Phenomenology of a pseudoscalar inflaton: naturally large non-gaussianity

Marco Peloso, University of Minnesota

Neil Barnaby, M.P., PRL 106, 181301 (2011)

Neil Barnaby, Ryo Namba, M.P., JCAP 009, 1104, (2011)

Neil Barnaby, Enrico Pajer, MP, in progress

- Inflation & particle production
- $\phi - A_\mu$ coupling in axion-inflation

⇒ detectable non-gaussianity of characteristic ($\sim$ equilateral) shape

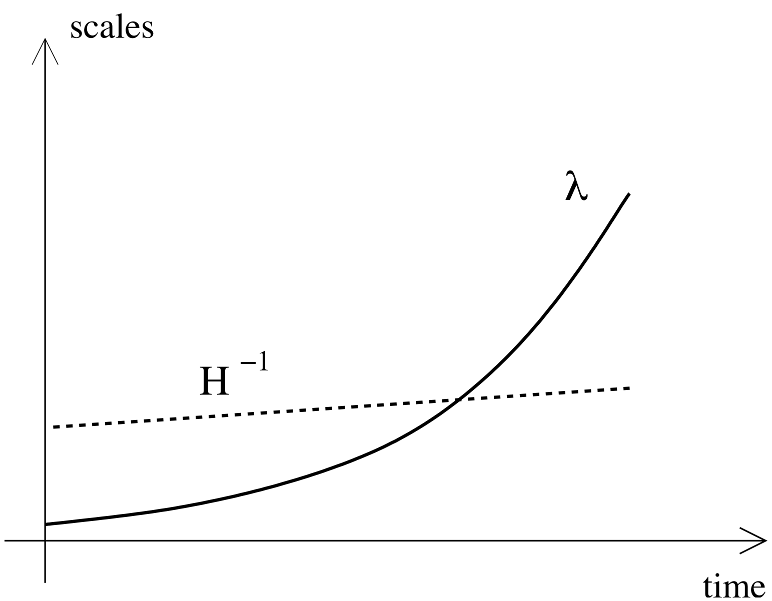
⇒ $+$ detectable gravity waves

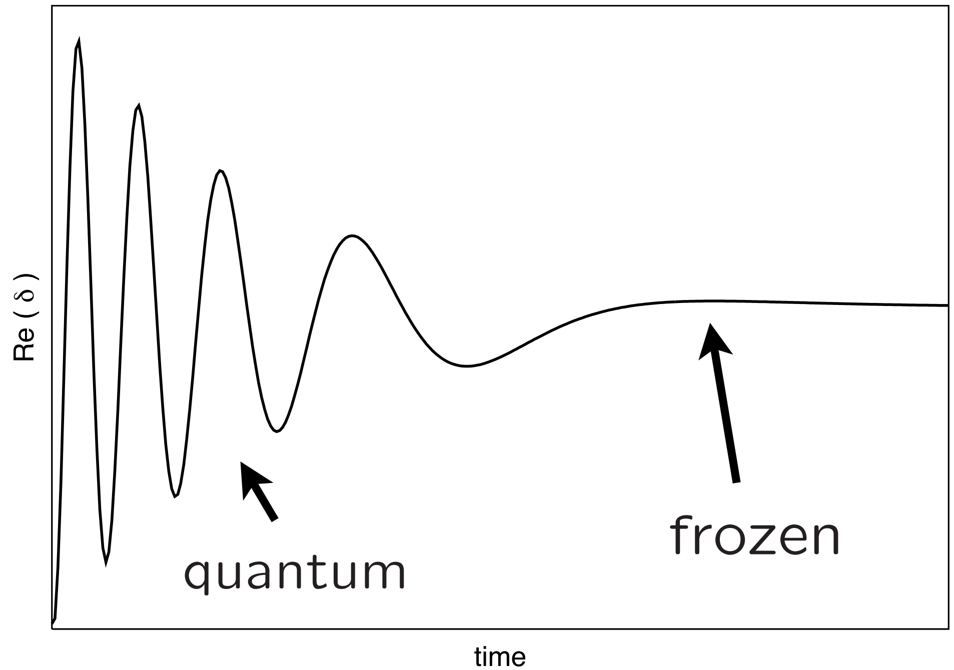
Inflation is a postulated era of accelerated expansion at $t \ll 1$s that solves many problems of big-bang cosmology (horizon, flatness, monopole,....)

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, ...

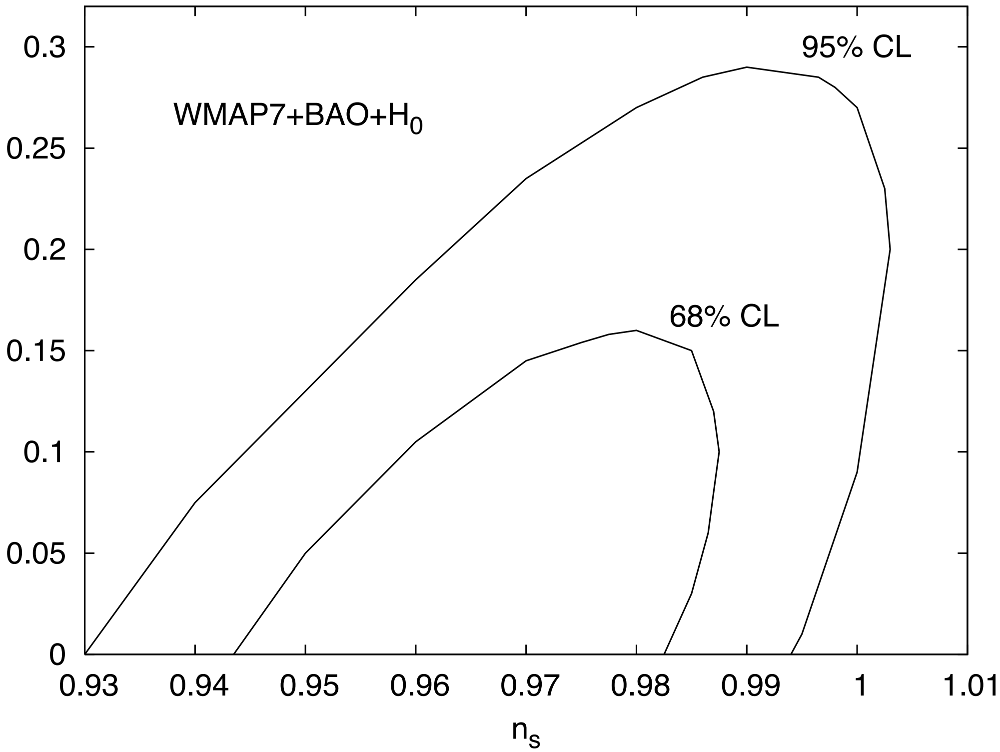




Simplest models:

→ nearly scale invariance $P \propto k^{n_s - 1}$, $n_s \simeq 1$

→ $r = \dfrac{\text{gravity waves}}{\text{density inhom.}} < 1$



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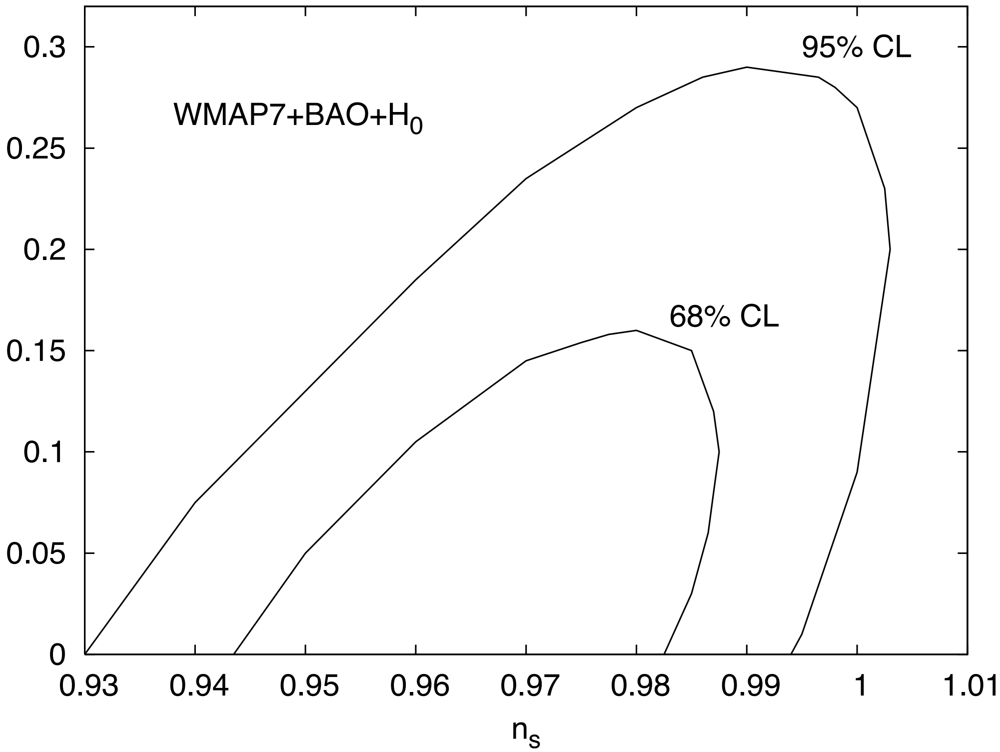

$$V^{1/4} = 10^{16}\,\text{GeV}\left(\frac{r}{0.01}\right)^{1/4}$$

$$\Delta\phi \gtrsim M_p \left(\frac{r}{0.01}\right)^{1/2}$$

Lyth '96

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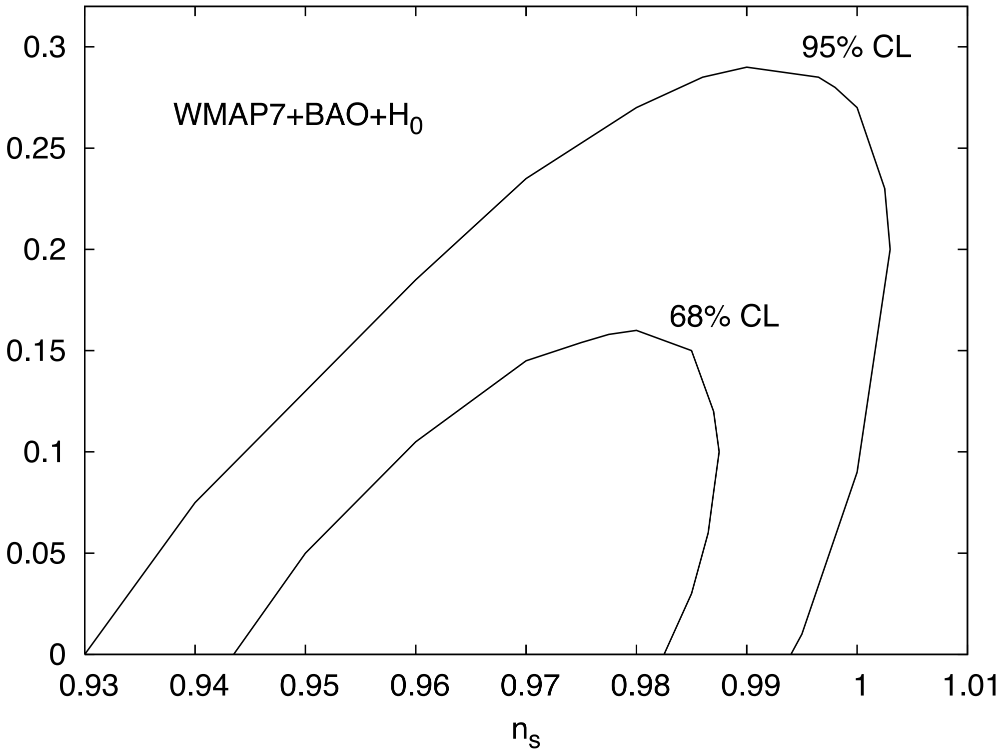

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Several experiments

with goal $r \lesssim 0.01 - 0.05$:

Satellite: Planck

Balloon: EBEX, PIPER, SPIDER

Ground: ABS, ACTpol, BICEP2 CLASS, Keck Array, POLAR

PolarBeaR, QUBIC, QUIET, QUIJOTE, SPTpol

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

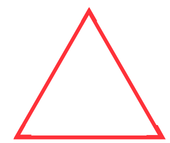
Lots of shapes $\longrightarrow$ lots of information !

