Axion inflation with gauge fields: backreaction and signatures

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- Axion-like inflaton coupled to a U(1) gauge field
- Improved understanding of backreaction of the produced gauge fields
- Concrete realizations with multiple axions

- Scale of inflation (unknown) from primordial GW signal

$$r \equiv \frac{P_{GW}}{P_\zeta} \lesssim 0.03 - 0.04 \qquad \text{Planck + ground-based CMB}$$

Slow roll inflation + standard assumption of $\delta\rho$ and GW from amplification of vacuum modes (due to the inflationary expansion)

$$V^{1/4} \simeq 10^{16}\,\text{GeV}\left(\frac{r}{0.01}\right)^{1/4}, \quad \Delta\phi \gtrsim M_p\left(\frac{r}{0.01}\right)^{1/2} \quad \text{Lyth '96}$$

- Observation is great for knowing V, but not problem-free

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

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

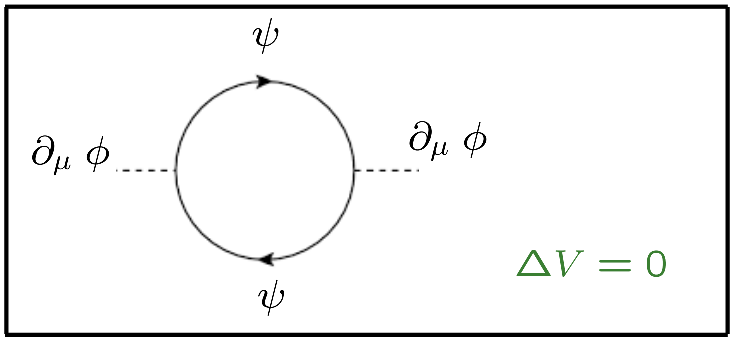
Hard to achieve flatness $\dfrac{M_p V'}{V}, \dfrac{M_p^2 V''}{V} \ll 1$ unless $M \gg M_p$

Axion inflation

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. $\Delta V \propto V_{\cancel{\text{shift}}}$
- Shift symmetry tells us little about V

Observations $\nearrow$ No observable signal in generic vanilla slow-roll apart from CMB / LSS (~ 7 e-folds of inflation)

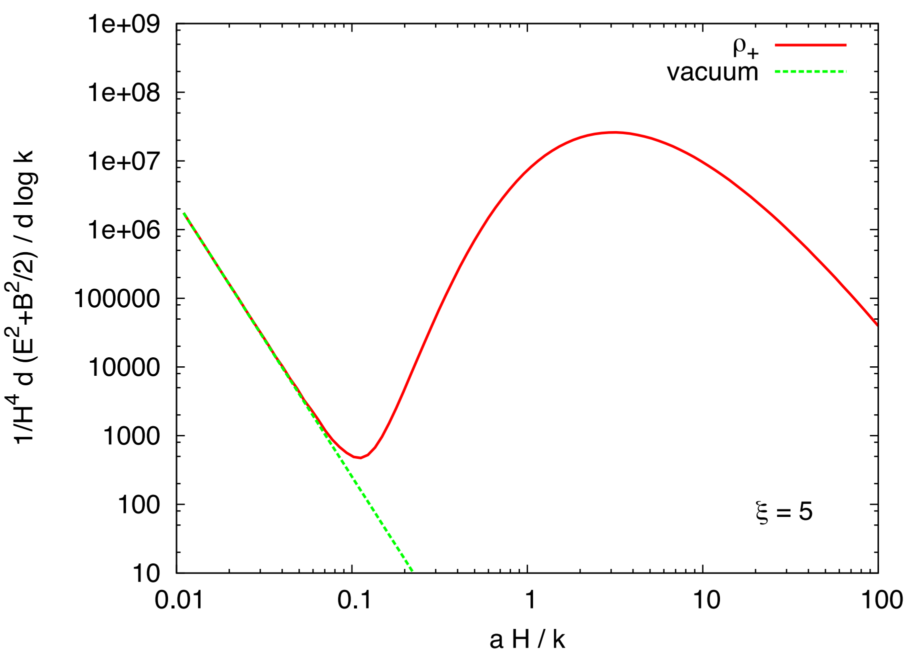
Observations $\searrow$ Rich phenomenology, exponentially sensitive to V, from the shift-symmetric $\phi F \tilde{F}$ interaction

