Gravitational Waves from a B-L Phase Transition

GWs as a key to the early universe and BSM physics

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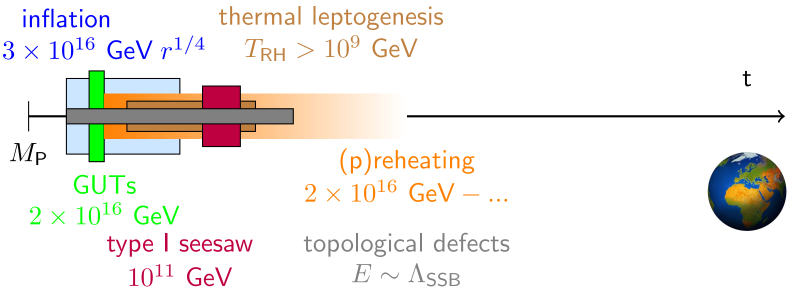
The eye of a needle for model builders



- strong motivation for new physics at very high energy scales
  $\Rightarrow$ potential GW sources
- Spectrum determined with no* new parameters
- In this talk: inflation, preheating, cosmic strings

Gravitational waves as a unique window to the very early universe

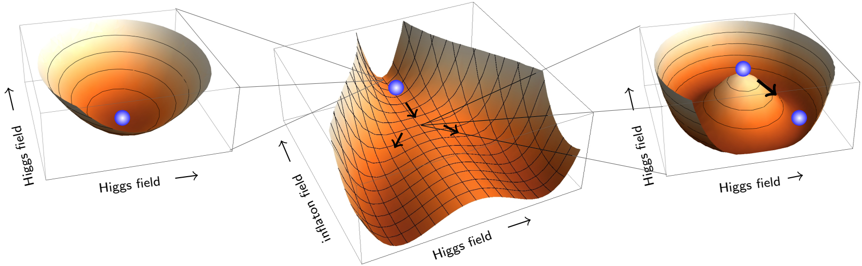
Outline

- a minimal supersymmetric model
  of particle physics and the early universe

- gravitational waves from
  - inflation
  - preheating
  - cosmic strings

- comparison with observational prospects and caveats

An example: SSB of $U(1)_{B-L}$ at the GUT scale



$$W = \frac{\sqrt{\lambda}}{2}\,\Phi\,(v_{B-L}^2 - 2\,S_1 S_2) + \frac{1}{\sqrt{2}} h_i^n n_i^c n_i^c S_1 + h_{ij}^\nu n_i^c \mathbf{5}_j^* H_u + W_{MSSM}$$

Before

- hybrid inflation

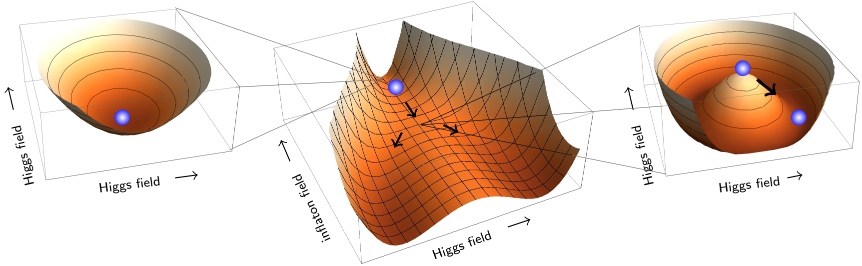
Phase transition

- tachyonic preheating
- cosmic strings

After

- reheating
- leptogenesis
- dark matter

An example: SSB of $U(1)_{B-L}$ at the GUT scale



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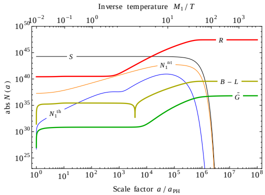

Three sources of gravitational waves

Inflation [Rubakov *et al.* '82, Turner *et al.* '93]

- scale independent quantum tensor perturbations
- red-shifted after horizon re-entry

Preheating [Garcia-Bellido, Figueroa '07, Kofman *et al.* '09,'10]

- GWs from bubble-collisions during phase transition
- at high frequencies, governed by small length-scales at preheating

Cosmic strings [Vilenkin '81, Hindmarsh *et al.* '12]

- extremely high energy density along cosmic strings $\sim V_{\text{inf}} \rightarrow$ GWs
- evolution of network complicated $\rightarrow$ need lattice simulations

Consistent picture at hand $\rightarrow$ calculate complete spectrum

Some useful properties of GWs

perturbations of the homogeneous background metric

$$ds^2 = a^2(\tau)(\eta_{\mu\nu} + h_{\mu\nu}(\boldsymbol{x}, \tau))dx^\mu dx^\mu$$

governed by linearized Einstein equation ($\tilde{h}_{ij} = a h_{ij}$, TT - gauge)

$$\tilde{h}''_{ij}(\boldsymbol{k}, \tau) + \Bigg(k^2 - \underbrace{\frac{a''}{a}}_{\sim a^2 H^2}\Bigg)\tilde{h}_{ij}(\boldsymbol{k}, \tau) = \underbrace{16\pi\, G\, a\, \Pi_{ij}(\boldsymbol{k}, \tau)}_{\text{source term from } \delta T_{\mu\nu}}$$

