Phenomenology of a pseudoscalar inflaton: naturally large non-gaussianity

Marco Peloso, University of Minnesota

Barnaby, MP, PRL 106 (2011)

Barnaby, Namba, MP, JCAP 009 (2011)

Barnaby, Pajer, MP, PRD 85 (2012)

A very natural class of slow-roll inflation can provide:

- Detectable equilateral NG
- Detectable GW at CMB scales
- Detectable running of $P_\zeta(k)$ and $f_{\rm NL}(k)$
- Detectable GW at interferometers

Inflation is a postulated era of accelerated expansion at $t \ll 1$s that solves many problems of big-bang cosmology (horizon, flatness, monopole,....)

Guth '81, Linde'82, Albrecht and Steinhardt '82

- Simplest source: scalar field ϕ with flat potential $\sim\ \Lambda$

- $\delta\phi\ \rightarrow$ inhomogeneities & structures in the universe

Bardeen, Guth, Hawking, Kodama, Mukhanov, Pi, Sasaki, Starobinsky, Steinhardt, Turner, ...

- Perturbations consistent with simplest inflationary models:

Adiabatic, nearly scale invariant, nearly gaussian, GW $< \delta\rho$

- Strong experimental effort to probe details of inflation through GW and through NG of the scalar perturbations

$$r \equiv \frac{P_{\rm GW}}{P_\zeta}\Big|_{k=0.002\,{\rm Mpc}^{-1}}$$

$r < 0.17$ at 95% C.L.

WMAP + SPT + H_0 + BAO

Keisler et al '11

From vacuum modes:

$$r \simeq 16\,\epsilon \quad , \quad \epsilon \equiv \frac{M_p^2}{2}\left(\frac{V'}{V}\right)^2$$

- $V^{1/4} = 10^{16}\,{\rm GeV}\left(\frac{r}{0.01}\right)^{1/4}$
- $\Delta\phi \simeq \frac{N}{H} \times \dot{\phi} \simeq N \times \sqrt{2\epsilon}\,M_p \simeq 0.35\,M_p\,\frac{N}{10}\left(\frac{r}{0.01}\right)^{1/2}$ Lyth '96

Several experiments

with goal $r \lesssim 0.01 - 0.05$:

S: Planck

B: EBEX, PIPER, SPIDER

G: ABS, ACTpol, BICEP2, CLASS
Keck Array, POLAR, PolarBear,
QUBIC, QUIET, QUIJOTE, SPTpol

Hard to keep the potential flat , $M_p \frac{V'}{V}$, $M_p^2 \frac{V''}{V} \ll 1$, over $\Delta\phi = 0.35\, M_p \, \frac{N}{10} \left(\frac{r}{0.01}\right)^{1/2}$

UV sensitive : $V = V_0 + \sum_i \lambda_i \frac{\phi^{4+i}}{M^i} \quad \Rightarrow \quad M > \Delta\phi$ Weinberg '08

Typical example, η problem in supergravity

$$V = e^{K/M_p^2} \left[K^{\phi\bar{\phi}} \, D_\phi W \, D_{\bar{\phi}} \bar{W} - \frac{3}{M_p^2} |W|^2 \right]$$

During inflation, $\cancel{\text{susy}}$ by an F-term, $F_X^2 = \Lambda^4$

$$\Rightarrow \quad V = e^{K/M_p^2} \left[\Lambda^4 + \ldots \right] = \Lambda^4 \left(1 + \frac{K\left(\phi, \bar{\phi}\right)}{M_p^2} + \ldots \right)$$

- A canonical Kähler, $K = \bar{\phi}\,\phi$, leads to $\eta = M_p^2 \frac{V''}{V} = 1 + \ldots$
- Symmetry ! Shift symmetry $K = \phi + \bar{\phi}$, and inflaton $=$ Im ϕ

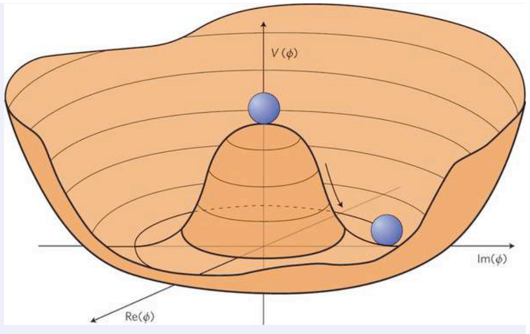
Kawasaki, Yamaguchi, Yanagida '00

QCD axion $\longrightarrow$ Inflaton axion

QCD instantons $\longrightarrow \begin{cases} \Delta\mathcal{L} = \frac{-g^2}{16\pi^2}\,\theta\, F\, \tilde{F} \\ \\ V = \Lambda^4\,[1 - \cos\theta] \end{cases}$

Limit neutron electric dipole moment $\Rightarrow$ $\theta \lesssim 10^{-10}$

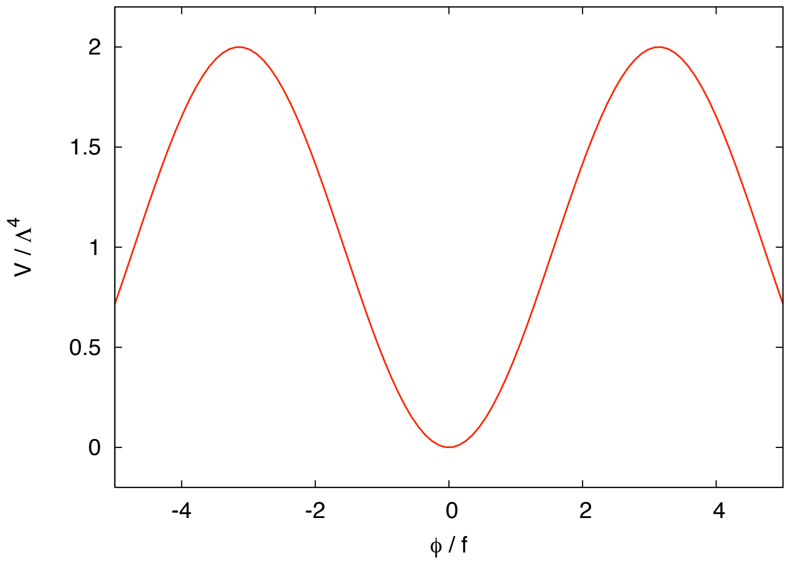
Peccei, Quinn '77: Chiral U(1) symmetry spontaneously broken $\Phi = (f + \rho)\ e^{i\phi/f}$