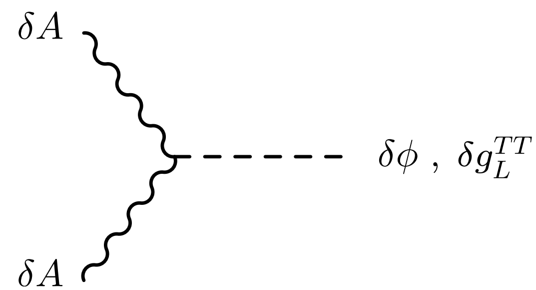
$\phi F\tilde{F}$ originally studied for magnetogenesis Turner, Widrow '88

Backreaction

$\phi(t) \longrightarrow \vec{A}(t,\vec{x})$ → Density perturbations, Gravitational waves

Physical ρ_A in one mode





- One tachyonic helicity at horizon crossing
- Then diluted by expansion
- Max energy $\propto e^{4\pi\xi}$, $\xi \equiv \frac{c_A\,\dot{\phi}}{2fH}$

Continuous production. Modes amplified at horizon crossing. At each moment there is a mode of the size of the horizon. $\neq$ scales probe $\neq$ portions of $V(\phi)$, with $\phi = \phi(t)$ evaluated when they exited the horizon

- Strong limit at CMB scales ($\xi_{\rm CMB} \lesssim 2.5$) from the non-Gaussianity of the sourced scalar perturbations Barnaby, MP '10

- Strong limit at much smaller scales produced at the end of inflation due to $\dot{\phi} \rightarrow \vec{A} \rightarrow$ GW at reheating Adshead, Giblin, Pieroni, Weiner '19 von Eckardstein, Schmitz, Sobol '25

- Better prospects at intermediate scales, where possibly observable in

  ★ 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; . . .

Reaching observable levels at intermediate scales requires an amount of $\vec{A}$ production typically leading to significant backreaction on $\phi(t)$. Recently improved understanding of backreaction $\rightarrow$ revision of these earlier results

Backreaction

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

(electromagnetic notation used for simplicity)

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

(1) Instantaneous backreaction — Analytic computations for $\xi \equiv \frac{c_A \dot{\phi}}{2fH} \simeq$ const

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

(3) Inhomogeneous backreaction — Full system

Instantaneous 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

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

Anber, Sorbo '09

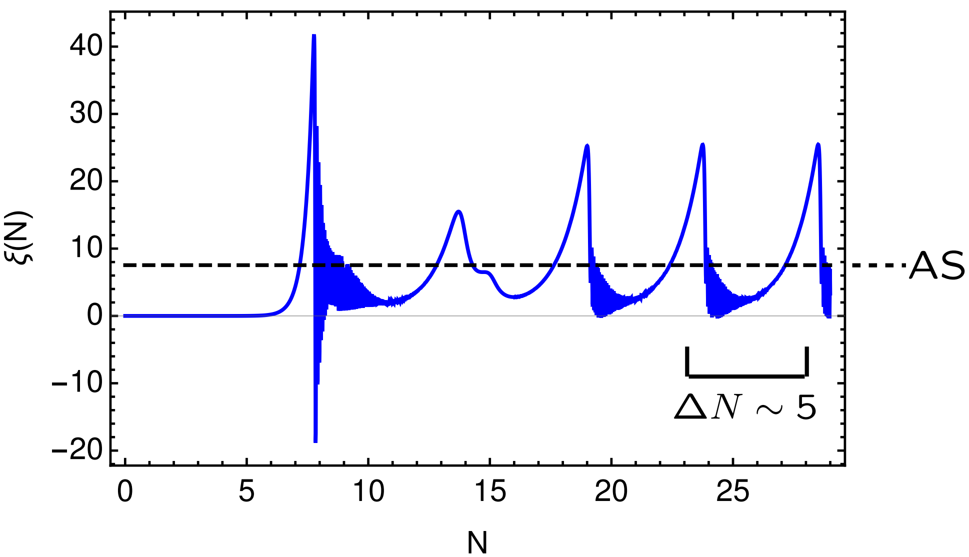
Homogeneous backreaction

$$\Delta A^0 = \cancel{\frac{c_A}{f} \left(\vec{\nabla}\phi\right) \cdot \left(\vec{\nabla} \times \vec{A}\right)}$$

$$\vec{A}_i - \Delta \vec{A} + \vec{\nabla} A^{0\prime} = \frac{c_A}{f} \left[\phi' \, \vec{\nabla} \times \vec{A} - \cancel{\vec{\nabla}\phi \times \left(\vec{A}' + \vec{\nabla} A^0\right)}\right]$$

No mode coupling for homogeneous ϕ

Can numerically integrate with a $1d$ grid for $A\left(\left|\vec{k}\right|\right)$



Oscillations of $\xi \propto \dot{\phi}$ about the instantaneous backreaction evolution

- Each vector mode needs finite time to grow before contributing to backreaction. Memory of the few previous e-folds

Domcke, Guidetti, Welling, Westphal '20

Inflaton speeds up $\rightarrow$ large $\vec{A}$ production $\rightarrow$ backreaction slows $\dot{\phi}$

$\rightarrow$ production stops, $\vec{A}$ diluted by expansion $\rightarrow$ Inflaton speeds up $\rightarrow$ ...

