Vector fields in (axion) inflation

Marco Peloso, University of Padua

Three class of models:

- Mass term $$-\frac{1}{4}F^2+\frac{1}{2}m^2\,A^2$$
- Nonstandard kinetic term $$-\frac{1}{4}f^2\,(\phi)\,F^2$$
- Pseudo-scalar interaction $$-\frac{1}{4}F^2-\frac{\phi}{4f}\,F\,\tilde{F}$$

"Mass term"

Leads to $\vec{A}$ amplification → Magnetogenesis

→ Statistical anisotropy, $P\left(\vec{k}\right)$

- Potential term $V\left(A_\mu A^\mu\right)$ — Ford '89
- Fixed norm $\lambda\left(A_\mu A^\mu - v^2\right)$ — Ackerman, Carroll, Wise '07
- Nonminimal coupling $A_\mu A^\mu R$ — Golovnev, Mukhanov, Vanchurin '08

  Kanno, Kirma, Soda, Yokoyama '08

  Chiba '08 Kovisto, Mota '08

All these vector models have ghost instabilities

Himmetoglu, Contaldi, MP '09

$$S = \int d^4x \sqrt{-g} \left[\frac{M_p^2}{2} R - \frac{F^2}{4} + \frac{\xi}{2} R A^2 \right]$$

Positive ξ $\equiv$ wrong sign mass

$\Rightarrow$ longitudinal vector is a ghost

(ghost = field with negative energy, not simply a tachyon)

Computation in Himmetoglu et al '09. Here, Stückelberg procedure:

$$A_\mu \to A_\mu^T + \frac{1}{M} \partial_\mu \phi$$

so that $+ M^2 A^2 \to M^2 A_\mu^T A^{\mu T} + \partial_\mu \phi \, \partial^\mu \phi$ (signature $- + + +$)

Moral: All the above above models introduce an "effective mass term" with " wrong sign", to sustain the vector field during inflation (anisotropic inflation, magnetogenesis). $\cancel{U(1)}$ invariance due to the $V(A)$ term generates a longitudinal mode, which, for the wrong sign, is a ghost.

Cure: search for models with unbroken U(1)

Non-standard kinetic term

$\mathcal{L} = -\frac{1}{4} I^2(\phi) F^2$ electric and magnetic fields $E_i = -\frac{\langle I \rangle}{a^2} A_i'$, $B_i = \frac{\langle I \rangle}{a^2} \epsilon_{ijk} \partial_j A_k$

- electric $\leftrightarrow$ magnetic duality for $\langle I \rangle \leftrightarrow \frac{1}{\langle I \rangle}$

Assume $I(\phi)$ and $\phi(t)$ combine to give $\langle I \rangle \propto a^n$

- Scale invariant $\vec{B}$ for $n = 2$ Ratra '92

e-folds of inflation

- Generally $\rho_B = \mathrm{O}(1)\, H^4 \times \begin{cases} 1 & , \; n < 2 \quad \text{blue} \\ N & , \; n = 2 \\ \mathrm{e}^{2(n-2)N} & , \; n > 2 \quad \text{red} \end{cases}$ backreaction pbm.

  $(n < -2 \;\rightarrow\;$ large $\rho_E)$

- EM coupling $e_{\text{physical}} = e\, I^{-1}(\phi) \propto a^{-n}$

  Strong coupling problem during inflation for $n > 0$ Demozzi, Mukhanov, Rubinstein '09

Functional form $I(\phi) = \exp\left[-\frac{n}{M_p}\int \frac{d\phi}{\sqrt{2\epsilon(\phi)}}\right] \rightarrow \langle I \rangle \propto a^n$

Martin, Yokoyama '07

$\epsilon = \frac{M_p^2}{2}\left(\frac{1}{V}\frac{dV}{d\phi}\right)^2 \ll 1$

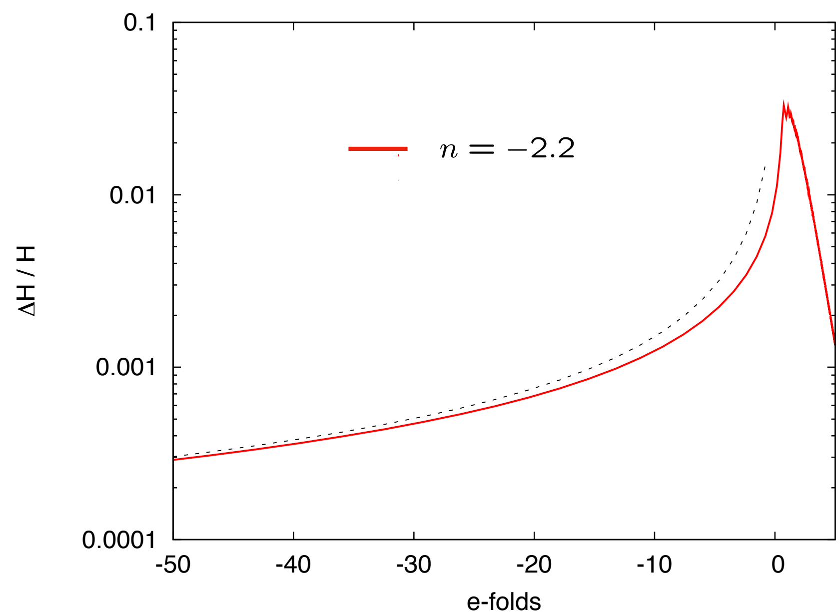
Anisotropic inflation

Watanabe, Kanno, Soda '09

$n = -2$ (no backreaction, nor strong coupling) $\rightarrow$ constant electric field at large scales $\equiv$ allows for uniform and constant $\left\langle \vec{E}^{(0)} \right\rangle$ across the universe

Accounting for slow roll corrections to dS

$$\frac{\Delta H}{H} \simeq \frac{2\rho_{E^{(0)}}}{V(\phi)} \simeq (|n| - 2)\,\epsilon$$



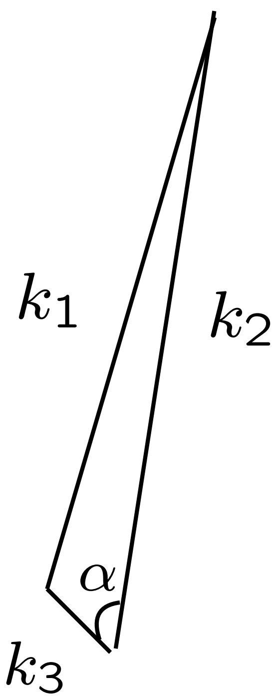
Phenomenology

Dulaney, Gresham '10
Gumrucuoglu, Himmetoglu, MP '10
Watanabe, Kanno, Soda '10

- Power spectrum $\left\langle \delta\phi^2 \right\rangle$

$$P\left(\vec{k}\right) = P\left(k\right)\left[1 + g_*\left(\hat{k}\cdot\hat{v}\right)^2\right] \qquad g_* \simeq -\frac{96\,N_{\rm CMB}^2}{\epsilon}\,\frac{\rho_{E^{(0)}}}{V\left(\phi\right)} \simeq 10^7\,\frac{\rho_{E^{(0)}}}{V\left(\phi\right)}$$

- Bispectrum $\left\langle \delta\phi^3 \right\rangle$ Barnaby, Namba, MP '12



Non-trivial dependence on α in the squeezed limit $k_3 \ll k_{1,2}$.

" .... This therefore appears as a signature of non-gaussianity from higher spin fields, and it may be an important distinguishing feature when the model is confronted with observations.... "

Barnaby, Namba, MP '12

Anisotropic inflation $(n = -2)$:

$$g_* = \mathrm{O}\left(10^7\right) \times \frac{\Delta H}{H}$$

Magnetogenesis $(n = +2)$:

$$\rho_B \simeq H^4\, N \;,\; g_* = 0$$

Electric $\leftrightarrow$ magnetic duality??

What does mean?

Bartolo, Matarrese, MP, Ricciardone '12

- $n = \pm 2$ produces scale-invariant and constant perturbations.

  Each mode leaves the horizon with energy H^4, and then frozen.

- "Random walk" addition of the modes that have left the horizon

  They add up to a classical homogeneous background. For vector fields, the background is a vector that points somewhere in space

➡ In any realization, CMB modes see a $\vec{V}_{\text{classical}}$ drawn by a statistical distribution of variance $\sim H^4 \left(N_{\text{tot}} - N_{\text{CMB}}\right)$

In $I^2 F^2$ case, $N_{\text{tot}} - N_{\text{CMB}} \simeq 5$ lead to a $g_* \sim 0.01$, ruled out

Axion inflation

$\Delta\phi > M_p$ not expected in a generic low-energy effective QFT

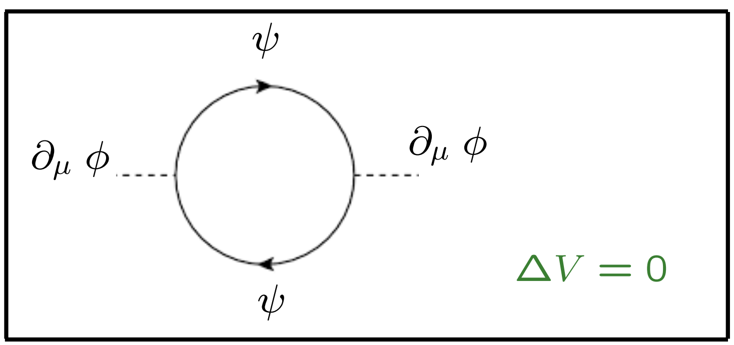
$$V = V_{\text{renormalizable}}(\phi) + \phi^4 \sum_{n=1}^{\infty} c_n \frac{\phi^n}{M^n}$$

Hard to achieve flatness $\dfrac{M_p V'}{V}, \dfrac{M_p^2 V''}{V} \ll 1$ unless $M \gg M_p$

Shift symmetry $\phi \to \phi + C$. E.g. axion (natural) inflation

Freese, Frieman, Olinto '90

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



Loops with only these couplings

do not modify the potential

- Smallness of $V_{\cancel{\text{shift}}}$ technically natural. $\Delta V \propto V_{\cancel{\text{shift}}}$

Common to identify axion inflation $\equiv$ "natural inflation"

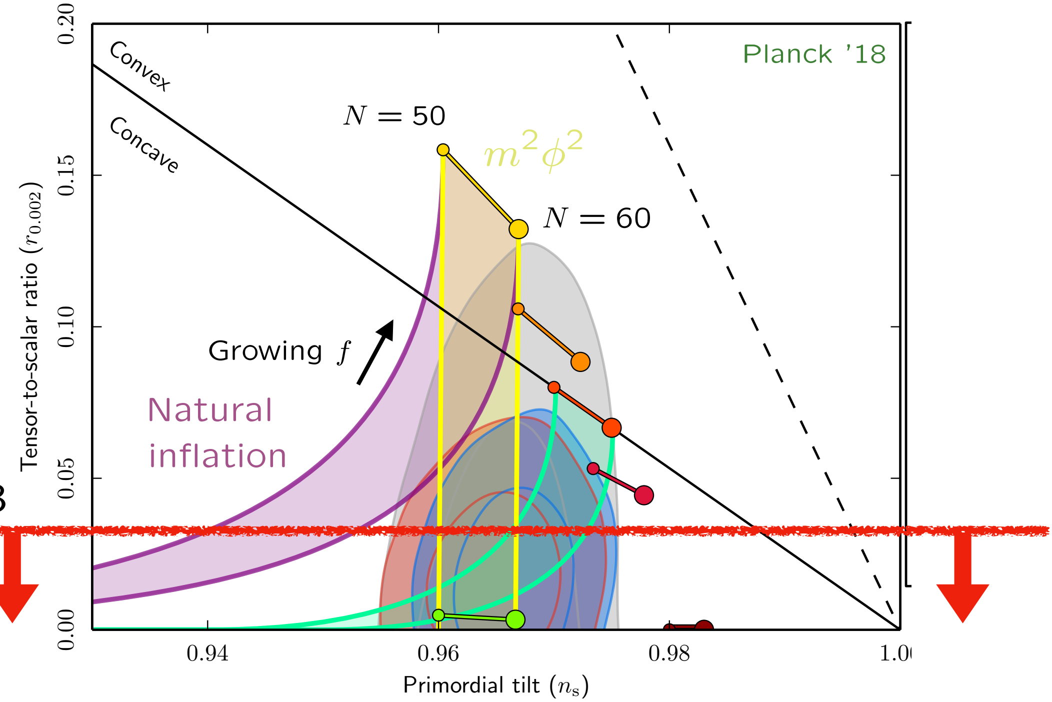
$$V = \Lambda^4 \left[1 - \cos\left(\frac{\phi}{f}\right)\right]$$

