Odd tensor modes from particle production during inflaton

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IAP, 04/03/13

LS, 1101.1525, JCAP
J. Cook and LS, 1109.0022, PRD

Odd*,** tensor modes from particle production during inflaton

*: parity violating (part I of the talk)

**: detectable by ground-based interferometers (part II of the talk)

LS, 1101.1525, JCAP
J. Cook and LS, 1109.0022, PRD

CMB information:
T modes (scalar),
E and B modes (polarization)

While T and E modes are parity-even,
B is parity-odd

<TB> and <EB> power spectra should vanish in parity-invariant CMB

What if Planck (or any other CMB polarization experiment) detects <TB>≠0?

Parity-violating dynamics in the very Early Universe?

An obvious source of primordial parity violation:

A pseudoscalar inflaton

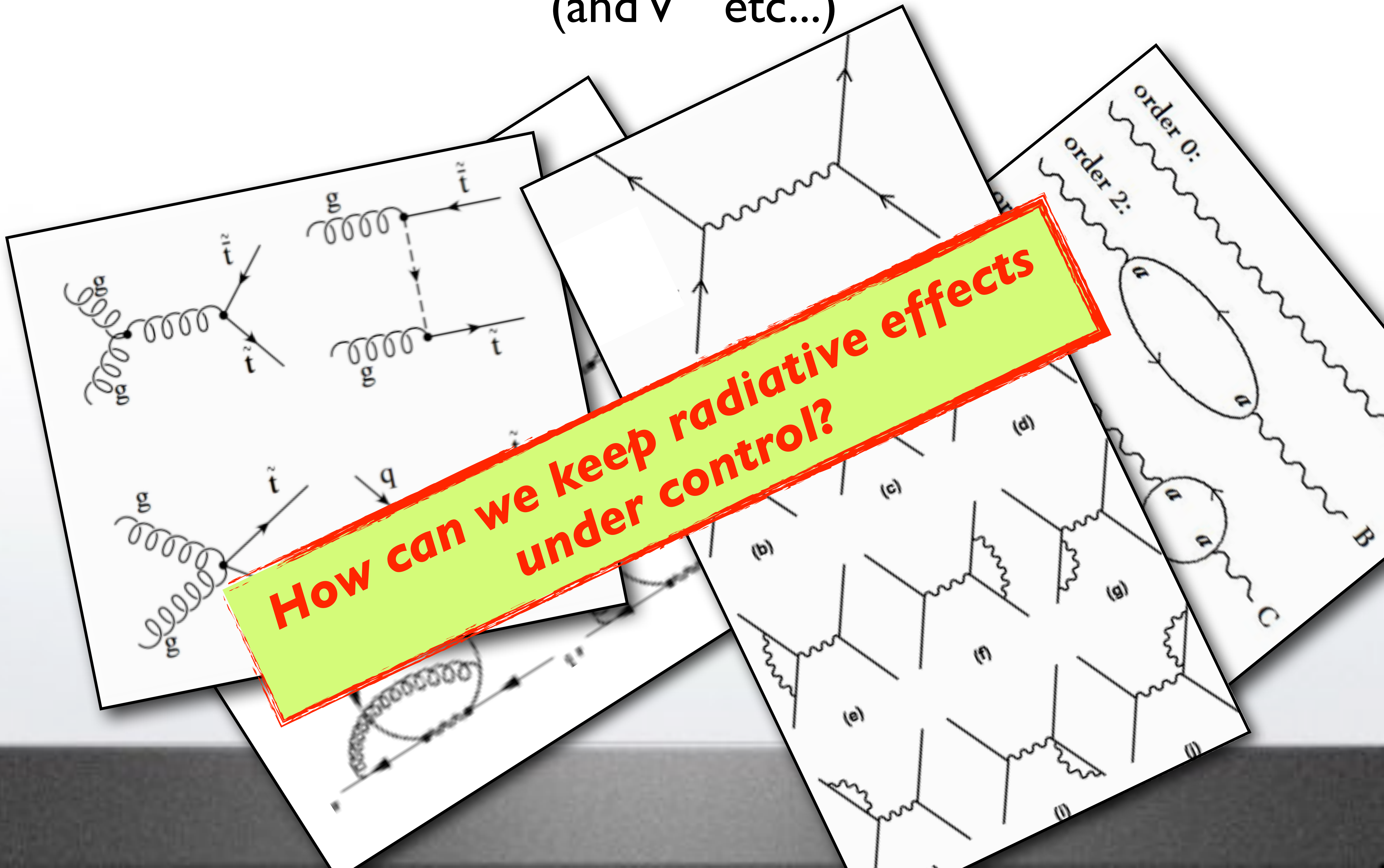
Why should we care about a pseudoscalar inflaton?

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...)



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

$$\varphi \longrightarrow \varphi + c$$

(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 ⇔ global U(1)

- Theory with a spontaneously broken global U(1)

$$\mathcal{L} = \partial_\mu H^* \, \partial^\mu H - \lambda \left(|H|^2 - v^2 \right)^2$$

- Decompose $H = (v + \delta H)\, e^{i\phi/v}$

  where δH is massive and φ is a massless Goldstone boson *(pseudoscalar)*

- The global U(1) is broken e.g. by some strong dynamics

$$\delta\mathcal{L} = \Lambda^3 \, (H + H^*) + \ldots$$

- A potential is generated: $\delta V \sim \Lambda^3 \, v \, \cos(\phi/v)$

Pseudo-Nambu-Goldstone boson
PNGb

...but this is not the *only* example...

