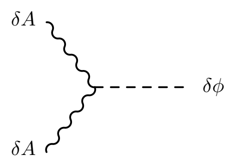
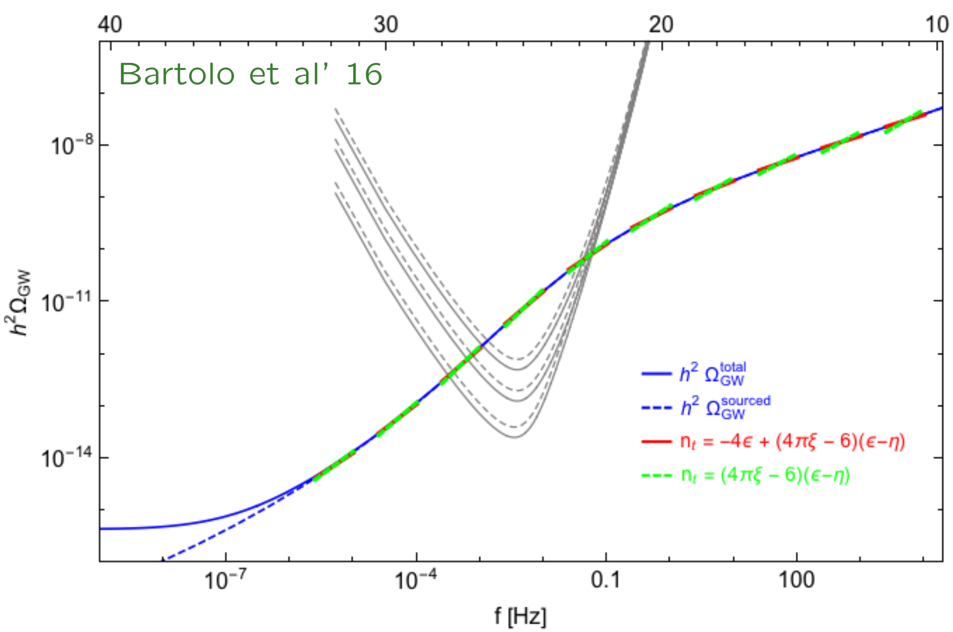
Marco Peloso, University of Minnesota

Gauge fields from a rolling axion: "technical" aspects

$$\frac{\phi}{f} F\tilde{F}$$



$$\phi(t) \longrightarrow \delta\vec{A} \begin{cases} \nearrow \delta\phi \\ \searrow \delta g \end{cases}$$



- CMB P_ζ , B_ζ
- GW @ CMB scales
- GW @ interferometer scales
- PBH

$$N \simeq 25 - \ln\left(\frac{f_{\rm GW}}{5\times 10^{-3}\,{\rm Hz}}\right) + \ln\left(\frac{H_N}{H_{60}}\right)$$

$$M_{\rm PBH,form.} \sim \text{few} \times 10^{-13}\, M_\odot\, e^{2(N-25)}$$

$$N \simeq 25 - \ln\left(\frac{f_{\rm GW}}{5\times10^{-3}\,{\rm Hz}}\right) + \ln\left(\frac{H_N}{H_{60}}\right) \qquad M_{\rm PBH,form.} \sim \text{ few} \times 10^{-13}\, M_\odot \, e^{2(N-25)}$$

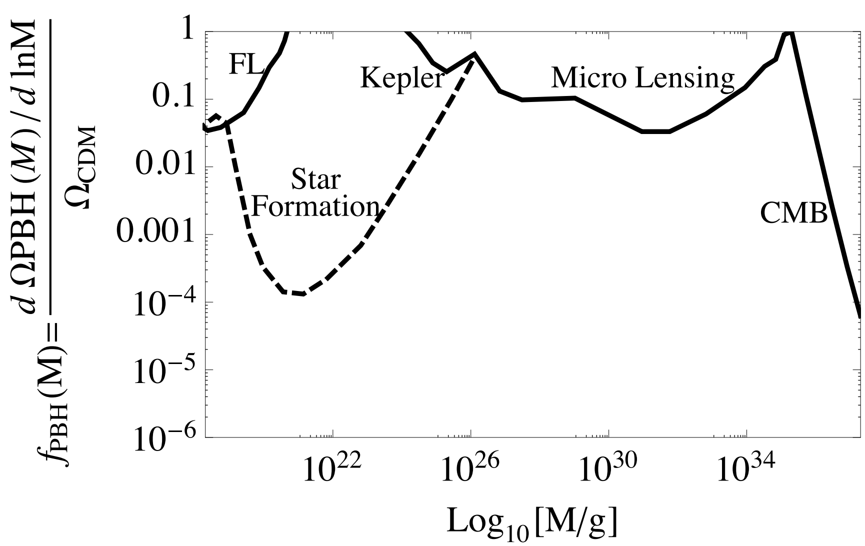
$$\delta\vec{A} \sim e^{\frac{\pi\dot\phi}{2fH}} \quad , \quad \text{naturally blue signals}$$

