Cosmological Collider Physics

2019 CERN LATIN-AMERICAN SCHOOL OF HEP

Córdoba, Argentina

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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

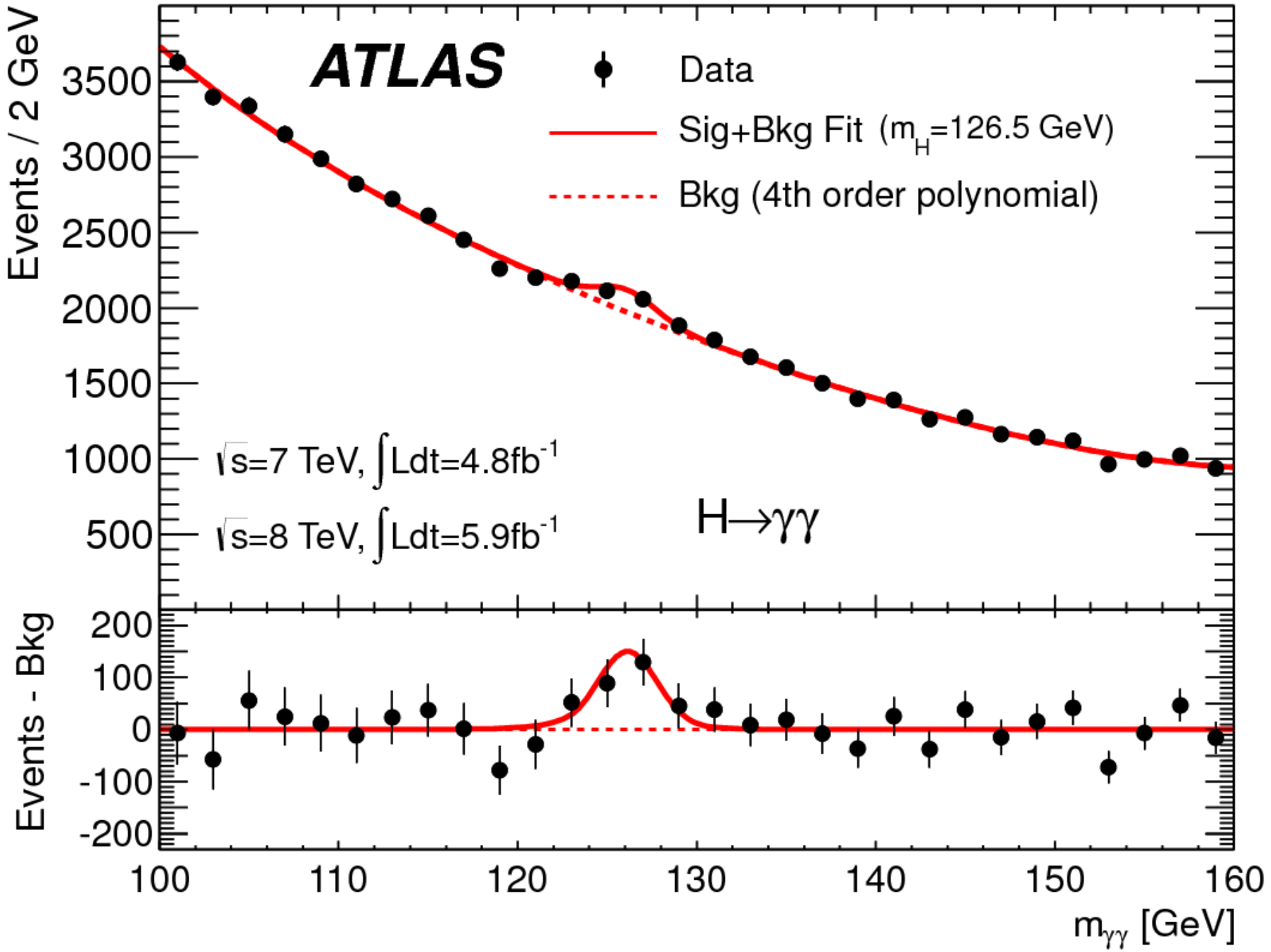
$$T \sim \frac{H}{2\pi} \ , \qquad\qquad 3M_{pl}^2 H^2 = V$$

- 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 - Particle physics


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]

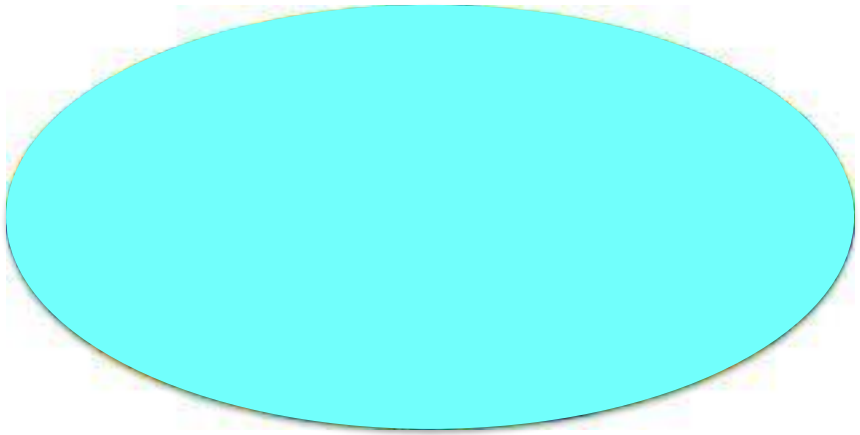
In Cosmology?

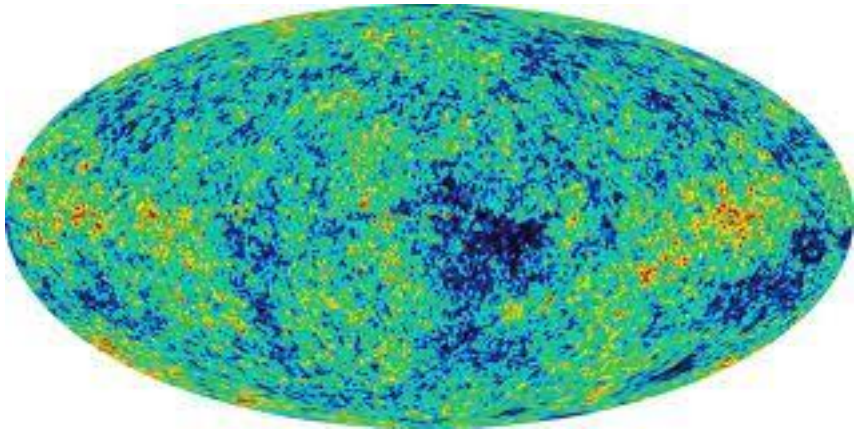
Some preliminaries

Guth, Linde, Mukhanov, Starobinski, Albrecht, Steinhardt, …

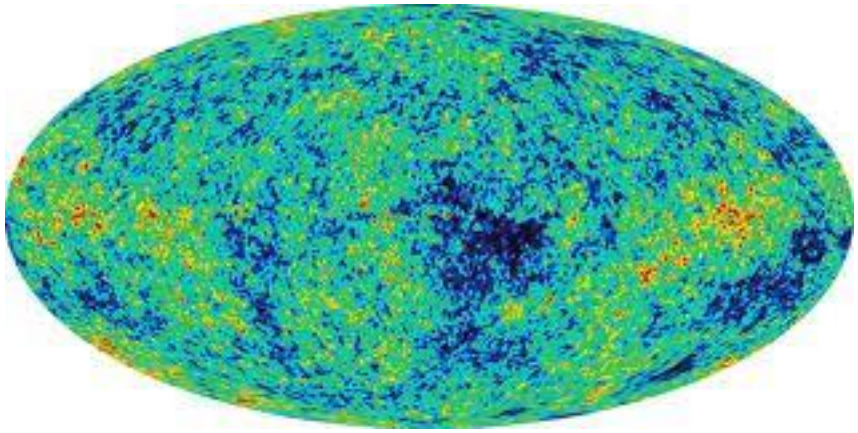
Inflation

- Period of expansion with almost constant acceleration.
- Produces a large homogeneous universe





Quantum mechanics is crucial for understanding the large scale geometry of the universe.



