

Inflation and String Theory

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Strings 2015, Bangalore

Based on: Arkani Hamed and JM,
JM and Pimentel

- Inflation is the leading candidate for a theory that produces the primordial fluctuations.
- The scale of inflation can be very high

$$H \lesssim 10^{14} \text{ Gev}$$

- Are there possible signatures from string theory ?

Standard Paradigm

String theory in ten dimensions



Gravity in ten dimensions



Compactify

Four dimensional effective theory

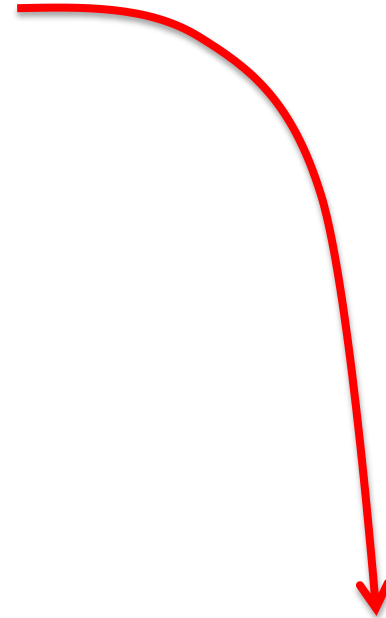


$$\int R + (\nabla\phi)^2 + V(\phi) + \dots$$

Constraints on the parameters of the effective theory ?

Is there a constraint on r (tensor/scalar ratio)?

Talk by Uranga, axion monodromy...

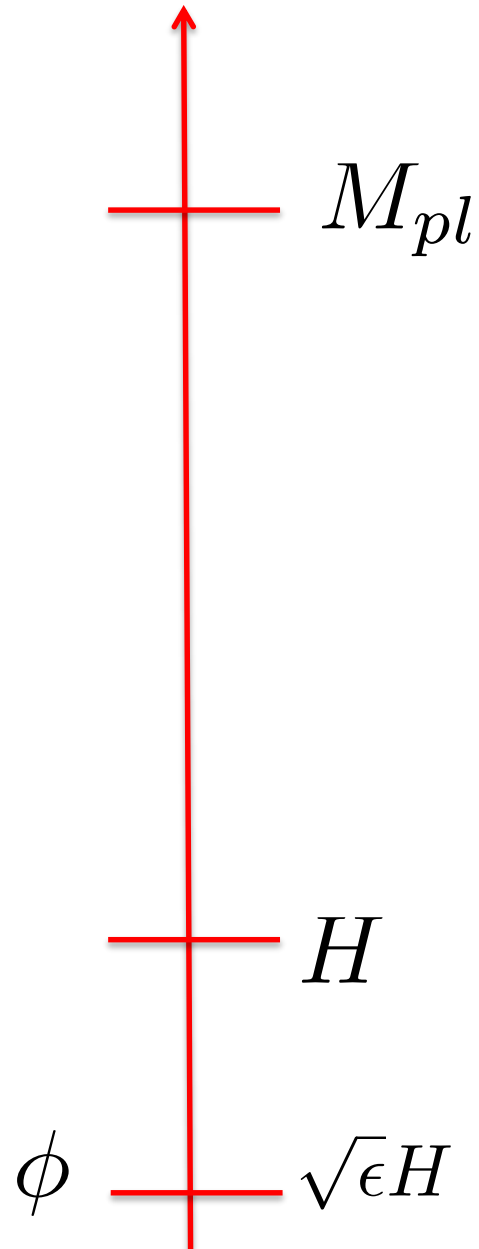


Main points

- There are terms in the effective theory that can only arise in string theory.
- We could also produce massive string states during inflation with specific signatures.

- Here we are talking about “strings” as a theory of *weakly coupled* higher spin particles.
- Inflation is very weakly coupled: $g_{eff} \sim \frac{H}{M_{pl}}$