$$k \gg aH : \; h_{ij} \sim \cos(\omega\tau)/a\,, \quad k \ll aH : \; h_{ij} \sim \text{const.}$$

useful plane wave expansion

$$h_{ij}\,(\boldsymbol{x}, \tau) = \sum_{P=+,\times} \int_{-\infty}^{+\infty} \frac{dk}{2\pi} \int d^2\hat{\boldsymbol{k}}\; h_P\,(\boldsymbol{k}) \quad \underbrace{T_k(\tau)}_{\sim a(\tau_i)/a(\tau)} \quad e^P_{ij}\big(\hat{k}\big)\, e^{-ik\left(\tau - \hat{\boldsymbol{k}}\boldsymbol{x}\right)}$$

transfer function , expansion coefficients , polarization tensor $P = +, \times$

Properties of GWs - II

Observable quantities:

$$\Omega_{\rm GW} = \frac{1}{\rho_c}\frac{\partial \rho_{\sf GW}(k,\tau)}{\partial \ln k}, \quad \rho_{\sf GW}(\tau) = \frac{1}{32\pi G}\left\langle \dot{h}_{ij}\left(\boldsymbol{x},\tau\right)\dot{h}^{ij}\left(\boldsymbol{x},\tau\right)\right\rangle$$

In principle: Calculate $T_{\mu\nu}$, work through equations above
In practice:

$$\rho_{\sf GW}(\tau) = \rho^{\rm qu}_{\sf GW}(\tau) + \rho^{\rm cl}_{\sf GW}(\tau)\ .$$

- classical sources (e.g. preheating, cosmic strings):

$$h_{ij}(\boldsymbol{k},\tau) = 16\pi G\,\frac{1}{a(\tau)}\int_{\tau_i}^{\tau} d\tau'\ a(\tau')\,\mathcal{G}(k,\tau,\tau')\,\Pi_{ij}(\boldsymbol{k},\tau')$$

- inflation (e.g. stochastic source):

$$\Omega_{\rm GW}(k,\tau) = \frac{r^2 A_s^2}{12}\,\frac{k^2}{a_0^2 H_0^2}\,T_k^2(\tau)$$

GWs from inflation

The transfer function T_k: $\frac{a(\tau_{\text{cr}})}{a_0} = \frac{a(\tau_{\text{cr}})}{a_{\text{RH}}} \frac{a_{\text{RH}}}{a_{\text{eq}}} \frac{a_{\text{eq}}}{a_0}$, $\quad k_x = a_x H_x$

- Adiabatic expansion of the universe:
  $\frac{H_1}{H_2} = \left(\frac{a_1}{a_2}\right)^{-\frac{3}{2}(1+\omega)}$, with e.g. $\frac{a_{\text{eq}}}{a_0} = \left(\frac{g_*^{\text{eq}}}{g_*^0}\right)\left(\frac{g_{*,s}^0}{g_{*,s}^{\text{eq}}}\right)^{4/3} \frac{\Omega_r}{\Omega_m}$

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- mode k entering during radiation domination ($\omega = 1/3$)
  $\frac{a(\tau_{\text{cr}})}{a_{\text{eq}}} = \frac{k H_{\text{eq}}}{k_{\text{eq}} H} \simeq \frac{k}{k_{\text{eq}}} \left(\frac{a(\tau_{\text{cr}})}{a_{\text{eq}}}\right)^{4/2}$
  $\to \frac{a(\tau_{\text{cr}})}{a_{\text{eq}}} = \frac{k_{\text{eq}}}{k} \left(\frac{g_*}{2 g_*^{\text{eq}}}\right)^{1/2} \left(\frac{g_{*,s}^{\text{eq}}}{g_{*,s}}\right)^{2/3} \propto 1/k \to \Omega_{\text{GW}} \propto k^0$

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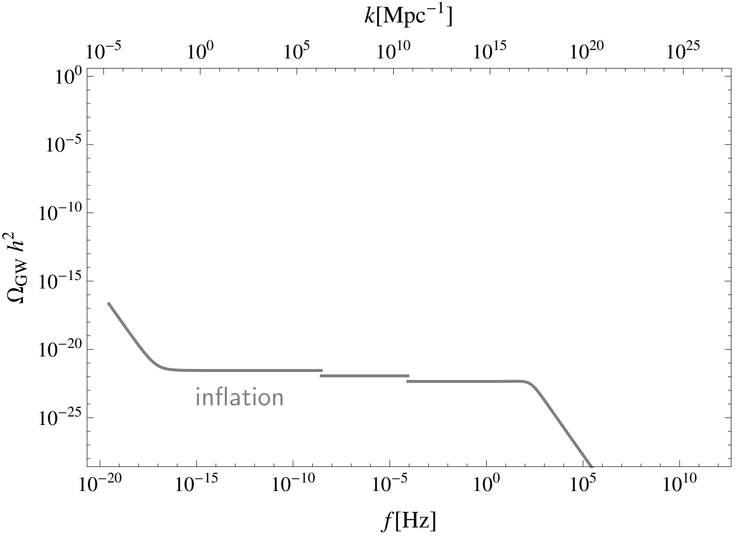
  $\rightarrow \frac{a(\tau_{\text{cr}})}{a_{\text{eq}}} = \frac{k_{\text{eq}}}{k} \left(\frac{g_*}{2 g_*^{\text{eq}}}\right)^{1/2} \left(\frac{g_{*,s}^{\text{eq}}}{g_{*,s}}\right)^{2/3} \propto 1/k \rightarrow \Omega_{\text{GW}} \propto k^0$

