Dirac neutrinos in the cosmic microwave background

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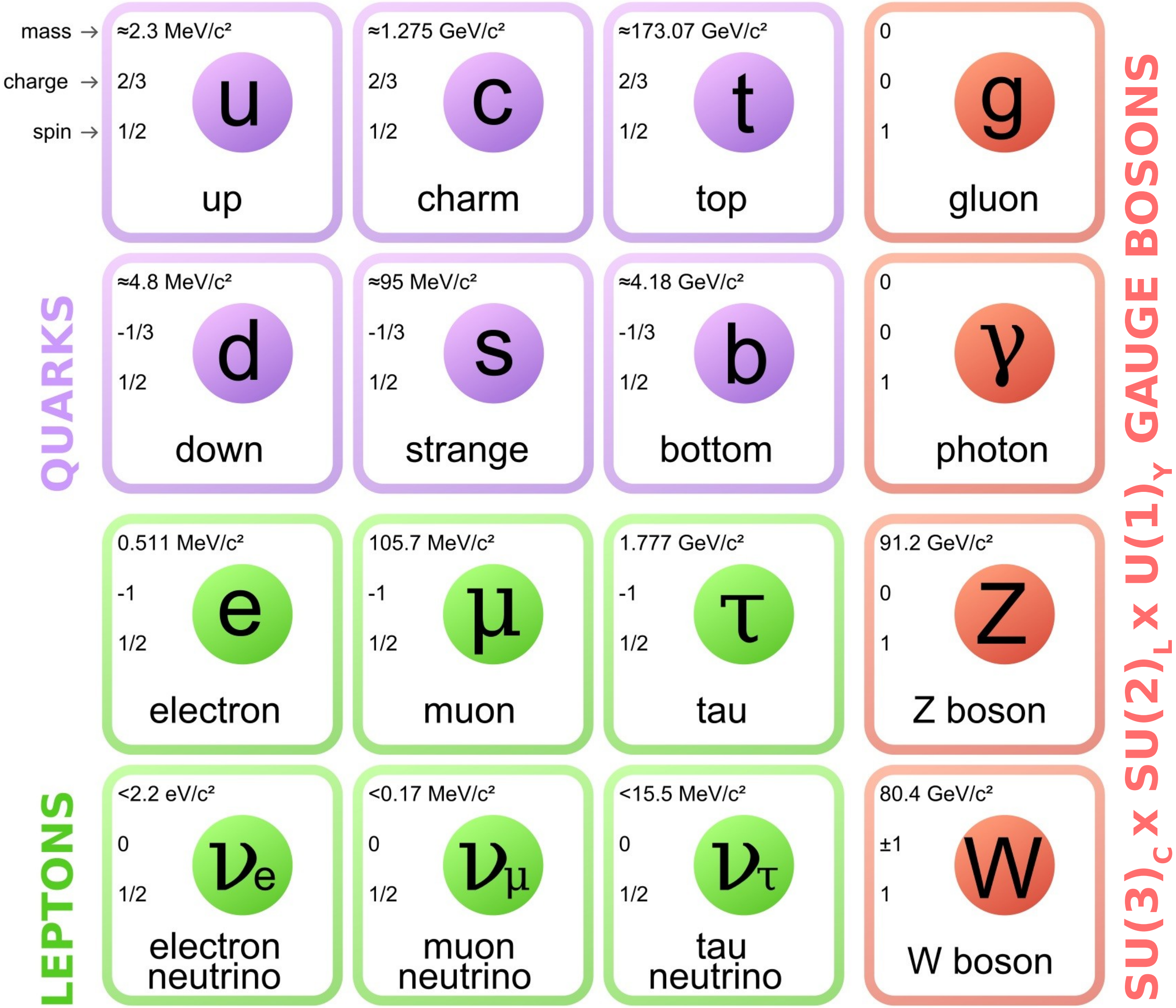
Standard Model of Particle Physics

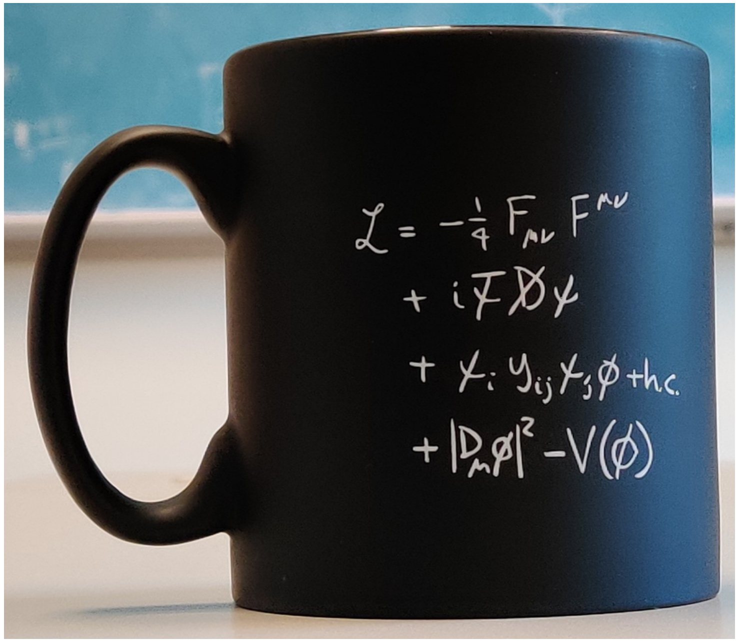


≈126 GeV/c²
0
0
H
Higgs boson

SCALARS

Englert & Higgs ‘13

[wikipedia]



Neutrinos oscillate!

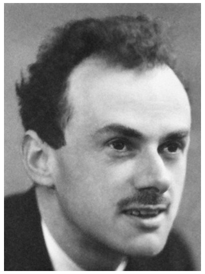
Kajita & McDonald '15

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

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

- Absolute masses unknown but below 0.8 eV. [KATRIN '19]
- Experimental program continues to pin down parameters (phases, mass scale, ordering).

Implications for theory?

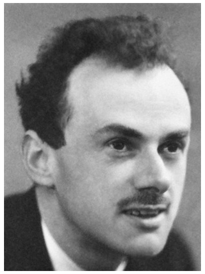


Neutrino mass = new particles

- Dirac neutrinos:
  - $\nu = \nu_L + \nu_R \neq \bar{\nu}$.
  - $U(1)_L$ conserved.
  - ν_R-ν_L-Higgs coupling:

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

  - Tiny Yukawa couplings.
  - ν_R is gauge singlet
    → difficult to see.



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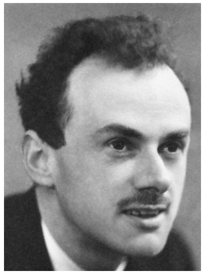
- Majorana neutrinos:
  - $\nu = \nu_L + \nu_L^c = \bar{\nu}$.
  - $U(1)_L$ broken.
  - Add $m_M \overline{\nu}_R^c \nu_R$?

$$m_\nu \simeq (y_\nu \langle H \rangle) \frac{1}{m_M} (y_\nu \langle H \rangle)^T \sim 1\,\mathrm{eV}\left(\frac{10^{12}\,\mathrm{GeV}}{m_M}\right) y_\nu^2.$$

  - ν_R is heavy gauge singlet.
  - Confirm via $0\nu\beta\beta$.

How to confirm Dirac neutrinos?



How to see Dirac neutrinos?

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

$$m_\nu = y_\nu \langle H \rangle$$
$$= 1\,\mathrm{eV}\left(\frac{y_\nu}{10^{-11}}\right).$$

  - Tiny Yukawa couplings.
  - ν_R is gauge singlet → difficult to see.

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

Dirac neutrinos = extra radiation?