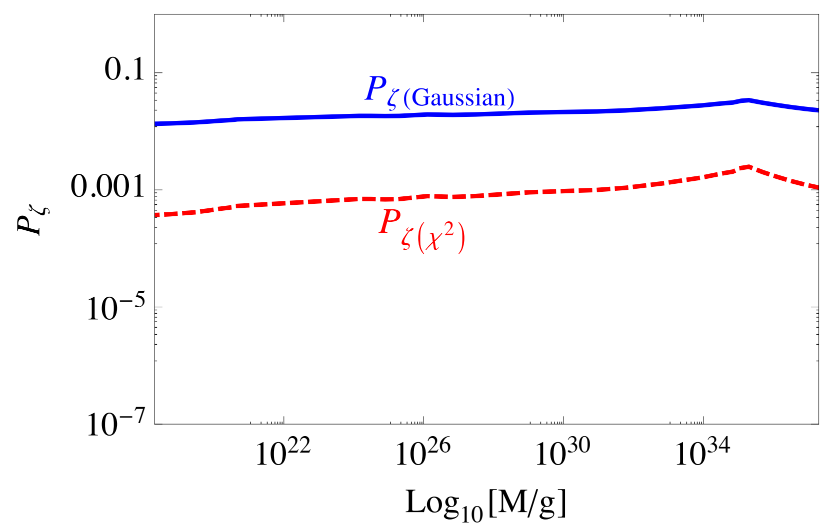
(1) Interesting GW production, compatible with PBH limits on ζ ?

(2) Interesting GW signals associated with PBH / large ζ ?

(more on this on Th)

Garcia-Bellido, MP, Unal '16, '17

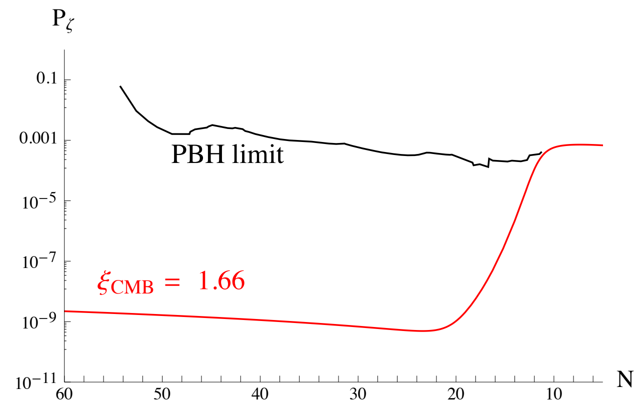


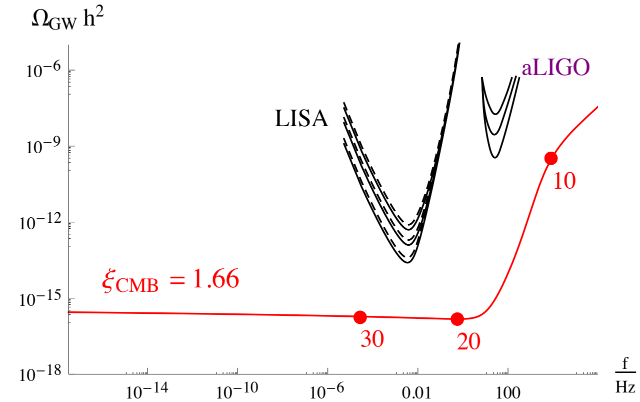


(any cosmological mechanism that produces GW @ LISA must respect this)

