Nonstandard tensor modes from a pseudoscalar inflaton

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PONT d'Avignon, 18/04/2011

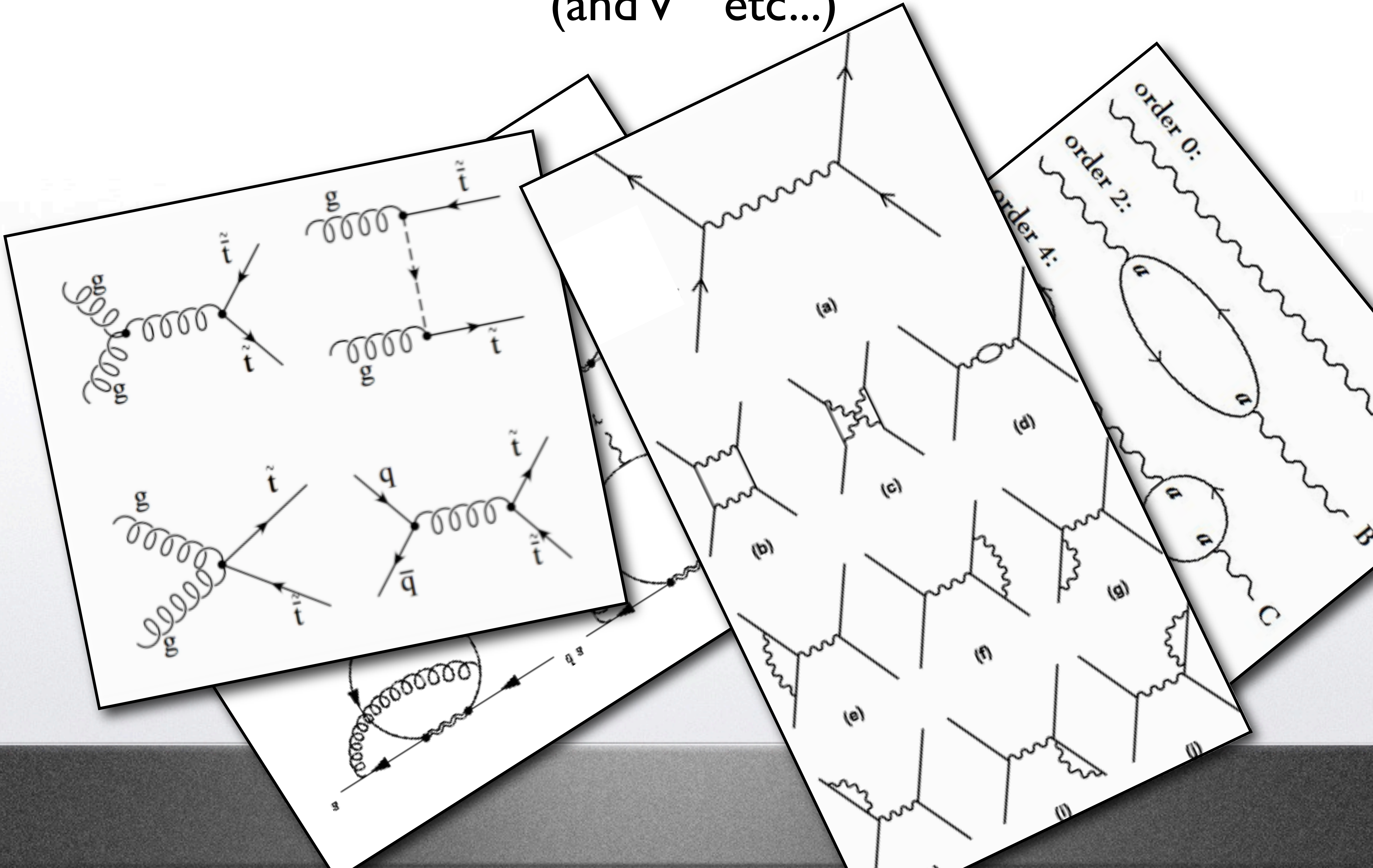
LS, 1101.1525, JCAP
J Cook, LS, in preparation

In order to be successful, a model of inflation needs "just" a scalar potential with small first and second derivatives in units of M_P

$$|V'(\phi)| << V(\phi)/M_P$$

$$|V''(\phi)| << V(\phi)/M_P^{\,2}$$

...but, in general, quantum loops will contribute to V’ and V”
(and V’” etc...)