Freese et al 1990

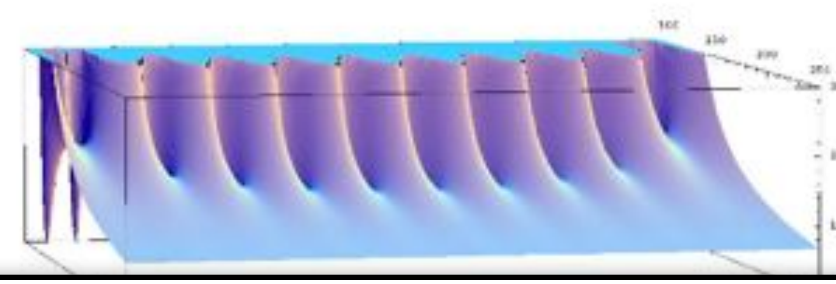
- *One* pNGB (natural inflation) $V(\phi) = \Lambda^4 \left(\cos(\phi/v) + 1\right)$

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

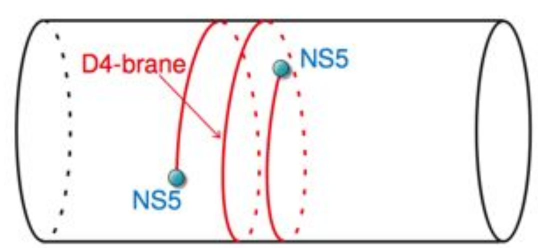


Dimopoulos et al 2005

- *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

and the pNGB is a pseudoscalar!

There are many well motivated models with

macroscopic parity violation in the Early Universe

How can this parity violation be transferred to the CMB?

If inflaton is a pseudoscalar (in particular a pNGB), it interacts with *U(1)* gauge fields via

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

(f=constant with dimensions of a mass)

The gauge field is decomposed into helicity-λ modes

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

The mode functions $A_\lambda{}^k(\tau)$ are sourced by the rolling ϕ:

$$A_\lambda'' + \left(\mathbf{k}^2 + \lambda\,\frac{\phi'}{f}\,|\mathbf{k}|\right) A_\lambda = 0$$

for λ=-, the "mass term" is negative and large for ~*1* Hubble time:

.Anber and LS 06

Exponential amplification of left handed modes only!

parity violation is transferred to the electromagnetic field

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

Primordial gravitational waves

Let us now focus on the tensor components of the metric

$$ds^2 = a^2(\tau)\,\left[-d\tau^2 + \left(\delta_{ij} + h_{ij}\left(\mathbf{x},\,\tau\right)\right)\,dx^i\,dx^j\right]$$

$$\sum_{ij} \delta^{ij}\,h_{ij} = \sum_{i} \partial_i\,h_{ij} = 0$$

the tensor mode has two components (=helicity ±2) so we can decompose it, in momentum space, into left-handed and right-handed modes

$$h_{ij}\left(\mathbf{k},\,\tau\right) = \sum_{\lambda=\pm} h_\lambda\left(\mathbf{k},\,\tau\right)\,\epsilon^{\lambda}_{ij}\left(\mathbf{k}\right)$$

Transferring parity violation to the gravitational waves

The energy of the electromagnetic field sources gravitational waves:

(note: this is an operator equation)

$$h''_\lambda + 2\,\frac{a'}{a}\,h'_\lambda + \mathbf{k}^2\,h_\lambda = \frac{2}{M_P^2}\,\Pi_\lambda^{ij}\,T_{ij}^{\rm EM}$$

$\equiv T_\lambda$

Projector on helicity-λ components

Spatial components of gauge field stress-energy tensor

since the RHS is known (computed in previous slides), can obtain h_λ formally with retarded propagator

The amplitude of the helicity-λ gravitational waves

If $G_k(\tau, \tau')$ is retarded propagator
for operator $d^2/d\tau^2+2\,(a'/a)\,d/d\tau + \boldsymbol{k}^2$, then

$$h_\lambda\left(\mathbf{k},\,\tau\right) = \frac{2}{M_P^2}\int d\tau'\,G_k\left(\tau,\,\tau'\right)\,T_\lambda\left(\mathbf{k},\,\tau'\right)$$

and from this we obtain the amplitude

$$\left\langle h_\lambda\left(\mathbf{k},\tau\right)\,h_\lambda\left(\mathbf{q},\tau\right)\right\rangle = \frac{4}{M_P^4}\int d\tau'\,G_k\left(\tau,\tau'\right)\int d\tau''\,G_q\left(\tau,\tau''\right)\,\left\langle T_\lambda\left(\mathbf{k},\tau'\right)T_\lambda\left(\mathbf{q},\tau''\right)\right\rangle$$

Parity violating gravitational waves

A_L and A_R have different amplitudes

$$<T_L T_L> \neq <T_R T_R>$$

$$<h_L h_L> \neq <h_R h_R>$$

Physics: in the limit of small transverse momentum two LH photons cannot create a RH graviton

Before computing the power spectrum of the tensors...

...note that to the special solution of the inhomogeneous equation for h_λ one should add the general solution of the homogeneous equation