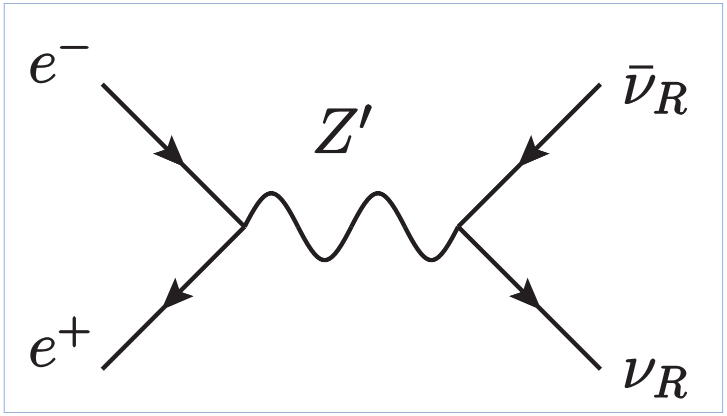
Entropy dilution

time

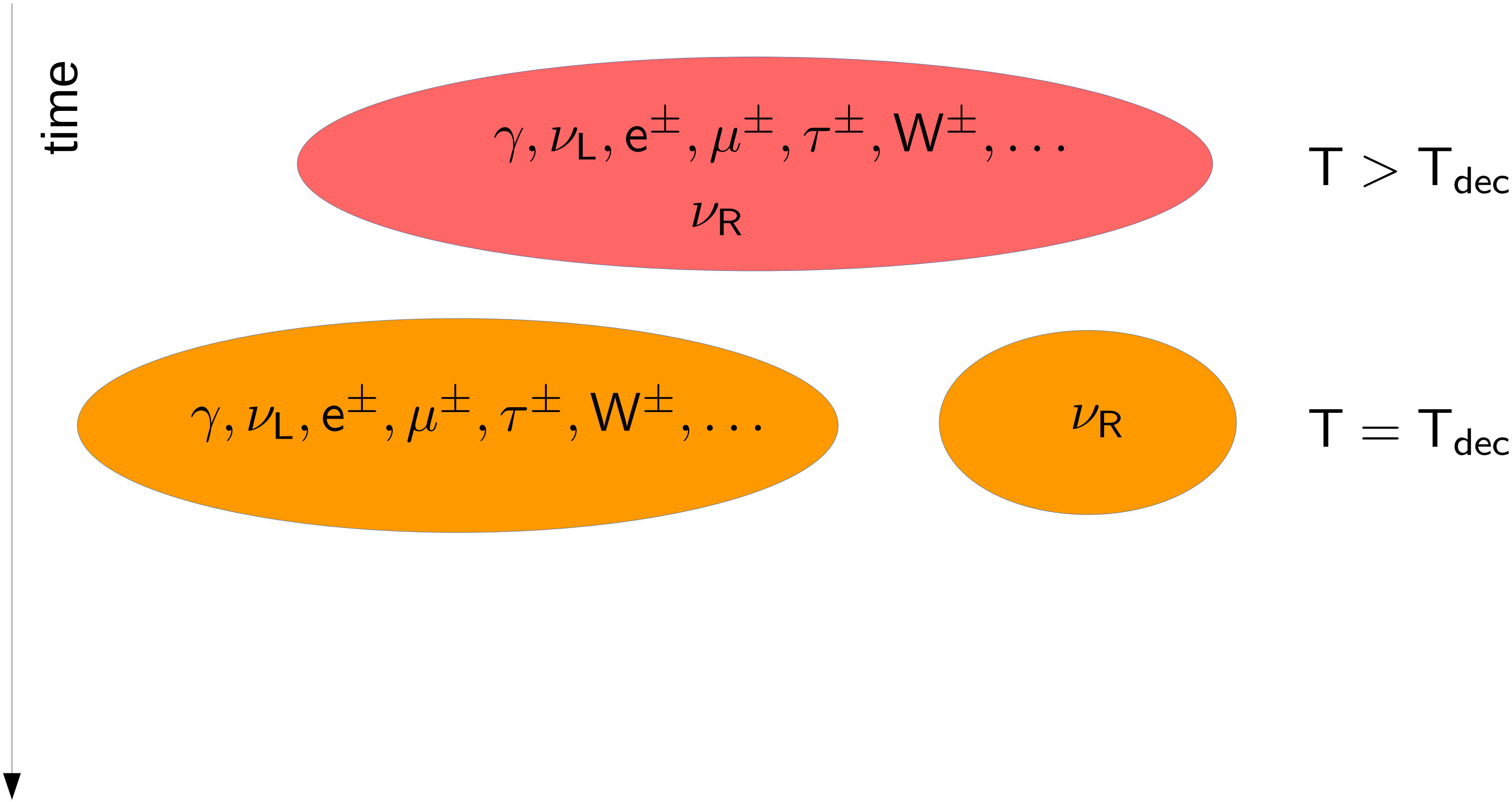
$\gamma, \nu_\mathrm{L}, \mathrm{e}^\pm, \mu^\pm, \tau^\pm, \mathrm{W}^\pm, \ldots$