The primordial fluctuations are nearly scale invariant

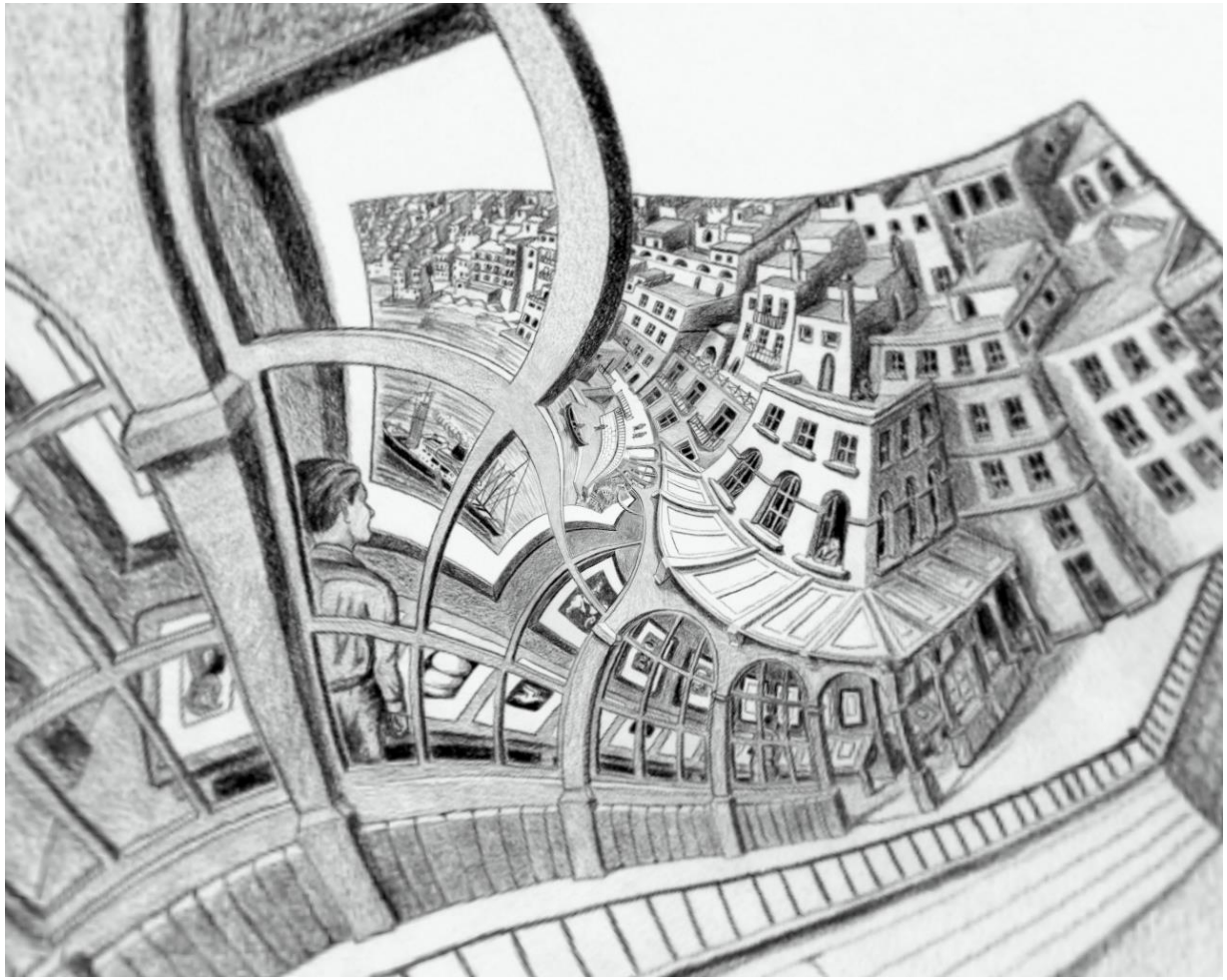
$\Psi[$ $] = \Psi[$ $]$

$\Psi[\, g_{\mu\nu}\,]$ = Probability (amplitude) for the shape of the universe

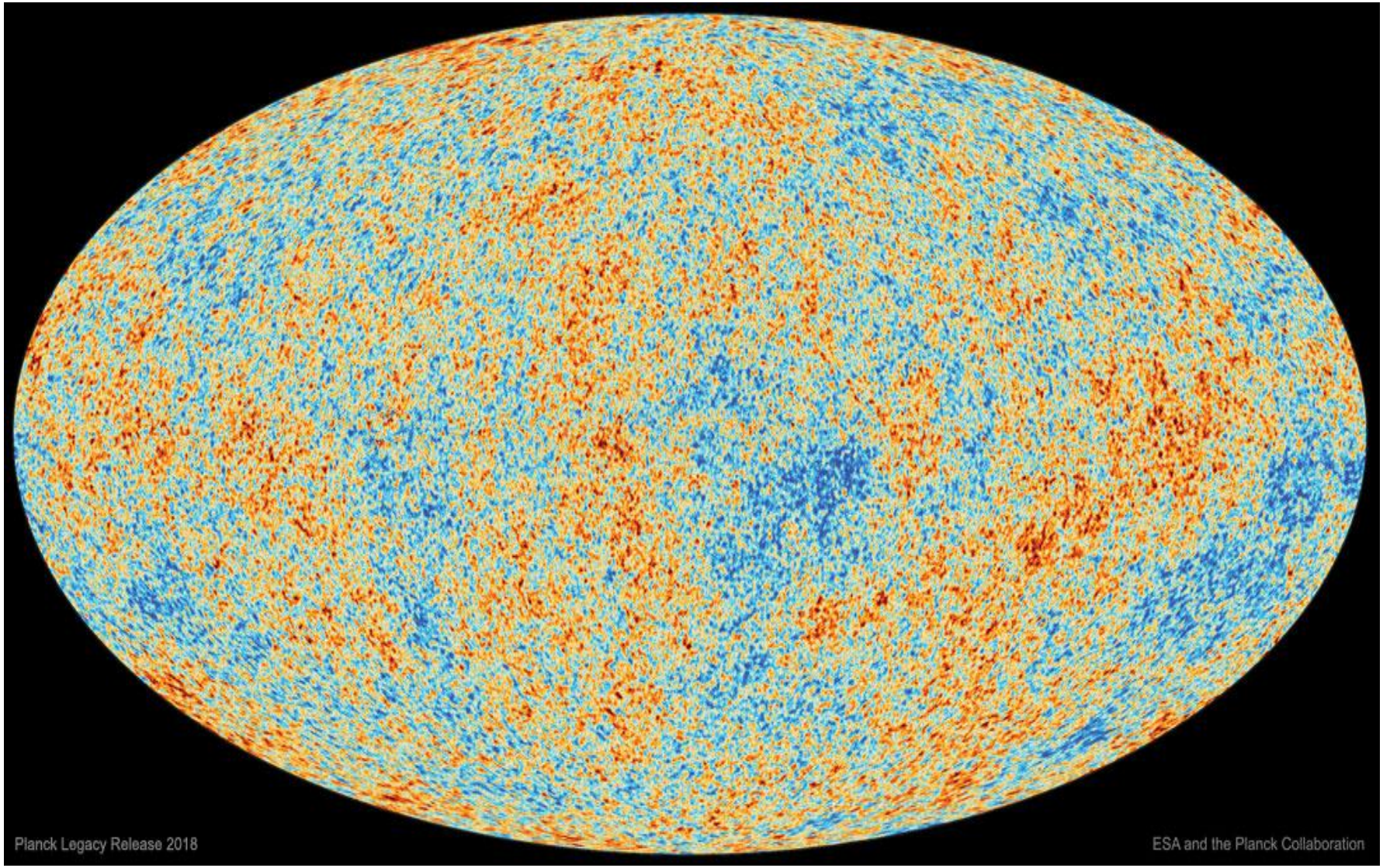
Scale invariance in physics

- If we rescale all coordinates → same physics (eg. electric force)
- Most of every day physics is not scale invariant → poor intuition, specially for interacting scale invariant theories.
- Condensed matter systems at 2^{nd} order phase transitions or quantum critical points.
- Chromodynamics at high energies

(Conformal invariance)