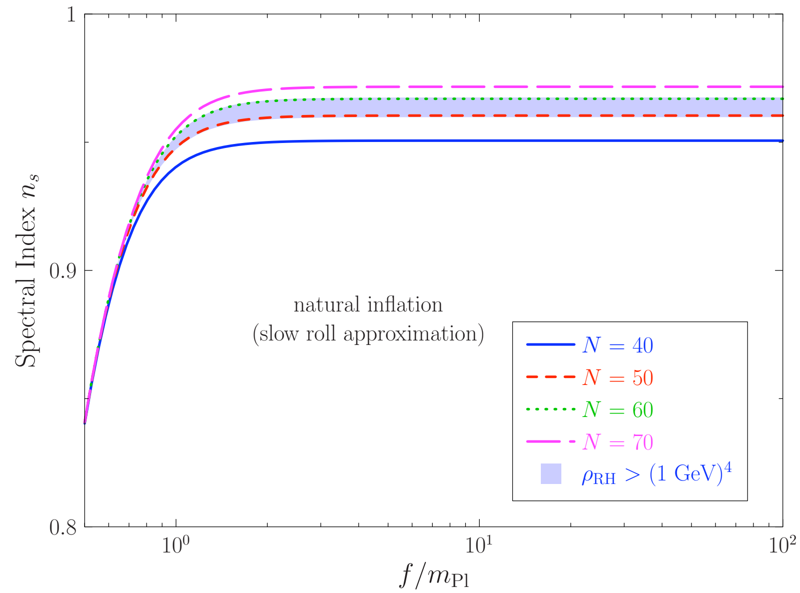


Symmetry is anomalous $\Rightarrow$ $\theta \rightarrow \theta + \dfrac{\phi}{f}$

- Smallness of Λ is technically natural. No perturbative ~~shift~~
- UV completion (ρ) relevant only at scales $> f$
- ϕ only derivatively coupled

Natural Inflation: Freese, Frieman, Olinto '90





Savage, Freese, Kinney '06

Problems with $f > M_p$

- $U(1)_{\rm PQ}$ broken above QG scale (gravitational instantons)
- Hard in weakly coupled string theory

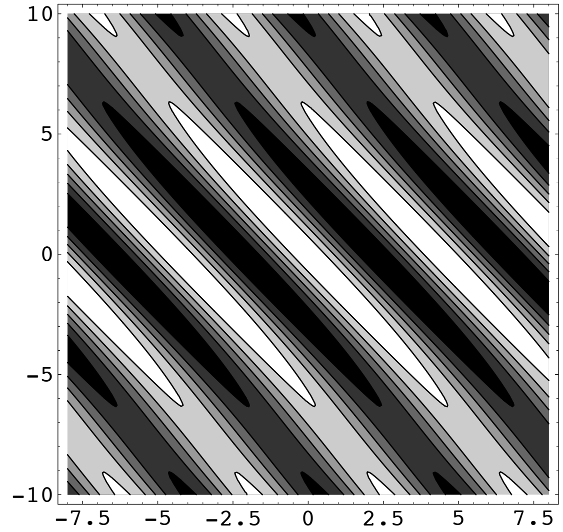
Kallosh, Linde, Linde, Susskind '95

Banks, Dine, Fox, Gorbatov '03

Effective theory under control for $H \ll f \ll M_p$

Two axions & gauge groups

Kim, Nilles, MP '04



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

$f_{\rm eff} >> f, g$ if $f_1/g_1 \simeq f_2/g_2$

N-flation

Dimopoulos, Kachru, McGrevy, Wacker '05

$$V = \sum_n \Lambda_n^4 \cos\left(\frac{\phi_n}{f_n}\right) \longrightarrow \ddot{\phi}_i + 3\,H\,\dot{\phi}_i + \frac{dV_i}{d\phi_i} = 0$$

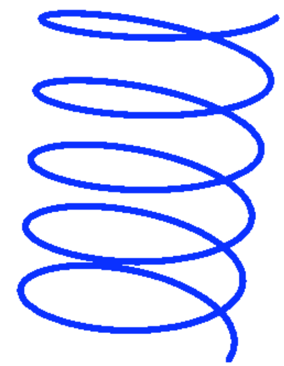
$$\propto V^{1/2} \approx N^{1/2}\, V_i$$

Collectively drive inflation, $f_{\rm eff} = \sqrt{N}\, f$

Axion monodromy

McAllister, Silverstein, Westphal '08

4D axion from a 10D two form



- Periodic ~~SHIFT~~ from instantons
- Nonperiodic ~~SHIFT~~ from

$$S_{\mathrm{DBI\,5D}} \propto T_5 \int d^6x \sqrt{-\det\,(g + B_2)} \;\Rightarrow\; \Delta V \propto T_5 \sqrt{L^4 + a^2} \approx T_5\, a$$

Dante's inferno

Berg, Pajer, Sjors '09

Controllable realizations of large field inflation $(V \propto \phi,\, \phi^2)$, with $f \ll M_p$

Alternative: Slow roll due to particle production

Anber, Sorbo '10, '12

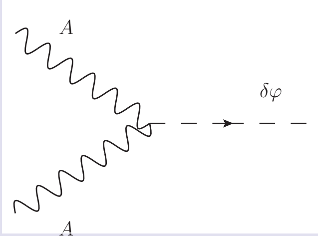
Couplings restricted by:

- Shift symmetry
- Parity
- Gauge invariance

$$\mathcal{L}_{\text{int}} = \frac{C}{f}\,\partial_\mu\phi\,\bar{\psi}\,\gamma^\mu\,\gamma_5\,\psi + \frac{\alpha}{f}\,\phi\,F_{\mu\nu}\,\tilde{F}^{\mu\nu}$$

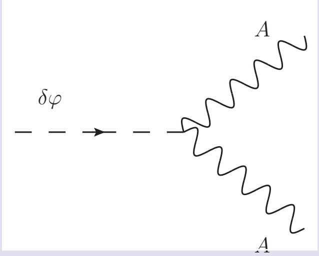
$$\Gamma_{\phi\to\psi\psi} \simeq \frac{C^2}{2\pi f^2}\,m_\phi\,m_\psi^2 \qquad\qquad \Gamma_{\phi\to AA} = \frac{\alpha^2}{64\pi\,f^2}\,m_\phi^3$$

1. $\varphi^{(0)} \to A + A$, non-perturbative depletion $\propto \dot{\varphi}^{(0)}$
   $\Longrightarrow$ Exponential growth of A
2. $A + A \to \delta\varphi$, inverse decay



$\Longrightarrow$ Significant contribution to $\delta\varphi$!

