UV Unitarity Violations In Nonminimally Coupled Scalar-Starobinsky Inflation

This presentation outlines briefly the work leading up to the paper
JCAP01(2023)029 or arXiv:2205.12836

prepared for

PPC 2023

XVI International Conference on Interactions between Particle Physics and Cosmology

OUTLINE

- Naive Predictions and their Fallacy
- (Traditional) Higgs' Inflation
- McDonald's Proposal (Palatini Only)
- Large Background, Small Background
- Antoniadis et al.'s Correction
- Scalar-Starobinsky Nonminimal Coupling
- Energies and Backgrounds
- Results: Metric and Palatini
- Conclusions

NAIVE PREDICTIONS AND THEIR FALLACY

- Consider the Lagrangian: $\mathcal{L} = \frac{1}{2}\phi\Box\phi + \frac{1}{\Lambda}\phi^2\Box\phi$
- The corresponding amplitude in the s-channel: $\mathcal{M}(\phi\phi \to \phi\phi) = \sim \frac{p^2}{\Lambda}\frac{1}{p^2}\frac{p^2}{\Lambda} \sim \frac{s}{\Lambda^2}$
- From this, we can estimate that the breakdown of the theory on grounds of unitarity happens as $E \to \Lambda$.
- This does <u>not</u> mean that the theory is not unitary, just that this diagram is insufficient to represent the physics of this process as $E \to \Lambda$.

Images and arguments taken from 'Quantum Field Theory and the Standard Model' by Matthew Schwartz

TRADITIONAL HIGGS' INFLATION

- Now, consider a perturbative approach involving $H = \frac{1}{\sqrt{2}}(\Phi_1 + i\Phi_2)$ as the Higgs' singlet scalar for Higgs' inflation:

$$\boxed{S = \int d^4x\sqrt{-g}\left[\left(1 + \frac{2\xi|H|^2}{M_{Pl}^2}\right)\frac{M_{Pl}^2 R}{2} - \partial_\mu H^\dagger \partial^\mu H - V(|H|)\right]}$$

- Going to the Einstein frame by taking the Weyl transformation: $g_{\mu\nu} \to \left(1 + \frac{\xi|H|^2}{M_P^2}\right) g_{\mu\nu}$
- Then, a perturbative expansion of Ω^{-2} using scalars around a background $\left(\Phi = \bar{\phi} + \phi\right)$.
- This perturbative expansion hinges on how <u>large</u> or <u>small</u> $\bar{\phi}$ is compared to M_P and ϕ.
- Estimated unitarity violation close to $M_P/\sqrt{\xi}$ (Palatini formalism) for EW vacuum ($\bar{\phi} \to 0$).

McDONALD'S PROPOSAL (Palatini Only)

arXiv:2007.04111 [hep-ph]

- Such estimations are only applicable in specific regimes and <u>cannot</u> be extrapolated.
- Claimed that within the interaction volume: $\langle \phi \rangle \sim E$.
- Suggested working around $\bar{\phi} \ll E$; did not spoil predictions as we can safely take the limit $\bar{\phi} \to 0$.
- He also assumed that working in the $\bar{\phi} \gg E$ limit and later <u>matching</u> the two could give us the whole picture; better than the 'naive predictions'.
- Also, proposed that predictions in the Jordan frame would be more accurate; could be recovered by looking at how fields transform between the frames.

