New Sources of Tensor Modes during inflation

w/ Senatore, Zaldarriaga

Tensor modes are a standard signature of inflation

Guth
Linde
Albrecht/
Steinhardt

$$\langle h_k \, h_{k'} \rangle = (2\pi)^3 \delta(k+k') \, P_h$$

$$P_h = \frac{4}{k^3} \frac{H^2}{M_p^2}$$

Lyth

$$\left(\frac{\Delta\phi}{M_p}\right) \simeq N_e \Bigg(\underbrace{\frac{P_h}{P_g}}_{r}\Bigg)^{\frac{1}{2}} \simeq \left(\frac{r}{0.01}\right)^{\frac{1}{2}}$$

(Slow Roll inflation)

Detectability $\Longleftrightarrow$ $\underset{H/M_p}{\underset{\sim}{h}} \gtrsim 10^{-6}$

→ It is often said that a detection of tensor modes (via CMB B-mode polarization)

⇒ • measurement of $H_{inflation} \gtrsim 10^{-6} M_p$

• determination that $\Delta\phi > M_p$

However, we'll see that

Quantum production of Classical GW
cf Chialva

sources can compete, producing

$$h \gtrsim 10^{-6} \quad \text{with} \quad \frac{H}{M_p} \leq 10^{-6}$$

Motivations

- systematic understanding of inflation & CMB signatures
- New window on exotics & top-down mechanisms

cf Pajer talk

New Sources of GW's

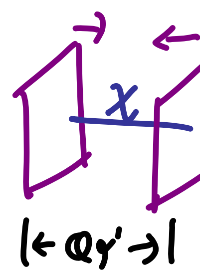
cf Chialva, Ng
Cook/Sorbo, ...

The inflaton ϕ generically couples to other degrees of freedom (e.g. for reheating)

For example, (Lev K + many)

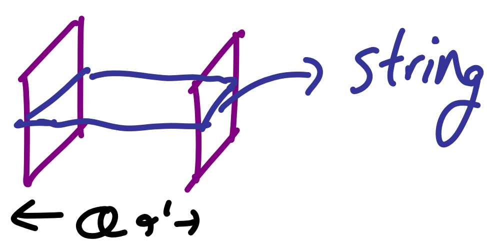
(1) $$\delta\mathcal{L} = g^2\phi^2\chi^2 \rightarrow m_\chi^2 = m_0^2 + \phi^2(t,\vec{x})$$

$\Rightarrow$ particle production

(brane picture: 

)

(2) $$T_{string}^2 = T_{min}^2 + \phi^2 M_0^2$$

(brane picture: 

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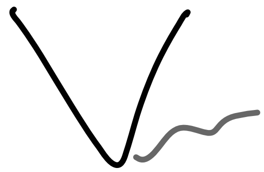
Production:

particles: $n_\chi \sim \dot\phi^{3/2} g^{3/2} \times e^{-\frac{\mu_0^2}{g\dot\phi}}$



associated scalar emission

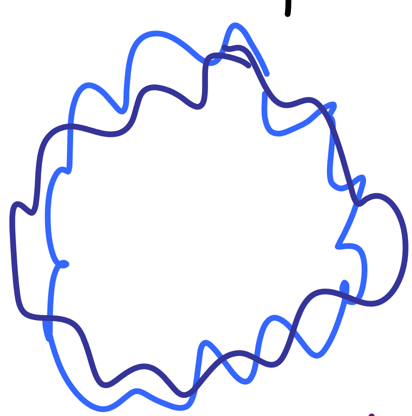
$\to \quad \rho_\phi \sim \frac{H^4}{\dot\phi^2} g^2 N_\chi$

strings:
w/ J. Polchinski
cf Spergel

- Tension $T(t)$ increases too fast to treat as collection of particles

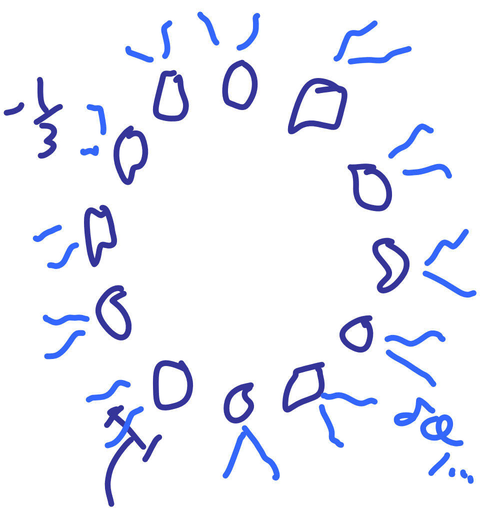
Result:

