Inflation as a probe of string theory

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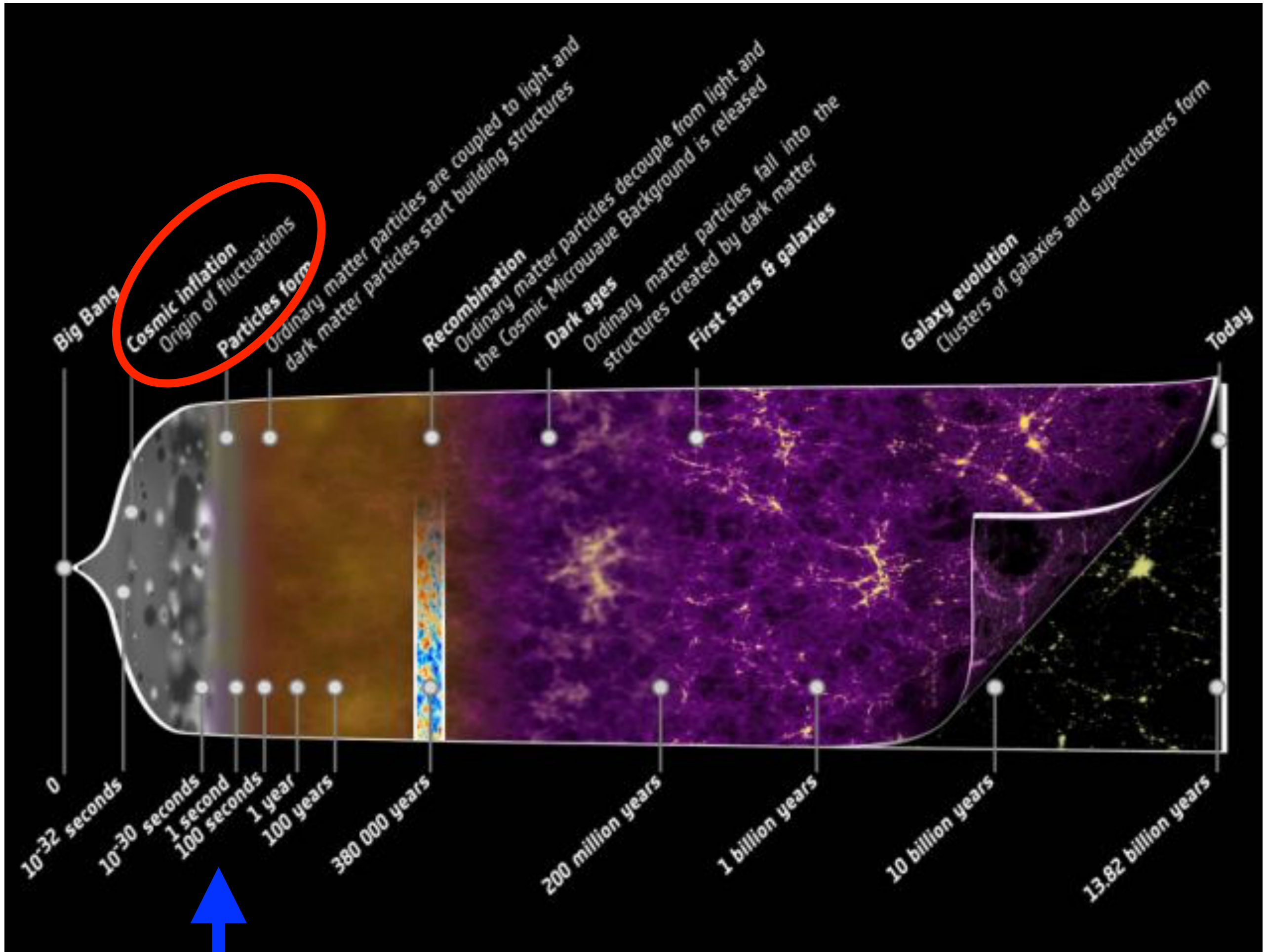
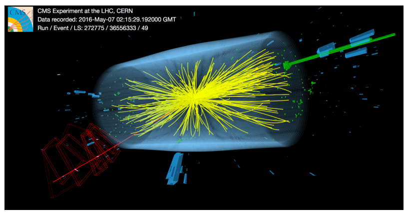
	(A01, C01)	x	B03
with	T. Kobayashi		K. Kogai
	D. Nitta		T. Matsubara
	T. Tanaka		A. J. Nishizawa
	J. Garriga		

Inflation in cosmic history



from ESA



Inflation from string theory

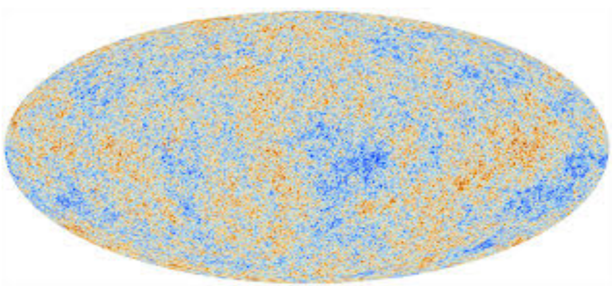
10D Superstring theory

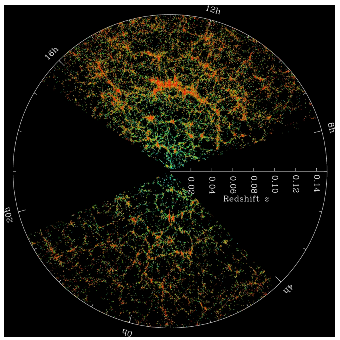
6D compactification

Moduli fields T ~ Geometrical DOFs → Inflaton?