...but, in general, quantum loops will contribute to V' and V''
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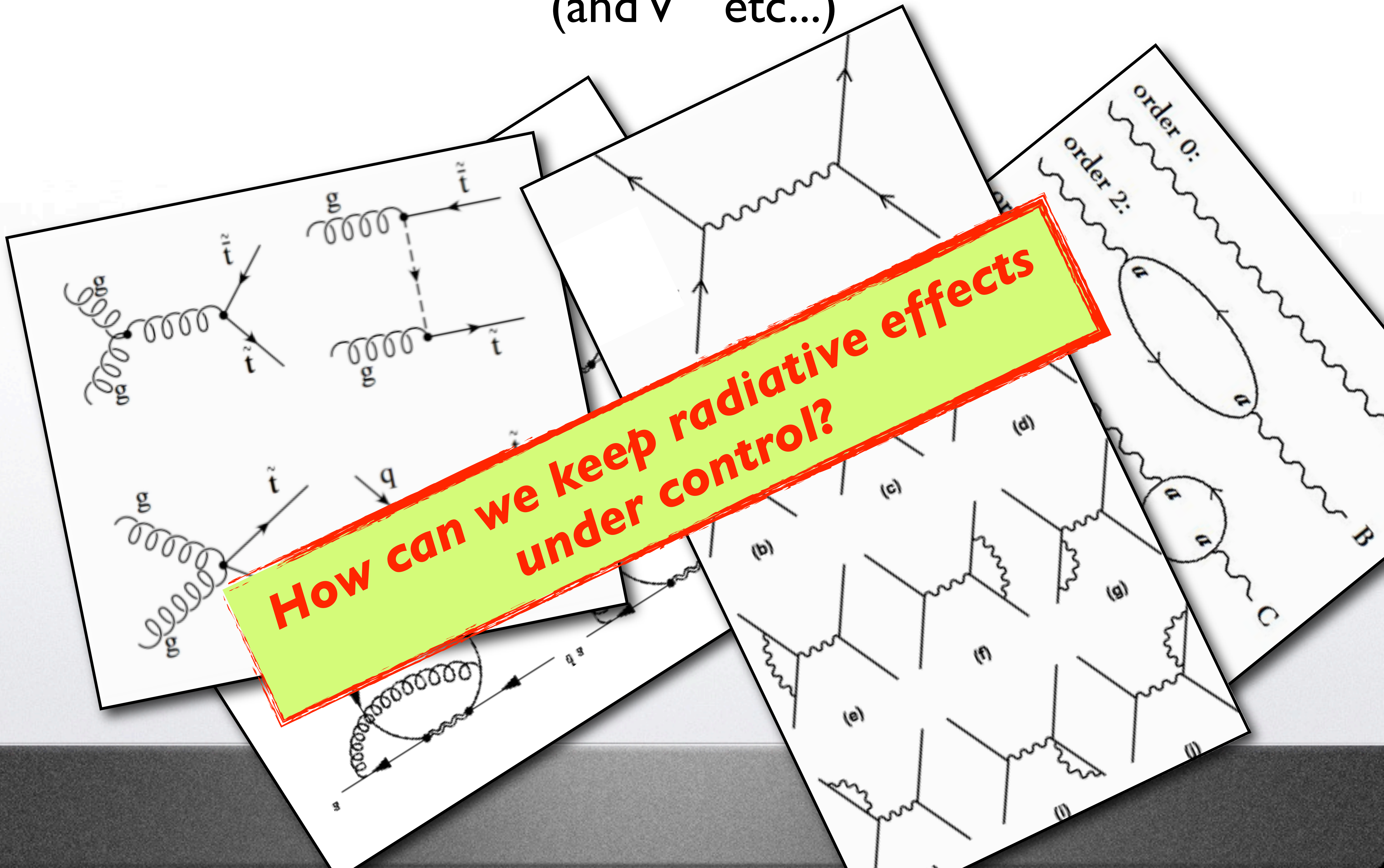


How can we keep radiative effects under control?

Quantities can be kept "controllably small" by ***symmetries***

A field ϕ has a *shift symmetry* if the theory that describes it is invariant under the transformation

$$\boxed{\varphi \longrightarrow \varphi + c}$$

(c=arbitrary constant)

If this symmetry is exact, the only possible potential for ϕ is $V(\phi)$=constant

(i.e. a cosmological constant)

an exact shift symmetry is an overkill...
...but we can break the symmetry a bit and generate a potential

An (important) example

If ϕ is a phase, then shift symmetry $\Leftrightarrow$ global $U(1)$

Flat potential for ϕ $\Leftrightarrow$ Nambu-Goldstone boson

Explicit breaking of global $U(1)$ $\Leftrightarrow$ $V(\phi)$ is generated

$\Downarrow$

pseudo-Nambu-Goldstone boson
(pNGb)

Freese et al 1990

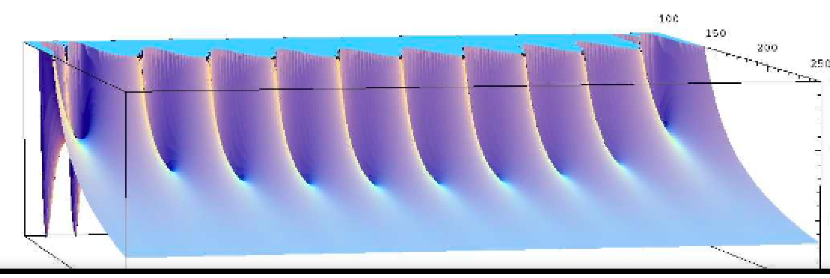
- *One* pNGB (natural inflation) $V(\phi) = \Lambda^4 \left(\cos(\phi/v) + 1\right)$

