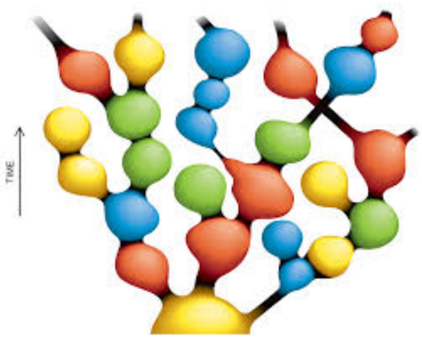
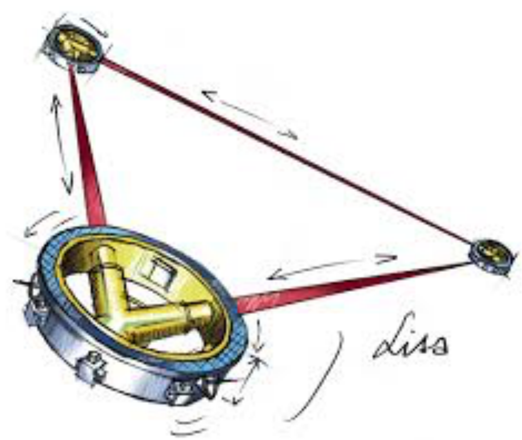
A large GW stochastic background at interferometer scales from axion inflation

Marco Peloso, University of Minnesota





with

Barnaby, Bartolo, Caprini, Crowder, Domcke,

Figueroa, Garcia-Bellido, Guzzetti Liguori,

Mandic, Matarrese, Mukohyama, Moxon, Namba,

Pajer, Petiteau, Ricciardone, Sakellariadou, Shiu,

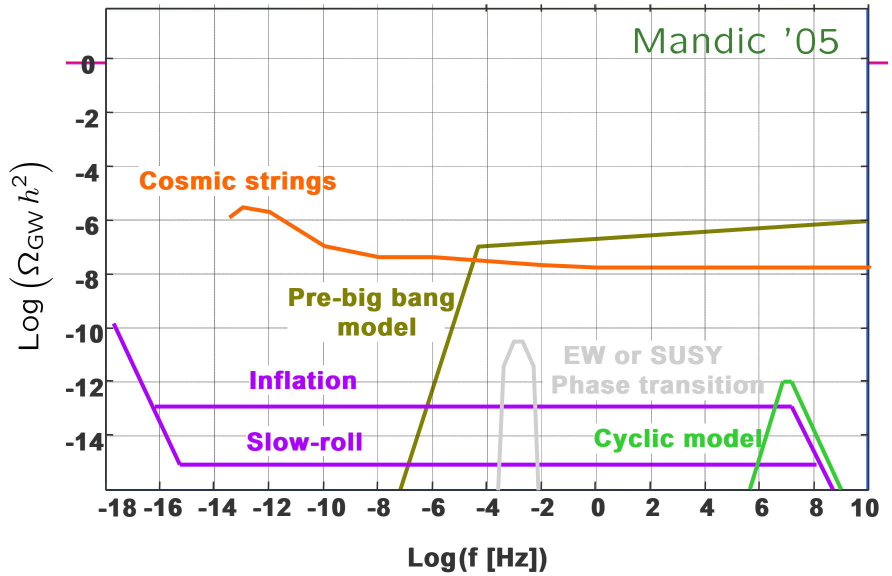
Shiraishi, Sorbo, Tasinato Unal, Zhou

- Over the years, several potential sources of stochastic GW background have been proposed

Pre-big bang cosmology,

cosmic strings,

(EW) phase transition



- GW from inflation ? Guaranteed signal from vacuum metric perturbations, amplified from inflationary expansion

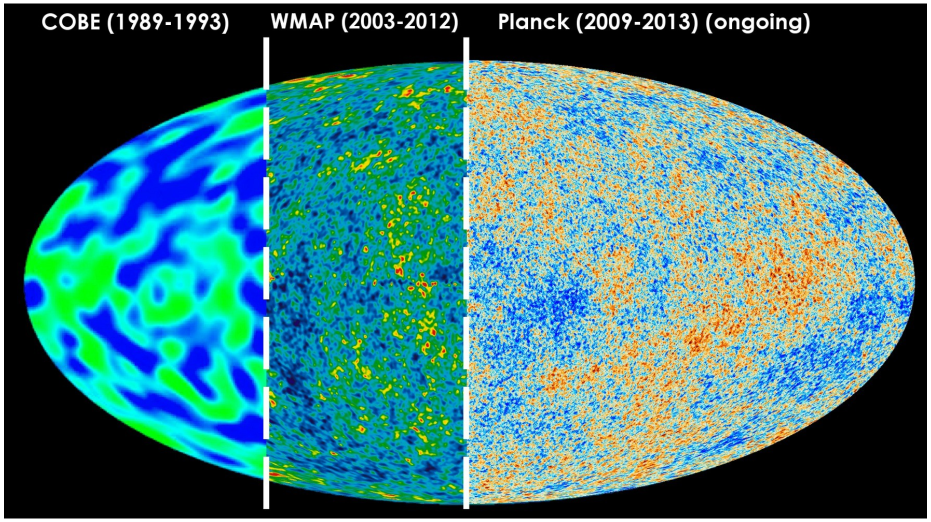
$$\Omega_{GW}\, h^2 \sim 3 \cdot 10^{-16} \left(\frac{H}{7 \cdot 10^{13}\,\mathrm{GeV}}\right)^2$$

