Coming Opportunities for UV-Sensitive Observables

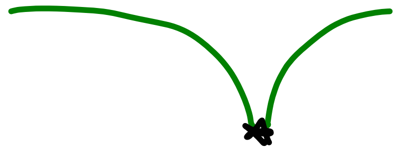
I. Generalities

II. Tensor Modes & UV Physics

New Sources of Tensor Modes during inflation

w/ Senatore, Zaldarriaga

General Relativity describes gravity accurately at long distances



$$S = \int d^4x \sqrt{g}\, \frac{\mathcal{R}}{G_N} + S_{matter} \rightarrow \mathcal{R}_{\mu\nu} - \frac{1}{2} g_{\mu\nu} \mathcal{R} = 8\pi G_N T_{\mu\nu}$$

GR breaks down for $\lambda_G \rightarrow 1$ (or before)

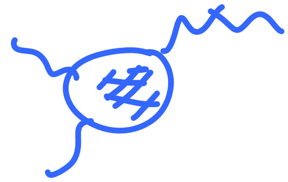
Quantum fluctuations / Classical UV physics $\rightarrow$

$$S = \int \left(\frac{\mathcal{R}}{G_N} - V(\phi)\right)\left(1 + \mathcal{R}\left(\frac{c_1}{M_*^2} + \hat{c}_1 G_N\right) + \dots\right)$$

$$+ \int (\partial\phi)^2 + k_1 \frac{(\partial\phi)^4}{M_*^2} + \dots$$

$\leftarrow$ scale of "new physics"

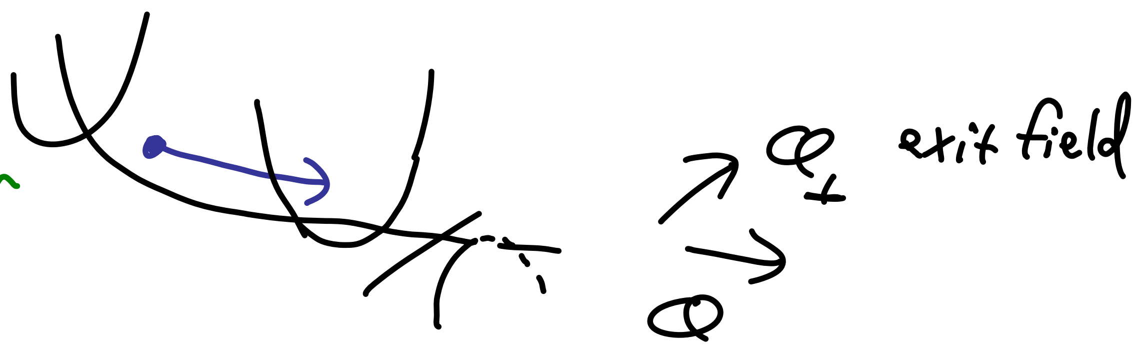
with corrections sensitive to short-distance physics



These corrections <u>matter</u> for inflation

e.g. A seemingly simple way to obtain inflation is to postulate a very flat potential for the inflaton $\phi(x)$.

Linde '93
hybrid inflation

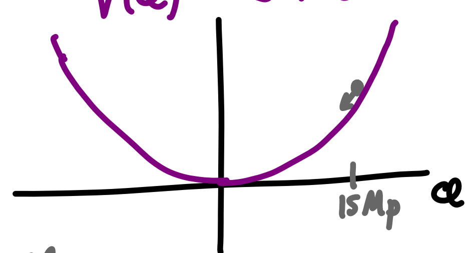


$$\varepsilon \equiv \frac{M_p^2}{2}\left(\frac{V'}{V}\right)^2 << 1 \qquad \eta \equiv M_p^2\left|\frac{V''}{V}\right| << 1$$

However, corrections from the UV physics can generate substructure in $\mathcal{L}(\phi, \partial\phi)$: $\frac{V(\phi-\phi_0)^2}{M_p^2} \to \Delta\eta \sim 1$

This UV sensitivity is greatest in the case of "chaotic inflation" A. Linde '83 where the inflaton φ ranges over more than a distance M_p

e.g. $V(\varphi) = \frac{1}{2} m^2 \varphi^2$



$$\left\{ \begin{aligned} \varepsilon &= \frac{1}{2}\left(\frac{V'}{V} M_p\right)^2 \\ \eta &= M_p^2 \left|\frac{V''}{V}\right| \end{aligned} \right\} \sim \left(\frac{M_p}{\varphi}\right)^2 \Rightarrow \varphi \sim 15 M_p$$