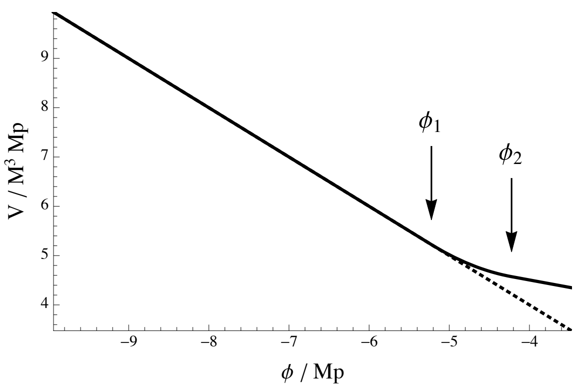
Highly model-dependent

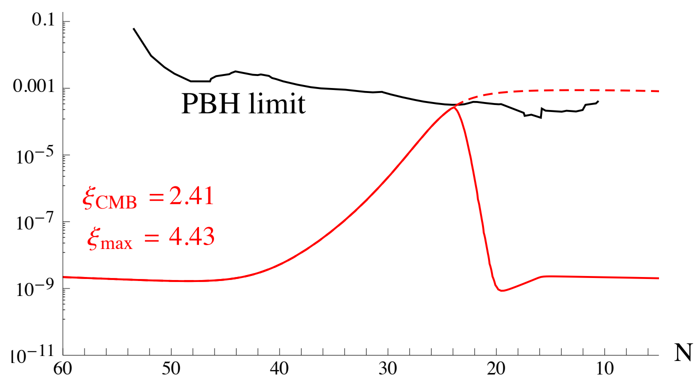
For $V \propto \phi$

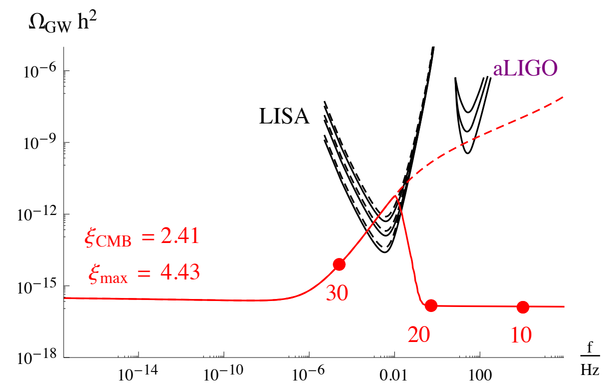




- Due to $\propto e^{\dot\phi}$, significant differences from a minor change of V







PBH bounds at LISA scales do not prevent GW to be seen at LISA

Bump from (i) a change in the inflaton potential, or (ii) an extra axion, with $m \simeq H$, rolling for a few e-folds at some given N

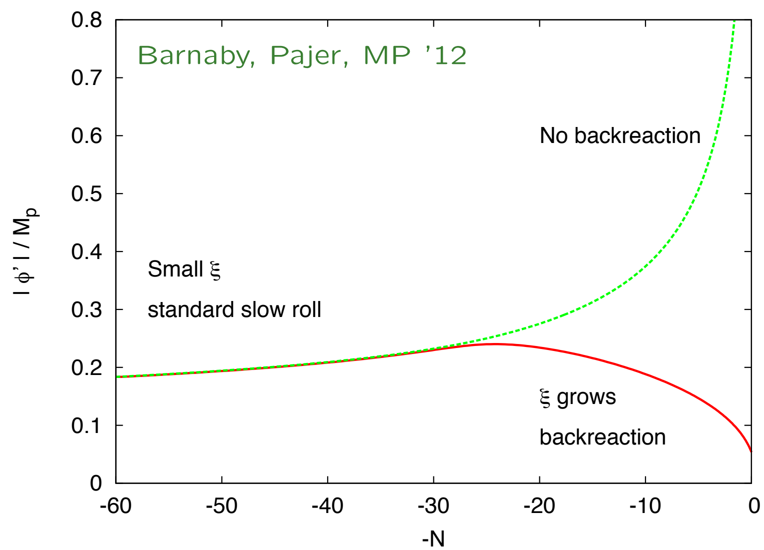
Backreaction

- Interesting GW and PBH for $\xi \equiv \frac{\dot\phi}{2fH} \simeq 5$. Too large $\delta\vec{A}$ production ?

- Backreaction on background $\phi^{(0)}$

$$\ddot\phi^{(0)} + 3H\dot\phi^{(0)} + \frac{dV}{d\phi} = \frac{\alpha}{f}\left\langle \vec{E}\cdot\vec{B}\right\rangle$$

relevant for $\xi \gtrsim 4.7$

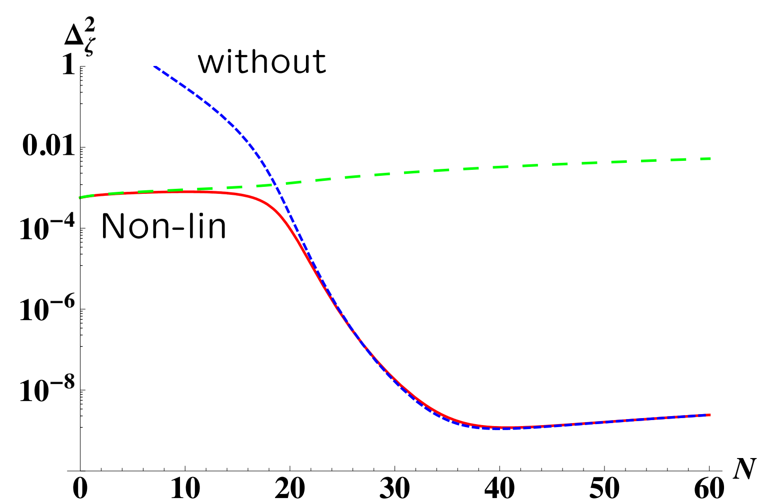


- $\delta\vec{A}\left[\xi\left[\dot\phi + \delta\dot\phi\right]\right] \;\rightarrow\;$ Nonlinearities in $\delta\phi$ equation. Friction also on $\delta\phi$

Anber, Sorbo '09

$$\delta\ddot\phi + 3\left[1 - \frac{2\pi\,\xi}{3H\dot\phi}\frac{\alpha}{f}\vec{E}\cdot\vec{B}\right]H\delta\dot\phi - \frac{\vec\nabla^2}{a^2}\delta\phi + m^2\delta\phi = \frac{\alpha}{f}\vec{E}\cdot\vec{B}$$

