Cosmological collider physics beyond the Hubble scale

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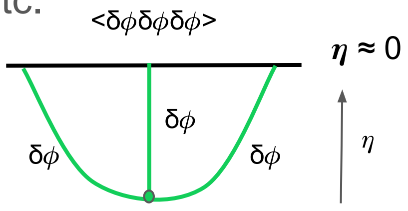
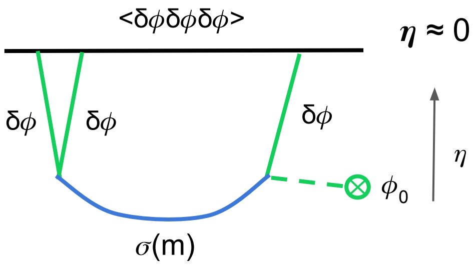
Preliminaries

- Quantum fluctuations of inflaton field ($\delta\phi$) seeded the density fluctuation seen across the sky today.
- The primordial density fluctuations are gaussian to a good precision. The two point function $\langle\delta\phi_k\delta\phi_{-k}\rangle$ contains all the information and non-gaussianity (NG) is either 0 or very small.
- In future, experiments like 21-cm cosmology, LSS survey will be sensitive to these small NGs.
- The shape of NG depends on the type of interaction, which is crucial in distinguishing different models beyond the standard slow roll inflation.
- E.g. Multi-field inflation, self interaction, heavy fields, higher-derivative interactions, curvaton scenario etc.



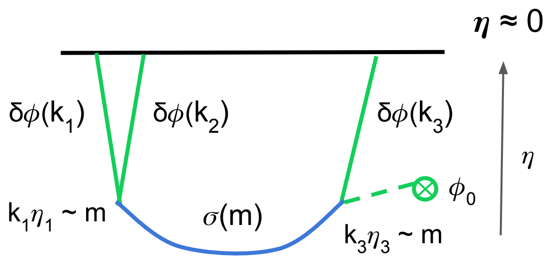


$$\eta H = -e^{-Ht}$$

“Cosmological collider”

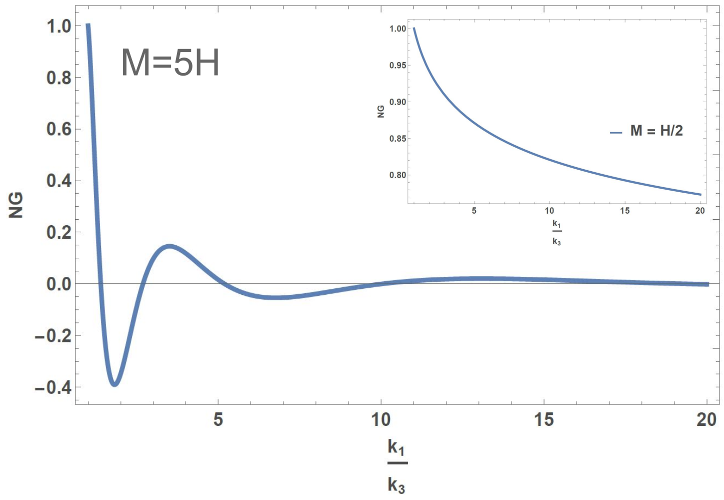
X. Chen, Y. Wang, 0911.3380
Nima Arkani-Hamed, J. Maldacena, 1503.08043,
X. Chen, Y. Wang, Z. Xianyu, 1612.08122

- Energy scale during inflation can be very high ~ 10^{15} GeV.
- Presents an opportunity to “see” physics at such high scales, which can not be achieved with terrestrial colliders.
- Heavy fields during inflation leave a unique non-analytic signature in the density fluctuations.