3. $\delta\varphi \to A + A$, perturbative decay



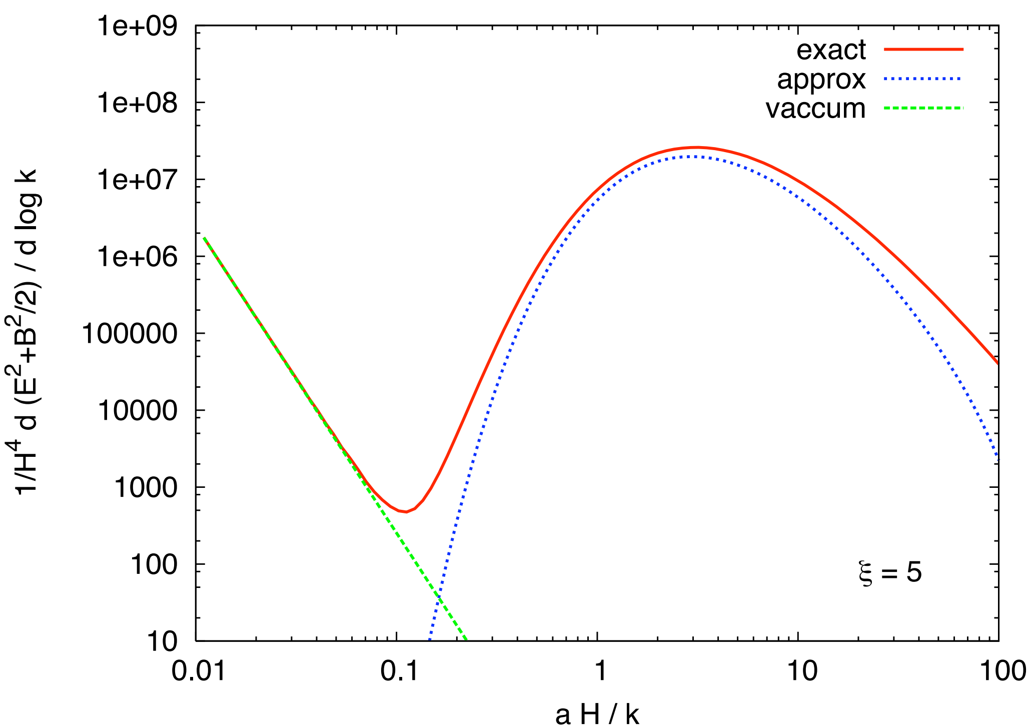
$\Longrightarrow$Important only AFTER inflation (reheating)

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

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

$$\Rightarrow \quad \left(\frac{\partial^2}{\partial\tau^2} + k^2 \mp 2\,a\,H\,k\,\xi\right) A_\pm(\tau,\,k) = 0 \qquad \xi \equiv \frac{\alpha\,\dot{\phi}^{(0)}}{2\,f\,H} \simeq \text{const.}$$

The eigefrequency of one helicity (say A_+, for $\dot{\phi}^{(0)} > 0$) becomes tachyonic for $a\,H > k$, namely after horizon crossing



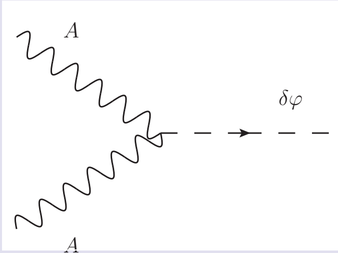
Physical effects only when mode has size $\sim$ horizon

Renormalization realized by

$$A_+ \simeq \frac{1}{\sqrt{2k}}\left(\frac{k}{2\xi a H}\right)^{1/4} e^{\pi\xi - 2\sqrt{2\xi k/(aH)}}$$

Anber, Sorbo '10

(2) $A + A \to \delta\varphi$, inverse decay



$\Longrightarrow$ Significant contribution to $\delta\varphi$!

Barnaby, MP '11; Barnaby, Namba, MP '11

$$\left[\partial_\tau^2 - \frac{a''}{a} - \nabla^2 + a^2 m^2 - \frac{3\phi'^2}{M_p^2}\right](a\,\delta_2\phi) \simeq \frac{\alpha}{f}\,a^3\,\vec{E}\cdot\vec{B}$$
$$-\frac{\phi' a^3}{2M_p^2\mathcal{H}}\left\{\frac{E^2+B^2}{2} + \frac{1}{a^4}\nabla^{-2}\partial_\tau\left[a^4\vec{\nabla}\cdot\left(\vec{E}\times\vec{B}\right)\right]\right\} + \mathrm{O}\left(\delta\phi^2,\,\delta g^2,\,\delta\phi\,\delta g\right)$$

- Full equation from 2nd order perturbation theory ($\delta g_{ij,\mathrm{scalar}} = 0$)
- Curvature pert. on uniform density hypersurfaces $\zeta = -\frac{H}{\dot{\phi}^{(0)}}\,\delta\phi$
- Disregard gravitational vertices for $f \ll M_p$

$$\left[\partial_\tau^2 + 2\,\mathcal{H}\partial_\tau - \nabla^2 + \left(a^2 m^2 - \frac{3\,\phi'^2}{M_p^2}\right)\right]\delta\phi = \frac{\alpha}{f}\,a^2\,\vec{E}\cdot\vec{B}$$

FT

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

Homogeneous solution,
standard cosmological pert.

$$\int d\eta'\,G_k\left(\eta,\,\eta'\right)\,\widehat{J_k}\left(\eta'\right)$$

- Operatorial nature of $\delta\phi_{\text{inv.decay}}$ from A (through $\widehat{J_k}$)

