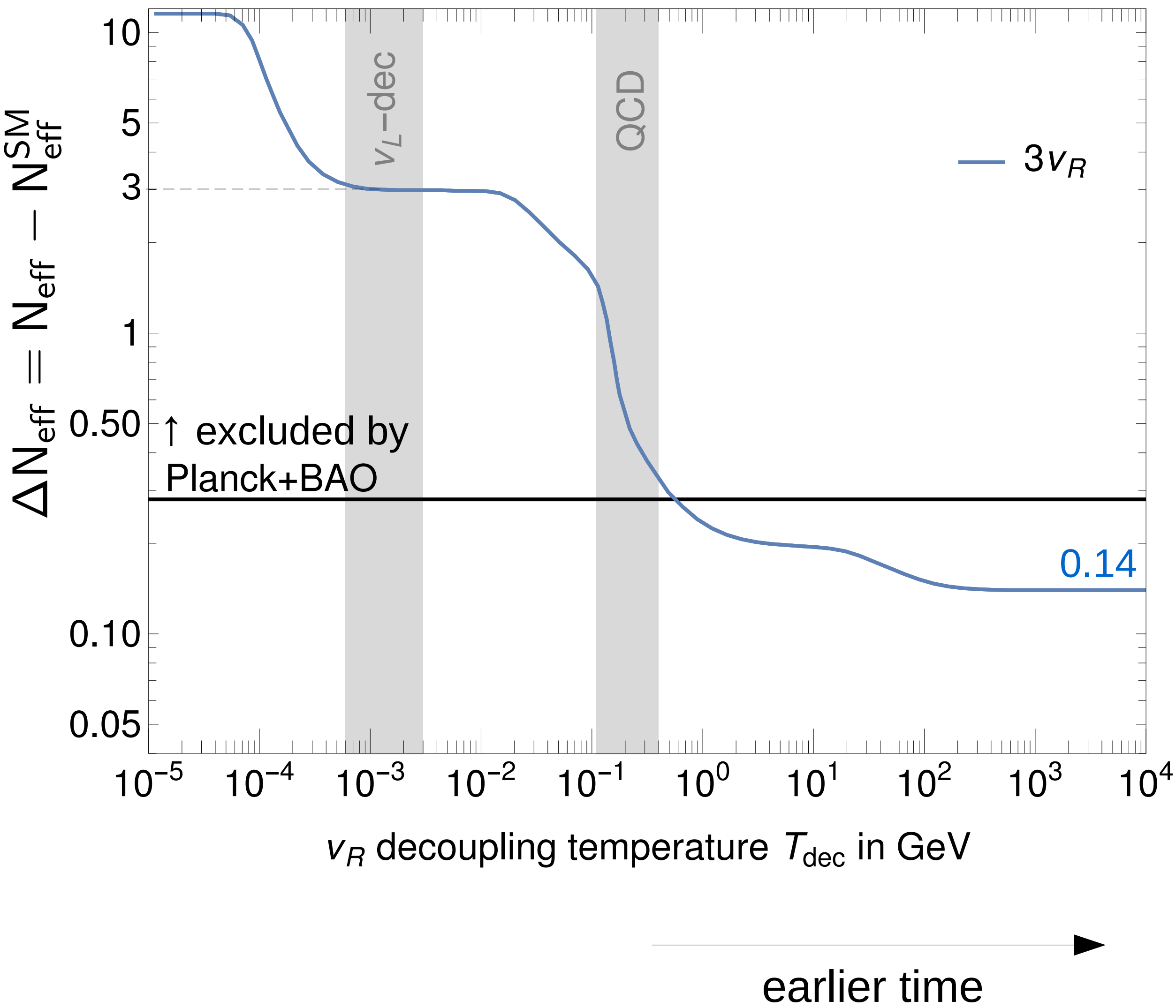
- SM bath does not see $\nu_R$ asymmetry b/c of tiny Yukawa... ⚡
- Easy fix: add second Higgs doublet $H_2$ with larger Yukawa:
  - Neutrinophilic 2HDM: $H_2$ with tiny VEV: $\langle H_2 \rangle \sim \text{eV}$

    [Wang, Wang, Yang, '06; Gabriel & Nandi, '07; Davidson & Logan, '09, '10]

    $\Rightarrow$ Small Dirac neutrino masses without tiny Yukawas.
  - $\nu_R$ asymmetry transferred to L doublet via $H_2$.
  - (B-L effectively conserved after $\Xi$ decoupling.)
  - Transferred to baryon asymmetry by sphalerons. ✓
- Dirac leptogenesis similar to Majorana leptogenesis.
- Requires thermalization of $\nu_R$: $N_{eff} > 3$!

# Number of effective neutrinos: $N_{eff}$

- $N_{eff}^{SM} \simeq 3.$



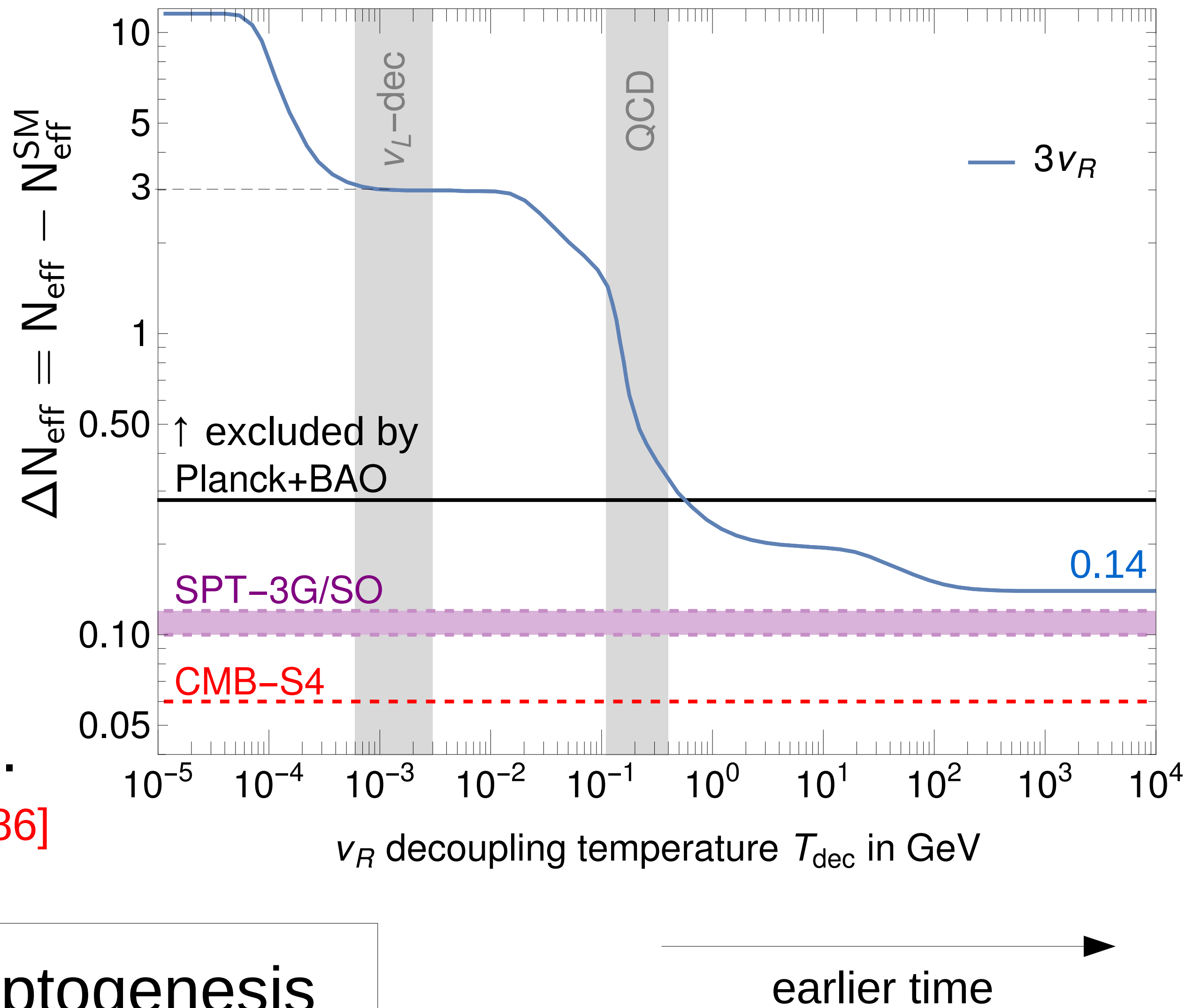
# Number of effective neutrinos: $N_{eff}$

- $N_{eff}^{SM} \simeq 3.$
- Improvement on $\Delta N_{eff}$ in CMB-S4.

  [Abazajian+, 1907.04473]

- Will probe if 3 $\nu_R$ were *ever* thermal!
- Strong constraint for any Dirac ν model.