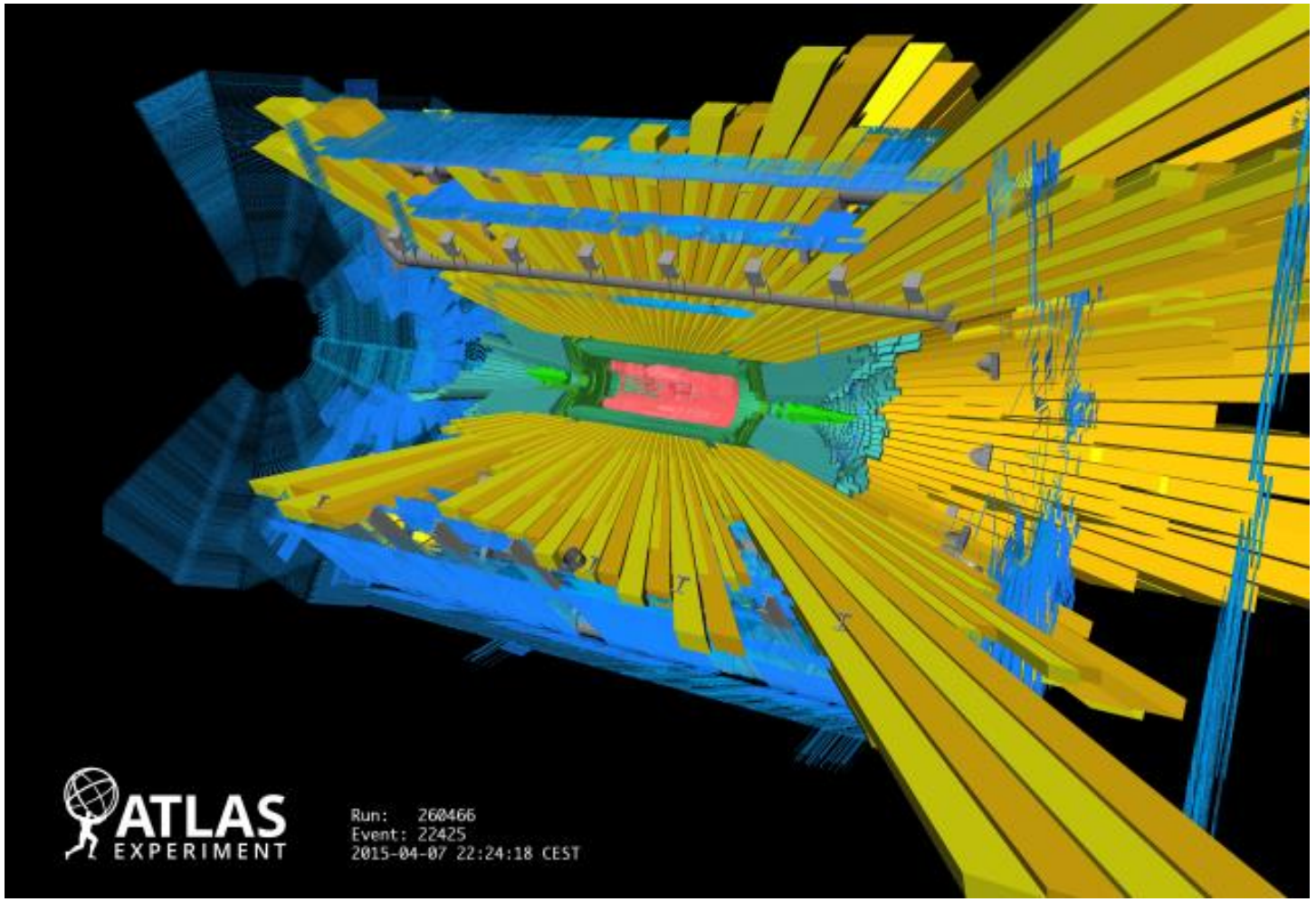


Cosmic microwave background → reflects the primordial density fluctuations.



- Measuring this map of radiation → Get the primordial fluctuations produced by inflation.
- Relatively simple and well understood linear physics between the two.

Analogy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- CMB map → like map of energy deposition on the calorimeter.

- Reflects fairly accurately the actual underlying energy distribution. But not exactly because of detector response is different for different particles, etc. But this physics is presumably well understood and one can the underlying energy flow.

- From the true energy flows, we would like to extract the particles that appear in the underlying lagrangian.

- If the short distance physics is weakly coupled, then there are some specific collider signatures that we could look for.

- The “mass bumps” discussed previously are a good example.

- In a collider experiment, the final answer is a two dimensional map of energy depositions.
- In cosmology, we have a two dimensional map of density fluctuations.
- In both cases there is an approximate scale invariance that governs a lot of the physics.
- The details are different.

Main difference

- In QCD → high energy processes give some localized jets. The interesting signals are in the positions and energies of these jets.

- In Cosmology, the basic energy distribution is approximately constant, with small fluctuations.
- The signal is almost gaussian.
- The interesting signals will be in small deviations from gaussianity.

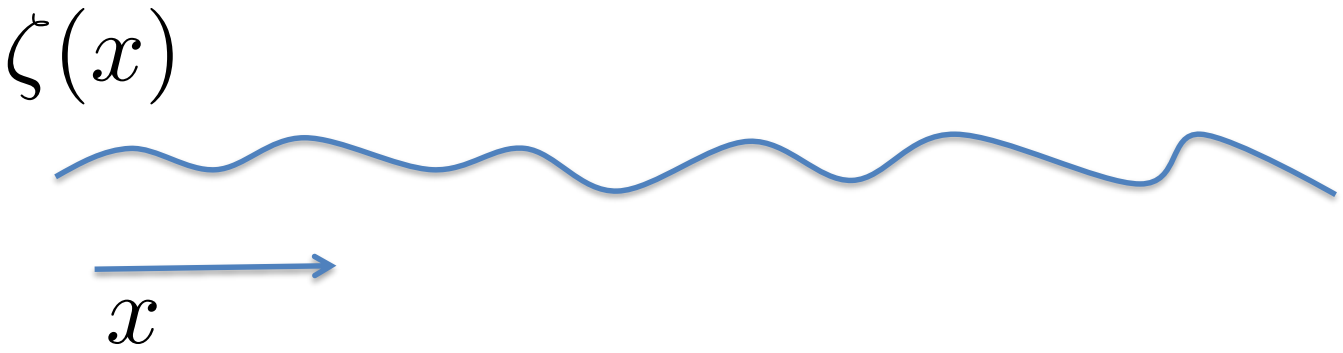
Analogy

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



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

Scale factor for the 3-metric on a time slice with constant density.

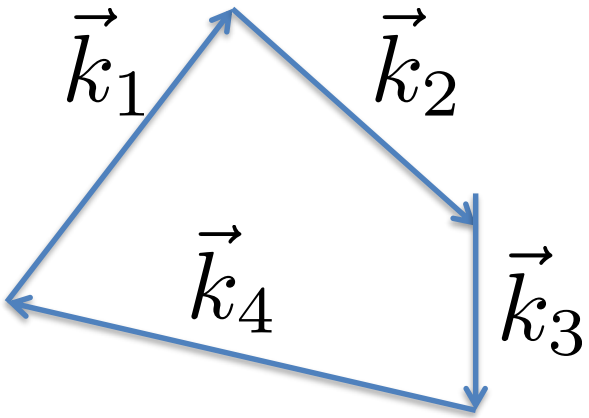
Kinematics

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

Fourier transform → set of momenta

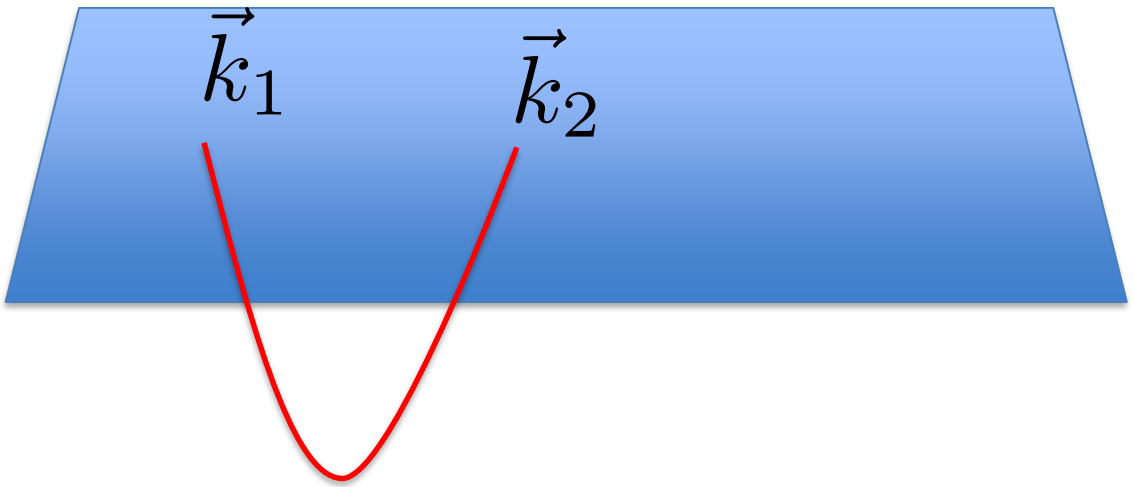
Statistical homogeneity of the universe → Momentum conservation