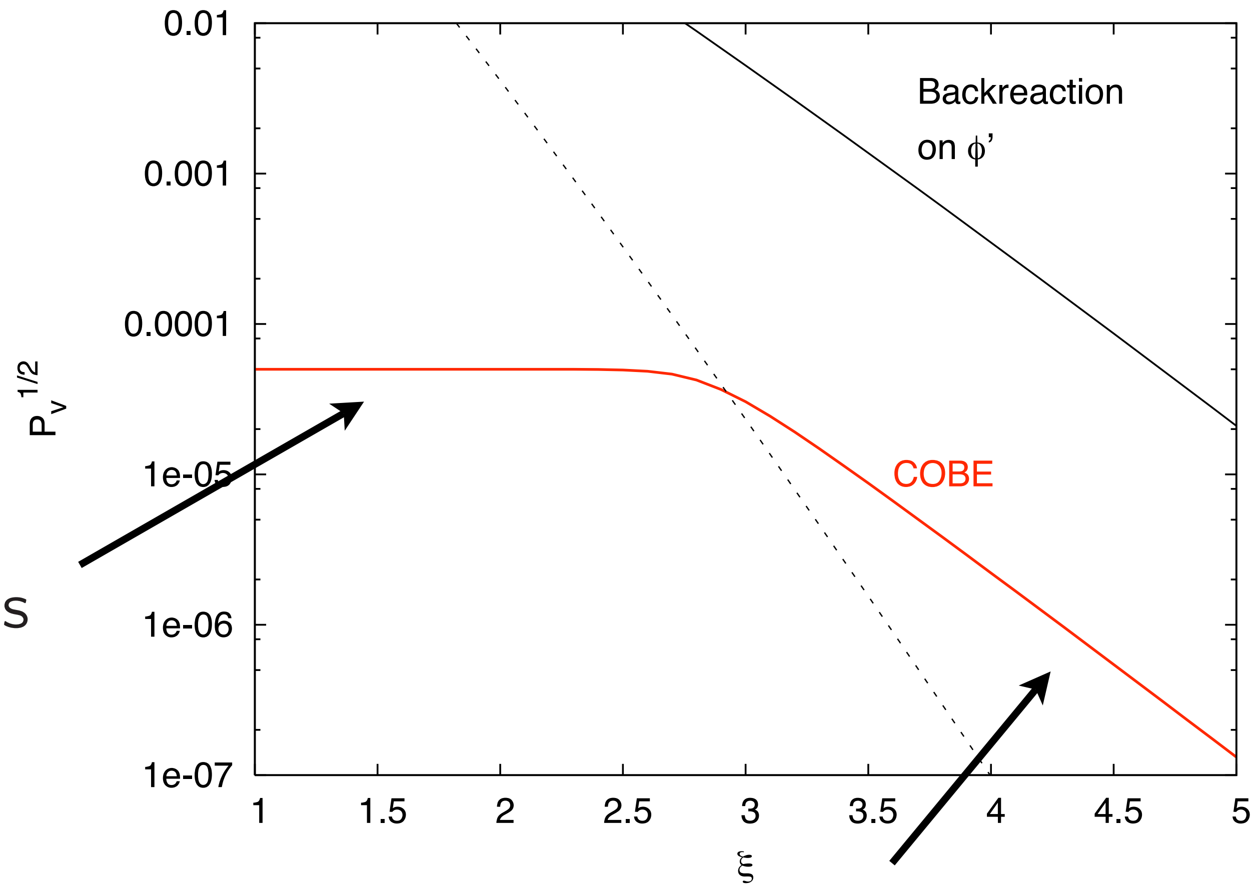
$$\Rightarrow \quad \langle\delta\phi_{\text{vacuum}}\,\delta\phi_{\text{inv.decay}}\rangle = 0$$

Namely, $\langle\delta\phi^2\rangle = \langle\delta\phi_{\text{vac}}^2\rangle + \langle\delta\phi_{\text{inv.dec}}^2\rangle$, $\langle\delta\phi^3\rangle = \langle\delta\phi_{\text{vac}}^3\rangle + \langle\delta\phi_{\text{inv.dec}}^3\rangle$

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

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

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



$\delta\phi_{\text{vac}}$ dominates
standard result

$\delta\phi_{\text{inv.decay}}$ dominates
need to decrease $\mathcal{P}_v$ exponentially

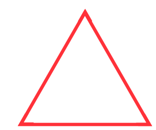
Non-gaussianity $\left\langle \delta(x)\, \delta(y)\, \delta(z) \right\rangle$

- Local form: $\delta(x) = \delta_g(x) + f_{NL}^{\text{local}}\, \delta_g^2(x)$ Komatsu, Spergel '00

  Multiple fields (curvaton); enhanced for $k_1 \ll k_2 \simeq k_3$

- Equilateral form:

  Inflaton interactions



- Orthogonal form, flattened form .....

WMAP7 95% CL bounds

$$-10 < f_{\text{NL}}^{\text{local}} < 74$$

$$-214 < f_{\text{NL}}^{\text{equil}} < 266$$

$$-410 < f_{\text{NL}}^{\text{orth}} < 6$$

Substantial improvement in near future from CMB (Planck) and LSS

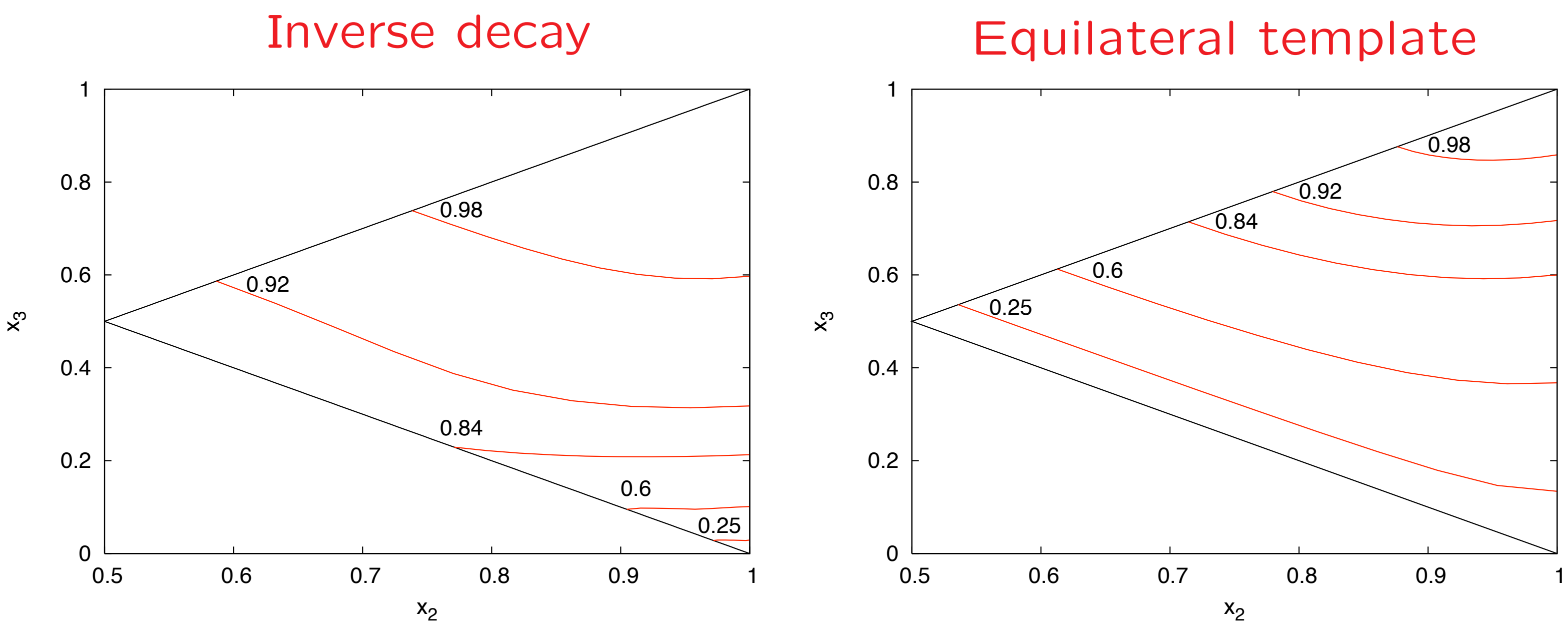
However, signal from vacuum modes in single field slow roll inflation,