$\dot\phi \to$



$\Delta t \sim \dot T^{-\frac{1}{3}}$

$\longrightarrow$



$\dot T^{-\frac{1}{3}}$

$\dot T^{-\frac{1}{3}} \Delta v \sim \frac{\dot T^{-\frac{1}{2}}}{r^{\frac{1}{2}}} \ll \dot T^{-\frac{1}{3}}$

→ Do these produce competitive GWs?

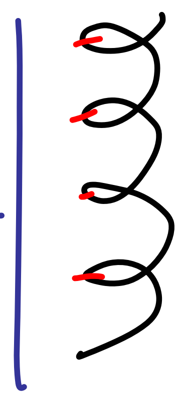
Of course inflation dilutes exotic high-scale relics; Produced particles, strings dilute in a Hubble time.

However, multiple events over $\Delta\phi_{inflation}$ are quite possible.

+ in e.g. monodromy, any production events are repeated many times

McAll. ES Westph.

Axion monodromy → string production



cf Trapped Infl

Green Hor Senatore ES

Kofman, Linde

Kaloper Sorbo Lawrence Roberts Pajer Barnaby Peloso

→ repleshinishing supply of GWs

This, plus the more general question of B-mode degeneracy, motivates analyzing this question.

Remarks

- For simplicity, work in regime where – no parametric resonance & resulting non-linearities cf DickB KinNg
  – $\delta\phi$ Green's function is the standard ($\approx$ free) one
- In monodromy inflation $V \sim \phi^{p<2}$ and e.g $r \sim .07$ $(p=1)$ from vacuum fluctuations

(Other classes of UV-complete inflation give different predictions, cf Renata Liam talks; it is an open problem to determine relative numbers or probabilities for this, N_e, etc.)

But here, we will consider $\downarrow \frac{H}{M_p}$ while obtaining tensors from new sources.

First, given these classical sources of GW's, is $h_{source} \gtrsim 10^{-6}$?

$$\sim \left(\frac{\rho_{GW}}{H^2 M_p^2}\right)^{1/2} \Bigg|_{\text{freeze-out},\ \omega \sim \frac{k}{a} \sim H} \sim \frac{[\partial(h M_p)]}{H M_p}\Bigg|_{\omega \sim \frac{k}{a} \sim H}$$

$$\rho_{GW} \sim \rho_{production} \cdot \left(\frac{H}{\omega}\right)^4$$ inflationary dilution

Low-frequency sources ($\omega \gtrsim H$) most efficient

- zeroeth-order check: $\rho_{sources} < \varepsilon H^2 M_p^2$.

  If converted $\rho_{sources} = \varepsilon H^2 M_p^2 \rightarrow \rho_{GW}\big|_{\omega = H}$

  would get $h \sim \sqrt{\varepsilon} \gg 10^{-6}$

- If all $\rightarrow$ GW of $\omega \sim \sqrt{\dot{\phi}}$,

  get $h_{source} \sim \frac{H}{M_p} \Rightarrow$ still (marginally) competitive

In general

$$
\begin{aligned}
\mathcal{S} &= \int d^4x\sqrt{-g}\left(\frac{1}{2}M_P^2\mathcal{R}+\mathcal{L}_\phi\right)+\mathcal{S}_X+\mathcal{S}_{XY} && (13)\\
\mathcal{S}_X &= -\sum_p\int d^4x\int d\tau\,\delta^{(4)}(x^\mu-x_p^\mu(\tau))\underline{m(\phi(t,\mathbf{x}))}\sqrt{-\mathrm{g}_{\mu\nu}(\mathbf{x}_\mathrm{p}(\tau))\frac{\mathrm{d}\mathbf{x}^\mu(\tau)}{\mathrm{d}\tau}\frac{\mathrm{d}\mathbf{x}^\nu(\tau)}{\mathrm{d}\tau}}\,\theta(\mathbf{t}-\mathbf{t}_\mathrm{p})\\
&\quad -\sum_s\int d^4x\int d^2\sigma\,\delta^{(4)}(x^\mu-x_s^\mu(\sigma))\underline{T(\phi(t,\mathbf{x}))}\sqrt{-\mathrm{Det}\mathrm{g}_{\mu\nu}(\mathbf{x}_\mathrm{s}(\sigma))\partial_\alpha\mathbf{x}^\mu(\sigma)\partial_\beta\mathbf{x}^\nu(\tau)}\,\theta(\mathbf{t}-\mathbf{t}_\mathrm{s})\\
& && (14)
\end{aligned}
$$

