Odd Tensor Modes from Inflation

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CMB Polarization, Minneapolis, 01/14/2015

Scalar perturbations during inflation ☛ rich phenomenology:

- Features
- Isocurvature
- Non vacuum states
- Nongaussianities
- Oscillations
- ...

Tensors typically assumed to be boring....

$$\mathcal{P}_t \propto \frac{H^2}{M_P^2}$$

H ↘ during inflation ☛ slightly red spectrum

This talk:

$\boxed{\text{Non-boring tensors}}$

The system

During inflation, a rolling pseudoscalar ϕ interacting with a *U(1)* gauge field via

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

(*f*=constant with dimensions of a mass)

The helicity-λ mode functions $A_\lambda(k,\tau)$ are sourced by 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!

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

Generation of parity violating, large amplitude gravitational waves

The energy of the electromagnetic field sources gravitational waves of helicity-λ h_λ:

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

Projector on helicity-λ components

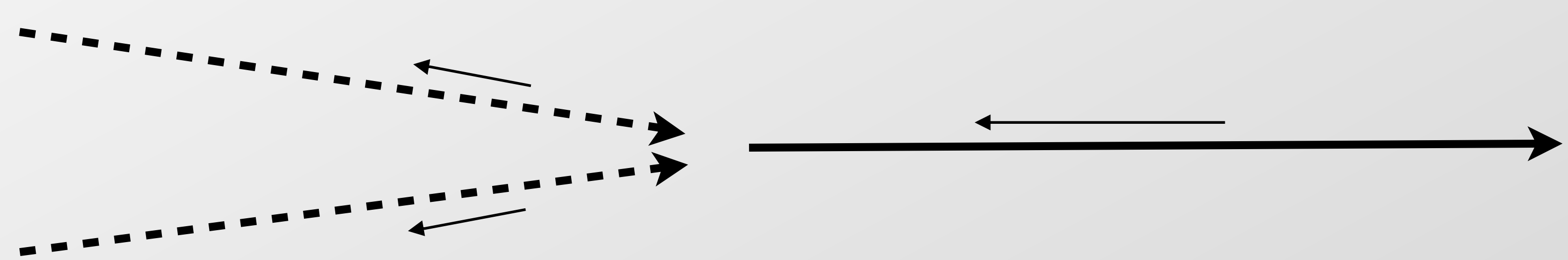
Spatial components of gauge field stress-energy tensor

Parity violating gravitational waves

A_L and A_R have different amplitudes

$$\langle h_L h_L \rangle \neq \langle h_R h_R \rangle$$

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



The parity-violating power spectrum

LS 2010

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

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

"standard"
parity-invariant part

parity-violation

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

How do we see the effect of parity violating GWs?

