High-frequency GW as probe of leptogenesis and dark matter

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Outline of the talk:

- Baryogenesis via Leptogenesis is a high scale, so need for high scale testability
- GW from preheating may probe scale of leptogenesis
- High-frequency GW from preheating
- Non-thermal DM production during preheating also testable via GW
- Conclusions
History of the Universe

Introductory baryogenesis via Leptogenesis:

Type I Seesaw

[Minkowski 77; Gell-Mann, Ramond, Slanski 79; Yanagida 80]

\[ \mathcal{L} \supset Y_\nu \bar{L}eHN + \frac{1}{2} M_N NN, \quad \epsilon \equiv i\sigma_2 \]

\[ m_\nu^{\text{Maj.}} \sim \frac{Y_\nu^2 v_H^2}{M_N} \]

\[ M_N \gg Y_\nu v_H \text{ small neutrino mass and mixing with RHN} \]

\[ m_\nu \approx 0.05 \text{ eV} \cdot Y_\nu^2 \cdot \frac{10^{15} \text{ GeV}}{M_N}, \quad |V_{\nu N}|^2 = \frac{Y_\nu^2 v_H^2}{M_N^2} = \frac{m_\nu}{M_N} \]
History of the Universe

Baryon asymmetry and baryon-to-photon-ratio

Observation typically phrased in terms of

$$\eta \equiv \frac{n_B}{n_\gamma} \bigg|_{\text{today}} = \begin{cases} 5.93 \times 10^{-10} & \text{BBN} \\ 6.12 \times 10^{-10} & \text{CMB} \end{cases}$$

or alternatively $n_B - n_B^{-}$:

$$\Delta_B \equiv \frac{n_B - n_B^{-}}{s} = \begin{cases} 8.47 \times 10^{-11} & \text{BBN} \\ 8.74 \times 10^{-11} & \text{CMB} \end{cases}$$

- $T < 100 \text{ GeV}$: $n_B - n_B^{-} = \text{const.}$ (up to redshift)

- $n_B \big|_{\text{today}} \gg n_B^{-} \big|_{\text{today}}$ and $n_\gamma \big|_{\text{today}} = 413 \text{ cm}^{-3} \simeq s/7 \big|_{\text{today}}$

- Why is $\Delta_B \neq 0$?
History of the Universe

Vanilla Leptogenesis

[Fukugita, Yanagida 1986] Decays of lightest RHN $N \rightarrow LH$, $N \rightarrow \bar{L} H^*$

\[ \frac{n_B - n_{\bar{B}}}{s} = c_{\text{sph.}} \cdot \frac{\epsilon_L}{Q_P} \cdot \kappa \cdot \frac{n_{\text{rel}}^N}{s} = 8 \times 10^{-11} \]

3 (small) numbers from Sakharov conditions
History of the Universe

Davidson Ibarra bound

1. \( \beta : \ \epsilon_{\text{sph.}} \approx 0.3 \)

2. \( CP : \ \epsilon_L \leq \frac{3}{8\pi} \frac{M_1 (m_3 - m_1)}{v_H^2} \)

3. out of eq.: \( \kappa \approx \min[1, \left( \frac{K}{\kappa_{\text{SM}}} \right), \frac{1}{K}] \)

\[ n^i_N = 0 \quad \text{dom.} \]

[Davidson, Ibarra 2002] \( M_1 \gtrsim \left( \frac{0.05 \text{ eV}}{m_3} \right) \cdot \left\{ \begin{array}{l} 5 \times 10^8 \text{ GeV} \quad n^i_N = n^\text{eq.}_N \\ 2.4 \times 10^9 \text{ GeV} \quad n^i_N = 0 \\ 1.74 \times 10^7 \text{ GeV} \quad n^i_N = \frac{\rho_{\text{Rad}}}{M_N} \end{array} \right\} \)
History of the Universe

Experimental probes

History of the Universe

Gravitational Waves from Early Universe

GWs during preheating

1. Add complementary channel to inflationary GWs.
2. GWs production during preheating is a consequence of the scattering of the classical inhomogeneities.
3. Observed frequency depends on the Hubble (typically high frequency): $f_{\text{peak}} \propto \sqrt{H}$
Detectable Gravitational Waves from Preheating

- The effective potential during reheating: \( V(\phi) \propto m^2 \phi^2 \)
- Peak frequency: \( f_{\text{peak}} \propto \sqrt{H} \propto \sqrt{m} \)
- Take \( m^2 \) as a free parameter.

Easther, Giblin, Jr., and Lim *PRL* 99, 221301 (2007)
History of the Universe

Gravitational Waves in Lattice

Finite Difference Codes:
LATTICEEASY
Defrost
HLATTICE
GABE
CosmoLattice

\[ \frac{d^2 y}{dx^2} \approx \frac{y_{i+1} - 2y_i + y_{i-1}}{(\delta x)^2} \]

pseudo-spectral code:
PSpectRe

\[ \nabla^2 \rightarrow - \vec{k} \cdot \vec{k} \]

Free from differencing noise.
History of the Universe

Gravitational Waves in Lattice

- The Model: $V = \frac{1}{2} m^2 \phi^2 + \frac{1}{2} g^2 \phi^2 \chi^2$

- The EoMs

$$\ddot{\phi} + 3H\dot{\phi} - \frac{1}{a^2} \nabla^2 \phi + \frac{\partial V}{\partial \phi} = 0,$$

$$\ddot{\chi} + 3H\dot{\chi} - \frac{1}{a^2} \nabla^2 \chi + \frac{\partial V}{\partial \chi} = 0,$$

$$H^2 = \frac{1}{3M_{\text{Pl}}^2} \left( V + \frac{1}{2} \dot{\phi}^2 + \frac{1}{2} \dot{\chi}^2 + \frac{1}{2a^2} |\nabla \phi|^2 + \frac{1}{2a^2} |\nabla \chi|^2 \right),$$