  [**Heeck** & Abazajian, 1908.03286]

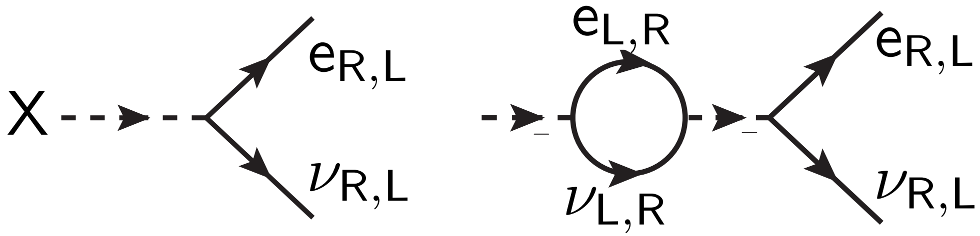


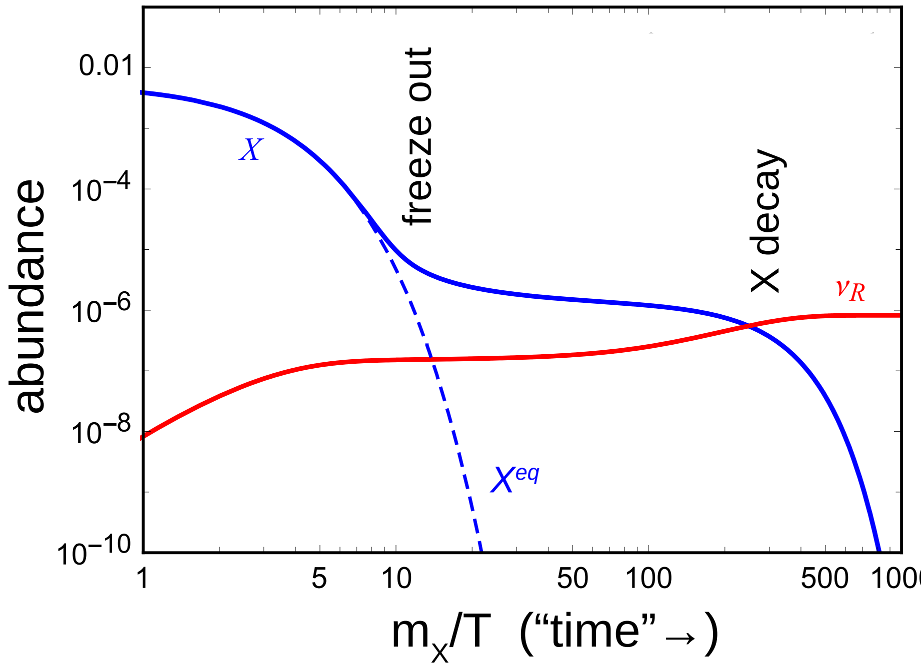

Testable ΔL = 4 Dirac leptogenesis

# Alternative: Neutrinogenesis

[Dick, Lindner, Ratz, Wright, PRL ‘00]

- Non-thermalization of $\nu_R$ might be key for matter/antimatter.
- Idea: new heavy particle X decays out of equilibrium into $\nu_{L,R}$.




[**Heeck**, Heisig, Thapa, 2304.09893]

- Loop-level CP asymmetry ε:

$$\Delta\nu = \nu_L - \bar{\nu}_L = -(\nu_R - \bar{\nu}_R) \neq 0$$

- $\nu_R$ are out of equilibrium, sphalerons convert Δν into baryon asymmetry

$$Y_{\Delta B} \simeq 10^{-3} \varepsilon \eta \overset{!}{\simeq} 10^{-10}.$$

# Dirac leptogenesis models

| Case | $SU(3)\times SU(2)\times U(1)$ | spin | $(B-L)(X)$ | Relevant Lagrangian terms that induce $X$ decay | $\Delta B$ |
|---|---|---|---|---|---|
| $a$ | $(\mathbf{1},\mathbf{1},-1)$ | 0 | $-2$ | $\nu_R e_R \bar{X},\ LL\bar{X}$ | 0 |
| $b$ | $(\mathbf{1},\mathbf{2},1/2)$ | 0 | 0 | $\bar{H}X,\ \bar{\nu}_R LX,\ \bar{L}e_R X,\ \bar{Q}_L d_R X,\ \bar{u}_R Q_L X,\ X^\dagger H^\dagger HH$ | 0 |
| $c$ | $(\mathbf{3},\mathbf{1},-1/3)$ | 0 | $-2/3$ | $d_R\nu_R X^\dagger,\ u_R e_R X^\dagger,\ Q_L L X^\dagger, u_R d_R X,\ Q_L Q_L X$ | 0 or 1 |
| $d$ | $(\mathbf{3},\mathbf{1},2/3)$ | 0 | $-2/3$ | $u_R\nu_R X^\dagger,\ d_R d_R X$ | 1 |
| $e$ | $(\mathbf{3},\mathbf{2},1/6)$ | 0 | $4/3$ | $\bar{Q}_L\nu_R X,\ \bar{d}_R LX$ | 0 |
| $f$ | $(\mathbf{1},\mathbf{2},-1/2)$ | 1/2 | $-1$ | $\bar{X}L,\ \bar{\nu}_R XH,\ \bar{X}e_R H$ | 0 |

[**Heeck**, Heisig, Thapa, 2304.09893]

- B-L is always conserved.
- X always has gauge interactions (same as SUSY sparticles).
  - Still not thermalized if $m_X$ is large, X can freeze in/out.
- $\nu_R$ number is broken, X has decays to $\nu_R$ and SM.
  - Hierarchy of rates $X \to \nu_R$ and $X \to$ SM important.
  - $|\varepsilon| \leq \min(B_R, B_L)$.

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| $c$ | $(\mathbf{3},\mathbf{1},-1/3)$ | 0 | $-2/3$ | $d_R\nu_R X^\dagger,\ u_R e_R X^\dagger,\ Q_L L X^\dagger, u_R d_R X,\ Q_L Q_L X$ | 0 or 1 |
| $d$ | $(\mathbf{3},\mathbf{1},2/3)$ | 0 | $-2/3$ | $u_R\nu_R X^\dagger,\ d_R d_R X$ | 1 |
| $e$ | $(\mathbf{3},\mathbf{2},1/6)$ | 0 | $4/3$ | $\bar{Q}_L\nu_R X,\ \bar{d}_R L X$ | 0 |
| $f$ | $(\mathbf{1},\mathbf{2},-1/2)$ | 1/2 | $-1$ | $\bar{X}L,\ \bar{\nu}_R XH,\ \bar{X}e_R H$ | 0 |

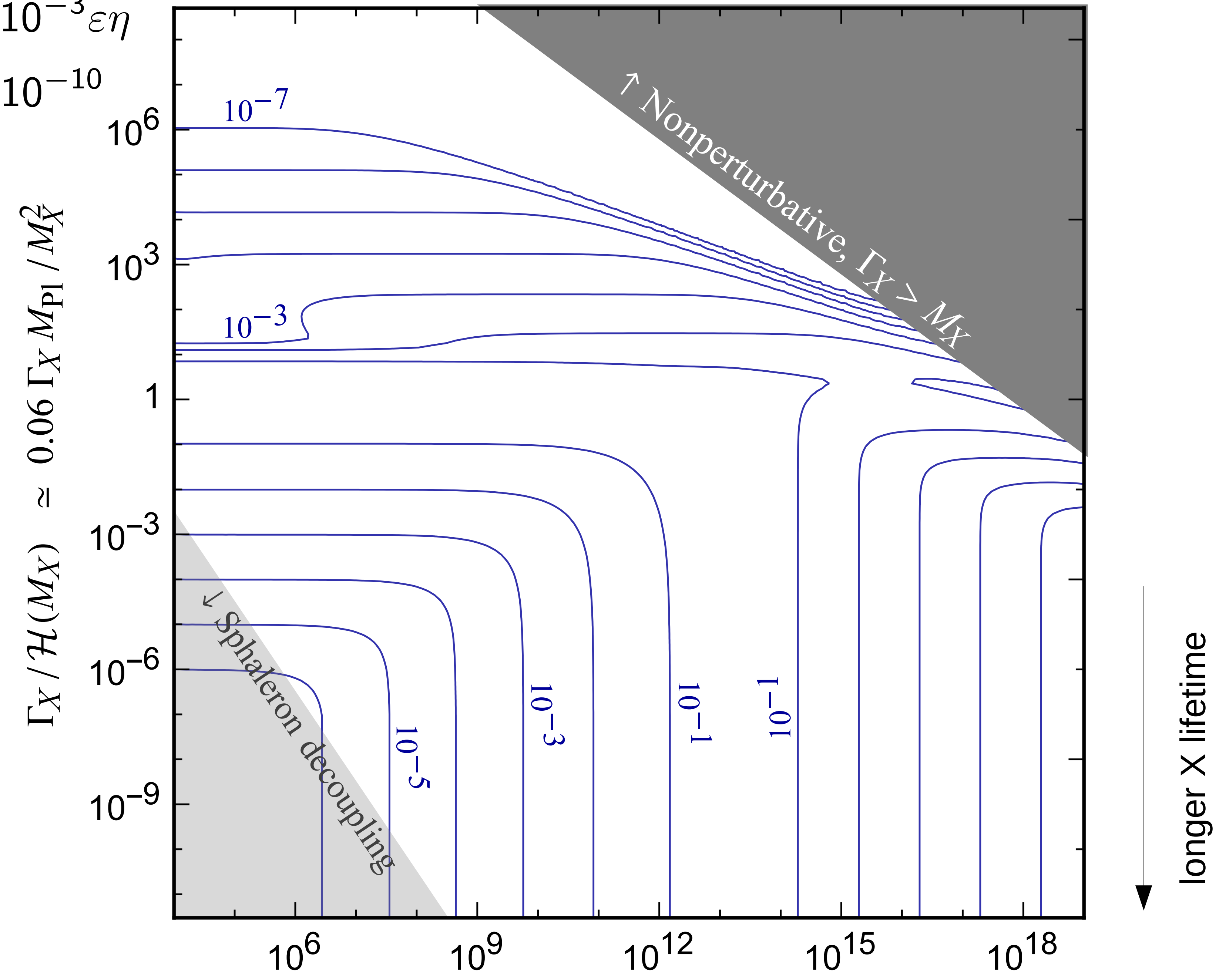
[**Heeck**, Heisig, Thapa, 2304.09893]

- B-L is always conserved.
- X always has gauge interactions (same as SUSY sparticles).
  - Still not thermalized if $m_X$ is large, X can freeze in/out.
- $\nu_R$ number is broken, X has decays to $\nu_R$ and SM.
  - Hierarchy of rates $X \to \nu_R$ and $X \to$ SM important.
  - $|\varepsilon| \leq \min(B_R, B_L)$.

