Title: Cosmological collider physics beyond the Hubble scale

Speakers: Arushi Ravindra Bodas

Series: Particle Physics

Date: November 09, 2021 - 1:00 PM

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Abstract: Non-gaussianity of primordial density perturbations can be sensitive to very heavy particles at the inflationary Hubble scale (H < 10^(13) GeV). However, the window of observability is often constrained to masses close to H. In this talk, I will discuss a mechanism (dubbed "chemical potential") for heavy complex scalar fields that can extend this window to masses as large as 60H. The mechanism utilizes the large kinetic energy of the inflaton to enhance particle production, and can impart observable non-gaussianity, f_NL~ O(0.01-10). In the second part of the talk, I will discuss another mechanism where the distinct signature of a heavy field can be imprinted at the level of the power spectrum by violating scale-invariance. This can be achieved through the onset of classical oscillations of the heavy field during inflation, instead of quantum production. We consider the possibility of observing such a signal in the stochastic gravitational wave (GW) background originating from a first-order phase transition in a hidden sector. The signal can be observably large in the GW map while being completely hidden in the standard curvature perturbations such as those of the CMB.

# Cosmological Collider Physics Beyond the Hubble Scale

Arushi Bodas (University of Maryland)

AB, Soubhik Kumar, Raman Sundrum JHEP 2021, 79
AB, Raman Sundrum 2112.xxxxx

**PI Seminar**

9 Nov. 2021

# Outline

- Introduction
  - Cosmological Collider Physics
  - Boltzmann-like suppression

- Part 1: "Chemical potential" production of heavy particles

  AB, S. Kumar, R. Sundrum JHEP 2021, 79

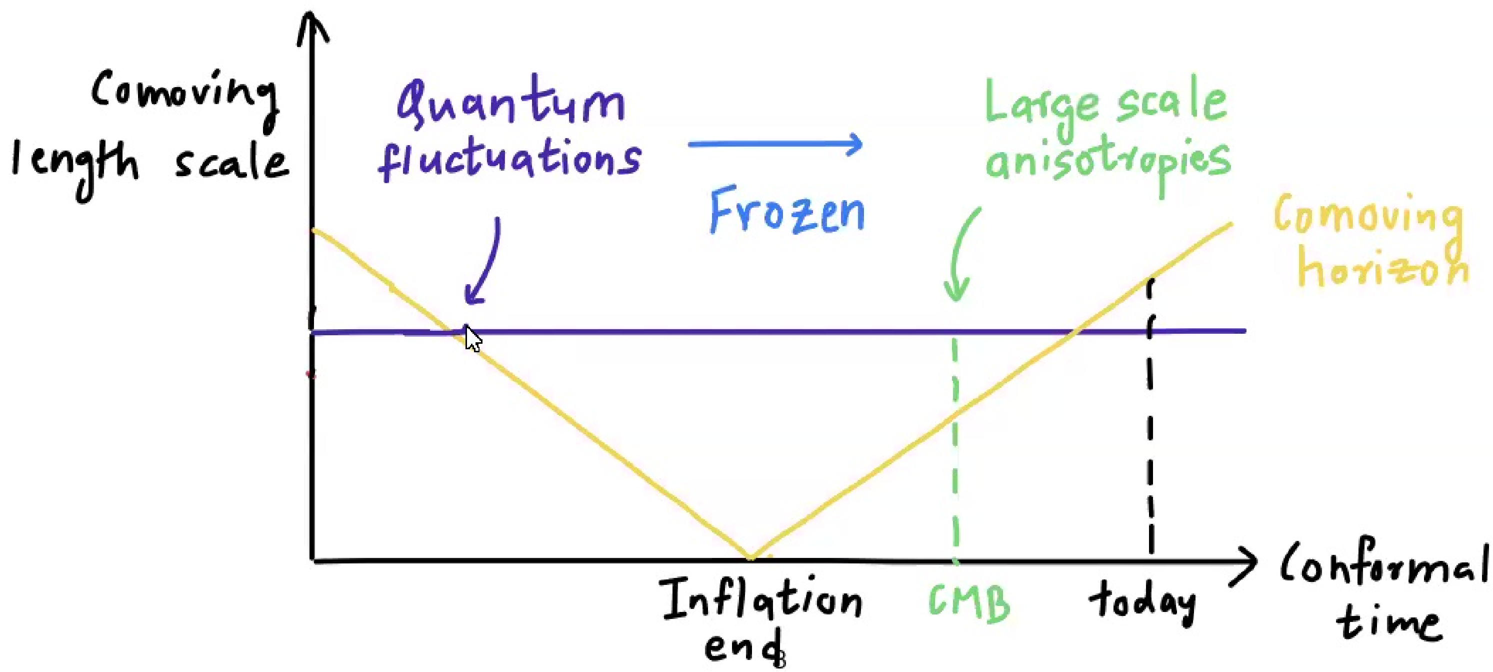
- Part 2: Classical oscillations of heavy field

  Ongoing

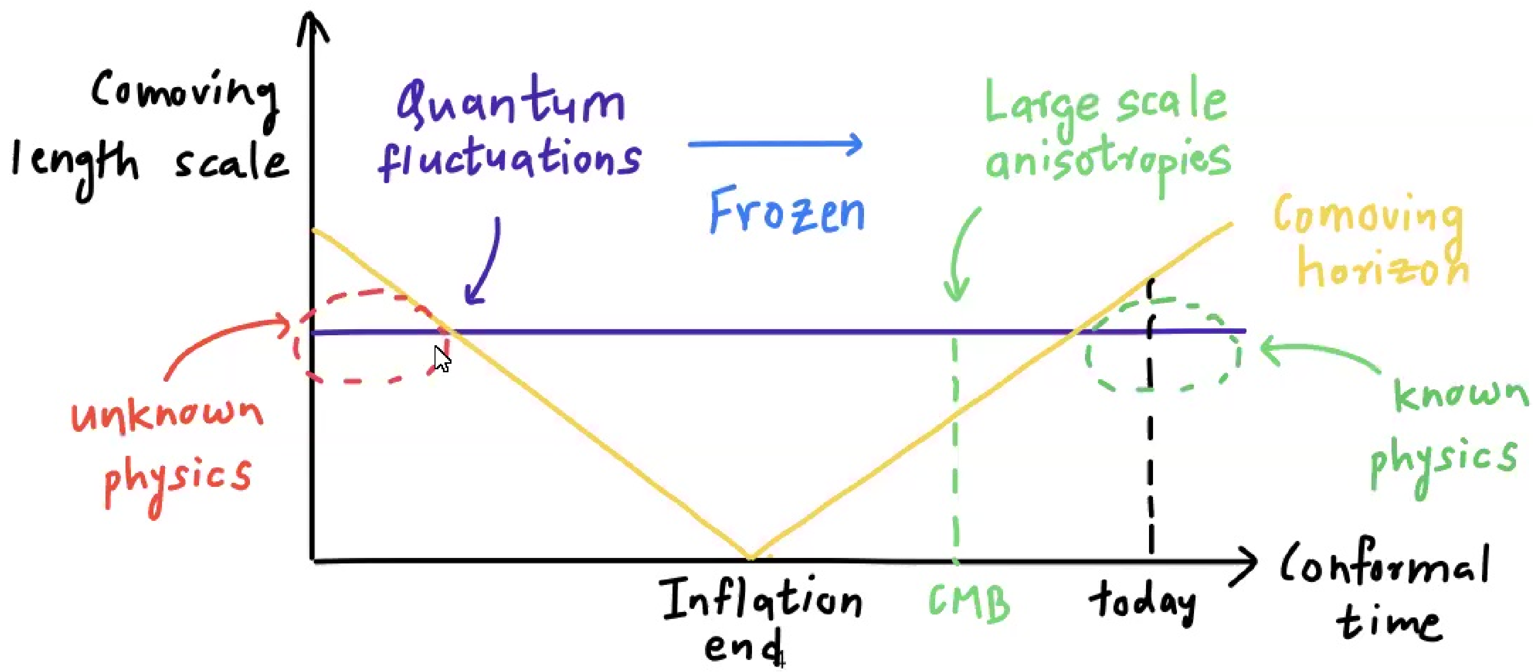
- Work in progress

- Quantum fluctuations of inflaton field $\delta\phi$ seed primordial density anisotropies

