Large scale structure as a probe of new particles

Haipeng An (Tsinghua University)

13th TeV Physics Working Group Meeting

Aug 21, 2018

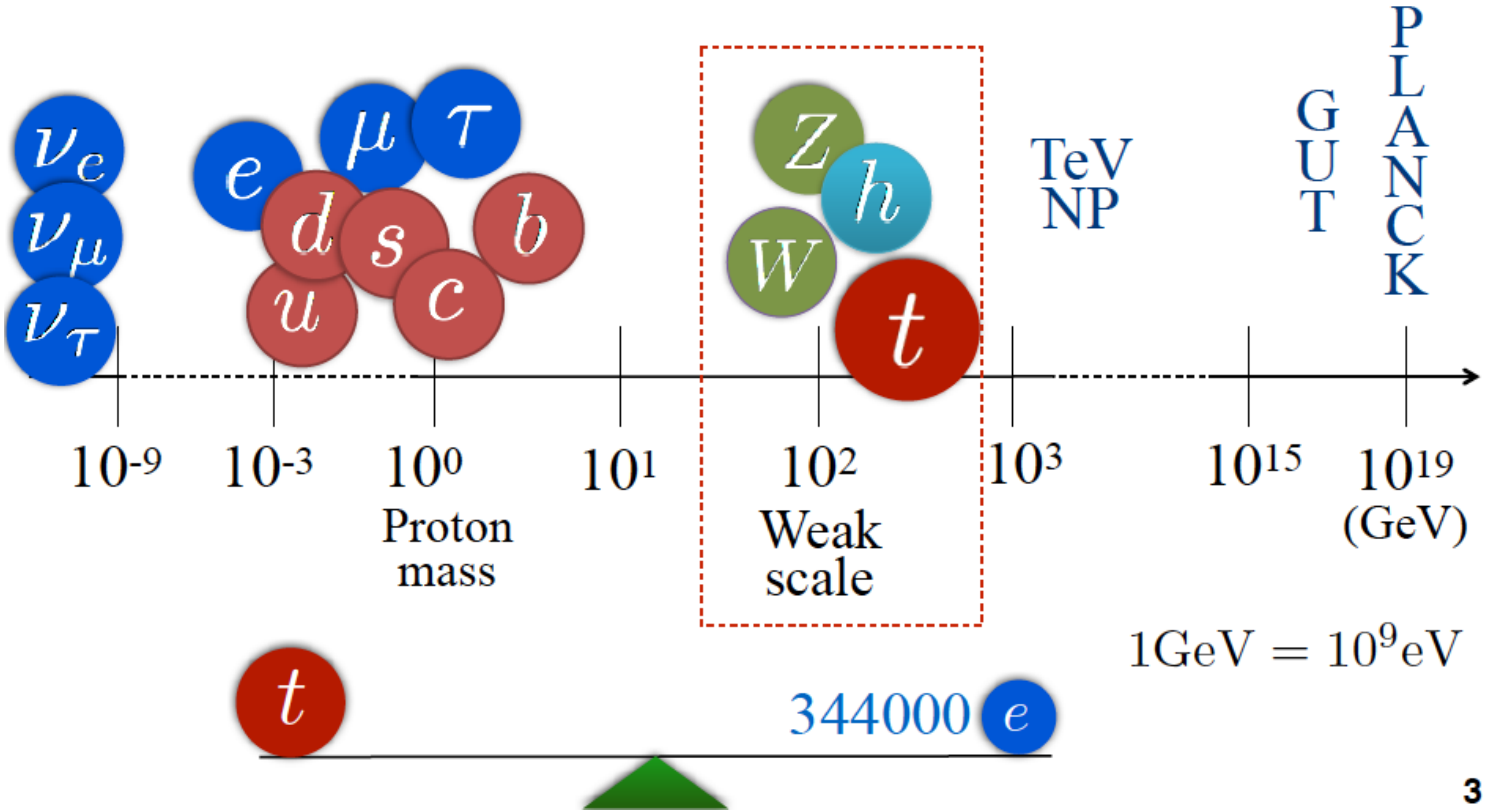
HA, M. McAneny, A.K.Ridgway, M.B.Wise, 1711.02667

HA, M. B. Wise, Zipei Zhang, 1806.05194

Two outstanding puzzles in SM

Origins of EWSB and Flavor breaking

(*W/Z Masses*) (*Fermion Mass*)



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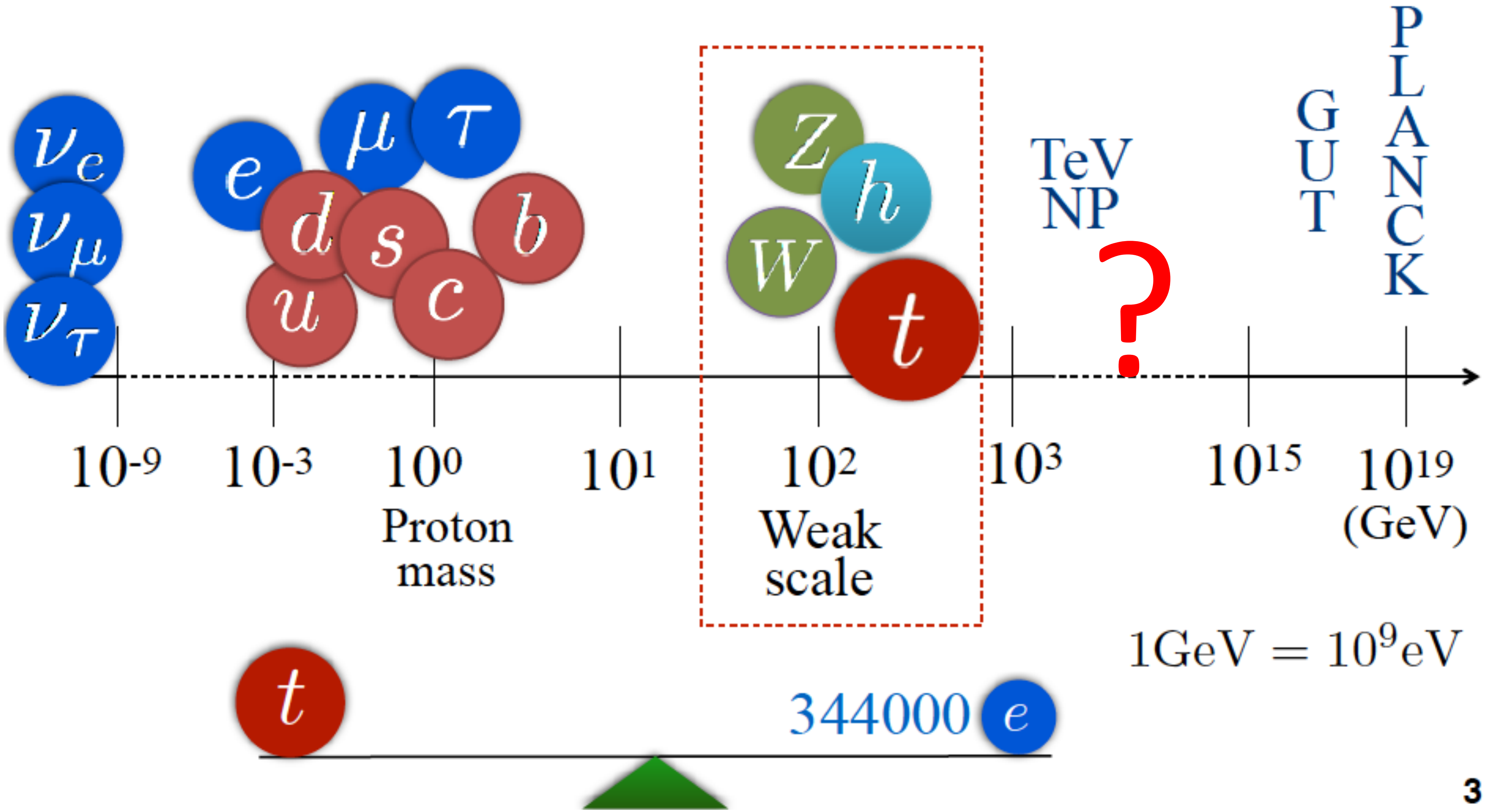
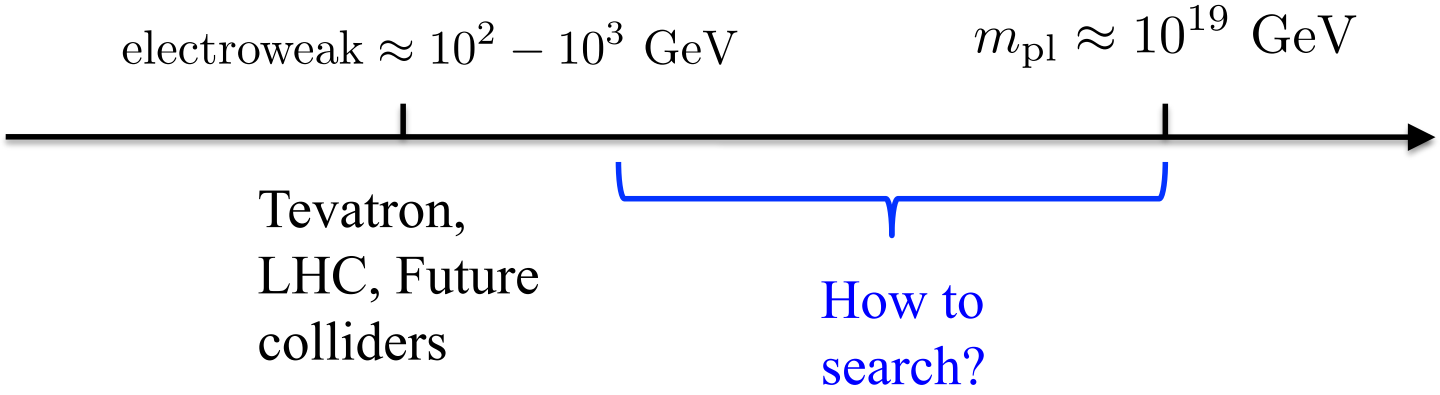


