Probing Gauge Boson Signals from Inflation

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NPKI workshop

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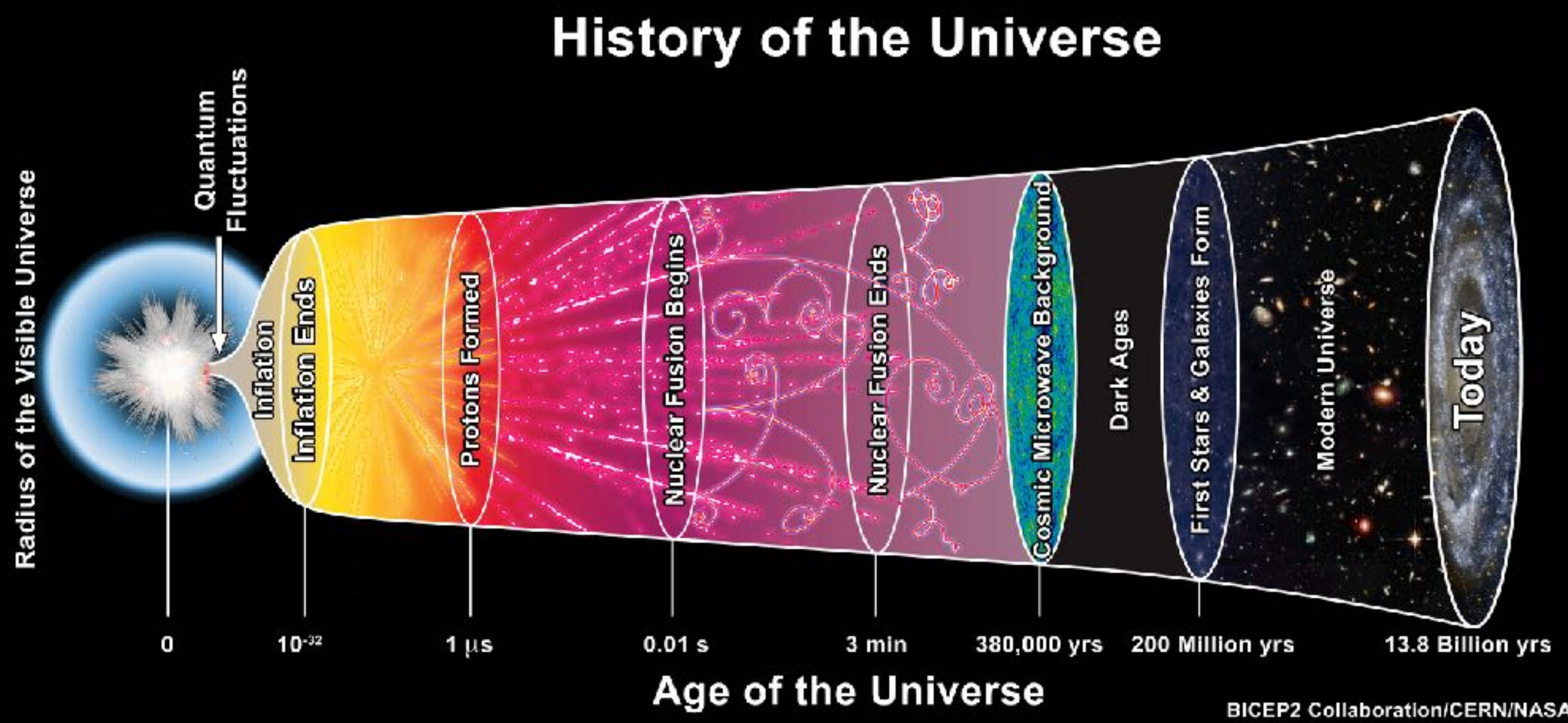
Outline

- Introduction
- Parity violation (4-point function) arXiv: 2211.14324

  with X. Niu, M. Rahat and K. Srinivasan
- Cosmological collider signals (3-point function)
- Gravitational waves signals (2-point function) arXiv: 2211.14331

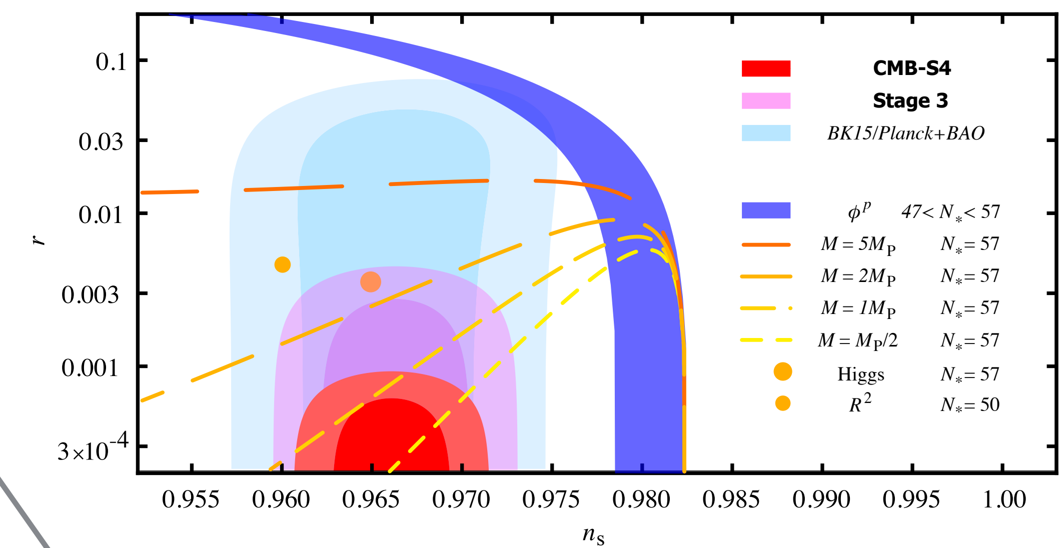
  with X. Niu, M. Rahat and K. Srinivasan
- Conclusion

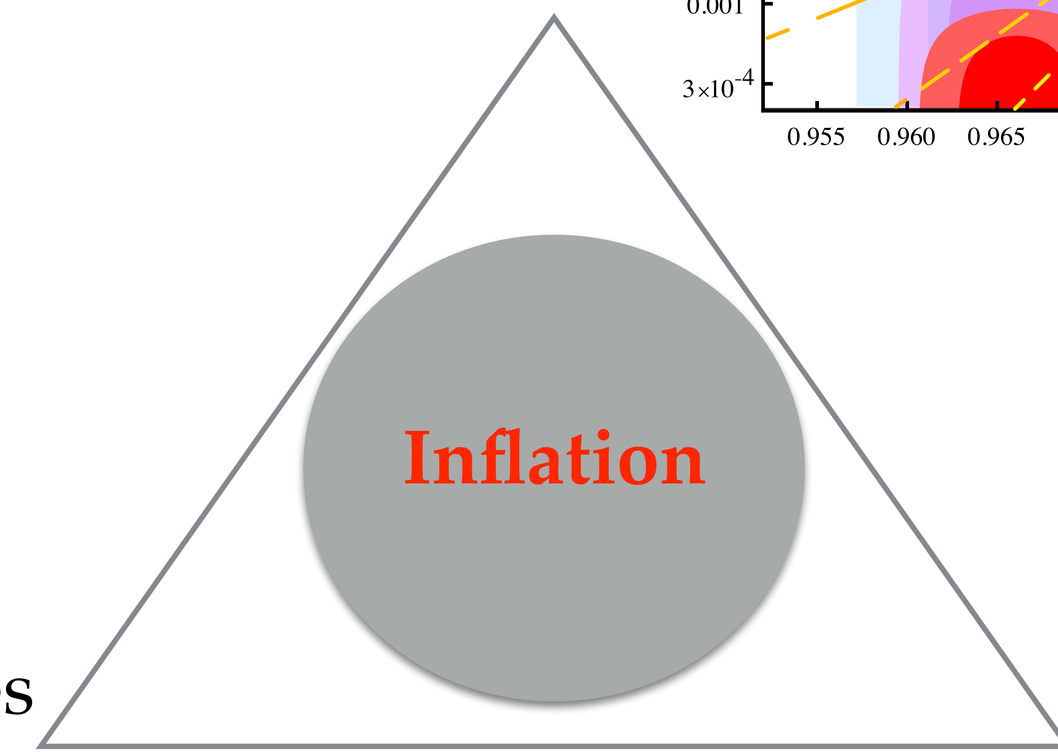


What is the standard inflationary model?
How do inflatons interact with the other particles?

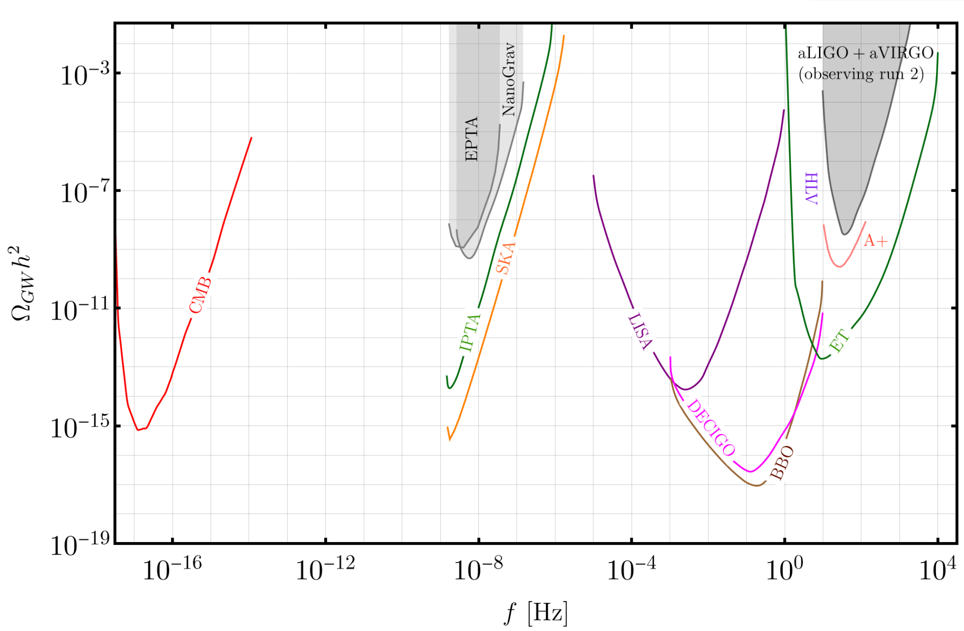
Future explorations

CMB

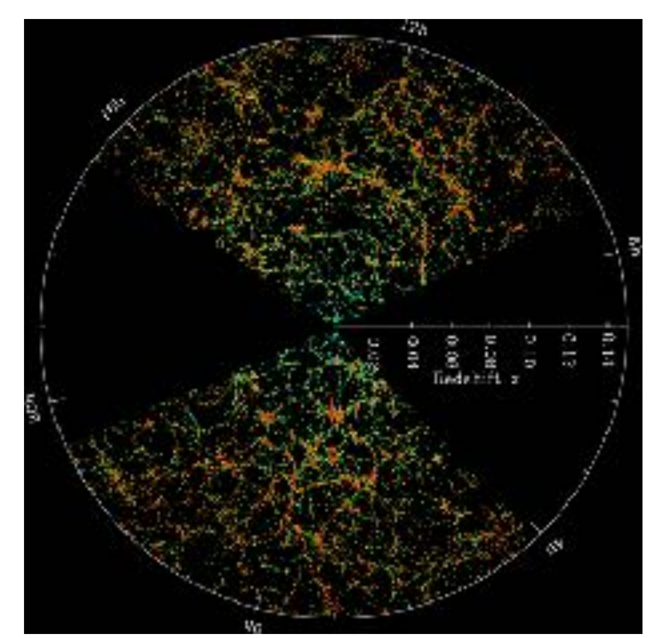




Gravitational waves



LSS



Axion as inflaton

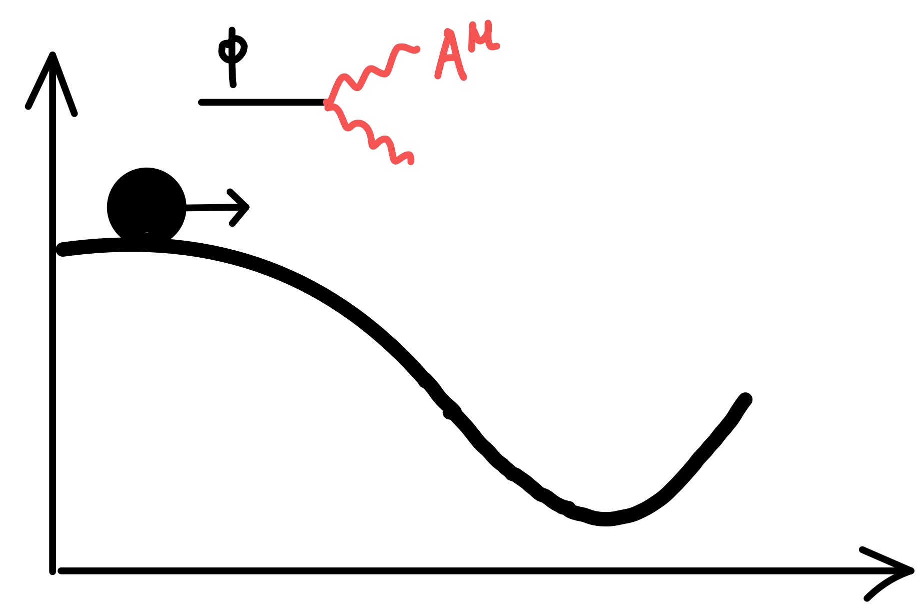
- axion-like particle as inflaton
  approximate shift-symmetry
  couples to gauge boson via anomaly term