➡ Proportional to inflationary expansion rate, $a \simeq e^{Ht}$

➡ Too small to be observed at LISA & AdvLIGO

Inflation and the CMB

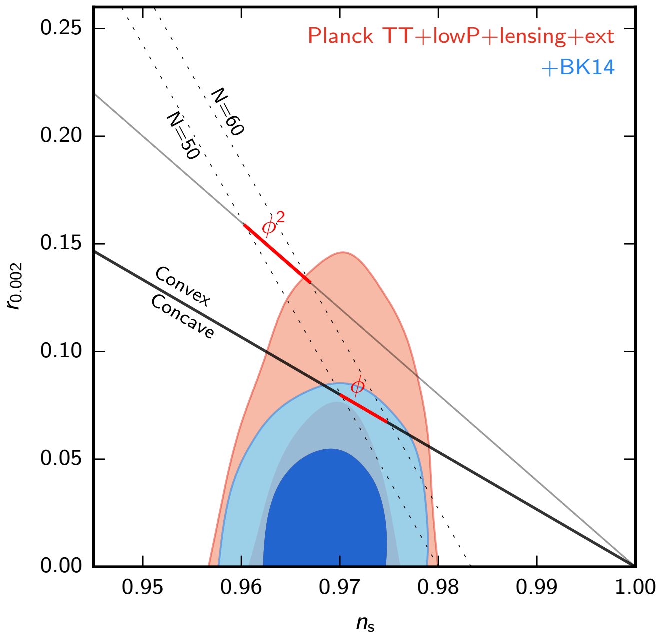
- Simplest models of inflation predict gaussian, adiabatic, super-horizon perturbations, in perfect agreement with observed Cosmic Microwave Background (CMB) radiation



- They also predict

$$r \equiv \frac{P_{\text{GW}}}{P_{\text{density}}} = \frac{\langle \delta g \, \delta g \rangle}{\langle \zeta \, \zeta \rangle} \simeq 0.07 \left(\frac{H}{7 \cdot 10^{13}\,\text{GeV}} \right)^2$$

where δg (GW) and ζ (density perturbations) are the vacuum modes amplified by the inflationary expansion



$\simeq$ scale invariance, $P_\zeta \propto \lambda^{1-n_s}$

- CMB and LSS strongly support the pardigm of inflation. However, they only probe modes $10^{-4} \lesssim k/\text{Mpc}^{-1} \lesssim 10^{-1}$. CMB distortions $\lesssim 10^4$.

  This is 18 of the 60 e-folds of "observable inflation", say $42 \lesssim N \lesssim 60$.

  Smaller scales largely unprobed

- GW interferometers are a window on much smaller scales. $k = 2\pi f$ gives $N \sim 25$ for LISA and $N \sim 15$ for AdvLIGO peak frequencies

- Unique opportunity from GW interferometers gives us strong motivation for studying scenarios of inflation with greater GW production:

Bartolo et al $\subset$ LISA Cosmology group, arXiv:1610.06481

➡ $\delta\rho \rightarrow$ primordial black holes $\rightarrow BH$ — S. Clesse's talk

➡ Spectator fields with small speed of sound

➡ EFT with broken spatial reparametrization — G. Tasinato's talk

➡ Particle production — This talk

We focus on a specific scenario, with a natural class of models of inflation

and with a mechanism of production $\propto \exp\left(\dot{\phi}\right)$

→ GW signal naturally grows at interferometer scales, while small at CMB scales

Axion* Inflation

Freese, Frieman, Olinto '90; ...

(review Pajer, MP '13)

- Shift symmetry $\phi \rightarrow \phi + C$ on couplings to other fields

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \phi)^2 + V_{\cancel{\text{shift}}}(\phi) + \frac{c_\psi}{f}\,\partial_\mu\phi\,\bar{\psi}\,\gamma^\mu\,\gamma_5\,\psi + \frac{\alpha}{f}\,\phi\,F_{\mu\nu}\,\tilde{F}^{\mu\nu}$$

Slow roll inflation requires very flat potential V, and, generically,

hard to explain why V protected against quantum corrections.

With shift symmetry, $\Delta V \propto V_{\cancel{\text{shift}}}$

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* Not the QCD axion; reference values $f \sim 10^{16}\,\text{GeV}$, $m_\phi \simeq 10^{13}\,\text{GeV}$

- Strong restriction on allowed couplings. Interesting effects from

$$\mathcal{L} \supset -\frac{1}{4}F^2 - \frac{\alpha}{4f}\,\phi^{(0)}\;F\,\tilde{F}$$

Turner, Widrow '88

Garretson, Field, Carroll '92

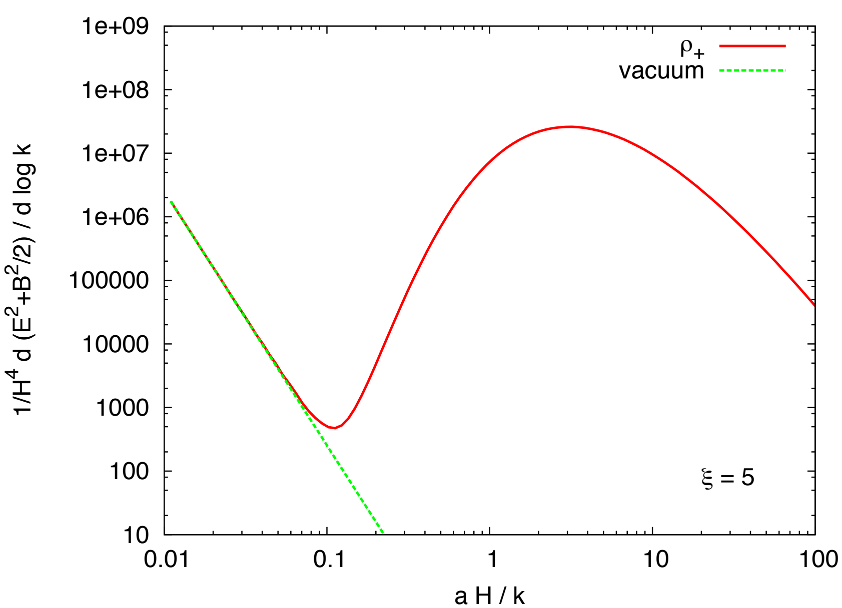
Anber, Sorbo '06

Classical motion $\phi^{(0)}\,(t)$ affects dispersion relations of $\pm$ helicities