- Local form: $\delta(x) = \delta_g(x) + f_{NL}^{\text{local}}\,\delta_g^2(x)$ Komatsu, Spergel '01

  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

- Virtue of inflation: simplest models work !

Single ϕ; flat V; slow-roll; canonical $(\partial\phi)^2$; standard initial vacuum

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Add a strong coupling !

Eg. $V = V(\phi) + g^2 (\phi - \phi_0)^2 \chi^2$

Chung, Kolb, Riotto, Tkachev '99
Romano, Sasaki '08
Barnaby, Huang, Kofman, Pogosyan '09
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- For most of the evolution, $m_\chi \sim g\phi \gg H$, no effect

- At $\phi = \phi_0$, nonadiabatic m_χ variation

$$\Rightarrow \quad n_\chi(t_0) = \exp\left(-\frac{\pi k^2}{k_*^2}\right) \quad , \quad k_* \equiv g\,|\dot{\phi}|$$

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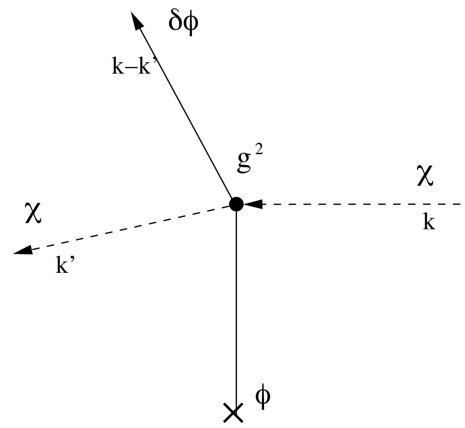
Two effects on inflaton ($\rightarrow$ metric) perturbations:



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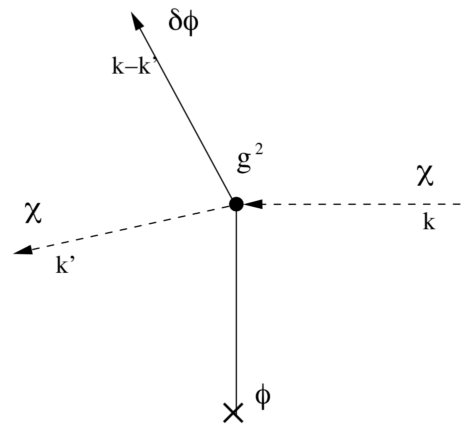
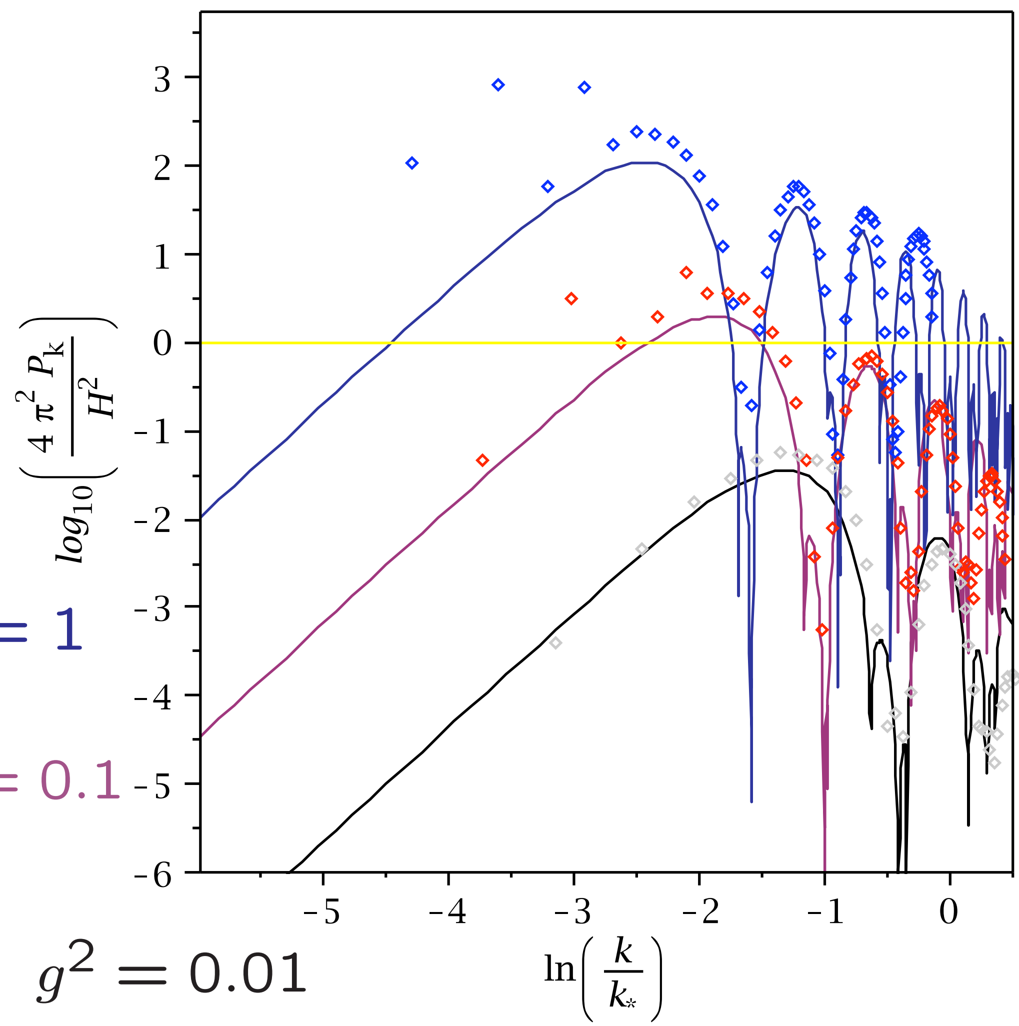




$g^2 = 1$

$g^2 = 0.1$

$g^2 = 0.01$

$$g^2 \lesssim O\left(10^{-2}\right)$$

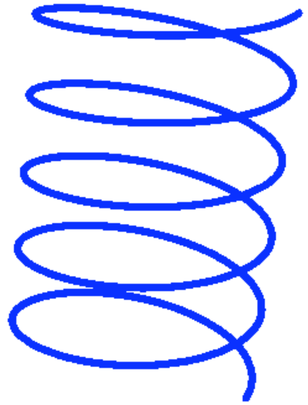
$$\text{for } 10^{-7} \lesssim \frac{k_*}{\text{Mpc}^{-1}} \lesssim 10^{-1}$$

Barnaby et al '09

Trapped inflation

Green, Horn, Senatore, Silverstein '09

(monodromy)



$$V = \frac{1}{2}m^2\phi^2 + \frac{g^2}{2}\sum(\phi - \phi_i)^2\,\chi_i^2$$

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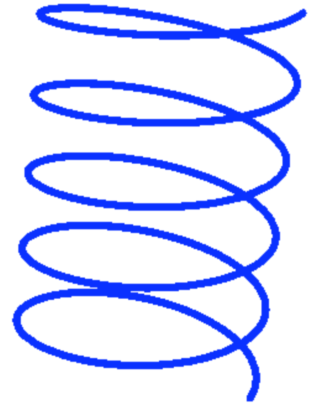

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Continuous production ($\Delta\phi_i$ small):

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- New source of $\delta\phi$ at all scales

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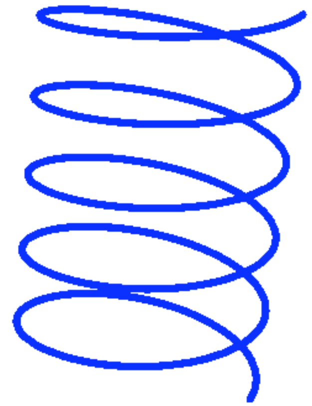

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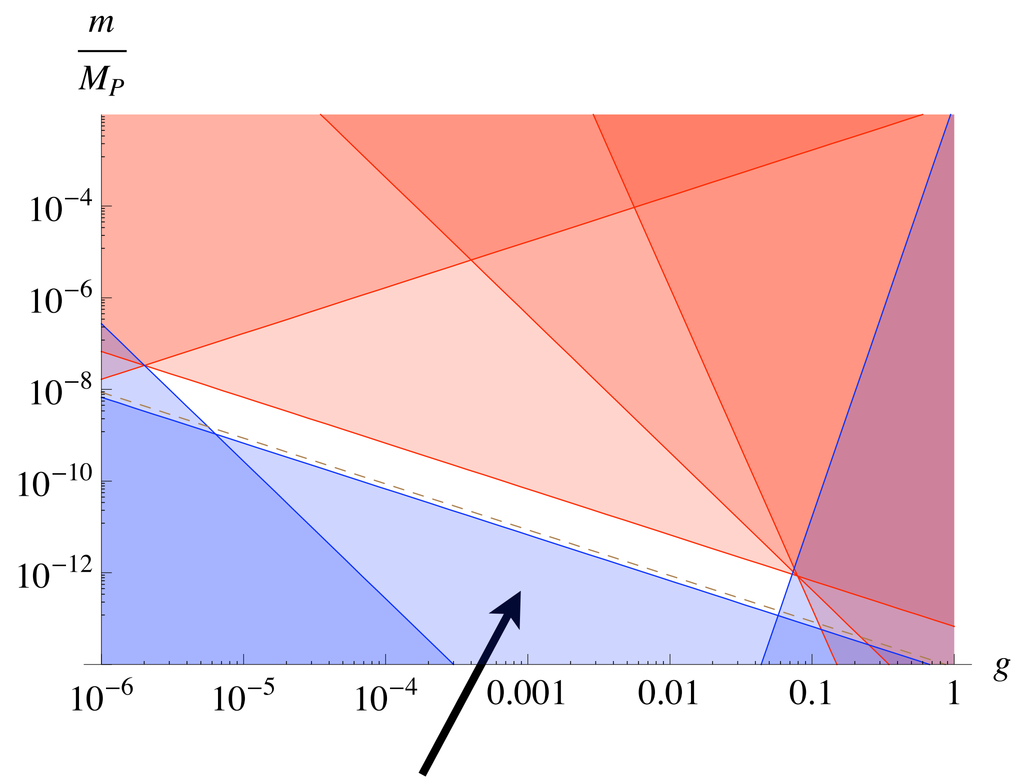
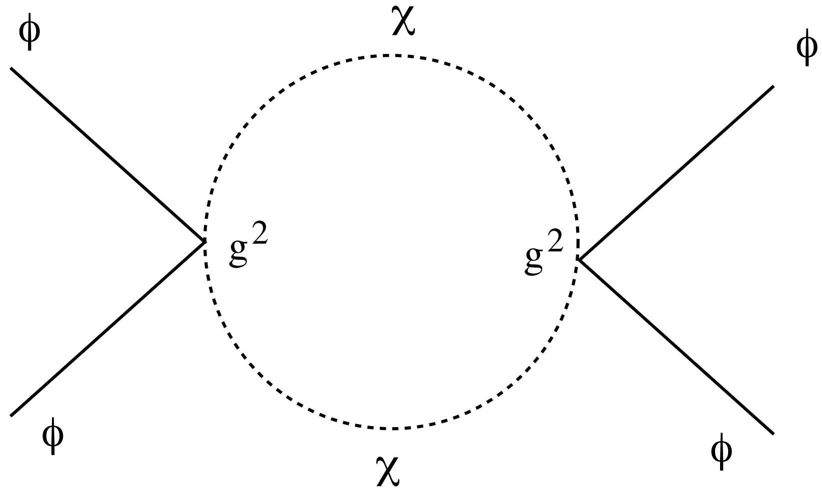
Estimated bounds:



Equilateral NG

- Strong couplings + Loops $\longrightarrow$ ~~flatness~~ ?