Energy scales

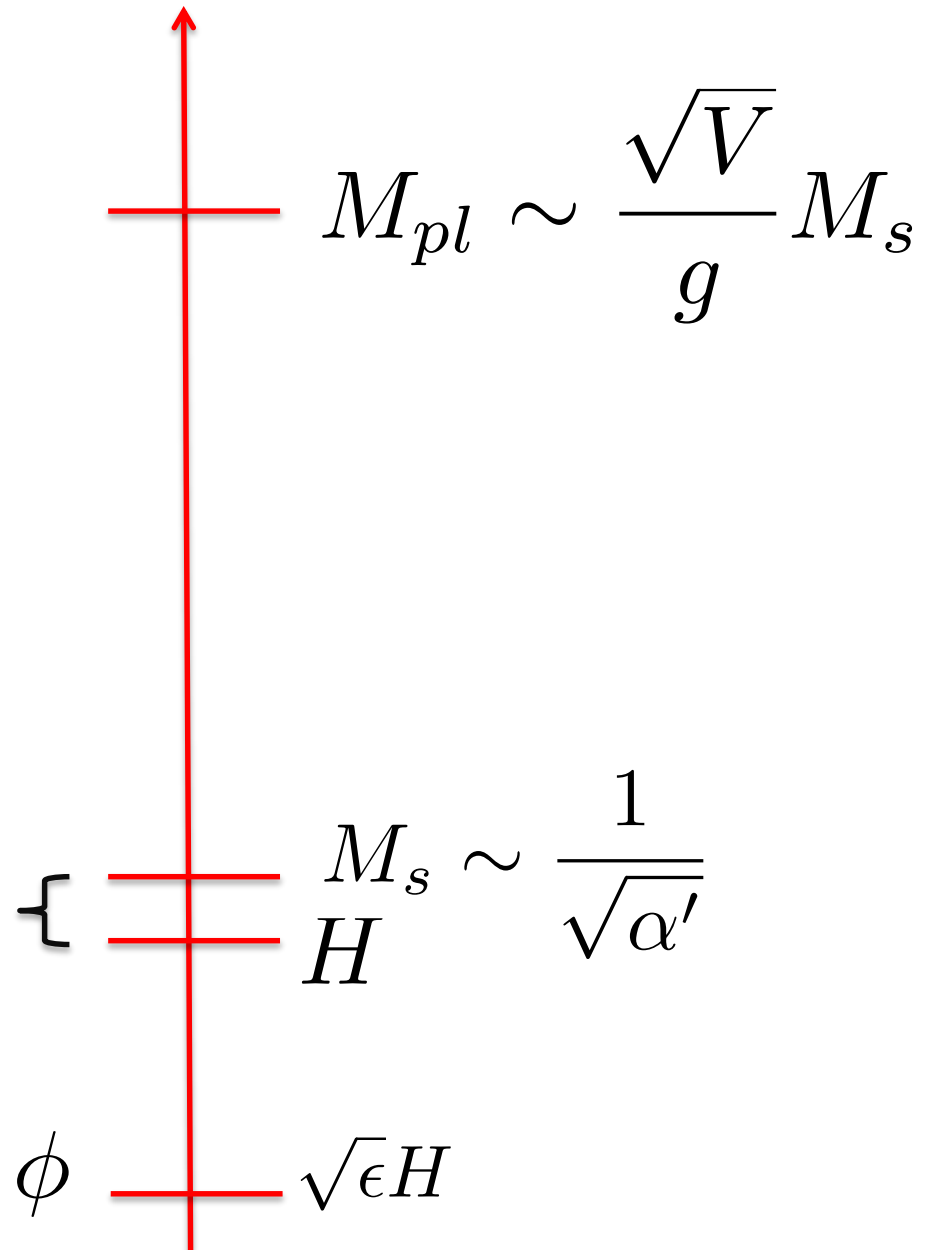


Energy scales

$$T = \frac{H}{2\pi} < T_{\text{Hagedorn}}$$

Stringy inflation

We do not know whether a Model of this sort is possible. It seems difficult.