$$S = \int d^4x\sqrt{-g}\left(\frac{1}{2}m_A^2 A^\mu A_\mu - \frac{1}{4\Lambda}\phi \tilde{F}^{\mu\nu}F_{\mu\nu}\right)$$

- A^μ gauge boson associated with a hidden $U(1)$
  or the Standard Model photon

- gauge boson mass 1) $m \ll$ Hubble scale H
  2) $m \sim H$

- during inflation $\phi \to \gamma\gamma$



Particle production during inflation

- one transverse mode is dominantly produced

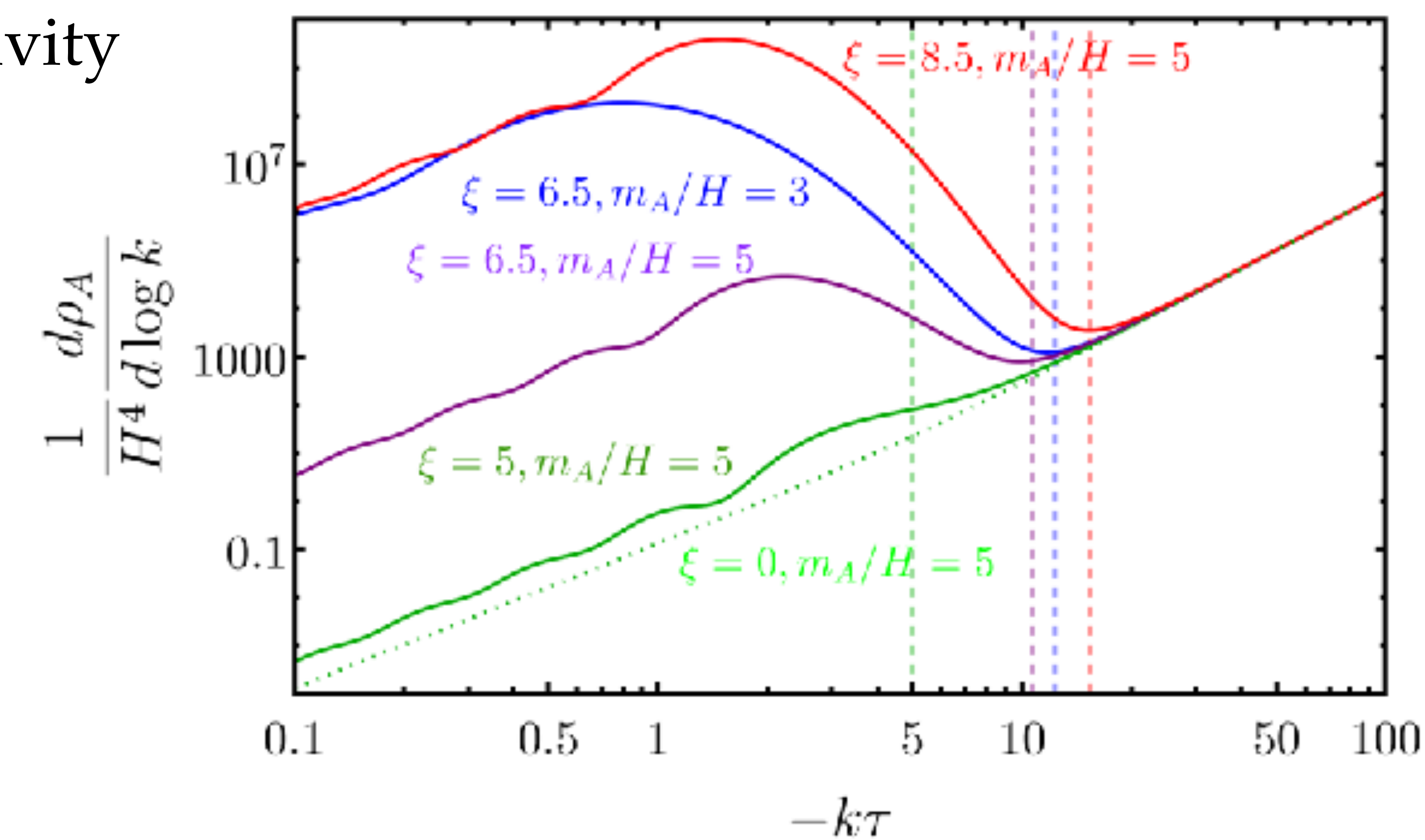
$$\partial_\tau^2 A_\pm(\tau,k) + \left(k^2 + a(\tau)^2 m_A^2 \pm \frac{2k\xi}{\tau}\right) A_\pm(\tau,k) = 0, \qquad \xi \equiv \frac{\dot\phi_0}{2\Lambda H}$$

- particle production via gravity during inflation

$$A \propto \exp(-\pi \frac{m_A}{H})$$

particle production via the Chern-Simons terms

$$A \propto \exp(+\pi\xi)$$



Corrections to inflationary perturbations

- inflation curvature perturbation $\zeta \sim \frac{H}{\dot{\phi}} \frac{H}{(2\pi)}$

  Power spectrum $\mathscr{P} \sim \frac{H^2}{\dot{\phi}^2} \frac{H^2}{(2\pi)^2}$

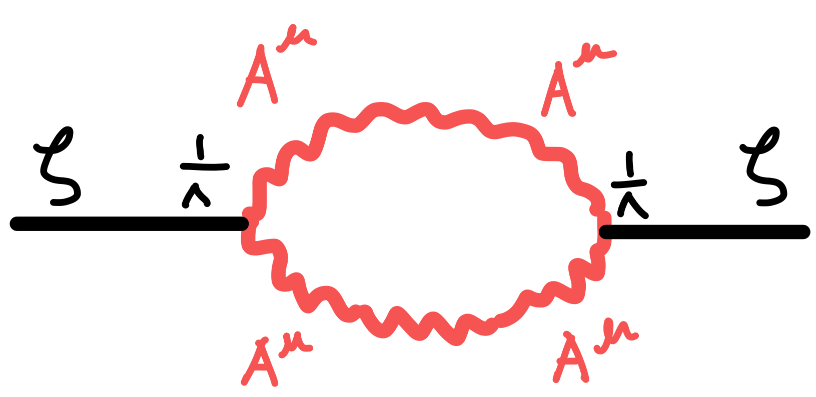
- corrections to n-point correlation functions

  $\langle \zeta \cdots \zeta \rangle \sim$ propagtors $\times$ vertices

  $$\text{vertices} \sim \frac{1}{\Lambda} = \frac{2H\xi}{\dot{\phi}}, \quad \text{propagator} \sim \langle AA \rangle \sim e^{2\pi\xi'}, \quad \xi' \equiv \xi - \frac{m}{H}$$

- gauge boson loop correction

$$\mathscr{P} \sim \frac{1}{\dot{\phi}^2} \frac{1}{\Lambda^2} e^{4\pi\xi'} \sim \mathscr{P} \left(\mathscr{P} e^{4\pi\xi'} \right)$$

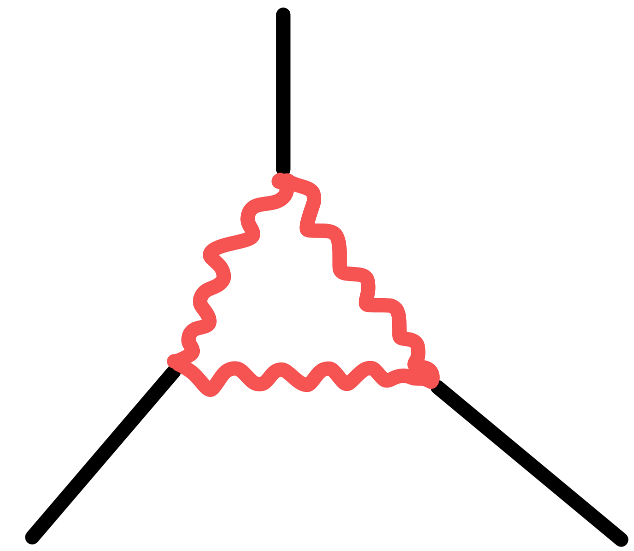


Distinct signals

- three-point function (cosmological collider)

$$\langle \zeta\zeta\zeta \rangle \sim \frac{1}{\dot{\phi}^3}\frac{1}{\Lambda^3} e^{3\times 2\pi\xi'} \sim \mathscr{P}^2 \left(\mathscr{P} e^{6\pi\xi'} \right)$$

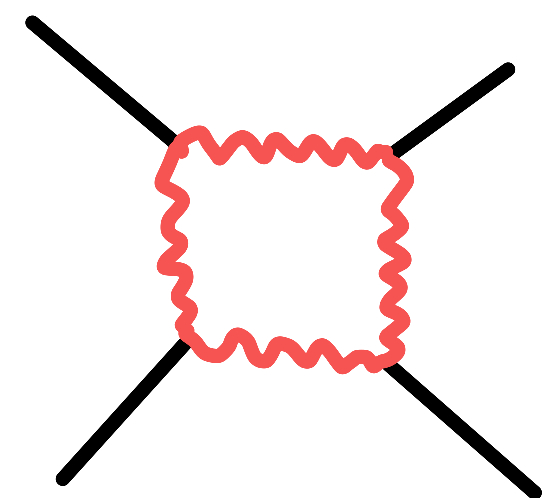
$$f_{NL} \sim \mathscr{P} e^{6\pi\xi'}$$



- four-point function (large-scale structure)

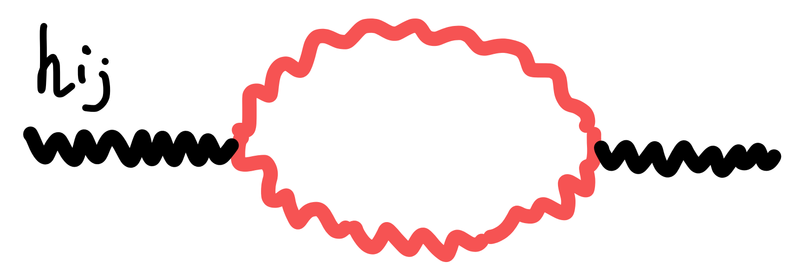
$$\langle \zeta\zeta\zeta\zeta \rangle \sim \frac{1}{\dot{\phi}^4}\frac{1}{\Lambda^4} e^{4\times 2\pi\xi'} \sim \mathscr{P}^3 \left(\mathscr{P} e^{8\pi\xi'} \right)$$