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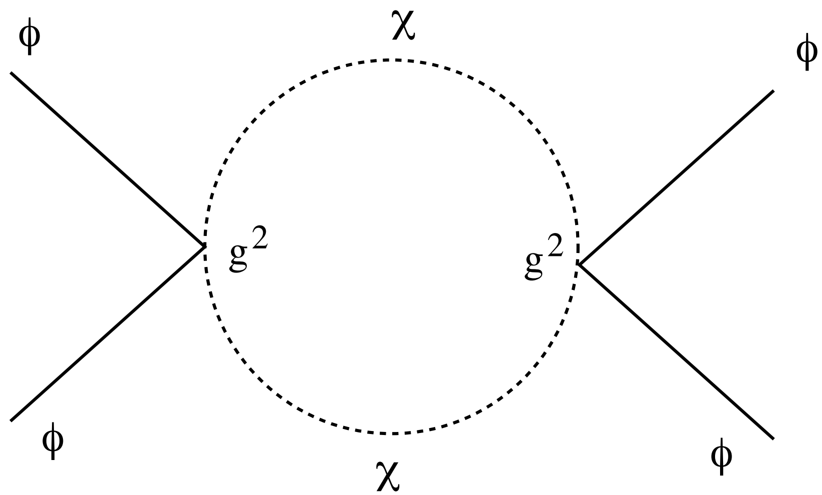

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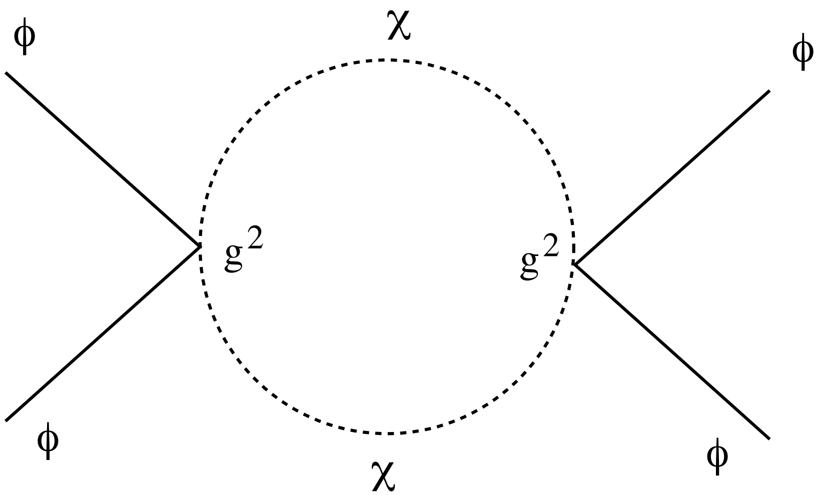

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- Suggests to limit ϕ couplings. Pessimism for NG ?

- Use symmetry. Ex: Shift symmetry for axion inflaton

Single field slow roll inflaton, with controllably flat potential

for which coupling to "matter" provides observable non-gaussianity

Barnaby, MP '11

QCD axion $\rightarrow$ Inflaton axion

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

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

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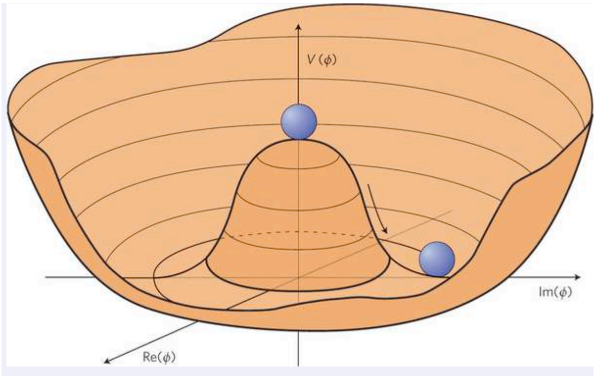

Peccei, Quinn '77: Chiral U(1) symmetry

spontaneously broken $\Phi = (f + \rho)\; e^{i\phi/f}$

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

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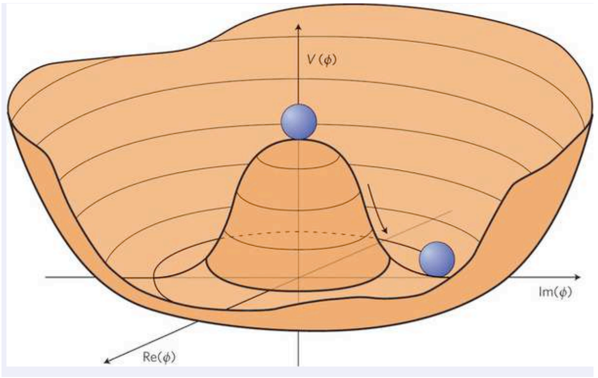


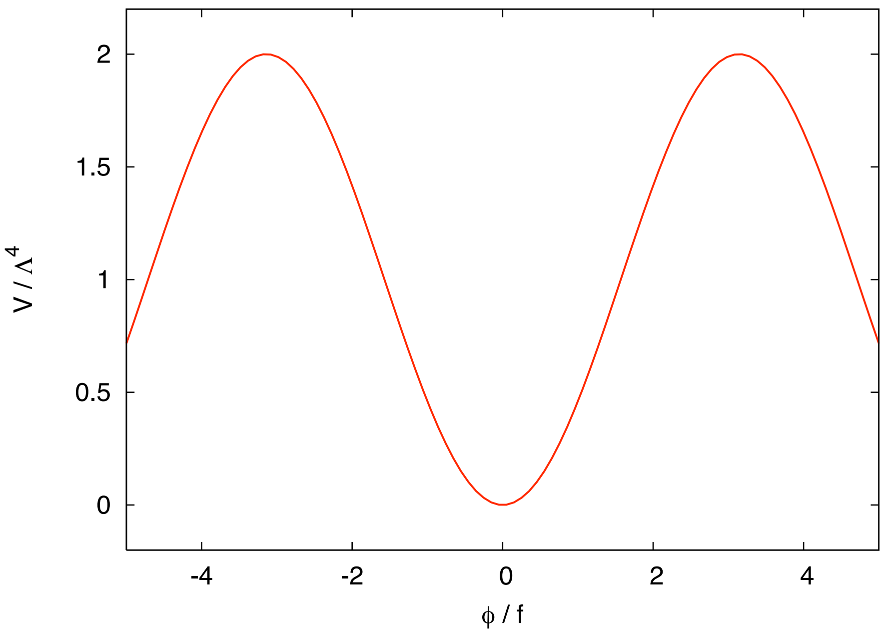
Symmetry is anomalous $\Rightarrow$ $\theta \rightarrow \theta + \frac{\phi}{f}$

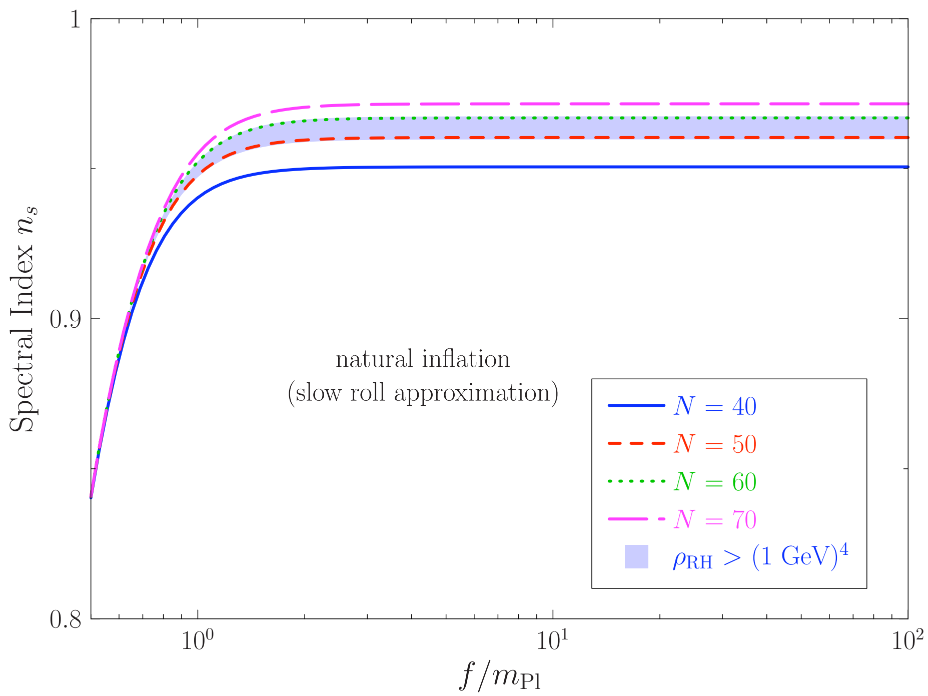
- Smallness of Λ is technically natural. No perturbative ~~shift~~

  So $\delta\Lambda \propto \Lambda$

- ϕ only derivatively coupled

Natural Inflation: Freese, Frieman, Olinto '90





Savage, Freese, Kinney '06

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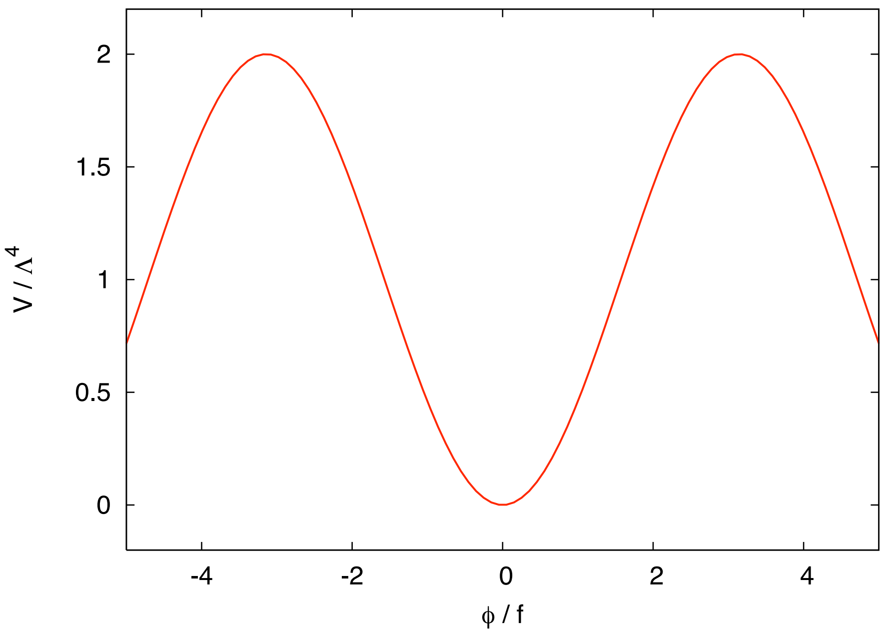
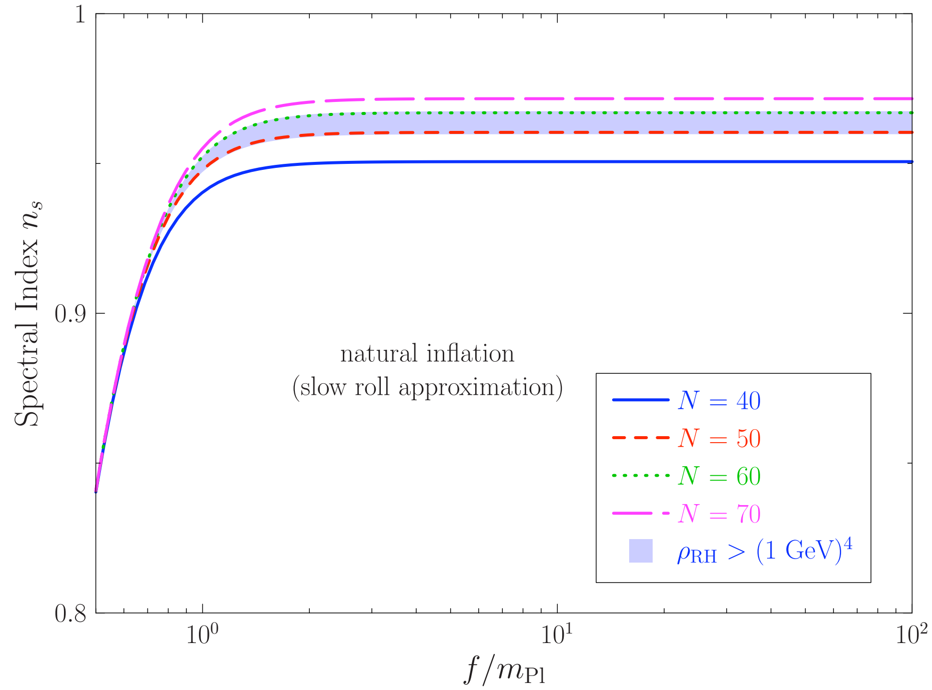




