Leptogenesis from a First-Order Lepton-Number Breaking Phase Transition

Andrew Long

TeVPA 2017

at Ohio State University

Aug 10, 2017

Kavli Institute
for Cosmological Physics
at The University of Chicago

based on work with Andrea Tesi & Lian-Tao Wang (1703.04902 & JHEP)

Exploding Lepton Bubbles!

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Executive Summary

In this talk, I'm going to …

… assume that lepton-number is broken spontaneously by the VEV of a new scalar singlet field that induces a Majorana mass for new sterile neutrinos. (light neutrino masses arise from the seesaw mechanism)

… assume that there was a corresponding cosmological phase transition in the early universe, and that it was first order.

… show that the baryon asymmetry of the universe can arise at this phase transition via the CP-violating scattering of heavy Majorana fermions from the bubble wall (similar to Cohen, Kaplan, & Nelson's original implementation of EW baryogenesis)

… calculate the predicted baryon asymmetry and discuss the associated phenomenology (gravitational waves, $0\nu\beta\beta$, dark radiation)

The Model

Minimal generalization of the leptogenesis model

Promote the Majorana mass parameter to a scalar field:

$$\Delta\mathscr{L} = -\frac{1}{2}M_N NN - \lambda_N LHN + \text{h.c.}$$

(type-I seesaw model; thermal leptogenesis)

$$\Downarrow$$

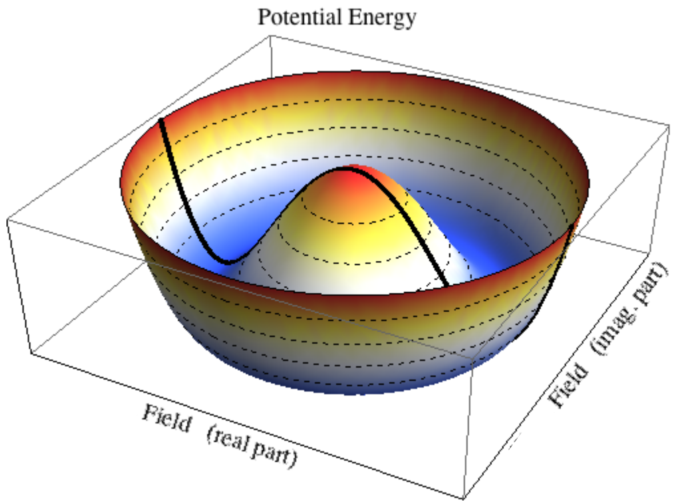
$$\Delta\mathscr{L} = -\frac{1}{2}\kappa SNN - \lambda_N LHN + \text{h.c.} - U(S)$$

(sometimes called the singlet Majoron model)

Now the theory has a $U(1)_L$ symmetry under which the charges are $Q_L(L) = +1$, $Q_L(N) = -1$, and $Q_L(S) = +2$.

Spontaneous L-number breaking

The scalar potential U(S) causes S to get a vev, which breaks lepton-number.



$$\longrightarrow \quad \langle S \rangle = v_S/\sqrt{2}$$

Yukawa interaction induces a Majorana mass

$$\Delta\mathscr{L} = -\frac{1}{2}\kappa S N N \;\longrightarrow\; -\frac{1}{2} M_N N N \quad \big(M_N = \kappa\langle S \rangle\big)$$

Light neutrino masses

Integrating out the heavy Majorana neutrinos N induces a Majorana mass for the light neutrinos

$$\Delta\mathscr{L} = -\frac{1}{2} M_N N N - \lambda_N L H N \ \longrightarrow\ -\lambda_N^2 \frac{LHLH}{M_N} \to -\frac{\lambda_N^2 v^2}{M_N} \nu\nu$$

Fiducial Parameters:

$$\kappa S N N \longrightarrow \kappa \sim 1$$

$$\lambda_N L H N \longrightarrow \lambda_N \sim 0.01 - 1$$

$$U(S) \longrightarrow v_S \sim 10^{10} - 10^{14}\ \mathrm{GeV}$$

$$M_N \sim \kappa v_S \sim 10^{10} - 10^{14}\ \mathrm{GeV}$$

$$m_\nu \sim \lambda_N^2 v^2 / M_N \sim 0.1\ \mathrm{eV}$$

Baryogenesis Overview

Overview of the Mechanism

① Thermal $U(1)_L$ symmetry restoration
② First order phase transition
③ Scattering on Wall (CP & L violation)
④ Transfer of L-number to SM
⑤ Washout Avoidance

Lepton-number unbroken

$$\langle S \rangle = 0$$
$$m_N = 0$$

(1) Initially <S> = 0 and the $U(1)_L$ symmetry is restored.