4D effective field theory

Evidence of string theory from observations





Contents

- Probe of high energy physics: String theory

  - Imprints of massive excitations w/non-zero spins

    w/T.Tanaka (2015, in preparation)

    w/K. Kogai, T. Matsubara, A. Nishizawa (in preparation)

    side remark…w/J. Garriga(2016)

  - Moduli inflation

    w/T. Kobayashi, D. Nitta (2016)

Energy scale hierarchy

Controllable example

E

M_{pl} :Planck scale

$1/M_s$

M_s :String scale

- Gravity is mediated by a particle
  Standard field theory description
  (10dim supergravity)

M_{KK} :Kaluza-Klein scale

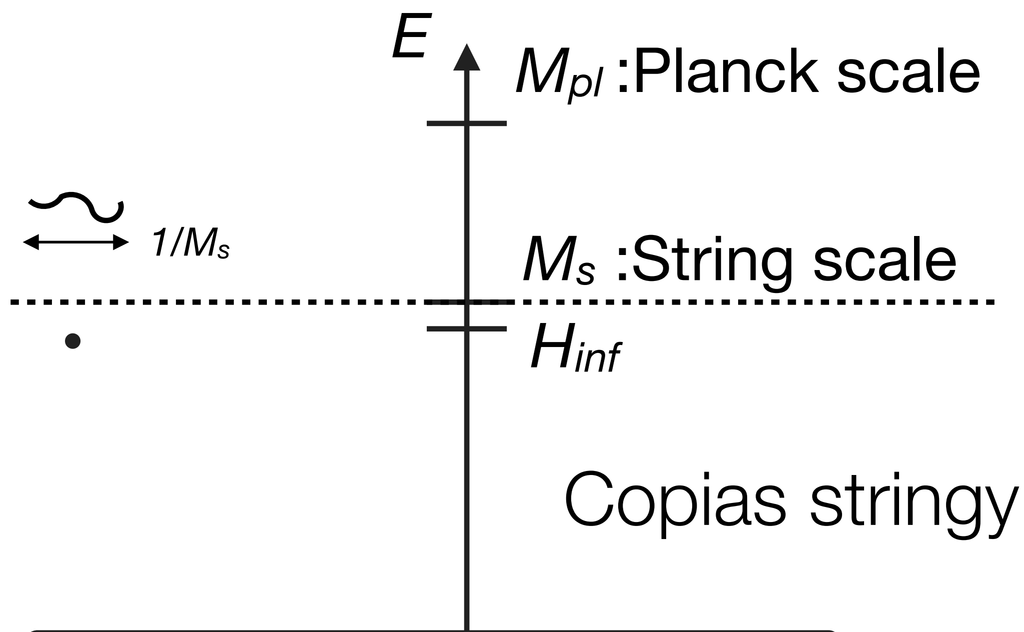
4dim effective field theory

$\Big\}\, H_{\text{inflation}}$

Cancellation of radiative corrections
N.B. η problem

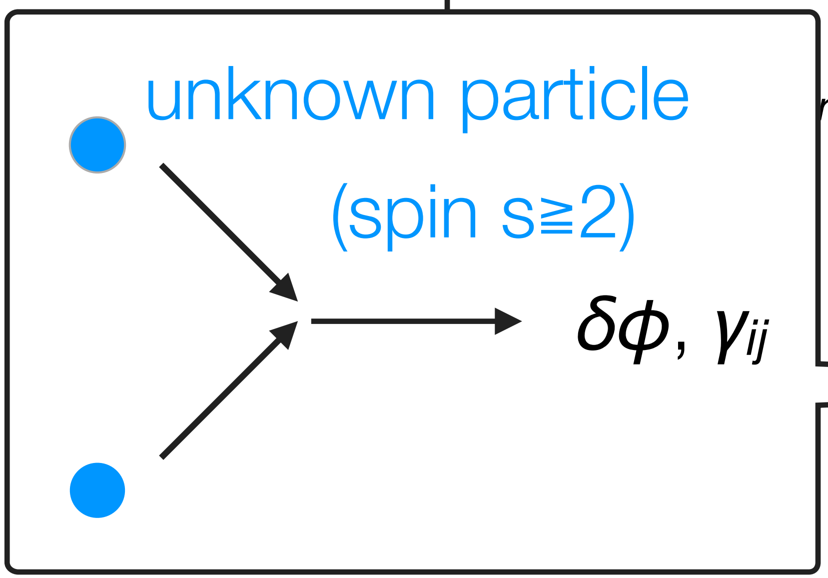
M_{SUSY} :SUSY breaking scale

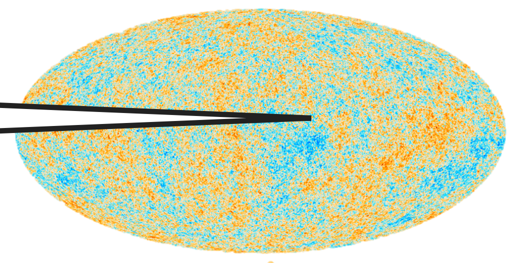
Energy scale hierarchy



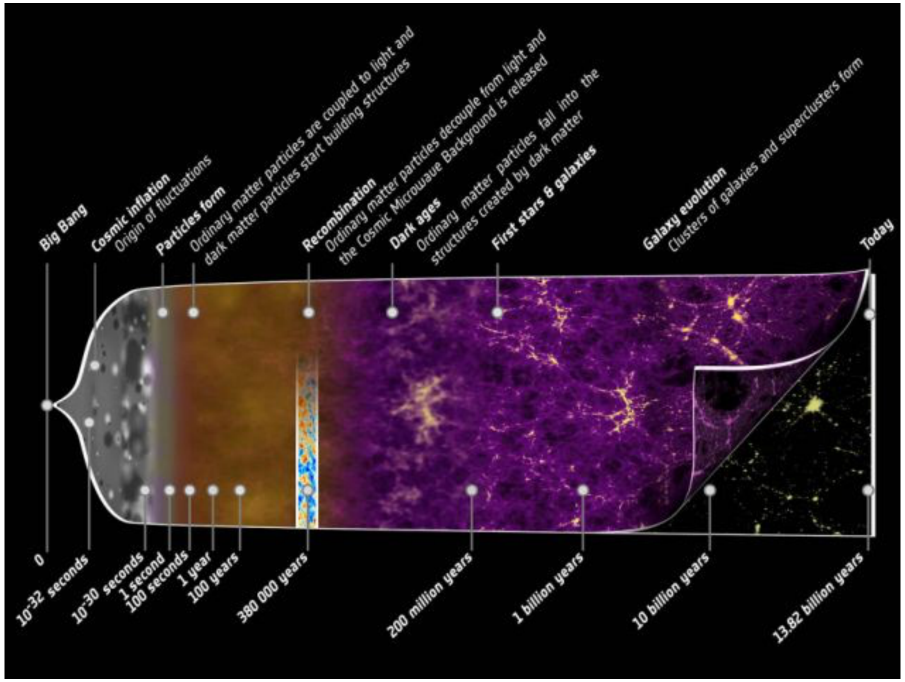
Copias stringy corrections during inflation

N.B. No successful model building yet.