$$\Rightarrow \quad \left(\frac{\partial^2}{\partial\tau^2} + k^2 \mp 2\,a\,H\,k\,\xi\right) A_\pm\,(\tau,\,k) = 0 \qquad \xi \equiv \frac{\alpha\,\dot{\phi}^{(0)}}{2\,f\,H} \simeq \text{const.}$$

One tachyonic helicity at horizon crossing

$$\frac{\text{third term}}{\text{second term}} \sim \frac{aH}{k} \simeq \lambda\,H$$



- Growth $A \sim e^{\pi\xi}$ at hor. cross.
- Then diluted away

(UV & IR finite)

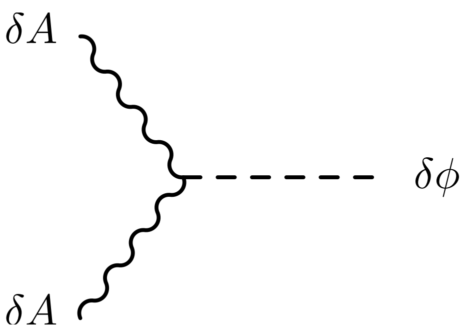
Sourced scalar perturbations from inverse decay

Barnaby, MP '10

Barnaby, Namba, MP '11

$$\delta\ddot{\phi} + 3H\delta\dot{\phi} - \frac{\vec{\nabla}^2}{a^2}\delta\phi + m^2\delta\phi = \frac{\alpha}{f}\vec{E}\cdot\vec{B}$$

(useful em notation. I am not implying this is the Standard Model photon)



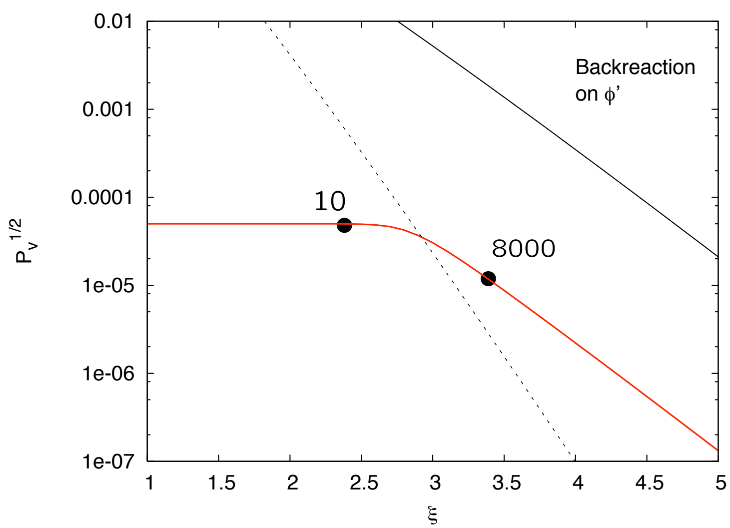
$$\delta\phi = \delta\phi_{\text{vacuum}} + \delta\phi_{\text{inv.decay}}$$

Uncorrelated, $\langle\delta\phi^n\rangle = \langle\delta\phi^n_{\text{vac}}\rangle + \langle\delta\phi^n_{\text{inv.dec}}\rangle$

$$P_\zeta(k) \simeq \mathcal{P}_v\left[1 + 7.5\cdot 10^{-5}\,\mathcal{P}_v\,\frac{e^{4\pi\xi}}{\xi^6}\right]$$

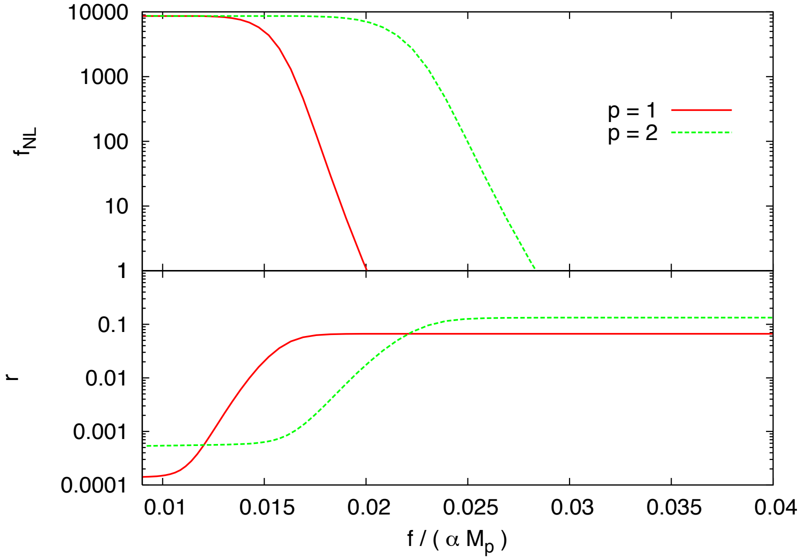
$$\mathcal{P}_v^{1/2} \equiv \frac{H^2}{2\pi|\dot{\phi}|} \qquad (\xi > 1)$$

$$\xi \equiv \frac{\alpha\,\dot{\phi}}{2fH}$$



Sourced δ highly non-gaussian (equilateral); $f_{\text{NL,equil}} = -4 \pm 43$ Planck '15