$$\boldsymbol{N} = \text{massless, left-handed anti-lepton}$$

$$\overline{\boldsymbol{N}} = \text{massless, right-handed lepton}$$

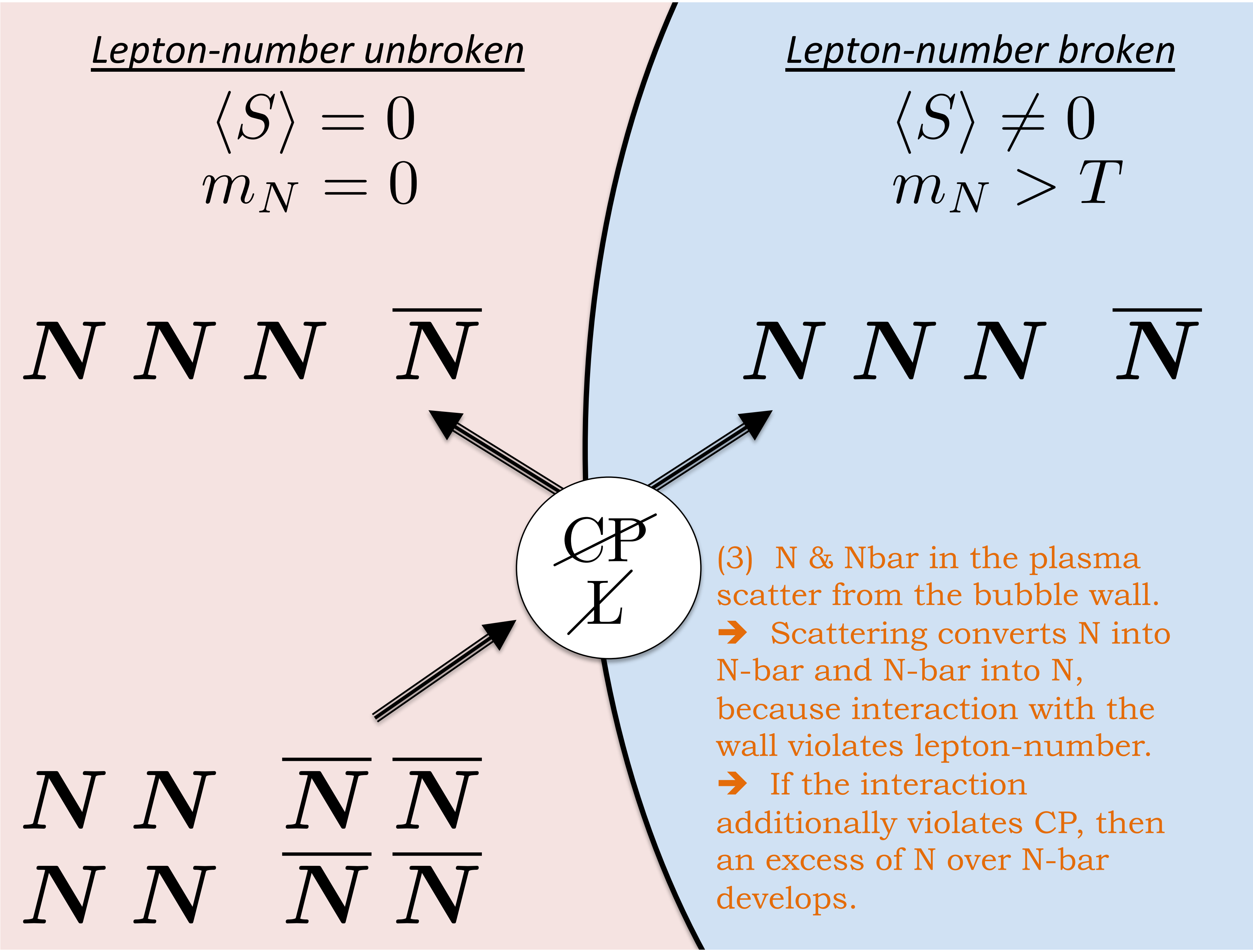
Lepton-number unbroken

$$\langle S \rangle = 0$$
$$m_N = 0$$

Lepton-number broken

$$\langle S \rangle \neq 0$$
$$m_N > T$$

(2) The $U(1)_L$-breaking phase transition is first order. Bubbles of broken phase nucleate and expand.



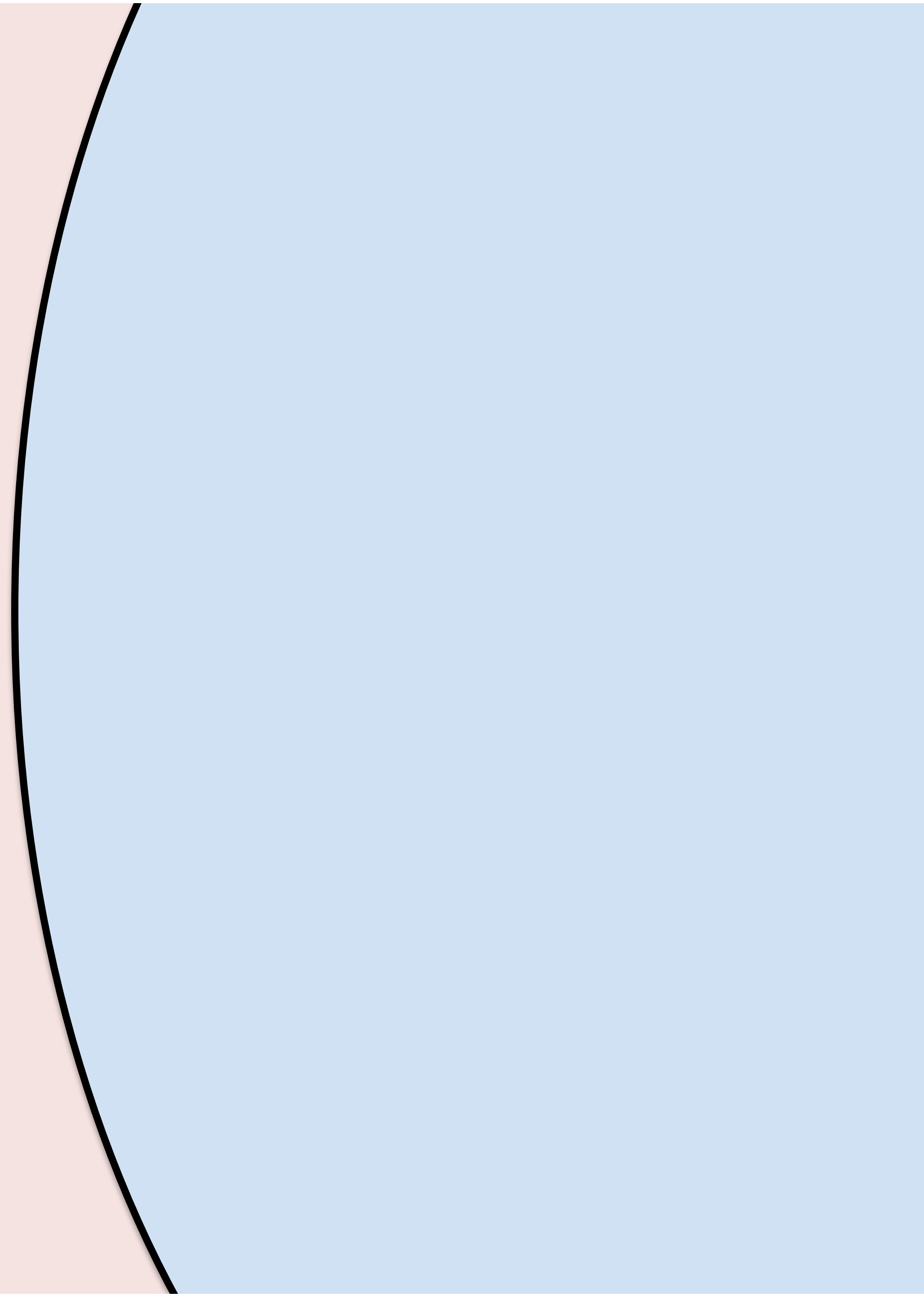
Lepton-number unbroken
$\langle S \rangle = 0$
$m_N = 0$
Lepton-number broken
$\langle S \rangle \neq 0$
$m_N > T$
$N\ N\ N\ \overline{N}$
$N\ N\ N\ \overline{N}$
$\cancel{CP}$
$\cancel{L}$
$N\ N\ \overline{N}\ \overline{N}$
$N\ N\ \overline{N}\ \overline{N}$
(3) N & Nbar in the plasma scatter from the bubble wall.
➔ Scattering converts N into N-bar and N-bar into N, because interaction with the wall violates lepton-number.
➔ If the interaction additionally violates CP, then an excess of N over N-bar develops.

