

Title: Dissipation during inflation

Date: Mar 15, 2016 11:00 AM

URL: <http://pirsa.org/16030074>

Abstract: <p>I will discuss phenomena associated with particle production and field excitation during inflation. In the first part of the talk I will present several
signatures that can originate from the coupling of an axion inflaton to gauge fields. In the second part I will test the robustness of the standard
implications associated with the detection of a gravity wave (GW) signal at CMB scales, by discussing what conditions can allow a visible
sourced GW background that exceeds the vacuum one (without simultaneously overproduce scalar perturbations), and by providing a concrete
example. In the final part I will review the phenomenology of trapped inflation, which is an interesting and minimal mechanism where particle
production
provides the main friction for the motion of the inflaton.</p>

Dissipation during inflation

Marco Peloso, University of Minnesota

- Non-gaussianity
- Sourced GW
- Warm / trapped inflation

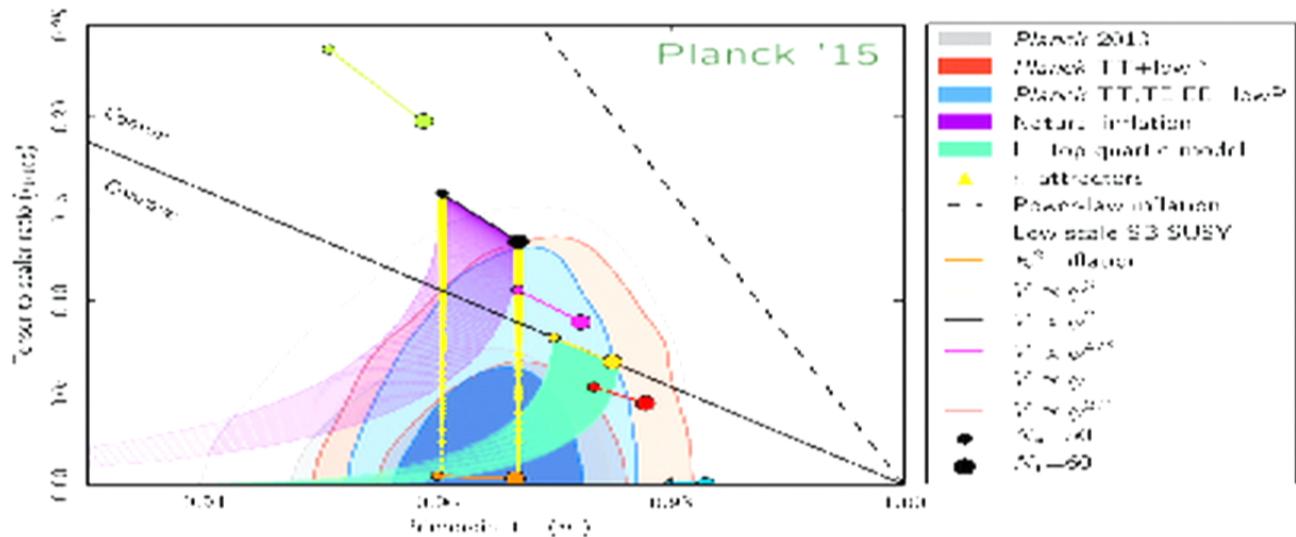
In collaboration with

Barnaby, Biagetti, Crowder, Dimastrogiovanni, Fasiello,
Kim, Komatsu, Mandic, Mukohyama, Moxon, Namba,
Nilles, Pajer, Pearce, Shiu, Shiraishi, Sorbo, Unal, Zhou

- Nearly scale invariant primordial scalar perturbations; tensor \ll scalar

$$P_s \propto k^{n_s - 1}$$

$$r = \frac{P_t}{P_s}$$



- No observed departure from (primordial) gaussianity, $\langle \zeta^3 \rangle \ll \langle \zeta^2 \rangle^{3/2}$
- Agreement with standard single field slow roll

$$r, n_s - 1, f_{NL} = O(\epsilon, \eta)$$

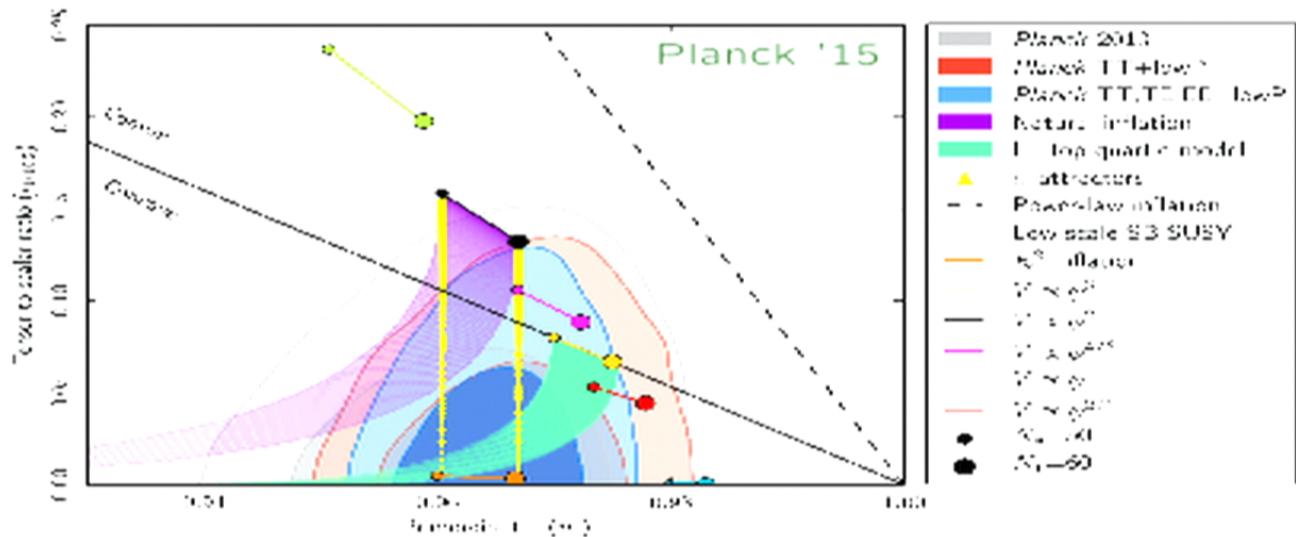
$$\epsilon \equiv \frac{M_p^2}{2} \left(\frac{V_\phi}{V} \right)^2 \ll 1$$

$$\eta \equiv M_p^2 \frac{V_{\phi\phi}}{V} \ll 1$$

- Nearly scale invariant primordial scalar perturbations; tensor \ll scalar

$$P_s \propto k^{n_s - 1}$$

$$r = \frac{P_t}{P_s}$$



- No observed departure from (primordial) gaussianity, $\langle \zeta^3 \rangle \ll \langle \zeta^2 \rangle^{3/2}$
- Agreement with standard single field slow roll

$$r, n_s - 1, f_{NL} = \mathcal{O}(\epsilon, \eta)$$

$$\epsilon \equiv \frac{M_p^2}{2} \left(\frac{V_\phi}{V} \right)^2 \ll 1$$

$$\eta \equiv M_p^2 \frac{V_{\phi\phi}}{V} \ll 1$$

$$\phi = \phi^{(0)} + \delta\phi , \quad S_{\delta\phi} = S_{\text{free}}^{(2)} + S_{\text{int}} \quad \delta\phi \text{ is gaussian if } S_{\text{int}} = 0$$

Small NG due to small ϕ -interactions

- gravity is weak
- self-interactions constrained by slow roll (e.g., $\Delta V = \frac{\lambda}{4}\phi^4 \Rightarrow \lambda < 10^{-13}$)
- interactions with other fields ! (considered for reheating)

$$\phi = \phi^{(0)} + \delta\phi , \quad S_{\delta\phi} = S_{\text{free}}^{(2)} + S_{\text{int}} \quad \delta\phi \text{ is gaussian if } S_{\text{int}} = 0$$

Small NG due to small ϕ -interactions

- gravity is weak
- self-interactions constrained by slow roll (e.g., $\Delta V = \frac{\lambda}{4}\phi^4 \Rightarrow \lambda < 10^{-13}$)
- interactions with other fields ! (considered for reheating)

In this talk:

	Reheating in axion inflation, NG,
(i) $\Delta\mathcal{L} = -\frac{\phi}{f} F \tilde{F}$	$P_\zeta(k)$, GW @ interferometers, primordial black holes, ...
(ii) $\Delta\mathcal{L} = -\frac{\sigma}{f} F \tilde{F}$	GW @ CMB scales
(iii) $\Delta\mathcal{L} = \sum_i g_i^2 (\phi - \phi_{0i})^2 \chi_i^2$	Trapped inflation

$$\phi = \phi^{(0)} + \delta\phi , \quad S_{\delta\phi} = S_{\text{free}}^{(2)} + S_{\text{int}} \quad \delta\phi \text{ is gaussian if } S_{\text{int}} = 0$$

Small NG due to small ϕ -interactions

- gravity is weak
- self-interactions constrained by slow roll (e.g., $\Delta V = \frac{\lambda}{4}\phi^4 \Rightarrow \lambda < 10^{-13}$)
- interactions with other fields ! (considered for reheating)

In this talk:

	Reheating in axion inflation, NG,
(i) $\Delta\mathcal{L} = -\frac{\phi}{f} F \tilde{F}$	$P_\zeta(k)$, GW @ interferometers, primordial black holes, ...
(ii) $\Delta\mathcal{L} = -\frac{\sigma}{f} F \tilde{F}$	GW @ CMB scales
(iii) $\Delta\mathcal{L} = \sum_i g_i^2 (\phi - \phi_{0i})^2 \chi_i^2$	Trapped inflation

$$\phi = \phi^{(0)} + \delta\phi , \quad S_{\delta\phi} = S_{\text{free}}^{(2)} + S_{\text{int}} \quad \delta\phi \text{ is gaussian if } S_{\text{int}} = 0$$

Small NG due to small ϕ -interactions

- gravity is weak
- self-interactions constrained by slow roll (e.g., $\Delta V = \frac{\lambda}{4}\phi^4 \Rightarrow \lambda < 10^{-13}$)
- interactions with other fields ! (considered for reheating)

In this talk:

- | | | |
|--|-------------------|---|
| | | Reheating in axion inflation, NG, |
| (i) $\Delta\mathcal{L} = -\frac{\phi}{f} F \tilde{F}$ | \longrightarrow | $P_\zeta(k)$, GW @ interferometers,
primordial black holes, ... |
| (ii) $\Delta\mathcal{L} = -\frac{\sigma}{f} F \tilde{F}$ | \longrightarrow | GW @ CMB scales |
| (iii) $\Delta\mathcal{L} = \sum_i g_i^2 (\phi - \phi_{0i})^2 \chi_i^2$ | \longrightarrow | Trapped inflation |

$$\phi = \phi^{(0)} + \delta\phi , \quad S_{\delta\phi} = S_{\text{free}}^{(2)} + S_{\text{int}} \quad \delta\phi \text{ is gaussian if } S_{\text{int}} = 0$$

Small NG due to small ϕ -interactions

- gravity is weak
- self-interactions constrained by slow roll (e.g., $\Delta V = \frac{\lambda}{4}\phi^4 \Rightarrow \lambda < 10^{-13}$)
- interactions with other fields ! (considered for reheating)

In this talk:

	Reheating in axion inflation, NG,
(i) $\Delta\mathcal{L} = -\frac{\phi}{f} F \tilde{F}$	$P_\zeta(k)$, GW @ interferometers, primordial black holes, ...
(ii) $\Delta\mathcal{L} = -\frac{\sigma}{f} F \tilde{F}$	GW @ CMB scales
(iii) $\Delta\mathcal{L} = \sum_i g_i^2 (\phi - \phi_{0i})^2 \chi_i^2$	Trapped inflation

