Cosmological Collider Physics

COSMO 2015

Warsaw

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IAS

Based on: N. Arkani-Hamed and JM, arXiv: 1503.0804

- According to inflationary theory cosmological perturbations have a quantum mechanical origin.
- They were created during inflation

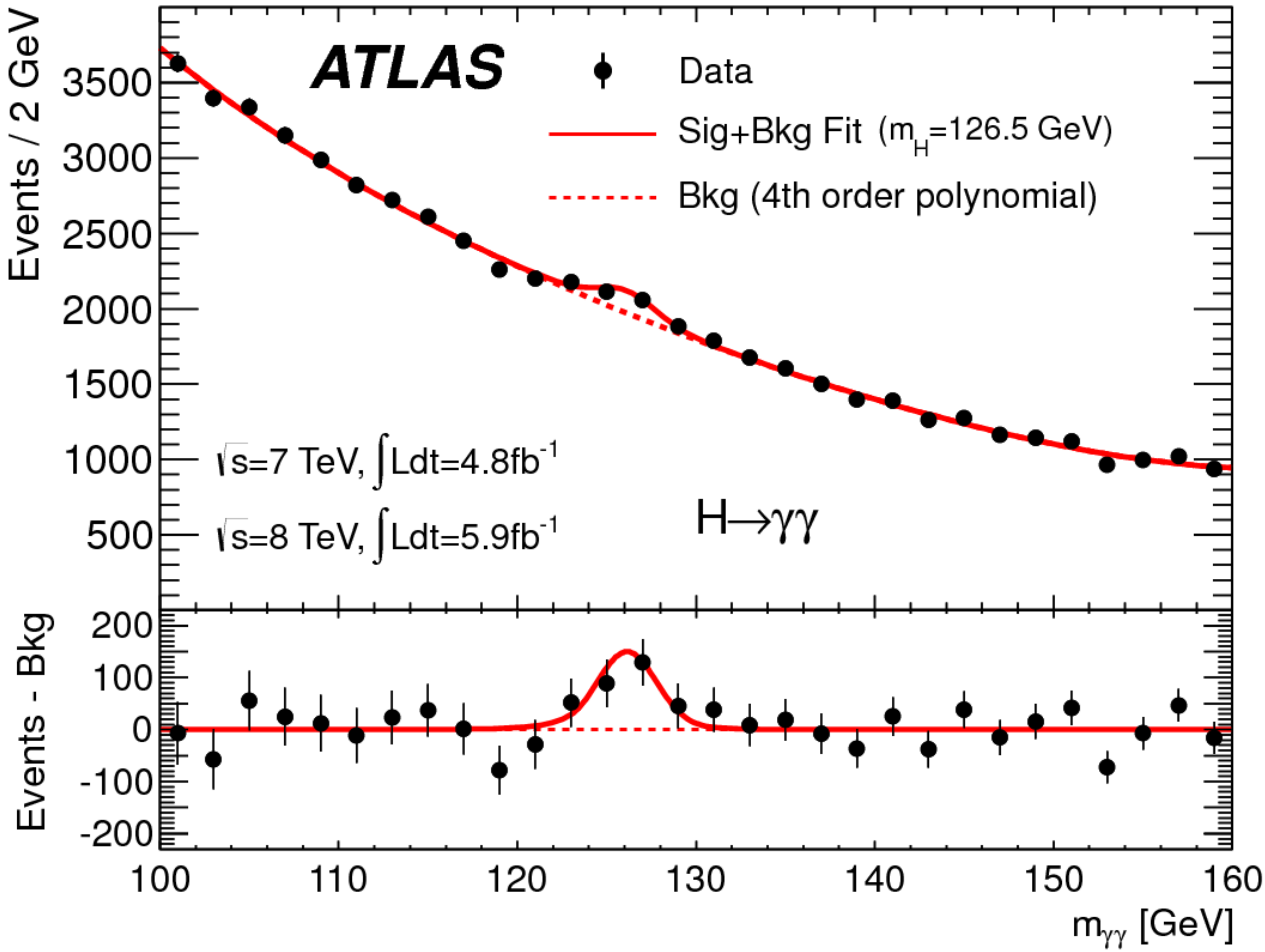
$$T \sim \frac{H}{2\pi} \ , \qquad\qquad 3M_{pl}^2 H^2 = V$$

- Relevant modes have energies of order H.
- Hubble scale could be as high as 10^{14} Gev !

- New particles and their interactions during inflation → leave a small imprint on the perturbations.
- We need to do the ``collider physics'', i.e. go from the signatures to the basic interactions.

- How do we recognize new particles, measure their masses and spins ?

In flat space


ATLAS
Data
Sig+Bkg Fit (m_H=126.5 GeV)
Bkg (4th order polynomial)
√s=7 TeV, ∫Ldt=4.8fb-1
√s=8 TeV, ∫Ldt=5.9fb-1
H→γγ
Events / 2 GeV
Events - Bkg
m_γγ [GeV]
500
1000
1500
2000
2500
3000
3500
200
100
0
-100
-200
100
110
120
130
140
150
160

In Cosmology

Non-Gaussianities

- Study non-gaussianities in the cosmological correlators.

- Can be produced by self interactions of the inflaton.

$$\int (\nabla\phi)^2 + \lambda(\nabla\phi)^4$$

- There are interesting patterns produced by new particles.

$$\int (\nabla\phi)^2 + (\nabla\sigma)^2 + m^2\sigma^2 + \lambda\sigma(\nabla\phi)^2$$