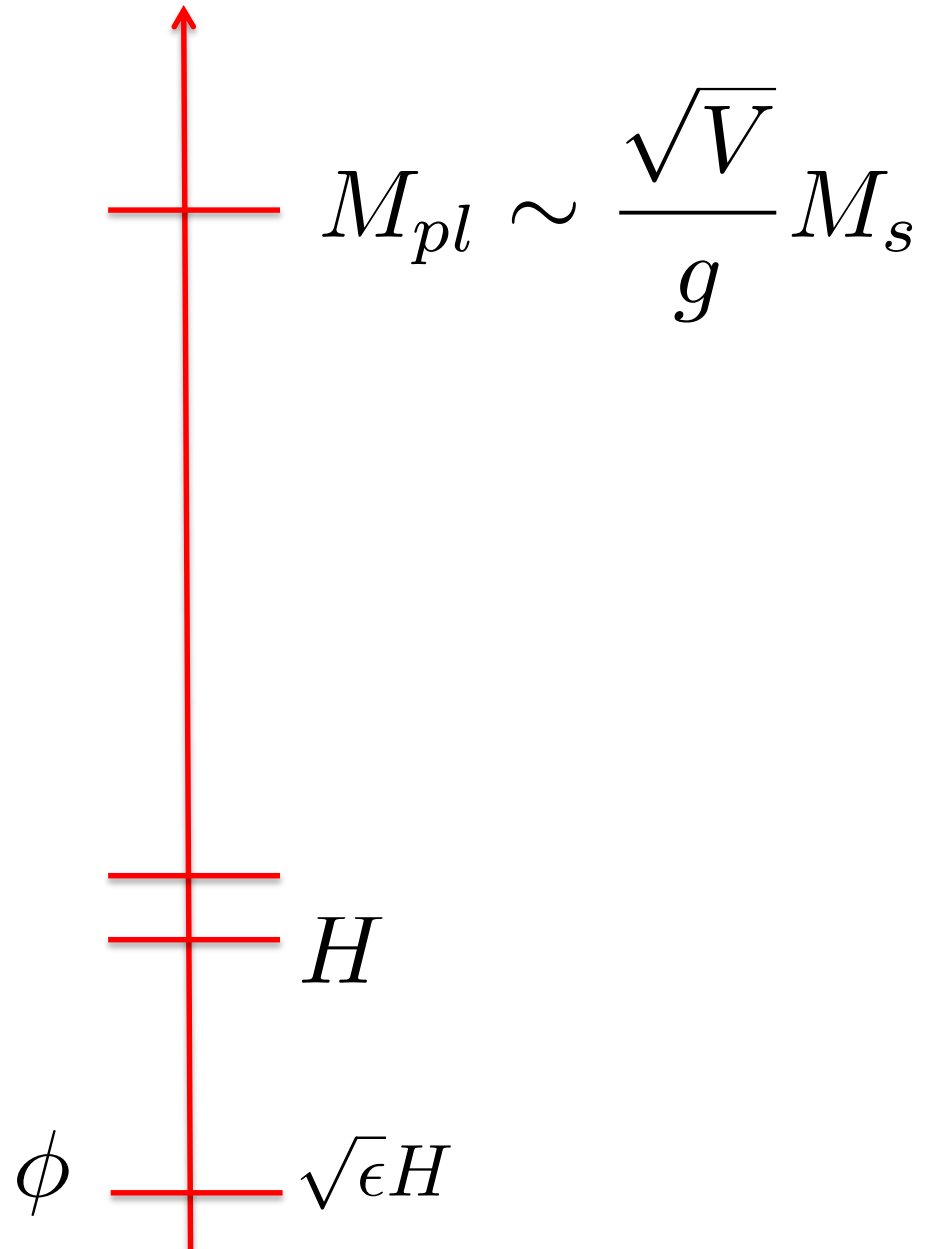
Energy scales

$M_{\text{KK}}, M_{\text{partners}}$

Quasi-single field inflation

Chen, Wang

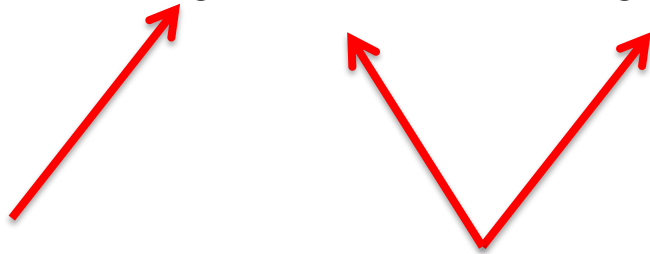
Noumi, Yamaguchi, Yokoyama,
Assassi, Baumann, Green, Porto,
Senatore, Silverstein, Zaldarriaga,
Suyama, Yamaguchi,...



Effects of new particles

- Virtual: Integrating them out (classically).
Local terms in the effective theory

$$\frac{M_{pl}^2}{H^2} \left[(\nabla\chi)^2 + \frac{H^2}{M_s^2} (\nabla^2\chi)^2 + \frac{H^2}{M_s^2} (\nabla\chi)^4 + \dots \right], \quad g_{eff} = \frac{H}{M_{pl}}$$



2pt:
Kaloper, Kleban,
Lawrence, Shenker,
Susskind.
Easter, Greene,
Kinney, Shiu, ...

Larger than expected from
gravity as an effective theory

$$M_s \rightarrow M_{pl}$$

Effects of new particles

- Virtual: Integrating them out (classically). Local terms in the effective theory

$$\left(\frac{H}{M_s}\right)^n$$

- Real particles which then decay and imprint signatures on the inflaton. Non-local in the effective theory.

$$\exp\left(-\frac{M_s}{H}\right)$$

- Producing cosmic strings

$$\exp\left(-\frac{M_s^2}{H^2}\right)$$

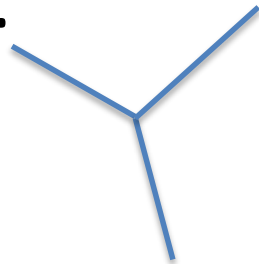
Copeland, Myers,
Polchinski

Virtual corrections

- Are there local corrections that do not arise classically in local gravity theories ? (Einstein + QFT)
- Example: Three graviton vertex correction.

$$A_{grav} \sim \epsilon^3 k^2, \quad \int R$$

$$A_{other} \sim \epsilon^3 k^6, \quad \int R^3 \quad o(H^4 / M_s^4)$$



Why is R^3 a signature of strings?

- In flat space \rightarrow This leads to an asymptotic causality violation that cannot be fixed (at tree level) by adding new particles with spins $S \leq 2$

Camanho, Edelstein, JM, Zhiboedov

- Need higher spin particles \rightarrow Regge behavior of amplitudes.

Observability

- The gravity two point function has not yet been observed.
- The three point function is much harder...
- Because gravity is weakly coupled...

$$g_{eff} \sim \frac{H}{M_{pl}}$$

New particles

- Massless or very light particles (specially spin zero ones) can give rise to large effects:

- Isocurvature fluctuations
- Non gaussianities in the squeezed limit.
- None observed so far...

Enqvist, Sloth, Wands,
Lyth, Moroi, Takahashi

$$m \sim \sqrt{\epsilon} H$$

New massive particles

- Are produced for $m \sim H$
- Massive particles are rapidly diluted by the expansion of the universe.
- Could lead to interesting effects if they decay to the inflaton.