$f_{\text{NL}} = \mathrm{O}\left(10^{-2}\right)$, out of reach

Shape of NG $\quad \langle \delta\phi_{\mathbf{k_1}} \delta\phi_{\mathbf{k_2}} \delta\phi_{\mathbf{k_3}} \rangle = \delta^{(3)}\left(\vec{k}_1 + \vec{k}_2 + \vec{k}_3\right) S\left(\frac{k_2}{k_1}, \frac{k_3}{k_1}\right)$

- At any moment, only gauge modes with $\lambda \sim H^{-1}$ present
- Inverse decay $\delta A + \delta A \to \delta\phi$ with $\lambda \sim H^{-1}$
- Gives correlations only between $\delta\phi$ modes of comparable λ

S maximal for $k_1 = k_2 = k_3$ $\qquad \left(k = \frac{a}{\lambda}\right)$

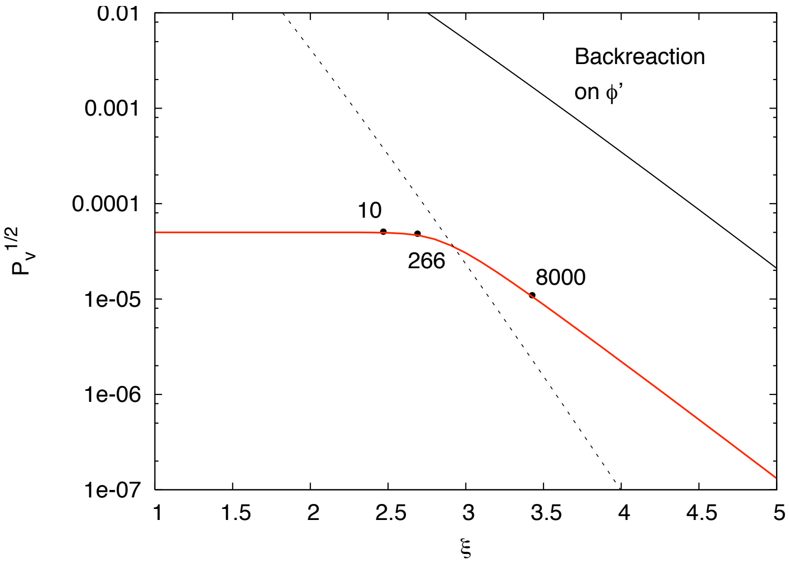


$x_3 \le x_2 \le 1$

$x_2 + x_3 \ge 1$

$\cos\left(B_{\rm id}, B_{\rm eqil}\right) \simeq 0.94$

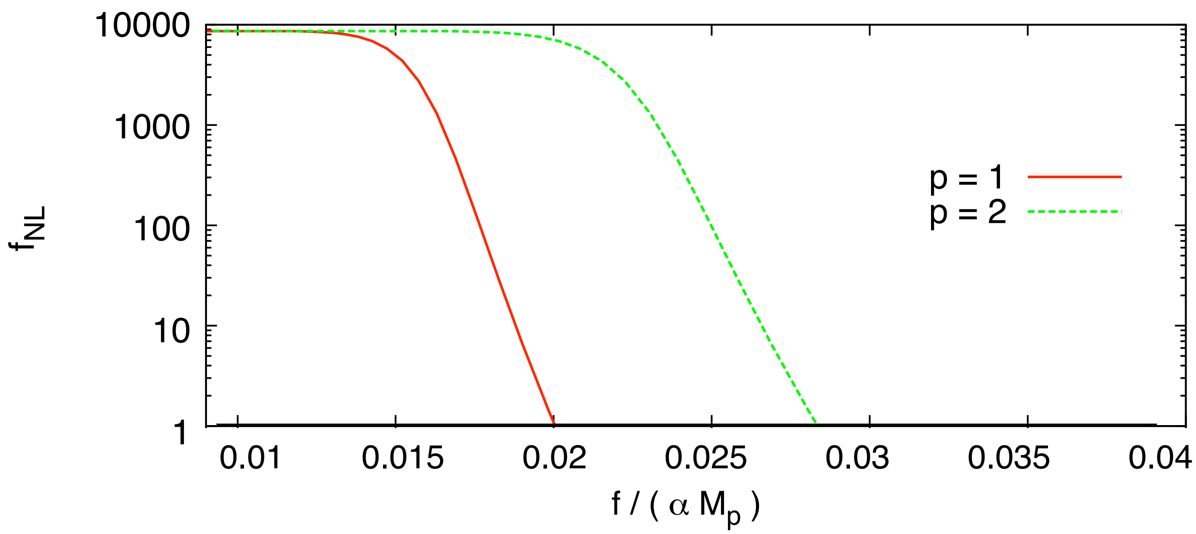
Babich, Creminelli, Zaldarriaga '04



$\delta\phi_{\rm id} \sim A^2$ highly non-gaussian

Current bound $f_{\rm NL}^{\rm equil} < 266$

forces $P_{\rm inv.dec} < P_{\rm vac}$



$V \propto \phi^p$

$\frac{f}{\alpha} \gtrsim 10^{16}$ GeV $\quad\sim$ 5 orders of magnitude stronger than analogous coupling of QCD axion to photons

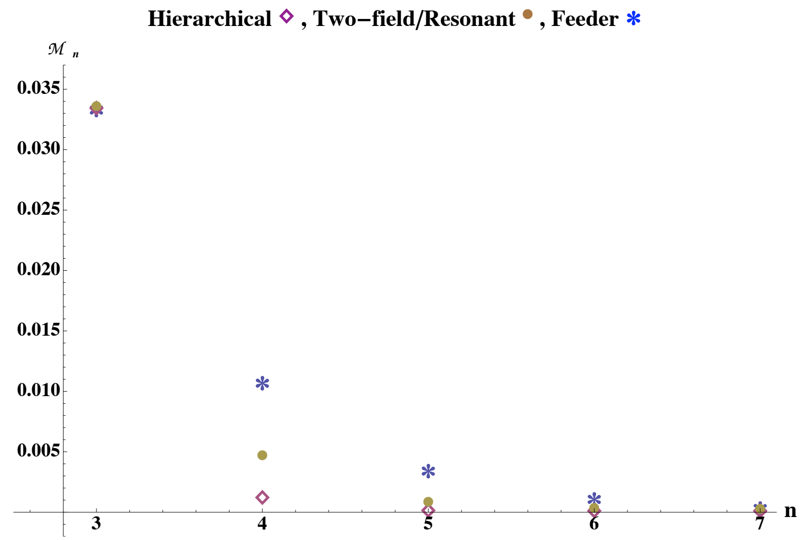
Distinctive scaling of correlators $\mathcal{M}_n \sim \frac{\langle \zeta^n \rangle_c}{\langle \zeta^2 \rangle^{n/2}}$

