Cosmological collider physics beyond the Hubble scale

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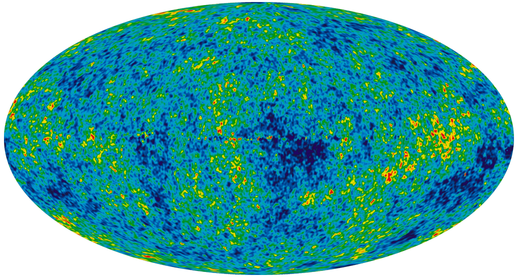
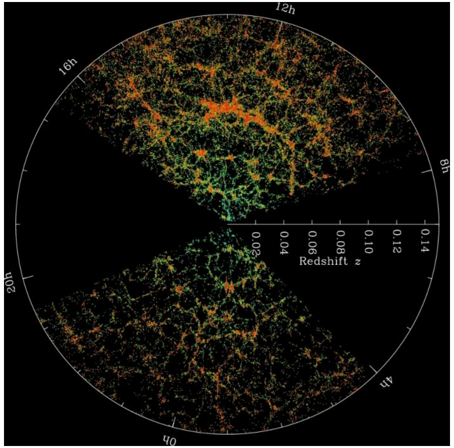
Universe is homogeneous with small inhomogeneities

CMB





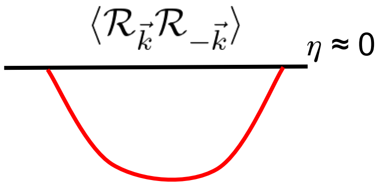
LSS

Density fluctuations seeded by the *'quantum fluctuations'* of the inflaton field that sources inflation.

Properties of fluctuations

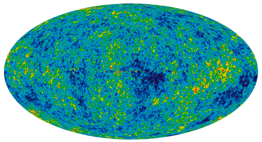
- Scale-invariant
- Adiabatic
- Gaussian

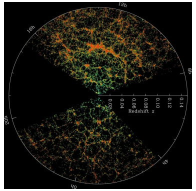
⇒ Quantum fluctuations of a scalar field in (quasi) de-Sitter spacetime



$$\langle \mathcal{R}_{\vec{k}} \mathcal{R}_{-\vec{k}} \rangle$$

Curvature perturbation

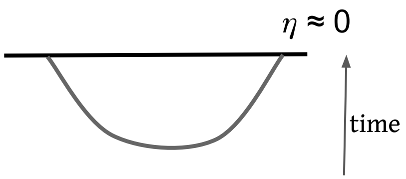




New physics affecting statistics of fluctuations → Macroscopic observables like CMB, LSS etc

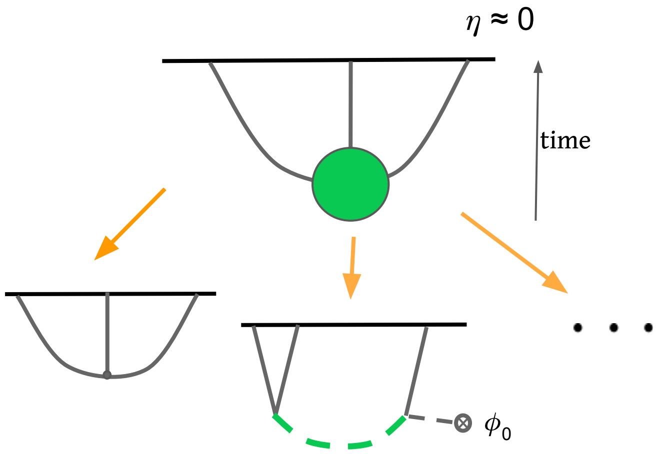
Detectors of physics at high energy scales (10^{13} GeV)!