$$h''_\lambda + 2\,\frac{a'}{a}\,h'_\lambda + \mathbf{k}^2\,h_\lambda = 0$$

parity-invariant

uncorrelated to component sourced by ϕ

exists in standard inflation models

The parity-violating power spectrum

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

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

"standard"
parity-invariant part

parity-violation

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

Detection prospects related to observability of nonzero <*EB*> and/or <*TB*>

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

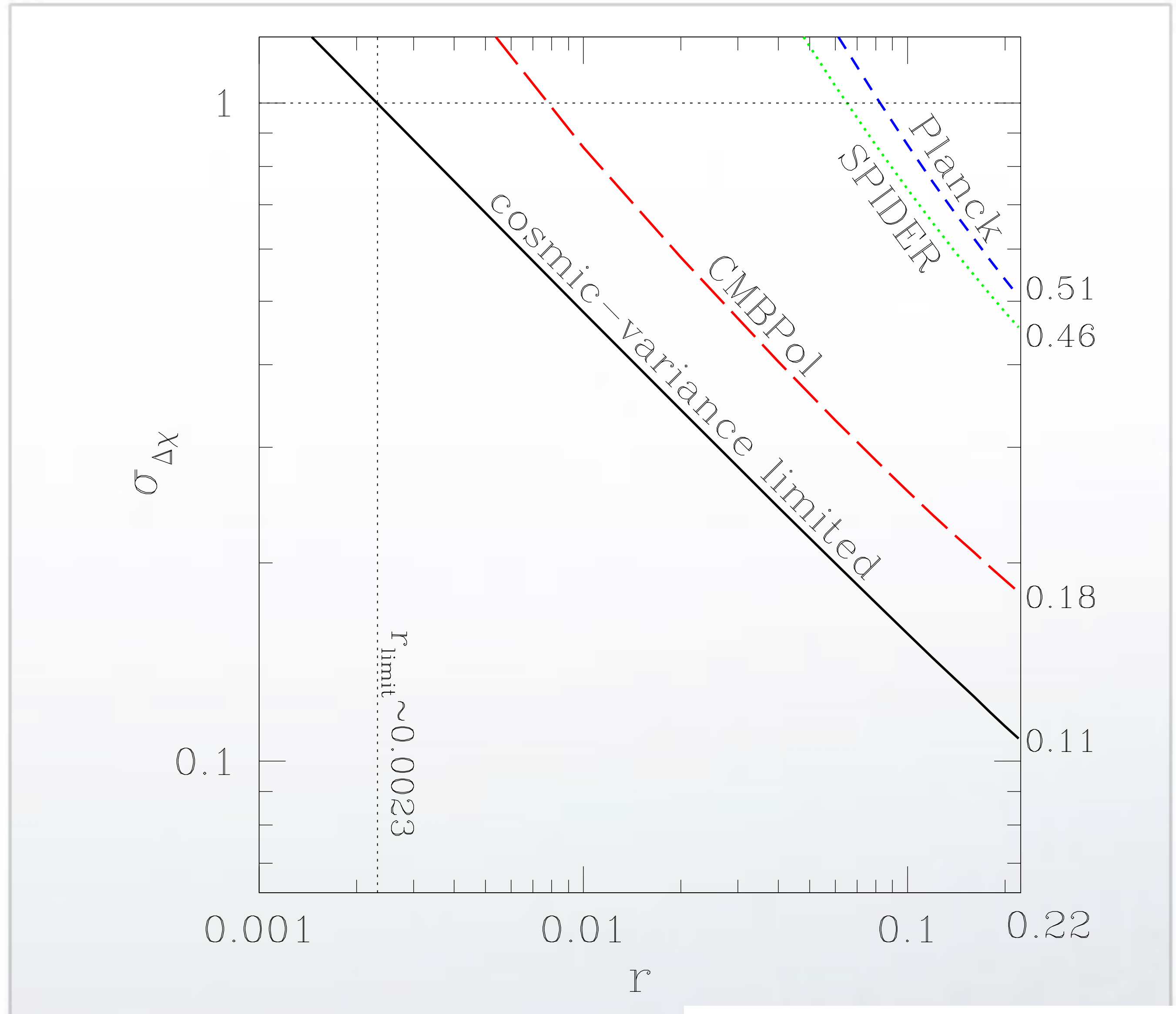
Depend on two parameters

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

tensor-to-scalar ratio

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

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 portion of parameter space. But...

Constraints from nongaussianities

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

Barnaby Peloso 10

NONGAUSSIANITIES

Strong constraint on ξ (<2.6)

Parity violation not detectable in the simplest version of this model without violating constraints from nongaussianities

Back to our question: suppose we see $\langle TB \rangle \neq 0$.
Can we explain this observation in this scenario?

I.e., ways out

i) A CURVATON

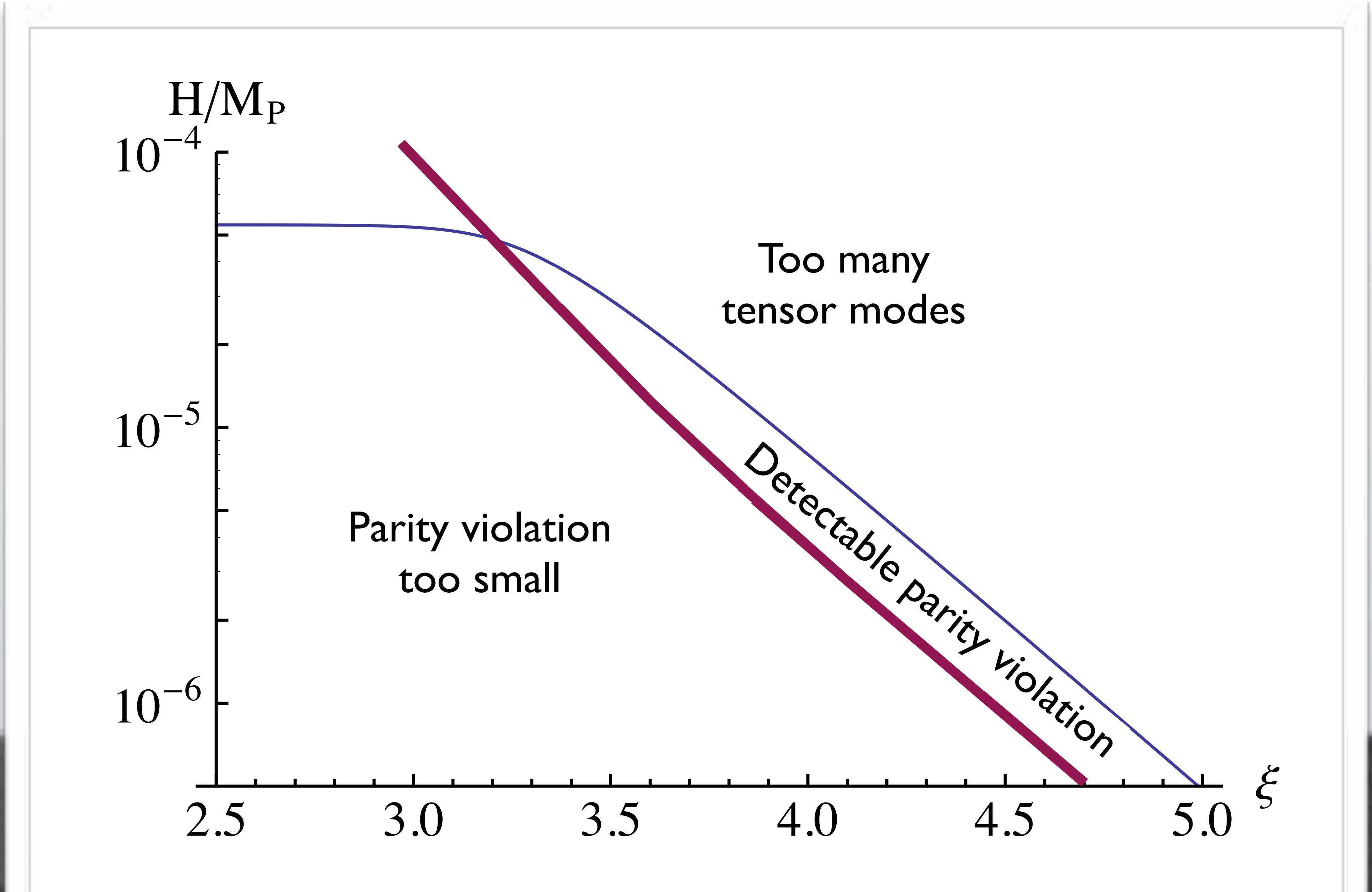
Most of the primordial perturbation is due to a second field with nearly-gaussian perturbations.

