Nonstandard tensor modes from inflaton

Lorenzo Sorbo

UMass Amherst

Nordita, July 18th 2017

Motivation

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

& important experimental programs on GWs, both at CMB and at smaller scaler

How to get less boring tensors?

excited modes of other fields during inflation

(induced by the time dependent inflating background)

additional source of GWs

(*GWs inherit properties of excited degrees of freedom*)

Prototypical example

Inflaton ϕ interacts with another scalar χ via

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

When ϕ crosses ϕ_0, χ becomes temporarily massless and is cheap to produce

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

that can source the tensor modes

Unfortunately...

Cook, LS 11,
Senatore, Silverstein,
Zaldarriaga 11

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

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

Nonrelativistic modes do not generate GWs

(more on this later)

Let us try something different… LS 2011

If inflaton is a pseudoscalar with (broken) shift symmetry

(well motivated by naturalness),

it interacts with *(abelian)* gauge field 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 helicity-λ mode functions A_λ are coupled to $\phi(t)$:

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

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

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

parity violating system,
parity violating gauge modes

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

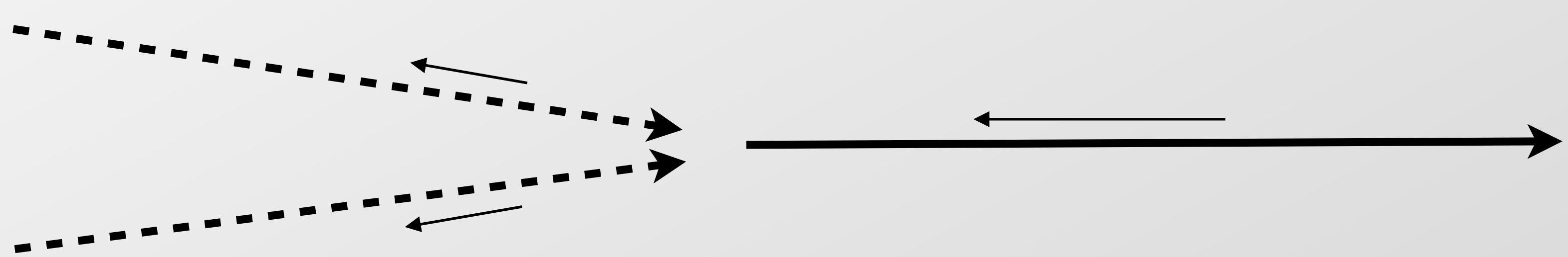
…and the energy of the electromagnetic field sources gravitational waves….

Projector on helicity-λ components

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



Parity violating gravitational waves

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

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

“standard”
parity-invariant part

parity-violation!

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

Photons source metric perturbations
in a 2→1 process

(equilateral)

nongaussianities

Photons source metric perturbations in a 2→1 process:

Cook, LS 13

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

Large nongaussianities in tensors!

<hhh>~<hh>$^{3/2}$

But also…

Barnaby Peloso 10
Ferreira Sloth 14

NONGAUSSIANITIES in scalar modes

↓

Strong constraint on the model $\xi\ (<2.6)$

↓

Effects above not detectable in the simplest version of this model without violating constraints from f_{NL}

Way out

Namba Peloso
Shiraishi LS Unal 15

Way out: field coupled to vectors is not the inflaton, and rolls only for a few efoldings (see Peloso talk)