Kim, Nilles and Peloso 2004

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

Blanco-Pillado et al 2004

- PNGBs and moduli

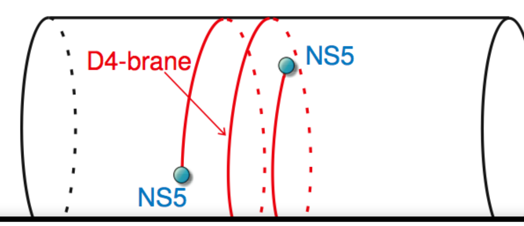


Dimopoulos et al 2005

- *Many* pNGBs $\mathcal{L} = -\sqrt{-g}\sum_{i=1}^{N}\left\{\frac{1}{2}(\partial\phi_i)^2 + \Lambda_i^4\left[1 + \cos(\phi_i/f_i)\right]\right\}$

Silverstein and Westphal, 2008

- Monodromy



Kaloper and LS, 2008
Kaloper, Lawrence and LS, 2010

- Mixing with 4-form $L= \frac{M_{Pl}^2}{2}R - \frac{1}{2}(\nabla\phi)^2 - \frac{1}{48}F_{\mu\nu\lambda\sigma}^2 + \frac{\mu\phi}{24}\frac{\epsilon^{\mu\nu\lambda\sigma}}{\sqrt{g}}F_{\mu\nu\lambda\sigma} + \ldots)$

The bottom line:

there are many well motivated models of pNGB inflation

The pNGB is a pseudoscalar:

macroscopic parity violation in the Early Universe

Is it possible to observe the effect
of such parity violation?

Imprinting parity violation on the CMB

If inflaton is a pseudoscalar (in particular a pNGB), it interacts with the gauge fields via

$$\mathcal{L}_{\phi FF} = \frac{\phi}{f}\, \epsilon_{\alpha\beta\gamma\delta}\, F^{\alpha\beta}\, F^{\gamma\delta}$$

(f=a free parameter with dimensions of a mass)

in Coulomb gauge $A_0=0$, $\nabla A=0$, decompose into helicity modes

$$\mathbf{A}(\mathbf{x},t) = \sum_{\lambda=\pm} \int \frac{d^3\mathbf{k}}{(2\,\pi)^{3/2}} \left[a_{\mathbf{k}}^{\lambda}\, A_{\lambda}^{\mathbf{k}}(t)\, \mathbf{e}^{\lambda}(\mathbf{k}) e^{i\mathbf{k}\mathbf{x}} + a_{\mathbf{k}}^{\lambda\,\dagger}\, A_{\lambda}^{*\,\mathbf{k}}(t)\, \mathbf{e}^{\lambda\,*}(\mathbf{k}) e^{-i\mathbf{k}\mathbf{x}}\right]$$

Transferring parity violation to the gauge modes

The mode functions $A_\lambda^k(t)$ are sourced by $\phi_0(t)$, and obey

$$\ddot{A}_\lambda + H\,\dot{A}_\lambda + \left(\frac{\mathbf{k}^2}{a^2} + \lambda\,\frac{\dot\phi}{f}\,\frac{|\mathbf{k}|}{a}\right) A_\lambda = 0$$

for $\lambda = -$, the "mass term" is negative for ~ 1 Hubble time:

Exponential amplification of <u>left handed modes only</u>!

parity violation is transferred to the electromagnetic field

$$A_L \propto \exp\left\{\frac{\pi}{2}\,\frac{\dot\phi}{f\,H}\right\}$$

Then gauge modes have energy...
...and source the tensor modes!

$$\ddot{h}_\lambda + 3\,\frac{\dot{a}}{a}\,\dot{h}_\lambda + \frac{\mathbf{k}^2}{a^2}\,h_\lambda = \frac{2}{M_P^2}\,\Pi_\lambda^{ij}\,T_{ij}^{\mathrm{EM}}$$

Helicity-λ tensor modes

Projector on helicity-λ components

Spatial components of gauge field stress-energy tensor

Parity violation is transferred from the gauge to the tensor modes

A_+ and A_- have different amplitudes

$$\Pi_+^{ij}\, T_{ij} \neq \Pi_-^{ij}\, T_{ij}$$

$$h_+ \neq h_-$$

$$\mathcal{P}_R(\mathbf{k}) = \frac{H^2}{\pi^2 M_P^2}\left(1 + 9 \times 10^{-7} \frac{H^2}{M_P^2} \frac{e^{4\pi\xi}}{\xi^6}\right)$$

$$\mathcal{P}_L(\mathbf{k}) = \frac{H^2}{\pi^2 M_P^2}\left(1 + 2 \times 10^{-9} \frac{H^2}{M_P^2} \frac{e^{4\pi\xi}}{\xi^6}\right)$$

"standard" parity-invariant part

parity-violation!

$$\xi \equiv \frac{\dot{\phi}}{2\, f\, H} \gtrsim 1$$

How can parity violating tensor modes be detected?

