Gravitational wave and parity-odd signals of massive gauge boson at the Cosmological collider

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Selling points and motivations

- How to recognize the presence of heavy($m \sim O(H)$) particles during inflation?
- Conventional Approach: **Cosmological Colliders**

Three-point correlation scalar perturbation functions oscillate with the "squeezed shape". Frequency is related to the mass.[1]

- Current study: **Gravitational wave** interferometers as particle detectors
- Motivations: CMB constrains and more: $f_{NL} \sim O(1)$ SPHEREX in next year!

Parity-Violation signals [2] BOSS

[1] arXiv 0911.3380 X.Chen, Y.Wang. 1109.0292 D.Baumann, D.Green. 2004.02887 Y.Wang, Z.Xianyu. 1508.08043 N.Arkani-Hamed, J. Maldacena ··· ···

[2] arXiv 2206.03625 J. Hou, Z. Slepian, R.N. Cahn. 2206.04227 Oliver H.E. Philcox

Massive gauge boson production

- $\mathcal{L} = -\frac{\phi}{4\Lambda}\tilde{F}^{\mu\nu}F_{\mu\nu} + \frac{1}{2}m_A^2 A^\mu A_\mu - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \partial_\mu\phi\partial^\mu\phi$
- Chemical potential ξ overcome the Boltzmann suppression: $e^{-\pi\frac{m}{H}} \to e^{\pi(\xi-\frac{m}{H})}$

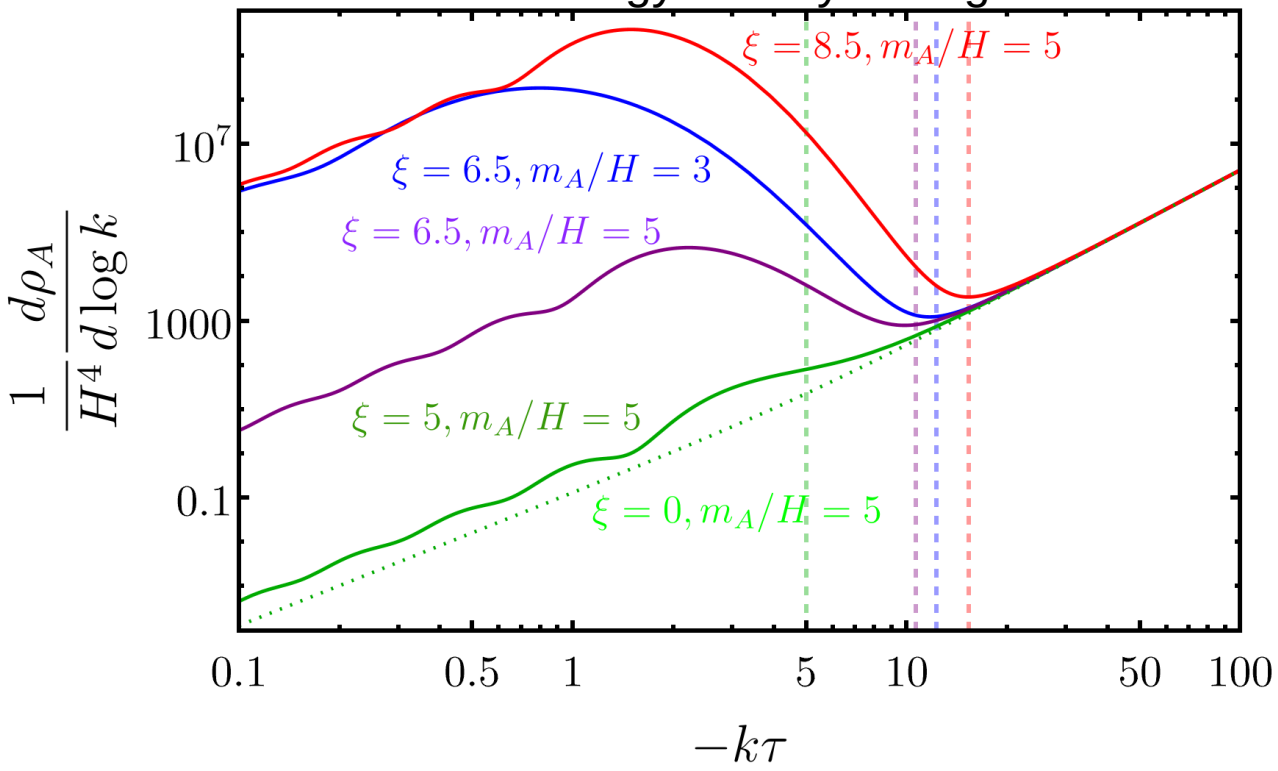
$$\xi \equiv \frac{\dot{\phi}}{2\Lambda H}$$

$$\rho_A = \frac{1}{2}\left\langle \boldsymbol{E}^2 + \boldsymbol{B}^2 + \frac{m_A^2}{a^2}\boldsymbol{A}^2 \right\rangle$$