Couplings in axion inflation

Freese, Frieman, Olinto '90

. . . (review Pajer, MP '13)

$$\mathcal{L} = \frac{1}{2} (\partial_\mu \phi)^2 + V_{\text{shift}}(\phi) + \frac{c_\psi}{f} \partial_\mu \phi \bar{\psi} \gamma^\mu \gamma_5 \psi + \frac{\alpha}{f} \phi F_{\mu\nu} \tilde{F}^{\mu\nu}$$

- Smallness of V_{shift} technically natural. $\Delta V \propto V_{\text{shift}}$

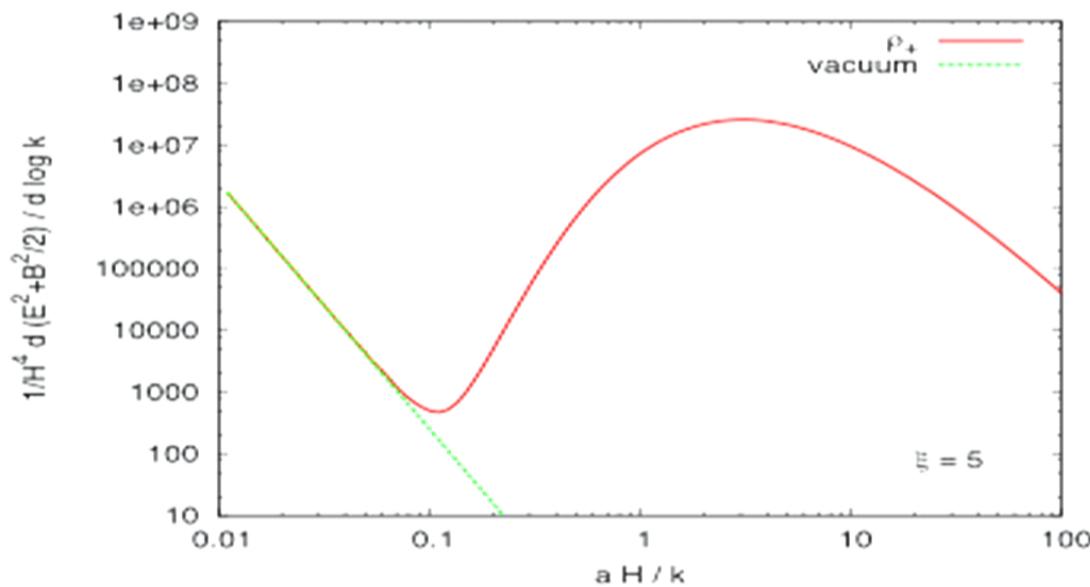
$$\mathcal{L} \supset -\frac{1}{4}F^2 - \frac{\alpha}{4f} \phi^{(0)} F \tilde{F}$$

Classical motion $\phi^{(0)}(t)$ affects dispersion relations of \pm helicities

$$\rightarrow \left(\frac{\partial^2}{\partial \tau^2} + k^2 \mp 2aHk\xi \right) A_{\pm}(\tau, k) = 0 \quad \xi \equiv \frac{\alpha \dot{\phi}^{(0)}}{2fH} \simeq \text{const.}$$

One tachyonic helicity at horizon crossing

Anber, Sorbo '06



- Growth $A \sim e^{\pi\xi}$
at hor. cross.
- Then diluted away

(UV & IR finite)

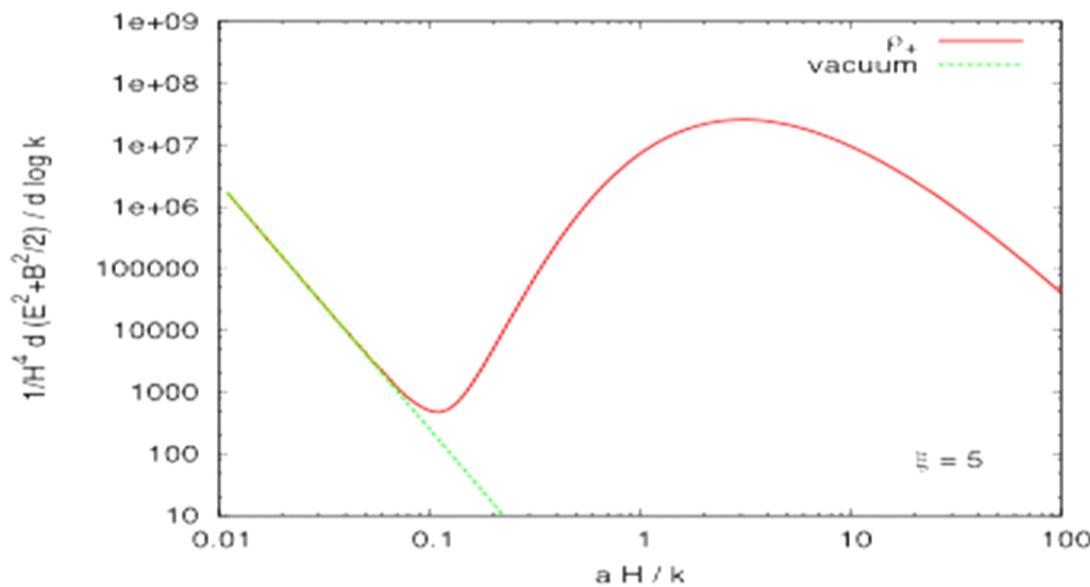
$$\mathcal{L} \supset -\frac{1}{4}F^2 - \frac{\alpha}{4f} \phi^{(0)} F \tilde{F}$$

Classical motion $\phi^{(0)}(t)$ affects dispersion relations of \pm helicities

$$\rightarrow \left(\frac{\partial^2}{\partial \tau^2} + k^2 \mp 2aHk\xi \right) A_{\pm}(\tau, k) = 0 \quad \xi \equiv \frac{\alpha \dot{\phi}^{(0)}}{2fH} \simeq \text{const.}$$

One tachyonic helicity at horizon crossing

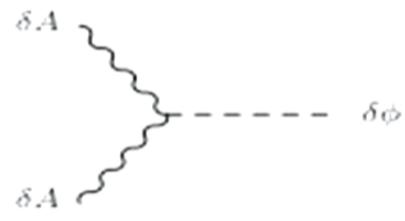
Anber, Sorbo '06



- Growth $A \sim e^{\pi\xi}$
at hor. cross.
- Then diluted away

(UV & IR finite)

$$\delta \ddot{\phi} + 3H\delta\dot{\phi} - \frac{\vec{\nabla}^2}{a^2}\delta\phi + m^2\delta\phi = \frac{\alpha}{f}\vec{E} \cdot \vec{B}$$



(Additional interactions due to δg negligible for $\frac{\alpha}{f} \gg \frac{1}{M_p}$)

$$\delta\phi = \delta\phi_{\text{vacuum}} + \delta\phi_{\text{inv.decay}}$$

Barnaby, MP '10

$$\text{Uncorrelated, } \langle \delta\phi^n \rangle = \langle \delta\phi_{\text{vac}}^n \rangle + \langle \delta\phi_{\text{inv.dec}}^n \rangle$$

Barnaby, Namba, MP '11

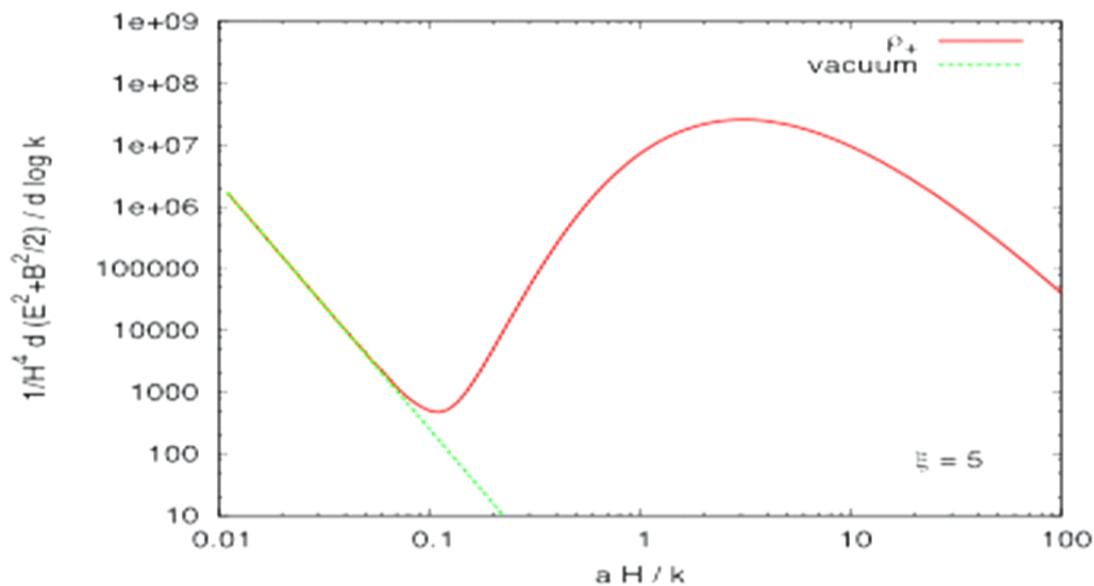
$$\mathcal{L} \supset -\frac{1}{4}F^2 - \frac{\alpha}{4f} \phi^{(0)} F \tilde{F}$$

Classical motion $\phi^{(0)}(t)$ affects dispersion relations of \pm helicities

$$\rightarrow \left(\frac{\partial^2}{\partial \tau^2} + k^2 \mp 2aHk\xi \right) A_{\pm}(\tau, k) = 0 \quad \xi \equiv \frac{\alpha \dot{\phi}^{(0)}}{2fH} \simeq \text{const.}$$

One tachyonic helicity at horizon crossing

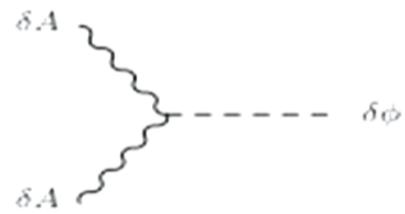
Anber, Sorbo '06



- Growth $A \sim e^{\pi\xi}$
at hor. cross.
- Then diluted away

(UV & IR finite)

$$\delta \ddot{\phi} + 3H\delta\dot{\phi} - \frac{\vec{\nabla}^2}{a^2}\delta\phi + m^2\delta\phi = \frac{\alpha}{f}\vec{E} \cdot \vec{B}$$



(Additional interactions due to δg negligible for $\frac{\alpha}{f} \gg \frac{1}{M_p}$)

$$\delta\phi = \delta\phi_{\text{vacuum}} + \delta\phi_{\text{inv.decay}}$$

$$\text{Uncorrelated, } \langle \delta\phi^n \rangle = \langle \delta\phi_{\text{vac}}^n \rangle + \langle \delta\phi_{\text{inv.dec}}^n \rangle$$