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

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

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

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

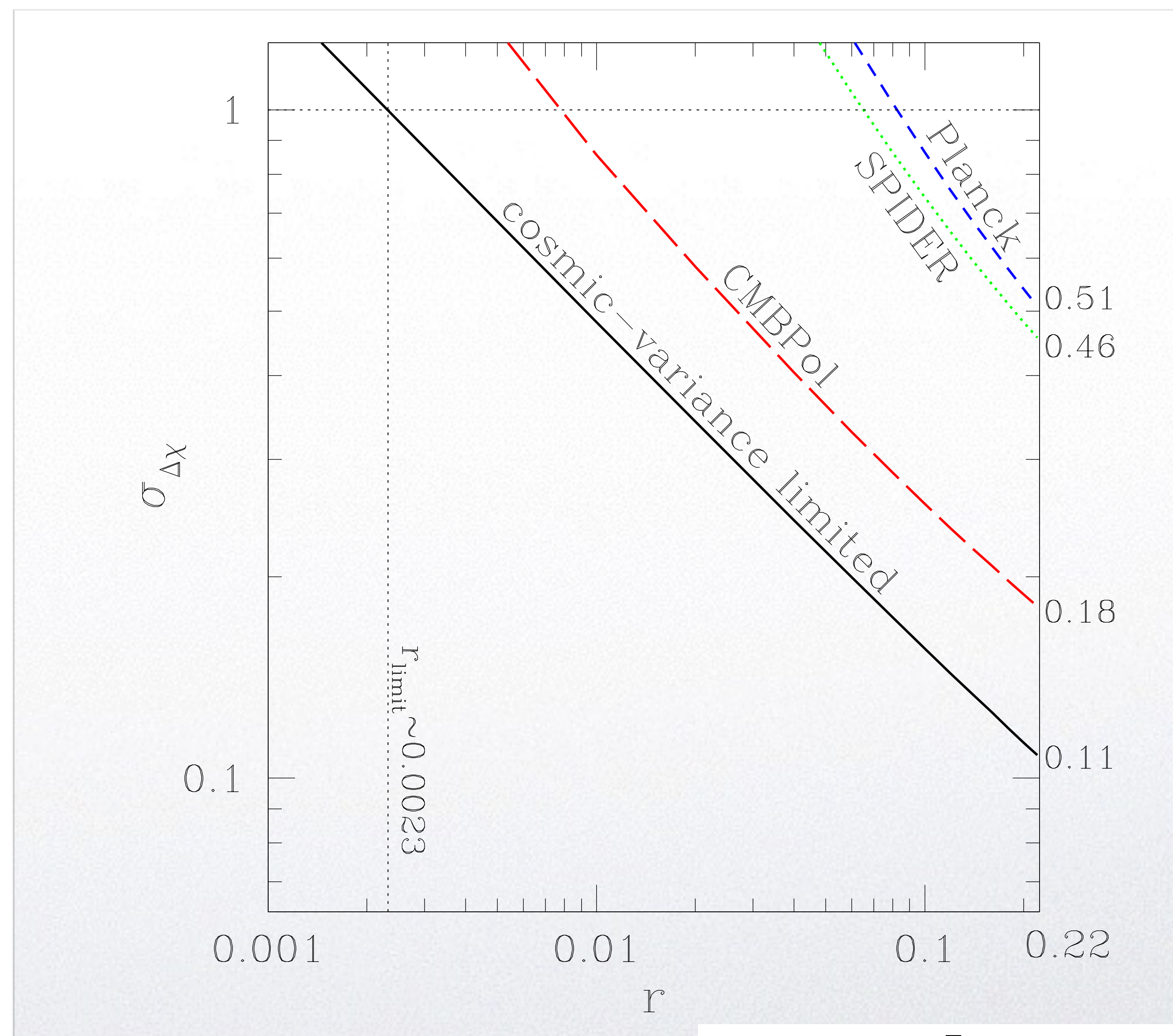
Depend on two parameters

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

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

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

(more recent analysis)

Ferte and Grain 14

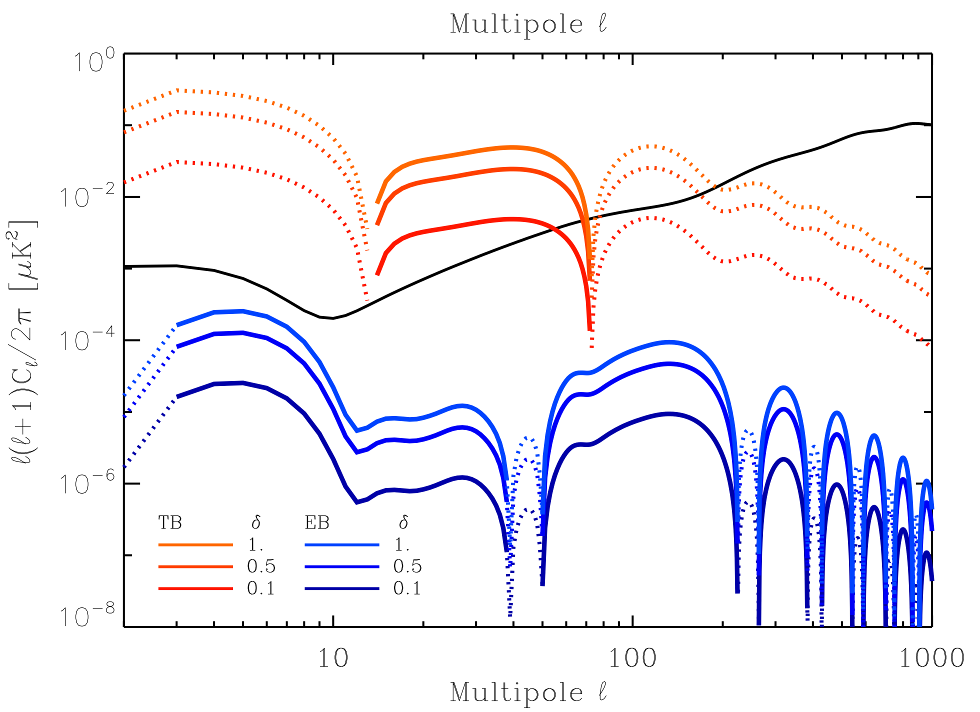


FIG. 1: *Upper panel:* Angular power spectra for *primary* CMB anisotropies for BB (black curve), TB (red curves) and EB (blue curves) correlations. The parameters $r_{(+)}$ is set equal to 0.05 and δ varies from 0.1 (meaning 10% of parity violation) to 1 (100% of parity violation). Solid lines correspond to positive values of the angular power spectra and dashed lines correspond to negative values. Changing from (δ) to $(-\delta)$ with $r_{(+)}$ unchanged changes the sign of C_ℓ^{TB} and C_ℓ^{EB} and leaves C_ℓ^{BB} unaffected. We note that smaller $|\delta|$ translates into smaller $|r_{(-)}|$. *Lower panel:* Same as upper panel but taking into account the impact of gravitational lensing.

Satellite mission:

	$\delta = 1$	$\delta = 0.5$
$r_{(+)} = 0.2$	5.46	2.5
$r_{(+)} = 0.1$	3.67	1.51
$r_{(+)} = 0.05$	2.35	1.11

TABLE II: Signal-to-noise ratio on $r_{(-)}$, $(\mathrm{S/N})_{r_{(-)}}$, as derived from a pure pseudospectrum reconstruction of the angular power spectra. We remind that for a given value of $r_{(+)}$ and δ, the value of $r_{(-)}$ is $r_{(-)} = \delta \times r_{(+)}$.