Savage, Freese, Kinney '06

Problems with $f > M_p$

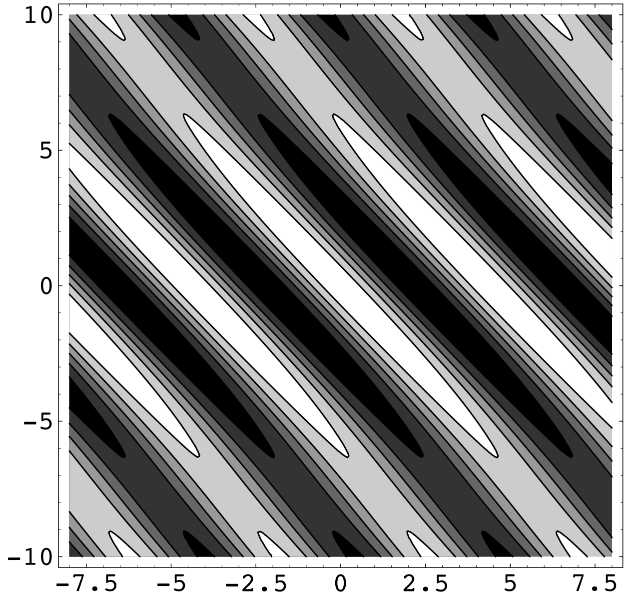
- $U(1)_{\rm PQ}$ broken above QG scale
- Hard in weakly coupled string theory

Kallosh, Linde, Linde, Susskind '95

Banks, Dine, Fox, Gorbatov '03

Two axions & gauge groups

Kim, Nilles, MP '04



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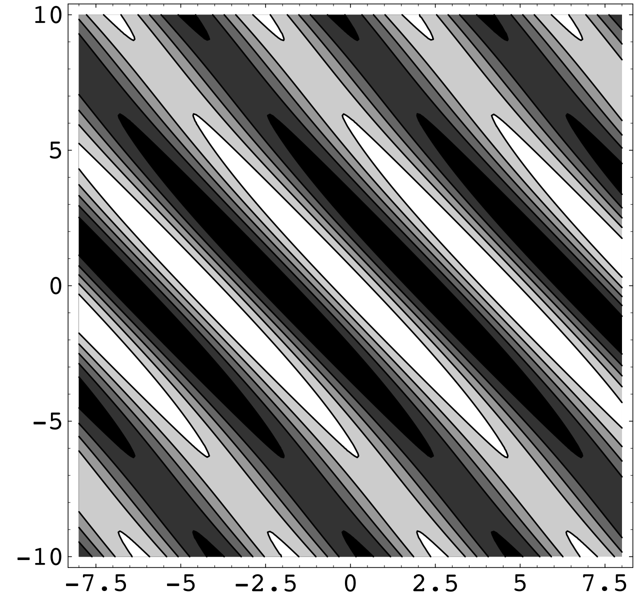

N-flation

Dimopoulos et al '05

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

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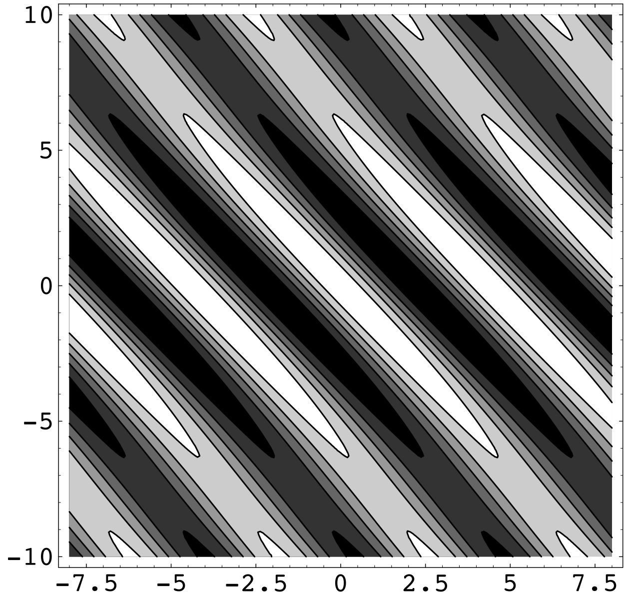

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$\Delta V \propto \phi$ from brane wrapping

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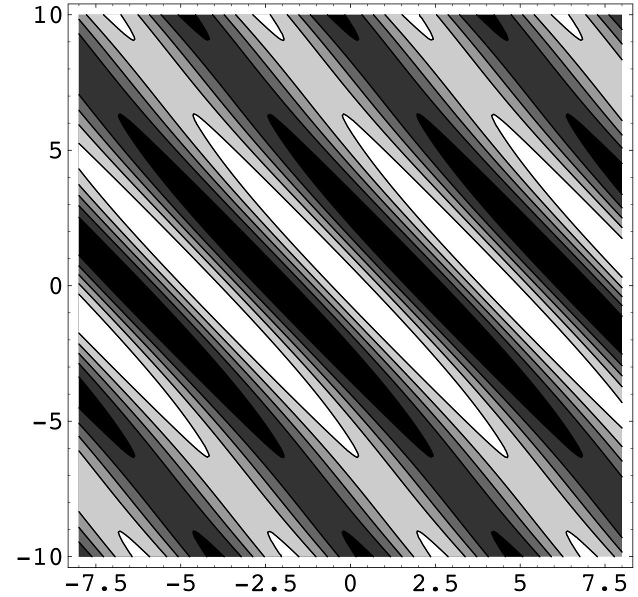

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Dante's inferno

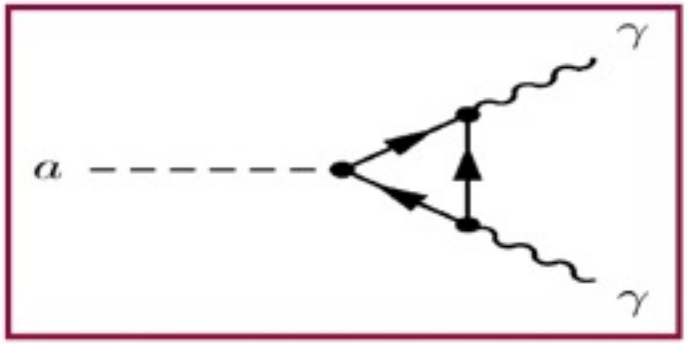
Berg, Pajer, Sjors '09

Axion-4form mixing

Kaloper, Sorbo '08

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

$$\mathcal{L} \supset -\frac{\alpha}{f}\phi F\tilde{F}$$



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- Generally present, not “extra ingredient”

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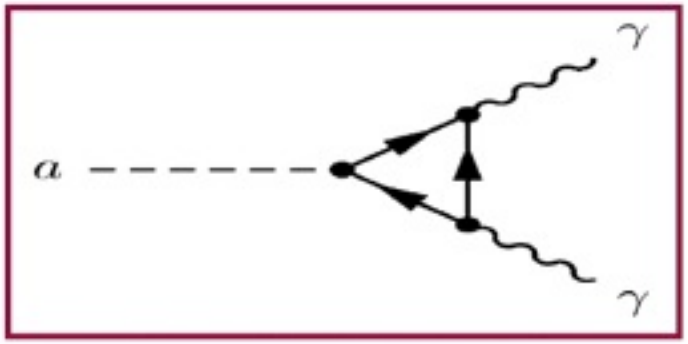

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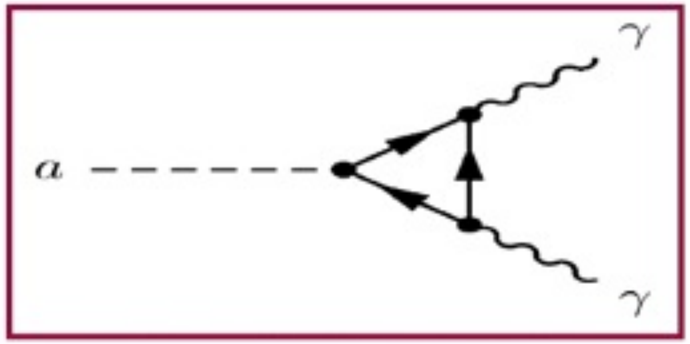

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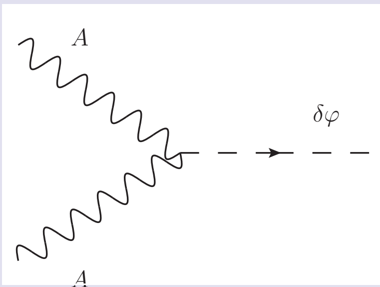

$\Longrightarrow$ Significant contribution to $\delta\varphi$!

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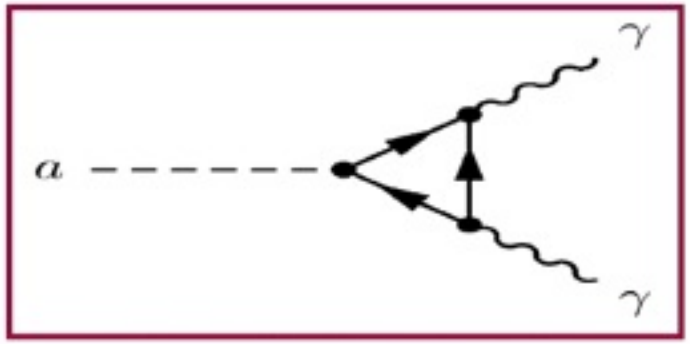

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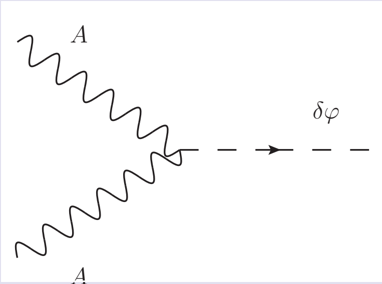

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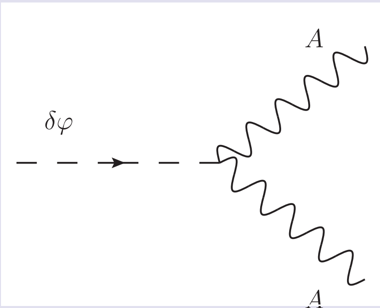
3. $\delta\varphi \to A + A$, perturbative decay



$\Longrightarrow$ 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

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

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tachyonic for $a \, H > k$, namely after horizon crossing

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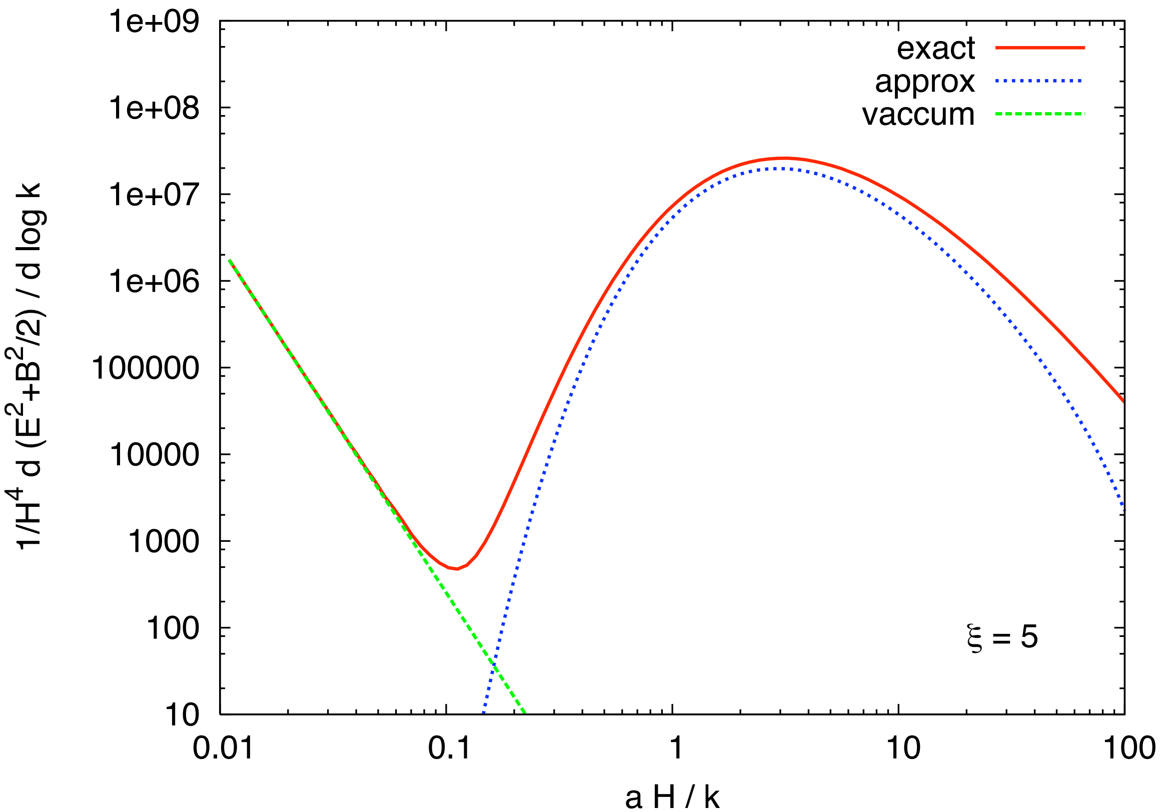