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

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

$$\delta A'' + \left(k^2 - \frac{k\,\bar{\phi}'}{f}\right)\delta A = \frac{c_A\,\bar{A}}{f}\,\delta\phi' \longrightarrow \text{Formal solution } \delta A\left[\delta\phi'\right]$$

Memory kernel

$$\Rightarrow \quad \delta\phi''(\tau) + 2aH\delta\phi'(\tau) + a^2 V\delta\phi(\tau) = \int^\tau d\tau'\,K\left(\tau,\,\tau'\right)\,\delta\phi'\left(\tau'\right)$$

Solution $\delta\phi = \sum_i c_i\, a^{\zeta_i}$. AS stability

determined by Sign Re ζ_i

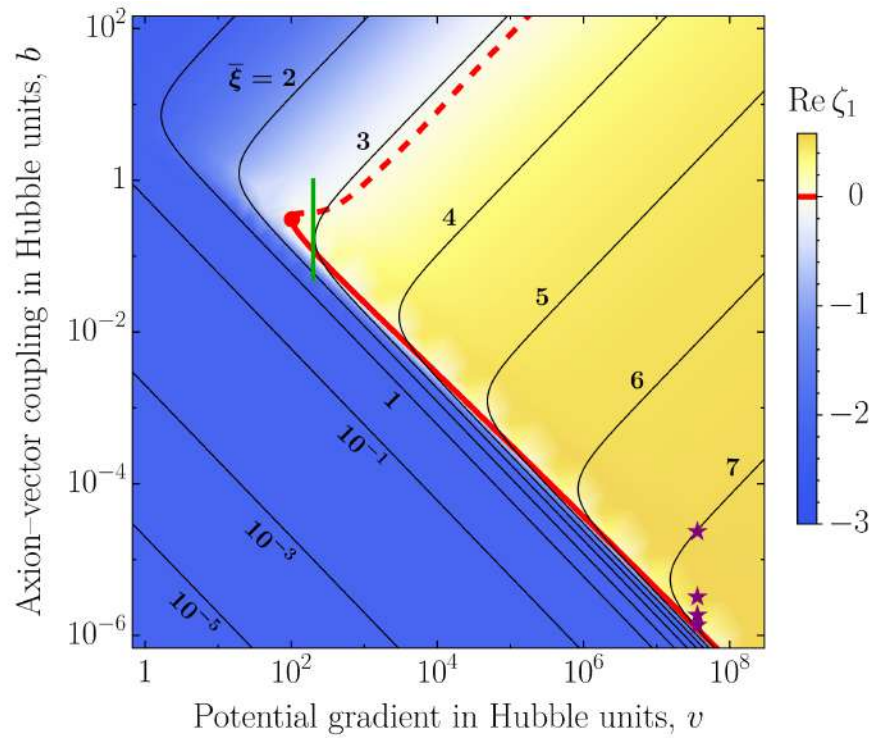
(while Im ζ_i $\rightarrow$ oscillations)

