Heavy-Lifting of Gauge Theories by Cosmic Inflation

SUSY 17, TIFR, India

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Motivation

- Cosmic Inflation can explain both why CMB sky is so uniform and why we see *small* fluctuations on it.
- Scale of inflation: H is not known but currently bounded $H < 5 \times 10^{13}$ GeV. (Planck '15)
- Is it possible to probe particle physics of that era? Inaccessible to terrestrial colliders!
- The study of Non-Gaussianity of primordial fluctuations provides precisely such a tool: spectroscopy of masses and spins!

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Non-Gaussianity : Generalities

Non-Gaussianity : A Measure of Interactions

- Observed data is consistent with being Gaussian. Higher point odd correlators $\Rightarrow$ interactions.
- Leading is the (dimensionless) bispectrum,

$$F(k_1, k_2, k_3) = \frac{\langle \mathcal{R}(\vec{k}_1)\mathcal{R}(\vec{k}_3)\mathcal{R}(\vec{k}_3)\rangle'}{\langle \mathcal{R}(\vec{k}_1)\mathcal{R}(-\vec{k}_1)\rangle\langle \mathcal{R}(\vec{k}_3)\mathcal{R}(-\vec{k}_3)\rangle}$$

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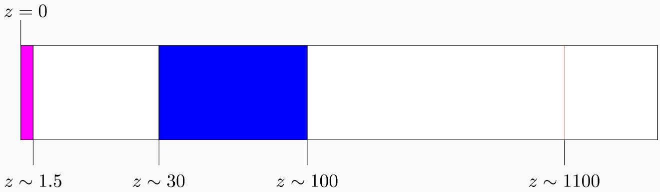
- Conventional "magnitude" of non-Gaussianity,

$$f_{\mathrm{NL}} = \frac{5}{18}F(k, k, k)$$

- Currently we only have bounds, roughly $|\delta f_{\mathrm{NL}}| \lesssim \mathcal{O}(10)$(Planck '15)

Future Experiments and Cosmic Variance

- Precision determined roughly by the number of modes: $\delta f_{\mathrm{NL}} \sim \frac{1}{\sqrt{N_{\mathrm{modes}}}} 10^4$



PLANCK : $N_{\mathrm{Modes}} \sim 10^7 \rightarrow \delta f_{\mathrm{NL}} \sim 10$	Completed.
EUCLID : $N_{\mathrm{Modes}} \sim 10^{10} \rightarrow \delta f_{\mathrm{NL}} \sim 1$	2020
21-cm : $N_{\mathrm{Modes}} \sim 10^{16} \rightarrow \delta f_{\mathrm{NL}} \sim 0.001$	20??

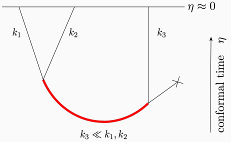
(Alvarez et. al. '14; Loeb, Zaldarriaga '04)

- For this talk, we consider only cosmic variance limited precision: $\delta f_{\mathrm{NL}} \sim 10^{-3} - 10^{-4}$

Non-Gaussianity from $m \sim H$

NG from $m \sim H$

- New interactions: $(\phi(t,\vec{x}) = \phi_0(t) + \xi(t,\vec{x}))$



- In the squeezed limit, $k_3 \ll k_1 \approx k_2$ (an "OPE" limit on the late time slice)

$$F \propto \left(\frac{k_3}{k_1}\right)^{\Delta}; \quad \Delta = \frac{3}{2} \pm i\sqrt{\frac{m^2}{H^2} - \frac{9}{4}}$$

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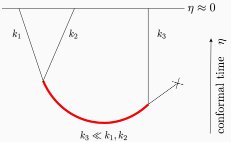

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- *Non-analytic* scaling and angular dependence of F $\Rightarrow$ the mass and spin of the particle. (Chen, Wang '09,'12; Baumann, Green '11; Assassi et. al. '12; Noumi et. al. '12; Arkani-Hamed, Maldacena '15; Lee et. al. '16 ...)
- Pure inflationary "background" is *analytic* (Maldacena '03; Creminelli, Zaldarriaga; Cheung et. al. '07).

Spinning Particles

- Higher spin particles can arise from string theory, but here we restrict to point particle EFT: expect only nonzero spins in the form of gauge bosons.
- Evidence for a gauge theory needs a detection of spin-1 induced NG.
- Couple gauge theory to inflationary dynamics.