Analogy

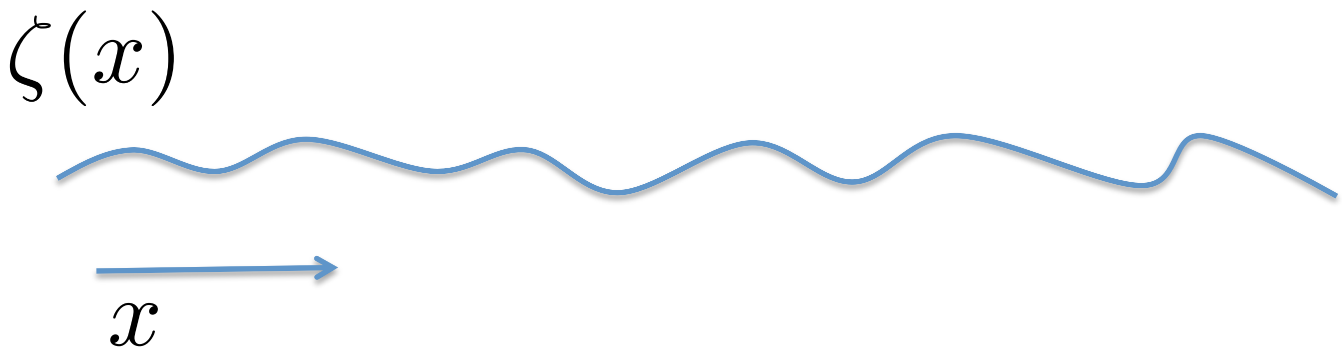
QCD		Cosmology
Hadrons	=	galaxies
Hadronization	=	Structure formation
Energy correlators	=	correlators of primordial density fluctuations.
Weak coupling at high energies	=	weak coupling during inflation
Approximate scale invariance	=	approximate scale invariance of wavefunction = approximate de-Sitter invariance.
OPE of energy correlators	=	squeezed limits of primordial correlators.
Time → scale	=	time → scale

Both are controlled by

(slightly broken) conformal symmetry

Basic Observable

Primordial Curvature Perturbations



$$\langle \zeta(x_1) \cdots \zeta(x_n) \rangle$$

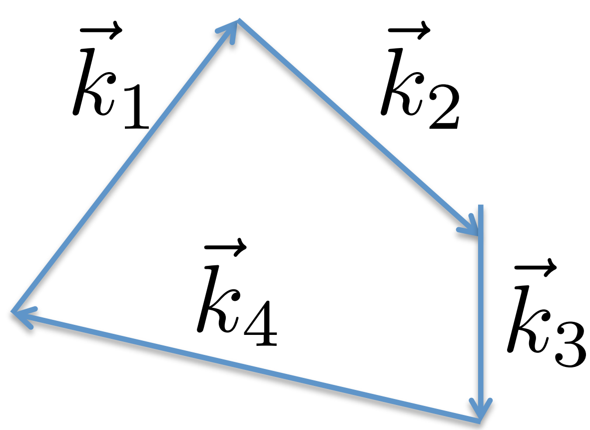
Kinematics

$$\langle \zeta(x_1)\zeta(x_2)\cdots\zeta(x_n)\rangle \to \langle \zeta(k_1)\cdots\zeta(k_n)\rangle$$

Fourier transform → set of momenta

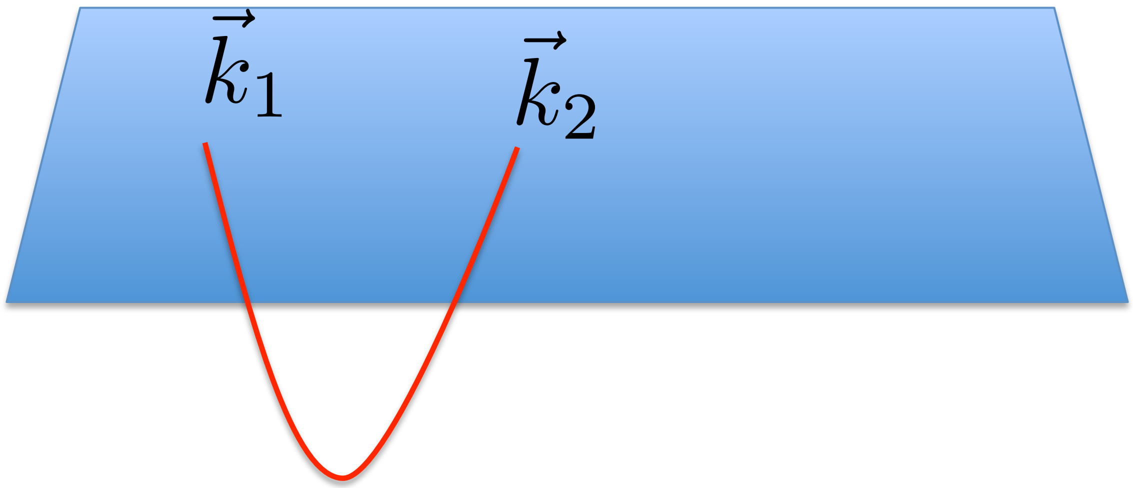
Statistical homogeneity of the universe → Momentum conservation

This is similar to amplitudes. But no ``energy conservation”.