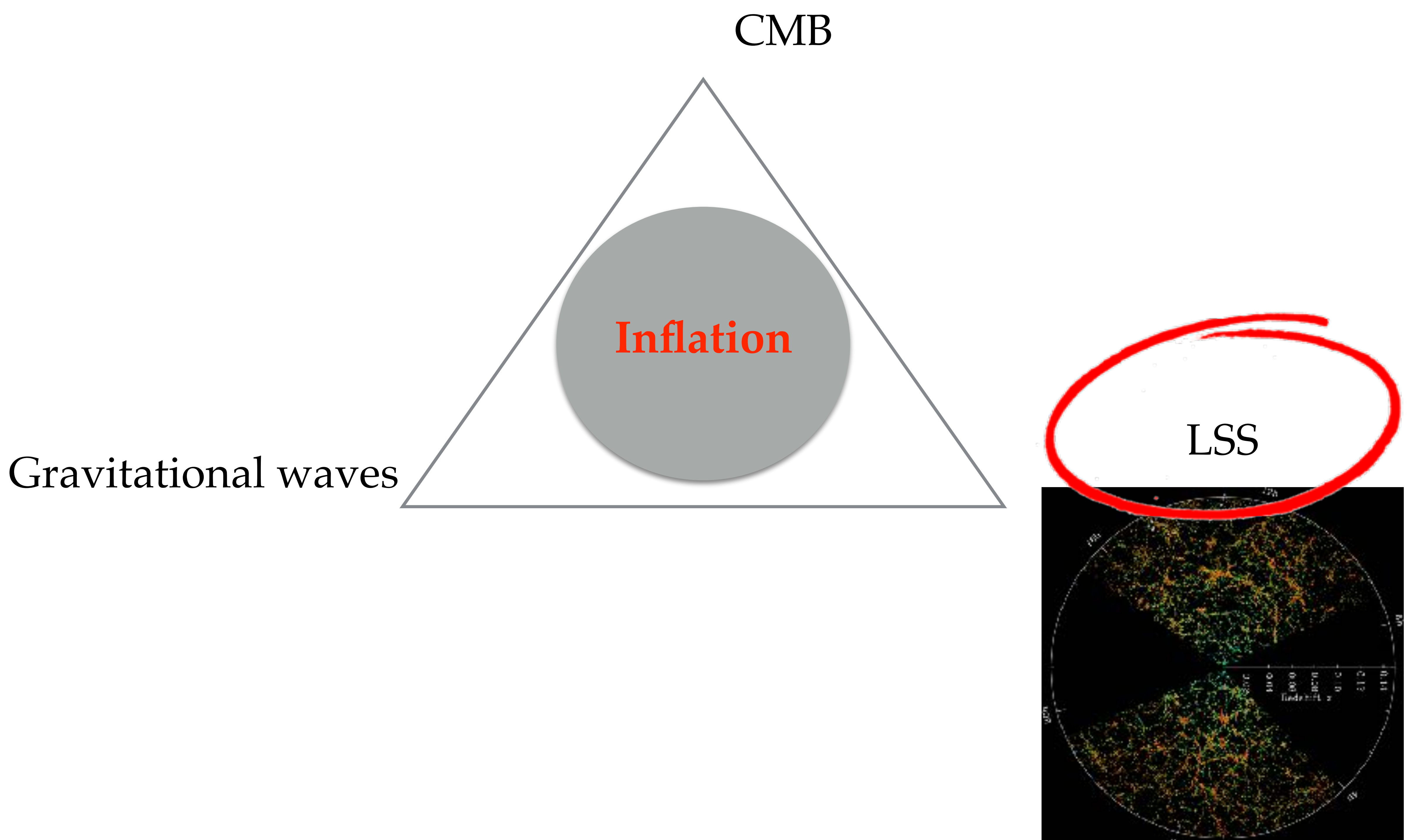
$$\tau_{NL} \sim \mathscr{P} e^{8\pi\xi'}$$



- gravitational waves

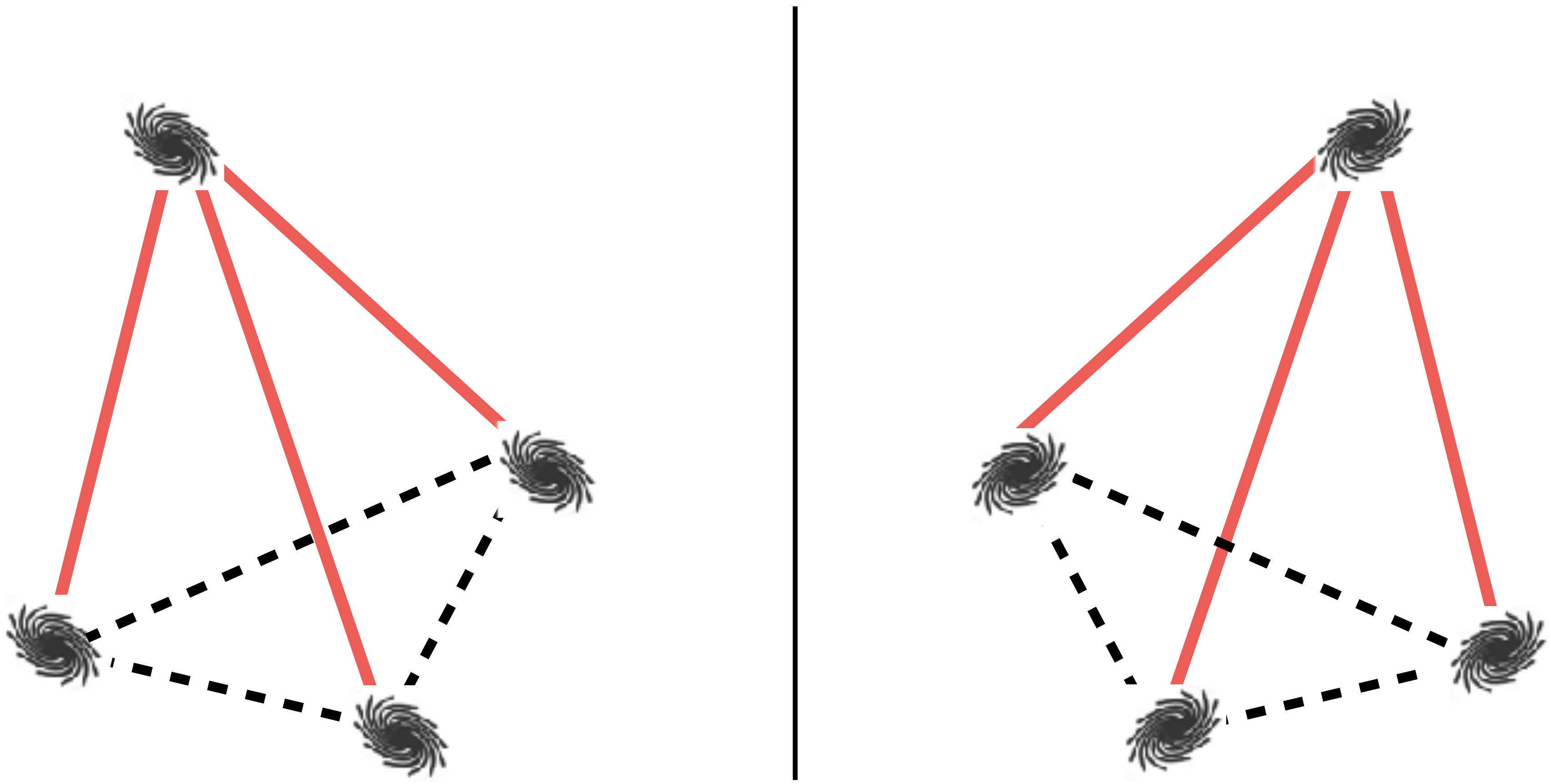
$$\langle h^+ h^+ \rangle \sim \frac{H^4}{M_{\rm pl}^4} e^{2\times 2\pi\xi'} \sim \mathscr{P}_h \left(\mathscr{P}_h e^{4\pi\xi'} \right)$$




CMB
Inflation
Gravitational waves
LSS

Parity violation in galaxy survey

- four point correlation functions of galaxy overdensity
  parity vs rotation



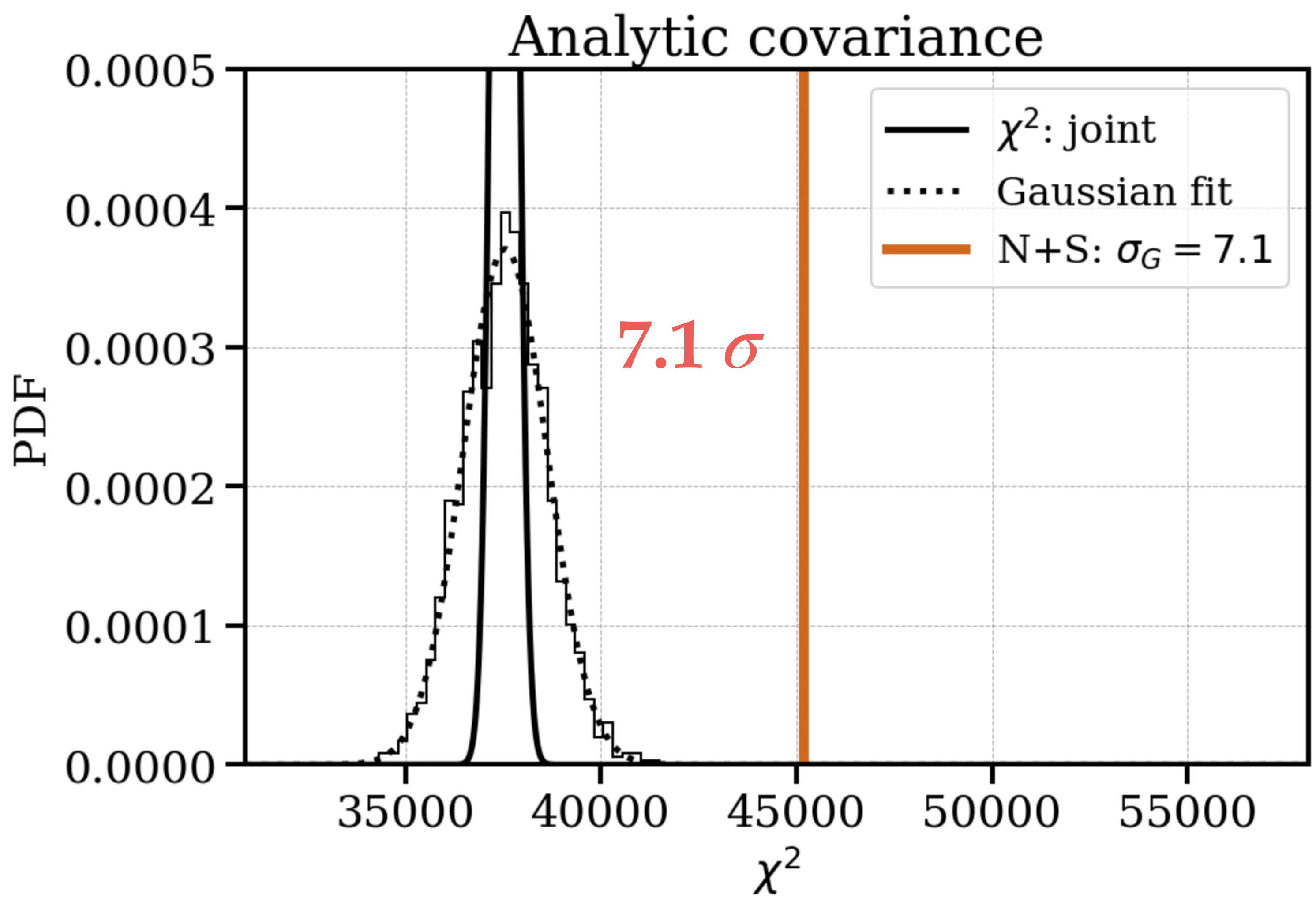
- In momentum space, four-point function

$$\mathbf{k}_1 \cdot \mathbf{k}_2 \quad \rightarrow \quad \mathbf{k}_1 \cdot \mathbf{k}_2$$
$$\mathbf{k_1} \times (\mathbf{k}_2 \cdot \mathbf{k}_3) \quad \rightarrow \quad -\mathbf{k_1} \times (\mathbf{k}_2 \cdot \mathbf{k}_3)$$

