Axion inflation & primordial gravitational waves

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UMass Amherst

Peloso, LS, 2209.08131
Garcia-Bellido, Papageorgiou, Peloso, LS, 2303.13425
von Eckardstein, Peloso, Schmitz, Sobol, LS, 2309.04254
Corba', LS 2403.03338, Corba' 2504.13156

Axion inflation

Pseudoscalar, quasi-shift symmetric inflaton, radiatively stable

theoretically very attractive

"natural" coupling to U(1) gauge fields:

$$\mathcal{L}(\varphi,\, A^\mu) = \frac{1}{2}\partial_\mu\varphi\partial^\mu\varphi - V(\varphi) - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{\alpha}{4f}\varphi F^{\mu\nu}\tilde{F}^{\mu\nu}$$

EOM for helicity-λ modes of photon

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

Amplification of chiral vectors

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

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

Exponential amplification of **left-handed modes only**
(parity violation)

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

Very rich phenomenology, including…

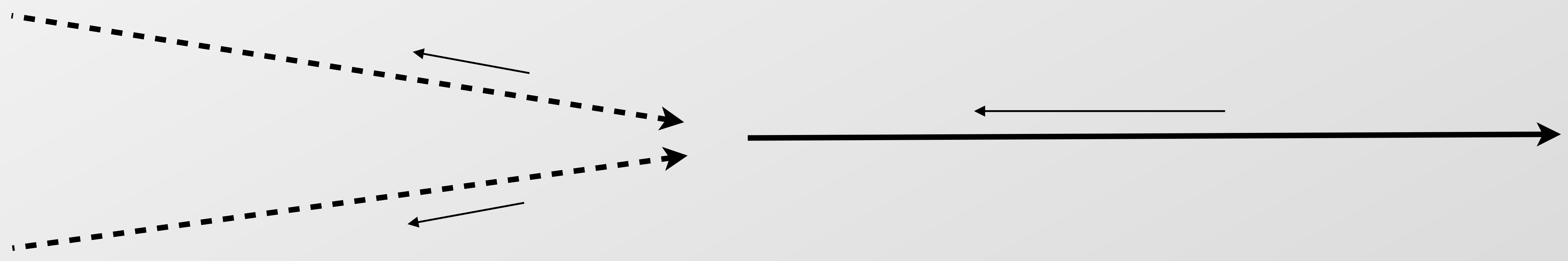
- Cosmological magnetic fields
- Baryogenesis
- Nongaussianities
- Features in scalar and tensor power spectrum
- Blue tensors
- Primordial Black Holes
- Parity violation in CMB
- …

(Chiral) gravitational waves

LS 11

$$A_\mu + A_\nu \to \delta g_{\mu\nu}$$

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



(Chiral) gravitational waves

$$A_\mu + A_\nu \rightarrow \delta g_{\mu\nu}$$

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

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

"standard"
parity-invariant part

parity-violation

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

Phenomenology

...but also, very large f_{NL}

Barnaby Peloso 10

$$A_\mu + A_\nu \to \delta\varphi$$

When effect of photons is large enough, f_{NL}~10^4

LARGE AXION INDUCED TENSORS AT CMB SCALES
RULED OUT

(at least in simple models)

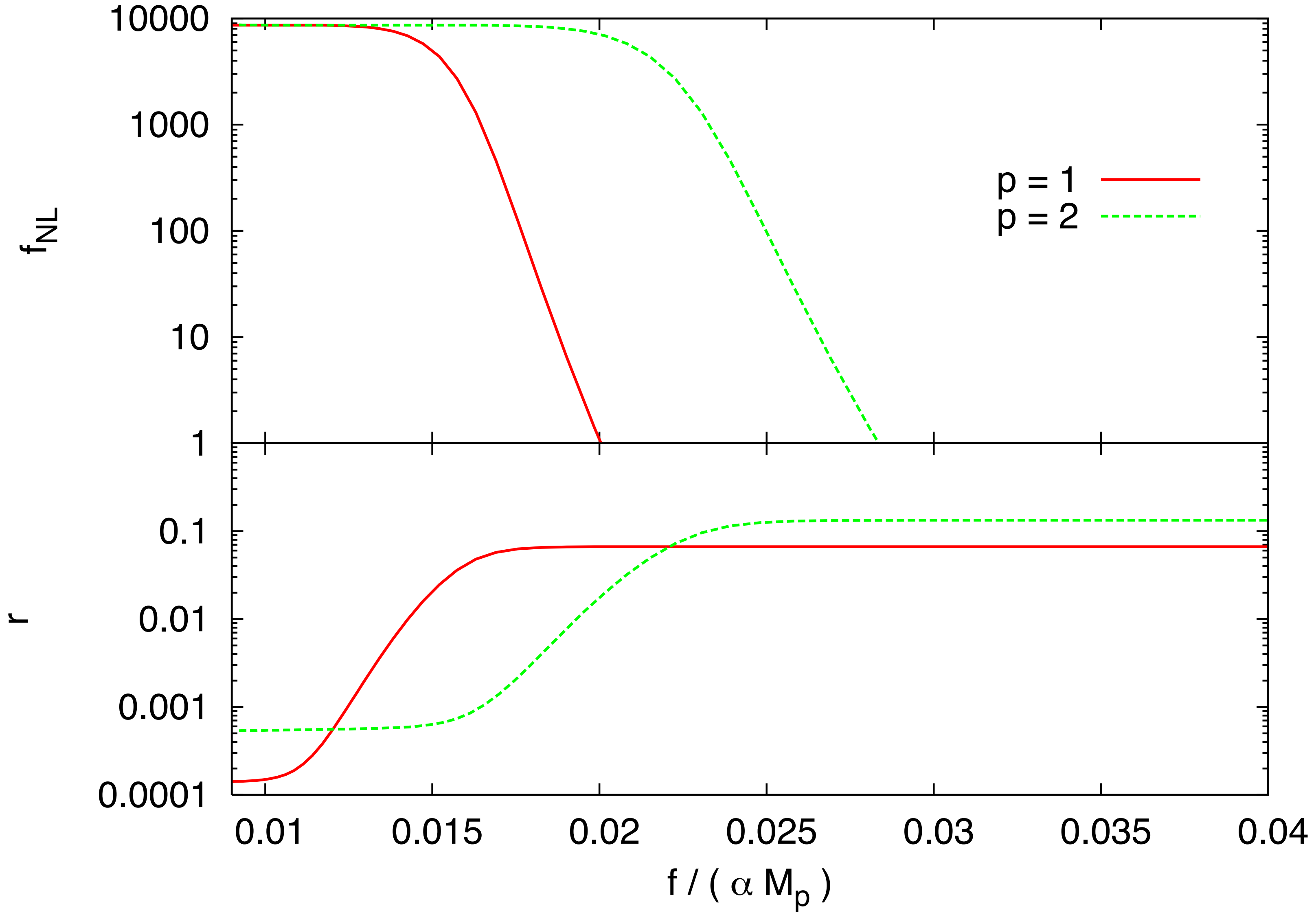


FIG. 2: Observational predictions for the large-field power-law inflation model (11) with $p = 1, 2$ and assuming $N_e \cong 60$. The spectral index is $n_s = 0.975, 0.967$ for $p = 1, 2$. At small f/α the coupling of ϕ to $F\tilde{F}$ is stronger and nongaussianity is large. The tensor-to-scalar ratio decreases at strong coupling; however, the decrease is important only at values of f/α which are ruled out by the current bound on $f_{NL}^{\rm equil}$.