Search for new physics

- Collider physics



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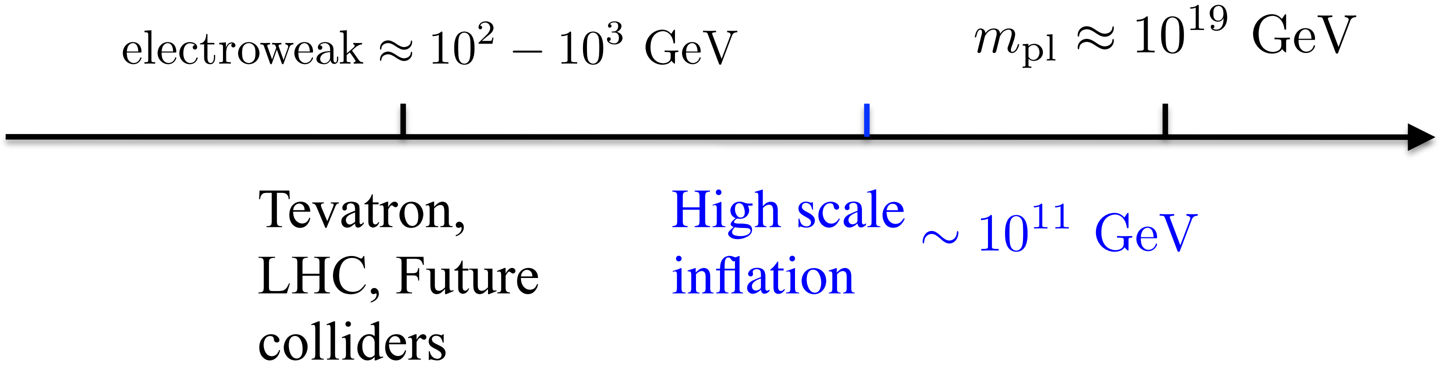
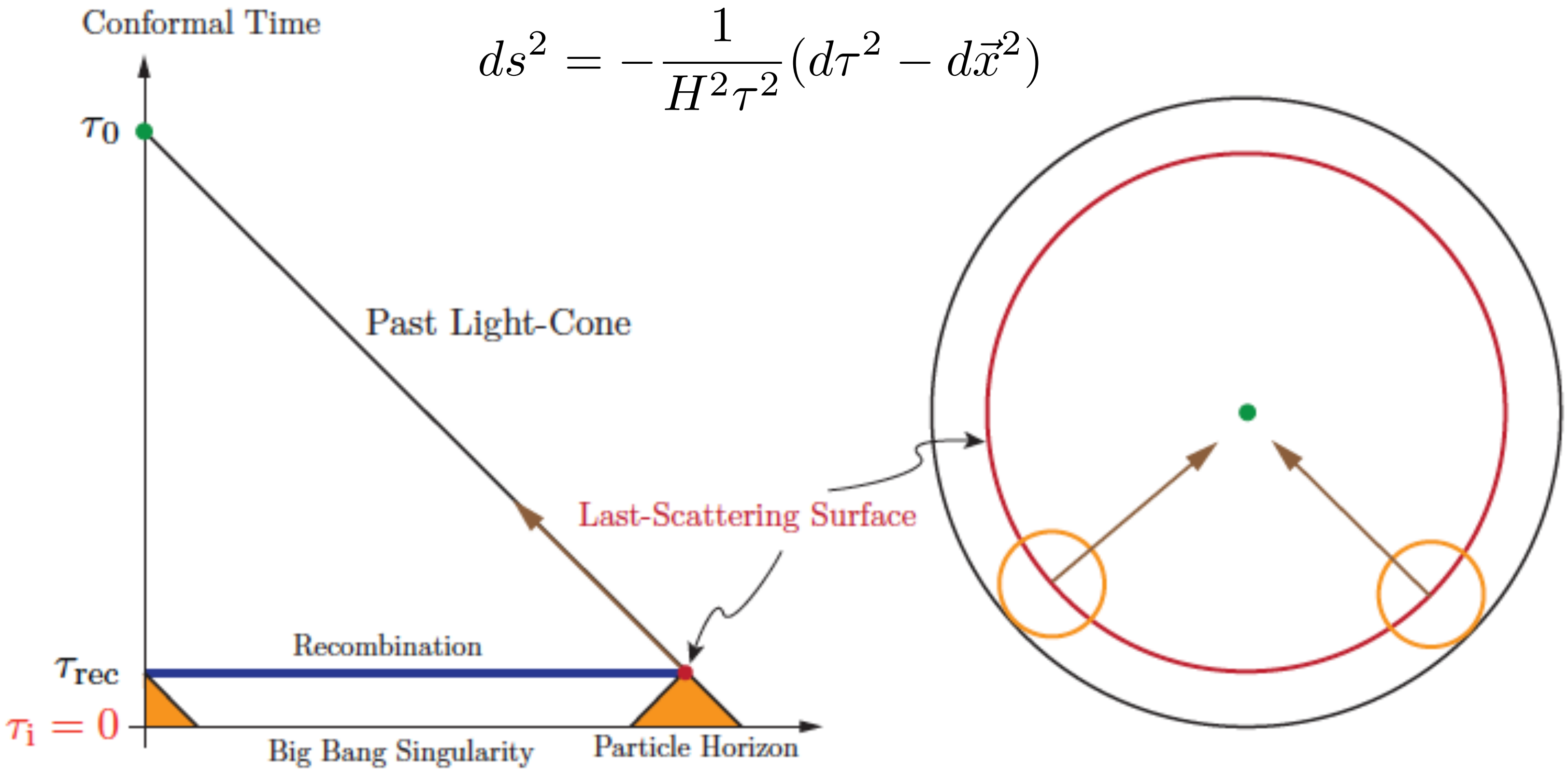
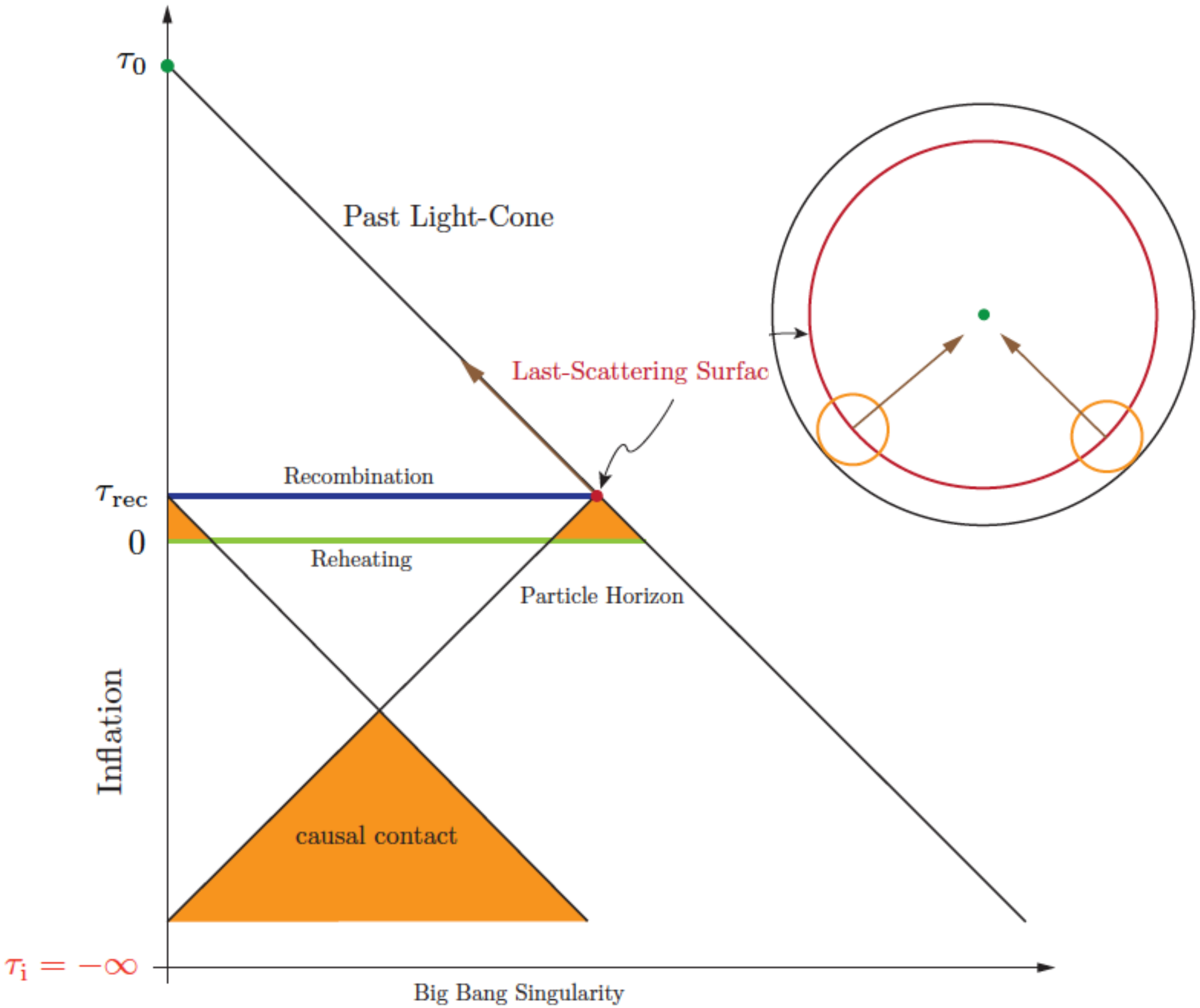


Why inflation?

