Title: Cosmological collider physics

Date: May 02, 2015 09:45 AM

URL: http://pirsa.org/15050141

Abstract:

Cosmological Collider Physics

GaryFest
Santa Barbara
2016

Juan Maldacena
IAS

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

Nuclear Physics B360 (1991) 197–209
North-Holland

BLACK STRINGS AND p-BRANES

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Received 4 March 1991

It is shown that low-energy string theory admits a variety of solutions with the structure of an extended object surrounded by an event horizon. In particular there is a family of black string solutions, labelled by the mass and axion charge per unit length, corresponding to a string in ten dimensions surrounded by an event horizon. The extremal member of this family is the known supersymmetric singular solution corresponding to a macroscopic fundamental string. A similar family of solutions is found describing a fivebrane surrounded by an event horizon, whose extremal member is a previously discovered non-singular supersymmetric fivebrane. Additional charged, extended black hole solutions are presented for each of the antisymmetric tensors that arise in heterotic and type II string theories.

REVIEW D VOLUME 42, NUMBER 6 15 SEPTEMBER 1990

Strings in strong gravitational fields

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(Received 22 March 1990)

String propagation in exact plane-wave solutions (with nonzero axion and dilaton fields) is analyzed. In these backgrounds, strings can undergo transitions from one state to another. Selection rules are derived which describe allowed and forbidden transitions of the string. It is shown that singular plane waves result in infinitely excited strings. An example is given of a solution whose singular properties are the opposite of an orbifold: it is geodesically complete, but still singular from the standpoint of string theory. Some implications of these results are discussed.

Strings on plane waves

$$-Y_{-1}^2 - Y_0^2 + Y_1^2 + \cdots Y_d^2 = -R^2$$

$$SO(2,d)$$

Quasinormal Modes of AdS Black Holes and the Approach to Thermal Equilibrium

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Abstract

We investigate the decay of a scalar field outside a Schwarzschild anti de Sitter black hole. This is determined by computing the complex frequencies associated with quasinormal modes. There are qualitative differences from the asymptotically flat case, even in the limit of small black holes. In particular, for a given angular dependence, the decay is always exponential - there are no power law tails at late times. In terms of the AdS/CFT correspondence, a large black hole corresponds to an approximately thermal state in the field theory, and the decay of the scalar field corresponds to the decay of a perturbation of this state. Thus one obtains the timescale for the approach to thermal equilibrium. We compute these timescales for the strongly coupled field theories in three, four, and six dimensions which are dual to string theory in asymptotically AdS spacetimes.

Now the talk…

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

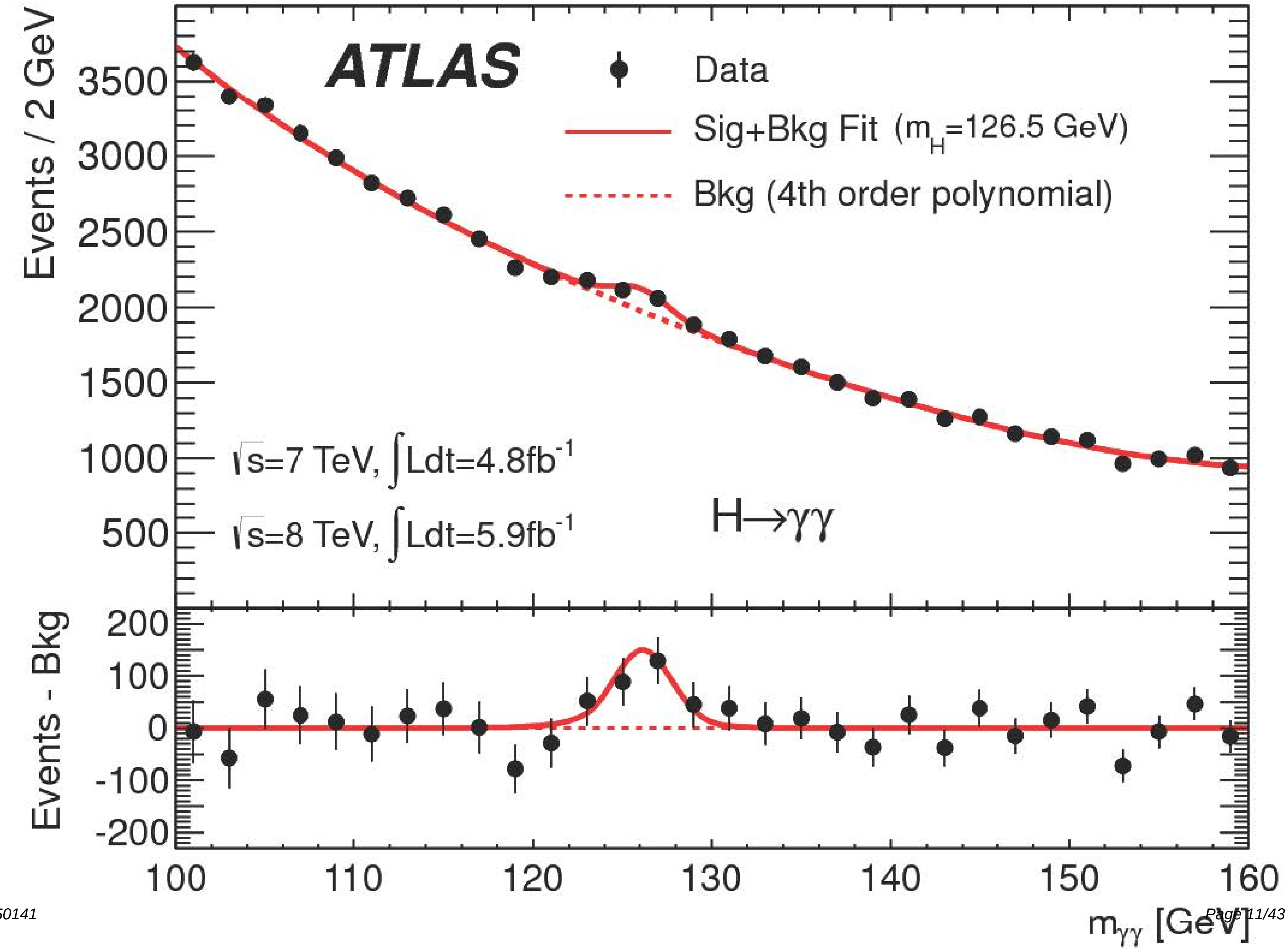
$$H \ , \qquad\qquad 3M_{pl}^2 H^2 = V$$