GWs at smaller scales

But constraints on f_{NL} on CMB scales only!

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

Cook LS 11

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

ξ typically *increases* during inflation

↓

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

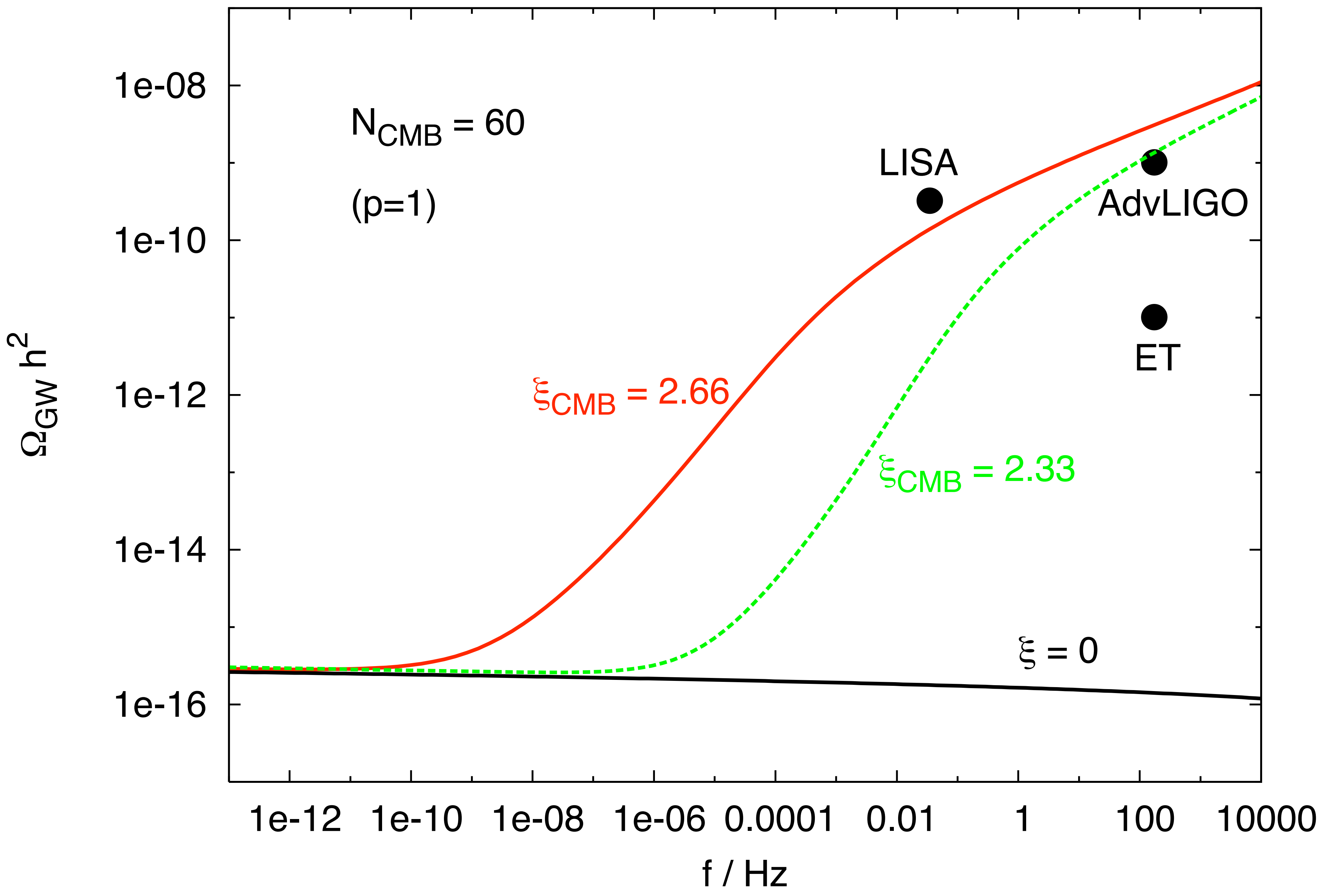
↓

might be detected by GW interferometers!

GWs at smaller scales

But constraints on f_{NL} on CMB scales only!

Inflationary gravitational waves for LIGO (LISA…)?



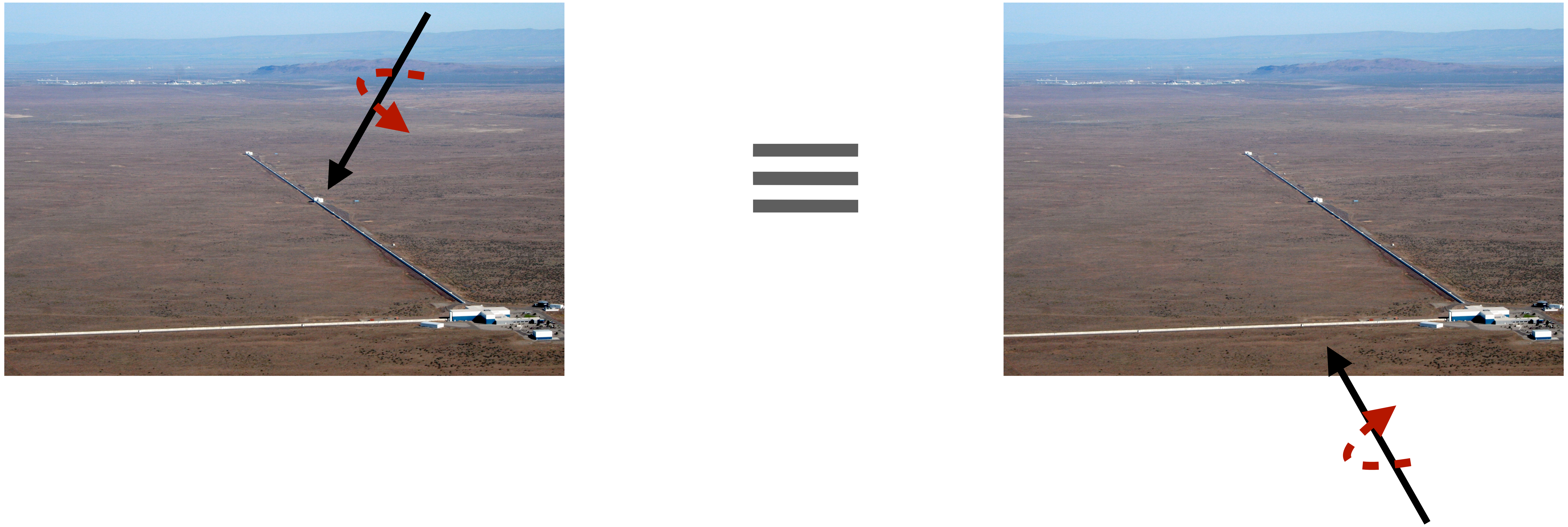
Barnaby Pajer Peloso 11

Parity violation

Is parity violation in stochastic GWs detectable by interferometers?