- The vertical dashed line shows the **beginning** of boson production:

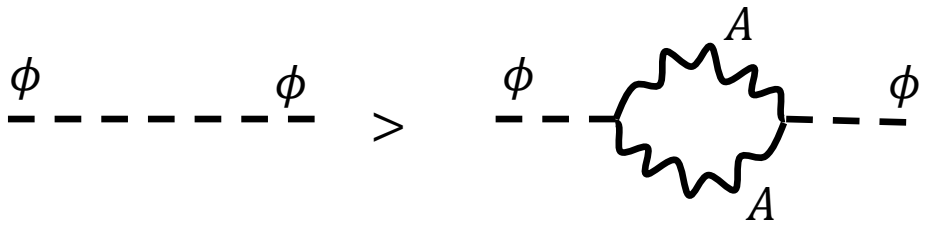
$$-k\tau = \xi + \sqrt{\xi^2 - \frac{m_A^2}{H^2}}$$

Evolution of energy density for a given mode

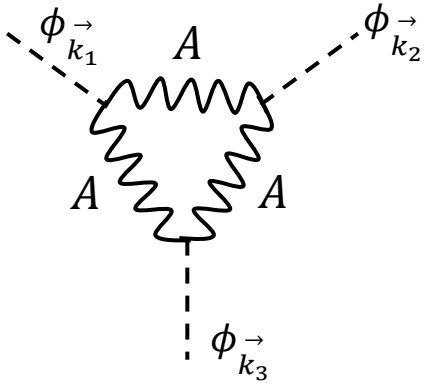


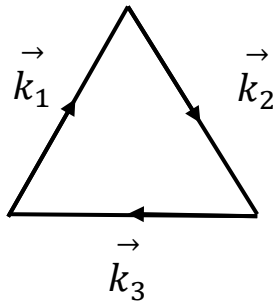
Phenomenological Constrains at CMB

- Backreaction shouldn't affect standard inflation
- Tensor-to-scalar ratio $r < 0.056$[1]
- Power spectrum domain at Tree level $P_\zeta^\phi > P_\zeta^A$