Freese, Frieman, Olinto '90

★ Ruled out

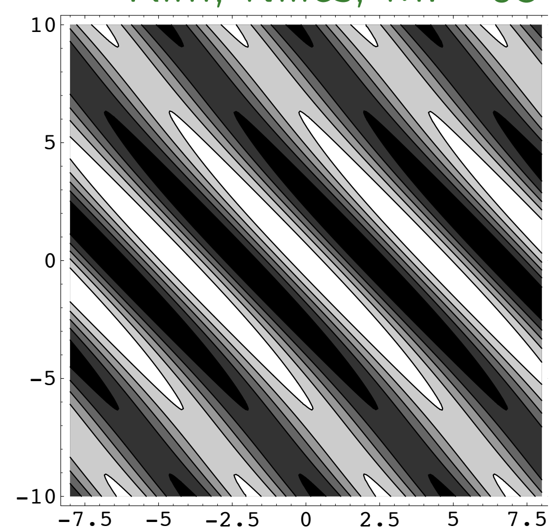
★ $f > M_p$ in range shown

$r \lesssim 0.03$



Aligned natural inflation

Kim, Nilles, MP '05



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

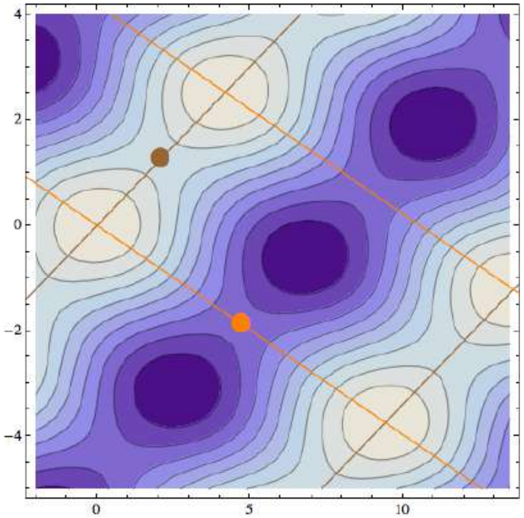
$$f_{\text{eff}} \gg f_i,\ g_i \quad \text{if} \quad \frac{f_1}{g_1} \simeq \frac{f_2}{g_2}$$

- Proposed to produce $f_{\text{eff}} > M_p$ from sub-Planckian f_i, g_i

(gravitational instanton corrections may still be a problem)

- In agreement with CMB

Heavy ψ

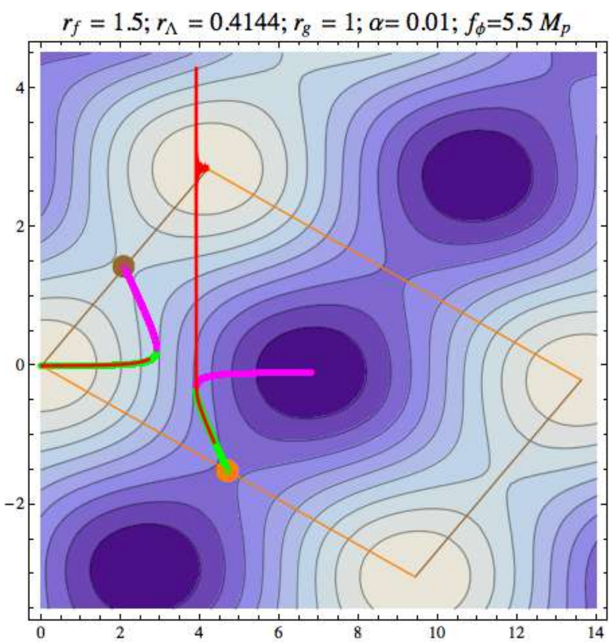


Light combination ϕ

denote by ϕ (ψ) the light (heavy) eigenstate

Fields rescaled $\simeq$ curvature in 2 directions

inflation on valleys with $\dfrac{\partial V}{\partial \psi} = 0\,,\ \ \dfrac{\partial^2 V}{\partial \psi^2} > 0$

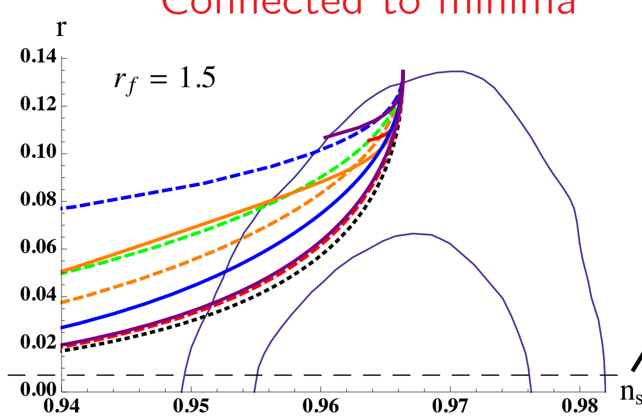


MP, Unal '15

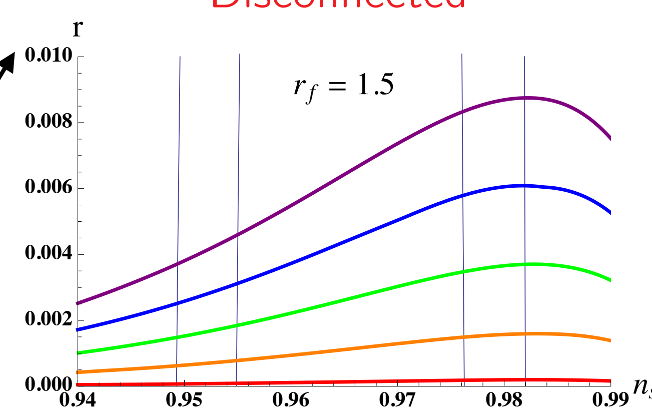
For some parameters inflationary trajectories ending because

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

Connected to minima



Disconnected

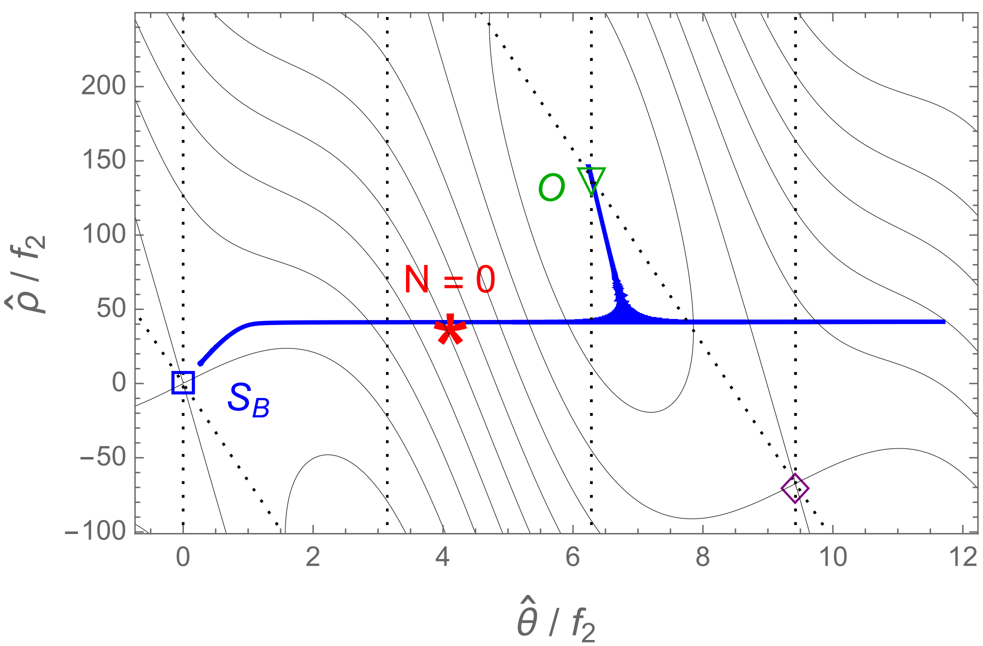


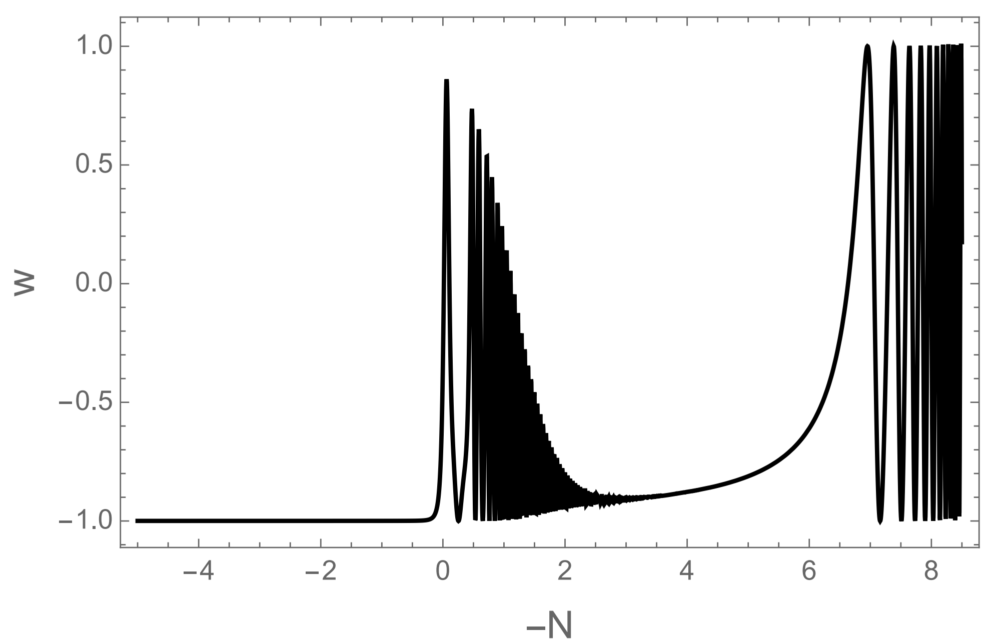
All above natural inflation

Target for CMB-S4, LiteBIRD, ...

Solved analytically: n_{s-1} and r given as analytic functions of the model parameters and number of e-folds in Greco, MP '24

Also shown that, after leaving the metastable inflationary valley, system often reaches a stable inflationary valley, so two-stage inflation





Fast oscillations → enhanced power at intermediate scales. Potential signature of the model, Greco, MP 2507.xxxxx

Vector production from $\frac{c_A\,\phi}{f}\,F\,\tilde{F}$

Turner, Widrow '88

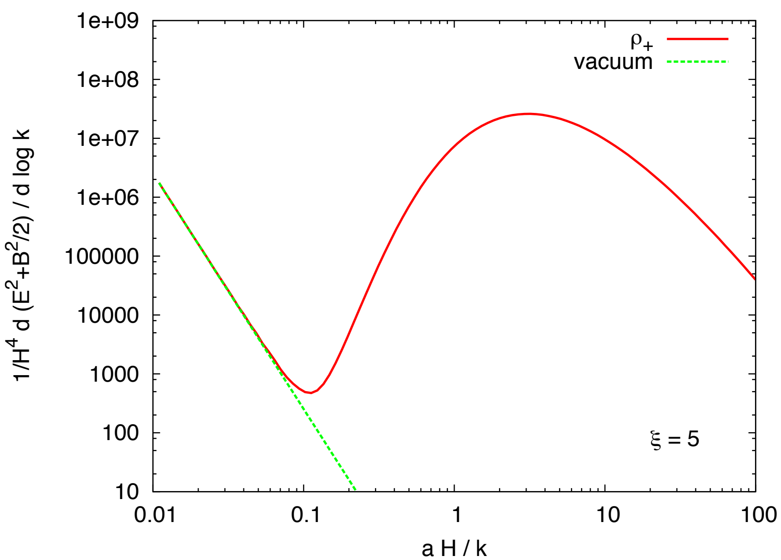
Garretson, Field, Carroll '92

Anber, Sorbo '06

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

helicity

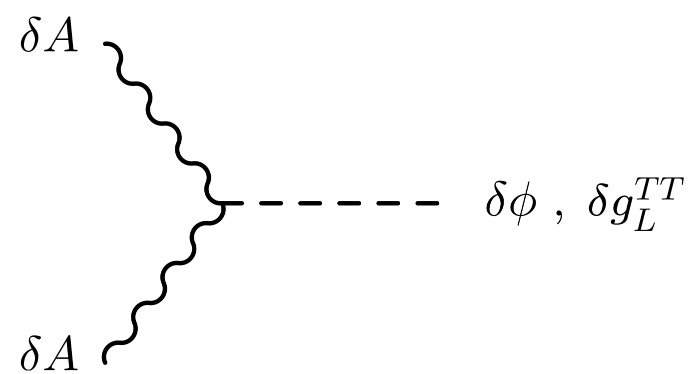
Physical ρ in one mode



- 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



- Sourced GW are chiral   Sorbo '11
- Sourced scalars non-Gaussian $\rightarrow\ f/c_A \gtrsim 10^{16}\,\text{GeV}$ Barnaby, MP '10
- GW less produced ($1/M_p$ vs c_A/f) and not obsservable

General lesson: Several mechanisms for additional GW, result in a decrease of r once also extra density perturbations are accounted for

Observation of GW through the CMB	$\longleftrightarrow$	$V^{1/4} \simeq 10^{16}\,\text{GeV} \left(\frac{r}{0.01}\right)^{1/4}$ $\Delta\phi \gtrsim M_p \left(\frac{r}{0.01}\right)^{1/2}$

Robust!