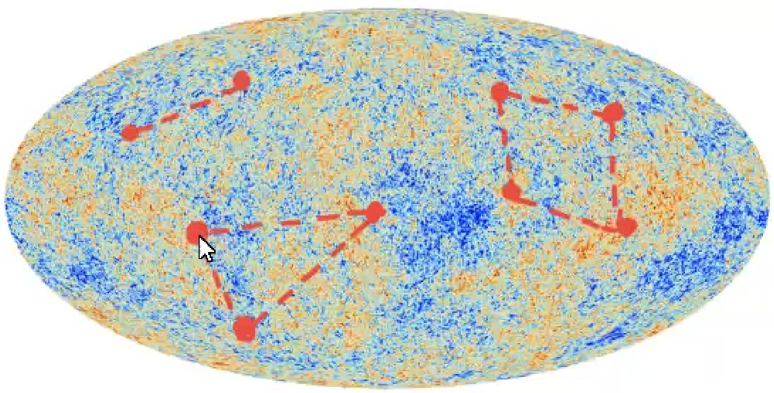
- Fluctuations frozen on superhorizon scales → Large scale anisotropies



- “Late” time observations of density fluctuations give information about physics at subhorizon scales during inflation



# Non-gaussianity (NG): A probe of high energy physics

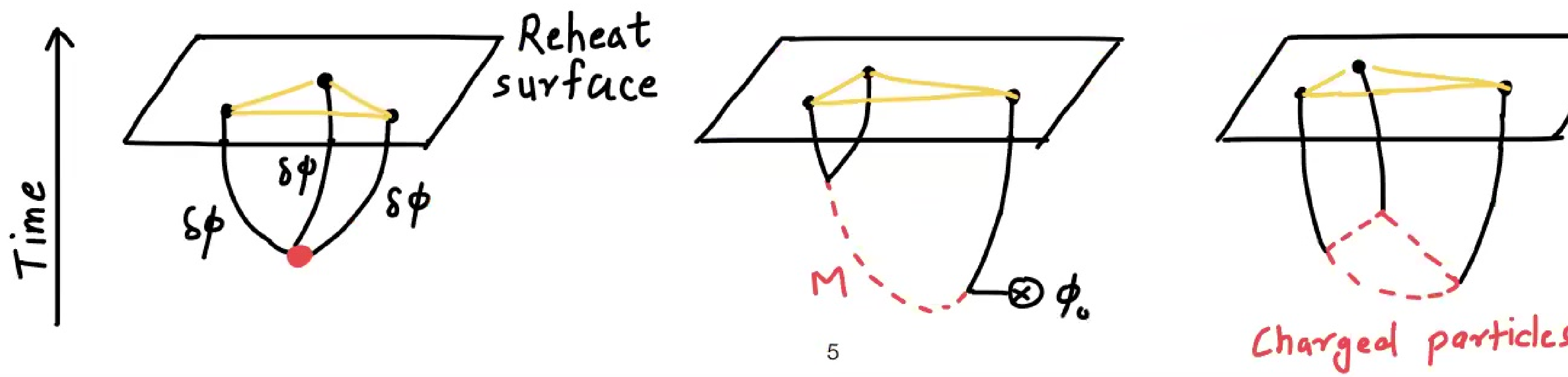


$$\langle \delta T(\hat{n}_1)\,\delta T(\hat{n}_2)\cdots\delta T(\hat{n}_n)\rangle\,|_{\rm CMB} \propto \langle \delta\phi(\hat{n}_1)\,\delta\phi(\hat{n}_2)\cdots\delta\phi(\hat{n}_n)\rangle\,|_{\rm reheat}$$

Fourier transform

$$\langle \delta\phi_{\vec{k}_1}\,\delta\phi_{\vec{k}_2}\cdots\delta\phi_{\vec{k}_n}\rangle$$

Momentum conservation $\Longrightarrow \vec{k}_1 + \vec{k}_2 + \cdots + \vec{k}_n = 0$

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# Cosmological Collider Physics

- NG: possible direct detection of particles with masses $M \sim H(\lesssim 10^{13}\,\mathrm{GeV})$!
- Cosmological collider: non-analytic signature of propagating heavy particles
  On-shell production during inflation

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

# Cosmological Collider Physics

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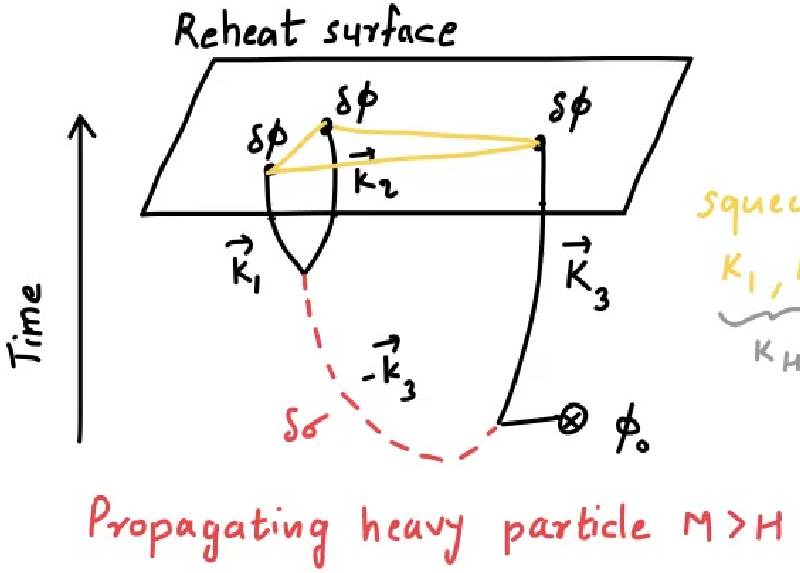



squeezed triangle
$\underbrace{k_1, k_2}_{k_H} \gg \underbrace{k_3}_{k_S}$

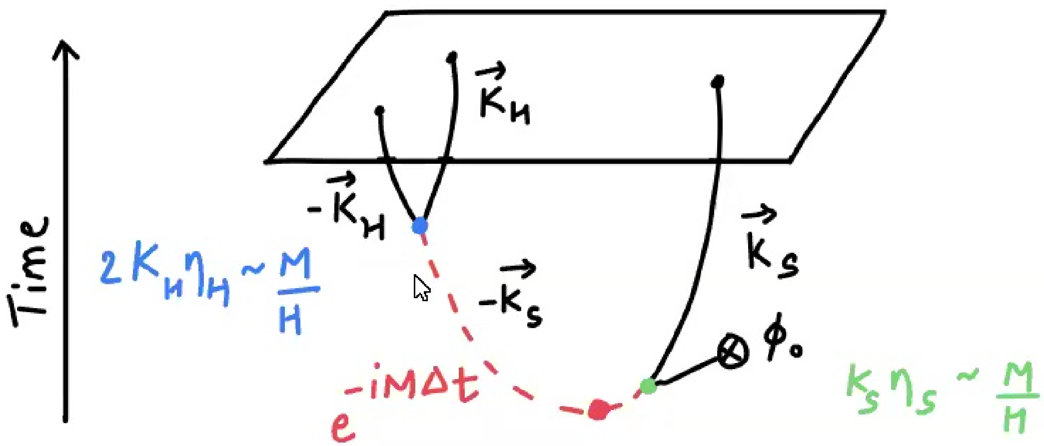
$$\langle \delta\phi_{\vec{k}_1}\delta\phi_{\vec{k}_2}\delta\phi_{\vec{k}_3}\rangle \propto \left(\frac{k_H}{k_S}\right)^{-3/2+i\sqrt{(M/H)^2-9/4}}$$

$$\xrightarrow{M>3H/2} \left(\frac{k_H}{k_S}\right)^{-3/2} \underbrace{\cos\left(\frac{M}{H}\log\left(\frac{k_H}{k_S}\right)\right)}$$

oscillatory dependence
frequency $\propto M/H$

# Origin of non-analytic signature

- On-shell production and propagation of heavy particles
- Time translation + Spatial scaling = Symmetry $\rightarrow$ $\Delta t$ depends only on the ratio of momenta $\dfrac{k_S}{k_H}$
- $\omega^2(t) = k_{phys}^2 + M^2 \rightarrow$ Particle produced when $k_{phy} \lesssim M$