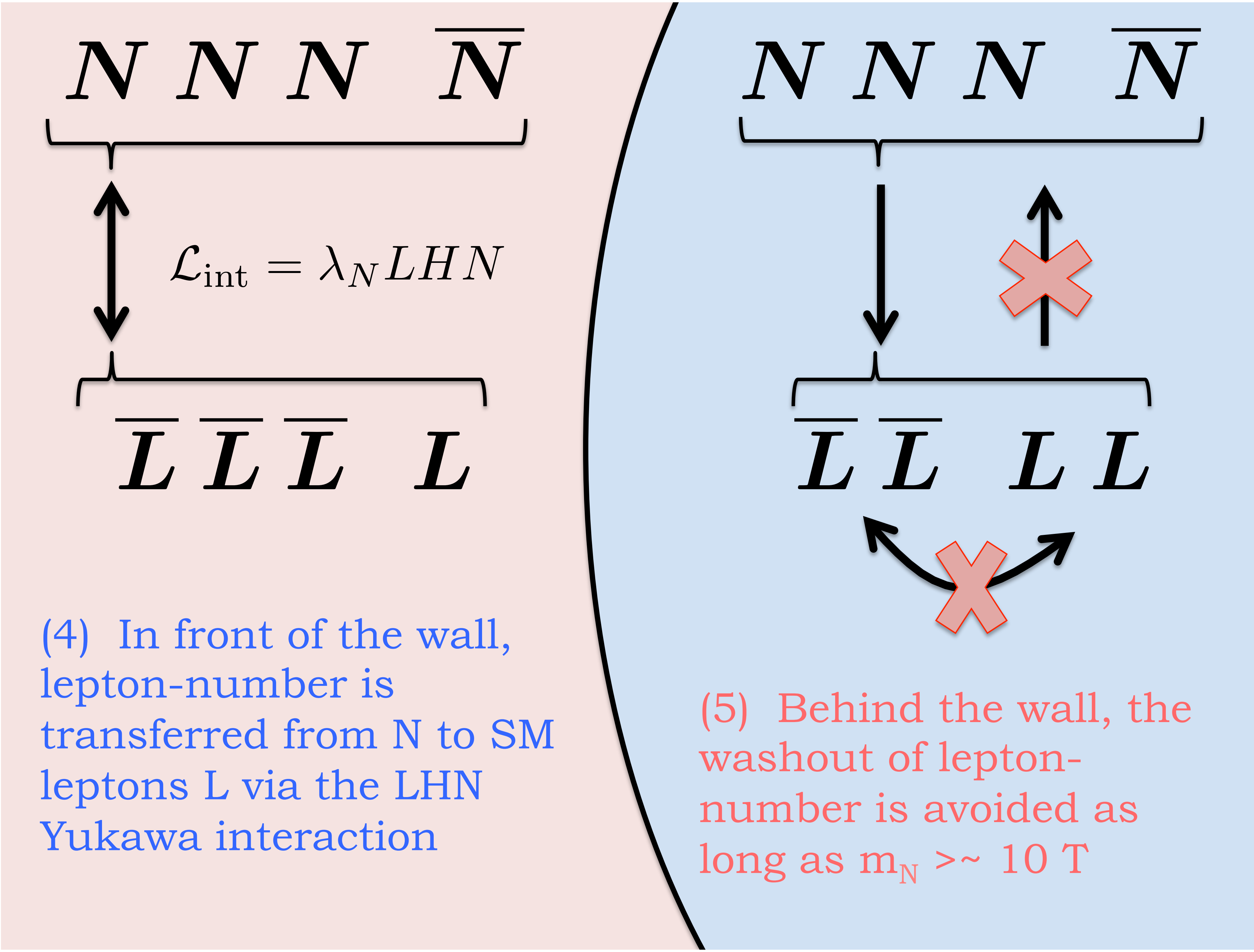
$$\underbrace{\boldsymbol{N\ N\ N\ \ \overline{N}}}$$

$$\Big\updownarrow \qquad \mathcal{L}_{\text{int}} = \lambda_N LHN$$

$$\overbrace{\boldsymbol{\overline{L}\ \overline{L}\ \overline{L}\ \ L}}$$

(4) In front of the wall, lepton-number is transferred from N to SM leptons L via the LHN Yukawa interaction





$N\ N\ N\ \overline{N}$
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$\overline{L}\ \overline{L}\ \overline{L}\ L$
(4) In front of the wall, lepton-number is transferred from N to SM leptons L via the LHN Yukawa interaction
$N\ N\ N\ \overline{N}$
$\overline{L}\ \overline{L}\ L\ L$
(5) Behind the wall, the washout of lepton-number is avoided as long as m_N >~ 10 T

Overview of the Mechanism

① **Thermal $U(1)_L$ symmetry restoration**
② **First order phase transition**
③ **Scattering on Wall (CP & L violation)**
④ **Transfer of L-number to SM**
⑤ **Washout Avoidance**

Some similarity with an early implementation of EW baryogenesis: Cohen, Kaplan, & Nelson (1990, 91)
Related work by: Shu, Tait, & Wagner (2007); Fornal, Shirman, Tait, & West (2017); Cline, Kainulainen, & Tucker-Smith (2017)

It's the best of both worlds ...

As in thermal leptogenesis we have a framework that naturally accommodates the light neutrino masses and predicts that the light neutrinos are Majorana particles.

As in electroweak baryogenesis we have a first order phase transition, which furnishes complementary cosmological observables (gravitational waves).

Estimate the baryon asymmetry

The resultant baryon asymmetry

The baryon-to-entropy ratio can be expressed as

number density of B-number

N-to-L conversion factor (via LHN)

N-number source (rate per unit volume) at the wall

$$\frac{n_{\mathrm{B}}}{s} = f_{\mathrm{L}\to\mathrm{B}}\,\varepsilon_{L\leftrightarrow\bar{L}}\,f_{N\to L}\,\varepsilon_{N\leftrightarrow\bar{N}}\,\frac{L_w}{v_w}\,\frac{S_N^{\not{\mathrm{C}}\mathrm{P}}}{s}$$

entropy density of plasma

L-to-B conversion factor (via sphaleron)

asymmetry washout factors

wall passage time

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entropy density of plasma

L-to-B conversion factor (via sphaleron)

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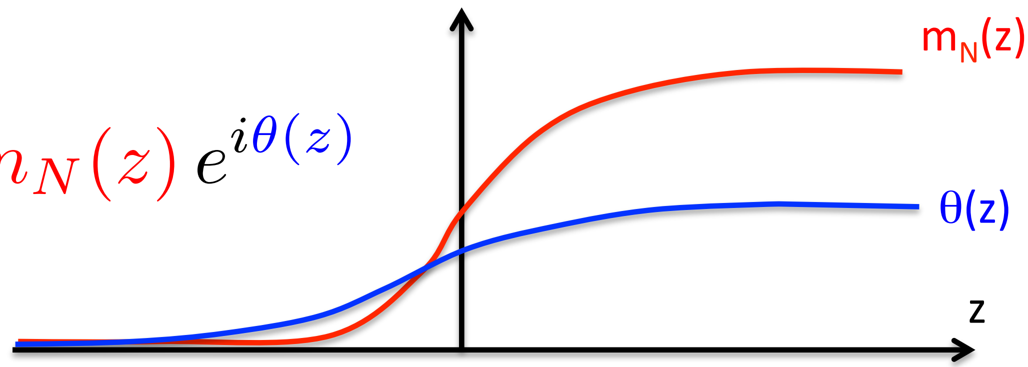
wall passage time

CP-violating source of N-number $S_N^{C\!\!\!/P}$

At the wall, the Majorana mass acquires a non-trivial profile

$$M_N(z) = m_N(z)\, e^{i\theta(z)}$$



Due to the phase gradient, N and N-bar effectively see potential energy barriers of different heights.