Physical effects only when

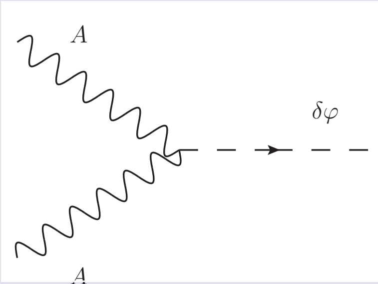
mode has size $\sim$ horizon

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 '09

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



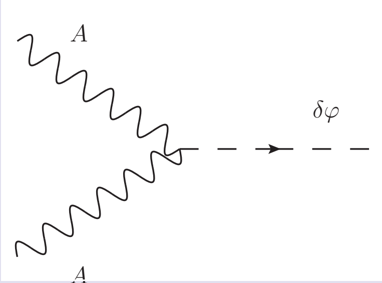
$\Longrightarrow$ Significant contribution to $\delta\varphi$!

$$\phi^{(0)} + \delta\phi \ , \ \delta A_\mu \ , \ g_{\mu\nu} + \delta g_{\mu\nu}$$

- Above trilinear vertex is $\propto \dfrac{\alpha}{f}$ Ignore gravitational interactions

for $\dfrac{\alpha}{f} \gg \dfrac{1}{M_p}$

2. $A + A \to \delta\varphi$, inverse decay



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- Above trilinear vertex is $\propto \frac{\alpha}{f}$ for $\frac{\alpha}{f} \gg \frac{1}{M_p}$ Ignore gravitational interactions

- In $\delta g_{ij,\text{scalar}=0}$ gauge, at leading order in slow roll

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

- Curvature pert. on uniform density hypersurfaces $\zeta = -\frac{H}{\dot\phi^{(0)}}\,\delta\phi$

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

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↑

Homogeneous solution,

standard cosmological pert.

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FT

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standard cosmological pert.

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

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FT

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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 $\widehat{J_k}$)

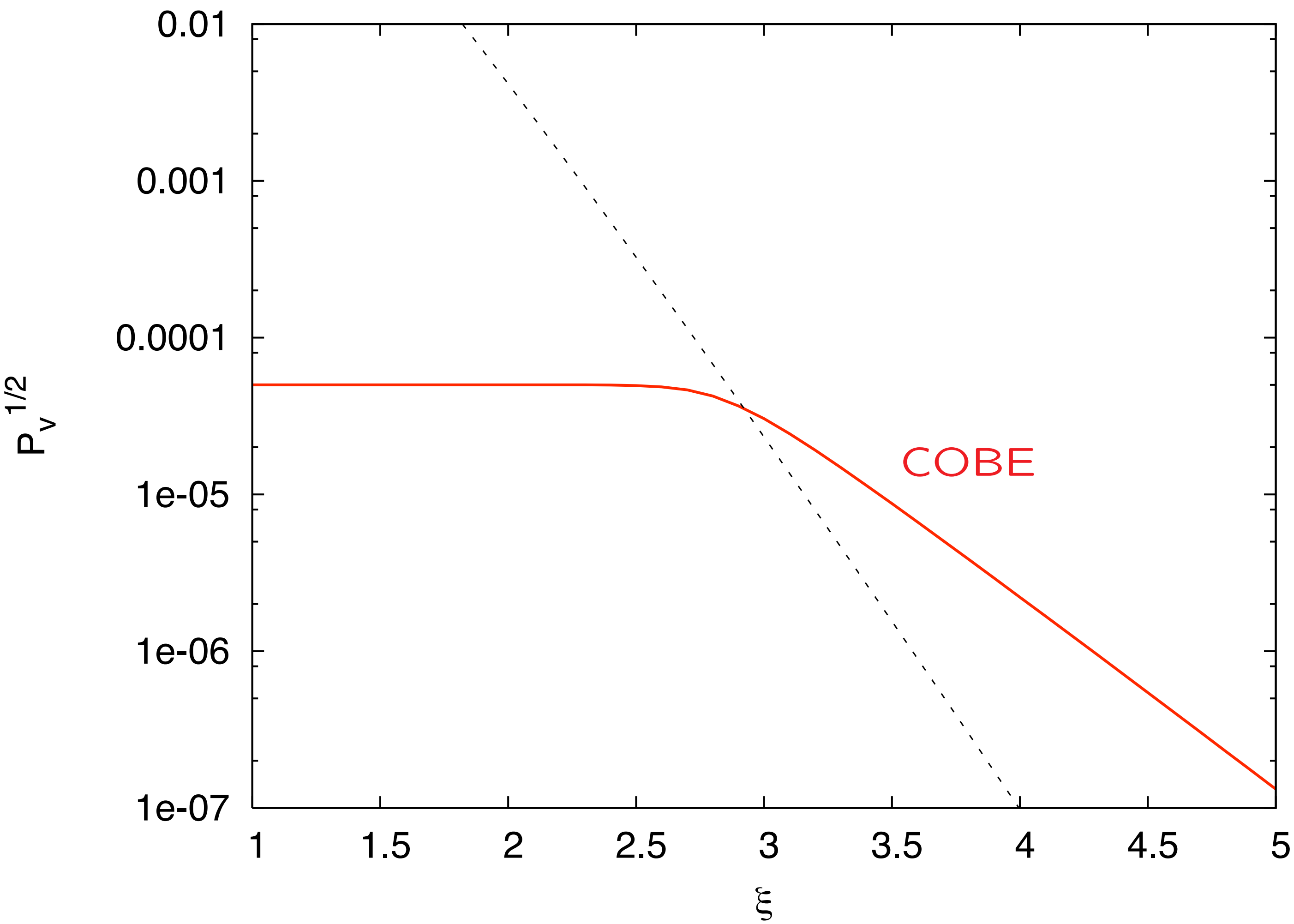
⇒ $\langle\delta\phi_{\text{vacuum}}\,\delta\phi_{\text{inv.decay}}\rangle = 0$

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

$$P_\zeta(k) = \mathcal{P}_v \left(\frac{k}{k_0}\right)^{n_s - 1} \left[1 + 7.5 \cdot 10^{-5}\, \mathcal{P}_v \frac{e^{4\pi\xi}}{\xi^6}\right]$$

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

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



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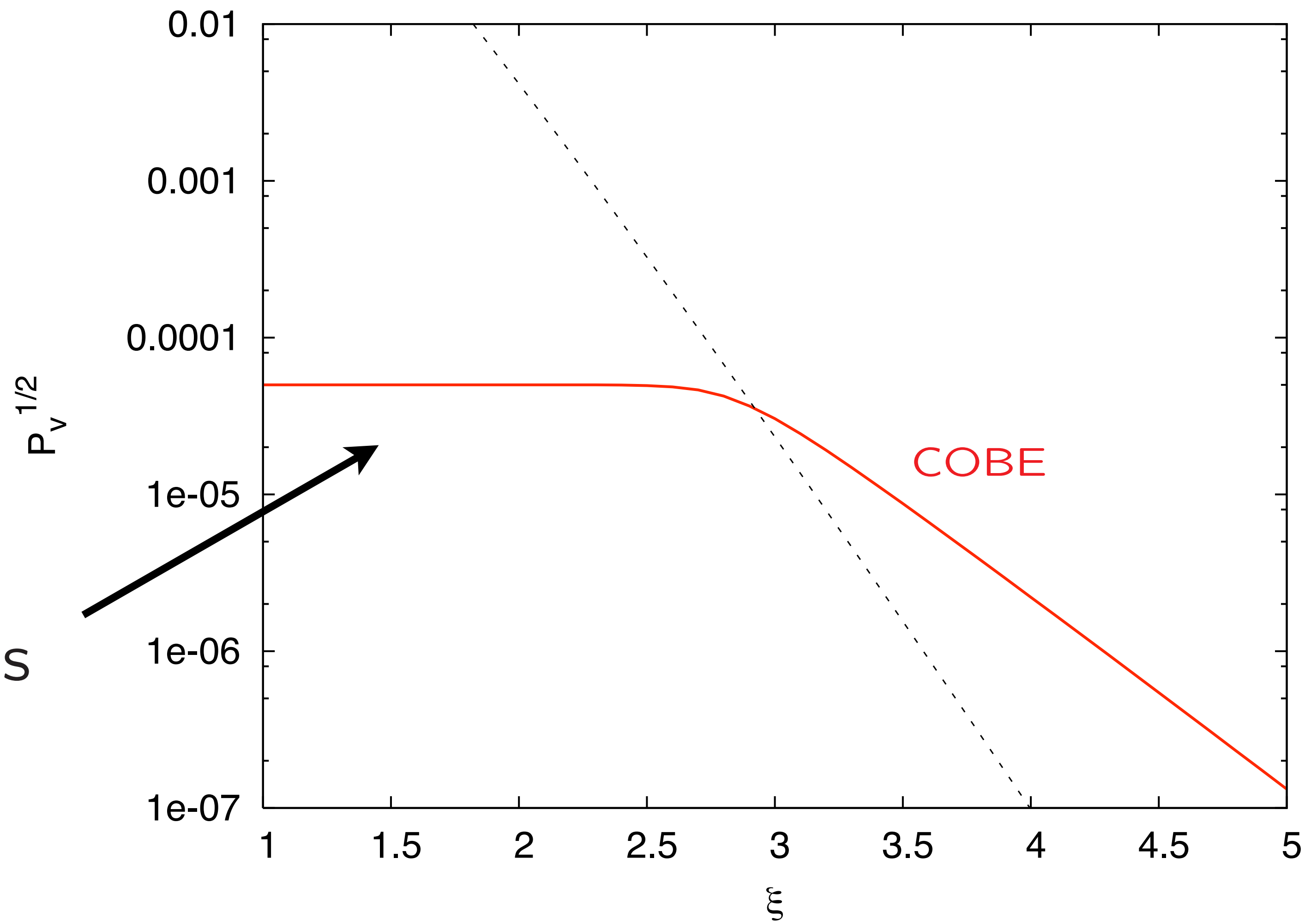
$\delta\phi_{\rm vac}$ dominates
standard result