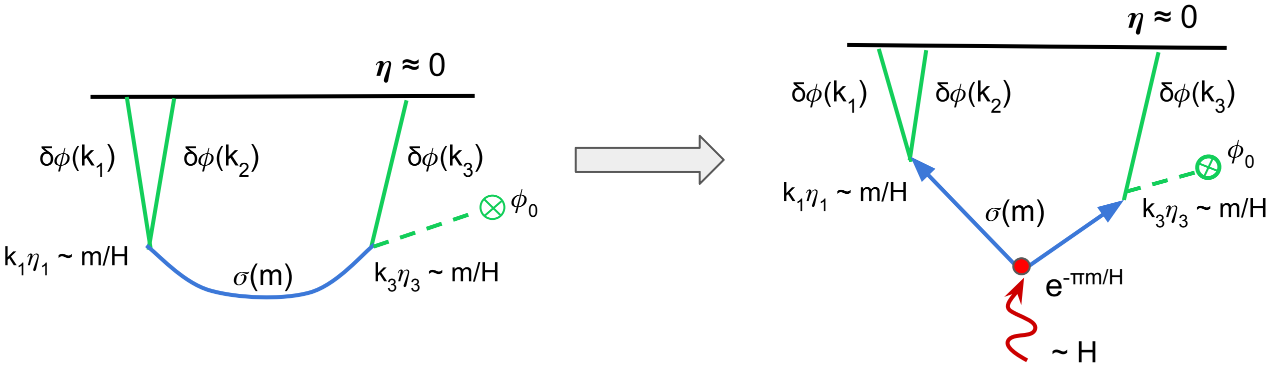
$$e^{-im\Delta t} \rightarrow \left(\frac{\eta_3}{\eta_1}\right)^{-im/H} \rightarrow \left(\frac{k_1}{k_3}\right)^{-im/H}$$

Oscillatory signal in “squeezed limit”,
$k_1, k_2 >> k_3$.



Boltzmann-like suppression

- Expanding space-time can produce particles, even though we start with an empty vacuum.
- Typical energy (~ temperature) of the background ~ H. Excitations of energy m>>H suffer Boltzmann-like suppression ~ $e^{-\pi m/H}$.



- This exponential suppression quickly makes the signal smaller than the physical limit coming from cosmic variance.
- This severely limits the range of new physics that can be explored close to H.
- Solution: Chemical potential!

“Chemical potential” ~ $\partial_\mu \phi \, \mathcal{J}^\mu$

N. Barnaby et al, 1102.4333,
P. Adshead et al, 1803.04501,
L. Wang, Z. Xianyu, 2004.02887

- The inflaton vev effectively provides chemical potential during slow roll.
- This idea has been proposed in the context of fermions and gauge bosons.
- Such signals have been studied at loop level, which is loop-suppressed and generally difficult to calculate without suitable approximations.
- We demonstrate a simple implementation of this mechanism in complex scalar fields (χ) at tree level.
- Chemical potential corresponds to a non-zero time component of a gauge field, which can be removed by a field redefinition if U(1) is conserved.

$$|(\partial_t + i\lambda)\chi|^2 - |\partial_i \chi|^2 - M^2|\chi|^2 \xrightarrow{\chi \to e^{-i\lambda t}\tilde{\chi}} |\partial\tilde{\chi}|^2 - M^2|\tilde{\chi}|^2$$

- We introduce a small explicit symmetry-breaking term, which will get a non-trivial phase under this field redefinition.

Model description

Good derivative expansion in $\frac{(\partial\phi)^2}{\Lambda_1^2}$

$\Lambda_1 > \sqrt{\dot{\phi}_0} \implies \lambda \lesssim 60H$

$\lambda \mathcal{J}_0$, $\lambda = \frac{\dot{\phi}_0}{\Lambda_1}$

$$\mathcal{L}_\chi = \sqrt{-g}\left\{-|\partial\chi|^2 - M^2|\chi|^2 - \underbrace{\frac{i\partial_\mu\phi}{\Lambda_1}\left(\partial^\mu\chi^\dagger\chi - \partial^\mu\chi\chi^\dagger\right)}_{\text{chem pot term}} - \frac{c\,(\partial\phi)^2}{\Lambda_1^2}|\chi|^2 - \underbrace{\frac{(\partial\phi)^2}{\Lambda_2}(\chi+\chi^\dagger)}_{\text{symm breaking term}}\right\}$$

$$\chi = e^{-\phi/\Lambda_1}\tilde{\chi}$$

Phase from chemical potential

$$\mathcal{L} = \sqrt{-g}\left\{-|\partial\tilde{\chi}|^2 - M^2|\tilde{\chi}|^2 + (1-c)\frac{(\partial\phi)^2}{\Lambda_1^2}|\tilde{\chi}|^2 - \frac{(\partial\phi)^2}{\Lambda_2}\left(\tilde{\chi}\,e^{-i\phi/\Lambda_1} + \tilde{\chi}^\dagger\,e^{i\phi/\Lambda_1}\right)\right\}$$