- No corresponding term in the l.h.s. of δg equation



Linde, Mooij, Pajer '12

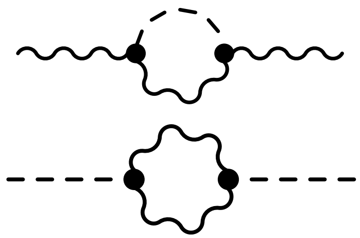
Perturbativity

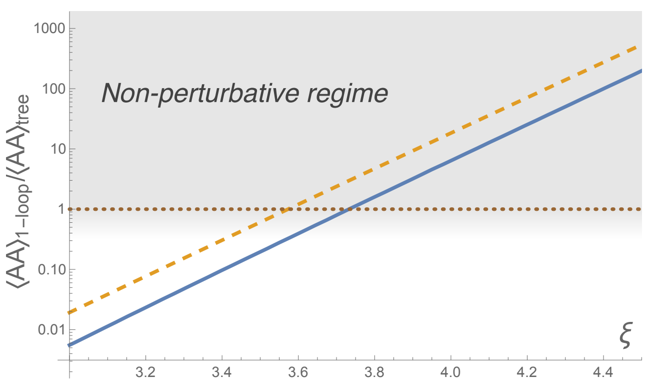
Ferreira, Ganc, Norea, Sloth '15

- Analysis limited to the regime of no backreaction

- $\delta\vec{A} \sim \mathrm{e}^{\frac{\pi\dot{\phi}}{2fH}} \quad \rightarrow$ Too large loops ?

$\delta^{(1)}\langle AA\rangle =$ $\delta^{(1)}\langle\phi\phi\rangle =$





$$\frac{\langle A_k A_q\rangle_{\text{1-loop}}}{\langle A_k A_q\rangle_{\text{tree}}} \approx 10^{-2}\ \xi^2\ e^{2\pi\xi}\ \mathcal{P}_s$$

Numerical $\longrightarrow$ *Perturbativity :* $\xi \lesssim 3.5$

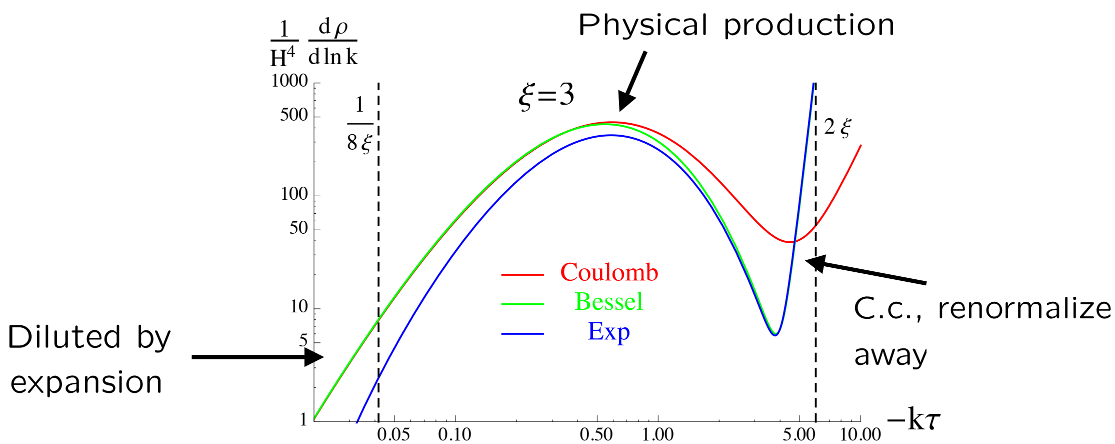
- Good idea, and valid concern; result appeared too strong

- "typical 10^{-2} loop factor " not from a computation. In this mechanism, loops $\rightarrow 10^{-5} - 10^{-4}$. Numerical result corrected in v2

Perturbativity 2

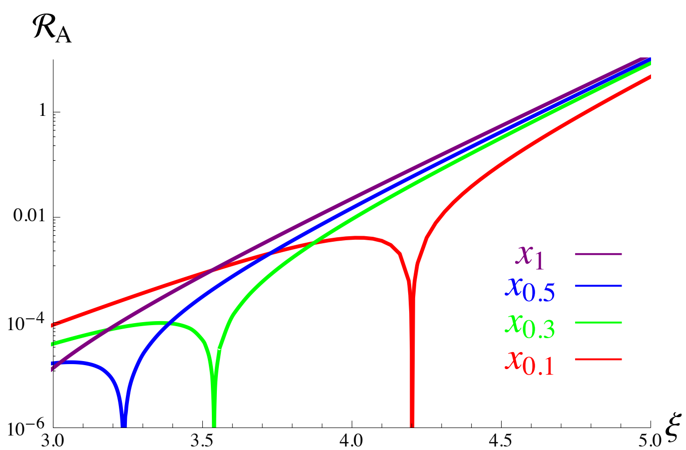
MP, Sorbo, Unal '16

- Reanalysis, also limited to the regime of no backreaction



- Use exp. approx, since used in computation of signatures

- require $\mathcal{R}_A \equiv \frac{\langle A\,A\rangle_{1-\text{loop}}}{\langle A\,A\rangle_{\text{tree}}} < 1$ at all relevant times

