Signatures of particle production during inflation

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$$V(\sigma) + \frac{\sigma}{4f} F\tilde{F}$$

- Namba, MP, Shiraishi, Sorbo, Unal '15
- Bartolo et al, '16
- García-Bellido, MP, Unal '16, '17

$$V(\phi) + g^2 (\phi - \phi_0)^2 \chi^2$$

- Pearce, MP, Sorbo '16, '17

- In many models, inflationary evolution is uneventful. Nearly exponential expansion led by a weakly coupled & slow rolling scalar

→ Nearly scale invariant signals

→ Small NG

→ No guaranteed GW signal at CMB scales

→ Very hard to detect signals at smaller scales ($<$ 10 e-folds from CMB+LSS)

- In contrast, strong ongoing/forthcoming/discussed experimental advance

CMB polarization & distortions, LSS, GW @ smaller scales ...

New windows to probe potential and interactions (of the inflaton, and possibly of other fields) at specific epochs during inflation

$$\Delta \mathcal{L} = \frac{\phi}{f} F \tilde{F}$$ coupling

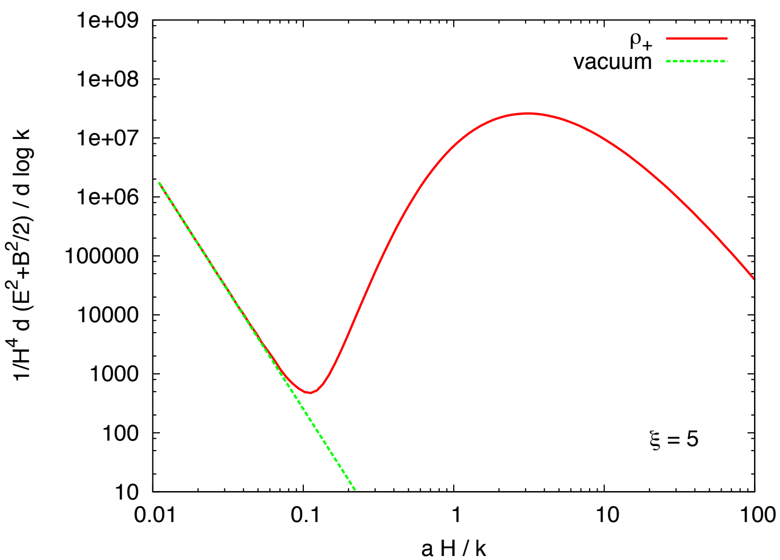
Turner, Widrow '88

Garretson, Field, Carroll '92

Anber, Sorbo '06

$$\Rightarrow \quad \left(\frac{\partial^2}{\partial \tau^2} + k^2 \mp 2\, a\, H\, k\, \xi \right) A_{\pm} (\tau,\, k) = 0 \qquad \xi \equiv \frac{\alpha\, \dot{\phi}^{(0)}}{2\, f\, H} = \mathrm{O}\,(1)$$

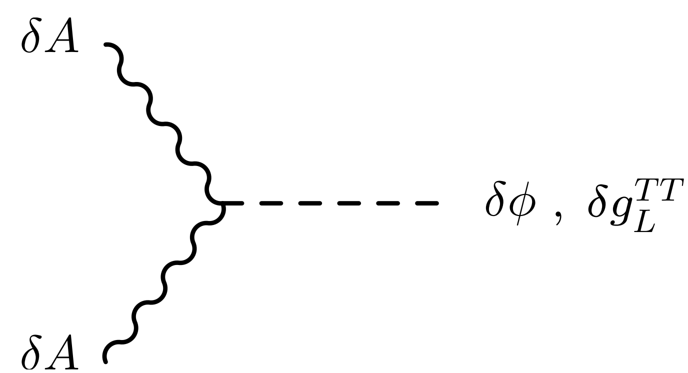
Physical ρ in one mode



- One tachyonic helicity at horizon crossing
- Then diluted by expansion
- Max amplitude $A_+ \propto \mathrm{e}^{\pi \xi}$

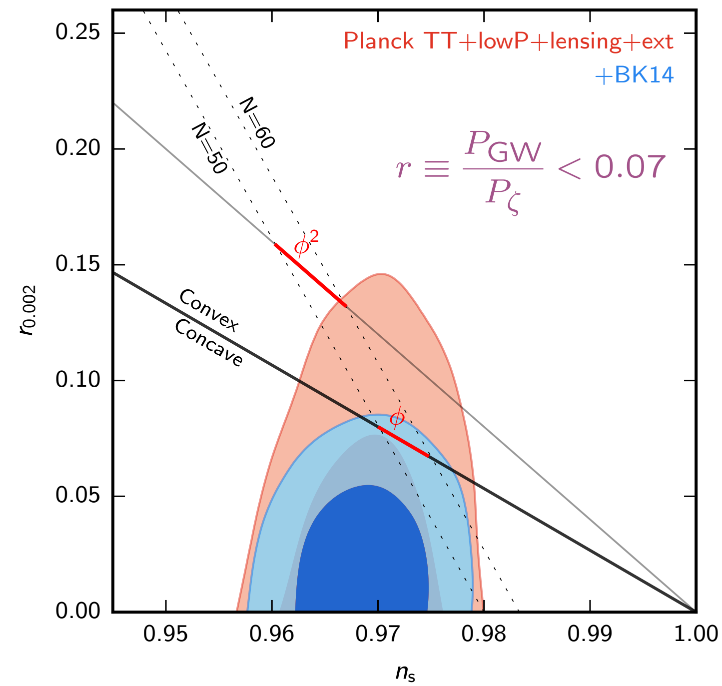
Amplified gauge fields source scalar and tensor perturbations