Parity violation Signals in BOSS data

Measurement of Parity-Odd Modes in the Large-Scale 4-Point Correlation Function of SDSS BOSS DR12 CMASS and LOWZ Galaxies

[arXiv 2206.03625] J. Hou, Z. Slepian, R. Cahn



Probing parity violation with the four-point correlation function of BOSS galaxies

[arXiv 2206.04227] O.Philcox

2.9 σ

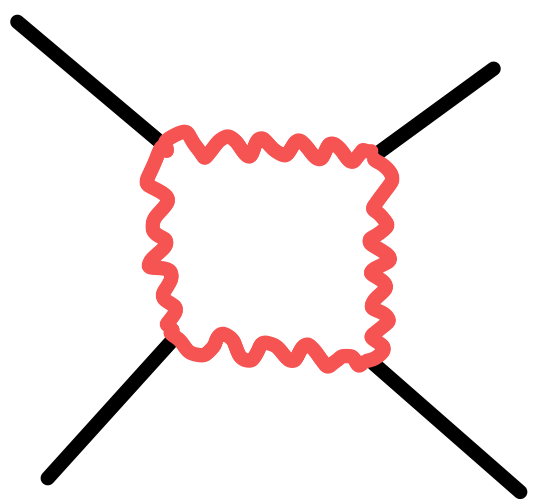
Inflation as the origin of the parity odd signals

- Cosmological evolution by gravity does not give parity violation signals in the large scale structure

- most of the models of inflation do not break the parity

- ghost inflation, non-standard vacuum, etc
  Without tuning, trispectrum signals are tiny

- parity signal $\phi \to \gamma\gamma$,
  parity odd signal from
  only one polarization of gauge bosons is produced
  chemical potential ξ enhances the trispectrum



In-in formalism

- in-in formalism to derive the n-point function   *S. Weinberg* [hep-th/0506236]

$$\langle \mathcal{O}(\tau)\rangle = \left\langle \left[\bar{T}\exp\left(i\int_{-\infty}^{\tau} d\tau H_I(\tau)\right)\right] \mathcal{O}_I(\tau) \left[T\exp\left(-i\int_{-\infty}^{\tau} d\tau H_I(\tau)\right)\right]\right\rangle$$

- parity odd of four point is a imaginary part

$$\text{Parity}: \quad \left\langle \prod_i^n \zeta(t,\mathbf{k}_i)\right\rangle \to \left\langle \prod_i^n \zeta(t,-\mathbf{k}_i)\right\rangle = \left\langle \prod_i^n \zeta(t,\mathbf{k}_i)\right\rangle^*$$

- parity odd signals from gauge bosons

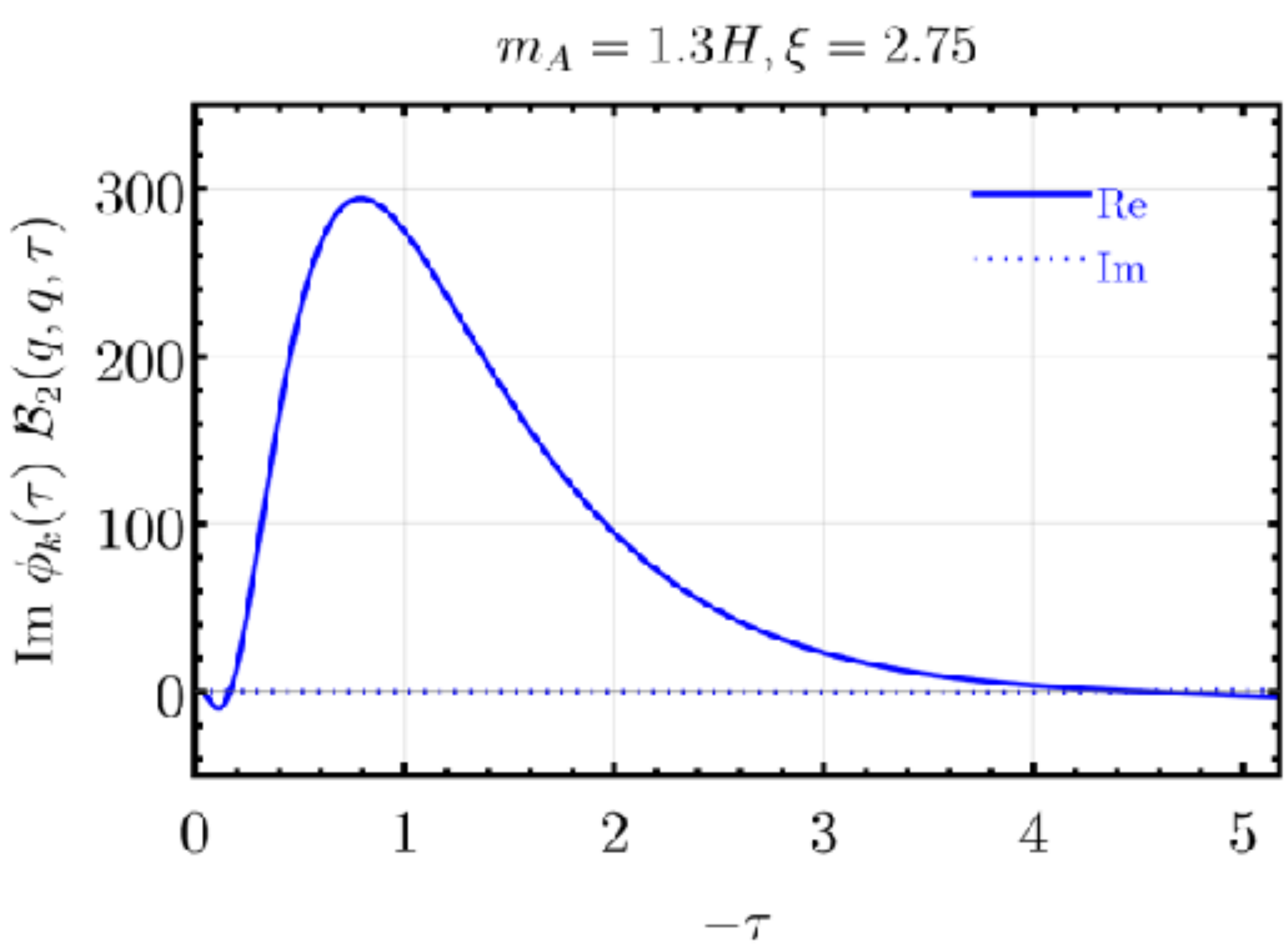
$$\mathbf{A}(\tau,\mathbf{x}) = \sum_{\lambda=\pm,0}\int \frac{d^3k}{(2\pi)^3}\left[\epsilon_\lambda(\mathbf{k}) a_\lambda(\mathbf{k}) A_\lambda(\tau,k) e^{i\mathbf{k}\cdot\mathbf{x}} + \text{h.c.}\right]$$

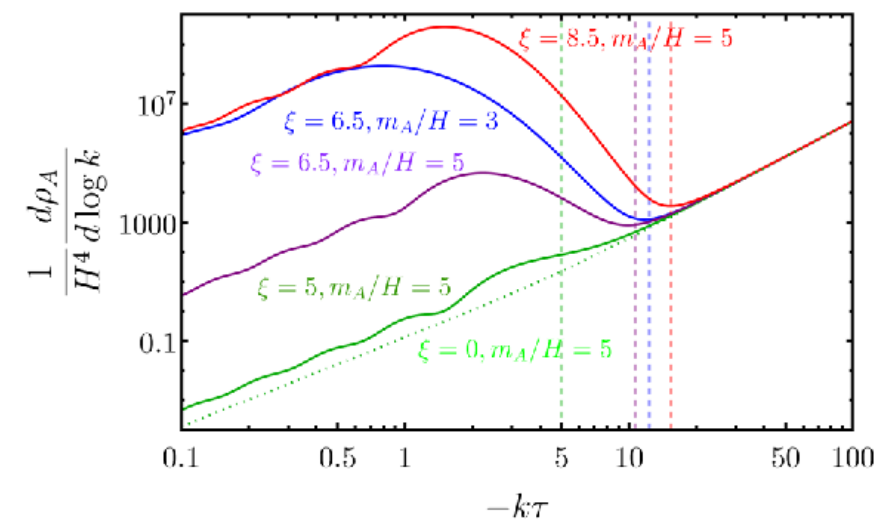
Polarization $\epsilon_\lambda(\mathbf{k})$ gives the imaginary part,
but the loop integration is involved due to the mode function $A_\lambda(\tau,k)$

Real mode function approximation

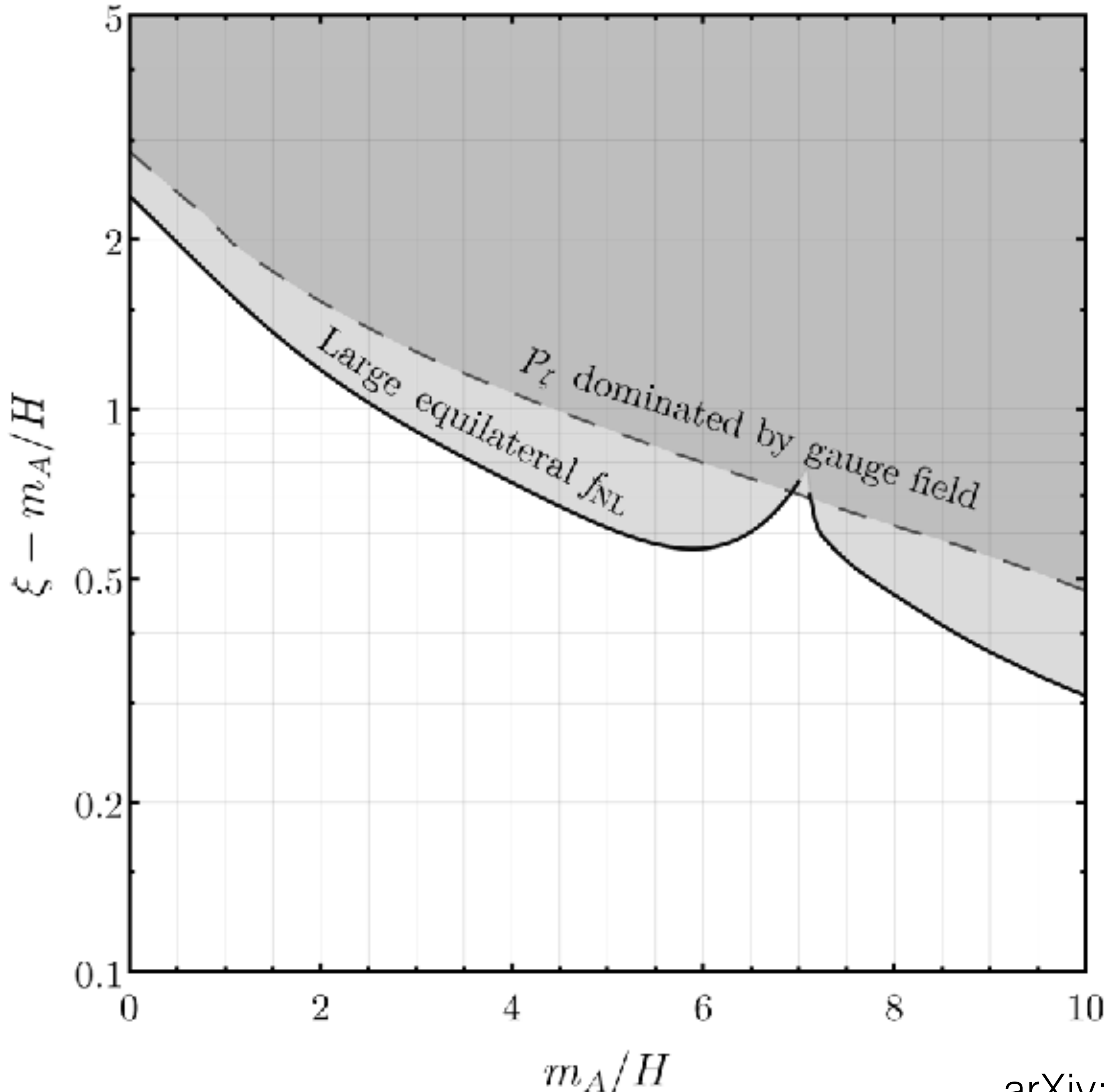
- in-in formalism gives $\mathcal{O}(100)$ terms and 7-dim integration