Barnaby, MP '10

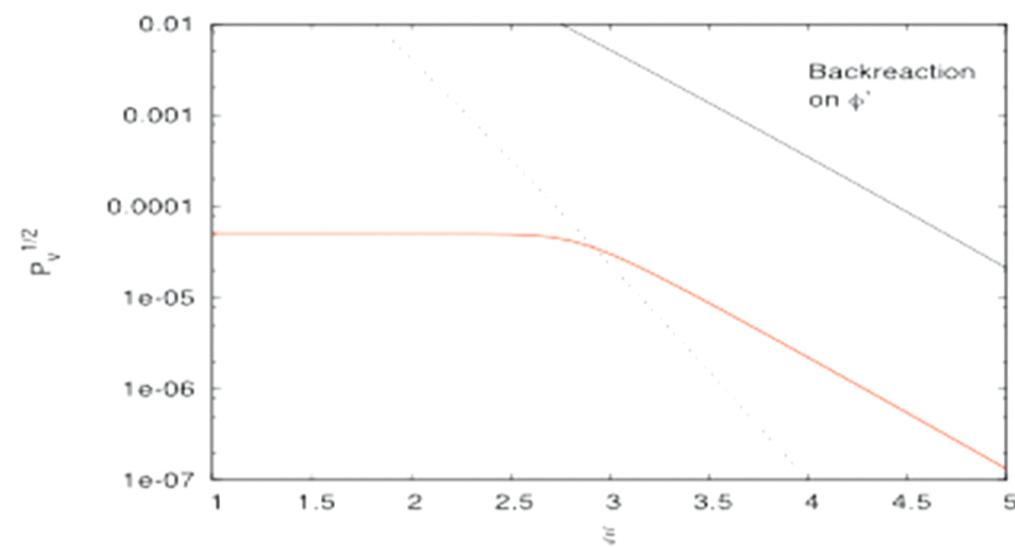
Barnaby, Namba, MP '11

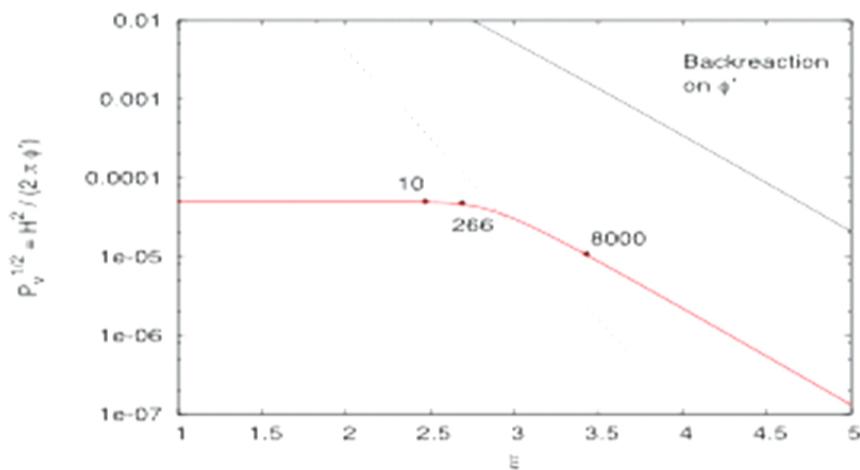
$$P_\zeta(k) \simeq \mathcal{P}_v \left[1 + 7.5 \cdot 10^{-5} \mathcal{P}_v \frac{e^{4\pi\xi}}{\xi^6} \right]$$

$$(\xi > 1)$$

$$\mathcal{P}_v^{1/2} \equiv \frac{H^2}{2\pi|\dot{\phi}|}$$

$$\xi \equiv \frac{\alpha}{f} \frac{|\dot{\phi}|}{2H}$$





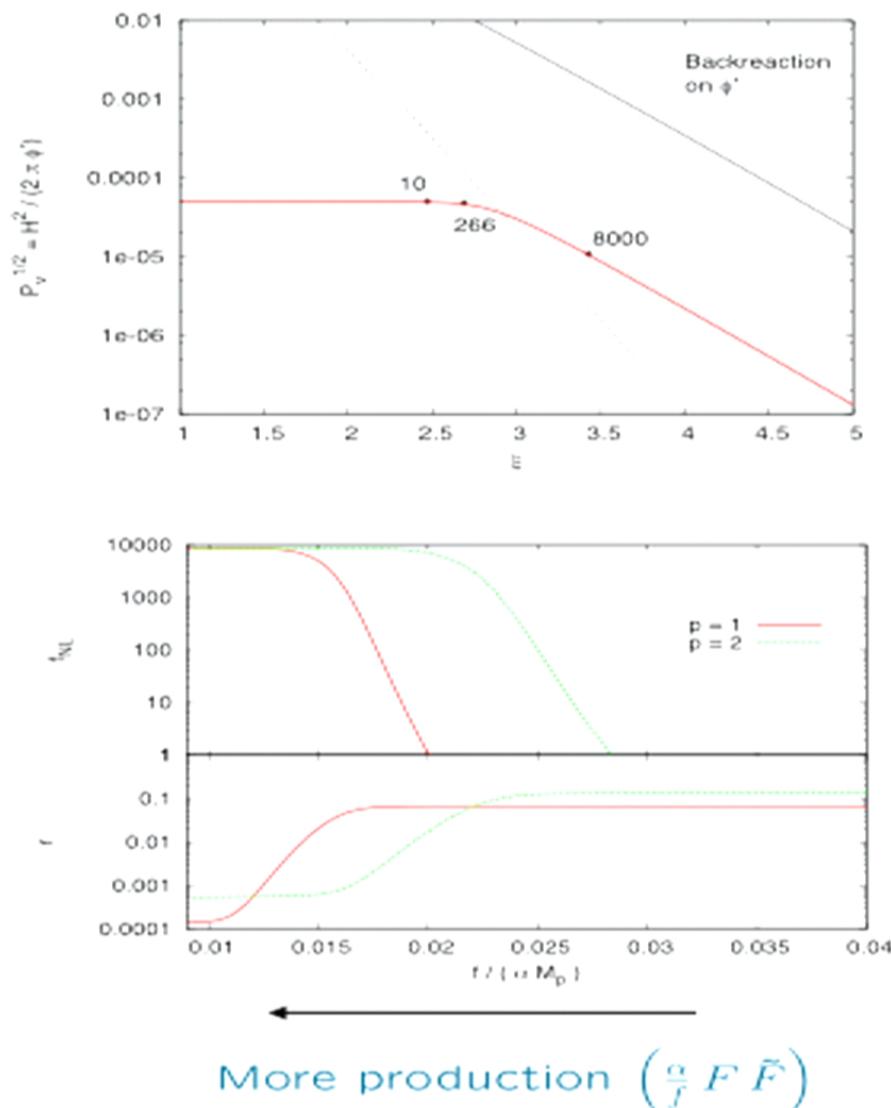
At any moment, only δA
with $\lambda \sim H^{-1}$ present



Nearly equilateral NG

$$f_{\text{NL}}^{\text{equil}} = -4 \pm 43 \quad \text{Planck '15}$$

$\delta A \sim e^{\pi\xi}$ so large variation in a
small window of $\xi = \mathcal{O}(1)$



At any moment, only δA with $\lambda \sim H^{-1}$ present



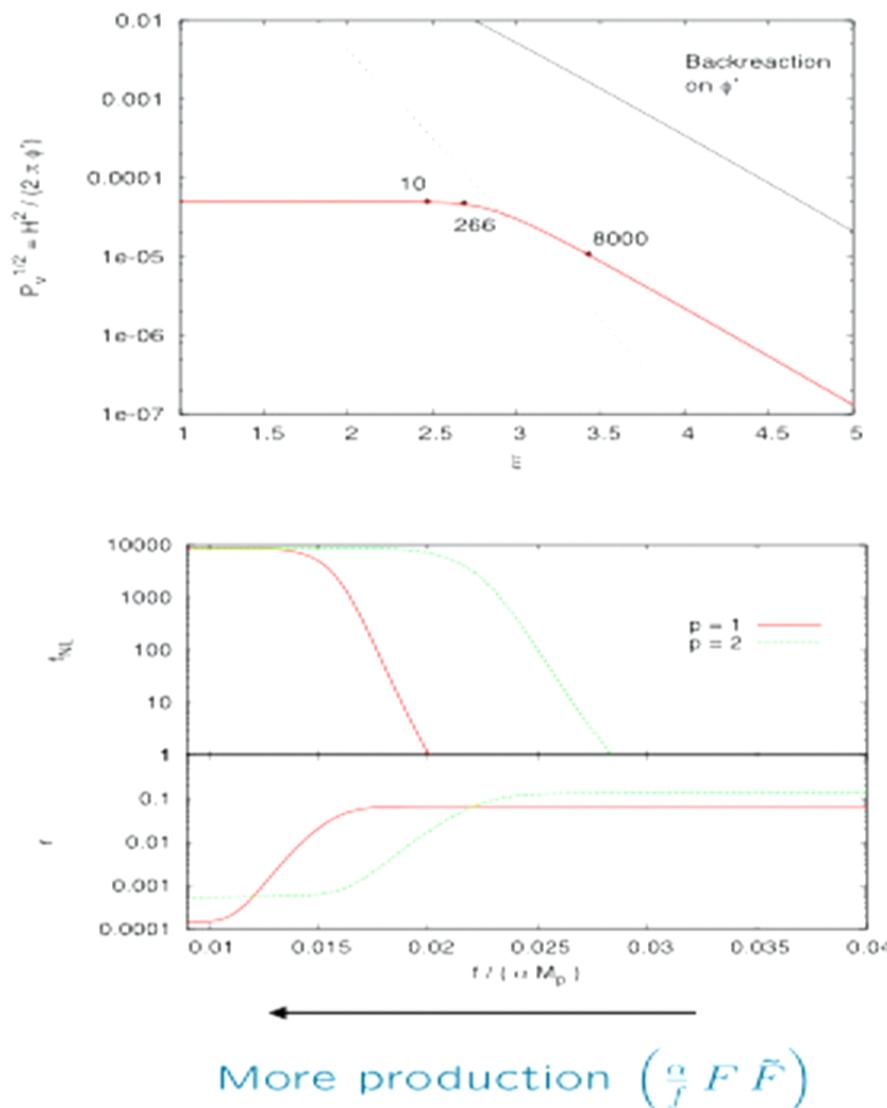
Nearly equilateral NG

$$f_{\text{NL}}^{\text{equil}} = -4 \pm 43 \quad \text{Planck '15}$$

$\delta A \sim e^{\pi \xi}$ so large variation in a small window of $\xi = \mathcal{O}(1)$

$\xi = \mathcal{O}(1)$ for $f/\alpha = \mathcal{O}(10^{16} \text{ GeV})$

More production \rightarrow smaller r
(sourced GW \ll sourced $\delta\phi$)



At any moment, only δA with $\lambda \sim H^{-1}$ present



Nearly equilateral NG

$$f_{NL}^{\text{equil}} = -4 \pm 43 \quad \text{Planck '15}$$

$\delta A \sim e^{\pi\xi}$ so large variation in a small window of $\xi = \mathcal{O}(1)$

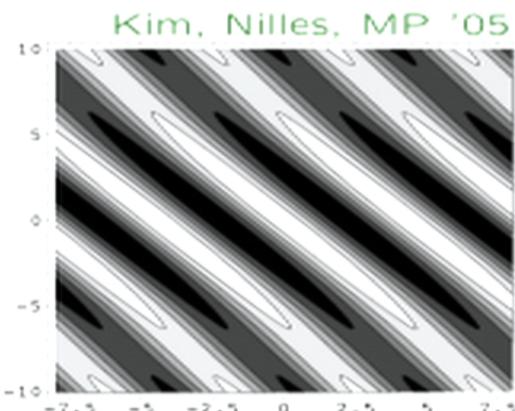
$\xi = \mathcal{O}(1)$ for $f/\alpha = \mathcal{O}(10^{16} \text{ GeV})$

More production \rightarrow smaller r
(sourced GW \ll sourced $\delta\phi$)