- λ changes M_{eff}
- c = 1, $M_{\text{eff}} = M$

$$M_{\text{eff}} = \sqrt{M^2 + (1-c)\lambda^2}$$

t-dependent phase, λ~ 60H (>>H)

$$\mathcal{H}_{\text{int}} \sim \beta\,(\delta\tilde{\chi})\,(\delta\phi)\,e^{-i\lambda t} + cc$$

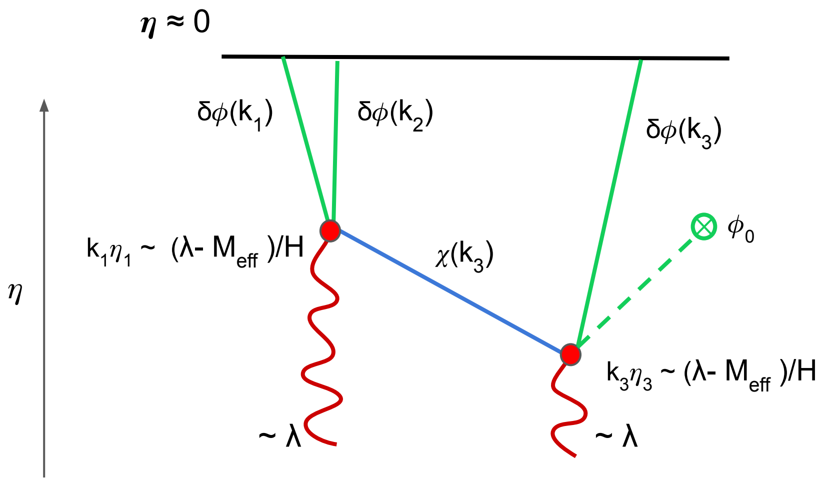
$$\mathcal{H}_3 \sim \rho\,(\delta\tilde{\chi})\,(\delta\phi)^2 e^{-i\lambda t} + cc$$

In-in diagrams

- We use in-in formalism to calculate late-time correlators of the inflaton fluctuations.

$$\langle\Omega|\,\hat{\mathcal{O}}(t)\,|\Omega\rangle = \langle 0|\left(\bar{T}e^{i\int_{-\infty(1+i\epsilon)}^{t_f} H_{\rm int}\,dt}\right)\hat{\mathcal{O}}\left(Te^{-i\int_{-\infty(1-i\epsilon)}^{t_f} H_{\rm int}\,dt}\right)|0\rangle \longrightarrow \begin{cases} I_{++} \\ I_{+-} \\ I_{-+} \\ I_{--} \end{cases}$$