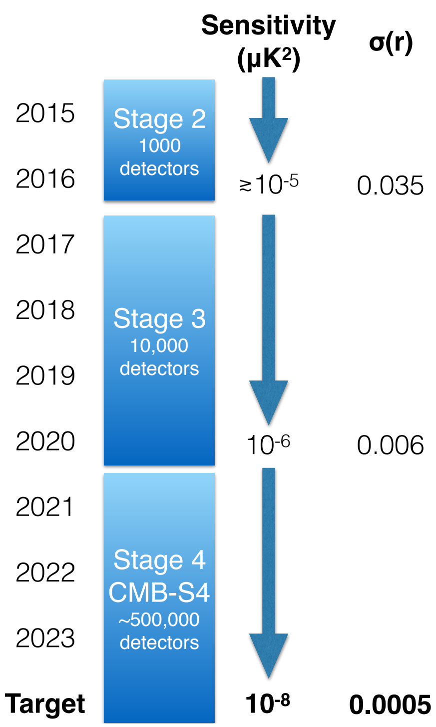
Barnaby, MP '10



GW at CMB scales

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





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- In single field slow-roll models

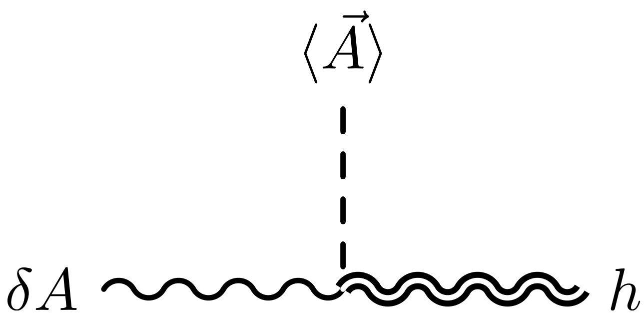
Scale of inflation $V^{1/4} \simeq 10^{16}\,\text{GeV} \left(\frac{r}{0.01}\right)^{1/4}$

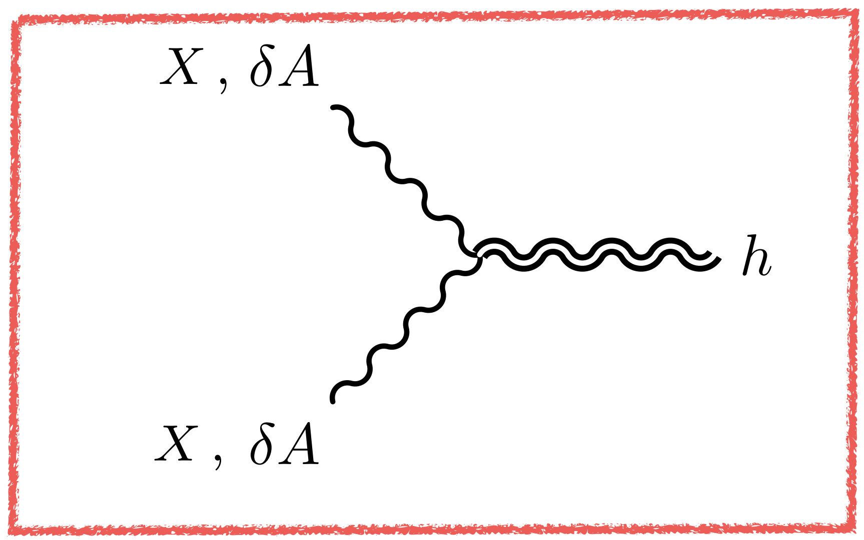
Inflaton excursion $\Delta\phi \gtrsim M_p \left(\frac{r}{0.01}\right)^{1/2}$ Lyth '96

Are we sure ?

GW from gauge fields

At this conference: Adshead, Agrawal, Caldwell, Dimastrogiovanni, Erfani, Fasiello, Ferreira, Komatsu, Maleknejad, Sfakianakis, Sorbo





In this talk

Sourced GW during inflation

$\mathcal{L} = (\phi - \phi_*)^2 \, \chi^2$ — 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

$\mathcal{L} = \frac{1}{2} \left(\delta\sigma'^2 - c_s^2 \, (\nabla \, \delta\sigma)^2 \right) \;\; , \;\; c_s \ll 1$ — Biagetti, Fasiello, Riotto '13; Biagetti, Dimastrogiovanni, Fasiello, MP '14

Models I worked on (standard GR and QM)

A field X produced during inflation, and $X \to h_{\text{sourced}} \gg h_{\text{vacuum}}$ (notation: $h \equiv \delta g^{TT}$)

- 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; Ferreira, Sloth '14; Mirbabayi, Senatore, Silverstein, Zaldarriaga '14; Namba et al '15

- No direct coupling with inflaton (Source gravitationally coupled to both GW and inflaton)
- Relativistic source (GW are produced by quadrupole moment; ζ by energy density)

Barnaby et al '12

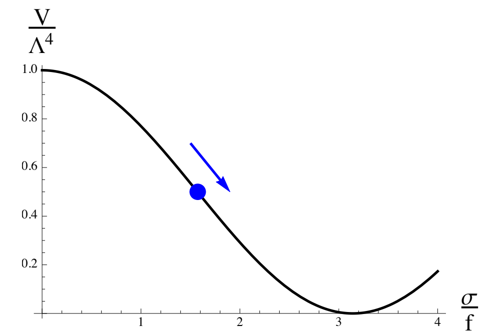
- Source active only for limited time (GW observed only on a small window;
  ζ provides constrains on many more scales)