First assume exact
de Sitter symmetry

Leading effect



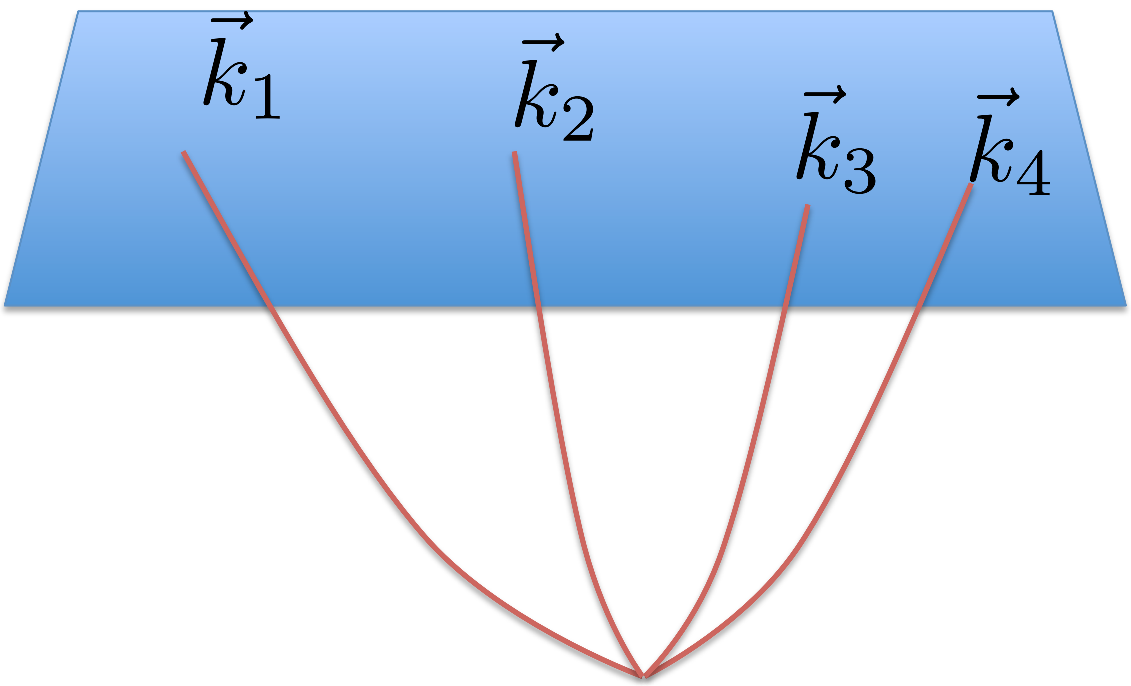
Two point function

$$\langle \phi_{\vec{k}_1} \phi_{\vec{k}_2} \rangle = \frac{H^2}{k_1^3} \delta^3(\vec{k}_1 + \vec{k}_2)$$

$$\langle \phi(0)\phi(x) \rangle \sim H^2 \log |x| + \cdots$$

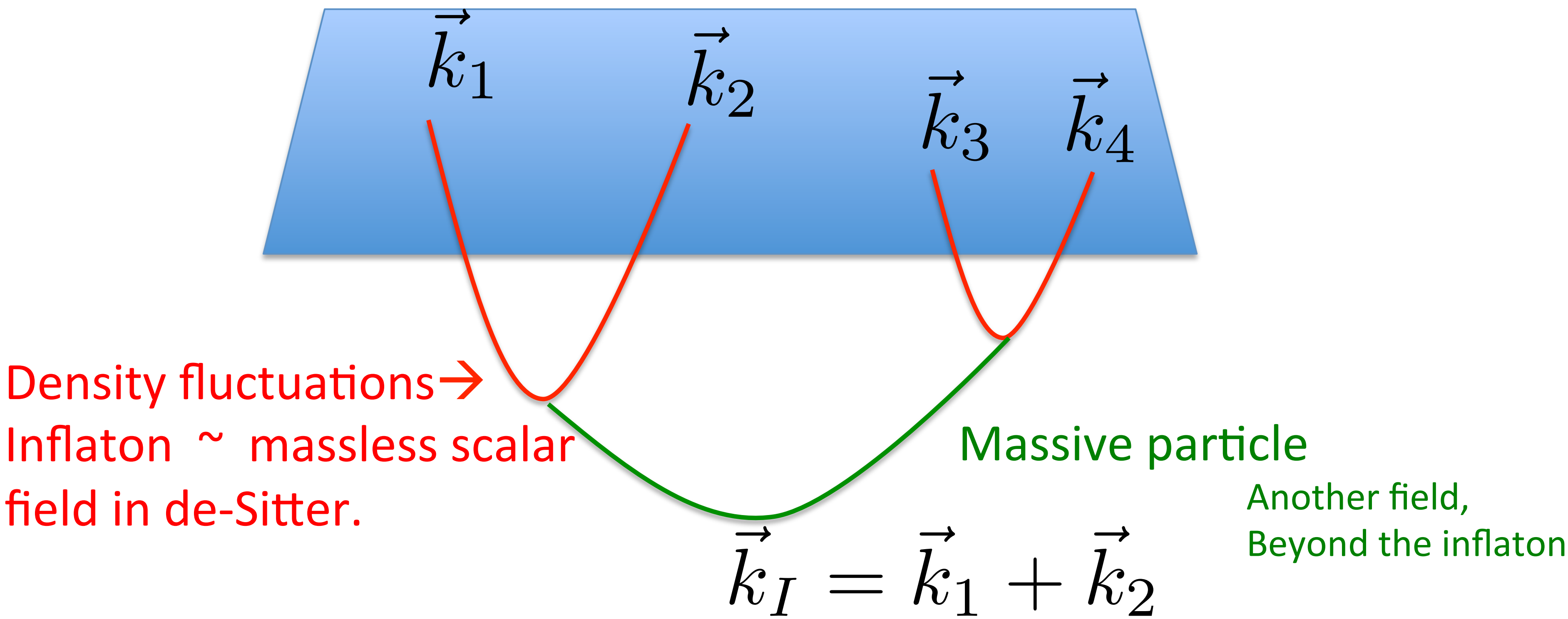
Four point function

- From self interactions



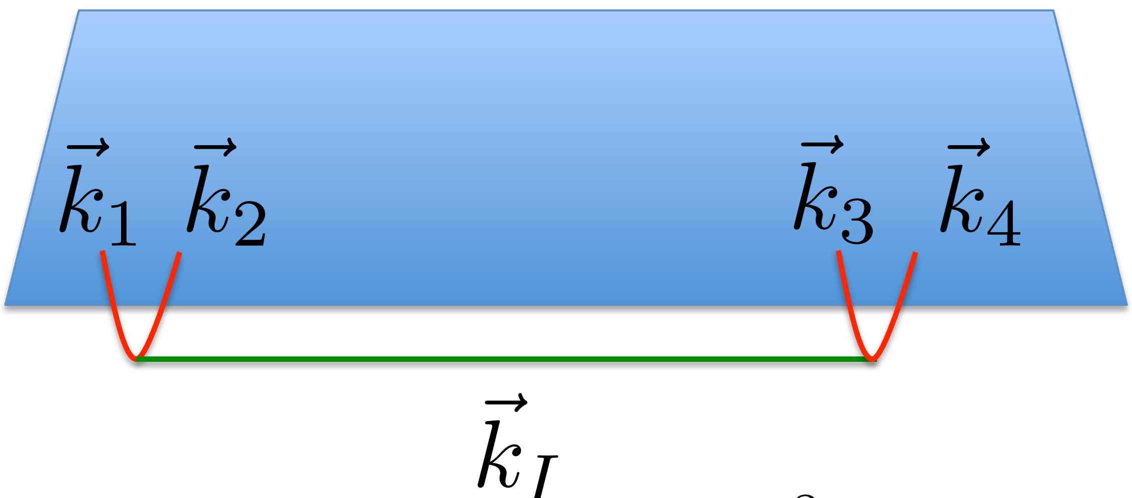
Four point function

- From a new massive particle existed during inflation, m of order H.