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

- Collisions → 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)
$\sqrt{s}$=7 TeV, $\int Ldt=4.8fb^{-1}$
$\sqrt{s}$=8 TeV, $\int Ldt=5.9fb^{-1}$
$H\rightarrow\gamma\gamma$
Events / 2 GeV
3500
3000
2500
2000
1500
1000
500
Events - Bkg
200
100
0
-100
-200
100
110
120
130
140
150
160
$m_{\gamma\gamma}$ [GeV]

In Cosmology

- Study non-gaussianities in the cosmological correlators.

- Interesting for the phenomenology of inflation

- Interesting conceptually, to understand how we reconstruct the past. Fossils → dinosaurs.
- What is the structure of the wavefunction, or probability distribution produced by inflation?

Analogy

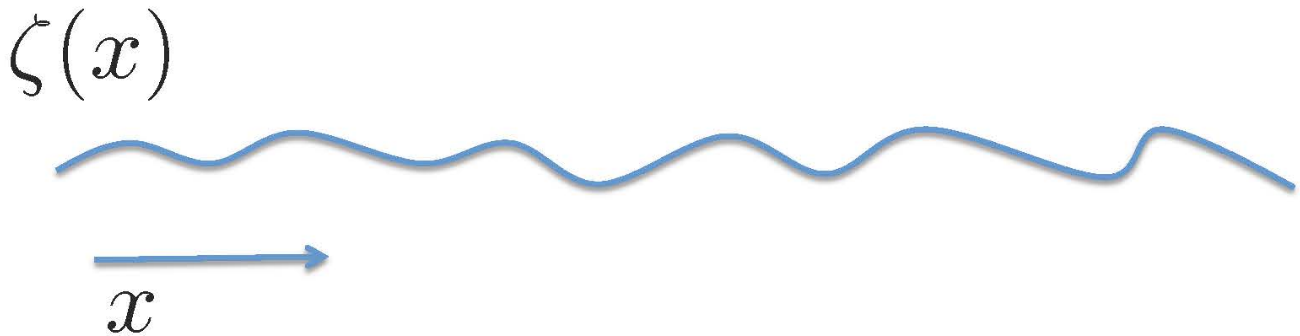
QCD		Cosmology
Hadrons	=	galaxies
Hadronization	=	Structure formation
Energy correlators	=	correlators of primordial density fluctuations.
Weak coupling at high energies	=	weak coupling during inflation
Approximate scale invariance	=	approximate scale invariance of wavefunction = approximate de-Sitter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