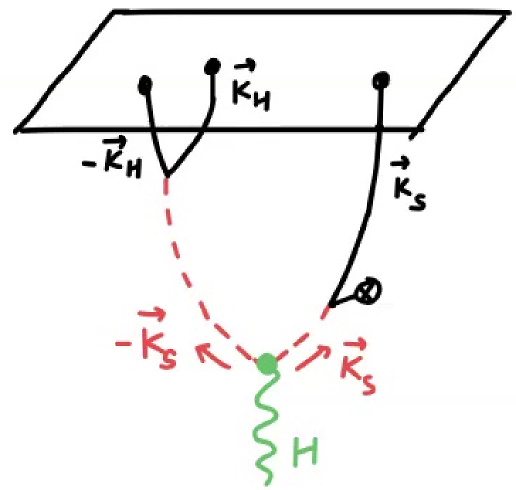



$$e^{-iM\Delta t} \rightarrow \left(\frac{\eta_H}{\eta_S}\right)^{-iM/H} \rightarrow \left(\frac{k_S}{k_H}\right)^{-iM/H}$$

# Exponential suppression

$$\langle \delta\phi_{k_1} \delta\phi_{k_2} \delta\phi_{k_3} \rangle \propto e^{-\pi \frac{M}{H}} \cos[(M/H)\log(k_H/k_S)]$$

- Inflationary background only provides energy $\sim H$ to produce excitation with energy $\sim M$
- Heuristic: Probability of excitation $P(\Delta E) \sim e^{-\frac{\Delta E}{T}}$, here $T \to T_{\text{Hawking}} = \dfrac{H}{2\pi}$
- Boltzmann-like suppression in the production amplitude $\sim \sqrt{\text{P(M)}} = e^{-\pi \frac{M}{H}}$
- Loss of non-analytic signature for $M \ll H$



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$$\langle \delta\phi_{k_1} \delta\phi_{k_2} \delta\phi_{k_3} \rangle \propto \boxed{e^{-\pi \frac{M}{H}}} \cos[(M/H)\log(k_H/k_S)]$$

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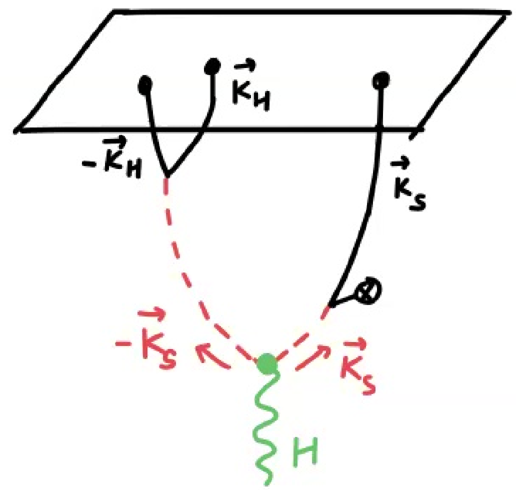
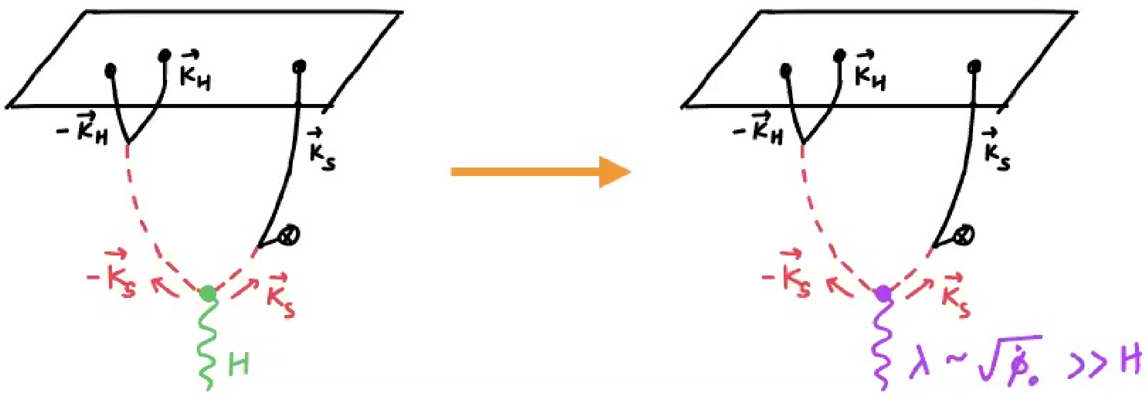
- Loss of non-analytic signature for $M \ll H$
- Limits observability of new physics close to $\sim H$



# Part 1:
# "Chemical potential" mechanism

# "Chemical potential"




- **Main idea**: Couple heavy field to a different high-frequency background source
- Utilize kinetic energy of the inflaton background $\sqrt{\dot{\phi}_0} \approx 60H \gg H$
- Our model is motivated by previous studies of chemical potential in spin-1/2 and spin-1 fields

P. Adshead et al, 1803.04501,
X. Chen et al, 1805.02656
A.Hook, J. Huang, D. Racco, 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

# The model

$$\mathscr{L}_\sigma = -\partial_\mu\sigma^\dagger\partial^\mu\sigma - M^2\sigma^\dagger\sigma - \frac{i\partial_\mu\phi}{\Lambda}(\sigma\partial^\mu\sigma^\dagger - \sigma^\dagger\partial^\mu\sigma)$$

$$-\frac{1}{\Lambda}\partial_\mu\phi J^\mu \supset \frac{\dot{\phi}_0}{\Lambda}J_0 = \lambda J_0$$

$\lambda$: chemical potential

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

$\Longrightarrow \Lambda > \sqrt{\dot{\phi}_0}$ and $\lambda < \sqrt{\dot{\phi}_0} \approx 60H$

Derivative coupling of $\phi$ preserves shift symmetry
ensures no radiative corrections to inflaton potential

Derivative operator
can be rotated away $\sigma = e^{-i\phi/\Lambda}\tilde{\sigma}$

$$\mathscr{L}_{\tilde{\sigma}} = -\partial_\mu\tilde{\sigma}^\dagger\partial^\mu\tilde{\sigma} - M^2\tilde{\sigma}^\dagger\tilde{\sigma}$$

- Must break U(1) explicitly → coupling to "thermal bath"

$$\mathcal{L}_\sigma = -\partial_\mu \sigma^\dagger \partial^\mu \sigma - M^2 \sigma^\dagger \sigma - \frac{i\partial_\mu \phi}{\Lambda}(\sigma \partial^\mu \sigma^\dagger - \sigma^\dagger \partial^\mu \sigma) + \boxed{\alpha(\sigma + \sigma^\dagger)}$$

$\sigma = e^{-i\phi/\Lambda}\tilde{\sigma}$ ↓

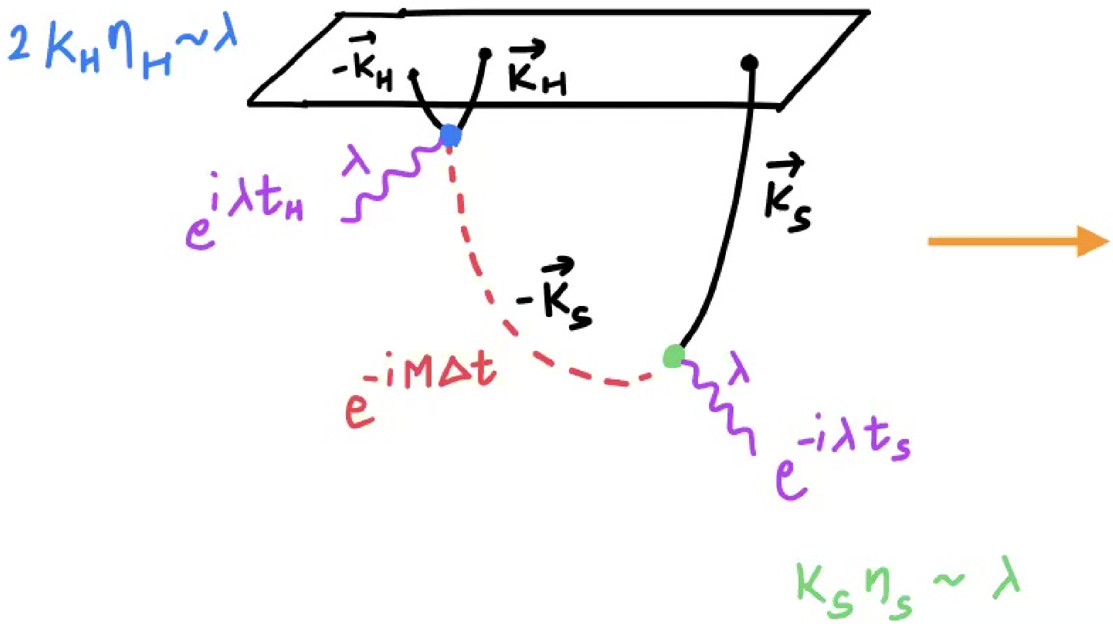
$$\mathcal{L}_{\tilde\sigma} = -\partial_\mu \tilde\sigma^\dagger \partial^\mu \tilde\sigma - M^2 \tilde\sigma^\dagger \tilde\sigma + \boxed{\alpha(\tilde\sigma e^{-i\phi/\Lambda}} + \tilde\sigma^\dagger e^{i\phi/\Lambda})$$