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



First assume exact
scale invariance.
Exactly de Sitter space

Leading effect



Two point function

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

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

Leading effect

Gaussian Random field → fully determined by its two point function.

Scale invariant.

Two point function

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

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

Non-Gaussianities

- Study non-gaussianities in the cosmological correlators.

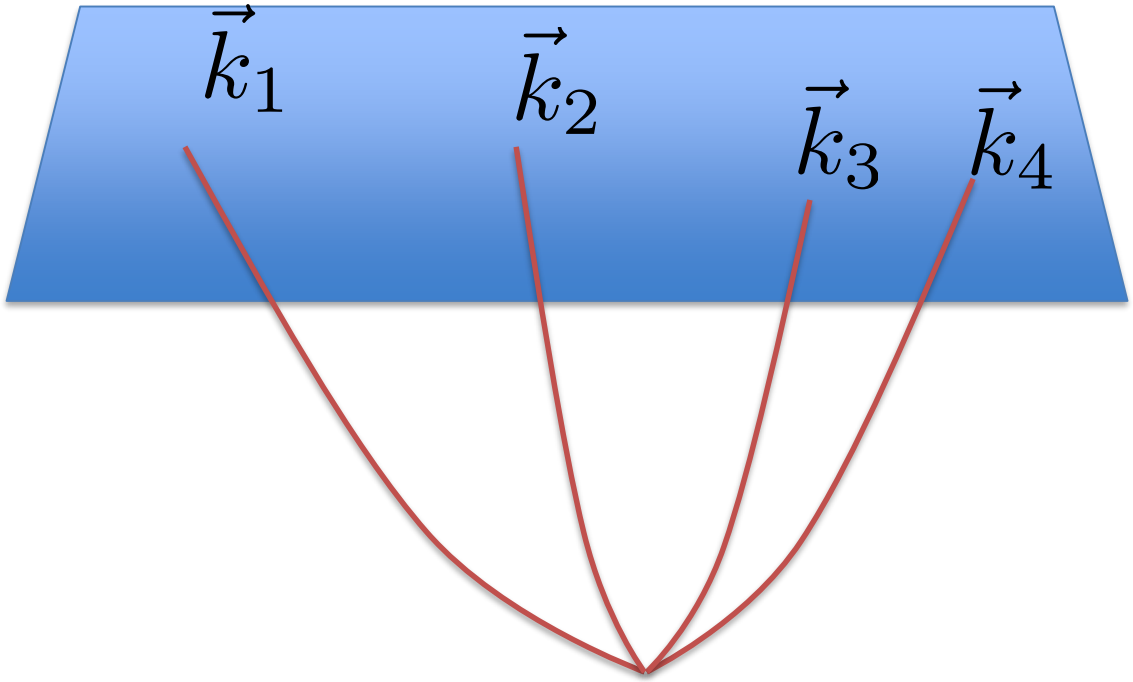
- Can be produced by self interactions of the inflaton. $\int (\nabla\phi)^2 + \lambda(\nabla\phi)^4$

- There are also interesting patterns produced by new particles.

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

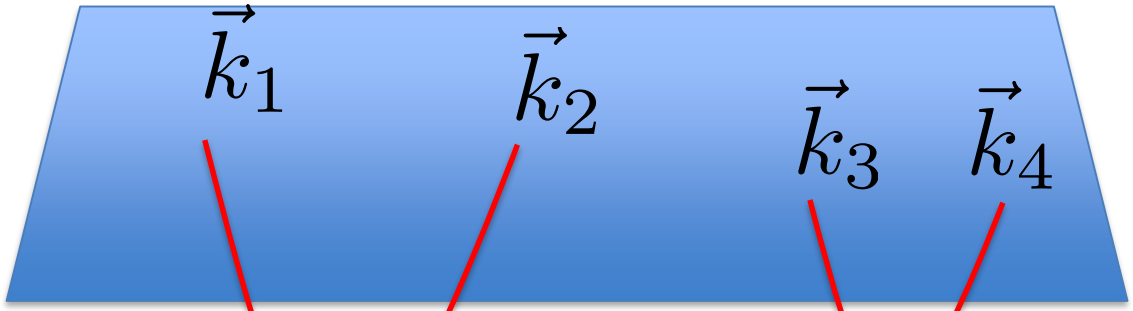
Four point function

- From self interactions



Four point function

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



Density fluctuations→
Inflaton ~ massless scalar field in de-Sitter.

