Searching for New Particles in the Large Scale Structure of the Universe

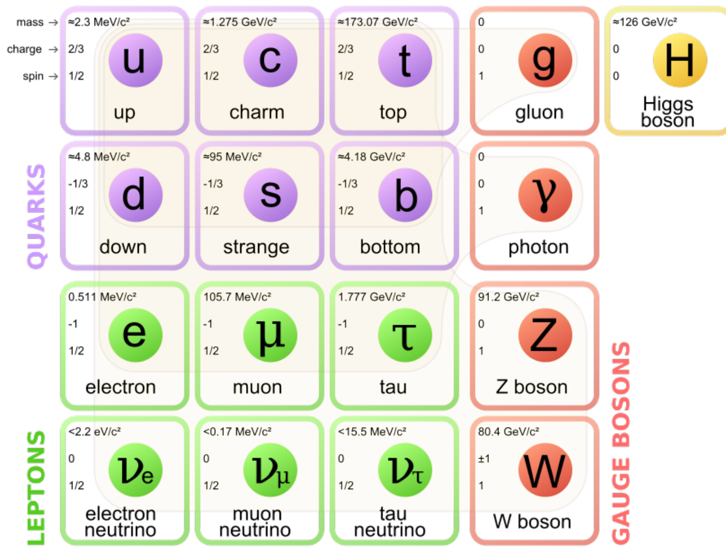
Haipeng An (Tsinghua University)

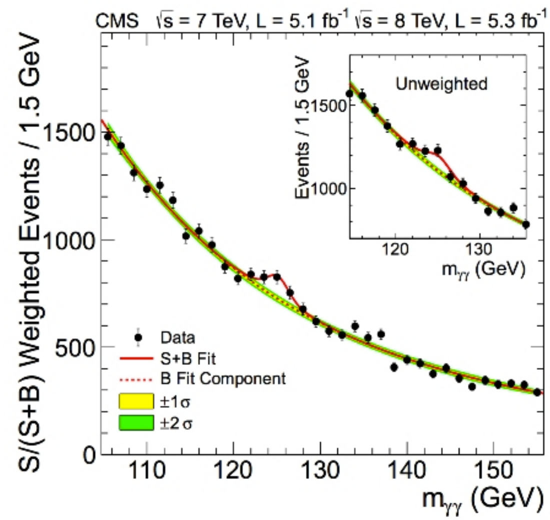
The 1st AEI workshop for BSM and the 9th KIAS workshop on Particle Physics and Cosmology