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 making 90% of primordial perturbations



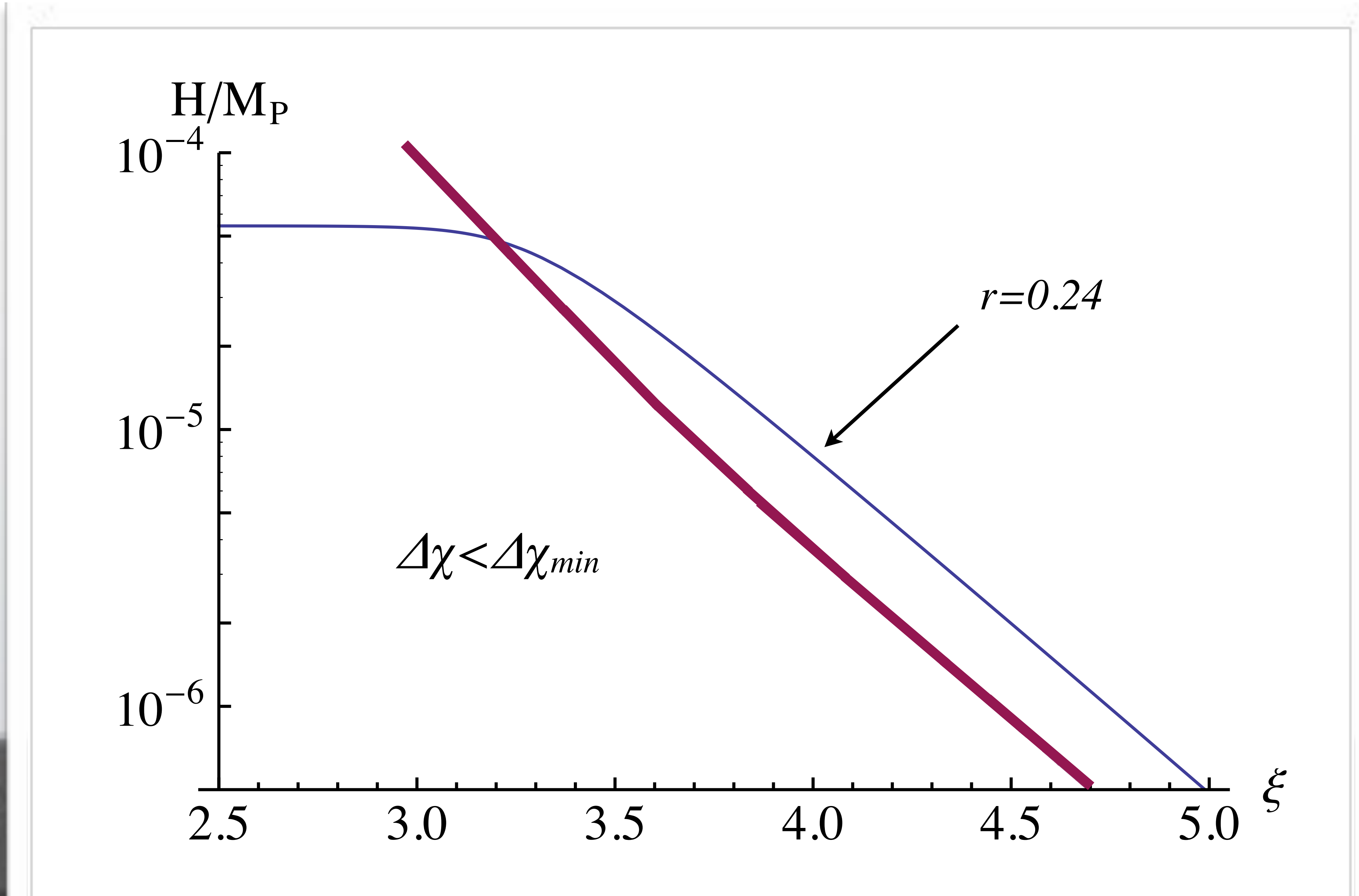
Note

Nonvanishing <EB> and <TB> could also be produced by some late-Universe effect (e.g. pseudoscalar quintessence)

Gluscevic and Kamionkowski 2010 have however shown that it is possible to distinguish a primordial <EB> and <TB> from a late one

...but most importantly

Standard relationship between amplitude of gravitational waves and H does not apply!



...which brings us to the second part of the talk...

