Title: Predictions for Nonlocal Inflation

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Abstract:

Outline

1. **Nonlocal QFT - Motivations & Examples**
2. Ghosts, Instabilities and IVP
3. Nonlocal Inflation
4. Predictions for Nongaussianity

Nonlocal Fundamental Theories

- Nonlocal theories of the form

$$\mathcal{L} = \frac{1}{2}\phi F(\Box)\phi - V(\phi)$$

with nontrivial $F(z)$ arise in:

– String field theory.
– p-adic strings, strings quantized on a random lattice.[a]
– Unparticle effective actions.
– Brane-world constructions.[b]

- Similar nonlocal theories arise in:

– QFT with a minimal length scale[c] (eg LQG, DSR).
– Noncommutative geometry.

[a] Biswas, Grisaru & Siegel (2005).

[b] de Rham (2007).

[c] Hossenfelder (2007).

Example: p-adic String Theory

- ⋆ Toy model of the bosonic string tachyon.[a]
- ⋆ World-sheet coordinates of the string are restricted to the field of p-adic numbers.
- ⋆ All amplitudes of the lowest state can be computed exactly and one can determine a simple field-theoretic Lagrangian which reproduces them:

$$\mathcal{L} = \frac{m_s^4 \, p^2}{g_s^2 \, (p-1)} \left[-\frac{1}{2} \phi p^{-\frac{\Box}{2m_s^2}} \phi + \frac{1}{p+1} \phi^{p+1} \right]$$

- ⋆ Contains infinitely many derivatives: $e^{-\Box} = 1 - \Box + \cdots$
- ⋆ Derived for p a prime number but the theory can be sensibly continued to other values.

[a] Brekke, Freund, Olson & Witten (1987).

(Non)Local Limit

- The field equation for the p-adic scalar is:

$$p^{-\frac{\Box}{2m_s^2}}\phi = \phi^p$$

- Infinite order in derivatives, can be re-cast as an integral equation.[a]
- In the limit $p \to 1$ this equation becomes local:[b]

$$\Box\phi = 2m_s^2\phi\ln\phi$$

- For $p \gg 1$ the nonlocal structure plays an important role in the dynamics.
  - Limit $p \gg 1$ will be most intesting for cosmology...

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[a] Zwiebach (2002).

[b] Gerasimov & Shatashvili (2000).

Applications of Nonlocal QFT

Interesting applications of nonlocal theories:

1. Improved UV behaviour:
   - ⋆ finite QFT,
   - ⋆ solution to the hierarchy problem, $\cdots$
2. Novel cosmologies:[a]
   - ⋆ self-inflation,
   - ⋆ bouncing cosmologies,
   - ⋆ quintessence with $\omega < -1, \cdots$
3. Implications for cosmological constant problem.[b]
4. Inflation.[c]

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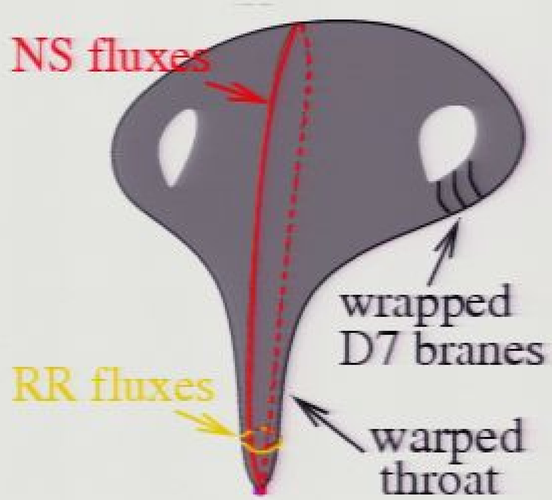
[a] Khoury (2006); Biswas et al. (2006); Aref'eva, Calcagni, Joukovskaya, Koshelev, Vernov, Vladimirov, Volovich,...

[b] Dvali et al. (2007); de Rham et al. (2007).

[c] NB, Biswas, Cline.

Nonlocal Inflation

- ⋆ Can we embed inflation into nonlocal theories?
- ⋆ Motivation: flat potentials surprisingly hard to obtain in realistic settings. (KKLMMT; Baumann et al. (2007); Burgess, Cline, Firouzjahi, Leblond, Shandera, Tye...)



- ⋆ Perhaps inflation doesn't require flat potentials...
- ⋆ Nonlocal structure gives a way to realize inflation with very steep potential which is also predictive, gives $f_{NL} \gg 1$.

Problems/Complications

- Difficulties of working with higher derivative theories are well known:[a]
  - Instabilities, ghosts, $\cdots$
  - Difficulties in setting up IVP.
- Any application to physics must address fundamental issues:
  - When can nonlocal theories be ghost-free?[b]
  - Can one make rigorous sense of the IVP in infinite order theories?[c]
- Before discussing cosmology need to make a detour to discuss formalism...