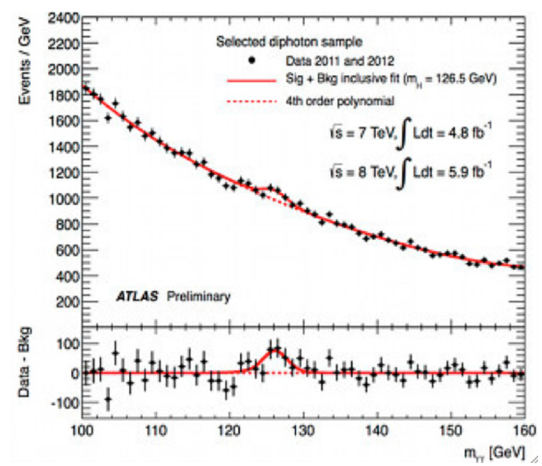
Nov 3-8, 2019

HA, M. McAneny, A.K.Ridgway, M.B.Wise, Zipei Zhang, 1711.02667, 1806.05194

The standard model is very successful







Collider physics

LHC, p p collision

$E_{\rm cm} = 13\ {\rm TeV}$

CEPC, e+ e- collision

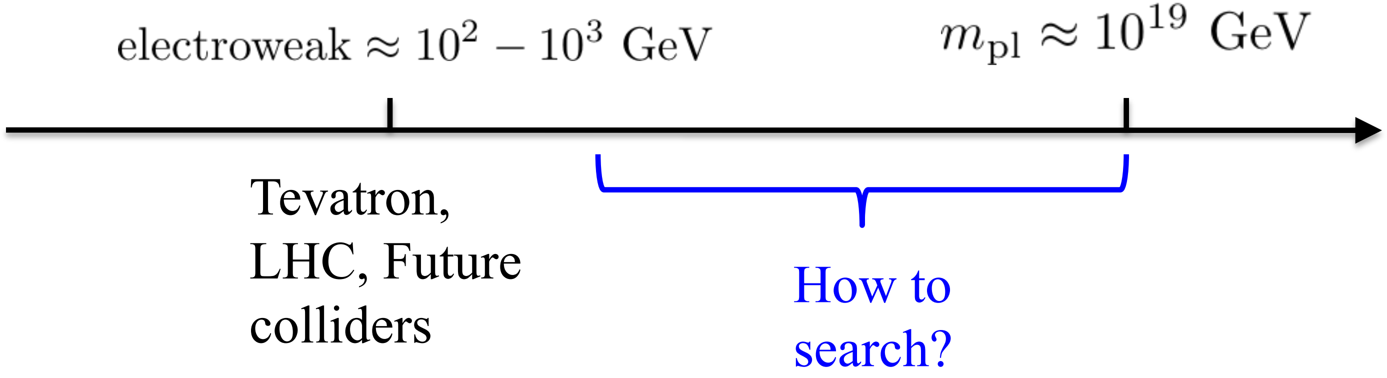
$E_{\rm cm} \approx 240\ {\rm GeV}$

SPPC, p p collision

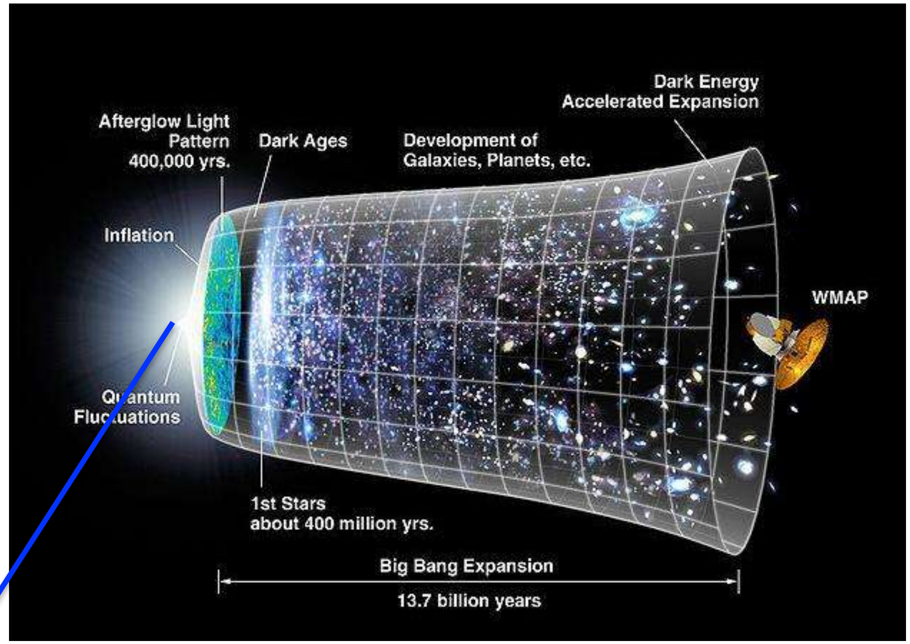
$E_{\rm cm} \sim 100\ {\rm TeV}$

Search for new physics

- Collider physics



The expansion of the Universe

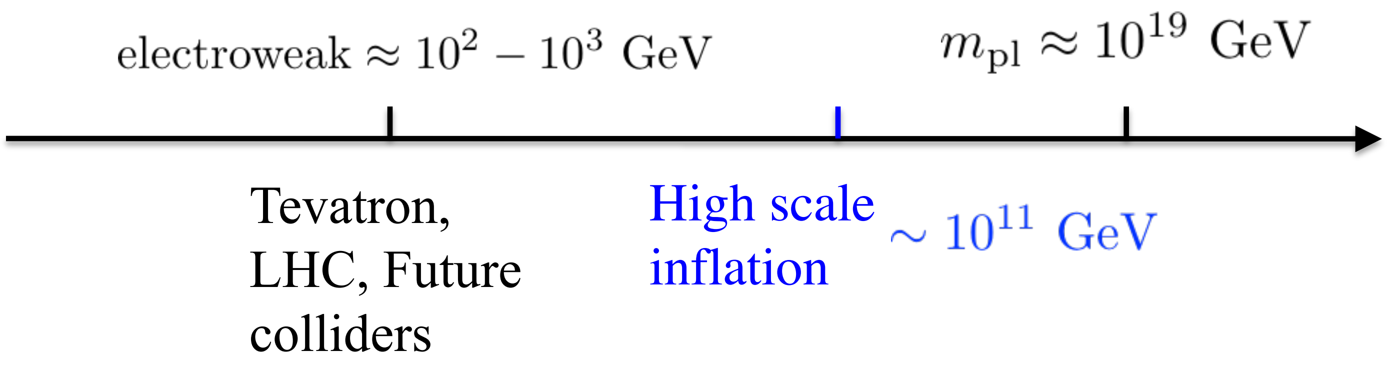


Inflation

1. Solves the causality problem
2. Solves the flatness problem
3. Solves the magnetic monopole problem

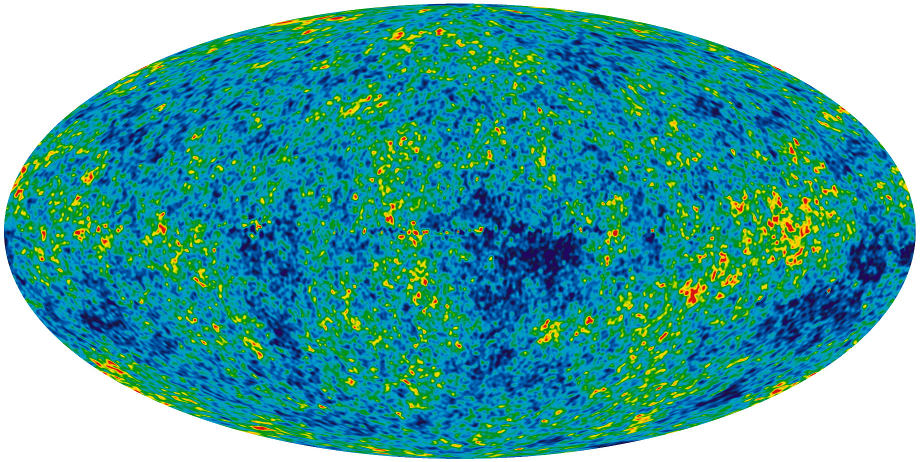
Search for new physics

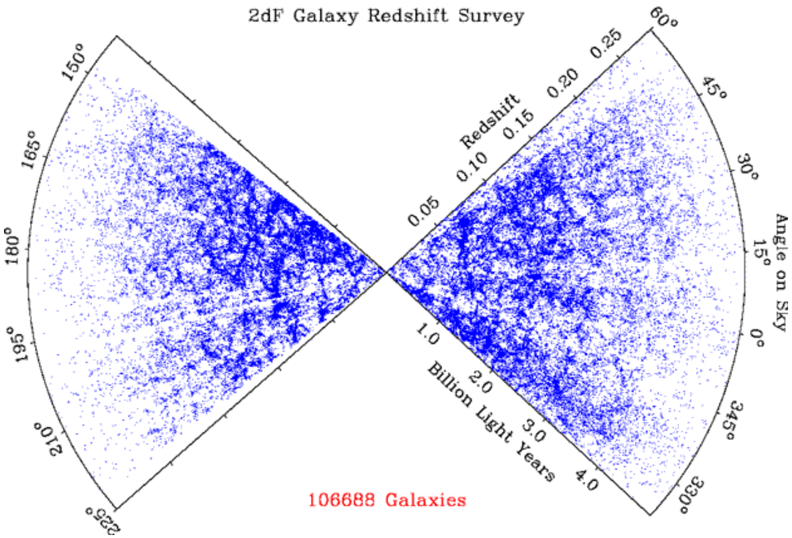
- Collider physics



The seeds of today's Universe

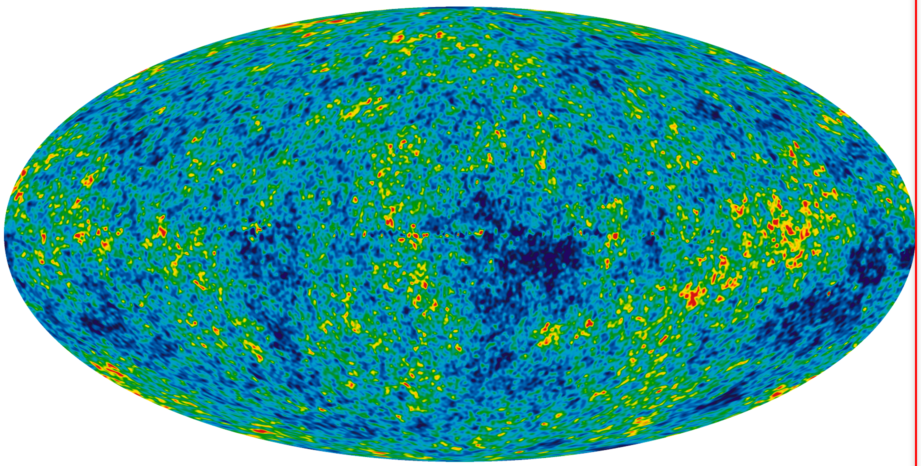
- Quantum fluctuation of the inflaton field provides the seed of today's large scale structure of the universe.

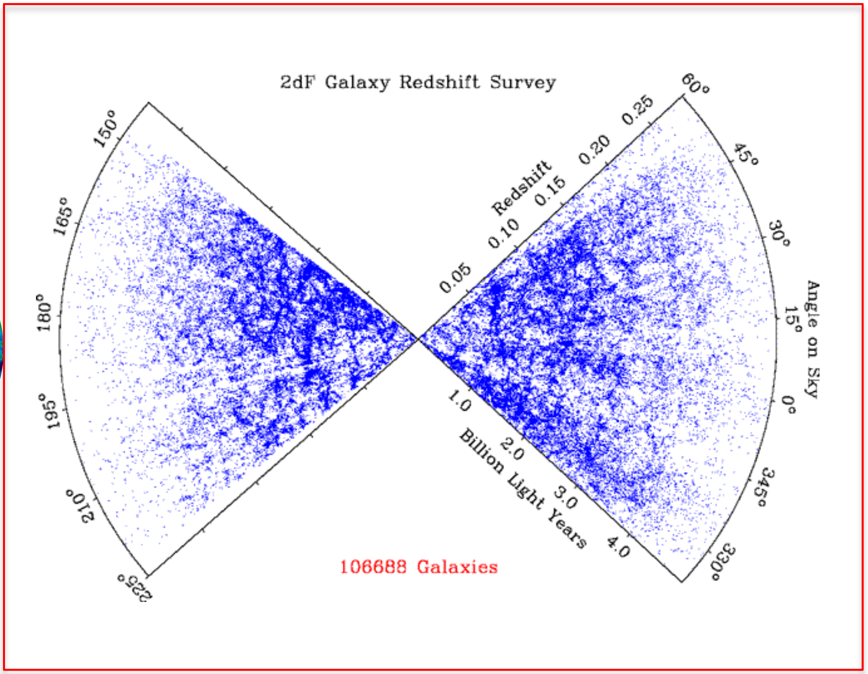




The seeds of today's Universe

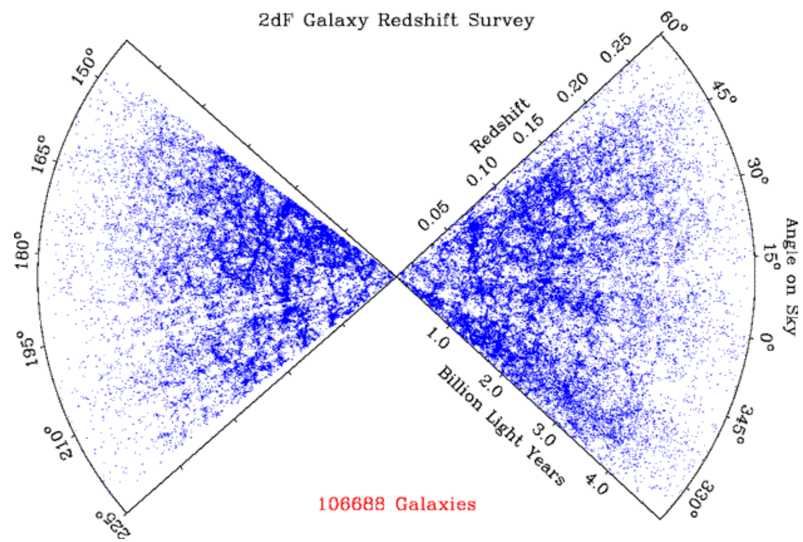
- Quantum fluctuation of the inflaton field provides the seed of today's large scale structure of the universe.





Outline

- General idea
- Quasi-single field inflation
- 2pt result
- 3pt result
- Loop-induced effect
- Summary



Inflation era

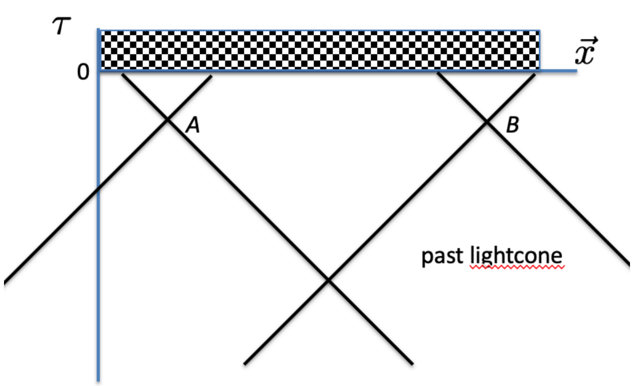
- Homogeneous and isotropic

$$ds^2 = dt^2 - a^2(t)(dx^2 + dy^2 + dz^2)$$

During inflation: $a(t) = e^{Ht}$

$$ds^2 = a^2(\tau)(d\tau^2 - dx^2 - dy^2 - dz^2)$$

During inflation: $a(\tau) = -\dfrac{1}{H\tau}$



$$-\infty < \tau < 0$$

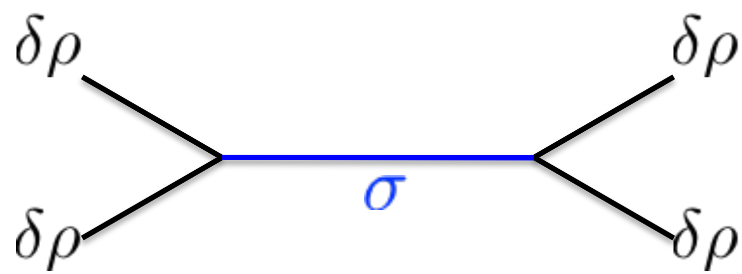
How to search for new particles

- If there are new fields coupled to the inflaton field, their information can print onto the CMB and the LSS, too.

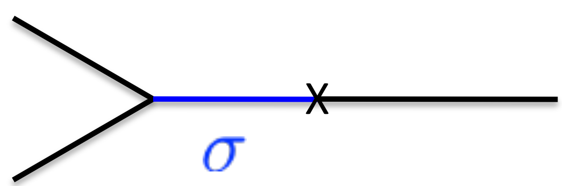
$\phi \longrightarrow \delta\phi \longrightarrow \Phi \longrightarrow \delta\rho$ { CMB / Galaxy survey

Inflaton — Inflaton perturbation — Curvature perturbation — Density perturbation

$\sigma\phi^2 \longrightarrow \sigma\delta\rho^2$



$\sigma\delta\rho$



Search for new particles

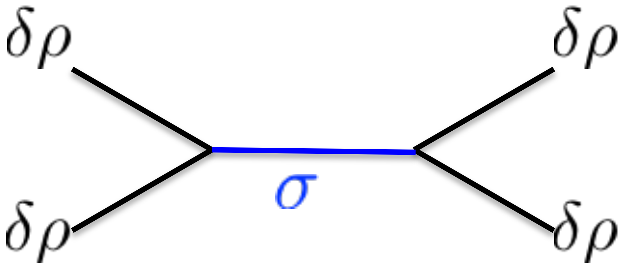
- It is difficult to measure 3pt and 4pt in galaxy surveys.

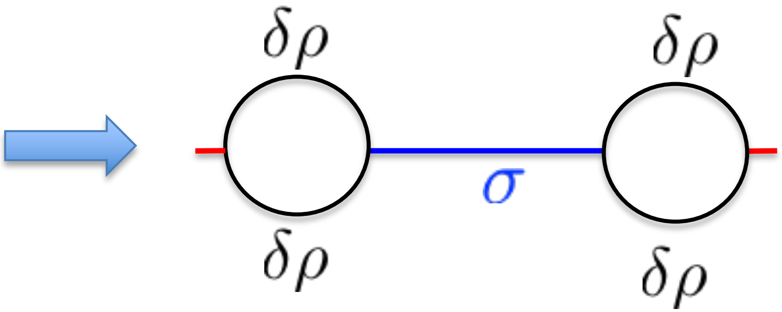
- What about two-point functions?
  - Very well measured.
  - Nonlinearity is needed.

