Sourced GW from axion inflation

Marco Peloso, University of Minnesota

- Sourced scalar and tensor perturbations
- CMB phenomenology
- Interferometer phenomenology

In collaboration with

Barnaby, Biagetti, Crowder, Dimastrogiovanni, Fasiello,

Garcia-Bellido, Kim, Komatsu, Mandic, Mukohyama, Moxon,

Namba, Nilles, Pajer, Pearce, Shiu, Shiraishi, Sorbo, Unal, Zhou

- CMB in agreement with simplest models of slow-roll inflation

$$r \equiv \frac{P_{\rm GW}}{P_\zeta} \quad , \quad n_s - 1 \equiv \frac{d \ln P_\zeta}{d \ln k} \quad , \quad f_{\rm NL} \sim \frac{\langle \zeta^3 \rangle}{\langle \zeta^2 \rangle^2} \;=\; {\rm O}\left(\epsilon , \eta\right)$$

$$\epsilon \equiv \frac{M_p^2}{2} \left(\frac{V_{,\phi}}{V} \right)^2 \ll 1$$

$$\eta \equiv M_p^2 \, \frac{V_{,\phi\phi}}{V} \ll 1$$

- Flatness and gaussianity $\rightarrow$ small inflaton self-couplings

$$\left(\text{e. g.,} \;\; \Delta V = \frac{\lambda}{4} \phi^4 \;\; \Rightarrow \;\; \lambda < 10^{-13} \right)$$

- Shift symmetry on couplings to other fields

Freese, Frieman, Olinto '90; . . .

(review Pajer, MP '13)

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

has the advantage that

➡ Smallness of $V_{\cancel{\rm shift}}$ technically natural. $\Delta V \propto V_{\cancel{\rm shift}}$

➡ Constrained couplings to matter (predictivity)

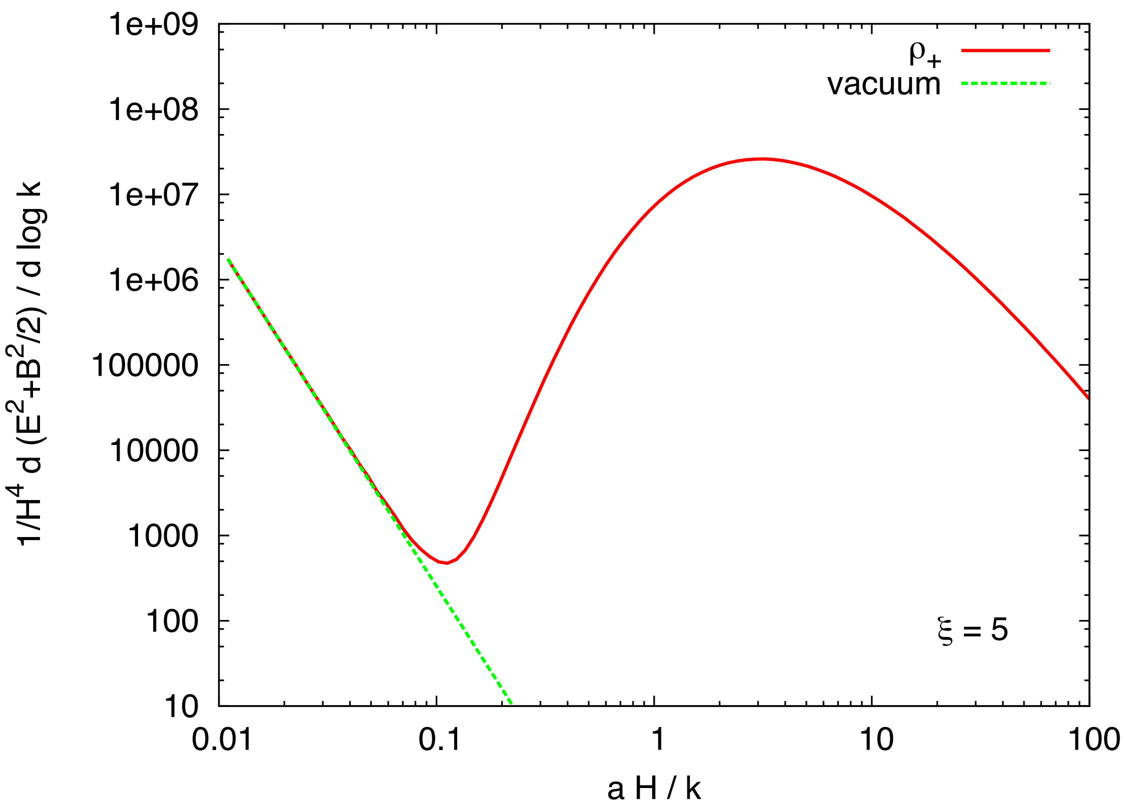
$$\mathcal{L} \supset -\frac{1}{4} F^2 - \frac{\alpha}{4f} \phi^{(0)} \; F \tilde{F}$$

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

Anber, Sorbo '06



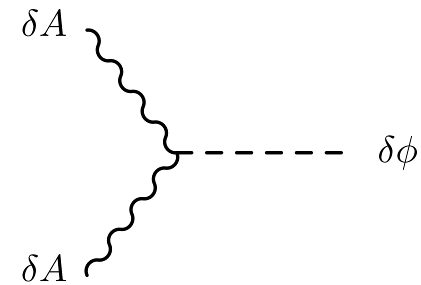
- Growth $A \sim e^{\pi \xi}$

  at hor. cross.

- Then diluted away

(UV & IR finite)

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



(Additional interactions due to δg negligible for $\frac{\alpha}{f} \gg \frac{1}{M_p}$)