Squeezed limit

$$k_I = |k_I| \ll |\vec{k}_i| = k_i \ , \qquad i = 1, 2, 3, 4$$



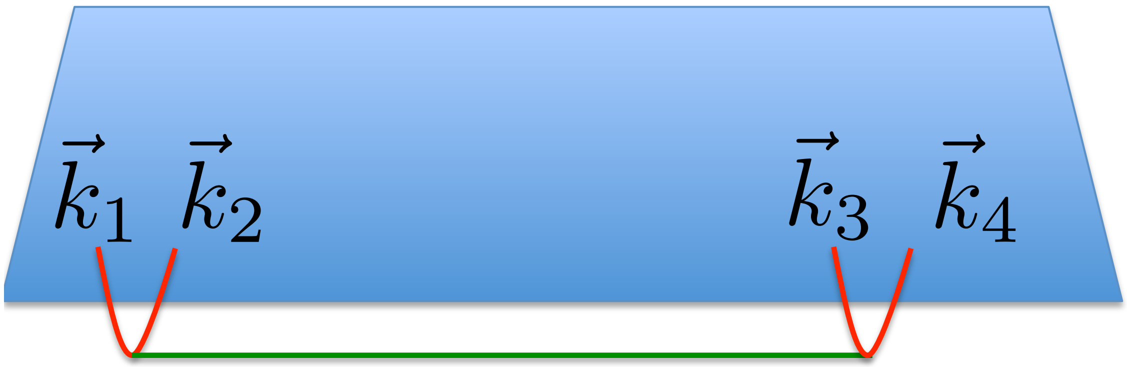
Chen, Wang, (quasi single field), Noumi, Yamaguchi, Yokoyama, Assassi, Baumann, Green, Senatore, Silverstein, Zaldarriaga, Suyama, Yamaguchi,...

$$\mu = \sqrt{m^2/H^2 - 9/4}$$

$$\frac{\langle 4pt \rangle}{\langle 2pt \rangle^2} \propto \frac{1}{k_I^3} \left[\left(\frac{k_I^2}{k_1 k_3} \right)^{\frac{3}{2} + i\mu} e^{i\delta} + c.c. \right]$$

This non-trivial power of k_I → signature of a new physical particle.
Not obtained from self interactions.

$$\frac{\langle 4pt \rangle}{\langle 2pt \rangle^2} \sim e^{-\pi\mu} \frac{1}{k_I^3} \left[\left(\frac{k_I^2}{k_1 k_3} \right)^{\frac{3}{2}+i\mu} e^{i\delta} + c.c. \right]$$



$$\mu = \sqrt{m^2/H^2 - 9/4}$$

We see clear oscillations a function of the log of the ratio of scales

Boltzman suppression $\quad e^{-\pi\mu} \quad \text{vs.} \quad 1/(\mu)^k$

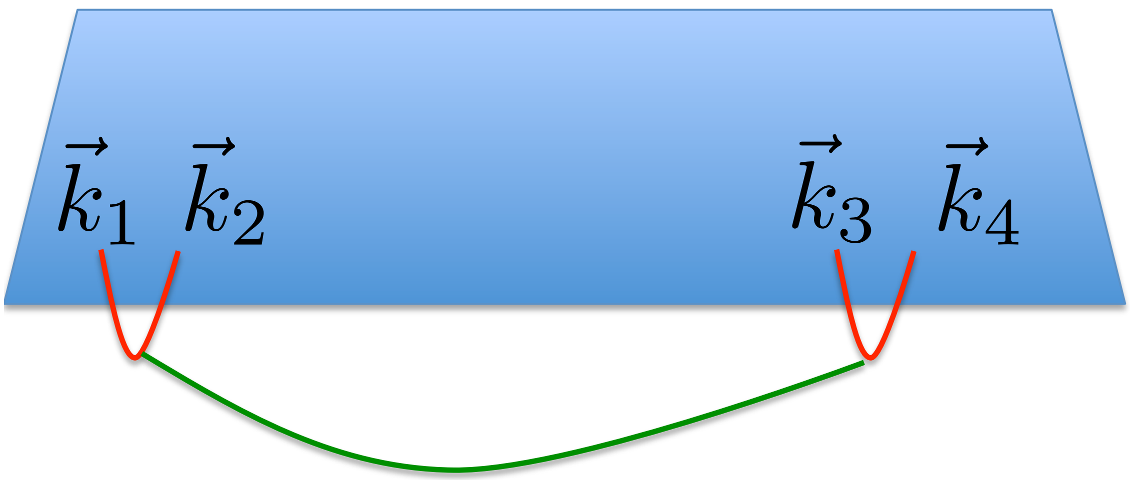
Interference effect: $\quad \Psi_{\text{nopair}} + e^{-\pi\mu}\Psi_{\text{pair}}$

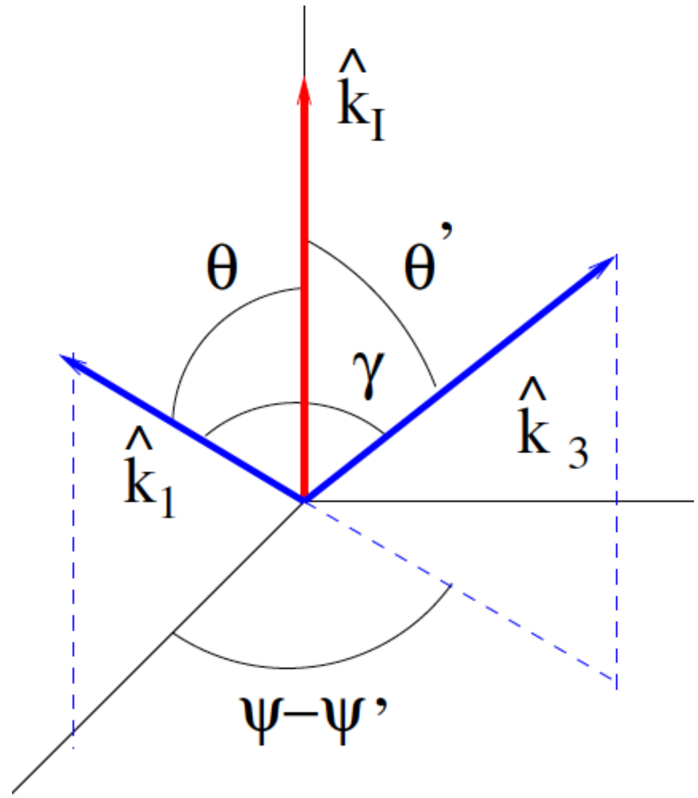
Phase is a function of the mass.