→ Shift symmetry maintained when accompanied by $\tilde\sigma$ rotation

$e^{-i\phi/\Lambda} = e^{-i(\dot\phi_0/\Lambda)t} e^{-i\delta\phi/\Lambda} = e^{-i\lambda t} e^{-i\delta\phi/\Lambda}$ ↓

Interactions→ $$\mathcal{H}_{int} \supset -i\left(\frac{\alpha}{\Lambda}\right)\delta\tilde\sigma\,\delta\phi e^{-i\lambda t} - \left(\frac{\alpha}{\Lambda}\right)^2 \delta\tilde\sigma\,(\delta\phi)^2 e^{-i\lambda t} + h.c.$$

High frequency time-dependence $\boxed{\lambda \lesssim 60H}$




## Non-analytic signature

$$e^{-i(M-\lambda)\Delta t} \rightarrow \left(\frac{k_S}{k_H}\right)^{-i(M-\lambda)}$$

# Calculation

- In-in formalism
  Bunch-Davies vacuum $|0\rangle$
  Expectation value of $\hat{\mathcal{O}} = \delta\phi_{\vec{k}_1} \cdots \delta\phi_{\vec{k}_n}$ at the reheat surface
  $$\langle \hat{\mathcal{O}}(t_r) \rangle = \langle 0 | (\bar{T} e^{i \int_{-\infty(1-i\epsilon)}^{t_r} \mathcal{H}_{int} dt}) \; \hat{\mathcal{O}}(t_r) \; (T e^{-i \int_{-\infty(1+i\epsilon)}^{t_r} \mathcal{H}_{int} dt}) | 0 \rangle$$

- At tree-level
  $$\langle \hat{\mathcal{O}}(t_r) \rangle = \langle 0 | \left( i \int^{t_r} \mathcal{H}_{int} dt \right) \hat{\mathcal{O}}(t_r) \left( -i \int^{t_r} \mathcal{H}_{int} dt \right) | 0 \rangle + \langle 0 | \hat{\mathcal{O}}(t_r) \left( - \int_{-\infty}^{t_r} \mathcal{H}_{int}(t_1) dt_1 \int_{-\infty}^{t_1} \mathcal{H}_{int}(t_2) dt_2 \right) | 0 \rangle + h.c$$

- Fluctuations of (complex) heavy field $\tilde{\sigma}$
  $\delta\tilde{\sigma}(\vec{k}, \eta) = \bar{f}(k, \eta) \hat{a}_{-\vec{k}} + f(k, \eta) \hat{b}^{\dagger}_{\vec{k}}$ where $f(k, \eta) = e^{\pi\mu/2} (-\eta)^{3/2} H_{i\mu}^{(2)}(-k\eta) \xrightarrow{(-k\eta)\to\infty} e^{-ik\eta}$
  $\mu = \sqrt{(M/H)^2 - 9/4} \approx M/H$

- Time ordering can be simplified: production at $k_S$ vertex and decay at $k_H$ vertex

- $\langle \delta\phi_{k_1}\delta\phi_{k_2}\delta\phi_{k_3}\rangle = C_{+-} + C_{--} + C_{-+} + C_{++}$ (+ : Anti time ordered, - :Time ordered)

- $$C_{+-} \propto \int_{-\infty}^{0} \frac{d\eta_1}{\eta_1^4}\frac{d\eta_2}{\eta_2^4} \langle\, \delta\phi\, \delta\tilde{\sigma}^\dagger (-\eta_1)^{-i\lambda} \cdot (\delta\phi\delta\phi\delta\phi)_r \cdot \delta\phi\, \delta\tilde{\sigma}^2 (-\eta_2)^{i\lambda} \,\rangle$$

- Time integral at $k_S$ vertex: $$I_{k_S}^{(-)} = (+i)\int_{-\infty}^{0} \frac{d\eta}{\eta^4}\left(\frac{(1+ik_3\eta)e^{-ik_3\eta}}{2k_3^3}\right)(-\eta)^{-i\lambda} \times \underbrace{\left(N_f^*(-\eta)^{3/2}H_{i\mu}^{(1)}(-k_3\eta)\right)}_{\bar{f}_{k_3}(\eta)}$$
$$= \frac{i\sqrt{\pi}}{4}\frac{1}{k_3^{3/2-i\lambda}}\left[I_1\left(-\frac{5}{2}-i\lambda,1\right) - iI_1\left(-\frac{3}{2}-i\lambda,1\right)\right]$$
Time integral at $k_S$ vertex: $$I_{k_H}^{(+)} = \frac{-i\sqrt{\pi}}{8k_1^3k_2^3k_3^{1/2+i\lambda}}\left[k_3^2\left\{I_2\left(-\frac{5}{2}+i\lambda,p\right) + ipI_2\left(-\frac{3}{2}+i\lambda,p\right) - \frac{p^2}{4}I_2\left(-\frac{1}{2}+i\lambda,p\right)\right\}\right],$$
where $p = \dfrac{k_H}{k_S}$ controls how squeezed the triangle configuration is

- $$I_1(n,p) = \frac{(i/2)^n}{\sqrt{\pi}\,\Gamma(n+3/2)}\Gamma(n+1+i\mu)\Gamma(n+1-i\mu)\,{}_2F_1(n+1-i\mu, n+1+i\mu, n+3/2, (1-p)/2)$$
$$I_2(n,p) = \frac{(-i/2)^n}{\sqrt{\pi}\,\Gamma(n+3/2)}\Gamma(n+1+i\mu)\Gamma(n+1-i\mu)\,{}_2F_1(n+1+i\mu, n+1-i\mu, n+3/2, (1-p)/2)$$

- In short, 3-point correlation can be calculated exactly
The expressions can be simplified to study the relevant limit: $\lambda, M \gg H$, and $k_H/k_s \gg 1$

# Results

- Shape of non-gaussianity

$$F(k_1,k_2,k_3) = \frac{5}{6}\frac{\langle \mathscr{R}_{k_1}\mathscr{R}_{k_2}\mathscr{R}_{k_3}\rangle}{(\langle \mathscr{R}_{k_1}\mathscr{R}_{k_1}\rangle\langle \mathscr{R}_{k_3}\mathscr{R}_{k_3}\rangle + \text{combi.})}$$

where $\mathscr{R} = H\frac{\delta\phi}{\dot{\phi}_0}$ (spatially flat gauge)

- Squeezed limit

$$F_{\text{oscil}}(k_1,k_2,k_3) = |f_{\text{oscil}}| \left( e^{i\delta(M,\lambda)}\left(\frac{k_H}{k_S}\right)^{-3/2+i(\lambda-M)} + c.c. \right)$$

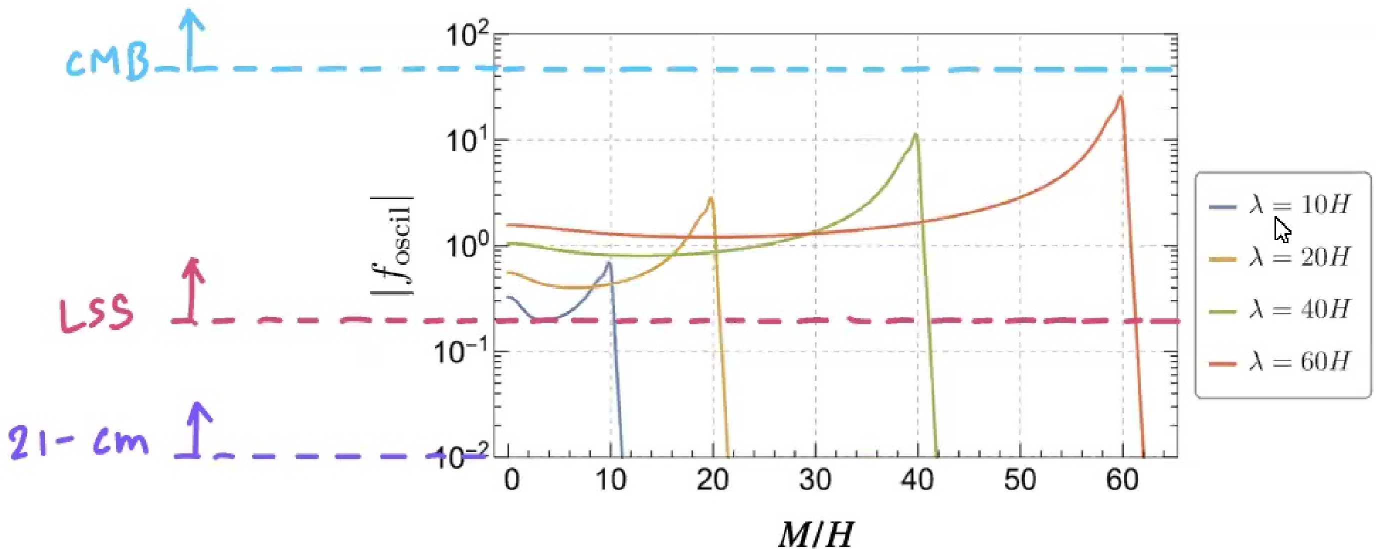
- Amplitude of NG (generally $f_{\text{NL}}$)