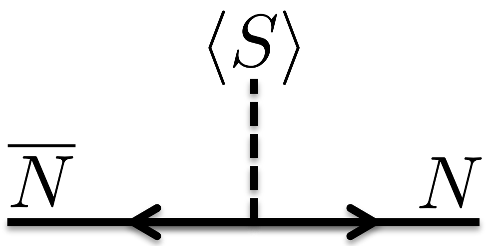
$$E \to E \pm \partial_z \theta(z)$$

Consequently, N and N-bar have different probabilities to be reflected. We denote the reflection probabilities as R and R-bar.

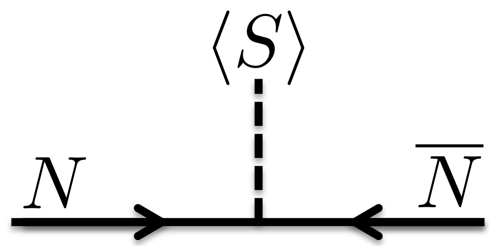
CP-violating source of N-number $S_N^{\not{C}\not{P}}$

This formalism was developed by Huet & Nelson (1995). Can also calculate source w/ semi-classical force formalism (see: Joyce, Prokopec, Turok; Cline, Kainulainen; Konstandin)

When a reflection occurs, lepton-number is violated



probability R



probability R-bar

Consequently, the wall becomes a source of N-number:

$$S_N^{\not{C}\not{P}}(z) = \frac{2}{\tau} \int_{-\infty}^{\infty} \frac{\mathrm{d}p_x}{2\pi} \int_{-\infty}^{\infty} \frac{\mathrm{d}p_y}{2\pi} \int_{0}^{\infty} \frac{\mathrm{d}p_z}{2\pi} \left(f_N^{(\mathrm{out})} - f_N^{(\mathrm{in})} \right) \left(\mathcal{R} - \bar{\mathcal{R}} \right)$$

thermalization time scale

phase space distribution functions (Fermi-Dirac) for particles incident on the wall from the bubble exterior (out) and interior (in)

differential reflection probability arising from CP-violating effects, which goes as dθ/dz

CP-violating source of N-number $S_N^{C\!\!\!/P}$

The integral evaluates to

$$S_N^{C\!\!\!/P}(T) \approx \frac{\gamma_w v_w}{\pi^2}\, m_N(T)^3\, \frac{\theta(T)}{L_w}\, \min\left[(T\tau)^3\,,\, 0.1(T\tau)^{-1}\right] e^{-m_N(T)/T}$$

Boltzmann suppression

In the regime T << m_N, only particles in the tail of the most momentum distribution have enough energy to enter the bubble.

When all particles are reflected, R = R-bar = 1, the CP-violating effects vanish. Hence, the Boltzmann suppression.

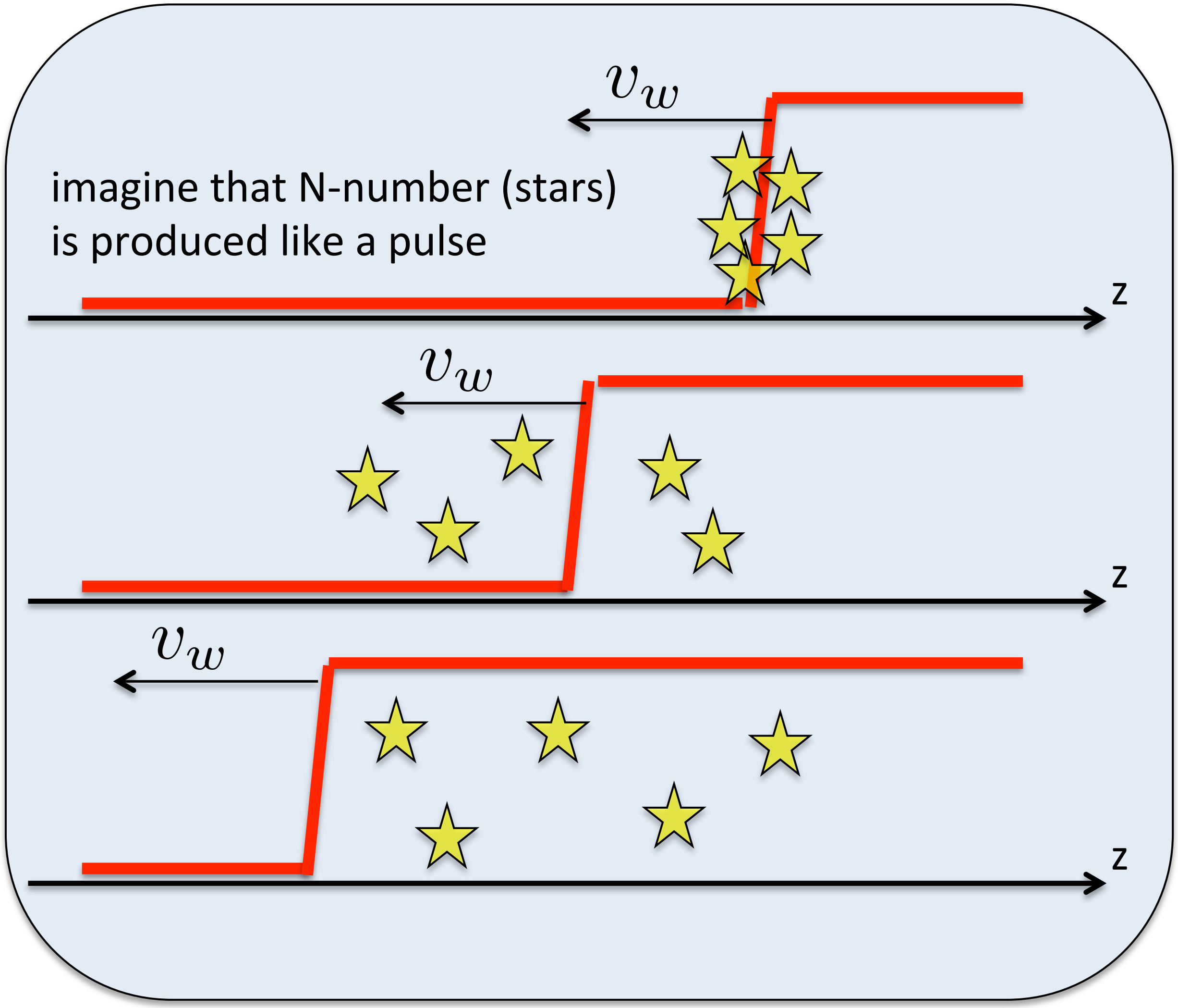
N-number diffusion

The sourced *N*-number diffuses away from the bubble wall.

$$\Delta x_{\rm diff} = \sqrt{D_N \Delta t}$$
$$\Delta x_{\rm wall} = v_w \Delta t$$

become equal when

$$L_{\rm d} = D_N / v_w$$
$$\tau_{\rm d} = D_N / v_w^2$$



N-number diffusion

The sourced *N*-number diffuses away from the bubble wall.