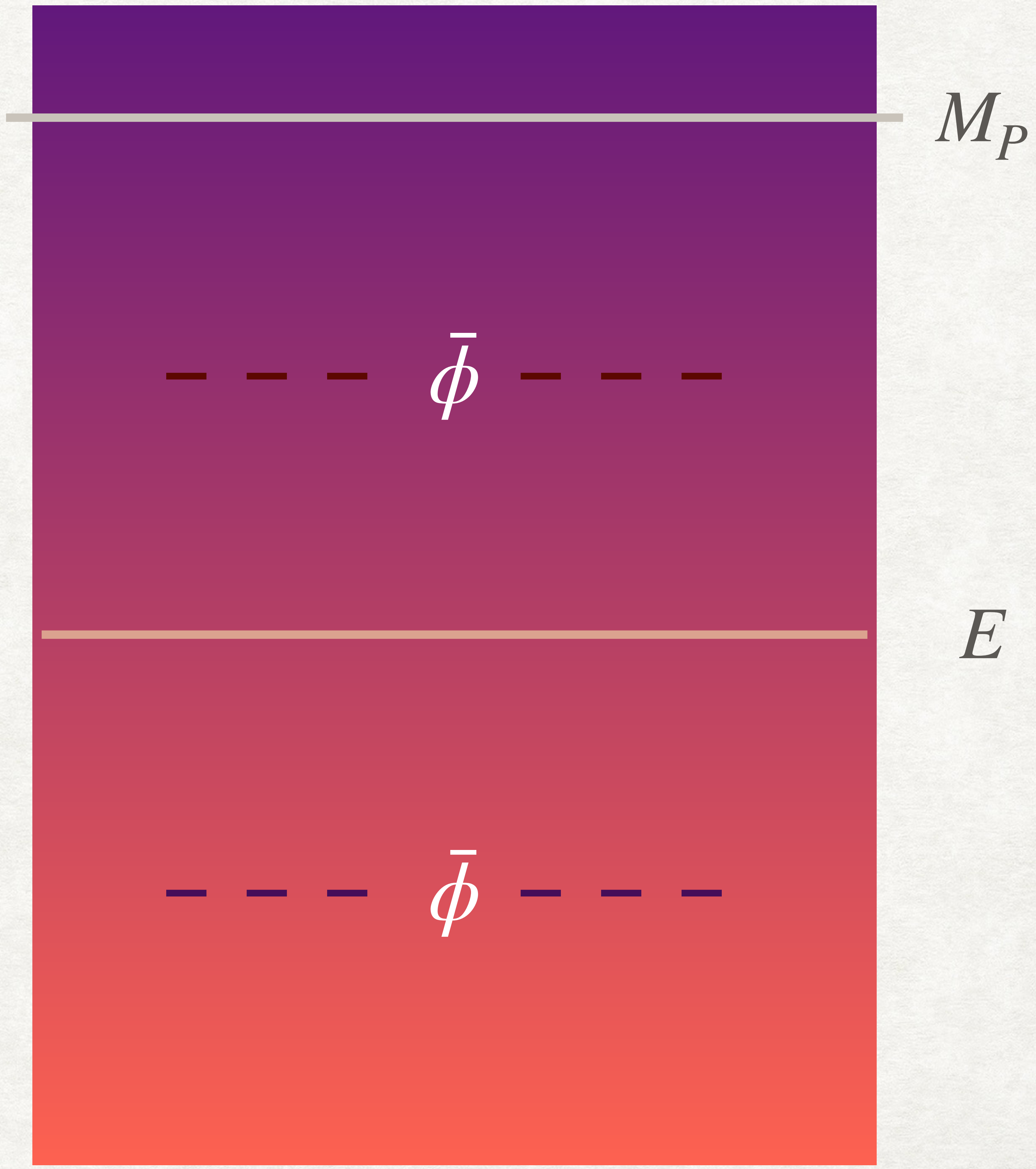
LARGE BACKGROUND, SMALL BACKGROUND

- The two regimes correspond to the two epochs in the cosmological paradigm.

- Inflation $\implies$ $\bar{\phi}$ is large.

- Reheating $\implies$ EW vacuum $\implies \bar{\phi} \sim 0.$

- McDonald suggested working around an inflationary background, matching to make predictions for the reheating era.



ANTONIADIS ET AL.'S CORRECTION

arXiv:2203.10040 [hep-ph]

- The paper is actually an addendum to arXiv:2106.09390 [hep-th] which called out McDonald's proposals.
- Holds the key to circumventing one McDonald's problematic assumptions regarding matching.
- The authors essentially sum the infinite terms in the Taylor series using form factors:

$$\bar{G} = 1 + \frac{\xi\bar{\phi}^2}{M_P^2}, \qquad x^2 = \frac{\xi\bar{\phi}^2}{M_P^2\bar{G}}.$$

- Avoid any discrepancy between the large background and the small background regimes, at least at the level of perturbative expansion.

SCALAR-STAROBINSKY COUPLING

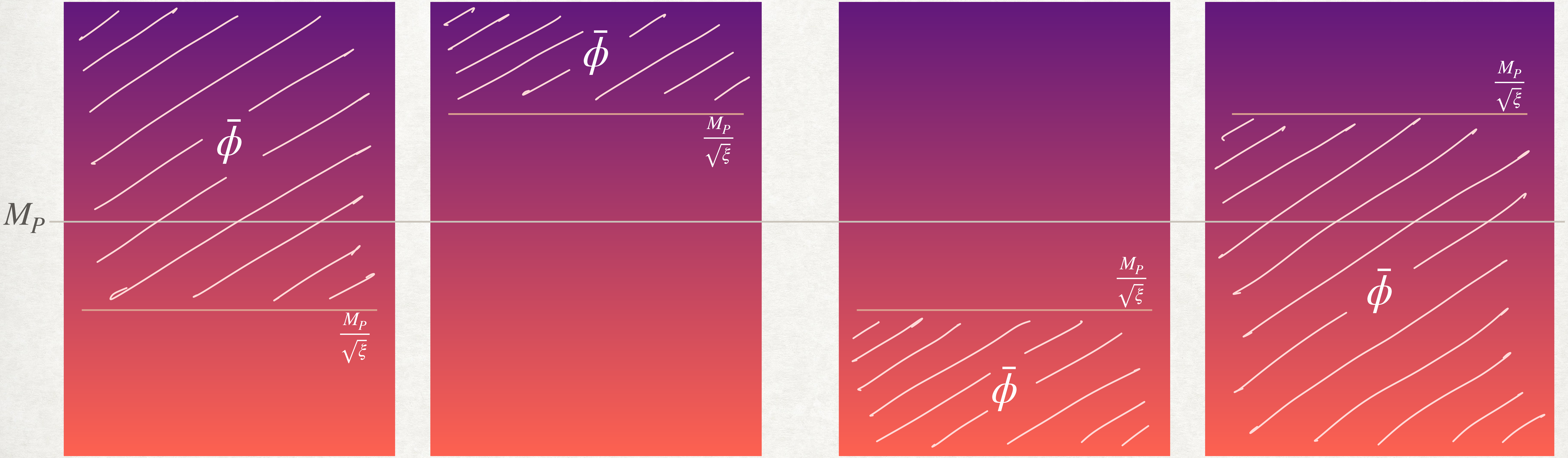
$$S = \int d^4x\sqrt{g}\left[\frac{M_P^2}{2}\left(1+\frac{\xi|\Phi|^2}{M_P^2}\right)\left(R+\frac{\alpha}{2M_P^2}R^2\right)-|\partial\Phi|^2\right]$$