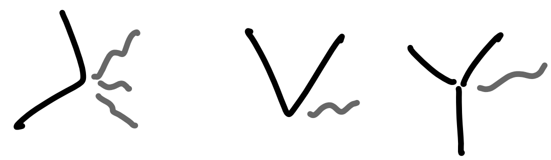
Inflaton ϕ coupled to gravity, sources X (particle/string), and other sectors Y.

* coupling to ϕ $\Rightarrow$ $\delta\phi$ perturbations controlled by $\partial_\phi m$ or $\partial_\phi T$ along with tensor modes

Gravity Waves:

(cf Weinberg GR/cosmo)

$$\frac{dE}{d\Omega} = \frac{2}{8\pi M_p^2}\int_0^\infty d\omega\,\omega^2\left(T^{\lambda\nu *}T_{\lambda\nu} - \tfrac{1}{2}|T^\lambda_\lambda|^2\right)$$

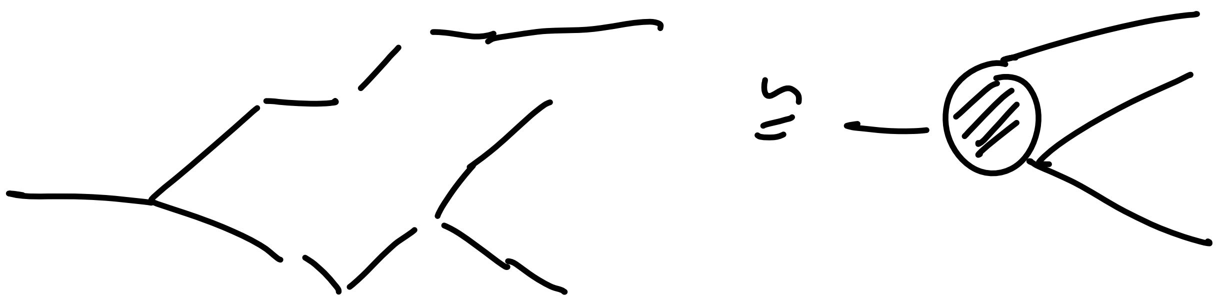
Bremsstrahlung 

$$\frac{dE}{d\Omega d\omega} = \frac{\omega^2}{16\pi^3 M_p^2}\sum_{N,M}\frac{\eta_N\eta_M}{P_N\cdot k\; P_M\cdot k}\left[(P_N\cdot P_M)^2 - \tfrac{1}{2}m_N^2 m_M^2\right]$$

for $k \ll \Delta x$, and const p^μ between collisions

$$\eta = \pm 1 \begin{cases} \text{incoming line} \\ \text{outgoing line} \end{cases}$$

- Each event $\rightarrow$ uniform power in ω, but subsequent events interfere



Suppression factors & Constraints

- redshift
- interference for $\Delta x < \omega^{-1}$

$\Rightarrow$ no gain from multiple collisions

- $\not\approx$ spherical symmetry
- $p^0(t) \longrightarrow$ additional factors of ω

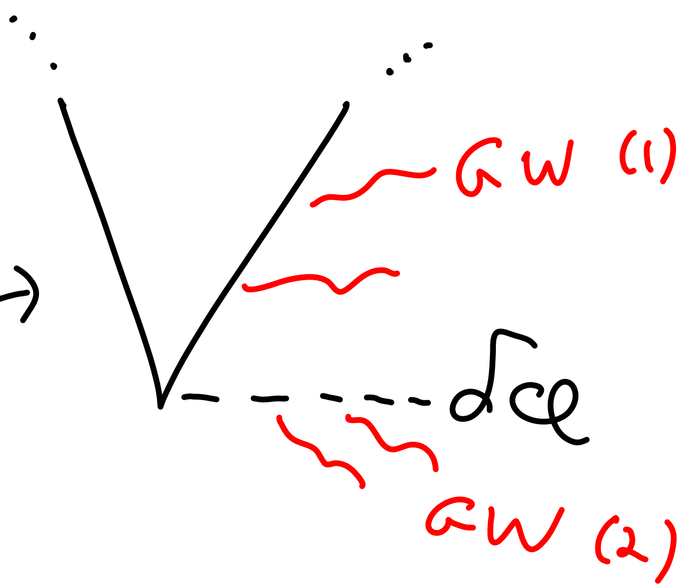
$$T^{\mu\nu}_{part} = \sum_n \delta^{(3)}(\vec{x} - \vec{x}(t)) \frac{p_n^\mu p_n^\nu}{p^0(t)} \theta(t)$$