Interesting test of the quantum nature of fluctuations.

Spin

$$\langle 4pt \rangle \sim F(\gamma, \theta, \theta')$$

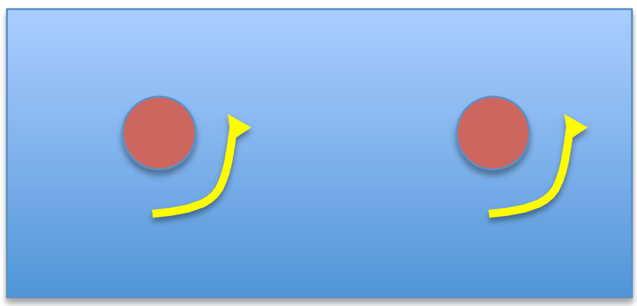


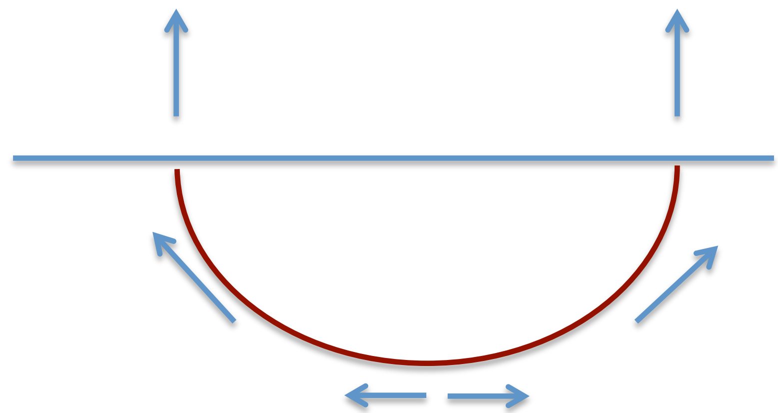


Further evidence of quantum mechanics ! →
View it as a measurement of the correlated spins of pair of produced particles.

There is a constraint on their masses.

Spin





$$\langle \epsilon_1^s.O\epsilon_2^s.O\rangle \sim \frac{[\epsilon_1.\epsilon_2 - 2(\epsilon_1.\hat{x})(\epsilon_2.\hat{x})]^s}{|x|^{2\Delta}}$$

Overall size estimate

$$\frac{\langle 4pt\rangle}{\langle 2pt\rangle^2} \sim \frac{H^2}{M_{pl}^2}\frac{e^{-\pi\mu}}{k_I^3}\left[\left(\frac{k_I^2}{k_1 k_3}\right)^{\frac{3}{2}+i\mu} e^{i\delta} + c.c.\right]$$

Overall size is small. $\lambda \sim 1/M_{pl}$

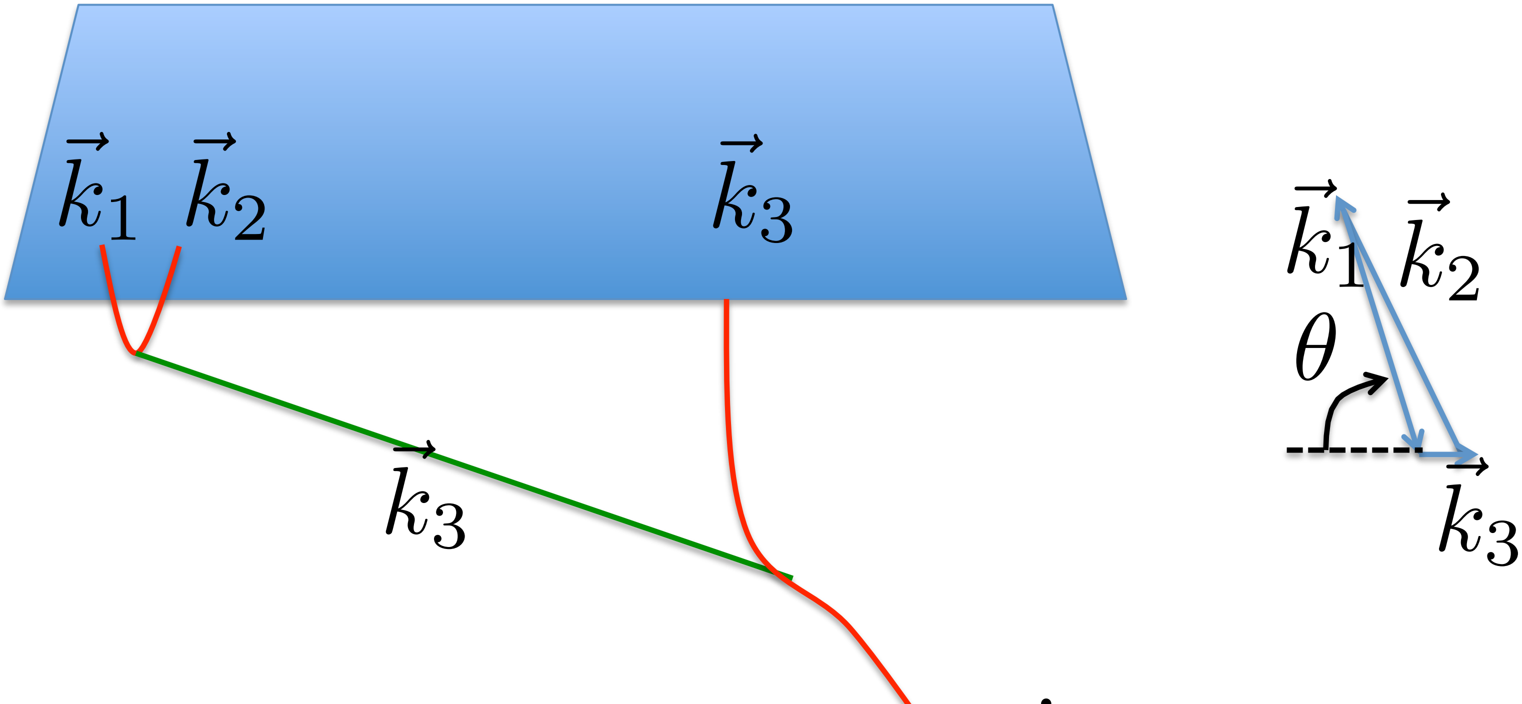
One factor of H/M from each interaction.