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

Barnaby, MP '10

Barnaby, Namba, MP '11

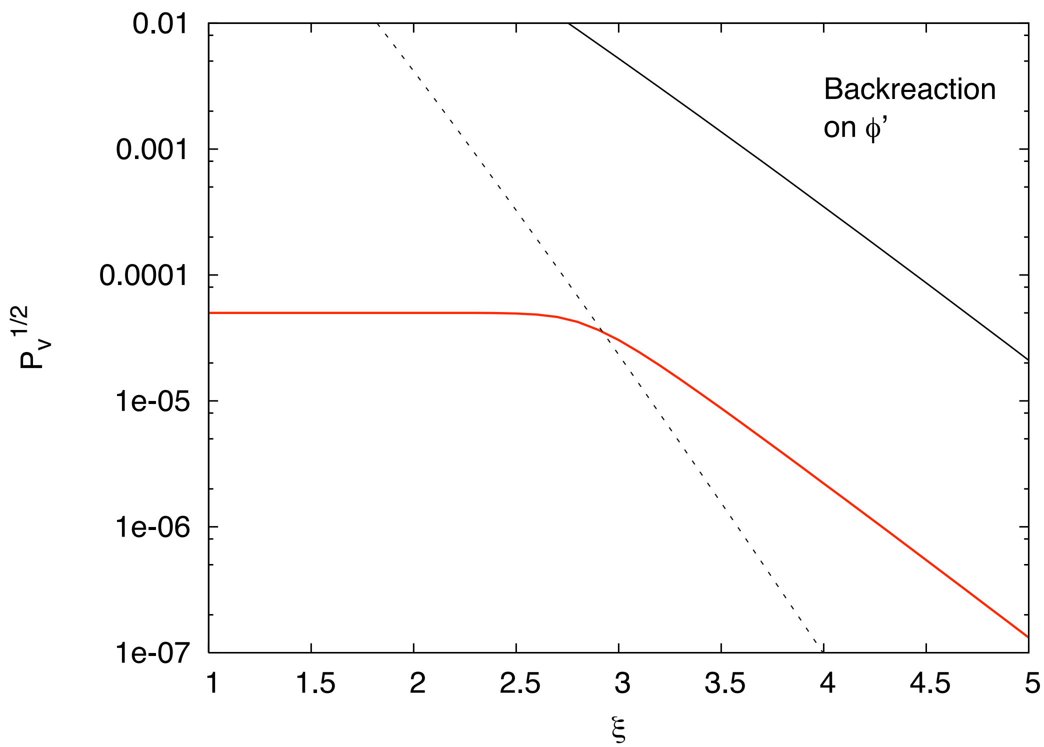
Uncorrelated, $\langle\delta\phi^n\rangle = \langle\delta\phi^n_{\text{vac}}\rangle + \langle\delta\phi^n_{\text{inv.dec}}\rangle$

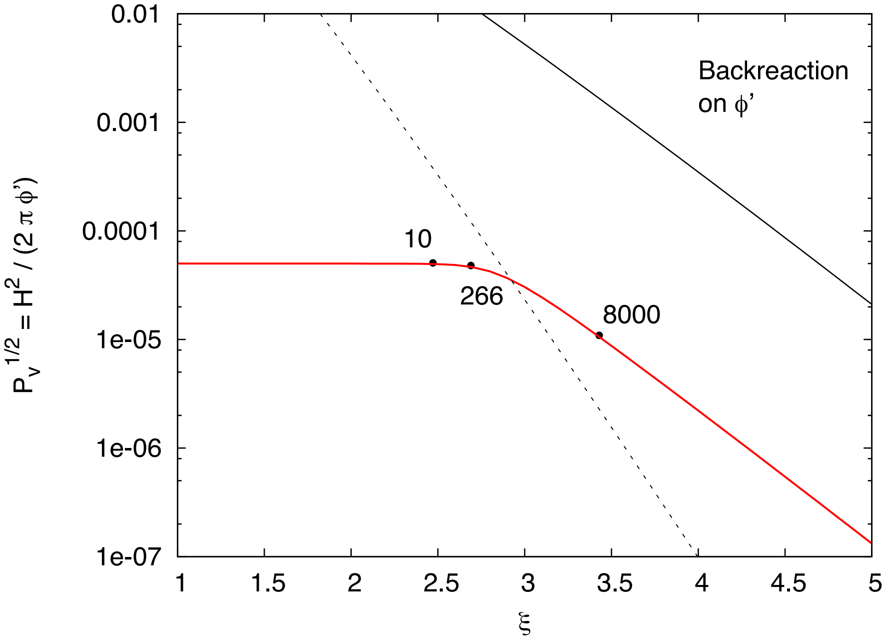
$$P_\zeta(k) \simeq \mathcal{P}_v\left[1 + 7.5\cdot 10^{-5}\,\mathcal{P}_v\,\frac{e^{4\pi\xi}}{\xi^6}\right]$$

$(\xi > 1)$

$$\mathcal{P}_v^{1/2} \equiv \frac{H^2}{2\pi|\dot{\phi}|}$$

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

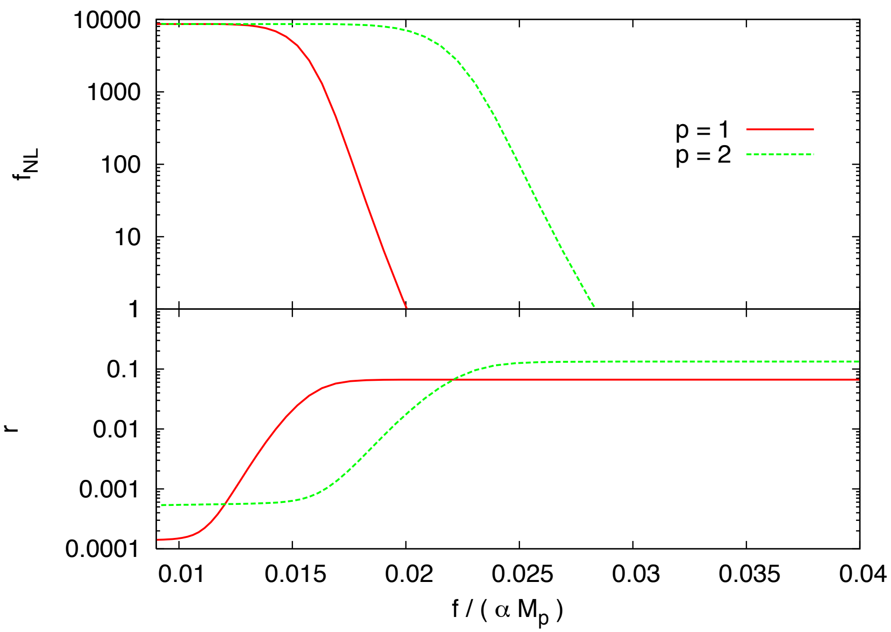




At any moment, only δA with $\lambda \sim H^{-1}$ present

Nearly equilateral NG

$f_{NL}^{\rm equil} = -4 \pm 43$ Planck '15



$\delta A \sim e^{\pi\xi}$ so large variation in a small window of $\xi = O(1)$

$\xi = O(1)$ for $f/\alpha = O\left(10^{16}\,\text{GeV}\right)$

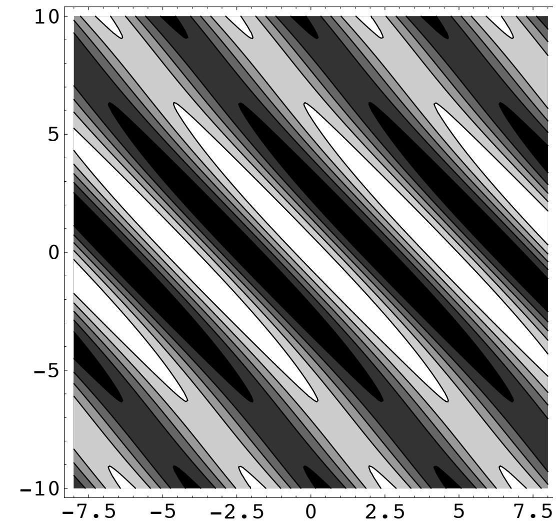
More production $\rightarrow$ smaller r

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

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

- $f \gtrsim 7\, M_p$ needed in $V = \Lambda^4 \left[1 + \cos\left(\frac{\phi}{f}\right)\right]$. Values $f \simeq 10^{-2}\, M_p$ relevant for models with sub-Planckian axion scale, but effective $\Delta\phi > M_p$