- $\Phi^2 R^2$ coupling inspired by background behaviour in arXiv:1705.07945 and as one-loop correction in arXiv:2007.10395.
- Unitarity analysis performed for all limits of ξ and α. Later, matched with physical inflation models using observational constraints on parameters from different potentials.
- Example: arXiv:1705.07945 found that for safe exit from the inflationary epoch, for their model, α was small & negative, while no constraints were directly put on ξ.
- Similarly, a Higgs'-like inflation model found in arXiv:1701.03814 imposes $\xi \gg 1$ with no constraints on α.

ENERGIES AND BACKGROUNDS

$$\bar{\phi} \gg \frac{M_P}{\sqrt{\xi}}$$

$$\bar{\phi} \ll \frac{M_P}{\sqrt{\xi}}$$



$\xi \gg 1$ | $0 < \xi < 1$ | $\xi \gg 1$ | $0 < \xi < 1$

E scales from 0 to M_P; shaded region shows range of $\bar{\phi}$

METRIC FORMULATION RESULTS

			Unitarity up to M_P	$\|\alpha\| \to 0$ limit
$\|\alpha\| \ll 1$	Large Background	$b^2 \to 1$	Safe	Unsafe
		$b^2 \to 1/2$	Safe	Unsafe
		$b^2 \to 0$	Safe if $\frac{\alpha^2 \xi \bar{\phi}_1^2}{M_P^2} \leq 1$	Safe
	Small Background	$\xi \gg 1$	Unsafe	Unsafe
		$0 < \xi < 1$	Safe	Safe
$\|\alpha\| \to 1$	Large Background	$b^2 \to 1, 1/2$	NA	
		$b^2 \to 0$	Unsafe	
	Small Background	$\xi \gg 1$	Safe	
		$0 < \xi < 1$	Safe	
$\|\alpha\| \gg 1$	Large Background	$b^2 \to 1$	NA	
		$b^2 \to 1/2$	Unsafe	
		$b^2 \to 0$	Unsafe	
	Small Background	$\xi \gg 1$	NA	
		$0 < \xi < 1$	Unsafe	

where $b^2 = \dfrac{6\xi x^2}{1 + 6\xi x^2}$

PALATINI FORMULATION RESULTS

			Unitarity up to M_P	$\lvert\alpha\rvert \to 0$ limit
$\lvert\alpha\rvert \ll 1$	Large Background	$\xi \gg 1$	Safe	Safe
		$0 < \xi < 1$	Safe	Safe
	Small Background	$\xi \gg 1$	Unsafe	Safe
		$0 < \xi < 1$	Safe	Safe
$\lvert\alpha\rvert \to 1$	Large Background	$\xi \gg 1$	Safe	
		$0 < \xi < 1$	Safe	
	Small Background	$\xi \gg 1$	Unsafe	
		$0 < \xi < 1$	Safe	
$\lvert\alpha\rvert \gg 1$	Large Background	$\xi \gg 1$	Safe if $\lvert\alpha\rvert \leq \xi$	
		$0 < \xi < 1$	Safe if $\frac{\lvert\alpha\rvert M_P^2}{\xi \bar{\phi}_1^2} \leq 1$	
	Small Background	$\xi \gg 1$	Unsafe	
		$0 < \xi < 1$	Unsafe	

CONCLUSIONS

- For the inflation scenario in arXiv:1705.07945, in the metric formulation, unitarity is preserved in inflation and reheating epochs for $0 < \xi < 1$. $\xi \to \frac{1}{6}$ is lucrative, but considering the safety of $\alpha \to 1$, the viable range is $\xi \ll 1$. In the Palatini formulation, the safe limit is again $0 < \xi < 1$.

- For a Higgs'-like inflation, we were unable to find any viable ranges based on the present analysis. This was primarily due to computational constraints for $|\alpha| \geq 1$.

- McDonald's assumption about the continuity of the scattering amplitude when working around a small or large background doesn't hold (also proved by Antoniadis et al. in arXiv:2106.09390 [hep-th]).

THANK YOU