- $f \gtrsim 7 M_p$ needed in $V = \Lambda^4 [1 + \cos(\frac{\phi}{f})]$. Values $f \simeq 10^{-2} M_p$ relevant for models with sub-Planckian axion scale, but effective $\Delta\phi > M_p$
E.g., Monodromy, N-flation, Aligned Natural Inflation

$$V = \Lambda_1^4 \left[1 - \cos \left(\frac{\theta}{f_1} + \frac{\rho}{g_1} \right) \right] + \Lambda_2^4 \left[1 - \cos \left(\frac{\theta}{f_2} + \frac{\rho}{g_2} \right) \right]$$

$$f_{\text{eff}} \gg f_i, g_i \quad \text{if} \quad \frac{f_1}{g_1} \simeq \frac{f_2}{g_2}$$



(gravitational instanton corrections may still be a problem if $f_{\text{eff}} > M_p$)

$$\alpha \equiv \frac{f_1 g_2 - f_2 g_1}{f_1 g_2 + f_2 g_1} \ll 1 \quad \text{alignment parameter}$$

MP, Unal '15

$\psi \equiv$ heavy combination

Effective scale : $f_\psi = \mathcal{O}(f_i, g_i)$

$\phi \equiv$ light combination

Effective scale : $f_\phi = \mathcal{O}\left(\frac{f_i}{\alpha}, \frac{g_i}{\alpha}\right)$

- $f \gtrsim 7 M_p$ needed in $V = \Lambda^4 [1 + \cos(\frac{\phi}{f})]$. Values $f \simeq 10^{-2} M_p$ relevant for models with **sub-Planckian axion scale**, but effective $\Delta\phi > M_p$
E.g., Monodromy, N-flation, Aligned Natural Inflation

$$V = \Lambda_1^4 \left[1 - \cos \left(\frac{\theta}{f_1} + \frac{\rho}{g_1} \right) \right] + \Lambda_2^4 \left[1 - \cos \left(\frac{\theta}{f_2} + \frac{\rho}{g_2} \right) \right]$$

$$f_{\text{eff}} \gg f_i, g_i \quad \text{if} \quad \frac{f_1}{g_1} \simeq \frac{f_2}{g_2}$$

(gravitational instanton corrections may still be a problem if $f_{\text{eff}} > M_p$)

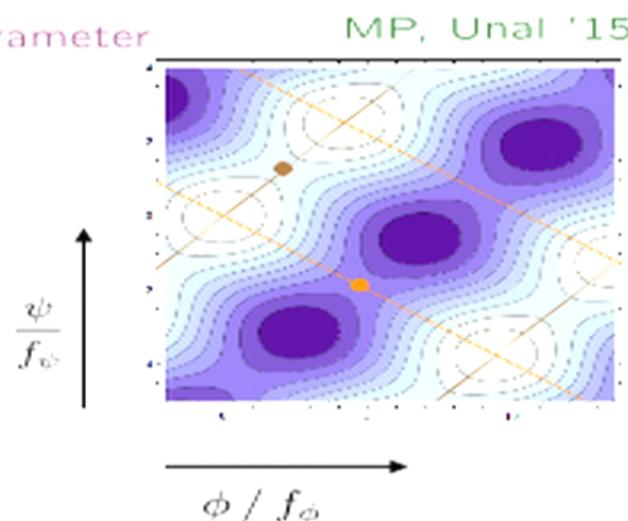
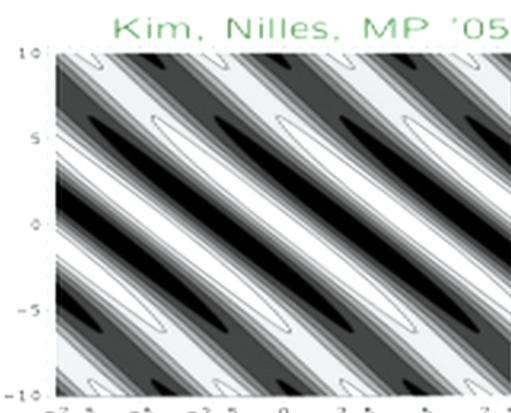
$$\alpha \equiv \frac{f_1 g_2 - f_2 g_1}{f_1 g_2 + f_2 g_1} \ll 1 \quad \text{alignment parameter}$$

$\psi \equiv$ heavy combination

Effective scale : $f_\psi = \mathcal{O}(f_i, g_i)$

$\phi \equiv$ light combination

Effective scale : $f_\phi = \mathcal{O}\left(\frac{f_i}{\alpha}, \frac{g_i}{\alpha}\right)$

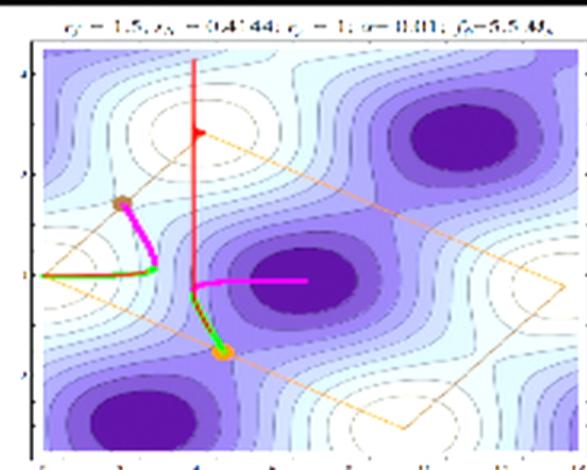


Fields rescaled
 \simeq curvature
 in 2 directions
 ψ much heavier
 Inflation along
 valleys $\frac{\partial V}{\partial \psi} = 0$

Stable valleys, $\frac{\partial V}{\partial \psi} = 0$, $\frac{\partial^2 V}{\partial \psi^2} > 0 \rightarrow$ inflationary trajectories

Unstable crests, $\frac{\partial V}{\partial \psi} = 0$, $\frac{\partial^2 V}{\partial \psi^2} < 0$

For some parameters inflationary trajectories ending because
(1) reach a minimum or (2) become unstable in heavy direction

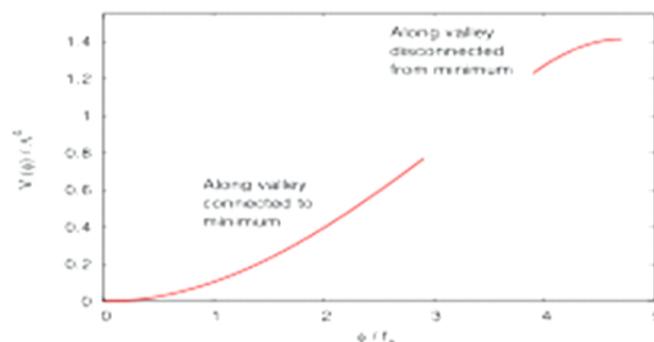


Stable valleys , $\frac{\partial V}{\partial \psi} = 0$, $\frac{\partial^2 V}{\partial \psi^2} > 0 \rightarrow$ inflationary trajectories

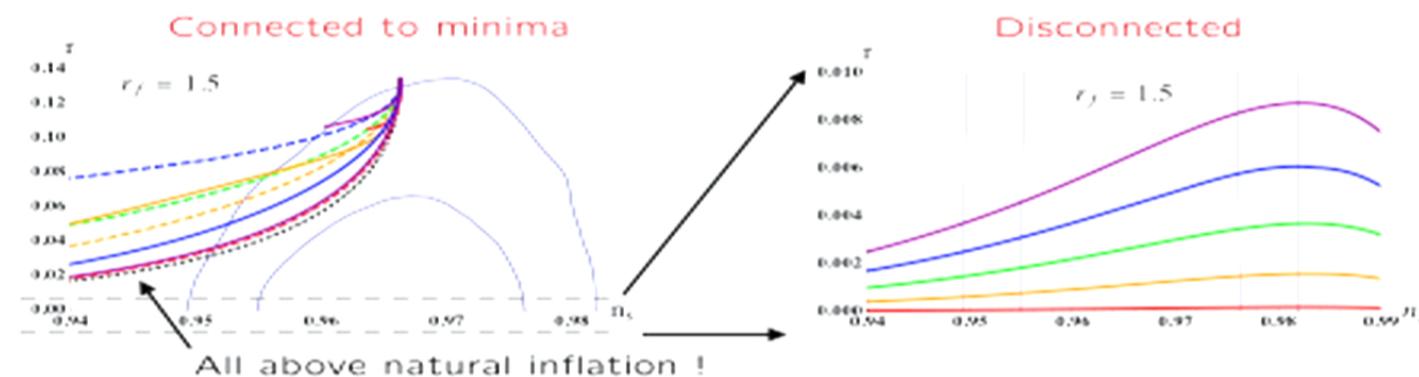
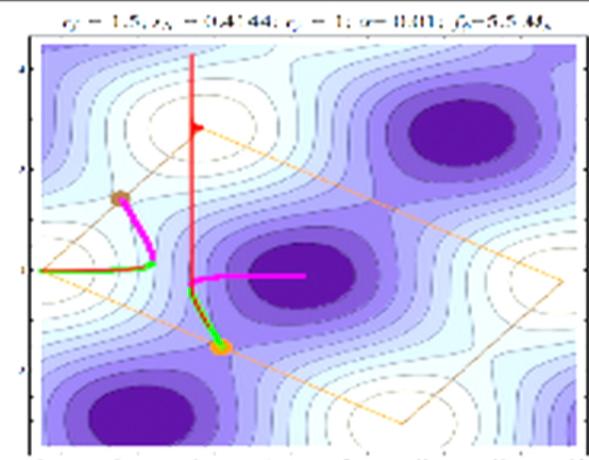
Unstable crests , $\frac{\partial V}{\partial \psi} = 0$, $\frac{\partial^2 V}{\partial \psi^2} < 0$

For some parameters inflationary trajectories ending because

(1) reach a minimum or (2) become unstable in heavy direction



Trajectories (2) have a flatter potential (\equiv smaller $\epsilon \propto V'^2/V^2$)
and so smaller GW (recall $r = 16\epsilon$)



$\delta A \sim e^{\pi\xi}$ and $\xi \propto \frac{\dot{\phi}}{H}$. Inflaton speeds up during inflation

\Rightarrow other interesting effects / signatures

- For instance, growth of $P_\zeta(k)$

Meerburg, Pajer '12

$$P_\zeta \simeq \mathcal{P}_v \left[1 + 7.5 \cdot 10^{-5} \mathcal{P}_v \frac{e^{4\pi\xi}}{\xi^6} \right] \rightarrow \mathcal{P}_* \left(\frac{k}{k_*} \right)^{n_s - 1} \left[1 + \mathcal{P}_* \left(\frac{k}{k_*} \right)^{n_s - 1} f_2(\xi(k)) e^{4\pi\xi_*} \left(\frac{k}{k_*} \right)^{2\pi\xi_* \eta_*} \right]$$

$\xi_* = \xi$ when Planck pivot scale left horizon

$\delta A \sim e^{\pi\xi}$ and $\xi \propto \frac{\dot{\phi}}{H}$. Inflaton speeds up during inflation

\Rightarrow other interesting effects / signatures

- For instance, growth of $P_\zeta(k)$

Meerburg, Pajer '12

$$P_\zeta \simeq \mathcal{P}_v \left[1 + 7.5 \cdot 10^{-5} \mathcal{P}_v \frac{e^{4\pi\xi}}{\xi^6} \right] \rightarrow \mathcal{P}_* \left(\frac{k}{k_*} \right)^{n_s - 1} \left[1 + \mathcal{P}_* \left(\frac{k}{k_*} \right)^{n_s - 1} f_2(\xi(k)) e^{4\pi\xi_*} \left(\frac{k}{k_*} \right)^{2\pi\xi_* \eta_*} \right]$$

$\xi_* = \xi$ when Planck pivot scale left horizon

NG : $\xi_* \leq 2.5$ (95% CL)