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

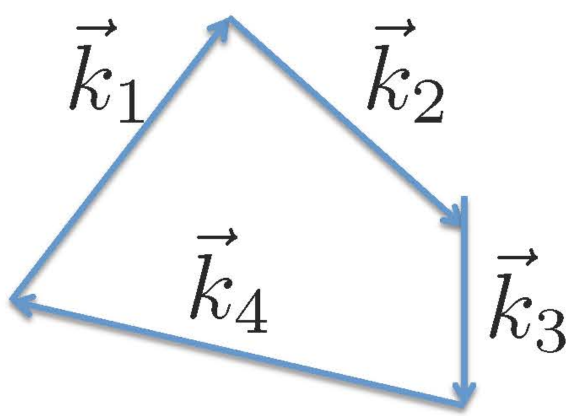
Kinematics

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

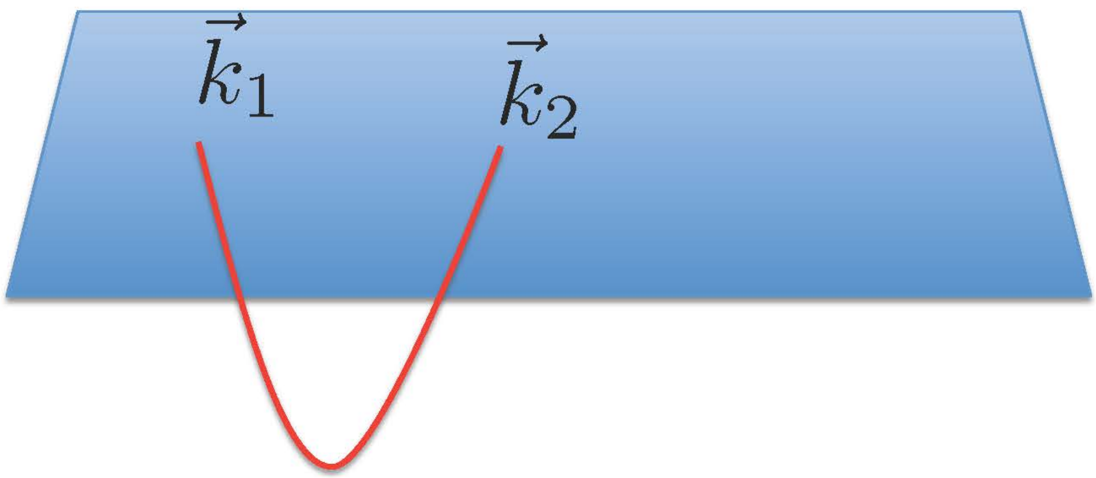
Fourier transform → set of momenta

Statistical homogeneity of the universe → Momentum conservation

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



Leading effect

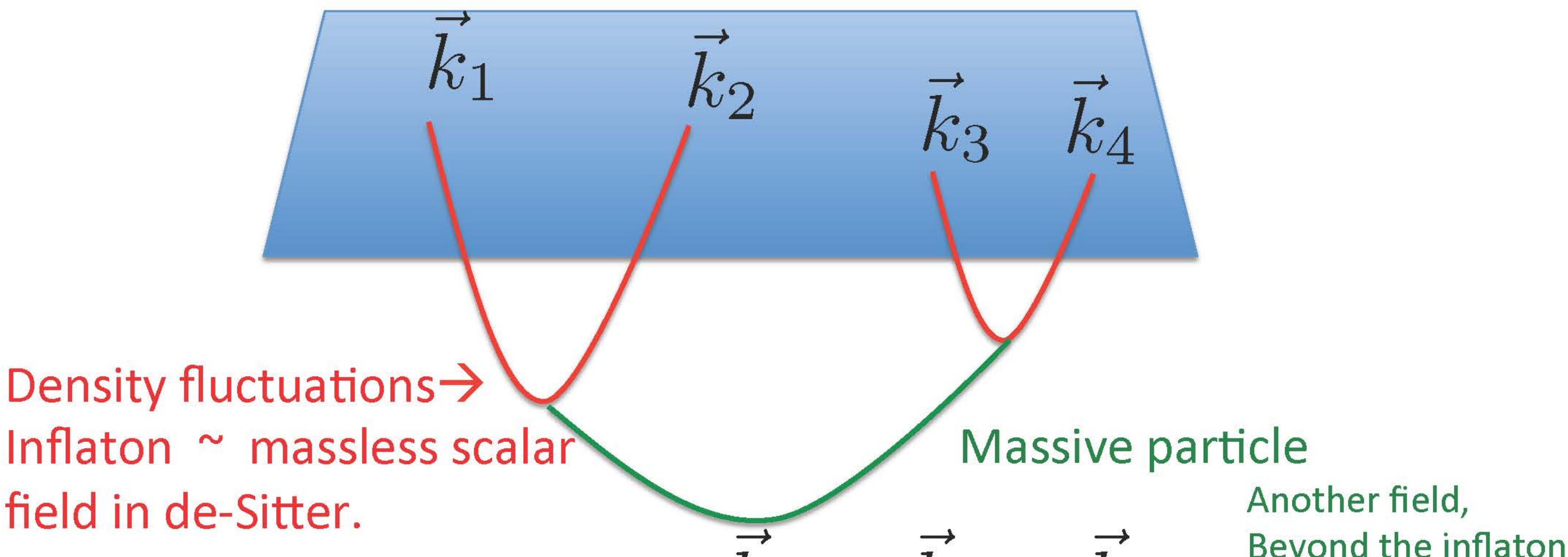


Two point function

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

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

- Suppose that a massive particle existed during inflation, m of order H.