CMB temperature fluctations and E modes are parity-even
B modes are parity-odd

Lue, Wang and Kamionkowski 98

$<TB>$, $<EB>$ should vanish
in parity invariant CMB

Detection prospects of a parity-violating primordial tensor modes

Saito Ichicki Taruya 07,
Contaldi Maguejio Smolin 08,
Gluscevic Kamionkowski 10

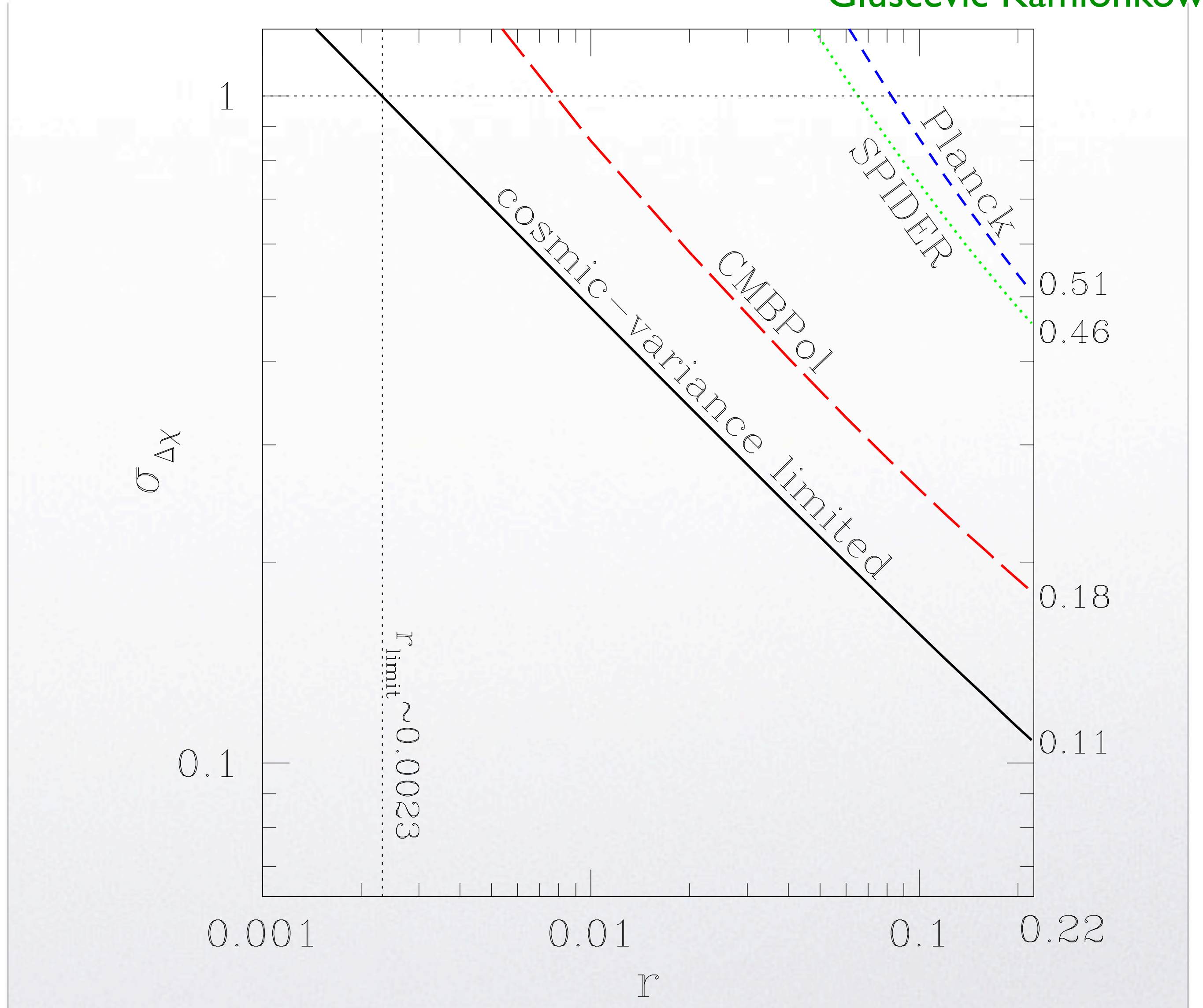
Depend on two parameters

$$r = \frac{\mathcal{P}_R + \mathcal{P}_L}{\mathcal{P}_T}$$

tensor-to-scalar ratio

$$\Delta\chi = 2\,\frac{\mathcal{P}_R - \mathcal{P}_L}{\mathcal{P}_R + \mathcal{P}_L}$$