Can we find a bigger effect ?

Three point functions

- Consider instead the inflationary background.
- Now, we have a time dependent background

$$\phi(t)$$

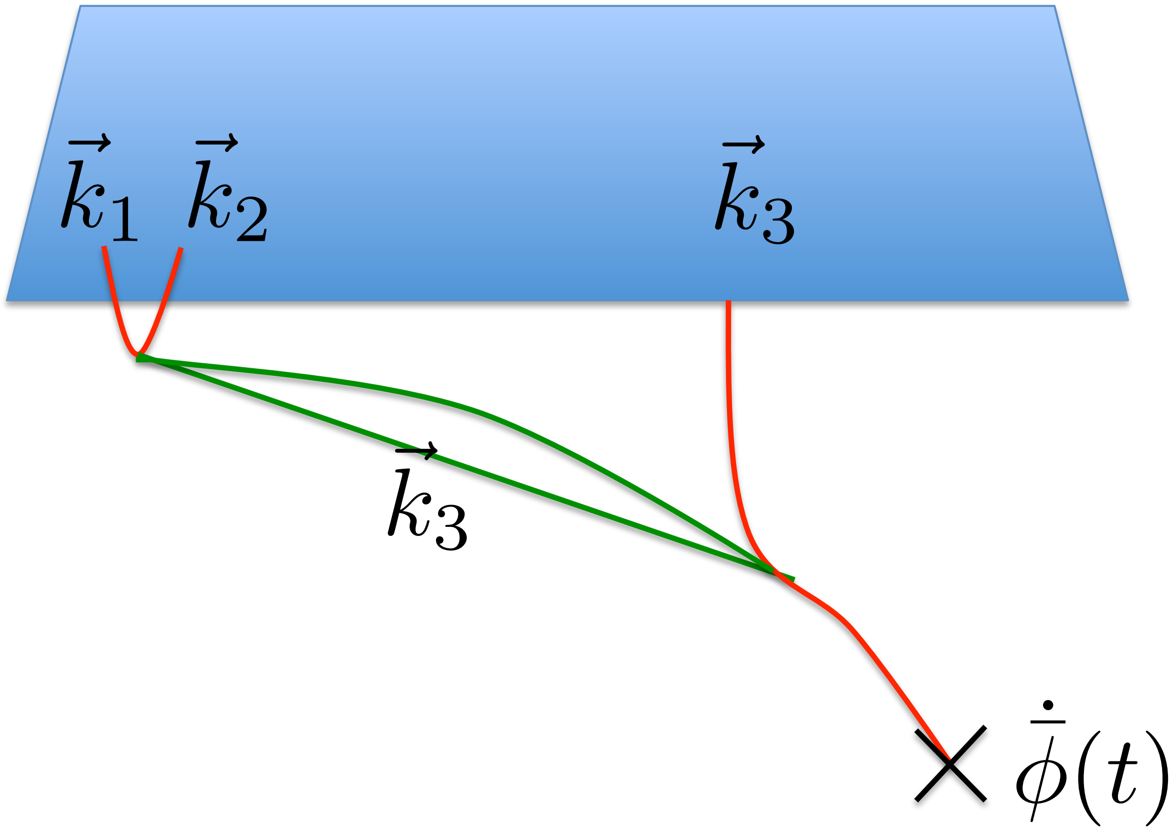


$$\times \; \dot{\phi}(t) \; \vec{k}_4 = 0$$

Only one very small coupling H/M_{pl}

Usual — Dilution

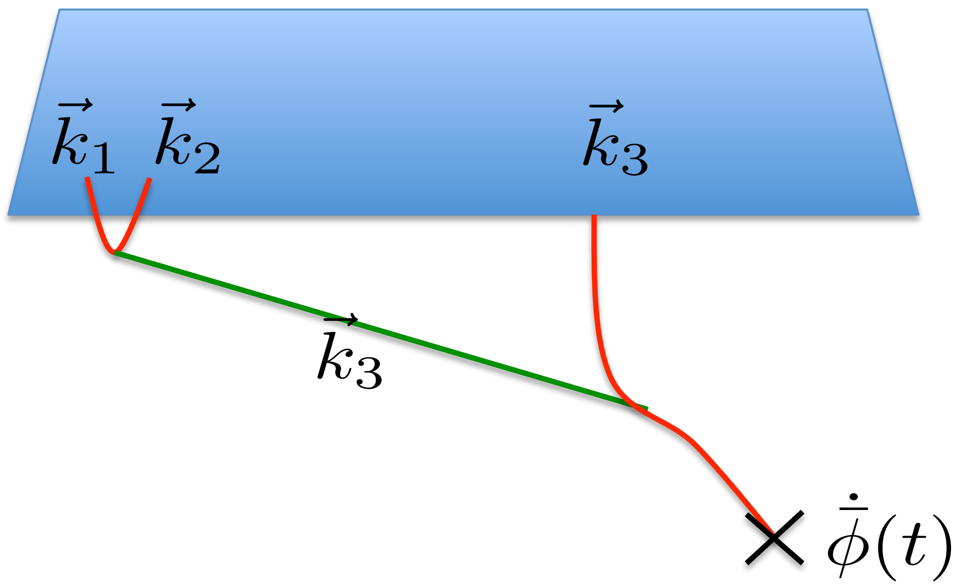
$$\langle 3pt \rangle \propto \frac{\dot{\phi}}{k_1^3 k_3^3} e^{-\pi\mu} \left[\left(\frac{k_3}{k_1} \right)^{\frac{3}{2}+i\mu} e^{i\delta} + c.c. \right] P_s(\cos\theta)$$



Loops →

give rise to a faster decay

$$\left(\frac{k_3}{k_1}\right)^{3+2i\mu}$$



Story: Particle is created by long wave mode k_3 . It then decays. We see interference between decay products and the original unperturbed state.