Bottom-line story



unknown particle

$\delta\phi,\ \gamma_{ij}$

Angular dep. NG

Galaxy shape

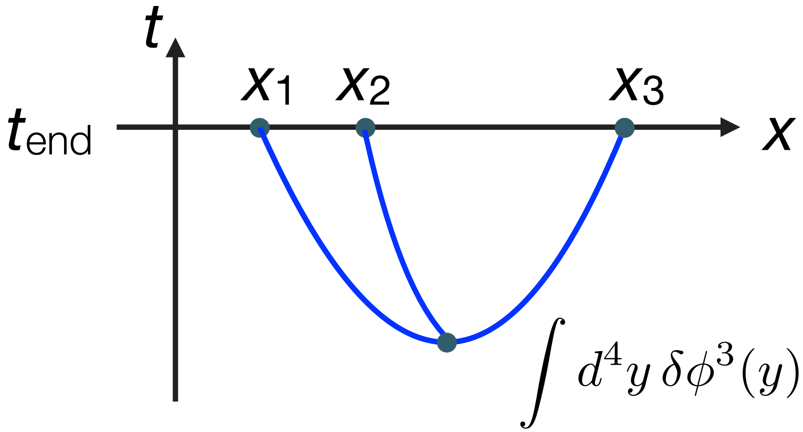
Brief diagrammatical explanation (1/3 slides)

Case 1: Only inflaton

<u>Bi-spectrum</u>

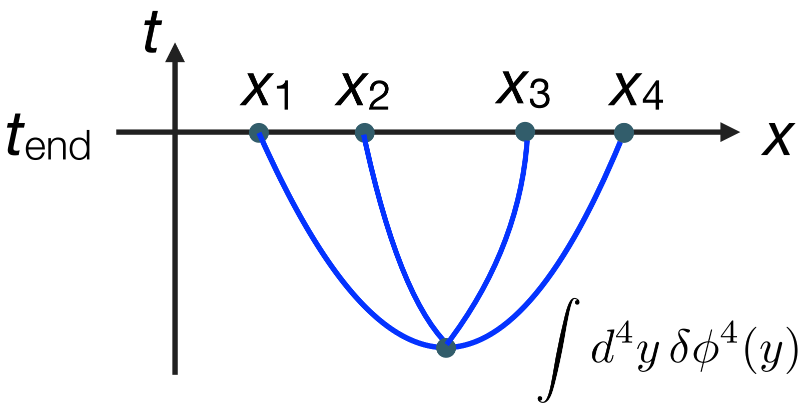
<δφ(x₁)δφ(x₂)δφ(x₃)>

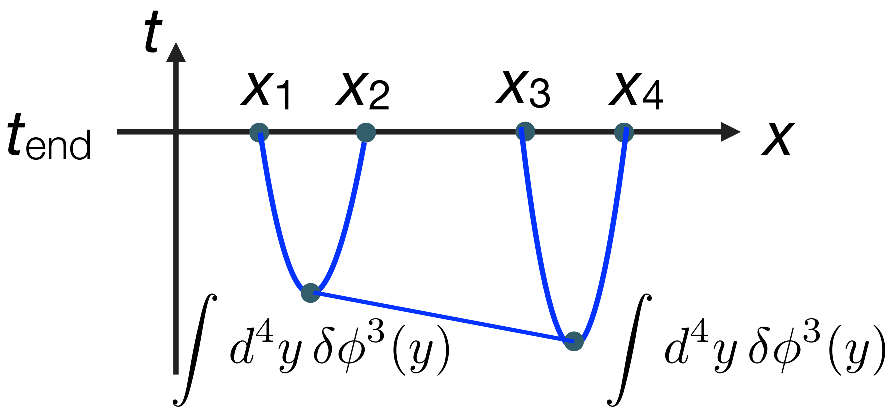
at t=$t_{\rm end}$: end of inflation



<u>Tri-spectrum</u>

<δφ(x₁)δφ(x₂)δφ(x₃)δφ(x₄)>

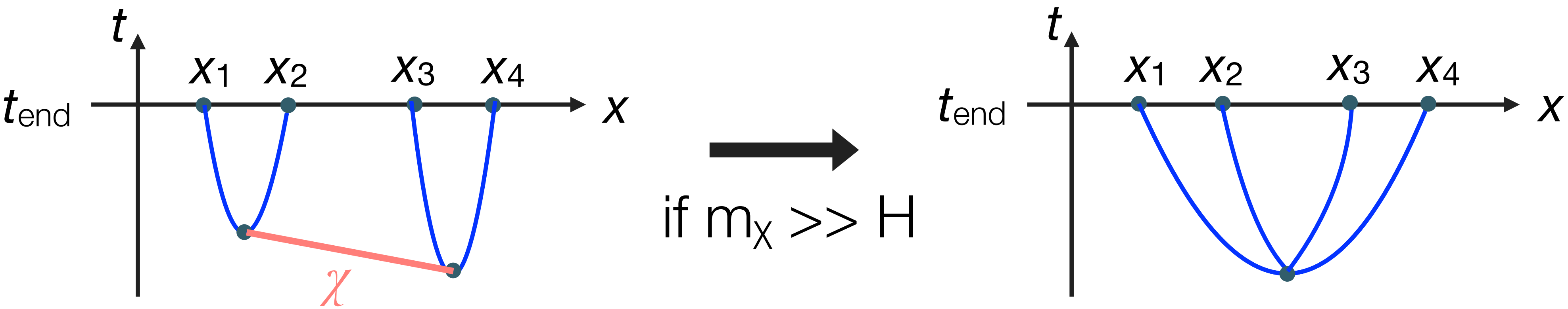




Brief diagrammatical explanation (2/3 slides)

Case 2: Inflaton + massive field χ

<u>Tri-spectrum</u> $\langle \delta\phi(x_1)\delta\phi(x_2)\delta\phi(x_3)\delta\phi(x_4)\rangle$



Recall propagator in flat space $\propto \frac{1}{k^2 - m_\chi^2} \sim -\frac{1}{m_\chi^2}$