- neglect the imaginary part of the mode function
  7-dim integration is factorized into 3+1+1+1+1 dim integration





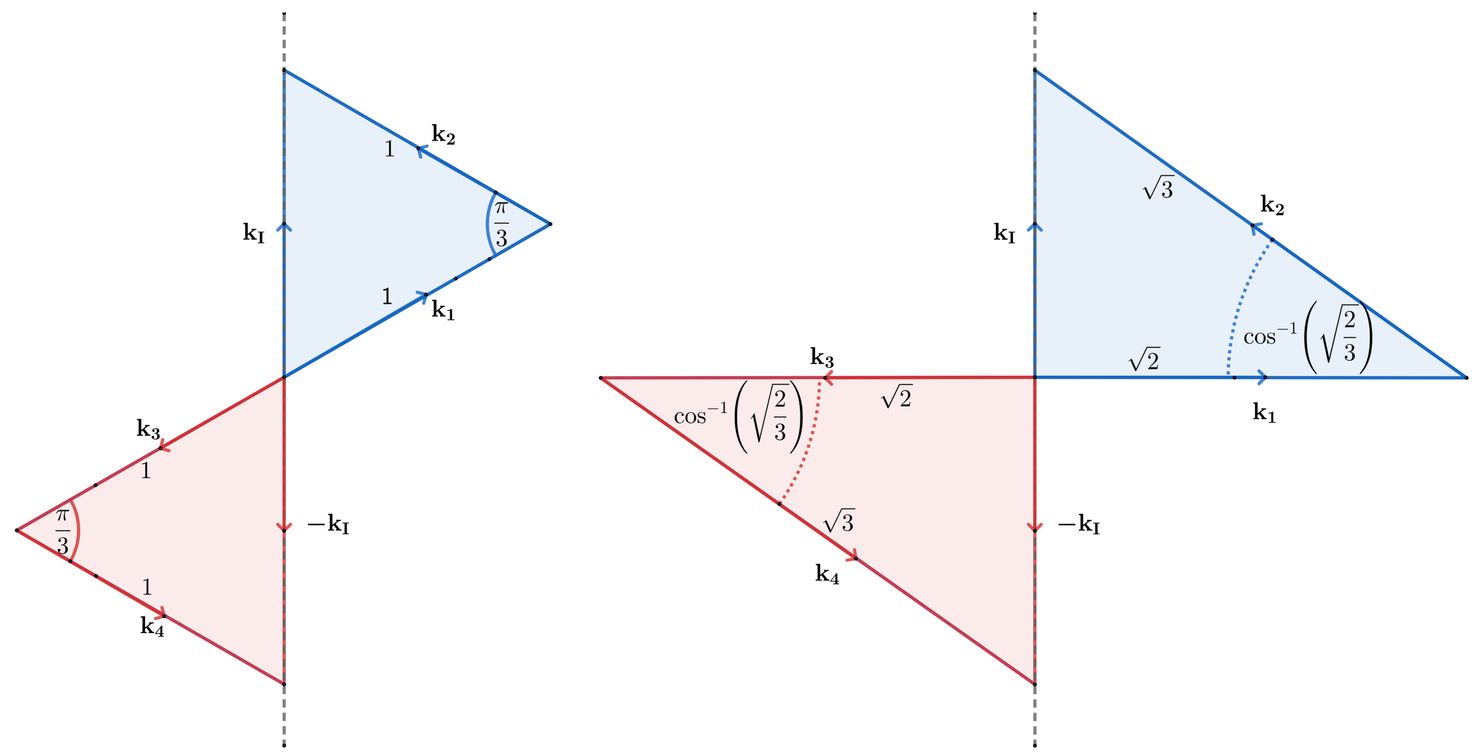
Constraints from CMB



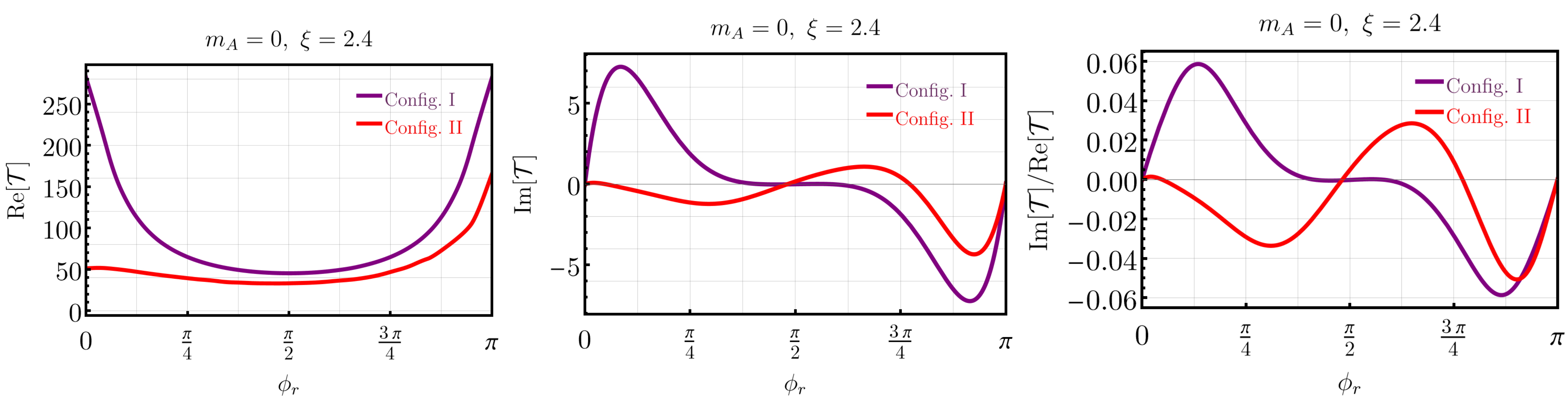
arXiv: 2211.14331

Parity odd and Parity even trispectrum

- two configurations

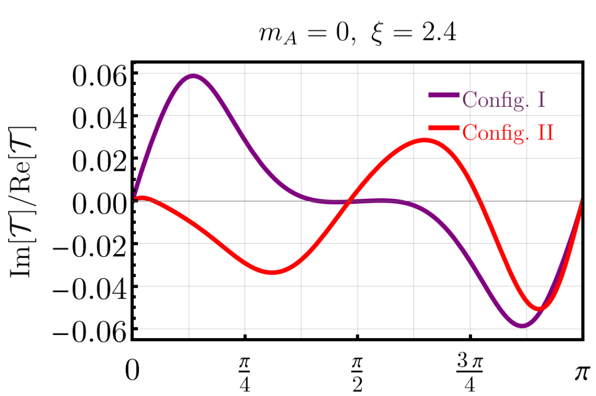


- Parity even (real part) and parity odd (imaginary part)