Interactions impart non-Gaussianities (NG)



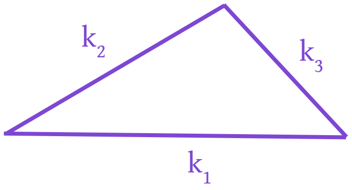
$$\langle \mathcal{R}_{\vec{k}} \mathcal{R}_{-\vec{k}} \rangle$$

Gaussian statistics



$$\langle \mathcal{R}_{\vec{k}_1} \mathcal{R}_{\vec{k}_2} \mathcal{R}_{\vec{k}_3} \rangle$$

non-Gaussianity



Momentum conservation

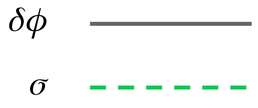
$$l \sim k r_{\text{cmb}}$$

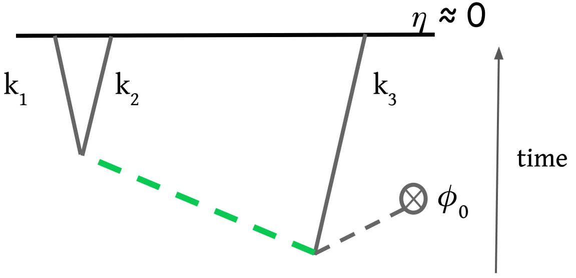
"Cosmological collider"

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

Heavy fields produced during inflation leave a unique non-analytic signature in inflaton n-point correlation fluctuations.

$$\mathcal{L}_{int} \supset (\partial\phi)^2\,\sigma$$



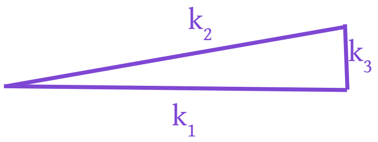


$$\langle \mathcal{R}_{\vec{k}_1}\mathcal{R}_{\vec{k}_2}\mathcal{R}_{\vec{k}_3}\rangle \propto e^{-\pi M/H}\left(\frac{k_1}{k_3}\right)^{-3/2+iM/H} P_s(\cos\theta)$$

Oscillation frequency
→ mass

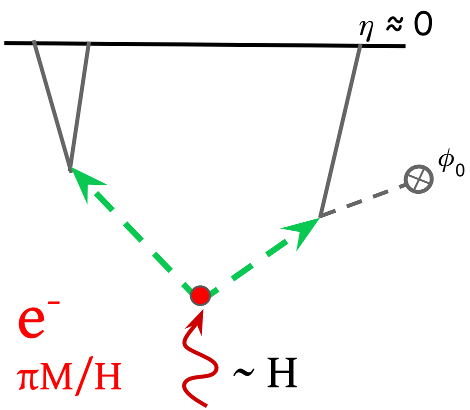
Angular dependence
→ spin

squeezed limit: $k_1 \sim k_2 \gg k_3$



Caveat- Boltzmann-like suppression

Space-time expansion provides energy ~ H_{infl} → $M \sim H_{infl}$ can be produced.

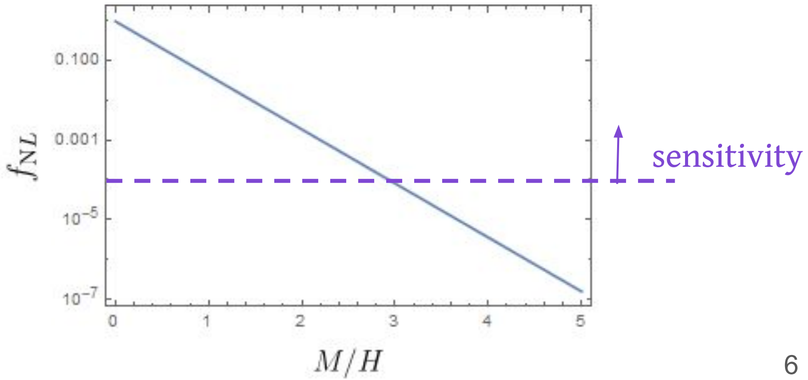


Production at $T_{Hawking} = H/2\pi$

For $M \gg H$, amplitude suppressed by Boltzmann factor ~ $e^{-M/2T} \sim e^{-\pi M/H}$

Loss of distinct signature for $M \ll H$.