Non-boring phenomenology! (and under perturbative control!)
Peloso LS Unal 16

$<EB>, <TB> \neq 0$

$<BBB>, <TBB>, etc \neq 0$

Bumps in B spectrum

Possible blue B spectra…

…which brings us to…

Inflationary GWs for interferometers

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

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

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 interferometers

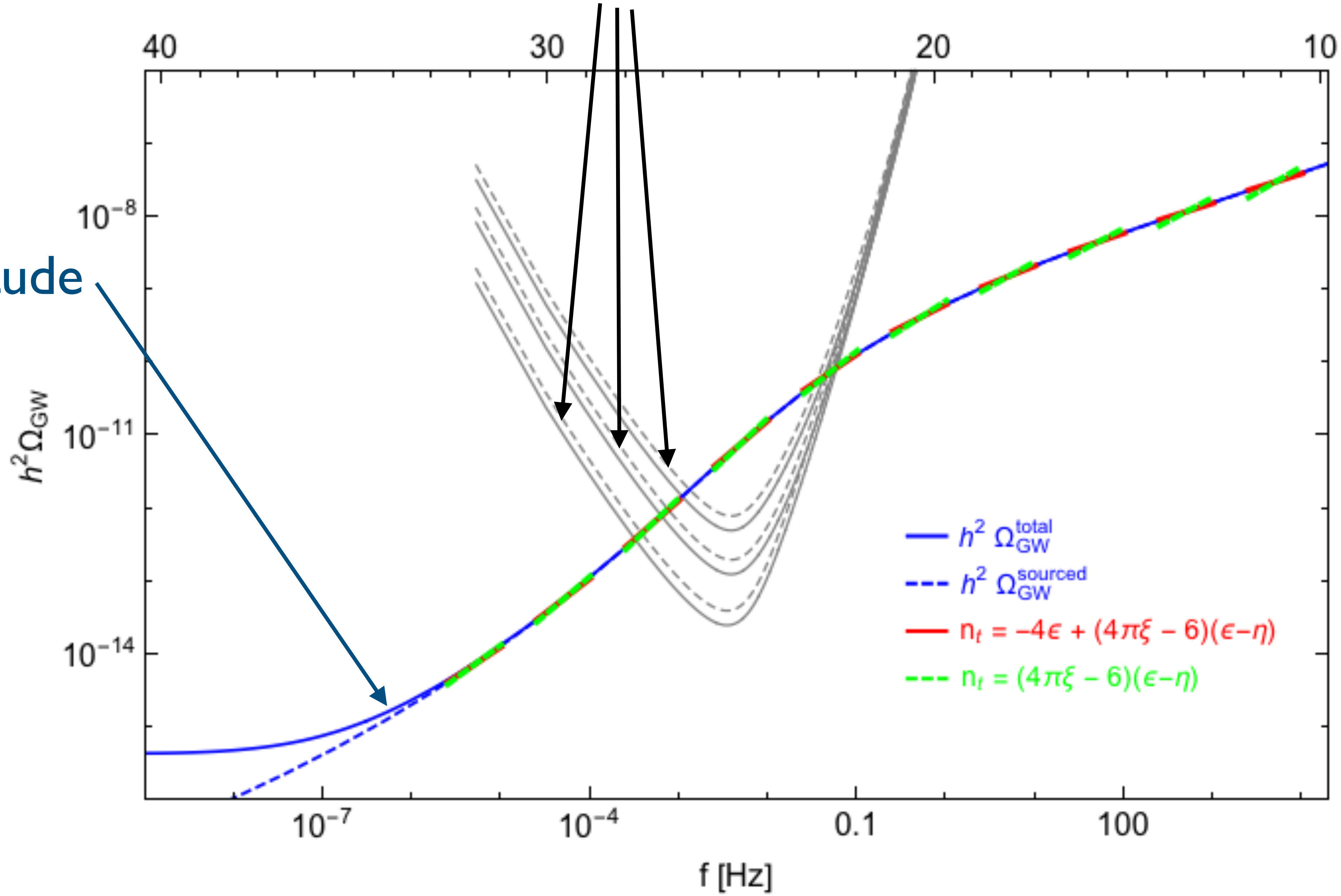
Note: constraints from f_{NL} do not apply at interferometer scales!

Example: chaotic inflation, f=M$_P$/35

Bartolo and many others 2016

LISA, various designs

GW amplitude



Back to explosive production of scalars

Prototypical example

Inflaton ϕ interacts with another scalar χ via

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

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...

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

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

$$\left(\frac{r_{\text{sourced}}}{r_{\text{vacuum}}} \lesssim 5 \times 10^{-7} \left(\frac{r_{\text{vacuum}}}{.07} \right) \right)$$

Nonrelativistic modes do not generate GWs

Idea: symmetry restoration → produce massless scalars

Goolsby-Cole, LS 17

$$\mathcal{L}_{\varphi\sigma} = -\frac{1}{2}\,\partial_\mu\varphi\partial^\mu\varphi - \frac{1}{2}\,\partial_\mu\sigma\partial^\mu\sigma - \frac{\mu}{2}\varphi\,\sigma^2 - \frac{\lambda}{4}\,\sigma^4 - V(\varphi)\,,$$