Seto Taruya 07

Not as long as system is Z_2-symmetric!



Parity violation

Is parity violation in stochastic GWs detectable by interferometers?

Seto 06, Domcke et al 19

The presence of cosmic GW background dipole breaks the symmetry → for LISA

$$\mathrm{SNR} \simeq \left(\frac{v}{10^{-3}}\right) \left|\frac{\sum_\lambda \lambda\, \Omega^\lambda_{GW} h^2}{1.4 \cdot 10^{-11}}\right| \sqrt{\frac{T}{3\,\mathrm{years}}}\,.$$

Additional detectors break the Z_2 symmetry

Crowder et al 12

→ for maximal chirality need $\Omega_{GW} \sim 10^{-8}$ for LIGO/Virgo/Kagra (already ruled out)

Domcke et al 19

→ an extra interferometer to maximize sensitivity?

Strong backreaction

Anber LS 09

Accounting for backreaction of vectors

$$\ddot{\phi} + 3\,H\,\dot{\phi} + V'(\phi) = -\quad \frac{\alpha}{f}\,\langle \vec{E}\cdot\vec{B}\rangle$$

with

$$\langle \mathbf{E}\cdot\mathbf{B}\rangle \propto e^{\pi\,\frac{\alpha\,|\dot{\phi}|}{f\;H}}$$

Strong backreaction regime:

$$V'(\phi) = -\quad \frac{\alpha}{f}\,\langle \vec{E}\cdot\vec{B}\rangle \quad \Rightarrow \quad \dot{\phi} \simeq \frac{f\,H}{\alpha\pi}\log(\dots)$$

Strong backreaction

NOTE: strong backreaction happens quite generally towards the end of inflation in phenomenologically interesting models

IMPORTANT

that we understand it well!

Strong backreaction

Looking more carefully into the backreacted equations…

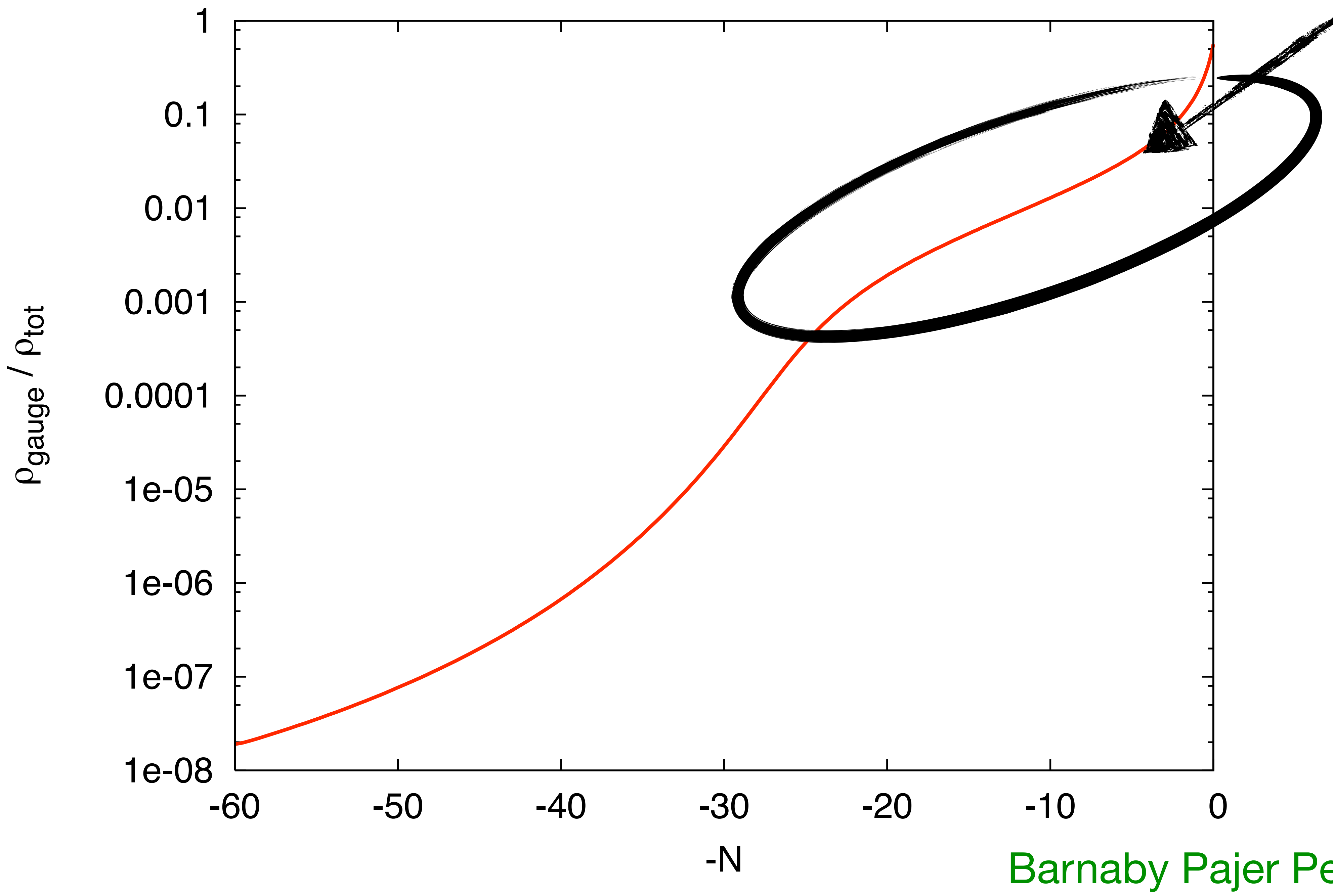
$$\ddot{\phi} + 3\,H\,\dot{\phi} + V'(\phi) = -\frac{\alpha}{f}\langle \mathbf{E}\cdot\mathbf{B}\rangle$$

Backreaction

with $\langle \mathbf{E}\cdot\mathbf{B}\rangle \propto e^{\pi\,\frac{\alpha\,|\dot{\phi}|}{f\;H}}$

Increases during inflation

Backreaction in action



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…an equation for ϕ only?

Strong backreaction

But remember $\langle \mathbf{E} \cdot \mathbf{B} \rangle = \int \mathbf{E}(\mathbf{k}) \cdot \mathbf{B}(\mathbf{k})\, d^3\mathbf{k}$

where $\mathbf{E}(\mathbf{k}, \mathrm{t})$ and $\mathbf{B}(\mathbf{k}, \mathrm{t})$ depend on $\mathbf{E}(\mathbf{k}, \mathrm{t'}<\mathrm{t})$, $\mathbf{B}(\mathbf{k}, \mathrm{t'}<\mathrm{t})$

Cannot use single equation local in time, **need numerics!**

$$\Phi'' + 2aH\Phi' + a^2\, V' = -\frac{\alpha^2}{4\pi^2 a^3\, f} \int dk\, k^2\, \frac{\partial}{\partial \tau} \left| A_+ \right|^2$$