Model a:

$Y_B \simeq 10^{-3}\varepsilon\eta \overset{!}{\gtrsim} 10^{-10}$

$B_R = 0.5$; $\eta$ (blue) = efficiency

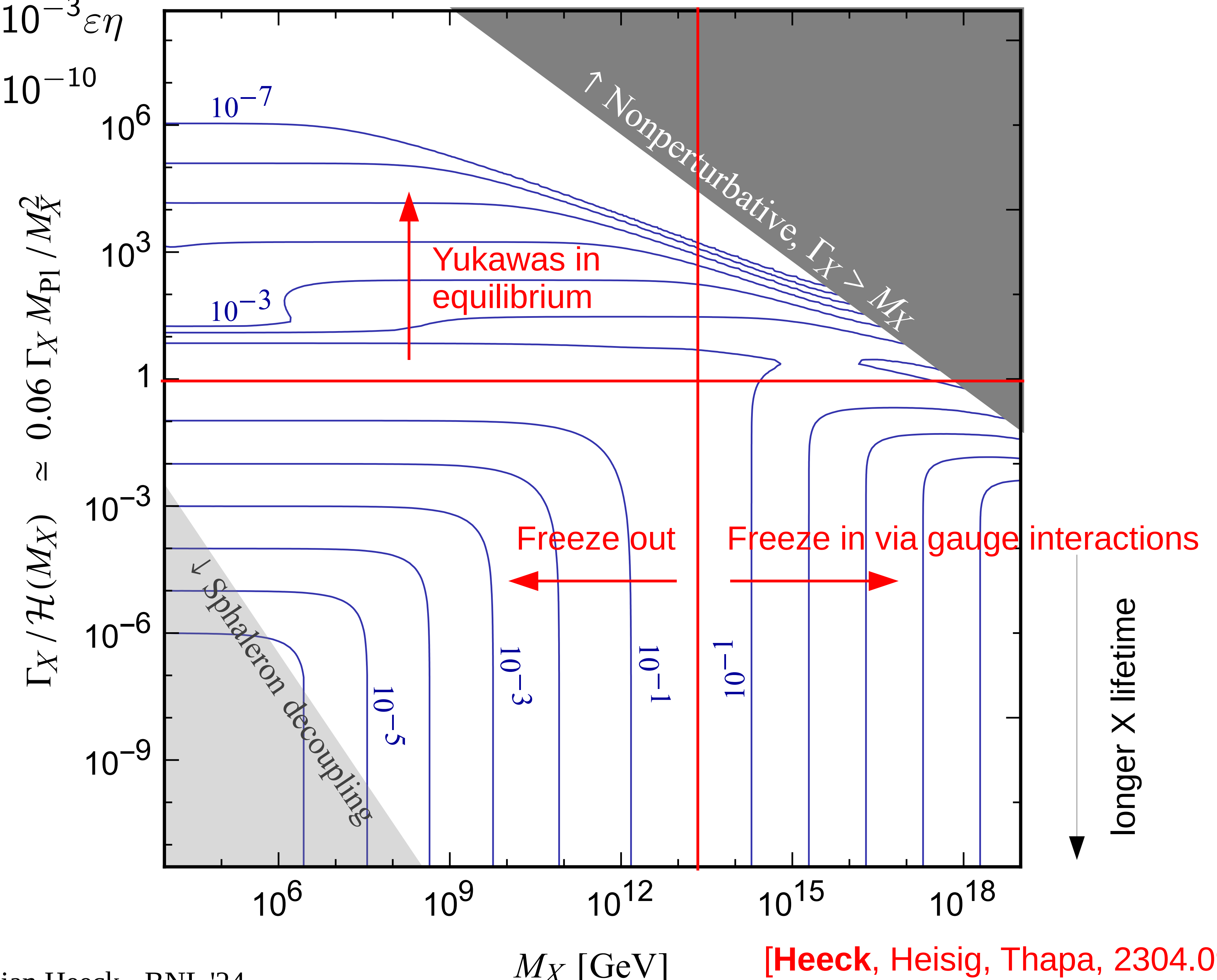



[**Heeck**, Heisig, Thapa, 2304.09893]

Model a:

$Y_B \simeq 10^{-3}\varepsilon\eta \overset{!}{\gtrsim} 10^{-10}$

$B_R = 0.5$; $\eta$ (blue) = efficiency

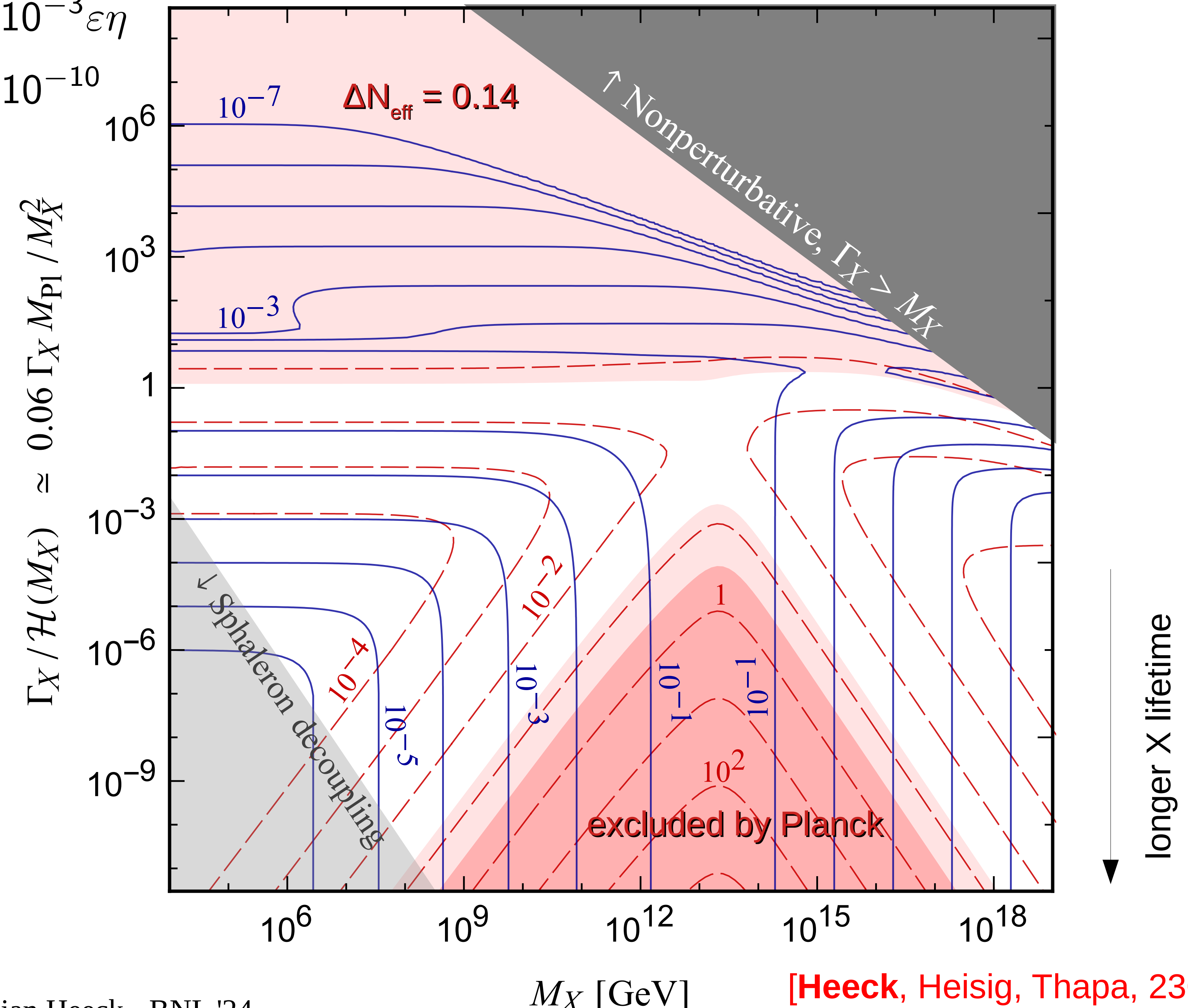



[**Heeck**, Heisig, Thapa, 2304.09893]