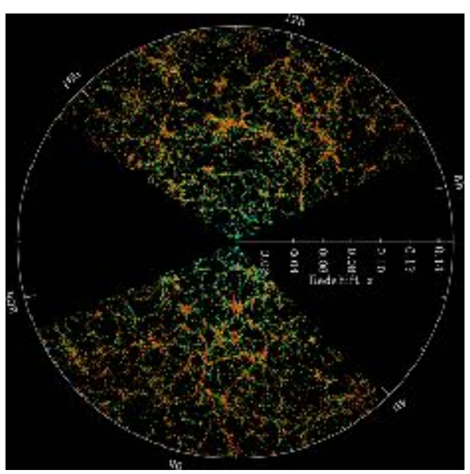


Summary

- real mode approximation to simplify the calculation

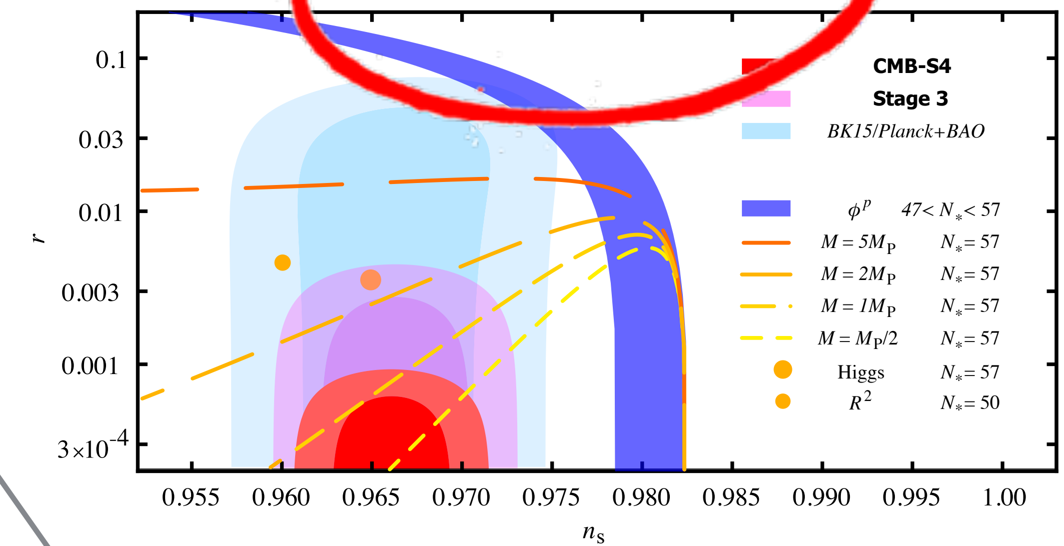


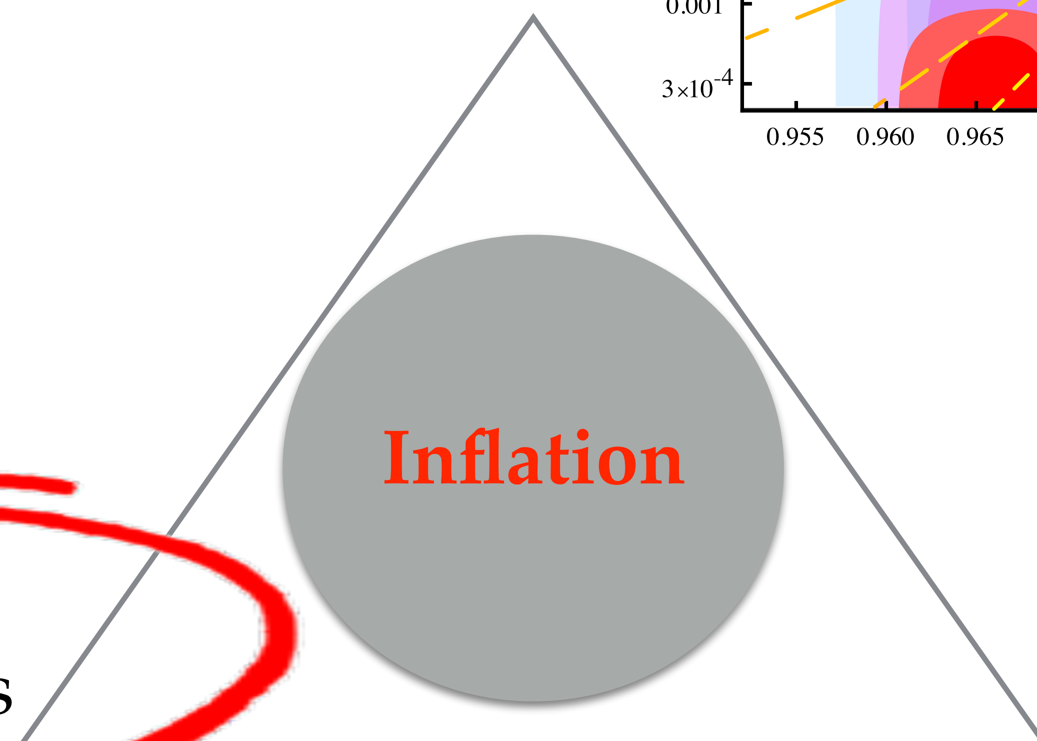
- parity odd ~ 10^{-2} parity even



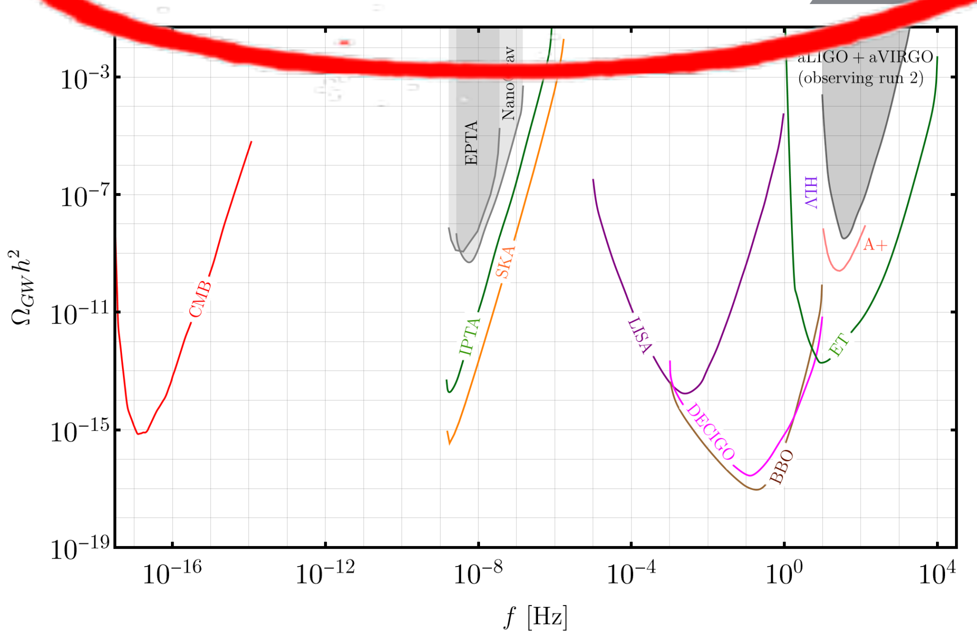
- future work: analyze the BOSS data to constrain the gauge boson production

CMB





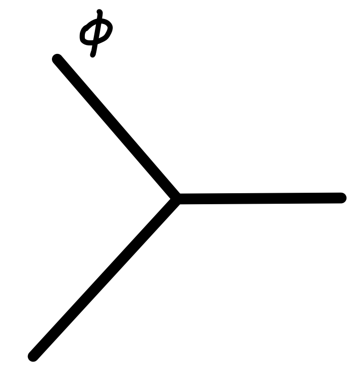
Gravitational waves



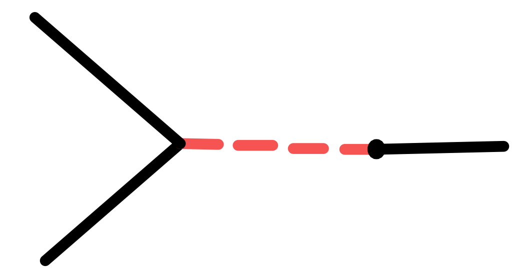
LSS

Cosmological collider physics

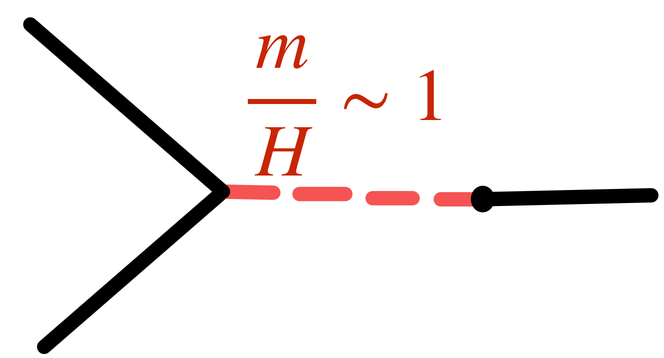
- f_{NL} ~ inflaton perturbation $\langle \phi\phi\phi \rangle$



- f_{NL} may detect the inflaton interactions



- exchanging particles gives an oscillating feature

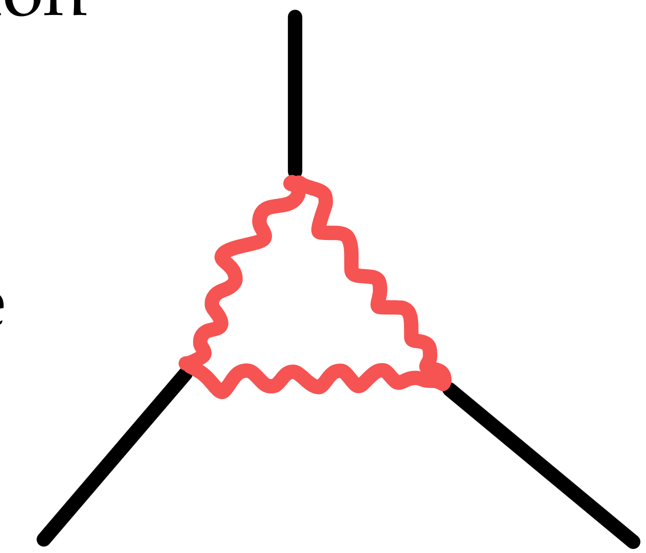


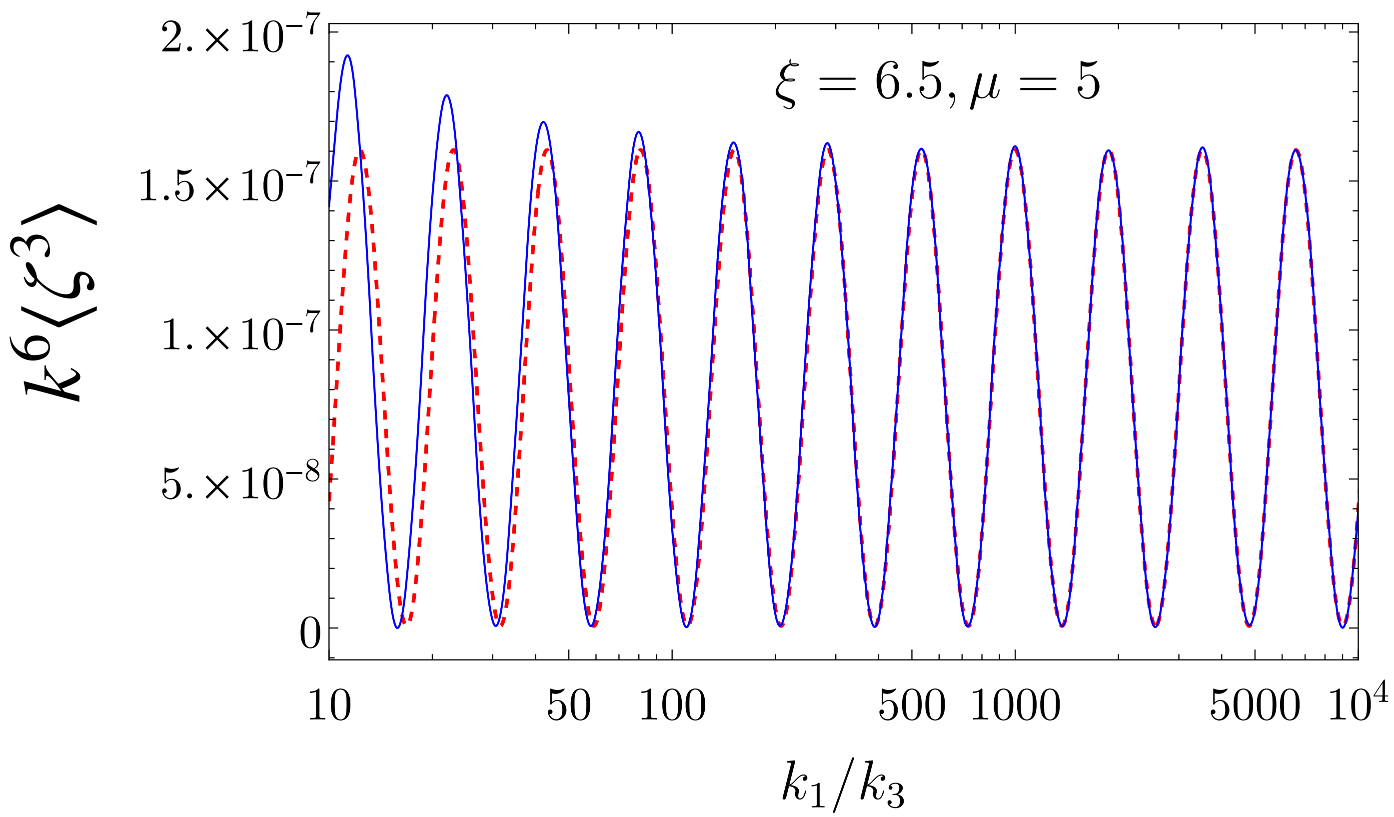
$$\langle \zeta\zeta\zeta \rangle \propto \left(\frac{k_1}{k_3}\right)^{3/2 \pm i\mu}, \quad \mu = \sqrt{\frac{m^2}{H^2} - \frac{9}{4}}$$

Chen, Wang 0911.3380
Arkani-Hamed, Maldacena 1503.08034

Cosmological collider physics for A_μ^+

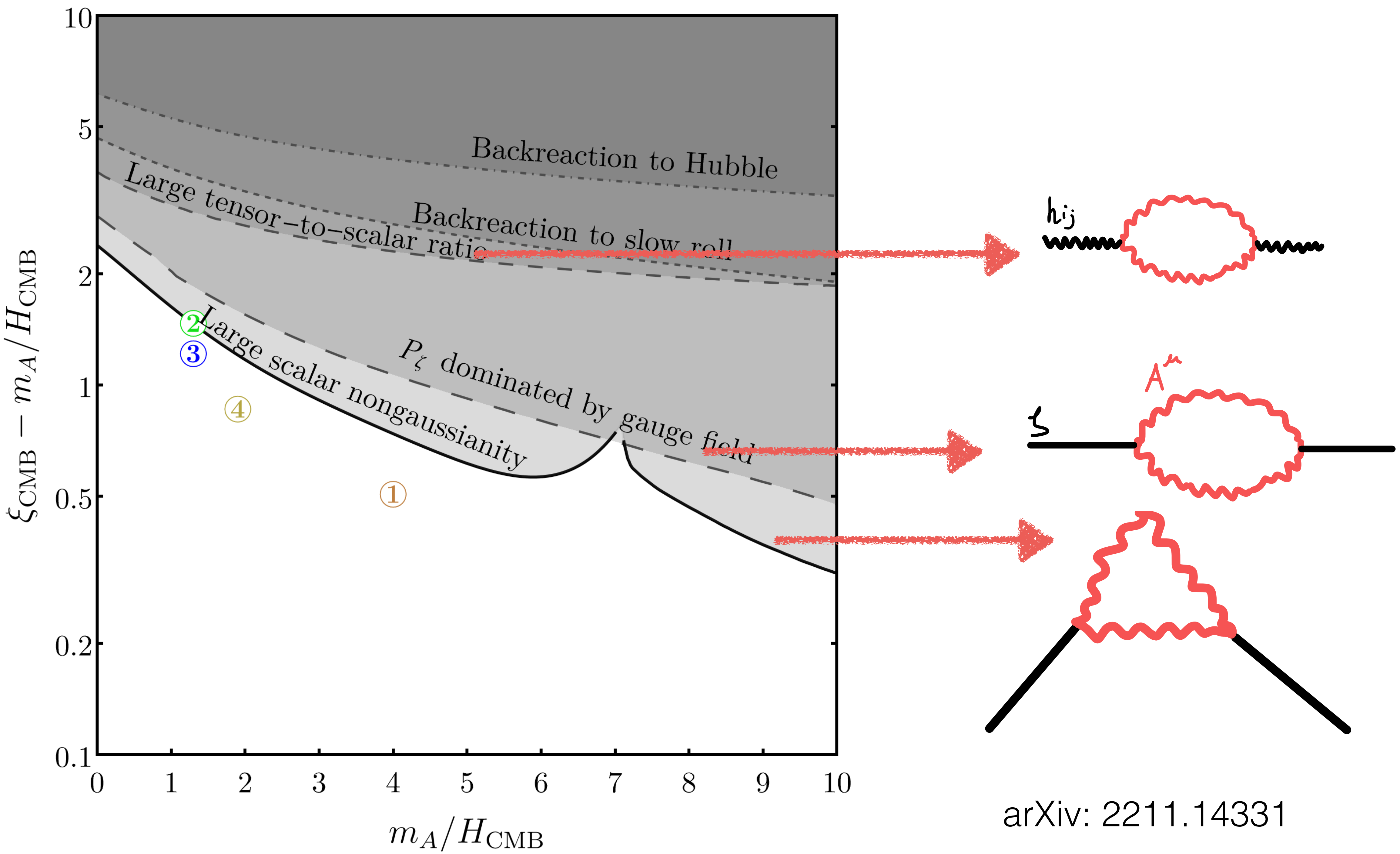
- cosmological collider physics signals are normally tiny. heavy particle production is suppressed during inflation $\sim e^{-\pi\mu}$
- gauge boson production enhances the production rate using the chemical potential $e^{\pi\xi'}$