chirality of primordial perturbations



From
Gluscevic Kamionkowski 10

For our system

$$\Delta\chi = \frac{4.3 \times 10^{-7}\,\frac{e^{4\,\pi\,\xi}}{\xi^6}\,\frac{H^2}{M_P^2}}{1 + 4.3 \times 10^{-7}\,\frac{e^{4\,\pi\,\xi}}{\xi^6}\,\frac{H^2}{M_P^2}}\,.$$

$$\xi \equiv \frac{\dot{\phi}}{2\,f\,H} = \sqrt{\frac{\epsilon}{2}}\,\frac{M_P}{f}$$

Exponential dependence on the coupling *1/f:*

in principle parity violation detectable for significant part of parameter space. But...

Constraints from nongaussianities

Barnaby Peloso 10

The produced electromagnetic modes backreact on the inflaton, contributing to its three-point function

NONGAUSSIANITIES

$$f_{NL}^{\text{equil}} \simeq 8.9\,\times 10^4\,\frac{H^6}{\epsilon^3\,M_P^6}\,\frac{e^{6\,\pi\,\xi}}{\xi^9}$$

Constraints from nongaussianities (2)

WMAP constrains $f_{NL}^{equil}<266$

$\xi<2.6$

$\Delta\chi<<1$

Parity violation will not be detectable in the simplest model without violating constraints from nongaussianities

Still, suppose we see $<EB>\neq 0$. Would this scenario be able to explain such an observation?

Ways out

i) A CURVATON

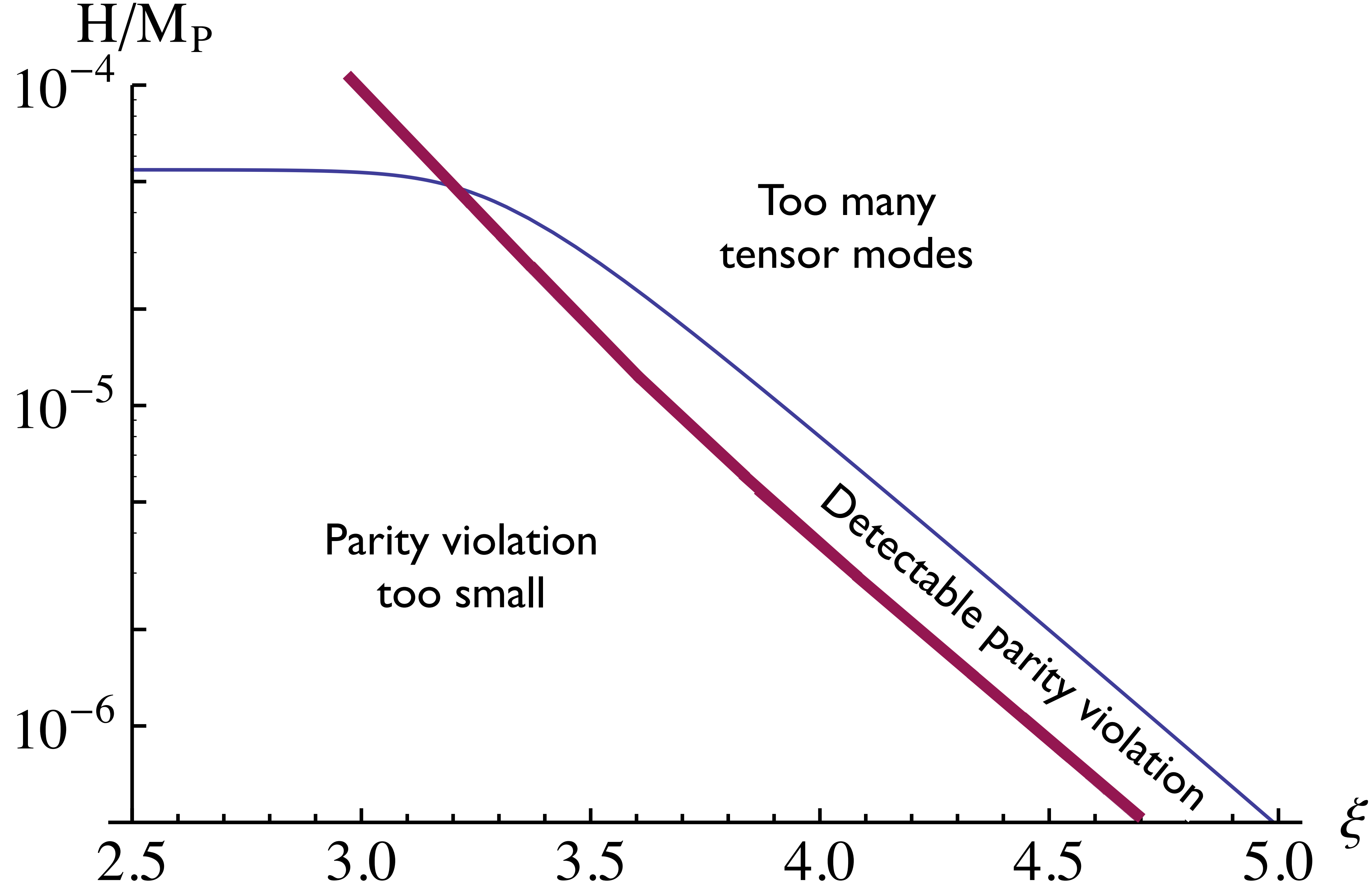
Most of the primordial perturbation is due to a second field with nearly-gaussian perturbations.