Model a:

$Y_B \simeq 10^{-3} \varepsilon\eta$
$\stackrel{!}{\gtrsim} 10^{-10}$

$B_R = 0.5$; $\eta$ (blue) and $\Delta N_{\rm eff}$ (red, dashed)

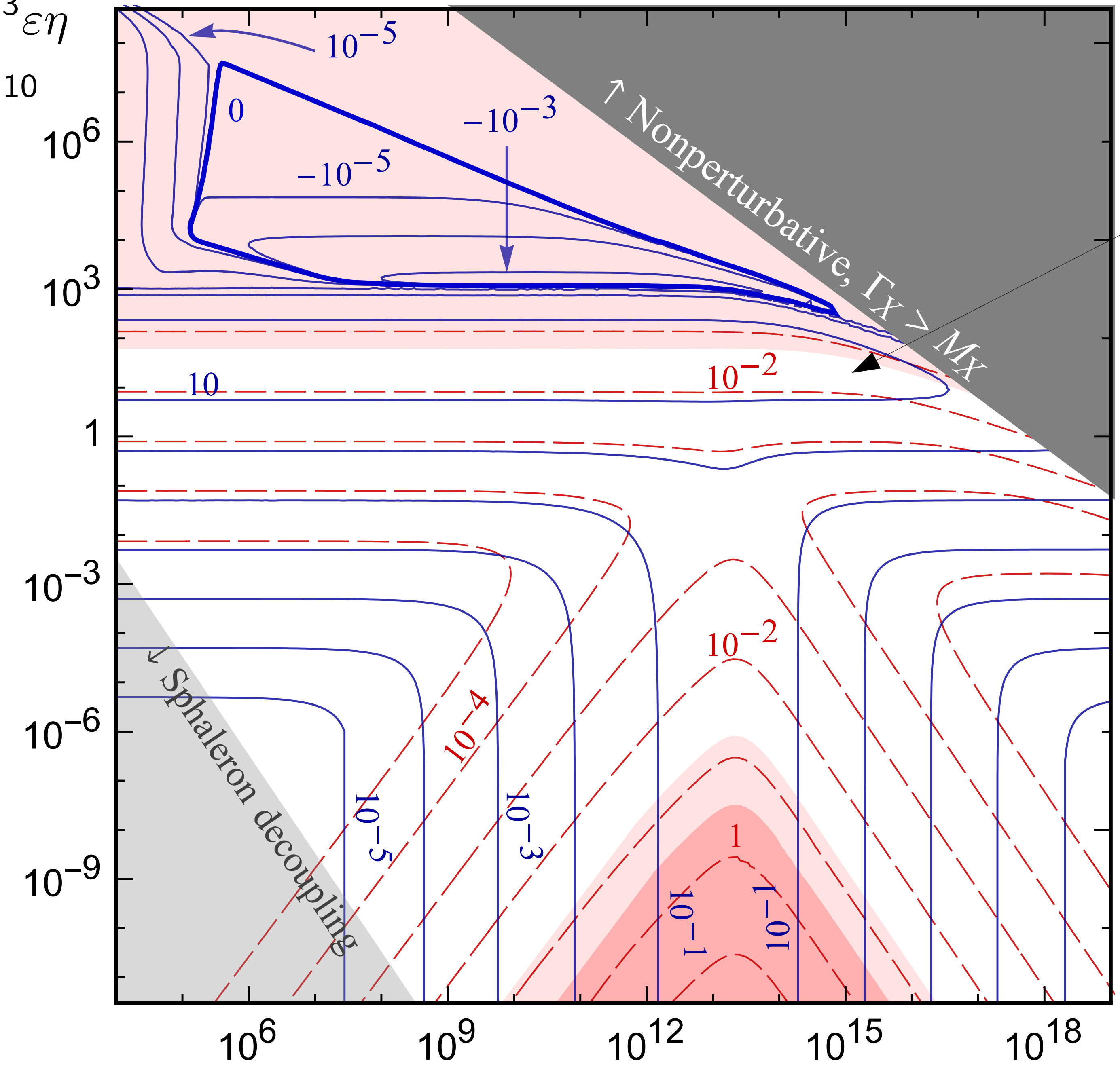



[**Heeck**, Heisig, Thapa, 2304.09893]

Model a:

$Y_B \simeq 10^{-3}\varepsilon\eta \overset{!}{\gtrsim} 10^{-10}$

$B_R = 0.01$; $\eta$ (blue) and $\Delta N_{\rm eff}$ (red, dashed)

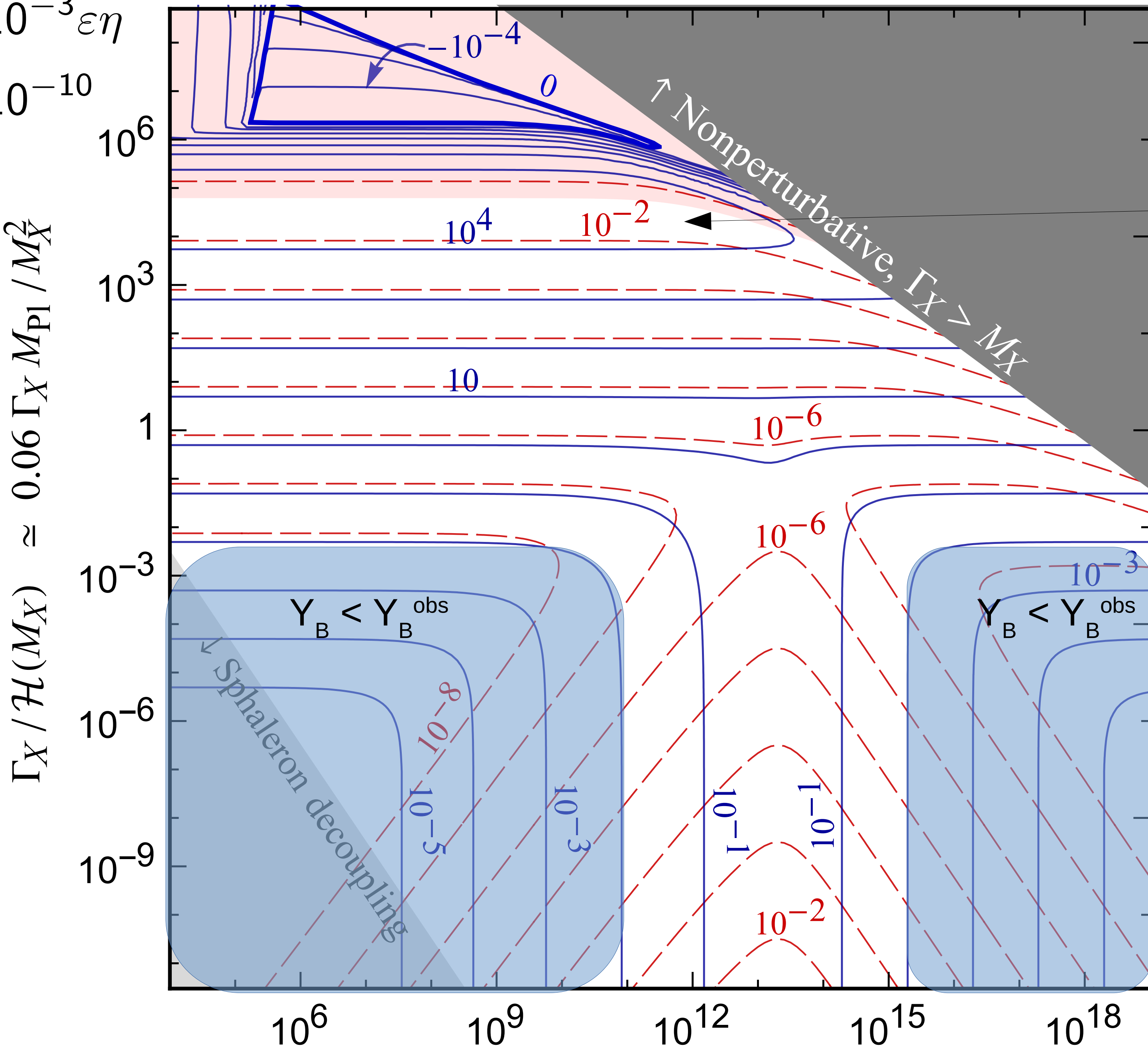



[**Heeck**, Heisig, Thapa, 2304.09893]

Model a:

$Y_B \simeq 10^{-3}\varepsilon\eta \overset{!}{\gtrsim} 10^{-10}$

$B_R = 10^{-5}$; $\eta$ (blue) and $\Delta N_{\rm eff}$ (red, dashed)




$X \to \nu_L$ in equilibrium, $X \to \nu_R$ not.