Gauge Theory and Non-Gaussianity

(partially) Higgsed Gauge Theory

- Neutral Higgs-type and Z-type particles can contribute at tree level.
- We can simply have a "fixed" tachyonic mass term like: $V \supset -\mu^2 \mathcal{H}^\dagger \mathcal{H}$ with $\mu \sim H$ from which it is plausible to have

$$m_h \sim H; \quad m_Z \sim H$$

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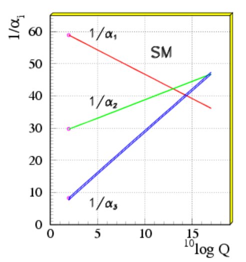
- Grand Unified Theories can be examples.



Alternately, couple to curvature

- Non-minimal coupling to gravity naturally gives,

$$cR\mathcal{H}^\dagger\mathcal{H} \quad \text{with} \quad R \approx 12H^2$$

- Plausible to have

$$m_h \sim H; \quad m_Z \sim H$$

- A time dependent "weak scale": is of the order H during inflation but can come down ($\ll H$) in the present era.
- "Heavy-lifting" of a low energy gauge theory.

Heavy-lifting of the Standard Model (SM) (+ Dark Sectors)

- Using SM RG running we can run up the ratio $\frac{m_h}{m_Z}$ to scale H (say known by Tensor modes measurement)
- Suppose via NG we see one spin-0 and one spin-1 resonance, and we also measure $\frac{m_{\text{spin-0}}}{m_{\text{spin-1}}}$
- If the two ratios match it would be a test of *un*-naturalness!

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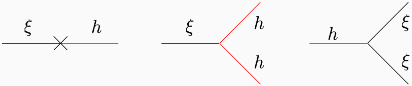
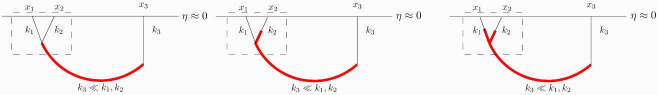
- If additional dark (gauge) sectors are present, we can have more than one measurable ratio and hence greater confidence on heavy-lifting in action.

Coupling between Higgs and inflaton

- In presence of (softly broken) shift symmetry inflaton self-interactions are generically given as an expansion in $\frac{(\partial\phi)^2}{\Lambda^4}$ with $\Lambda > \sqrt{\dot{\phi}_0} \sim 60H$
- The leading Higgs-inflaton interaction is $\frac{1}{\Lambda^2}(\partial\phi)^2\mathcal{H}^\dagger\mathcal{H}$



NG due to Higgs



- The strength of NG for triple exchange with no fine tuning

mass	$\lvert f_h^{\text{triple}} \rvert$
1.6 H	0.239
1.9 H	0.018
2.2 H	0.003

- $$F \propto f(\mu) \left(\frac{k_3}{k_1}\right)^{\frac{3}{2}+i\mu} + f(-\mu) \left(\frac{k_3}{k_1}\right)^{\frac{3}{2}-i\mu}$$

NG due to Z

- Coupling is strongly constrained by gauge invariance and spin-1 nature of Z:

$$\frac{1}{\Lambda^5}(\partial\phi)^2\partial_\mu\phi(\mathcal{H}^\dagger D^\mu\mathcal{H})$$

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$$F_Z^{\text{single}} = \left(\frac{v}{2\Lambda}\right)^2 \frac{1}{16\pi}\sin^2\theta\,\Gamma(\frac{3}{2}+i\mu)\Gamma(\frac{3}{2}-i\mu)\cosh(\pi\mu)\times$$

$$(7-5i\mu+16\mu^2+4i\mu^3)\Gamma(\frac{3}{2}+i\mu)^2\Gamma(-2-2i\mu)(1-i\sinh(\pi\mu))\left(\frac{k_3}{k_1}\right)^{\frac{5}{2}+i\mu}$$

$$+(\mu\to-\mu)$$

mass	$\lvert f_Z^{\text{single}}\rvert$
0.4 H	0.003
0.8 H	0.001

Lowering the Cutoff?

- Small NG was due to the fact that the cutoff had to be bigger than background K.E.

$$\Lambda > \sqrt{\dot{\phi}_0} \sim 60H$$

- Lowering the cutoff implies a breakdown of expansion in $\frac{(\partial\phi)^2}{\Lambda^4}$

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- Small NG was due to the fact that the cutoff had to be bigger than background K.E.