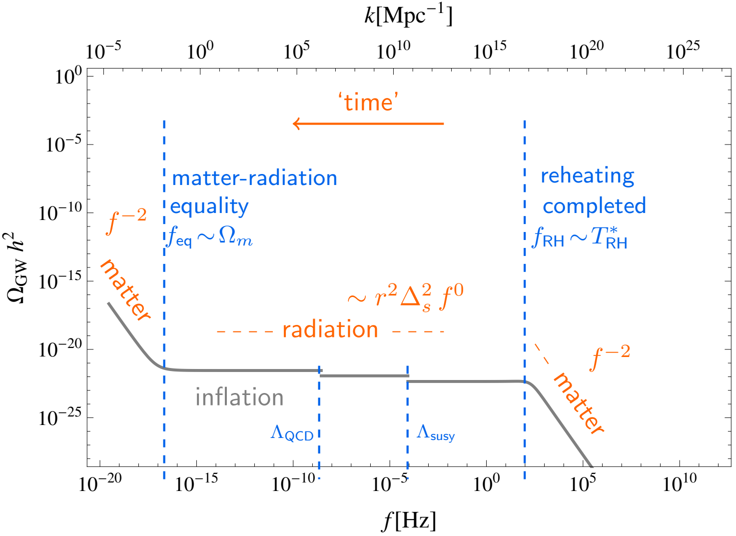
- mode k entering during matter domination ($\omega = 0$)
  $\frac{a(\tau_{\text{cr}})}{a_{\text{RH}}} = \frac{k H_{\text{RH}}}{k_{\text{RH}} H} = \frac{k}{k_{\text{RH}}} \left(\frac{a}{a_{\text{RH}}}\right)^{3/2}$
  $\rightarrow \frac{a}{a_{\text{RH}}} = \left(\frac{k_{\text{RH}}}{k}\right)^2 \propto 1/k^2 \rightarrow \Omega_{\text{GW}} \propto k^{-2}$

simple scale/frequency dependence, sensitive to expansion history

GWs from inflation

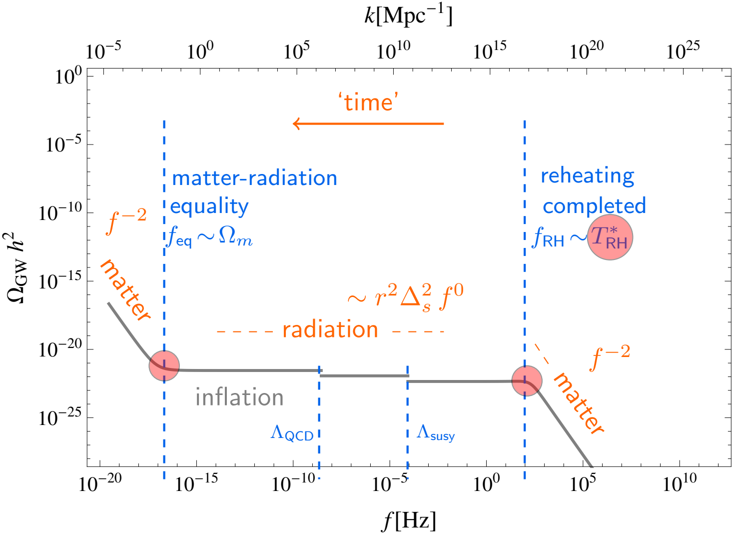


GWs from inflation



cosmological history imprinted on scale-invariant primordial spectrum

GWs from inflation



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GWs from cosmic strings

- translational invariance and isotropy of the source
- scaling (self-similar) regime [Durrer *et al.* '99]

$$\Rightarrow \langle \Pi_{ij}(\boldsymbol{k},\tau)\,\Pi^{ij}(\boldsymbol{k}',\tau')\rangle \approx (2\pi)^3 \frac{4v_{B-L}^4}{\sqrt{\tau\tau'}}\delta(\boldsymbol{k}+\boldsymbol{k}')\delta(x-x')\underbrace{\widetilde{C}(x)}_{\text{falls of rapidly for } x \gg 1}$$

with $x = k\tau > 1$ on sub-horizon scales.

- recall:

$$\rho_{\mathsf{GW}}(\tau) = \frac{1}{32\pi G}\left\langle \dot{h}_{ij}\,(\boldsymbol{x},\tau)\,\dot{h}^{ij}\,(\boldsymbol{x},\tau)\right\rangle$$

$$h_{ij}(\boldsymbol{k},\tau) = 16\pi G\,\frac{1}{a(\tau)}\int_{\tau_i}^{\tau} d\tau'\; a(\tau')\,\mathcal{G}(k,\tau,\tau')\,\Pi_{ij}(\boldsymbol{k},\tau')$$

with $\mathcal{G}(k,\tau,\tau') = \sin(k(\tau-\tau'))/k$ for sub-horizon scales

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with $x = k\tau > 1$ on sub-horizon scales.