How robust ? Cost for evading it ?

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

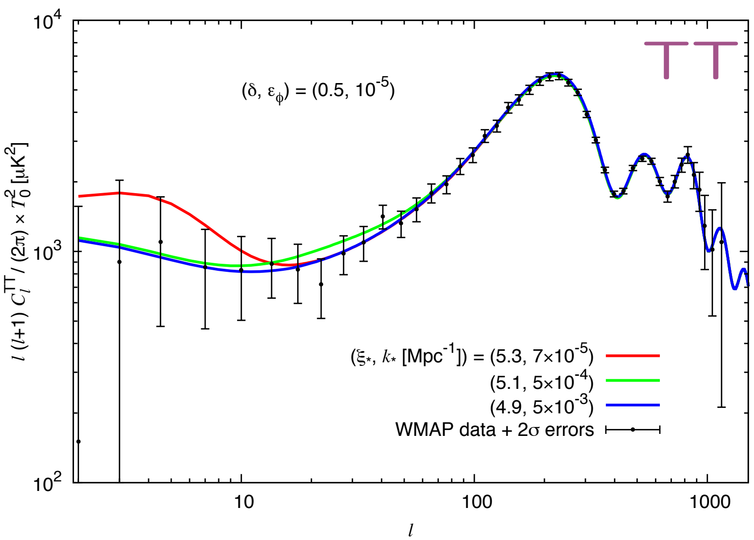
These 3 ingredients present in Namba, MP, Shiraishi, Sorbo, Unal '15

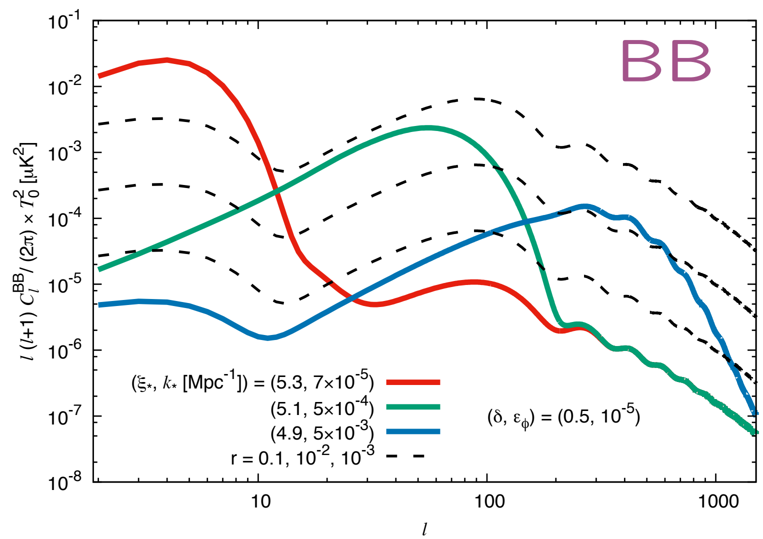
$$\mathcal{L} = \underbrace{-\frac{1}{2}(\partial\varphi)^2 - U(\varphi)}_{\text{inflaton sector}} \underbrace{- \frac{1}{2}(\partial\sigma)^2 - V(\sigma) - \frac{1}{4}F^2 - \frac{\alpha\,\sigma}{4f}F\tilde{F}}_{\text{extra sector}}$$

$m_\sigma = \mathrm{O}\,(H)$ so to roll for few e-folds

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

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

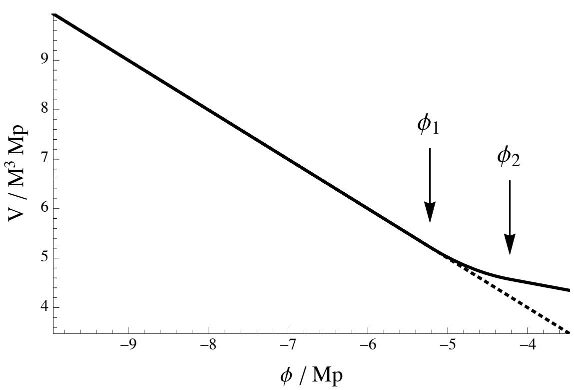
Moral: Hard, but not impossible, to violate $V \leftrightarrow r$ relation. Limits from scalar non-G $\rightarrow$ specific conditions $\rightarrow$ distinguish from vacuum GW

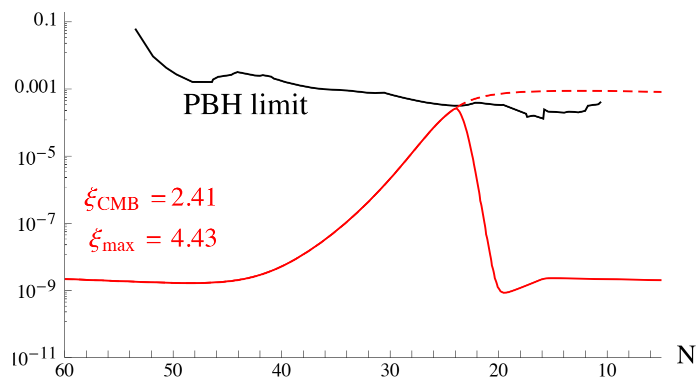
Naturally blue signals in axion inflation

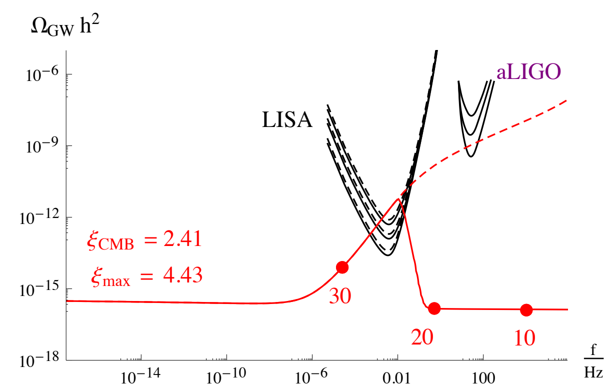
Back to production from inflaton   Recall $A_+ \propto e^{\pi\xi}$, $\xi = \dfrac{\dot{\phi}}{2fH} \propto \sqrt{\epsilon}$

Inflaton speeds up $\rightarrow$ signals naturally increase at smaller scales

- GW at interferometers   Cook, Sorbo '12; Barnaby, Pajer, MP '12
  Domcke, Pieroni, Binétruy '16
- PBH   Linde, Mooij, Pajer '12; Bugaev, Klimai '13
  Garcia-Bellido, MP, Unal '16, '17







CMB signatures $\rightarrow$ $\xi \lesssim 2.5$. In this regime, amplified $\vec{A}$ have negligible backreaction on the background dynamics. No longer the case for $\xi \gtrsim 5$

MP, Sorbo, Unal '16

Backreaction ★

$$\ddot{\phi} + 3H\dot{\phi} + \frac{dV}{d\phi} = \frac{c_A}{f}\,\vec{E}\cdot\vec{B}$$

$$H^2 = \frac{1}{3M_p^2}\left[\frac{1}{2}\dot{\phi}^2 + V + \frac{\vec{E}^2+\vec{B}^2}{2}\right]$$

(1) Steady state backreaction Analytic computations for $\xi \simeq$ const

(2) Homogeneous backreaction $\left\{\phi\,(t)\ ,\ \vec{A}\,(t,\,\vec{x})\right\}$

(3) Inhomogeneous backreaction Full system

★ SU(2) case in Iarygina, Sfakianakis, Sharma, Brandenburg'24

Steady state backreaction

- Strong backreaction regime studied by Anber, Sorbo '09

- Old idea of warm inflation $\ddot{\phi} + 3H\dot{\phi} + \boxed{V' = -\Gamma\,\dot{\phi}}$ Berera '95

  Dissipation reduces the inflaton motion. Can allow inflation in

  steep potentials (large V') and for reduced field excursion (small $\Delta\phi$)

  Both aspects might be beneficial in the recent swampland program

- Anber-Sorbo mechanism simple & well defined QFT realization

$$\ddot{\phi} + 3H\dot{\phi} + V' = \frac{c_A}{f}\, F\,\tilde{F}\left[\dot{\phi}\right]$$

Perfect balance assumed at all times $\rightarrow$ Steady state evolution

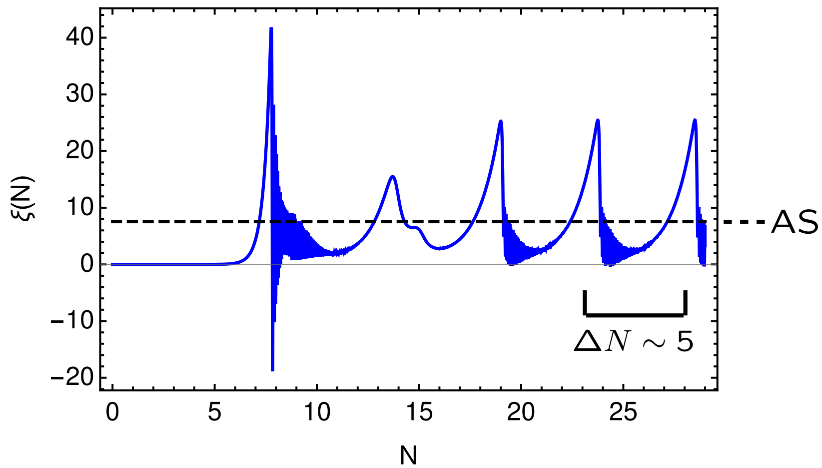
Anber, Sorbo '09

$$\Rightarrow \quad V' \simeq -2.4 \cdot 10^{-4}\,\frac{c_A\,H^4}{f}\,\frac{e^{2\pi\xi}}{\xi^4} \quad , \quad \xi \equiv \frac{c_A\,\dot{\phi}}{2fH}$$

Homogeneous backreaction (homogeneous ϕ)

Oscillations about AS from numerical integration of simplified system

Cheng, Dall'Agata, Domcke, Durrer, González-Martín, Garg, Gorbar, Guidetti, Lee, Momot, Ng, Notari, Papageorgiou, MP, Rudenok, Schmitz, Sobol, Sorbo, von Eckardstein, Tywoniuk, Vilchinskii, Welling, Westphal, . . .