B. Grinstein and M. Wise ApJ 1986.

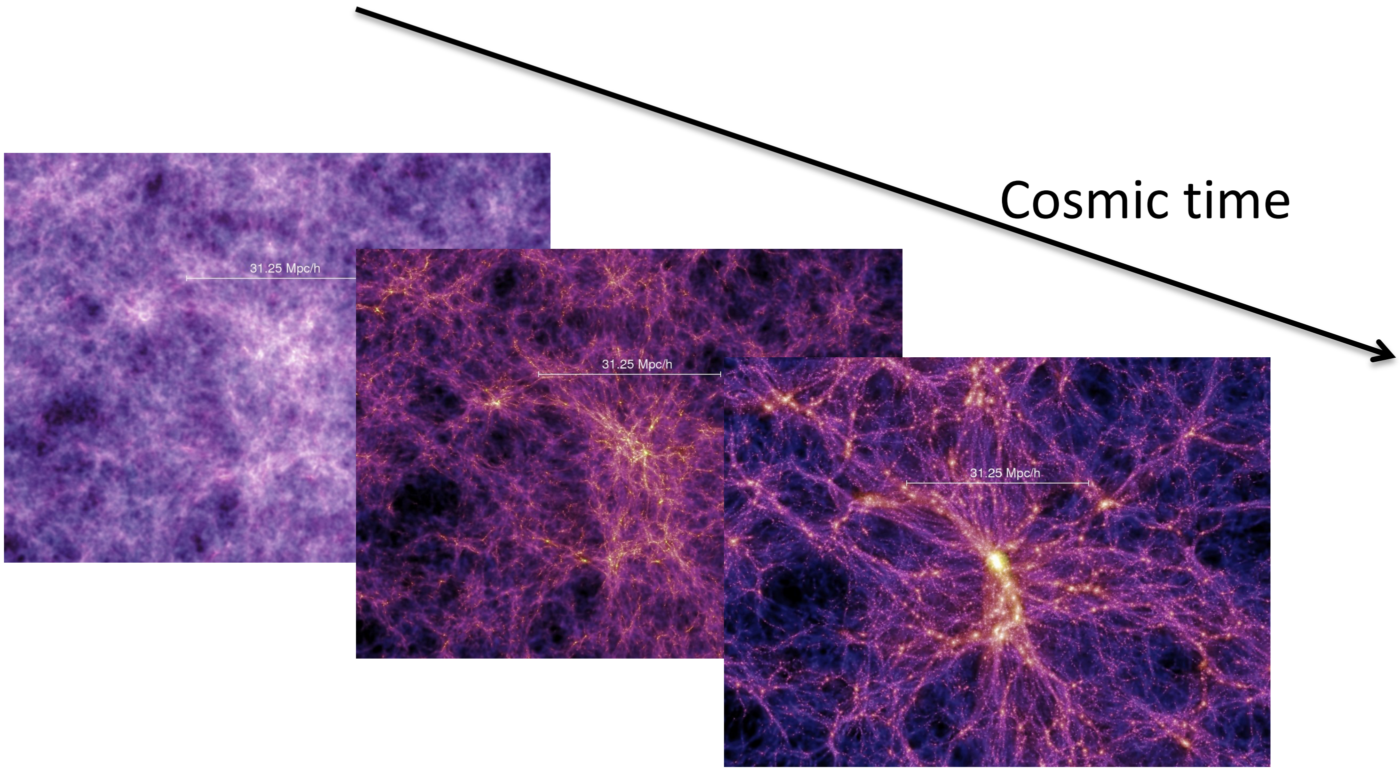
Dalal, Dore, Huterer, Shirokov PRD 2008

For primordial non-Gaussianity



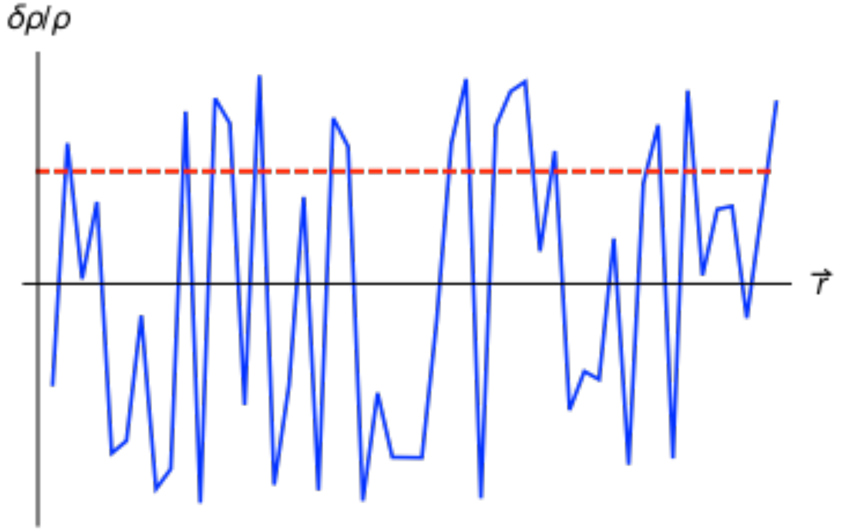


The large scale structure



Formation of galactic halos

- Galaxy or halo formation is nonlinear.



- Threshold model   Press and Schechter, Astrophys. J. 1974

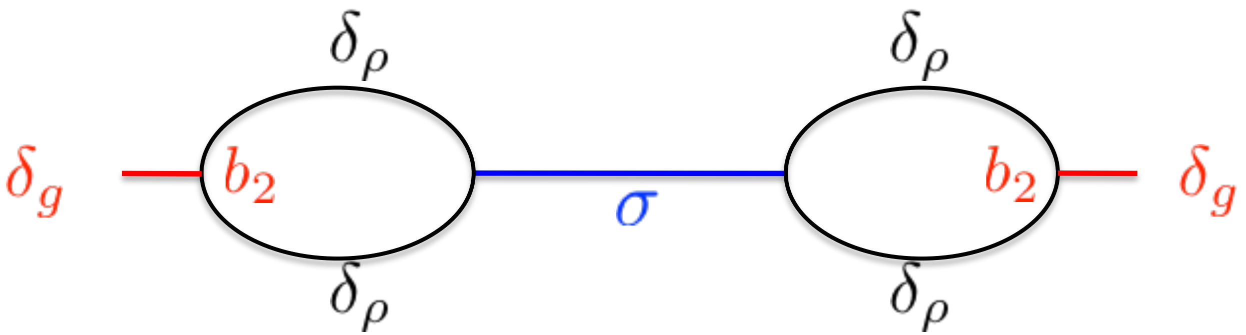
$$n_g(\mathbf{r}) = \Theta\left(\frac{\delta\rho(\mathbf{r})}{\bar{\rho}} - \delta_c\right)$$

Cosmic bias

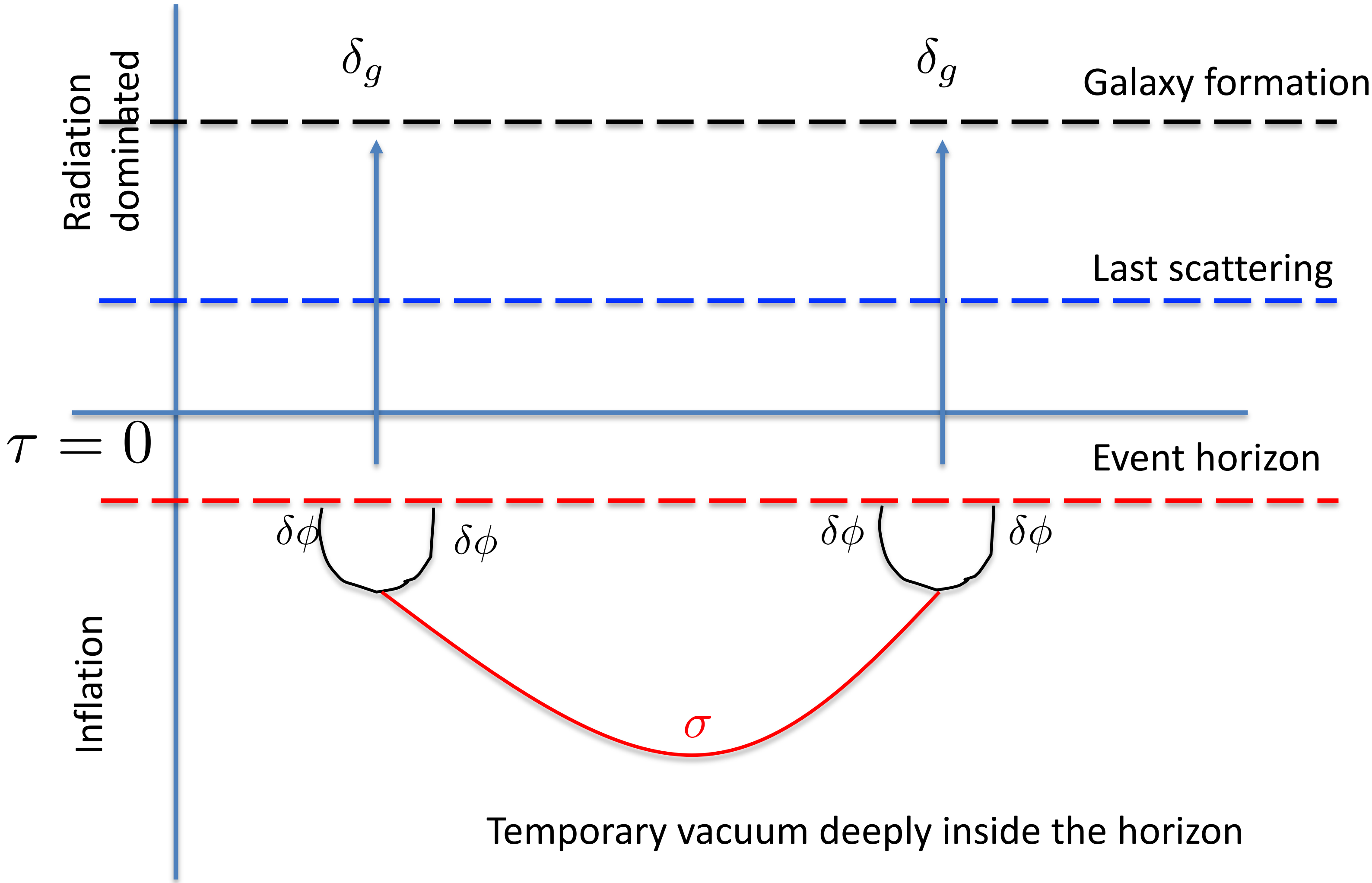
- Cosmological bias

$$\delta_g = b_1 \delta_\rho + \frac{1}{2} b_2 \left(\delta_\rho^2 - \langle \delta_\rho^2 \rangle \right) + \cdots$$

$$\delta_g \equiv \frac{\delta n_g}{\bar{n}_g} \qquad \delta_\rho \equiv \frac{\delta \rho}{\bar{\rho}}$$



What shall we calculate?



What shall we calculate?

$$\langle \delta_g(\vec{x}_1)\delta_g(\vec{x}_2)\rangle$$

Expectation value of the of the operator $\delta_g(\vec{x}_1)\delta_g(\vec{x}_2)$ in the temporary vacuum state deeply inside the horizon ($\tau \to -\infty$, the Bunch-Davies vacuum)

We need to calculate $\langle \delta\phi(\vec{x}_1)\delta\phi(\vec{x}_2)\delta\phi(\vec{x}_3)\delta\phi(\vec{x}_4)\rangle$ at $\tau \to 0$

$$\langle O(0)\rangle = \left\langle \left[\bar{T}\exp\left(i\int_{-\infty}^{0} H_I(t)dt\right)\right] O_I(t) \left[T\exp\left(-i\int_{-\infty}^{0} H_I(t)dt\right)\right]\right\rangle$$

Why this is interesting?