Quasi-single field inflation

Chen, Wang

Noumi, Yamaguchi, Yokoyama,

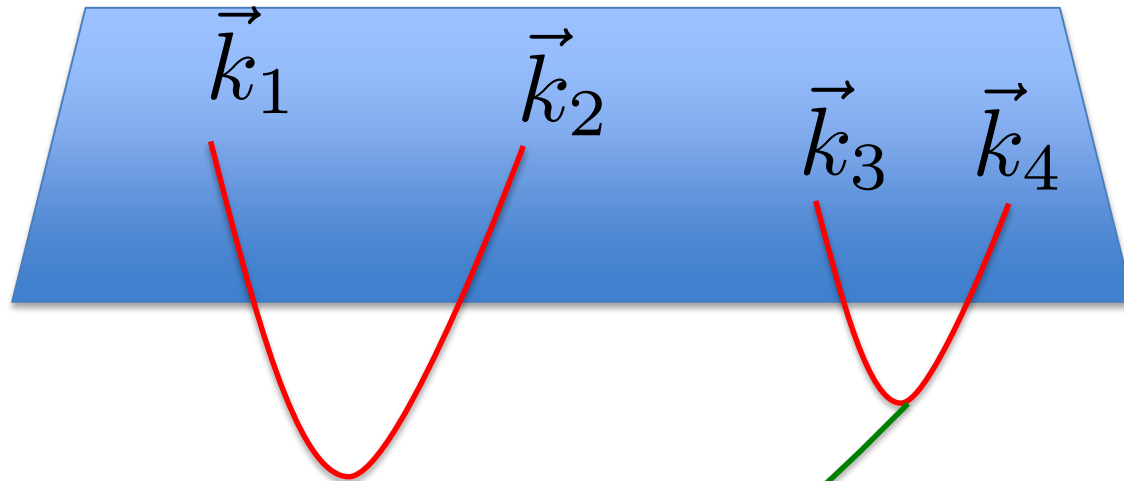
Assassi, Baumann, Green, Porto,

Senatore, Silverstein, Zaldarriaga,

Suyama, Yamaguchi,...

Four point function in de Sitter

$$\langle \zeta(k_1) \zeta(k_2) \zeta(k_3) \zeta(k_4) \rangle$$



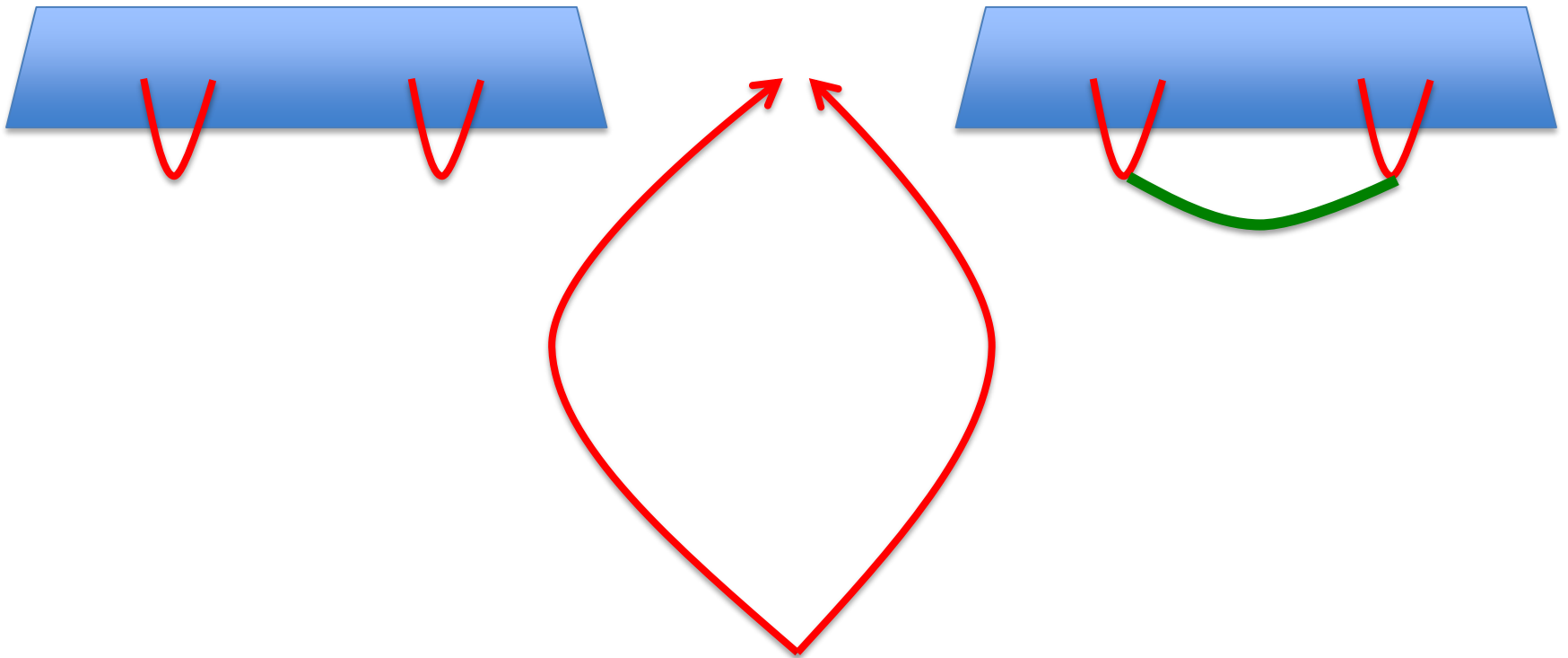
Inflaton \rightarrow massless scalar field in de-Sitter.