In General:

$$\boxed{\star \text{ "Lyth Bound"}: \quad \frac{\Delta\varphi}{M_p} \sim \left(\frac{r}{0.01}\right)^{\frac{1}{2}}}$$

UV sensitive if $\gtrsim 1$

observable

→ Control with approximate shift symmetry (Wilsonian 'natural')

UV Sensitivity of Inflation

① Terms of order $V \cdot \frac{(\varphi-\varphi_0)^2}{M_p^2}$ (dimension 6)

in the effective action can ruin inflation

② $\frac{\Delta\varphi}{M_p} \simeq r^{\frac{1}{2}} \frac{N_e}{\sqrt{24}}$ (Lyth)

GUT-scale inflation (with observable tensor modes) $\Leftrightarrow \Delta\varphi > M_p$

③ General Single-field inflation involves higher derivative terms which affect solution & perturbations

cf Non-Gaussianity

④ $g^2\varphi^2\chi^2$ couplings $\Rightarrow$ temporarily light fields affect evolution. ...

⑤ (mass > H)

<u>Heavy</u> fields affect results in a different way: they adjust in response to inflationary potential energy.

QFT toy model

$$V(\varphi_L, \varphi_H) = g^2 \varphi_L^2 \varphi_H^2 + m^2 (\varphi_H - \varphi_0)^2$$

$$\frac{\partial V}{\partial \varphi_H} \equiv 0 \Rightarrow V = \frac{g^2 \varphi_L^2}{g^2 \varphi_L^2 + m^2} m^2 \varphi_0^2$$

($\dot{\varphi}_H^2$ term subdominant)

flatter: energetically favorable.

⑥ Exit physics: defects, strings, oscillons, ...?

⑦ Entry Physics ?? bubble nucleation..

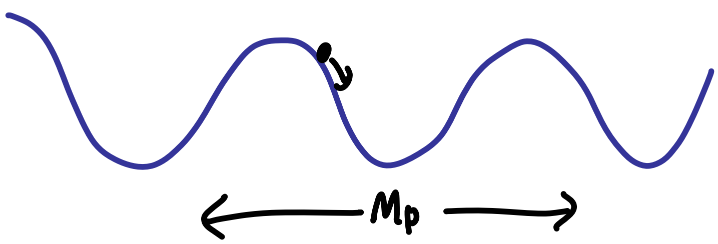
Tensor Modes

Large $\frac{\Delta\phi}{M_p}$.

<u>Axions</u> naturally respect an (approximate) shift symmetry $\phi \to \phi + \alpha$

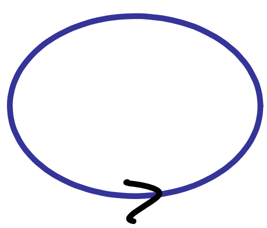
(couple via their derivatives)

→ "Natural Inflation"



$\Lambda^4 \sim e^{-\frac{\text{const}}{g^2}}$

Naturally small



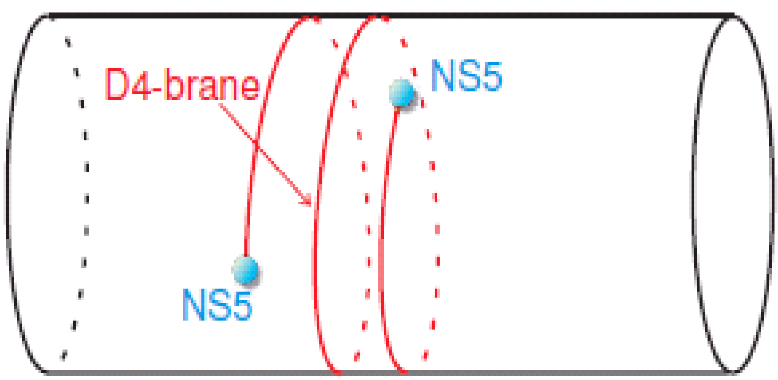
$a \simeq a+(2\pi)^2$

$\phi_a = f_a a$ — canonical scalar field

→ Does $\frac{\Delta\phi}{M_p} \gtrsim 1$, protected by shift symmetry, arise in string theory?