$$ds^2 = -\frac{1}{H^2\tau^2}(d\tau^2 - d\vec{x}^2)$$

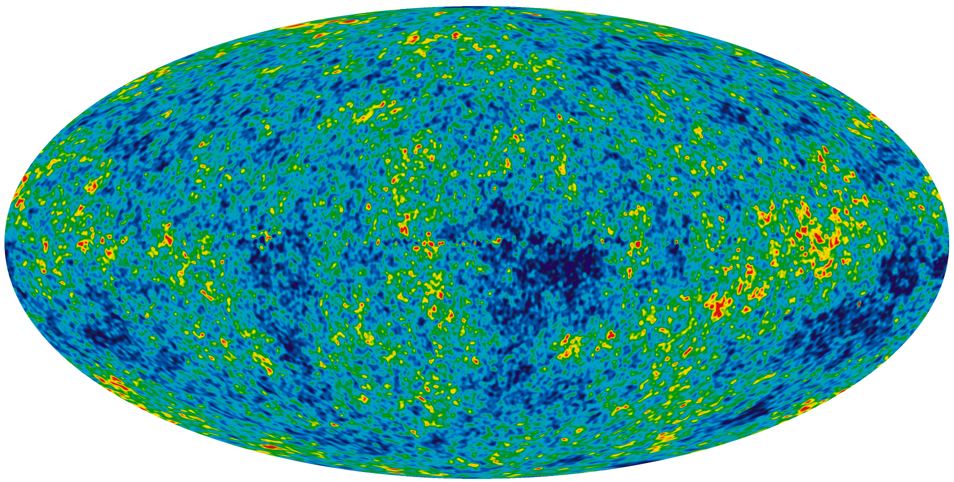


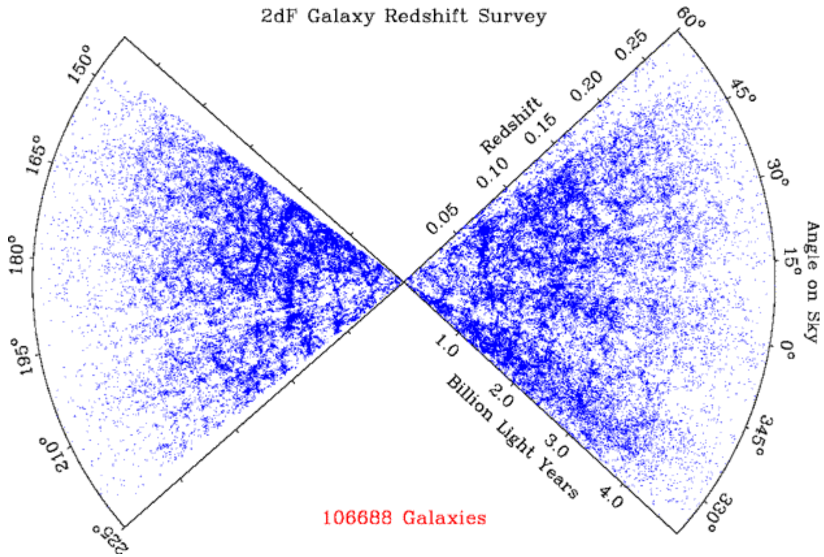
Why inflation?



The seeds of today's Universe

- Quantum fluctuation generates the original condition of the structure of the universe.



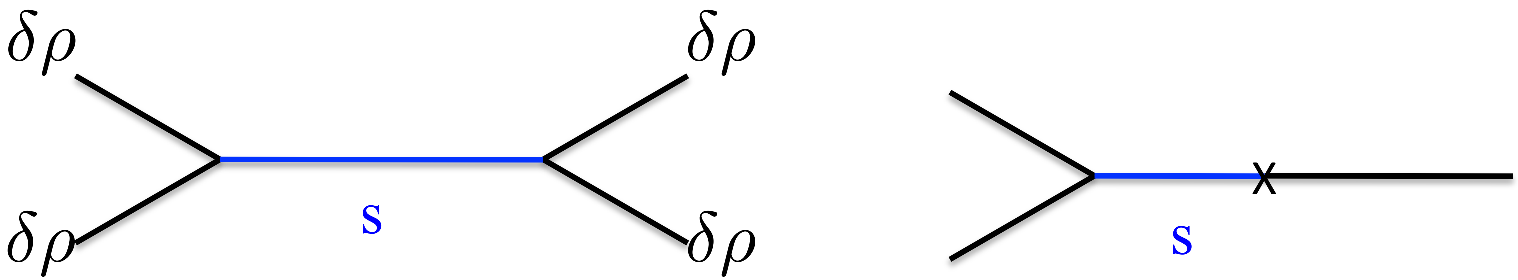


Search for new particles

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

$$\phi \longrightarrow \delta\phi \longrightarrow \Phi \longrightarrow \delta\rho$$