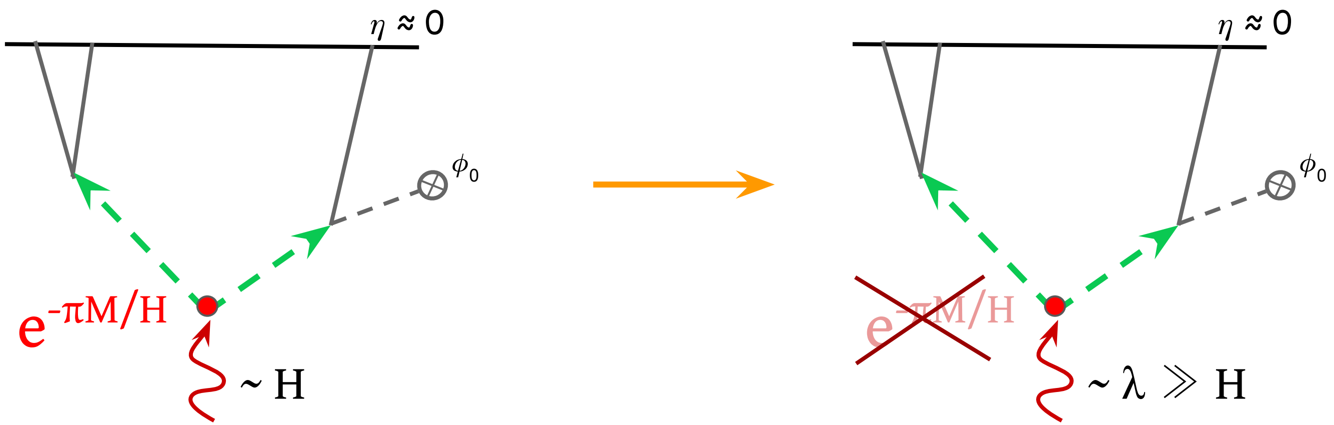
Severely limits the range as well as the reach of new physics that can be explored.



Motivation: Possible to overcome the suppression?

If high-frequency source $\lambda \gg H_{infl} \rightarrow$ $M \sim \lambda$ can be produced without suppression.

Extending thermal analogy $\rightarrow$ Chemical potential λ: $e^{-(E-\lambda)/T}$



Model description

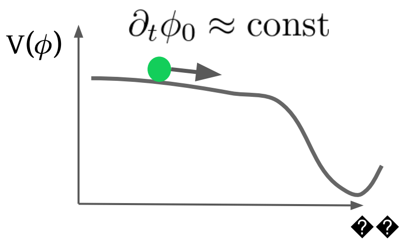
Consider a complex scalar field derivatively coupled to the inflaton with soft U(1)-breaking.

$$\mathcal{L}_\chi = \sqrt{-g}\left\{-|\partial\chi|^2 - M^2|\chi|^2 - \frac{i\partial_\mu\phi}{\Lambda}\left(\chi\partial^\mu\chi^\dagger - \chi^\dagger\partial^\mu\chi\right) - \frac{c\,(\partial\phi)^2}{\Lambda^2}|\chi|^2 + \alpha\left(\chi + \chi^\dagger\right)\right\}$$

Effective chemical potential:

$$-\frac{1}{\Lambda}\partial_\mu\phi J^\mu \supset \frac{\partial_t\phi_0}{\Lambda}J_0 = \lambda J_0$$

Symmetry-breaking term



Good derivative expansion in $\frac{(\partial\phi)^2}{\Lambda^4}$

$$\Lambda > \sqrt{\partial_t\phi_0} \implies \lambda \lesssim 60H$$

Planck'18

Model description

Minimal derivative coupling of inflaton to χ maintains radiative stability of inflaton potential

$$\mathcal{L}_\chi = \sqrt{-g}\left\{-|\partial\chi|^2 - M^2|\chi|^2 - \frac{i\partial_\mu\phi}{\Lambda}\left(\chi\partial^\mu\chi^\dagger - \chi^\dagger\partial^\mu\chi\right) - \frac{c\,(\partial\phi)^2}{\Lambda^2}|\chi|^2 + \alpha\left(\chi+\chi^\dagger\right)\right\}$$