Kim, Nilles, MP '05



E.g., Monodromy, N-flation, Aligned Natural Inflation

$$V = \Lambda_1^4 \left[1 - \cos\left(\frac{\theta}{f_1} + \frac{\rho}{g_1}\right)\right] + \Lambda_2^4 \left[1 - \cos\left(\frac{\theta}{f_2} + \frac{\rho}{g_2}\right)\right]$$

$f_{\rm eff} \gg f_i,\, g_i$ if $\frac{f_1}{g_1} \simeq \frac{f_2}{g_2}$

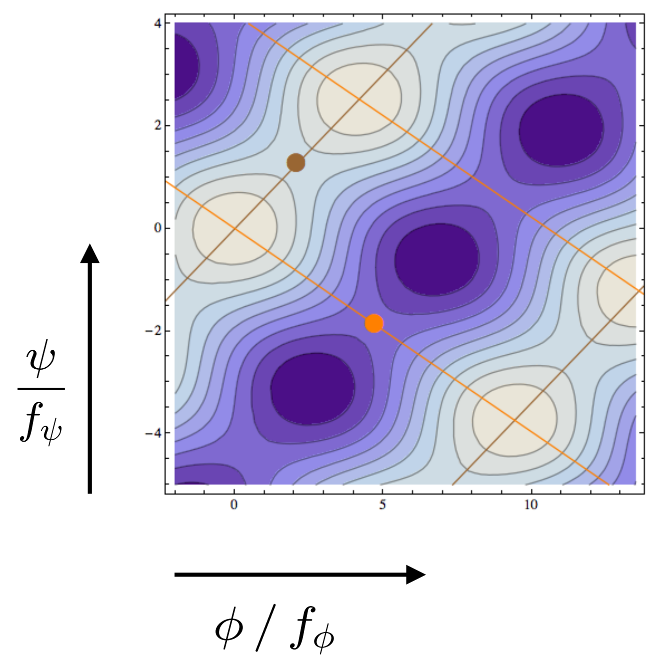
(gravitational instanton corrections may still be a problem if $f_{\rm eff} > M_p$)

$$\alpha \equiv \frac{f_1\, g_2 - f_2\, g_1}{f_1\, g_2 + f_2\, g_1} \ll 1$$ alignment parameter

MP, Unal '15

$\psi \equiv$ heavy combination
Effective scale : $f_\psi = O\,(f_i,\, g_i)$

$\phi \equiv$ light combination
Effective scale : $f_\phi = O\left(\frac{f_i}{\alpha},\, \frac{g_i}{\alpha}\right)$



Fields rescaled

$\simeq$ curvature

in 2 directions

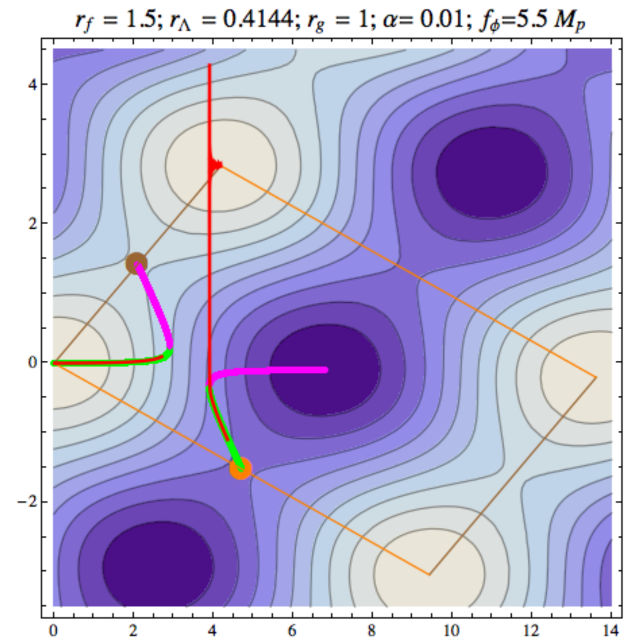
ψ much heavier

Inflation along

valleys $\frac{\partial V}{\partial \psi} = 0$

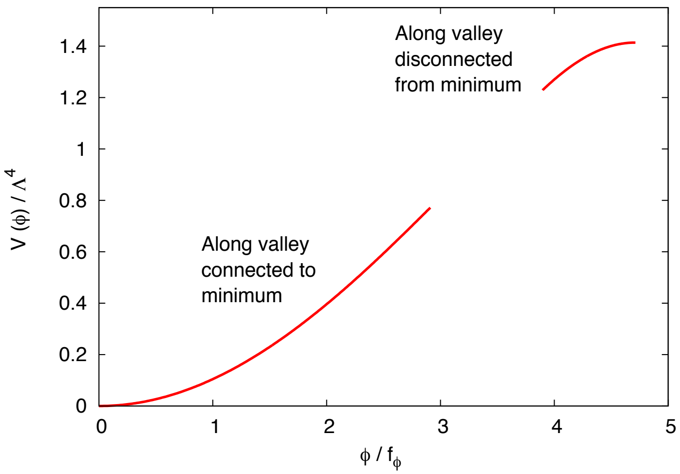
Stable valleys , $\dfrac{\partial V}{\partial \psi} = 0$, $\dfrac{\partial^2 V}{\partial \psi^2} > 0$ $\rightarrow$ inflationary trajectories

Unstable crests , $\dfrac{\partial V}{\partial \psi} = 0$, $\dfrac{\partial^2 V}{\partial \psi^2} < 0$