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 1109.0022

ξ *increases* during inflation

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

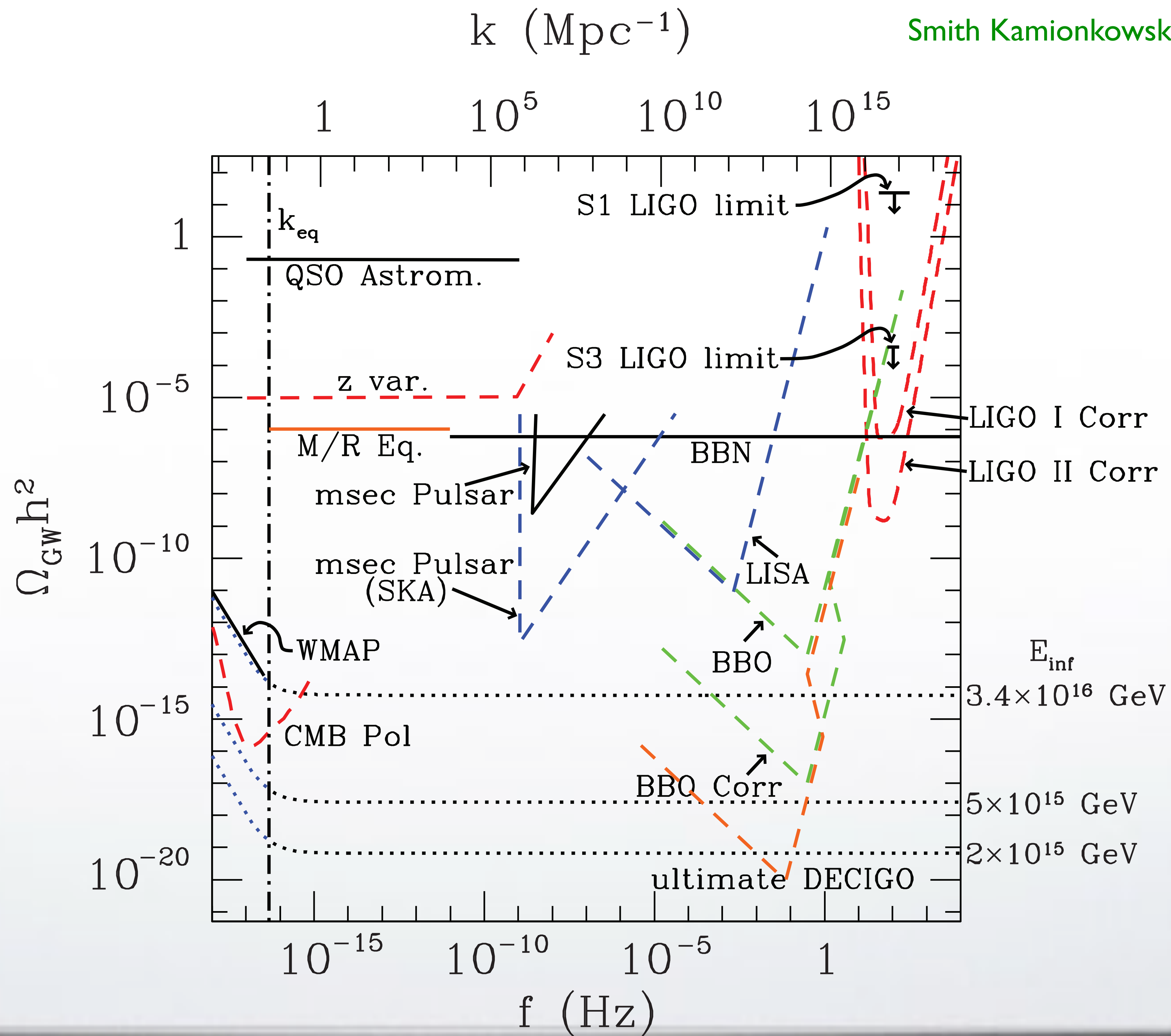
GWs produced towards the end of inflation (i.e. at smaller scales) have larger amplitude

might be detected by advanced LIGO!

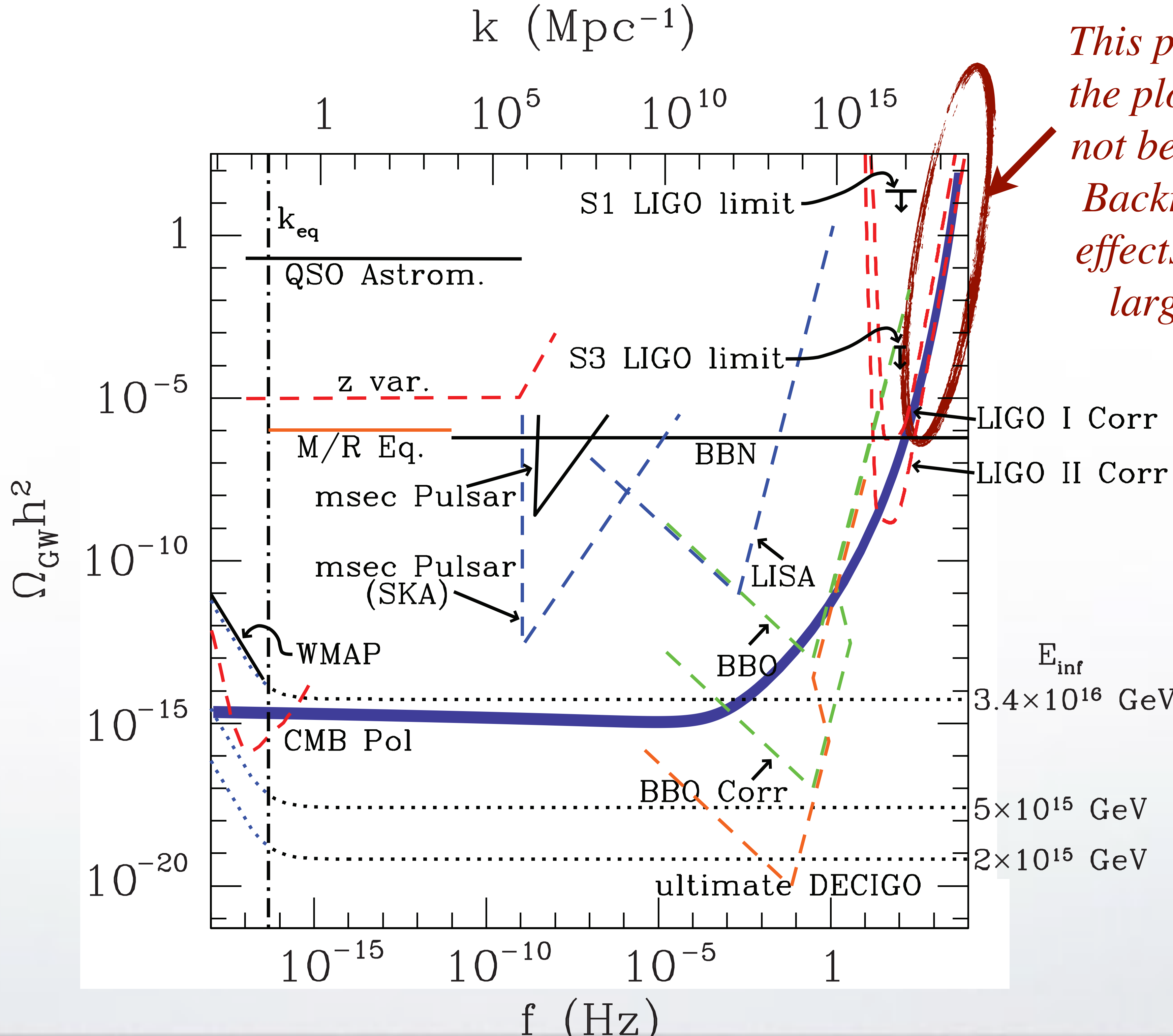
Note: constraints from f_{NL} do not apply at LIGO scales!