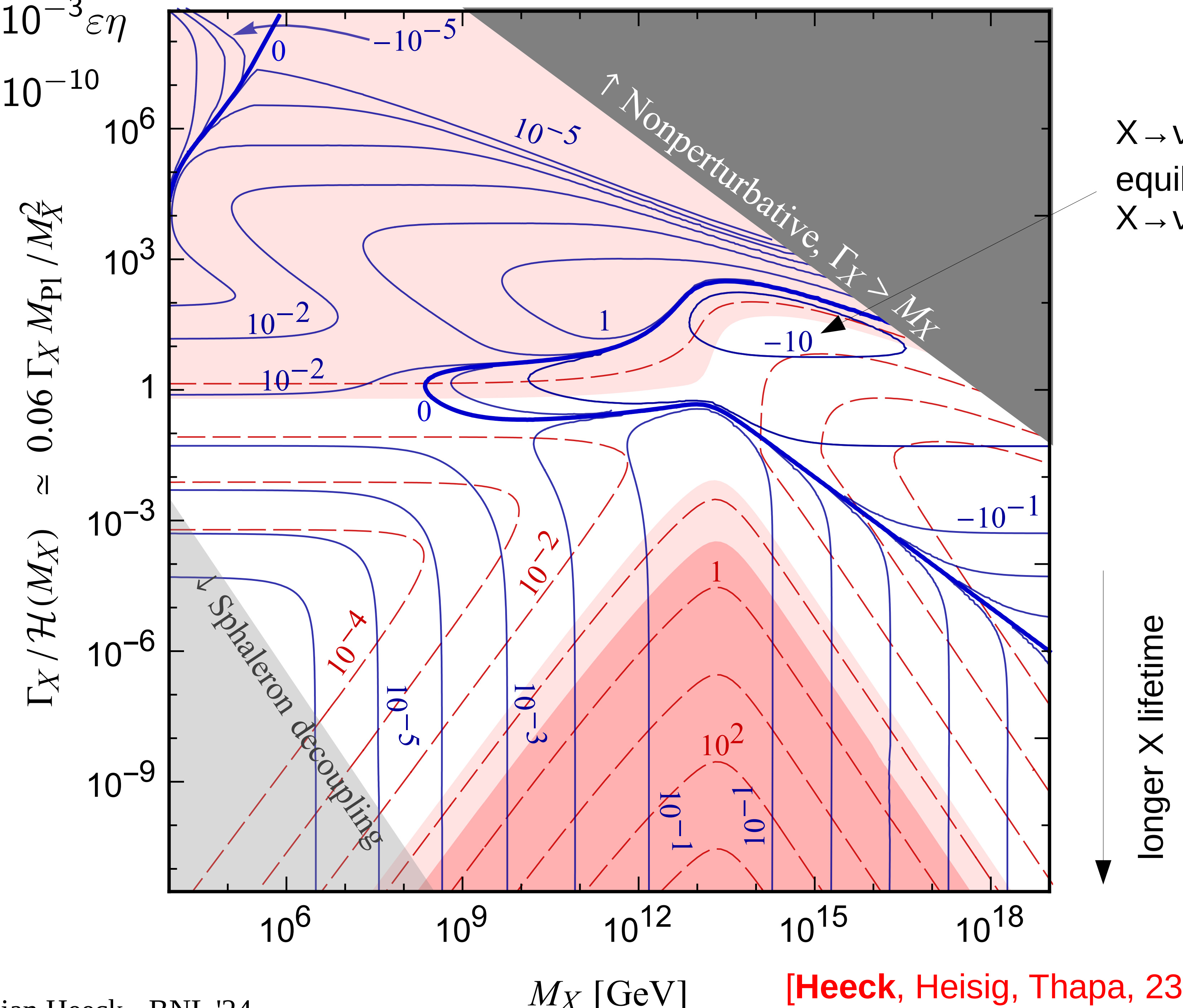
longer X lifetime

[**Heeck**, Heisig, Thapa, 2304.09893]

Model a:

$Y_B \simeq 10^{-3}\varepsilon\eta \overset{!}{\gtrsim} 10^{-10}$

$B_R = 0.99$; $\eta$ (blue) and $\Delta N_{\rm eff}$ (red, dashed)

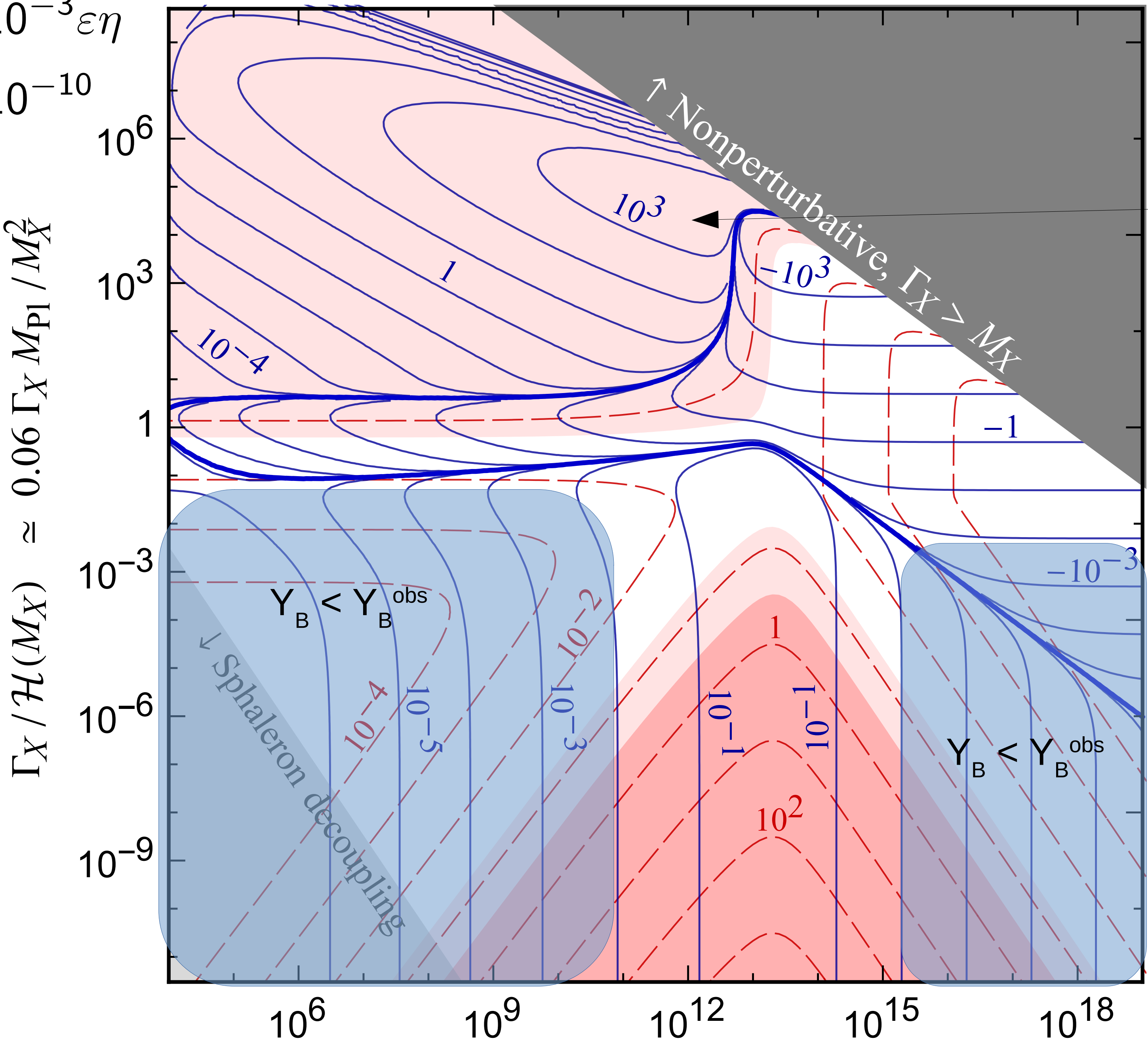



[**Heeck**, Heisig, Thapa, 2304.09893]

Model a:

$Y_B \simeq 10^{-3}\varepsilon\eta \overset{!}{\gtrsim} 10^{-10}$

$B_R = 1 - 10^{-5}$; $\eta$ (blue) and $\Delta N_{\rm eff}$ (red, dashed)




$X \to \nu_R$ in equilibrium, $X \to \nu_L$ not.

longer X lifetime

[**Heeck**, Heisig, Thapa, 2304.09893]

# Neutrinogenesis

- Very efficient asymmetry generation!
- Only works due to tiny Dirac neutrino masses.
- X decays into (high-energy) $\nu_R$: testable $\Delta N_{eff}$!
- More fun with Dirac leptogenesis:

| Case | $SU(3) \times SU(2) \times U(1)$ | spin | $(B-L)(X)$ | Relevant Lagrangian terms that induce $X$ decay | $\Delta B$ |
|---|---|---|---|---|---|
| $d$ | $(\mathbf{3}, \mathbf{1}, 2/3)$ | 0 | $-2/3$ | $u_R \nu_R X^\dagger,\ d_R d_R X$ | 1 |

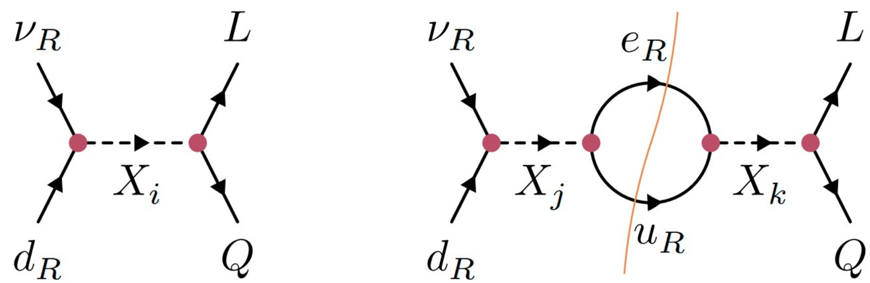
  - Don't even need sphalerons, can generate $\Delta \mathrm{B} = (\nu_\mathrm{R} - \bar{\nu}_\mathrm{R}) \neq 0$ directly! Predicts proton decay $\mathrm{p} \to \mathrm{K}^+ \bar{\nu}_\mathrm{R}$!