All these present in Namba, MP, Shiraishi, Sorbo, Unal '15

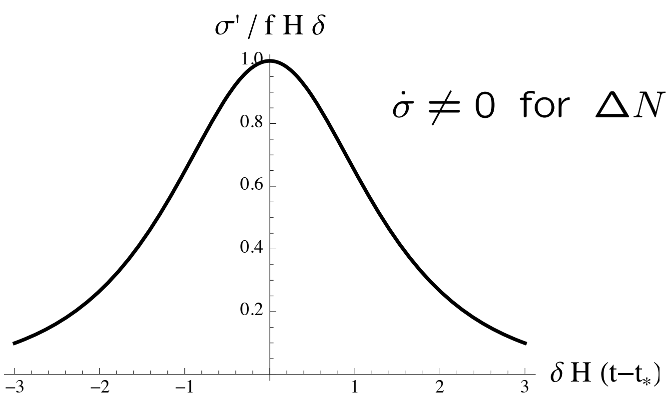
$$\mathcal{L} = \underbrace{-\frac{1}{2}(\partial\varphi)^2 - U(\varphi)}_{\text{inflaton sector}} \underbrace{-\frac{1}{2}(\partial\sigma)^2 - V(\sigma) - \frac{1}{4}F^2 - \frac{\sigma}{4f}F\tilde{F}}_{\text{extra sector}}$$

Simplest V for a pseudoscalar:

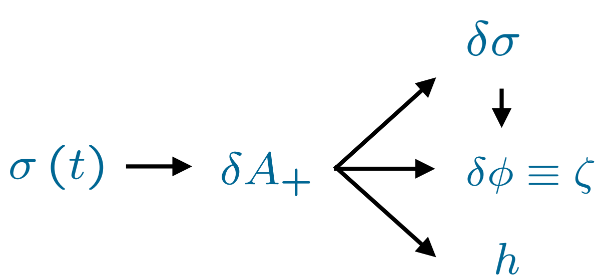
$$V(\sigma) = \frac{\Lambda^4}{2}\left[\cos\left(\frac{\sigma}{f}\right) + 1\right]$$



Mass of σ tuned to be comparable to H, $\delta \equiv \frac{\Lambda^4}{6H^2 f^2} = \frac{m^2}{3H^2} = \mathrm{O}(1)$



$\dot{\sigma} \neq 0$ for $\Delta N \simeq \frac{1}{\delta}$

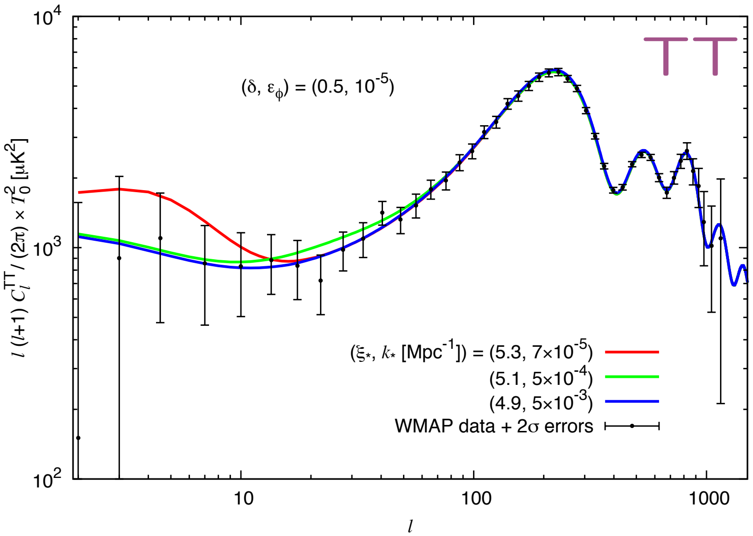


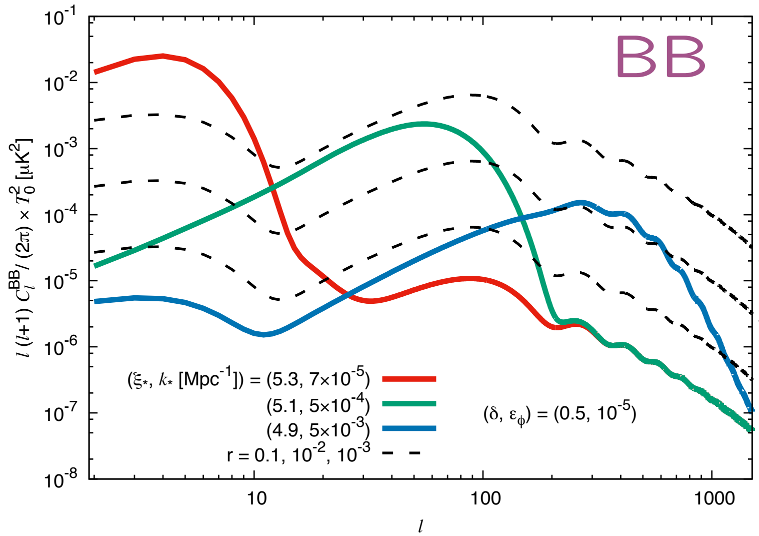
Bumps in ζ , h at scales that left the horizon while $\dot{\sigma} \neq 0$

- Gives visible r at arbitrarily small r_{vacuum} / scale of inflation

- Under perturbative control   MP, Sorbo, Unal '16

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





Shown for comparison: scale invariant

$r = 0.1$

$r = 0.01$

$r = 0.001$

- Distinguishable from vacuum GW by tensor running

- Also BBB (bump has $\langle h^3 \rangle \simeq \langle h^2 \rangle^{3/2}$) and TB (only h_L)