Prospects of direct detection of GWs of inflationary origin

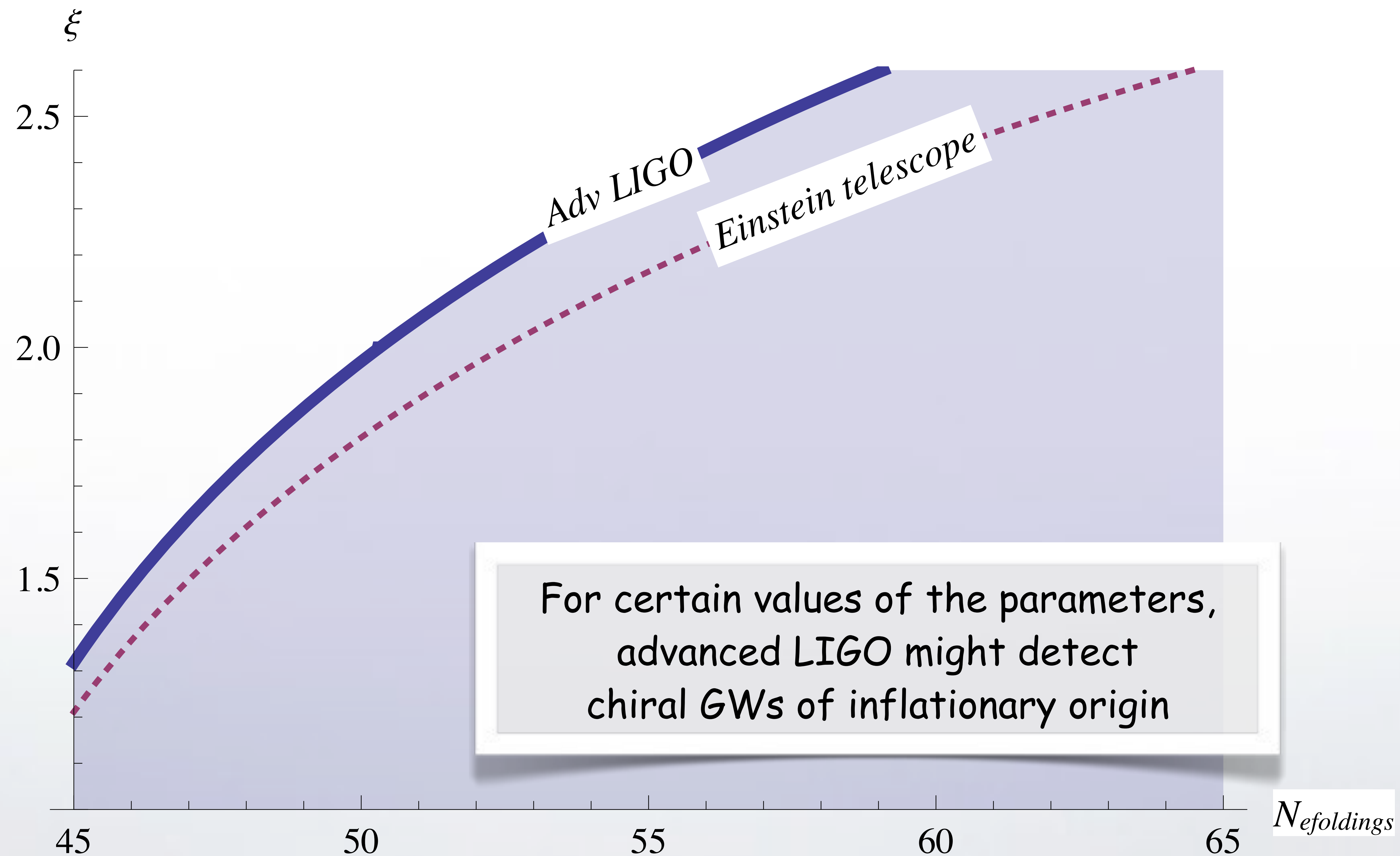
Smith Kamionkowski Cooray 06



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



This portion of the plot should not be trusted! Backreaction effects are too large here



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

A few comments

These tensor modes would be chiral!