- Perturbation of inflaton field (massless scalar)

$$\langle \delta\phi\delta\phi \rangle_k \sim \frac{1}{k^3} \quad \Longrightarrow \quad \langle \Phi\Phi \rangle_k \sim \frac{1}{k^3}$$

- The observables are related to the density perturbation $\delta\rho$.

$$\delta_\rho(\vec{k},a) \equiv \frac{\delta\rho(\vec{k},a)}{\bar{\rho}} = \frac{3}{5}\frac{k^2}{\Omega_m H_0^2}\Phi(\vec{k})T(k)D_1(a)$$

Why this is interesting?

- Perturbation of inflaton field (massless scalar)

$$\langle \delta\phi\delta\phi \rangle_k \sim \frac{1}{k^3} \quad \Longrightarrow \quad \langle \Phi\Phi \rangle_k \sim \frac{1}{k^3}$$

- The observables are related to the density perturbation $\delta\rho$.

$$\delta_\rho(\vec{k}, a) \equiv \frac{\delta\rho(\vec{k}, a)}{\bar{\rho}} = \frac{3}{5}\frac{k^2}{\Omega_m H_0^2}\Phi(\vec{k})T(k)D_1(a)$$

From the Poisson equation

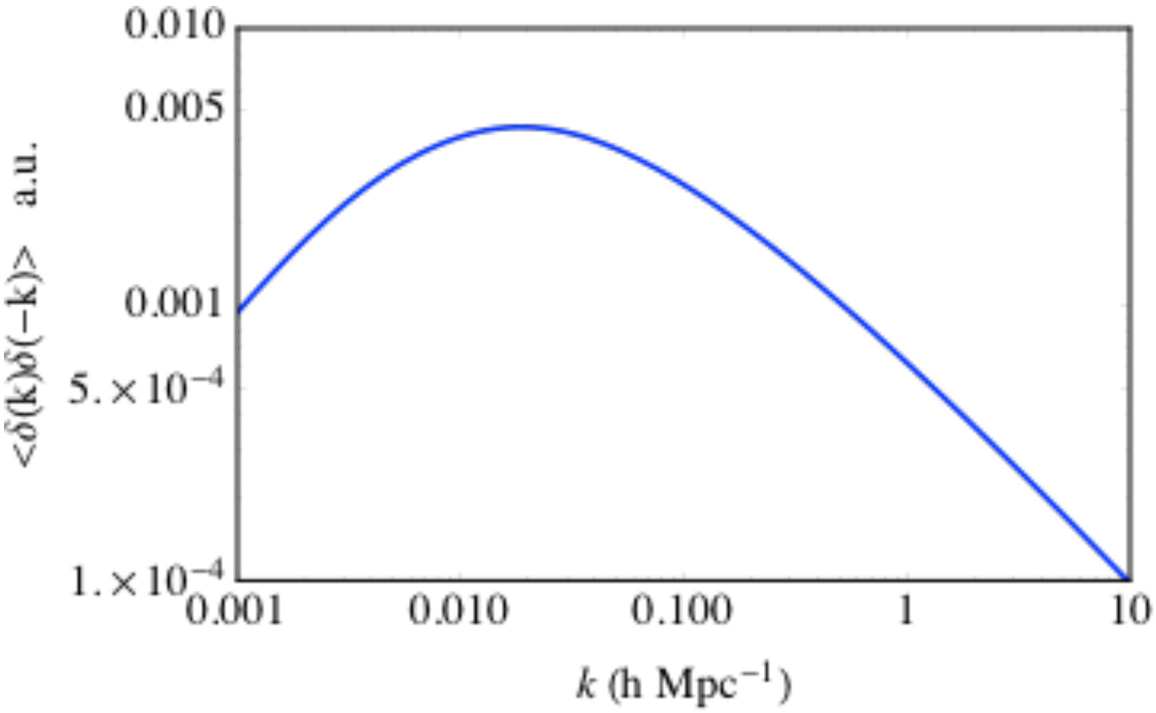
$$\nabla^2\Phi = 4\pi G\rho$$

Growth function

Transfer function

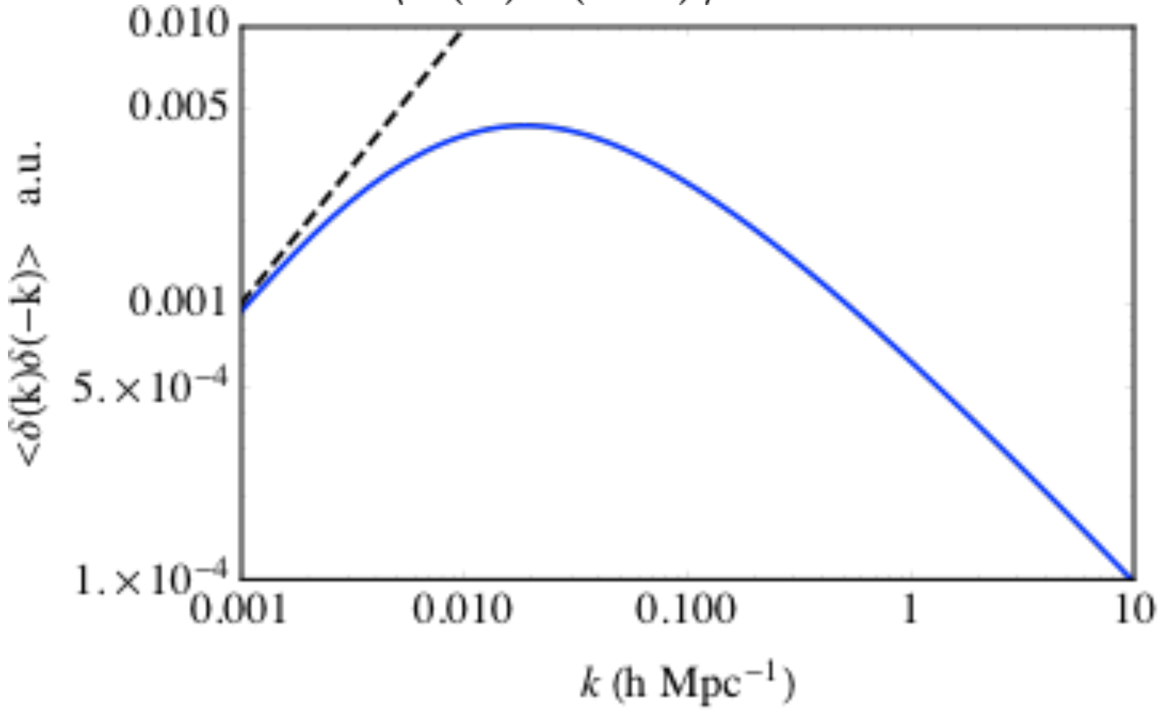
$$T(k) \to 1, \quad k \to 0$$

Why this is interesting?

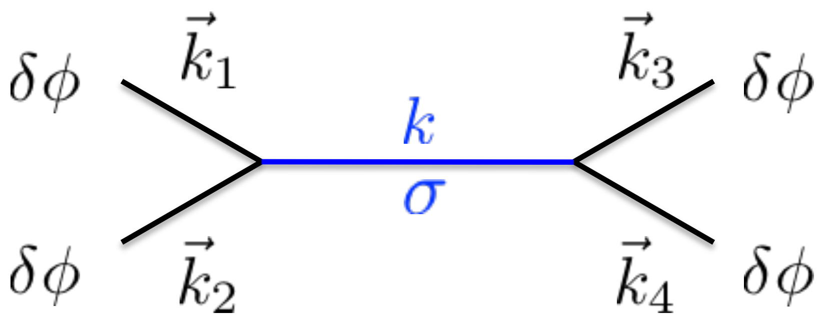


Why this is interesting?

Harrison-Zeldovich spectrum $\langle\delta(\vec{k})\delta(-\vec{k})\rangle \sim k$



Squeezed 4pt spectrum



$$k_1 \approx k_2 \gg k,\ k_3 \approx k_4 \gg k$$

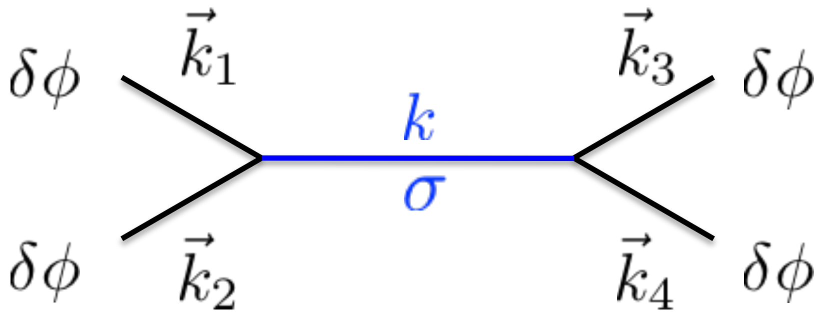
$$\langle \sigma\sigma \rangle_k \sim \frac{1}{k^3}\ ,\quad \text{if it is massless.}$$

$$\langle \delta\phi(\vec{k}_1)\delta\phi(\vec{k}_2)\delta\phi(\vec{k}_3)\delta\phi(\vec{k}_4) \rangle \sim \frac{1}{k^3}$$

⇓

$$\langle \delta_\rho(\vec{k}_1)\delta_\rho(\vec{k}_2)\delta_\rho(\vec{k}_3)\delta_\rho(\vec{k}_4) \rangle \sim ???$$

Squeezed 4pt spectrum



$$k_1 \approx k_2 \gg k,\ k_3 \approx k_4 \gg k$$

$$\langle \sigma\sigma \rangle_k \sim \frac{1}{k^3}\ , \quad \text{if it is massless.}$$

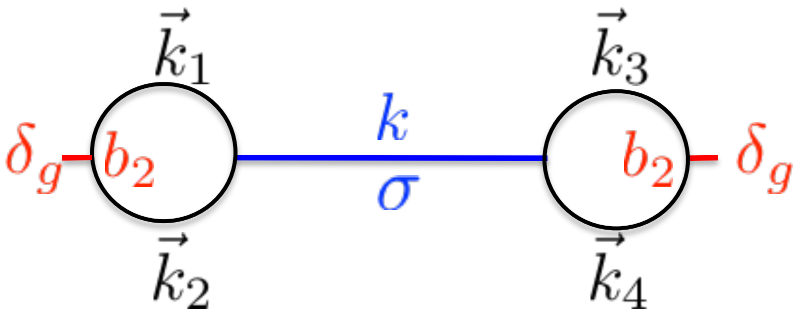
$$\langle \delta\phi(\vec{k}_1)\delta\phi(\vec{k}_2)\delta\phi(\vec{k}_3)\delta\phi(\vec{k}_4) \rangle \sim \frac{1}{k^3}$$

⇩

$$\langle \delta_\rho(\vec{k}_1)\delta_\rho(\vec{k}_2)\delta_\rho(\vec{k}_3)\delta_\rho(\vec{k}_4) \rangle \sim \frac{k_1^2 k_2^2 k_3^2 k_4^2}{k^3}$$

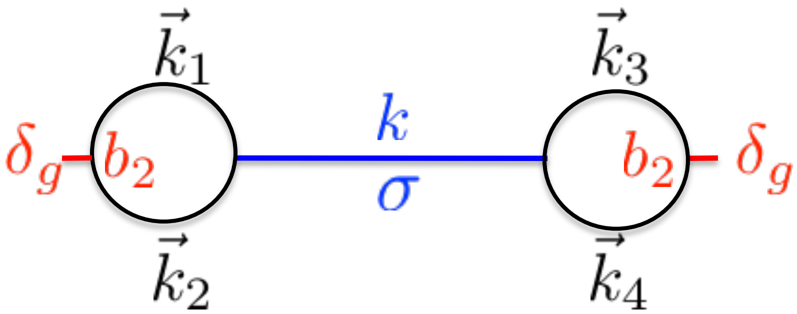
All the k_i's are short-distance!!