Planck '15

PS : $0.1 \leq \xi_* \leq 2.3$ (95% CL)

$$V = M^3 \phi \Rightarrow \frac{f}{\alpha} \gtrsim 0.021 M_p$$

$$V = \frac{m^2}{2} \phi^2 \Rightarrow \frac{f}{\alpha} \gtrsim 0.029 M_p \quad \left(\Delta \mathcal{L} = -\frac{\alpha}{4f} \phi F \tilde{F} \right)$$

- $\dot{\phi}$ keeps increasing. Unique opportunity to explore later stages of inflation
- As ξ grows, δA grows, and additional interactions with $\delta\phi$ relevant
Since $\dot{\phi} \rightarrow \xi \rightarrow \delta A$, first interaction estimated to be

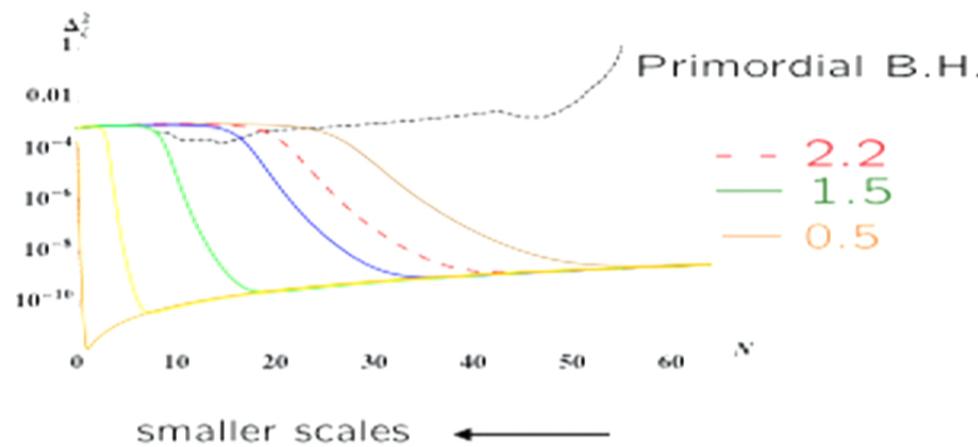
$$\ddot{\delta\phi} + 3 \left[1 - \frac{2\pi\xi\alpha}{3H\dot{\phi}f} \vec{E} \cdot \vec{B} \right] H\dot{\delta\phi} - \frac{\vec{\nabla}^2}{a^2}\delta\phi + m^2\delta\phi = \frac{\alpha}{f}\vec{E} \cdot \vec{B}$$
Anber, Sorbo '09

- $\dot{\phi}$ keeps increasing. Unique opportunity to explore later stages of inflation
- As ξ grows, δA grows, and additional interactions with $\delta\phi$ relevant
Since $\dot{\phi} \rightarrow \xi \rightarrow \delta A$, first interaction estimated to be

$$\ddot{\delta\phi} + 3 \left[1 - \frac{2\pi\xi\alpha}{3H\dot{\phi}f} \vec{E} \cdot \vec{B} \right] H\dot{\delta\phi} - \frac{\vec{\nabla}^2}{a^2} \delta\phi + m^2 \delta\phi = \frac{\alpha}{f} \vec{E} \cdot \vec{B} \quad \text{Anber, Sorbo '09}$$

Scalar perturbations may grow to above primordial black hole bound

Linde, Mooij, Pajer '13



(a order 1 change in P_ζ
can make a big difference)

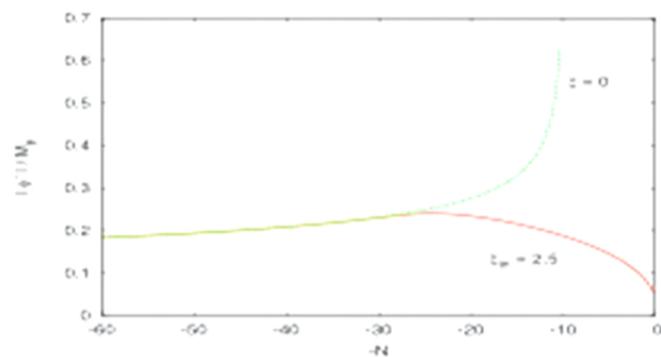
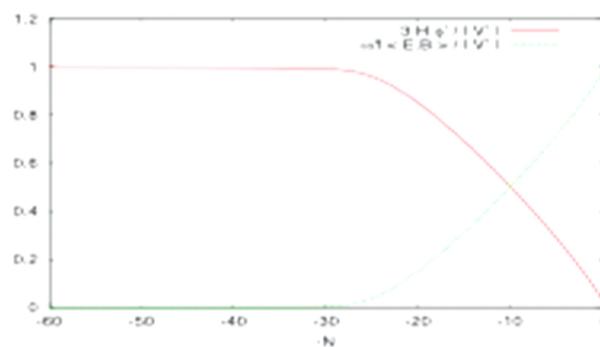
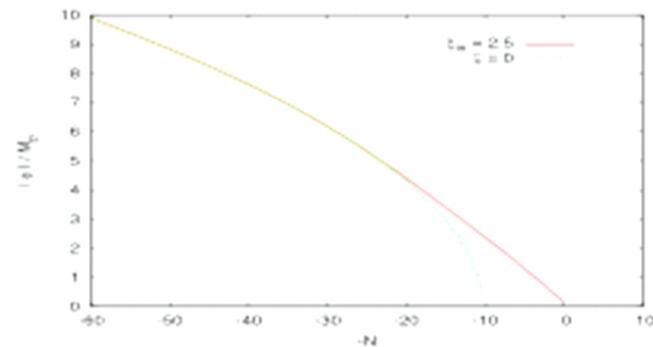
- Chiral GW production $A_+ A_+ \rightarrow h_L$ at interferometer scales

Cook, Sorbo '11

- For precise GW signature, account for backreaction of created A on $\phi(t)$

E.g. $V \propto \phi$

Barnaby, Pajer, MP '11



Chiral GW @ interferometers

$$\langle s_1 s_2 \rangle \propto \Omega_{GW}(f) [\gamma_I(f) + \Pi(f) \gamma_\Pi(f)]$$

$$\Pi \equiv \frac{P_R - P_L}{P_R + P_L} \quad \begin{matrix} \gamma \text{ depend on orientations of the} \\ \text{detectors and on the GW frequency} \end{matrix}$$

- Need three detectors To determine Ω_{GW} and Π

Chiral GW @ interferometers

$$\langle s_1 s_2 \rangle \propto \Omega_{GW}(f) [\gamma_I(f) + \Pi(f) \gamma_\Pi(f)]$$

$$\Pi \equiv \frac{P_R - P_L}{P_R + P_L} \quad \begin{matrix} \gamma \text{ depend on orientations of the} \\ \text{detectors and on the GW frequency} \end{matrix}$$

- Need three detectors To determine Ω_{GW} and Π

Chiral GW @ interferometers

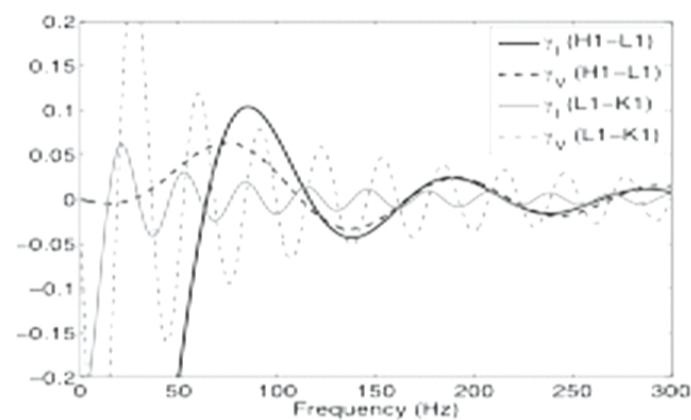
$$\langle s_1 s_2 \rangle \propto \Omega_{GW}(f) [\gamma_I(f) + \Pi(f) \gamma_\Pi(f)]$$

$$\Pi \equiv \frac{P_R - P_L}{P_R + P_L} \quad \gamma \text{ depend on orientations of the detectors and on the GW frequency}$$

- Need three detectors To determine Ω_{GW} and Π

Assume $|\Pi| = 1$. How large does signal need to be to detect GW and exclude $\Pi = 0$ at 2σ ?

Seto, Taruya '07 applied to current interferometers in Crowder, Namba, Mandic, Mukohyama, MP '12



- Vacuum modes : $V^{1/4} = 10^{16} \text{ GeV} \left(\frac{r}{0.01}\right)^{1/4}$. $\Delta\phi \gtrsim M_p \left(\frac{r}{0.01}\right)^{1/2}$
- How robust ?
- Lyth '96
- Mechanisms of GW production with standard GR & QM, e.g.

$$\mathcal{L} = (\phi - \phi_*)^2 \chi^2$$

Cook, Sorbo '11

Senatore, Silverstein, Zaldarriaga '11

$$\mathcal{L} = \sigma F \tilde{F}$$

Barnaby, Moxon, Namba, MP, Shiu, Zhou '12

Namba, MP, Shiraishi, Sorbo, Unal '15

$$\mathcal{L} = \frac{1}{2} (\delta\sigma'^2 - c_s^2 (\nabla \delta\sigma)^2) , \quad c_s \ll 1$$

Biagetti, Fasiello, Riotto '13

Models

I worked on

A field X produced during inflation, and $X \rightarrow h_{\text{sourced}} \gg h_{\text{vacuum}}$

- Small GW production found in above works. Why is it small ?

Barnaby et al '12

To increase h_{sourced} vs. ζ_{sourced} :

Rule 1: Source of GW in a sector gravitationally coupled to inflaton

E. g. $V(\phi) + V(\sigma) + \frac{g^2}{2} (\sigma - \sigma_*)^2 A_\mu A^\mu$

- Small GW production found in above works. Why is it small ?

Barnaby et al '12

To increase h_{sourced} vs. ζ_{sourced} :

Rule 1: Source of GW in a sector gravitationally coupled to inflaton

$$\text{E.g. } V(\phi) + V(\sigma) + \frac{g^2}{2} (\sigma - \sigma_*)^2 A_\mu A^\mu$$

Canonical inflaton / GW mode satisfy $\left(\partial_\tau^2 - \frac{a''}{a} + k^2 \right) Q_i \simeq J_i$, with

$$J_\phi \simeq \frac{\dot{\phi}}{2M_p^2 Ha} \int \frac{d^3 p}{(2\pi)^{3/2}} \left[\hat{k}_i \hat{k}_j \left(M^2 - \partial_\tau^{(1)} \partial_\tau^{(2)} \right) - M^2 \delta_{ij} \right] A_i(\vec{p}) A_j(\vec{k} - \vec{p})$$

$$J_\lambda = \frac{\Pi_{mn,\lambda}^*(\hat{k})}{a M_p} \int \frac{d^3 p}{(2\pi)^{3/2}} \left[\delta_{mi} \delta_{nj} \left(-\partial_\tau^{(1)} \partial_\tau^{(2)} + M^2 \right) + \epsilon_{mai} \epsilon_{nbj} p_a (k - p)_b \right] A_i(\vec{p}) A_j(\vec{k} - \vec{p})$$

Recall $\partial_\tau \simeq M \gg p$. Big cancellation on tensor source

Non-relativistic quanta have suppressed quadrupole moment

- Small GW production found in above works. Why is it small ?