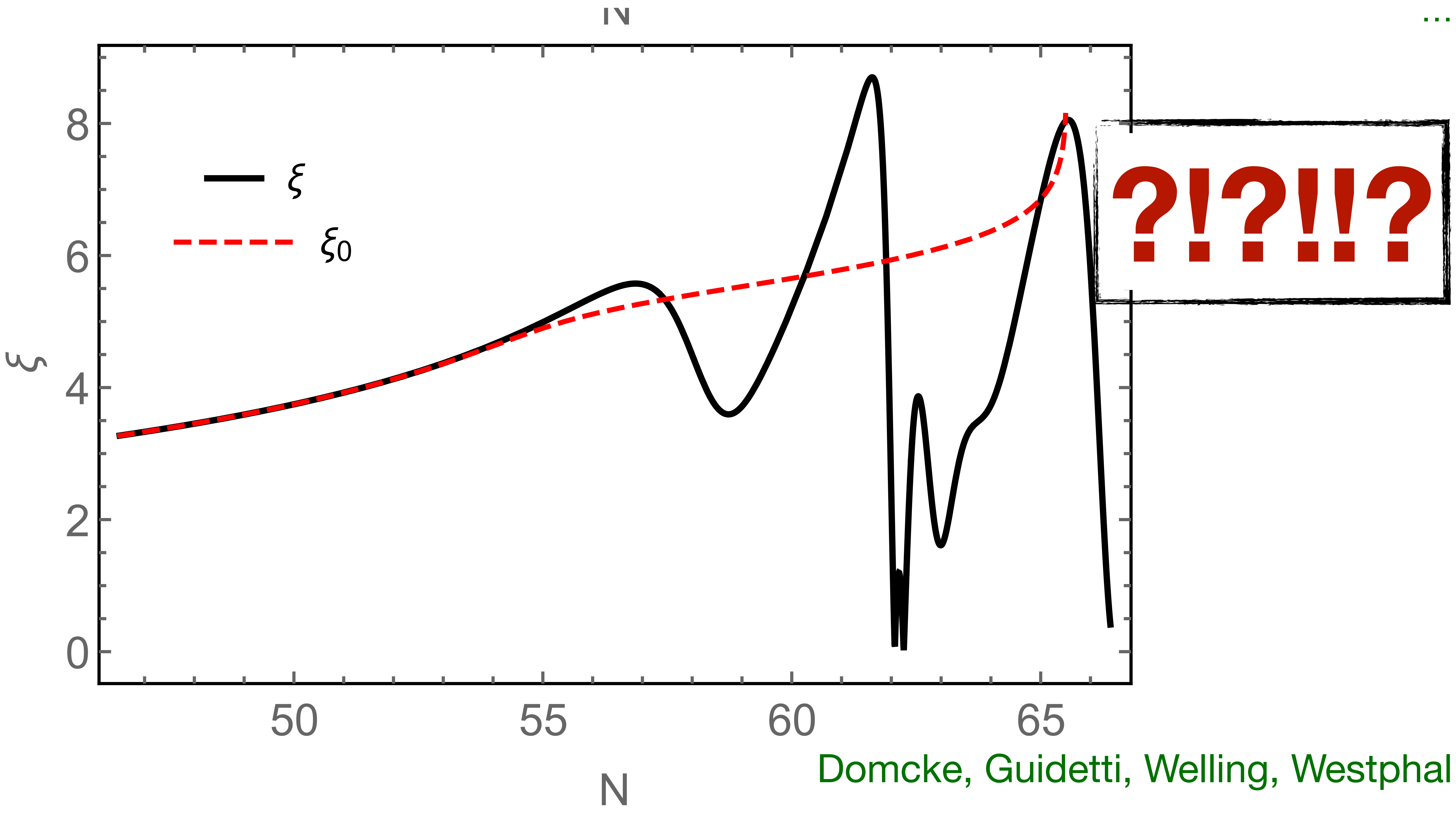
$$A''_+ + k^2 A_+ - \frac{\alpha\, \Phi'}{f} A_+ = 0$$

(neglecting inflation gradients and non-amplified helicity of gauge field)

Strong backreaction

Numerical result with uniform inflaton and one helicity of photon only

Cheng, Lee, Ng, 15
Notari, Tywoniuk 16
Dall'Agata, Gonzalez-Martin, Papageorgiou, Peloso 19
Domcke, Guidetti, Welling, Westphal 20
Gorbar, Schmitz, Sobol, Vilchinwskii 21
…



Domcke, Guidetti, Welling, Westphal 20

Strong backreaction

Where is this coming from?

Notari, Tywoniuk 16
Domcke, Guidetti, Welling, Westphal 20

$\langle \mathbf{E} \cdot \mathbf{B} \rangle$ does not react instantly to change in ξ

~~$$\ddot{\phi}(t) + 3\,H\,\dot{\phi}(t) + V'(\phi(t)) = -\frac{\alpha}{f}\langle \mathbf{E} \cdot \mathbf{B} \rangle(t)$$~~

$$\ddot{\phi}(t) + 3\,H\,\dot{\phi}(t) + V'(\phi(t)) = -\frac{\alpha}{f}\int^t K(t,\,t')\langle \mathbf{E} \cdot \mathbf{B} \rangle(t')\,dt' \simeq -\frac{\alpha}{f}\langle \mathbf{E} \cdot \mathbf{B} \rangle(t - \Delta t)$$

Strong backreaction

Analytical study for small perturbations around $\phi(t)=\bar{\Phi}(t)$...