Massive particle

Another field,
Beyond the inflaton

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

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,…

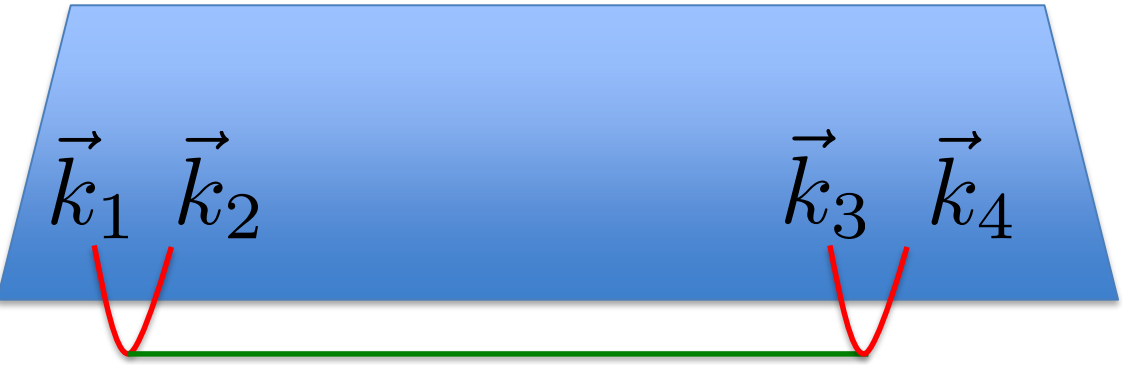
$$\mu = \sqrt{m^2/H^2 - 9/4}$$

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

$\vec{k}_I$

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

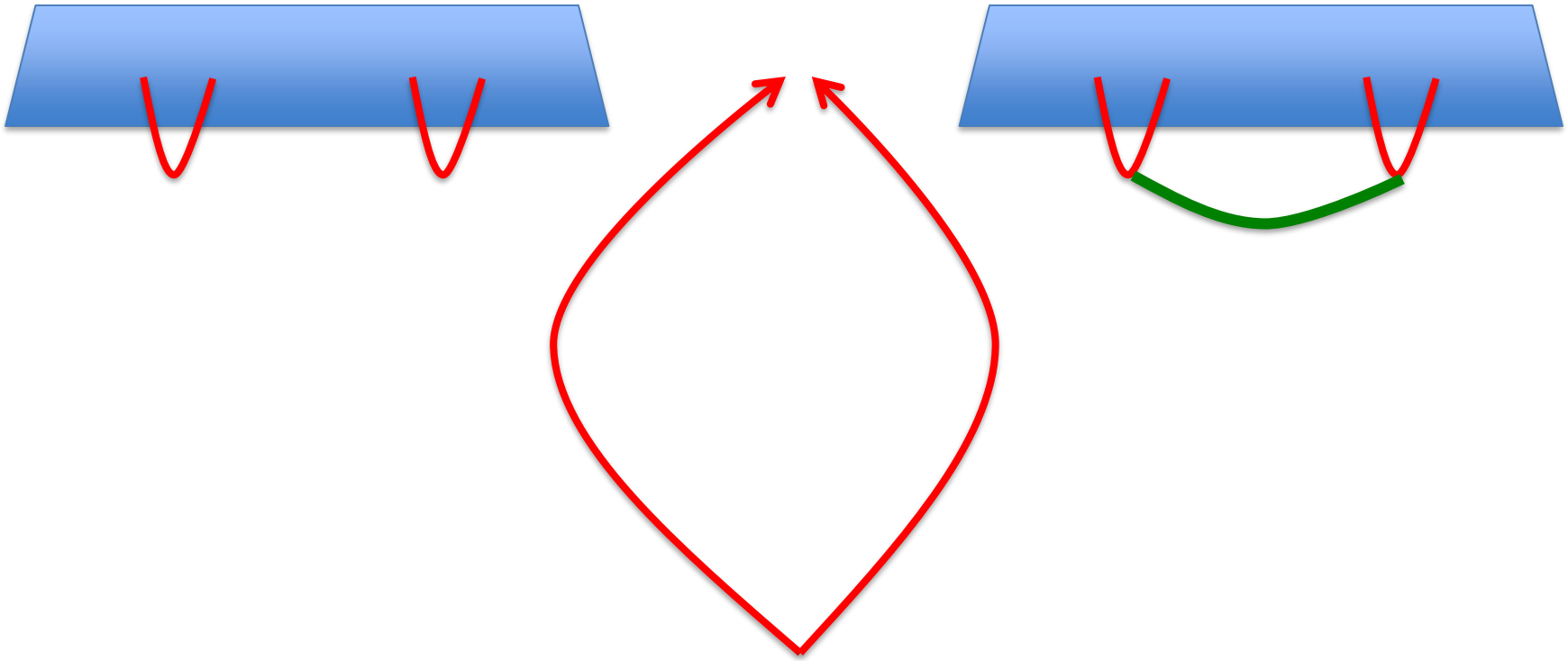
Interference effect: $\Psi_{\rm nopair} + e^{-\pi\mu}\Psi_{\rm pair}$

Phase is a function of the mass.

Interesting test of the quantum nature of fluctuations.

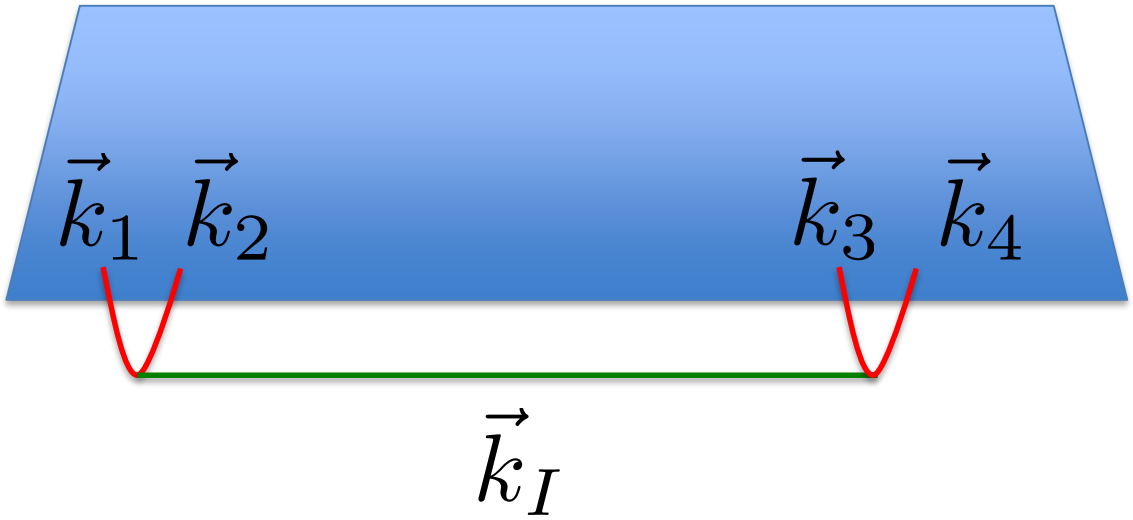
Cosmological double slit experiment

$$\left|\Psi_{\mathrm{nopair}} + \Psi_{\mathrm{pair}}\right|^2$$



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

Oscillatory for real μ → oscillations of the wavefunction



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

Volume dilution

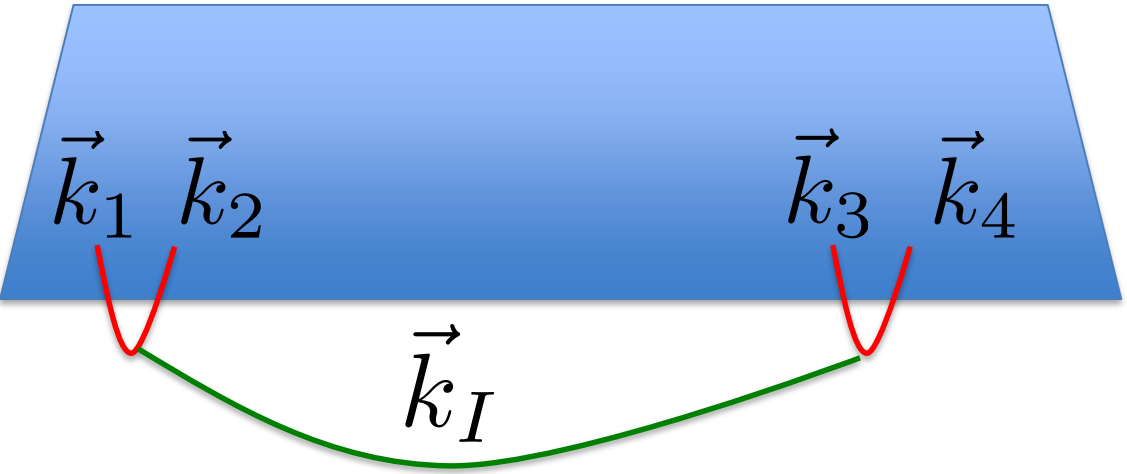
$$\langle 4pt \rangle \propto e^{-\pi\mu} \left[\left(\frac{k_I^2}{k_1 k_3} \right)^{\frac{3}{2}+i\mu} e^{i\delta} + c.c. \right]$$

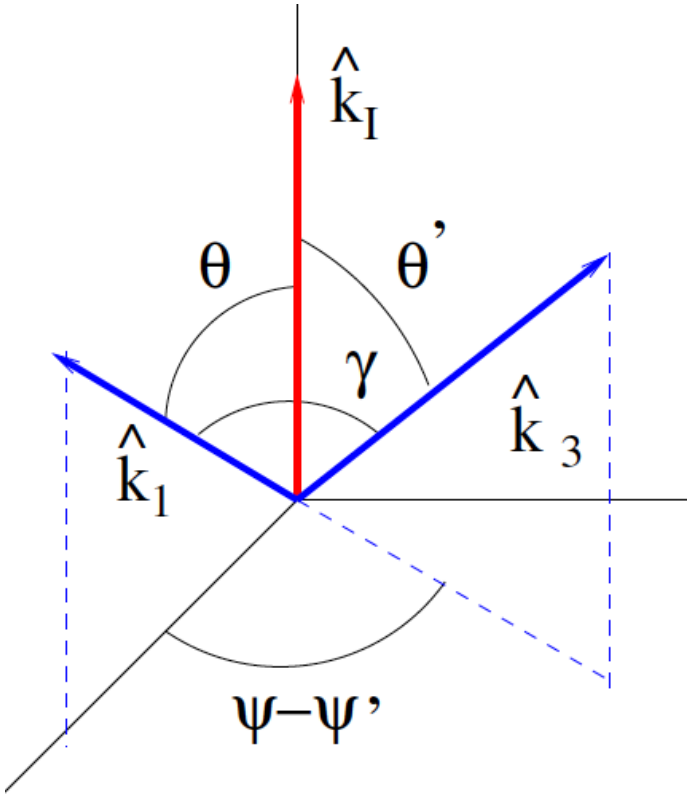
Explicit phase, function of μ

Test of quantum mechanics

Spin

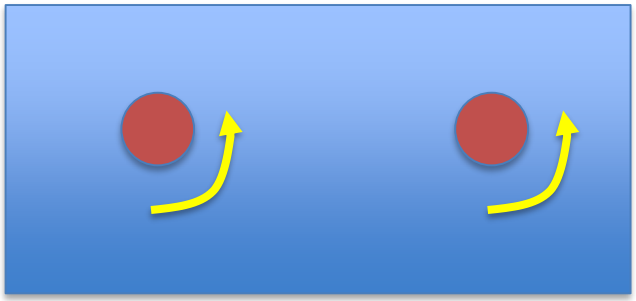
$$\langle 4pt \rangle \sim F(\gamma, \theta, \theta')$$