Field redefinition: $\chi = e^{-i\phi/\Lambda}\,\tilde{\chi}$

Phase from chemical potential

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

Shift symmetry maintained by $\tilde{\chi}$ rotation

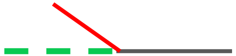
Model description

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

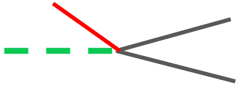
$$M_{eff} = \sqrt{M^2 + (1-c)\lambda^2}$$

$$e^{-i\frac{\phi}{\Lambda}} = e^{-i\frac{(\partial_t\phi_0)t}{\Lambda}}\, e^{-i\frac{\delta\phi}{\Lambda}}$$

$$\mathcal{H}_{mix} \supset \delta\tilde{\chi}\ \delta\phi\ e^{-i\lambda t} + cc$$



$$\mathcal{H}_{int} \supset \delta\tilde{\chi}\ (\delta\phi)^2 e^{-i\lambda t} + cc$$

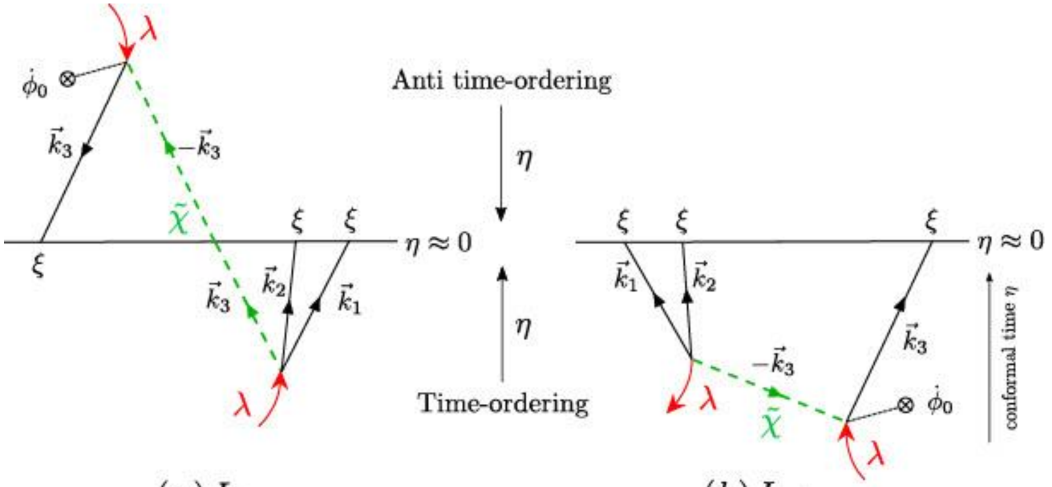


High frequency source λ ~ 60H ≫ H

Contribution to 3-point function

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

$$\langle \mathcal{R}_{\vec{k}_1} \mathcal{R}_{\vec{k}_2} \mathcal{R}_{\vec{k}_3} \rangle|_{\eta\to 0} = \langle 0| \left(\bar{T} e^{i\int_{-\infty}^{0} H_{\rm int}\, d\eta} \right) \mathcal{R}_{\vec{k}_1} \mathcal{R}_{\vec{k}_2} \mathcal{R}_{\vec{k}_3} \left(T e^{-i\int_{-\infty}^{0} H_{\rm int}\, d\eta} \right) |0\rangle$$



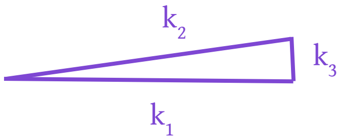
(a) I_{+-} (b) I_{++}

$$\mathcal{H}_{mix} \supset \delta\tilde\chi\ \delta\phi\ e^{-i\lambda t} + {\rm cc}$$

$$\mathcal{H}_{int} \supset \delta\tilde\chi\ (\delta\phi)^2\ e^{-i\lambda t} + {\rm cc}$$