    [**Heeck**, Heisig, Thapa, 2304.09893]

Neutrinogenesis is fascinating!

# Neutrinogenesis via scattering

- What if the universe never reached T ~ $M_X$?
  - Scattering via off-shell X.
  - CP asymmetry now requires *three* different X couplings.

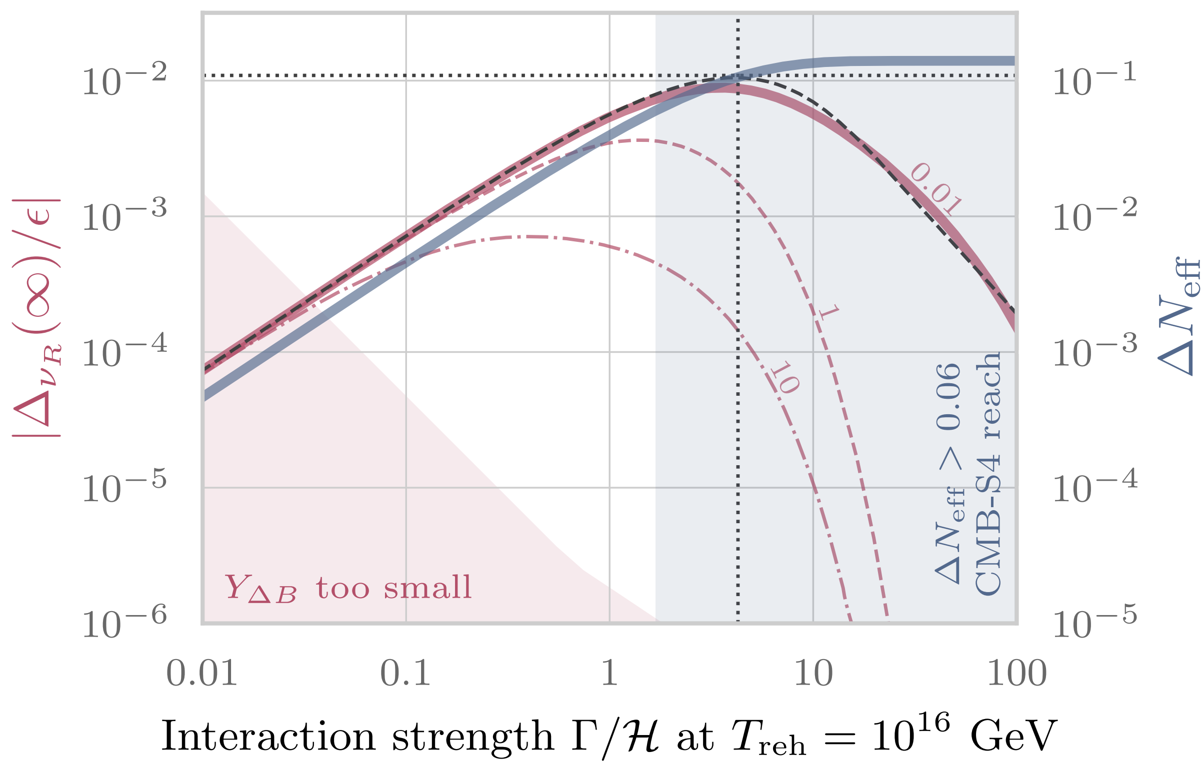



| Case | $SU(3)\times SU(2)\times U(1)$ | spin | $(B-L)(X)$ | Relevant Lagrangian terms that induce $X$ decay | $\Delta B$ |
|---|---|---|---|---|---|
| $c$ | $(\mathbf{3},\mathbf{1},-1/3)$ | 0 | $-2/3$ | $d_R\nu_R X^\dagger$, $u_R e_R X^\dagger$, $Q_L L X^\dagger$, ~~$u_R d_R X$, $Q_L Q_L X$~~ | 0 ~~or 1~~ |

  - No source term for $\nu_R$ asymmetry: wash in.

- Works well, $T_{reh} < 10^{12}$ GeV requires careful study of flavor effects.

[Blažek, **Heeck,** Heisig, Maták, Zaujec 2404.16934]

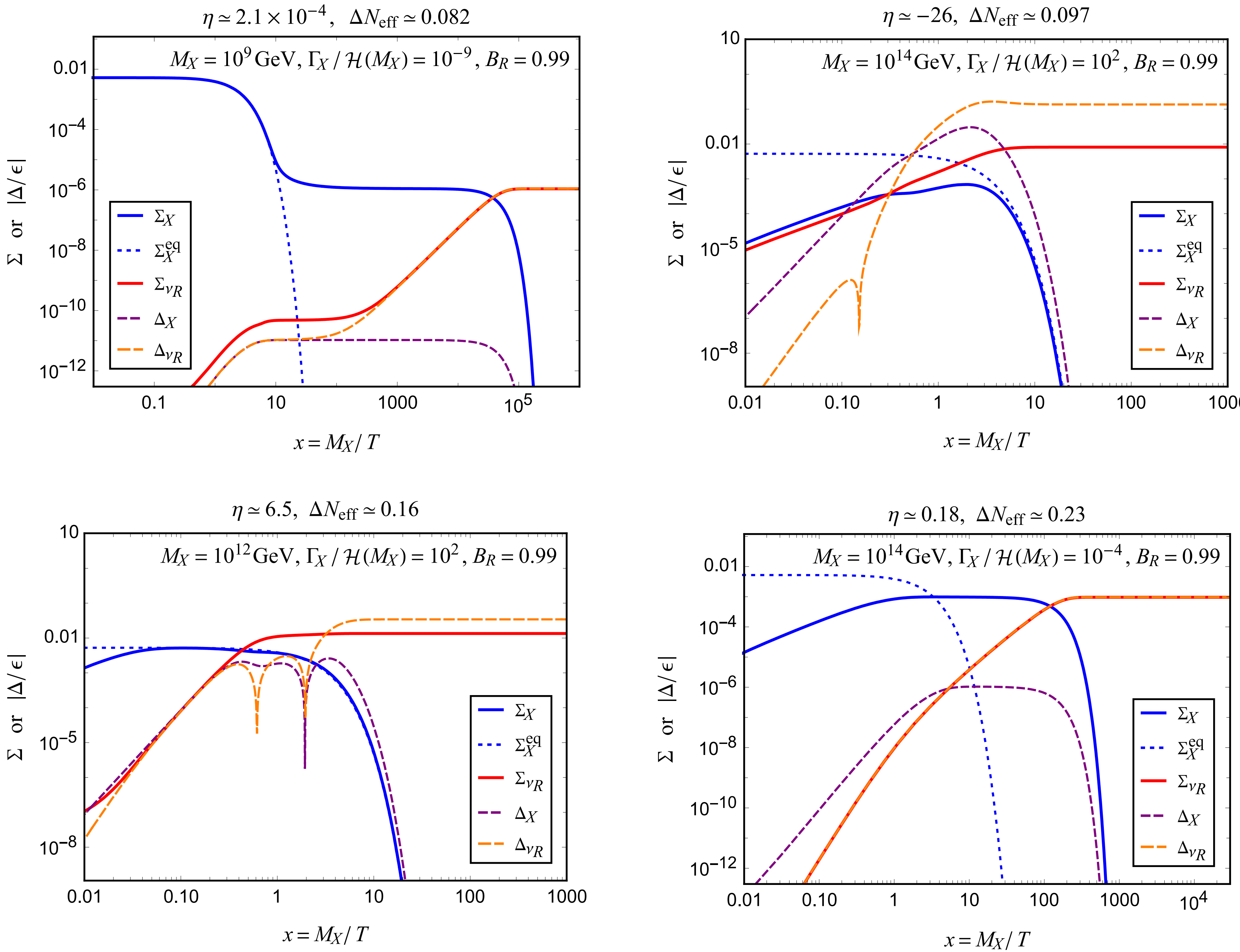


# Summary

- Dirac vs. Majorana is an important question.
- Majorana neutrinos have more parameters and more pheno:
  - $0\nu\beta\beta$, collider signatures, lepton flavor violation,…
  - seesaw and leptogenesis are nice (and untestable)!
- Dirac neutrinos *most economic* $M_\nu$ solution, and can still
  - explain baryon asymmetry by exploiting ν properties;
  - generically expect enhanced $N_{eff}$ from ultra-light $\nu_R$.
- Fate of lepton number is experimental question!