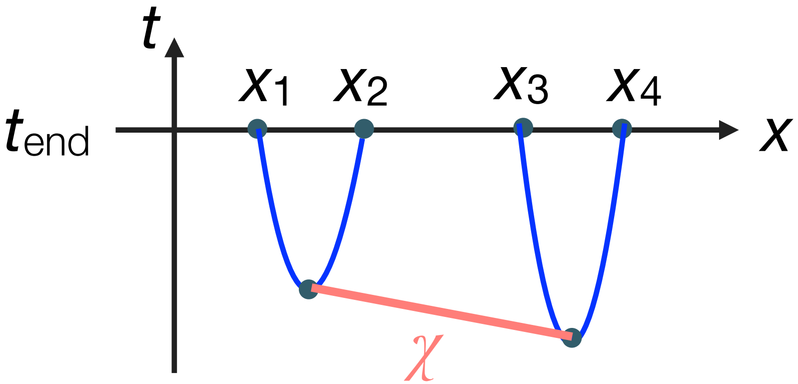
Total action of ϕ = Original action + Radiative corrections of χ

Both are local contributions.

Brief diagrammatical explanation (3/3 slides)

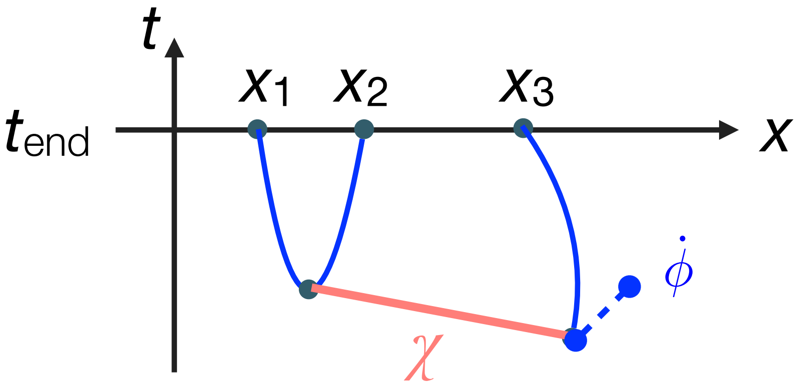
Case 2: Inflaton + massive field χ w/ $m_\chi \sim H$

Tri-spectrum $\langle \delta\phi(x_1)\delta\phi(x_2)\delta\phi(x_3)\delta\phi(x_4) \rangle$



oscillatory feature
(through interference)

Bi-spectrum $\langle \delta\phi(x_1)\delta\phi(x_2)\delta\phi(x_3) \rangle$

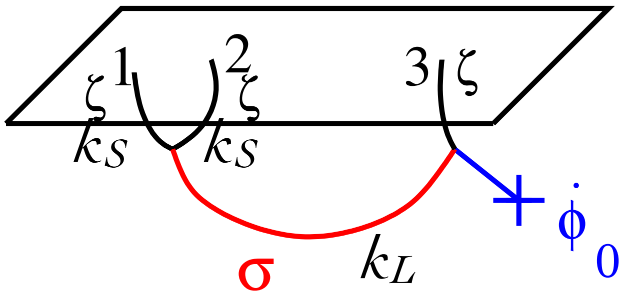


$$(k_L/k_S)^{i\mu}$$

$$\mu \equiv \sqrt{(m_\chi/H)^2 - (9/4)}$$

for s=0

Summary of results "until Hubble crossing"



Chen&Wang(09)

Arkani-Hamed & Maldacena(15)

$$B_\phi(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3 = \mathbf{k}_L) = \sum_{\ell=0,2,\ldots} A_\ell \underline{\mathcal{P}_\ell(\hat{\mathbf{k}}_L \cdot \hat{\mathbf{k}}_S)} \left(\frac{k_L}{k_S}\right)^\Delta P_\phi(k_L) P_\phi(k_S) \left[1 + \mathcal{O}\left(\frac{k_L^2}{k_S^2}\right)\right]$$

$\mathcal{P}_l$: Legendre polynomial

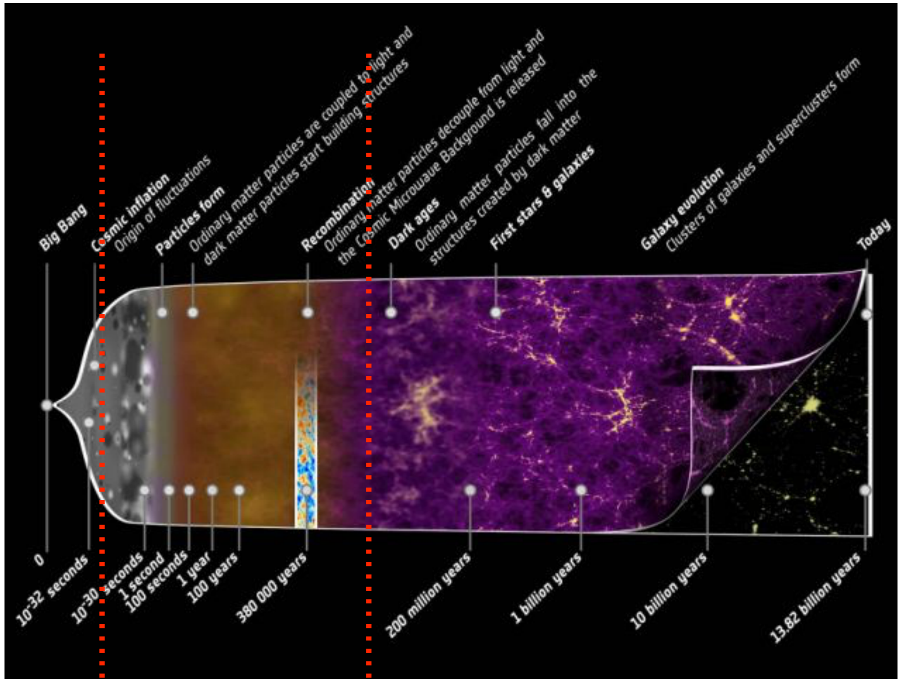
Angular dependence

- Including loop diagrams
- Spectrum at the Hubble crossing

$$\Delta = \frac{3}{2} \pm i\mu$$

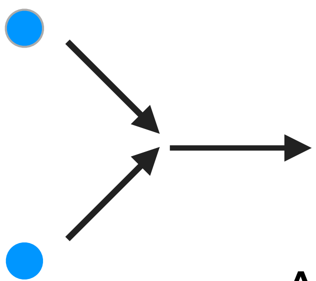
N.B. *l*=0 is standard local type bi-spectrum.