- Interpreted as delayed effect between the moment the gauge quanta are produced and the moment they backreact on $\phi\,(t)$

Domcke, Guidetti, Welling, Westphal '20

Analytical study: $\phi(t) = \bar{\phi}(t) + \delta\phi(t)$, $A^\mu\left(t, \vec{k}\right) = \bar{A}^\mu\left(t, \vec{k}\right) + \delta A^\mu\left(t, \vec{k}\right)$

of the homogeneous inflaton & gauge modes around the AS solution

MP, Sorbo '22

$$\delta\phi'' + 2aH\delta\phi' + a^2V''\delta\phi = -\frac{c_A}{fa^2}\int\frac{d^3k}{(2\pi)^3}\frac{k}{2}\frac{\partial}{\partial\tau}\left[\bar{A}\,\delta A^* + \bar{A}^*\,\delta A\right]$$

$$\delta A'' + \left(k^2 - \frac{k\,\bar{\phi}'}{f}\right)\delta A = \frac{c_A\,\bar{A}}{f}\,\delta\phi'$$

- Formally solve 2nd eq for δA as a function of $\delta\phi'$

$$\delta A(\tau, k) = \frac{c_A\,k}{f}\int^\tau d\tau' G_k\left(\tau, \tau'\right)\,\bar{A}\left(\tau', k\right)\delta\phi'\left(\tau'\right)$$

- Insert solution in 1st eq $\rightarrow$ integro-differential eq for $\delta\phi$

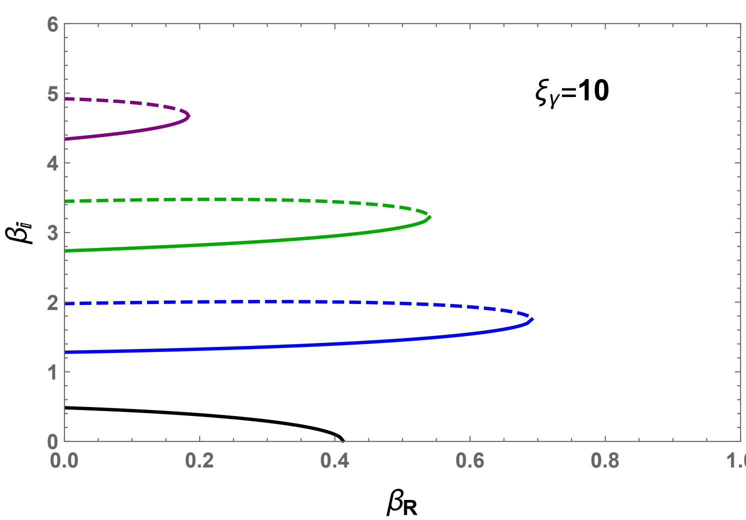
$$\delta\phi''(\tau) + 2aH\delta\phi'(\tau) + a^2 V''\delta\phi(\tau) \simeq$$

$$\frac{c_A^2}{f^2 a^2}\frac{\mathrm{e}^{2\pi\xi}}{2^8\pi^2\xi^5}\int^{\tau}\frac{d\tau'}{(-\tau')^4}\delta\phi'(\tau')\,\frac{\partial}{\partial\tau}\int_0^{4\xi_\gamma^2} dy\, y^3\sqrt{\tau\tau'}\left[\mathrm{e}^{-4\sqrt{y}} - \mathrm{e}^{-4\sqrt{y}\sqrt{\frac{-\tau}{-\tau'}}}\right]$$

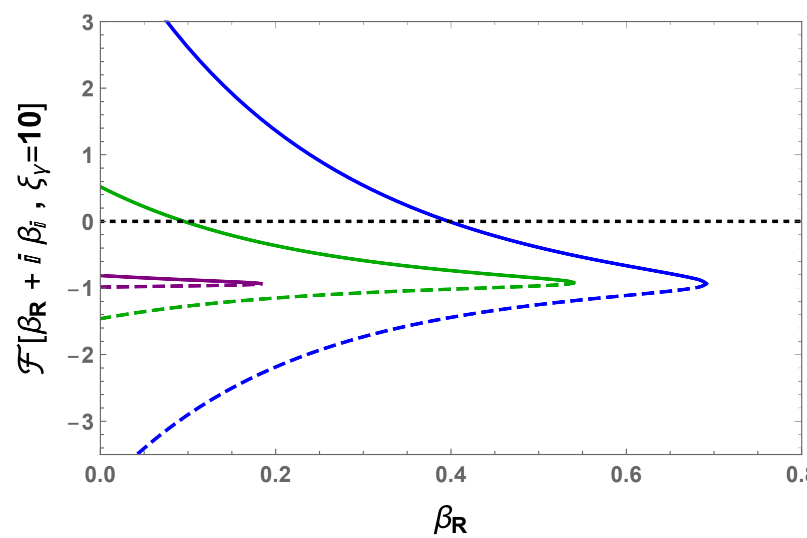
- Look for $\delta\phi \propto (-\tau)^{-\beta} \equiv a^{\mathrm{Re}\,\beta}\cos(\mathrm{Im}\,\beta \times N + \mathrm{phase})$

Inserting this and doing the integrals $\rightarrow$ homogeneous eq in time (all terms scale as $\tau^{-\beta-2}$). Therefore left wih an algebraic equation for complex β.

$$\frac{\xi f V''}{c_A(-V')} \simeq \frac{4\beta(\beta+3)}{(2\beta-1)(2\beta+7)}\left[\frac{1}{(8\xi_\gamma)^{2\beta-1}}\frac{\Gamma(2\beta+8)}{\Gamma(9)} - 1\right] \equiv \mathcal{F}[\beta,\,\xi_\gamma]$$



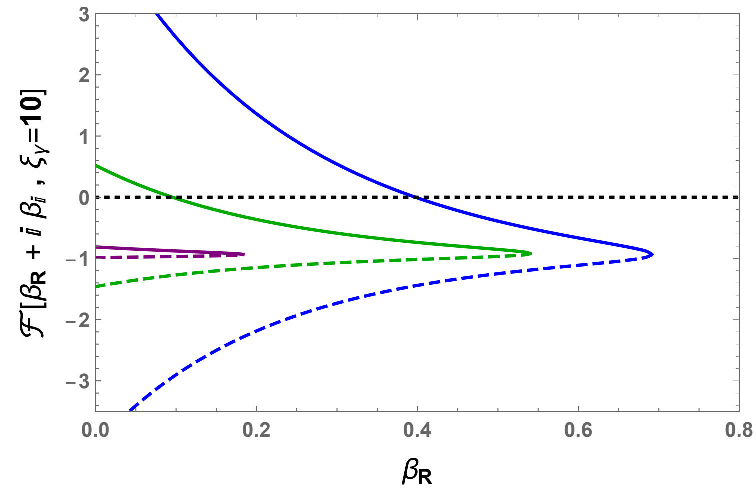
Curves of real $\mathcal{F}$



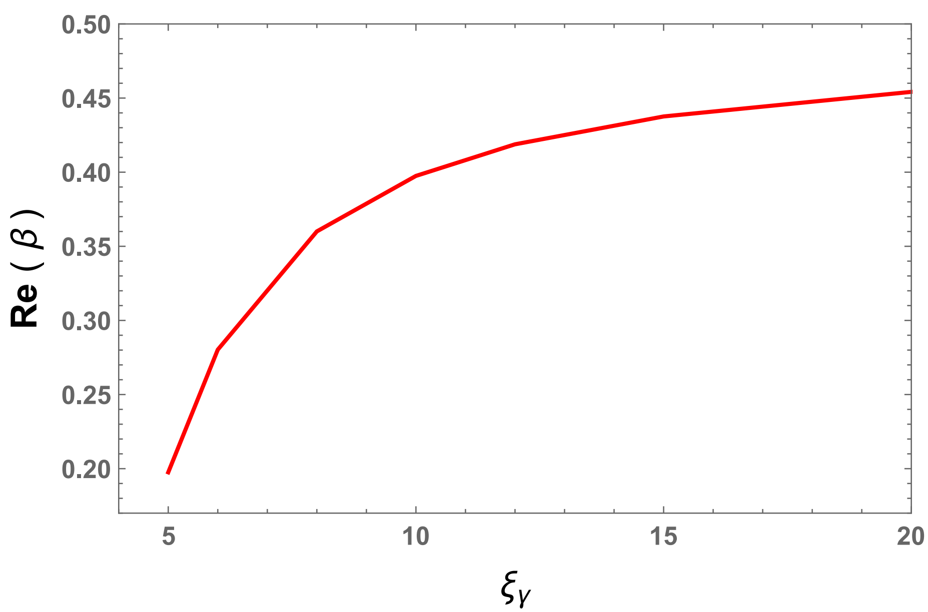
$$\delta\phi \propto (-\tau)^{-\beta} \equiv a^{\mathrm{Re}\,\beta} \cos\left(\mathrm{Im}\,\beta \times N + \mathrm{phase} \right)$$

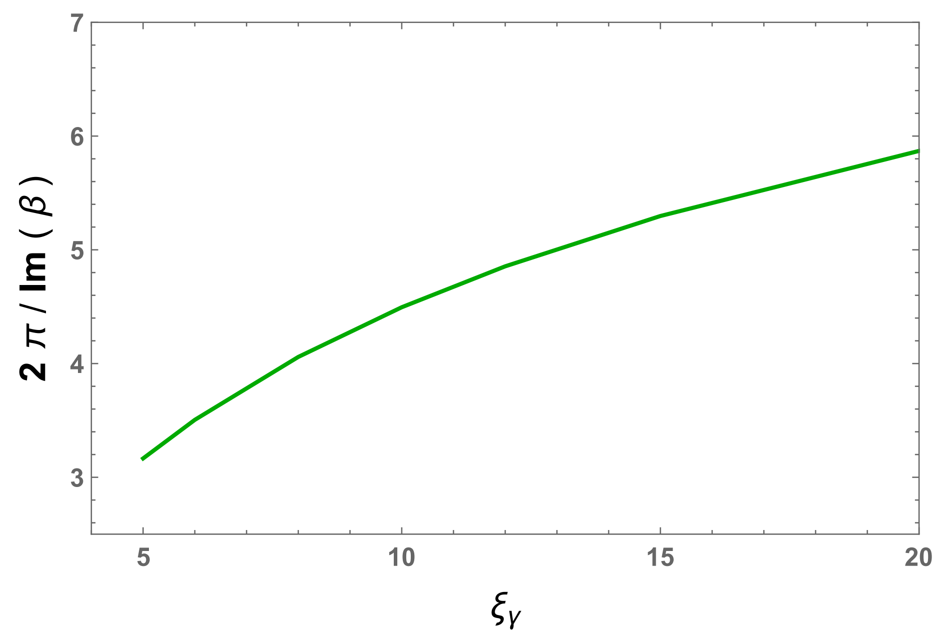
$$\frac{\xi f V''}{c_A(-V')} \simeq \frac{4\beta(\beta+3)}{(2\beta-1)(2\beta+7)} \left[\frac{1}{(8\,\xi_\gamma)^{2\beta-1}} \frac{\Gamma(2\beta+8)}{\Gamma(9)} - 1 \right] \equiv \mathcal{F}[\zeta, \xi_\gamma]$$

$$\frac{\rho_A}{\rho_\phi} \sim \left| \frac{\xi f V''}{c_A(-V')} \right| \ll 1 \text{ in AS}$$



$\delta\phi(t)$ linear combination of these modes → Look for most unstable solution (greatest β_R) with $\mathcal{F} = 0$





Bursts of GW production

- Expect gauge field amplification and related phenomenology enhanced at scales O (H) when $\dot{\phi}$ is maximum $\rightarrow$ Recurrent peaks in power spectra

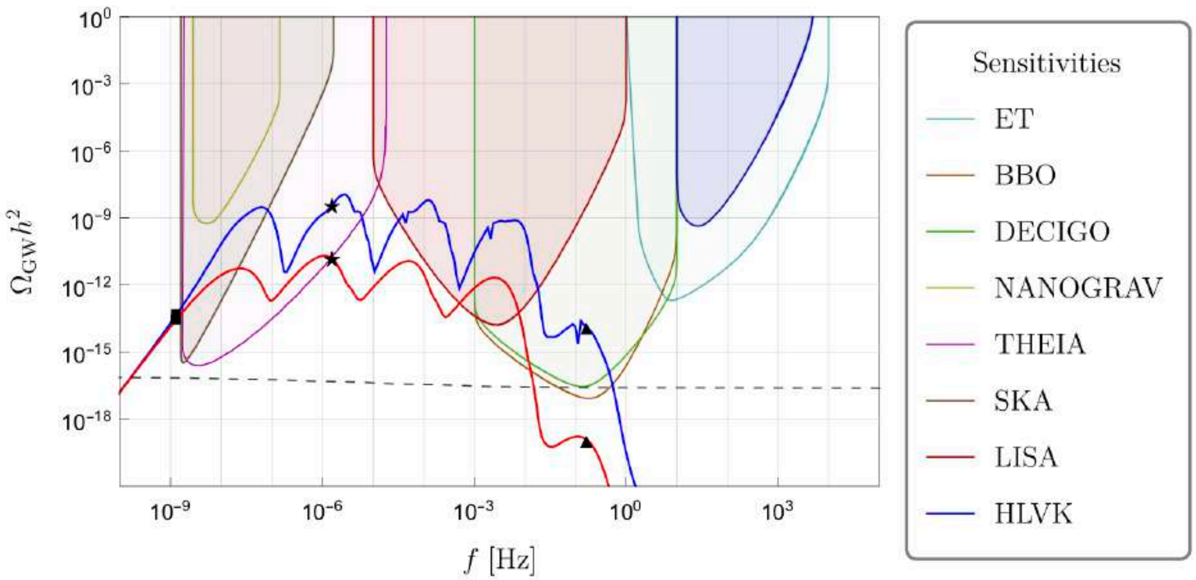
- Correlated peaks across different GW observatories

Garcia-Bellido, Papageorgiou, MP, Sorbo '23

Pulsar Timing Arrays

Astrometry

Interfrometers



- Based on homogeneous backreaction: $\phi\,(t) + \vec{A}\,(t,\,\vec{x})+$ linear $\delta g_{\mu\nu}^{TT}\,(t,\,\vec{x})$

Can we trust it?