Massive particle

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

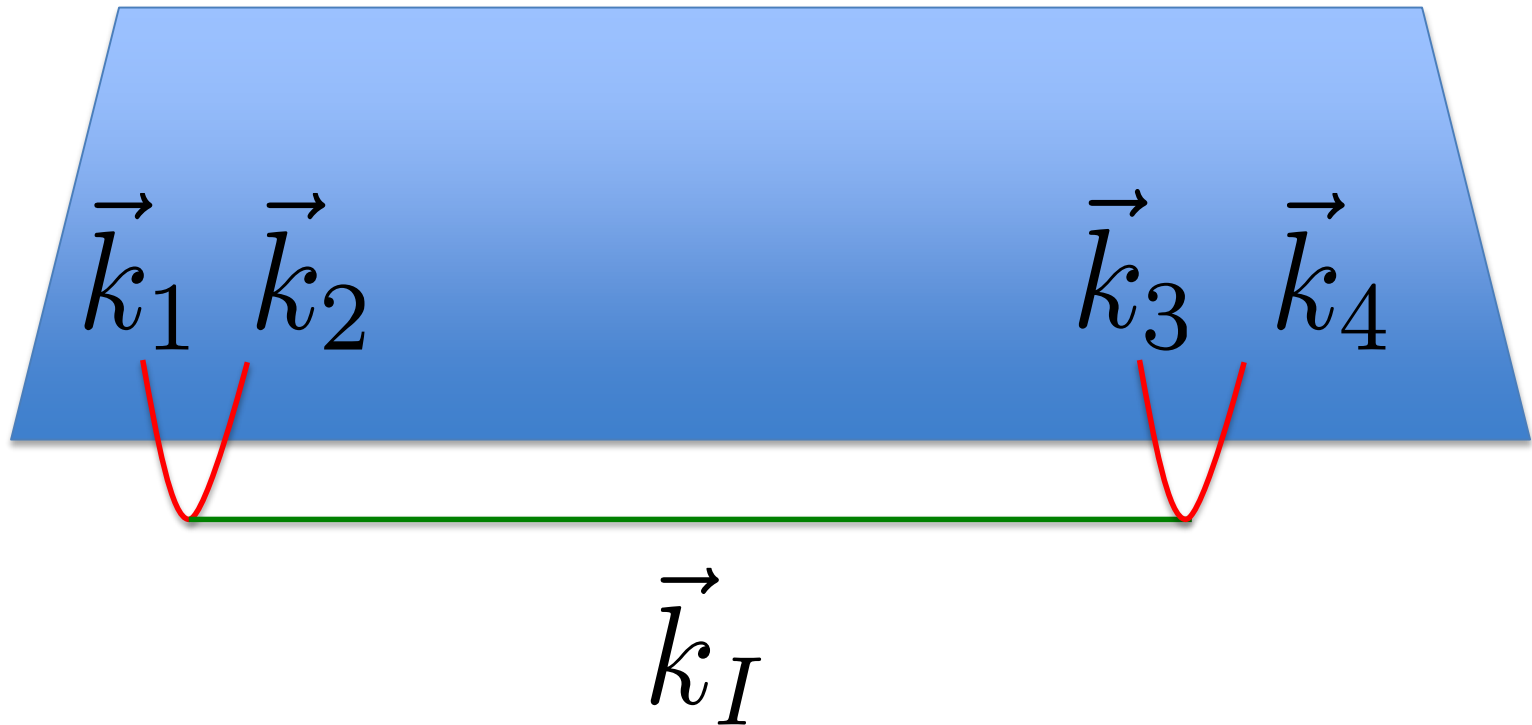
Cosmological double slit experiment

$$|\Psi_{\text{nopair}} + \Psi_{\text{pair}}|^2$$



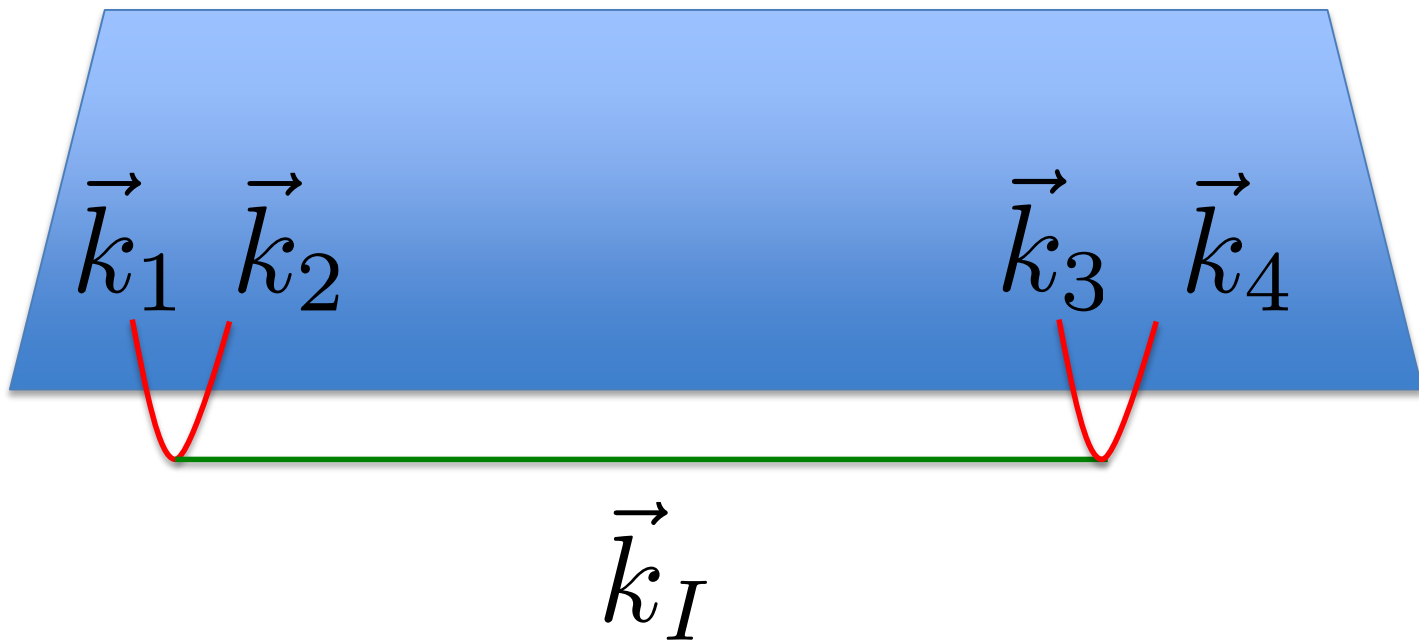
Interesting limit :

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



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

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