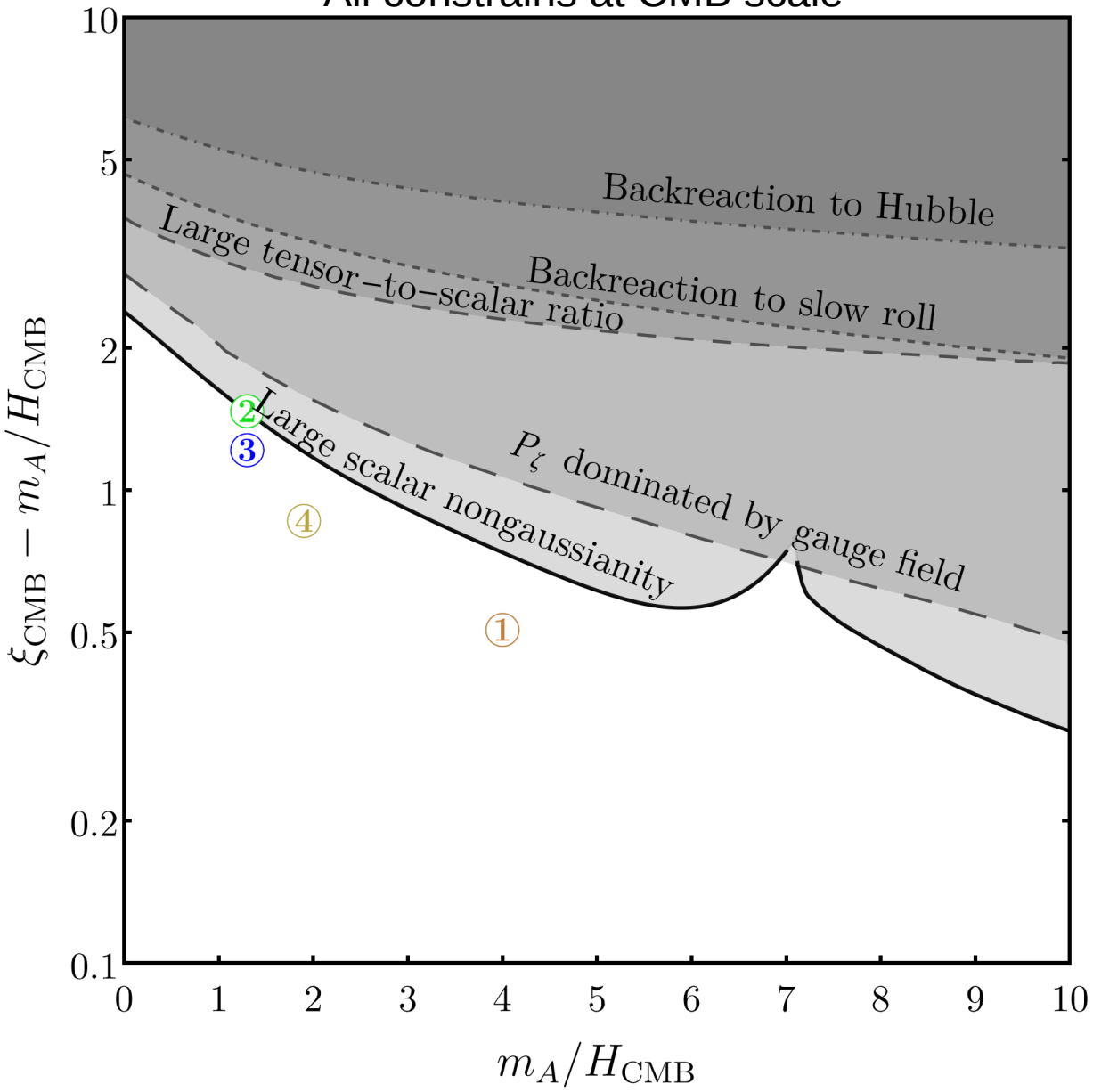


- Non-Gaussianity $f_{NL}^{equil} < -27 \pm 47$[1]





All constrains at CMB scale



[1] Planck 2018 arXiv 1905.05697 and 1807.06211

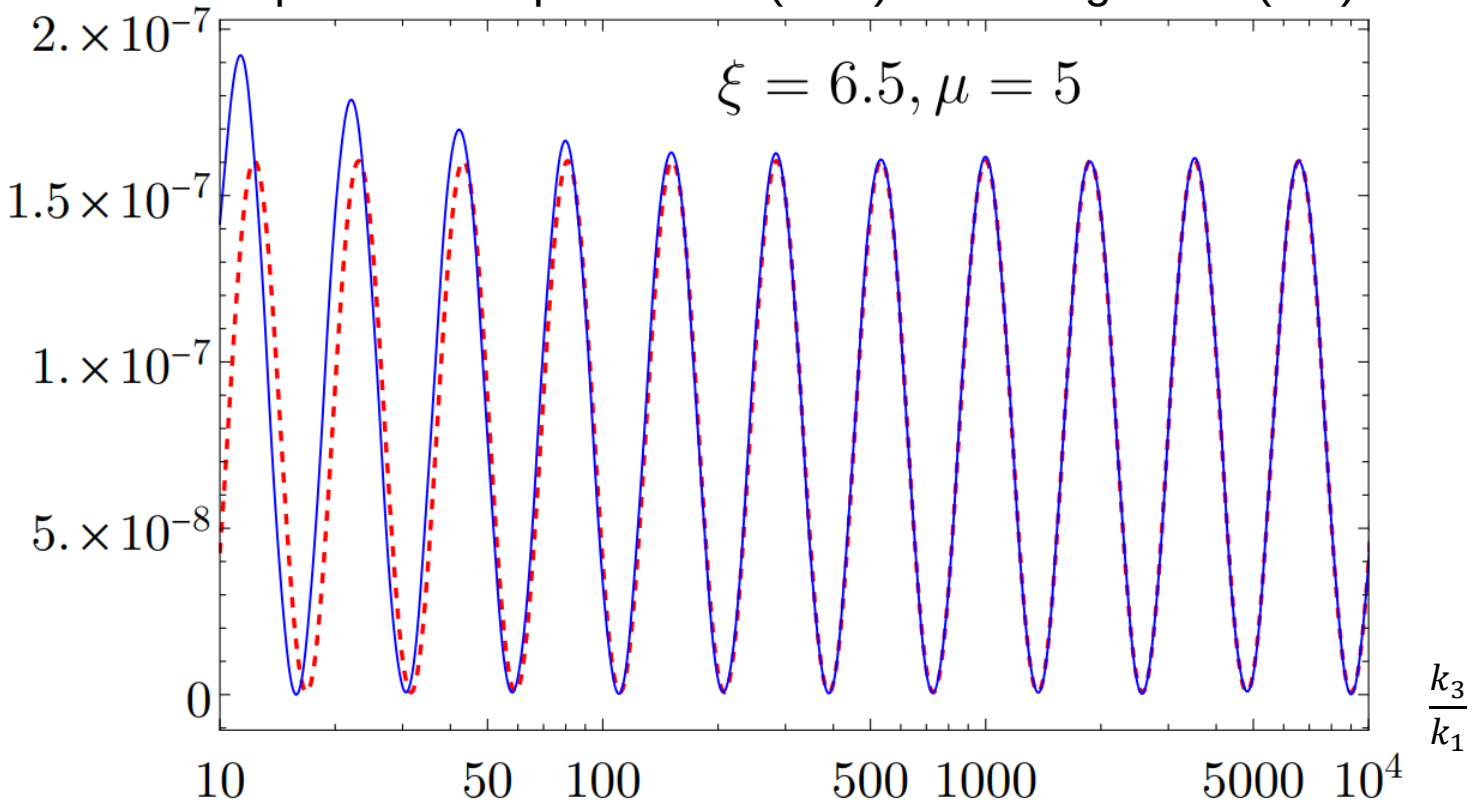
Signals from three-point correlation functions