Inflaton	Inflaton perturbation	Curvature perturbation	Density perturbation



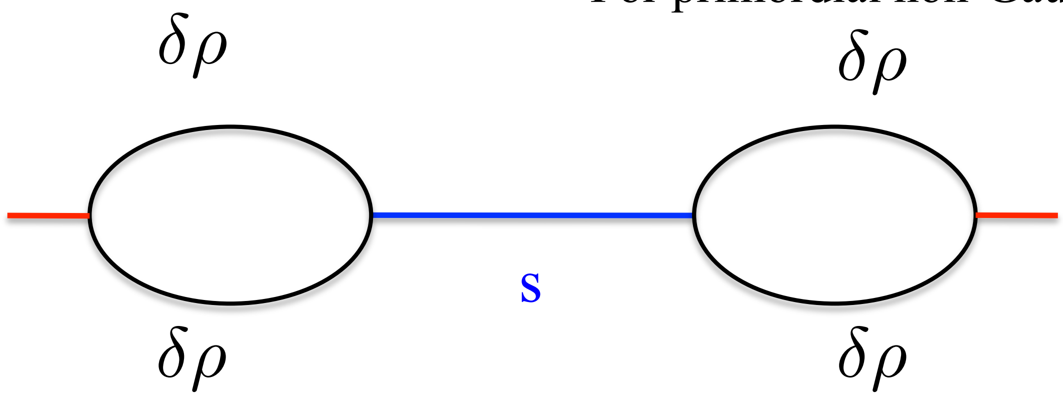
Search for new particles

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

B. Grinstein and M. Wise ApJ 1986.

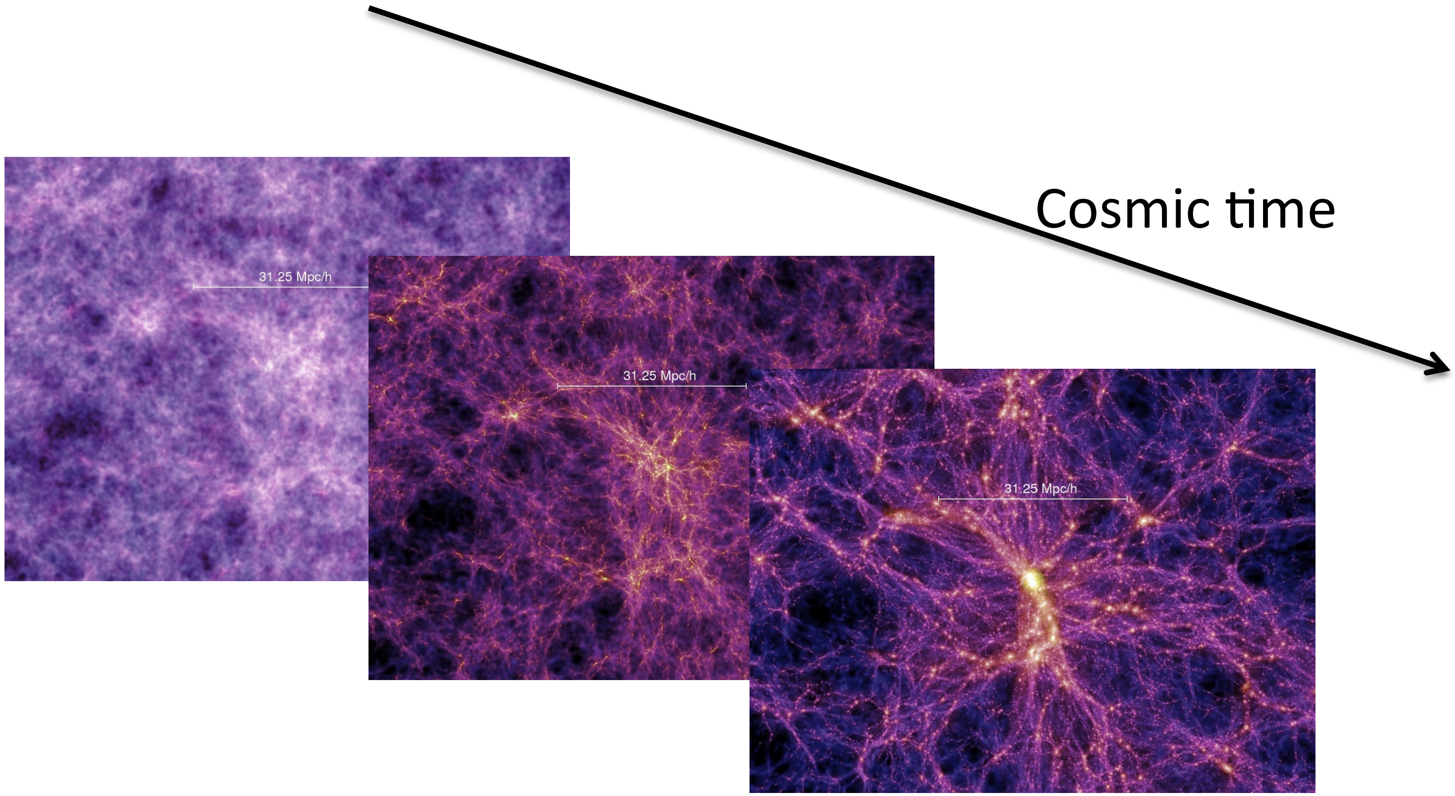
Dalal, Dore, Huterer, Shirokov PRD 2008

For primordial non-Gaussianity



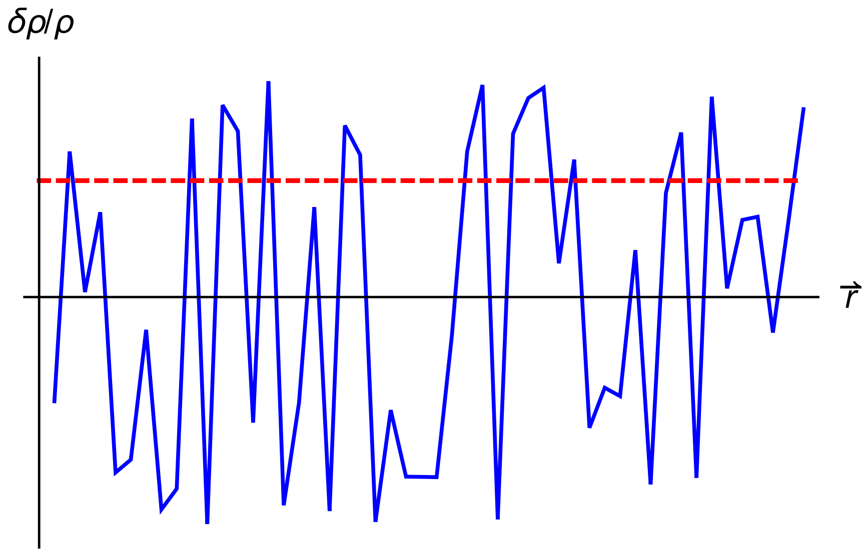
  - In this work, we are going to generate to particles.

The large scale structure



Formation of galactic halos

- Galaxy or halo formation is nonlinear.



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

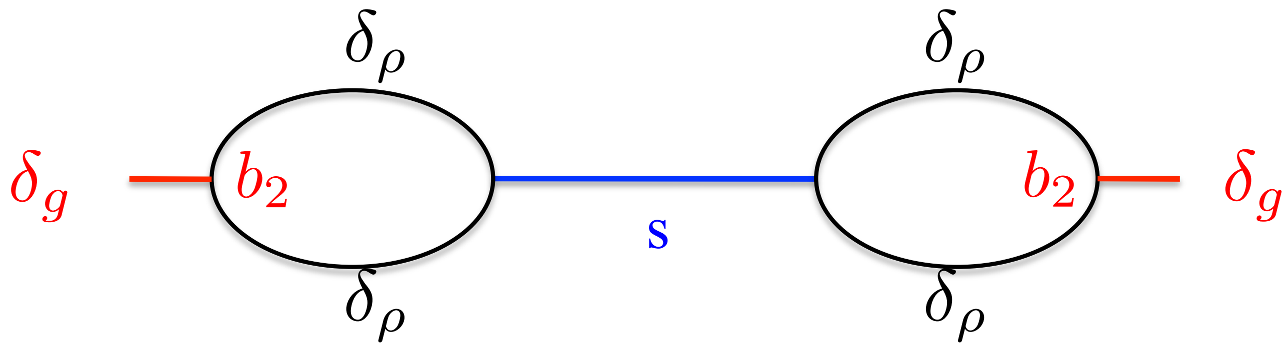
$$n_g(\mathbf{r}) = \Theta\left(\frac{\delta\rho(\mathbf{r})}{\bar{\rho}} - \delta_c\right)$$

Cosmic bias

- Cosmological bias

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

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



Why this is interesting?

- Massless scalar field

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

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

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

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From the Poisson equation

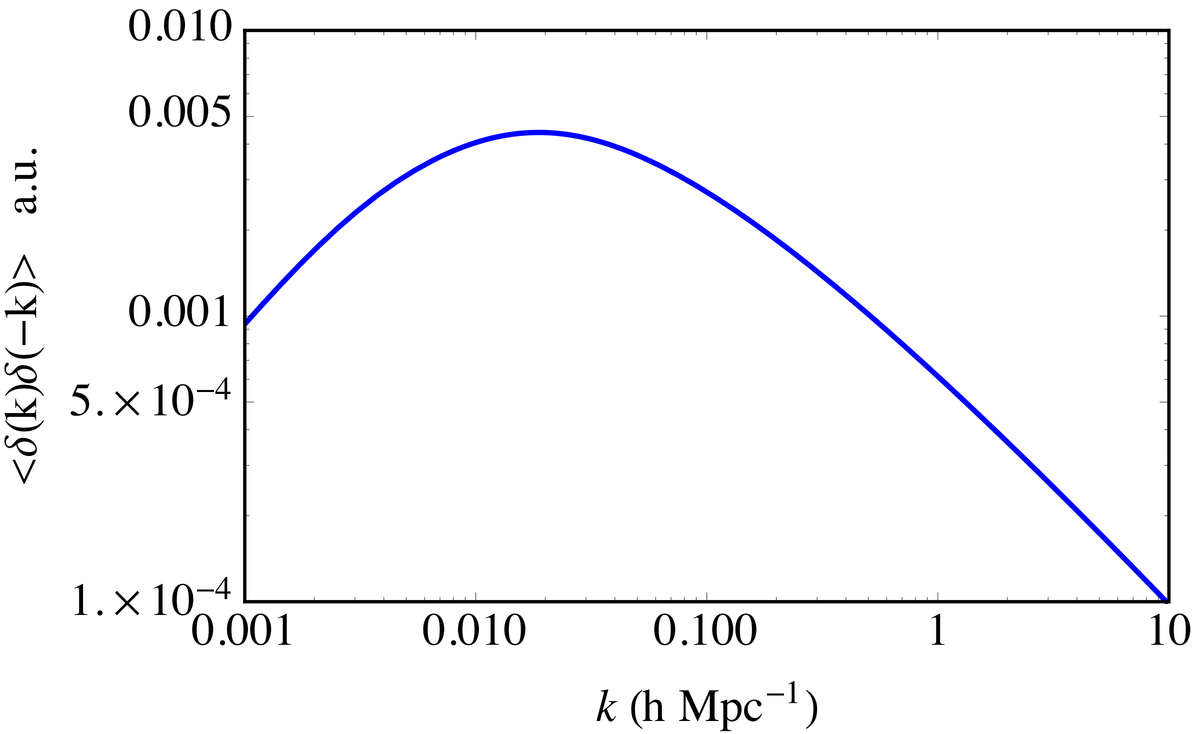
$$\nabla^2\Phi = 4\pi G\rho$$

Transfer function

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

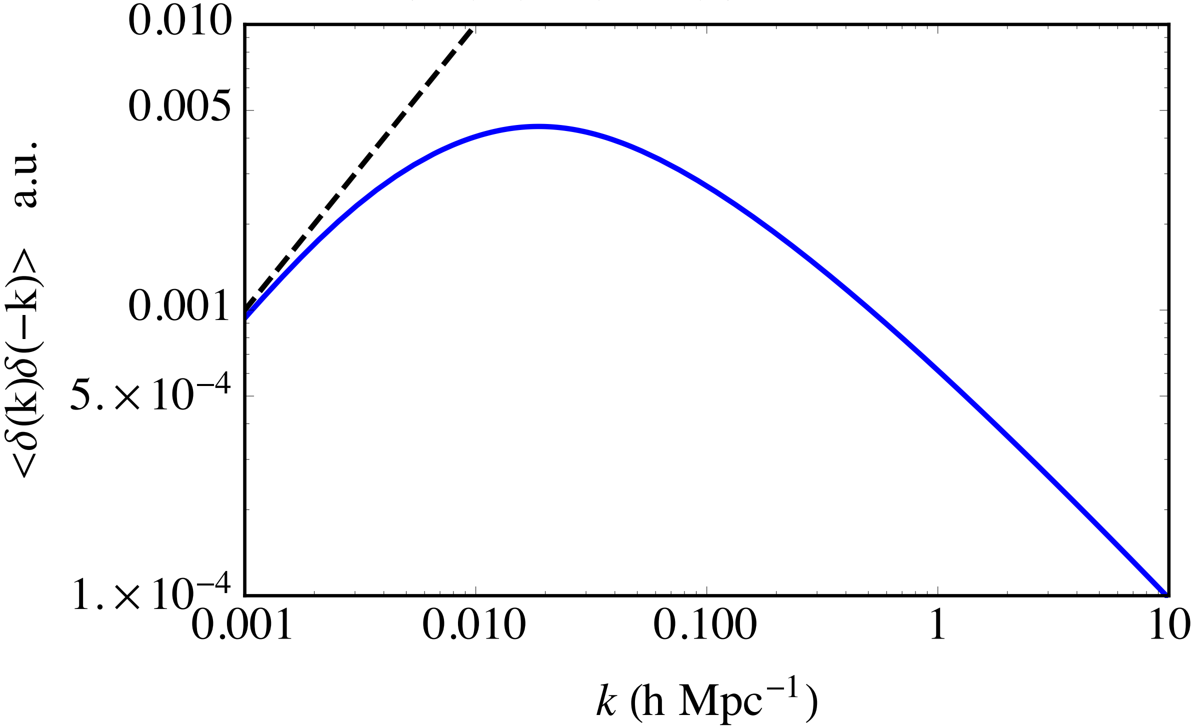
Growth function

Why this is interesting?