3-point correlation function

To quantify NG, we define $F(k_1, k_2, k_3) = \frac{5}{6} \frac{\langle \mathcal{R}_{k_1} \mathcal{R}_{k_2} \mathcal{R}_{k_3} \rangle}{(\langle \mathcal{R}_{k_1} \mathcal{R}_{k_1} \rangle \langle \mathcal{R}_{k_3} \mathcal{R}_{k_3} \rangle + \text{combi.})}$



squeezed limit: $k_1 \sim k_2 \gg k_3$

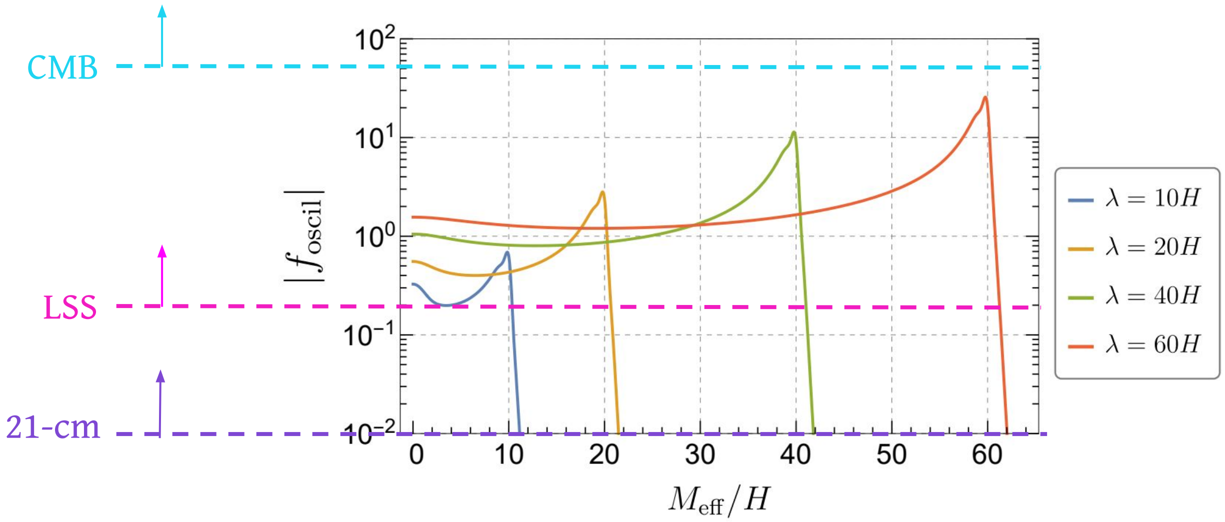
$$F_{\text{squeezed}} = f_{\text{oscil}}(M_{\text{eff}}, \lambda) \left(\frac{k_1}{k_3} \right)^{-3/2 + i(M_{\text{eff}} - \lambda)} + cc$$

Oscillatory signal

$$|f_{\text{oscil}}| = \frac{5\pi}{12\sqrt{2}} \times 10^{-2} \frac{\lambda^{7/2}}{M_{\text{eff}}^{1/2} (\lambda^2 - M_{\text{eff}}^2)}$$

No Boltzmann suppression!