For some parameters inflationary trajectories ending because

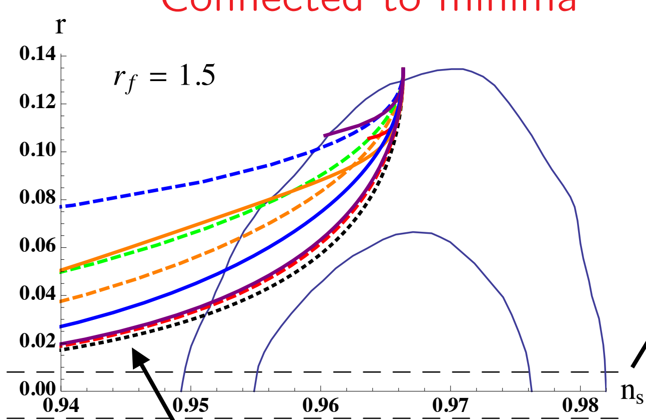
(1) reach a minimum or (2) become unstable in heavy direction



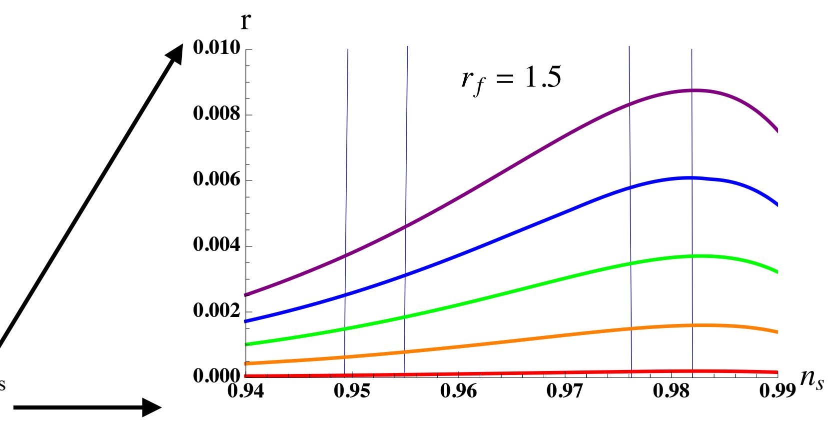
Trajectories (2) have a flatter potential $\left(\equiv \text{ smaller } \epsilon \propto V'^2/V^2\right)$

and so smaller GW (recall $r = 16\,\epsilon$)

Connected to minima

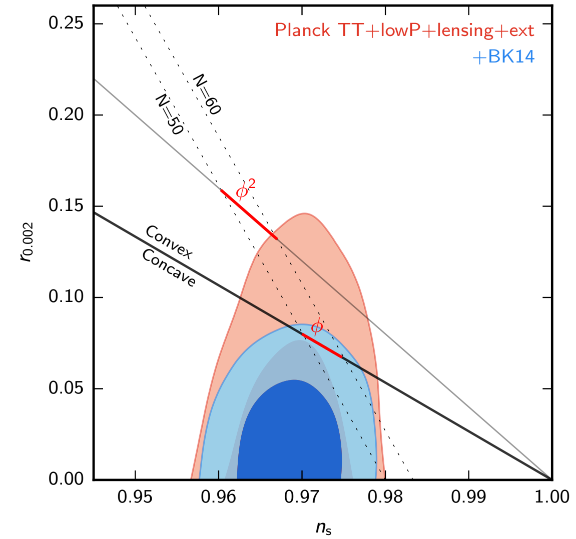


Disconnected



All above natural inflation !

GW at CMB scales



- With latest Keck Array : $r < 0.07$

- Strong experimental program, from ground, balloon, and (proposed) satellite

Ground Based

Chile	Have data	Current or planned freqs
* ABS	■	145 GHz
ACTPol/AdvACt	■	30, 40, 90, 150, 230 GHz
POLARBEAR	■	90, 150 GHz
* CLASS	□	40, 90, 150 GHz
Antarctica		
* BICEP/KECK	■	90, 150, 220 GHz
SPTPol	■	90, 150 GHz
QUBIC-Bolo int.	2016	90, 150, 220 GHz
Elsewhere (for now)		
B-Machine –WMRS	■	40 GHz
* GroundBIRD, LiteBIRD	2016	150 GHz
* GLP – Greenland	TBD	150, 210, 270 GHz
* MuSE-Multimoded	TBD	44, 95, 145, 225, 275 GHz
QUIJOTE –Canaries, HEM	■	11-20, 30 GHz

Balloons

	Have data	Current or planned freqs
* EBEX	■	150, 250, 210 GHz
LPSE	TBD	5 chan 40-250 GHz
* PIPER	2015	200, 270, 350, 600 GHz
* SPIDER	□	90, 150, 280 GHz

L. Page, Ferrara, Dec. 2014

- Multi-frequency is key, to eliminate dust

CMB-S4 Science Book 1610.02743

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

- Vacuum modes : $V^{1/4} = 10^{16}\,\text{GeV} \left(\frac{r}{0.01}\right)^{1/4}$. $\Delta\phi \gtrsim M_p \left(\frac{r}{0.01}\right)^{1/2}$

How robust ? Lyth '96

$\mathcal{L} = (\phi - \phi_*)^2 \, \chi^2$ Cook, Sorbo '11

Senatore, Silverstein, Zaldarriaga '11

$\mathcal{L} = \sigma \, F \, \tilde{F}$ Barnaby, Moxon, Namba, MP, Shiu, Zhou '12

Namba, MP, Shiraishi, Sorbo, Unal '15

$\mathcal{L} = \frac{1}{2} \left(\delta\sigma'^2 - c_s^2 \left(\nabla \, \delta\sigma \right)^2 \right)$, $c_s \ll 1$ Biagetti, Fasiello, Riotto '13

Biagetti, Dimastrogiovanni, Fasiello, MP '14

Models I worked on (standard GR and QM)

Alternative mechanism in chromonatural inflation

Maleknejad; Obata, Soda; Dimastrogiovanni, Fastello Fujita; Adshead, Martinec, Sfakianakis, Wyman '16

A field X produced during inflation, and $X \to h_{\text{sourced}} \gg h_{\text{vacuum}}$

- Real question h_{sourced} vs. ζ_{sourced}. Whatever sources GW is also at least gravitationally coupled to ζ Barnaby, MP '10; Barnaby et al' 12; Mirbabayi, Senatore, Silverstein, Zaldarriaga '14; Namba et al '15

Burst of particle production

$$V = V(\phi) + \frac{g^2}{2}(\phi - \phi_*)^2 \chi^2$$

Number. Value reached by the inflaton during inflation

Chung, Kolb, Riotto, Tkachev '99

Romano, Sasaki '08

Barnaby, Huang, Kofman, Pogosyan '09

Green, Horn, Senatore, Silverstein '09

Lopez Nacir, Porto, Senatore, Zaldarriaga '11

Pearce, MP, Sorbo '16

- For most of the evolution, $m_\chi \sim g\phi,\ g\phi_* \gg H$, no effect
- At $\phi = \phi_*$, nonadiabatic m_χ variation

$$\Rightarrow \quad n_\chi(t_*) = \exp\left(-\frac{\pi k^2}{g\,\dot{\phi}}\right)$$

Cook, Sorbo '11

Produced χ sources $\delta\phi$ (later). Also, source of GW

Senatore, Silverstein, Zaldarriaga '11

Analogously for $V(\phi) + \frac{g^2}{2}(\phi - \phi_*)^2\, A_\mu A^\mu$ Cook, Sorbo '11

For the following slide, keep in mind that quanta of χ, A_μ produced when massless, but - due to motion of ϕ - quickly become non-relativistic.