Improved precision in determination of ζ_i

von Eckardstein, MP, Schmitz, Sobol, Sorbo '23

Sobol, von Eckardstein, Koch, Gurevich, Thiele, Schmitz '26

Kulkarni, Sorbo '26

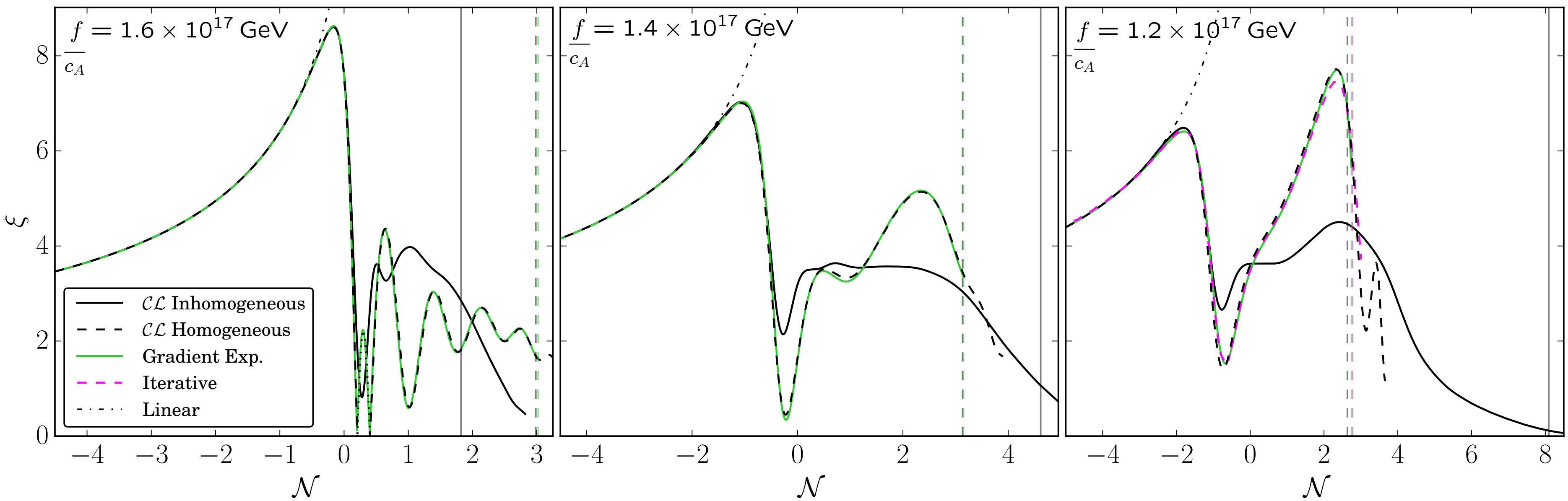


Inhomogeneous backreaction

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

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

Lizarraga, C. Lòpez-Mediavilla, Urio '25; Jamieson, A. Caravano, Komatsu '25



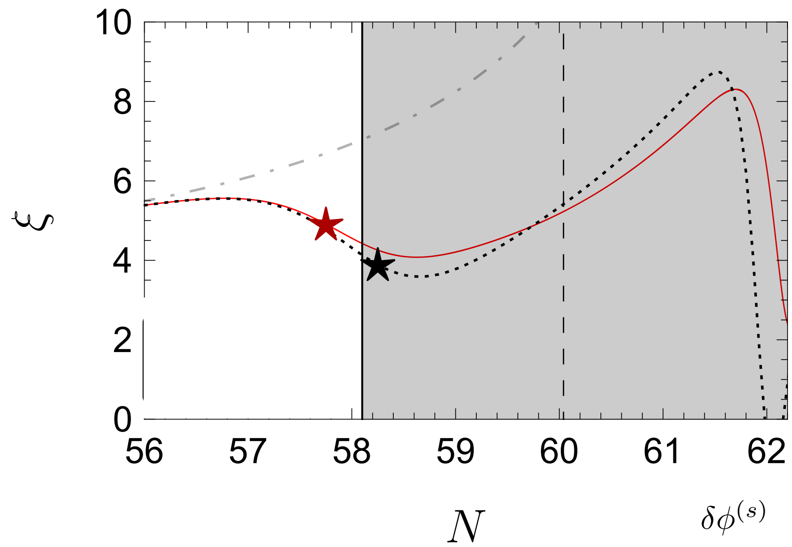
Figueroa et al '23

- Oscillatory pattern signals coherency during inflation. Broken by spatial gradient of inflaton, quickly arising from amplified $\vec{A}$
- Expensive lattice computations (must control UV and IR in exponentially expanding background). $\lesssim 7$ e-folds, here chosen at the end of inflation.
- Hard to get general conclusions, very strong sensitivity to couplings