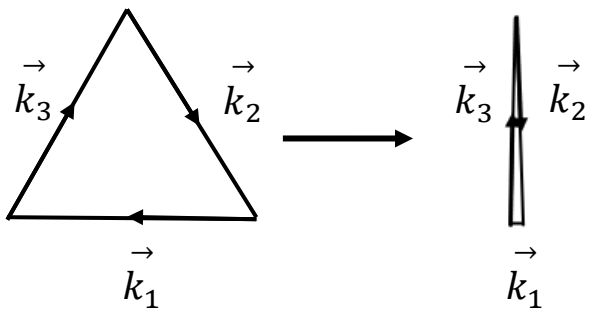
- **Oscillation patten** in squeezed three-point

$$\left\langle \zeta_{\vec{k}_1} \zeta_{\vec{k}_2} \zeta_{\vec{k}_3} \right\rangle \propto S\left(\frac{k_3}{k_1}, \frac{k_2}{k_1}\right) \xrightarrow{squeezed} a + b\cos\left(2\mu \log\left(\frac{k3}{k1}\right) + \theta\right)$$

$$\mu \equiv \sqrt{\frac{m_A^2}{H^2} - \frac{1}{4}}$$

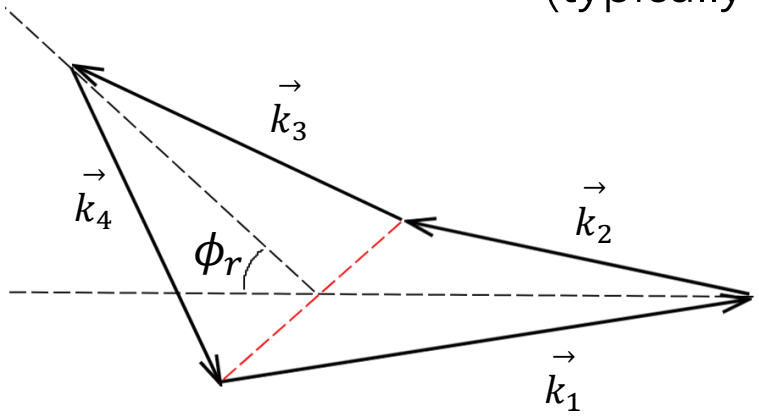
Squeezed shape function(blue) and fitting curve (red)





Signals from four-point correlation functions

- **Parity-violation** happens when P-transformation can't be achieved by rotation.
  (typically four external momenta are NOT in a plane)