ν_R

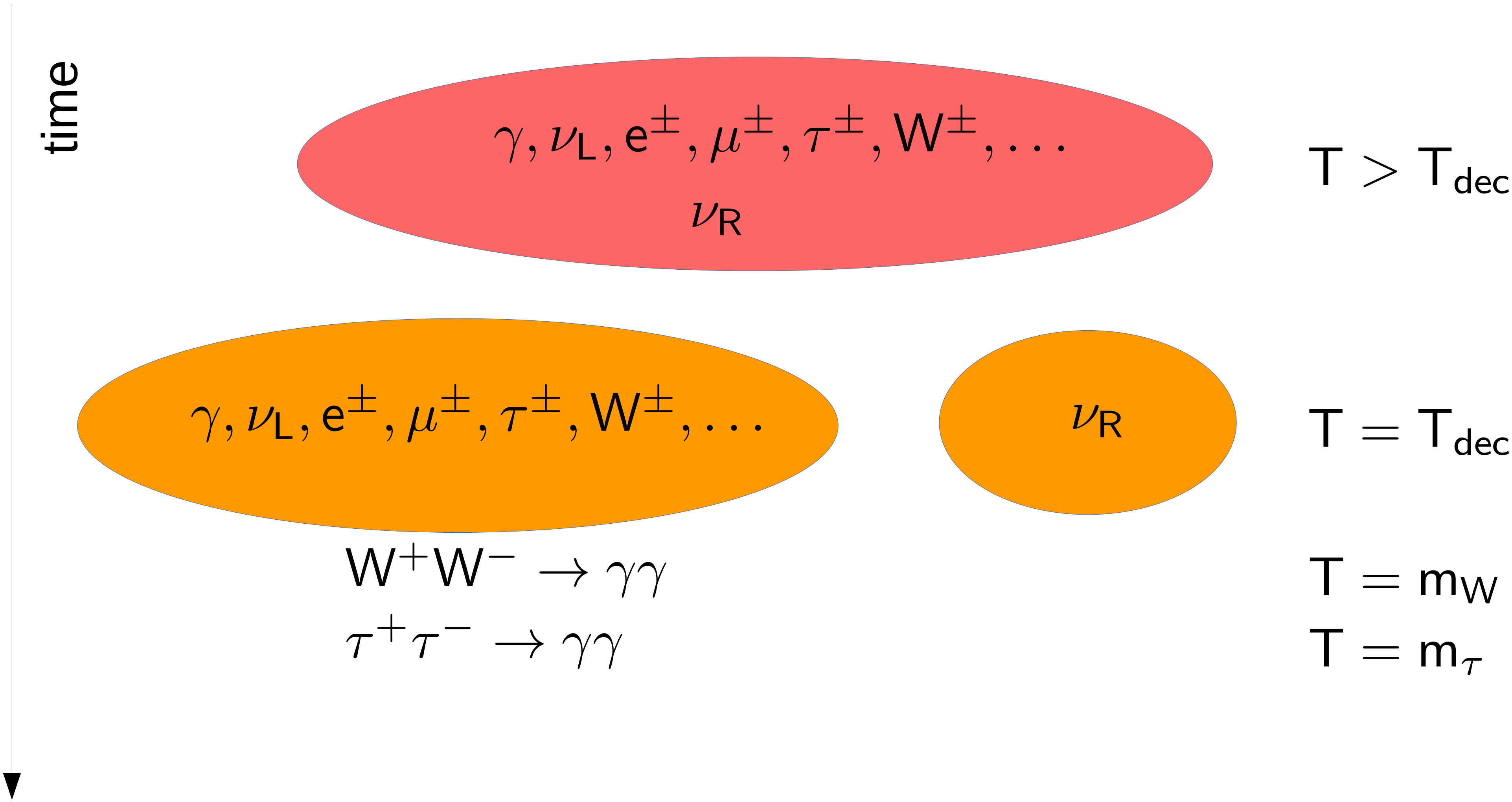
$\mathrm{T} > \mathrm{T}_\mathrm{dec}$



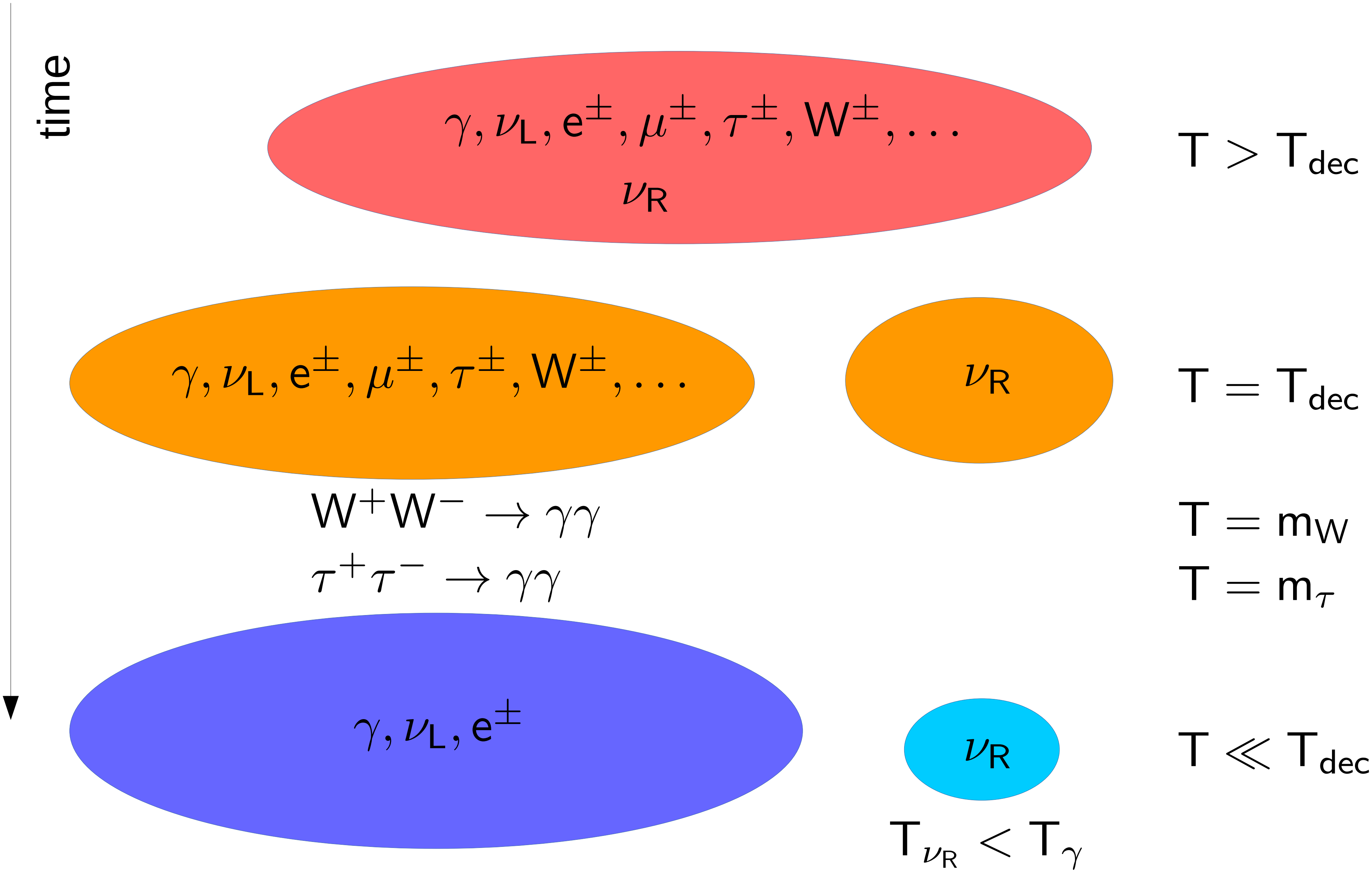
Entropy dilution



Entropy dilution

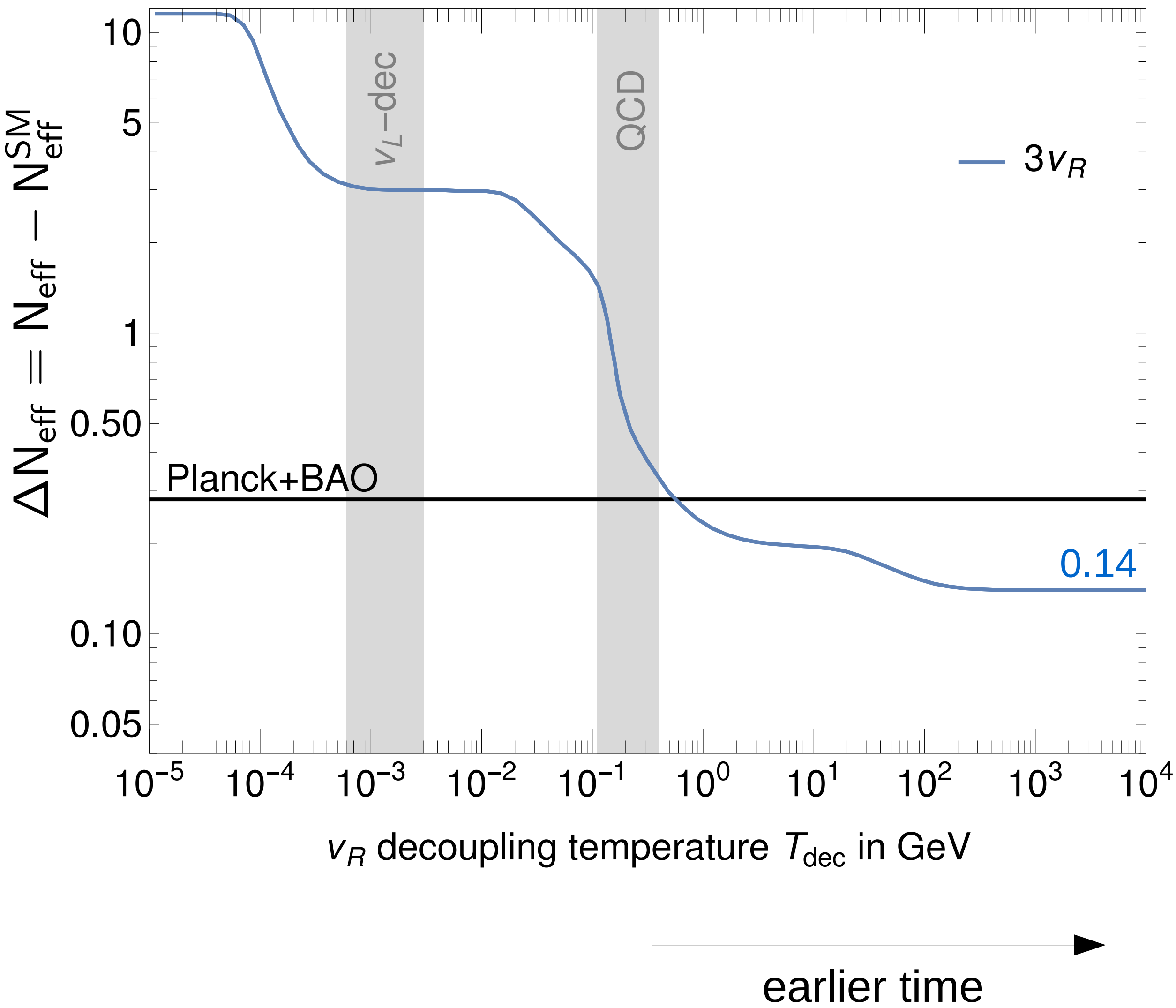


Entropy dilution



Number of effective neutrinos: N_{eff}

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



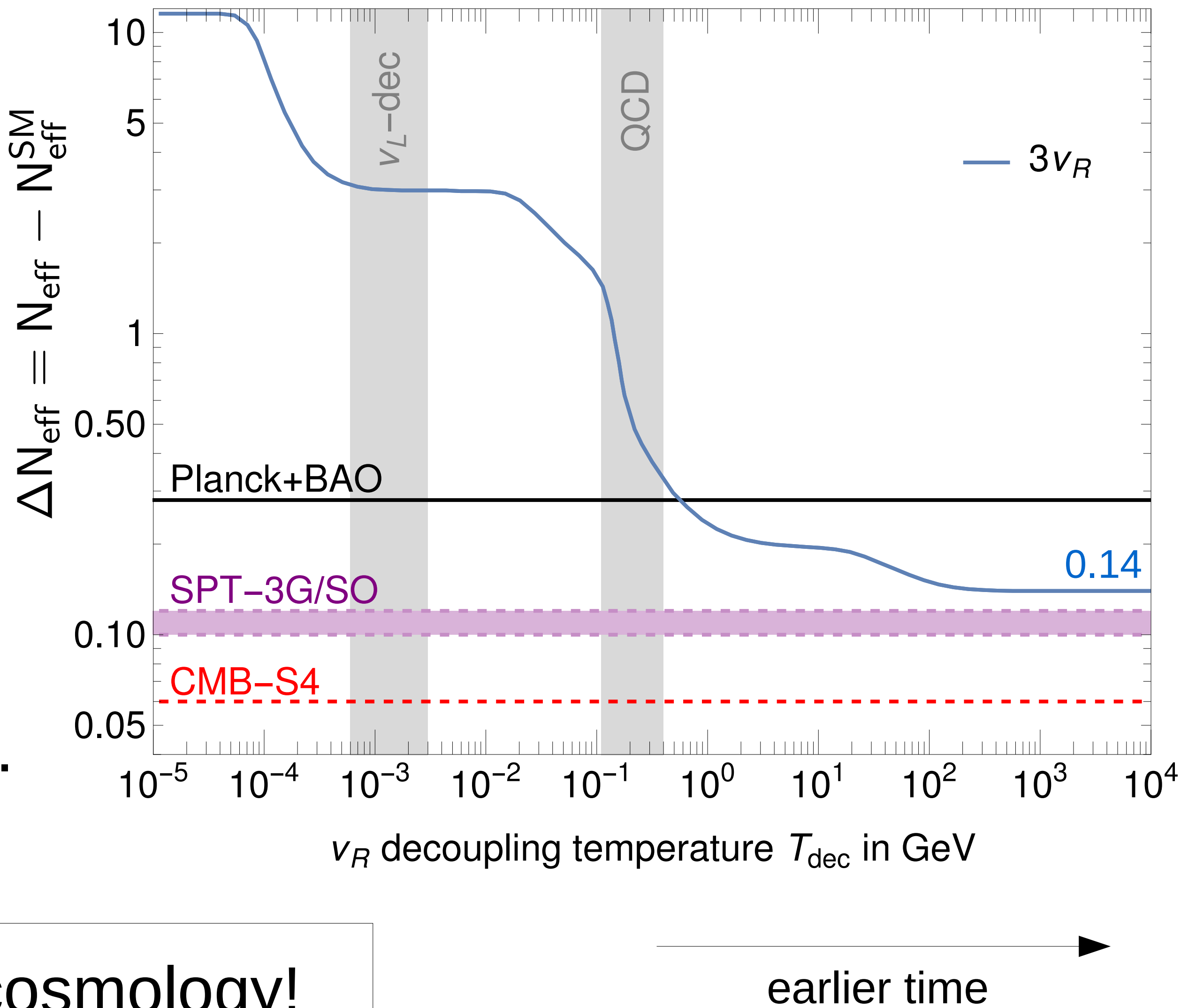
Number of effective neutrinos: N_{eff}

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

  [Abazajian+, 1907.04473]