- resulting spectrum:

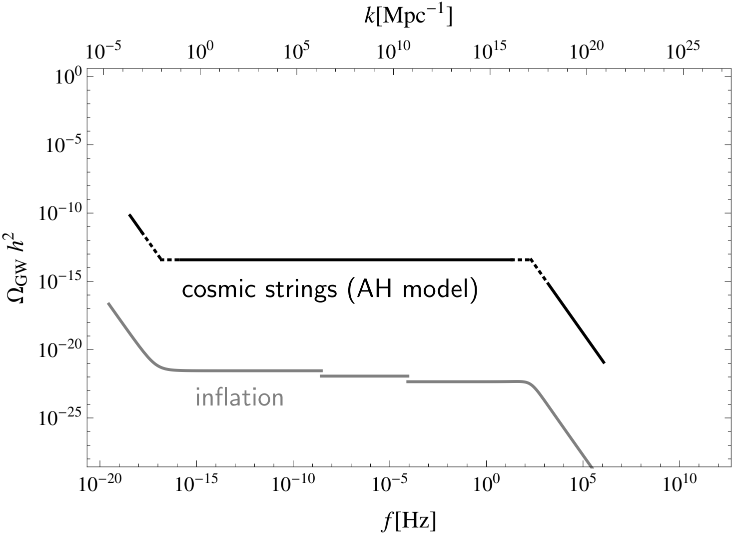
$$\Rightarrow \Omega_{\mathrm{GW}} = \frac{k^2}{3\pi^2 H_0^2 a_0^2}\left(\frac{v_{B-L}}{M_P}\right)^4 \underbrace{\int_{x_i}^{x_0} \frac{\overbrace{a^2(x/k)}^{\text{extract } k\text{-dep.}}}{a_0^2\, x}\widetilde{C}(x)\,dx}_{\rightarrow \text{const., dominated by lower boundary } x_i = \mathcal{O}(1)}$$

$x_i \in$ radiation dom.: $a \propto k^{-1} \rightarrow \Omega_{\mathrm{GW}} \propto k^0$ [Figueroa, Hindmarsh, Urrestilla '12]

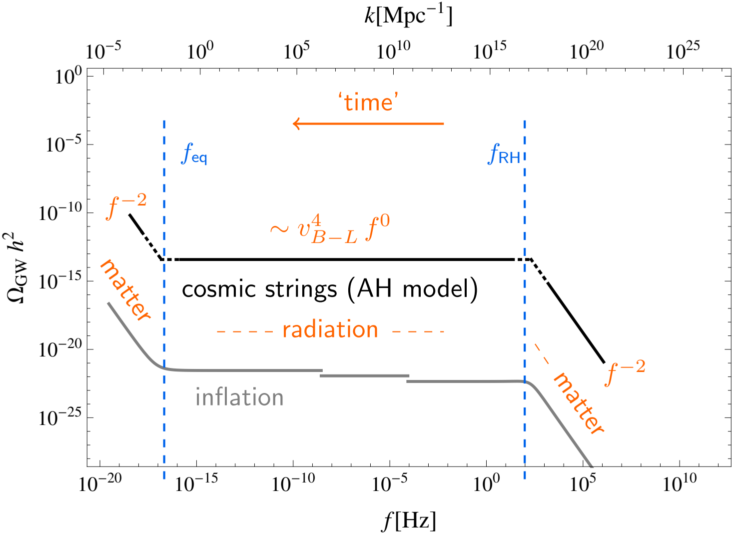
$x_i \in$ matter dom.: $a \propto k^{-2} \rightarrow \Omega_{\mathrm{GW}} \propto k^{-2}$