- scalar perturbations ρ: $\frac{h}{\rho} \leq 10^{-1}$

Illustrative examples

① Production itself:

$\phi^2\chi^2$ interaction



(i) $m(\phi) \propto \phi \sim g\dot{\phi}\, t$

$$\Rightarrow \frac{dE^{(1)}_{GW}}{d\omega} \sim \left(\frac{E}{M_p}\right)^2 \times \left(\frac{\omega}{E}\right)^2$$

$p^0(t)$

$$\frac{dE^{(2)}_{GW}}{d\omega} \sim \left(\frac{E_{\delta\phi}}{M_p}\right)^2 \times 1$$

... both too small

(ii) $m(\varphi)$ saturates $\rightarrow$ $g\dot{\varphi}\, t_c$

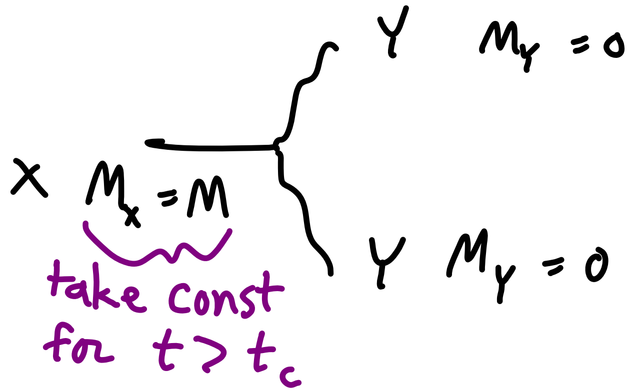
(easily possible including couplings to heavy flds cf "Flattening" Dong Horn ES, AW)

$$\frac{dE}{d\omega} \sim \left(\frac{E}{M_p}\right)^2$$

Gives a few orders of magnitude, with

- $\frac{\rho^2}{\hbar^2} \sim \frac{1}{\epsilon^2}$
- $\Gamma \leq H$ self-consistent (no interference)
- NG OK

(2) Decays



$$\frac{dE}{d\omega\, d\Omega} = \frac{1}{4\pi^2}\,\frac{M^2}{M_p^2} \times N_X$$

$$\to h^2 \sim \frac{E \cdot H^3}{\rho_{Tot}} \sim \frac{\rho_X}{\rho_{Tot}}\,\frac{HM}{M_p^2} \le \varepsilon \frac{H}{M_p}$$

$$M \sim g\,\dot{\varphi}\, t_c \sim g\sqrt{\epsilon}\, M_p\, (H t_c)$$

leads to (for $\frac{\rho_X}{\rho_{Tot}} \sim \epsilon$)

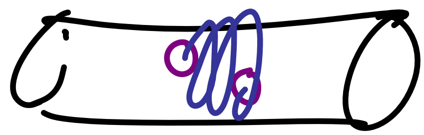
$$\frac{H}{M_p} \sim \frac{10^{-12}}{g\,\epsilon^{3/2}}$$ with $h \sim 10^{-6}$

- Scalar emission (comes from production) ok, again $\frac{s^2}{h^2} \sim \frac{1}{\epsilon^2}$

③ Scattering Bremsstrahlung

- similar analysis, some examples with gain of 10^{few}

④ Strings:

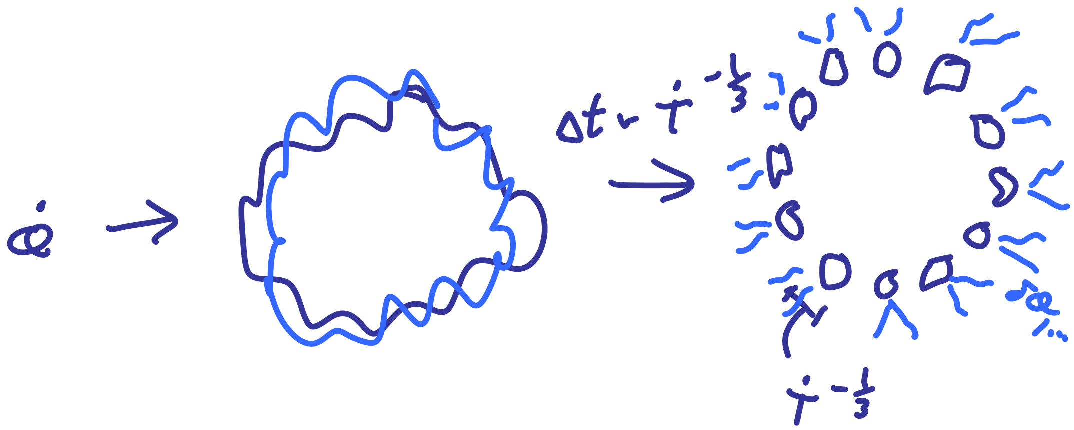


e.g. axion monodromy inflation

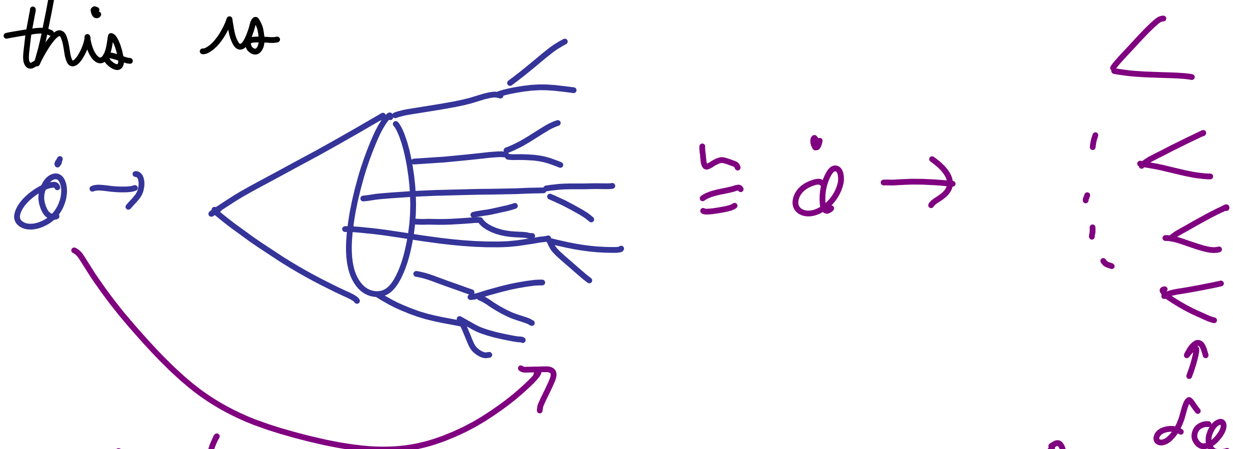
- $T(\varphi) = \sqrt{(\eta M_p \varphi)^2 + T_0^2}$

$\simeq \eta M_p \varphi$ $\Rightarrow$ coupling to φ along w/ h

$\sim \dot{T} t$



In terms of $\omega \sim H$ Bremsstrahlung this is



$\delta\alpha$ particles $k \sim \dot{T}^{\frac{1}{3}}$

(intermediate processes interfere $\Rightarrow 0$.)

$$\rightarrow \frac{dE}{d\omega} \sim \frac{\dot{T}^{2/3}}{M_p^2} N_{loops} N_{rings}$$

$$\left(\frac{E}{M_p}\right)^2$$

This leads to

$$h^2 \sim \underbrace{\left(\frac{H}{M_p}\right)^2}_{\substack{\text{scale of}\\ h^2 \text{ from}\\ \text{vacuum fluctuations}}} N_{rings} \underbrace{\frac{\dot{T}}{H M_p^2}}_{\eta\sqrt{\epsilon}}$$

$$\rightarrow \quad h^2_{\substack{\text{string}\\ \text{sources}}} \sim 10^{-12} > h_{\substack{\text{vac}\\ \text{fluctuations}}}$$

for $N_{rings} > \dfrac{1}{\eta\sqrt{\epsilon}}$

satisfies constraints easily.

Note: here, no scalar Bremsstrahlung at $\omega < \dot{T}^{\frac{1}{3}}$ since dce decay products are $\simeq$ free.