$$|f_{\text{oscil}}| \xrightarrow{\lambda>M>H} \frac{5\pi}{12\sqrt{2}} \times 10^{-2} \frac{\lambda^{7/2}}{M^{1/2}(\lambda^2 - M^2)H}$$

$\to O(10-100)$

Ensures only % level correction to power spectrum, conservative Planck, 1807.06211

# Strength of NG

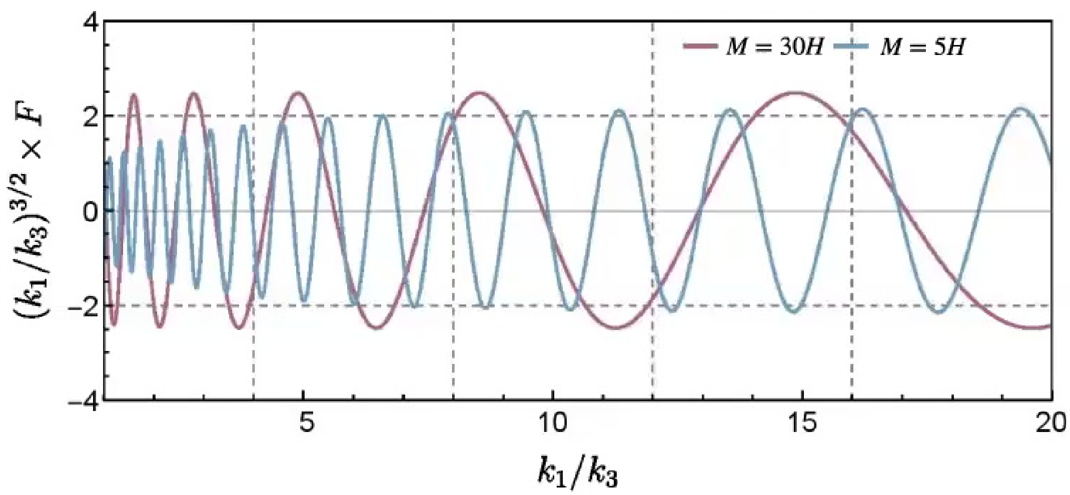



- Observable NG for an extended range of masses $M \lesssim \lambda < 60H$
- Peak at $M \approx \lambda$ due to resonance
- Signal drops as $e^{\frac{-\pi M^2}{2\lambda H}}$ for $M > \lambda$

M. Alvarez et al, 1412.4671
A. Loeb and M. Zaldarriaga, astro-ph/0312134
J. B. Muñoz, Y. Ali-Haïmoud, and M. Kamionkowski, 1506.04152

# Shape of NG

- Frequency is $(\lambda - M)$ instead of $M$
- As $M$ increases and gets closer to $\lambda$, frequency decreases
- Can we independently determine $\lambda$ and $M$?

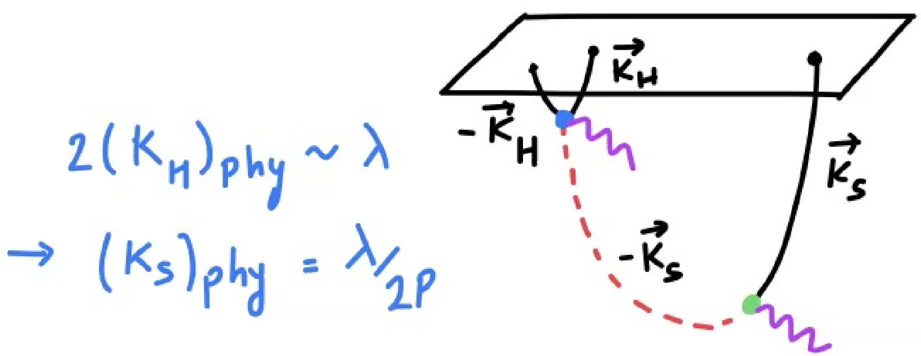



$\lambda = 40H$

$$F_{\rm oscil} \xrightarrow{k_H/k_s \gg 1} |f_{\rm oscil}| \left( \left(\frac{k_H}{k_S}\right)^{-3/2} \cos[(\lambda - M)\log(k_H/k_S) + \delta] + c.c. \right)$$

# Extracting $M$ and $\lambda$

- Yes! Exploit dependence of oscillation frequency on squeezing $p = \frac{k_H}{k_S}$
- $\Delta t = \log p \;\rightarrow\;$ Time of decay of heavy particle controlled by $p$




- If $\frac{\lambda}{2p} < M,\ (k_s)_{phys} < M \rightarrow$ Non-relativistic at decay, information about $M$ is imprinted in NG

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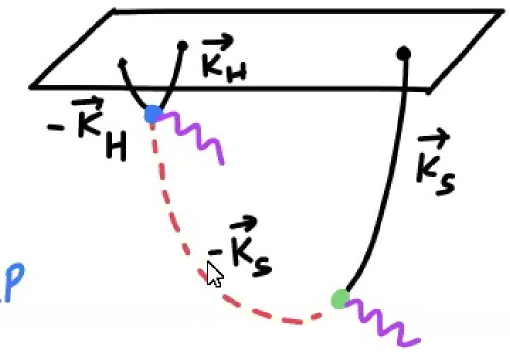
$2(K_H)_{phy} \sim \lambda$

$\rightarrow (K_s)_{phy} = \lambda/2p$




$(K_s)_{phy} \sim \lambda > M$

- If $\dfrac{\lambda}{2p} < M, \ (k_s)_{phys} < M \rightarrow$ Non-relativistic at decay, information about $M$ is imprinted in NG
- If $\dfrac{\lambda}{2p} > M, \ (k_s)_{phys} > M \rightarrow$ Relativistic at decay, no information about $M$ can be imprinted in NG

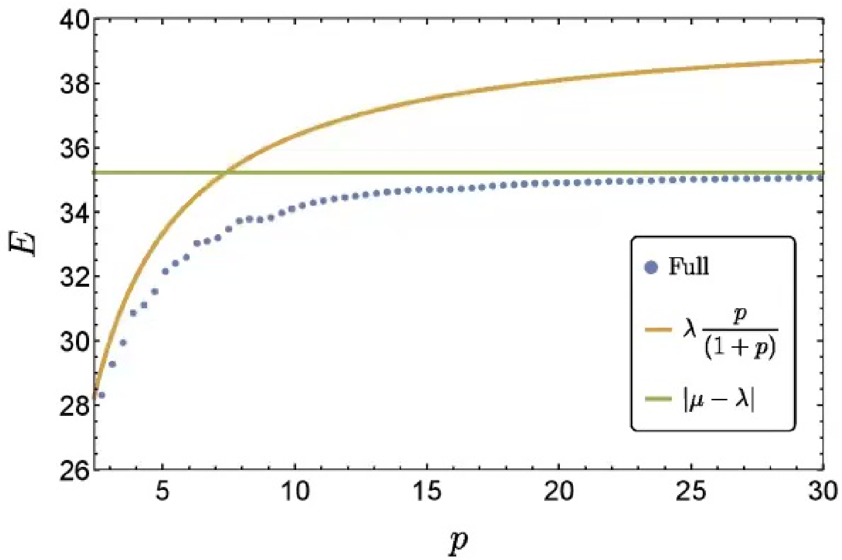
Large p: non-relativistic at decay

$$E(p) \rightarrow \lambda - M$$

$$\langle \delta\phi_{k_H} \delta\phi_{k_H} \delta\phi_{k_S} \rangle \propto \cos[E(p) \log p]$$

$$E(p) \rightarrow \lambda \left( \frac{p}{1+p} \right)$$

Moderate p: Relativistic at decay




$M = 5H, \lambda = 40H$

- Feature unique to models with chemical potential
- Exact calculation allows us to see it in this model!