Realm of homogeneous backreaction

Domcke, Papageorgiou, MP, Sandner '26

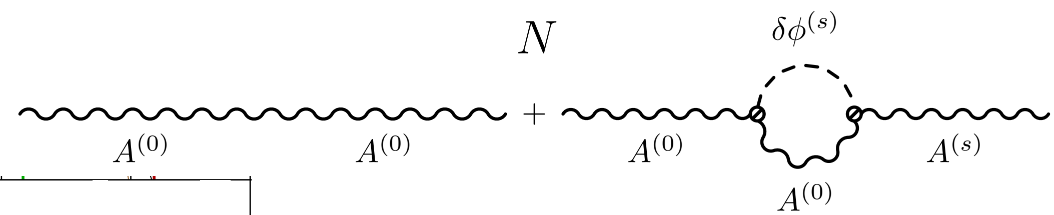
Assess it without lattice

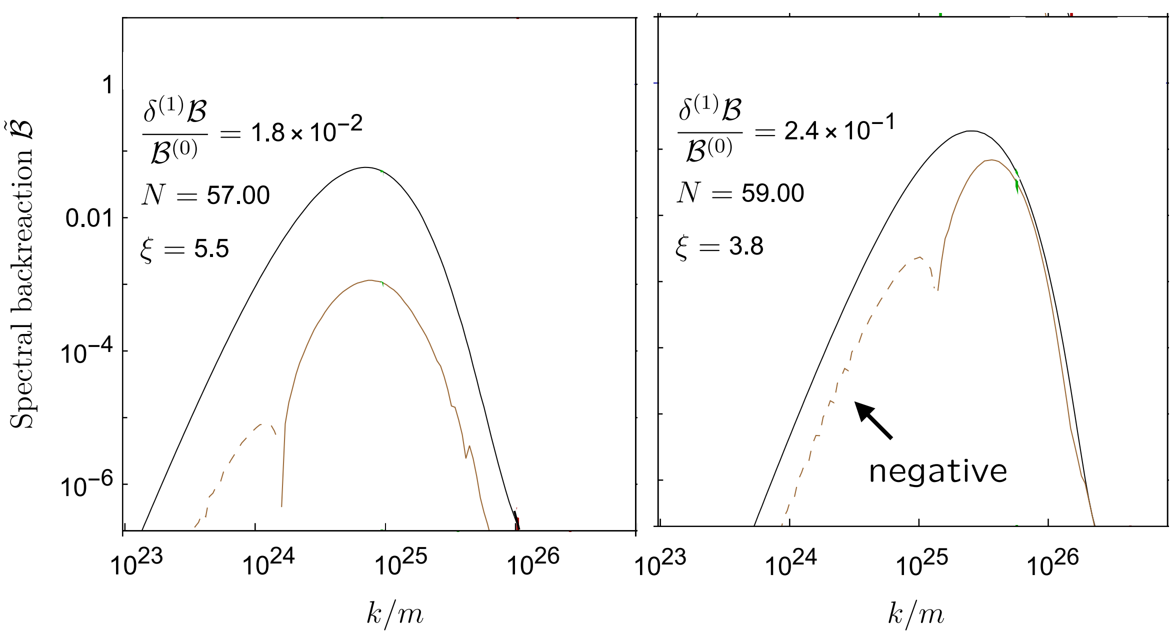


★ Add $\phi-$gradients perturbatively

compare evolution with / without

★ Compute $\langle \vec{E}\cdot\vec{B}\rangle^{(0)} + \delta\langle \vec{E}\cdot\vec{B}\rangle$





IR $\to$ UV transfer

from mode-mode coupling

Homogeneous backreaction accurate for $\rho_{\phi,\text{gradient}}/\rho_{\phi,\text{kinetic}} \lesssim$ few %

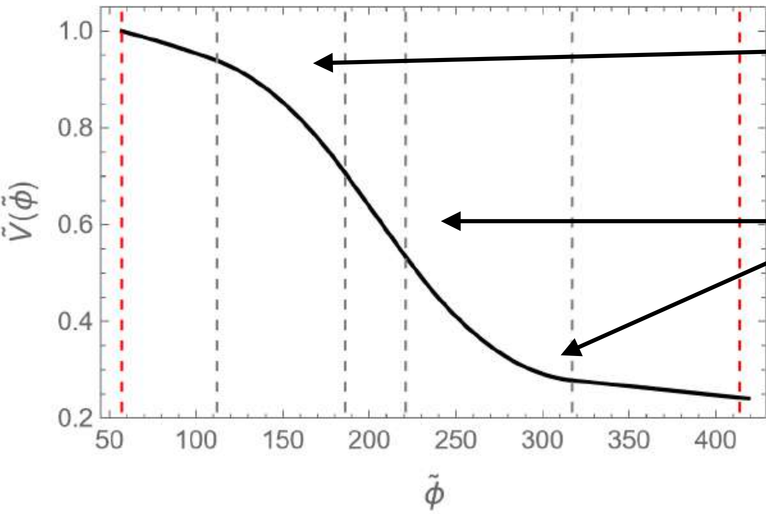
Domcke, Ema, Sandner '23

Phenomenology

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

Teuscher, Durrer, Martineau, Barrau '26

Piecewise potential (better motivated model next)