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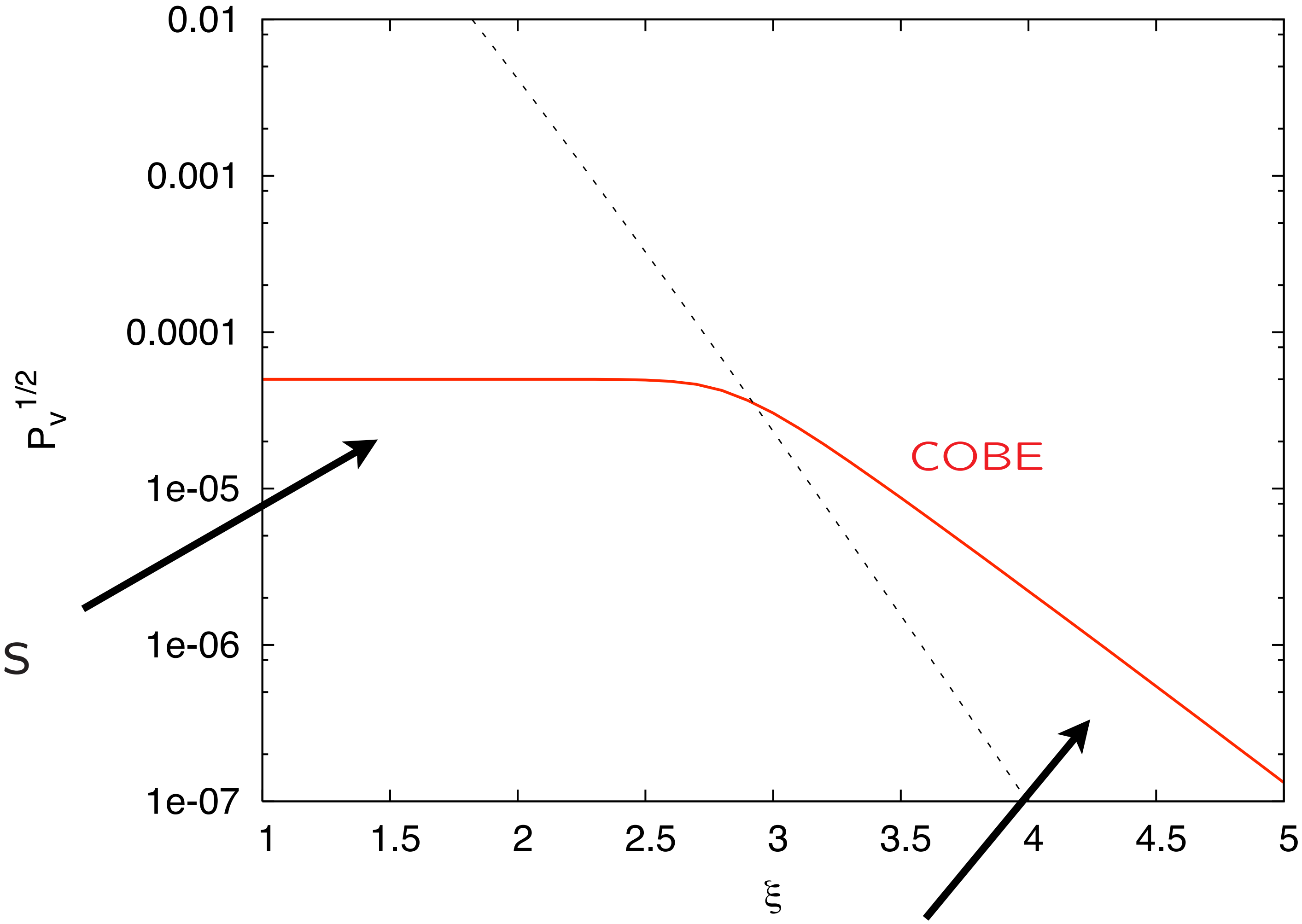


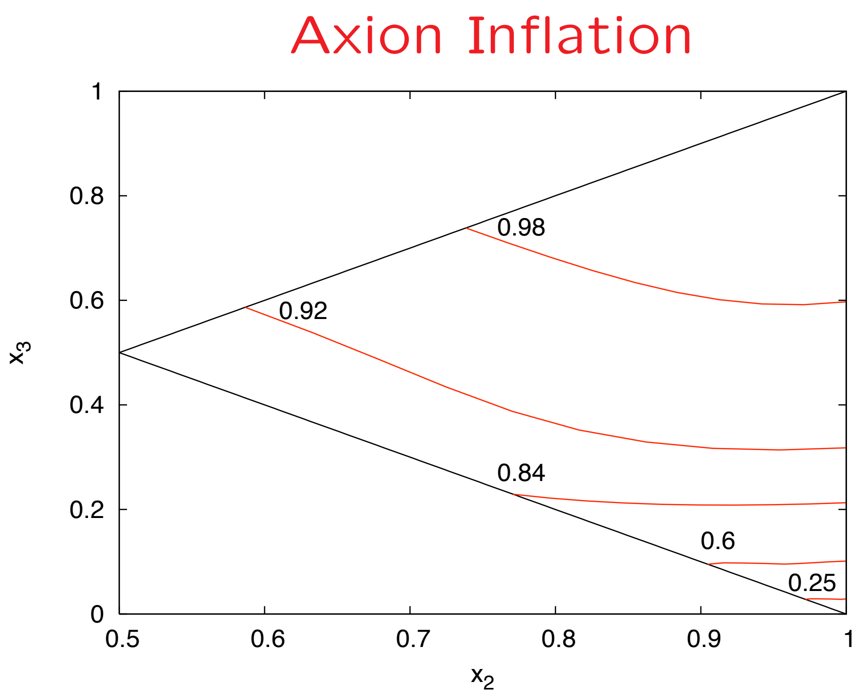
$\delta\phi_{\text{vac}}$ dominates

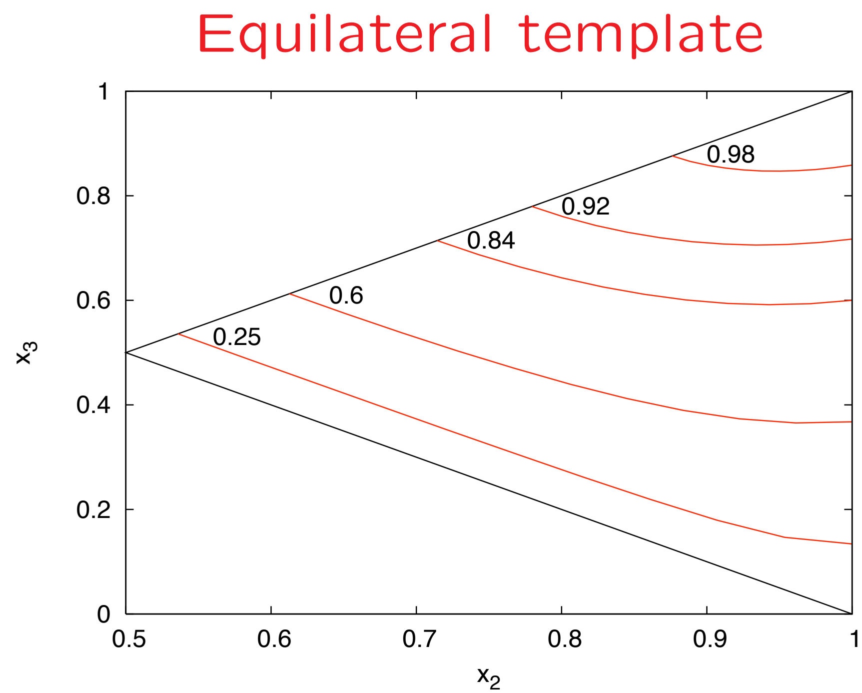
standard result

$\delta\phi_{\text{inv.decay}}$ dominates

need to decrease $\mathcal{P}_v$ exponentially

$$\langle \zeta_{\mathbf{k}_1} \zeta_{\mathbf{k}_2} \zeta_{\mathbf{k}_3} \rangle \propto k_1^{-6} \, x_2^2 \, x_3^2 \, S(x_2, x_3) \quad , \quad x_i \equiv \frac{k_i}{k_1}$$



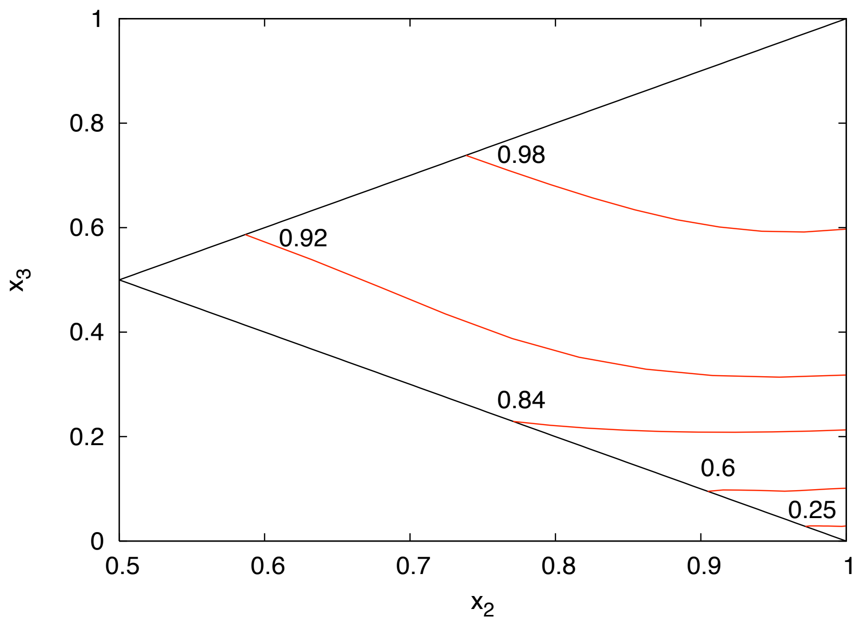


$$x_3 \leq x_2 \leq 1$$

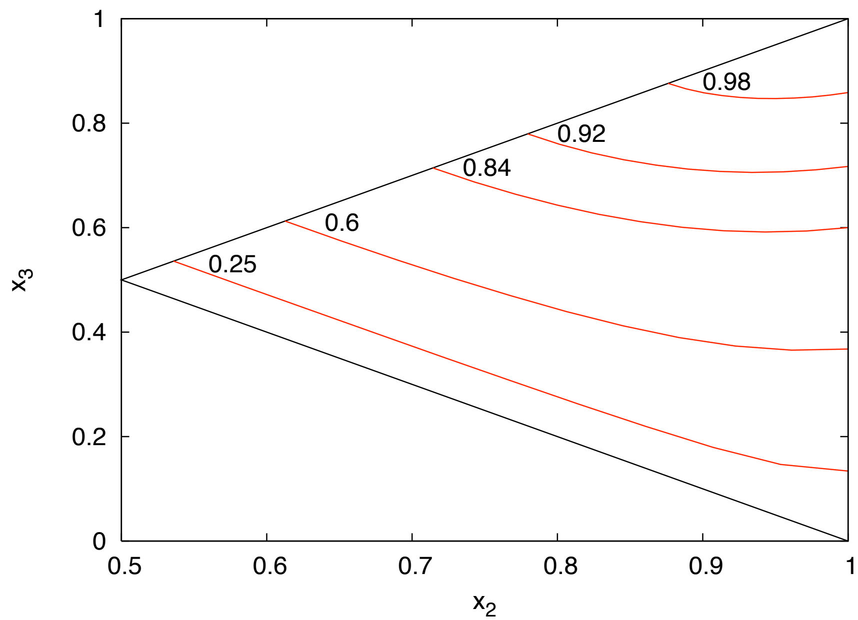
$$x_2 + x_3 \geq 1$$

$$\langle \zeta_{\mathbf{k_1}} \zeta_{\mathbf{k_2}} \zeta_{\mathbf{k_3}} \rangle \propto k_1^{-6}\, x_2^2\, x_3^2\, S\,(x_2,\, x_3) \quad , \quad x_i \equiv \frac{k_i}{k_1}$$

Axion Inflation

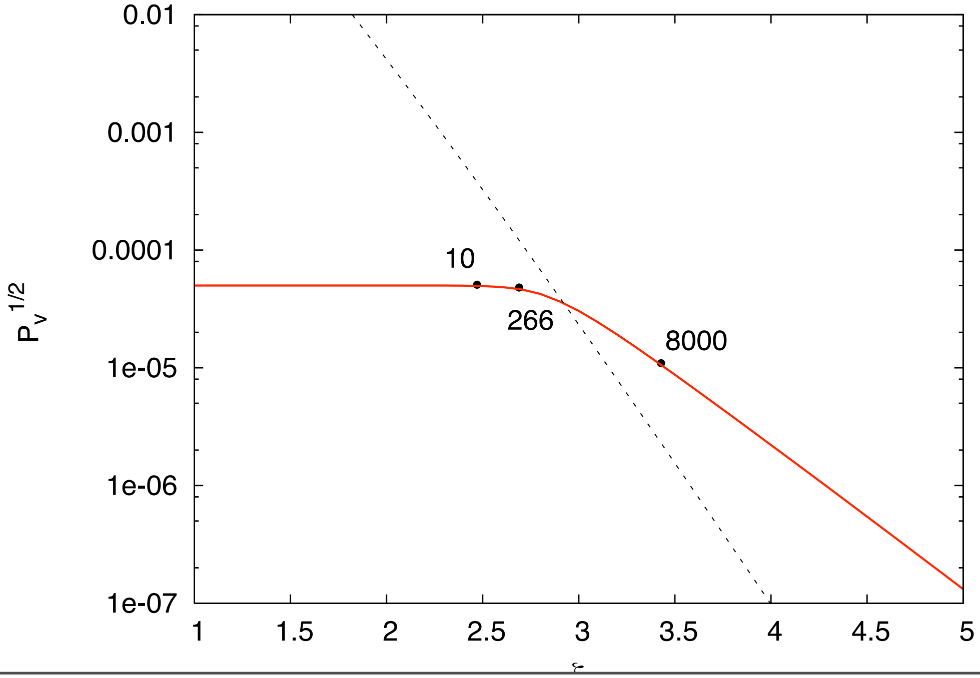


Equilateral template



$$x_3 \leq x_2 \leq 1$$

$$x_2 + x_3 \geq 1$$



$$f_{NL}^{\text{inv.dec.}} \simeq 4.4 \cdot 10^{10}\, \mathcal{P}_v^3\, \frac{e^{6\pi\xi}}{\xi^9}$$