Constrains axion decay constant $f > \mathrm{O}\left(10^{16}\,\text{GeV}\right)$



Gauge field also produces GW, $\delta A + \delta A \to h$

However, more production $\to$ smaller $r^{1/2} = \frac{h_{\text{vacuum}} + h_{\text{sourced}}}{\zeta_{\text{vacuum}} + \zeta_{\text{sourced}}}$

(sourced GW $\ll$ sourced $\delta\phi$)

More production $\left(\frac{\alpha}{f} F \tilde{F}\right)$

General issue: how to increase h_{sourced} more than δ_{sourced} ?

Barnaby et al 12; Mirababayi, Senatore, Silverstein, Zaldarriaga '14;

Ferreira, Sloth '14; Namba et al '15

Huge experimental activity to detect GW through CMB polarization

Vacuum GW signal $\leftrightarrow$ scale of inflation $\quad V^{1/4} = 10^{16}\,\text{GeV} \left(\frac{r}{0.01}\right)^{1/4}$

How robust ? Can sourced GW change this ?

CMB-S4 Science Book 1610.02743

2.6.3 Distinguishing vacuum fluctuations from other particle physics sources of B modes

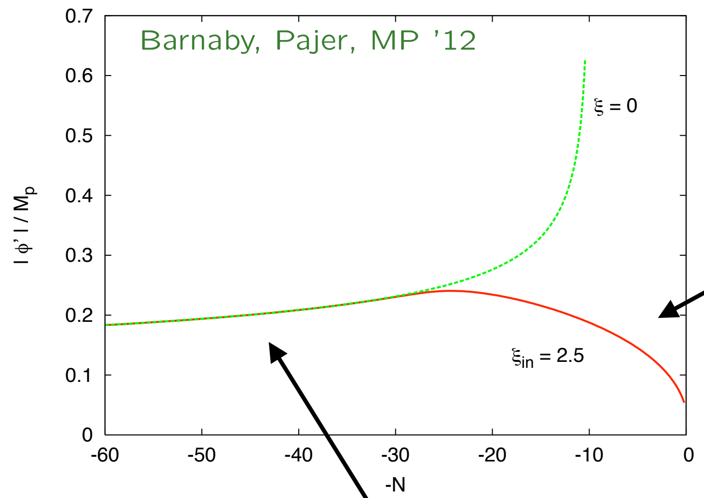
Blue spectra from $\phi F \tilde{F}$

$\delta A \sim e^{\pi \xi}$ and $\xi \propto \frac{\dot{\phi}}{H}$. Inflaton speeds up during inflation