From 4pt to 2pt



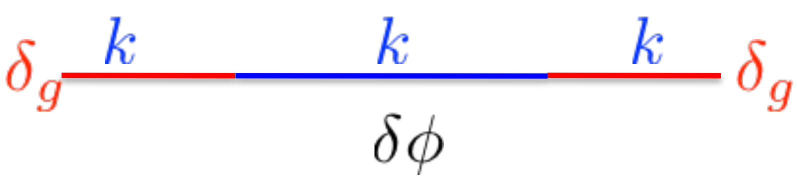
$$\langle \delta_g(\vec{k})\delta_g(-\vec{k})\rangle \sim \frac{b_2^2}{k^3}$$

From 4pt to 2pt



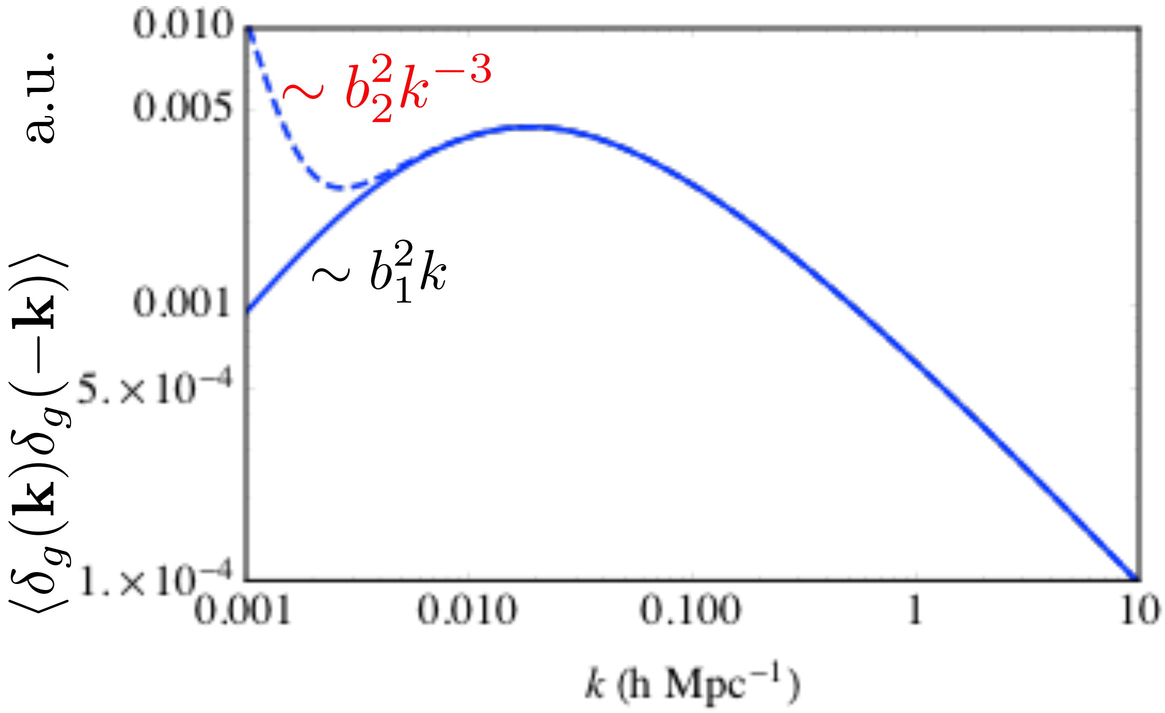
$$\langle \delta_g(\vec{k})\delta_g(-\vec{k})\rangle \sim \frac{b_2^2}{k^3}$$

Background from single field inflation without light mediator



$$\langle \delta_g(\vec{k})\delta_g(-\vec{k})\rangle \sim b_1^2 k$$

The expected signal of light fields



Quasi-single field inflation

- A new field couples to the inflaton

Quasi-single field inflation: Xingang Chen, Yi Wang 0911.3380
Cosmological collider physics: Nima Arkani-hamed, Juan Maldecena 1503.08043

$$\mathcal{L} = \sqrt{-g}\left[\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi\left(1+\frac{\sigma}{\Lambda}\right) - V(\phi) + \frac{1}{2}g^{\mu\nu}\partial_\mu\sigma\partial_\nu\sigma - V(\sigma)\right]$$

$$\phi \to \phi_0 + \delta\phi$$

Drives the inflation

Quantum fluactuation

Quasi-single field inflation

- $\mathcal{L} = \sqrt{-g}\left[\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi\left(1+\frac{\sigma}{\Lambda}\right) - V(\phi) + \frac{1}{2}g^{\mu\nu}\partial_\mu\sigma\partial_\nu\sigma - V(\sigma)\right]$

$$ds^2 = a^2(\tau)(d\tau^2 - dx^2 - dy^2 - dz^2)$$

$$\mathcal{L}^{(2)} = \frac{1}{2}a^2\left(\delta\phi'^2 - (\nabla\delta\phi)^2\right) + \frac{1}{2}a^2\left(\sigma'^2 - (\nabla\sigma)^2\right)$$
$$-\frac{1}{4}a^4 m_\sigma^2\sigma^2 + a^3\frac{\dot{\phi}_0}{\Lambda}\sigma\delta\phi'$$

$$\mathcal{L}^{(3)} = \frac{a^2\sigma}{2\Lambda}\eta^{\mu\nu}\partial_\mu\delta\phi\partial_\nu\delta\phi$$

Scale invariance

$$ds^2 = \frac{1}{H^2\tau^2}\left(d\tau^2 - dx^2 - dy^2 - dz^2\right)$$

Invariant under $\vec{x} \to c\vec{x}\ ,\ \tau \to c\tau$

(The full isometry group is much larger)

Propagators are invariant under isometric transformations

E.X. 2pt of a massive scalar in de Sitter space

$$\langle\sigma(\tau,\vec{x})\sigma(\tau',\vec{x}')\rangle = \frac{\Gamma(\frac{3}{2}+i\mu)\Gamma(\frac{3}{2}-i\mu)}{(4\pi)^2}\ {}_2F_1(\frac{3}{2}+i\mu,\frac{3}{2}-i\mu,2;1-\frac{1}{w})$$

$$w = 4\left[\frac{\tau\tau'}{-(\tau-\tau')^2+|\vec{x}-\vec{x}'|^2+i\epsilon}\right] \qquad \mu = \sqrt{\frac{m^2}{H^2}-\frac{9}{4}}$$

Out of the event horizon

- The physical object we are interested in are all the limit that

$$\tau \to 0$$

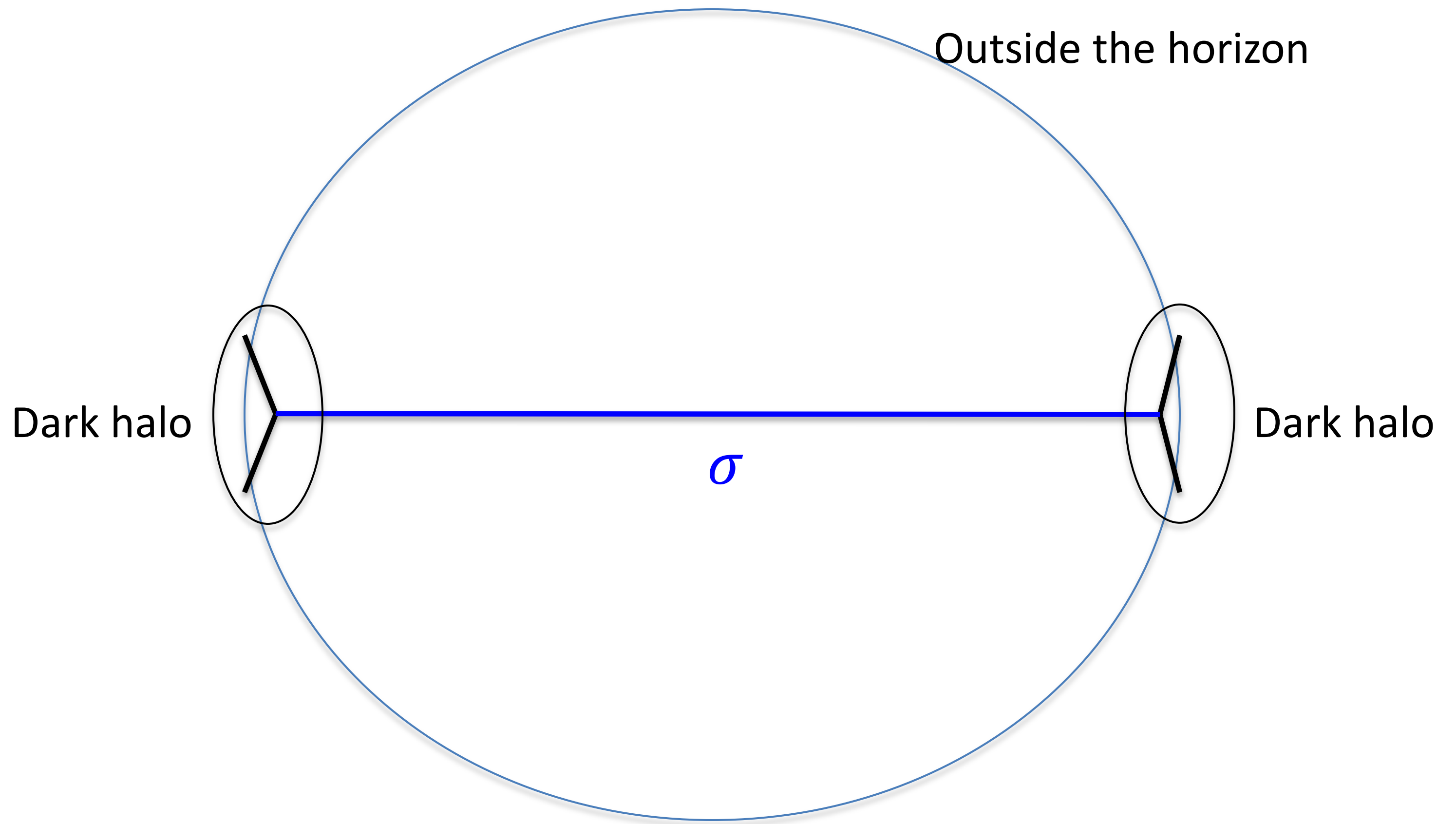
- All the operators can be expanded as powers of τ.