- Few GW in simplest implementation (more possibilities Senatore et al '11)

How to increase h_{sourced} vs. ζ_{sourced} ?

Barnaby et al '12

Rule 1: Source of GW in a sector gravitationally coupled to inflaton

E. g. $$V(\phi) + V(\sigma) + \frac{g^2}{2}(\sigma - \sigma_*)^2 \, A_\mu \, A^\mu$$

Canonical inflaton / GW mode satisfy $\left(\partial_\tau^2 - \frac{a''}{a} + k^2\right) Q_i \simeq J_i$, with

$$J_\phi \simeq \frac{\dot{\phi}}{2M_p^2 H a} \int \frac{d^3p}{(2\pi)^{3/2}} \left[\hat{k}_i \hat{k}_j \left(M^2 - \partial_\tau^{(1)} \partial_\tau^{(2)}\right) - M^2 \delta_{ij}\right] A_i(\vec{p}) \, A_j\left(\vec{k} - \vec{p}\right)$$

$$J_\lambda = \frac{\Pi^*_{mn,\lambda}\left(\hat{k}\right)}{a M_p} \int \frac{d^3p}{(2\pi)^{3/2}} \left[\delta_{mi}\delta_{nj}\left(-\partial_\tau^{(1)}\partial_\tau^{(2)} + M^2\right) + \epsilon_{mai}\epsilon_{nbj} p_a (k-p)_b\right] A_i(\vec{p}) \, A_j\left(\vec{k} - \vec{p}\right)$$

Recall $\partial_\tau \simeq M \gg p$. Big cancellation on tensor source

Non-relativistic quanta have suppressed quadrupole moment

Rule 2: Source of GW should be relativistic

Both rules satisfied by $V_\phi(\phi) + V_\sigma(\sigma) + \frac{\sigma}{f} F \tilde{F}$

- A_+ produced by rolling $\sigma(t)$, different from inflaton ϕ
- Due to helicity, $A + A \to h$ stronger than $A + A \to \delta\phi$ (both gravitational)
- However, large $\delta\sigma$ production. As long as σ is rolling, linearly coupled (again, gravitational effect) to $\delta\phi$. Significant $A + A \to \delta\sigma \to \delta\phi$

Ferreira, Sloth '14

Rule 3: Source effective only for limited time

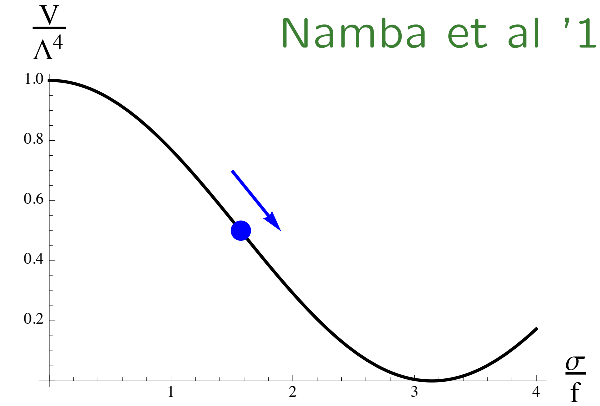
Namba, MP, Shiraishi, Sorbo, Unal '15

- Less time for δsource $\to$ $\delta\phi$
- Can produce modes at $\ell \lesssim 100$ (good for GW, looser limits from NG)

Bump in δ_{sourced}, h_{sourced} on scales that left horizon while source effective

Namba et al '15

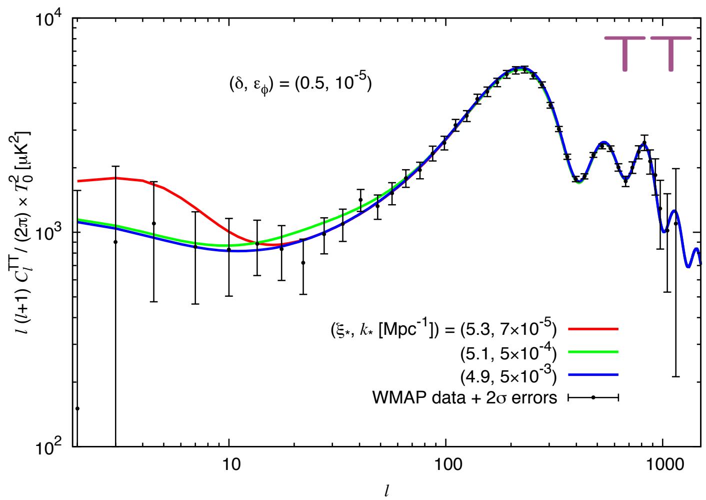
Simplest potential for a pseudoscalar : $V(\sigma) = \frac{\Lambda^4}{2}\left[\cos\left(\frac{\sigma}{f}\right) + 1\right]$

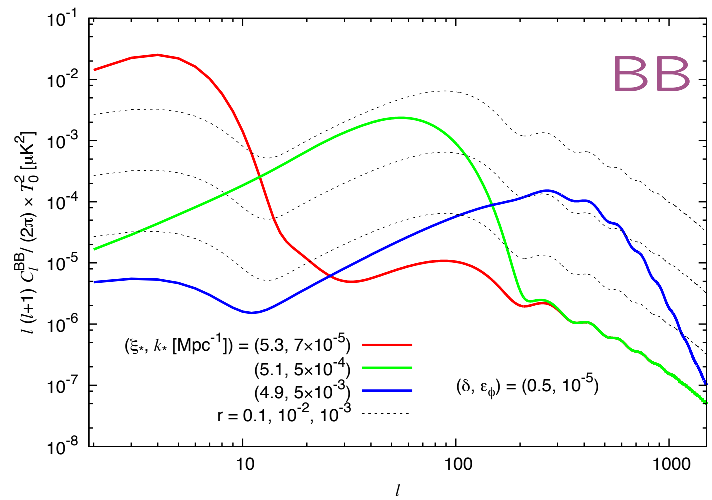


Slow roll sol. $\dot{\sigma} = \frac{f H \delta}{\cosh\left[\delta H \left(t - t_*\right)\right]}$, where $\delta \equiv \frac{\Lambda^4}{6H^2 f^2} = \frac{m^2}{3H^2}$