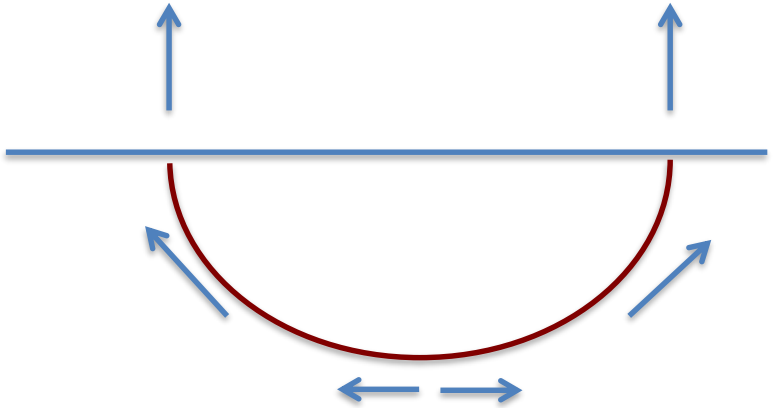




Further evidence of quantum mechanics ! →
View it as a measurement of the correlated spins of pair of produced particles.

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.

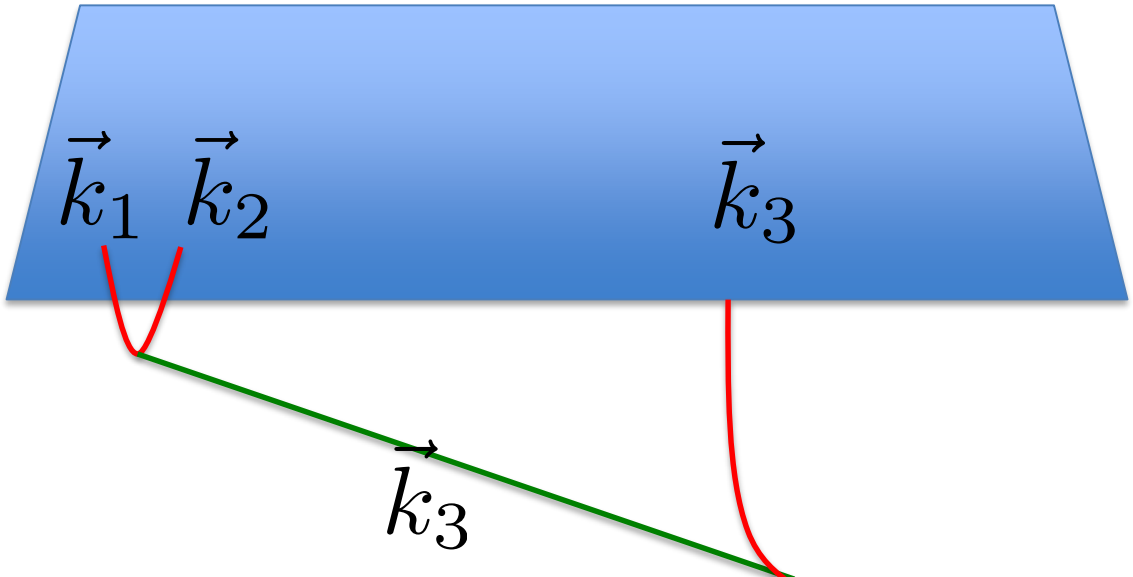
Can we find a bigger effect ?