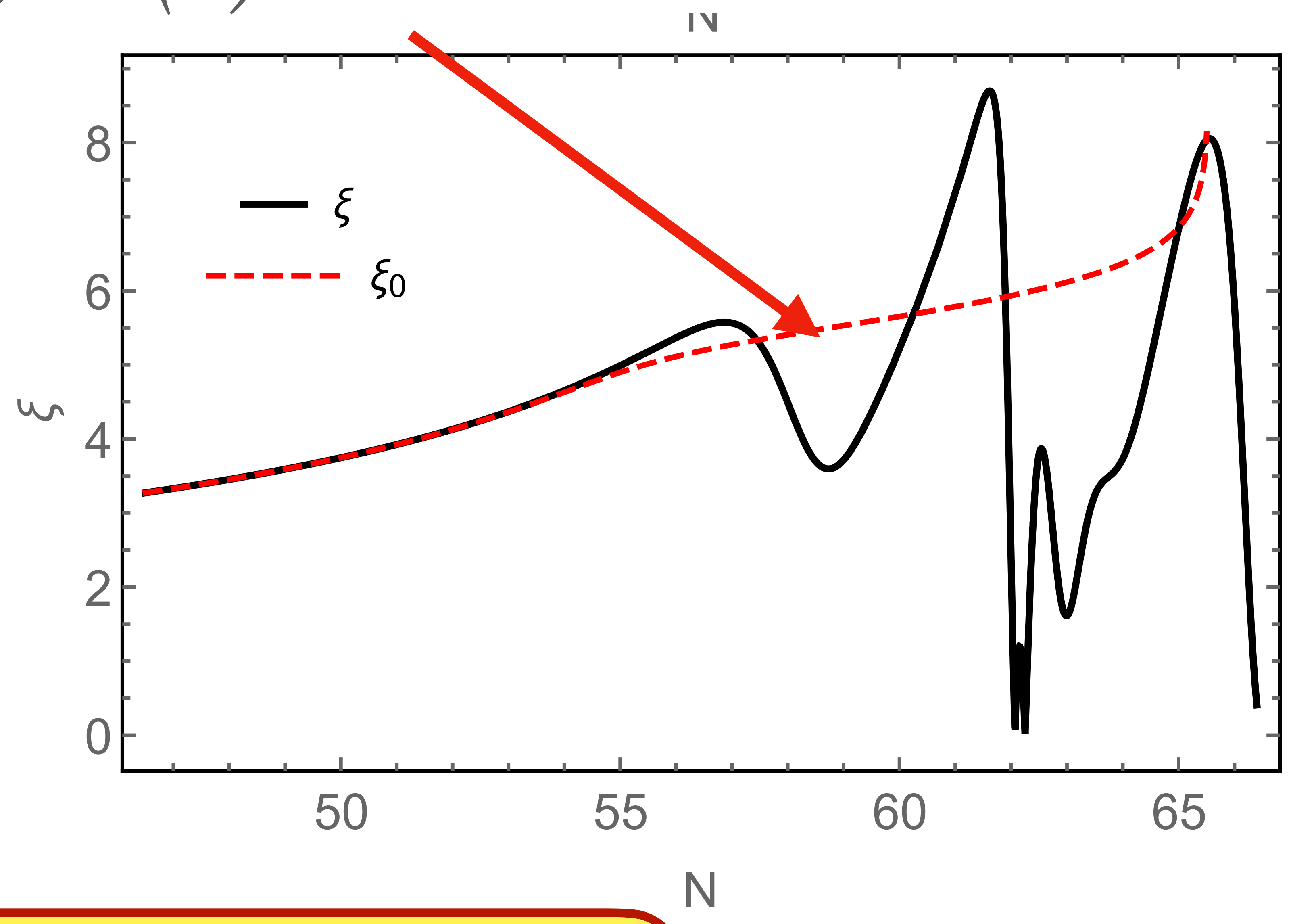
Peloso, LS, 2209.08131

where...
$$\ddot{\bar{\Phi}} + 3\,H\,\dot{\bar{\Phi}} + V'(\bar{\Phi}) = -\frac{\alpha}{f}\langle \mathbf{E}\cdot\mathbf{B}\rangle(H,\,\dot{\bar{\Phi}})$$

with the RHS computed assuming H, $\dot{\bar{\Phi}}(t)=const.$

writing
$$\Phi = \bar{\Phi} + \delta\Phi \quad , \quad A = \bar{A} + \delta A$$

look for solution
$$\delta\Phi \propto (-\tau)^{\alpha}$$



Always at least one root with α complex and $Re[\alpha]<-0$!

Inflationary gravitational waves for LIGO (LISA…)?

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

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

LS 2011

ξ increases during inflation

large amplitude at short (interferometer) scales

Cook, LS 2010

How does this change with more realistic $\xi(t)$?