$\Rightarrow$ naturally greater effects at later times $\equiv$ smaller scales

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

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



Large ξ, friction from gauge field amplification

Anber, Sorbo '09

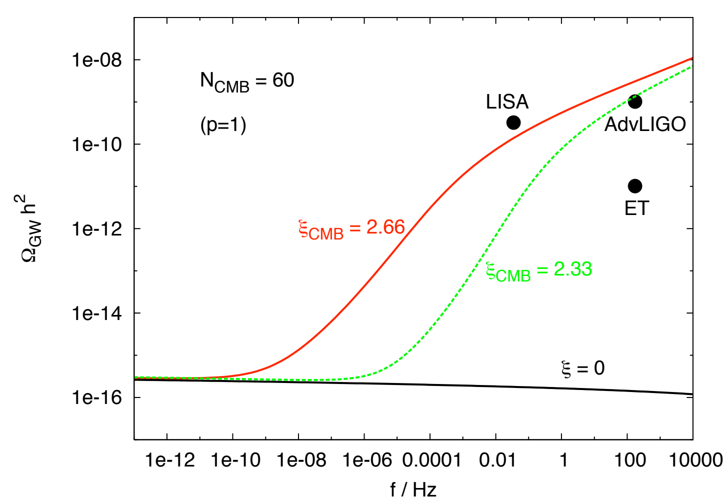
Small ξ standard slow-roll

- Larger GW production at interferometer scales

Cook, Sorbo '11

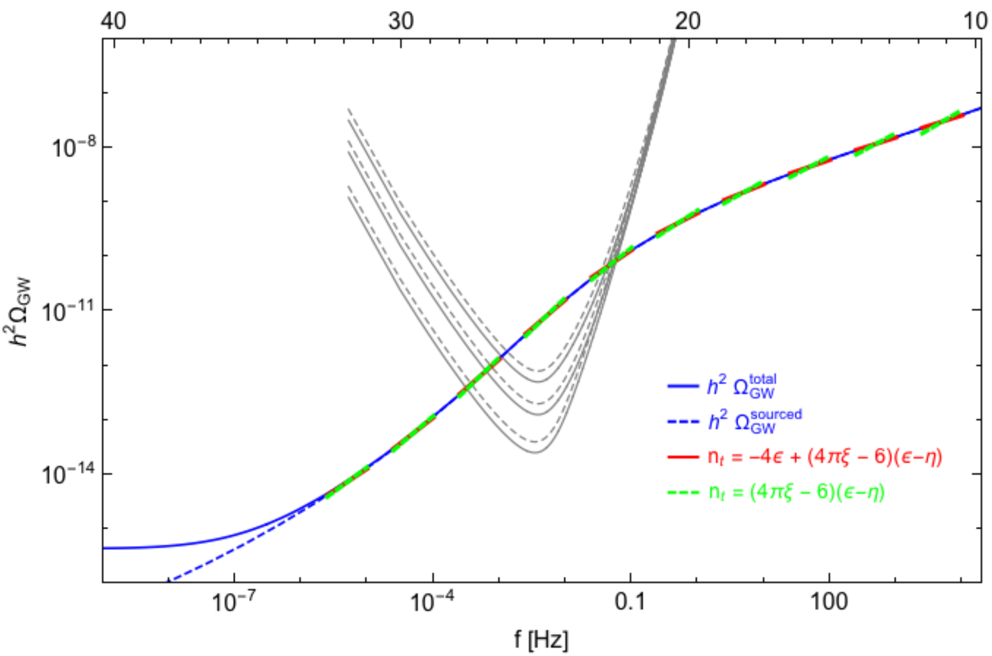
Barnaby, Pajer, MP '12

Domcke, Pieroni, Binétruy '16



Characterization of the GW signal

Bartolo et al' 16



$V = \frac{m^2}{2}\phi^2$, Axion scale $= M_p/35$

Name	A5M5	A5M2	A2M5	A2M2	A1M5	A1M2
Arm length [km]	5M	5M	2M	2M	1M	1M
Duration [years]	5	2	5	2	5	2

$$\Omega_{GW}\, h^2 \simeq 1.5 \cdot 10^{-13} \frac{H^4}{M_p^4} \frac{e^{4\pi\xi}}{\xi^6} \quad , \quad \xi \gg 1$$

$$n_T \simeq (4\pi\xi - 6)\,(\epsilon - \eta)$$

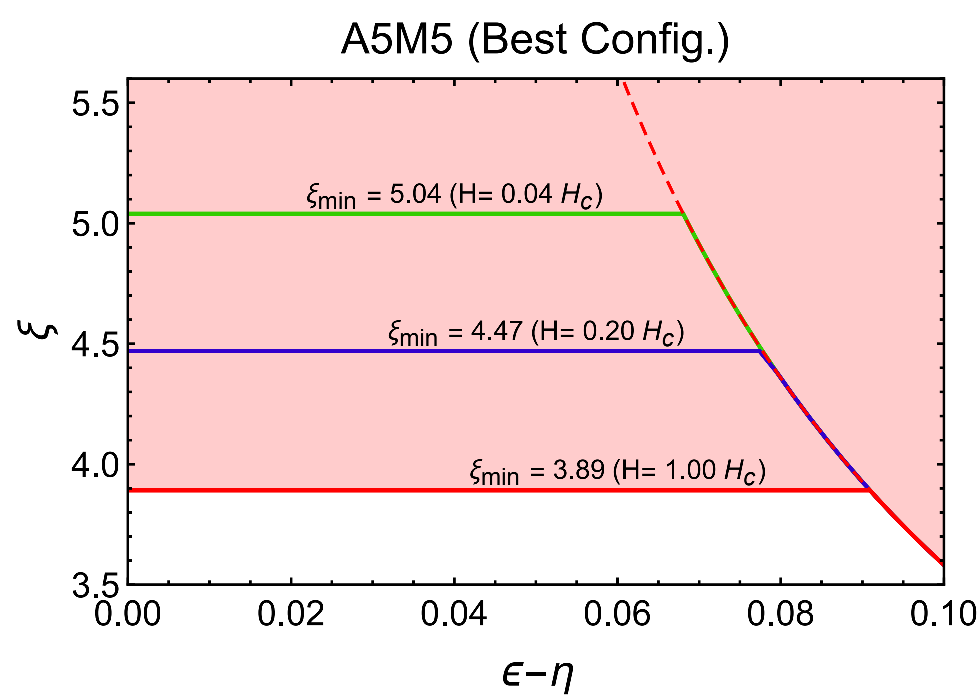
$$\left(\epsilon \equiv -\frac{\dot{H}}{H^2} \ , \ \eta \equiv -\frac{\ddot{\phi}}{H\,\dot{\phi}} \right)$$

Region with signal

above A5M5 sensitivity

$H_c = 6.4 \cdot 10^{13}$ Hubble rate

at $N = 25$ in $V = \frac{m^2}{2}\phi^2$



Larger scalar perturbations ζ at smaller scales

Meerburg, Pajer '12;
Linde, Mooij, Pajer '12

- As in the CMB case, the main obstacle in getting sourced visible GW at LISA is to avoid simultaneous overproduction of ζ

- Uncertainty in scalar perturbations in large ξ regime. Beside r.h.s additional effect from $A\left[\xi\left[\dot{\phi}+\delta\dot{\phi}\right]\right]$. Friction also on $\delta\phi$

Anber, Sorbo '09

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

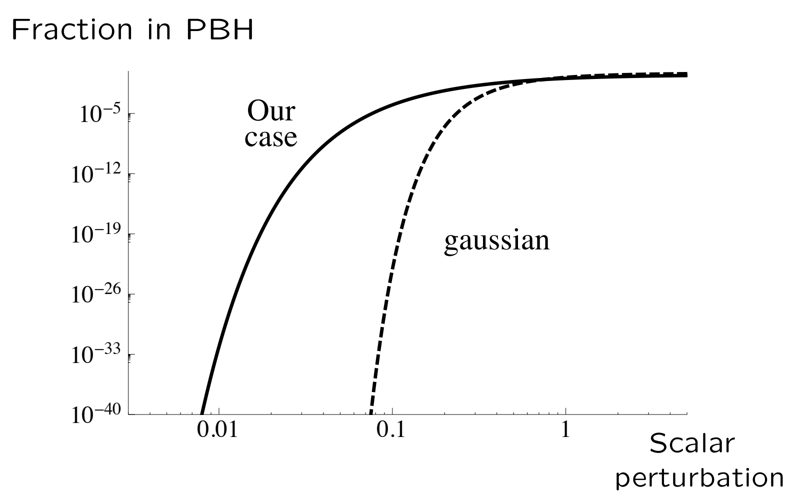
- Other terms may become relevant in the large ξ regime (this problem is absent for ζ at CMB scales, and for GW)