  Testable at $> 3\sigma$ at LiteBIRD   Shiraishi et al '16

Moral: Hard, but not impossible, to violate $V \leftrightarrow r$ relation. Requires

specific conditions, that allow to distinguish from vacuum GW

Naturally blue signals in axion inflation

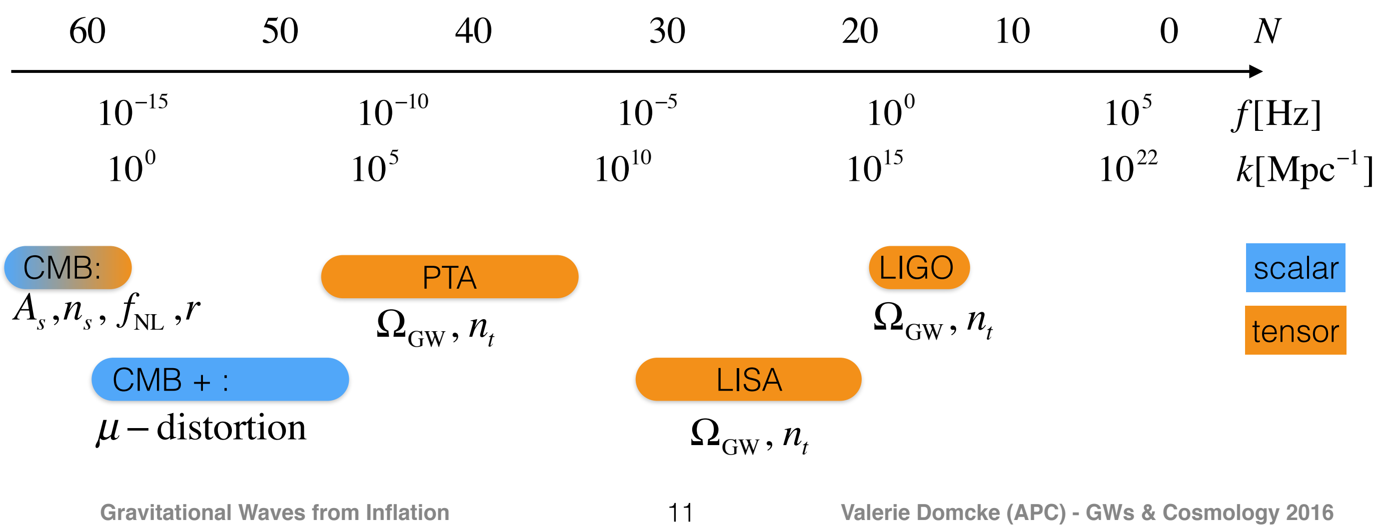
Consider now $\Delta\mathcal{L} = -\frac{\phi}{4f} F\tilde{F}$ where $\phi =$ inflaton

Freese, Frieman, Olinto '90

Recall $A_+ \propto e^{\pi\xi}$, $\xi = \frac{\dot{\phi}}{2fH} \propto \sqrt{\epsilon}$