[a] Woodard (1989).

[b] NB, Biswas, Cline, Prokushkin (2008).

[c] NB, Kamran (2007).

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Finite High Derivative Corrections

- ⋆ Addition of finite higher derivative terms always leads to trouble...
- ⋆ Example: Lee & Wick (1969) model

$$\mathcal{L}_{LW} = \frac{1}{2}\phi\Box\phi - \frac{1}{2M^2}\phi\Box^2\phi - \frac{1}{2}m^2\phi^2 + \cdots$$

assume $M^2 \gg m^2$.

- ⋆ Classical EOM

$$\left(\Box - \frac{1}{M^2}\Box^2 - m^2\right)\phi = 0$$

requires four initial data.

Lee-Wick Theory

- ⋆ Propagator has two poles ⇒ two physical states!

$$G(p^2) \propto \frac{1}{-p^2 - p^4/M^2 - m^2} \sim \underbrace{\frac{1}{-p^2 - m^2}}_{\text{reg, mass } m} - \underbrace{\frac{1}{-p^2 - M^2}}_{\text{ghost, mass } M}$$

- ⋆ Ghost = excitation with wrong-sign kinetic term

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⋆ Ghost $=$ excitation with wrong-sign kinetic term

Multi-Particle Decomposition

- ⋆ Can see explicitly by introducing auxiliary fields $\chi_{1,2}$:

$$\chi_1 = \left(\frac{\Box}{M^2} - 1\right)\phi$$
$$\chi_2 = \left(\frac{\Box}{m^2} - 1\right)\phi$$

- ⋆ Lagrangian decomposes as

$$\mathcal{L}_{LW} \cong -\left[\frac{1}{2}(\partial\chi_1)^2 + \frac{m^2}{2}\chi_1^2\right] + \left[\frac{1}{2}(\partial\chi_2)^2 + \frac{M^2}{2}\chi_2^2\right] + \mathcal{L}_{\rm int}$$

- ⋆ Wrong sign kinetic term. So what?

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What's Wrong with Ghosts?

- Hamiltonian is unbounded from below!

$$\mathcal{H}_{LW} = + \left[\frac{1}{2}\dot{\chi_1}^2 + \frac{m^2}{2}\chi_1^2 \right] - \left[\frac{1}{2}\dot{\chi_2}^2 + \frac{M^2}{2}\chi_2^2 \right] + \mathcal{H}_{\rm int}$$

- Unstable: dynamics drives system to become arbitrarily excited.
- This is a classical pathology (QFT can be made unitary).
- Note: taking M^2 larger only makes things worse!
- Only way to salvage the theory is by imposing auxiliary constraints.[a]

[a] Cutkosky et al. (1969).

Counting Initial Data

- ⋆ Problem is VERY general:

$$S = S\left[\phi, \Box\phi, \cdots, \Box^N \phi\right]$$

$$\begin{aligned} N &= \text{(num poles in propagator)} \\ &= \text{(num physical states)} \\ &= \frac{1}{2}\,\text{(num initial data)} \\ &= \frac{1}{2}\,\text{(dim phase space)} \end{aligned}$$

- ⋆ Ostrogradksi Theorem: Hamiltonian is always unstable, except in the local case $N = 1$.
- ⋆ Larger N just makes things worse. What about $N = \infty$?

Infinite Order Theories

$$\mathcal{L} = \frac{1}{2}\phi F(\Box)\phi - V(\phi)$$

$$F(z) = \sum_{n=0}^{\infty} a_n z^n$$

- ⋆ EOM is infinite order. How many initial data?

$$F(\Box)\phi = V'(\phi)$$

- ⋆ Stability intimitely related to initial data counting. Infinite order PDEs very different from $N \gg 1$.
- ⋆ Formal treatment of IVP infinite order PDEs.[a]
  - Systematic prescription for counting data.
  - Rigorous study of pseudo-differential operators $f(\partial_t)$.

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Pole Counting in Nonlocal Theories

- ⋆ Consider nonlocal theory:

$$\mathcal{L} = \frac{1}{2}\phi\,\Gamma(\Box)(\Box - m^2)\,\phi$$

with $\Gamma(z)$ having no zeroes (eg $\Gamma(z) \sim e^{-z}$).

- ⋆ EOM:

$$\Gamma(\Box)\left(\Box - m^2\right)\phi = 0$$

- ⋆ Propagator has only one pole:

$$G(p^2) \sim \frac{1}{\Gamma(-p^2)}\frac{1}{-p^2 - m^2}$$

- ⋆ Only a single physical excitation $\Rightarrow$ only 2 initial data!
- ⋆ Ostrogradski construction doesn't apply.