- At CMB scales, overproduction of ζ meant NG of ζ, and running of n_s

Barnaby, MP '10; Meerburg, Pajer '12

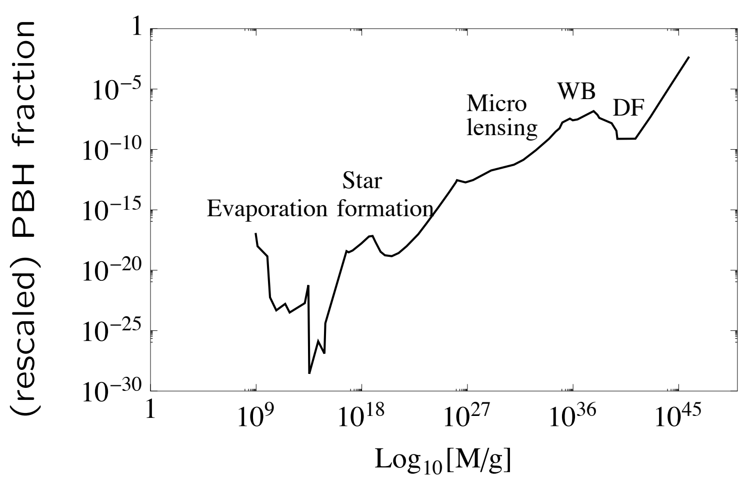
- At small scales, it means too many primordial black holes (PBH)

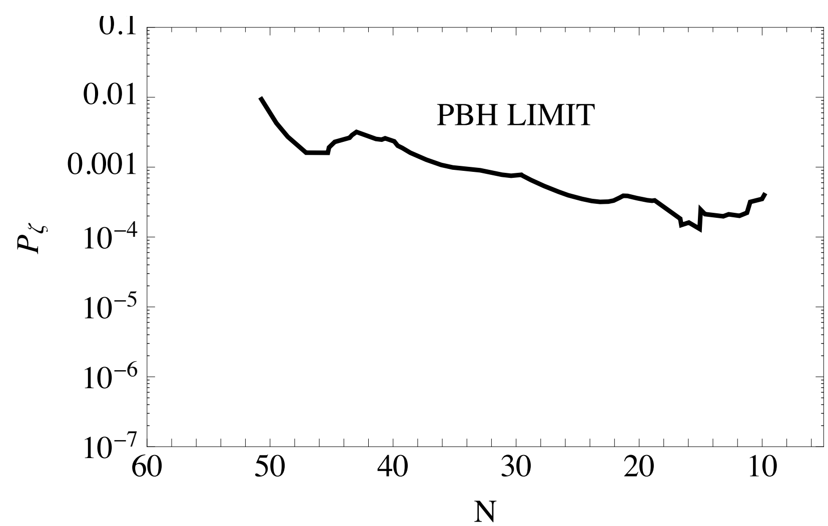
Linde, Mooij, Pajer '12



- For any given ζ, many more PBH in our case wrt gaussian ζ

- Small change in $\zeta \rightarrow$ huge change in PBH fraction

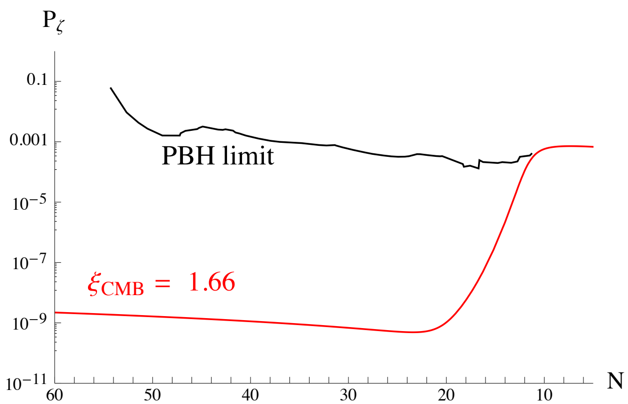


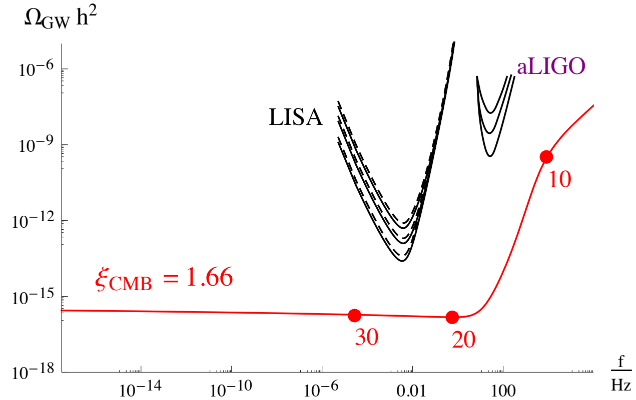


Updated by Garcia-Bellido, MP, Unal '16 from Carr et al '09

- In chaotic inflation, PBH bound (if computation of ζ is accurate) prevents GW from being observable