* Basic <u>period</u> small compared to M_p

The basic mechanism is very simple :

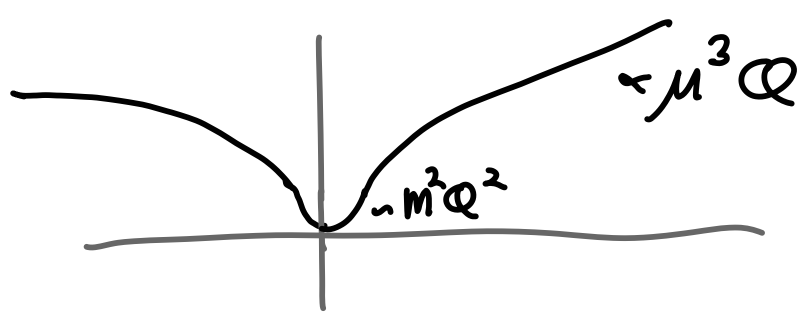


["T-dual" to axions]

- "NS5" branes position periodic on this circle, until add stretched "D4" brane

$$V(\phi) \sim \mu^3 \sqrt{\phi^2 + M_p^2}$$

→ Novel prediction for inflaton potential

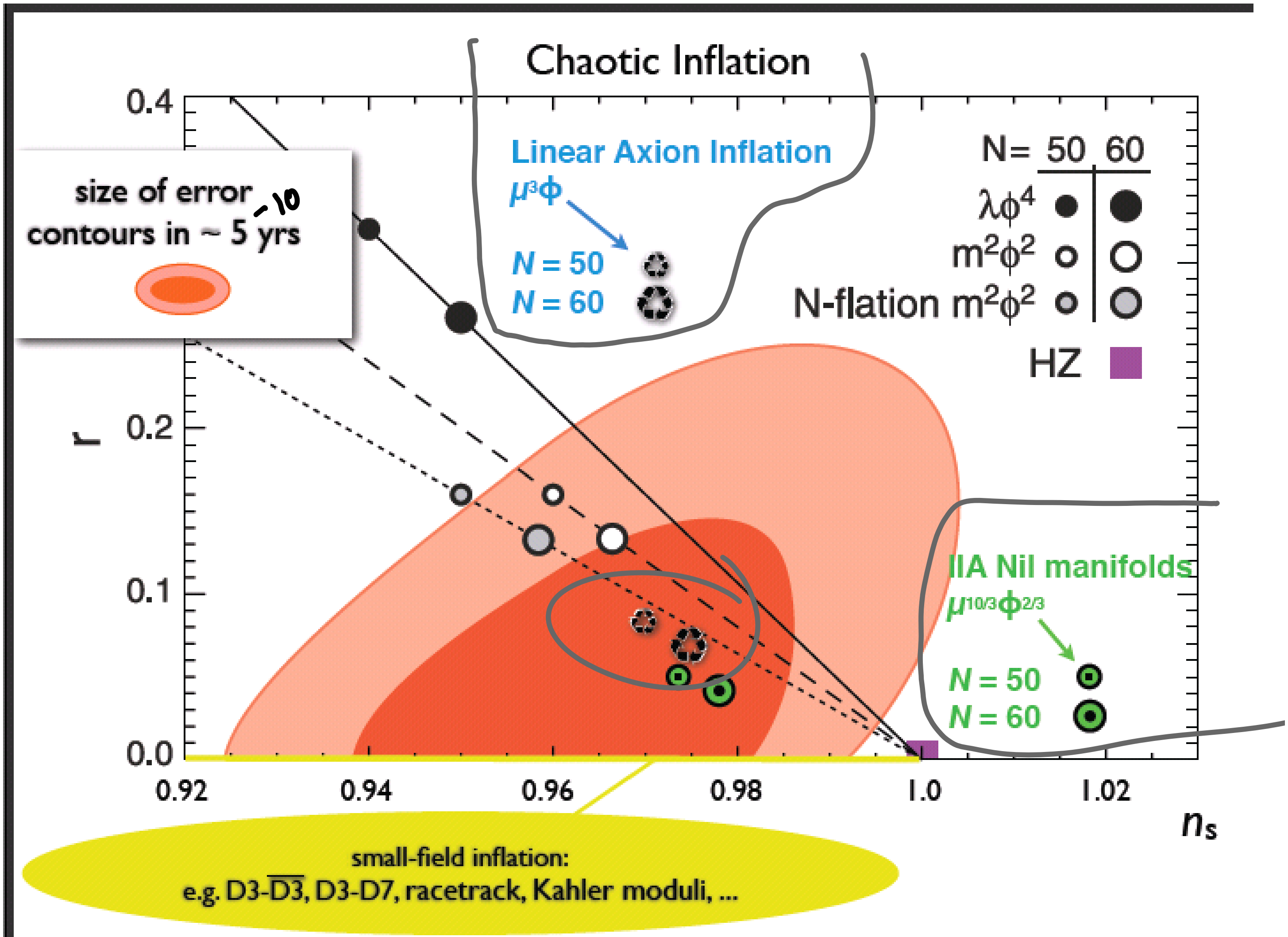


$$+$$

$$\left(e^{-\frac{8\pi^2}{g^2}} \cos\frac{\phi}{f} \right.$$

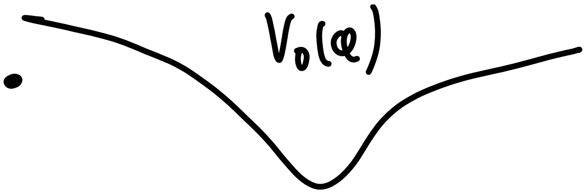
Result :

WMAP



$$r = 0.07$$
$$n_s \simeq 0.98$$
$$V(\varphi) \simeq \mu^3 \varphi + \Lambda^4 \cos\left(\frac{\varphi}{2\pi f}\right)$$

Because of the symmetry, and oscillating nature of the (instanton-suppressed) corrections, these predictions are robust $\Rightarrow$ falsifiable

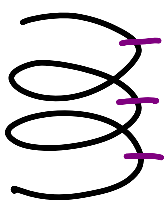
- 

  Flattened potential is the result of the adjustment of heavy fields

- Model-dependent oscillations

  $$V(\varphi) = V_0(\varphi) + \Lambda^4 \cos\frac{\varphi}{f}$$

  can lead to visible signatures in $\langle \zeta \cdots \zeta \rangle$

- 

  repeated production of particles/strings