$\phi(t) \to A_+ \to \zeta, h$

Inflaton speeds up $\to$ signal naturally grows at small scales

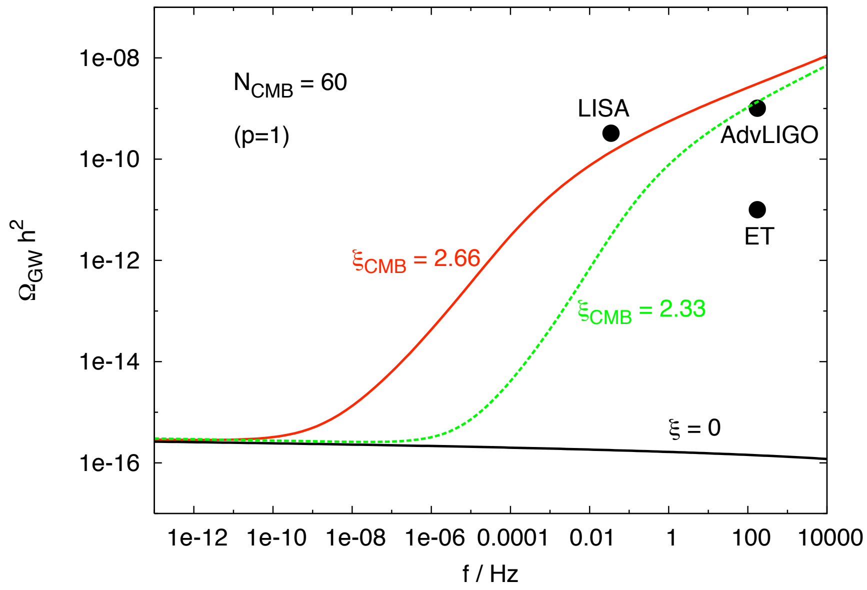


(i) GW at interferometer scales — Cook, Sorbo 11; Barnaby, Pajer, MP '12

(ii) Primordial Black Holes — Linde, Mooij, Pajer '12

Characterization of the GW signal

Barnaby, Pajer, MP '12

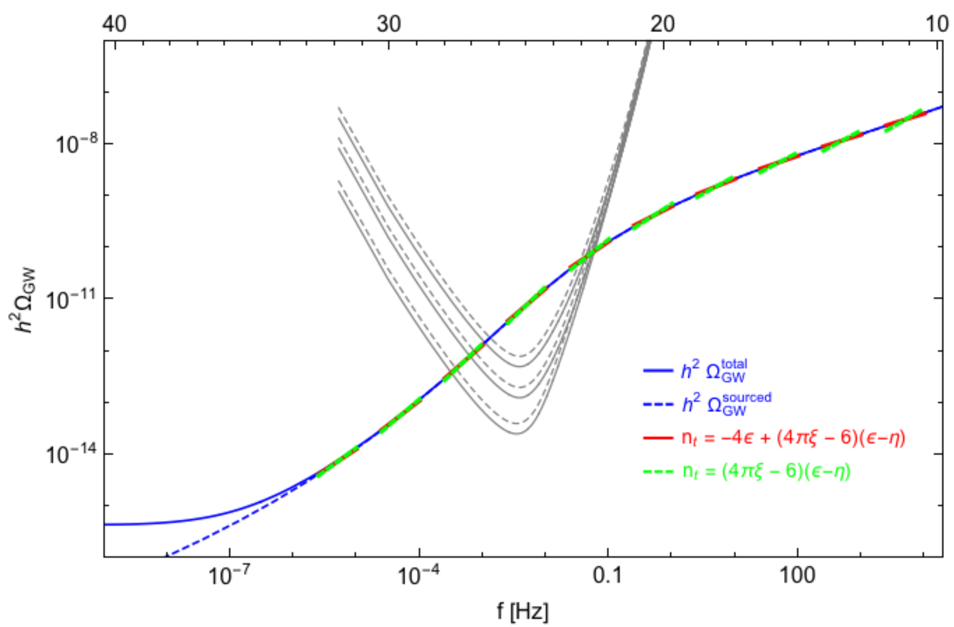


Full evolution and comparison

with experiments

Bartolo et al' 16

LISA Cosmology group



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

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

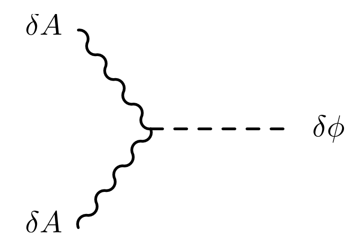
- Again, must avoid overproduction of ζ. Risk is too many PBH

- 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

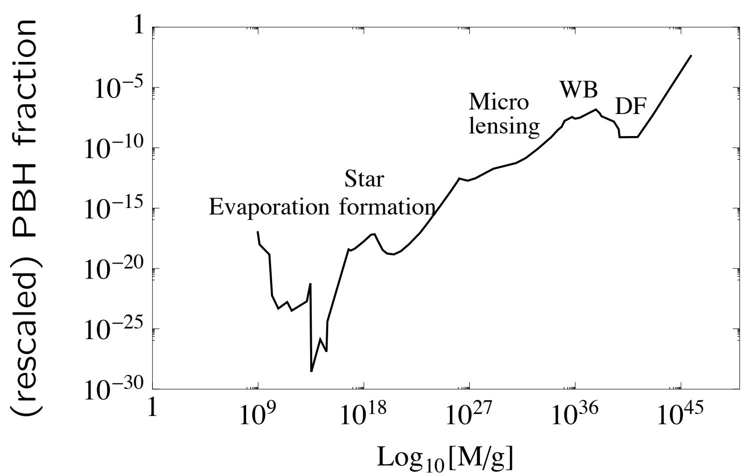
$$\delta\ddot\phi + 3\left[1 - \frac{2\pi\,\xi}{3H\dot\phi}\frac{\alpha}{f}\vec{E}\cdot\vec{B}\right]H\delta\dot\phi - \frac{\vec\nabla^2}{a^2}\delta\phi + m^2\delta\phi = \frac{\alpha}{f}\vec{E}\cdot\vec{B}$$

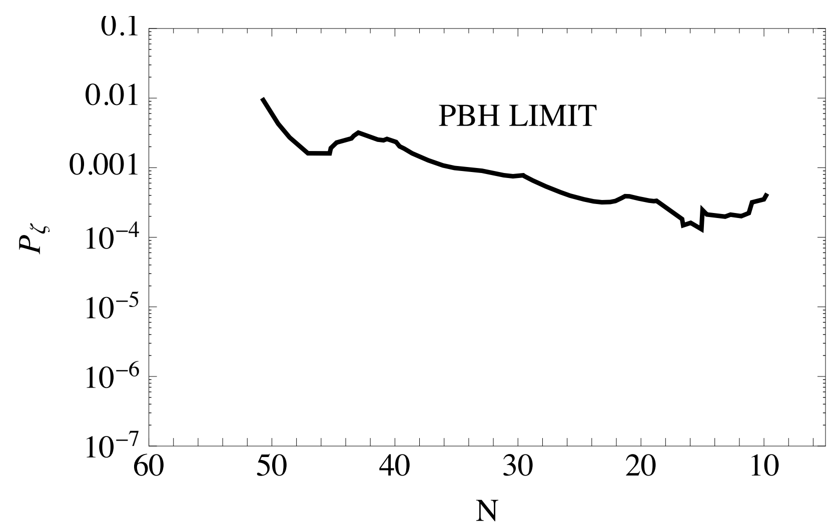


(lattice computations along lines of Adshead, Giblin, Scully, Sfakianakis '15)