As usual, the problem is sourced GW vs. scalar perturbations. Add $\delta\phi$ (perturbatively) and see when it is no longer safe to neglect it

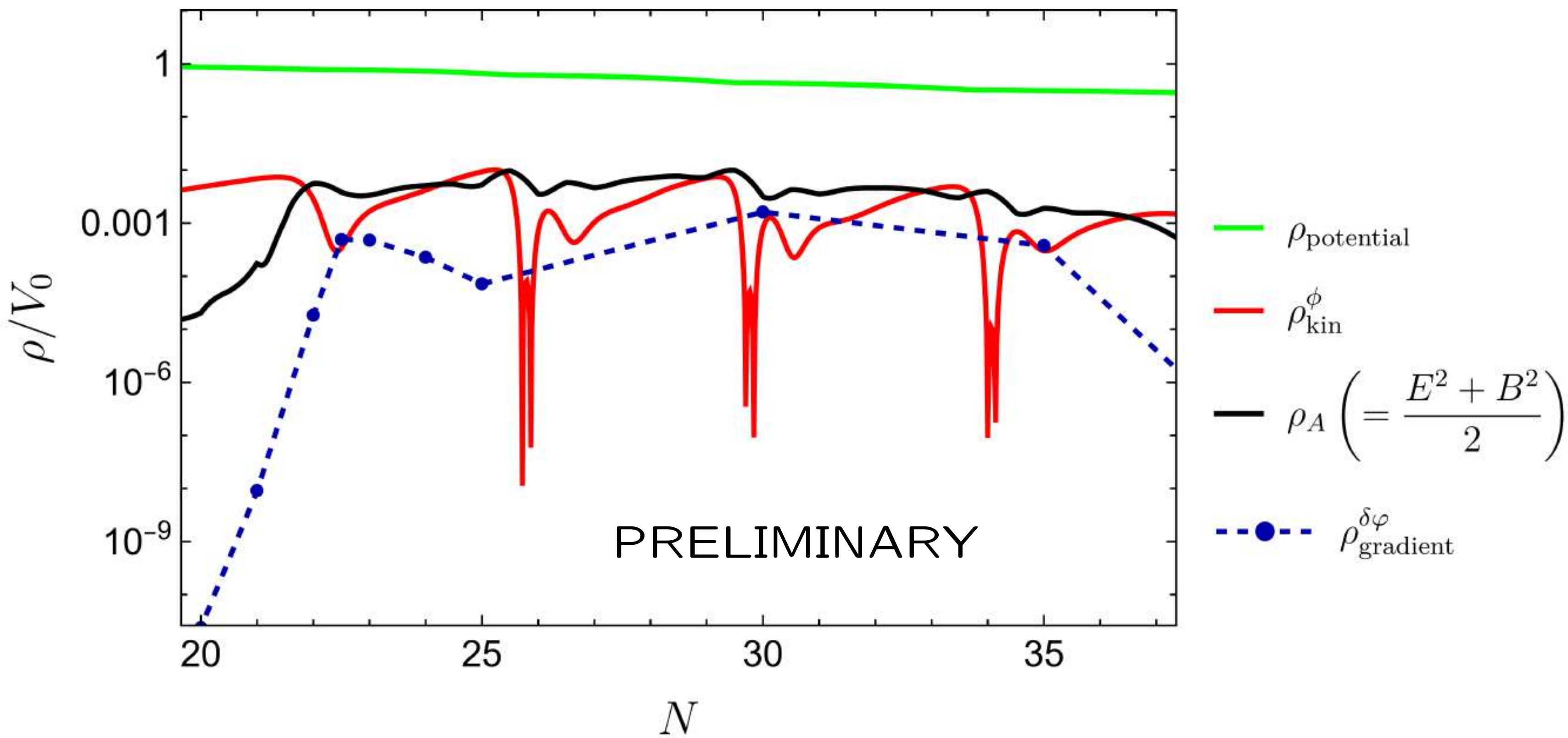
★ Within the Gradient Expansion Formalism

Domcke, Ema, Sandner '24

Durrer, von Eckardstein, Garg, Schmitz, Sobol, Vilchinskii '24

★ In the $\left\{\phi(t)\,,\,\vec{A}_{\vec{k}}(t)\right\} + \left\{\delta\phi,\,\delta g^{TT}_{\mu\nu}\right\}$ system

Barbon, Ijaz, MP 2507.xxxxx



Inhomogeneous backreaction - weak backreaction regime

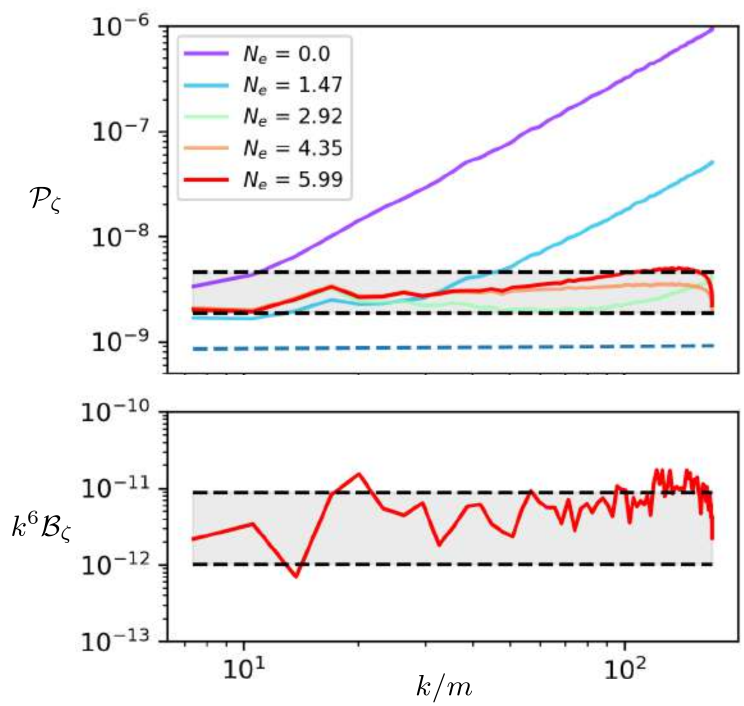
- Analytic results for power spectrum $P \propto \left\langle \delta\phi^2 \right\rangle$ and bispectrum $B \propto \left\langle \delta\phi^3 \right\rangle$ in this regime based on several approximations: constant ξ and H, specific UV regularization Barnaby, MP '10

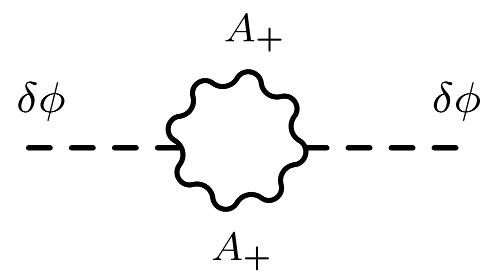
- Under control (backreaction and perturbativity) for $\xi \lesssim 5$

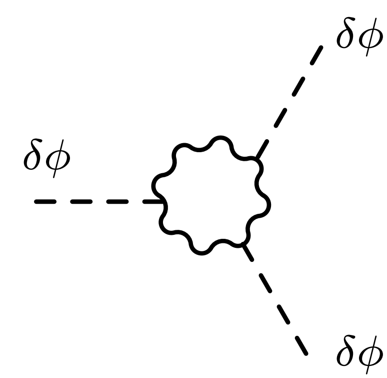
MP, Sorbo, Unal '16

- Excellent agreement with full lattice simulations

Caravano, Komatsu, Lozanov, Weller '22





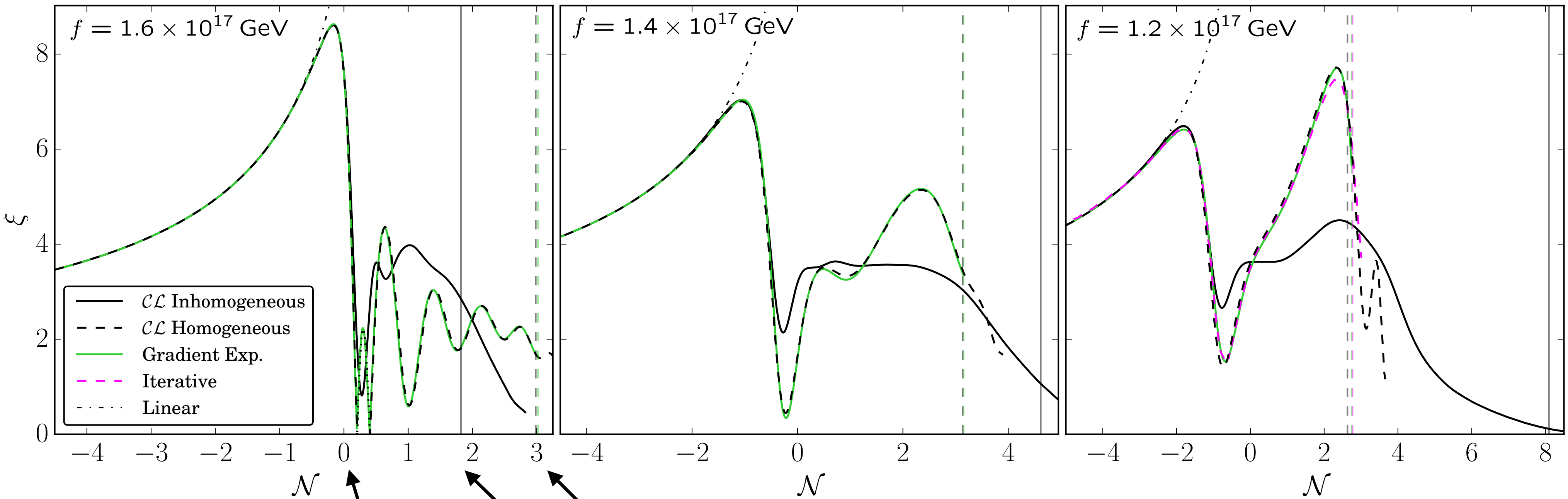


Inhomogeneous backreaction - strong backreaction regime

Reheating: Adshead, Cuissa, Figueroa, Florio, Giblin, Pieroni, Scully, Sfakianakis, Shaposhnikov, Torrenti, Valkenburg, Weiner, . . .