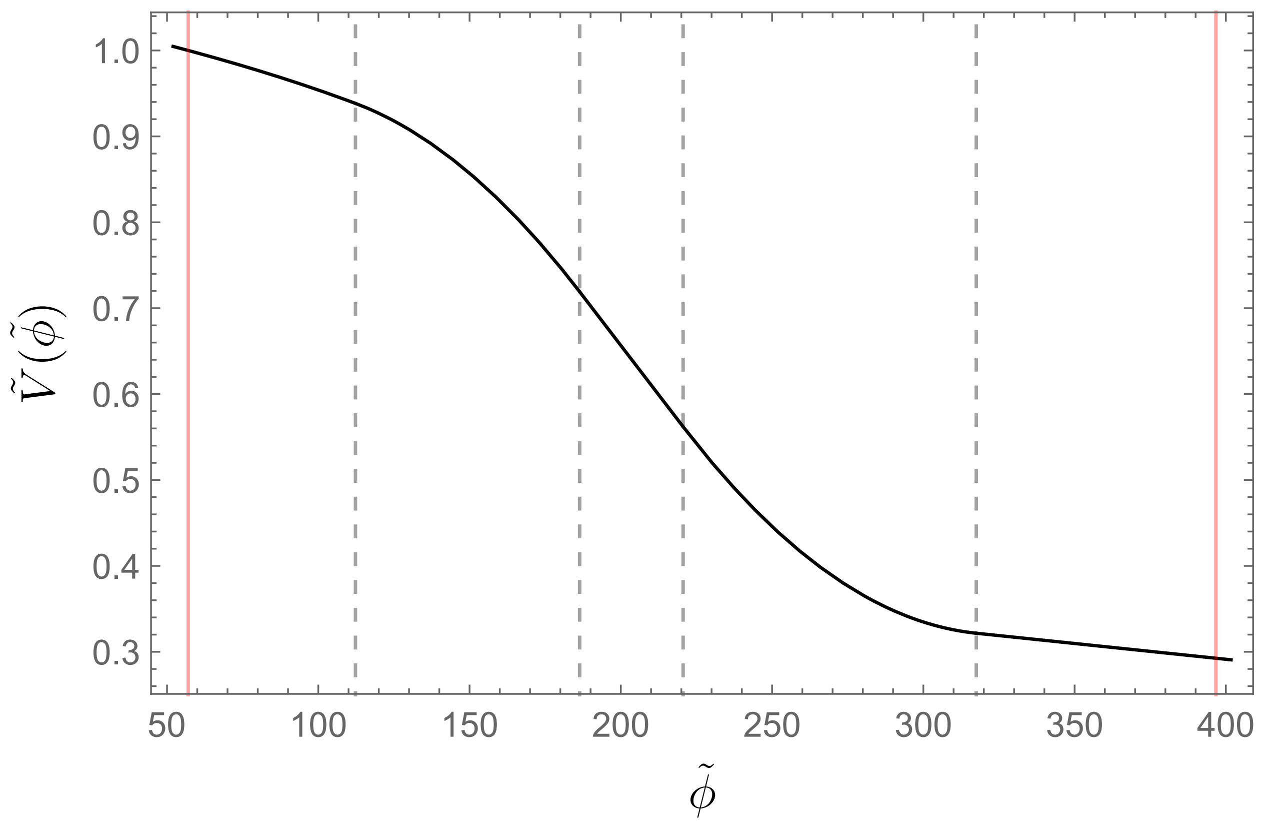
Gravitational waves for interferometers

Need numerical solution of background

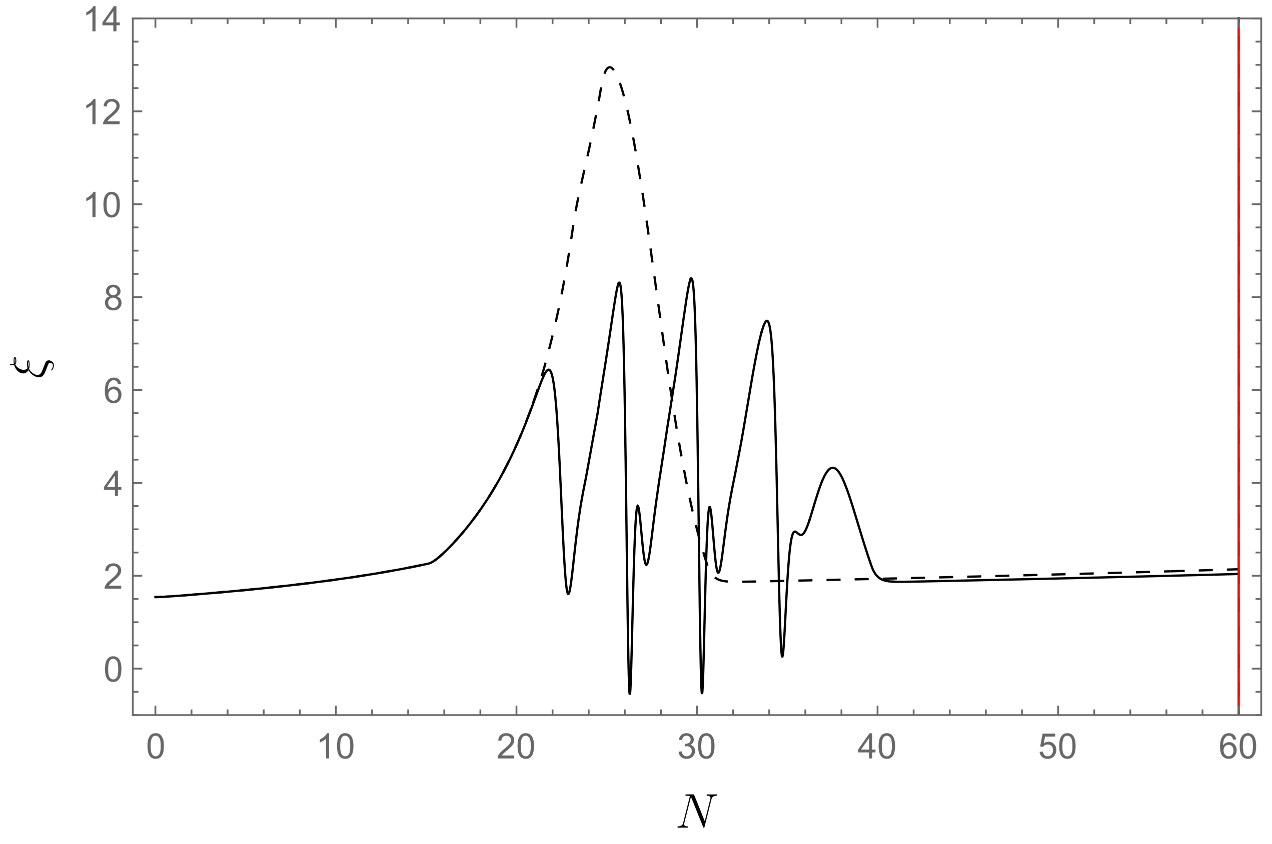
Garcia-Bellido, Papageorgiou, Peloso, LS 23