ii) MANY GAUGE FIELDS

Contributions to f_{NL} add incoherently. With $\sim 10^3$ gauge fields f_{NL} safely small

constraint from nongaussianities is evaded

E.g. parameter space for curvaton contributing 90% of primordial perturbations



Discussion

Planck will improve bound on tensor modes and might even detect them!

It will be important to look for nonvanishing $<EB>$ and $<TB>$

The scenario presented above can give rise to those correlators


MONTY PYTHON'S
And Now For Something
DIFFERENT
SOMEHOW
DVD

Inflationary GWs for LIGO

$$\mathcal{P}_R(\mathbf{k}) = \frac{H^2}{\pi^2 M_P^2}\left(1 + 9\times 10^{-7}\frac{H^2}{M_P^2}\frac{e^{4\pi\xi}}{\xi^6}\right)$$

$$\mathcal{P}_L(\mathbf{k}) = \frac{H^2}{\pi^2 M_P^2}\left(1 + 2\times 10^{-9}\frac{H^2}{M_P^2}\frac{e^{4\pi\xi}}{\xi^6}\right)$$

Cook, LS in progress

ξ *increases* during inflation

$$\xi \equiv \frac{\dot{\phi}}{2\, f\, H} \gtrsim 1$$

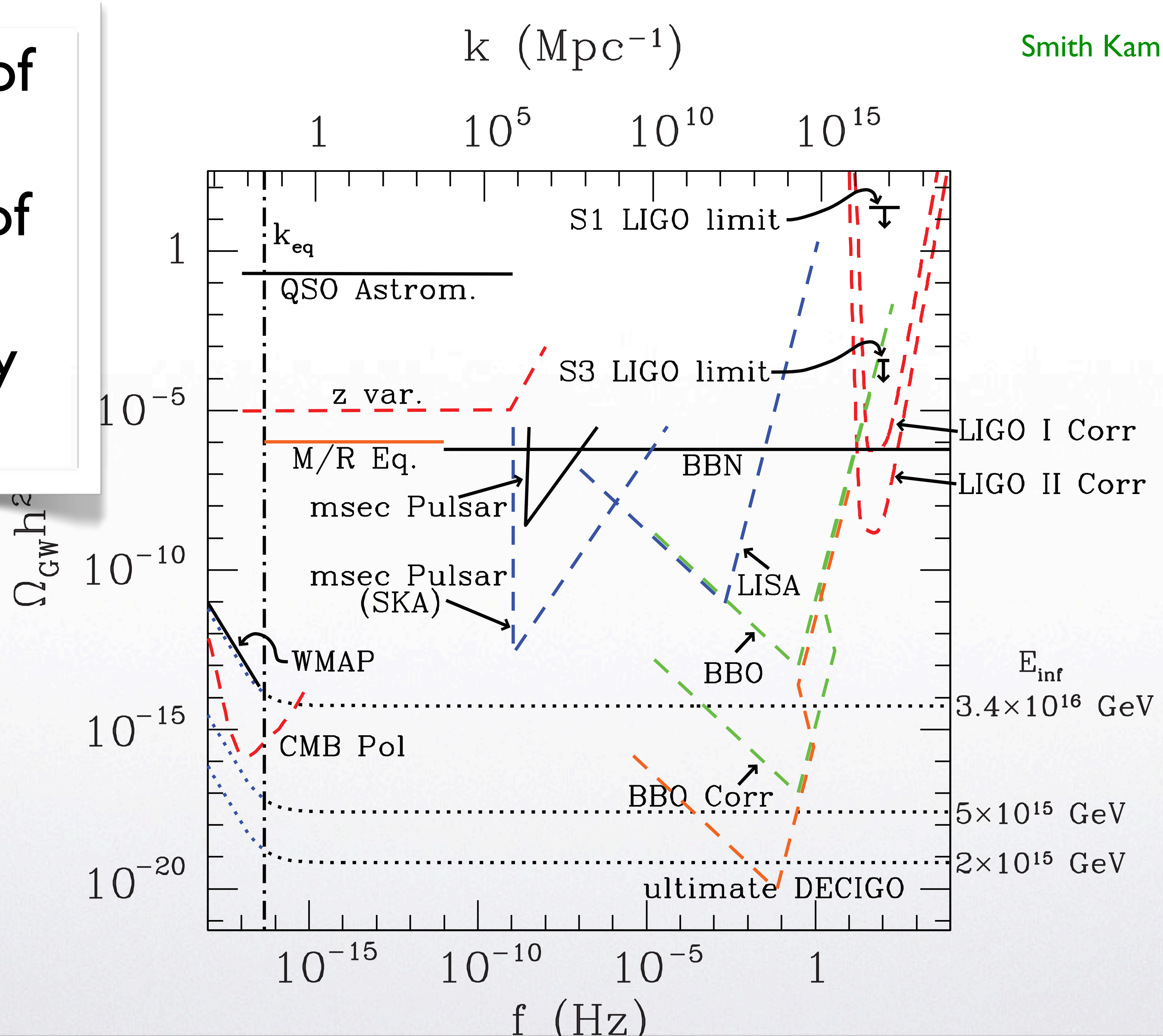
GWs produced towards the end of inflation (i.e. at smaller scales) have larger amplitude