Balloon/Ground

$r_{(-)}$ \ $r_{(+)}$	0.2	0.1	0.07	0.05	0.03	0.007
0.2	1.22					
0.1	0.43	0.64				
0.07	0.29	0.4	0.487			
0.05	0.2	0.28	0.326	0.38		
0.03	0.12	0.16	0.188	0.216	0.27	
0.007	0.03	0.037	0.043	0.049	0.06	0.1

TABLE III: Signal-to-noise on $r_{(-)}$ for different values of $r_{(+)}$ in the case of small-scale (ballon-borne or ground-based) experiments, and using a mode-counting expression for the error bars on the angular power spectra reconstruction.

For our system

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

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

Exponential dependence on the coupling *1/f*

In principle sizable parity violation in large portion of parameter space.
Anything more?

Photons source metric perturbations
in a 2→1 process

(equilateral)

nongaussianities

Photons source metric perturbations in a 2→1 process:

$$\langle \hat{h}_-(\mathbf{k}_1)\, \hat{h}_-(\mathbf{k}_2)\, \hat{h}_-(\mathbf{k}_3)\, \rangle_{\rm equil} = 6.1 \times 10^{-10}\, \frac{\delta(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3)}{k^6}\, \frac{H^6}{M_P^6}\, \frac{e^{6\pi\xi}}{\xi^9}$$

Large nongaussianities in tensors:

$$\boldsymbol{\langle hhh \rangle \sim \langle hh \rangle^{3/2}}$$

Constraints from the scalar sector?

Barnaby Peloso 10

If ϕ is the inflaton, then gauge modes backreact on it, contributing to its three-point function