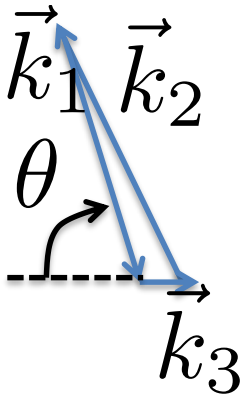
Three point functions

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

$$\phi(t)$$

$$\dot{\phi} \neq 0$$





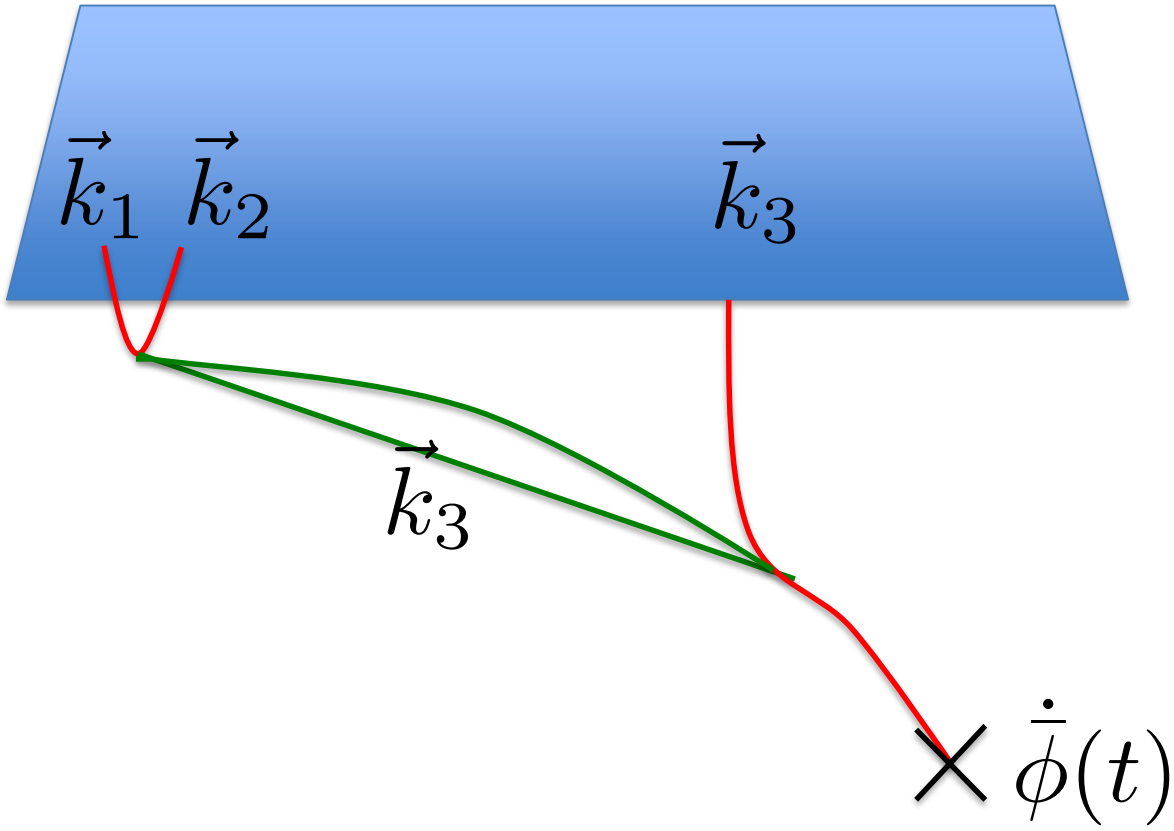
Only one very small coupling H/M_{pl}

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

Usual 3pt

Dilution

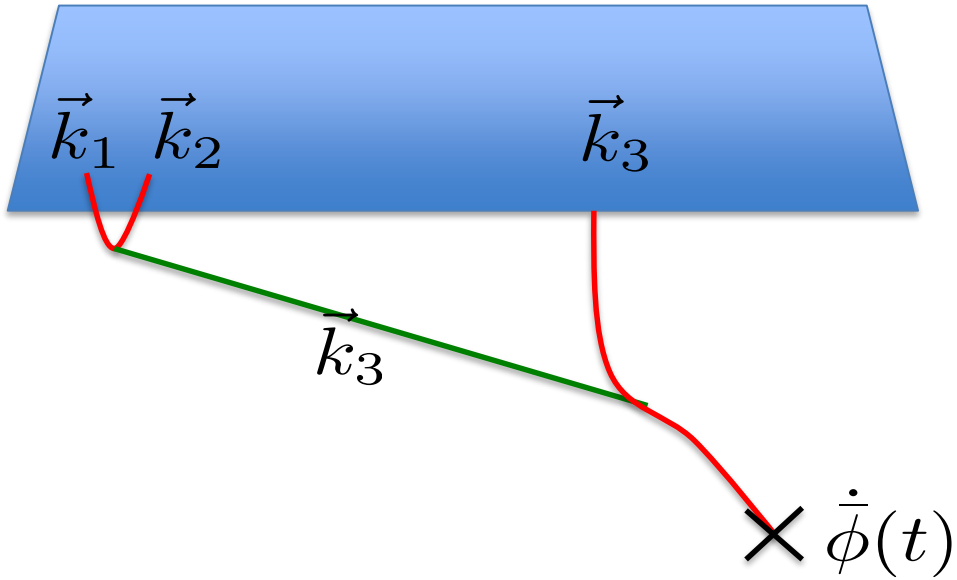
$$\langle 3pt \rangle \propto \frac{\dot{\bar{\phi}}}{k_1^3 k_3^3} e^{-\pi\mu} \left[\left(\frac{k_3}{k_1} \right)^{\frac{3}{2}+i\mu} e^{i\delta} + c.c. \right] P_s(\cos\theta)$$



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

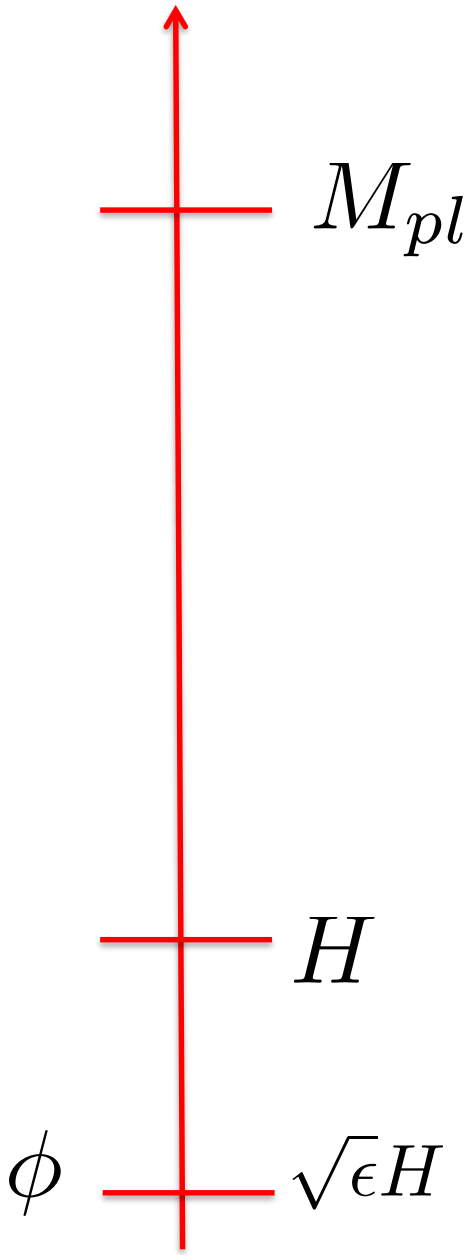
Finding massive particles

- 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.

Energy scales during inflation



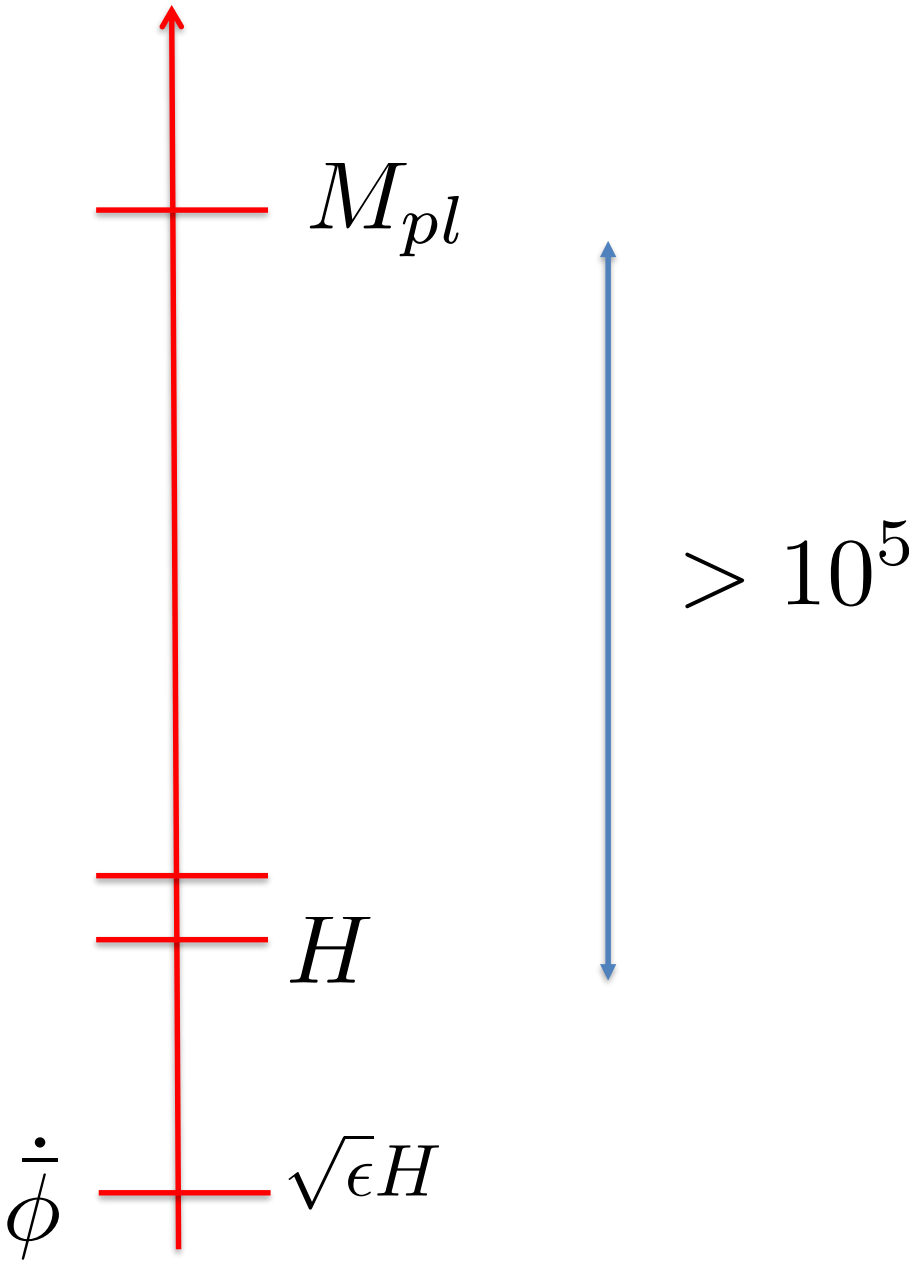
Energy scales

The effects we were discussing are interesting if new particles have masses of order H.

$$M_{\rm KK}, \quad M_{\rm partners}$$

Quasi-single field inflation

Chen, Wang
Noumi, Yamaguchi, Yokoyama,
Assassi, Baumann, Green, Porto,
Senatore, Silverstein, Zaldarriaga,
Suyama, Yamaguchi,…



How difficult is it to detect ?

Short summary of current observational status

- Scalar fluctuations and a small deviations from scale invariance. (about 4 percent).