- PBH production enhanced by the χ^2 statistics of ζ

Avelino '05

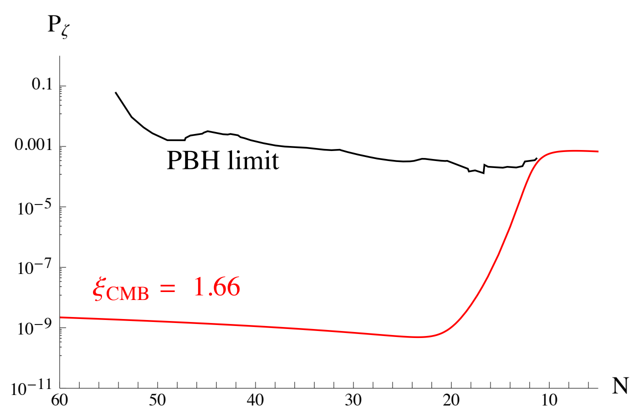


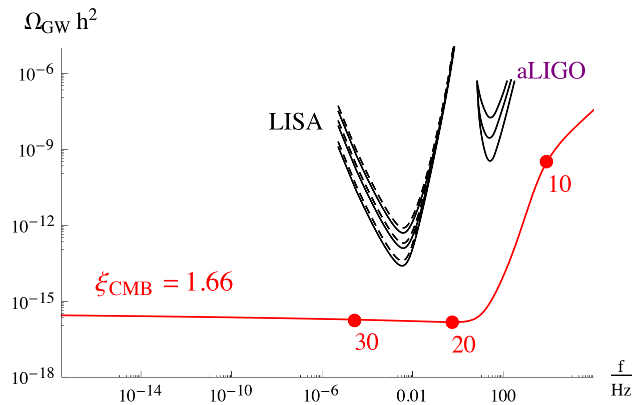


Updated by Garcia-Bellido, MP, Unal '16
from Carr et al '09

- In chaotic inflation, PBH bound prevents GW from being observable

Linde, Mooij, Pajer '13



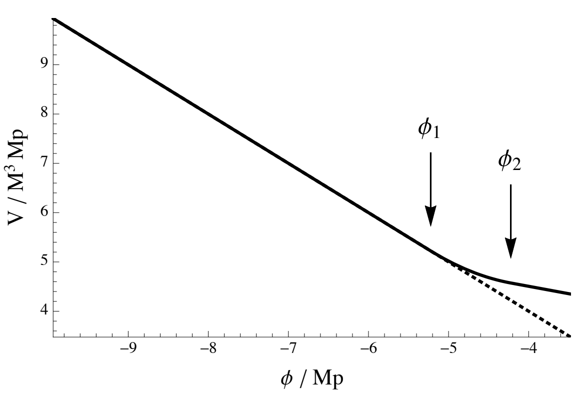


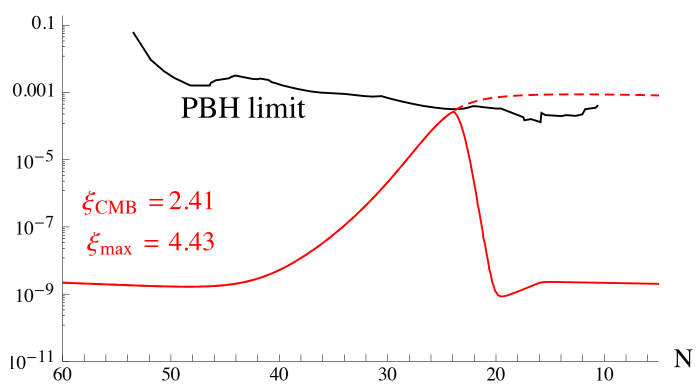
- In relating $N \simeq 10$ with $N \simeq 25$, a given $V(\phi)$ must be assumed.

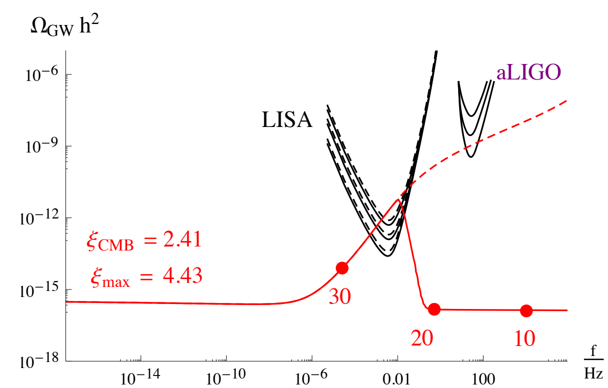
PBH bounds at LISA scales do not prevent GW from being seen at LISA

Garcia-Bellido, MP, Unal '16

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







PBH Dark Matter

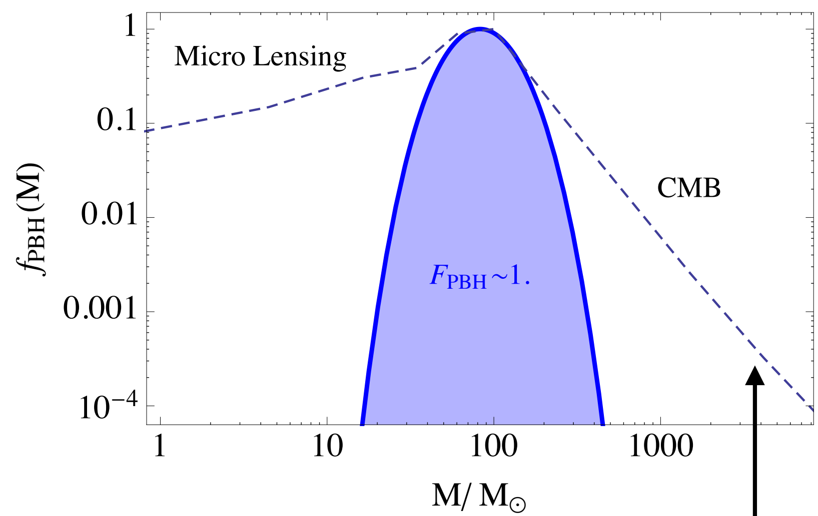
Bird et al '16

Clesse, García-Bellido '16

Suggested that LIGO events might be

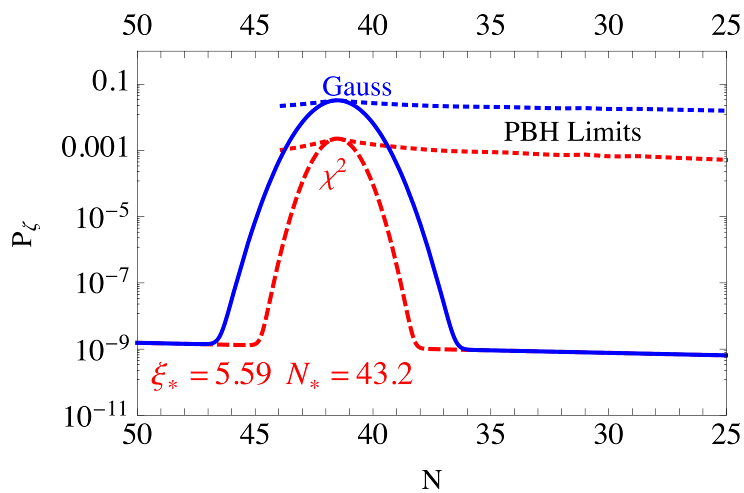
due to PBH accounting for present DM

$$f_{\rm PBH} \equiv \frac{1}{\rho_{\rm CDM}} \frac{d\,\rho_{\rm PBH}}{d\,\ln M}$$