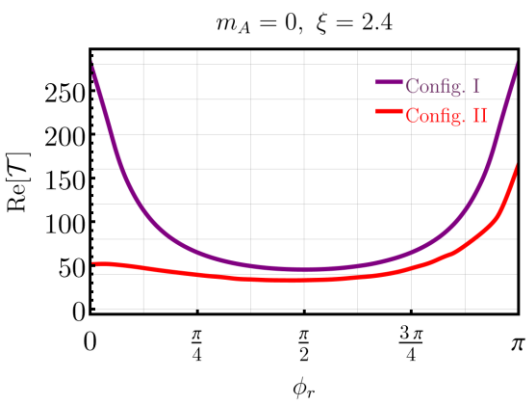
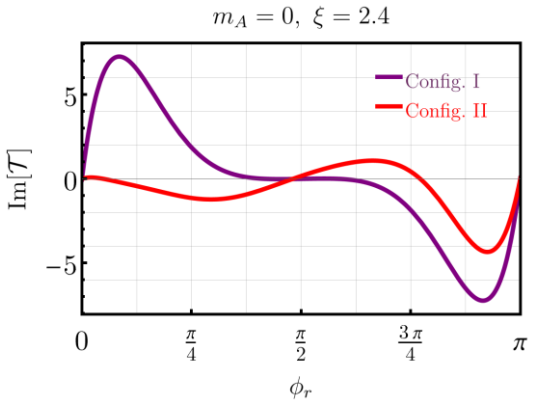
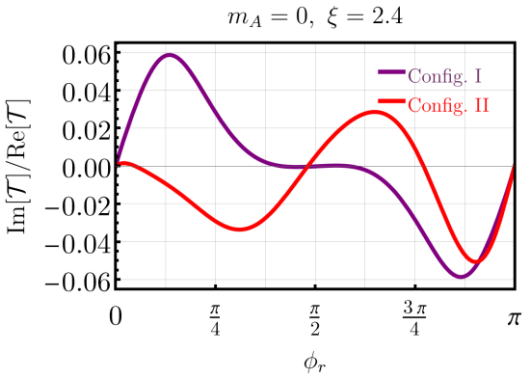
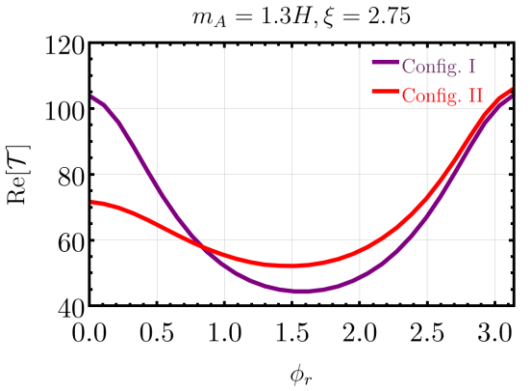
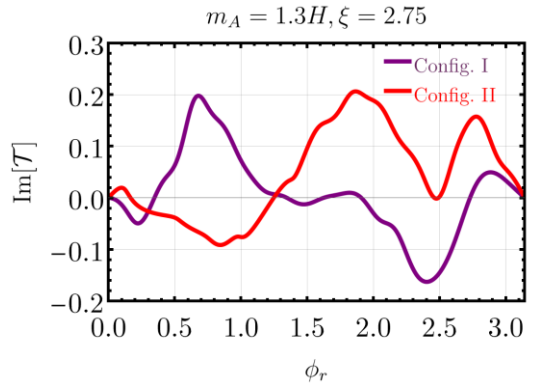
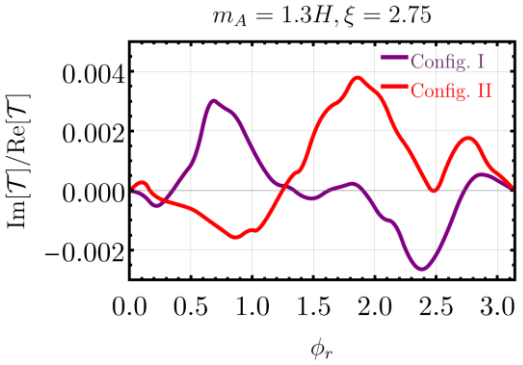
Two-point and three-point are P-even.
Four-point is the simplest configuration for P-odd

- $\left\langle \zeta_{\vec{k}_1} \zeta_{\vec{k}_2} \zeta_{\vec{k}_3} \zeta_{\vec{k}_4} \right\rangle \propto T_{(k1,k2,k3,k4)} \rightarrow \overset{P-even}{Re[T]} + \overset{P-odd}{Im[T]}$