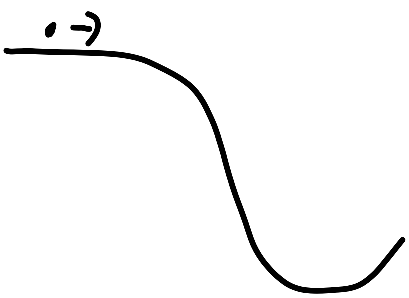
  $\longrightarrow$ novel signatures

  Open direction: new discovery window(s), systematics of detailed signatures.

- Small-field inflation also possible, in other directions in field space.

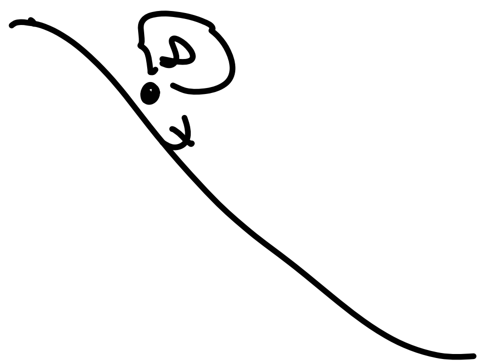
Non-Gaussianity Roughly Speaking, 2 classes of Inflation Mechanisms:

→ Slowly diluting potential energy



Flat potential

NG only from substructure, e.g. oscillations, in $V(\phi)$



Steep potential, but interactions slow the field. $\Rightarrow$ NG.

↪ e.g. brane motion limited by Speed of light (DBI)

Now Systematic (EFT) understanding for single-field; new effects for multiple fields

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

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

(slow Roll inflation)

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

→ 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 sources can compete, producing

cf Chialva

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

Motivations

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

New Sources of GW's

cf Chialva, Ng
Cook/Sorbo, ...