# Comments

- The mechanism can be easily generalized to two real scalars with similar masses
  Explicit U(1) breaking occurs at quadratic level $m^2(\sigma^2 + \sigma^{\dagger 2})$, which can be treated perturbatively if $m \ll M$

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  Explicit U(1) breaking occurs at quadratic level $m^2(\sigma^2 + \sigma^{\dagger 2})$, which can be treated perturbatively if $m \ll M$

- Spin -1/2
  $\mathcal{L}_{int} \sim \partial_\mu \phi J_5^\mu$ , broken by Dirac mass term $M\bar{\psi}\psi$
  NG $\propto e^{-\pi M^2/4\lambda H}$, Thus range of observable masses $M \lesssim \sqrt{\lambda}$

P. Adshead et al, 1803.04501,
X. Chen et al, 1805.02656
A.Hook, J. Huang, D. Racco, 1908.00019
L. Wang, Z. Xianyu, 1910.12876

- Spin -1
  $\mathcal{L}_{int} \sim \phi F\tilde{F}$ , leads to overproduction
  $M$ must be tuned close to $\lambda$ in order to avoid back-reaction

W. Garretson et al, 9209238
N. Barnaby et al, 1102.4333,
L. Wang, Z. Xianyu, 2004.02887
...

- Leading contribution at loop level with higher spin fields, exact calculation not possible due to non-trivial time dependences
  In our model of complex scalar, dominant contribution is at tree level, hence NG can be calculated exactly

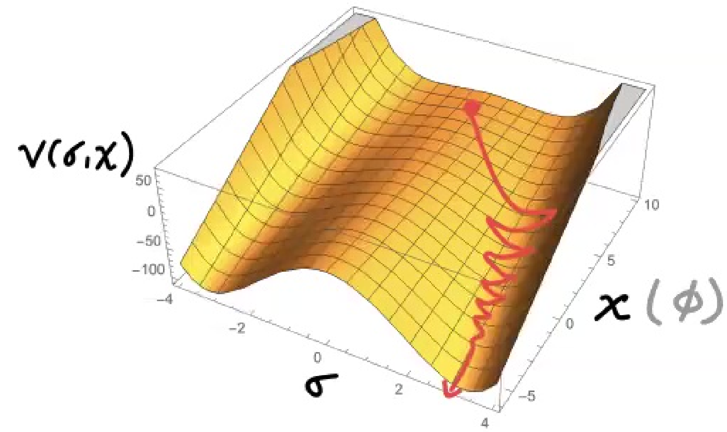
# Part 2:
# Classically oscillating heavy field

# Coherent oscillations: No suppression!

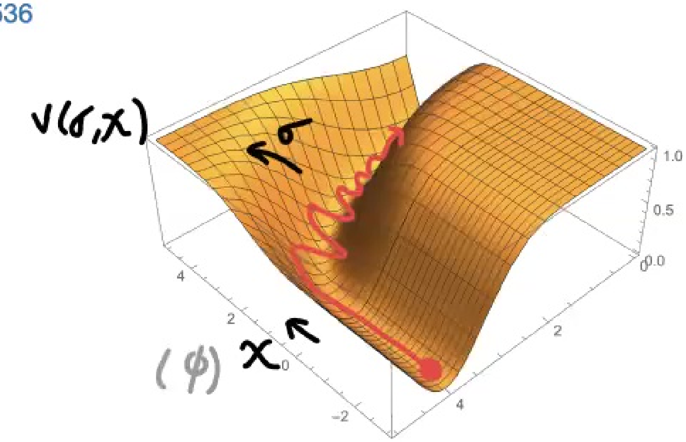
- Heavy field $\sigma$ is "kicked" at time $t_c$ during inflation

- Undergoes coherent oscillations with frequency $m_\sigma$ and dilutes due to inflation

$$\langle \sigma(t) \rangle \sim \sigma_0 \left( \frac{a(t)}{a(t_c)} \right)^{3/2} \cos[m_\sigma (t - t_c)]$$




- Examples:
  Intermediate "waterfall" — X. Chen, M. Hossein Namjoo, 1404.1536
  Sudden turn in field trajectory — A. Achucarroa et al, 1010.3693; X. Chen, 1104.1323



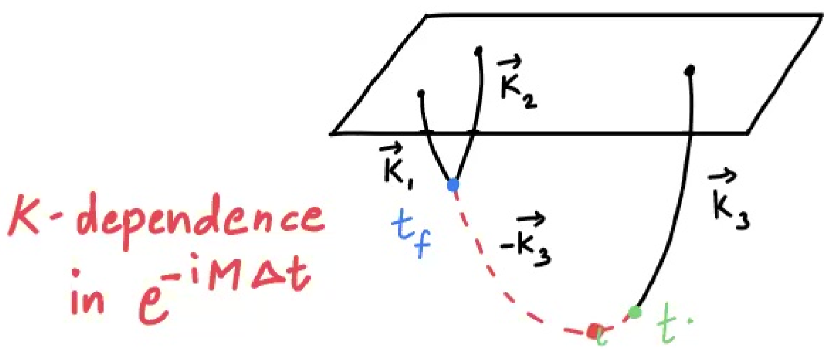

- Heavy field is classically excited, no Boltzmann-like suppression

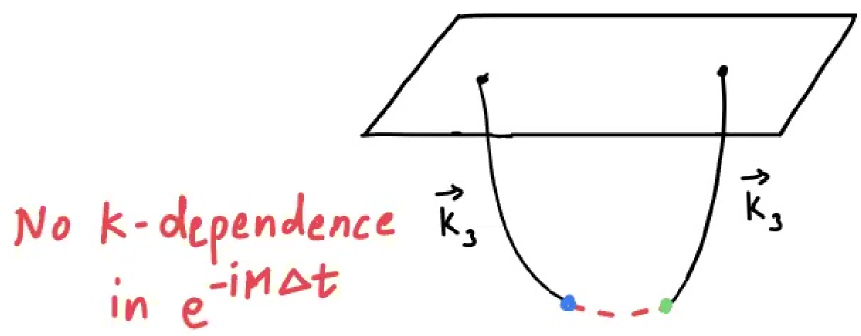
- Cosmological collider signature can appear at the level of power spectrum

- Production of heavy particles through quantum fluctuations cannot imprint non-analytic signature in 2-point correlations

- In 3-point functions,
  Time translation + Spatial scaling = Symmetry
  $\Delta t \sim \log\left(\frac{k_H}{k_S}\right)$

- In 2-point function,
  momentum conservation $\Longrightarrow$ no non-trivial ratio of momenta
  $\Delta t \sim \frac{1}{M}$