- Gravitational waves being transverse and traceless (TT) part of the metric perturbation in the synchronous gauge sourced by TT-part of the anisotropic stress of the scalar field ($\Pi_{ij} = [\partial \phi_i \partial \phi_j]^{\text{TT}}$)

$$\ddot{h}_{ij} + 3H\dot{h}_{ij} - \frac{1}{a^2} \nabla^2 h_{ij} + \frac{\partial V}{\partial \phi} = \frac{2}{M_{\text{Pl}}^2 a^2} \Pi_{ij}$$
The observed GWs spectrum today:

- The GW energy density is given by
  \[ \rho_{GW}(t) = \frac{M_{Pl}^2}{4} \langle \dot{h}_{ij}(x, t) \dot{h}_{ij}(x, t) \rangle_{\nu}, \]  

- The spectrum of the energy density of GWs (per logarithmic momentum interval) observable today:
  \[ \Omega_{GW,0} h^2 = \frac{\frac{h^2}{\rho_{crit}} \frac{d \rho_{GW}}{d \ln k}}{\frac{a_e^4 \rho_e}{a_{0, crit}^4 \rho_{crit,0}}} \]
  \[ = \Omega_{rad,0} h^2 \Omega_{GW,e} \left( \frac{a_e}{a_*} \right)^{1 - 3w} \left( \frac{g_*}{g_0} \right)^{-1/3}, \]  

- The observed frequency corresponding to a wave vector \( k \) is
  \[ f = 1.32 \times 10^{10} \frac{k}{\sqrt{M_{Pl} H_e}} \]
Depending upon the mass of the scalar field, GW can be detectable, cannot go below ET due to BBN bounds. BLACK = 120 MeV
History of the Universe

Phenomenology-I: Inflaton as Dark Matter

1. Incomplete inflaton decay for massive inflaton with four-legged interactions.

2. The frozen inflaton component can act as dark matter candidate. Reheating will complete via higgs coupled to inflaton.

3. The ratio of the average energy density of this oscillation mode to the number density of photons being given by (Liddle 2008):

\[
\xi_{\text{dm},0} \equiv \frac{\rho_{\phi}}{n_{\gamma,0}} \simeq 0.04 \left( \frac{m_{\phi}}{M_{\text{Pl}}} \right)^{1/2} \left( \frac{\Phi_*}{M_{\text{Pl}}} \right)^2 M_{\text{Pl}},
\]  

4. The current dark matter per photon

\[
\xi_{\text{dm},0} = 1.1 \times 10^{-27} M_{\text{Pl}}
\]
History of the Universe

Phenomenology-II: Matter-antimatter Asymmetry

- A complete decay of inflaton is possible via perturbative decay term (The original proposal of reheating).
- Inflaton can decay into right-handed neutrinos. The successive decays of the right-handed neutrinos into Higgs and lepton doublets will bring in efficient reheating and can also generate the baryon asymmetry of the universe via non-thermal leptogenesis.
- Preheating produces a non-zero initial density of the daughter fields, thereby enhances the baryon-to-photon ratio compared to the ordinary reheating scenario.
- The parameters fixed from preheating are jointly probed in GWs detectors and the measurement for baryon asymmetry.
The Perturbative decay of inflaton

- The Boltzmann eqs (Antusch 2018):
  \[ \dot{n}_\phi(t) + 3H(t)n_\phi(t) + \Gamma_\phi n_\phi(t) = 0, \]
  \[ \dot{n}_N(t) + 3H(t)n_N(t) + \Gamma_N n_N(t) - 2\Gamma_\phi n_\phi(t) = 0, \]
  \[ \dot{\rho}_{\text{rad}}(t) + 4H(t)\rho_{\text{rad}}(t) - \Gamma_N m_N n_N(t) - \left(1 - 2\frac{m_N}{m_\phi}\right)\Gamma_\phi m_\phi n_\phi(t) = 0, \]
  \[ H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{1}{3M^2_{Pl}} (\rho_\phi + \rho_N + \rho_{\text{rad}}) \quad (5) \]

- Equation for the evolution of the effective lepton number density \( n_L \) (Antusch 2010):
  \[ \dot{n}_L(t) + 3H(t)n_L(t) = \epsilon \Gamma_N n_N(t) \quad (6) \]

\( \epsilon \) is the CP-violation per RH-neutrino decay.
Possible extensions

- The baryon to photon ratio

\[ \left| \frac{n_B}{n_\gamma} \right| \sim \left| \frac{n_L}{s} \right| = 10^{-15} \frac{T_{re}}{\text{GeV}} \frac{m_X}{m_\phi}, \]  

- Preheating produce a non-zero initial density of the daughter fields.

![Graph showing \( \rho_X / \rho_\phi \) vs. \( m_X / m_\phi \)]
Result

Observed baryon-to-photon ration and corresponding GWs strain.

\[ m_\phi = 10^{13}\text{GeV} \]

\[ m_\phi = 10^{10}\text{GeV} \]
History of the Universe

In absence of other observables/signatures, Gravitational waves can help us explore the primordial dark ages.
The frozen inflaton component can solve the mystery of dark matter in the universe.
The successive decay of right-handed neutrino can solve the puzzle of matter-antimater asymmetry of our universe.
GWs are useful tool to explore other particle physics and cosmology connection.
Thank You