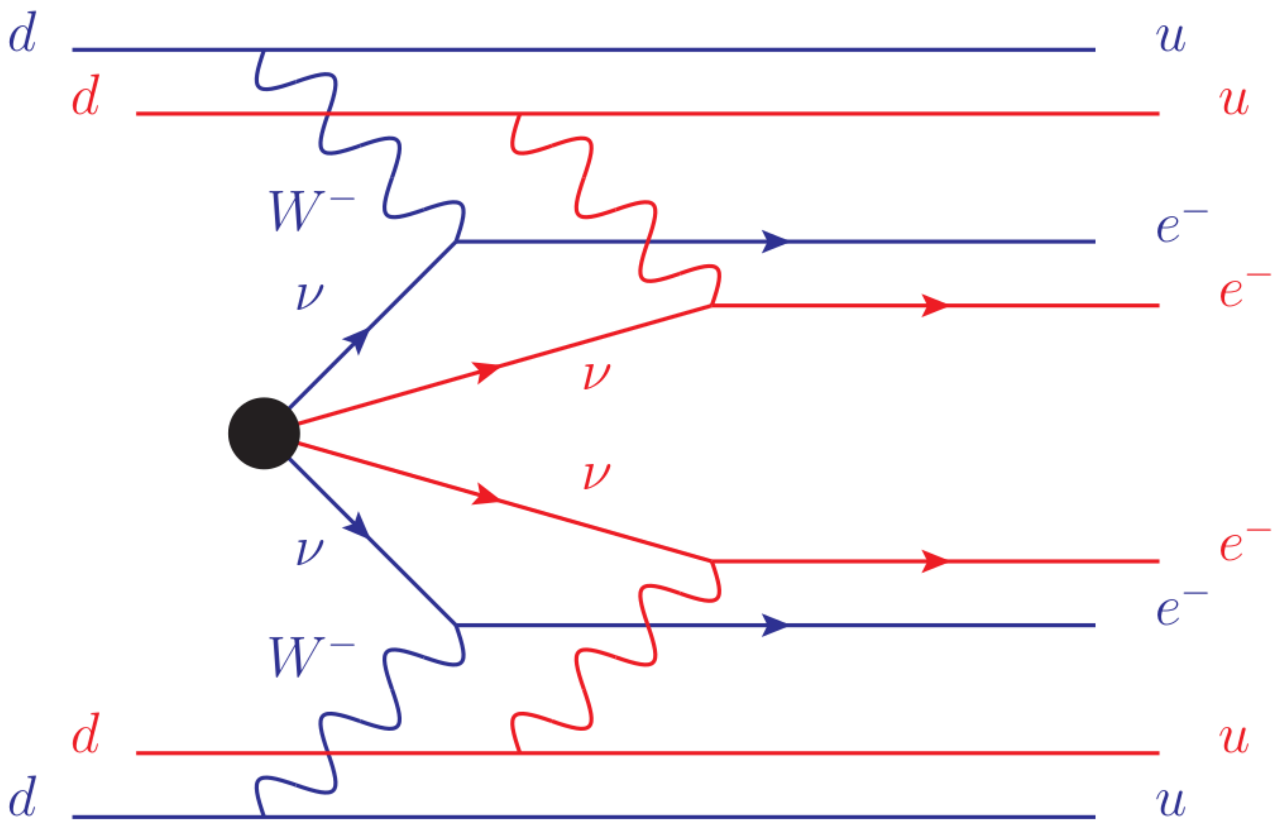
Dirac neutrinos deserve attention too!

# Backup


η ≃ 2.1 × 10^−4, ΔN_eff ≃ 0.082
M_X = 10^9 GeV, Γ_X / H(M_X) = 10^−9, B_R = 0.99
η ≃ −26, ΔN_eff ≃ 0.097
M_X = 10^14 GeV, Γ_X / H(M_X) = 10^2, B_R = 0.99
η ≃ 6.5, ΔN_eff ≃ 0.16
M_X = 10^12 GeV, Γ_X / H(M_X) = 10^2, B_R = 0.99
η ≃ 0.18, ΔN_eff ≃ 0.23
M_X = 10^14 GeV, Γ_X / H(M_X) = 10^−4, B_R = 0.99
Σ or |Δ/ϵ|
x = M_X / T
Σ_X
Σ_X^eq
Σ_νR
Δ_X
Δ_νR

# Neutrinoless Quadruple-Beta Decay 0ν4β

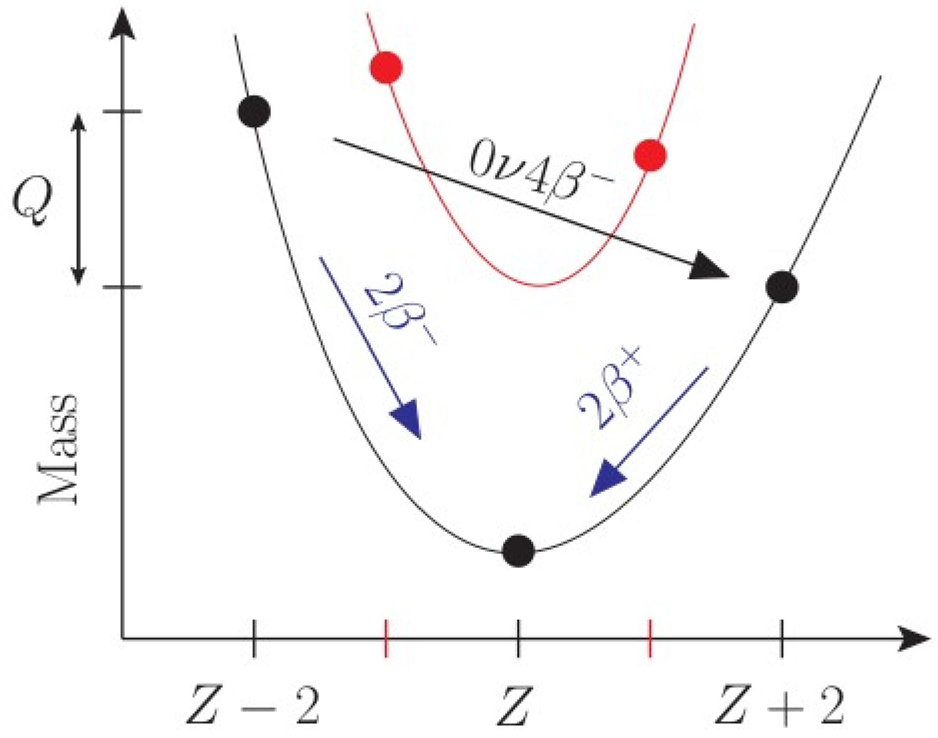
$(A, Z) \to (A, Z+4) + 4\,e^-$ via $\mathcal{O} = (\overline{\nu}_L^c \nu_L)^2/\Lambda^2$:




[**Heeck** & Rodejohann, 1306.0580]

# Candidate Nuclei

- Experimental aspects of $0\nu4\beta$ independent of underlying mechanism.
- Need beta-stable initial state:




- Decay modes: $0\nu4\beta$ and $2\nu2\beta$ ($0\nu2\beta$ forbidden by $\mathbb{Z}_4^L$).

[**Heeck** & Rodejohann, 1306.0580]