Current constraints at the CMB scale

- the equilateral shape of nonGaussianity is the most constraining one $f_{\rm NL}^{\rm eq} = -25 \pm 47$



arXiv: 2211.14331

Beyond CMB scale

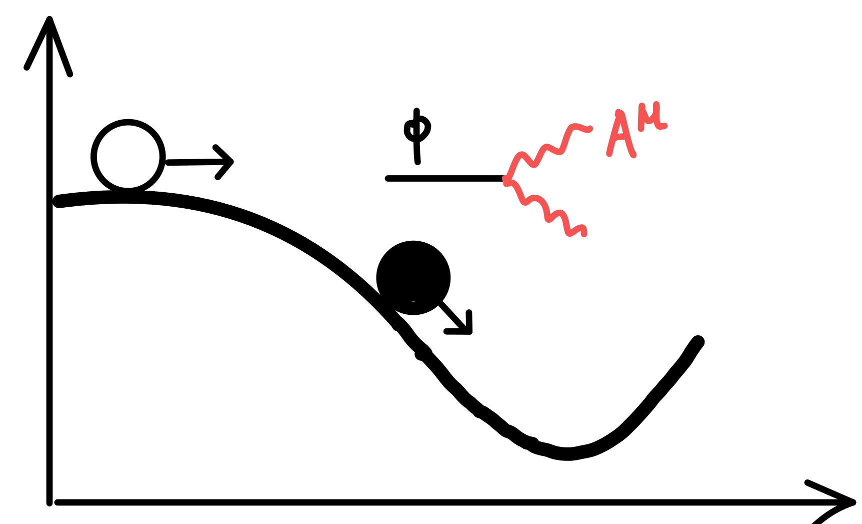
- gauge field's backreaction

$$\ddot{\phi}_0 + 3H\dot{\phi}_0 + \frac{dV}{d\phi_0} = \frac{1}{\Lambda}\langle \mathbf{E}\cdot\mathbf{B}\rangle$$

$$3H^2 M_{\rm Pl}^2 - \frac{1}{2}\dot{\phi}_0^2 - V = \frac{1}{2}\left\langle \mathbf{E}^2 + \mathbf{B}^2 + \frac{m_A^2}{a^2}\mathbf{A}^2 \right\rangle$$

- the backreaction is negligible at the CMB
  at the late stage of inflation, $\dot{\phi}$ becomes large

$$\xi \equiv \frac{\dot{\phi}_0}{2\Lambda H}$$

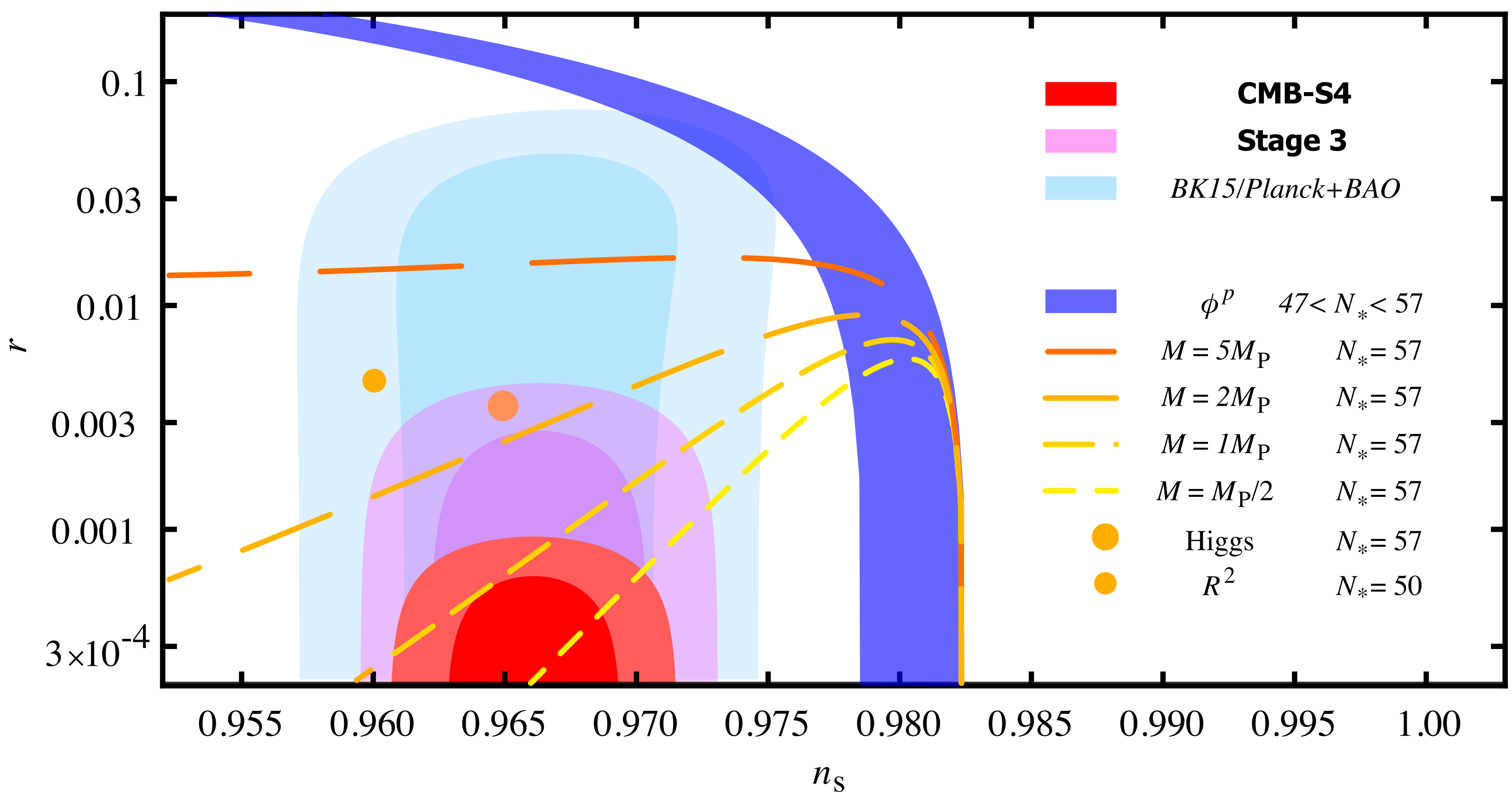


- we need to specify an inflationary model to know the evolution of $\dot{\phi}$

Inflationary model

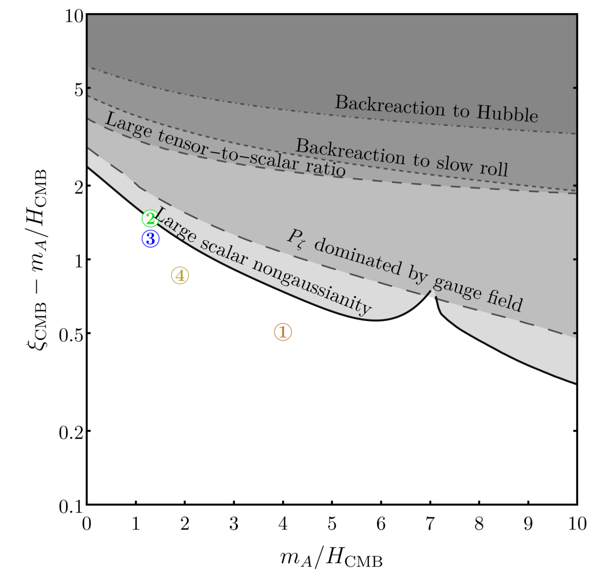
- Starobinsky model

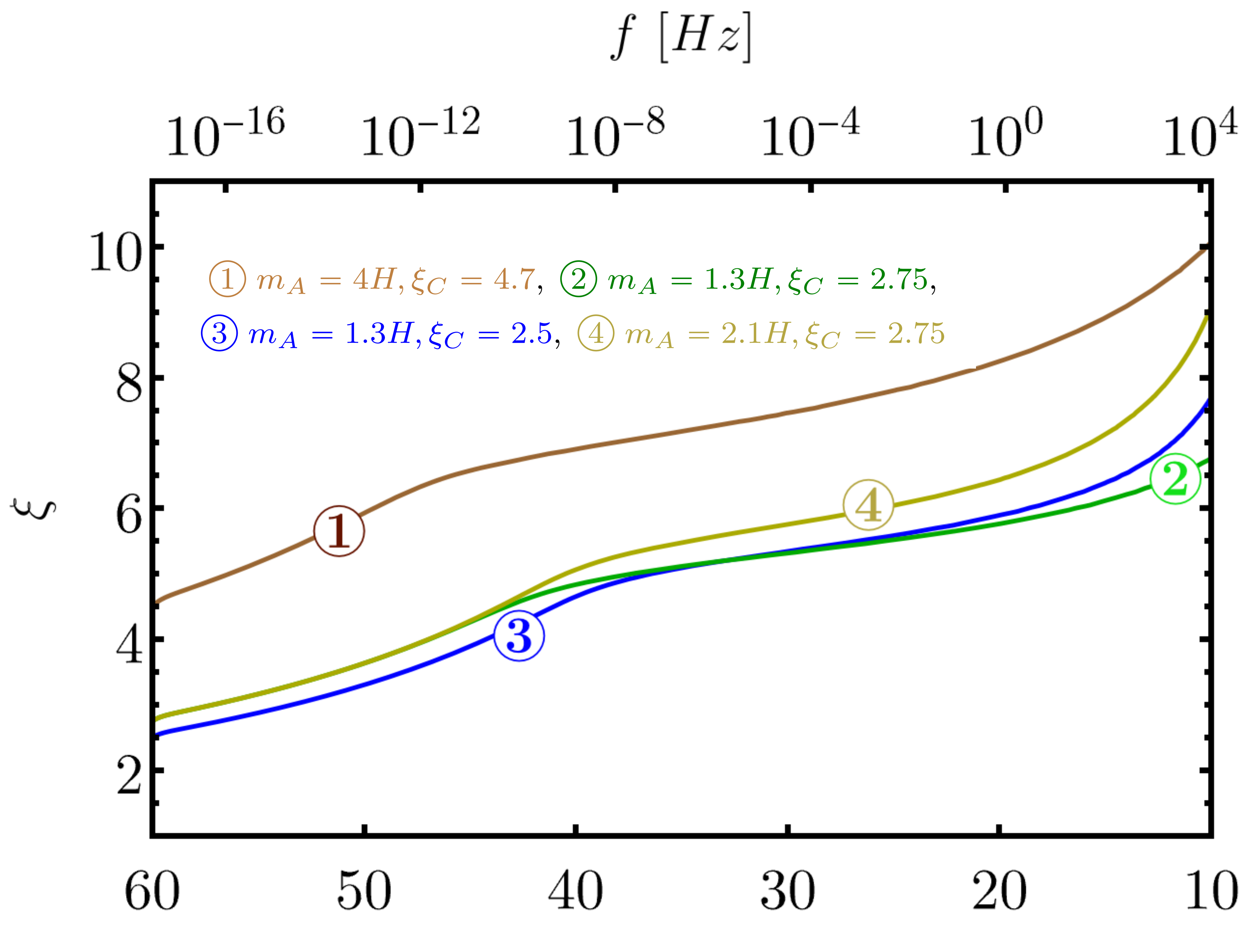
$$V(\phi) \sim V_0 \left(1 - e^{-\gamma\phi}\right)^2$$