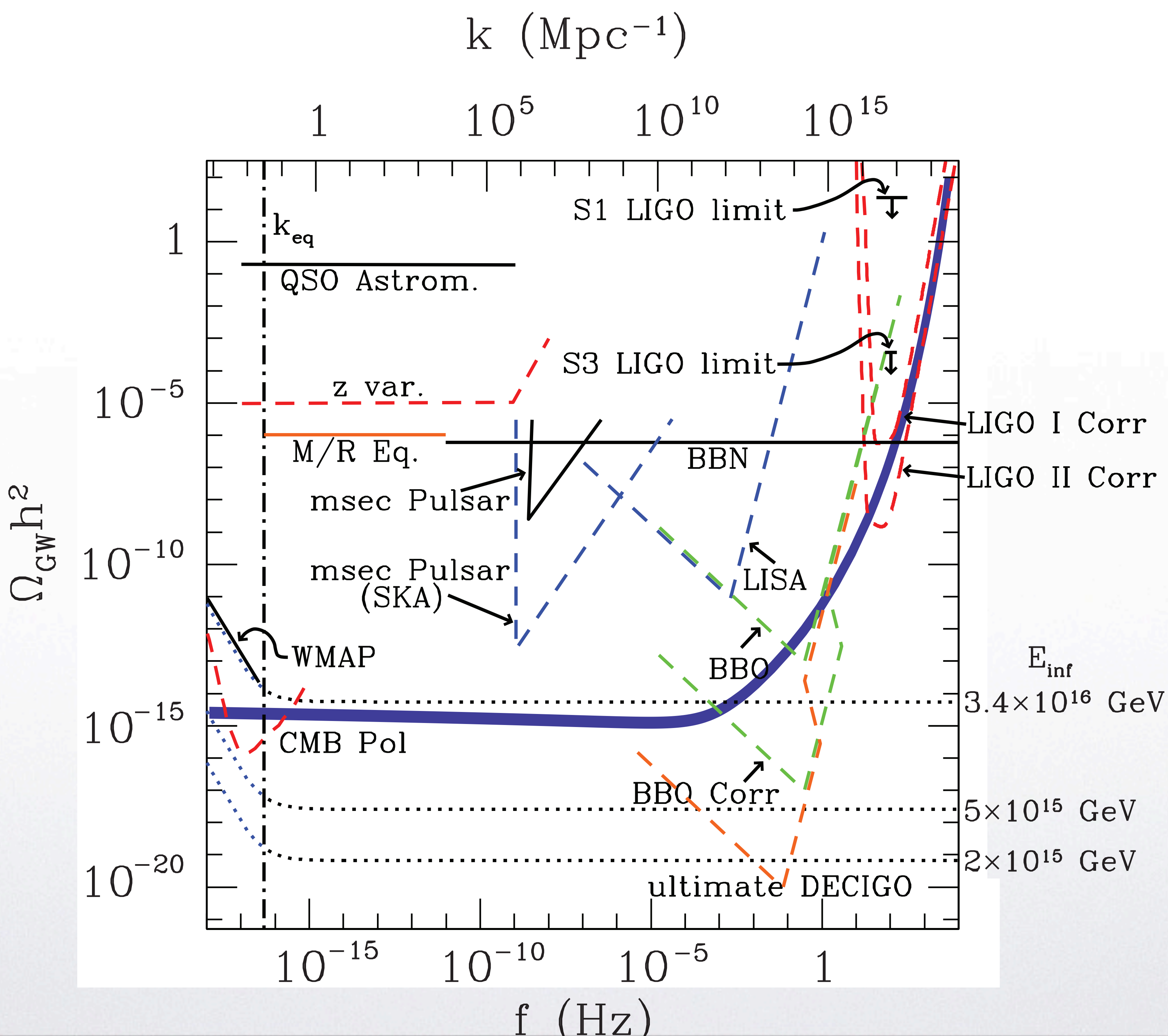
might be detected by advanced LIGO!