Bottom-line story



Hubble crossing

unknown particle



$\delta\phi$, γ_{ij}

Angular dep. NG

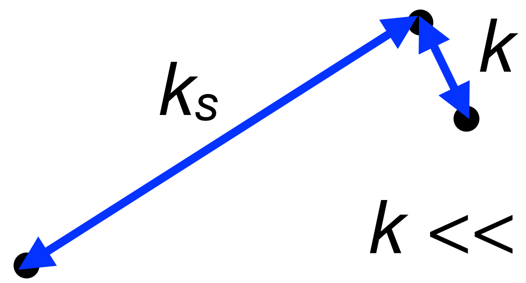
Galaxy shape

Scale dependent bias

Primordial perturbations are origin of all structures

Bias: Mismatch between distributions of DM and galaxies

Dalal et al.(07)



$k << k_s$

Fractional over-density of galaxy δ_n

$$\delta_n(z, k) = [b_L(z) + \underline{\delta b(z, k)}]\delta(z, k)$$

Correlation w/ shorter scale modes ($\rightarrow f_{NL}^{local}$)

$\Rightarrow$ Scale dependent bias $\delta b(z, k)$

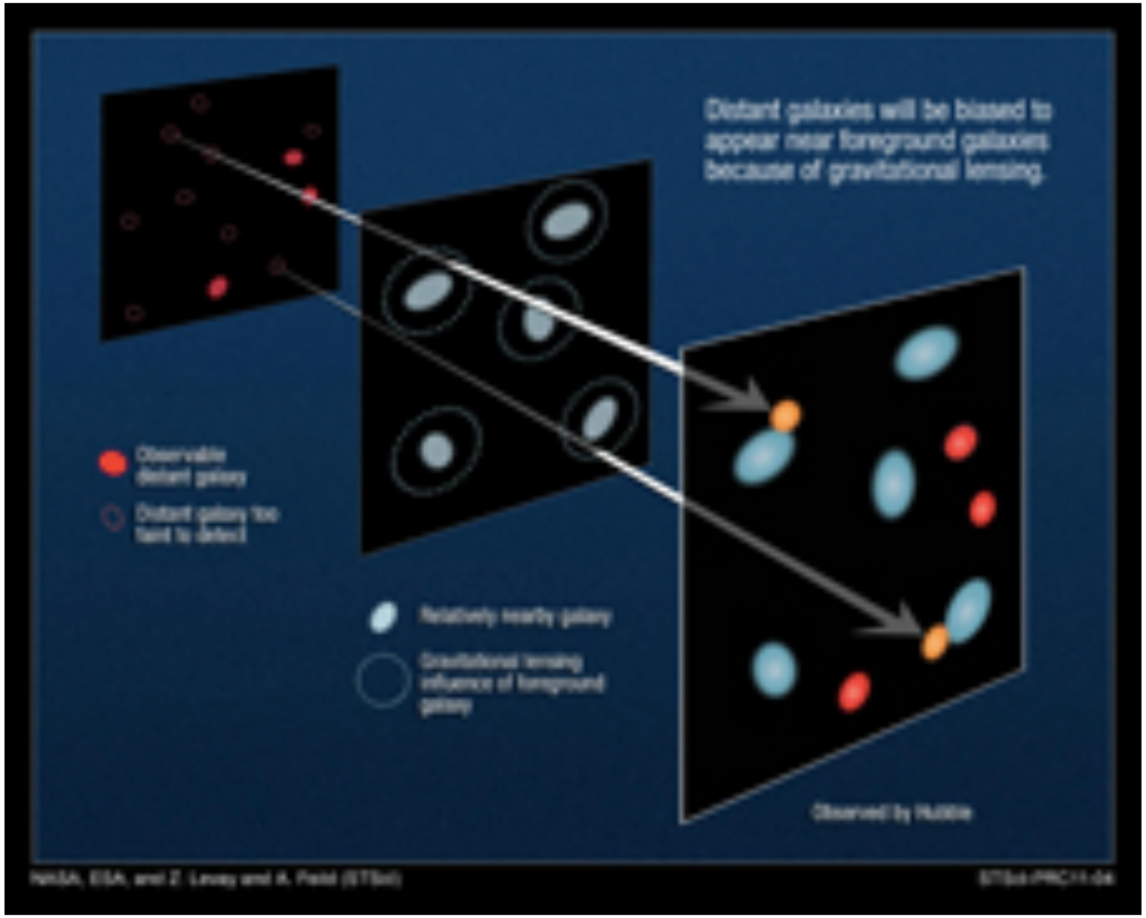
Cosmic shear

Angular dependent local-type bi-spectrum *Schmidt et al.(15, 16)*

→ Scale dependent bias of galaxy shape

intrinsic shear

+ lensing shear

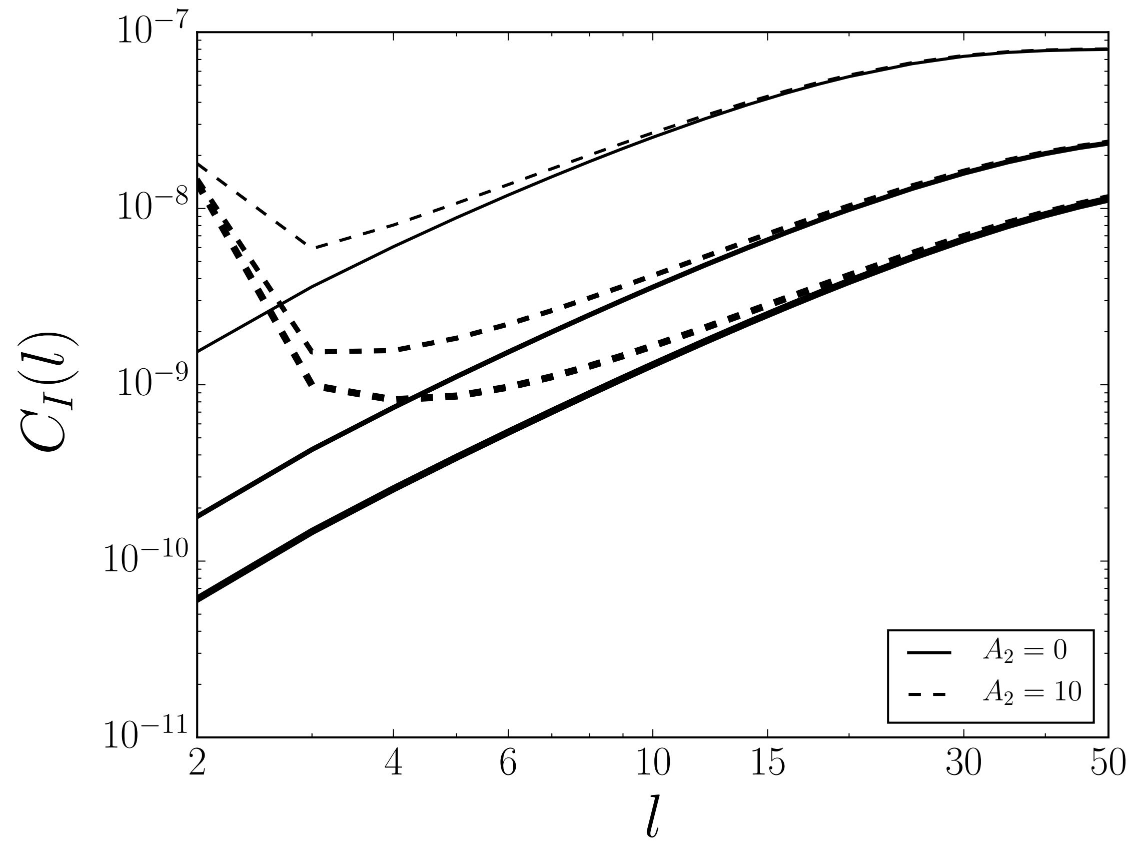


from NASA

Constraints on angular dependent NG

Schmidt et al.(15, 16)

Auto-correlation of cosmic shear (= intrinsic + WL)



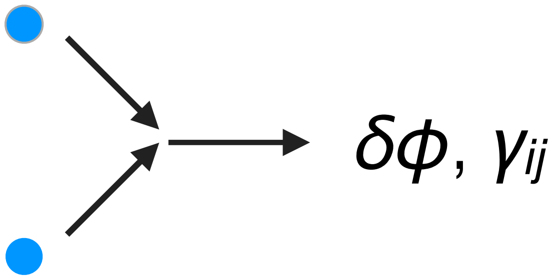