inflaton $\varphi<0 \Rightarrow \langle\sigma\rangle\neq 0$

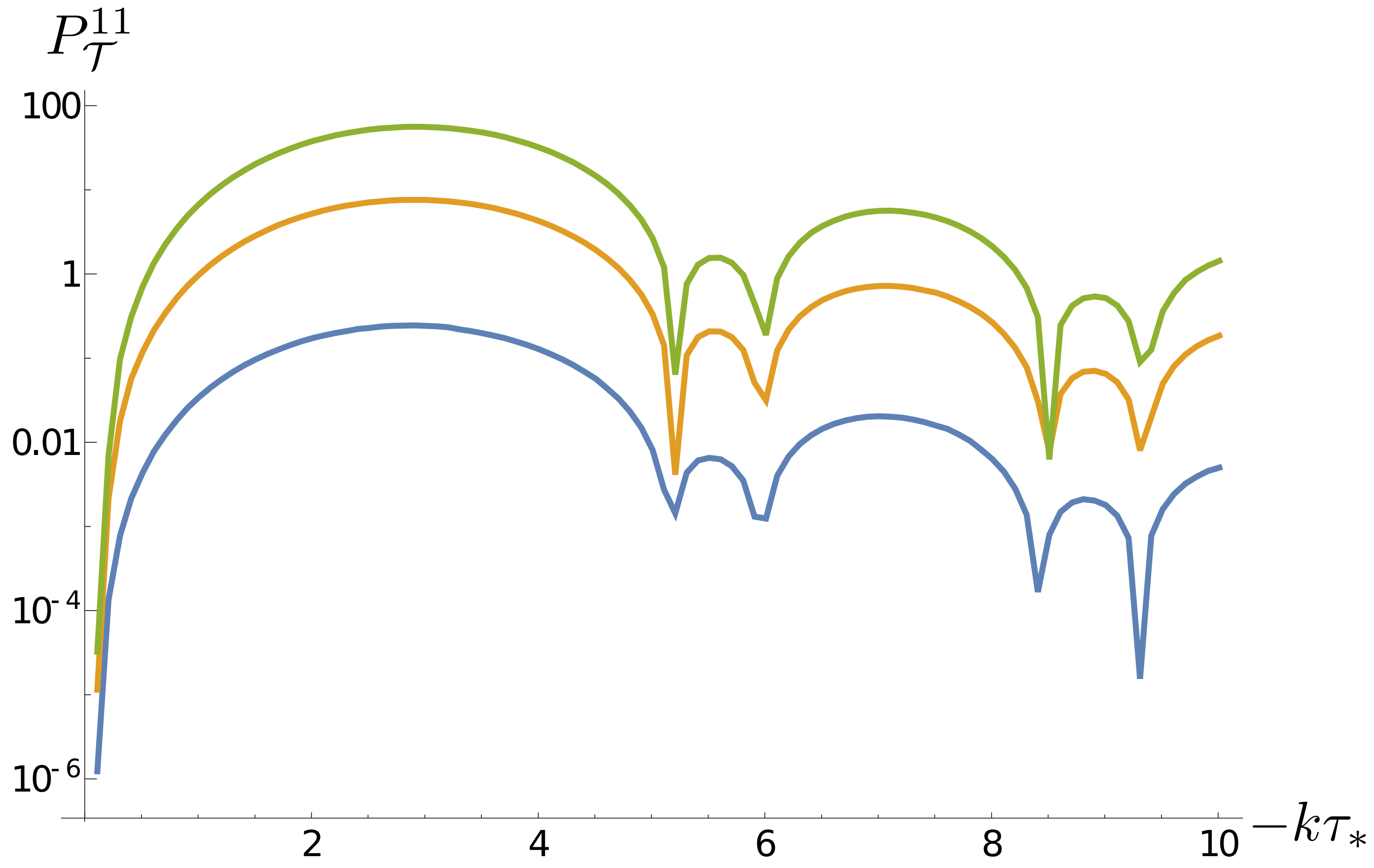
inflaton $\varphi>0 \Rightarrow \langle\sigma\rangle = 0$

…and the field σ determines mass of auxiliary field χ…

$$\mathcal{L}_\chi = -\frac{1}{2}\partial_\mu\chi\partial^\mu\chi - \frac{h^2}{2}\sigma^2\chi^2,$$

…that sources GWs…

Induced tensor spectrum (arbitrary units)



Amplitude at peak

$$P_h(k) = 2.5 \times 10^{-6}\,\frac{H^4}{M_P^4}\,\frac{\Lambda_\chi^5}{H^5}\,.$$

$$\Lambda_\chi^3 \equiv \frac{h^2\,\mu}{\lambda}\,\dot{\varphi}_*$$

After imposing many constraints on the model…

$$\frac{r_{\rm sourced}}{r_{\rm vacuum}} \simeq \left(\frac{r_{\rm vacuum}}{0.07}\right) \left(\frac{\Lambda_\chi}{620\,H}\right)^5 \ll 5 \times 10^{-4} \left(\frac{r_{\rm vacuum}}{0.07}\right)$$

at CMB scales (imposing amplitude of scalars unchanged)

…about 3 orders of magnitude more than original case of massive χ 🙂

…but still too small (for a single χ species)😞

After imposing many constraints on the model…

…at interferometer scales (no CMB constraints):

$$\Omega_{\rm GW}\, h^2 \ll 1.3 \times 10^{-12}\ (\epsilon\, |\eta|)^{5/3}$$

(compare to LISA sensitivity $\sim 10^{-13}$)

Before concluding…

work in progress with Adshead, Pearce, Peloso and Mike Roberts

Large GWs from fermions?