Barnaby et al '12

To increase h_{sourced} vs. ζ_{sourced} :

Rule 1: Source of GW in a sector gravitationally coupled to inflaton

$$\text{E.g. } V(\phi) + V(\sigma) + \frac{g^2}{2} (\sigma - \sigma_*)^2 A_\mu A^\mu$$

Canonical inflaton / GW mode satisfy $\left(\partial_\tau^2 - \frac{a''}{a} + k^2 \right) Q_i \simeq J_i$, with

$$J_\phi \simeq \frac{\dot{\phi}}{2M_p^2 Ha} \int \frac{d^3 p}{(2\pi)^{3/2}} \left[\hat{k}_i \hat{k}_j \left(M^2 - \partial_\tau^{(1)} \partial_\tau^{(2)} \right) - M^2 \delta_{ij} \right] A_i(\vec{p}) A_j(\vec{k} - \vec{p})$$

$$J_\lambda = \frac{\Pi_{mn,\lambda}^*(\hat{k})}{a M_p} \int \frac{d^3 p}{(2\pi)^{3/2}} \left[\delta_{mi} \delta_{nj} \left(-\partial_\tau^{(1)} \partial_\tau^{(2)} + M^2 \right) + \epsilon_{mai} \epsilon_{nbj} p_a (k - p)_b \right] A_i(\vec{p}) A_j(\vec{k} - \vec{p})$$

Recall $\partial_\tau \simeq M \gg p$. Big cancellation on tensor source

Non-relativistic quanta have suppressed quadrupole moment

Rule 2: Source of GW should be relativistic

Both rules satisfied by $V_\phi(\phi) + V_\sigma(\sigma) + \frac{\sigma}{f} F \tilde{F}$ Barnaby et al '12

- A_+ produced by rolling $\sigma(t)$, different from inflaton ϕ
- Due to helicity, $A+A \rightarrow h$ stronger than $A+A \rightarrow \delta\phi$ (both gravitational)

Both rules satisfied by $V_\phi(\phi) + V_\sigma(\sigma) + \frac{\sigma}{f} F \tilde{F}$ Barnaby et al '12

- A_+ produced by rolling $\sigma(t)$, different from inflaton ϕ
- Due to helicity, $A+A \rightarrow h$ stronger than $A+A \rightarrow \delta\phi$ (both gravitational)

Both rules satisfied by $V_\phi(\phi) + V_\sigma(\sigma) + \frac{\sigma}{f} F \tilde{F}$ Barnaby et al '12

- A_+ produced by rolling $\sigma(t)$, different from inflaton ϕ
- Due to helicity, $A + A \rightarrow h$ stronger than $A + A \rightarrow \delta\phi$ (both gravitational)
- However, large $\delta\sigma$ production. As long as σ is rolling, linearly coupled (again, gravitational effect) to $\delta\phi$. Significant $A + A \rightarrow \delta\sigma \rightarrow \delta\phi$

Ferreira, Sloth '14

Rule 3: Source effective only for limited time

Namba, MP, Shiraishi,
Sorbo, Unal '15

- Less time for $\delta\text{source} \rightarrow \delta\phi$
- Can produce modes at $\ell \lesssim 100$ (good for GW, looser limits from NG)

- Small GW production found in above works. Why is it small ?

Barnaby et al '12

To increase h_{sourced} vs. ζ_{sourced} :

Rule 1: Source of GW in a sector gravitationally coupled to inflaton

$$\text{E.g. } V(\phi) + V(\sigma) + \frac{g^2}{2} (\sigma - \sigma_*)^2 A_\mu A^\mu$$

Canonical inflaton / GW mode satisfy $\left(\partial_\tau^2 - \frac{a''}{a} + k^2 \right) Q_i \simeq J_i$, with

$$J_\phi \simeq \frac{\dot{\phi}}{2M_p^2 Ha} \int \frac{d^3 p}{(2\pi)^{3/2}} \left[\bar{k}_i \bar{k}_j \left(M^2 - \partial_\tau^{(1)} \partial_\tau^{(2)} \right) - M^2 \delta_{ij} \right] A_i(\vec{p}) A_j(\vec{k} - \vec{p})$$

$$J_\lambda = \frac{\Pi_{mn,\lambda}^*(\hat{k})}{a M_p} \int \frac{d^3 p}{(2\pi)^{3/2}} \left[\delta_{mi} \delta_{nj} \left(-\partial_\tau^{(1)} \partial_\tau^{(2)} + M^2 \right) + \epsilon_{mai} \epsilon_{nbj} p_a (k - p)_b \right] A_i(\vec{p}) A_j(\vec{k} - \vec{p})$$

Recall $\partial_\tau \simeq M \gg p$. Big cancellation on tensor source

Non-relativistic quanta have suppressed quadrupole moment

Rule 2: Source of GW should be relativistic

Both rules satisfied by $V_\phi(\phi) + V_\sigma(\sigma) + \frac{\sigma}{f} F \tilde{F}$ Barnaby et al '12

- A_+ produced by rolling $\sigma(t)$, different from inflaton ϕ
- Due to helicity, $A+A \rightarrow h$ stronger than $A+A \rightarrow \delta\phi$ (both gravitational)
- However, large $\delta\sigma$ production. As long as σ is rolling, linearly coupled (again, gravitational effect) to $\delta\phi$. Significant $A+A \rightarrow \delta\sigma \rightarrow \delta\phi$

Ferreira, Sloth '14

Rule 3: Source effective only for limited time

Namba, MP, Shiraishi,
Sorbo, Unal '15

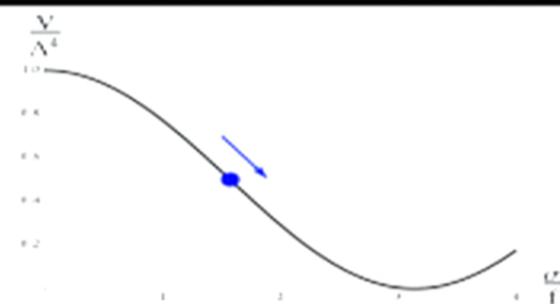
- Less time for $\delta\text{source} \rightarrow \delta\phi$
- Can produce modes at $\ell \lesssim 100$ (good for GW, looser limits from NG)

Bump in δ_{sourced} , h_{sourced} on scales that left horizon while source effective

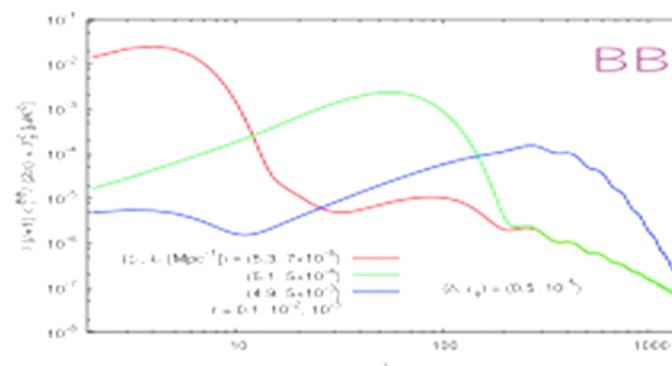
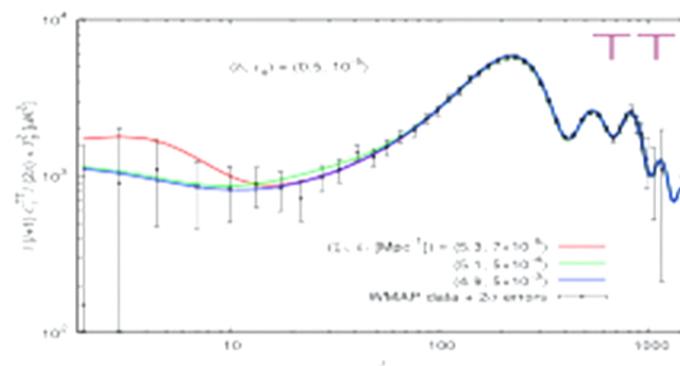
Simplest potential for a pseudoscalar : $V(\sigma) = \frac{\Lambda^4}{2} \left[\cos\left(\frac{\sigma}{f}\right) + 1 \right]$

Slow roll sol. $\dot{\sigma} = \frac{fH\delta}{\cosh[\delta H(t - t_*)]}$, where $\delta \equiv \frac{\Lambda^4}{6H^2f^2} = \frac{m^2}{3H^2}$

$\dot{\sigma}_{\text{max}}$ at $t = t_*$, when $\sigma = \frac{\pi f}{2}$ $\dot{\sigma} \neq 0$ for $\Delta N \sim \frac{1}{\delta}$



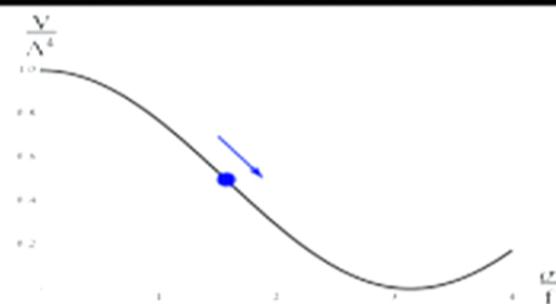
Three examples with $\epsilon_0 = 10^{-5}$ (so that $r_{\text{vacuum}} = 16\epsilon$ is unobservable):



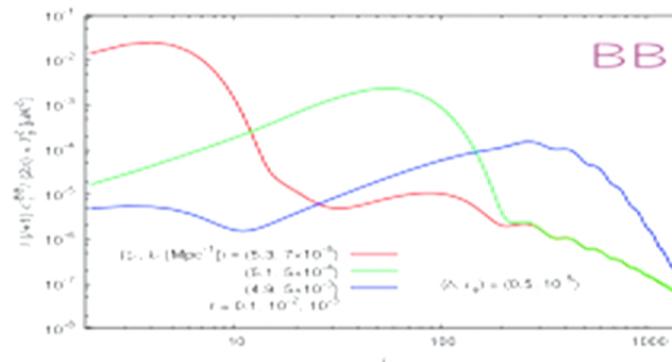
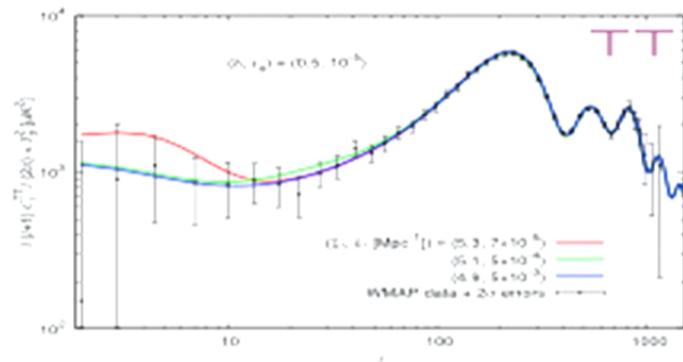
Simplest potential for a pseudoscalar : $V(\sigma) = \frac{\Lambda^4}{2} \left[\cos\left(\frac{\sigma}{f}\right) + 1 \right]$

Slow roll sol. $\dot{\sigma} = \frac{fH\delta}{\cosh[\delta H(t - t_*)]}$, where $\delta \equiv \frac{\Lambda^4}{6H^2f^2} = \frac{m^2}{3H^2}$

$\dot{\sigma}_{\text{max}}$ at $t = t_*$, when $\sigma = \frac{\pi f}{2}$ $\dot{\sigma} \neq 0$ for $\Delta N \sim \frac{1}{\delta}$



Three examples with $\epsilon_0 = 10^{-5}$ (so that $r_{\text{vacuum}} = 16\epsilon$ is unobservable):