Spectrum dominated by horizon-sized cosmic strings

GWs from cosmic strings

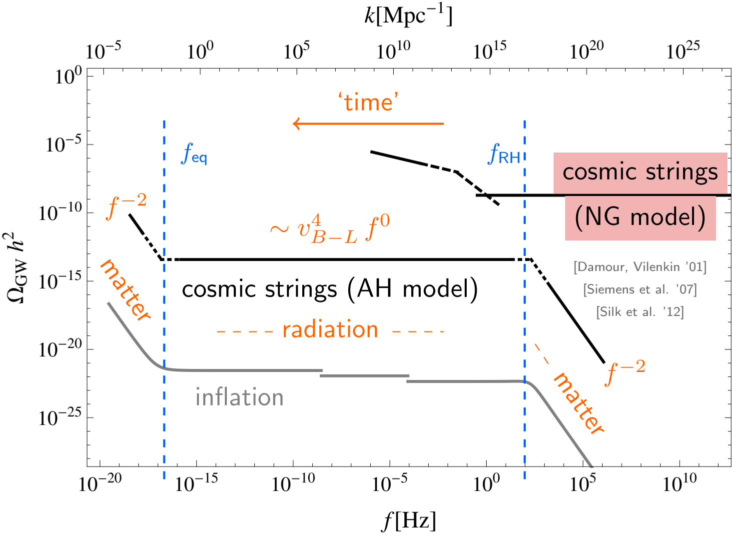


GWs from cosmic strings



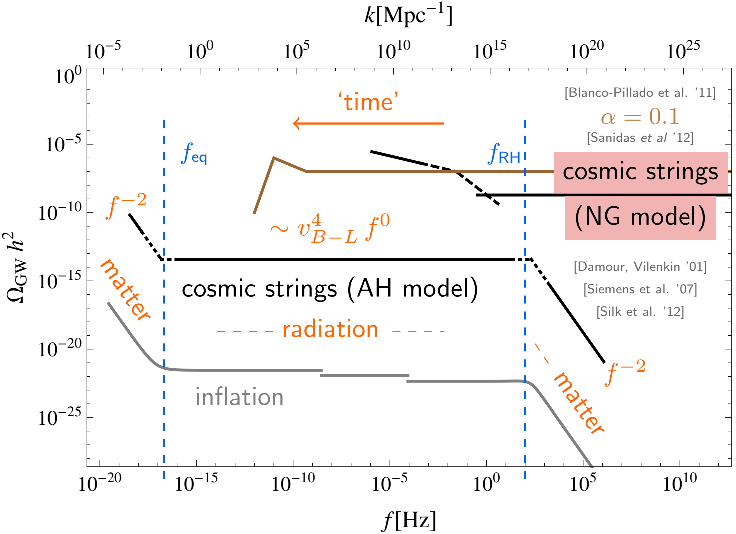
same spectral shape as for inflation, potentially very different amplitude

GWs from cosmic strings



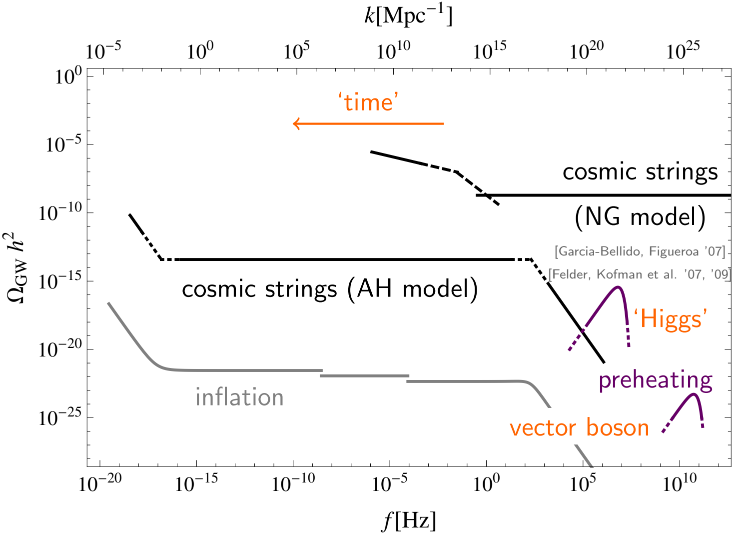
large uncertainties from loop size and decay mode

GWs from cosmic strings



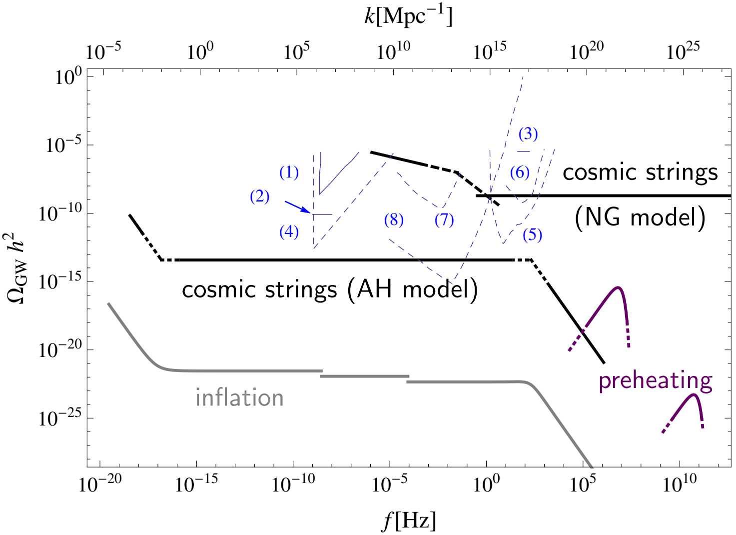
large uncertainties from loop size and decay mode

GWs from preheating



high frequency peaks, determined by m_S, m_V, H_{PH}, $a_{\text{PH}}/a_{\text{RH}}$

Parameter dependencies / observational prospects



(1) millisecond pulsar timing, (2) EPTA, (3) LIGO, (4) SKA, (5) ET, (6) advanced LIGO, (7) eLISA, (8) BBO/DECIGO

Conclusion and Outlook

- early universe model based on spontaneous breaking of $U(1)_{B-L}$:
GW spectrum fully* determined by Lagrangian parameters
$\rightarrow$ GWs can be a powerful tool to discriminate models

- inflation: GW spectrum is sensitive to the entire cosmological history

- cosmic strings: can enhance inflation-type spectrum by many order of magnitudes. But large uncertainties.