Infinite Derivative Dynamics

- ⋆ Theorem: pole counting exhausts all allowed initial data.[a]
  - Single pole infinite order theories can be ghost-free!
  - Even some multi-pole theories are okay.[b]
- ⋆ Exorcism: Pseudo-differential operator theory provides a way to redefine $F(\Box)$ so as to render otherwise pathological theories ghost-free!

[a] NB & Kamran (2007).

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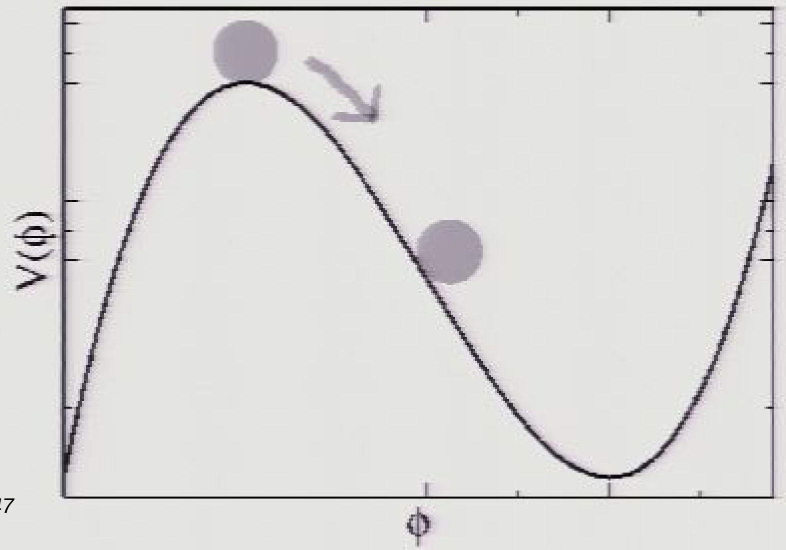
Nonlocal Hill-Top Inflation

- Seek inflation in theories of the form:

$$\mathcal{L} = \frac{1}{2}\phi F(\Box)\phi - U(\phi)$$

$$F(z) = \sum_{n=1}^{\infty} c_n z^n$$

$$U(\phi) = U_0 - \frac{\mu^2}{2}\phi^2 + \frac{g}{3}\phi^3 + \cdots$$



- Seek inflationary solution rolling away from $\phi = 0$.
- In string theory examples corresponds to inflation during brane decay.

Naive Derivative Truncation

- Naively expect that during slow roll high derivative corrections are negligible:

$$\begin{aligned}\mathcal{L} &= \frac{1}{2}\phi F(\Box)\phi - U(\phi) \\ &\cong -\frac{1}{2}(\partial\phi)^2 - U_0 + \frac{\mu^2}{2}\phi^2 + \mathcal{O}(\Box^2) + \cdots\end{aligned}$$

- Expect that inflation is only possible when $|\eta| \sim M_p^2 |U''/U| \ll 1 \Rightarrow \mu^2 \ll H^2$.
- Naive picture is not always correct: can still obtain slow roll even when $M_p^2|U''/U| \gg 1$!
- Most models of string cosmology follow this approach...

Nonlocal Dynamics

Near the top of the potential ($\phi = 0$) have:

$$\mathcal{L} = \frac{1}{2}\phi F(\Box)\phi - \left(U_0 - \frac{\mu^2}{2}\phi^2 + \cdots\right)$$

- Equation of motion:

$$F(\Box)\phi = -\mu^2\phi$$

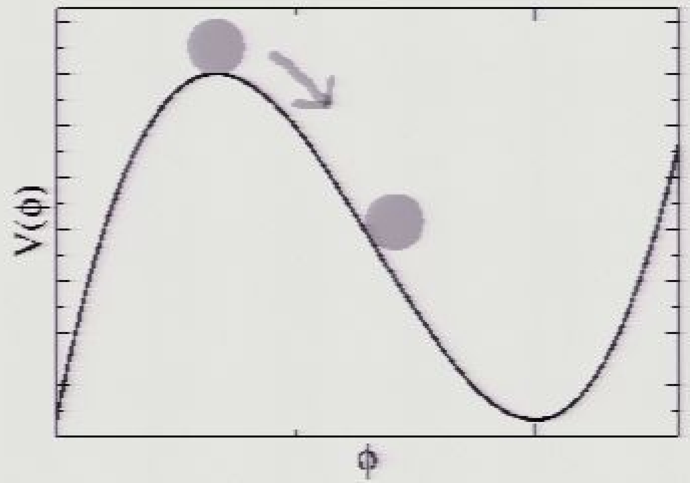
- Can obtain solution by taking:

$$\Box\phi = -\omega^2\phi \quad \text{if} \quad F\left(-\omega^2\right) = -\mu^2$$

- Dual to a local theory with mass ω.
- The effective mass, ω^2, can be small even naive mass μ^2 is large!