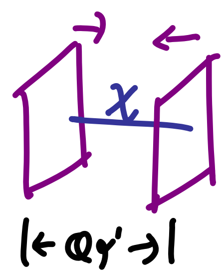
The inflaton ϕ generically couples to other degrees of freedom (e.g. for reheating)

(Lev K + many)

For example,

(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: 

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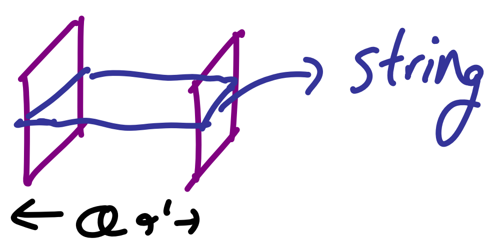
(2) $$T_{string}^2 = T_{min}^2 + \phi^2 M_0^2$$

(brane picture: 

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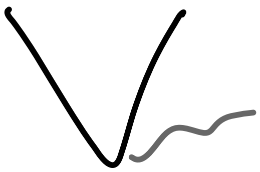
Production :

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



associated scalar emission

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

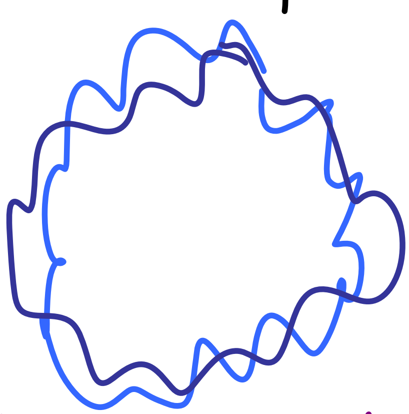
strings:

w/ J. Polchinski
cf Spergel

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

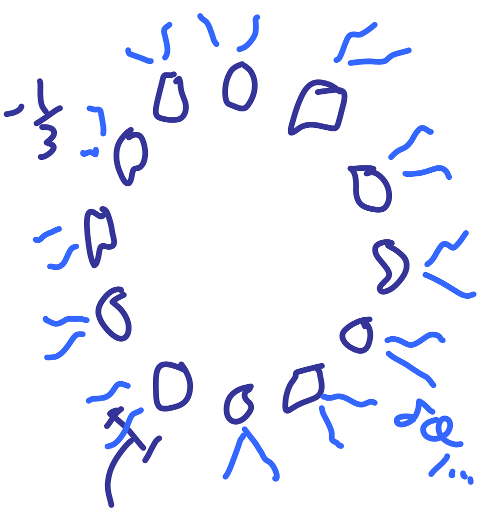
Result:

$\dot{\phi} \to$



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

$\to$



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

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

→ Do these produce competitive GWs?

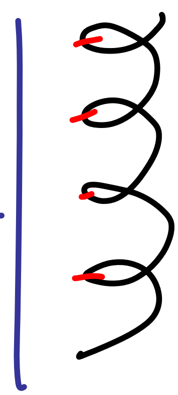
Of course inflation dilutes exotic high-scale relics; Produced particles, strings dilute in a Hubble time.

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 Horn 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.

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

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

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

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

$$\mathcal{S} = \int d^4x\sqrt{-g}\left(\frac{1}{2}M_P^2\mathcal{R} + \mathcal{L}_\phi\right) + \mathcal{S}_X + \mathcal{S}_{XY} \tag{13}$$

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

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

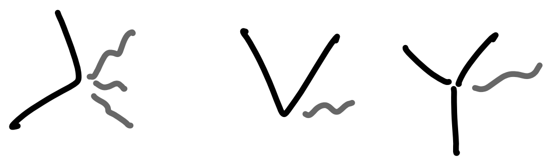
* coupling to ϕ $\Rightarrow$ $\delta\phi$ perturbations controlled by $\partial_\phi m$ or $\partial_\phi T$ along with tensor modes