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

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

Backreaction

- $\xi \simeq 20$ to obtain slow roll from energy dissipation into A_μ

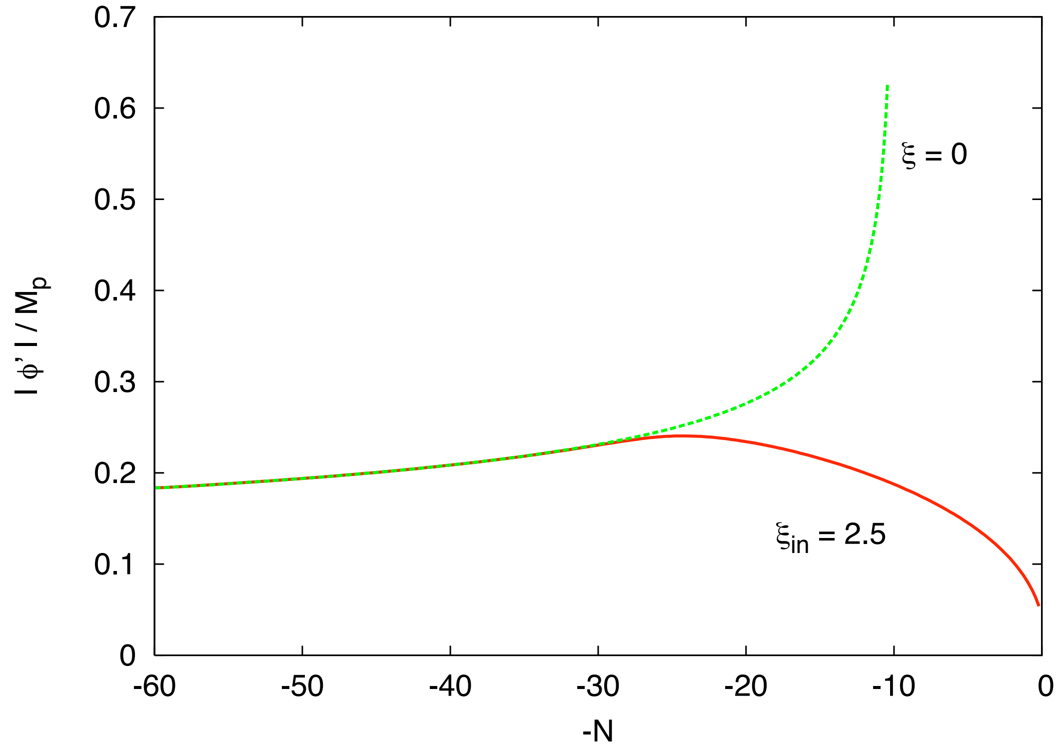
  Anber, Sorbo '09

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

- $\xi \propto \dot{\phi}/H$, can increase during inflation

Ex: $V = \mu^3 \phi$ (case shown here)

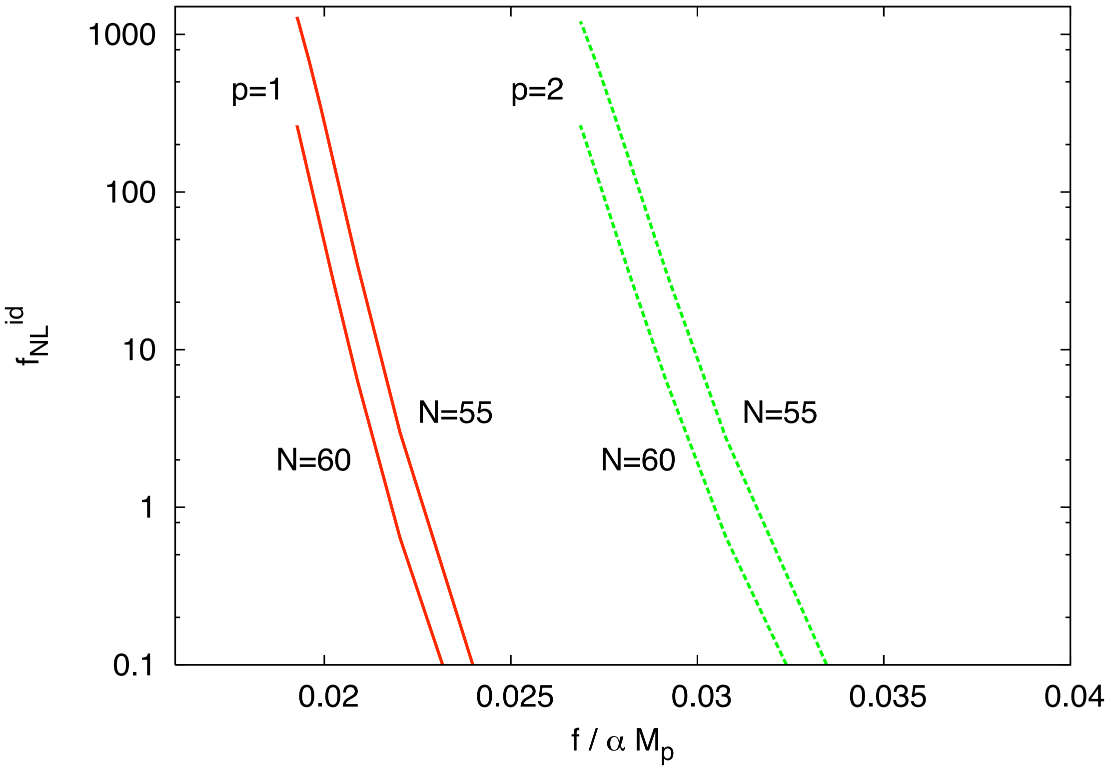
extra $N = 10$ e-folds if $\xi_{\rm in} \simeq 2, 5$.

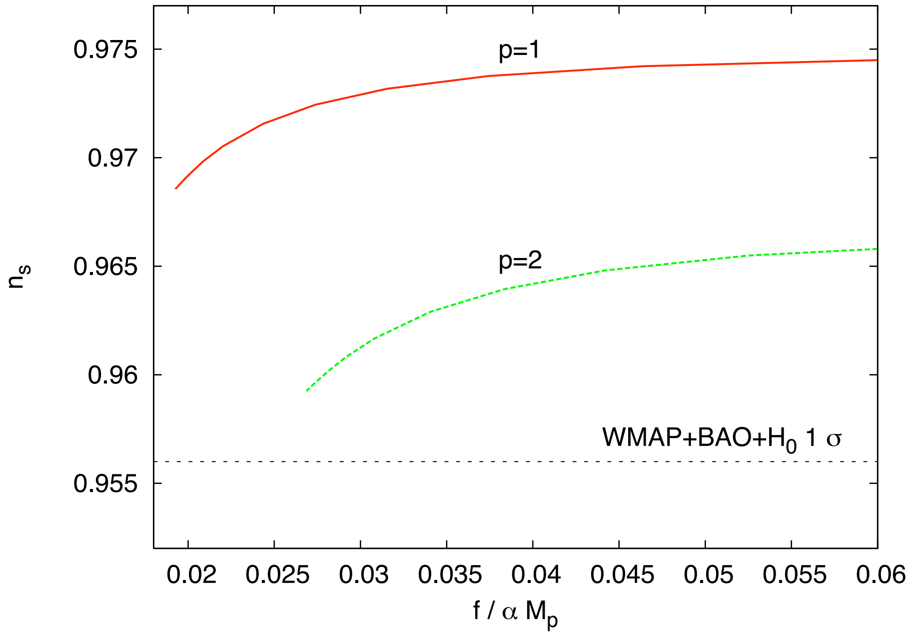


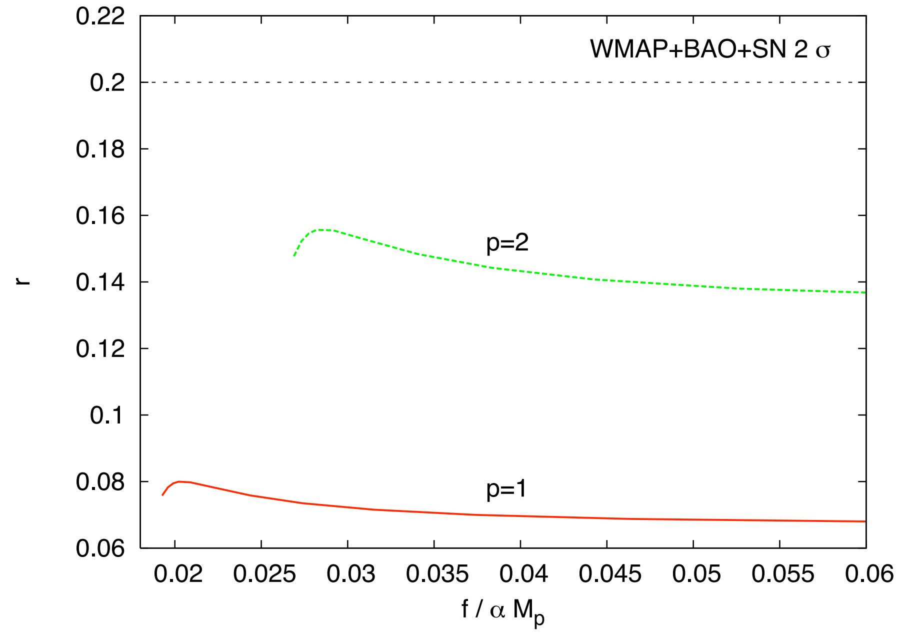
However, 60 e-folds from $\phi_{\rm in}^{(0)} \simeq 10\, M_p$ rather than $\simeq 11\, M_p$.

Increased n_{s-1}, r

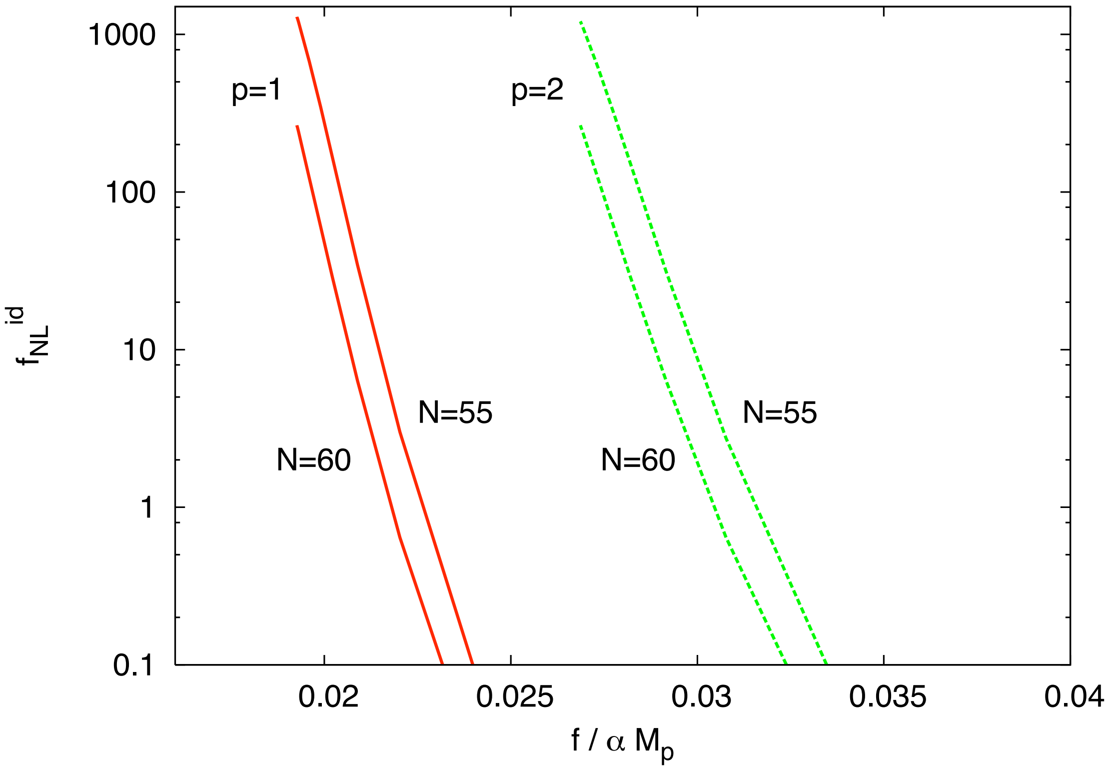
$V \propto \phi^p$, $p = 1, 2$ $\quad (\, \xi \propto 1/f \,)$