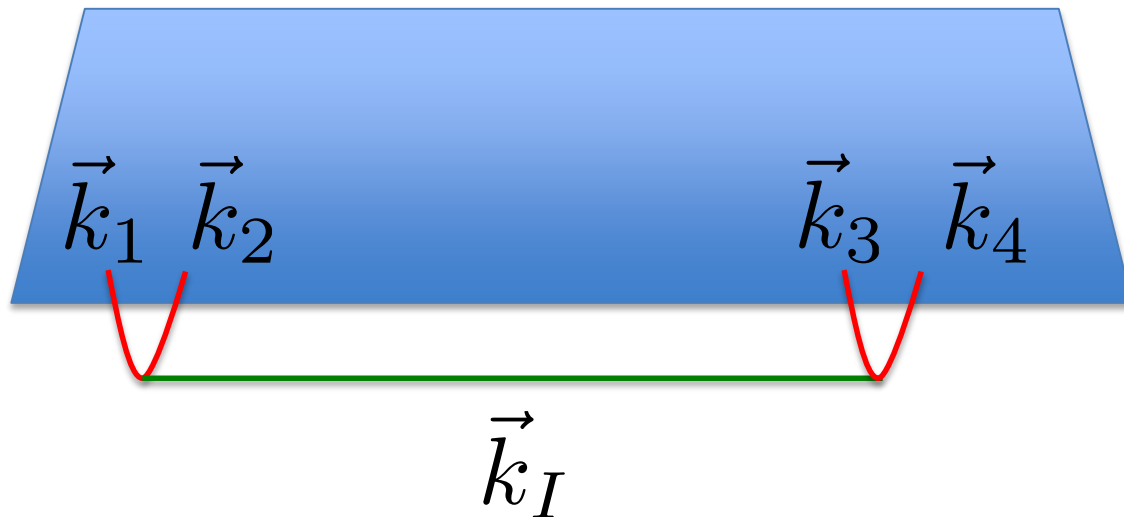


$$\langle 4pt \rangle \propto e^{-\pi\mu} \left[\left(\frac{k_I^2}{k_1 k_3} \right)^{\frac{3}{2} + i\mu} e^{i\delta} + \left(\frac{k_I^2}{k_1 k_3} \right)^{\frac{3}{2} - i\mu} e^{-i\delta} \right]$$

Non trivial power law behavior in the ratio of scales.

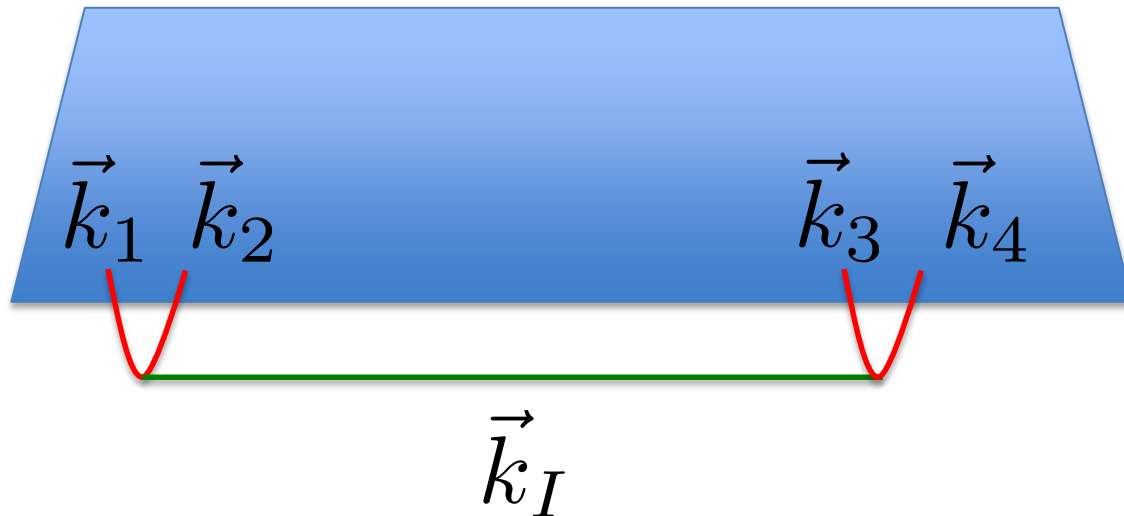
Oscillatory for real $\mu \rightarrow$ oscillations of the wavefunction