- GW have the potential to rule our or detect GUT-scale cosmic strings, measurement of T_{RH}, extra degrees of freedom,..

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Thank you!

backup slides

GWs from inflation

Shape of the spectrum governed by transfer function:

$$\Omega_{\rm GW}(k,\tau) = \frac{A_t}{12}\,\frac{k^2}{a_0^2 H_0^2}\,T_k^2(\tau)\,, \quad T_k(\tau) = \frac{a(\tau_k)}{a(\tau)} \text{ with } k = a(\tau_k)H(\tau_k)$$

Consider frequency intervals $[k_0, k_{\rm eq}),\ [k_{\rm eq}, k_{\rm RH}),\ [k_{\rm RH}, k_{\rm PH})$:

$$f_{\rm eq} = 1.57\times 10^{-17}\,{\rm Hz}\left(\frac{\Omega_m h^2}{0.14}\right)\,, \qquad f_{\rm RH} = 4.25\times 10^{-1}\,{\rm Hz}\left(\frac{T_*}{10^7\,{\rm GeV}}\right)$$

$$f_{\rm PH} = 1.93\times 10^{4}\,{\rm Hz}\left(\frac{\lambda}{10^{-4}}\right)^{1/6}\left(\frac{10^{-15}\,v_{B-L}}{5\,{\rm GeV}}\right)^{2/3}\left(\frac{T_*}{10^7\,{\rm GeV}}\right)^{1/3}$$

$$\Rightarrow T_k \simeq {\Omega_r}^{1/2}\left(\frac{g_*^k}{g_*^0}\right)^{1/2}\left(\frac{g_{*,s}^0}{g_{*,s}^k}\right)^{2/3}\frac{k_0}{k}\times\begin{cases}\frac{1}{\sqrt{2}}\,k_{\rm eq}/k\,, & k_0 \ll k \ll k_{\rm eq}\\ 1\,, & k_{\rm eq} \ll k \ll k_{\rm RH}\\ \sqrt{2}\,R^{1/2}\,C_{\rm RH}^3\,k_{\rm RH}/k\,, & k_{\rm RH} \ll k \ll k_{\rm PH}\end{cases}$$

GWs from tachyonic preheating

- f_{PH}: typical scale of reheating, red-shifted
- $\Omega_{\mathsf{GW}}^{(\mathsf{max})}$: redshift of $\Omega_{\mathsf{GW}}^{\mathsf{PH}}(k_{\mathsf{PH}}) \simeq \; c_{\mathsf{PH}} \, (d_{\mathsf{PH}} H_{\mathsf{PH}})^2$
- $(d_{\mathsf{PH}}^{(s)})^{-1} = (\lambda v_{B-L} \dot{\phi}_c)^{1/3}, \quad (d_{\mathsf{PH}}^{(v)})^{-1} \sim m_G$

$$f_{\mathsf{PH}}^{(s)} \simeq 6.3 \times 10^6 \text{ Hz} \left(\frac{M_1}{10^{11} \text{ GeV}}\right)^{1/3} \left(\frac{5 \times 10^{15} \text{ GeV}}{v_{B-L}}\right)^2 \left(\frac{m_S}{3 \times 10^{13} \text{ GeV}}\right)^{7/6}$$

$$\Omega_{\mathsf{GW}}^{(s,\mathsf{max})} h^2 \simeq 3.6 \times 10^{-16} \, \frac{c_{\mathsf{PH}}}{0.05} \left(\frac{M_1}{10^{11} \text{ GeV}}\right)^{\frac{4}{3}} \left(\frac{5 \times 10^{15} \text{ GeV}}{v_{B-L}}\right)^{-2} \left(\frac{m_S}{3 \times 10^{13} \text{ GeV}}\right)^{-\frac{4}{3}}$$

$$f_{\mathsf{PH}}^{(v)} \simeq 7.5 \times 10^{10} \text{ Hz} \; g \left(\frac{M_1}{10^{11} \text{ GeV}}\right)^{1/3} \left(\frac{m_S}{3 \times 10^{13} \text{ GeV}}\right)^{-1/2}$$

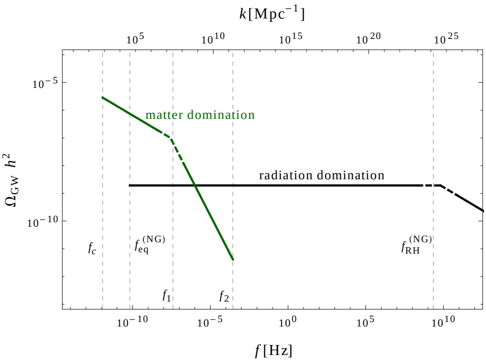
$$\Omega_{\mathsf{GW}}^{(v,\mathsf{max})} h^2 \simeq 2.6 \times 10^{-24} \, \frac{1}{g^2} \, \frac{c_{\mathsf{PH}}}{0.05} \left(\frac{M_1}{10^{11} \text{ GeV}}\right)^{\frac{4}{3}} \left(\frac{5 \times 10^{15} \text{ GeV}}{v_{B-L}}\right)^2 \left(\frac{m_S}{3 \times 10^{13} \text{ GeV}}\right)^2$$