Signal strength

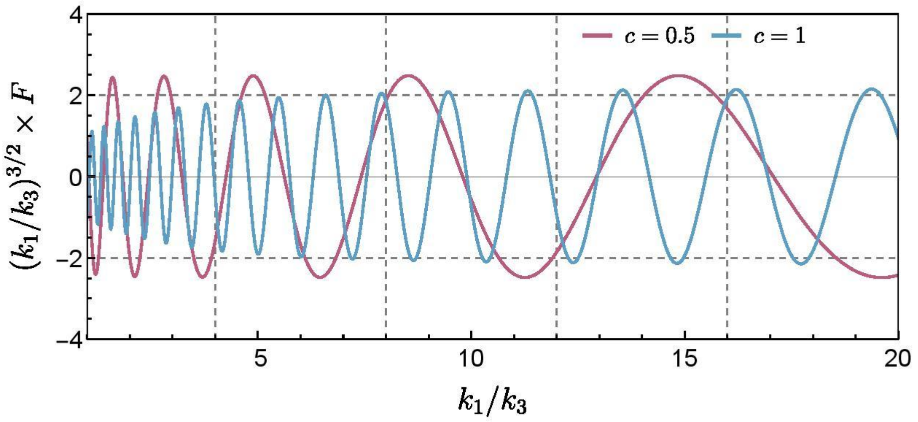


- Large NG for $M_{eff} \lesssim \lambda$
- Observable at LSS and 21-cm
- Peak at $M_{eff} \approx \lambda$ due to resonance

Oscillatory signature

Function of both M_{eff} and λ

$$F_{\rm squeezed} = f_{\rm oscil}(M_{\rm eff}, \lambda) \left(\frac{k_1}{k_3}\right)^{-3/2+i(M_{\rm eff}-\lambda)} + cc$$



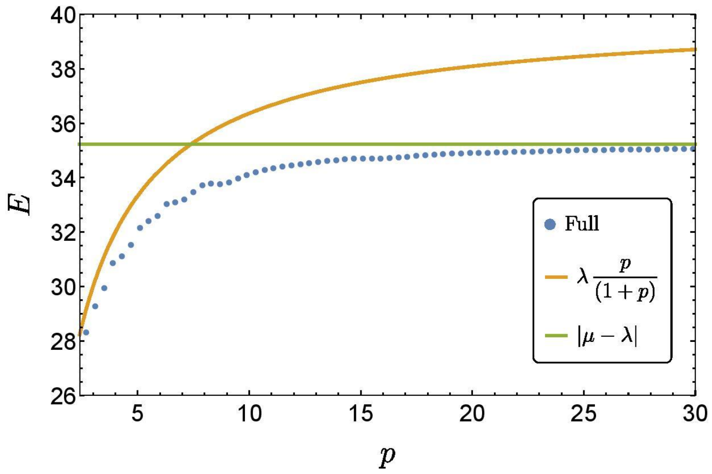
M_{eff} = 5H, M_{eff} = 30, λ = 40H

- Distinct oscillatory signature.
- Many observable oscillations before $(k_3/k_1)^{3/2}$ dilution makes the signal unobservable.

Extracting effective mass

- Use change in non-analytic exponent as a function of $p = k_1/k_3$ to extract M_{eff}.
- $E(p)$ is the oscillation frequency

$$E(p) = \begin{cases} \lambda & \leftarrow \text{Small p} \\ |M_{\mathrm{eff}} - \lambda| & \leftarrow \text{Large p} \end{cases}$$