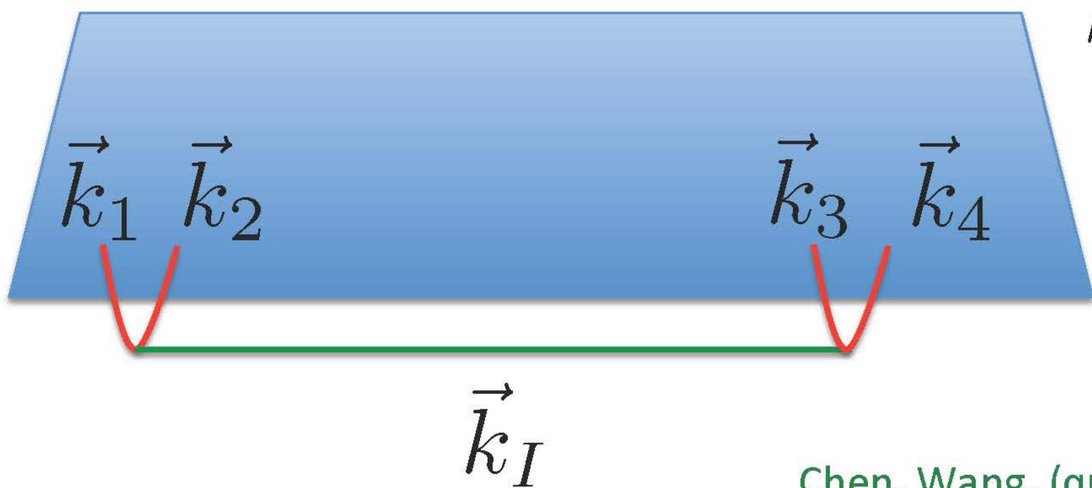


$$\vec{k}_I = \vec{k}_1 + \vec{k}_2$$

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

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

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



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

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

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

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

Boltzman suppression

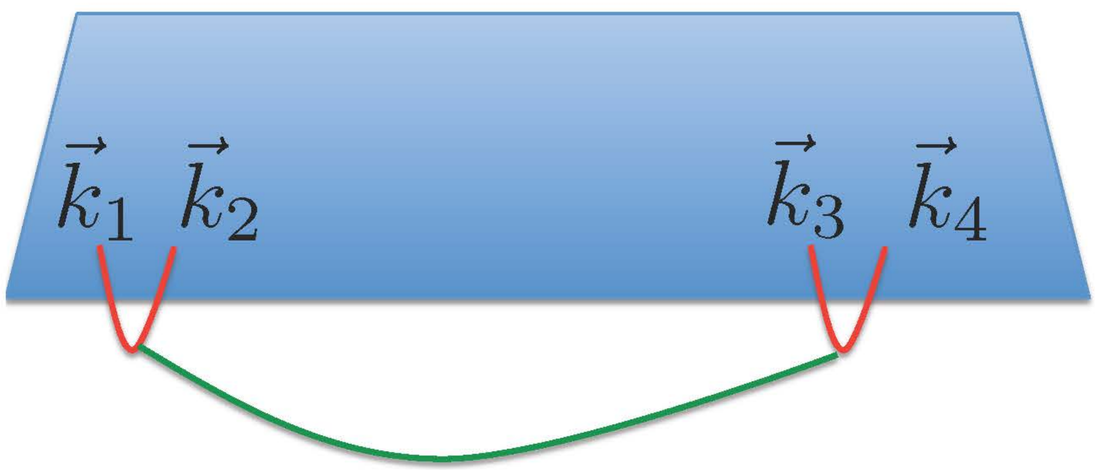
Interference effect: $\Psi_{\rm nopair} + e^{-\pi\mu}\Psi_{\rm pair}$

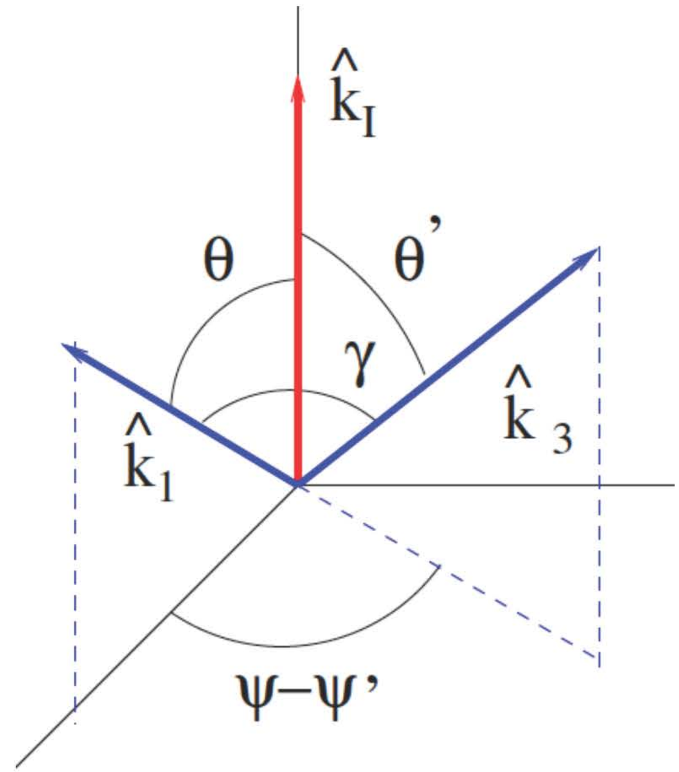
Phase is a function of the mass.