Note: this would happen for parameters consistent with constraints from f_{NL}

Prospects of direct detection of GWs of inflationary origin

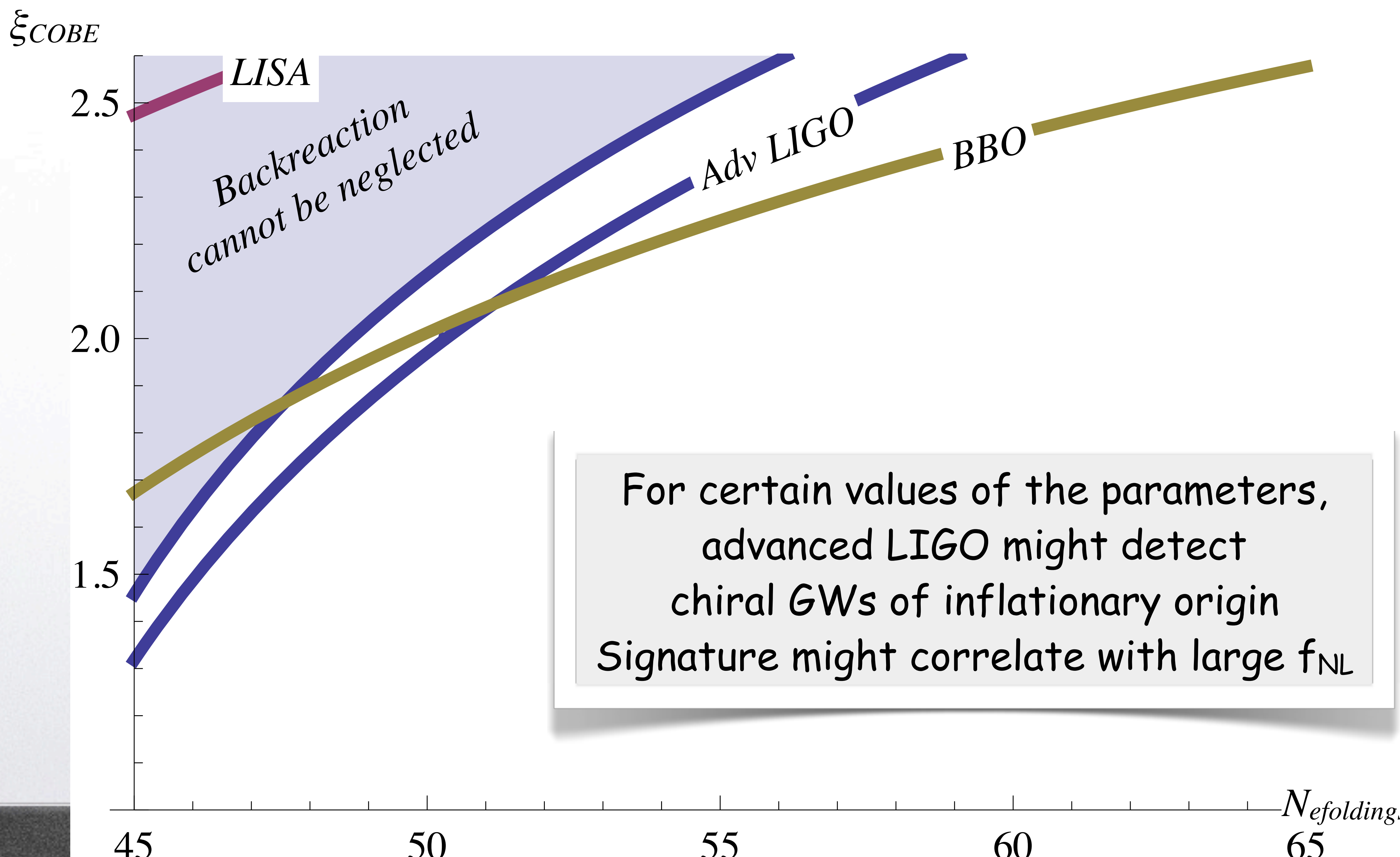
Smith Kamionkowski Cooray 06





N=50 efoldings
$V(\phi)=m^2\phi^2/2$,
$\xi_{COBE}=2.1$

$\xi_{COBE} > 2.6 \Rightarrow f_{NL}$ too large



For certain values of the parameters, advanced LIGO might detect chiral GWs of inflationary origin

Signature might correlate with large f_{NL}

Conclusions

- Models of pseudoscalar inflation very well motivated
- We have shown they naturally lead to a chiral spectrum of gravitational waves
- In simplest model, strong constraints from nongaussianities
- However, candidate explanations if nonvanishing $<EB>$ and $<TB>$ is observed
- The same mechanism could also generate GWs observable by advanced LIGO