- **Observations:** P-even[1] $\tau_{NL} < \ (-5.8 \pm 6.5) \times 10^4$
  P-odd in BOSS galaxy with around 7σ[2] and 3σ[3]

[1] Planck 2018 arXiv 1905.05697
[2] arXiv 2206.03625
[3] arXiv 2206.04227

Signals from four-point correlation functions

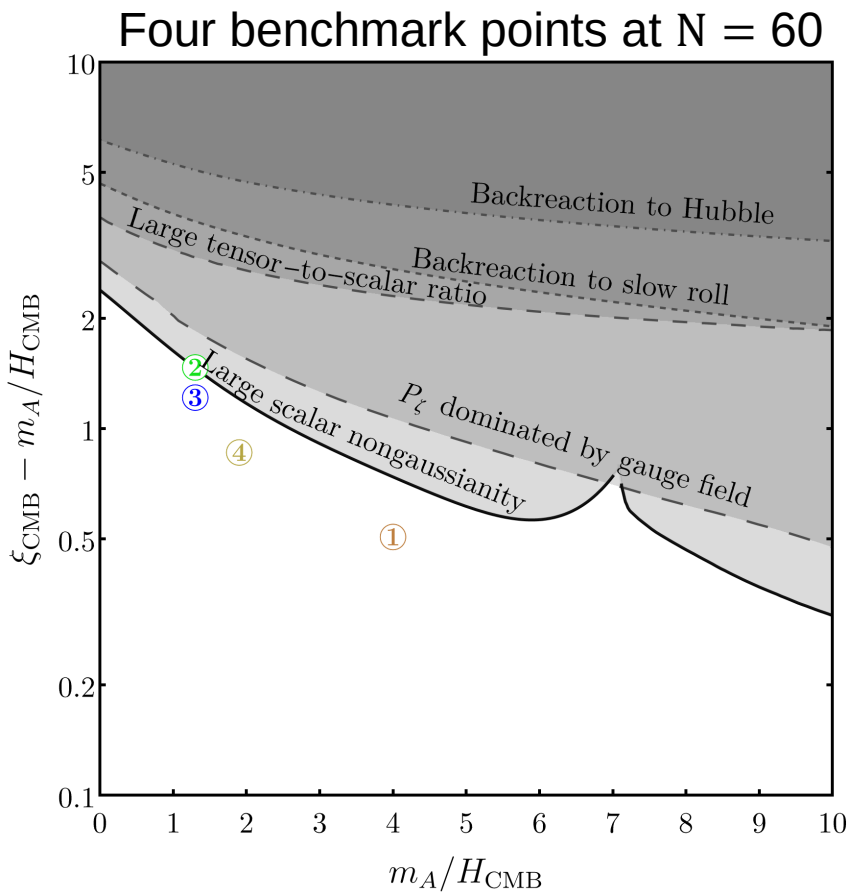
$P-even$	$P-odd$	$odd/_{even}$
		
		