Interesting test of the quantum nature of fluctuations.

Spin

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

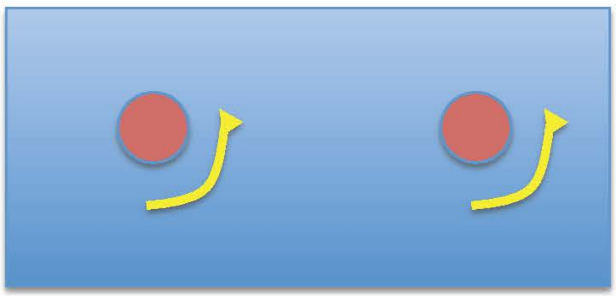




Further evidence of quantum mechanics ! →
View it as a measurement of the correlated spins of pair of produced particles.

There is a constraint on their masses.

Spin



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

$$\langle j_z(0) j_z(z) \rangle \sim \frac{1}{z^2}$$

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

Overall size is small.

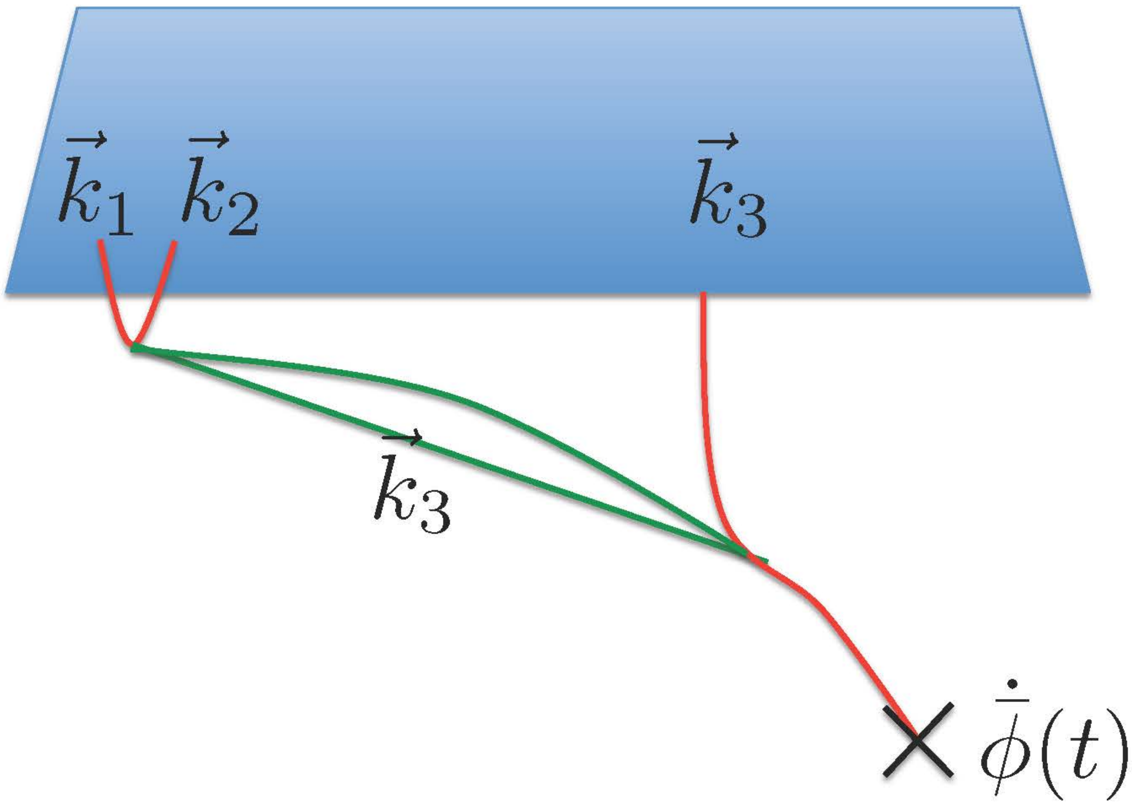
One factor of H/M from each interaction.

Can we find a bigger effect ?