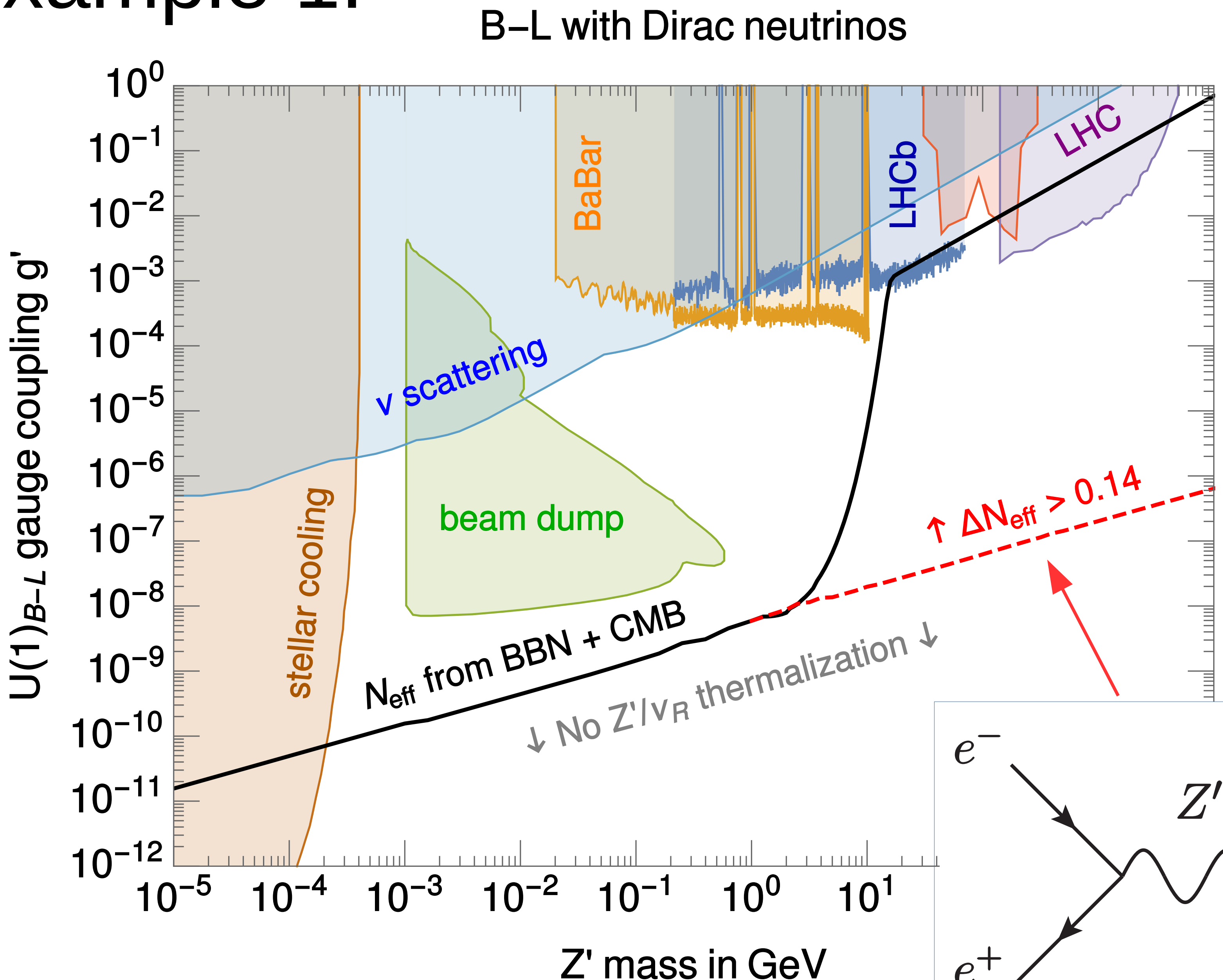
- Will probe if 3 ν_R were *ever* thermal!
- Strong constraint for any Dirac ν model.

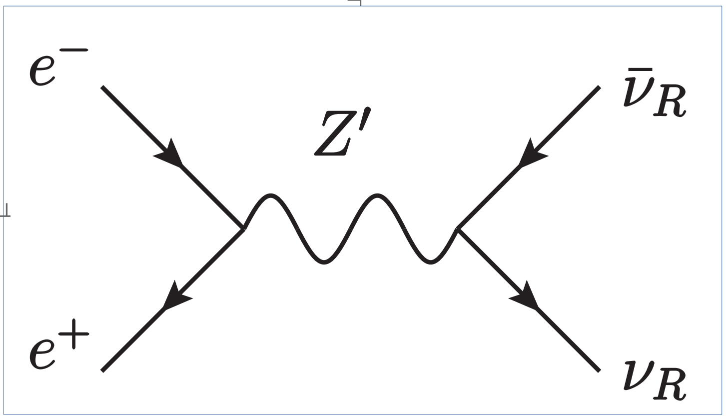
  [**Heeck** & Abazajian, PRD '19]



Dirac vs. Majorana via cosmology!

Example 1:



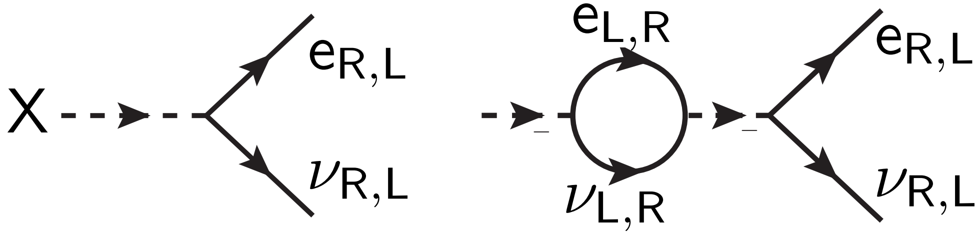


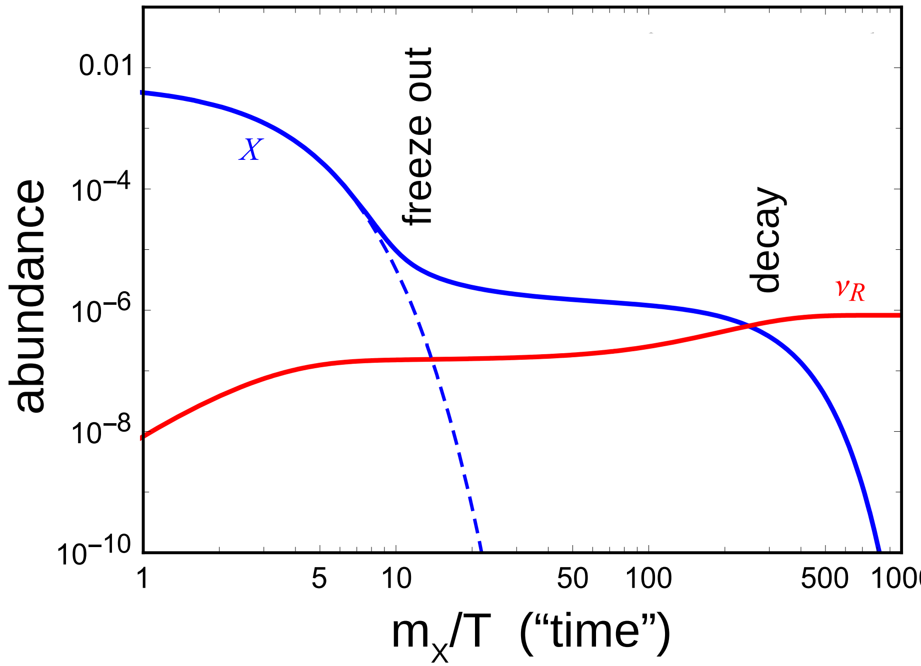
[**Heeck**, PLB '14; **Heeck** & Abazajian, PRD '19]

Example 2: Dirac leptogenesis

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

- Non-thermalization of ν_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:

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

- ν_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	ΔB
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	$4/3$	$\bar{Q}_L\nu_R X,\ \bar{d}_R L X$	0
f	$(\mathbf{1},\mathbf{2},-1/2)$	$1/2$	-1	$\bar{X}L,\ \bar{\nu}_R X H,\ \bar{X}e_R H$	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.
- ν_R number is broken, X has decays to ν_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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d	$(\mathbf{3},\mathbf{1},2/3)$	0	$-2/3$	$u_R\nu_R X^\dagger,\ d_R d_R X$	1
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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]

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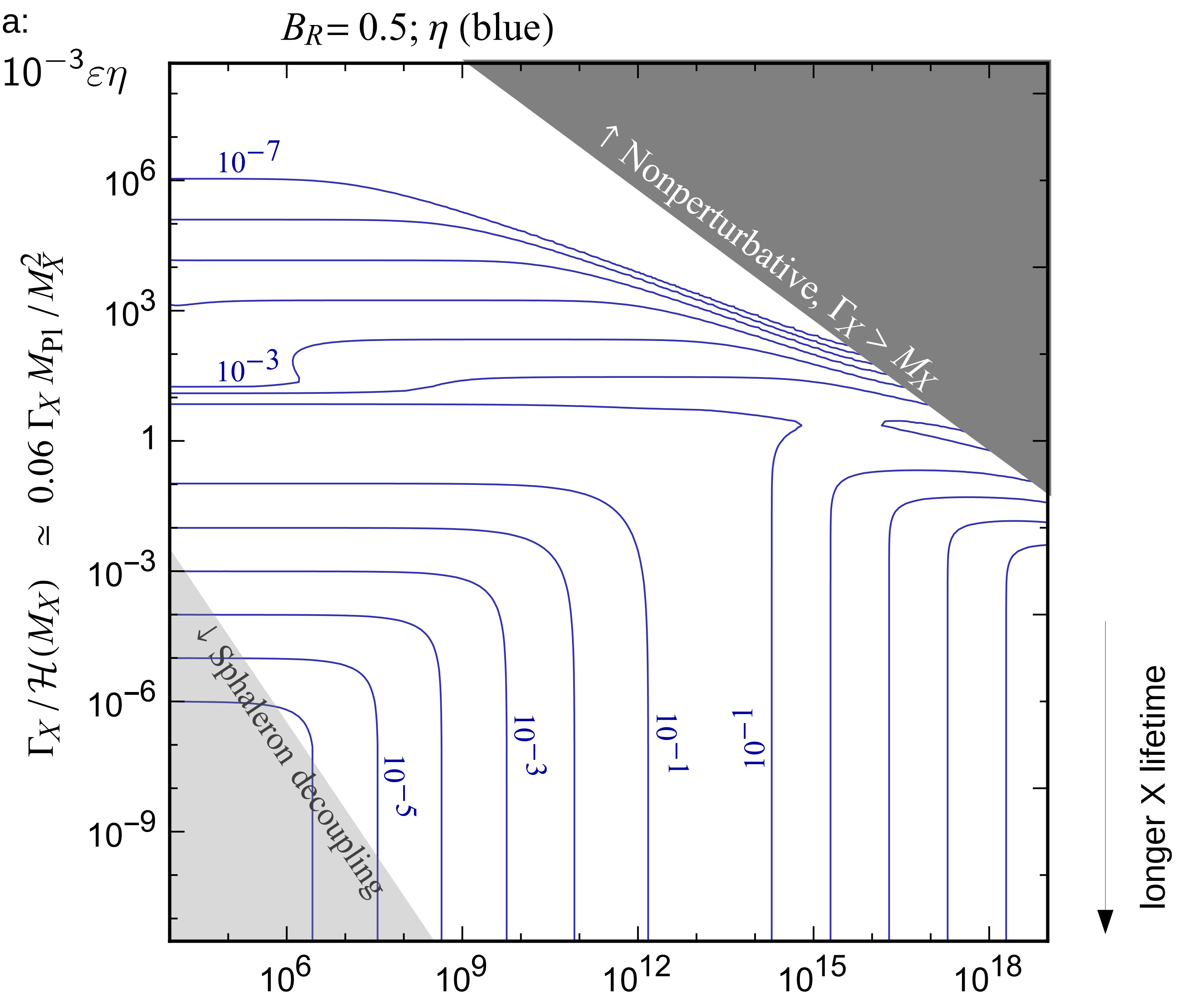
Model a:

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



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

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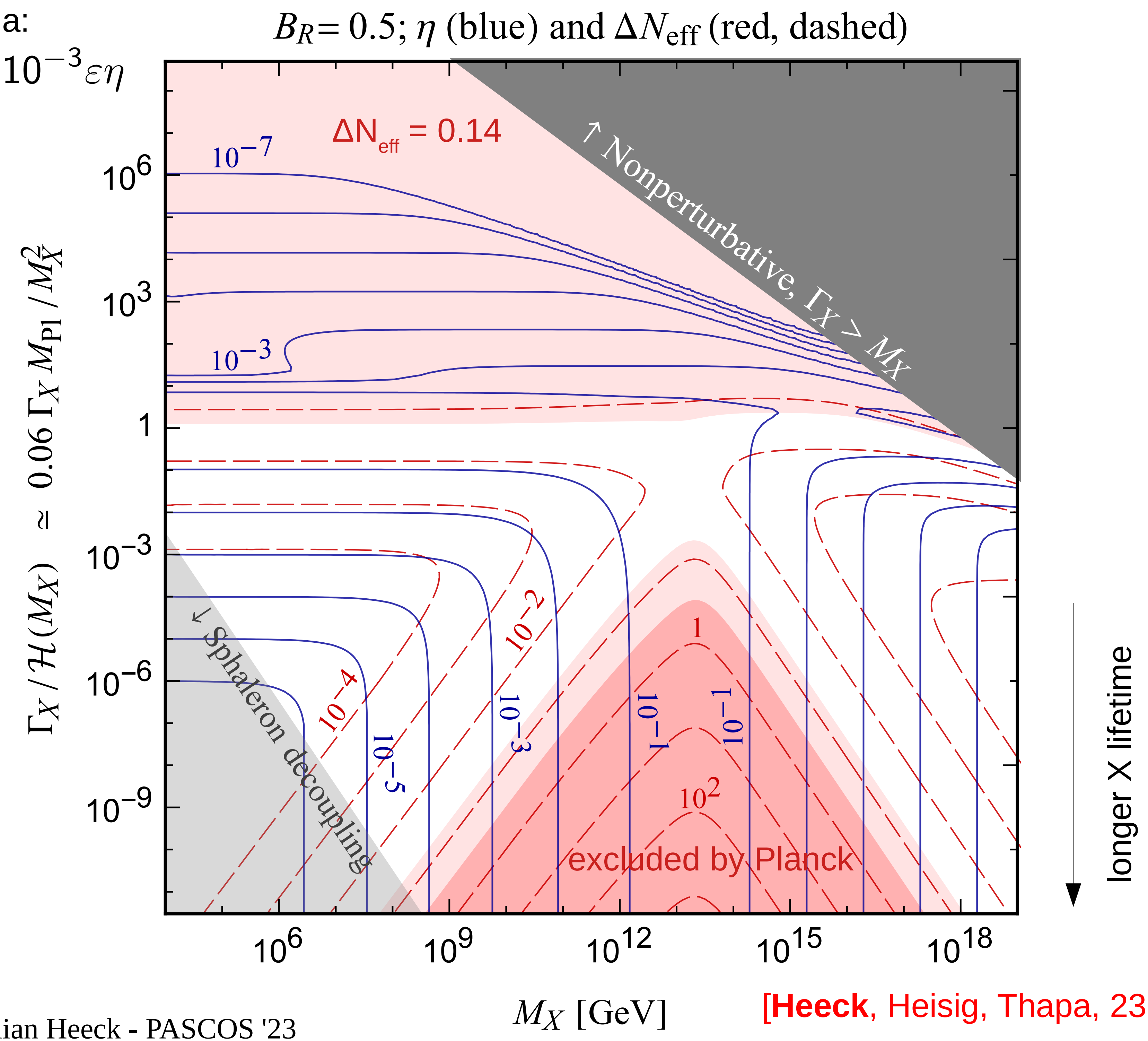
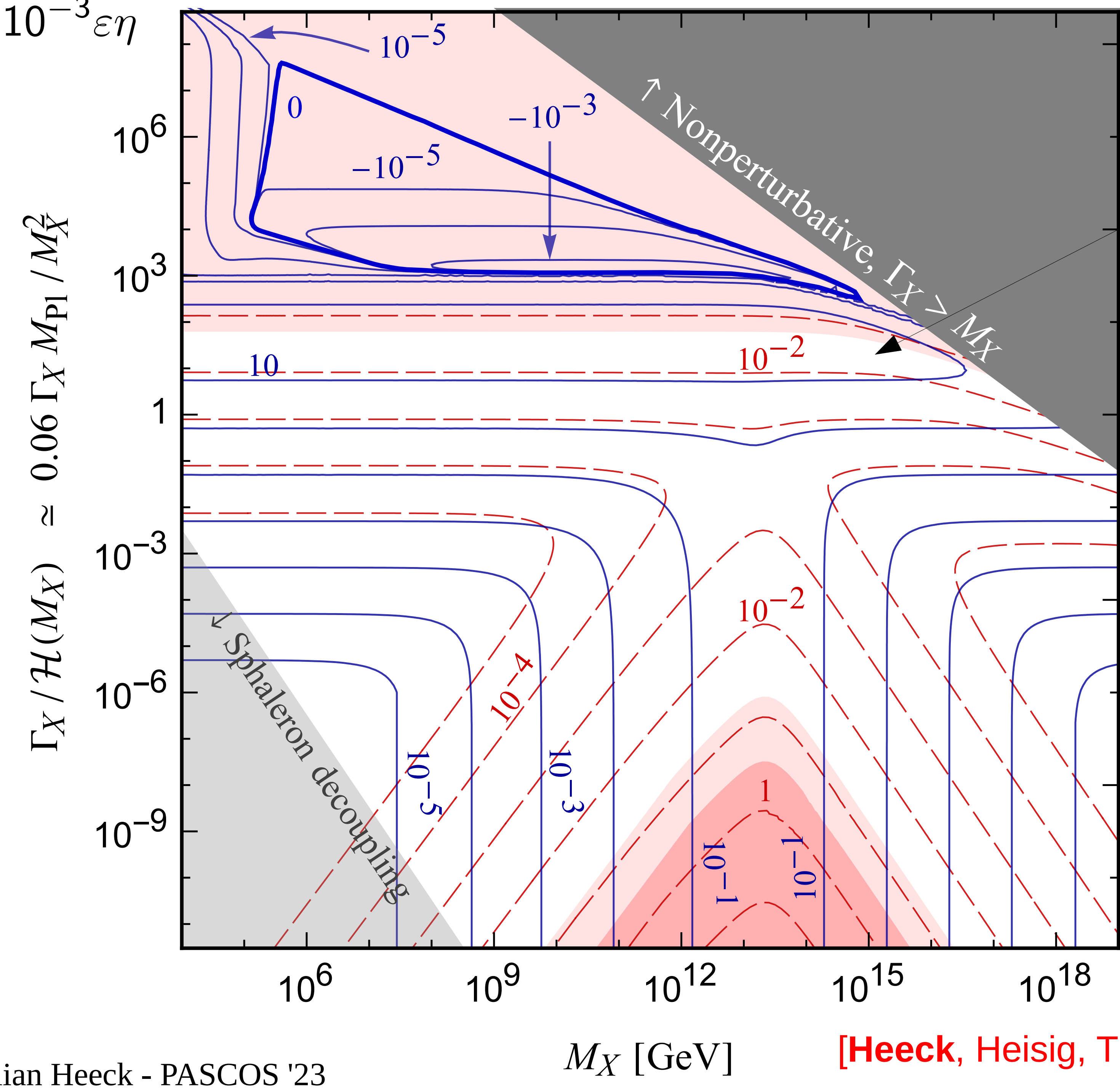


[**Heeck**, Heisig, Thapa, 2304.09893]

Model a:

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

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



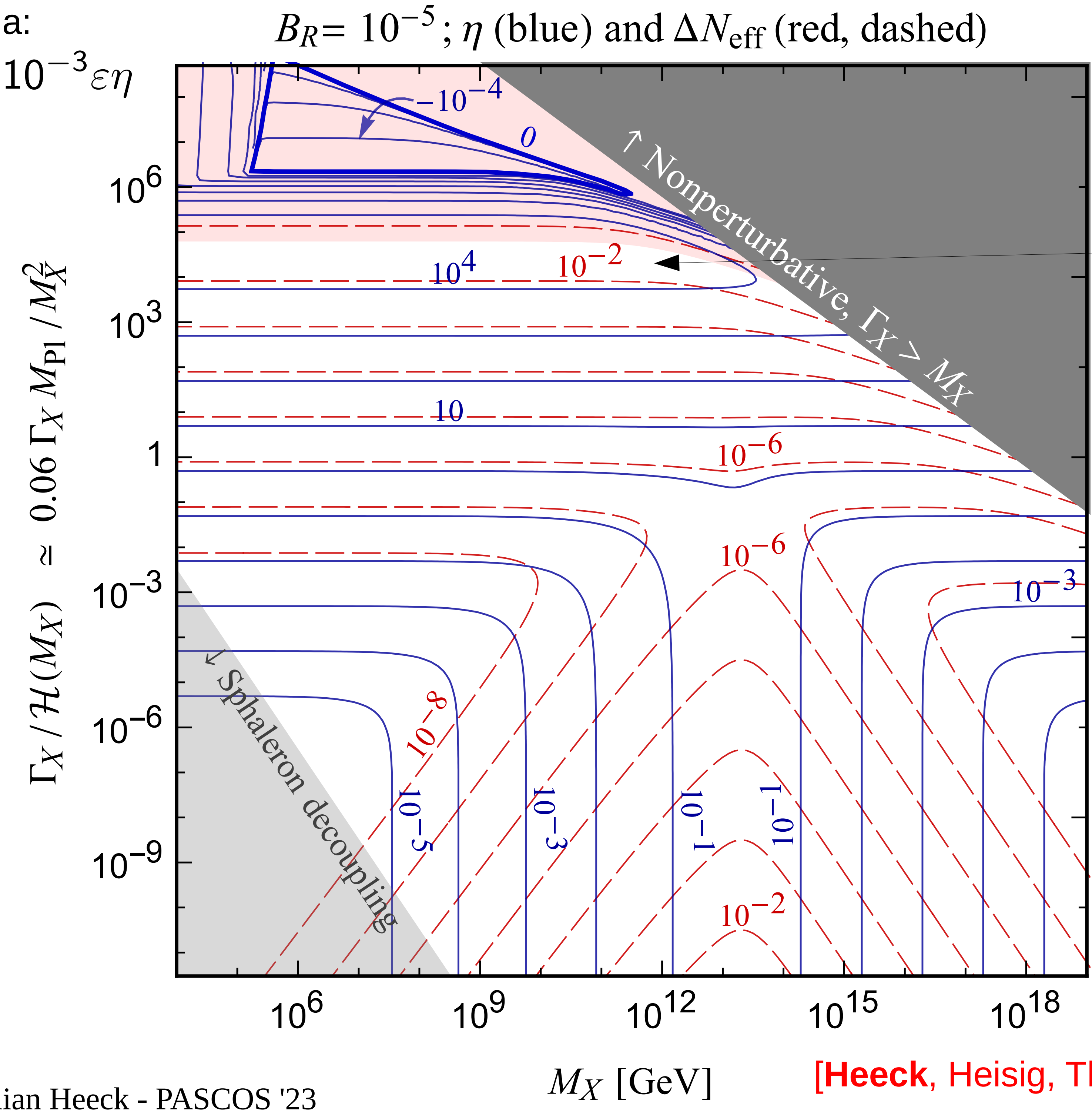
$X \to \nu_L$ in equilibrium, $X \to \nu_R$ not.

longer X lifetime

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

Model a:

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



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

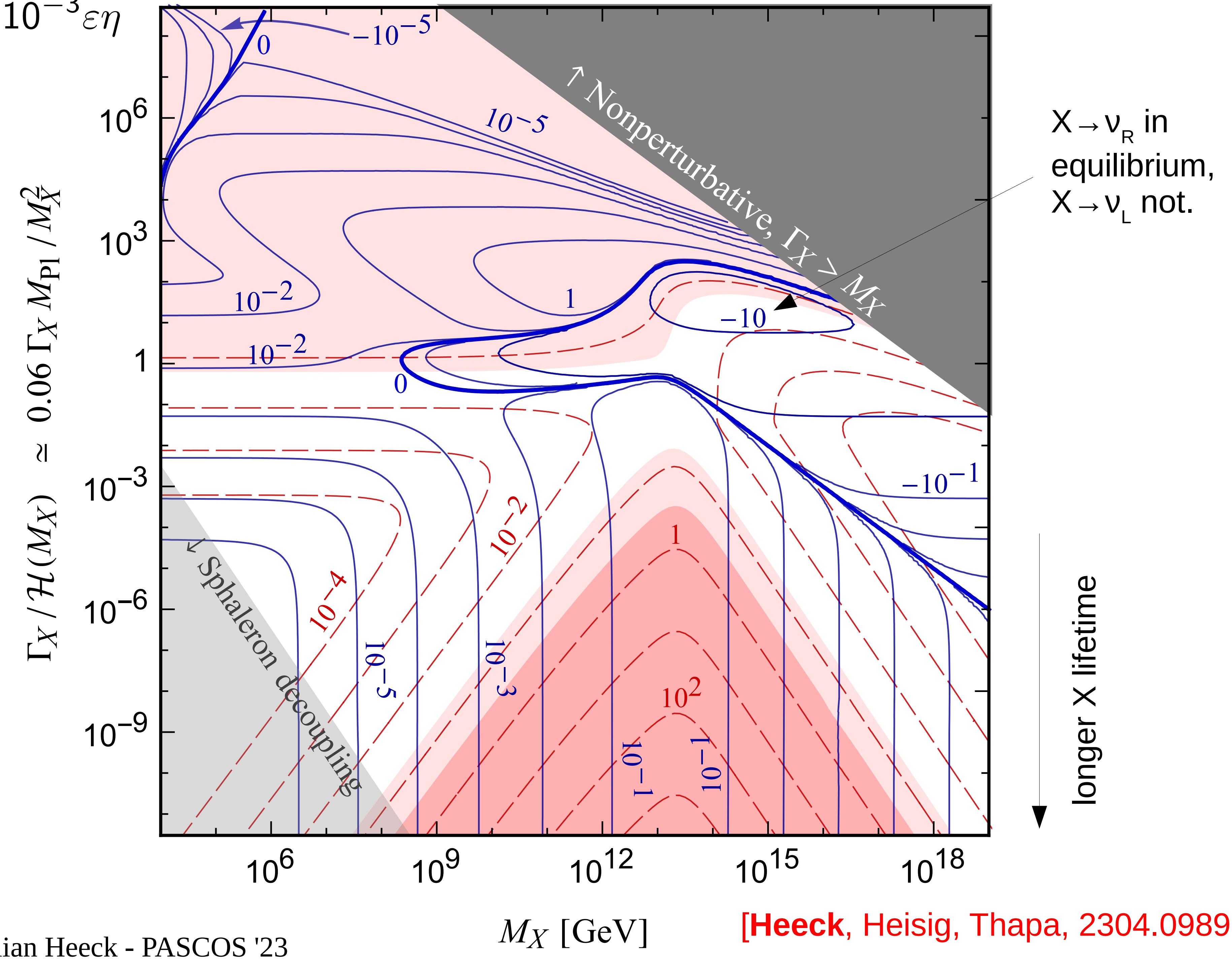
longer X lifetime

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

Model a:

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

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

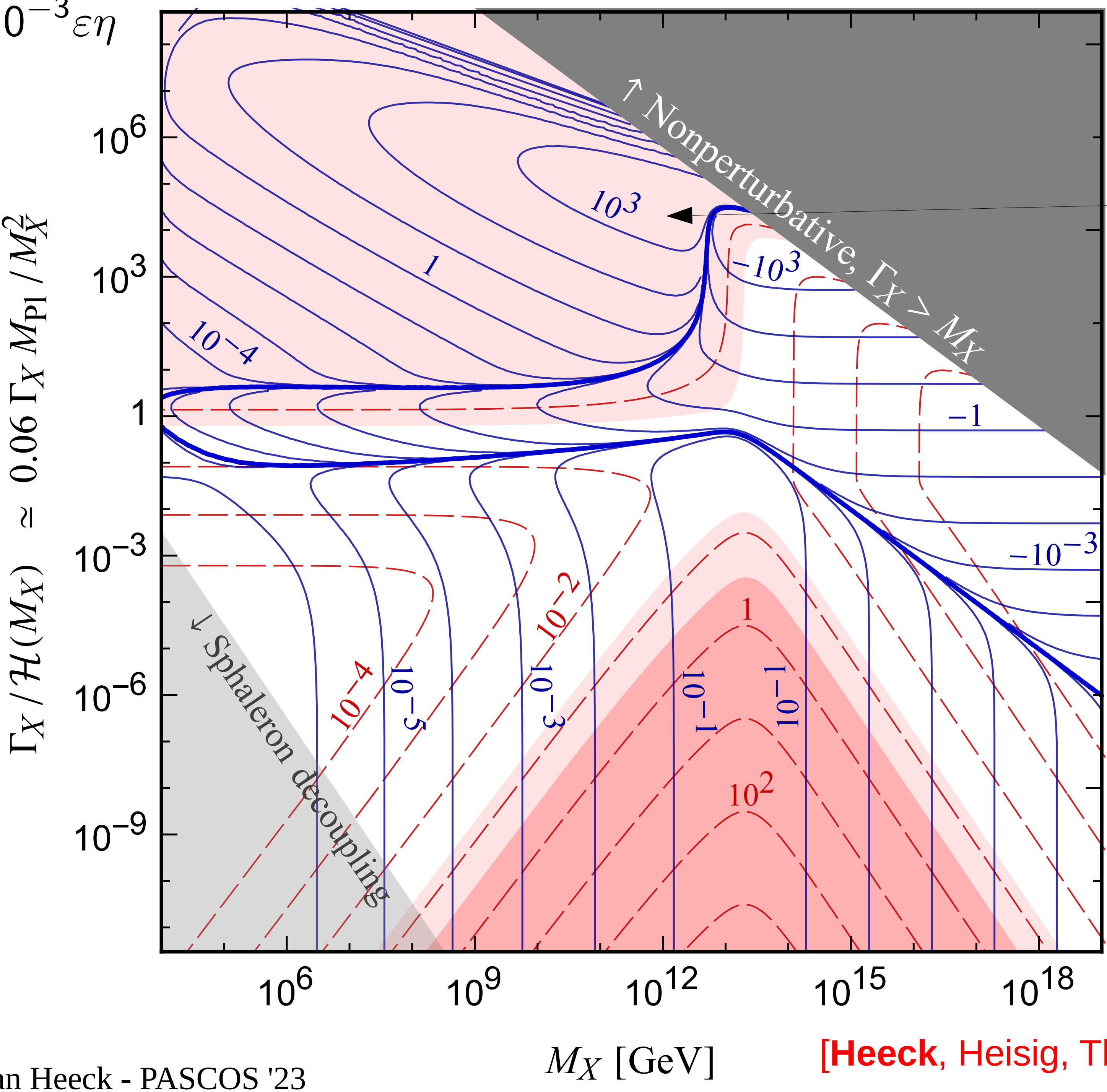


[**Heeck**, Heisig, Thapa, 2304.09893]

Model a:

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

$B_R = 1 - 10^{-5}$; η (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]

Dirac leptogenesis

- Very efficient asymmetry generation!
- X decays into (high-energy) ν_R: testable ΔN_{eff}!
- Even works if X are too heavy to be on-shell: Dirac leptogenesis *via scattering*. [**Heeck**, Heisig, Thapa, 2306.13707]
- 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	ΔB
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 $\Delta B = (\nu_R - \bar{\nu}_R) \neq 0$ directly! Predicts proton decay $p \to K^+ \bar{\nu}_R$!