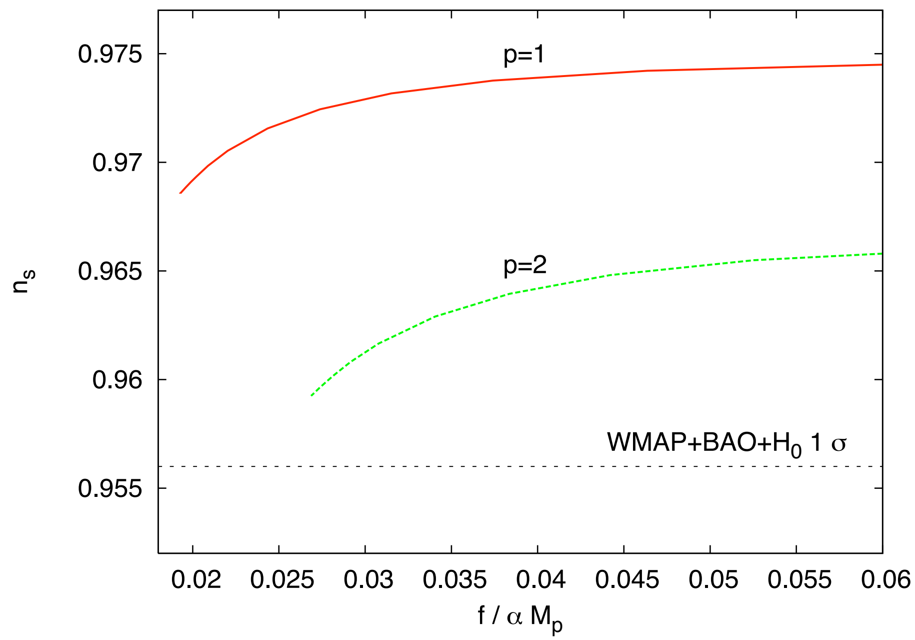


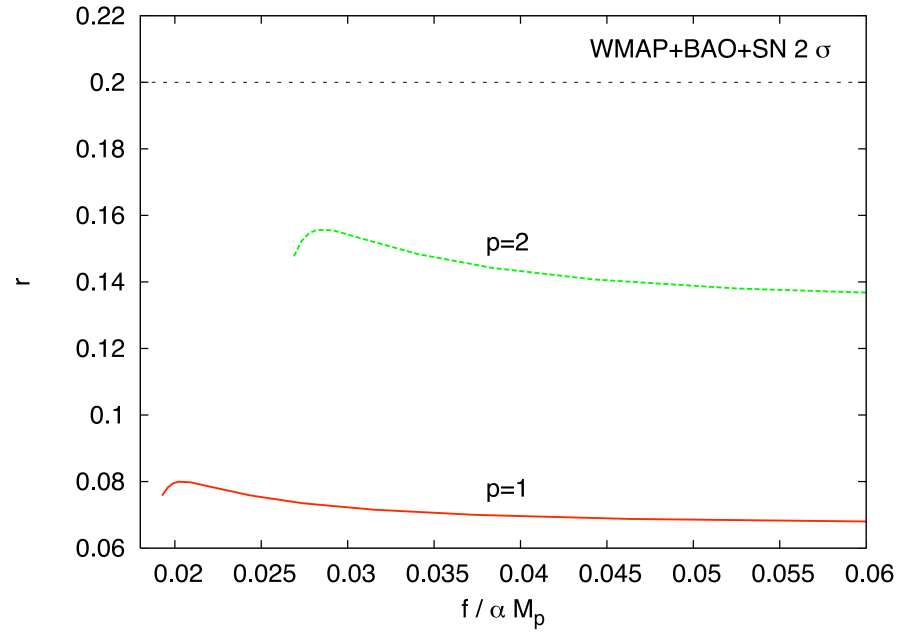




$V \propto \phi^p$, $p = 1, 2$ $\quad$ ($\xi \propto 1/f$)







Detectable $f_{\rm NL}$, $n_s - 1$, r

for $f \sim 10^{-2}\, \alpha\, M_p$

Natural value in controlled

realizations of axion inflation

- Gauge quanta also produce GW. $P_{h,AA} \ll P_{h,vac}$ when NG limit respected

Barnaby, Peloso '11

- If ξ grows sufficiently during inflation, potential LIGO / LISA signal

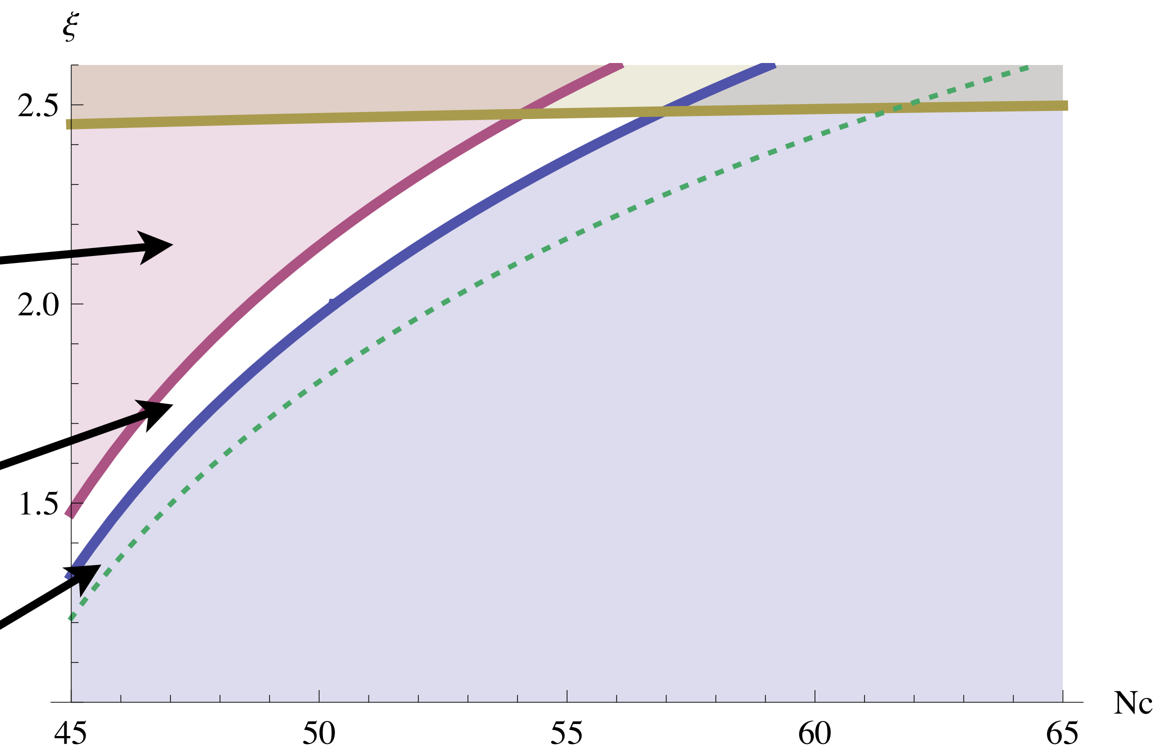
Cook, Sorbo '11

$$V = \frac{1}{2} m^2 \phi^2$$

Too large NG

Advanced LIGO

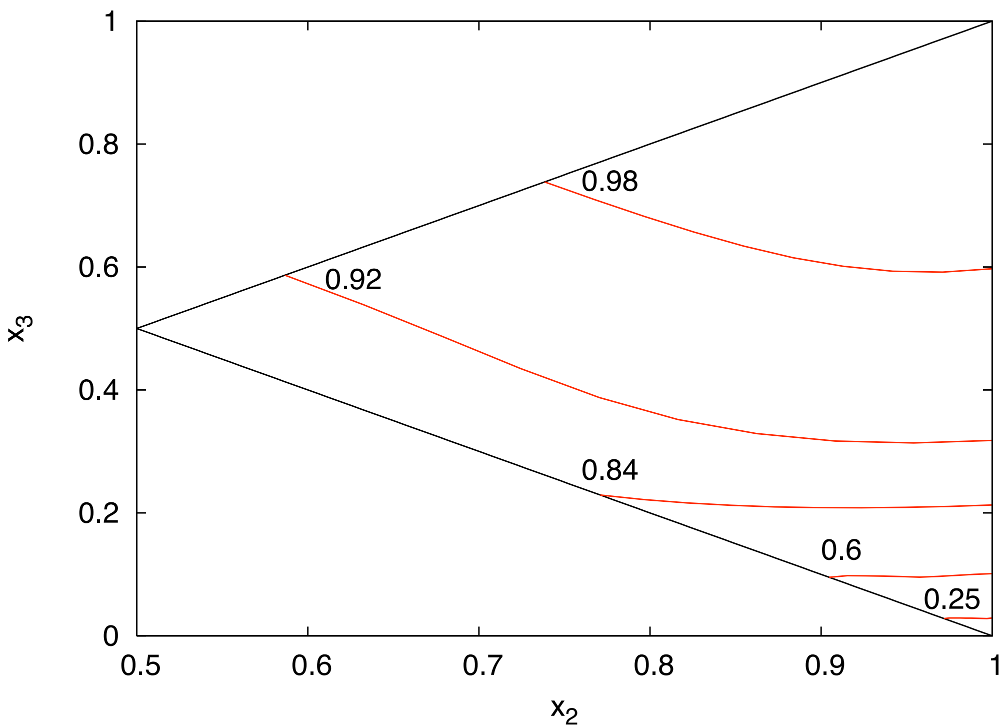
Einstein telescope

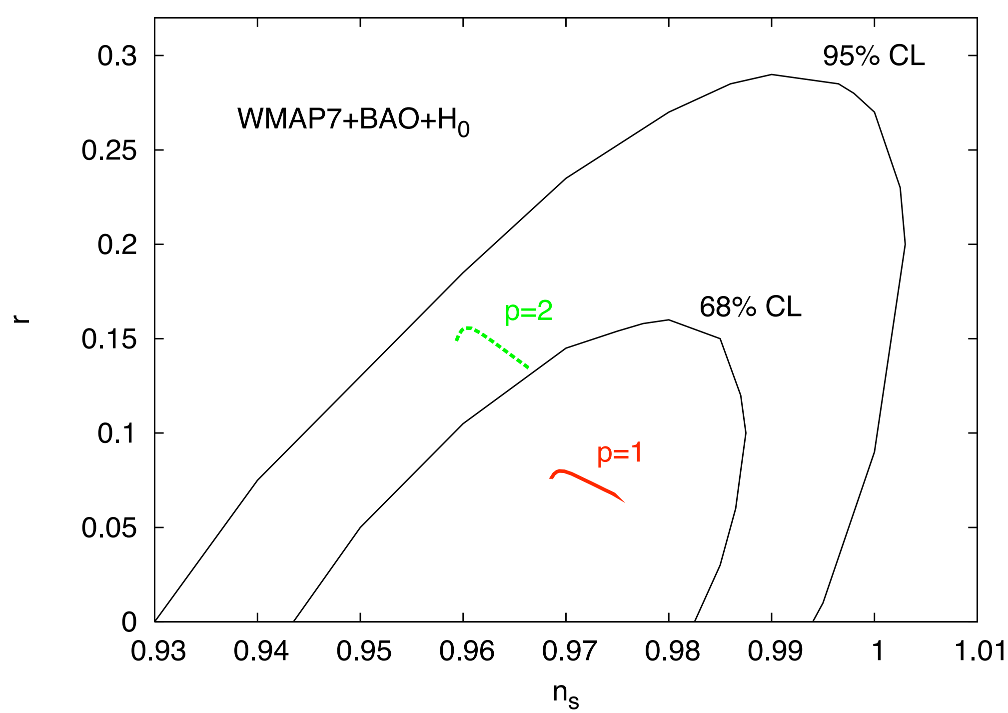


Conclusions

- Mechanism for large nongaussianity in models of single slowly rolling inflaton, with controllably flat poential

- Distinctive, and observable, phenomenology





- Already now, $\frac{f}{\alpha} \gtrsim 10^{16}$ GeV

($\sim$ 5 orders of magnitude stronger than limit on QCD axion-photon coupling)