Three point functions

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

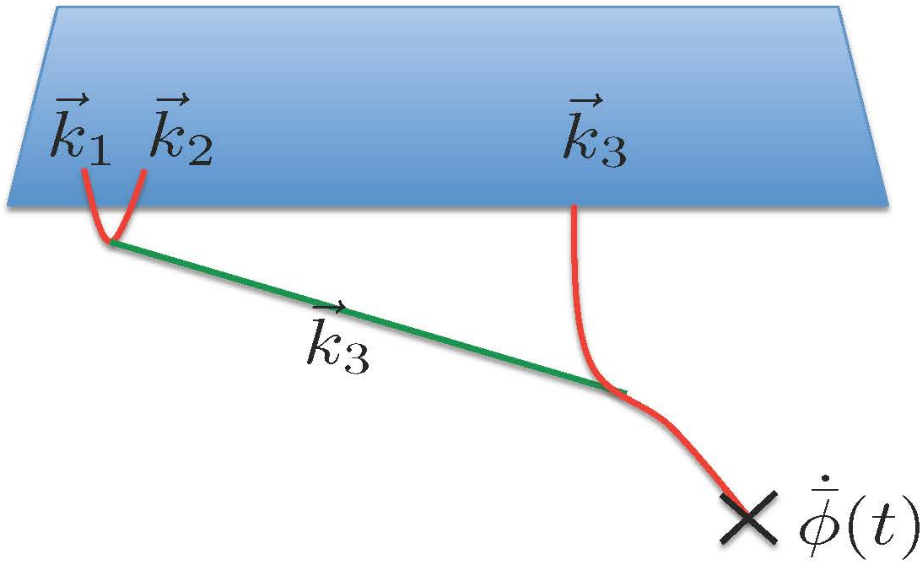
$$\phi(t)$$



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

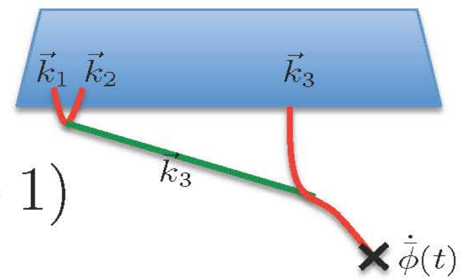
- Collider → peaks in the invariant mass distribution.
- Cosmology → peaks in the Fourier transform of the cosmological correlator as a function of

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

- Spin → angular dependence.

How difficult is it to detect ?

- Compare it with standard three point function.
- The standard 3 point function can be viewed as exchanging a graviton.



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

Kundu, Shukla, Trivedi

- This one has extra factors of

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

- Both 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 !

Bounds on masses of spinning particles

$$\frac{m^2}{H^2} \geq s(s-1)$$

Higuchi,

Deser Waldron

Comes from the fact that in de-Sitter we have a null state when the inequality is saturated. Follows simply from representation theory.

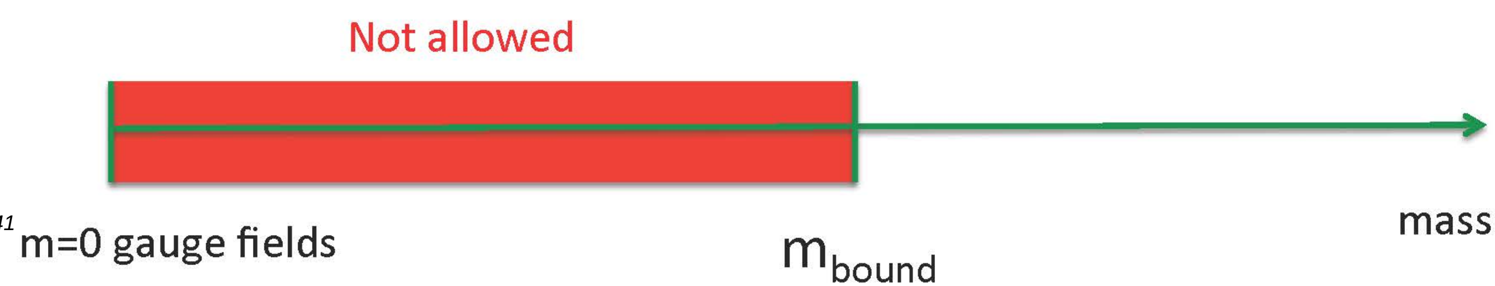
Saturation = ``partially massless field''.

No AdS analog.

Wavefunctional of the universe becomes unbounded for the longitudinal mode when the inequality is violated.

$$\frac{m^2}{H^2} \geq s(s-1)$$

- For spin =1 → no bound
- For spin = 2 → there is a non-trivial bound.
- There cannot be any particles with masses between the graviton and this bound!.
- Kaluza –Klein theory → Size of internal dimension should be smaller than the size of de-Sitter.
- Spin > 2 : Vasiliev theory is <u>not</u> smoothly connected to an ordinary Einstein theory.