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

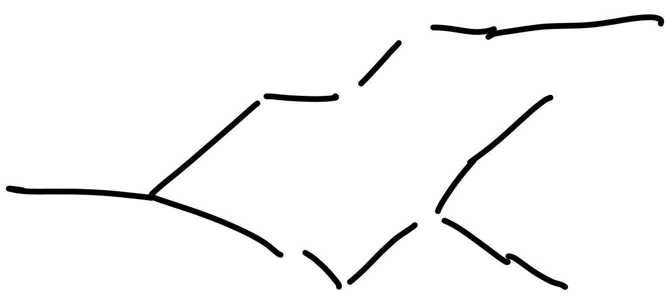
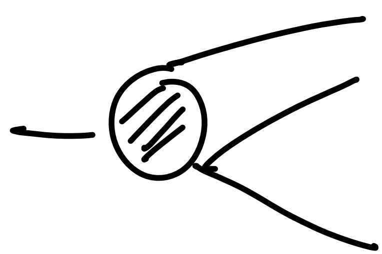


$$\frac{dE}{d\Omega d\omega} = \frac{\omega^2}{16\pi^3 M_p^2}\sum_{N,M}\frac{\eta_N\eta_M}{P_N\cdot k\; P_M\cdot k}\left[(P_N\cdot P_M)^2 - \tfrac{1}{2}m_N^2 m_M^2\right]$$

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, <u>but</u> subsequent events interfere

 $\simeq$ 

Suppression factors & Constraints

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

$\Rightarrow$ no gain from multiple collisions

- $\approx$ spherical symmetry
- $p^0(t) \longrightarrow$ additional factors of ω

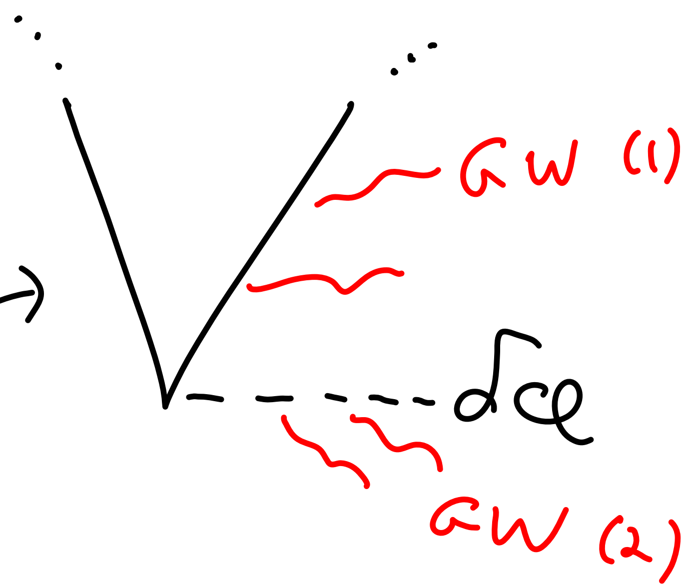
$$T^{\mu\nu}_{part} = \sum_n \delta^{(3)}(\vec{x} - \vec{x}(t)) \frac{p_n^\mu p_n^\nu}{p^0(t)} \theta(t)$$

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

Illustrative examples

① Production itself:

$\phi^2 \chi^2$ interaction



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

$$\Rightarrow \frac{dE_{GW}^{(1)}}{d\omega} \sim \left(\frac{E}{M_p}\right)^2 \times \underbrace{\left(\frac{\omega}{E}\right)^2}_{p^0(t)}$$

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

... both too small

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

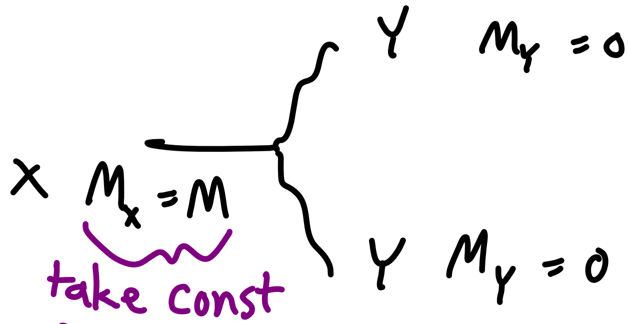
(easily possible including couplings to heavy flds cf "Flattening" Dong Horn ES, AW)

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

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



take const for $t > t_c$

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

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

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

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

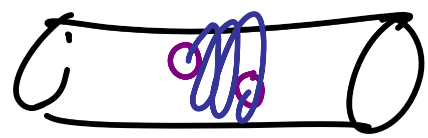
$$\frac{H}{M_p} \sim \frac{10^{-12}}{g\,\epsilon^{3/2}} \quad \text{with } h \sim 10^{-6}$$

- 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 :