- $$\langle \sigma(\tau, \vec{x}) \sigma(\tau', \vec{x}') \rangle \to C \frac{(\tau\tau')^{\Delta}}{|\vec{x} - \vec{x}'|^{2\Delta}} \qquad \Delta = \frac{3}{2} - \sqrt{\frac{9}{4} - \frac{m_\sigma^2}{H^2}}$$

- In Fourier space

$$\langle \sigma(\tau, \vec{k}) \sigma(\tau', \vec{k}') \rangle \to C' \frac{(\tau\tau')^{\Delta}}{k^{3-2\Delta}} (2\pi)^3 \delta^3(\vec{k} - \vec{k}')$$

Outside of horizon



The equation of motion

- EOM

$$\mathcal{L}^{(2)} = \frac{1}{2}a^2\left(\delta\phi'^2 - (\nabla\delta\phi)^2\right) + \frac{1}{2}a^2\left(\sigma'^2 - (\nabla\sigma)^2\right)$$
$$-\frac{1}{4}a^4 m_\sigma^2\sigma^2 + a^3\frac{\dot{\phi}_0}{\Lambda}\sigma\delta\phi'$$

$$\delta\phi_k'' - \frac{2\delta\phi_k'}{\tau} + k^2\delta\phi_k - \frac{\dot{\phi}_0}{\Lambda H}\left(\frac{\sigma_k}{\tau} - \frac{3\sigma_k}{\tau^2}\right) = 0$$

$$\sigma_k'' - \frac{2\sigma_k'}{\tau} + \left(k^2 + \frac{m_\sigma^2}{H^2\tau^2}\right)\sigma_k + \frac{\dot{\phi}_0}{\Lambda H}\frac{\delta\phi_k'}{\tau} = 0$$

The equation of motion

- EOM $$\mathcal{L}^{(2)} = \frac{1}{2}a^2\left(\delta\phi'^2 - (\nabla\delta\phi)^2\right) + \frac{1}{2}a^2\left(\sigma'^2 - (\nabla\sigma)^2\right) - \frac{1}{4}a^4 m_\sigma^2\sigma^2 + a^3\frac{\dot{\phi}_0}{\Lambda}\sigma\delta\phi'$$

- $k\tau \to 0$ $$\delta\phi_k'' - \frac{2\delta\phi_k'}{\tau} + \cancelto{0}{k^2}\delta\phi_k - \frac{\dot{\phi}_0}{\Lambda H}\left(\frac{\sigma_k}{\tau} - \frac{3\sigma_k}{\tau^2}\right) = 0$$ $$\sigma_k'' - \frac{2\sigma_k'}{\tau} + \left(\cancelto{0}{k^2} + \frac{m_\sigma^2}{H^2\tau^2}\right)\sigma_k + \frac{\dot{\phi}_0}{\Lambda H}\frac{\delta\phi_k'}{\tau} = 0$$

Invariant under $\tau \to c\tau$ (Euler's differential equations)

General solution $\delta\phi \sim \tau^\alpha, \sigma \sim \tau^\alpha,$

Scaling indices

General solution $\delta\phi \sim \tau^{\alpha}, \sigma \sim \tau^{\alpha},$

$$\alpha_0 = 0\ , \quad \alpha_{\pm} = \frac{3}{2} \pm \sqrt{\frac{9}{4} - \frac{\mu^2}{H^2}}\ , \quad \alpha_3 = 3$$

$$\mu^2 = m_\sigma^2 + \left(\frac{\dot{\phi}_0}{\Lambda}\right)^2$$

Scaling indices

General solution $\delta\phi \sim \tau^{\alpha}, \sigma \sim \tau^{\alpha},$

$$\alpha_0 = 0 \;, \quad \alpha_{\pm} = \frac{3}{2} \pm \sqrt{\frac{9}{4} - \frac{\mu^2}{H^2}} \;, \quad \alpha_3 = 3$$

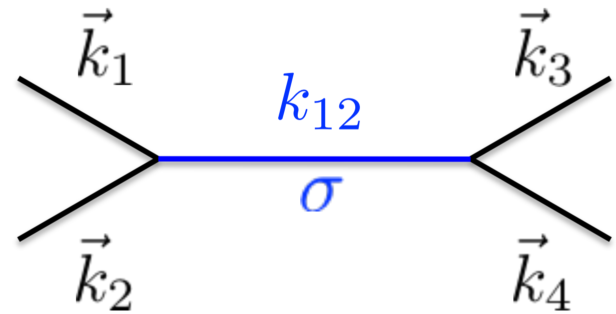
$$\mu^2 = m_\sigma^2 + \left(\frac{\dot{\phi}_0}{\Lambda}\right)^2$$

$\delta\phi$

For the intermediate state

The leading contribution of $<\sigma\sigma>$ is from $\dfrac{(\tau\tau')^{\alpha_-}}{k^{3-2\alpha_-}}$

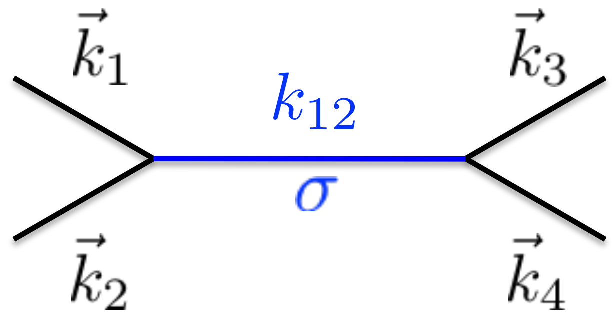
4pt result



- Real calculation is needed to get the coefficients, we developed an IR effective theory to calculate them analytically.

$$N_\zeta^{(4)}(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3,\mathbf{k}_4) = \left(\frac{H^2}{\dot\phi_0}\right)^4 \left(\frac{V'''}{H}\right)^2 \left(\prod_{i=1}^4 \frac{1}{k_i^3}\right) \frac{1}{k_{12}^3} \frac{(3\mu/2)^4 H^8}{2(\mu^2+m^2)^6}$$
$$\times \left[\left(k_1^3 k_2^{\alpha_-} + k_1^{\alpha_-} k_2^3\right)\left(k_3^3 k_4^{\alpha_-} + k_3^{\alpha_-} k_4^3\right)\left(\frac{k_{12}}{k_{UV_{12}} k_{UV_{34}}}\right)^{2\alpha_-} \right.$$
$$+ 2\left(1 - \frac{2}{3}\left(\frac{k_{UV_{34}}}{k_{UV_{12}}}\right)^{\alpha_-}\right)(k_1^3 k_2^{\alpha_-} + k_1^{\alpha_-} k_2^3)(k_3 k_4)^{\alpha_-} \frac{k_{12}^3}{k_{UV_{12}}^{2\alpha_-} k_{UV_{34}}^{\alpha_-}}$$
$$\left. + \frac{2}{3}(k_1 k_2)^{\alpha_-}\left(k_3^3 k_4^{\alpha_-} + k_3^{\alpha_-} k_4^3\right)\frac{k_{12}^3}{k_{UV_{12}}^{3\alpha_-}} \right] + \text{cyc. perm}(\mathbf{k}_2,\mathbf{k}_3,\mathbf{k}_4)$$

4pt result



- Real calculation is needed to get the coefficients, we developed an IR effective theory to calculate them analytically.

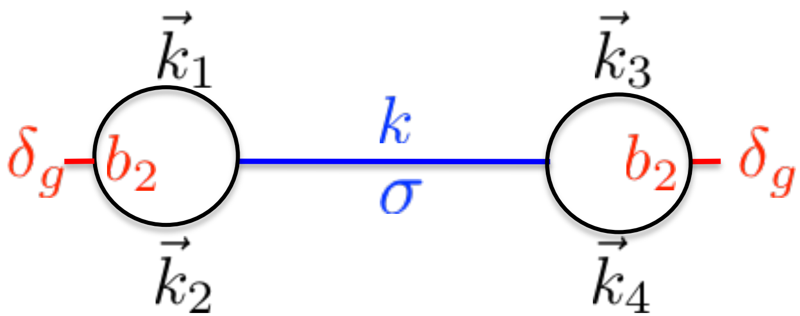
$$N_\zeta^{(4)}(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3,\mathbf{k}_4) = \left(\frac{H^2}{\dot\phi_0}\right)^4 \left(\frac{V'''}{H}\right)^2 \left(\prod_{i=1}^{4}\frac{1}{k_i^3}\right) \frac{1}{k_{12}^3} \frac{(3\mu/2)^4 H^8}{2(\mu^2+m^2)^6}$$
$$\times \left[\left(k_1^3 k_2^{\alpha_-} + k_1^{\alpha_-} k_2^3\right)\left(k_3^3 k_4^{\alpha_-} + k_3^{\alpha_-} k_4^3\right) \left(\frac{k_{12}}{k_{UV_{12}} k_{UV_{34}}}\right)^{2\alpha_-} \right.$$
$$+ 2\left(1 - \frac{2}{3}\left(\frac{k_{UV_{34}}}{k_{UV_{12}}}\right)^{\alpha_-}\right)(k_1^3 k_2^{\alpha_-} + k_1^{\alpha_-} k_2^3)(k_3 k_4)^{\alpha_-} \frac{k_{12}^3}{k_{UV_{12}}^{2\alpha_-} k_{UV_{34}}^{\alpha_-}}$$
$$\left. + \frac{2}{3}(k_1 k_2)^{\alpha_-}\left(k_3^3 k_4^{\alpha_-} + k_3^{\alpha_-} k_4^3\right) \frac{k_{12}^3}{k_{UV_{12}}^{3\alpha_-}} \right] + \text{cyc. perm}(\mathbf{k}_2,\mathbf{k}_3,\mathbf{k}_4)$$

$$\frac{1}{k_{12}^{3-2\alpha_-}}$$

2pt of galaxy distribution

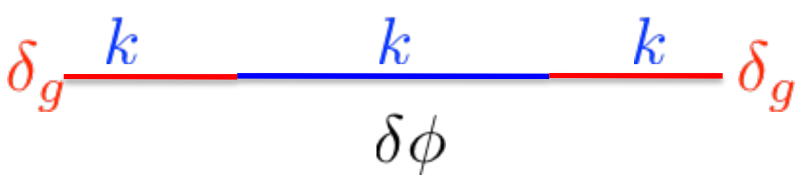
- A new field couples to the inflaton

$$\mathcal{L} = \sqrt{-g}\left[\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi\left(1+\frac{\sigma}{\Lambda}\right) - V(\phi) + \frac{1}{2}g^{\mu\nu}\partial_\mu\sigma\partial_\nu\sigma - V(\sigma)\right]$$



$$\langle\delta_g(\vec{k})\delta_g(-\vec{k})\rangle \sim \frac{b_2^2}{k^{3-2\alpha_-}}$$