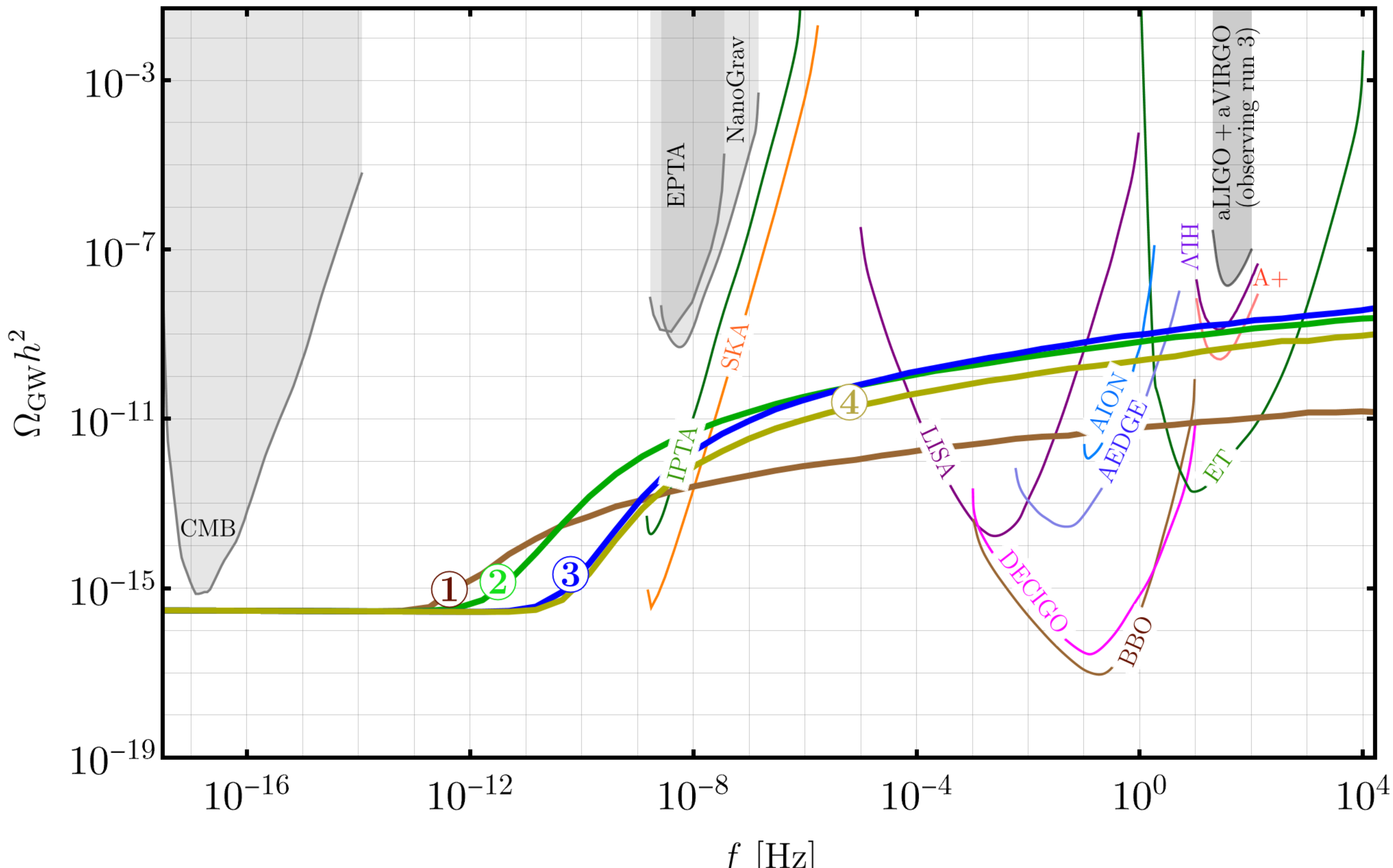
Four bench mark models

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





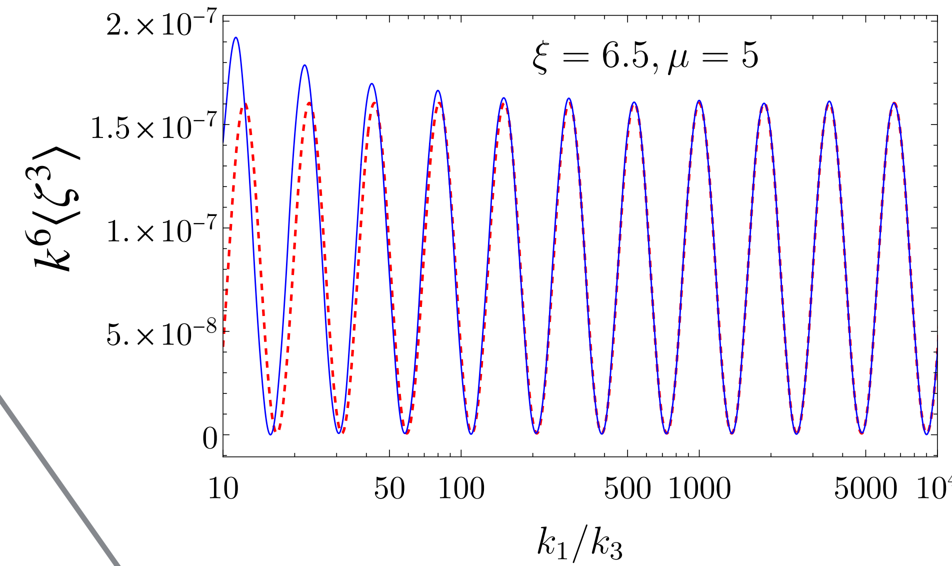
Gravitational wave signals

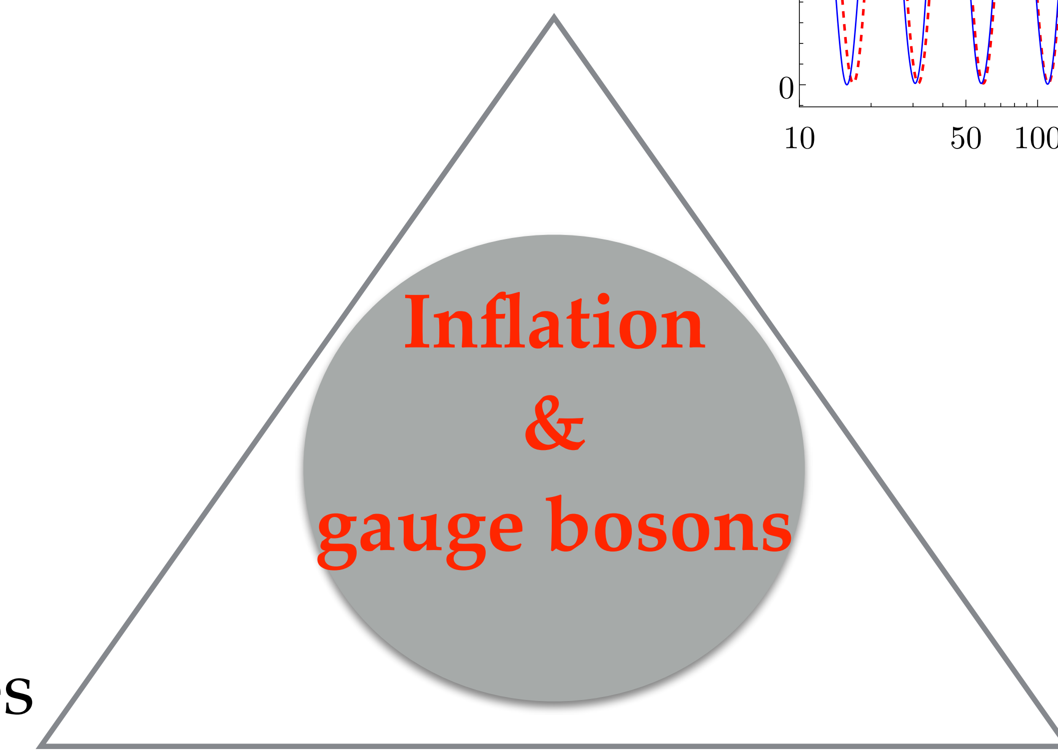


① $m_A = 4H, \xi_C = 4.7$, ② $m_A = 1.3H, \xi_C = 2.75$,
③ $m_A = 1.3H, \xi_C = 2.5$, ④ $m_A = 2.1H, \xi_C = 2.75$

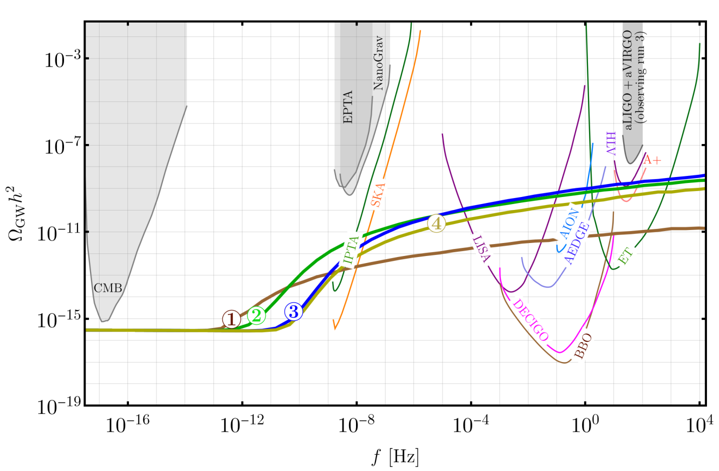
Conclusion

CMB

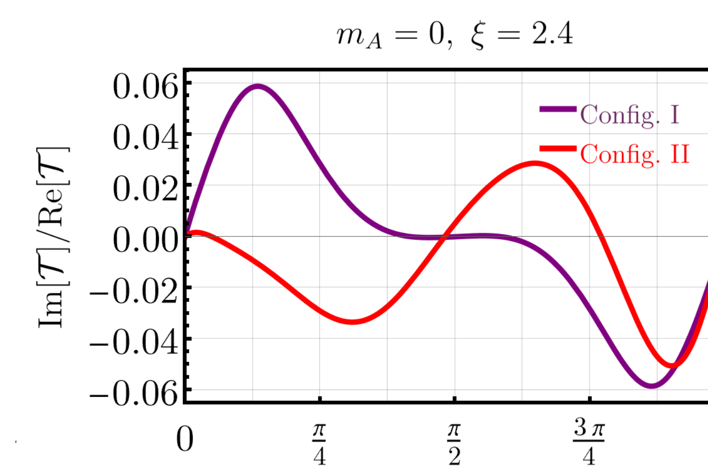




Gravitational waves



LSS



Primordial black holes