Multi-tracer can constrain up to $\Delta(\tilde{b}_I^{\rm NG} A_2) = 47$

Bottom-line story, summary and questions

Hubble crossing | end of inflation | Hubble crossing | clustering | now

Q1. Large scale time evolution?

spinning particle



$$B_\phi(\mathbf{k}_s,\mathbf{k}_L)=\sum_{l=0,2,\cdots}A_l\mathcal{P}_l(\hat{\mathbf{k}}_L\cdot\hat{\mathbf{k}}_S)...$$

ex. spin s=2 particle

Galaxy shape

2nd moment

Q2. Unique signal of s=2 particle?

Large scale evolution

What about in single clock inflation case?

Single clock $\partial_t\zeta = O((k/aH)^2)$

Wands et al. (00), Weinberg (03), Lyth et al (04), Langlois&Vernizzi (05),...

- Energy conservation $\nabla^\mu T^0{}_\mu = 0$
- Holds also at non-linear order

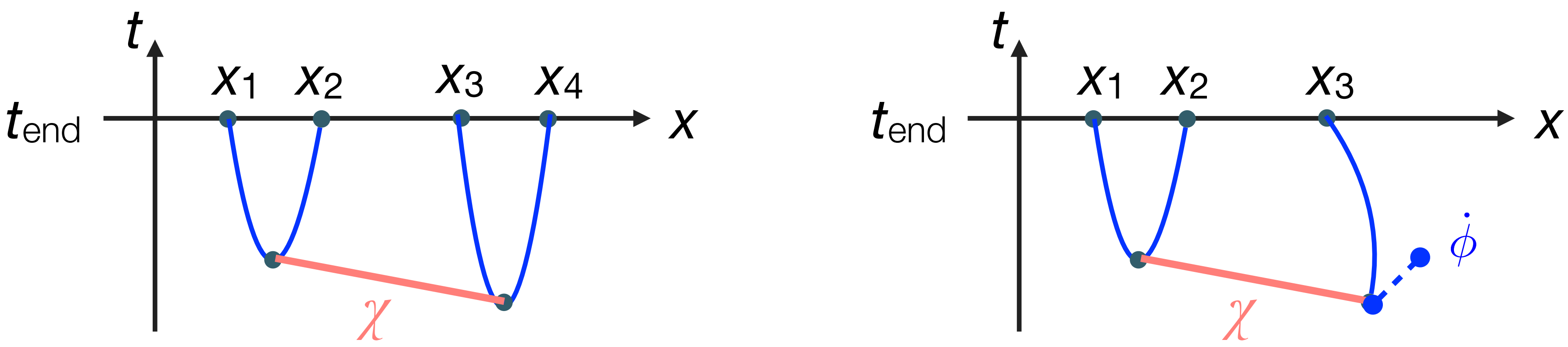
(ex) Single inflaton in Einstein gravity

$$\zeta'' + 2\frac{z'}{z}\zeta' - \cancel{\partial^2\zeta} = 0$$

What if w/ s ≠ 0 massive fields?

Is ζ still conserved in time w/radiative corrections of intermediate massive non-zero spin fields?

recall e.g.