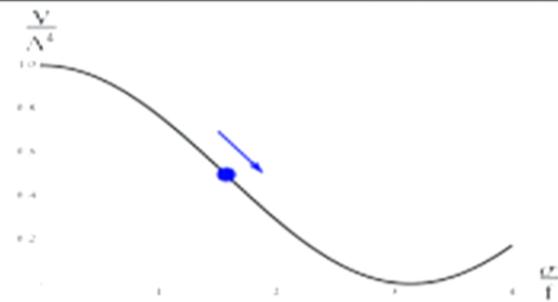


Shown for comparison:
scale invariant
 $r = 0.1$
 $r = 0.01$
 $r = 0.001$

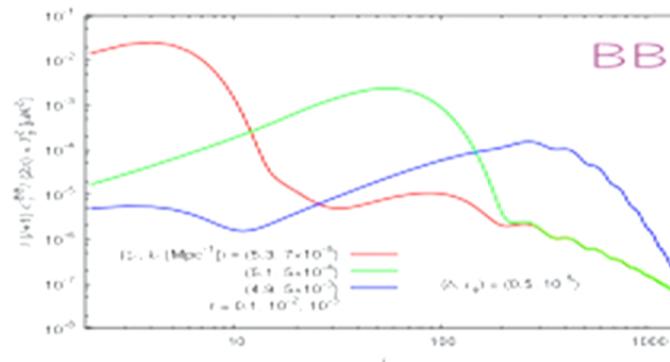
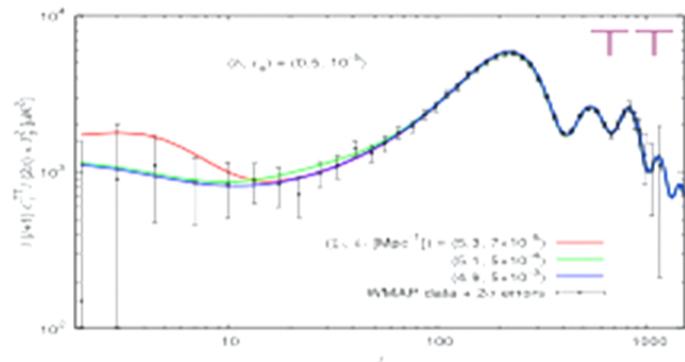
Simplest potential for a pseudoscalar : $V(\sigma) = \frac{\Lambda^4}{2} \left[\cos\left(\frac{\sigma}{f}\right) + 1 \right]$

Slow roll sol. $\dot{\sigma} = \frac{fH\delta}{\cosh[\delta H(t - t_*)]}$, where $\delta \equiv \frac{\Lambda^4}{6H^2f^2} = \frac{m^2}{3H^2}$

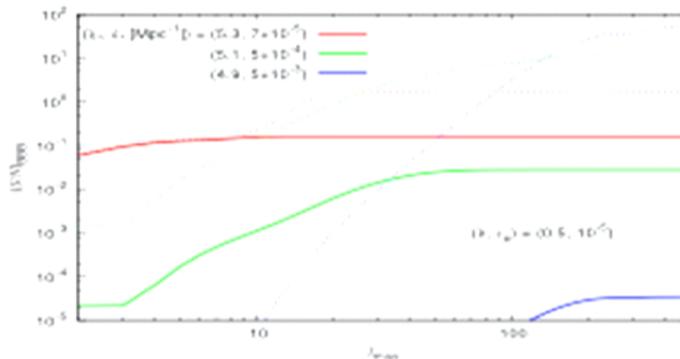
$\dot{\sigma}_{\text{max}}$ at $t = t_*$, when $\sigma = \frac{\pi f}{2}$ $\dot{\sigma} \neq 0$ for $\Delta N \sim \frac{1}{\delta}$



Three examples with $\epsilon_0 = 10^{-5}$ (so that $r_{\text{vacuum}} = 16\epsilon$ is unobservable):



Shown for comparison:
scale invariant
 $r = 0.1$
 $r = 0.01$
 $r = 0.001$



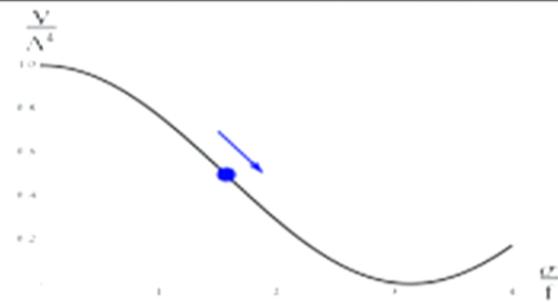
BBB

- Can be distinguished from vacuum by tensor running and BBB
(in principle also TB,
but we found small S/N)

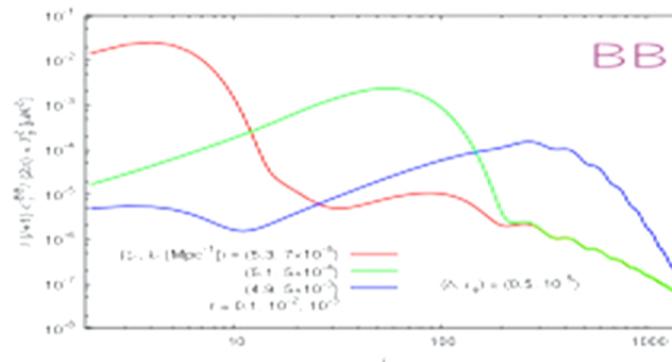
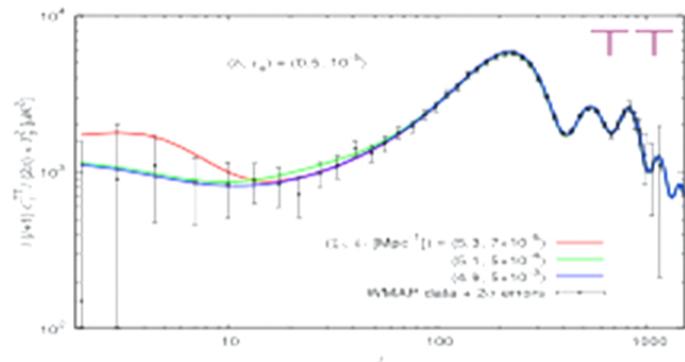
Simplest potential for a pseudoscalar : $V(\sigma) = \frac{\Lambda^4}{2} \left[\cos\left(\frac{\sigma}{f}\right) + 1 \right]$

Slow roll sol. $\dot{\sigma} = \frac{fH\delta}{\cosh[\delta H(t - t_*)]}$, where $\delta \equiv \frac{\Lambda^4}{6H^2f^2} = \frac{m^2}{3H^2}$

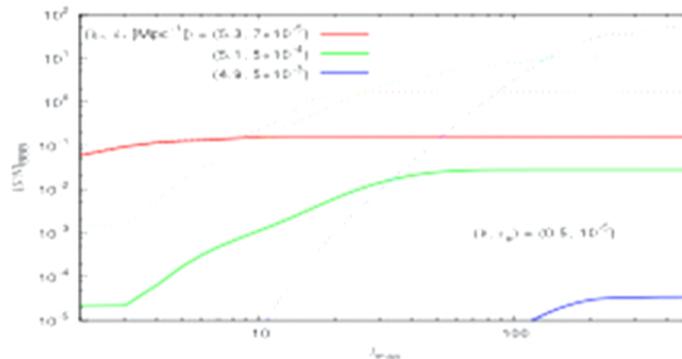
$\dot{\sigma}_{\text{max}}$ at $t = t_*$, when $\sigma = \frac{\pi f}{2}$ $\dot{\sigma} \neq 0$ for $\Delta N \sim \frac{1}{\delta}$



Three examples with $\epsilon_0 = 10^{-5}$ (so that $r_{\text{vacuum}} = 16\epsilon$ is unobservable):

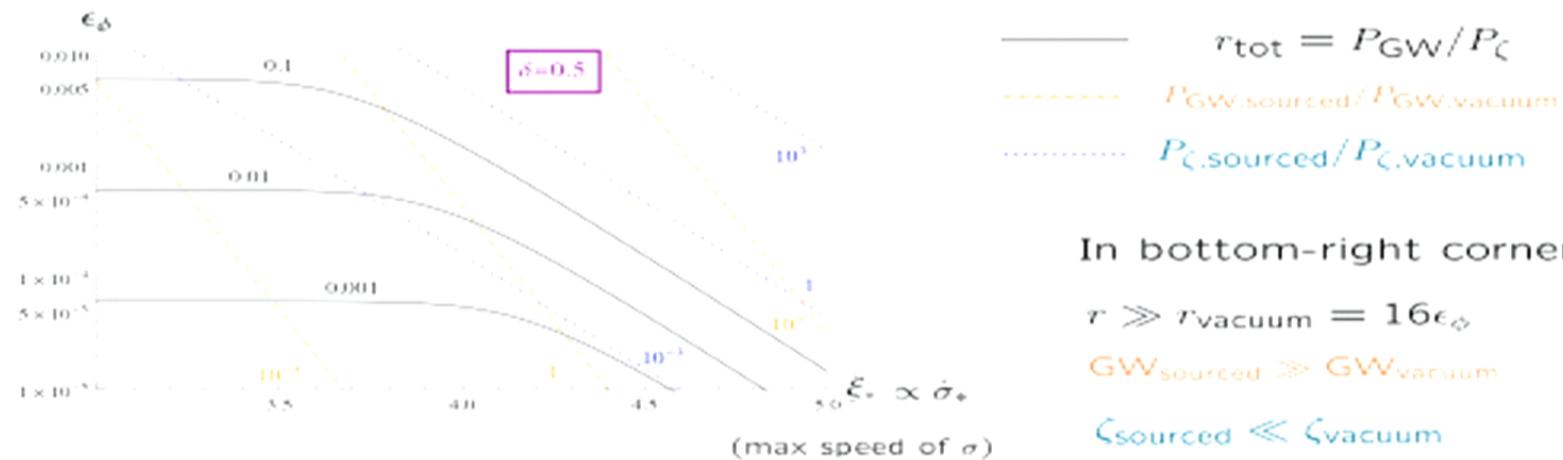


Shown for comparison:
scale invariant
 $r = 0.1$
 $r = 0.01$
 $r = 0.001$



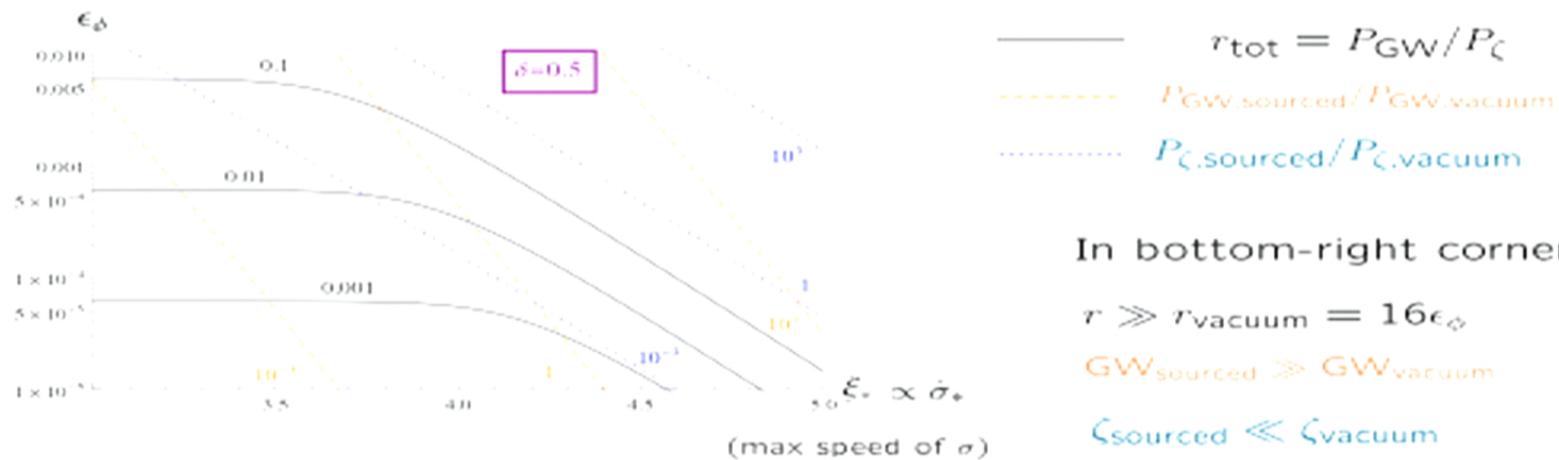
- Can be distinguished from vacuum by tensor running and BBB
(in principle also TB,
but we found small S/N)