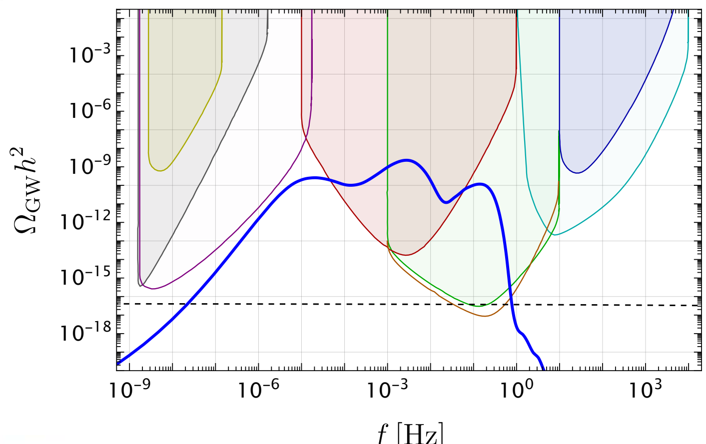
Negligible $\vec{A}$ production at CMB and in final stages of inflation

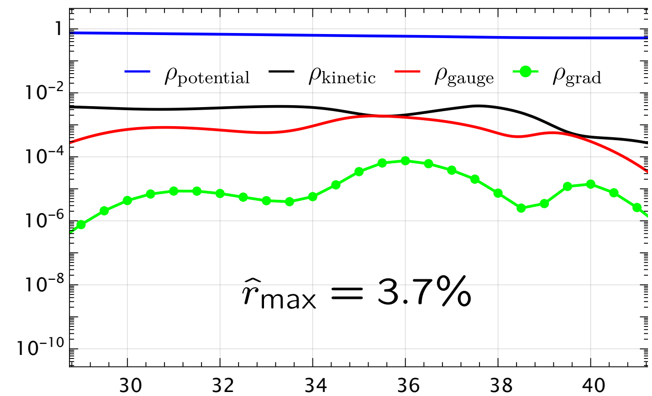
Potential steepens at intermediate scales: $\dot{\phi} \to \vec{A} \to$ GW, PBH

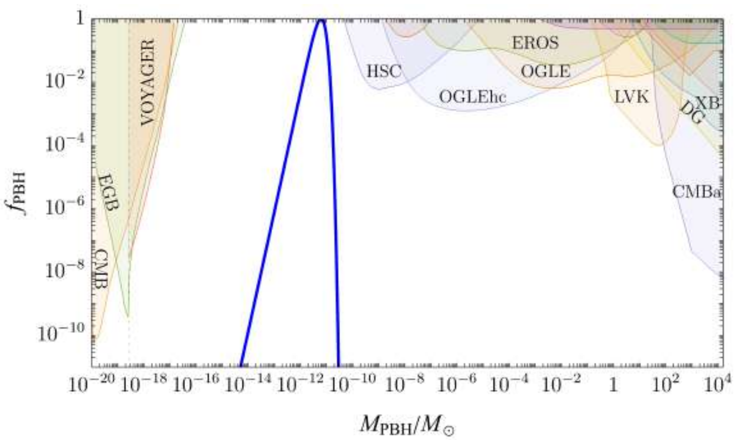
Two examples:

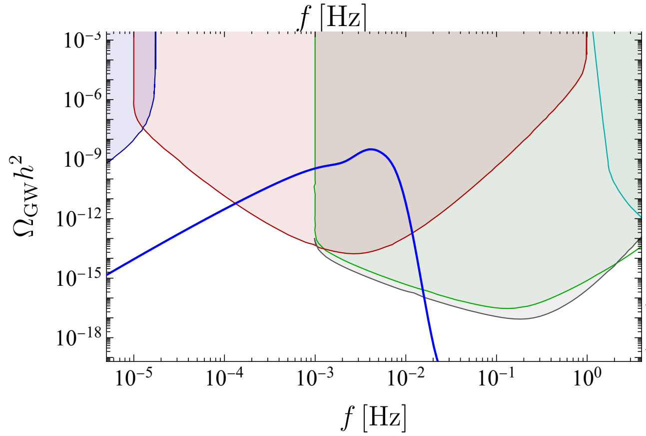
Barbon, Ijaz, MP '25

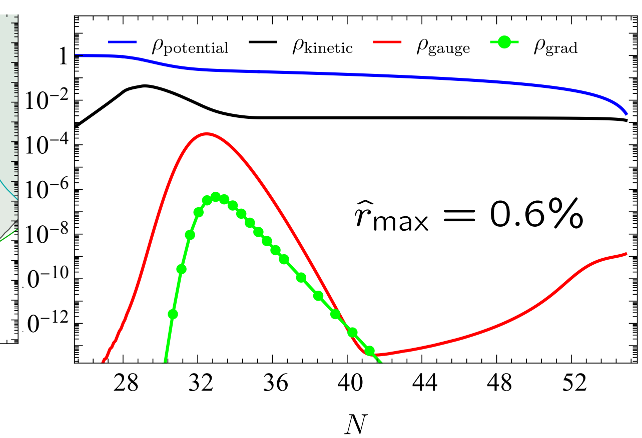
Franciolini, Ijaz, MP '26











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

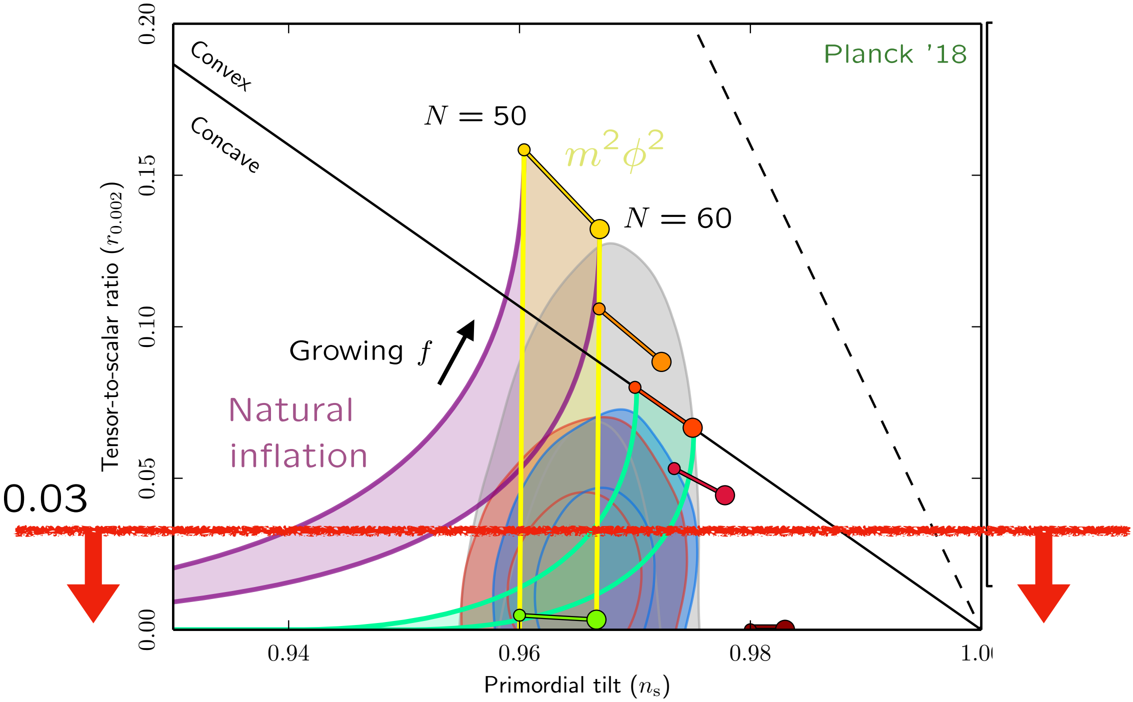
$$V = \Lambda^4 \left[1 - \cos\left(\frac{\phi}{f}\right)\right]$$