De Sitter isometries and conformal symmetry

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

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

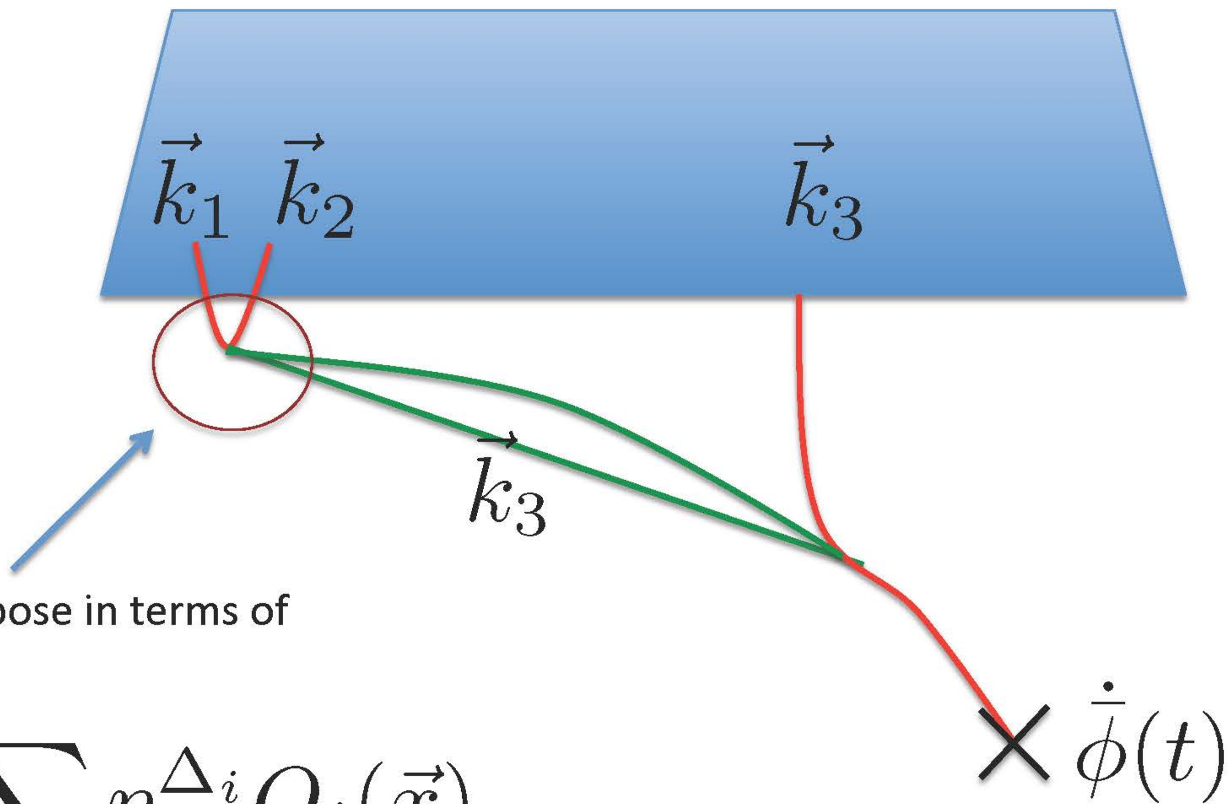
Invariant under de-Sitter isometries.

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



Decompose in terms of

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

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

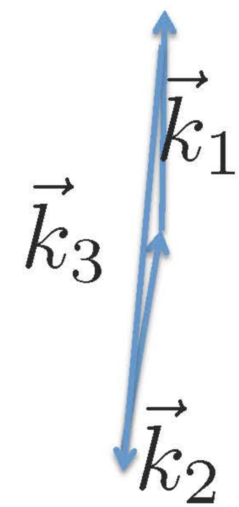
$$\sum_i \left(\frac{k_3}{k_1}\right)^{\Delta_i} c_i$$

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.

The OPE 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.

Analytic structure of correlator

- Singularities: Small momentum, or small intermediate momentum → essentially OPE.
- No ``colinear'' singularities when:



- Related to the absence of particles in the initial adiabatic vacuum state.
- There can be such singularities when we continue

$$|\vec{k}_i| \to -|\vec{k}_i|$$

Signature of local interactions

- Signature of local interactions are in singularities when:

$$k_t = \sum_{i=1}^{n} |k_i| \to 0$$

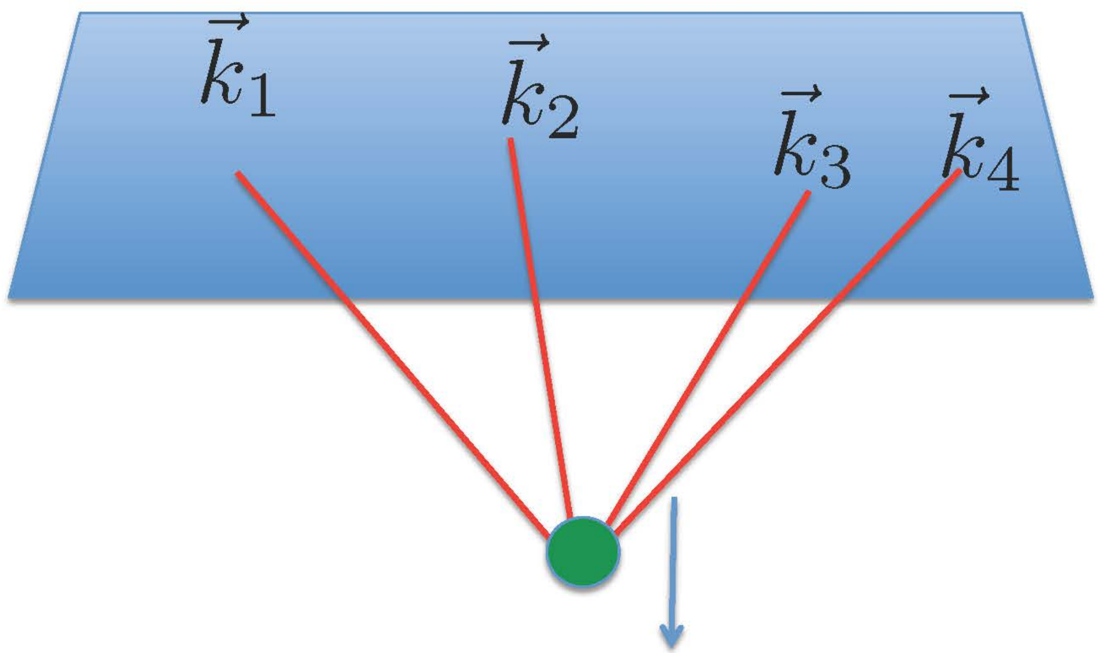
$$C(k_i) \sim \frac{\mathcal{A}}{k_t^p} + \cdots$$