χ : Massive fields with arbitrary integer spins

Conservation of ζ

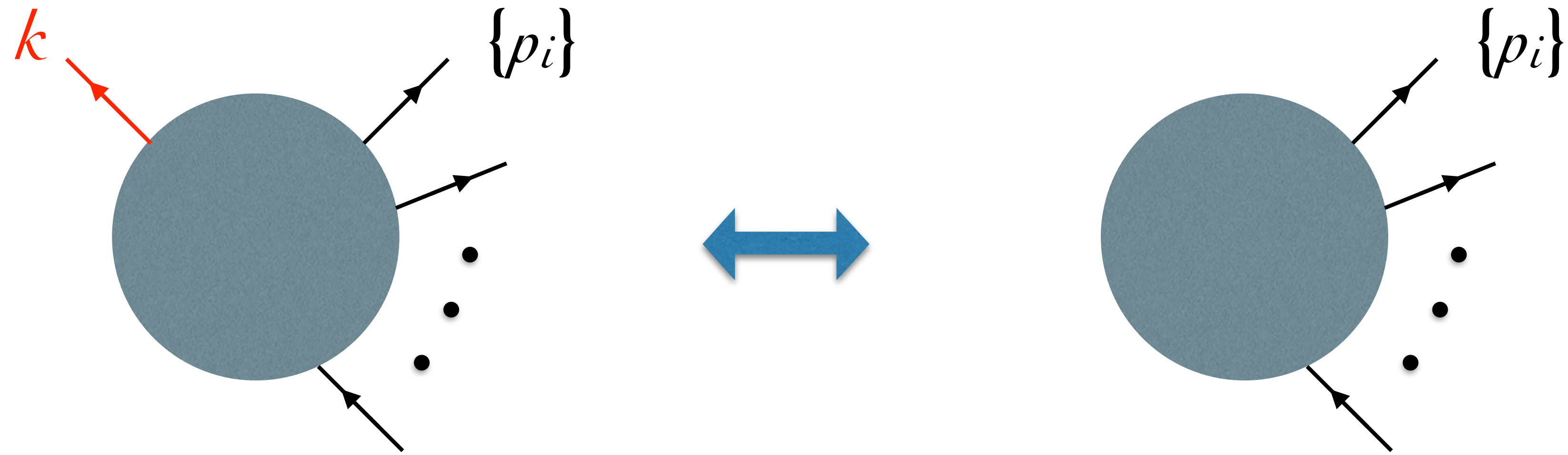
Radiative corrections of massive spinning fields do not yield any time evolution of ζ at large scales, in case the following conditions are fulfilled:

T. Tanaka & Y.U. (15, in progress)

- To be perturbative

- To satisfy soft theorem

Soft theorem as a key for conservation



- Weinberg's theorem

Graviton scattering in flat space

$$\mathcal{M}_n(q_1, \cdots, q_{n-1}, k) = \lim_{k\to 0} \sum_{a=1}^{n-1} \frac{\epsilon_{\mu\nu} q_a^\mu q_a^\nu}{k \cdot q_a} \mathcal{M}_{n-1}(q_1, \cdots, q_{n-1})$$

- Consistency relation for ζ

$C^{(n)}$: n-point fn. for ζ

$$\lim_{k_n \to 0} \frac{\mathcal{C}^{(n)}(\{\boldsymbol{k}_i\}_n)}{P(k_n)} = -\left(\sum_{i=2}^{n-1} \boldsymbol{k}_i \cdot \partial_{\boldsymbol{k}_i} + 3(n-2)\right) \mathcal{C}^{(n-1)}(\{\boldsymbol{k}_i\}_{n-1})$$

Soft theorem a.k.a. consistency relation

- Dilatation $\in$ Large gauge transformations

$$x^i \to e^s x^i \qquad \chi_s(t, e^s x^i) = \chi(t, x^i)$$

Ward-Takahashi identity

$$Q_{dil}|\Psi\rangle = 0$$

- Consistency relation (Soft theorem)

$$\left[\sum_{i=2}^{n} \boldsymbol{k}\cdot\partial_{\boldsymbol{k}} + (n-1)d\right]\langle\chi(\boldsymbol{k}_1)\cdots\chi(\boldsymbol{k}_n)\rangle' = -\lim_{k\to 0}\frac{\langle\zeta(\boldsymbol{k})\chi(\boldsymbol{k}_1)\cdots\chi(\boldsymbol{k}_n)\rangle'}{P_\zeta(k)}$$

χ: Massive spin 0

Conservation of ζ

Radiative corrections of massive spinning fields do not yield any time evolution of ζ at large scales, in case the following conditions are fulfilled:

T. Tanaka & Y.U. (15, in progress)

- To be perturbative
- To satisfy soft theorem

Ward-Takahashi id. of large gauge trans.

→ Restricts the initial conditions of χ

Gauge/Gravity correspondence (1 slide)

- Holographic principle relates

't Hooft(92), Susskind(95)
Maldacena(97),...

(d+1)-dim gravity theory $\longleftrightarrow$ d-dim field theory
+ RG flow

- Application to cosmology

Strominger(01), Witten(01),
Maldacena(97),...

4-dim inflationary spacetime $\overset{?}{\longleftrightarrow}$ 3-dim deformed CFT

\# of fields | # of deformations

Conservation of ζ in single clock model | Absence of anomalous dim of EM tensor

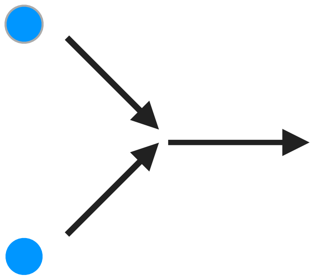
Garriga & Y.U. (2016)

Bottom-line story, summary and questions

Hubble crossing | end of inflation | Hubble crossing | clustering | now

Q1. Large scale time evolution?

spinning particle



$\delta\phi$, γ_{ij}

$$B_\phi(\mathbf{k}_s, \mathbf{k}_L) = \sum_{l=0,2,\cdots} A_l \mathcal{P}_l(\hat{\mathbf{k}}_L \cdot \hat{\mathbf{k}}_S)\ldots$$