Barnaby, Shandera '12

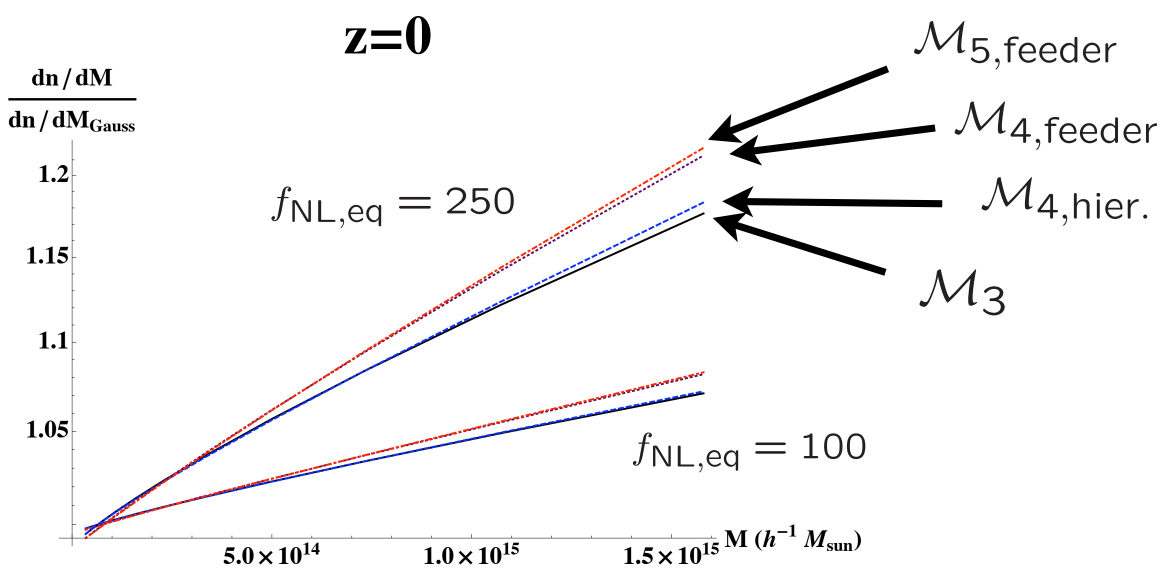
Hierarchical scaling: $\mathcal{M}_n \sim \left(I^2\, P_\zeta\right)^{\frac{n-2}{2}}$

(Curvaton, varying sound speed)

"Feeder" $\mathcal{M}_n \sim \left(f_{\mathrm{NL,id}}\, \mathcal{P}^{1/2}\right)^{n/3}$



Mass function



Backreaction

- Gauge fields produced at expense of kinetic energy of ϕ
- $\xi \simeq 20 \;\rightarrow$ sufficiently long inflation from dissipation

  Anber, Sorbo '10

- $\xi \lesssim 2.5$ from NG. No backreaction when CMB perturbations produced

  However, $\xi \propto \dot{\phi}/H$ can increase, and backreaction at later stages

  Barnaby, Pajer, MP '12

$$\ddot{\phi}^{(0)} + 3\,H\,\dot{\phi}^{(0)} + \frac{d\,V}{d\,\phi} = \frac{\alpha}{f}\,\vec{E}\cdot\vec{B}$$

$$\langle \vec{E}\cdot\vec{B}\rangle \simeq -2.4\cdot 10^{-4}\,\frac{H^4}{\xi^4}\,\mathrm{e}^{2\pi\xi}$$

$$H^2 = \frac{1}{3\,M_p^2}\left[\frac{1}{2}\,\dot{\phi}^{(0)2} + V + \frac{\vec{E}^2+\vec{B}^2}{2}\right]$$

$$\langle \frac{\vec{E}^2+\vec{B}^2}{2}\rangle \simeq 1.4\cdot 10^{-4}\,\frac{H^4}{\xi^3}\,\mathrm{e}^{2\pi\xi}$$

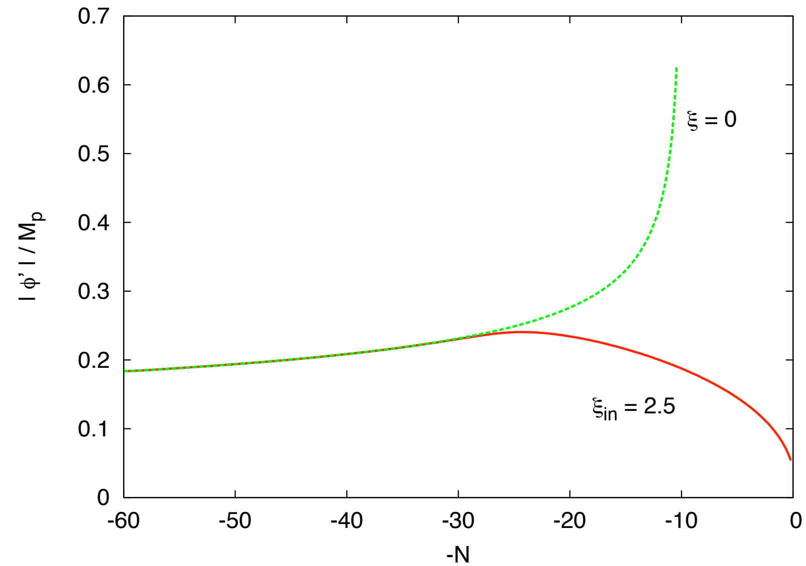
$$\frac{H^2}{2\pi|\dot{\phi}^{(0)}|} \ll 13\,\xi^{3/2}e^{-\pi\xi} \qquad \frac{H}{M_p} \ll 146\,\xi^{3/2}e^{-\pi\xi}$$