Linde, Mooij, Pajer '13



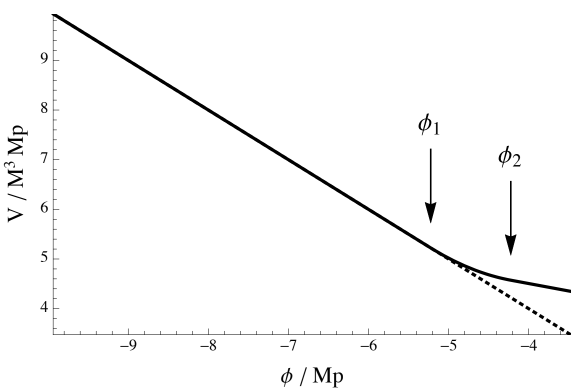


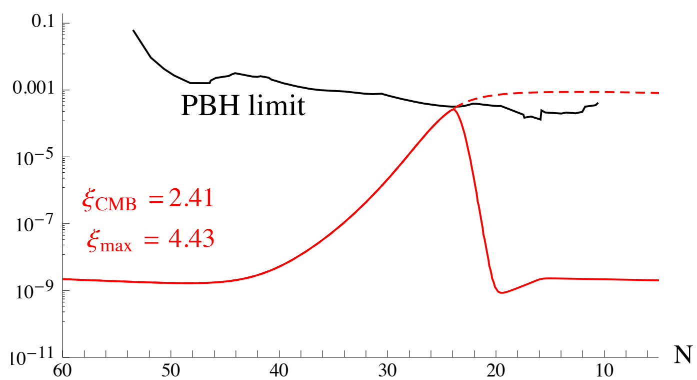
- In relating $N \simeq 10$ with $N \simeq 25$, a given $V(\phi)$ must be assumed.

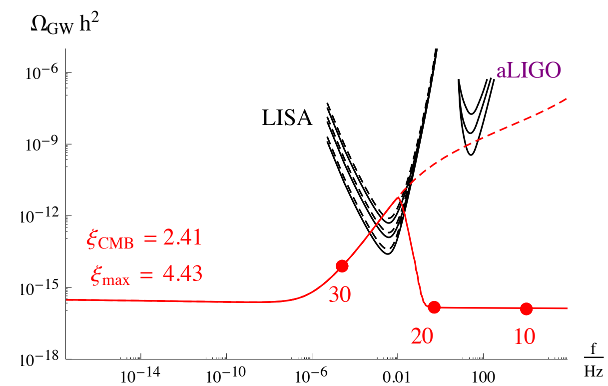
Do PBH bounds at the LISA scales prevent GW to be seen at LISA ?

Garcia-Bellido, MP, Unal '16

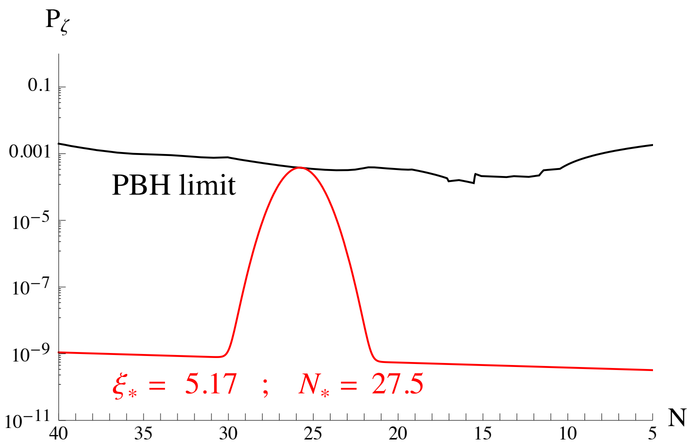
- Due to $\propto e^{\dot{\phi}}$, significant differences from a minor change of V