We describe this process with a transport equation:

$$v_w n_N' - D_N n_N'' \approx -\Gamma_N \, n_N + S_N^{\not{\mathrm{C}}\mathrm{P}}$$

where

… v_w is the wall speed

… D_N is the diffusion coefficient

… Γ_N is the washout rate due to *N* <--> *N*-bar flips (active at the wall, and inside the bubble)

… S_N is the CP-violating source (only active at the wall)

N-number diffusion

In front of the wall, the solution is

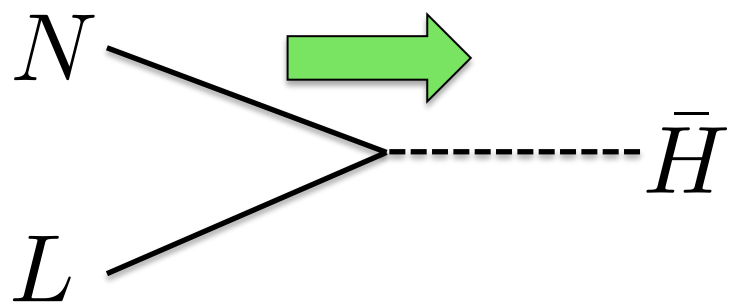
$$n_N(z) \approx \min\left[1, \frac{1}{\sqrt{\Gamma_N D_N / v_w^2}}\right] \frac{L_w}{v_w} S_N^{\not{C}\not{P}} e^{v_w z / D_N}$$

The *N*-number precedes the wall for a distance D_N/v_w.

The amplitude is suppressed due to washout.

Conversion into L-number $f_{N \to L}$

In front of the wall, the *N*-number excess pushes the *LHN* Yukawa interaction out of equilibrium.



The excess of *N*'s becomes a deficit of *L*'s – a negative *L*-number.

$$n_L \approx -\left(\Gamma_{LHN} \frac{D_N}{v_w^2}\right) n_N$$

where $\Gamma_{\rm LHN}$ is the thermally-averaged *LHN* interaction rate.

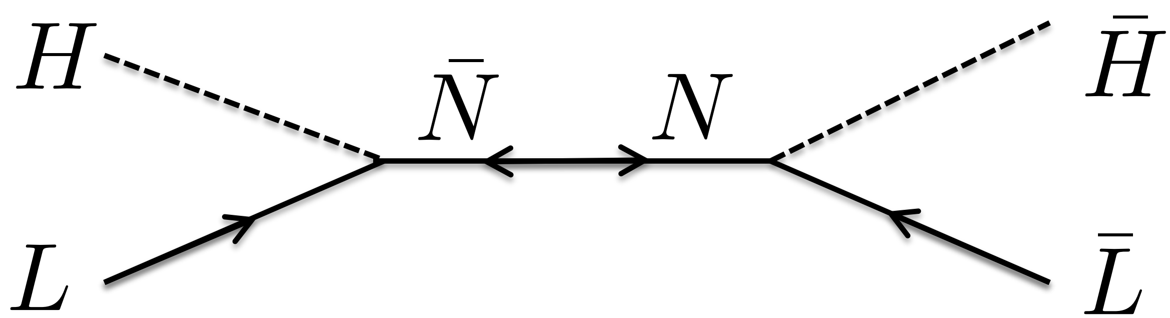
$$\Gamma_{\rm LHN} \sim \lambda_N^2 \frac{m_H(T)^2}{T^2} \sim \frac{m_N m_\nu}{v^2} \frac{m_H(T)^2}{T^2}$$

b/c of seesaw: neutrino mass suppression makes conversion inefficient unless m_N >> v

Lepton-number washout avoidance $\varepsilon_{L\to\bar{L}}$

The L-number diffuses into the bubble where $U(1)_L$ is broken.

Lepton-number is threatened to be washed out by processes like



The lepton-number will be suppressed by a washout factor

$$\varepsilon_{L\leftrightarrow\bar{L}} = \exp\Big[-\int_{t_{\rm L}}^{\infty} {\rm d}t'\,\Gamma_{\rm w.o.}(t)\Big] = \exp\Big[-\int_{0}^{T_{\rm L}} \frac{{\rm d}T}{T}\,\frac{\Gamma_{\rm w.o}(T)}{H(T)}\Big]$$

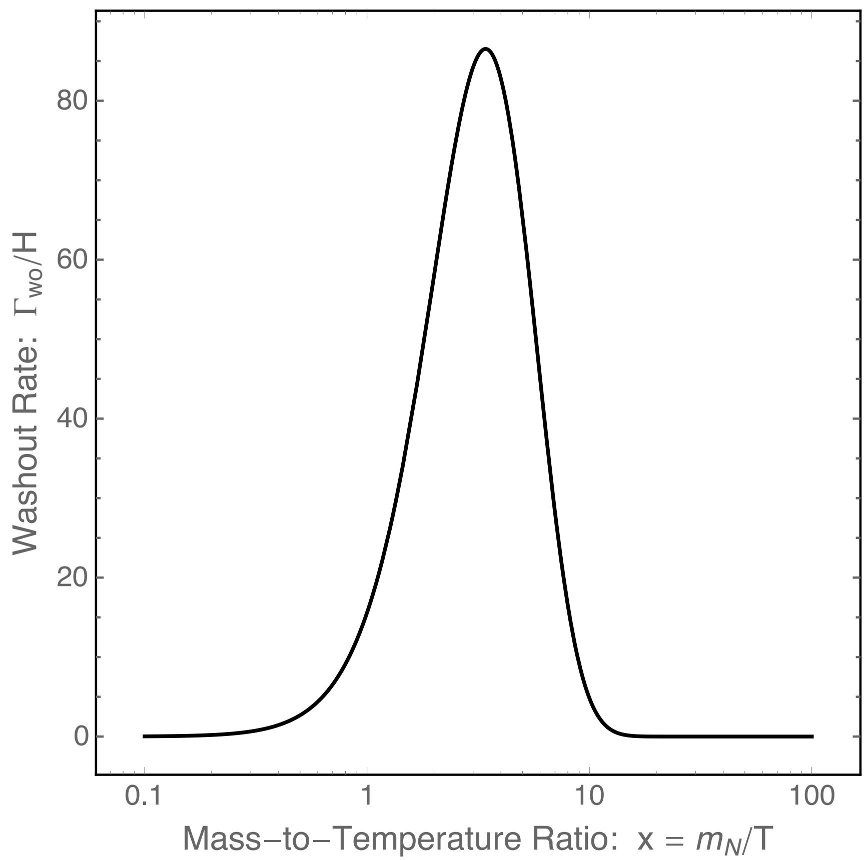
$$\Gamma_{\rm w.o.} \sim \lambda_N^2\, m_N^{5/2}\, T^{-3/2}\, e^{-m_N/T}$$