NONGAUSSIANITIES

Planck constraints on $f_{NL}{}^{equil}$

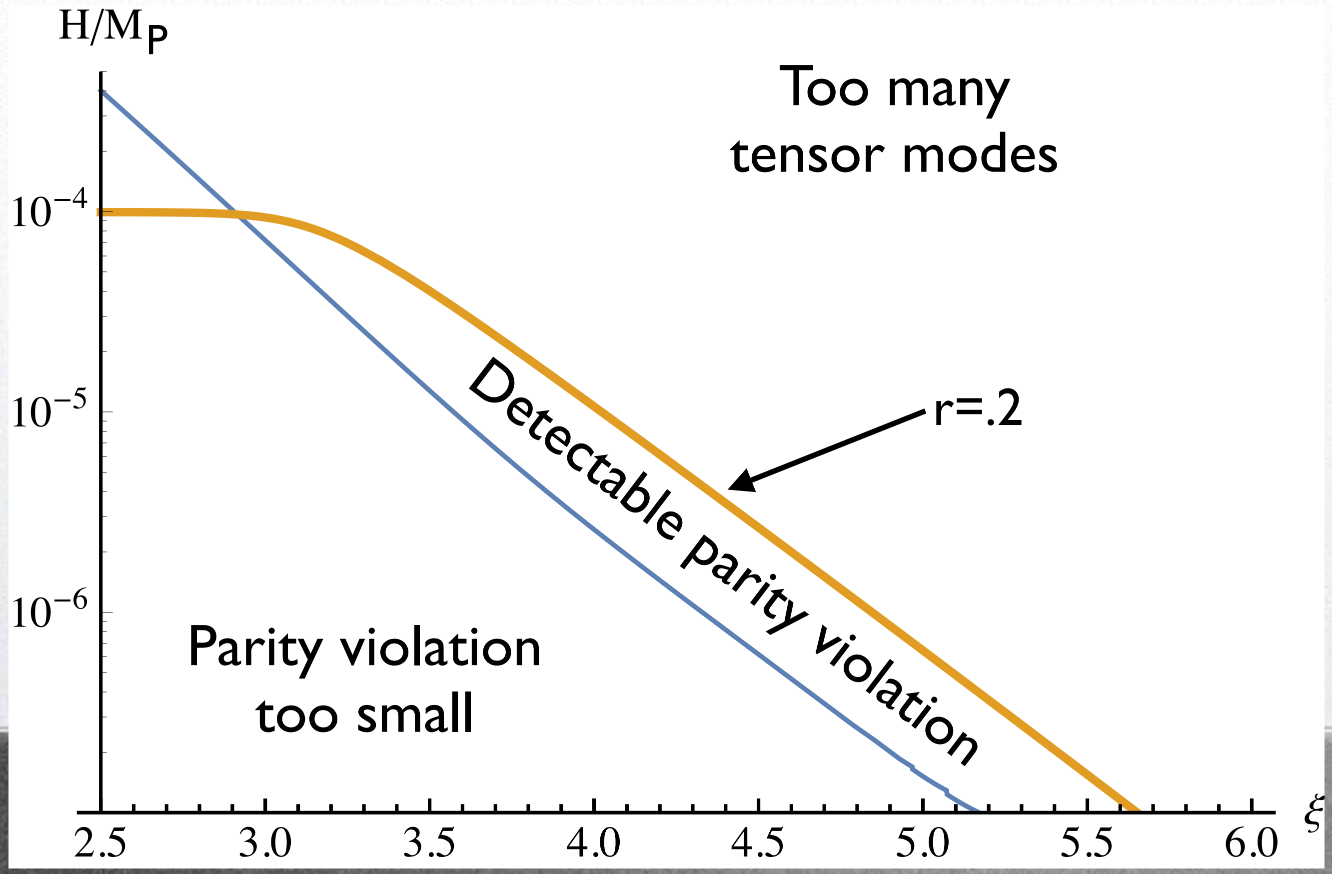
$\Delta\chi << 1$

Parity violation not detectable in this simplest model

One possible (and inelegant) way out:

MANY, MANY GAUGE FIELDS

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



Note however:

$r \cong 7\ \varepsilon^2$

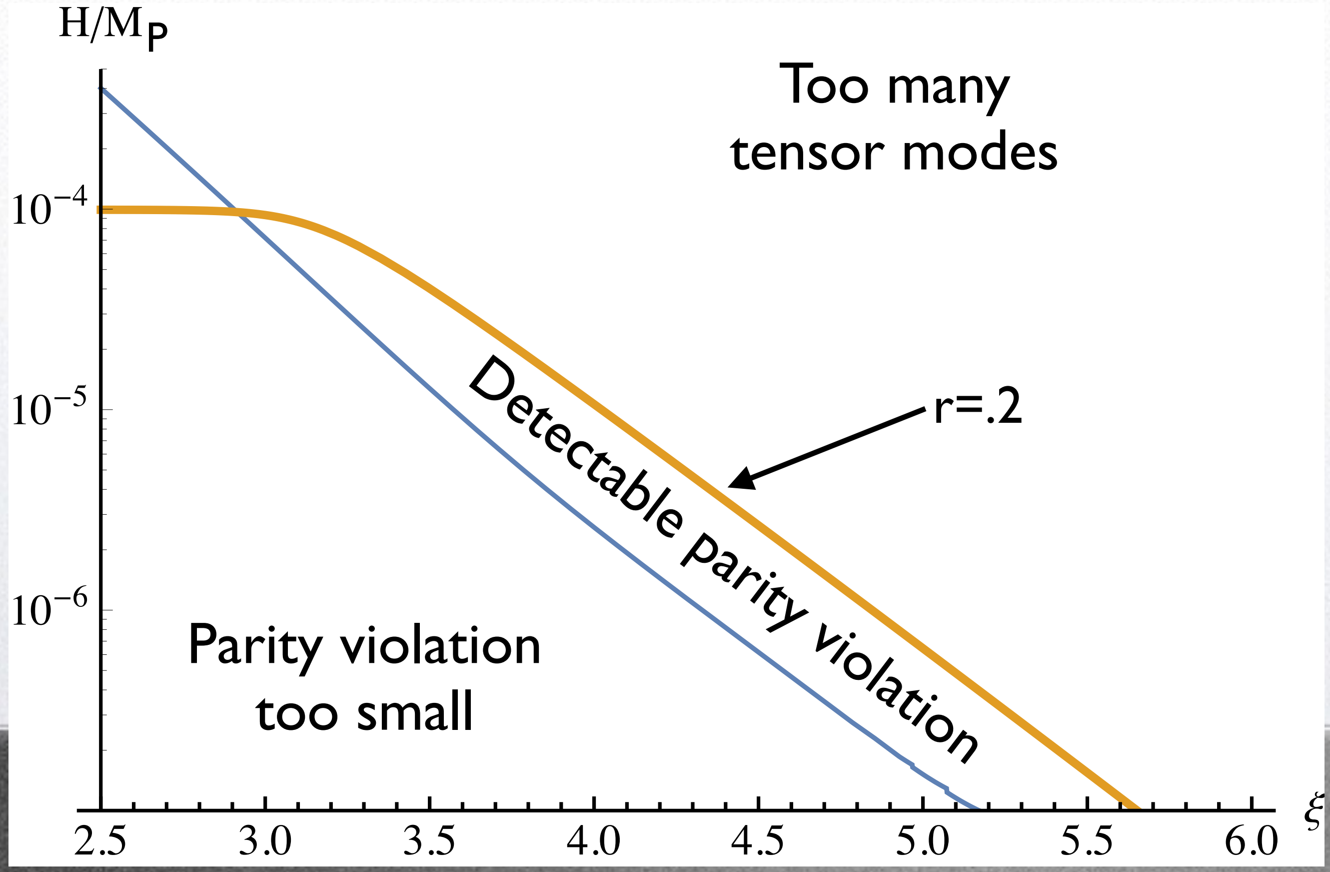
(need $\varepsilon \sim 1/10$ at $\ell \lessapprox 100$)

(see also Mirbabayi et al 14)

Incidentally:

IN THIS SCENARIO RELATION BETWEEN r AND H^2/M_P^2 DOES NOT HOLD!