Caravano, Komatsu, Lozanov, Weller '22; Figueroa, Lizarraga, Urio, Urrestilla, '23; Caravano, MP '24;

Sharma, Brandenburg, Subramanian, Vikman '24; Figueroa, Lizarraga, Loayza, Urio, Urrestilla '24



Figueroa et al '23

Homogeneous backreaction

End inflation
no backreaction

Inhomogeneous backreaction

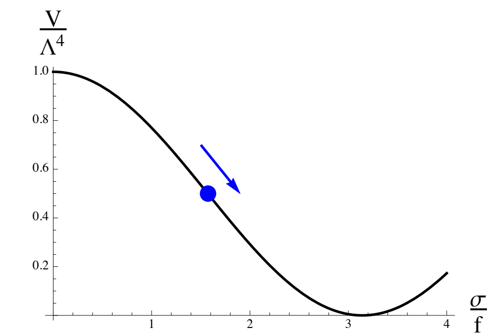
- Extremely challenging (relatively fewer N)
- Reduced oscillatory pattern
- Strong sensitivity to coupling

Spectator axion on the lattice

Caravano, MP '24

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

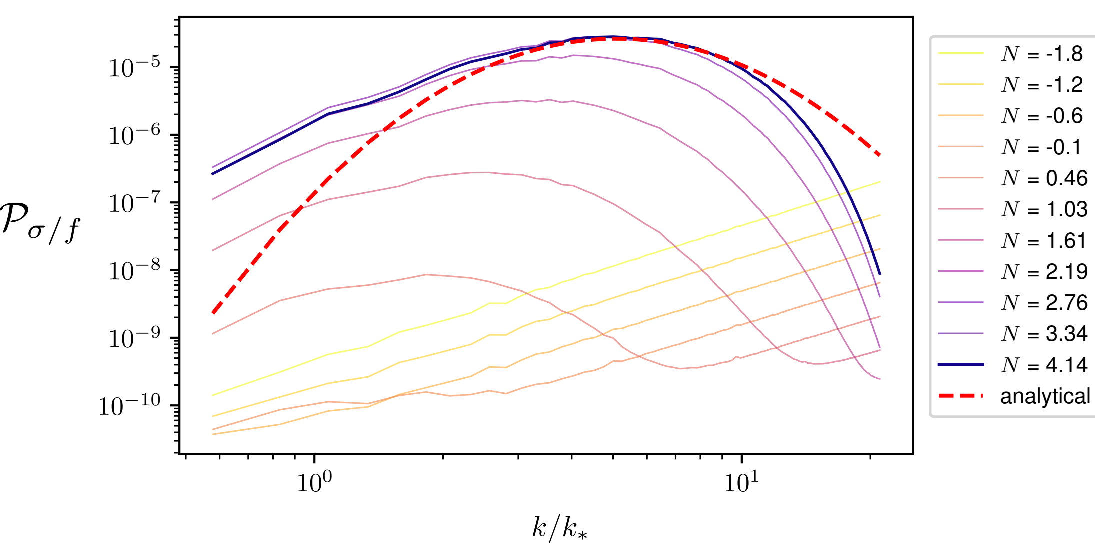
$$V(\sigma) = \frac{\Lambda^4}{2}\left[\cos\left(\frac{\sigma}{f}\right) + 1\right]$$



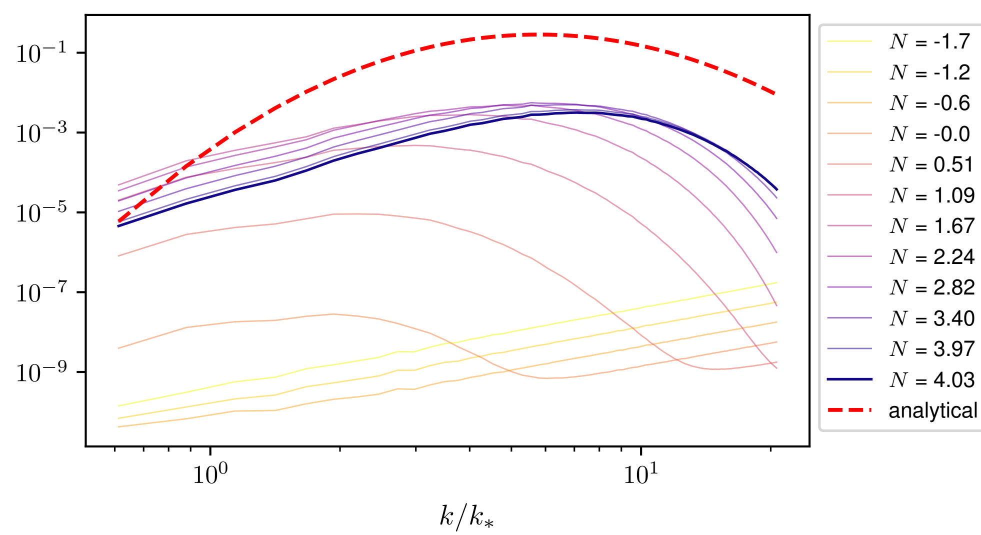
Axion rolls for $\Delta N = \frac{3H^2}{m^2} = \mathcal{O}(1)$ e – folds of inflation

- Gives visible r at small r_{vacuum} / scale of inflation
- Relevant dynamics covered by the lattice

Weak backreaction ($\xi_{\max} = 5$)

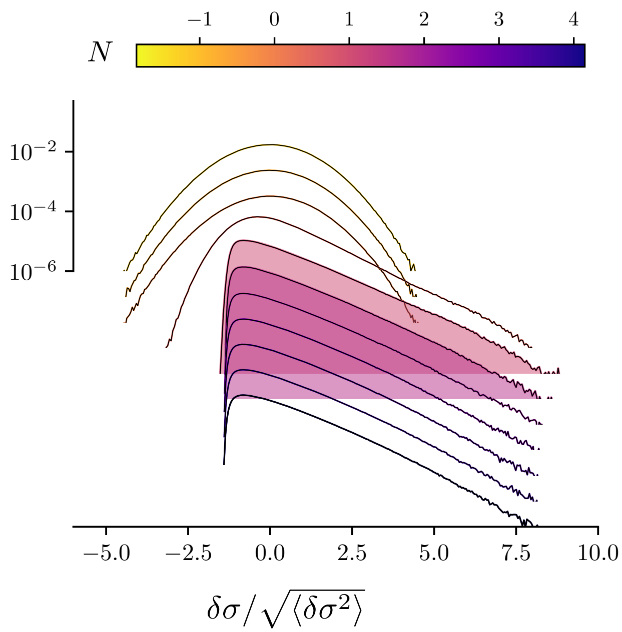


Strong backreaction ($\xi_{\max} = 6$)

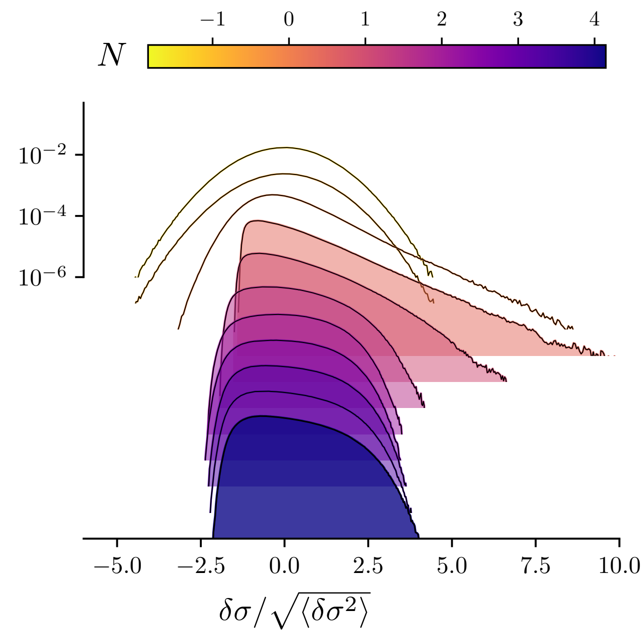


Statistics (1-point probability density function)

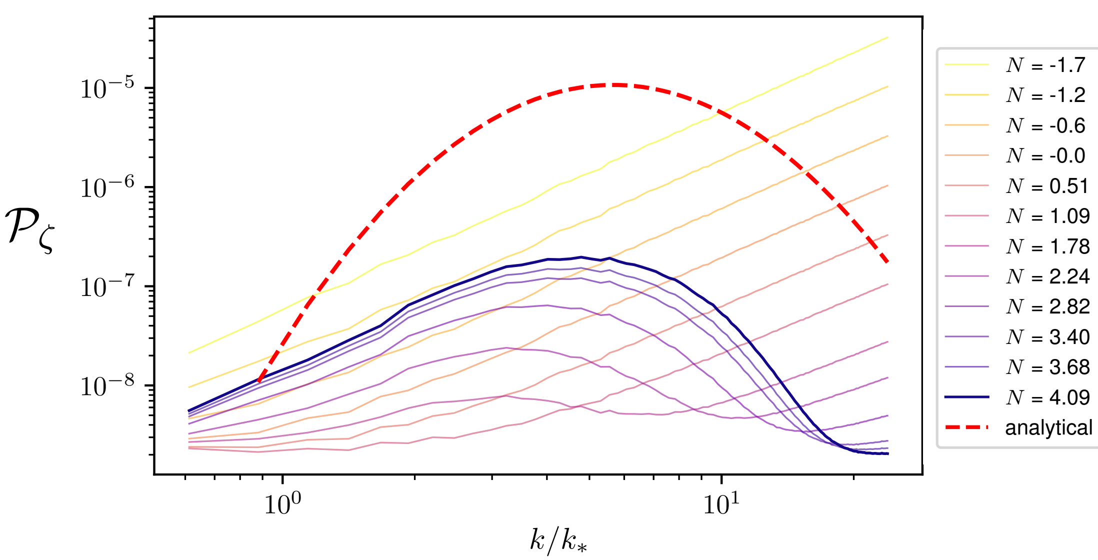
Weak backreaction ($\xi_{\max} = 5$)

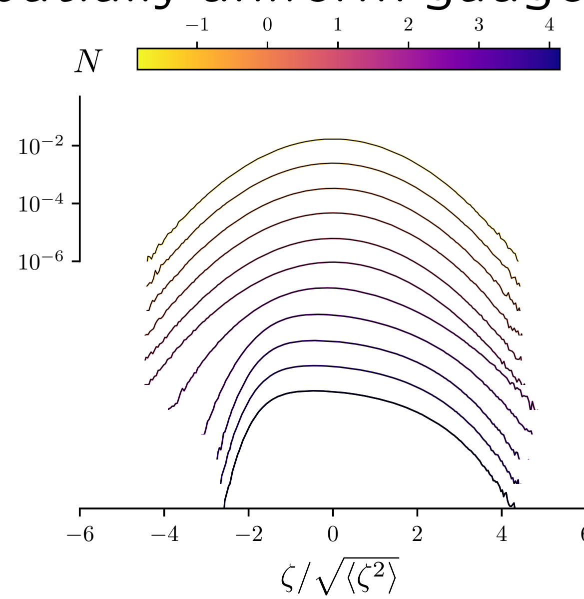


Strong backreaction ($\xi_{\max} = 6$)



Scalar petrurbations (added linearly, in the spatially uniform gauge)





Increased sourced tensor / scalar at small c_s

Kume, MP, Bartolo '25

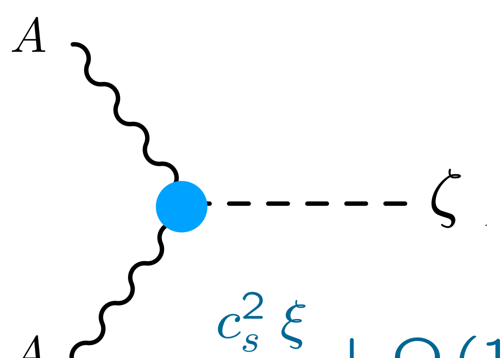
$$\mathcal{L} = K(X) - V(\phi) - \frac{\phi}{4f} F\tilde{F} \quad , \quad X \equiv -\frac{1}{2}(\partial\phi)^2$$

Canonical mode : $v = \frac{a\sqrt{K'}}{c_s}\,\delta\phi \quad , \quad c_s^2 \equiv \frac{K'}{K' + \dot{\phi}^2 K''}$ sound speed

Production parameter : $\xi \equiv \frac{\dot{\phi}}{2Hf} = \sqrt{\frac{\epsilon}{2K'}}\,\frac{M_p}{f}$

$\Rightarrow$ coupling $\frac{\delta\phi}{4f} F\tilde{F} = \frac{1}{4aM_p}\, c_s \sqrt{\frac{2}{\epsilon}}\, \xi\, v\, F\tilde{F}$

Curvature perturbations : $\zeta = -\frac{H}{\dot{\phi}}\,\delta\phi = -\frac{c_s}{\sqrt{2\epsilon}}\,\frac{v}{aM_p}$