Stretching the Inflaton Potential

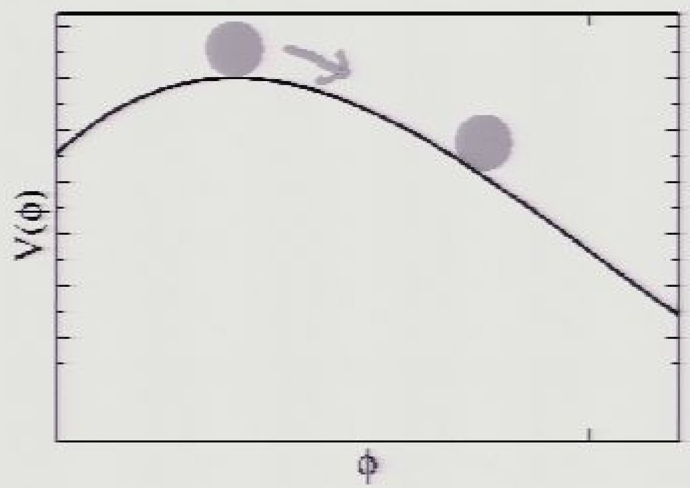
$$\mathcal{L} = \left[\frac{1}{2}\phi F(\Box)\phi - \left(U_0 - \frac{\mu^2}{2}\phi^2 + \cdots\right)\right]$$



$$\mathcal{L} = \frac{1}{2}\phi\Box\phi - U(\phi) + \mathcal{O}(\Box^2)$$

$$U(\phi) = U_0 - \frac{\mu^2}{2}\phi^2 + \cdots$$

Steep potential, higher derivative terms slow the rolling.



$$\mathcal{L}_{\mathrm{dual}} = \frac{1}{2}\varphi\Box\varphi - V(\varphi)$$

$$V(\varphi) = U_0 - \frac{\omega^2}{2}\varphi^2 + \cdots$$

Effective potential in dual local theory is stretched.[a]

[a] Lidsey (2007).

Example: p-adic Inflation

Explicit example in p-adic string theory:[a]

$$\mathcal{L} = \frac{m_s^4}{g_p^2}\left[\frac{1}{2}\phi\left(1 - p^{-\frac{\Box}{2m_s^2}}\right)\phi - U(\phi)\right]$$

$$U(\phi) = \underbrace{\frac{p-1}{2(p+1)}}_{\equiv U_0} - \underbrace{\frac{p-1}{2}}_{\mu^2 \equiv p-1}\phi^2 + \cdots$$

- ⋆ Naively don't expect slow roll since $\mu^2 \sim p \gg 1$ but effective mass, $\omega^2 = -2m_s^2$, insensitive to p.
- ⋆ COBE normalization constrains $g_s/\sqrt{p} \sim 10^{-7}$ so for $g_s \sim 1$ have $p \gg 1$. $\Rightarrow$ Strongly nonlocal!
- ⋆ Predictions: $n_s < 1$, $r < 0.006$, $m_s < 10^{-6} M_p$, $\cdots$

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Including Interactions

Include the cubic term in the action:

$$\mathcal{L} = \frac{1}{2}\phi F(\Box)\phi - U(\phi)$$

$$U(\phi) = U_0 - \frac{\mu^2}{2!}\phi^2 + \frac{g}{3!}\phi^3 + \cdots$$

- ⋆ For $g \neq 0$ the correspondence between local and nonlocal theories breaks down.
- ⋆ Expect $\langle\phi^3\rangle \propto f_{NL} \propto g$ so for large g the nongaussianity could be large.
- ⋆ In conventional models $g \gg 1$ would spoil inflaton but this need not be true in nonlocal theories!
- ⋆ In p-adic inflation:

$$|g| \sim p^2 \gg 1 \quad \text{for} \quad p \lesssim 10^{13}$$

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Field Redefinitions

For ghost-free theory:

$$\mathcal{L} = \frac{1}{2}\phi\Gamma(\Box)(\Box + \omega^2)\phi - U_0 - \frac{g}{3!}\phi^3 + \cdots$$

(where $\Gamma(z)$ has no zeroes).

- ⋆ Nonlocal field redef $\varphi = \Gamma(\Box)^{1/2}\phi$ gives

$$\mathcal{L} = \frac{1}{2}\varphi(\Box + \omega^2)\varphi - U_0 - \frac{g}{3!}\left(\Gamma(\Box)^{-1/2}\varphi\right)^3 + \cdots$$

- ⋆ Canonical kinetic structure, nonlocality in the interactions.
- ⋆ Appropriate starting point to match onto standard perturbation theory calculation.