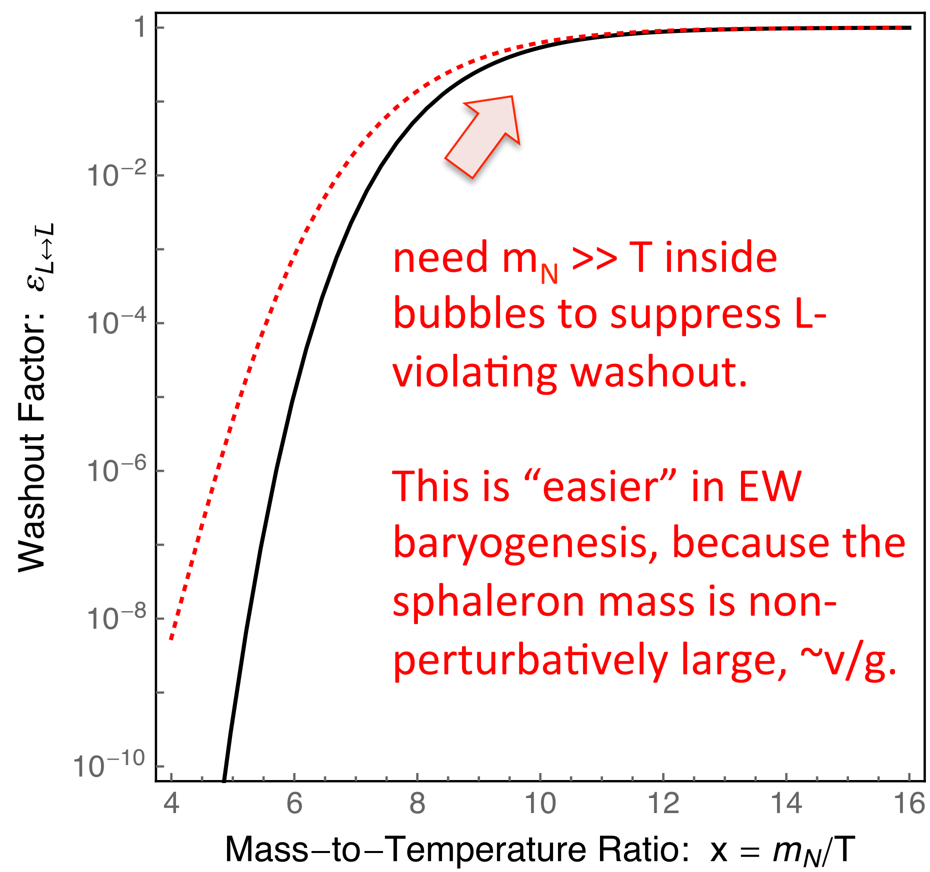
Boltzmann suppression

Lepton-number washout avoidance $\varepsilon_{L \to \bar{L}}$

We evaluate the washout factor…

$$\varepsilon_{L \leftrightarrow \bar{L}} \approx \exp\Big[-32.5\, x^{5/2}\, e^{-x}\Big]_{x = m_N(T_\mathrm{L})/T_\mathrm{L}}$$



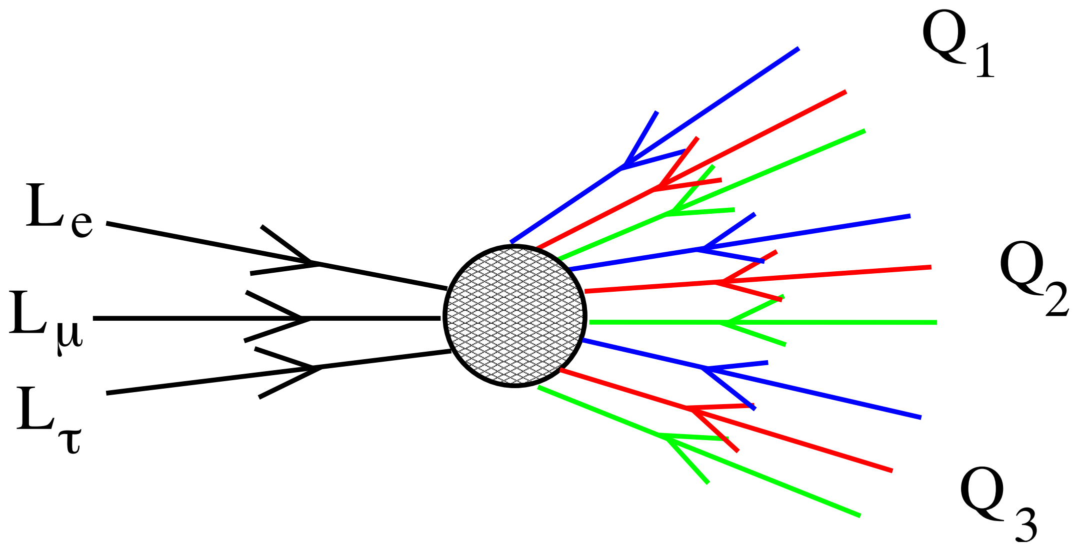


Conversion into baryon-number $f_{L\to B}$

Just like in thermal leptogenesis, the lepton-number is converted into baryon-number by the SM electroweak sphaleron processes.

Harvey & Turner (1990)

$$n_{\rm B} = -\frac{28}{79}\, n_{\rm lep}$$



Putting it all together ...

The predicted baryon-to-entropy ratio is

$$\frac{n_{\rm B}}{s} \approx \pm\frac{28}{79} \times \min\left[1, \frac{1}{\sqrt{\Gamma_N D_N/v_w^2}}\right] \times \left(\Gamma_{LHN}\frac{D_N}{v_w^2}\right) \times \exp\left[-\int_0^{T_{\rm L}} \frac{{\rm d}T}{T}\frac{\Gamma_{\rm w.o}(T)}{H(T)}\right]$$
$$\times \frac{45}{2\pi^4}\frac{\theta(T)}{g_*}\frac{m_N(T)^3}{T^3}\min\left[(T\tau)^3\,,\, 0.1(T\tau)^{-1}\right] e^{-m_N(T)/T}$$

and in the parameter regime of interest, this reduces to

$$\frac{n_{\rm B}}{s} \approx \pm\left(8.2\times 10^{-3}\right)\frac{\Gamma_{LHN} D_N/v_w^2}{T\tau\sqrt{\Gamma_N D_N/v_w^2}} \exp\left[-\int_0^{T_{\rm L}} \frac{{\rm d}T}{T}\frac{\Gamma_{\rm w.o}(T)}{H(T)}\right]\frac{\theta(T)}{g_*}\frac{m_N(T)^3}{T^3}\, e^{-m_N(T)/T}$$