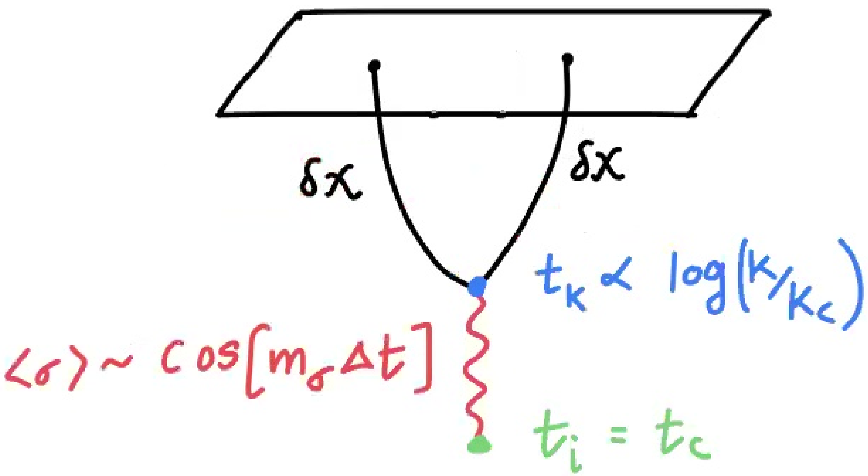



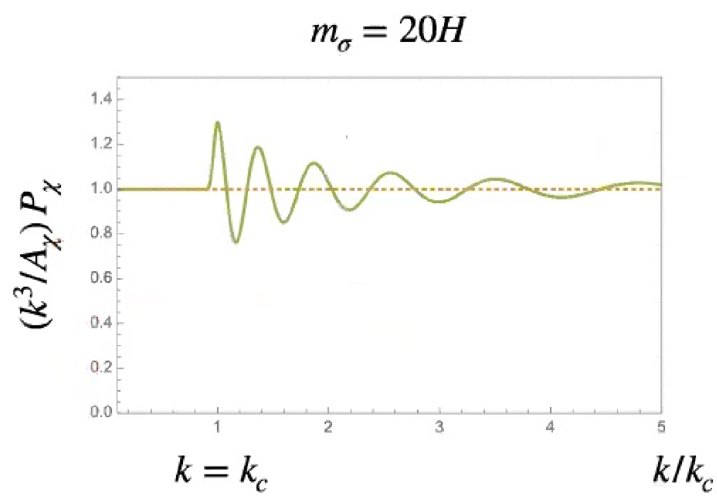
- $\langle \sigma(t) \rangle$ decays to fluctuations of (nearly) massless field $\chi$ through $\mathscr{L}_{int} \sim \sigma(\partial_\mu \chi \partial^\mu \chi)$

- Condition for decay: frequency matching $m_\sigma = 2k_{phy} = \frac{k}{a(t_k)}$

$$t_k = H^{-1} \log\left(\frac{k}{m_\sigma}\right) \rightarrow \Delta t = H^{-1} \log\left(\frac{k}{k_c}\right)$$

where $k_c$ = first mode produced at $t_c$




$$\Delta\langle \delta\chi(\vec{k})\delta\chi(-\vec{k})\rangle = \alpha \left(\frac{k}{k_c}\right)^{-3/2} \cos[m_\sigma \log(k/k_c)]$$

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  momentum conservation $\Longrightarrow$ no non-trivial ratio of momenta
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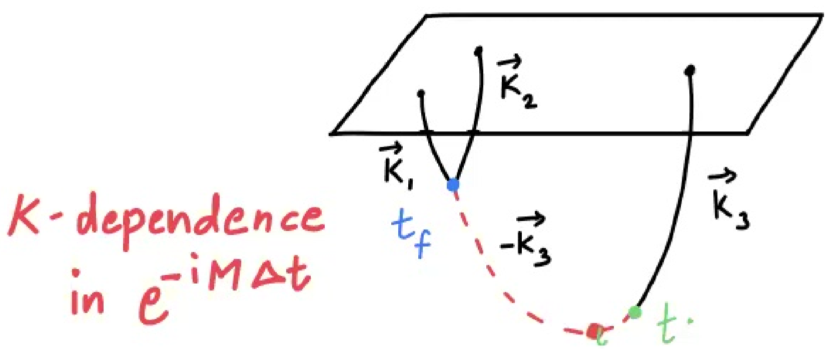
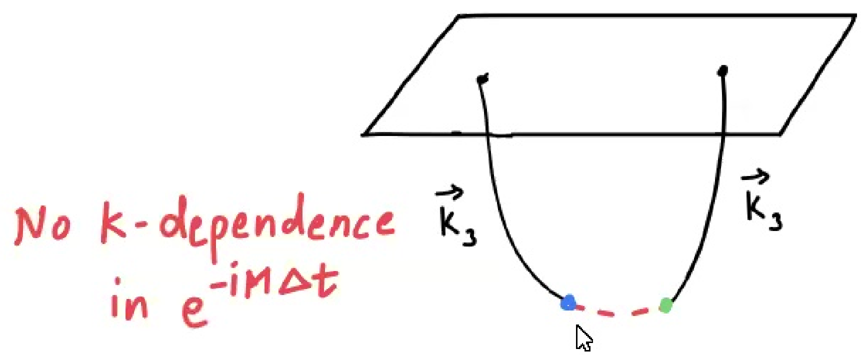
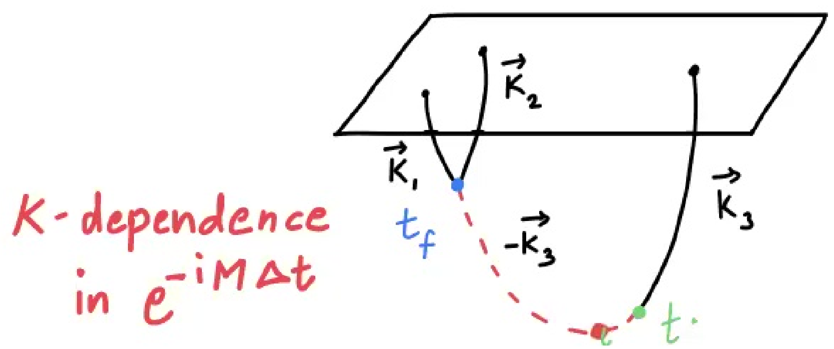


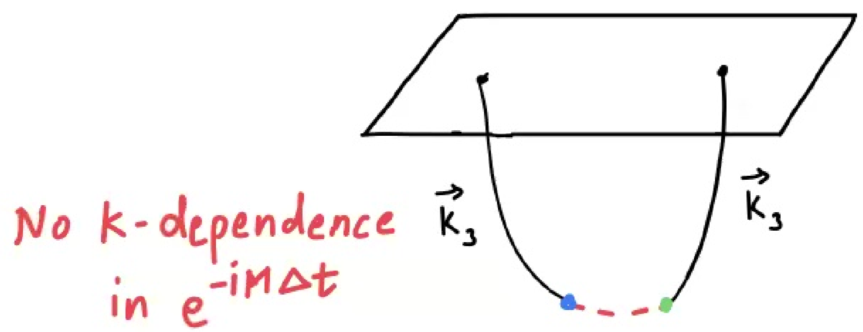



- Production of heavy particles through quantum fluctuations cannot imprint non-analytic signature in 2-point correlations

- In 3-point functions,
  Time translation + Spatial scaling = Symmetry
  $\Delta t \sim \log\left(\frac{k_H}{k_S}\right)$

- In 2-point function,
  momentum conservation $\Longrightarrow$ no non-trivial ratio of momenta
  $\Delta t \sim \frac{1}{M}$




- Breaking of time translation invariance by the background

  Onset of classical oscillations of heavy field at $t_c$ : $\langle \sigma(t) \rangle \sim \sigma_0 \left(\frac{a(t)}{a(t_c)}\right)^{3/2} \cos[m_\sigma(t - t_c)]\,\theta(t - t_c)$

- $\chi$ can be the inflaton, but such scale-invariance-violating features are highly constrained to be < few % of the power spectrum

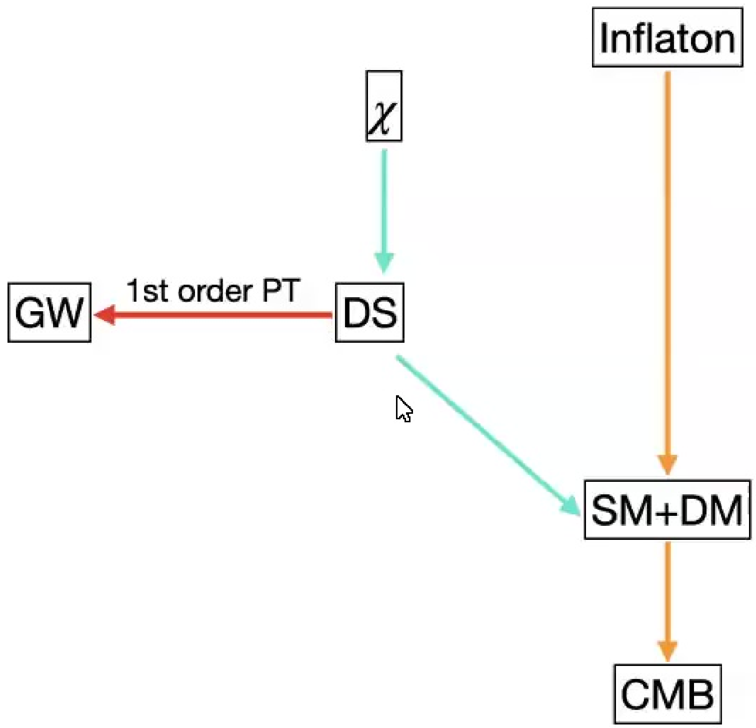
Planck, 1807.06211
X. Chen, M. Hossein Namjoo, Y. Wang, 1411.2349