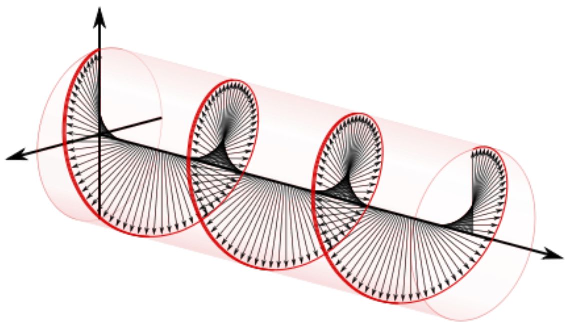


- Strongest constraint $\xi < 4.7$ at x_1 (when ρ_A maximum)

Perturbativity ok in the regime of validity of the analysis

Chiral GW at ground-based interferometers

- ϕ psudoscalar. Operator $\frac{\phi}{f} F \tilde{F}$, in presence of a definite $\phi(t)$, breaks parity

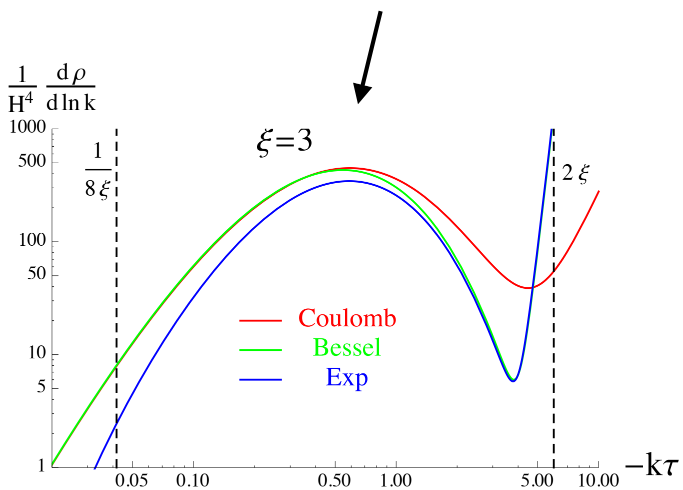


$$\left(\frac{\partial^2}{\partial \tau^2} + k^2 \mp \frac{ak}{f} \frac{d\phi}{dt} \right) A_\pm (\tau, k) = 0$$

$+$ left handed

$-$ right handed

- Physical production of one mode only,



say $A_+ \longrightarrow \delta\phi \, , \quad h_L \, , \quad h_R$

- Individual PS preserve parity

$$\left\langle f_i \left(\vec{k}_1 \right) \, f_i \left(\vec{k}_2 \right) \right\rangle = \left\langle f_i \left(\vec{k}_2 \right) \, f_i \left(\vec{k}_1 \right) \right\rangle = P_i \left(k \right) \delta^{(3)} \left(\vec{k}_1 + \vec{k}_2 \right)$$

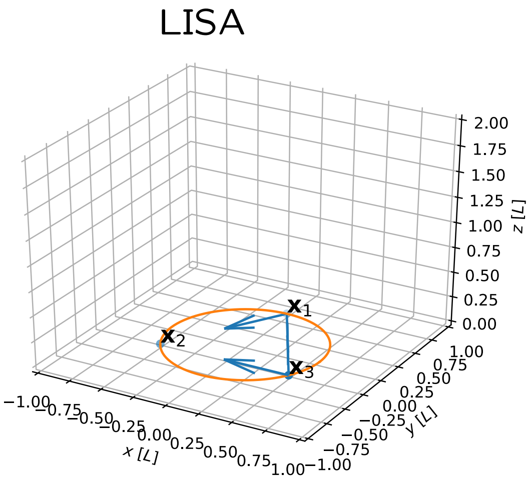
- Breaking of parity results in $\langle h_L \, h_L \rangle \neq \langle h_R \, h_R \rangle$

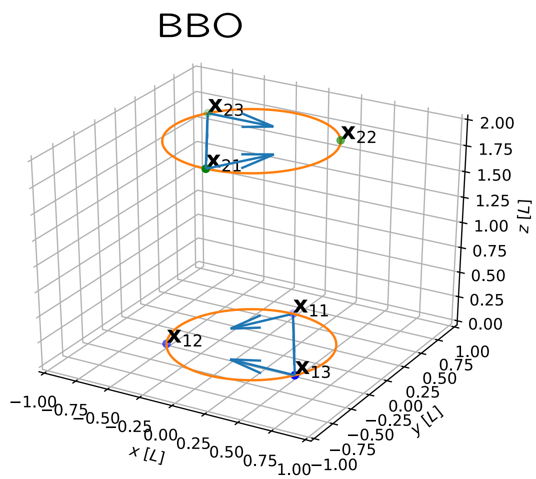
Can we detect this ?