Perturbed Field Equations

Canonical field equation:

$$(\Box + \omega^2)\varphi = \frac{g}{2}\Gamma(\Box)^{-1/2}\left[\Gamma(\Box)^{-1/2}\varphi\right]^2$$

- Gaussian perturbations:

$$(\Box + \omega^2)\delta_1\varphi \cong 0$$

insensitive to nonlocality.

- Second order:

$$(\Box + \omega^2)\delta_2\varphi \cong \frac{g}{2}\Gamma(\Box)^{-1/2}\left[\Gamma(\Box)^{-1/2}\delta_1\varphi\right]^2 + \cdots$$

- Nonlocal structure in source term mimics a large cubic coupling V''', leads to $f_{NL} \gg 1$

Nonlinearity Parameter

- ⋆ Calculation is simplest using Seery, Malik & Lyth (2008) formalism.
- ⋆ Results:

$$f_{NL} = \frac{5}{6} \underbrace{\xi_{\text{eff}}}_{\propto g} \left[N_\star + \frac{3}{\sum_i k_i^3} \left(k_t \sum_{i<j} k_i k_j - \frac{4}{9} k_t^3 \right) \right] + \cdots$$

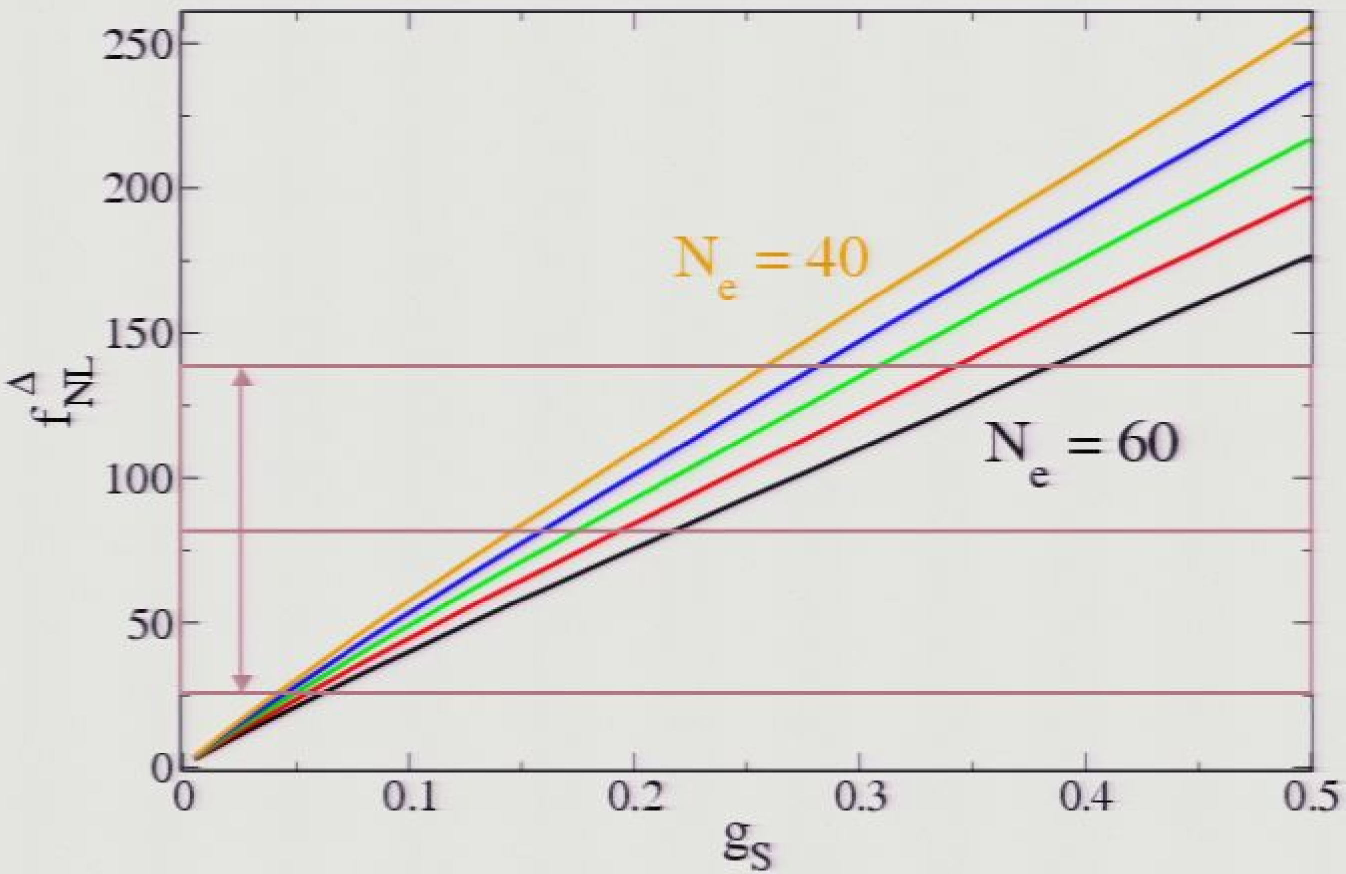
- ⋆ For p-adic inflation have

$$f_{NL}^{\triangle} \sim 10^{-3} \frac{\sqrt{p}}{\ln p}$$

for $p \gg 1$. (Recall: $p \sim 10^{13}$ for $g_s \sim 1$.)

- ⋆ In the local limit $p \to 1$ have $f_{NL} \sim n_s - 1$.

p-adic Inflation



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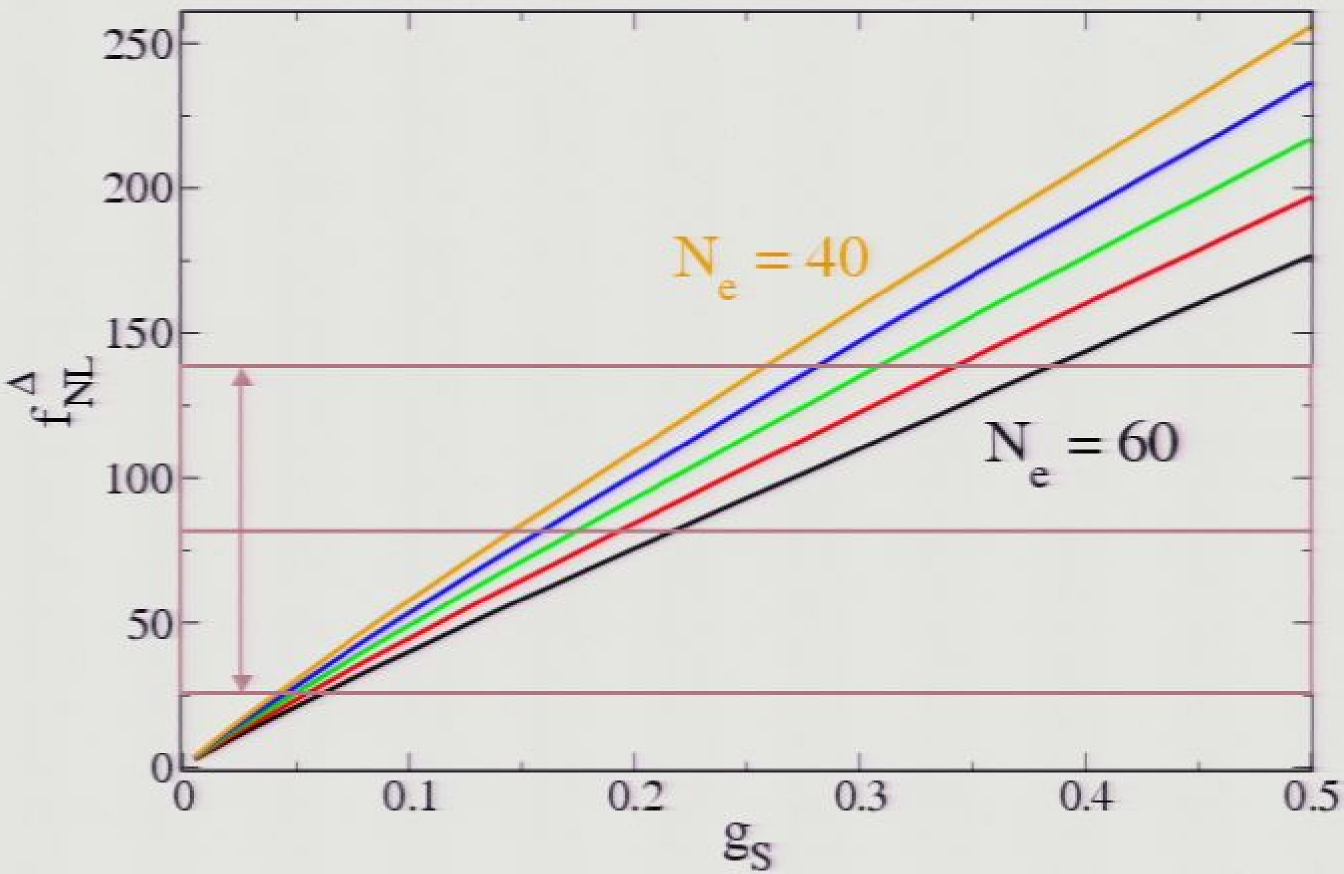