$\dot{\sigma}_{\text{max}}$ at $t = t_*$, when $\sigma = \frac{\pi f}{2}$ $\dot{\sigma} \neq 0$ for $\Delta N \sim \frac{1}{\delta}$

Three examples with $\epsilon_\phi = 10^{-5}$ (so that $r_{\text{vacuum}} = 16\,\epsilon$ is unobservable):



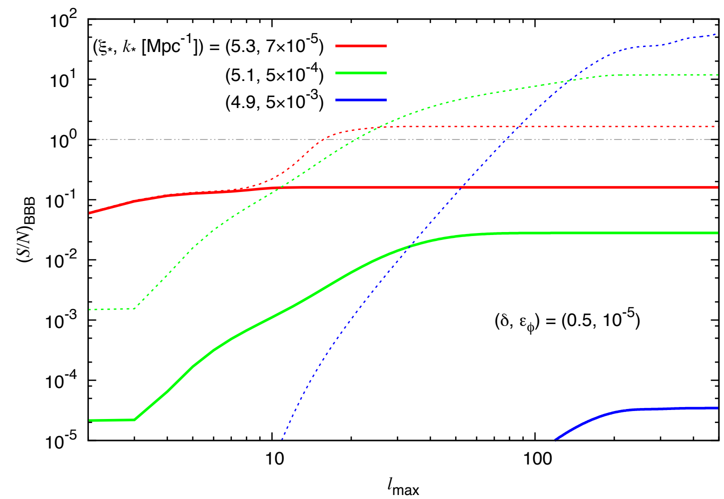


Shown for comparison: scale invariant

$r = 0.1$

$r = 0.01$

$r = 0.001$



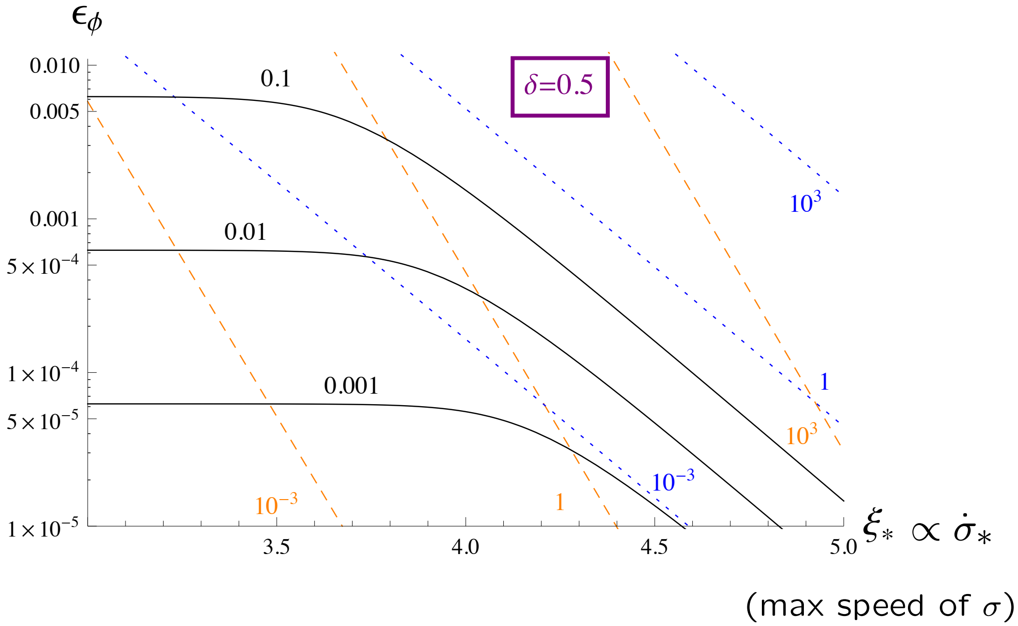
BBB

- Can be distinguished from vacuum by tensor running and *BBB*

(in principle also TB, but we found small S/N)

- Vacuum mechanism for GW very robust

- Under specific conditions, can produce visible r at arbitrarily small r_{vacuum} / scale of inflation



$r_{\text{tot}} = P_{\text{GW}}/P_\zeta$

$P_{\text{GW,sourced}}/P_{\text{GW,vacuum}}$

$P_{\zeta,\text{sourced}}/P_{\zeta,\text{vacuum}}$

In bottom-right corner

$r \gg r_{\text{vacuum}} = 16\epsilon_\phi$

$\text{GW}_{\text{sourced}} \gg \text{GW}_{\text{vacuum}}$

$\zeta_{\text{sourced}} \ll \zeta_{\text{vacuum}}$

- Computations under perturbative control

Ferreira, Ganc, Noreña, Sloth '15

MP, Sorbo, Unal '16

- At small ϵ_ϕ, we have $\dot{H}$ controlled by $\dot{\sigma} > \dot{\phi}$ at the bump.

Not a problem: In this model n_s controlled by $\eta_\phi \simeq 10^{-2} \gg \epsilon_\phi,\ \epsilon_\sigma$

GW at interferometers

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

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

$\Rightarrow$ other interesting effects / signatures

- For instance, growth of $P_\zeta(k)$

Meerburg, Pajer '12

$$P_\zeta \simeq \mathcal{P}_v \left[1 + 7.5 \cdot 10^{-5} \mathcal{P}_v \frac{e^{4\pi\xi}}{\xi^6} \right] \rightarrow \mathcal{P}_* \left(\frac{k}{k_*} \right)^{n_s - 1} \left[1 + \mathcal{P}_* \left(\frac{k}{k_*} \right)^{n_s - 1} f_2(\xi(k)) \, e^{4\pi\xi_*} \left(\frac{k}{k_*} \right)^{2\pi\xi_* \eta_*} \right]$$

$\xi_* = \xi$ when Planck pivot scale left horizon

NG : $\xi_* \leq 2.5$ (95% CL)

PS : $0.1 \leq \xi_* \leq 2.3$ (95% CL)

Planck '15

$$V = M^3 \phi \;\Rightarrow\; \frac{f}{\alpha} \gtrsim 0.021 \, M_p \qquad\qquad V = \frac{m^2}{2} \phi^2 \;\Rightarrow\; \frac{f}{\alpha} \gtrsim 0.029 \, M_p$$