Chirality from space

Smith, Caldwell '16

Thorne, Fujita, Katayama, Komatsu, Shiraishi '17



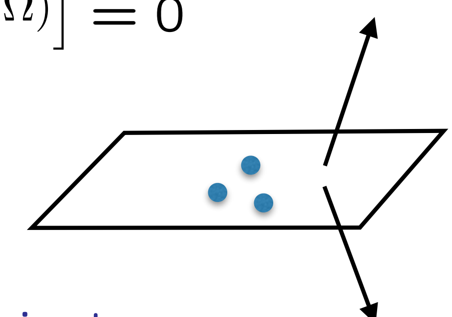


$$\langle h_{R/L}(f,\hat{\Omega})h^*_{R/L}(f',\hat{\Omega}')\rangle = \frac{\delta(f-f')\delta^2(\hat{\Omega}-\hat{\Omega}')}{4\pi}\;[I\,(f) \pm V\,(f)]$$

$$\langle s^{X_1}(f)s^{X_2}(f')\rangle = \frac{1}{2}\delta(f-f')\left[\mathcal{R}_I^{X_1X_2}(f)I(f) + \mathcal{R}_V^{X_1X_2}(f)V(f)\right]$$

$$\mathcal{R}_V^{X_1X_2}(f) = \frac{1}{4\pi}\int d^2\hat{\Omega}\left[F^+_{X_1}(f,\hat{u}\cdot\hat{\Omega})F^{\times *}_{X_2}(f,\hat{u}\cdot\hat{\Omega}) - F^{\times}_{X_1}(f,\hat{u}\cdot\hat{\Omega})F^{+*}_{X_2}(f,\hat{u}\cdot\hat{\Omega})\right] = 0$$

even odd under parity



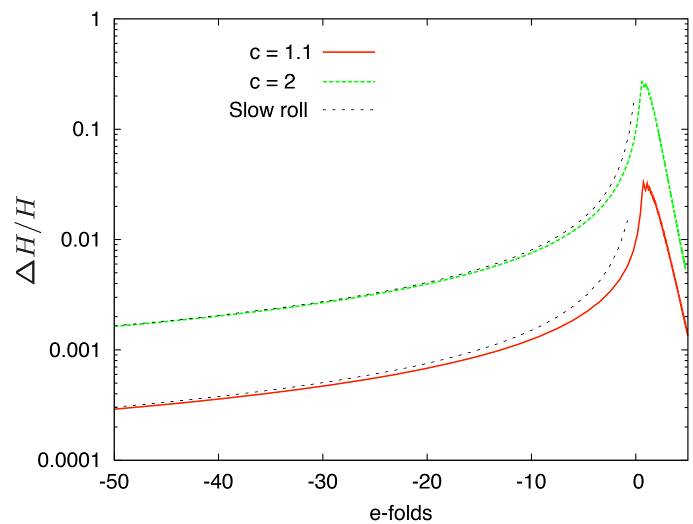
$$F_X^P(f,\hat{\Omega}\cdot\hat{u}) = D_{ij}^X(f,\hat{u}\cdot\hat{\Omega})e_{ij}^P(\hat{\Omega})$$

assumes statistical isotropy

Violation of statistical isotropy:

- EFT of broken spatial reparametrizations Ricciardone, Tasinato

- anisotropic inflation



Watanabe, Kanno, Soda '09

$\delta g - \delta\phi$ mixing

$\rightarrow h_+ \neq h_\times$

This type of models require large $\phi - \vec{A}$ mixing, to sustain anisotropy

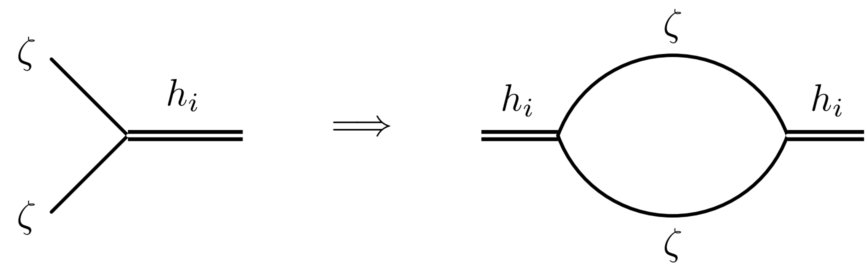
$\Rightarrow$ Non – gaussianity

$$\langle h\,h\,h\rangle \neq 0 \ \overset{?}{\rightarrow}\ \langle s\,(t_1)\,s\,(t_2)\,s\,(t_2)\rangle \neq 0$$

- PBH formed from large overdensities at re-entry. Unavoidably, also $\zeta + \zeta \to h$
- At equal f_{PBH}, greater P_ζ required in Gaussian case $\to$ greater GW