Senatore Silverstein
Zaldarriaga11



also note

Tensor 3-pt function suppressed as scalar 3-pt function

⬇

Parity-violating spectra, but gaussian tensors

One more possible way out:

ϕ IS NOT THE INFLATON

Barnaby et al 12

(let us call it σ here)

however…

Ferreira and Sloth 14

during *super-horizon* evolution isocurvature σ modes mix with curvature perturbation:

$$\delta\phi/\delta\sigma = \int \frac{d^3\mathbf{k}}{(2\pi)^{3/2}}\, e^{i\mathbf{kx}}\, \frac{Q_{\phi/\sigma}}{a(\tau)}$$

$$\boxed{\begin{aligned} Q_\phi'' + \left(k^2 - \frac{1}{\tau^2}\, M_{\phi\phi}\right) Q_\phi - \frac{1}{\tau^2}\, M_{\phi\sigma}\, Q_\sigma &= 0 \\ Q_\sigma'' + \left(k^2 - \frac{1}{\tau^2}\, M_{\sigma\sigma}\right) Q_\sigma - \frac{1}{\tau^2}\, M_{\phi\sigma}\, Q_\phi &= \frac{a^3}{f}\, (\mathbf{E}\cdot\mathbf{B})\,(\mathbf{k}) \end{aligned}}$$

$$M_{ij} = \begin{pmatrix} 2 + 9\,\epsilon_\phi - 3\,\eta_\phi & 6\,\Theta\,\epsilon_\phi \\ 6\,\Theta\,\epsilon_\phi & 2 + 3\,\epsilon_\phi\,\left(1 + 2\,\Theta^2\right) - 3\,\eta_\sigma \end{pmatrix}, \qquad \Theta \equiv \frac{\dot\sigma}{\dot\phi}$$

One more possible way out:

ϕ IS NOT THE INFLATON

(let us call it σ here)

Even if $\sigma \neq \phi$, contribution to ζ
same as in case where ϕ is the inflaton,
times ε times ΔN

# of efoldings
of rolling of σ

One more possible way out:

ϕ IS NOT THE INFLATON

(let us call it σ here)

Even if $\sigma \neq \phi$, contribution to ζ
same as in case where ϕ is the inflaton,
times ε times ΔN

can have $\Delta N << 60$:

assuming induced scalar perturbations < standard ones,

$r \lesssim O(\text{few})/\Delta N^2$

Note: constraints from f_{NL} weaker as nongaussian contribution is strongly scale-dependent !

Conclusion

(partial)

Existence proof of

Parity violation

+

Large tensor nongaussianities

=

Interesting phenomenology in the CMB.

(some work with model building needed, though)

Intermezzo

A "natural" coupling that might lead to nonvanishing $<EB>$ and $<TB>$ is

$$\delta\mathcal{L} = \frac{\phi}{f'}\epsilon_{\alpha\beta\gamma\delta}\, R^{\alpha\beta}{}_{\mu\nu}\, R_{\gamma\delta}{}^{\mu\nu}$$

however...

Lyth Quinbay Rondriguez 05
Satoh 10

Action for tensor modes in theory with $\phi\, R\, \tilde{R}$

$$\mathcal{S} = \sum \frac{1}{2} \int d\tau \, \frac{d^3 k}{(2\,\pi)^3} A_\lambda \left(|h'_\lambda|^2 - k^2 \, |h_\lambda|^2 \right)$$

$$A_\lambda = 1 - \lambda \frac{k}{a} \, \frac{\dot{\phi}}{2\, f' \, M_P^2}$$

for k too large one of the modes is strongly coupled and/or a ghost

if we choose parameters so to stay away from strongly coupled regime, then effect on tensor modes is too weak

More fun with GWs...

…back to the case where the inflaton is directly coupled to the gauge field...