# Candidates for Nuclear ΔL = 4 Processes

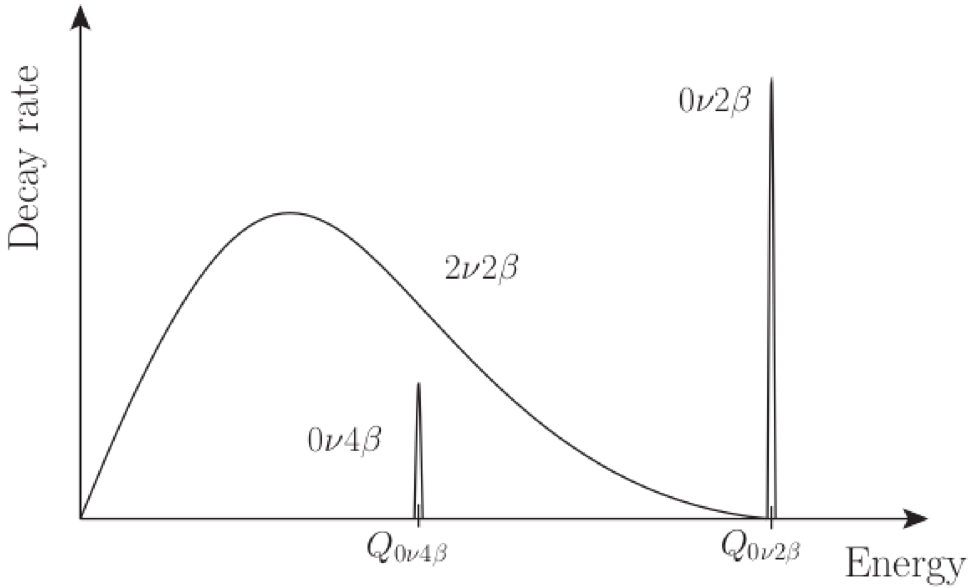
| | $Q_{0\nu 4\beta}$ | Other decays | NA/% |
|---|---|---|---|
| ${}^{96}_{40}\mathrm{Zr} \to {}^{96}_{44}\mathrm{Ru}$ | 0.629 MeV | $\tau^{2\nu 2\beta}_{1/2} \simeq 2 \times 10^{19}$ y | 2.8 |
| ${}^{136}_{54}\mathrm{Xe} \to {}^{136}_{58}\mathrm{Ce}$ | 0.044 MeV | $\tau^{2\nu 2\beta}_{1/2} \simeq 2 \times 10^{21}$ y | 8.9 |
| ${}^{150}_{60}\mathrm{Nd} \to {}^{150}_{64}\mathrm{Gd}$ | 2.079 MeV | $\tau^{2\nu 2\beta}_{1/2} \simeq 7 \times 10^{18}$ y | 5.6 |
| | $Q_{0\nu 4\mathrm{EC}}$ | | |
| ${}^{124}_{54}\mathrm{Xe} \to {}^{124}_{50}\mathrm{Sn}$ | 0.577 MeV | — | 0.095 |
| ${}^{130}_{56}\mathrm{Ba} \to {}^{130}_{52}\mathrm{Te}$ | 0.090 MeV | $\tau^{2\nu 2\mathrm{EC}}_{1/2} \sim 10^{21}$ y | 0.106 |
| ${}^{148}_{64}\mathrm{Gd} \to {}^{148}_{60}\mathrm{Nd}$ | 1.138 MeV | $\tau^{\alpha}_{1/2} \simeq 75$ y | — |
| ${}^{154}_{66}\mathrm{Dy} \to {}^{154}_{62}\mathrm{Sm}$ | 2.063 MeV | $\tau^{\alpha}_{1/2} \simeq 3 \times 10^{6}$ y | — |
| | $Q_{0\nu 3\mathrm{EC}\beta^+}$ | | |
| ${}^{148}_{64}\mathrm{Gd} \to {}^{148}_{60}\mathrm{Nd}$ | 0.116 MeV | $\tau^{\alpha}_{1/2} \simeq 75$ y | — |
| ${}^{154}_{66}\mathrm{Dy} \to {}^{154}_{62}\mathrm{Sm}$ | 1.041 MeV | $\tau^{\alpha}_{1/2} \simeq 3 \times 10^{6}$ y | — |
| | $Q_{0\nu 2\mathrm{EC}2\beta^+}$ | | |
| ${}^{154}_{66}\mathrm{Dy} \to {}^{154}_{62}\mathrm{Sm}$ | 0.019 MeV | $\tau^{\alpha}_{1/2} \simeq 3 \times 10^{6}$ y | — |

[**Heeck** & Rodejohann, 1306.0580]

# Best Candidate: Neodymium

Decay channels:

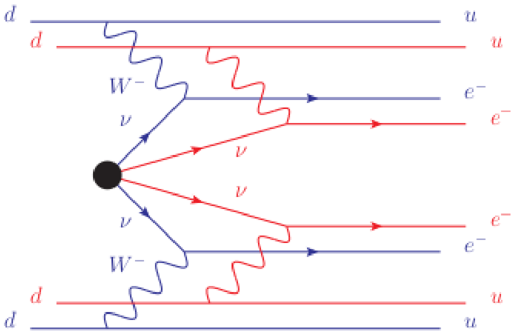
- ${}^{150}_{60}\mathrm{Nd} \to {}^{150}_{62}\mathrm{Sm}$ via $2\nu2\beta$ ($\tau^{2\nu2\beta}_{1/2} \simeq 7 \times 10^{18}\,\mathrm{y}$): two neutrinos and two electrons are emitted; the electrons have a continuous energy spectrum and total energy $E_{e,1} + E_{e,2} < 3.371\,\mathrm{MeV}$.
- ${}^{150}_{60}\mathrm{Nd} \to {}^{150}_{64}\mathrm{Gd}$ via $0\nu4\beta$. Four electrons with continuous energy spectrum and summed energy $Q_{0\nu4\beta} = 2.079\,\mathrm{MeV}$ are emitted. In this special case, the daughter nucleus is $\alpha$-unstable with half-life $\tau^{\alpha}_{1/2}({}^{150}_{64}\mathrm{Gd} \to {}^{146}_{62}\mathrm{Sm}) \simeq 2 \times 10^{6}\,\mathrm{y}$.




[**Heeck** & Rodejohann, 1306.0580; NEMO-3, PRL ‘17]

# Neutrinoless Quadruple-Beta Decay Rate

$(A, Z) \to (A, Z+4) + 4\, e^-$ via $\mathcal{O} = (\overline{\nu}_L^c \nu_L)^2/\Lambda^2$:




- Very naive comparison with competing channel $2\nu 2\beta$:

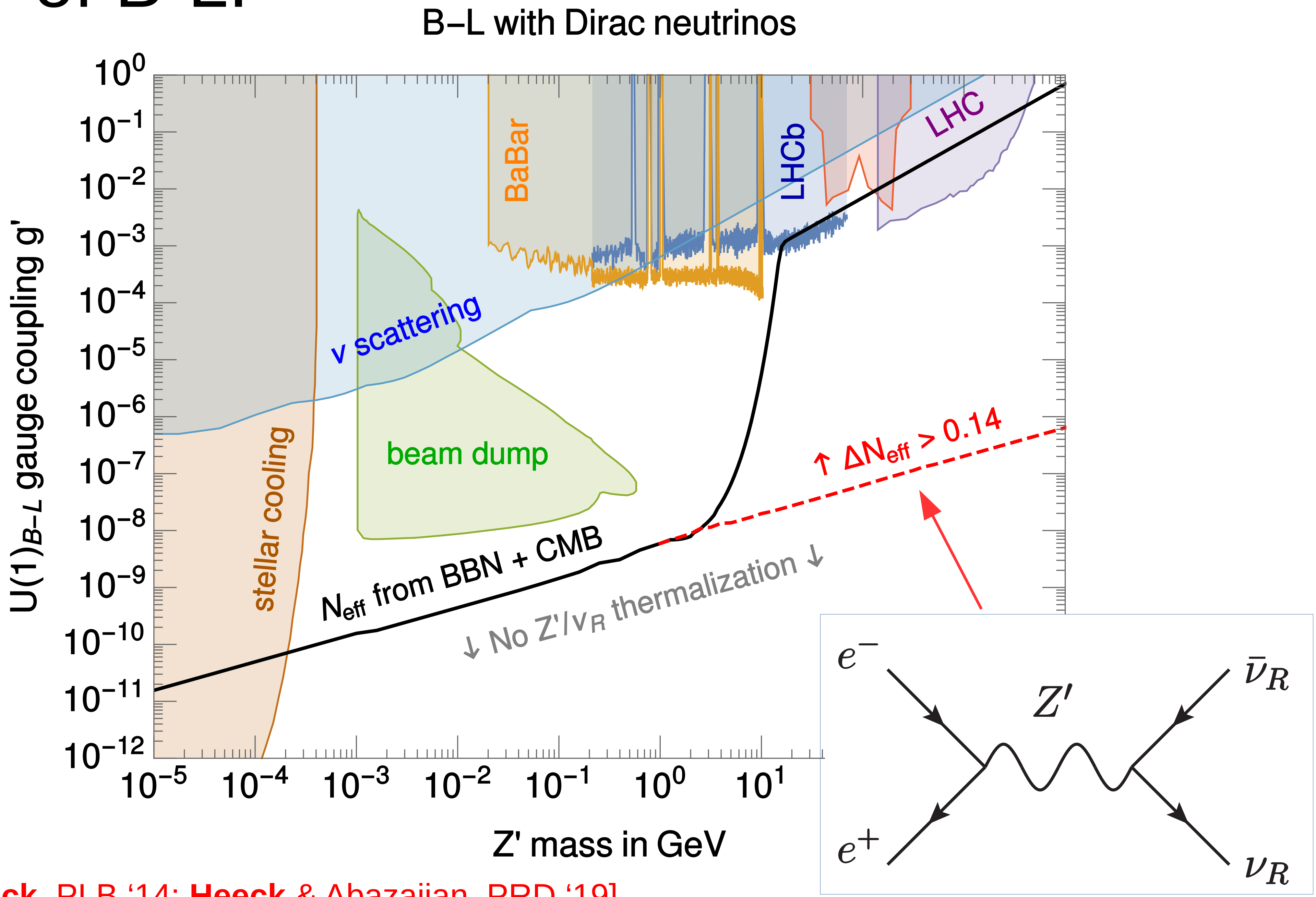
$$\frac{T_{1/2}^{0\nu 4\beta}}{T_{1/2}^{2\nu 2\beta}} \simeq \left(\frac{Q_{0\nu 2\beta}}{Q_{0\nu 4\beta}}\right)^{11} \left(\frac{\Lambda^4}{q^{12} G_F^4}\right) \simeq 10^{46} \left(\frac{\Lambda}{\mathrm{TeV}}\right)^4,$$

with $|q| \sim p_\nu \sim 1\,\mathrm{fm}^{-1} \simeq 100\,\mathrm{MeV}$.

- For $(\overline{\nu}_R^c \nu_R)^2/\Lambda^2$ additional mass-flip suppression $(m_\nu/q)^8$ or right-handed currents...
- Estimated rate in toy model unobservably small. Elaborate models with resonances overcome this?

[**Heeck** & Rodejohann, 1306.0580; Fonseca & Hirsch, 1804.10545]

# Z' of B-L:




[**Heeck**, PLB '14; **Heeck** & Abazajian, PRD '19]