Dirac leptogenesis is fascinating!

Summary

- Dirac vs. Majorana is an important question.
- Can confirm Majorana via $0\nu\beta\beta$, what about Dirac?
- Dirac neutrinos predict ultra-light ν_R!
- Could lead to detectable ΔN_{eff} in models that aim to explain
  - Dirac nature,
  - small neutrino mass,
  - the baryon asymmetry via leptogenesis.
- Soon we will now if Dirac neutrinos were ever thermalized!

Dirac neutrinos might show up soon!

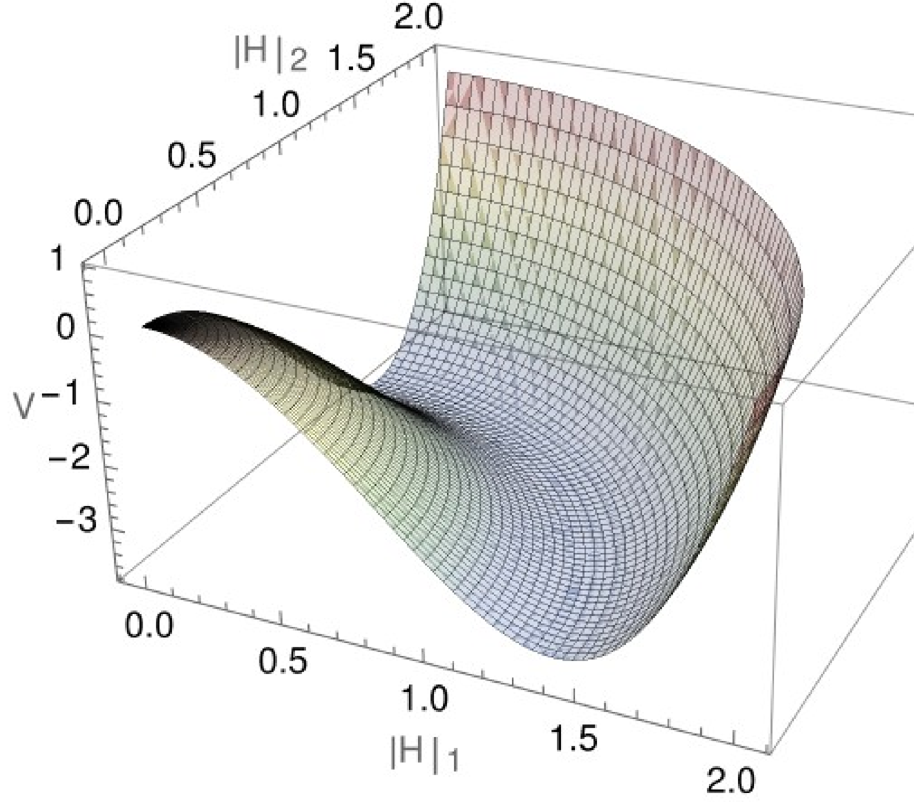
Backup

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:

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

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



- For neutrinos: no ν_R !

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

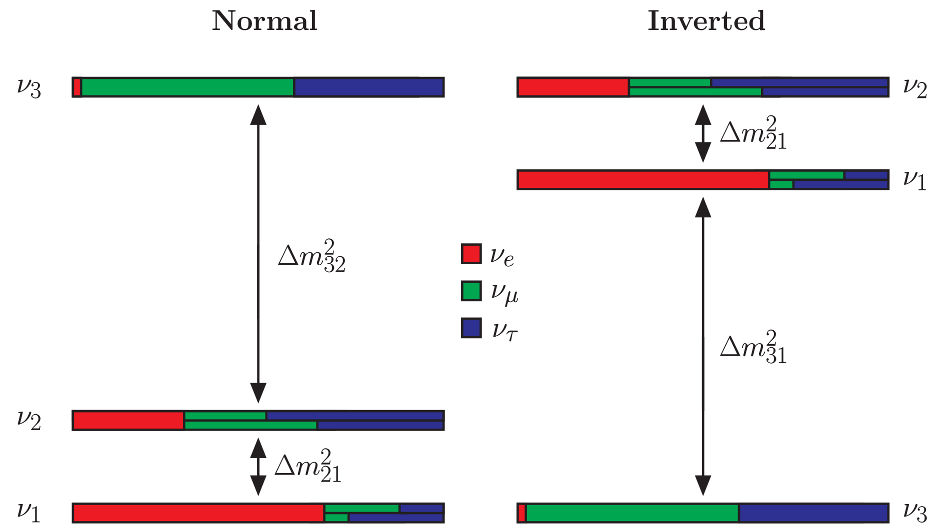
Broken L:

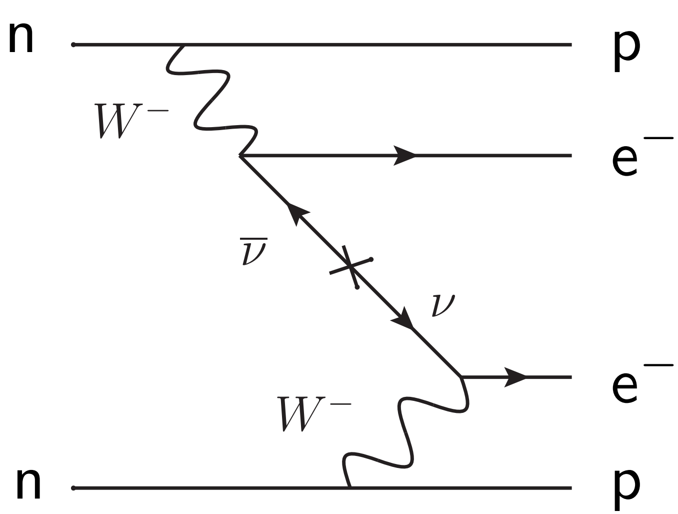
- Neutrinoless double-β decay:

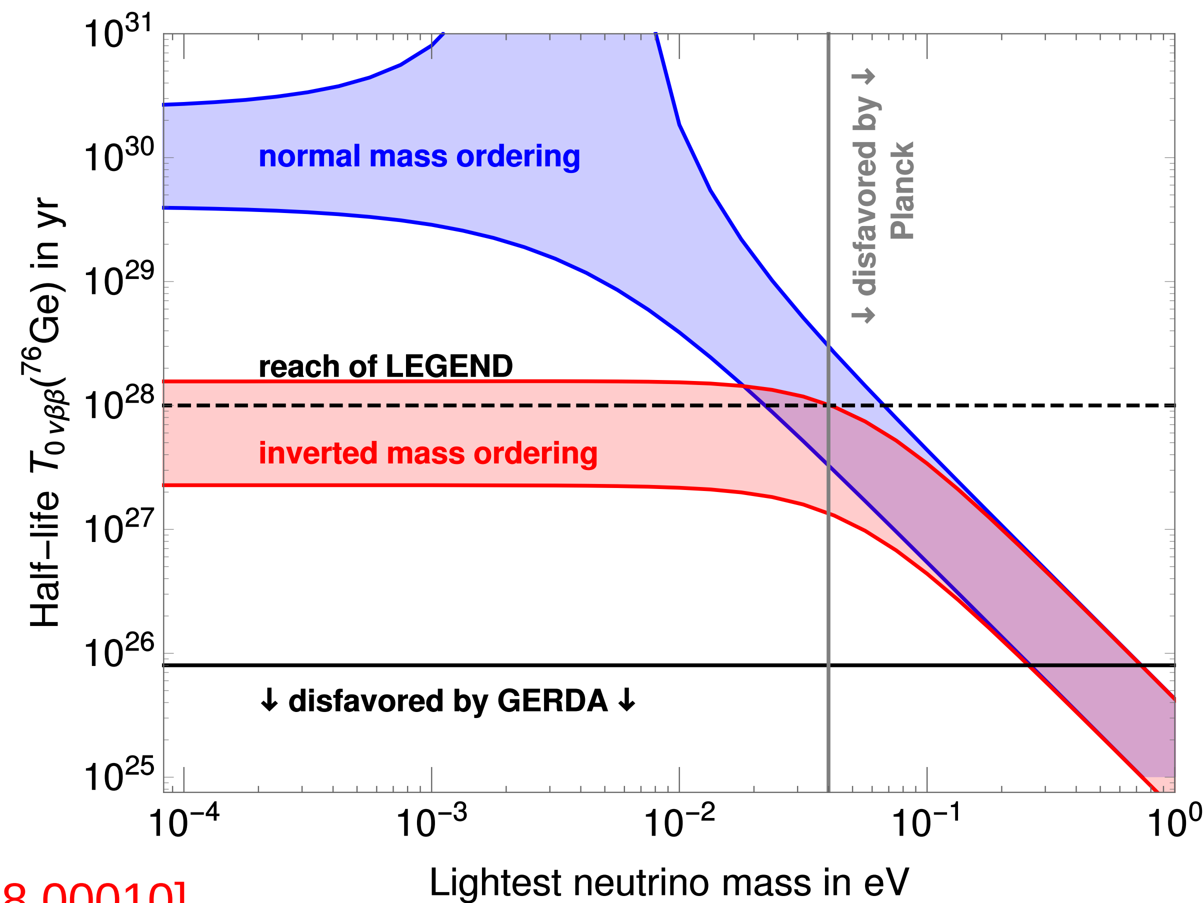
  (A,Z) → (A,Z+2) + 2 e⁻

  in β stable isotopes.