Break in the final ~ 25 e-folds

Inflaton slows down

Inflation lasts more

Ex: $V = \mu^3 \phi$, $\phi_{\rm in} = 10\, M_p$



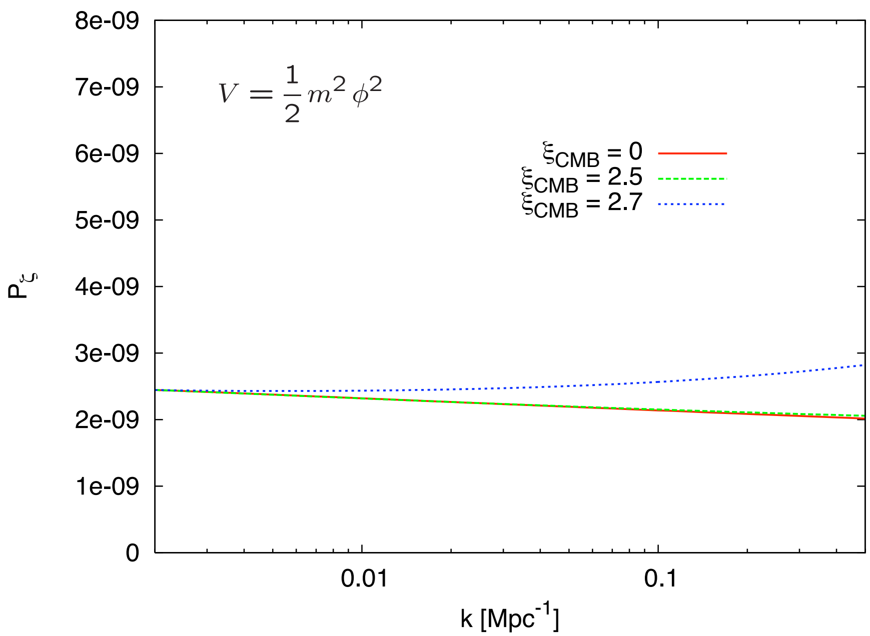
$\phi_{\rm in} = 10\, M_p$

50 e-folds ii $\xi = 0$

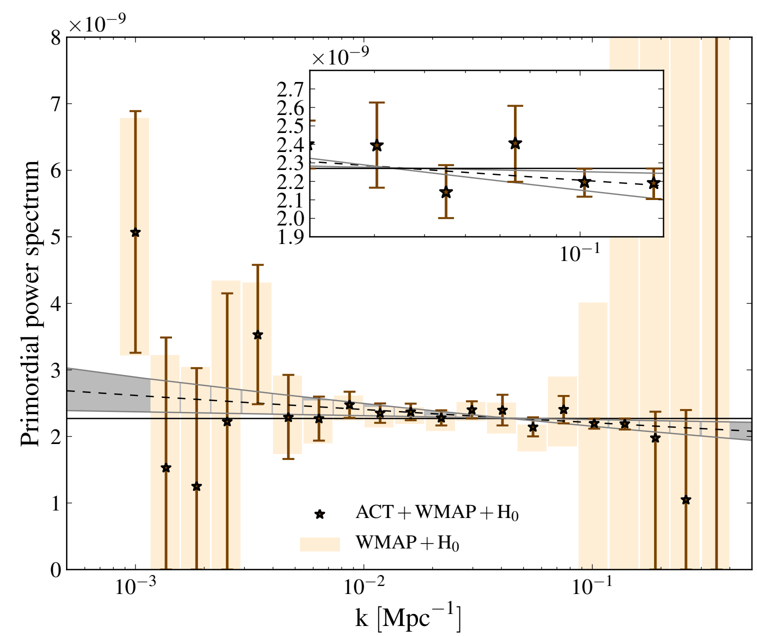
60 e-folds if $\xi_{\rm in} = 2.5$

Growing $\xi \;\rightarrow\;$ growing $P_\zeta\,(k)$

Hlozek et al '11



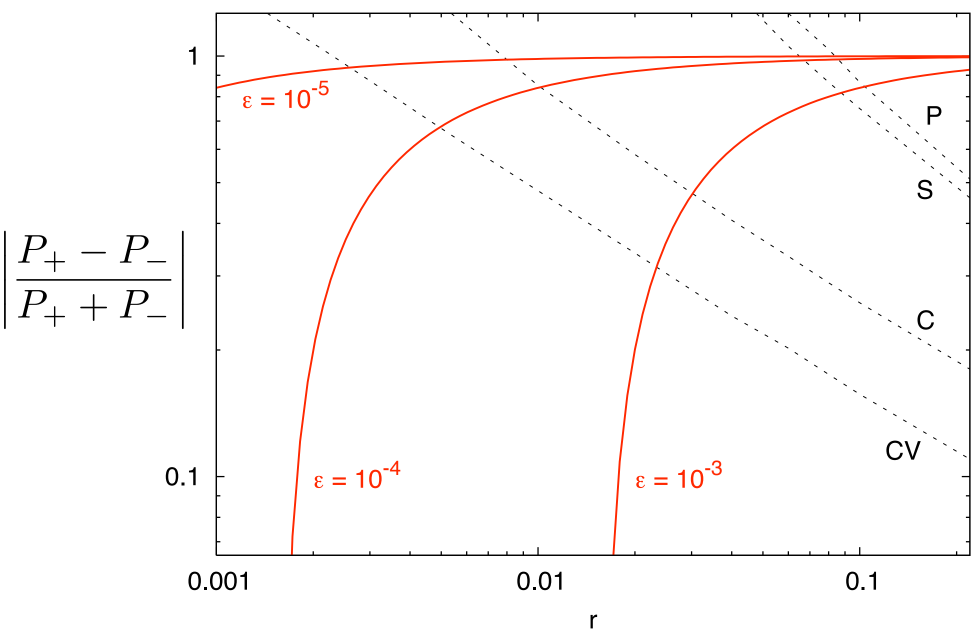
VS.



Gravity waves

- Gauge quanta also produce GW. $h_+ \gg h_- \to \langle TB \rangle, \langle EB \rangle \neq 0$
- $P_{h,AA} \ll P_{h,vac}$ when NG limit respected Barnaby, Peloso '11
- Decrease NG using $\sim$ 1000 gauge fields, or curvaton Sorbo '11
- Decrease NG is gauge field produced by $\psi \neq \phi$

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



Planck

SPIDER

CMB Pol

Cosmic variance

1σ limits from

Gluscevic, Kamionkowski '10

(Saito, Ichiki, Taruya '07)