$\frac{c_s^2\,\xi}{\epsilon} + \mathrm{O}(1)$ ← gravitational coupling

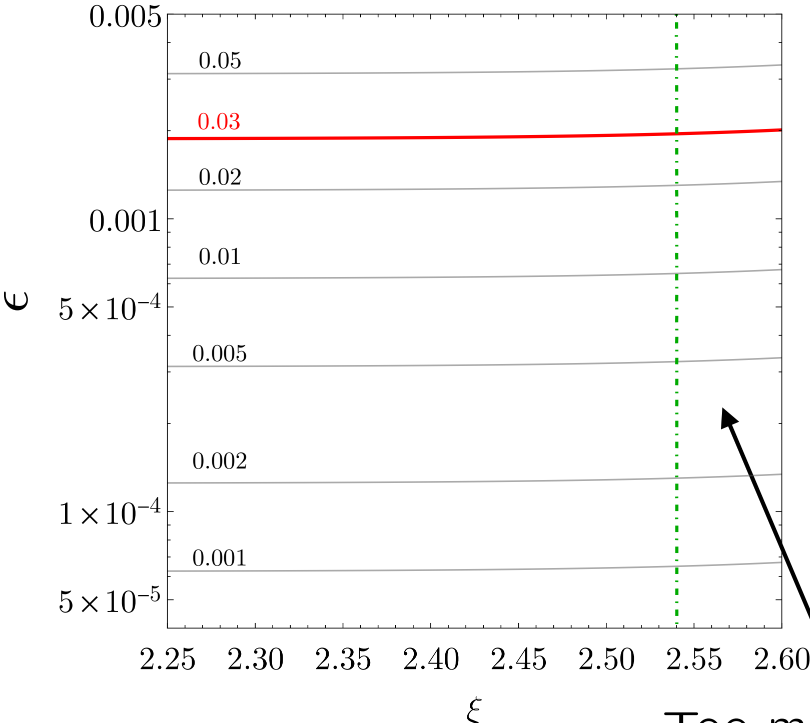
$$\Rightarrow \quad \zeta_s \sim \frac{H^2}{M_p^2}\, \mathrm{e}^{2\pi\xi} \left[\frac{c_s^2}{\epsilon} + \mathrm{O}\left(1\right)\right] \sim c_s^3\, P_\zeta^{(0)}\, \mathrm{e}^{2\pi\xi} \left[1 + \mathrm{O}\left(\frac{\epsilon}{c_s^2}\right)\right]$$

Time integration &
gauge amplitude

coupling

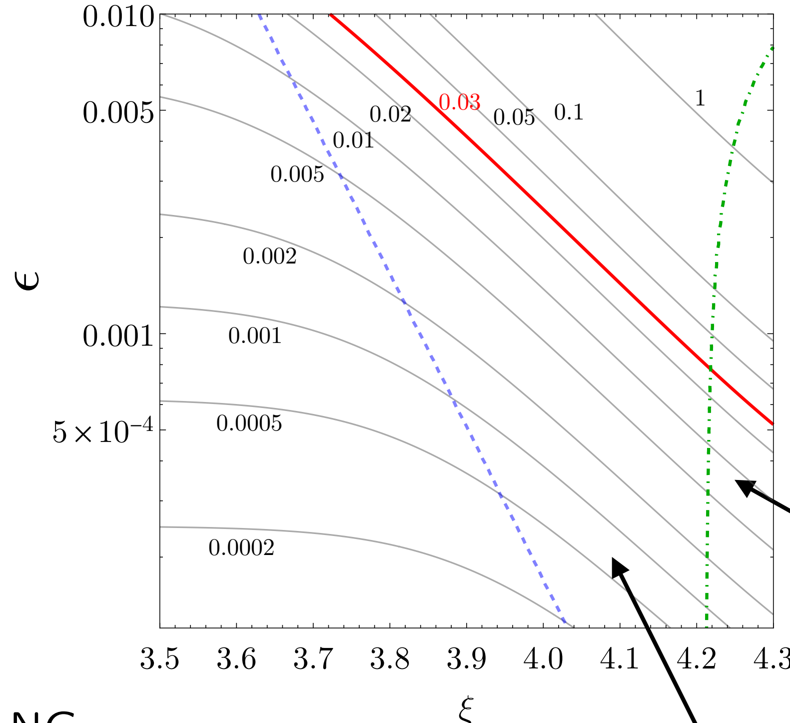
Tensor mode unaffected $\Rightarrow \quad \delta g_s^{TT} \sim \dfrac{H^2}{M_p^2}\, \mathrm{e}^{2\pi\xi} \sim c_s\, \epsilon\, P_\zeta^{(0)}\, \mathrm{e}^{2\pi\xi}$

r for $c_s = 1$



Too much NG

r for $c_s = 0.05$



Too much NG

Sourced tensor > vacuum

Conclusions

- Vector fields during inflation lead to distinct signatures but challenging theoretical realizations beyond pseudo-scalar coupling

- Axion inflation remains an interesting framework for large field inflation. Need to go beyond the simplest model and address $\Delta\phi > M_p$ in quantum gravity

- Gauge field amplification in axion inflation natural mechanism, with rich pheno (non-Gauss, chiral GW at many scales, PBH...)

- Old papers ($\sim$ 2010) analytical computations. Confirmed in the weak backreaction regime. Lattice simulations have matured to provide novel and interesting results for strong backreaction

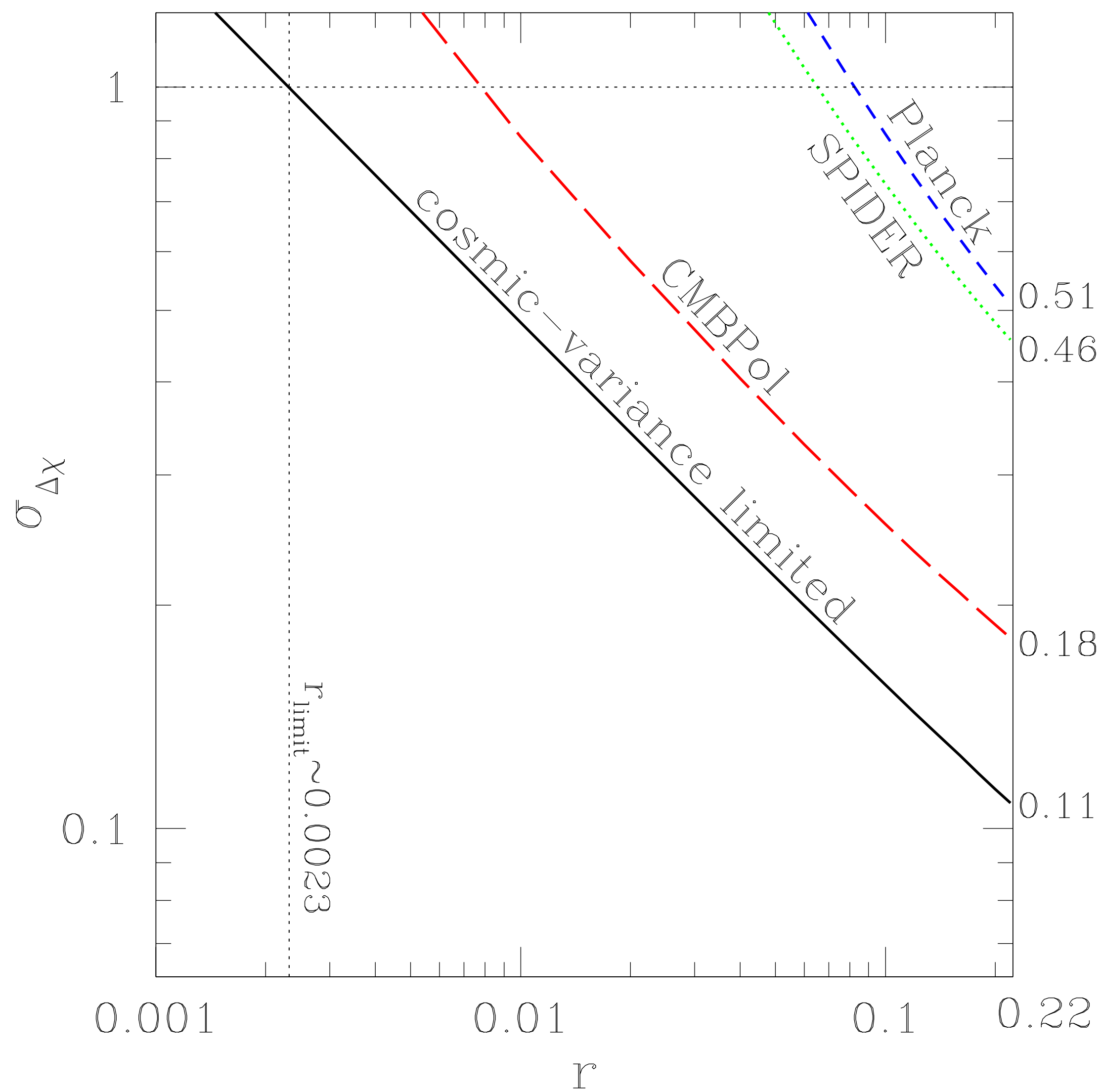
EXTRA

Testing a chiral SGWB

- @ CMB scales (TB & EB correlations)

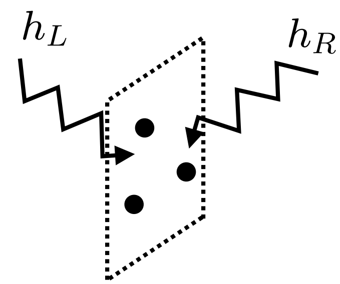
Gluscevic and Kamionkowski '10

$$\Delta\chi = \frac{P_L - P_R}{P_L + P_R}$$

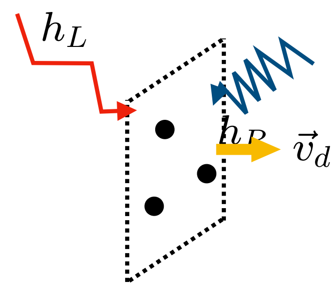


Measurement of GW polarization at LISA / ET

Two GWs related by a mirror symmetry produce the same response in a planar detector. Cannot detect net circular polarization of an isotropic SGWB



Isotropy in any case broken by peculiar motion of the solar system. Assumption, $v_d \simeq 10^{-3}$ as CMB



$$\mathrm{SNR}_{\mathrm{LISA}} \simeq \frac{v_d}{10^{-3}} \frac{\Omega_{\mathrm{GW,R}} - \Omega_{\mathrm{GW,L}}}{1.2 \cdot 10^{-11}} \sqrt{\frac{T}{3\,\mathrm{years}}}$$

Domcke, García-Bellido, MP, Pieroni
Ricciardone, Sorbo, Tasinato '19

(one order of magnitude greater than estimate in Seto '06)

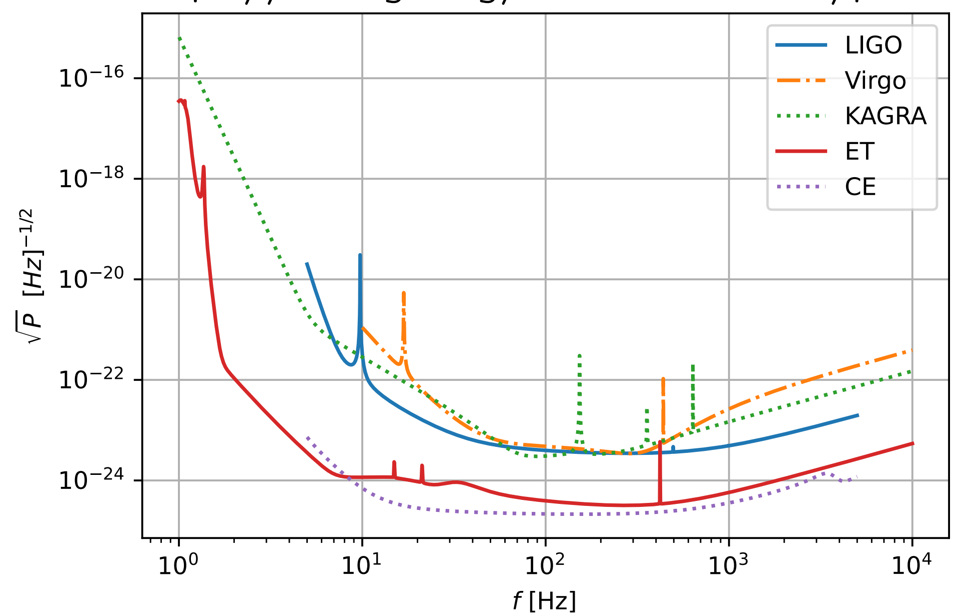
- Do the GW and the CMB dipole coincide ?
- One order of magnitude improvement with LISA-Taiji