★ Case of Gaussian ζ very well studied

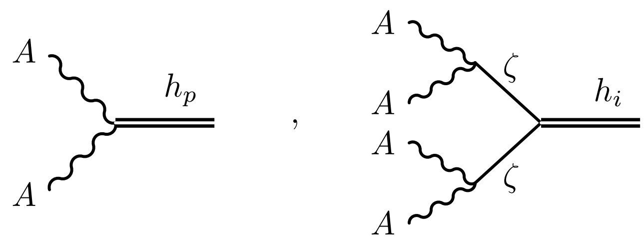
Ananda et al' 06; Baumann et al '07



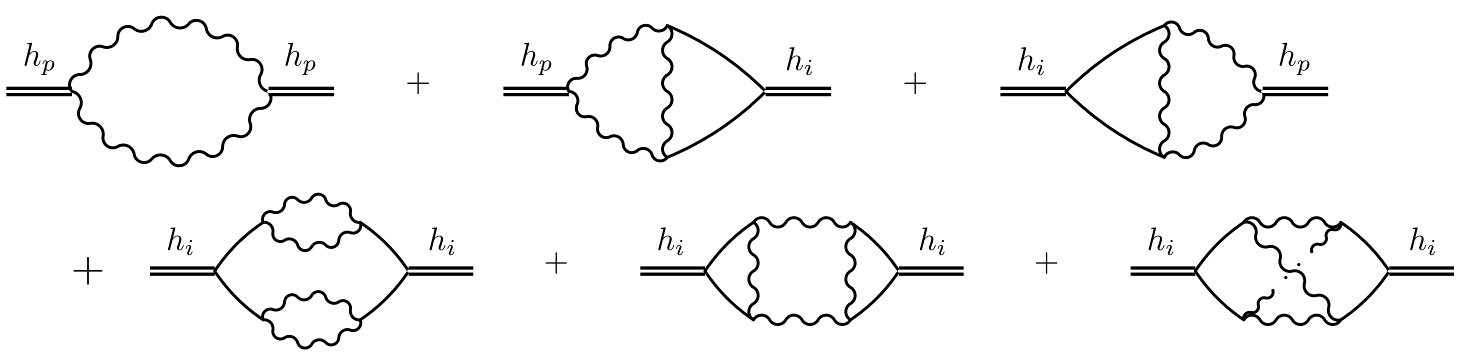
★ In NG case, peak value (but not scale-dependence) estimated

Nakama, Silk, Kamionkowski '16

In rolling axion (χ^2) model

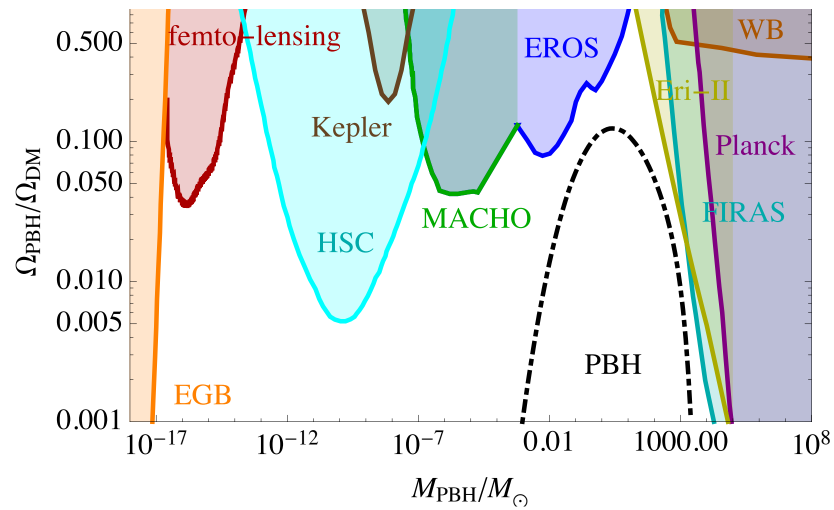


GW produced during inflation and by ζ at re-entry



Garcia-Bellido, MP, Unal '17

Perturbation statistics and GW @ LISA

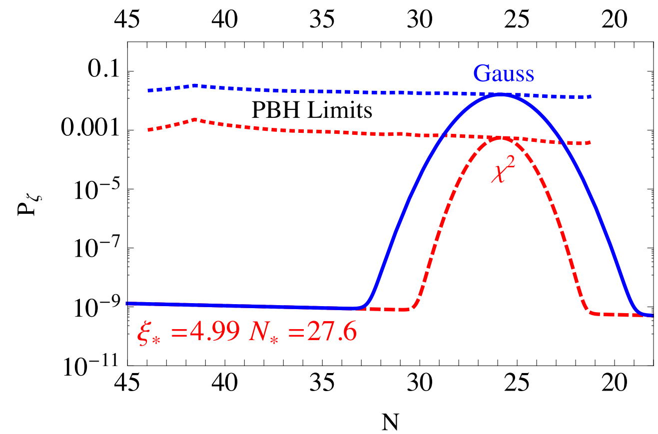


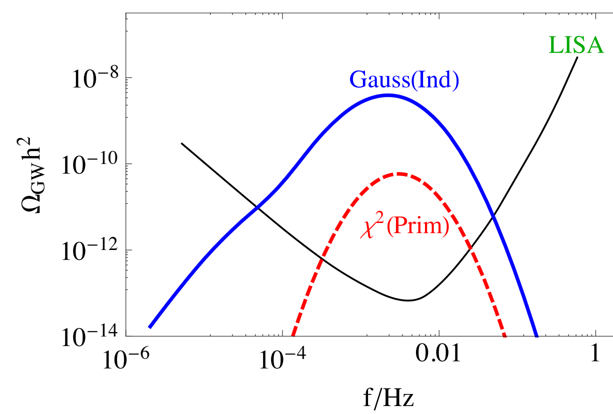
two PBH windows:

- $$M \sim 10^{21}\,\mathrm{g}\left(\frac{5\times 10^{-3}\,\mathrm{Hz}}{f}\right)^2$$

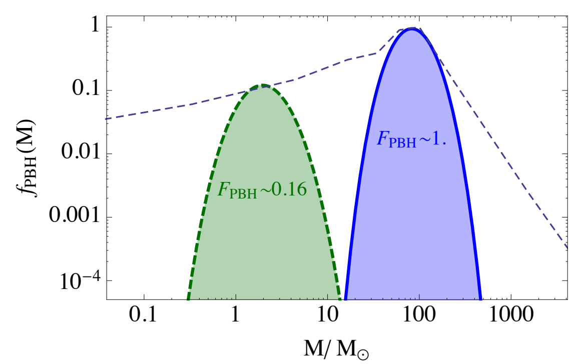
Bump from rolling axion
(primordial GW dominate)

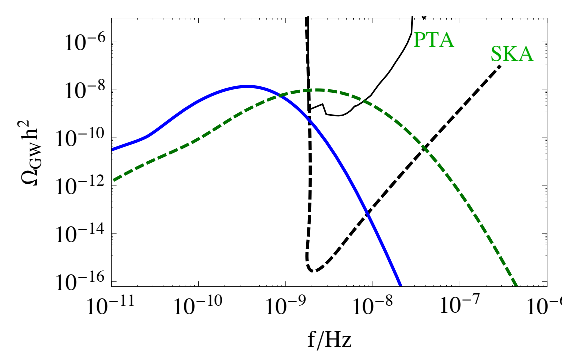
Gaussian bump
(no primordial GW)



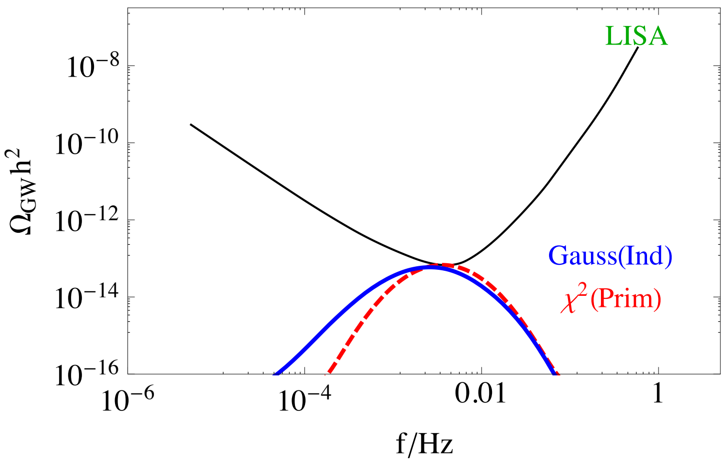


- $$M \sim 10^{33}\,\mathrm{g}\left(\frac{5\times 10^{-9}\,\mathrm{Hz}}{f}\right)^2$$



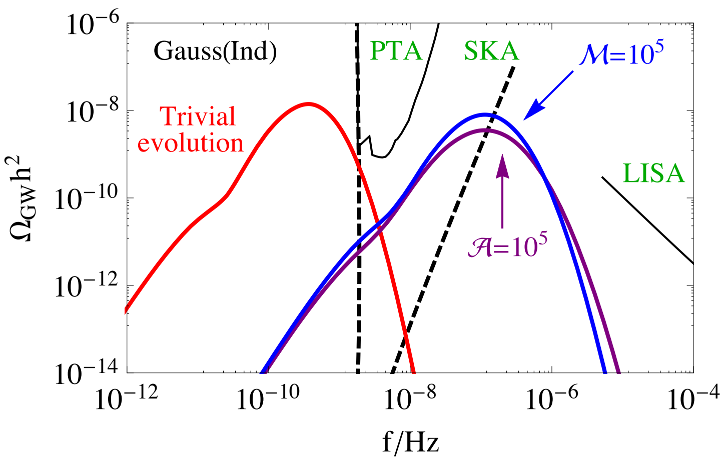


- Bounds / Signal from $P_\zeta \to P_h \to LISA$ typically much stronger than PBH bounds on P_ζ. Just relies on Einstein gravity !



ζ_c	$\frac{\Omega_{PBH}}{\Omega_{dm}}\Big\vert_{\chi^2}$	$\frac{\Omega_{PBH}}{\Omega_{dm}}\Big\vert_{\text{Gauss}}$
1	10^{-381}	10^{-3534}
0.3	10^{-307}	10^{-106}
0.06	10^{-11}	~ 1

- $f_{\text{peak}} \propto M_{\text{peak}}^{-1/2}$. Primordial and 2nd order GW give M_{peak} at formation



Same present PBH distribution;

$\neq$ merging and accretion

Much weaker evolution for $\sim 10^{21}$ g PBH