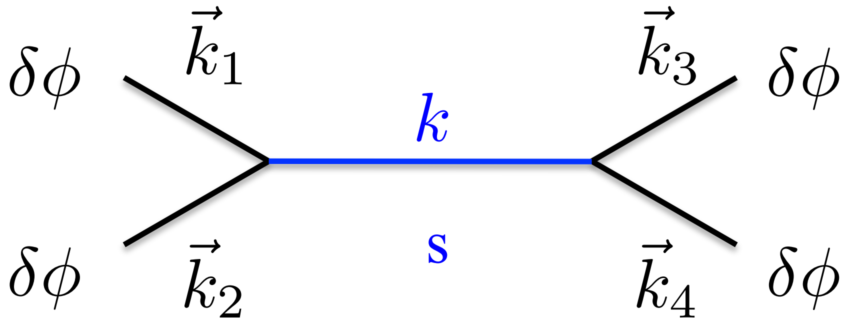


Why this is interesting?

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



Squeezed 4pt spectrum



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

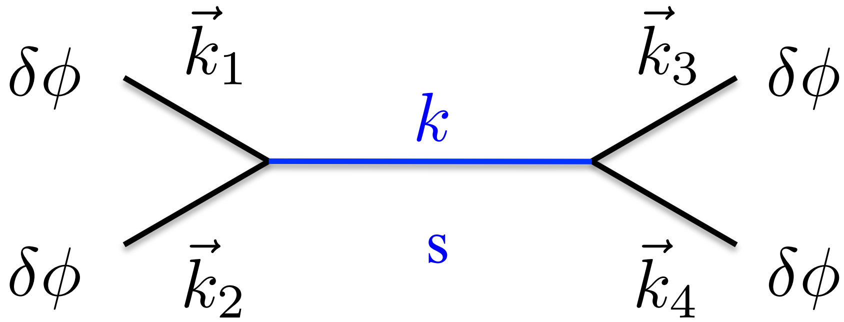
$$\langle \sigma\sigma \rangle_k \sim \frac{1}{k^3}\;, \quad \text{if it is massless.}$$

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

⇓

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

Squeezed 4pt spectrum



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

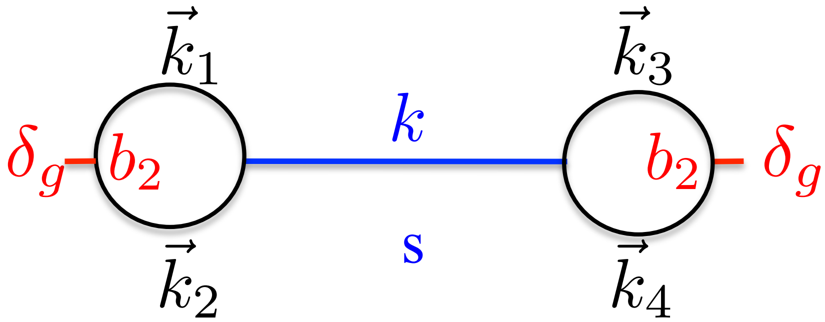
$$\langle \delta\phi(\vec{k}_1)\delta\phi(\vec{k}_2)\delta\phi(\vec{k}_3)\delta\phi(\vec{k}_4)\rangle \sim \frac{1}{k^3}$$

$$\Downarrow$$

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

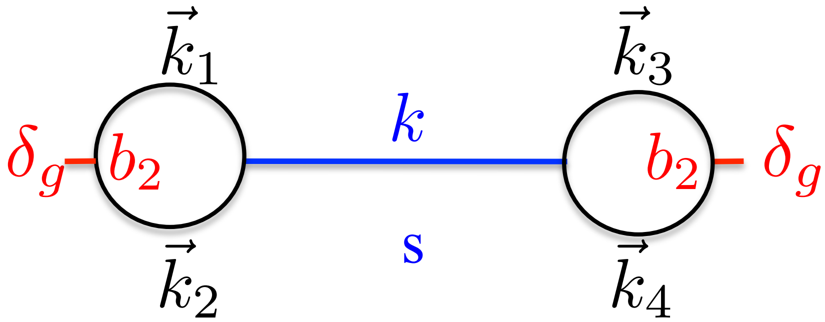
All the k_i's are short-distance!!

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



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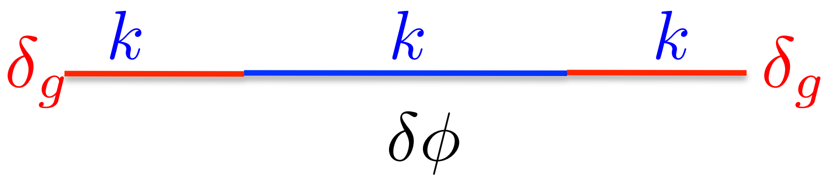
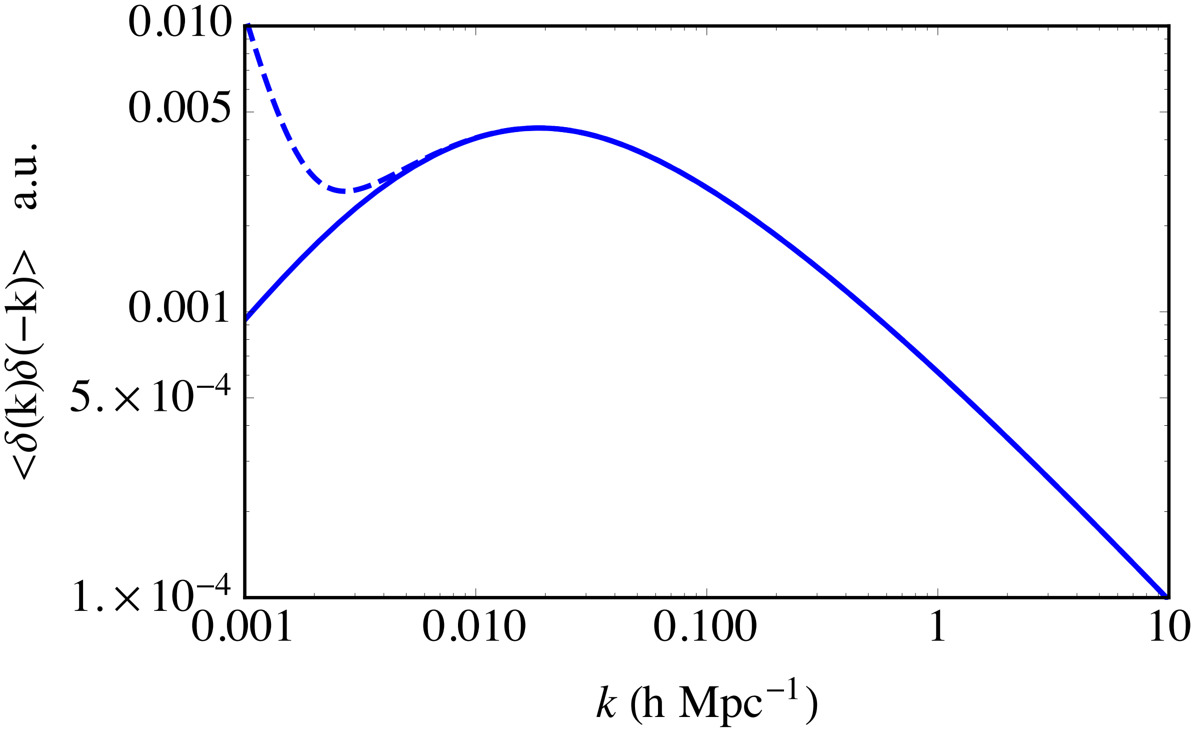


$$\langle \delta_g(\vec{k})\delta_g(-\vec{k})\rangle \sim b_1^2 k$$

The expected signal of light fields

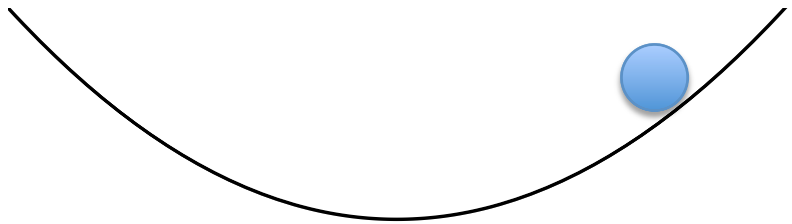


Outline

- Brief introduction of slow roll inflation
- Tree-level example
- One-loop example
- Summary and outlook

Slow roll model

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



$$\left|\frac{\dot\phi}{\phi H}\right| \ll 1\,, \quad \left|\frac{\ddot\phi}{H\dot\phi}\right| \ll 1$$

The simplest case $V(\phi) = \frac{1}{2}m_\phi^2\phi^2$

$$\ddot\phi + 3H\dot\phi + m^2\phi = 0 \quad \Longrightarrow \quad 3H\dot\phi + m^2\phi = 0$$

$\Longrightarrow$ $m^2 \ll H^2$

$\Longrightarrow$ A shift symmetry in ϕ field

Tree level example

- A new field couples to the inflaton

$$\mathcal{L} = \sqrt{-9}\left[\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi\left(1+\frac{s}{\Lambda}\right) - V(\phi) + \frac{1}{2}g^{\mu\nu}\partial_\mu s\partial_\nu s - V(\sigma)\right]$$