GWs from NG cosmic strings

Integrate over all redshifts and loop sizes ($\rightarrow h$)

$$\Omega_{\mathsf{GW}}(f) = \frac{2\pi^2 f^3}{3H_0^2} \int_0^{h_*} dh \int_0^{z_{\mathsf{PH}}} dz\, h^2 \frac{d^2 R}{dz dh}$$

$\rightarrow$ resulting spectrum:



A Useful Tool: Boltzmann Equations

- evolution of the phase space density $f_X(t,p)$:

$$\hat{\mathcal{L}} f_X(t,p) = \left(\frac{\partial}{\partial t} - \frac{\dot{a}}{a}\, p\, \frac{\partial}{\partial p}\right) f_X(t,p) = \sum C_X$$

- collision operator: $C_X(Xab.. \leftrightarrow ij..) =$

$$\frac{1}{2 g_X E_X} \int d\Pi(X|a,b,..;i,j,..)(2\pi)^4 \delta^{(4)}(P_{\text{out}} - P_{\text{in}})$$
$$\times \left[f_i f_j .. |\mathcal{M}(ij.. \to Xab..)|^2 - f_X f_a f_b .. |\mathcal{M}(Xab.. \to ij..)|^2\right]$$

- Friedmann equation: $3 M_P^2 \left(\frac{\dot{a}}{a}\right)^2 = \rho_{\text{tot}}$

Calculating the time evolution of phase space densities

An Example: Nonthermal N_1 Neutrinos

- Boltzmann equation:
  $\hat{\mathcal{L}} f_{N_1} = 2\, C_{N_1}(\phi_S \to N_1 N_1) + C_{N_1}(\psi_S \to \tilde{N}_1^* N_1) + C_{N_1}(N_1 \leftrightarrow \text{MSSM})$
  $+$ initial conditions: tachyonic preheating, $B-L$ gauge boson decay

- solution: comoving number density of *nonthermal* neutrinos

$$N_{N_1}^{\text{nt}}(t) = N_{N_1}^{\text{PH}}(t) + N_{N_1}^{G}(t) + N_{N_1}^{S}(t)$$

$$= N_{N_1}^{\text{PH}}(t_{\text{PH}})\, e^{-\Gamma_{N_1}^0 (t - t_{\text{PH}})} + N_{N_1}^{G}(t_G)\, \exp\left[-\int_{t_G}^{t} dt' \, \frac{M_1\, \Gamma_{N_1}^0}{\mathcal{E}_{N_1}(m_G/2; t_G, t')}\right]$$

$$+ \int_{t_{\text{PH}}}^{t} dt'\, a^3(t')\, \gamma_{S,N_1}(t')\, \exp\left[-\int_{t'}^{t} dt''\, \frac{M_1\, \Gamma_{N_1}^0}{\mathcal{E}_{N_1}(m_S/2; t', t'')}\right]$$

with

$$\gamma_{S,N_1}(t) := 2\, \frac{N_{\phi_S}(t)}{a(t)^3}\, \Gamma^0_{\phi_S \to N_1 N_1} + \frac{N_{\psi_S}(t)}{a(t)^3}\, \Gamma^0_{\psi_S}$$

$$\mathcal{E}_{N_1}(E_0; t', t) := E_0\, \frac{a(t')}{a(t)} \left\{1 + \left[\left(\frac{a(t)}{a(t')}\right)^2 - 1\right] \left(\frac{M_1}{E_0}\right)^2\right\}^{1/2}$$

An Example: Nonthermal N_1 Neutrinos

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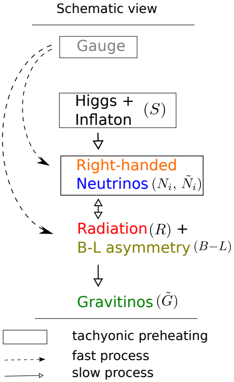
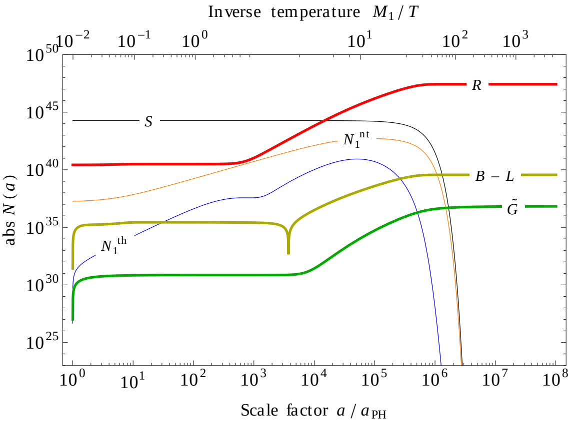
$$
\begin{aligned}
N_{N_1}^{\text{nt}}(t) &= N_{N_1}^{\text{PH}}(t) + N_{N_1}^{G}(t) + N_{N_1}^{S}(t) \\
&= N_{N_1}^{\text{PH}}(t_{\text{PH}})\, e^{-\Gamma_{N_1}^0 (t - t_{\text{PH}})} + N_{N_1}^{G}(t_G)\, \exp\left[-\int_{t_G}^{t} dt' \, \frac{M_1\, \Gamma_{N_1}^0}{\mathcal{E}_{N_1}(m_G/2; t_G, t')}\right] \\
&\quad + \int_{t_{\text{PH}}}^{t} dt' \, a^3(t')\, \gamma_{S,N_1}(t')\, \exp\left[-\int_{t'}^{t} dt'' \, \frac{M_1\, \Gamma_{N_1}^0}{\mathcal{E}_{N_1}(m_S/2; t', t'')}\right]
\end{aligned}
$$