Numerically,

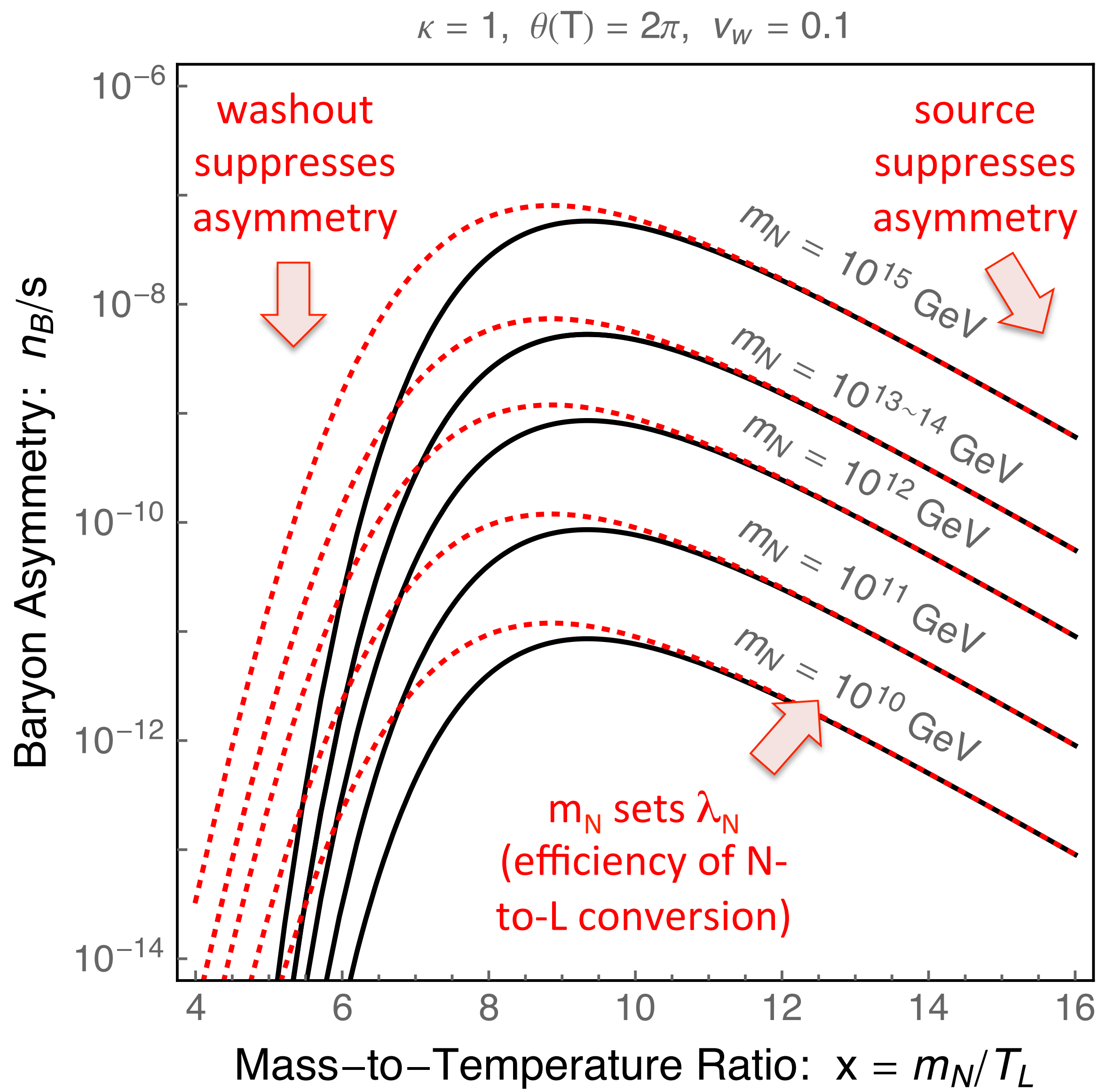
$$\frac{n_{\rm B}}{s} \approx (1\times 10^{-7})\left(\frac{m_N(T_{\rm L})}{10^{14}\ {\rm GeV}}\right)\left(\frac{\theta(T_{\rm L})}{\pi}\right)\left(\frac{v_w}{0.1}\right)^{-1}\left(\frac{g_*}{106.75}\right)^{-1}\left(\frac{x^2 e^{-x} e^{-32.5\, x^{5/2} e^{-x}}}{4\times 10^{-3}}\right)$$

Final Baryon Asymmetry …

Note that the dependence on κ (the SNN Yukawa coupling) has dropped out.

Sitting at x ~ 9, we are bounded below by exponential washout suppression & bounded above by exponential source suppression.

Lowering m_N lowers λ_N (through the seesaw relation). This makes the N→L conversion less efficient & suppresses the baryon asymmetry.