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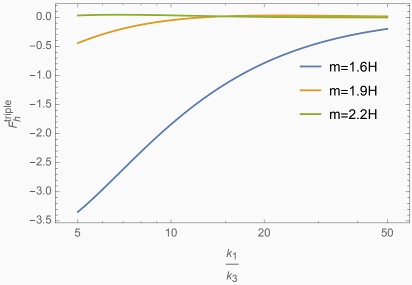
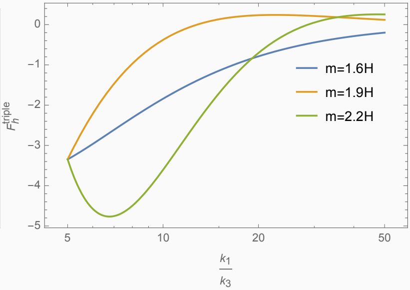
- Lowering the cutoff implies a breakdown of expansion in $\frac{(\partial\phi)^2}{\Lambda^4}$
- However, one can take a more agnostic view about what dynamics gives rise to inflationary background, and focus entirely on the fluctuation modes about it.
- Can be done consistently using effective field theory formalism. (Cheung et. al. '07)

NG due to Higgs

mass	$\lvert f_h^{\text{triple}} \rvert$
1.6 H	10.1
1.9 H	0.772
2.2 H	0.148

Observable by EUCLID, LSST





NG due to Z

- Single exchange diagram yields a weak but observable NG

mass	$\lvert f_Z^{\text{single}} \rvert$
0.4 H	0.003
0.8 H	0.001

- The double exchange diagram is parametrically enhanced by $\frac{\dot{\phi}_0}{\Lambda^2} \sim 30$ for $\sqrt{\dot{\phi}_0} = 60H; \Lambda = 10H$

Conclusion

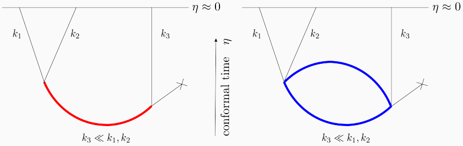
Conclusion

- Observed spectrum of density fluctuations is Gaussian, there is a minimal amount NG, discovering which would be extremely important and would constitute a non-trivial test of our understanding of inflationary dynamics.
- Higgs and Z type bosons coming out of (partially) Higgsed gauge theories can leave observable signatures in future LSS and 21-cm experiments.
- It is possible that such signatures: a) might corroborate specific GUT theories, or b) in presence of the "Heavy-Lifting" mechanism we can test whether low energy gauge-Higgs theories can be extrapolated up to high scale, possibly testing the Naturalness principle.

Back-up

Unbroken Gauge Theory

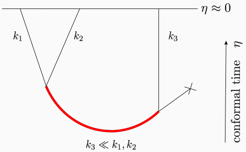
- Inflaton carries the internal quantum numbers of the vacuum.
- Either gauge singlets or loops of gauge charged states can contribute to NG



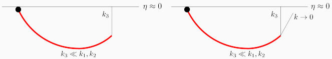
- But gauge bosons remain massless: can not do mass spectroscopy.
- Loops are expected to be small: difficult to see even massive charges.

Late Time dS Isometries

- At $\eta \approx 0$, isometries of $(3+1)D$ de Sitter spacetime $\equiv$ symmetry generators of $3D$ conformal group.
- Thus approximate dS isometries $\Rightarrow$ approximate conformal symmetry of cosmological correlators.
- For slow roll inflation: the power spectrum should be approximately scale invariant i.e. $\frac{1}{k^3}$ after Fourier transform.
- This does not rely on dS/CFT, but is a necessary starting point.



- Squeezed limit is just the “OPE” limit on the late time slice, and the diagram simplifies:



- We now get a “2 point” function which is constrained by late time conformal symmetry:

$$\langle \mathcal{O}_\Delta(\vec{x}_2)\mathcal{R}(\vec{x}_3)\rangle_{\text{inf}} \propto |x_{23}|^{-\Delta}$$

Minimal Non-Gaussianity (NG)

- For pure inflationary dynamics,

$$F^{\text{Single Field}}(k_1, k_2, k_3)|_{k_3 \ll k_1, k_2} = (1 - n_s) + \mathcal{O}\left(\frac{k_3}{k_1}\right)^2 .$$

- This is too small for both CMB and LSS, but promising with 21-cm experiments.
- Moving beyond minimal field content one can have,

$$f_{\text{NL}} \sim \mathcal{O}(1)$$

Backgrounds

- In the post-hot big bang era modes can develop non-primordial NG, for example, due to non-linearity of gravity
- But they can be modeled using standard cosmology, can only be cosmic variance limited (?)
- But there are primordial “backgrounds” from pure inflationary dynamics which however carry no angular or non-analytic momentum dependence.
- Multi-field inflation models can have angular dependence, but no non-analyticity.
- Recent studies (using 21-cm) for scalars have been done, but need to build useful templates for spin-1 and higher (Meerburg et. al. ’15)