Ali-Hamoud, Kamionkowski '16

Weaker limit than Ricotti et al '07



Required primordial P_ζ if perturbations obey

Gaussian distribution

χ^2 distribution (from rolling axion)

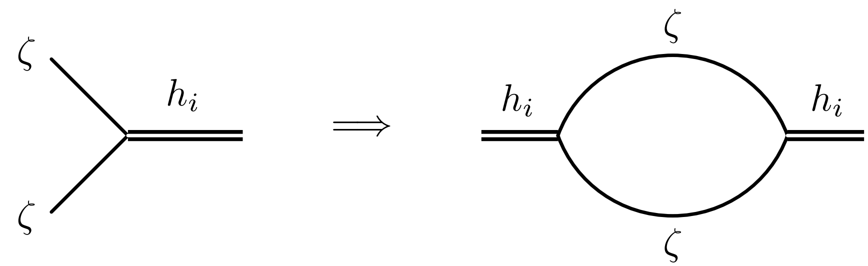
- Can we experimentally tell one from the other ?
- Can we learn about PBH evolution from formation up to today ?

García-Bellido, MP, Unal '17

- PBH formed from large overdensities at re-entry. Unavoidably, also $\zeta + \zeta \to h$
- At equal $f_{\rm PBH}$, greater P_ζ required in Gaussian case $\to$ greater GW
- $f \sim {\rm nHz} \sqrt{\frac{10\, M_\odot}{M_{\rm PBH}}}$ GW signal at PTA scales, great experimental improvement

★ Case of Gaussian ζ very well studied

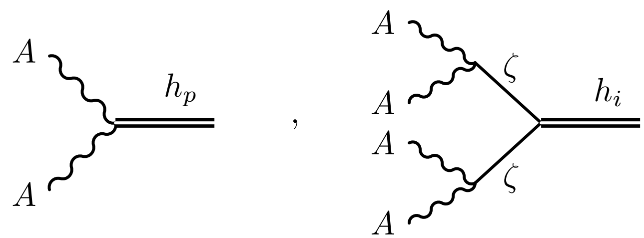
Ananda et al' 06; Baumann et al '07



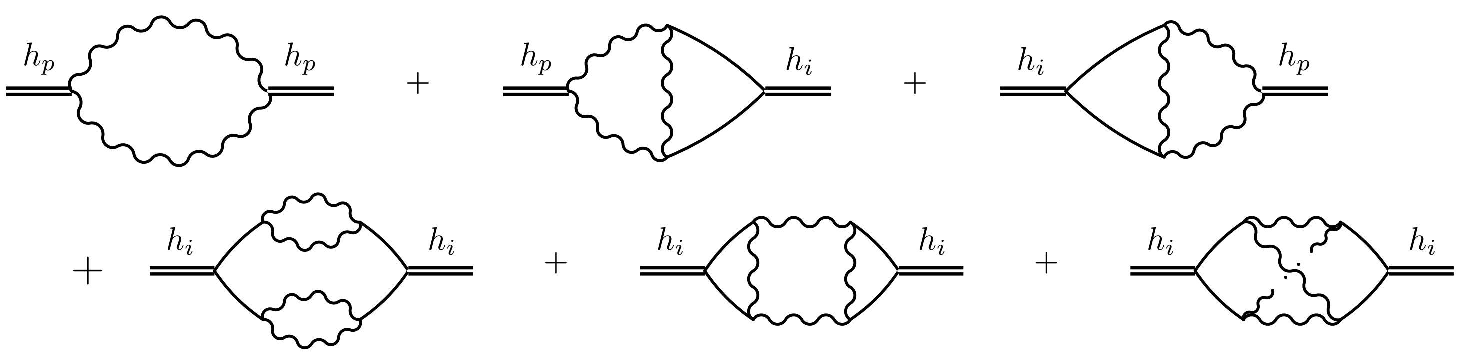
★ In NG case, peak value (but not scale-dependence) estimated

Nakama, Silk, Kamionkowski '16

In rolling axion (χ^2) model

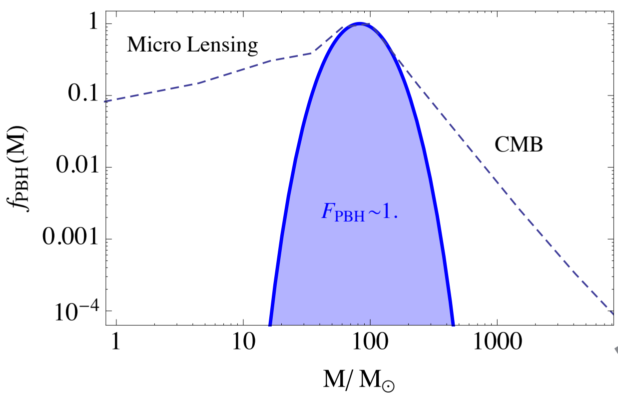


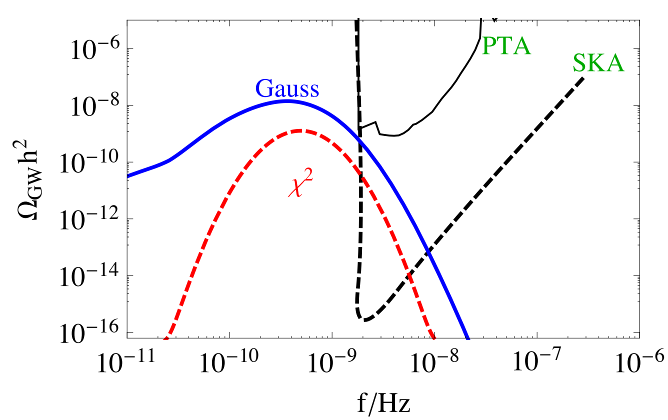
GW produced during inflation   and by ζ at re-entry