$M_{\mathrm{eff}} = 5H$, $\lambda = 40H$

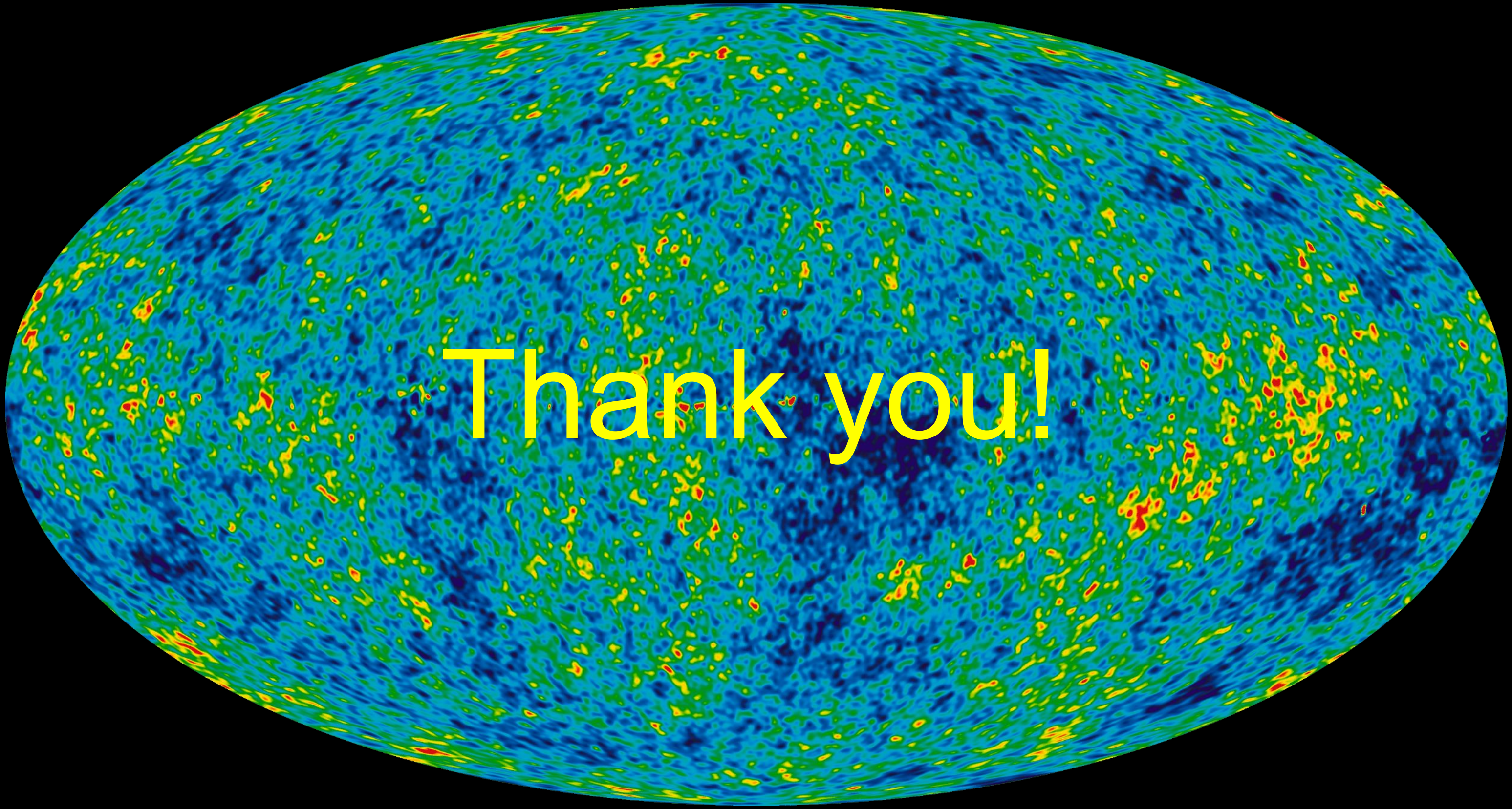
Previous studies of non-zero spin

- Similar chemical potential ideas have been proposed in the context of fermions and gauge bosons, but with qualitative differences.
- Signal is at loop level and generally difficult to calculate.
- For fermions, the mass reach is $M \lesssim (\dot{\phi}_0 H^2)^{1/4}$~ 10H, as opposed to full $\sqrt{\dot{\phi}_0}$ for scalars.
- For spin-1 bosons, although the mass reach is ~ 60H, fine-tuning of mass close to chemical potential is required to get large signal while avoiding instability and loss of perturbative control.

P. Adshead et al, 1803.04501,
X. Chen et al, 1805.02656
A.Hook et al, 1908.00019
L. Wang, Z. Xianyu, 1910.12876
W. Garretson et al, 9209238
N. Barnaby et al, 1102.4333,
L. Wang, Z. Xianyu, 2004.02887
….

Conclusions

- Cosmological collider physics → "direct detection" of heavy fields.
- Harness inflaton KE~ $(60H)^4$ through chemical potential to overcome the Boltzmann suppression.
- We demonstrate implementation of chemical potential mechanism for a pair of real scalars at tree level in an analytically tractable way.
- The model predicts observable NG for a large range of masses with the maximum reach of $M_{max} \simeq 60H$, which can be as large as 10^{15} GeV (!)
- A schematic way to determine effective mass from the data is sketched.



Thank you!