Example for steep-ish potential @ intermediate times

$V(\phi)$



$\xi(N)$



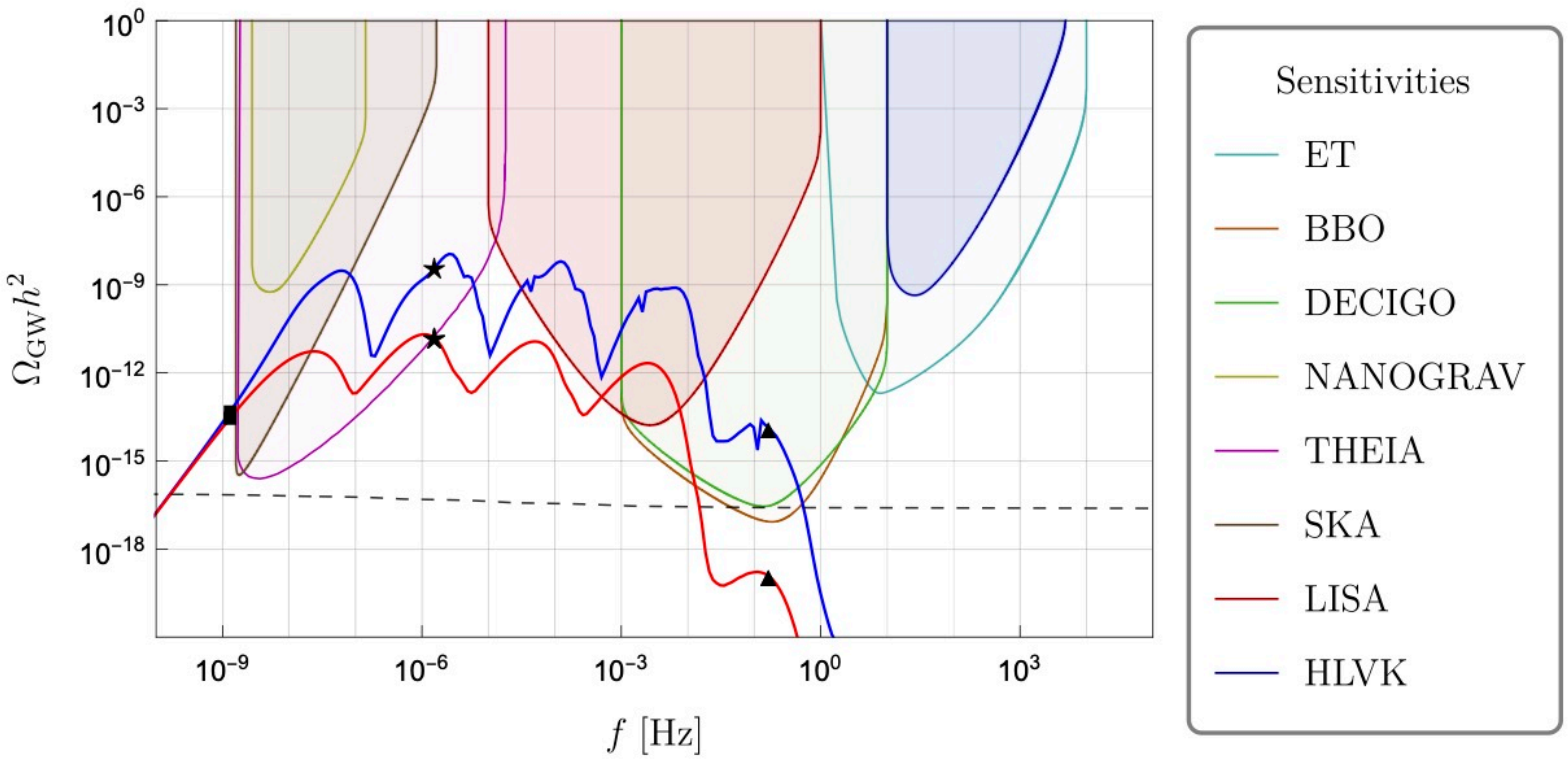
Gravitational waves for interferometers

Flashes of gravitational waves from axion inflation

Garcia-Bellido, Papageorgiou, Peloso, LS 23

Example for steep-ish potential @ intermediate times

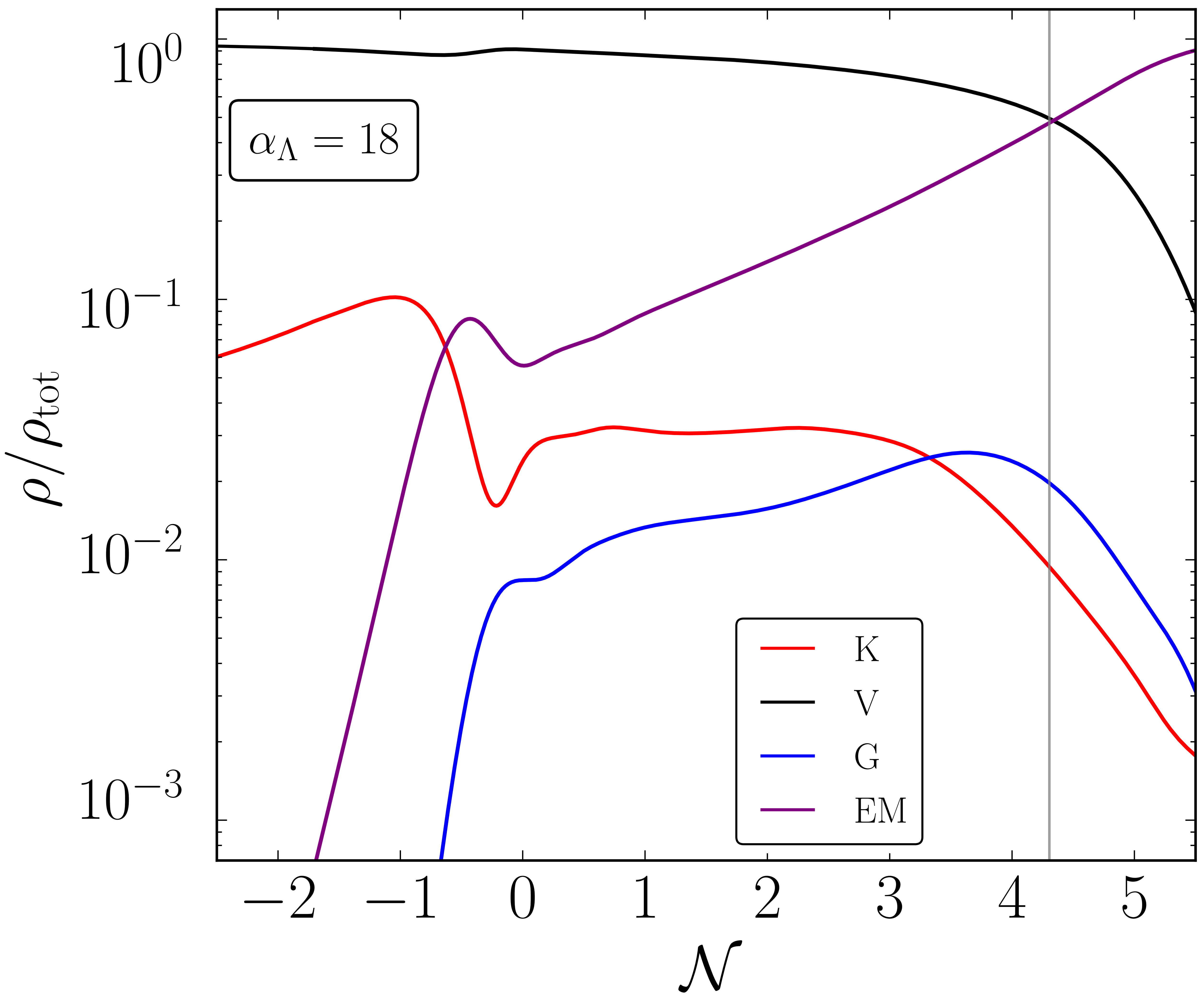
- ***Peaks!***
- ***Parity violation!***
- ***PTAs!***
- ***LISA!***



Gravitational waves for interferometers

Lattice studies show that oscillations do not last

Caravano, Komatsu, Lozanov, Weller 22
Figueroa et al 23, 24
(but, see also Caravano Peloso 24)
One more



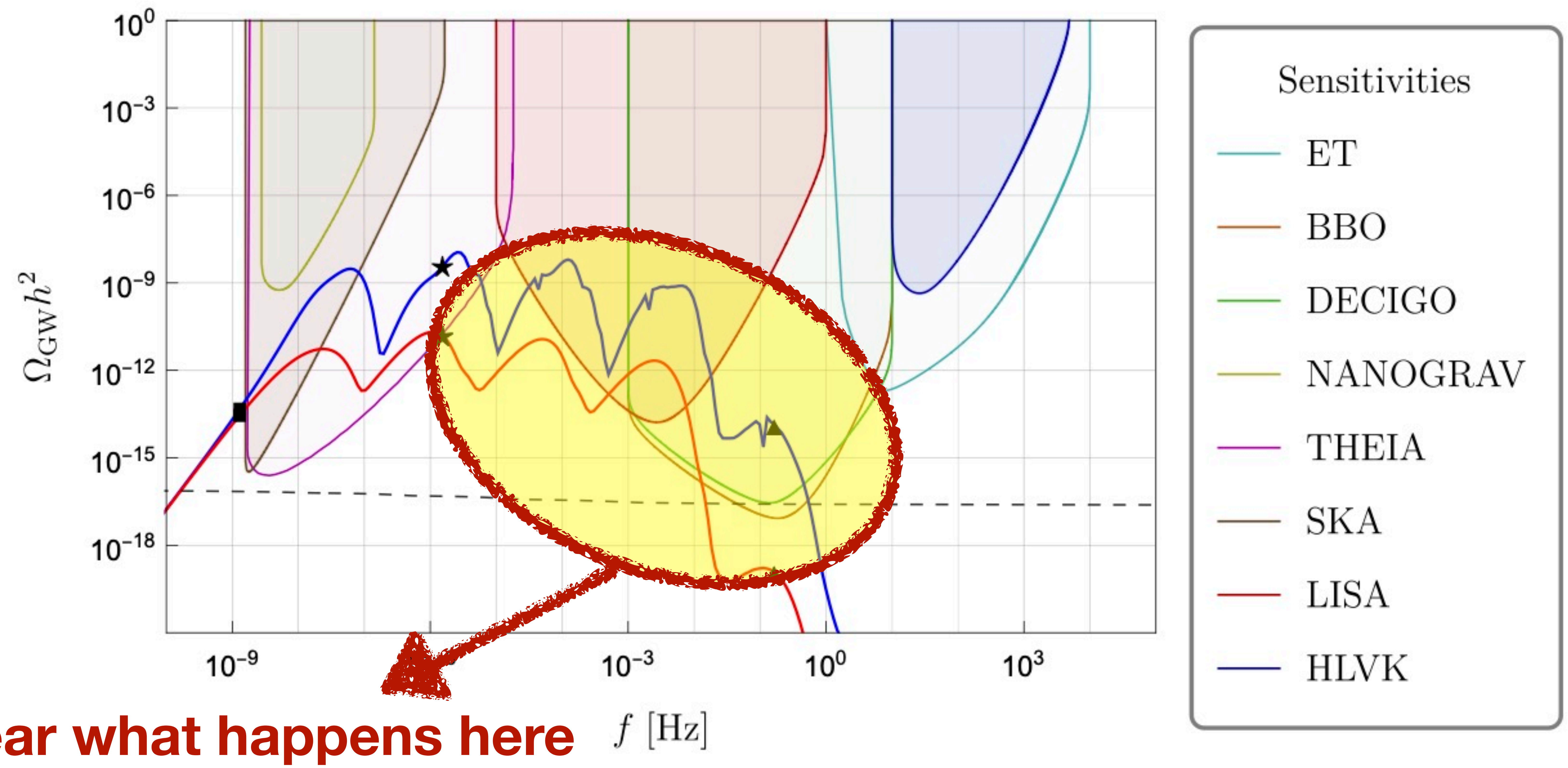
Inflaton gradients appear to be large and to affect the dynamics a lot!
Only one oscillation or so in ξ

Flashes of gravitational waves from axion inflation

Garcia-Bellido, Papageorgiou, Peloso, LS 23

Example for steep-ish potential @ intermediate times

- ***Peaks!***
- ***Parity violation!***
- ***PTAs!***
- ***LISA!***



Not clear what happens here

Correlators

Other features?