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 11

ξ *increases* during inflation

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

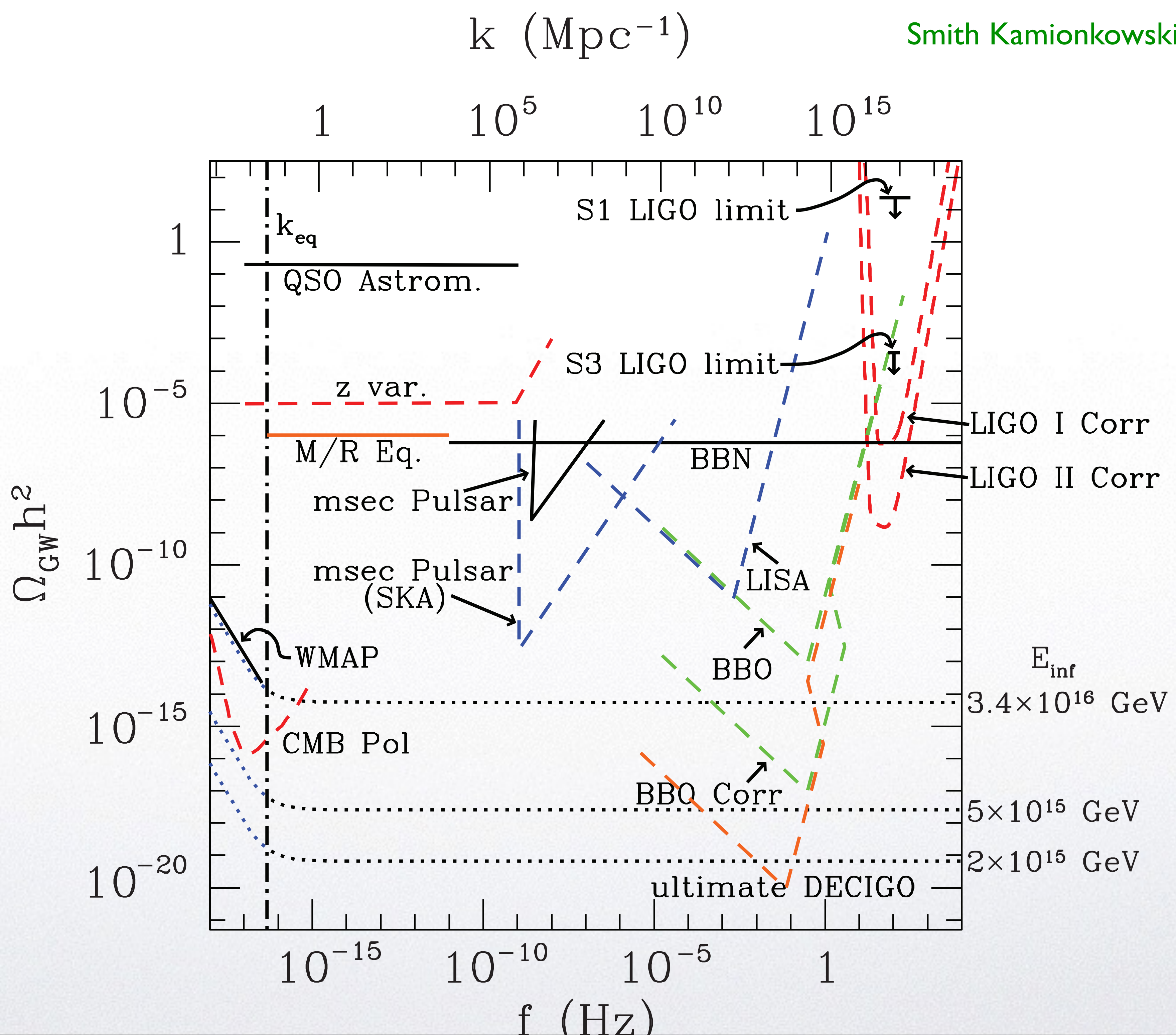
GWs produced towards the end of inflation (i.e. at smaller scales) have larger amplitude

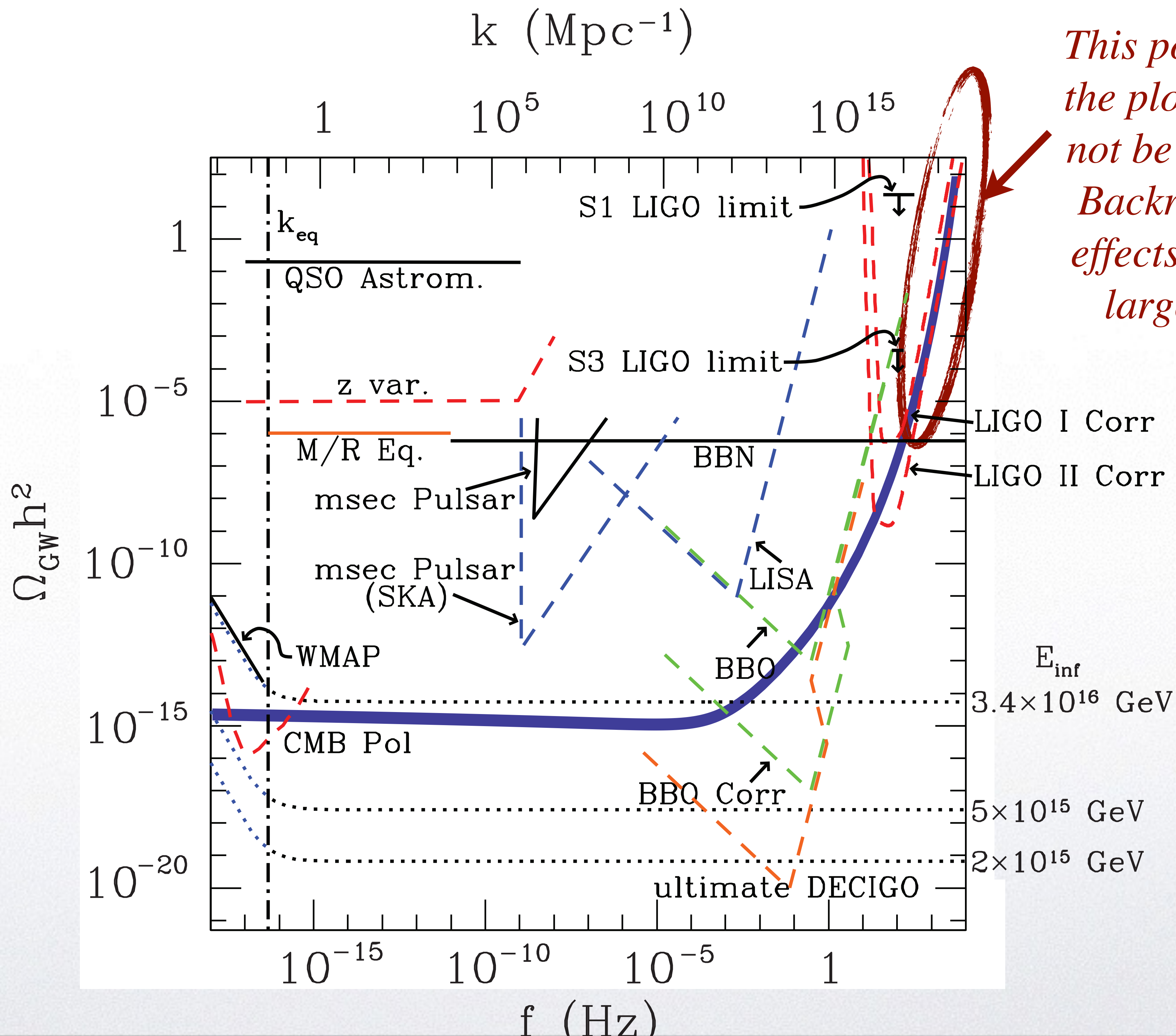
might be detected by advanced LIGO!

