On Testing Superstring Theories with Gravitational Waves

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Standard Model and general relativity incomplete
(m_ν, dark components, many free parameters,...)

$\rightarrow$ no quantum gravity (space-time singularities)
$\rightarrow$ **string theory** $\rightarrow$ compactification / model
$\rightarrow$ string theory is extremely versatile (landscape)
$\Rightarrow$ Is some string model the **fundamental theory of Nature?**
$\Rightarrow$ **need for** generic (general) **properties and tests** for them

As physical theory string model needs to be falsifiable!

Moduli...

1) describe the compactified extra dimensions.
2) have gravitational coupling strength only $\Rightarrow \tau_\phi \sim M_{\text{pl}}^2/m_\phi^3$.
3) must be stabilized $\rightarrow$ measured parameters take well-defined values.
4) have m_ϕ typically $\mathcal{O}\left(m_{3/2}\right)$.
5) perform coherent oscillations with $\phi_{\text{i}} \sim M_{\text{pl}}$ if displaced from origin.
6) bring in the well-known **cosmological moduli problem**:

   5) $\Rightarrow$ Universe becomes matter dominated $\rightarrow$ overclosure ↯
   $\Rightarrow$ matter needs to be diluted (thermal inflation) or $\tau_\phi < t_{\text{BBN}} \sim 0.1$ s for successful primordial nucleosynthesis $\Rightarrow m_\phi > \mathcal{O}\left(10^4 \text{ GeV}\right)$
   $\rightarrow$ **intermediate matter dominated phase**

With 4) $\Rightarrow$ constraint on SUSY breaking scale: $m_{3/2} \sim m_\phi > \mathcal{O}\left(10^4 \text{ GeV}\right)$

To circumvent our test: $\tau_\phi \lesssim 10^{-22}$ s $\ll t_{\text{BBN}} \Leftrightarrow m_\phi \gtrsim 10^{12}$ GeV $\gg 10^4$ GeV

Gravitational wave background from inflation

Inflation

1) solves horizon and flatness problem.
2) generates scale invariant ($n_s = 1, n_T = 0$) spectrum of scalar and tensor (gravitational waves) fluctuations:

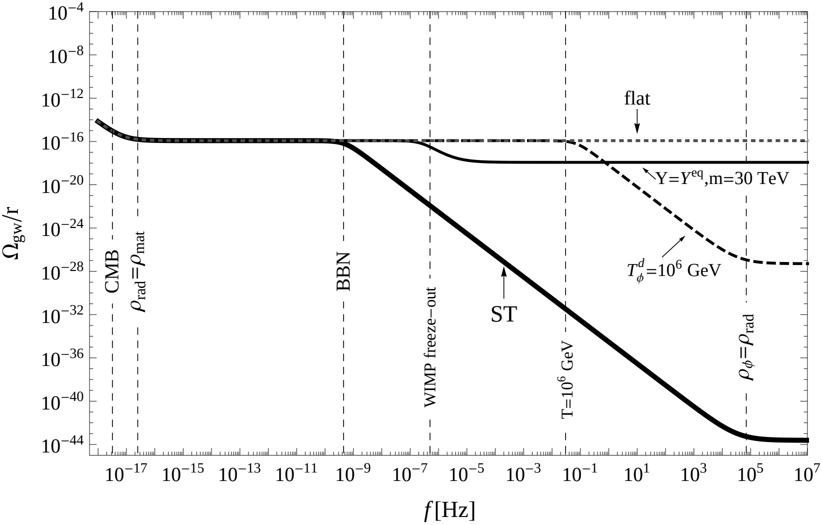
$$\Omega_{\rm gw}(k) = \frac{r\Delta^2_{\mathcal{R}}}{12\pi^2}\Omega_{\rm rad} \qquad \text{with } \Delta^2_{\mathcal{R}} \simeq 2\times 10^{-9},\ \Omega_{\rm rad} \simeq 5\times 10^{-5},$$

r < 0.2 : tensor-to-scalar ratio $\rightarrow$ **observable in CMB** (B-mode polarization)

Since $\rho_{\rm gw} \propto a^{-4}$ while $\rho_{\rm mat} \propto a^{-3}$,
suppression of modes inside the horizon expected $\rightarrow$