- $\dot\phi$ keeps increasing. Unique opportunity to explore later stags of inflation

- As ξ grows, δA grows, and additional interactions with $\delta\phi$ relevant

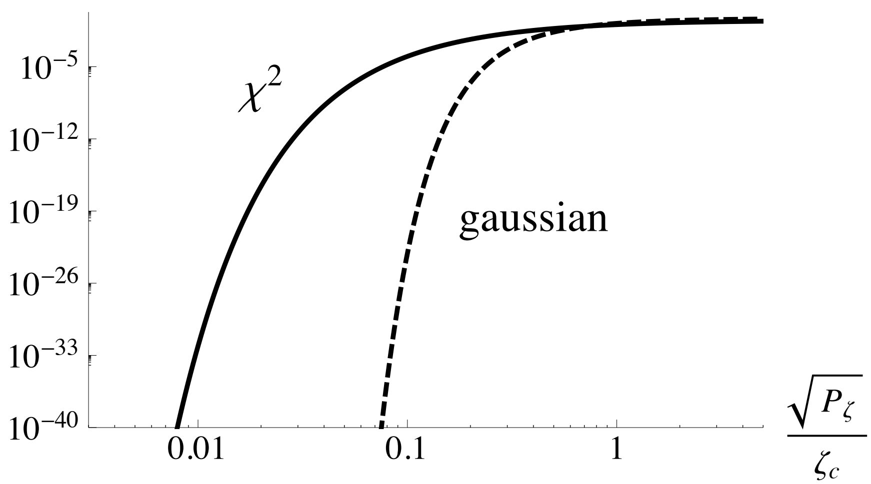
  Since $\dot\phi \to \xi \to \delta A$, first interaction estimated to be

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

Anber, Sorbo '09

Scalar perturbations may grow to above primordial black hole bound

Linde, Mooij, Pajer '13



- Non-gaussian statistics of ζ_{sourced} enhances PBH fraction

  - Large uncertainty, related to validity of the above equation

- Chiral GW production $A_+ A_+ \to h_L$ at interferometer scales

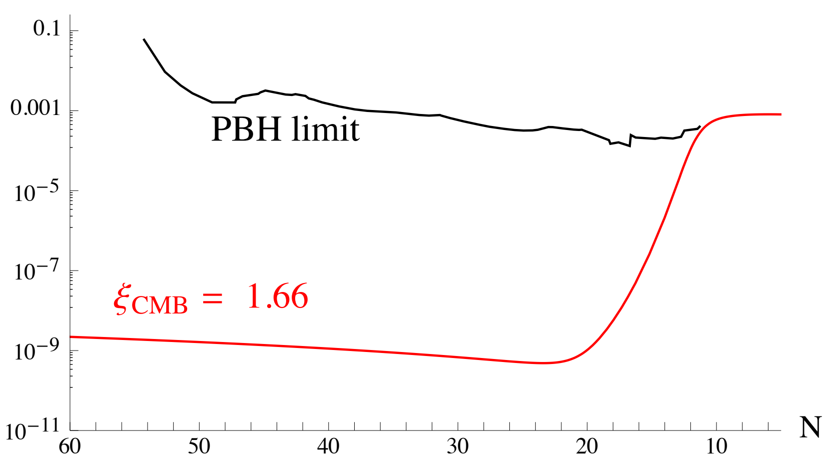
Cook, Sorbo '11; Barnaby, Pajer, MP '11; Domcke, Pieroni, Binétruy '16;

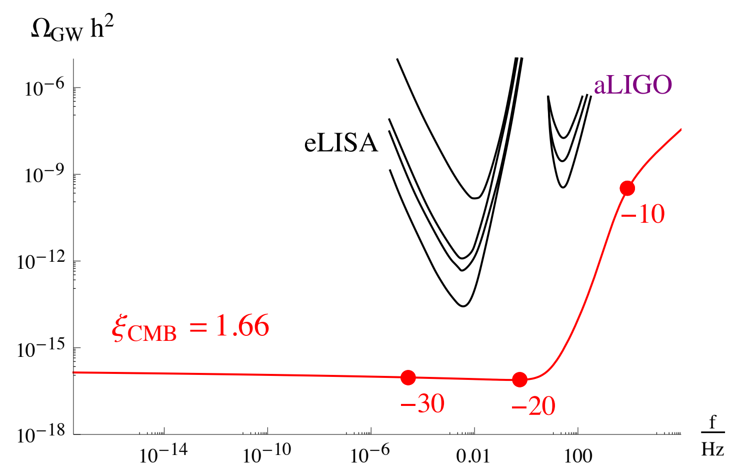
- New window on inflation; CMB / LSS for $10^{-4} \lesssim k/\text{Mpc}^{-1} \lesssim 10^{-1}$; CMB distortions down to 10^4. This is 18 e-folds, say from 42 to 60

- LISA peaks at $N \sim 25$; AdvLIGO at $N \sim 15$

- In chaotic inflation, PBH bound (if accurate) prevents GW from being observable.