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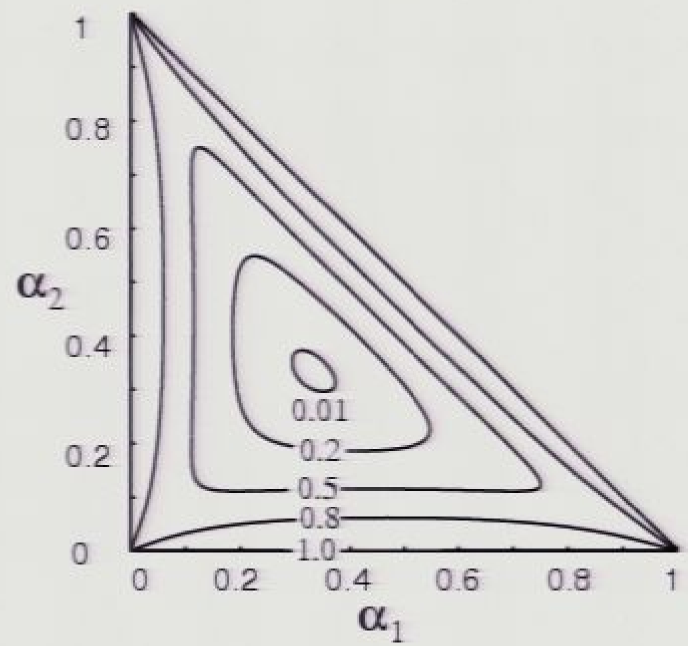
Comparison to DBI Models

- ⋆ Formally very different from DBI:
  - High powers of $\Box$ rather than $(\partial\phi)^2$ leads to infinite order EOM, distinctive dynamics.
  - Sound speed $c_s = 1$ rather than $c_s \ll 1$.
  - Inflation is coming from brane decay rather than motion down a warped throat, $\cdots$
- ⋆ Dynamics: inflation is NOT fast roll; $\ddot{\phi} \ll H\dot{\phi}$, $\dot{\phi}^2 \ll H^2 M_p^2$.
- ⋆ Observationally: shape of NG makes p-adic model distinguishable.



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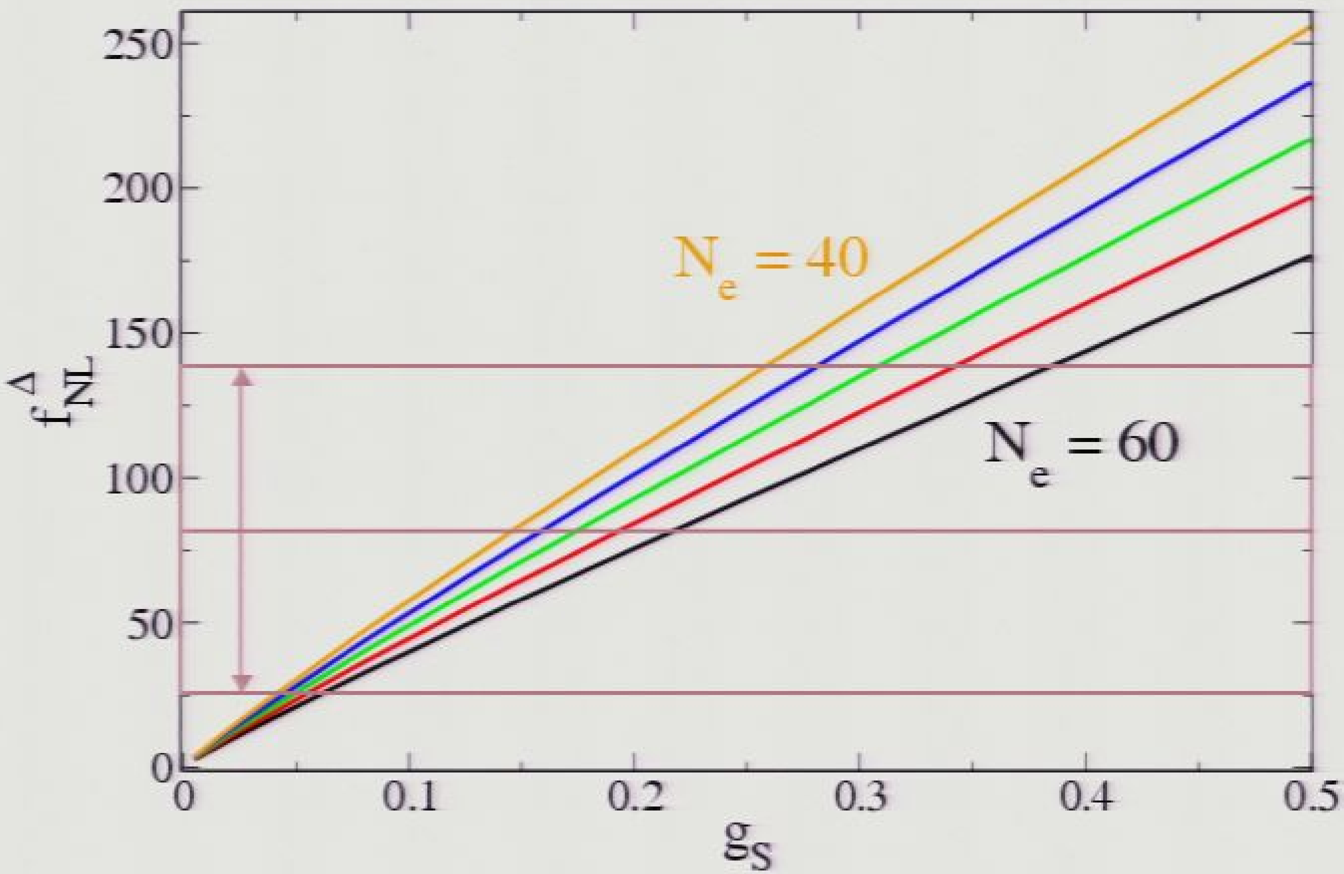