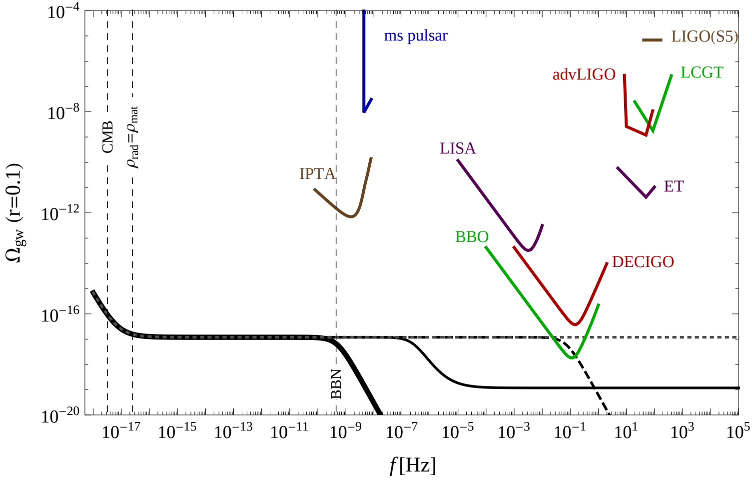
> Matter dominated phase leaves imprint on the gravitational wave background from inflation

The gravitational wave spectrum today



- after BBN expansion history known→ before unknown!
- frequency $f = k/(2\pi)$ corresponds to Hubble radius at re-entry.

Observation opportunities



Prediction: Unmodified signal on CMB scales and no signal in gravitational wave detectors

in words

"If gravitational wave experiments will detect the signal from the inflationary gravitational wave background as expected from the CMB, this will rule out all string models that contain at least one scalar with a mass $\lesssim 10^{12}$ GeV (corresponding to the sensitivity of BBO) that acquires a large initial oscillation amplitude after inflation and has only gravitational interaction strength."

$\rightarrow$ signal qualitatively the same for thermal inflation!

$\rightarrow$ correspondingly high SUSY breaking scale may well render superstring theories unobservable !$\lightning$!

What have we done?

1) Find general solution of evolution equation for gravitational waves assuming power law expansion $\rightarrow$ analytical
2) Compute transfer function of an intermediate matter dominated phase by matching $\rightarrow$ rad-mat-rad $\rightarrow$ analytical
3) Find simple and accurate analytic approximation to the exact result:

$$T^2(k;\eta_\mathrm{e},\eta_\mathrm{b}) = \frac{1}{\frac{\eta_\mathrm{e}^2}{\eta_\mathrm{b}^2}\left(\frac{2\pi c}{k\eta_\mathrm{b}} - \frac{2\pi}{k\eta_\mathrm{e}} + 1\right)^{-2} + 1}$$

with $c = 0.5$ (best-fit).

η_b : conformal time when matter domination begins
η_e : conformal time when matter domination ends

4) Compare resulting spectra to detection opportunities.

Caveats and how to circumvent

- ☹ large enough r to have any detection at all (Pixie down to 10^{-3})
- ☹ high enough reheating temperature $\rightarrow T_\mathrm{R} \gtrsim 10^9$ GeV (BBO sensitivity)
- ☹ BBO-like experiments need to be build
- ! existence and initial displacement of moduli $\rightarrow$ cp. known moduli problem
- ? probing SUSY breaking scale requires m_ϕ–$m_{3/2}$ **relation**
  $\rightarrow$ **always there?** when?*
- ☺ thermal inflation or any other dilution does not circumvent the test!

Other nonstandard cosmologies may lead to the same qualitative observation (see next slide) $\Rightarrow$ no proof possible

Test is quite solid
but does in no way work the other way around as a proof.

*Refering to [Acharya, Kane, Kuflik, 10] at least one modulus with $m_\phi \lesssim m_{3/2}$ in all known string models in which all moduli are stabilized.

Insertion/Outlook

- Other physics may also lead to nonstandard expansion history $\Rightarrow$ imprint on the gravitational wave background
- Example: massive species that decouples while in thermal equilibrium and decays before WIMP freeze-out (axino, modulino,...)
- Other examples known. More to find!
- transfer function easily generalized to other equations of state ($p = \omega\rho$) $\rightarrow$ exponents of 2 $\rightarrow 2(1-3\omega)/(1+3\omega)$

Full expansion history could be read-off the gravitational wave background

Conclusions

- ☹ If gravitational wave background observable in CMB,
- ☺ proposed test quite solid. ($\rightarrow$ cp. cosmological moduli problem)
- ☺ For $m_\phi \simeq m_{3/2}$ test applies up to $m_{3/2} \sim 10^{12}$ GeV (BBO sensitivity)
  $\rightarrow$ relation always there? when? ...?
- $\rightarrow$ $m_{3/2} > 10^{12}$ GeV may well render superstring theories unobservable!↯!
- ☺ No other possibility proposed to probe such high SUSY breaking scales, albeit indirectly.

$\Rightarrow$ Motivation to build BBO-like experiments

Combining future CMB polarization measurements with very sensitive gravitational wave probes can provide a crucial test for a large class of string theories.

Thank you for your attention!

Hopefully, there are comments/questions?