Linde, Mooij, Pajer '13

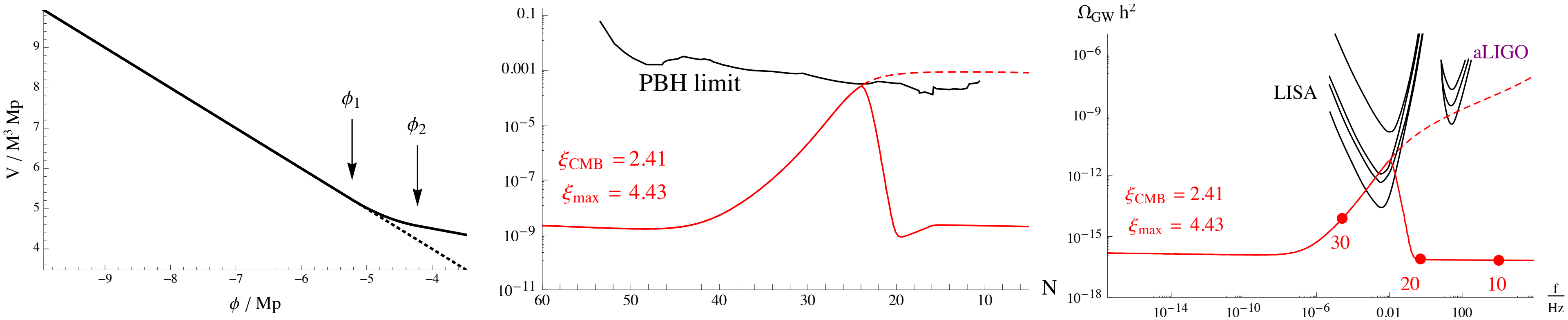




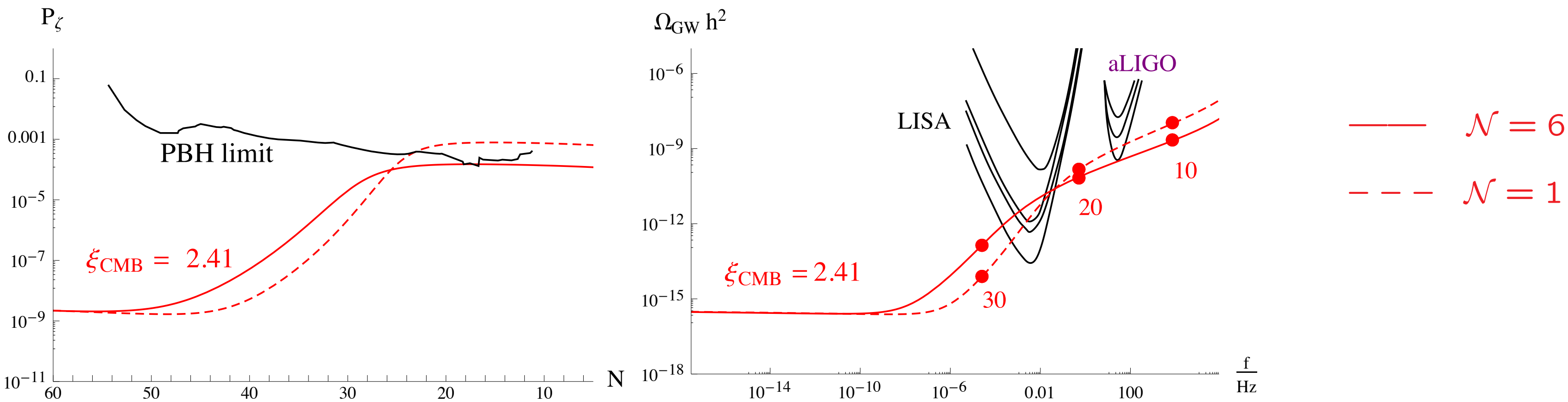
GW @ interferometers vs. PBH

Garcia-Bellido, MP, Unal '16

- PBH at $N \sim 10$. GW (particularly LISA) probe $\neq$ scales
- Due to $\propto e^{\dot{\phi}}$, significant differences from a minor change of V



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



- GW signal is non-gaussian, $k^6 \, \langle h_L^3 \rangle'_{\rm equil} \simeq 23 \, {\rm P}_{\rm GW}^{3/2}$ and chiral

Cook, Sorbo '13

Chiral GW @ interferometers

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

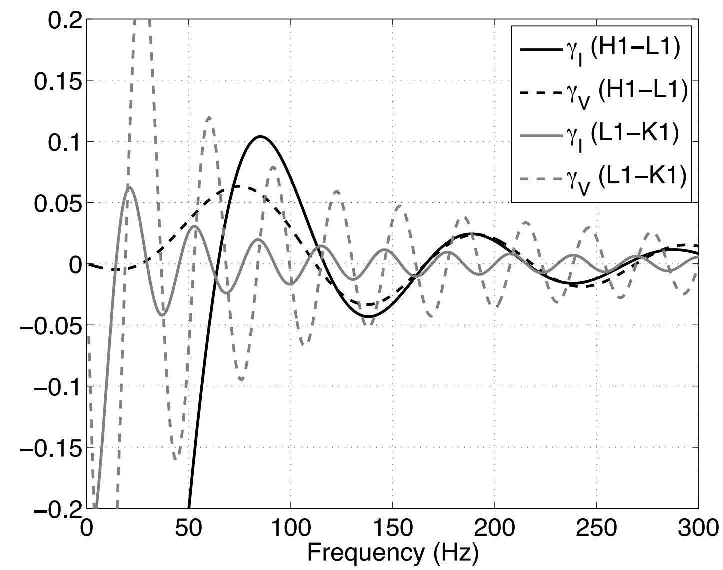
$$\Pi \equiv \frac{P_R - P_L}{P_R + P_L}$$

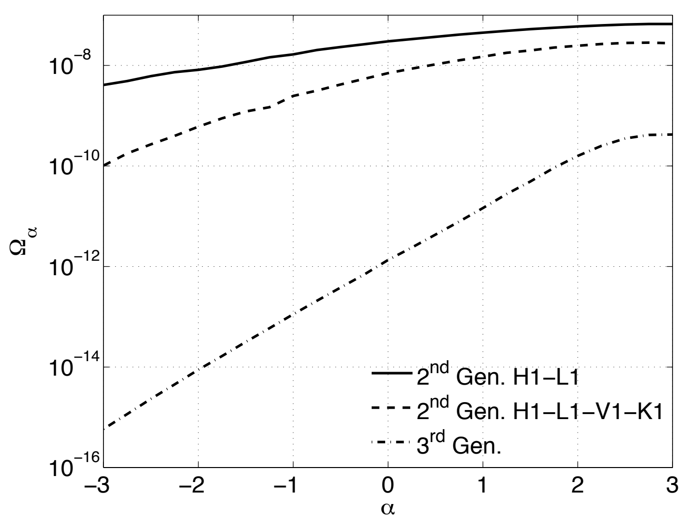
γ depend on orientations of the detectors and on the GW frequency

- Need three detectors To determine $\Omega_{\rm GW}$ and Π

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

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





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

Axion inflation $V \propto \phi^p$

Detector Network	p	ξ (sensitivity)	ξ (exclude $\Pi = 0$)
$2^{\rm nd}$ Gen H1-L1-V1-K1	1	2.3	2.8
$2^{\rm nd}$ Gen H1-L1-V1-K1	2	2.2	2.6
$3^{\rm rd}$ Gen	1	1.8	2.0
$3^{\rm rd}$ Gen	2	1.9	2.0

Conclusions

- Simplest model for axion inflaton starts to be in tension with CMB.

  Not so for multi-fields. $f/\alpha \gtrsim 10^{-2} M_p$ for coupling to any gauge field.

- $r = 16\,\epsilon$ very robust. Possible to violate this (existence proof)

  but hard to source GW without disturbing ζ. Distinctive

  properties (running tensor tilt, non-gaussianity, chirality)

- Increase of signal at smaller scales naturally opens potential

  observational window on $N \sim 15 - 25$. Again, fight against $P_\zeta \rightarrow PBH$

  Not a no-go (uncertainty, $\neq$ scales). Distinctive properties can help

  discriminate against astrophysical background