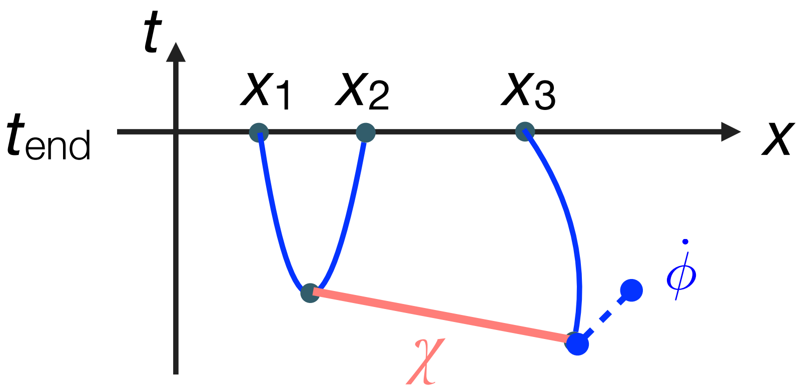
ex. spin s=2 particle

Galaxy shape

2nd moment

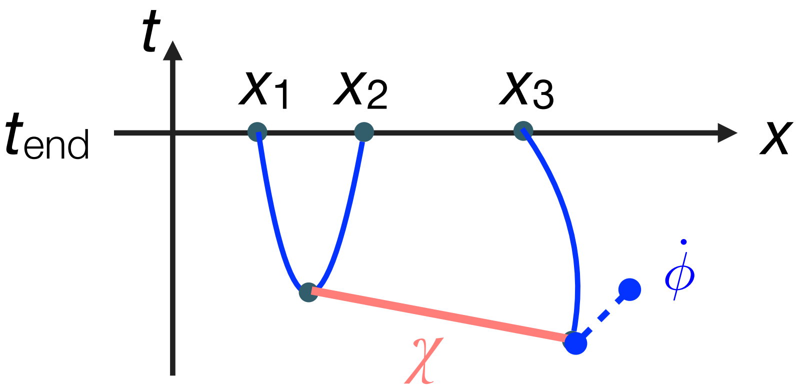
Q2. Unique signal of s=2 particle?

Other source?



$$B_\phi(\mathbf{k}_s,\, \mathbf{k}_L) \supset A_2 \mathcal{P}_2(\hat{\mathbf{k}}_L \cdot \hat{\mathbf{k}}_S) P_\phi(k_L) P_\phi(k_S)$$

χ: Massive spin 2 field w/ $H^2 \leqq m^2$



$$B_\phi(\mathbf{k}_s,\, \mathbf{k}_L) \supset \bar{A}_2 \mathcal{P}_2(\hat{\mathbf{p}} \cdot \hat{\mathbf{k}}_S) P_\phi(k_L) P_\phi(k_S)$$

χ: Spin 1 field

$\mathbf{p}$: 3 vector

Q2. Unique signal of s=2 particle?

Can we distinguish?

Kogai, Matsubara, Nishizawa & Y.U. (in progress)

	Spin 2	Spin 1
Intrinsic shear E-mode	Yes	Yes
Intrinsic shear B-mode	No	Yes
Non-diagonal in el		
m dependence	No	Yes

Qualitatively yes!

Quantitative analysis in progress

Contents

- Probe of high energy physics: String theory

  - Imprints of massive excitations w/non-zero spins

    w/T.Tanaka (2015, in preparation)

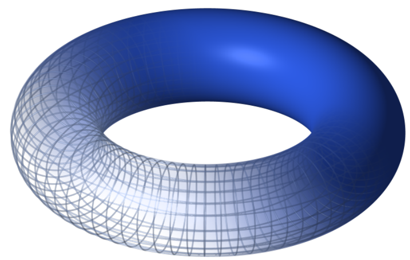
    w/K. Kogai, T. Matsubara, A. Nishizawa (in preparation)

  - Moduli inflation

    w/T. Kobayashi, D. Nitta (2016)

Moduli cosmology

10D Superstring theory



6D compactification

Moduli fields T ~ Geometrical DOFs

4D low energy effective field theory

Non-perturbative effects are, in general, hard to be fully captured.

- Piecewise analysis?

T-duality

- $R >> 1/M_s$

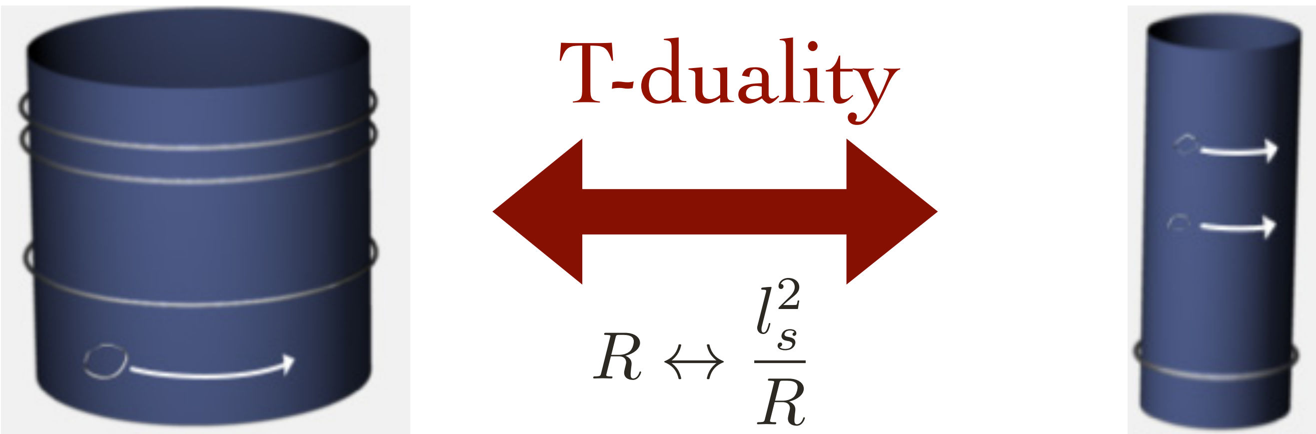
  Stringy corrections are perturbatively small.

- $R \lesssim 1/M_s$

  Stringy corrections can be large →Hard to compute.

Yet…, T-duality may keep this case calculable.

Large R



Small R

Modular invariant inflation

Modular invariance $\ni$ R $\rightarrow$ 1/R

- SL(2, Z) modular invariance

$$T \to \frac{aT - ib}{icT + d} \qquad ad - bc = 1 \qquad a, b, c, d \in \mathbf{Z}$$

- When modulus ($\rightarrow$ inflaton) Lagrangian is MI

Kobayashi, Nitta, Y.U.(16)

- Large field inflation is hardly realised.
- Yet, small field inflation is still possible.
- Consistent with Planck 15 in 95% C.L.

Summary

- Imprints of massive excitations w/non-zero spins
  - Presence of non-zero spin fields during inflation can be searched through galaxy shape measurements.
  - Angular dependent NGs from spin 2 and spin 1 have qualitative differences such as B-mode, mixing of ell.

- Inflation w/modular invariance
  - Large field is unfeasible, yet small field is still possible.

thanks.