$$\alpha_- \approx \frac{m_\sigma^2}{3H_{\rm inf}^2}$$

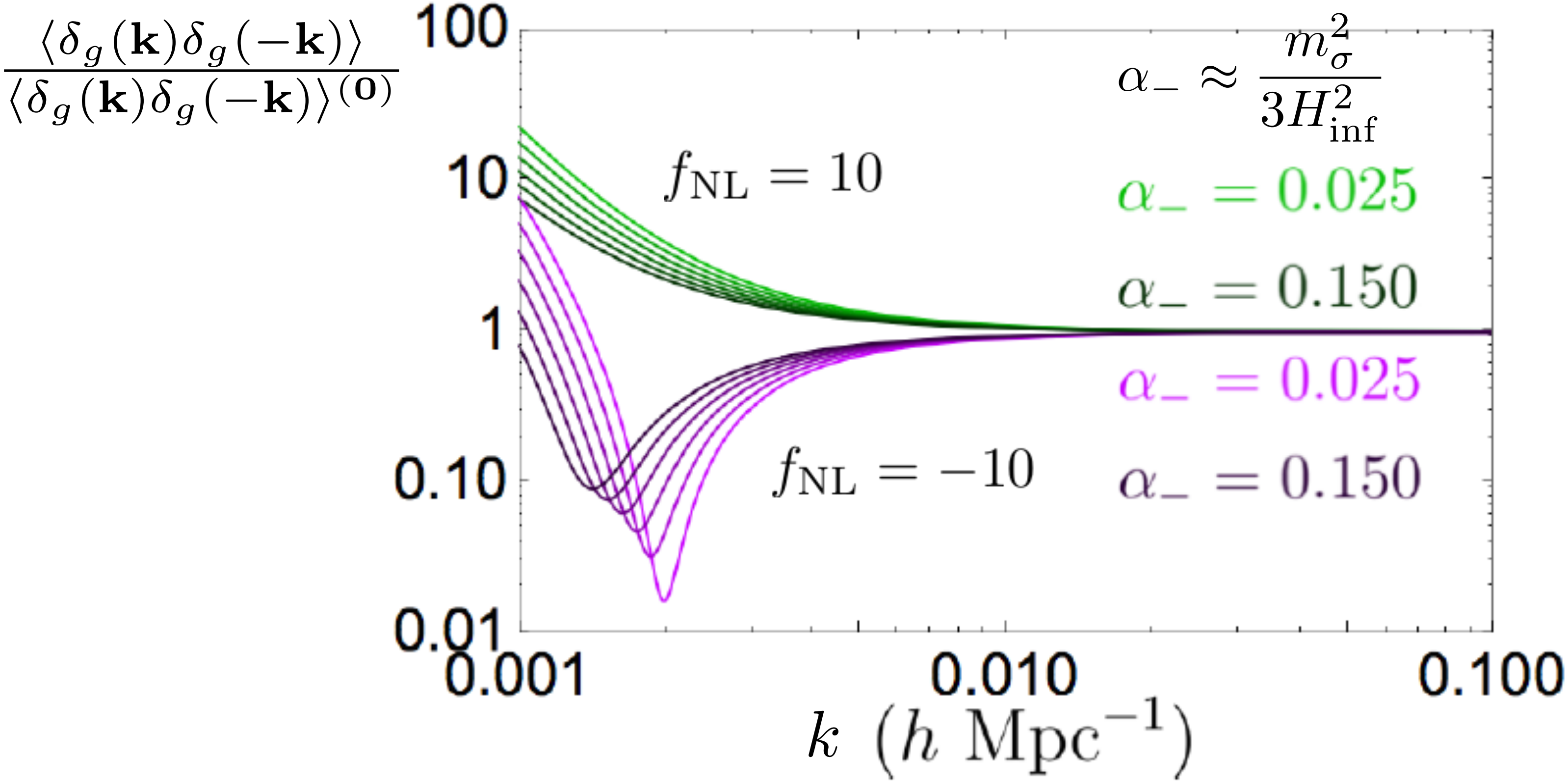


$$\langle\delta_g(\vec{k})\delta_g(-\vec{k})\rangle \sim b_1^2 k$$

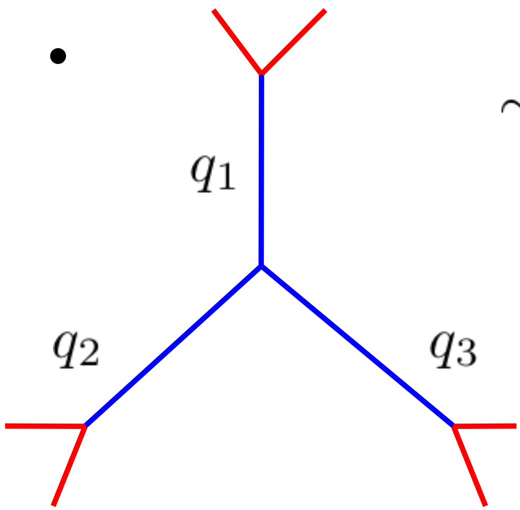
2pt of δ_g with light σ

•

HA, M. McAneny, A.K.Ridgway, M.B.Wise, 1711.02667

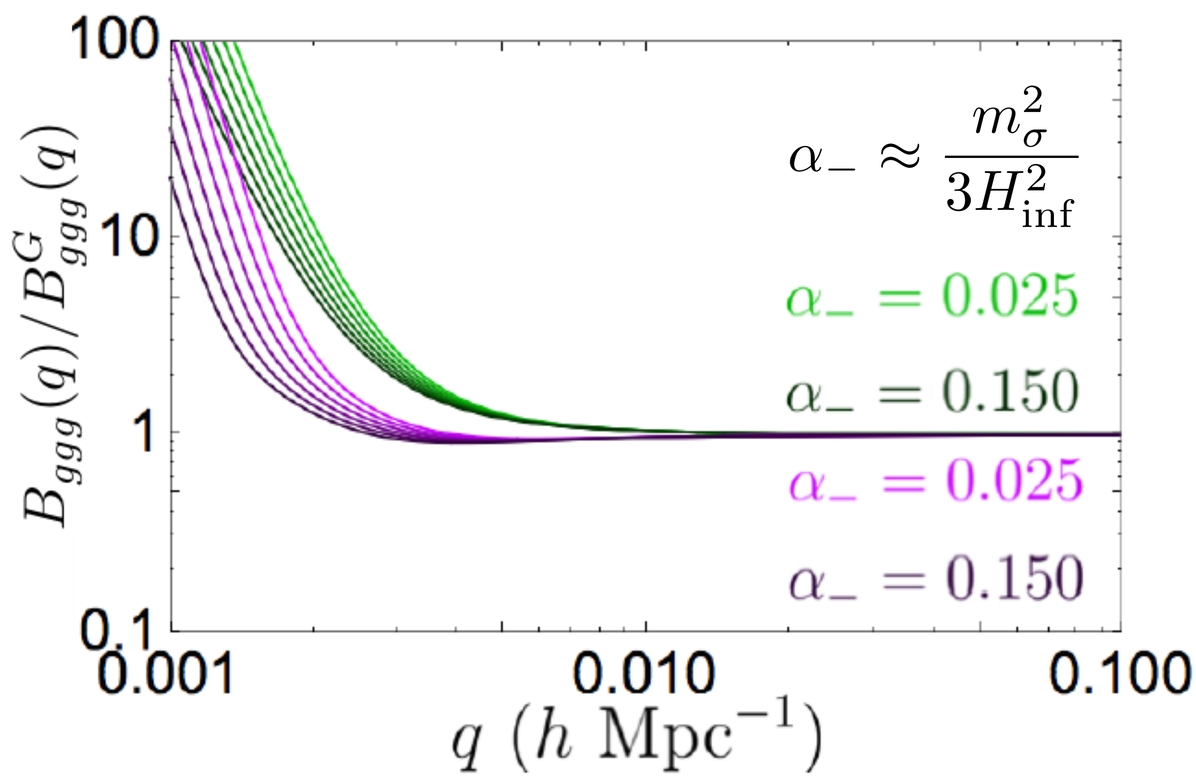


3pt of δ_g with light σ

- 

$$\sim \frac{1}{q^6}$$

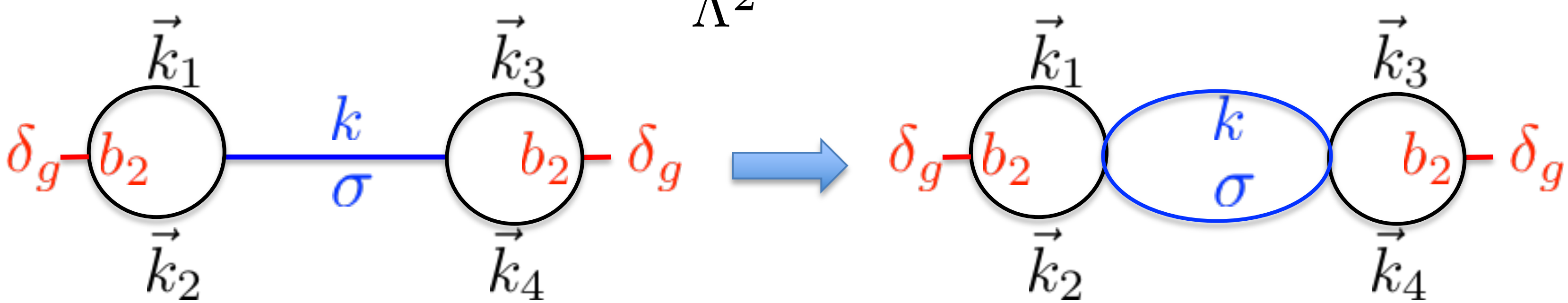
HA, M. McAneny, A.K.Ridgway, M.B.Wise, 1711.02667