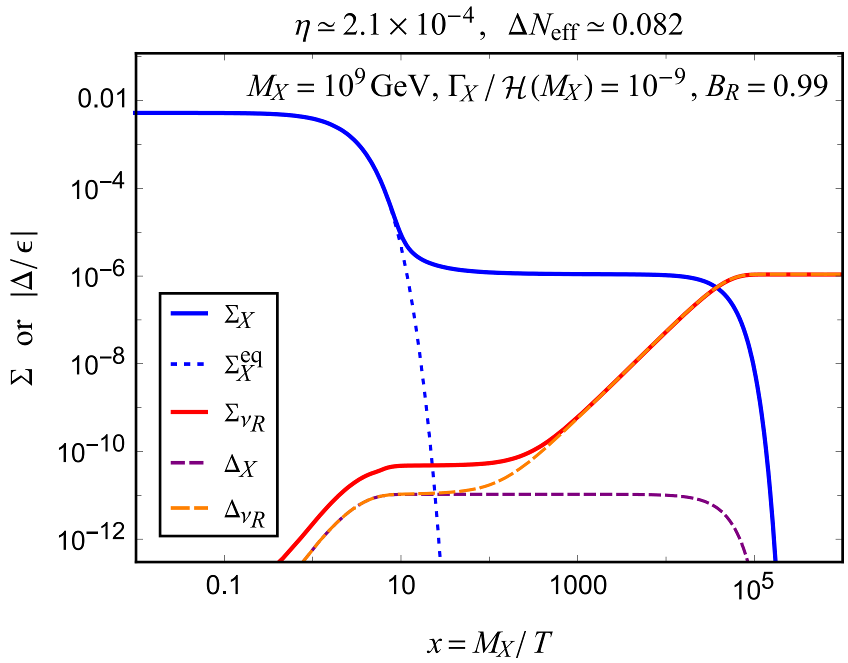
- Current limits ~ 10^{26} yr.
- 0ν2β ⇔ Majorana ν.

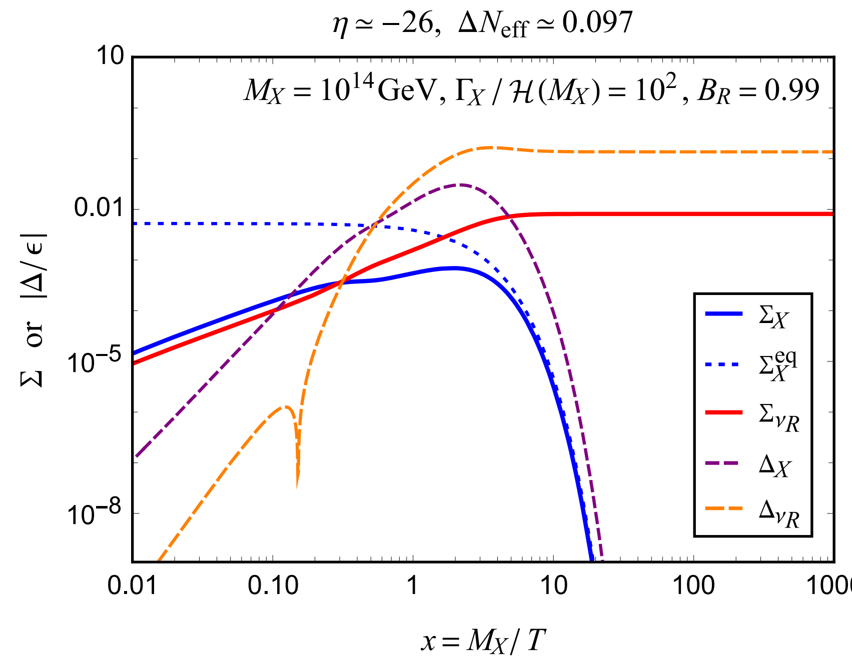


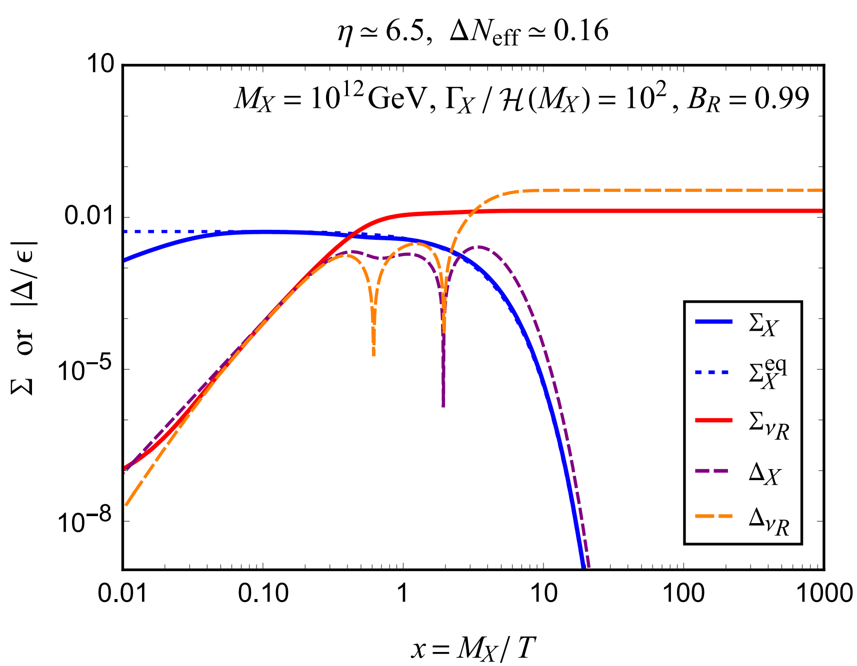


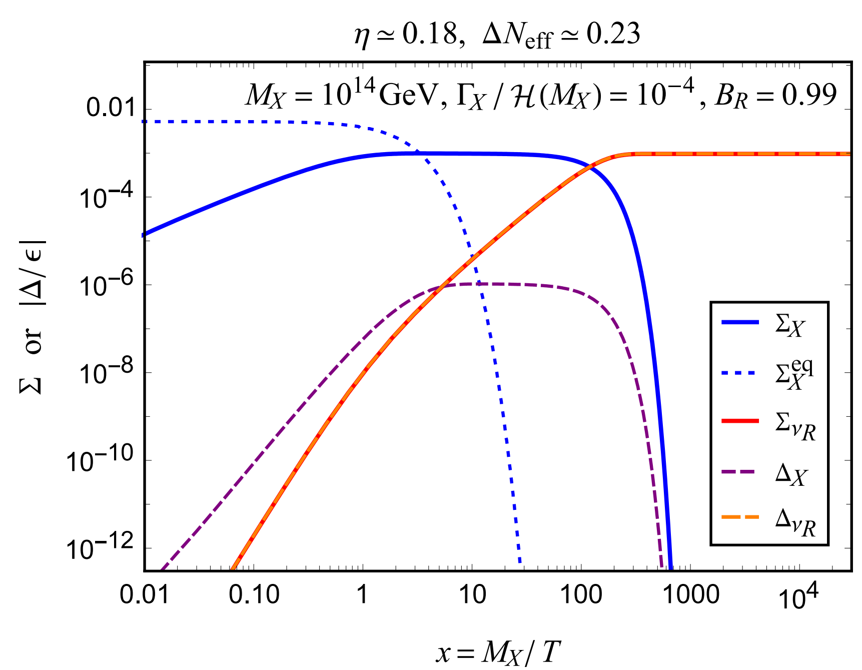


[Review: Perez, Wise, **Heeck** et al, 2208.00010]


$\eta \simeq 2.1 \times 10^{-4}$, $\Delta N_{\rm eff} \simeq 0.082$
$M_X = 10^9\,$GeV, $\Gamma_X / \mathcal{H}(M_X) = 10^{-9}$, $B_R = 0.99$
Σ_X
$\Sigma_X^{\rm eq}$
$\Sigma_{\nu R}$
Δ_X
$\Delta_{\nu R}$
Σ or $|\Delta/\epsilon|$
$x = M_X / T$


$\eta \simeq -26$, $\Delta N_{\rm eff} \simeq 0.097$
$M_X = 10^{14}\,$GeV, $\Gamma_X / \mathcal{H}(M_X) = 10^2$, $B_R = 0.99$
Σ_X
$\Sigma_X^{\rm eq}$
$\Sigma_{\nu R}$
Δ_X
$\Delta_{\nu R}$
Σ or $|\Delta/\epsilon|$
$x = M_X / T$


$\eta \simeq 6.5$, $\Delta N_{\rm eff} \simeq 0.16$
$M_X = 10^{12}\,$GeV, $\Gamma_X / \mathcal{H}(M_X) = 10^2$, $B_R = 0.99$
Σ_X
$\Sigma_X^{\rm eq}$
$\Sigma_{\nu R}$
Δ_X
$\Delta_{\nu R}$
Σ or $|\Delta/\epsilon|$
$x = M_X / T$


$\eta \simeq 0.18$, $\Delta N_{\rm eff} \simeq 0.23$
$M_X = 10^{14}\,$GeV, $\Gamma_X / \mathcal{H}(M_X) = 10^{-4}$, $B_R = 0.99$
Σ_X
$\Sigma_X^{\rm eq}$
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Δ_X
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Σ or $|\Delta/\epsilon|$
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