Like delta function
of energy conservation

- Gives the high energy limit of the bulk amplitudes.
- Note that we need to continue $|\vec{k}_i| \to -|\vec{k}_i|$
- Conformal invariance of C → lorentz invariance of A

Why ?

$$C \sim \int d\eta (\text{Propagators}) \sim \int d\eta \eta^{p-1} e^{i\eta k_t} \mathcal{A} \sim \frac{\mathcal{A}}{k_t^p}$$



String inflation?

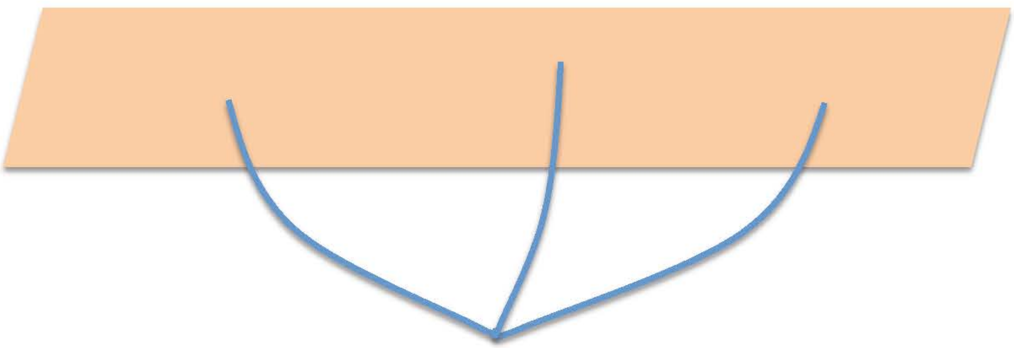
- Usual picture: Strings → 10d → KK theory → inflation.
- Another possibility:

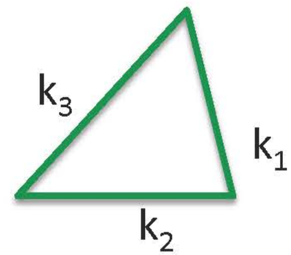
$$l_s \lesssim 1/H = R = \text{Hubble radius}$$

- Observations: higher spin massive particles!

- New structures in graviton three point functions.
- I do not know of a concrete stringy model…

Graviton 3pt function



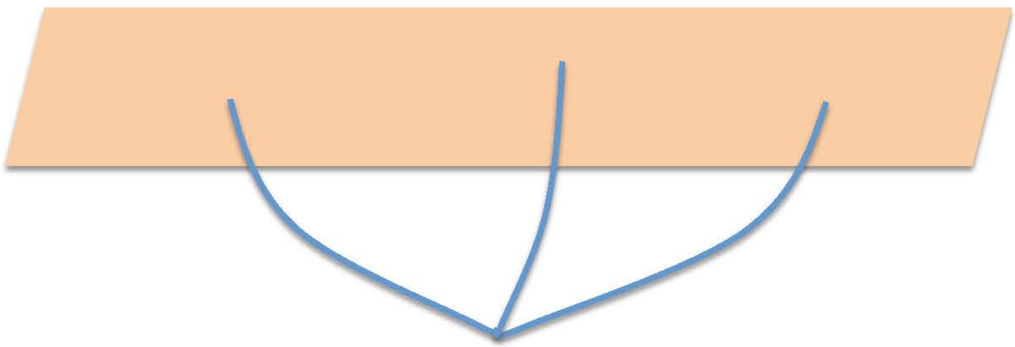


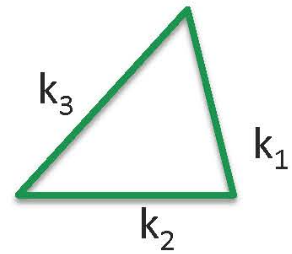
$$\frac{\langle hhh \rangle}{\langle hh \rangle^{3/2}} \sim \frac{H}{M_{pl}} \left[F_E(\text{shape}) + \alpha_4^2 H^4 F_2(\text{shape}) + o(\epsilon) \right]$$

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.
- Very interesting evidence of the quantum nature of the perturbations.
- It is useful to think about the conformal symmetry (or late time implications of de-Sitter isometries).
- Could be observable with futuristic experiments… (e.g. 21 cm tomography). After seeing other non-gaussian signals.

Happy Birthday Gary

Thank you !