From tree to loop

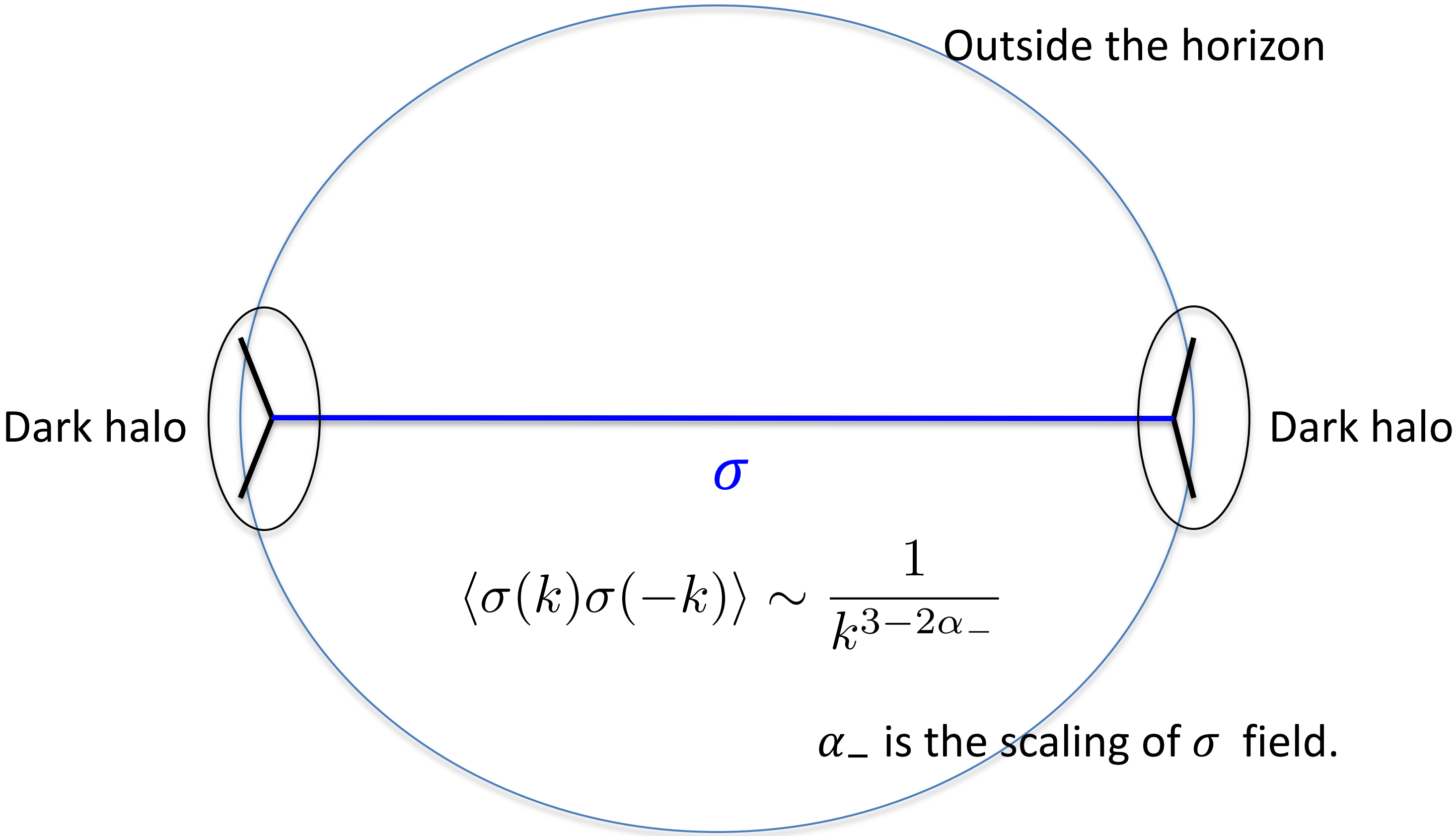
$$\mathcal{L} = \sqrt{-g}\left[\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi\left(1+\frac{\sigma}{\Lambda}\right) - V(\phi) + \frac{1}{2}g^{\mu\nu}\partial_\mu\sigma\partial_\nu\sigma - V(\sigma)\right]$$

Z_2 symmetry $\quad \dfrac{\sigma^2}{\Lambda^2}$



Do we still have the enhancement in small *k* region?

Outside of horizon

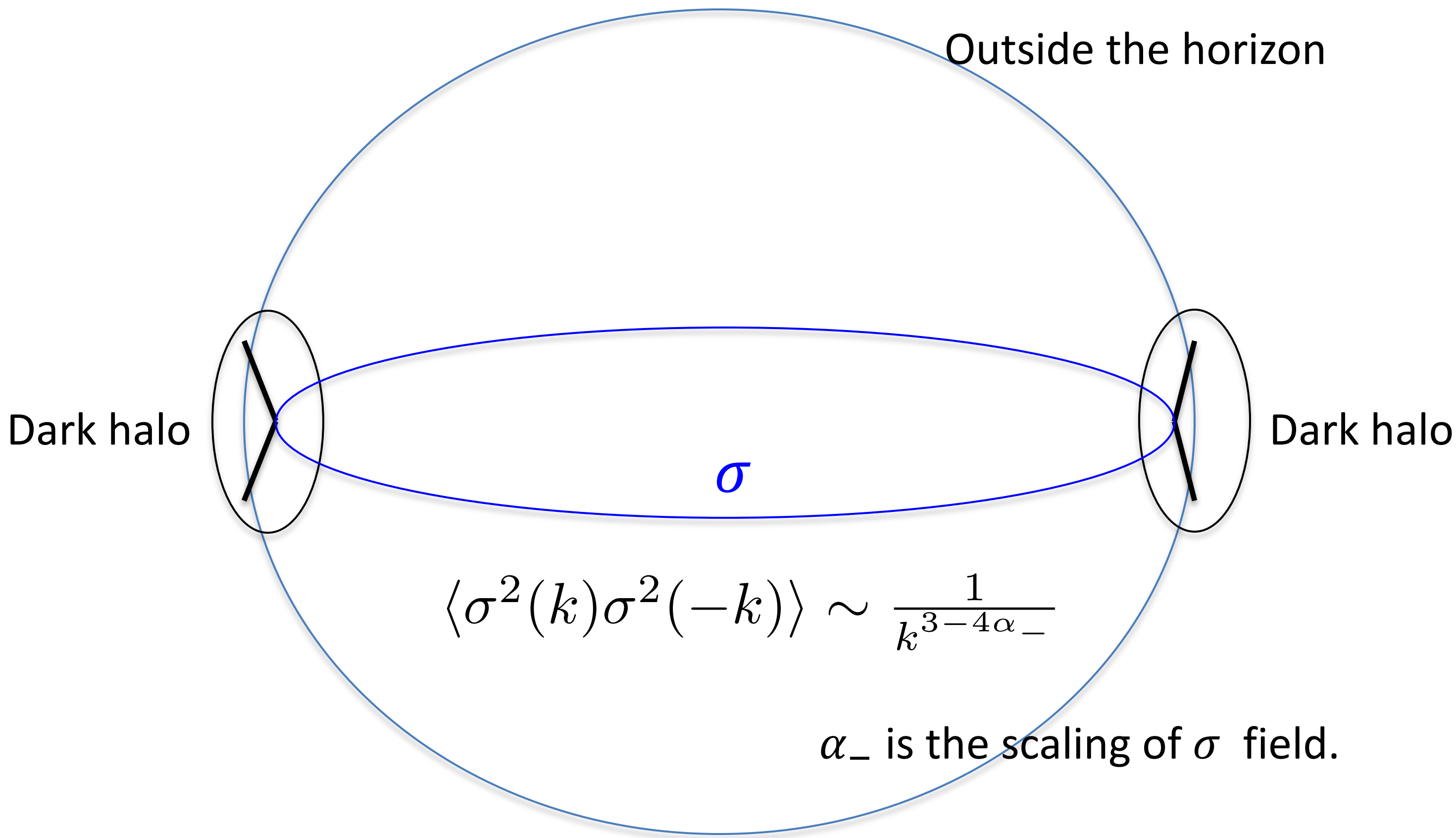


$$\langle \sigma(k)\sigma(-k)\rangle \sim \frac{1}{k^{3-2\alpha_-}}$$

α_- is the scaling of σ field.

$$\alpha_- \approx \frac{m_\sigma^2}{3H_{\rm inf}^2}$$

Light particle loop



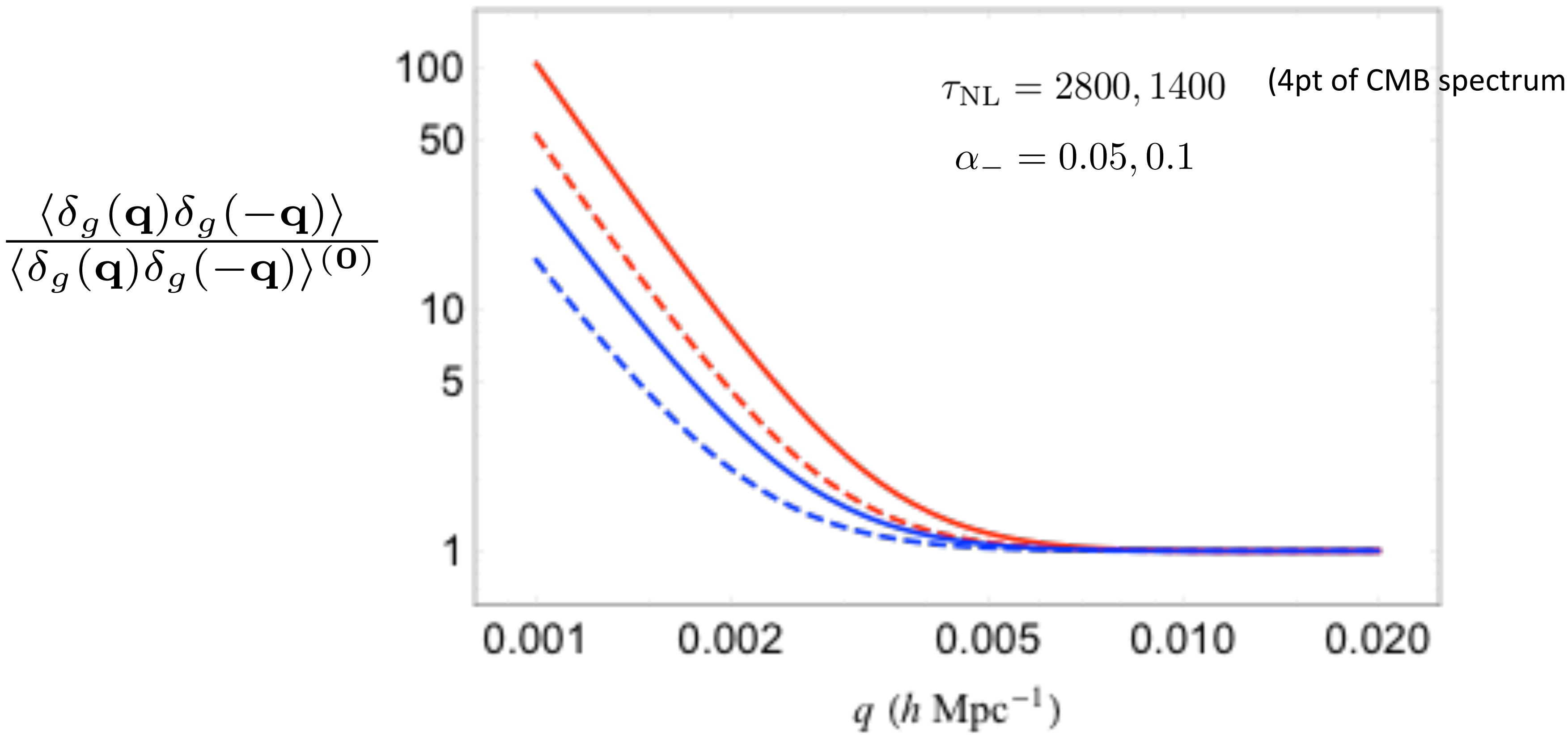
$$\langle \sigma^2(k)\sigma^2(-k)\rangle \sim \frac{1}{k^{3-4\alpha_-}}$$

α_- is the scaling of σ field.

$$\alpha_- \approx \frac{m_\sigma^2}{3H_{\rm inf}^2}$$

Light particle loop

HA, M. B. Wise, Z.-P. Zhang, arXiv:1806.05194



Summary

- We expect a rise in the small *k* region of the 2pt correlation function of the galaxy or cluster number distributions if there is a light field coupled to the inflaton field.
- This effect can be from both tree level and loop level diagrams.