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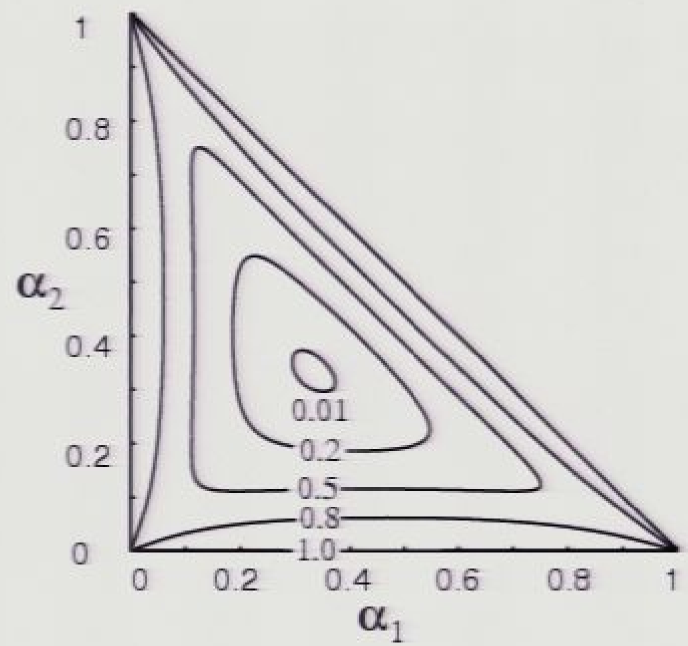

Conclusions

- ⋆ Study of high derivative theories is well-motivated.
- ⋆ Can systematically construct stable/ghost-free infinite order theories with well-posed Cauchy problem.
- ⋆ Nonlocal inflation can proceed even the naive potential is far too steep.
  - This structure is ubiquitous in ST. Perhaps inflation is easier to realize than previously throught?
- ⋆ Novel effect has observable signatures in the CMB: large f_{NL}.
- ⋆ Possibility of realizing similar phenomena in more realistic string theories.
  - Effect relies on UV completion: CMB as a probe of distinctly stringy phenomena!

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$$\mathcal{L} = \frac{1}{2}\varphi(\Box + \omega^2)\varphi - U_0 - \frac{g}{3!}\left(\Gamma(\Box)^{-1/2}\varphi\right)^3 + \cdots$$

- ⋆ Canonical kinetic structure, nonlocality in the interactions.
- ⋆ Appropriate starting point to match onto standard perturbation theory calculation.

Field Redefinitions

For ghost-free theory:

$$\mathcal{L} = \frac{1}{2}\phi\Gamma(\Box)(\Box + \omega^2)\phi - U_0 - \frac{g}{3!}\phi^3 + \cdots$$

(where $\Gamma(z)$ has no zeroes).

⋆ Nonlocal field redef $\varphi = \Gamma(\Box)^{1/2}\phi$ gives

$$\mathcal{L} = \frac{1}{2}\varphi(\Box + \omega^2)\varphi - U_0 - \frac{g}{3!}\left(\Gamma(\Box)^{-1/2}\varphi\right)^3 + \cdot$$

⋆ Canonical kinetic structure, nonlocality in the interactions.