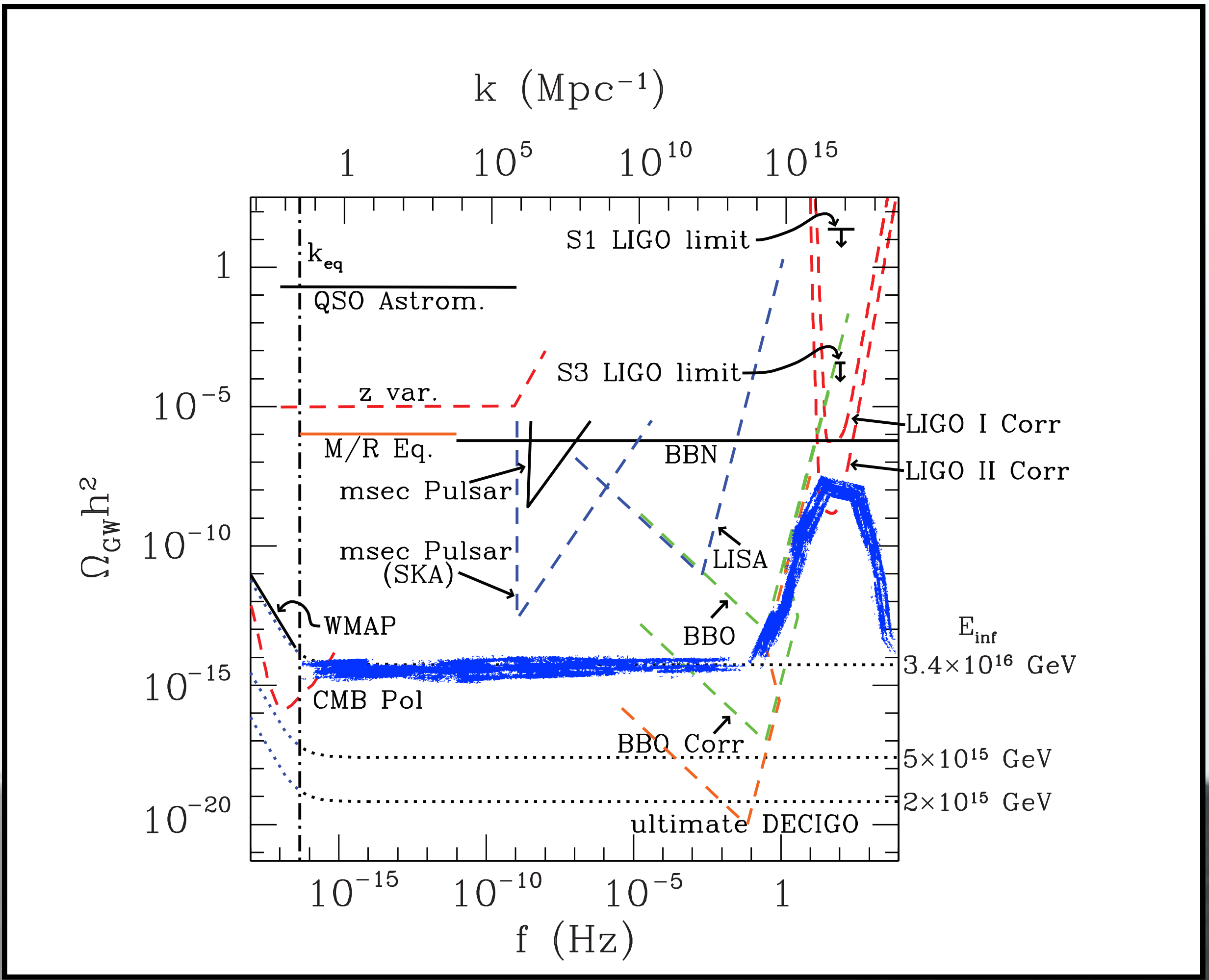
The GWs produced this way should be strongly nongaussian Cook, LS in prep

Signal might correlate with nongaussianities at CMB/LSS scales

Later on, Barnaby, Pajer and Peloso have performed a more accurate analysis. Qualitative behavior is confirmed.

Any other possibility?

Rather than steadily producing matter (such as photons) that in their turn produce GWs, ***matter could be produced explosively,*** leading to a feature in the primordial GW spectrum



Explosive production of matter during inflation

Possible e.g. if the inflaton ϕ interacts with another scalar χ via the coupling

$$\mathcal{L}_{\rm int} = -\frac{g^2}{2}(\phi - \phi_0)^2\chi^2$$

When ϕ crosses ϕ_0, χ becomes temporarily massless and it is "cheaply" produced

➽ about $\left(g\,\dot{\phi}_0\right)^{3/2}$ quanta of χ per unit volume are produced

that can source the tensor modes

Unfortunately...

Cook, LS 1109.0022, PRD

Senatore, Silverstein, Zaldarriaga 1109.0542

The effect is too small:

$$\begin{array}{c}\text{Height of feature}\\ \text{in GW spectrum}\end{array} \sim \begin{array}{c}\text{Height of standard}\\ \text{GW spectrum}\end{array} \times \left\{ 1 + \mathcal{O}\left(10^{-3}\right) \frac{H^2}{M_P^2} \left(\frac{g\,\dot{\phi}}{H^2} \right)^{3/2} \right\}$$