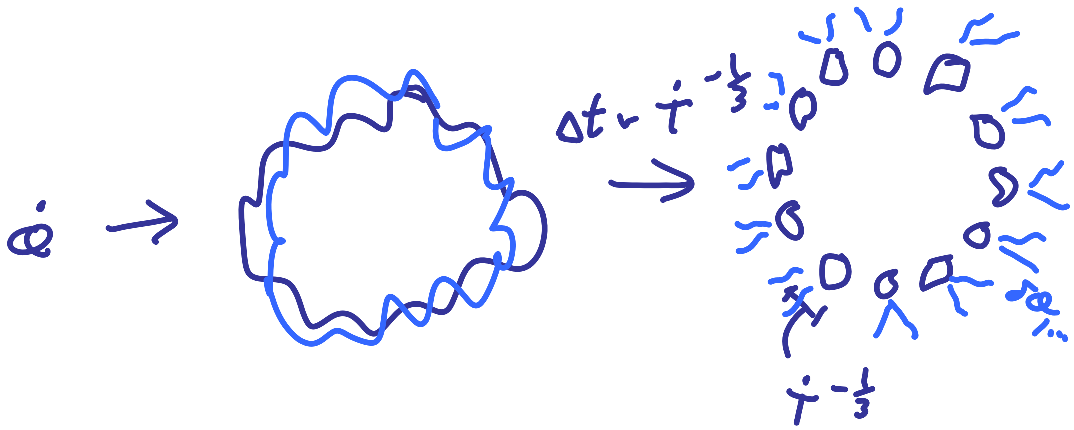


e.g. axion monodromy inflation

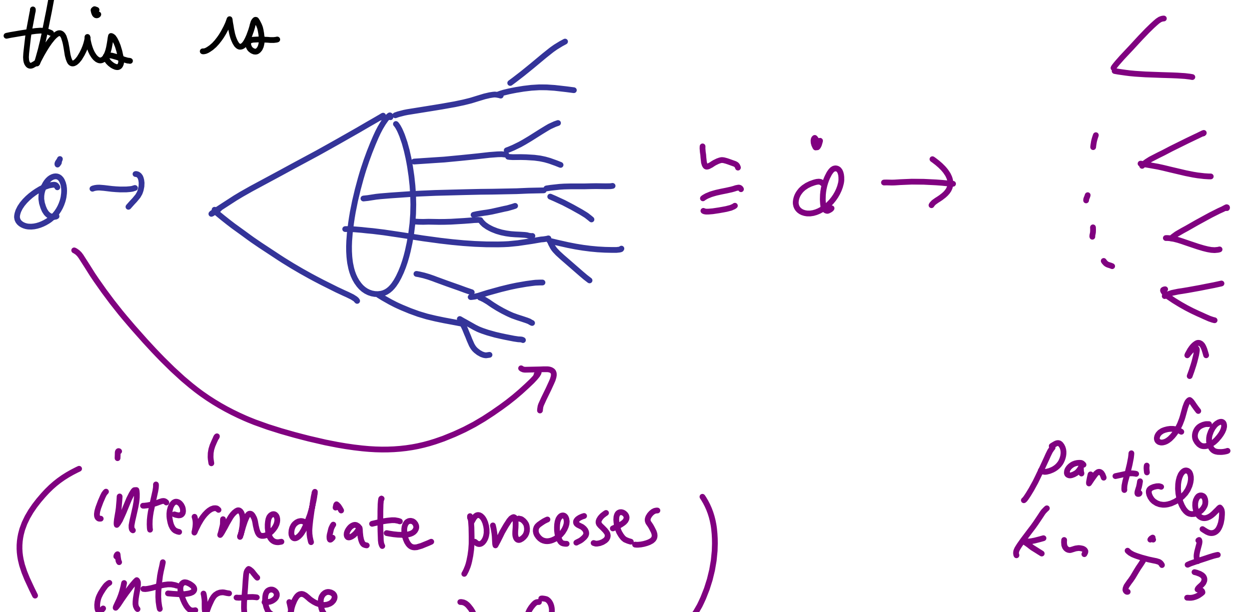
- $T(\phi) = \sqrt{(\eta M_p \phi)^2 + T_0^2}$

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

$\sim \dot{T} t$



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



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

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

This leads to

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

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

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

satisfies constraints easily.

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