- Large features possible in a spectator light field $\chi$ during inflation

- If $\chi$ decays to SM, it must have very small anisotropy to avoid isocurvature constraints → feature is diluted

- $\chi$ must reheat some dark sector (DS)

- Need a messenger: another CMB-like map recording primordial $\chi$ anisotropies → Gravitational wave (GW) background




M. Geller, A. Hook, R. Sundrum, Y. Tsai, 1803.10780

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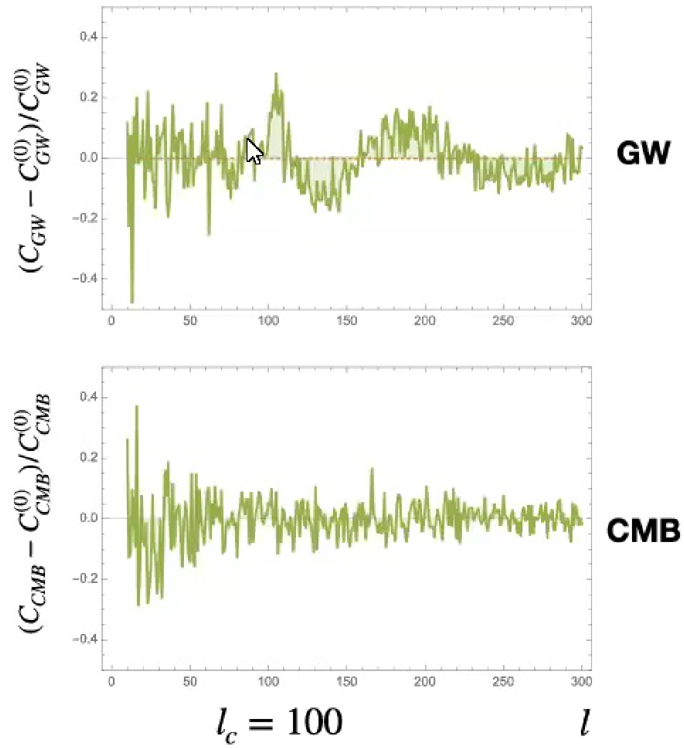
# Benchmark

$$\langle \delta_{GW}(\vec{k})\delta_{GW}(-\vec{k})\rangle = \frac{A_{GW}}{k^3}\left(1+\theta(k-k_c)\alpha\left(\frac{k}{k_c}\right)^{-3/2}\cos[m_\sigma \log(k/k_c)]\right) \xrightarrow[l\sim k\, d_{PT}]{\text{flat sky}} C_{GW}(l) \sim \frac{A_{GW}}{l(l+1)}\left(1+\theta(l-l_c)\frac{\alpha}{\sqrt{m_\sigma}}\left(\frac{l}{l_c}\right)^{-3/2}\cos[m_\sigma \log(l/l_c)]\right)$$

- Ultimate sensitivity limit is cosmic variance $\Delta C_l = \frac{C_l}{\sqrt{2l+1}}$
- Benchmark:

$$\alpha = 0.3,\ m_\sigma = 10H,\ \left(\frac{\rho_{DS}}{\rho_{SS}}\right)^2 = 0.1,\ \frac{A_{GW}}{A_{CMB}} = 0.01$$

- Amplitude of $\frac{\Delta P_{\mathscr{R}}}{P_{\mathscr{R}}} \simeq 3\times 10^{-4}$, below cosmic variance in CMB (and in LSS or 21-cm)



# Sensitivity of GW detectors

- $\Omega^{\rm peak}_{GW,0}h^2 = 1.3\times 10^{-6}\left(\frac{H_{\rm PT}}{\beta}\right)^2\left(\frac{\rho_{\rm PT}}{\rho_{\rm total}}\right)^2$

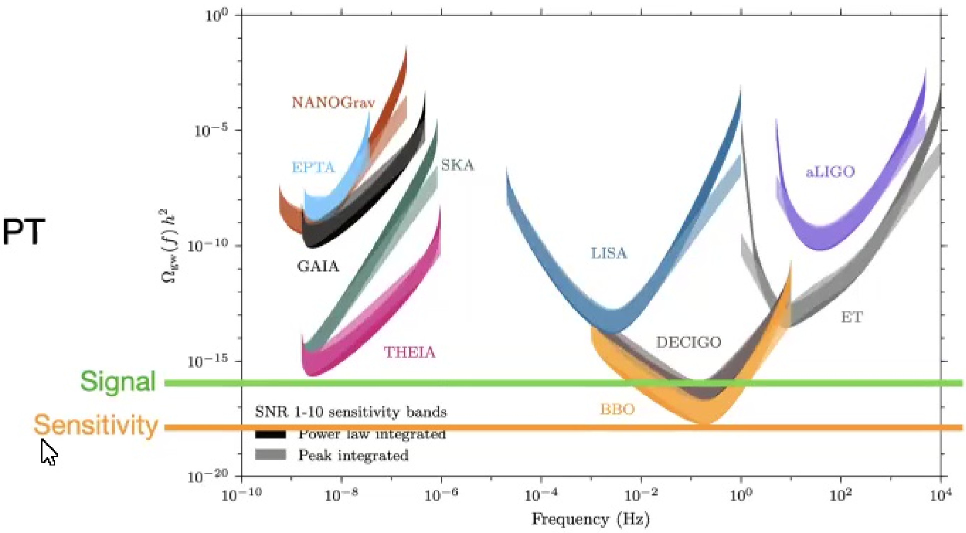
  $\beta$: bubble nucleation rate, $H_{\rm PT}$: Hubble constant at PT

- Anisotropy

  $$\delta\Omega_{GW,0}h^2(l) \sim \frac{\sqrt{A_{GW}}}{l}\,\Omega_{GW,0}h^2$$

- Need sensitivity to anisotropies till $l \sim O(100)$

- Benchmark: $(H_{\rm PT}/\beta)^2 = 10^{-1}, A_{\rm GW}/A_{\rm CMB} = 10^{-2}$




J. Garcia-Bellido, H. Murayama, G. White 2104.04778

$$\delta\Omega^{\rm signal}_{GW}h^2(l\sim 100) \approx 10^{-16}$$

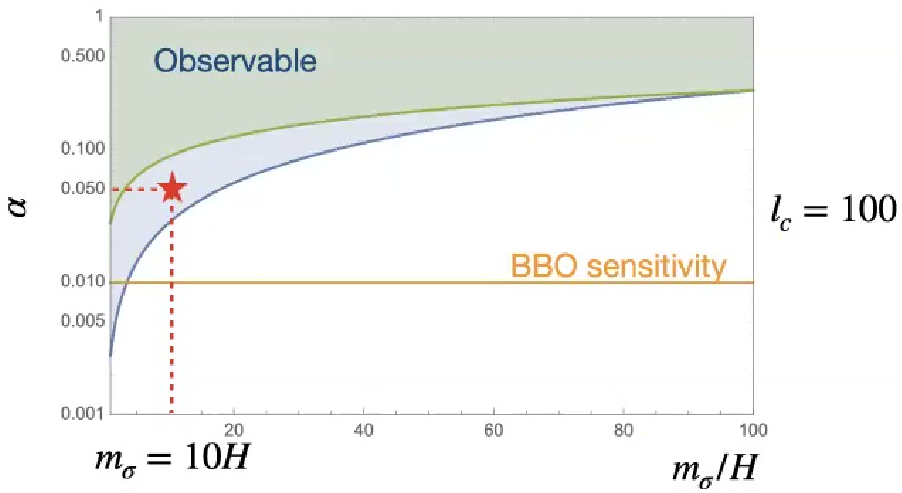
M. Geller, A. Hook, R. Sundrum, Y. Tsai, 1803.10780

# Observable parameter range

- Variance after binning
$$\Delta C_l = \frac{C_l}{\sqrt{(2l+1)\Delta l}}$$

- Maximum bin size $\Delta l < \frac{l_c}{m_\sigma}$

- Highly oscillatory signal cannot be resolved
$m_\sigma \lesssim l_c$



# Work in progress

- Generalizing chemical potential: spin-2 case
  EFT cutoff cannot be much larger than the mass of spin-2 field
  Two real spin-2 fields → KK-modes with similar masses, composites

- Possible to get larger GW signal or larger GW anisotropy such that features are visible over greater parameter range?

- Is there any interesting physics that can be seen in the cross-correlations of two independent maps (e.g. CMB and GW map)?

Thank you!