Boltzmann equation for N_1 solved semi-analytically

Solving the Boltzmann Equations





Tracking the evolution of the number densities of all species

Model Parameters

$$W = \frac{\sqrt{\lambda}}{2}\,\Phi\,(v_{B-L}^2 - 2\,S_1 S_2) + \frac{1}{\sqrt{2}} h_i^n n_i^c n_i^c S_1 + h_{ij}^\nu n_i^c \mathbf{5}_j^* H_u + W_{MSSM}$$

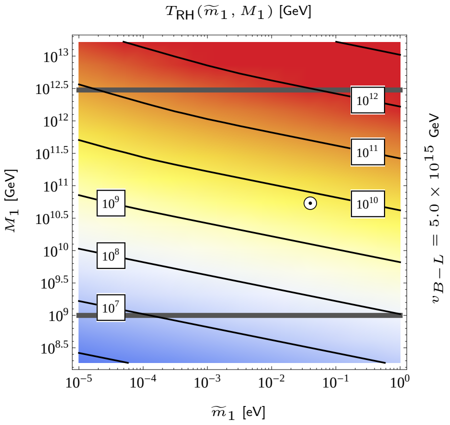
- parameters of the superpotential: λ, h_{ij}, v_{B-L}
- re-parametrize assuming hierarchical right-handed neutrinos

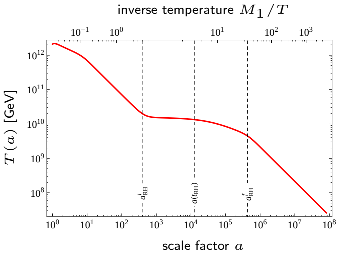
$$\Rightarrow \quad v_{B-L}\,, \quad M_1\,, \quad \widetilde{m}_1$$

  with $v_{B-L} = 5 \times 10^{15}$ GeV fixed by hybrid inflation + cosmic strings
- plus sparticle masses $m_{\tilde{g}} \equiv 1$ TeV, $m_{\tilde{G}}$

Model parameters: $v_{B-L}, M_1, \tilde{m}_1, m_{\tilde{G}}$

Reheating Temperature



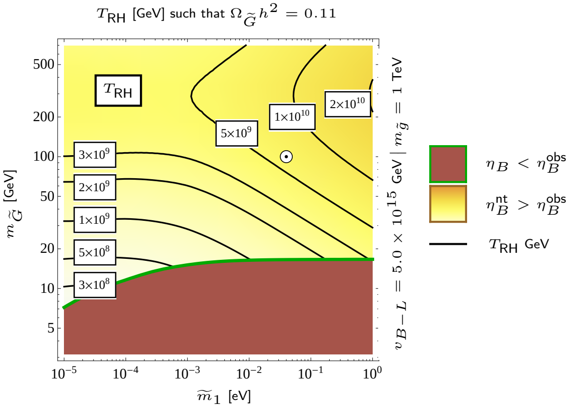


- plateau in temperature evolution
- controlled by neutrino physics parameters

T_{RH} plays a key role for both DM production and leptogenesis

Baryon Asymmetry and $\widetilde{G}$ Dark Matter

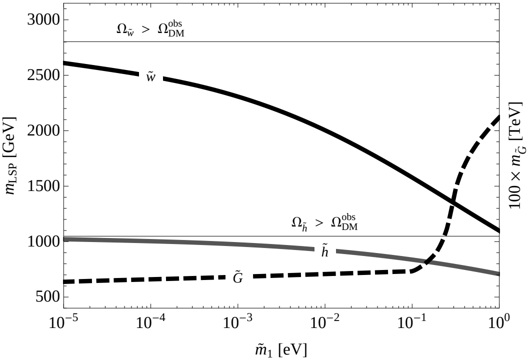
- requiring $\Omega_{\mathrm{DM}} = 0.11$ eliminates M_1
- insert maximal CP-asymmetry $\Rightarrow \eta_B \overset{!}{>} \eta_B^{\mathrm{obs}}$



Consistency of inflation, $\widetilde{G}$-DM and leptogenesis for $m_{\widetilde{G}} \gtrsim 10$ GeV

Neutralino LSP

$$\Omega^{\text{th}}_{\text{LSP}} h^2 + \Omega^{\tilde{G}}_{\text{LSP}} h^2 \stackrel{!}{=} 0.11$$



Consistency between inflation, leptogenesis, BBN and DM for *e.g.*
$m_1 = 0.05$ eV, $m_{\tilde{h}} < 900$ GeV, $m_{\tilde{G}} > 10$ TeV