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

Prospects of direct detection of GWs of inflationary origin

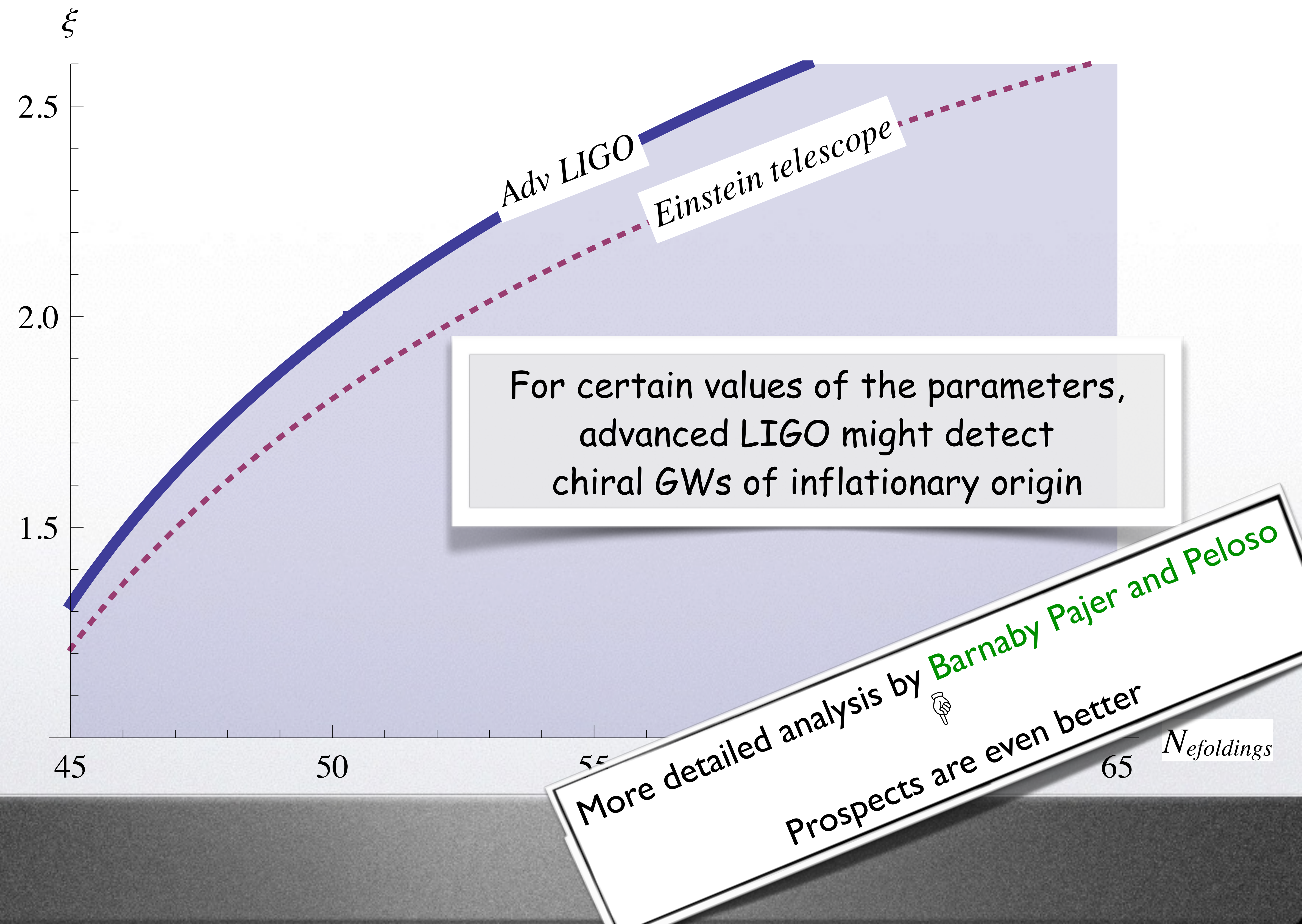
Smith Kamionkowski Cooray 06





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

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


ξ
2.5
2.0
1.5
45
50
55
65
$N_{efoldings}$
Adv LIGO
Einstein telescope
For certain values of the parameters,
advanced LIGO might detect
chiral GWs of inflationary origin
More detailed analysis by Barnaby Pajer and Peloso
Prospects are even better