Typically not an option, because of Pauli blocking… but…

$$\mathcal{L} = \bar{Y} \left[i\,\gamma^\mu\,\partial_\mu - m\,a - \frac{1}{f}\gamma^\mu\,\gamma^5\,\partial_\mu\phi \right] Y$$

(pseudoscalar inflaton φ, shift symmetric coupling to fermion Y)

Y has nonvanishing occupation number up to $k \sim \dot{\varphi}/f >> H$

Lots of fermions ⇒ Lots of GWs? f_{NL}?

Conclusions

- Various mechanisms of particle creation during inflation $\Rightarrow$ extra sources of tensors
- Disentangle amplitude of tensors r from energy scale of inflation
- Shift symmetric coupling to vector very successful with rich phenomenology
- Other options? Look more complicated…

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

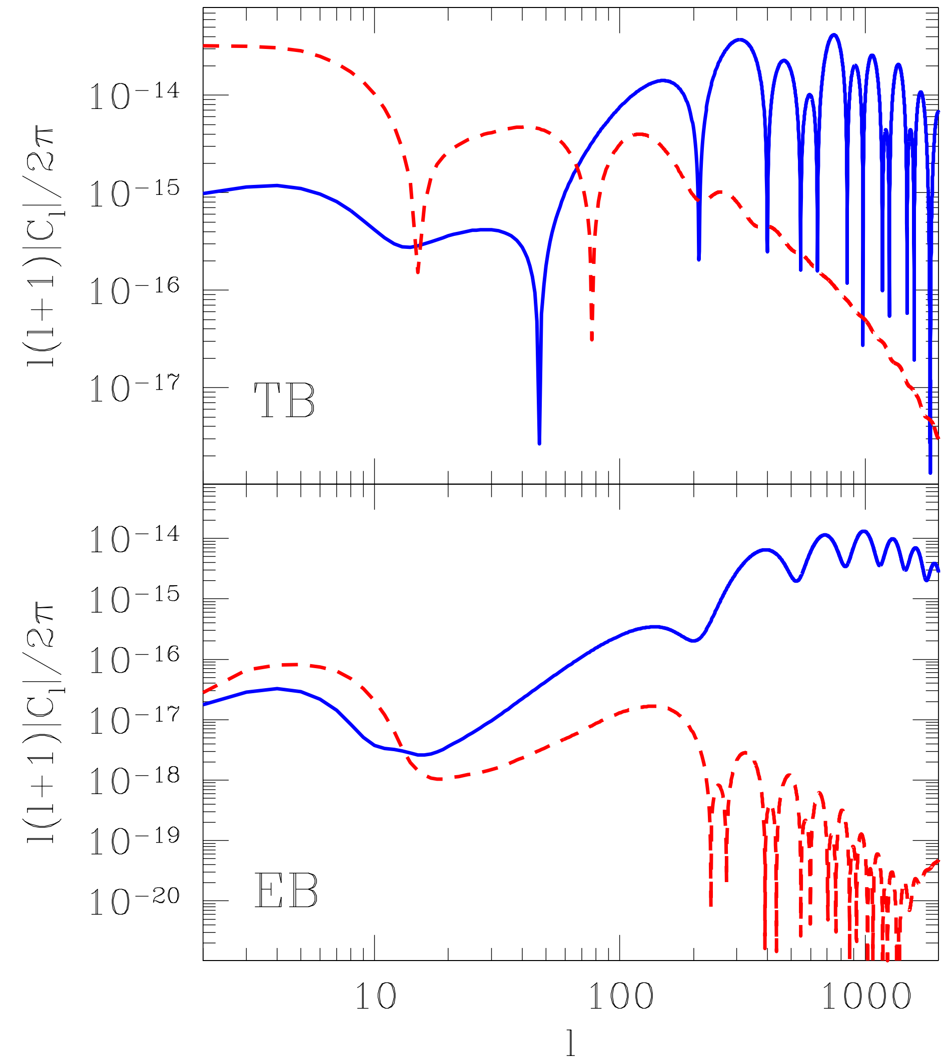


FIG. 5: We show TB and EB power spectra from chiral GWs for $\Delta\chi = 0.2$ and $r = 0.22$ (dashed red curves) and from cosmological birefringence for $\Delta\alpha = 5'$ (solid blue curves).

Also note

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