- The mode functions $e^{-iwt} \to H^{(1)}_{im/H}(-k\eta)$



I_{--}

- To quantify NG, we define

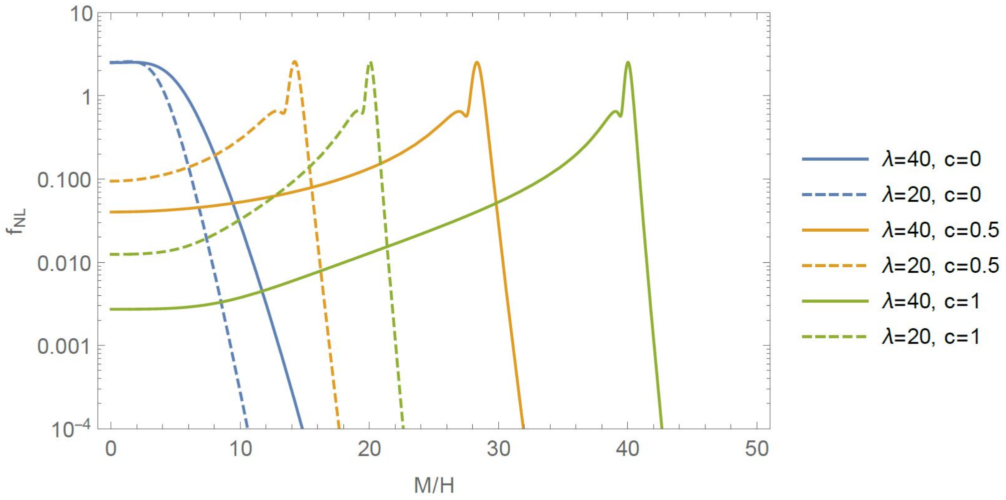
$$F(k_1,k_2,k_3) = \frac{\langle \mathcal{R}_{k_1}\mathcal{R}_{k_2}\mathcal{R}_{k_3}\rangle}{\langle\mathcal{R}\mathcal{R}\rangle_{k_1}\langle\mathcal{R}\mathcal{R}\rangle_{k_3}}$$

- In the squeezed limit and for λ > $M_{\rm eff}$,

$$F(k_{1/2}\gg k_3) \sim \frac{\lambda}{M_{\rm eff}(\lambda - M_{\rm eff})}\left(\frac{k_1}{k_3}\right)^{-3/2+i(M_{\rm eff}-\lambda)}$$

Strength of NG

f_{NL} indicates the size of NG when $k_1 \sim k_2 \sim k_3$ (equilateral configuration).



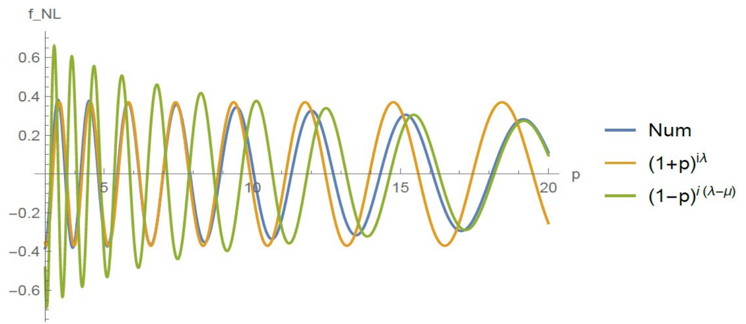
$$M_{\text{eff}} = \sqrt{M^2 + (1-c)\lambda^2)}$$

- Sizable NG for masses up to $\sqrt{c}\,\lambda$
- Eg, λ = 40H, c = 0.5, then accessible range is M $\lesssim$ 28H
- $\lambda_{max} \sim$ 60H, which means we can potentially 'see' masses upto O(10H)

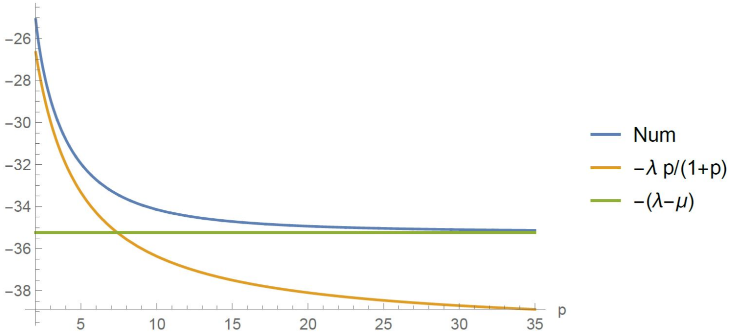
Extracting effective mass

- The non-analytic exponent contains information about M_{eff}.
- We exploit change in the non-analytic exponent as a function of $p = k_1/k_3$ to extract M_{eff}.

$$\langle(\delta\phi)^3\rangle \xrightarrow{k_{1/2}\gg k_3} \begin{cases} \xrightarrow{\lambda > M_{\rm eff}\, p} (1+p)^{-1+i\lambda} \\ \xrightarrow{\lambda < M_{\rm eff}\, p} (1-p)^{-\frac{3}{2}+i(\lambda-\mu)} \end{cases}$$