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

Quasi-single field inflation

- Perturbations $\phi = \phi_0 + \pi$ $\mu = \frac{\dot{\phi}_0}{\Lambda}$

$$\mathcal{L}_0 = \frac{1}{2(H\tau)^2}\left((\partial_\tau \pi)^2 - \nabla\pi\cdot\nabla\pi + (\partial_\tau s)^2 - \frac{m^2}{(H\tau)^2}s^2 - \nabla s\cdot\nabla s - \frac{2\mu}{H\tau}s\partial_\tau\pi\right)$$

$$\mathcal{L}_{\rm int} = \frac{1}{(H\tau)^4}\left(\frac{(H\tau)^2}{\Lambda}\left((\partial_\tau\pi)^2 - \nabla\pi\cdot\nabla\pi\right)s - \frac{V'''}{3!}s^3 - \frac{V^{(4)}}{4!}s^4\ldots\right)$$

$$ds^2 = -\frac{1}{H^2\tau^2}(d\tau^2 - d\vec{x}^2)$$

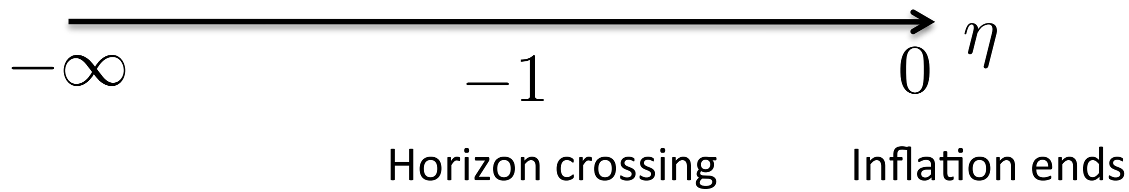
- Mode expansion $\eta = k\tau$

$$\pi(\mathbf{x},\tau) = \int\frac{d^3k}{(2\pi)^3}\left(a^{(1)}(\mathbf{k})\pi_k^{(1)}(\eta)e^{i\mathbf{k}\cdot\mathbf{x}} + a^{(2)}(\mathbf{k})\pi_k^{(2)}(\eta)e^{i\mathbf{k}\cdot\mathbf{x}} + \text{h.c.}\right)$$

$$s(\mathbf{x},\tau) = \int\frac{d^3k}{(2\pi)^3}\left(a^{(1)}(\mathbf{k})s_k^{(1)}(\eta)e^{i\mathbf{k}\cdot\mathbf{x}} + a^{(2)}(\mathbf{k})s_k^{(2)}(\eta)e^{i\mathbf{k}\cdot\mathbf{x}} + \text{h.c.}\right)$$

Quasi-single field inflation

- Conformal time



- Equations of motion

$$\pi_k^{(i)\prime\prime} - \frac{2\pi_k^{(i)\prime}}{\eta} + \pi_k^{(i)} - \frac{\mu}{H}\left(\frac{s_k^{(i)\prime}}{\eta} - \frac{3s_k^{(i)}}{\eta^2}\right) = 0$$

$$s_k^{(i)\prime\prime} - \frac{2s_k^{(i)\prime}}{\eta} + \left(1 + \frac{m^2}{H^2\eta^2}\right) s_k^{(i)} + \frac{\mu}{H}\frac{\pi_k^{(i)\prime}}{\eta} = 0$$

Outside horizon evolution

- Outside horizon

$$\pi_k^{(i)\prime\prime} - \frac{2\pi_k^{(i)\prime}}{\eta} + \pi_k^{(i)} - \frac{\mu}{H}\left(\frac{s_k^{(i)\prime}}{\eta} - \frac{3s_k^{(i)}}{\eta^2}\right) = 0$$

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Outside horizon evolution

- Outside horizon $\eta \to 0$

$$\pi_k^{(i)\prime\prime} - \frac{2\pi_k^{(i)\prime}}{\eta} + \cancel{\pi_k^{(i)}} - \frac{\mu}{H}\left(\frac{s_k^{(i)\prime}}{\eta} - \frac{3s_k^{(i)}}{\eta^2}\right) = 0$$

$$s_k^{(i)\prime\prime} - \frac{2s_k^{(i)\prime}}{\eta} + \left(\cancel{1} + \frac{m^2}{H^2\eta^2}\right) s_k^{(i)} + \frac{\mu}{H}\frac{\pi_k^{(i)\prime}}{\eta} = 0$$

- Scale invariance $\eta \to \alpha\eta$

$$\pi(\eta), s(\eta) \sim (-\eta)^{\Delta}$$

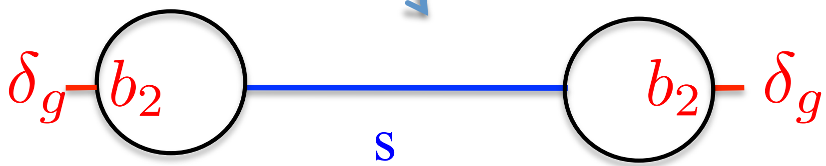
Outside horizon evolution

- $\pi(\eta), s(\eta) \sim (-\eta)^{\Delta}$

$$\Delta = \begin{cases} 0 \\ \frac{3}{2} - \sqrt{\frac{9}{4} - \frac{\mu^2+m^2}{H^2}} \\ \frac{3}{2} + \sqrt{\frac{9}{4} - \frac{\mu^2+m^2}{H^2}} \\ 3 \end{cases}$$

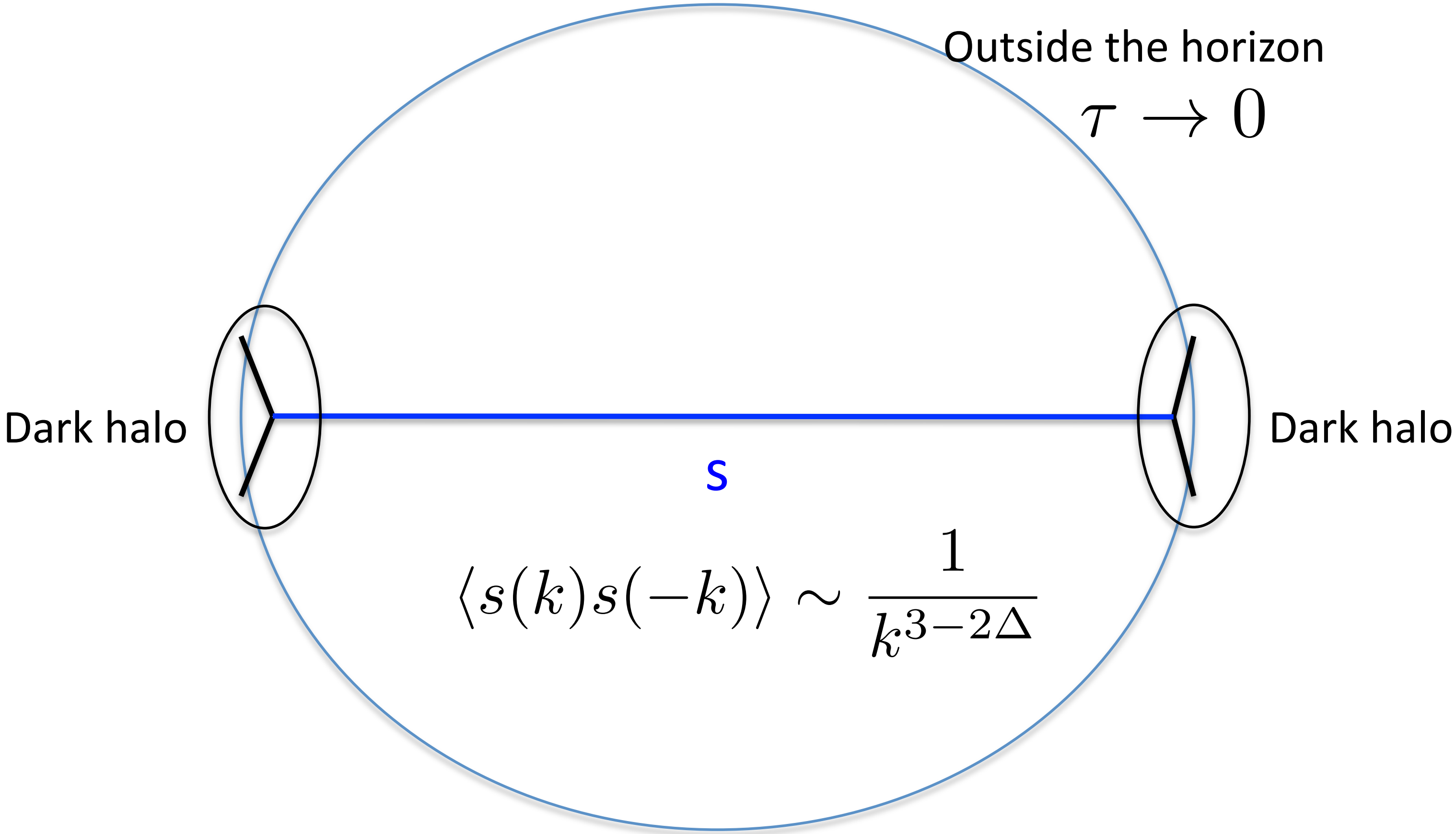
→ Seed of the LSS

$\ll 1, \; \mu^2 + m^2 \ll H^2$



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

Outside of horizon



Outside horizon effect theory

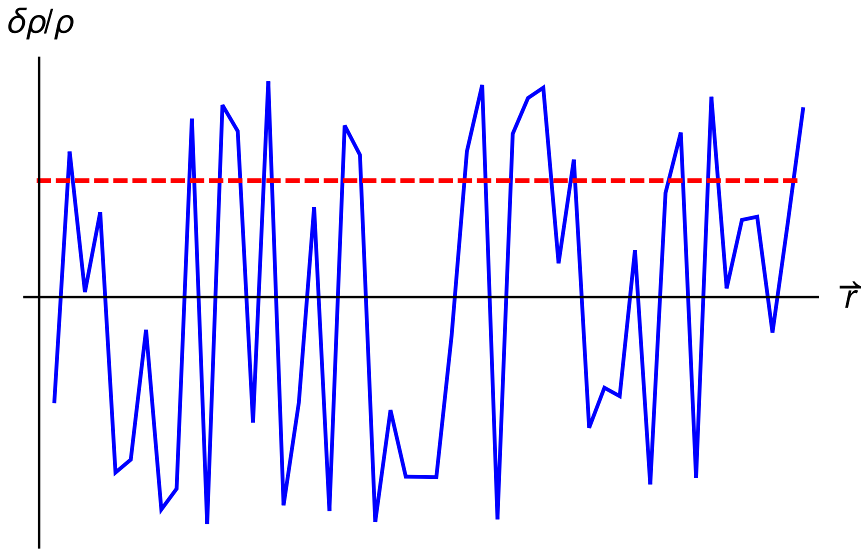
- Any correlation functions of π on the IR boundary can be calculated in this way. HA, M. McAneny, A. K. Ridgway, M. B. Wise 1711.02667
- 4pt at the squeezed limit

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

$$\langle \pi(\vec{k}_1, -\vec{k}_1 + \vec{q}, \vec{k}_3, -\vec{k}_3 - \vec{q}\rangle = \left(\frac{H^2}{\dot{\phi}_0}\right)^4 \left(\frac{V'''}{H}\right)^2 \frac{1}{q^{3-2\Delta}} \frac{1}{(k_1 k_3)^{3+\Delta}} \frac{3(\mu/2)^4 H^8}{(\mu^2+m^2)^6}$$

Formation of galactic halos

- Galaxy or halo formation is nonlinear.