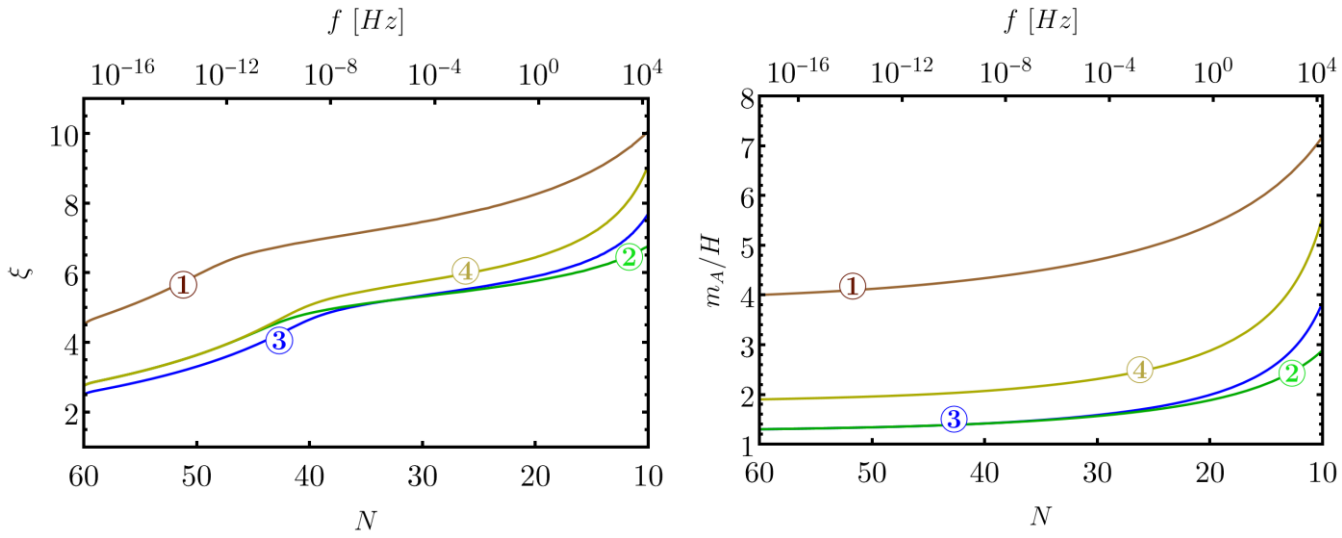
$\mathcal{O}(1\%)\sim\mathcal{O}(10\%)$

$\mathcal{O}(0.1\%)\sim\mathcal{O}(1\%)$

Signals from gravitational waves

- Chemical potential ξ and mass $\frac{m_A}{H}$ **evolve** due to slow roll and **backreaction.**