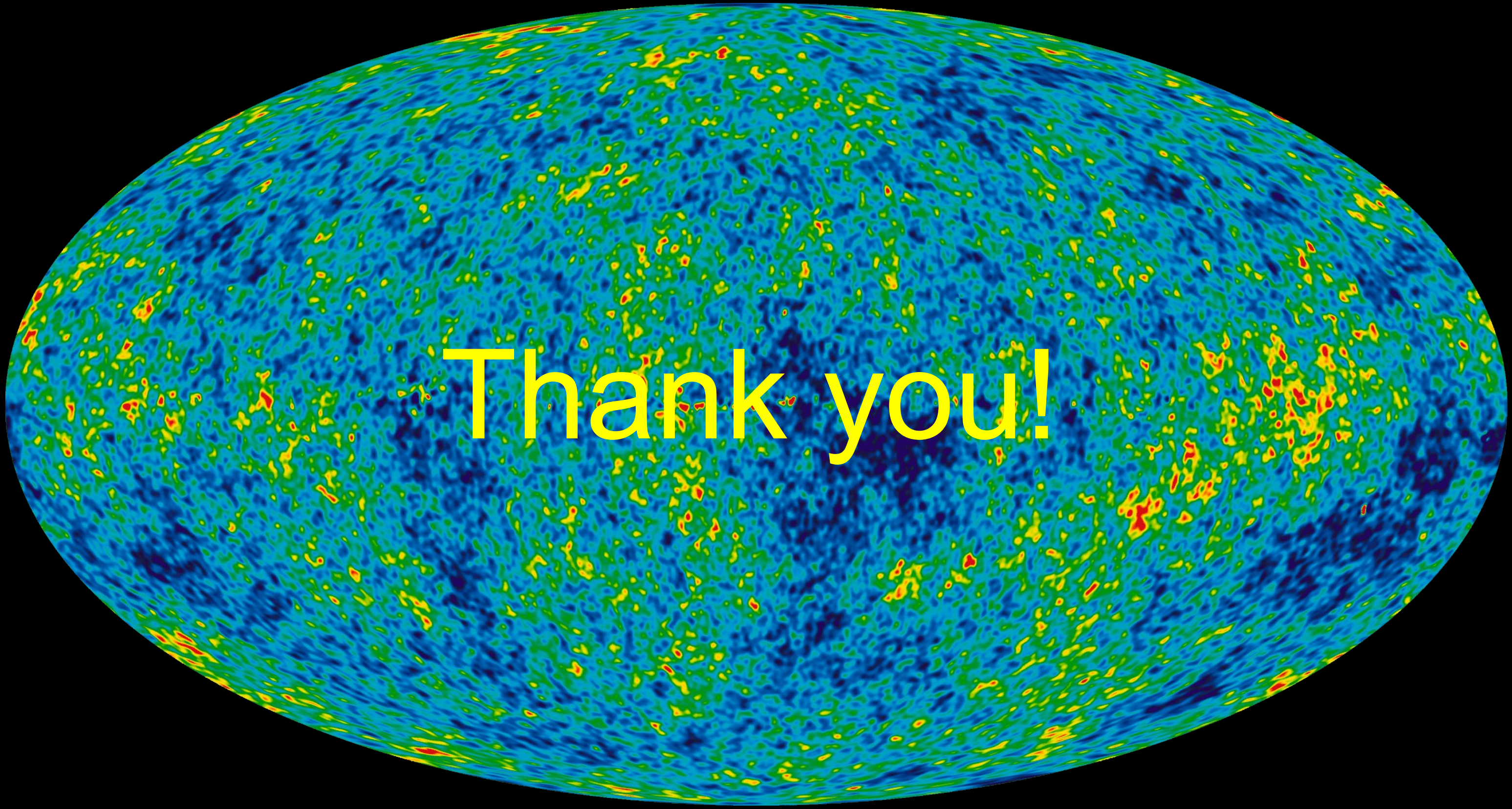


Extracting frequency



Conclusions

- We demonstrate a simple implementation of chemical potential mechanism for complex scalar fields at tree level.
- We get observable non-gaussianity for masses of the order of chemical potential, which can be as large as 60H (!)
- A schematic way to extract effective mass has also been demonstrated.


Thank you!