$\ell = \log \left(\frac{k_{short}}{k_{long}} \right) =$ Time, in e-folds, over which the intermediate particle propagates



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

Oscillatory for real $\mu \rightarrow$ oscillations of the wavefunction



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



Boltzmann suppression $e^{-\frac{m}{2T}}$

$$\left| \Psi_{\text{nopair}} + e^{-\pi\mu} \Psi_{\text{pair}} \right|^2$$

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

Volume dilution

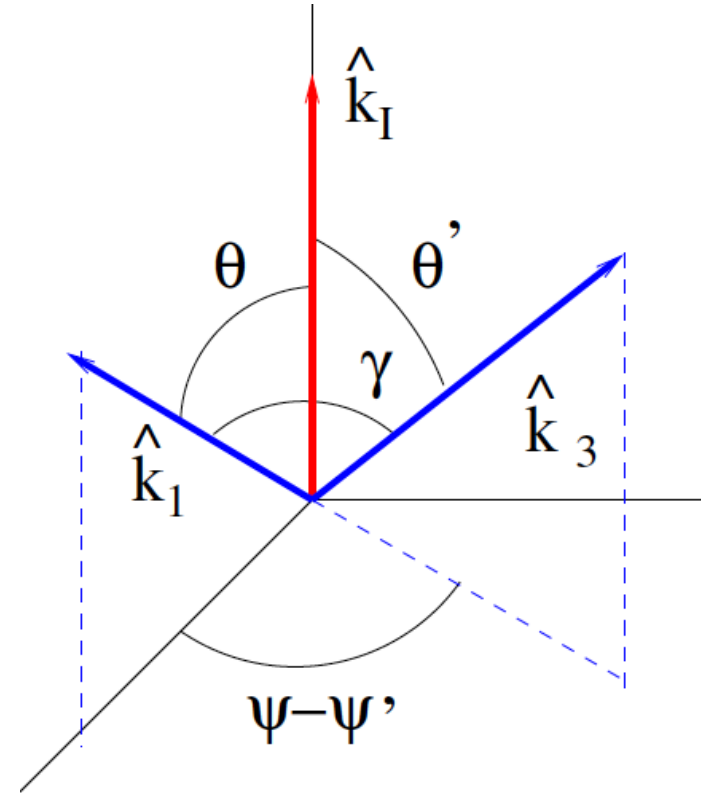
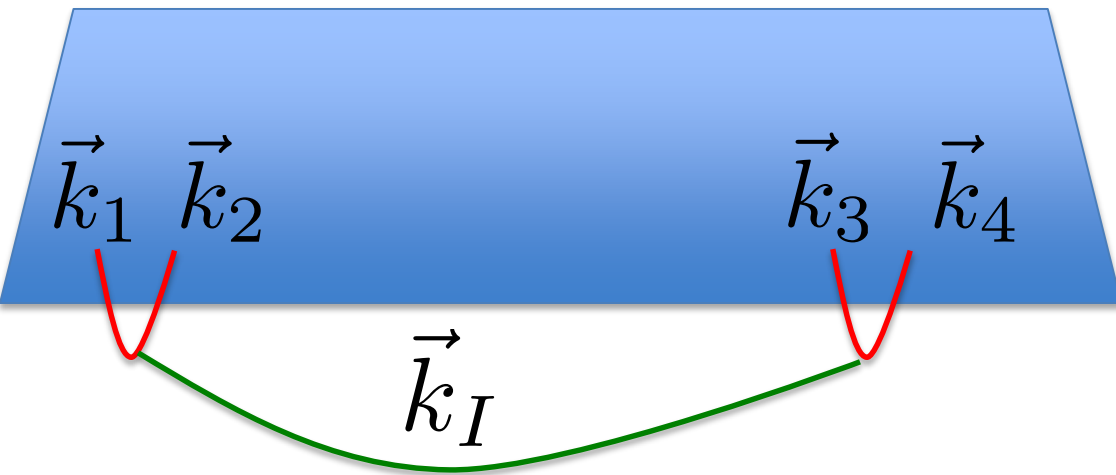
$$\langle 4pt \rangle \propto e^{-\pi\mu} \left[\left(\frac{k_I^2}{k_1 k_3} \right)^{\frac{3}{2} + i\mu} e^{i\delta} + c.c. \right]$$