N=60-50 slow roll and ξ increases faster than $\frac{m_A}{H}$

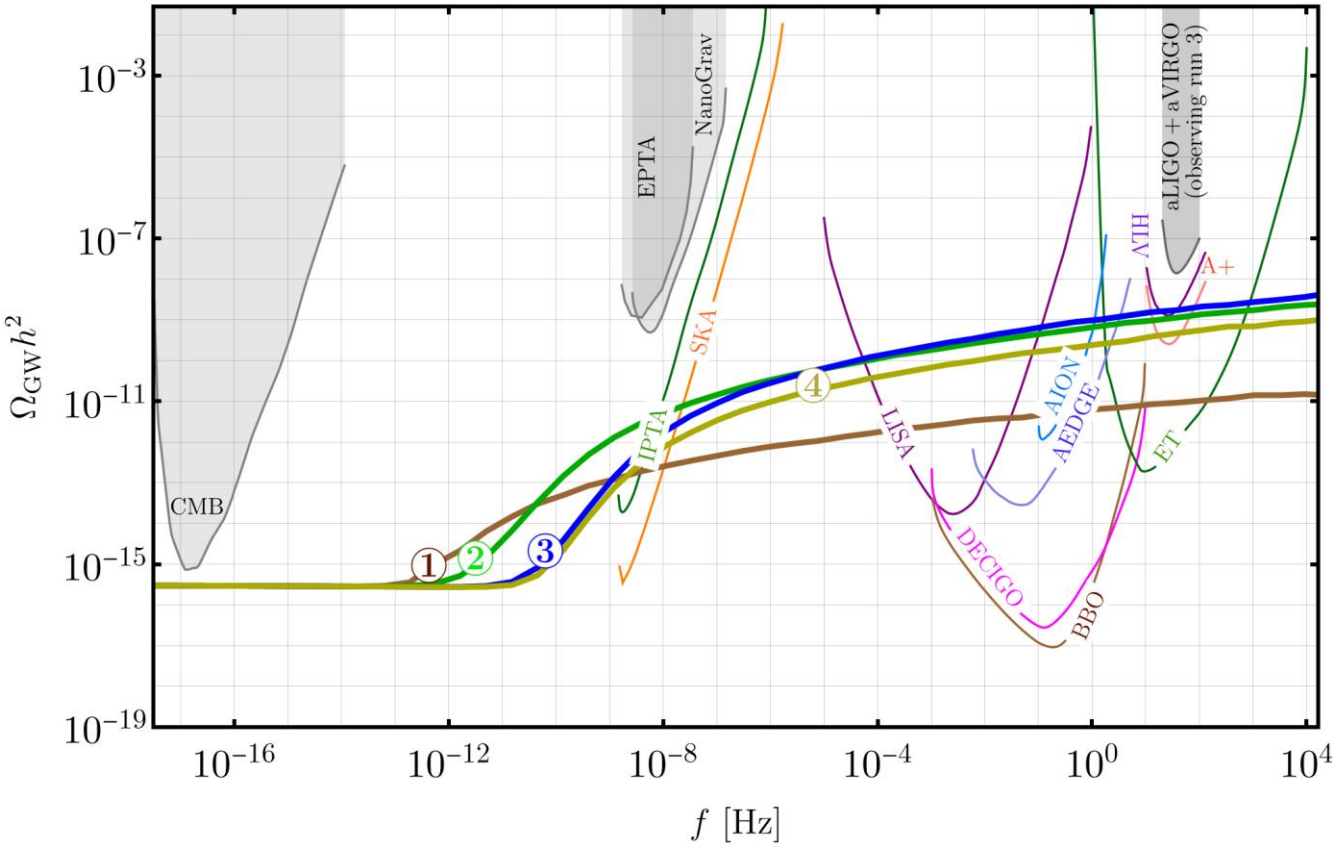
N=40~30 backreaction flatten ξ

N=10 slow roll break down

*Starobinsky potential is chosen.

Signals from gravitational waves

- Large chemical potential ξ dramatically enhances the GW.
- GW elude CMB scale, but can be detected at (future) interferometer scale.

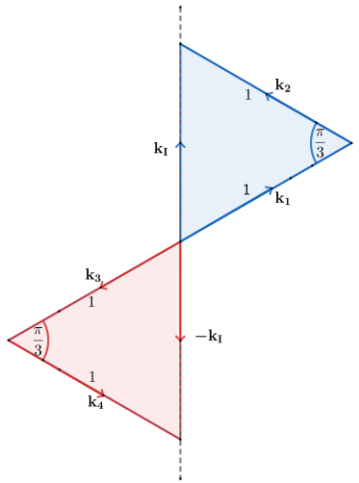


	ξ_{CMB}	$\frac{m_A}{H_{CMB}}$
①	4.7	4
②	2.75	1.3
③	2.4	1.3
④	2.75	2.1

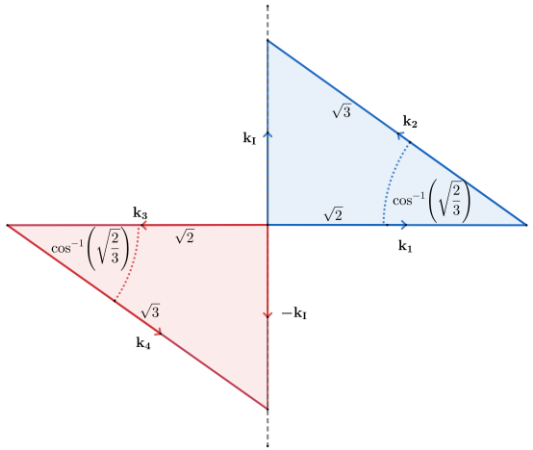
Conclusions

- Massive gauge boson can be **sufficiently produced** by Chern-Simons $\phi \tilde{F}^{\mu\nu} F_{\mu\nu}$
- We constrain Chemical potential and mass from CMB measured by Planck 2018
- We show **oscillation pattern** in Bispectrum and **P-violation** in Trispectrum
- We study the backreaction and evolution of chemical potential and mass. We show the **gravitational wave**(smaller than CMB scale) can be detected by the whole range of interferometers.

Signals from four-point correlation functions(Back-up)



Config. I



Config. II

Blue and red triangles rotate about the dashed line.

Why P-odd is Im[T](Back-up)

$$\zeta(t,\boldsymbol{x}) = \int \frac{d^3k}{(2\pi)^3}\zeta(t,\boldsymbol{k})e^{i\,\boldsymbol{k}\cdot\boldsymbol{x}}$$

$$= \int \frac{d^3k}{(2\pi)^3}\zeta^*(t,\boldsymbol{k})e^{-i\,\boldsymbol{k}\cdot\boldsymbol{x}}$$

$$\zeta(t,-\boldsymbol{x}) = \int \frac{d^3k}{(2\pi)^3}\zeta(t,\boldsymbol{k})e^{-i\,\boldsymbol{k}\cdot\boldsymbol{x}}$$

$\zeta^*(t,\boldsymbol{k})$ and $\zeta(t,\boldsymbol{k})$ share the same real part, but different Imaginary part.

Zigzag in massive P-odd(Back-up)

Add a **global** phase to make mode function to be mostly real

$$A_+(\tau,k) = \frac{1}{\sqrt{2k}} e^{+\frac{\pi\xi}{2}} W_{-i\xi,i\mu}(2ik\tau)$$

$$A_+(\tau,k) \to W^*_{-i\xi,i\mu}\,(2ik_*\tau_*)\; A_+(\tau,k)$$

Thus we simplify in-in formalism to fasten numerical calculation