Corba' LS 24

GW interferometers have poor but nonzero angular sensitivity

Bartolo et al 22

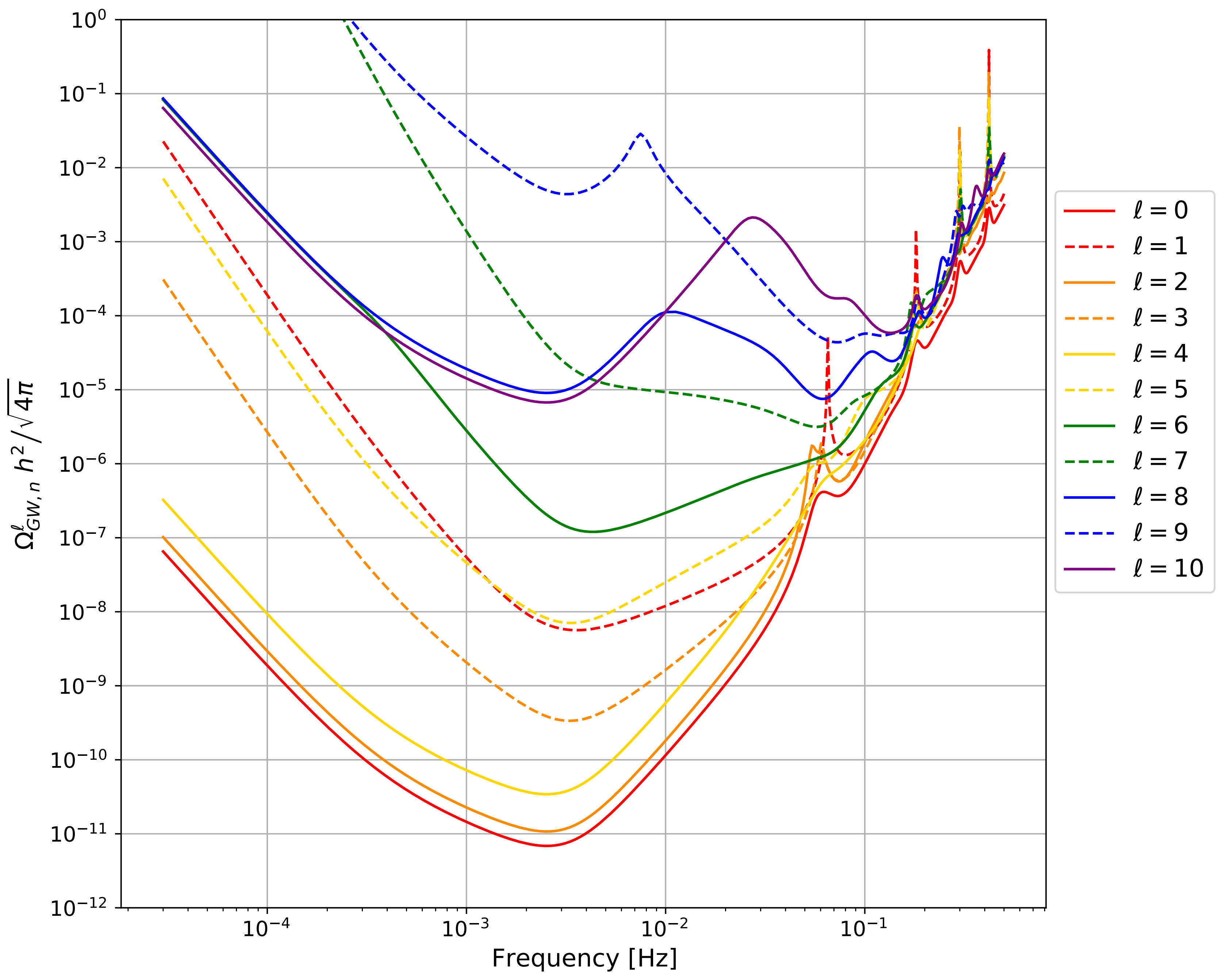


Figure 9: *Estimated LISA sensitivity to a given multipole ℓ of the SGWB, for multipoles up to $\ell = 10$. Even (odd) multipoles are shown with solid (dashed) lines. The sensitivity is obtained by optimally summing over the LISA channels, see Eqs. (4.42) and (4.43).*

Angular correlations of energy in GWs with scalar CMB perturbations?

Other features?

Corba' LS 24

Angular correlations of energy in GWs with scalar CMB perturbations?

Two sources of correlation

$$\Phi \longrightarrow A_\mu \begin{cases} \nearrow h_{\mu\nu} \\ \searrow \delta\Phi \end{cases}$$

$$\Phi + \delta\Phi \longrightarrow A_\mu + \delta A_\mu \longrightarrow h_{\mu\nu} + \delta h_{\mu\nu}$$

Dominant

Bartolo et al 19

$$\frac{1}{\Omega_{GW}^{\rm INT}\sqrt{\mathcal{P}_\zeta^{\rm CMB}}}\frac{k^3}{2\pi^2}\langle \Omega_{GW}(\mathbf{k},\,t_0)\,\zeta(-\mathbf{k},\,t_0)\rangle' \simeq -4\pi\,\xi\,\Delta\mathcal{N}_*\,(2\epsilon-\eta)\,\sqrt{\mathcal{P}_\zeta} \simeq 10^{-4} \div 10^{-2}$$

Other features?

Corba' 25

Two sources of correlation

$$\Phi \longrightarrow A_\mu \rightarrow h_{\mu\nu}, \quad A_\mu \rightarrow \delta\Phi$$

$$\Phi + \delta\Phi \longrightarrow A_\mu + \delta A_\mu \longrightarrow h_{\mu\nu} + \delta h_{\mu\nu}$$

Dominant

Angular anisotropies in Ω_{GW}

$$\frac{1}{\Omega_{GW}^2}\frac{k^3}{2\pi^2}\langle\Omega_{GW}(\mathbf{k},\,t_0)\,\Omega_{GW}(-\mathbf{k},\,t_0)\rangle' \simeq \frac{9.8\times10^{-5}}{\delta^2}\left(2\pi\frac{d\xi}{d\phi_0}\frac{\dot{\phi}_0}{H}\right)^2 \simeq 10^{-5} \div 10^{-1}$$

$$\delta \approx .05 \div .2$$

To sum up…

Axion inflaton/gauge dynamics very rich, even if consider only the GW sector

Motivates search in data!