- Vacuum mechanism for GW **very robust**
- Under specific conditions, can produce **visible r** at arbitrarily small r_{vacuum} / scale of inflation



(At very small ϵ_ϕ , we have \dot{H} controlled by $\dot{\sigma} > \dot{\phi}$ at the bump. No phenomenological consequences: In this model n_s controlled by $\eta_\phi \simeq 10^{-2} \gg \epsilon_\phi, \epsilon_\sigma$)

- Vacuum mechanism for GW **very robust**
- Under specific conditions, can produce **visible r** at arbitrarily small r_{vacuum} / scale of inflation



(At very small ϵ_ϕ , we have \dot{H} controlled by $\dot{\sigma} > \dot{\phi}$ at the bump. No phenomenological consequences: In this model n_s controlled by $\eta_\phi \simeq 10^{-2} \gg \epsilon_\phi, \epsilon_\sigma$)

Trapped inflation

Green, Horn, Senatore, Silverstein '09

- Very flat potential required for inflation, also $V = \frac{m^2 \phi^2}{2}$ ruled out
- Many models have $\Delta\phi > M_p$. Compatible with quantum gravity ?

Motivated by improvement in NG, reanalysis in Pearce, MP, Sorbo, '16
(in progress)

- We follow original system of equations for φ_0 ; $\delta\phi_1$, and constraints
- = parametric solutions; \neq numerical coefficient (we find 10^{-4} suppression in P_C)
- Following same rules, we extend equations to $\delta\phi_2$. We find $\langle \delta\phi_1^3 \rangle \gg \langle \delta\phi_1^2 \delta\phi_2 \rangle$

Motivated by improvement in NG, reanalysis in Pearce, MP, Sorbo, '16
(in progress)

- We follow original system of equations for φ_0 ; $\delta\phi_1$, and constraints
- = parametric solutions; \neq numerical coefficient (we find 10^{-4} suppression in P_C)
- Following same rules, we extend equations to $\delta\phi_2$. We find $\langle \delta\phi_1^3 \rangle \gg \langle \delta\phi_1^2 \delta\phi_2 \rangle$

$$\bullet \sim \frac{\partial}{\partial \phi} \left\langle \sum_i g^2 (\phi - \varphi)^2 \chi_i^2 \right\rangle \sim \sum_i g m_{\chi_i} \langle \chi_i^2 \rangle \sim \sum_i g n_{\chi_i}$$

$$n_k(t_*) = \frac{\theta(t - t_{0i})}{a^3} e^{-\frac{\chi_i^2}{\sqrt{10}}} \Rightarrow n_{\chi_i} \sim \frac{\theta(t - t_{0i}) (g \dot{\varphi}_0)^{3/2}}{a^3} \sum_i \rightarrow \int \frac{d\phi}{\Delta} \rightarrow \int \frac{1}{\Delta} \frac{d\varphi}{d\tilde{t}} d\tilde{t}$$

$$\Rightarrow \ddot{\varphi}_0 + 3H\dot{\varphi}_0 + V' + \int^t g^{5/2} \frac{\dot{\varphi}_0^{5/2}}{\Delta (2\pi)^3} \frac{a^3(t')}{a^3(t)} dt' = 0 \longrightarrow \dot{\varphi}_0 \simeq -\frac{1}{g} (24 \pi^3 H \Delta V')^{2/5}$$

- $\sim \frac{\partial}{\partial \phi} \left\langle \sum_i g^2 (\phi - \varphi)^2 \chi_i^2 \right\rangle \sim \sum_i g m_{\chi_i} \langle \chi_i^2 \rangle \sim \sum_i g n_{\chi_i}$

$$n_k(t_*) = \frac{\theta(t - t_{0i})}{a^3} e^{-\frac{\varphi_*^2}{\sqrt{m}}} \Rightarrow n_{\chi_i} \sim \frac{\theta(t - t_{0i}) (g \dot{\varphi}_0)^{3/2}}{a^3} \quad \sum_i \rightarrow \int \frac{d\phi}{\Delta} \rightarrow \int \frac{1}{\Delta} \frac{d\varphi}{dt} dt$$

$$\Rightarrow \ddot{\varphi}_0 + 3H\dot{\varphi}_0 + V' + \int^t g^{5/2} \frac{\dot{\varphi}_0^{5/2}}{\Delta (2\pi)^3} \frac{a^3(t')}{a^3(t)} dt' = 0 \longrightarrow \dot{\varphi}_0 \simeq -\frac{1}{g} (24 \pi^3 H \Delta V')^{2/5}$$

Must be below solid lines and above dashed lines

C_1, C_2 slow-roll. Determine $\varphi_{\text{end}}, \varphi_{60}$

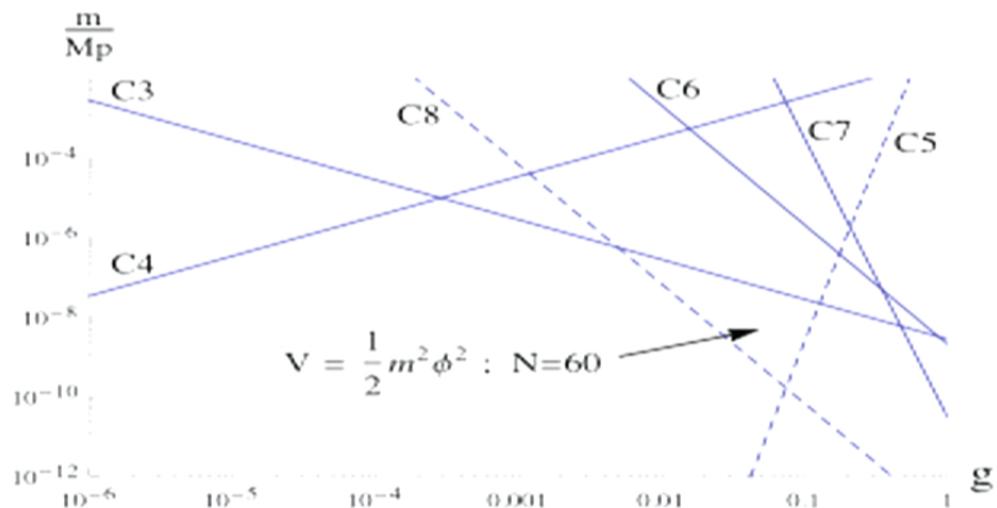
C_3 particle production dominant friction

C_4 fast χ_i production

C_5 quanta χ_i do not annihilate

C_6, C_7 frequent production, $\sum \rightarrow \int$

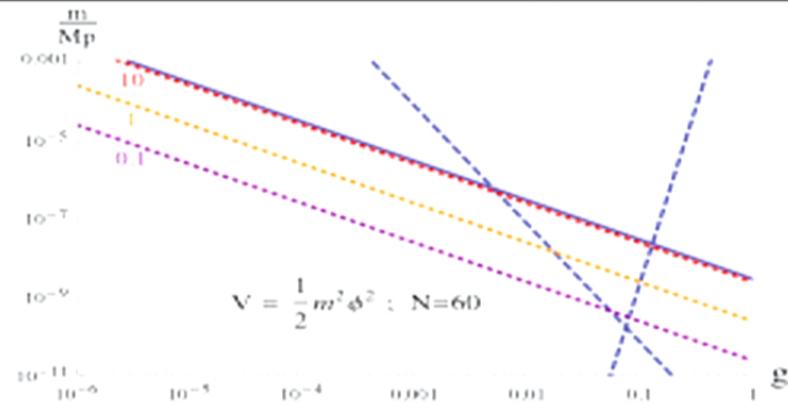
C_8 approx. in $\langle \delta\phi^n \rangle$ computation



Results

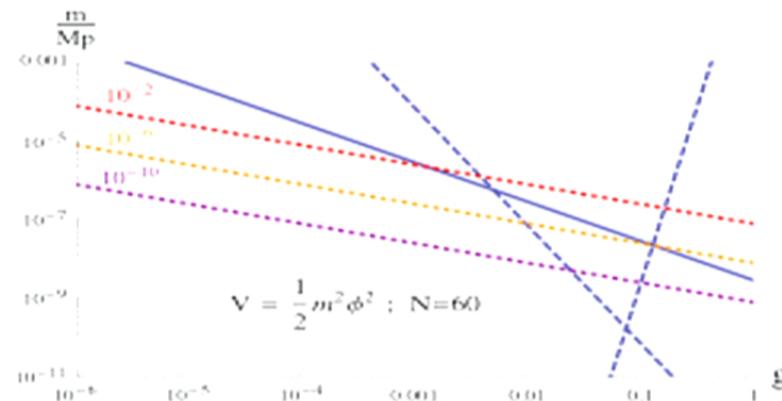
- $\frac{\varphi_{60}}{M_p} < 1$ possible

(cfr. $\phi_{60} \simeq 15.5 M_p$ in standard case)



- Right spectral tilt for $\Delta \propto \phi^\delta$, $-4.8 \lesssim \delta \lesssim -1.3$

- Small GW



- Non-gaussianity, $f_{NL, \text{equil.}} \sim -2$, independently of parameters

$$\langle \zeta^n \rangle' \propto \left(\frac{g^{9/4} H}{k^3 \Delta^{1/2} |\dot{\varphi}_0|^{1/4}} \right)^{n-1}$$

Conclusions

- $f/\alpha \gtrsim 10^{-2} M_p$ in axion inflation. True for coupling of axion inflaton to any gauge field. Potential signals at small scales
- $r = 16\epsilon$ very robust. Possible to violate this (existence proof) but hard to source GW without disturbing ζ
- Phenomenology of trapped inflation. Starting point original analysis
Different conclusions from \neq normalization, and $\neq \delta\phi_2$

Conclusions

- $f/\alpha \gtrsim 10^{-2} M_p$ in axion inflation. True for coupling of axion inflaton to any gauge field. Potential signals at small scales
- $r = 16\epsilon$ very robust. Possible to violate this (existence proof) but hard to source GW without disturbing ζ
- Phenomenology of trapped inflation. Starting point original analysis
Different conclusions from \neq normalization, and $\neq \delta\phi_2$

- $\dot{\phi}$ keeps increasing. Unique opportunity to explore later stages of inflation
- As ξ grows, δA grows, and additional interactions with $\delta\phi$ relevant
Since $\dot{\phi} \rightarrow \xi \rightarrow \delta A$, first interaction estimated to be

$$\ddot{\delta\phi} + 3 \left[1 - \frac{2\pi\xi\alpha}{3H\dot{\phi}f} \vec{E} \cdot \vec{B} \right] H\dot{\delta\phi} - \frac{\vec{\nabla}^2}{a^2}\delta\phi + m^2\delta\phi = \frac{\alpha}{f} \vec{E} \cdot \vec{B}$$
Anber, Sorbo '09

$\phi F \tilde{F}$ $G S A S A$

$S(E, B)$

$S[\dot{\varphi} + \delta\dot{\varphi}]$

$S[\varphi]$

$F \cdot \bar{B}$

...