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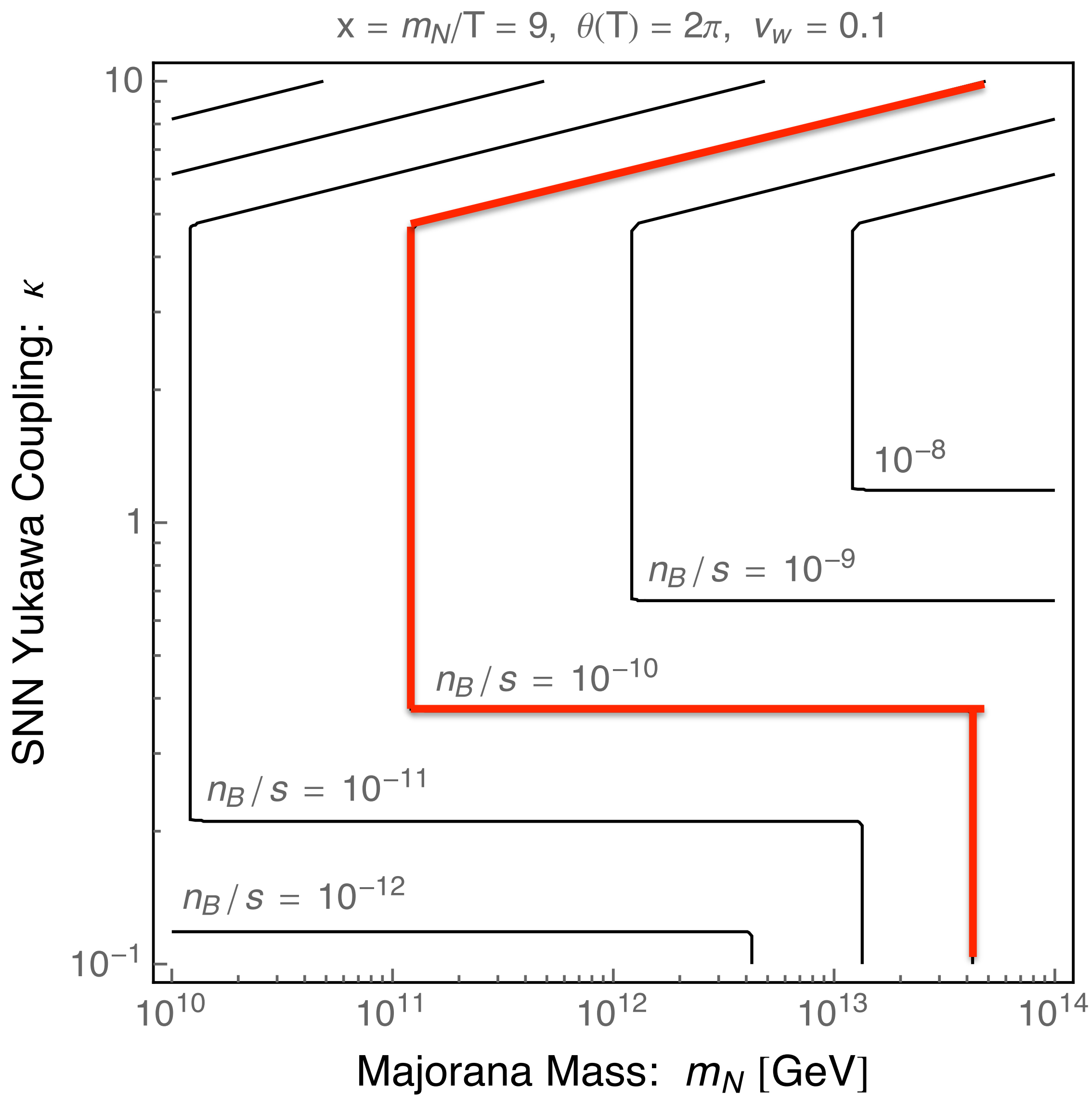

Phenomenology Highlights

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Neutrinoless Double Beta Decay – since the light neutrinos are Majorana particles, this lepton-number-violating channel is open.

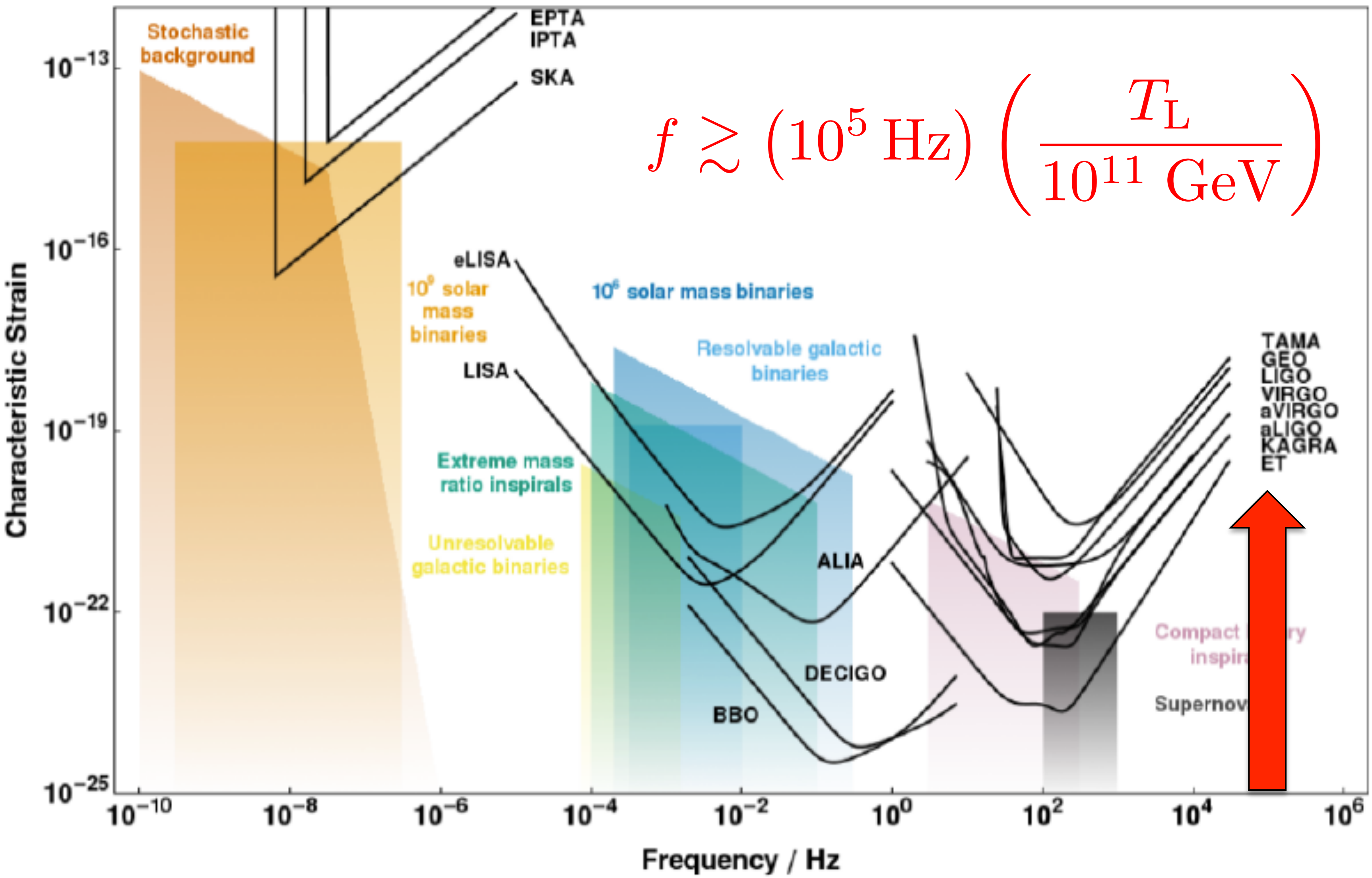
Majoron – the goldstone boson of spontaneously broken $U(1)_L$, which couples to the light neutrinos. However, if the scale of lepton-violation is as large as $v_L \sim 10^{12}$ GeV, the coupling is very suppressed (roughly m_ν / v_L), making the majoron difficult to probe.

Cosmic String Network– the breaking of a U(1) symmetry produces a network of topological defects, which persist in the universe today. As the strings gravitate, they produce gravitational wave radiation, which may be detectable with pulsar timing arrays.

Gravitational Waves – the first order $U(1)_L$-breaking phase transition creates GW's when the bubbles collide. The spectrum is expected to peak at, f >~ (10^5 Hz)(T_L / 10^{11} GeV), on the high side of LIGO.

Gravitational Wave Signature

$$f \gtrsim (10^5\,\mathrm{Hz}) \left(\frac{T_{\mathrm{L}}}{10^{11}\ \mathrm{GeV}} \right)$$



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