A striking evidence of quantum mechanics.

Phase of oscillation is calculable!.

Cosmological double slit experiment

Finding massive particles

- Collider → peaks in the invariant mass distribution.
- Cosmology → peaks in the Fourier transform of the cosmological correlator as a function of

$$\ell = \log(k_{short}/k_{long})$$

- Spin → angular dependence.

How difficult is it to detect ?

Compare it with the standard 3pt function

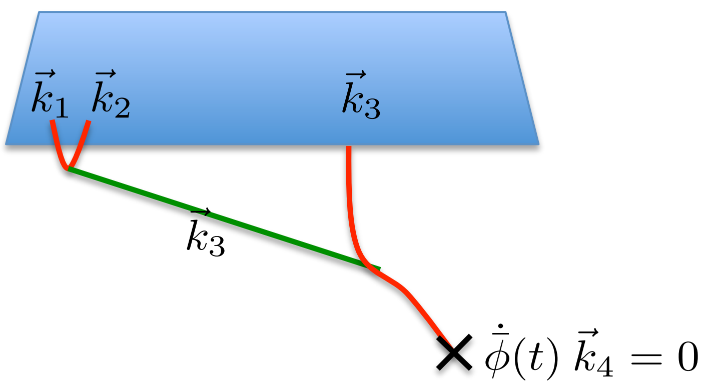
- The standard 3 point function can be viewed as exchanging a graviton.

Kundu, Shukla, Trivedi

Planck:

$$|f_{NL}^{\text{experimental}}| \lesssim 5 \,, \qquad f_{NL}^{\text{standard}} \sim (n_s - 1)$$

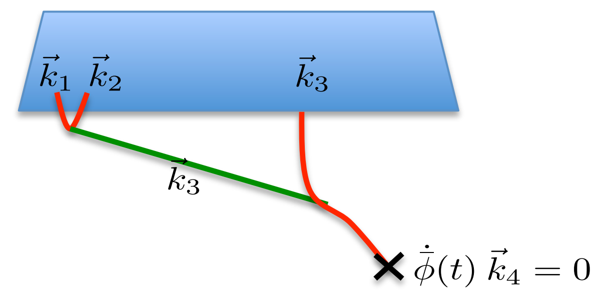
JM



How difficult is it to detect ?

- This one has extra factors of

$$(\lambda M_{pl})^2 e^{-\pi\mu} \left(\frac{k_3}{k_1}\right)^{3/2+i\mu}$$



- The last two suppress the signal. So the number of modes has to grow like the square of the above factor.
- The interactions could be larger than gravitational !

De Sitter isometries and conformal symmetry

$$ds^2 = \frac{-d\eta^2 + dx^2}{\eta^2}$$

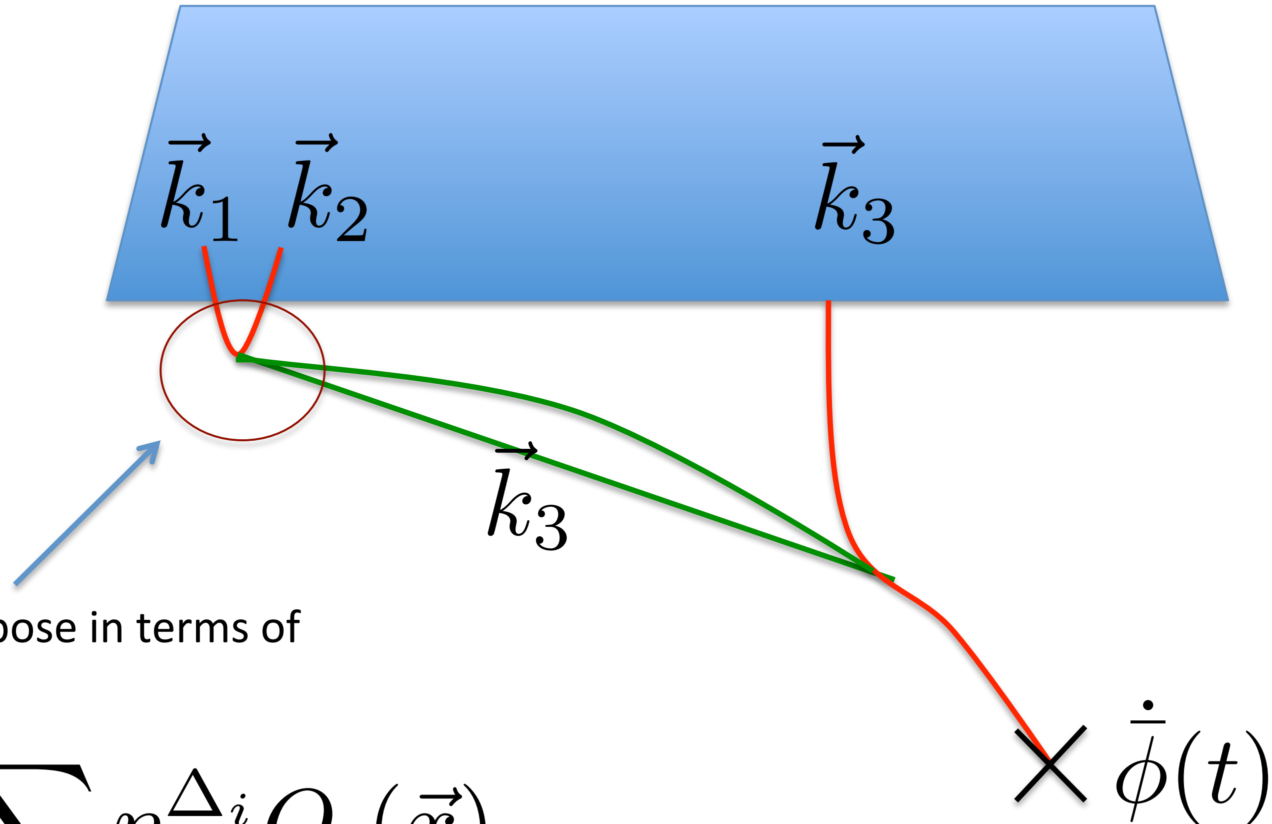
$$\langle \phi(\eta_1, \vec{x}_1) \cdots \phi(\eta_n, \vec{x}_n) \rangle$$

Invariant under de-Sitter isometries.