Orlando, Pieroni, Ricciardone '20

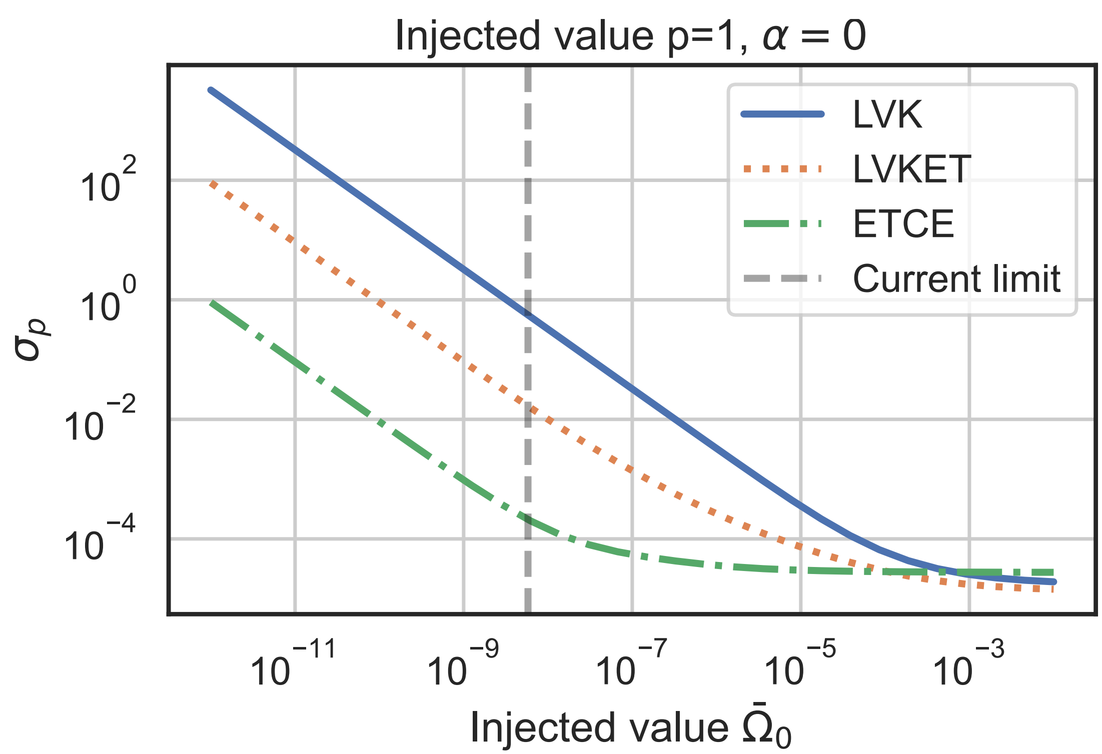
Measurement at ground-based interferometers

$$\Omega_{L/R} = \Omega_0 \left(\frac{f}{f_0}\right)^{\alpha} (1 \pm p)$$

https://dcc.ligo.org/LIGO-T1500293/public



Mentasti, Contaldi, MP ’23



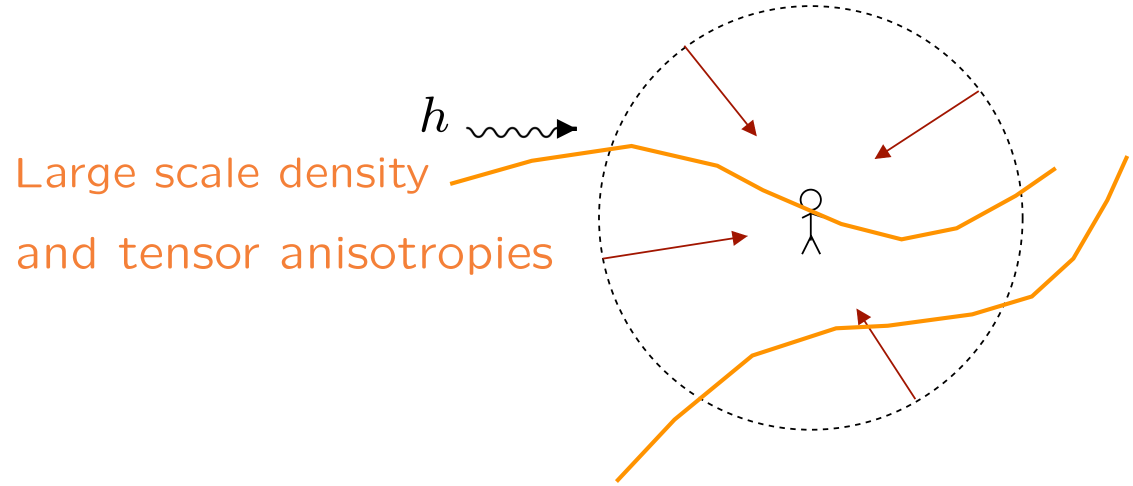
10 years observation

Large-scale SGWB anisotropies

Production mechanism

& propagation imprint

anisotropies in $\rho_{\mathrm{GW}}(\vec{n})$



- Treatment as CMB   Alba, Maldacena '15; Contaldi '16; Cusin, Pitrou, Uzan '17; Jenkins, Sakellariadou '18; Bartolo, Bertacca, Matarrese, MP, Ricciardone, Riotto, Tasinato '19

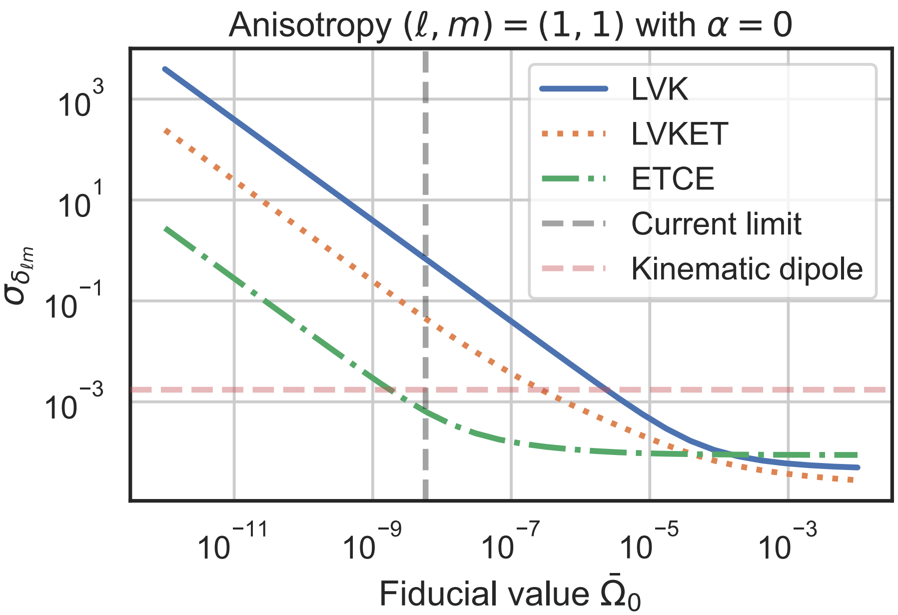
$$\Omega_{\mathrm{GW}}(f) \rightarrow \Omega_{\mathrm{GW}}(f, \hat{n}) \equiv \Omega_0 \left(\frac{f}{f_0}\right)^{\alpha} \sum_{\ell m} \delta^{\mathrm{GW}}_{\ell m} Y_{\ell m}(\hat{n})$$

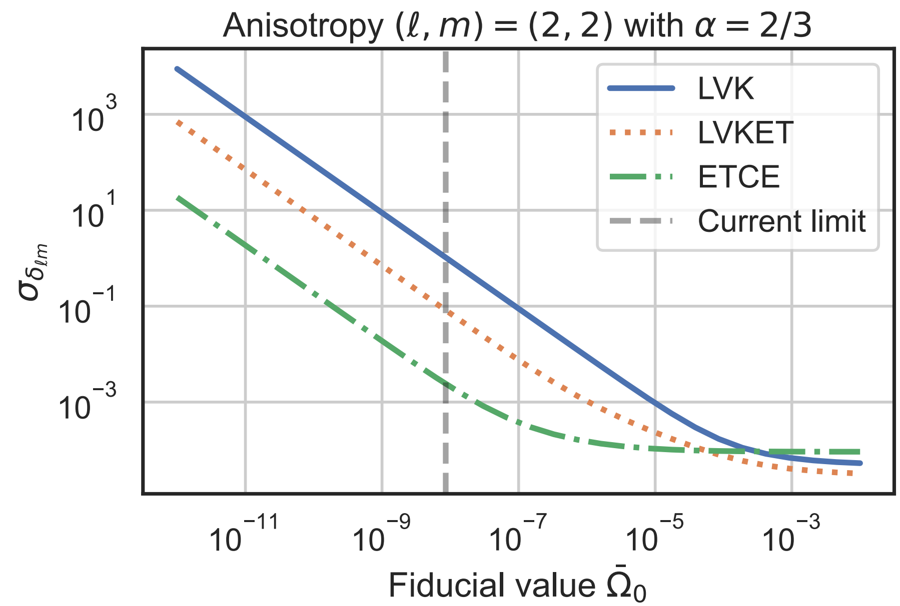
Bartolo et al '22, LISA CosWG

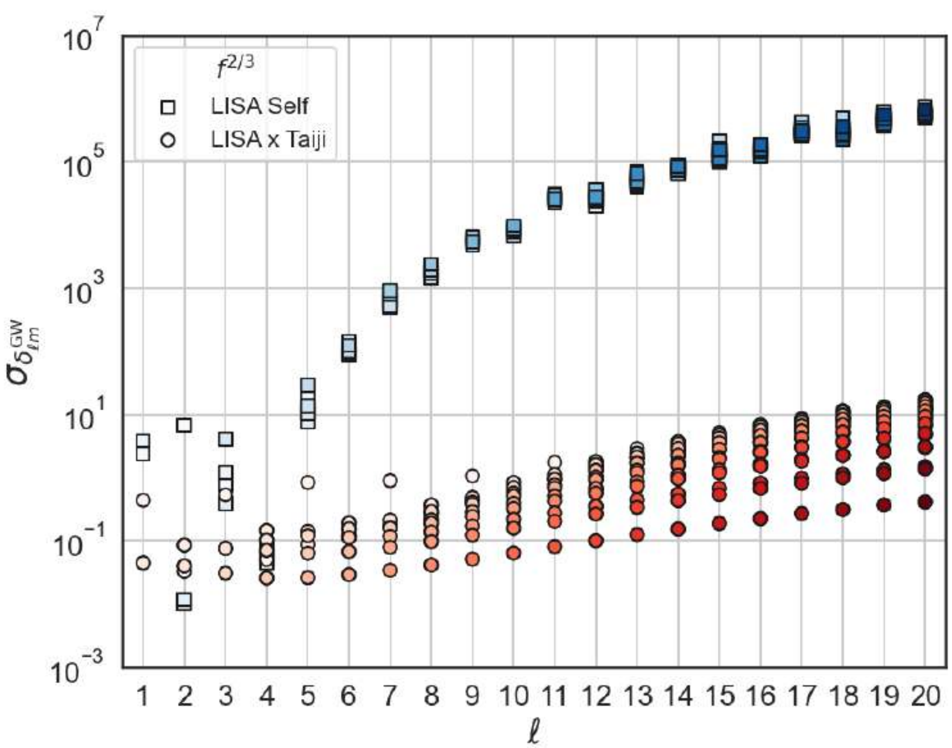
Amplitudes relative to the monopole,

$$\delta^{\mathrm{GW}}_{00} = \frac{1}{Y_{00}} = \sqrt{4\pi} \simeq 3.5$$

Mentasti, Contaldi, MP '23







Mentasti, Contaldi, MP '23

10 years

$$\Omega_{0,\text{fiducial}} = 2 \times 10^{-11}$$

at $f_0 = 1$ mHz