where the enhancement factor

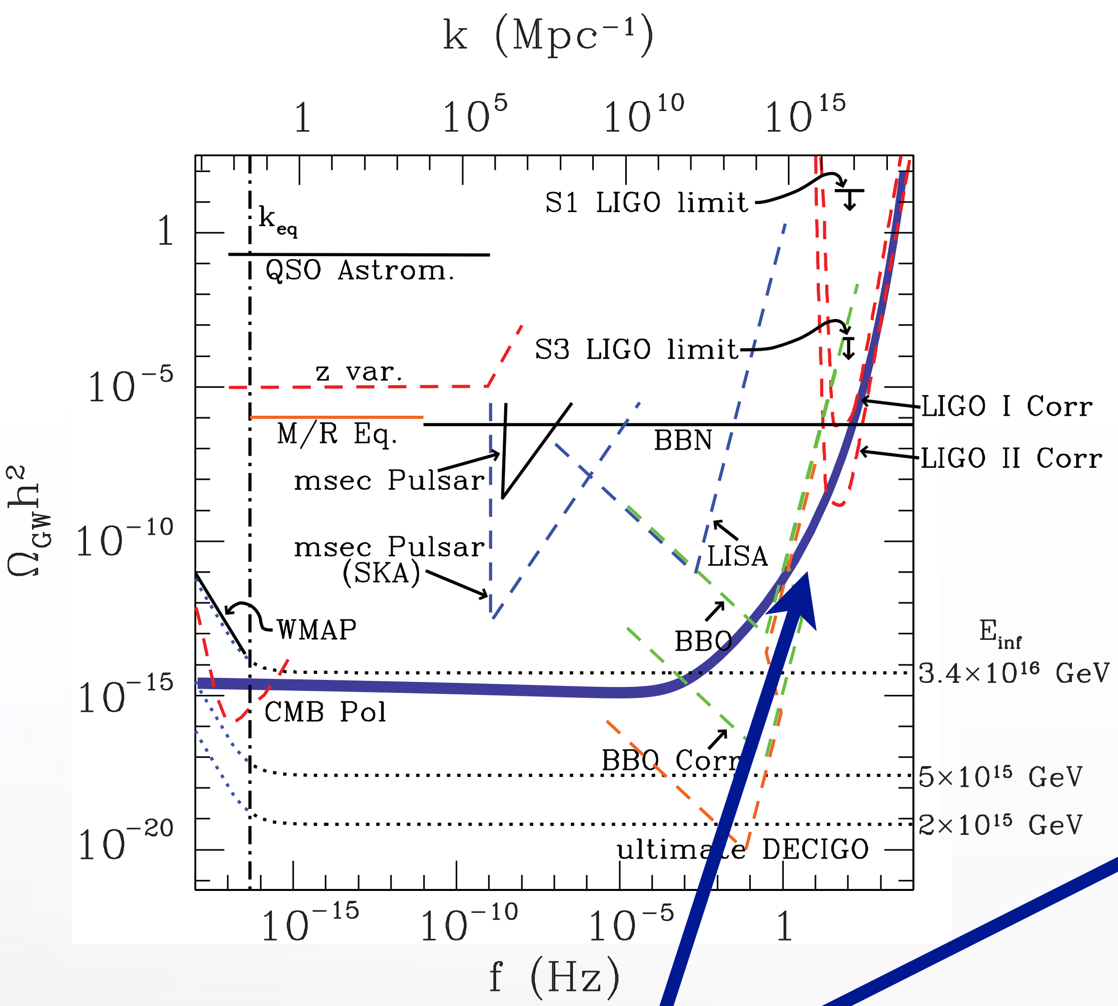
$$\simeq 10^{-3}\, g^{3/2}\, \epsilon^{3/4}\, \left(H/M_P\right)^{1/2} \ll 1$$

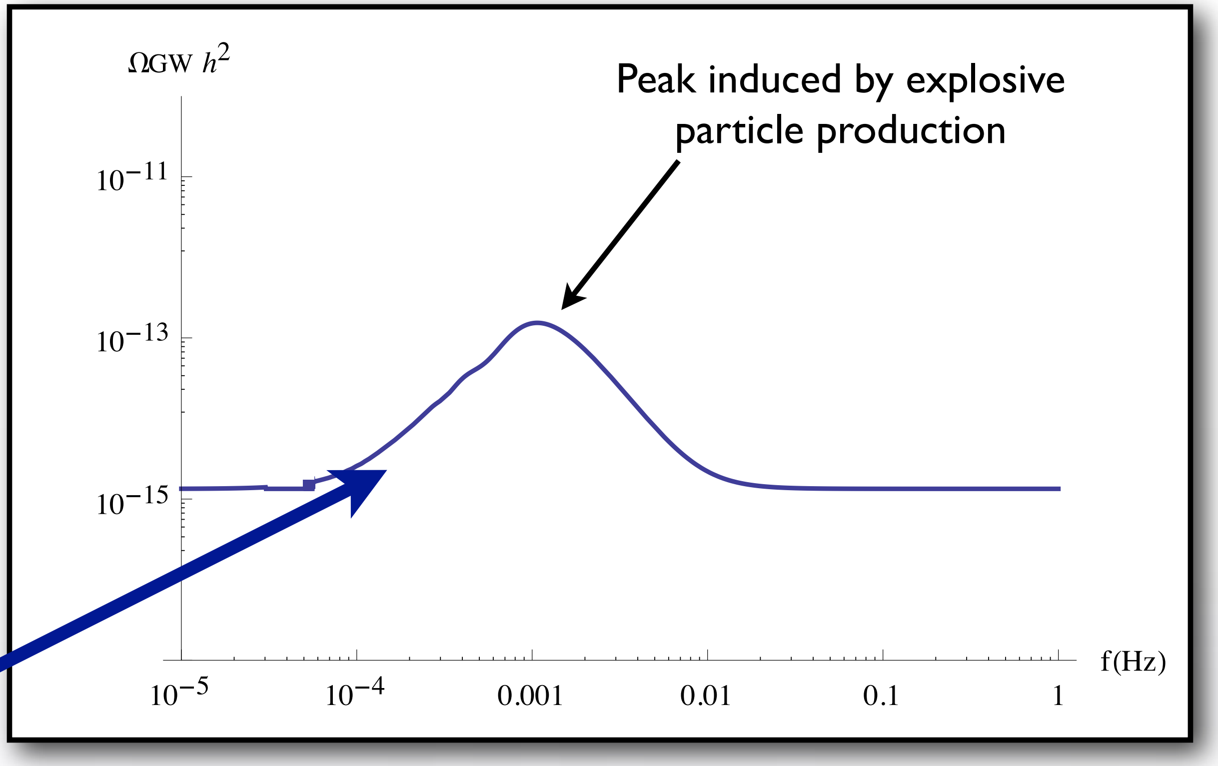
(even if one can devise ways out)

Kofman et al 2007

Nonrelativistic scalars waves in Minkowski space does not generate GWs (no quadrupole)

Before concluding...





In these regions the tensor spectrum is **BLUE!**
Example of (locally) blue tensor spectrum without violation of energy conditions

Conclusions

- Models of pseudoscalar inflation naturally lead to a chiral spectrum of gravitational waves
- In simplest model, strong constraints from nongaussianities
- However, "not too contrived" candidate explanation if nonvanishing $<EB>$ and $<TB>$ will be observed
- Same mechanism might lead to a stochastic background of gravitational waves detectable by advanced LIGO
- Production of tensor modes through explosive production of scalars (and vectors) typically inefficient