At late times, de-Sitter isometries act on x as conformal symmetries.

At late times we can often expand $\phi \sim \sum_i \eta^{\Delta_i} O_i(\vec{x})$ Strominger, Witten

3d operator of conformal dimension Δ_i



Decompose in terms of

$$\sum_i \eta^{\Delta_i} O_i(\vec{x})$$

Leads to

$$\sum_i \left(\frac{k_3}{k_1}\right)^{\Delta_i} c_i$$

$$\sum_i \left(\frac{k_3}{k_1}\right)^{\Delta_i} c_i$$

Powers that appear: Dimensions of 3d Operators →
energies of quasinormal modes in the de-Sitter static patch.
Can be complex!
Sensitive to the spectrum of masses in the theory.

Powers in the squeezed limit

=

Quasinormal mode spectrum

The squeezed region of the correlator, $k_3 << k_1$, k_2 is not where the largest non-gaussian signal lies.

But it is the region containing direct information about the spectrum of the theory.

$$e^{-\pi\mu} \quad \text{vs.} \quad 1/(\mu)^k$$

squeezed

Leading effect

Very stringy inflation?

- Usual picture: Strings → 10d → KK theory → inflation.
- Another possibility:

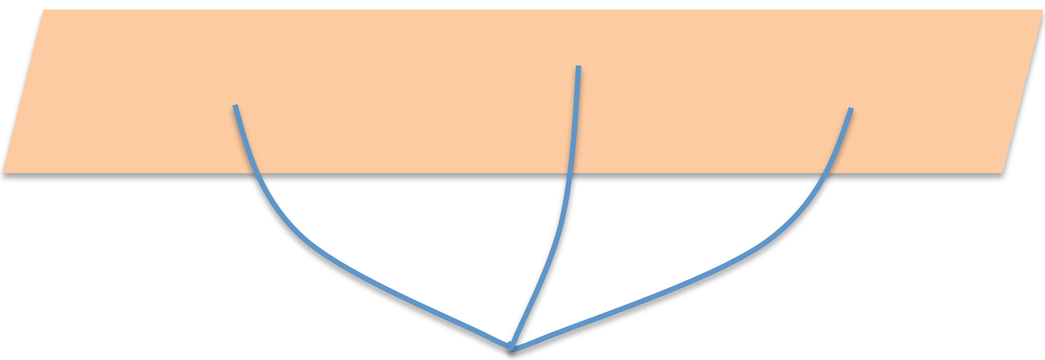
$$l_s \lesssim 1/H = R = \text{Hubble radius}$$

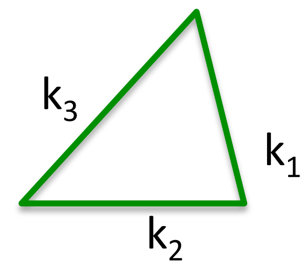
- Observations: higher spin massive particles!

- New structures in graviton three point functions.
- I do not know of a concrete stringy model…
- Could be evidence for string theory.

Higher spin (S>2) weakly coupled particles → String theory

Graviton 3pt function



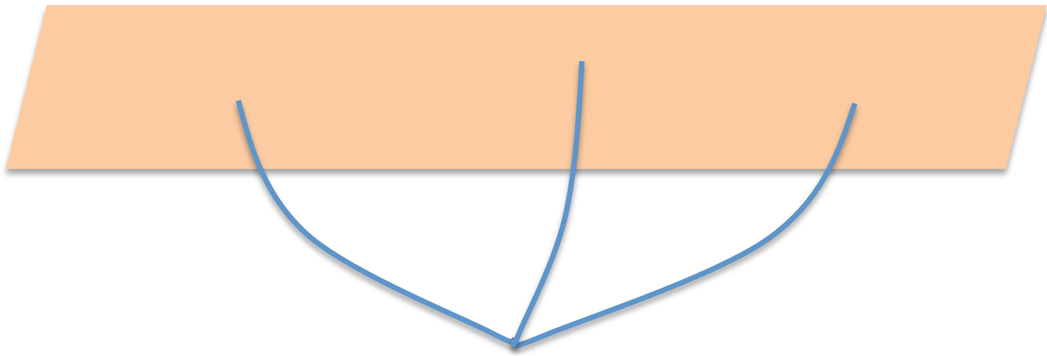


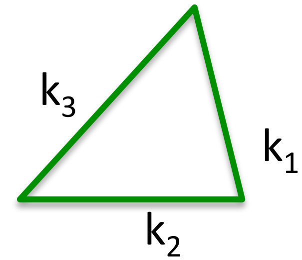
$$\frac{\langle hhh \rangle}{\langle hh \rangle^{3/2}} \sim \frac{H}{M_{pl}} \left[F_E(\text{shape}) + \alpha_4^2 H^4 F_2(\text{shape}) + o(\epsilon) \right]$$

JM, Pimentel

Overall small coupling

This is allowed by the approximate scale and conformal invariance of inflation





$$\frac{\langle hhh \rangle}{\langle hh \rangle^{3/2}} \sim \frac{H}{M_{pl}} \left[F_E(\text{shape}) + \alpha_4^2 H^4 F_2(\text{shape}) + o(\epsilon) \right]$$

JM, Pimentel

$$S = \frac{1}{G_N} \int R + \alpha_4^2 R^3 + \cdots$$

If this is observed + causality of the de-Sitter theory → massive higher spin states

This is only power suppressed in l_s H .

Camanho, Edelstein, J.M., Zhiboedov

Long string creation → suppressed exponentially as $e^{-\frac{2}{(l_s H)^2}}$

Conclusions

- Non gaussianities in cosmological correlators have very interesting information.
- Squeezed limit directly probes the spectrum of the theory during inflation.
- Mass and spin information.
- Very interesting evidence of the quantum nature of the perturbations.
- Could be observable with futuristic experiments… (e.g. 21 cm tomography). (After seeing other non-gaussian signals.)