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

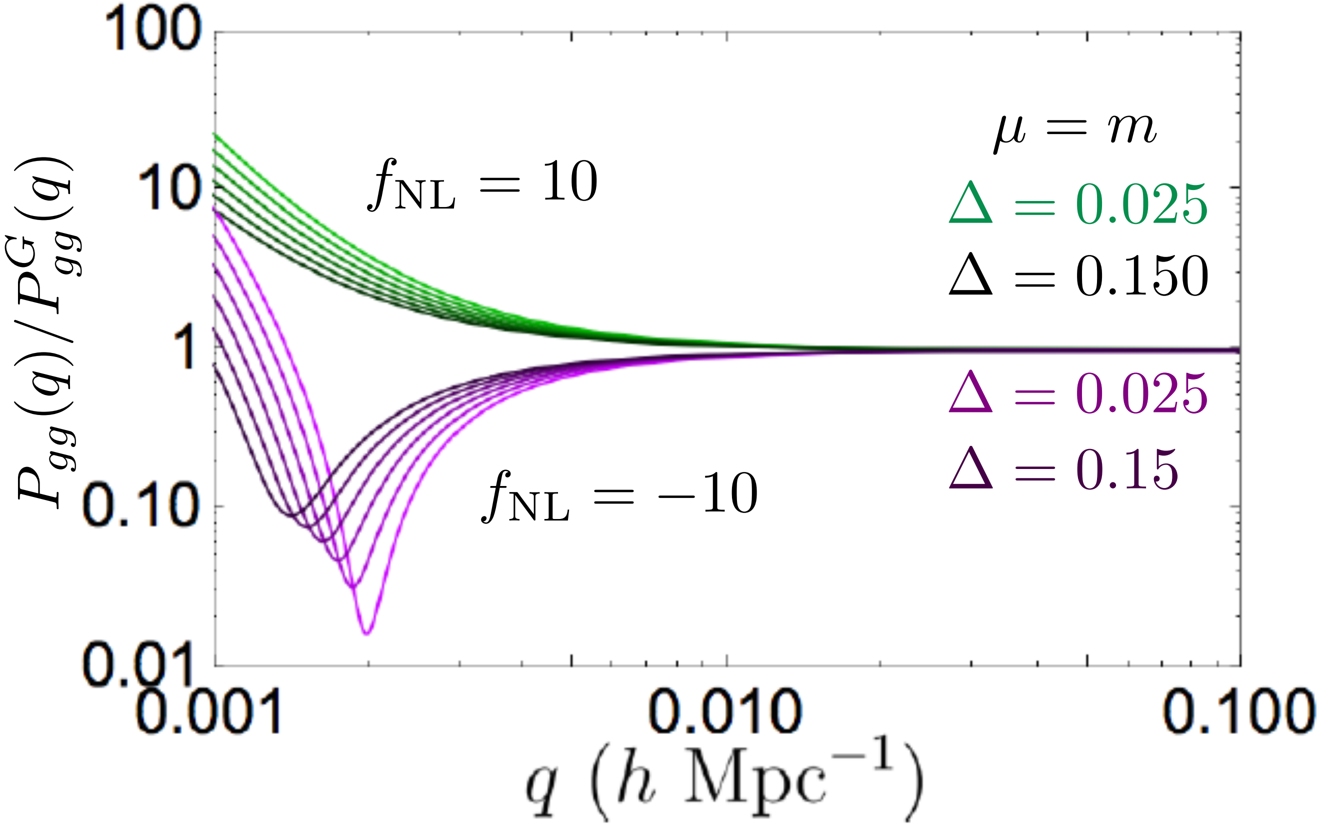
$$n_g(\mathbf{r}) = \Theta\left(\frac{\delta\rho(\mathbf{r})}{\bar{\rho}} - \delta_c\right)$$

2pt of δ_g with light *s*

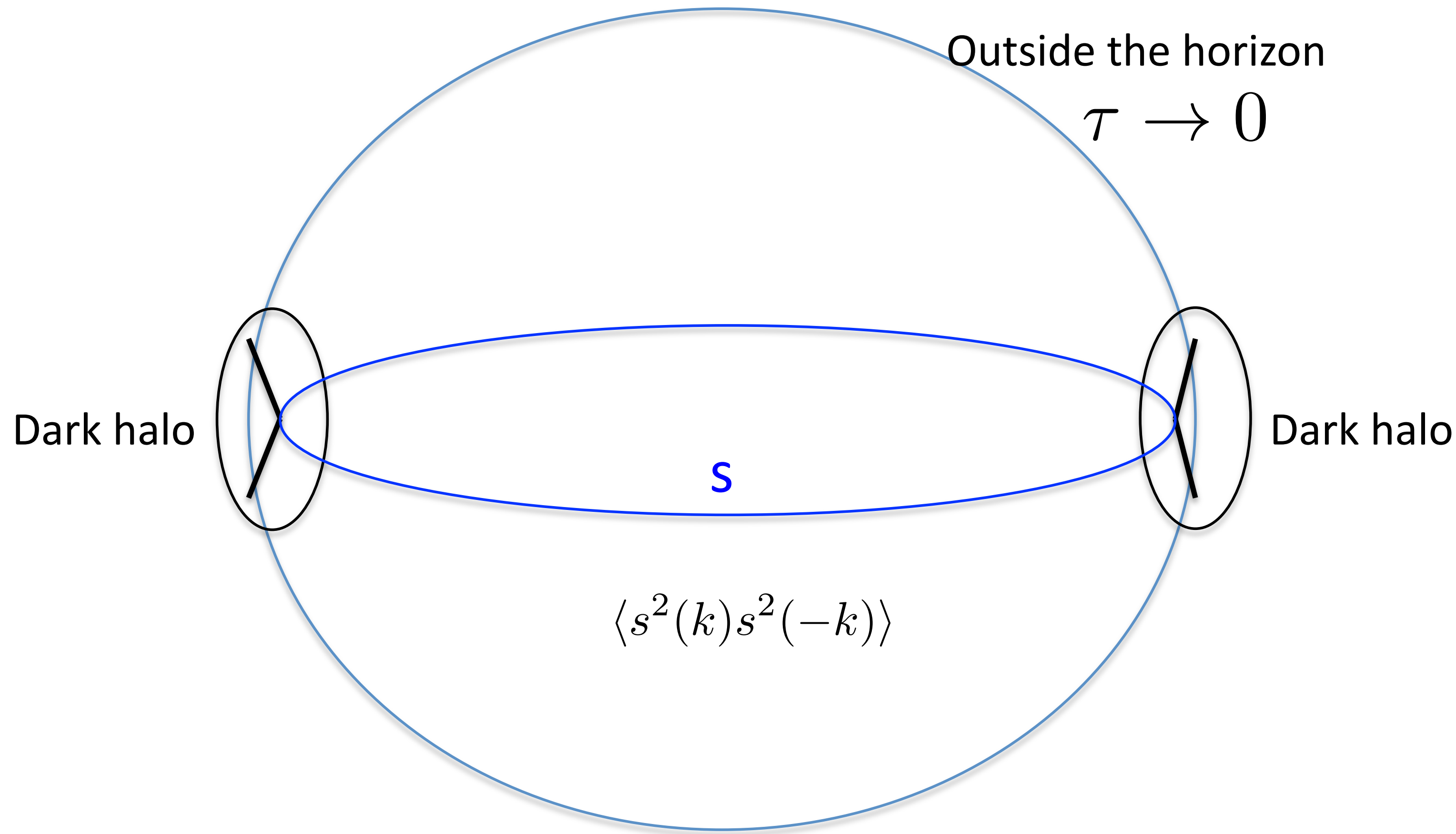
- $$P_{gg}(q) = P_{gg}^G\left[1 + \gamma(\mu, m)\left(\frac{2\beta(\mu, m)}{(qR)^{2-\Delta}} + \frac{\beta(\mu, m)^2}{(qR)^{4-2\Delta}}\right)\right]$$