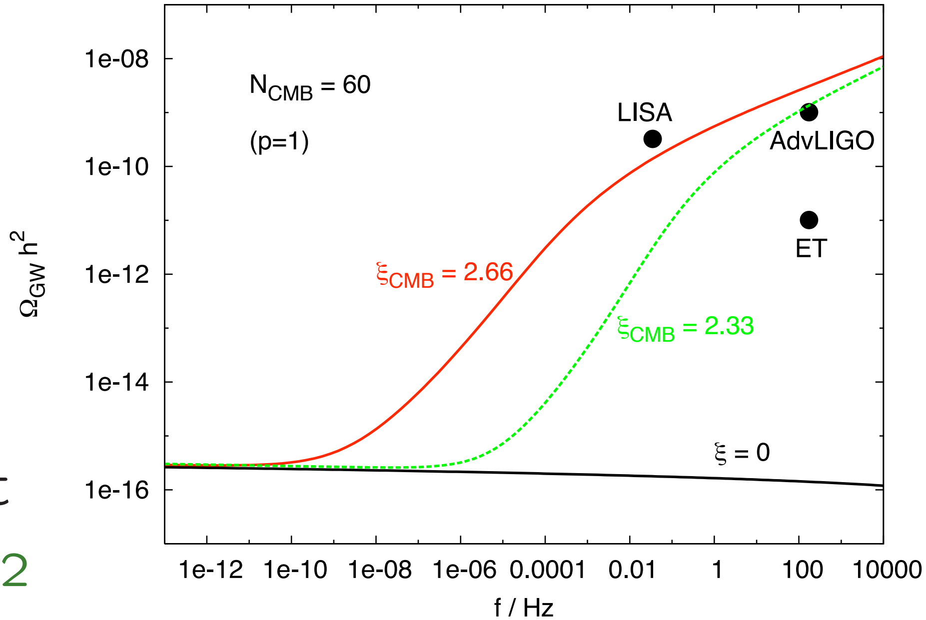
GW at interferometers

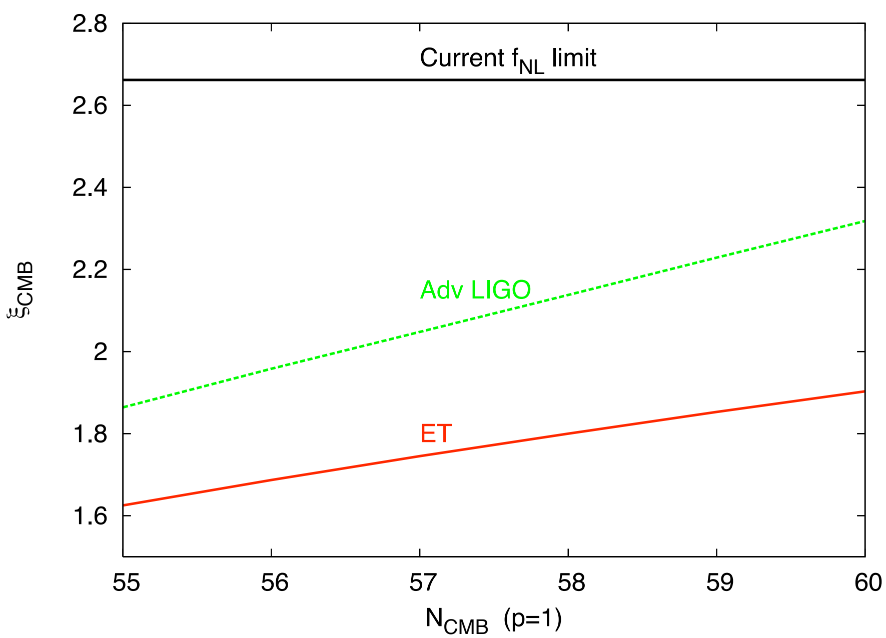
- No problem with ζ at interferometer scales

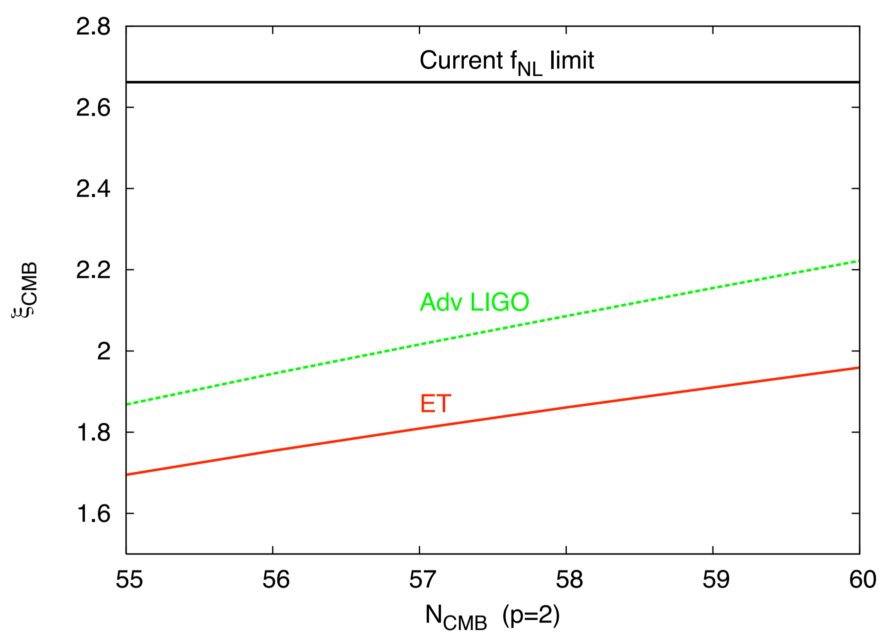
  Cook, Sorbo '11

- Precise computation requires taking backreaction into account

  Barnaby, Pajer, MP '12

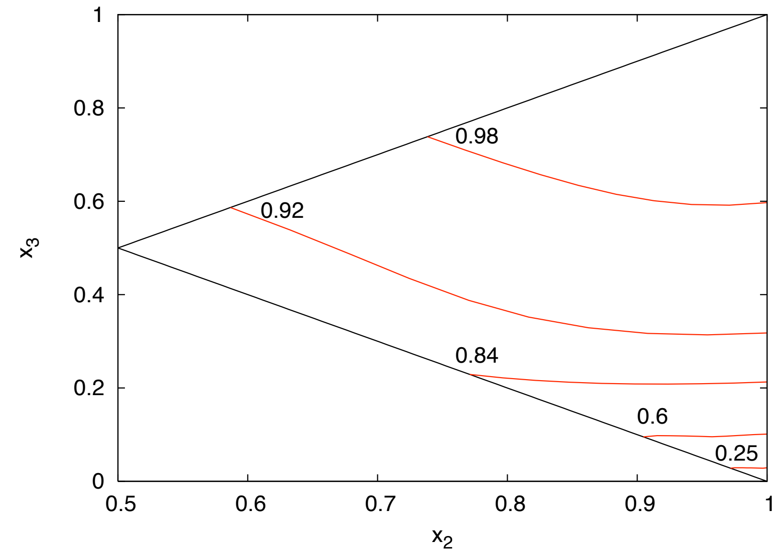






Conclusions

- Inflaton = axion in a very simple and motivated class of models



- (surprisingly) natural coupling for axion inflaton can lead to a very rich, and possibly correlated, phenomenology