García-Bellido, MP, Unal '17

Impact of different statistics





CMB distortion

(using Chluba et al '15)

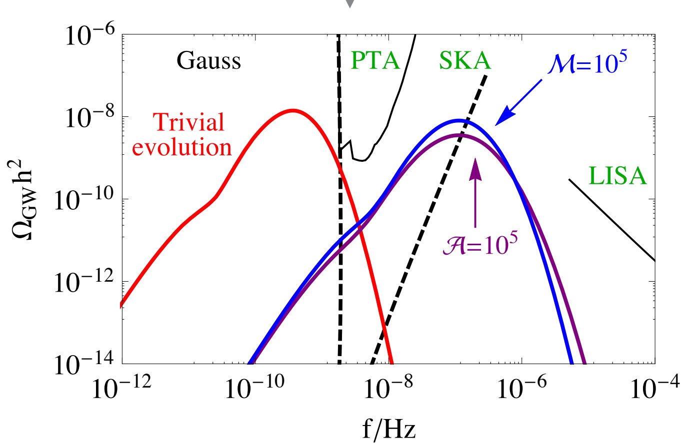
$\mu \simeq 4 \times 10^{-5}$

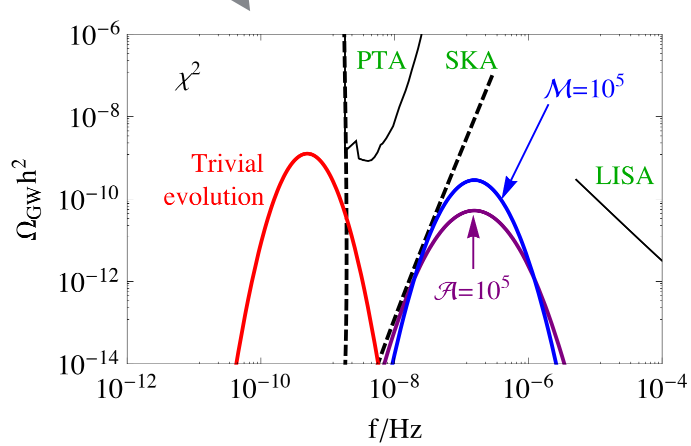
$\mu \simeq 3 \times 10^{-8}$

Impact of different evolution

These GW probe PBH mass distribution at formation, not at present

- Accretion increases mass of each PBH, and total PBH fraction by $\mathcal{A}$
- Merging increases mass of each PBH by $\mathcal{M}$





Smaller $M_{\text{formation}}$

Higher $f \propto M_{\text{formation}}^{-1/2}$

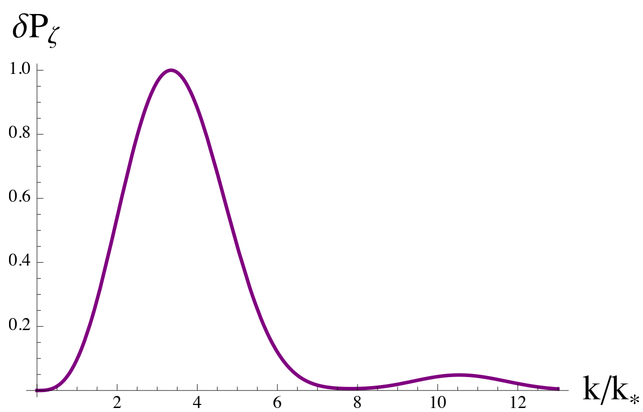
$$\Delta \mathcal{L} = -\frac{g^2}{2} (\phi - \phi_*)^2 \chi^2$$

1) Bump of $\chi-$ quanta production when $\phi(t) = \phi_*$ during inflation — Chung et al '99

Dominant ζ from $\delta\chi + \phi^{(0)} \to \delta\chi + \delta\phi$ — Barnaby, Kofman, et al '09

- Numerical + semi-analytic results replaced with analytical results

Pearce, MP, Sorbo '17



$$\delta P_\zeta \Big|_{\text{peak}} \simeq 300\, g^{7/2}\, P_\zeta$$

$$f_{\text{NL}}(k, k, k) \Big|_{\text{peak}} \simeq 90 \left(\frac{\delta P_\zeta}{0.1\, P_\zeta} \right)^{9/7}$$

2) Slow roll from dense $\sum_i (\phi - \phi_{*i})^2 \chi_i^2$, trapped inflation — Green et al '09

- Followed original computation, lifting the approx. $\langle \chi_i^2(t_1)\, \chi_j^2(t_2) \rangle \propto \delta_{ij}\, \delta(t_1 - t_2)$

Pearce, MP, Sorbo '16

Impact on PS normalization, region of parameter space, and NG

Conclusions

- Models of particle production / field amplification during inflation

- Observable effects at CMB scales: NG, n_s, GW $\qquad r \not\leftrightarrow H_{\text{inf}}$

  testable !

- Signatures at small scales $\equiv$ late times (from both scalar & tensor),

  which typically very hard to probe