A few comments

These tensor modes would be chiral! Crowder et al 12

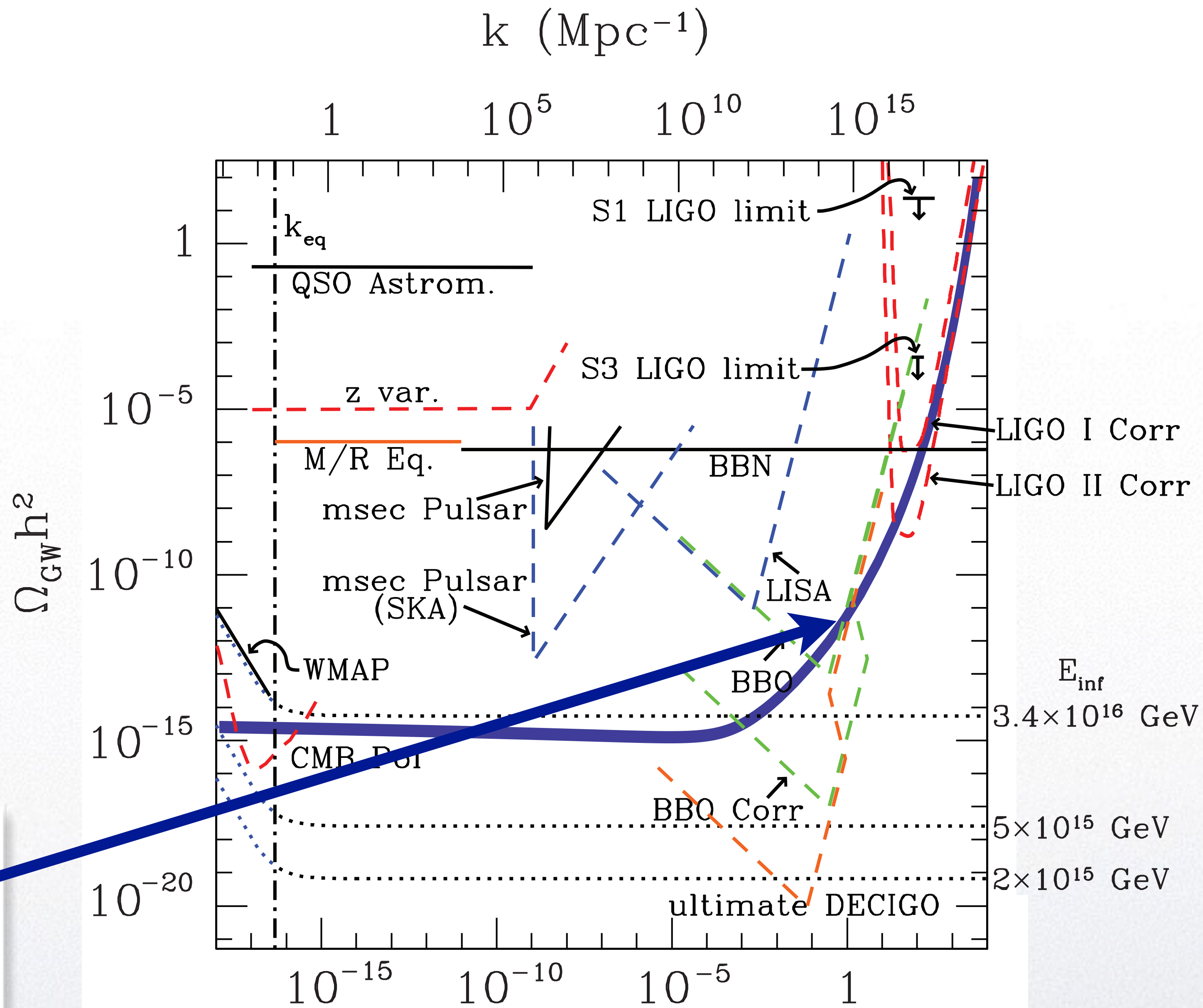
The GWs produced this way should be strongly nongaussian Thrane 12

Signal might correlate with nongaussianities at CMB/LSS scales

Large and nongaussian fluctuations at the end of inflation might generate primordial BHs

Linde and Pajer 13

And by the way....



Example of **BLUE** tensor spectrum without violation of energy conditions

Mukohyama et al 14: can use this mechanism to design features in tensor spectrum

Conclusion

Tensors can have a very rich phenomenology