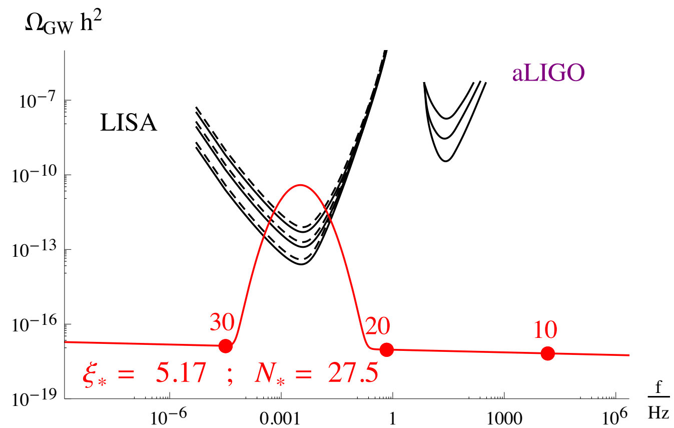




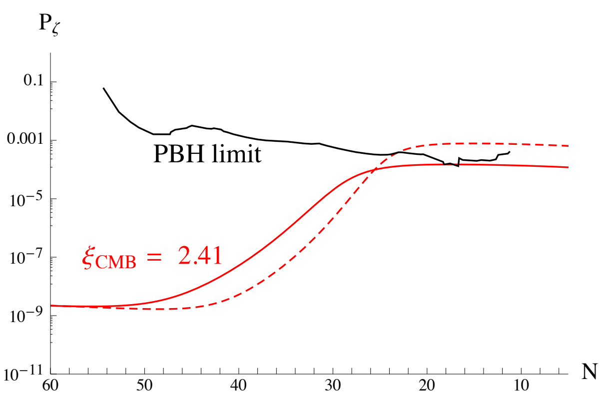


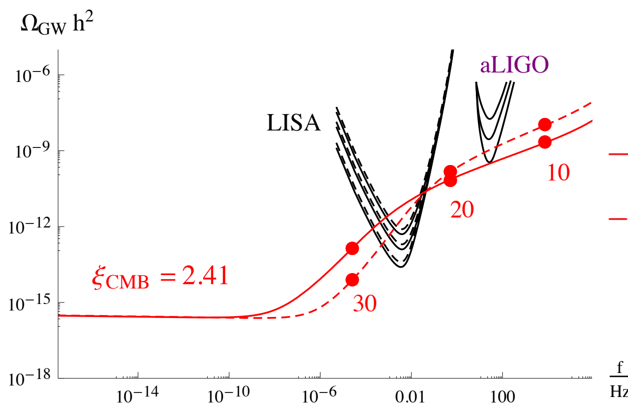
Same conclusion for localized production in $-\mathcal{L} \supset V(\phi) + V(\sigma) + \frac{\sigma}{4} F\tilde{F}$

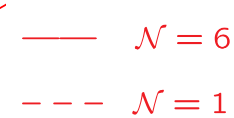




- If $\mathcal{N}$ gauge fields (eg. non-abelian), more backreaction, and $\frac{P_{GW}}{P_\zeta} \propto \mathcal{N}^2$







Domcke, Pieroni, Binétruy '16

Garcia-Bellido, MP, Unal '16

- A bump at $N \sim 40$ can give PBH, which are seeds of super massive BH, whose collisions can be probed at LISA. More details in Clesse's talk

Assume we see this. Can we distinguish it from astrophysical signal ?

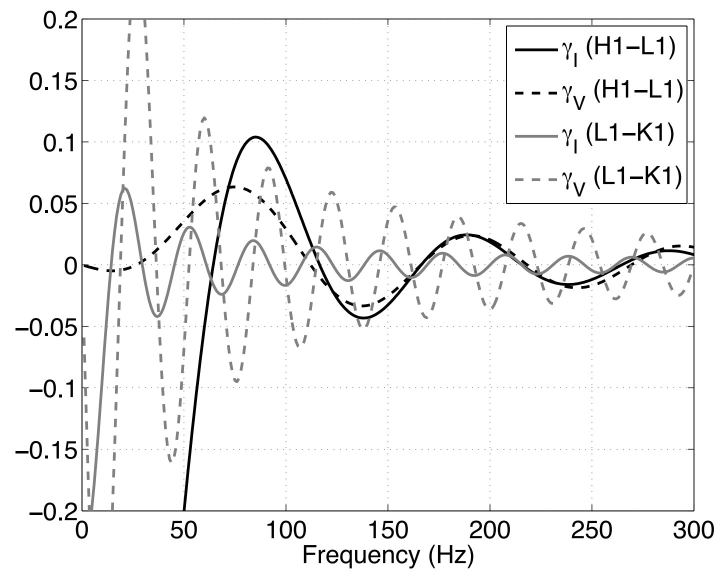
Chiral GW @ interferometers

Seto, Taruya '07 applied to current interferometers in Crowder, Namba, Mandic, Mukohyama, MP '12

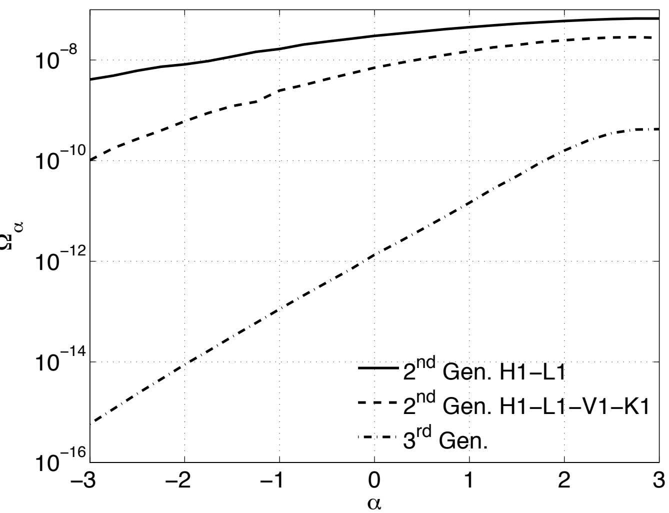
$$\langle s_1 s_2 \rangle \propto \Omega_{GW}(f) \left[\gamma_I(f) + \Pi(f) \gamma_\Pi(f) \right]$$

$$\Pi \equiv \frac{P_R - P_L}{P_R + P_L}$$

γ depend on orientations of the detectors and on the GW frequency



- Need three detectors To determine Ω_{GW} and Π



$$\Omega = \Omega_\alpha \left(\frac{f}{100\text{Hz}} \right)^\alpha$$

Assume $|\Pi| = 1$. How large does signal need to be to detect GW and exclude $\Pi = 0$ at 2σ ?

Non – gaussianity : $k^6 \left\langle h_L^3 \right\rangle_{\text{equil}} \simeq 23\, P_{\text{GW}}^{3/2}$, for any $V(\phi)$ and $\xi \gg 1$

Cook, Sorbo '13

Conclusions

- CMB+LSS probe only a small portion of inflation. GW interferometers offer a potential new window. Guaranteed vacuum signal is too small. Still, we can probe several inflationary mechanisms

- Among them, sourced GW in axion inflation is particularly interesting, since it naturally grows at interferometer scales

- As for CMB studies, fight between tensor and scalar production. Limits on scalars from PBH have theoretical uncertainty and are model-dependent

- Distinctive signatures: chirality and NG