Freese, Frieman, Olinto '90

★ Ruled out

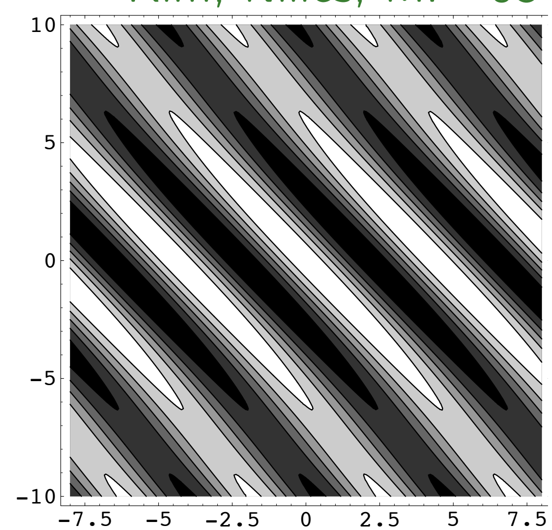
★ $f > M_p$ in range shown

$r \lesssim 0.03$



Aligned natural inflation

Kim, Nilles, MP '05



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

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

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

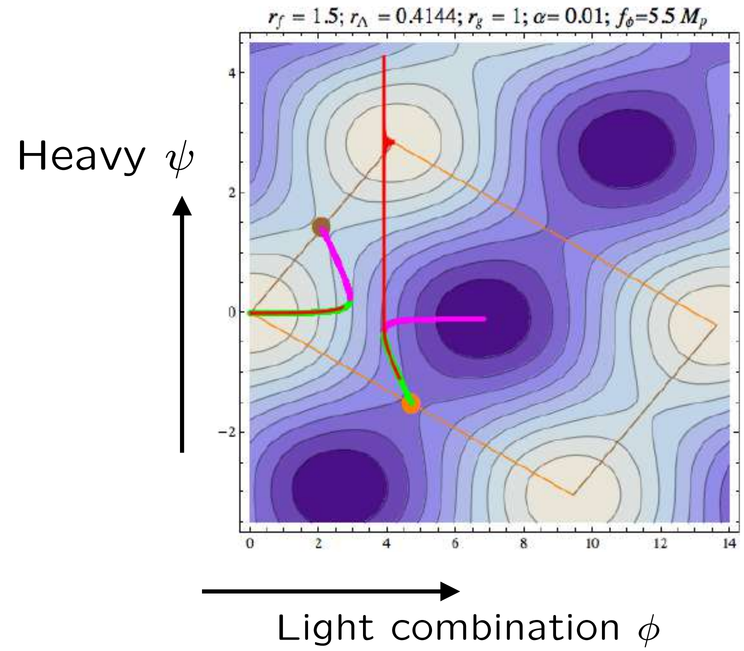
(gravitational instanton corrections may still be a problem)

- In agreement with CMB

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

Fields rescaled $\simeq$ curvature in 2 directions

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

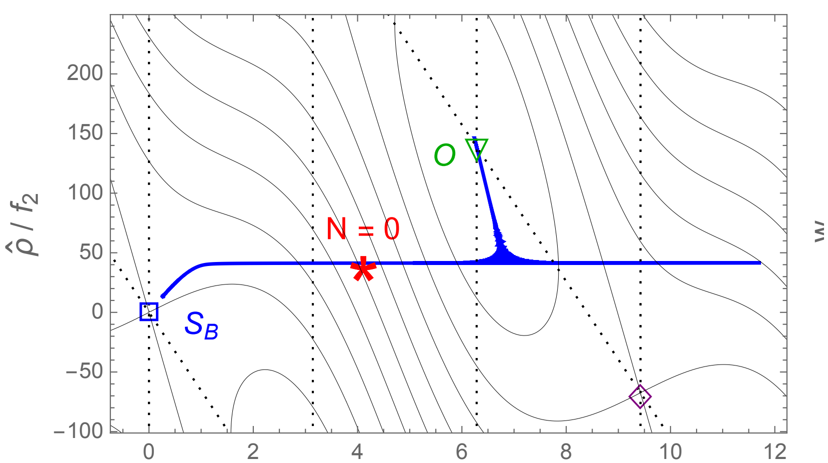


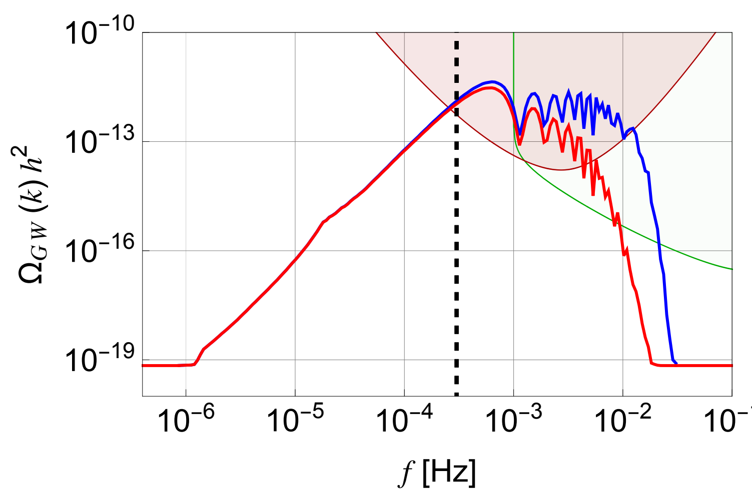
Inflationary trajectories ending because (1) reach a minimum or (2) become unstable in heavy direction. Agree with CMB MP, Unal '15

Depending on parameters, instability can be followed by a prolonged second phase of inflation. Large $\vec{A}$ amplification if $\phi_i F \tilde{F}$

Greco, MP '24

Greco '25





Conclusions

- Mechanism studied for long time. Earlier analytical results highly accurate at moderate couplings (CMB), but not intended as precision predictions at stronger coupling

- Lattice simulations are catching up and already producing relevant results. In parallel, we are developing tools to assess the validity of approximate methods and obtain reliable phenomenology

- $\phi F\tilde{F}$ mechanism mostly controlled by (i) coupling, (ii) slope V', (iii) field range with with large V'. Next $\rightarrow$ concrete models