b_1^2 $\quad b_1 b_2 \quad b_2^2$

R: size of galactic halo



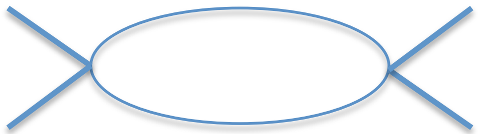
Light particle loop



Light particle loop

- Massless particle in flat space

$$\frac{1}{k^2}$$

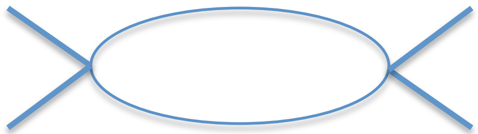


$$\int \frac{d^4p}{(2\pi)^4} \frac{1}{p^2(p+k)^2} \sim \log k$$

Light particle loop

- De Sitter space

$$\frac{1}{k^{3-2\Delta}}$$

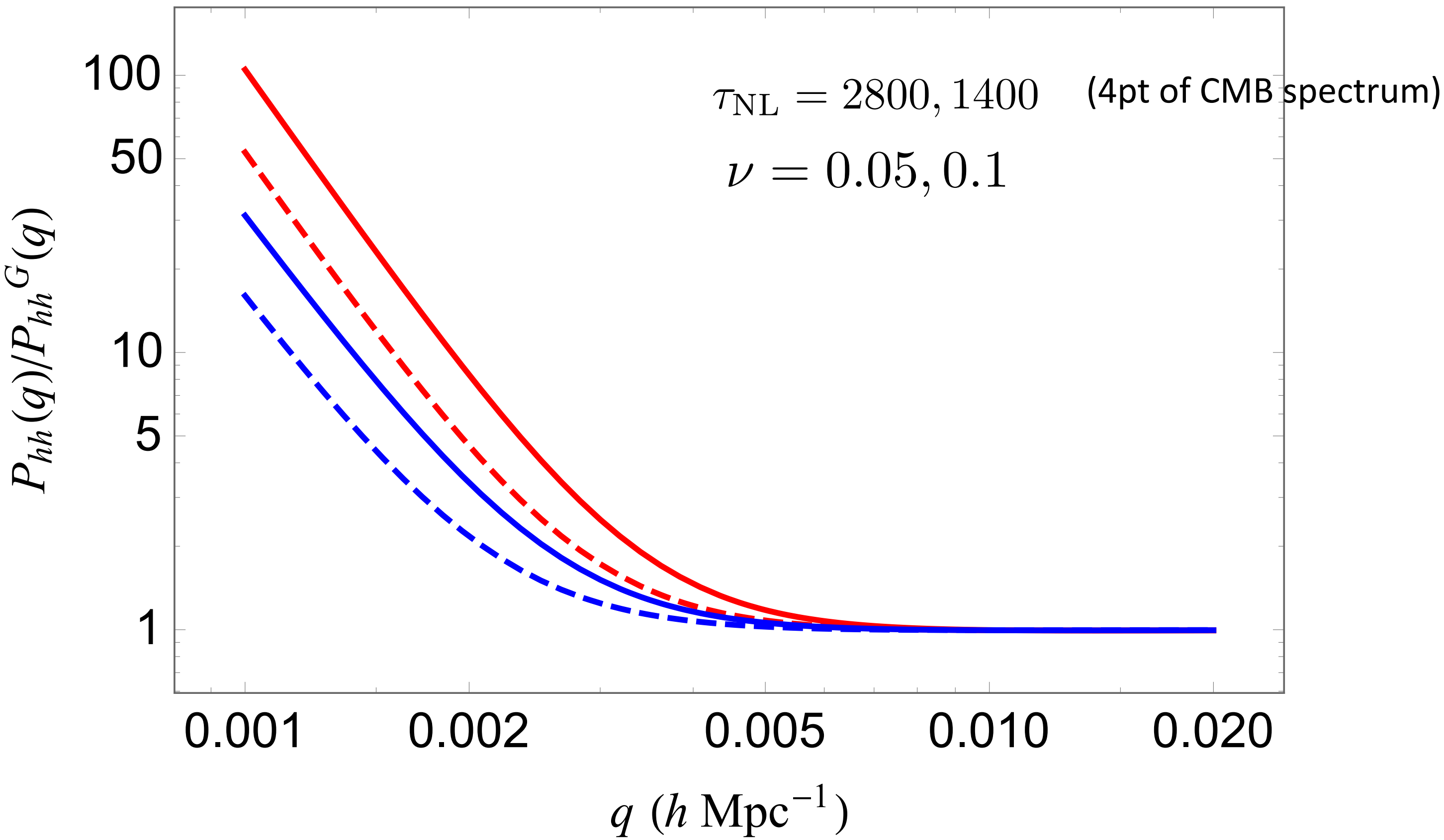


$$\frac{1}{k^{3-4\Delta}}$$

$$\Delta \approx \frac{m_s^2}{3H^2}$$

Light particle loop

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



Summary

- We expect a sharp rise in the small q region of the 2pt correlation function of the galactic halos if there is a light field coupled to the inflaton field.

- This effect can be from both tree level and loop level diagrams.

Outlook

- This calculation will be useful to the future 21cm survey and also Lyman-alpha survey.

- We need to consider the cosmic variance effect.

Outside horizon evolution

- Re-examine the free Lagrangian

0, outside the horizon

0, outside the horizon

$$\mathcal{L}_0 = \frac{1}{2(H\tau)^2}\left((\partial_\tau\pi)^2 - \nabla\pi\cdot\nabla\pi + (\partial_\tau s)^2 - \frac{m^2}{(H\tau)^2}s^2 - \nabla s\cdot\nabla s - \frac{2\mu}{H\tau}s\partial_\tau\pi\right)$$

- Due to the mass term, *s* has no constant component. We can integrate out pi as if it is a Lagrange multiplier.

$$\partial_\tau\pi = \frac{\mu}{H}\frac{s(\tau)}{\tau} \qquad \mathcal{L}_0^{\rm EFT} = \frac{1}{2(H\tau)^2}\left((\partial_\tau s)^2 - \frac{m^2+\mu^2}{(H\tau)^2}s^2 - \nabla s\cdot\nabla s\right)$$

- If $m^2 + \mu^2 \ll H^2$ this is a good approximation even for the inside-horizon-evolution of *s*.

Outside horizon evolution

- $$\mathcal{L}_0^{\rm EFT} = \frac{1}{2(H\tau)^2}\left((\partial_\tau s)^2 - \frac{m^2+\mu^2}{(H\tau)^2}s^2 - \nabla s\cdot\nabla s\right)$$

$$s_k(\eta) = H\sqrt{\frac{\pi}{4k^3}}(-\eta)^{3/2}H_\nu^{(1)}(\eta) \approx H(-\eta)^{\alpha_-}\frac{i}{k^{3/2}}\frac{1}{\sqrt{2}}$$

$$\alpha_- = \frac{3}{2} - \sqrt{\frac{9}{4} - \frac{\mu^2+m^2}{H^2}} \approx \frac{\mu^2+m^2}{3H^2}$$

- $$\partial_\tau\pi = \frac{\mu}{H}\frac{s(\tau)}{\tau} \quad \Rightarrow \quad \pi^{(i)}(0) = c_1^{(i)} + \int_{-\infty}^{0}\frac{\mu}{H}\frac{s^{(i)}(\eta')}{\eta'}d\eta'.$$

Outside horizon evolution

- $$\mathcal{L}_0^{\rm EFT} = \frac{1}{2(H\tau)^2}\left((\partial_\tau s)^2 - \frac{m^2+\mu^2}{(H\tau)^2}s^2 - \nabla s\cdot\nabla s\right)$$

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$$\sim \eta^{-1+\alpha_-}$$

$$\int_{-\infty}^{-1}\frac{\mu}{H}d\eta\,\eta^{-1+\alpha_-} \sim \frac{\mu H}{\mu^2+m^2}$$

Outside horizon effect theory

- Any correlation functions of π on the IR boundary can be calculated in this way. HA, M. McAneny, A. K. Ridgway, M. B. Wise 1711.02667
- General 4pt due to the V''' interaction

$$\mathcal{L}_{\text{int}} = \frac{1}{(H\tau)^4}\left(\frac{(H\tau)^2}{\Lambda}\left((\partial_\tau \pi)^2 - \nabla\pi\cdot\nabla\pi\right)s - \frac{V'''}{3!}s^3 - \frac{V^{(4)}}{4!}s^4\dots\right)$$

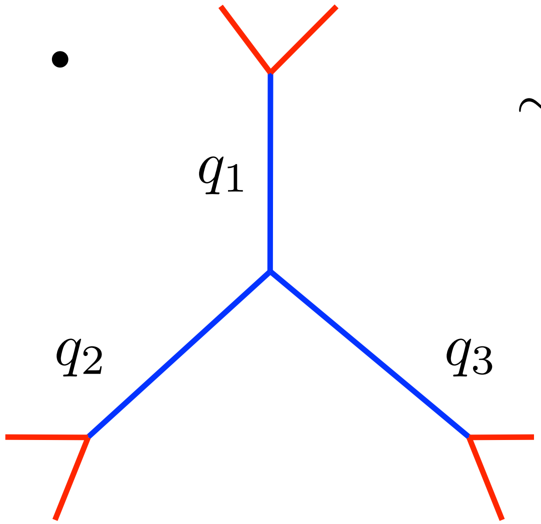
$$N_\zeta^{(4)}(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3,\mathbf{k}_4) = \left(\frac{H^2}{\dot\phi_0}\right)^4\left(\frac{V'''}{H}\right)^2\left(\prod_{i=1}^4\frac{1}{k_i^3}\right)\frac{1}{k_{12}^3}\frac{(3\mu/2)^4H^8}{2(\mu^2+m^2)^6}$$

$$\times\left[\left(k_1^3k_2^{\alpha_-}+k_1^{\alpha_-}k_2^3\right)\left(k_3^3k_4^{\alpha_-}+k_3^{\alpha_-}k_4^3\right)\left(\frac{k_{12}}{k_{UV_{12}}k_{UV_{34}}}\right)^{2\alpha_-}\right.$$

$$+2\left(1-\frac{2}{3}\left(\frac{k_{UV_{34}}}{k_{UV_{12}}}\right)^{\alpha_-}\right)(k_1^3k_2^{\alpha_-}+k_1^{\alpha_-}k_2^3)(k_3k_4)^{\alpha_-}\frac{k_{12}^3}{k_{UV_{12}}^{2\alpha_-}k_{UV_{34}}^{\alpha_-}}$$

$$\left.+\frac{2}{3}(k_1k_2)^{\alpha_-}\left(k_3^3k_4^{\alpha_-}+k_3^{\alpha_-}k_4^3\right)\frac{k_{12}^3}{k_{UV_{12}}^{3\alpha_-}}\right]+\text{cyc. perm}(\mathbf{k}_2,\mathbf{k}_3,\mathbf{k}_4)$$

3pt of δ_g with light σ

- 

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