- No non-gaussian deviations detected.

- Tensor (gravity wave) fluctuations not seen yet.

Compare it with the standard 3pt function

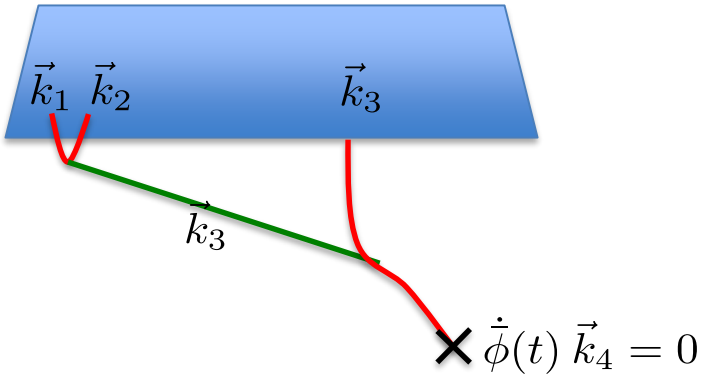
- The standard 3 point function can be viewed as exchanging a graviton.

Planck collaboration:

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

JM

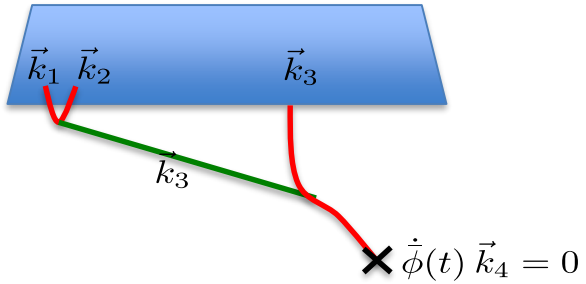
(non –gaussian “floor”)



How difficult is it to detect ?

- This one has extra factors of

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



- The last two suppress the signal. So the number of modes has to grow like the square of the above factor. Statistical "noise" (cosmic variance): $1/\sqrt{N}$
- The interactions could be larger than gravitational!

De Sitter isometries and conformal symmetry

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

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

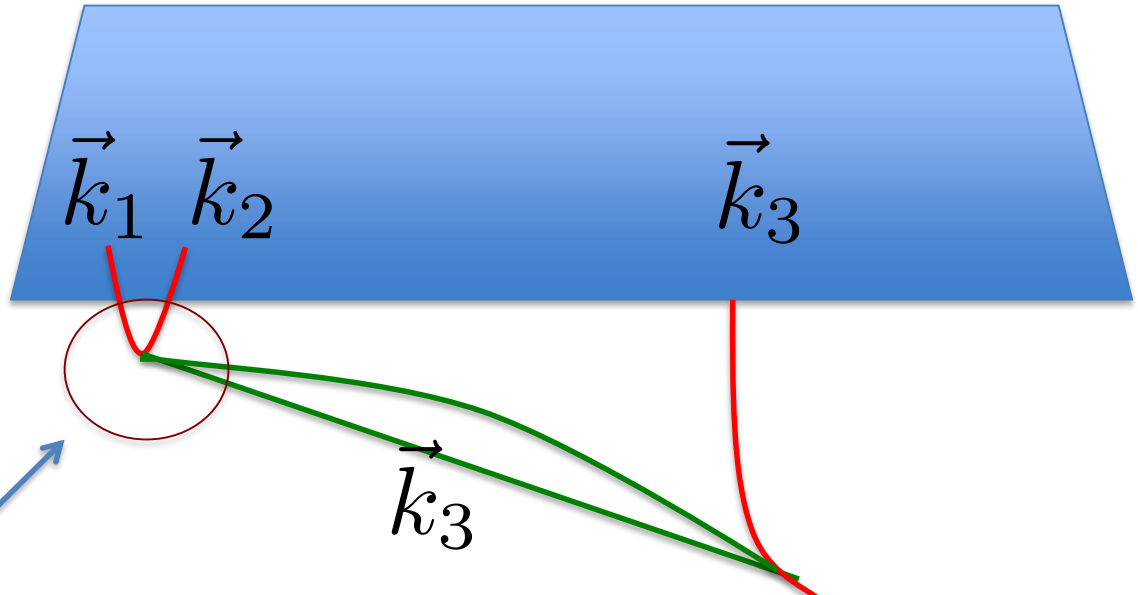
Invariant under de-Sitter isometries.

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

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

$$\times \dot{\bar{\phi}}(t)$$

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 in de Sitter

The squeezed region of the correlator, $k_3 << k_1$, k_2 is <u>not</u> 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

Real particle

Leading effect

Virtual effects → contact interactions

Very stringy inflation?

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

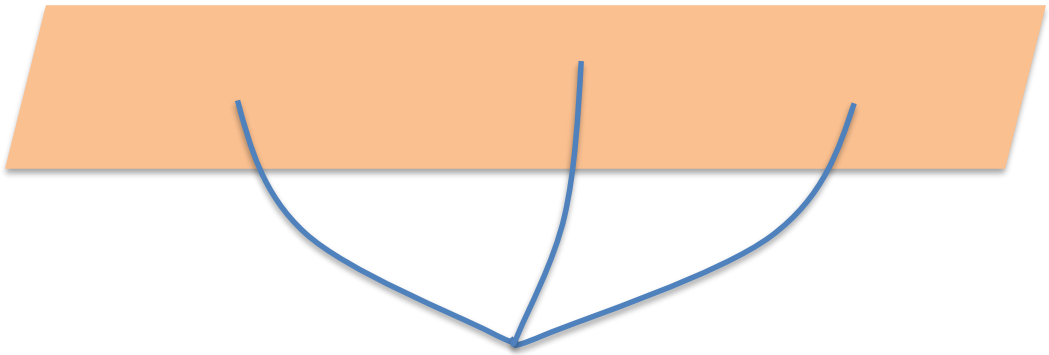
$$l_s \lesssim 1/H = R = \text{Hubble radius}$$

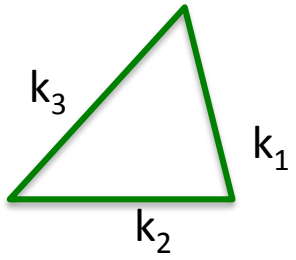
- Observations: higher spin massive particles!

- 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





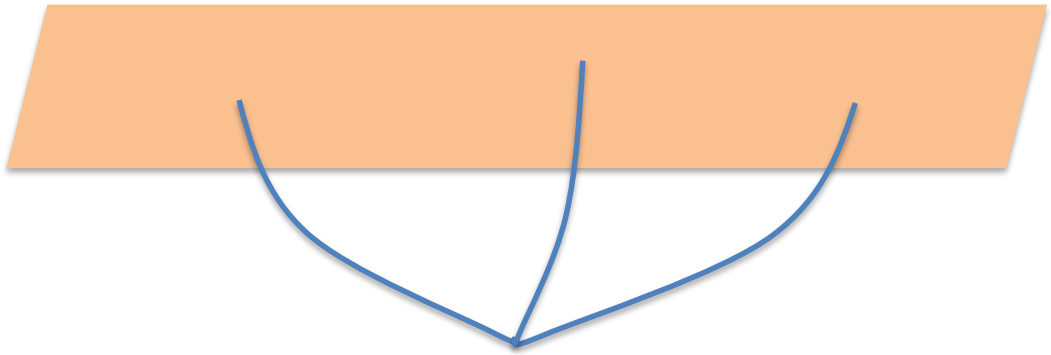
$$\frac{\langle hhh \rangle}{\langle hh \rangle^{3/2}} \sim \frac{H}{M_{pl}} \left[F_E(\text{shape}) + \alpha_4^2 H^4 F_2(\text{shape}) + o(\epsilon) \right]$$

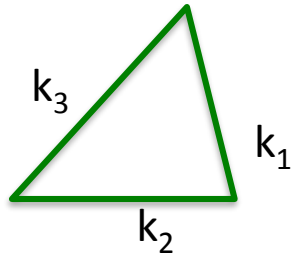
JM, Pimentel

Overall small coupling

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

Shape produced by the standard Einstein gravity theory





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

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….
- None seen yet…