Explicit phase, function of μ

Test of quantum mechanics

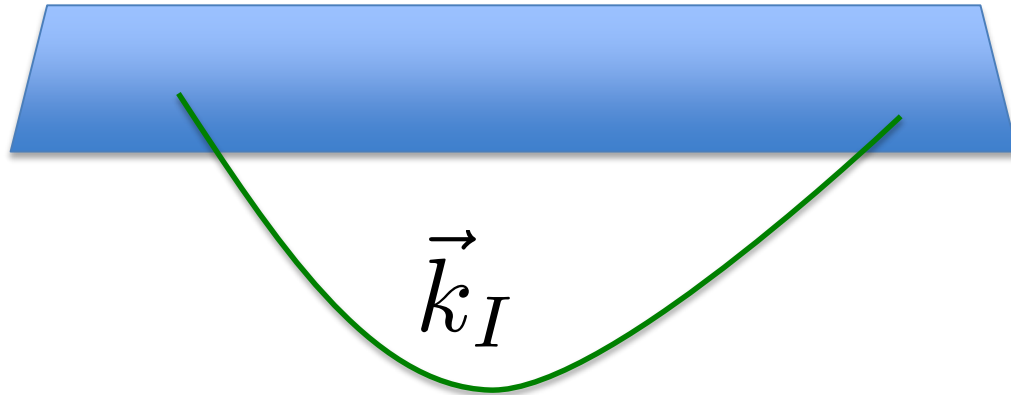
Spin

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



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

Spin



The answer mainly comes from the two point function from a massive spinning particle \rightarrow fixed by conformal symmetry

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

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



Overall size is small.

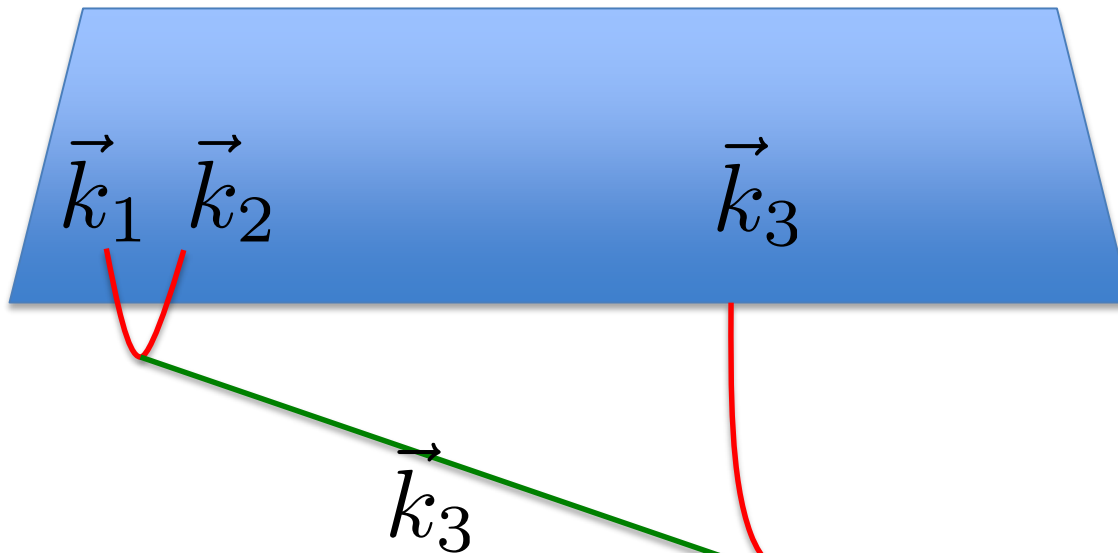
One factor of H/M from each interaction.

Can we find a bigger effect ?

Three point functions

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

$$\phi(t)$$



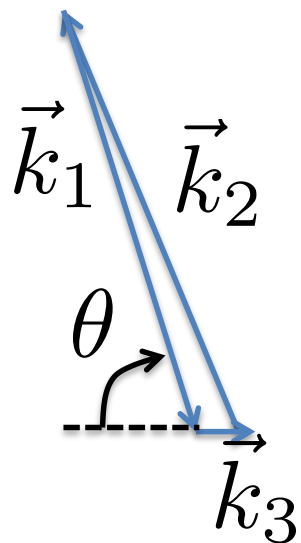
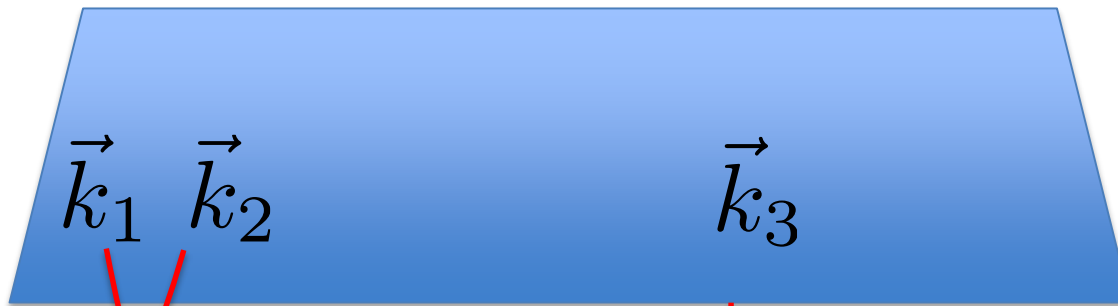
Only one very small coupling H/M_{pl}

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

Single field inflation

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

Spin:



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

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

How difficult is it to detect ?

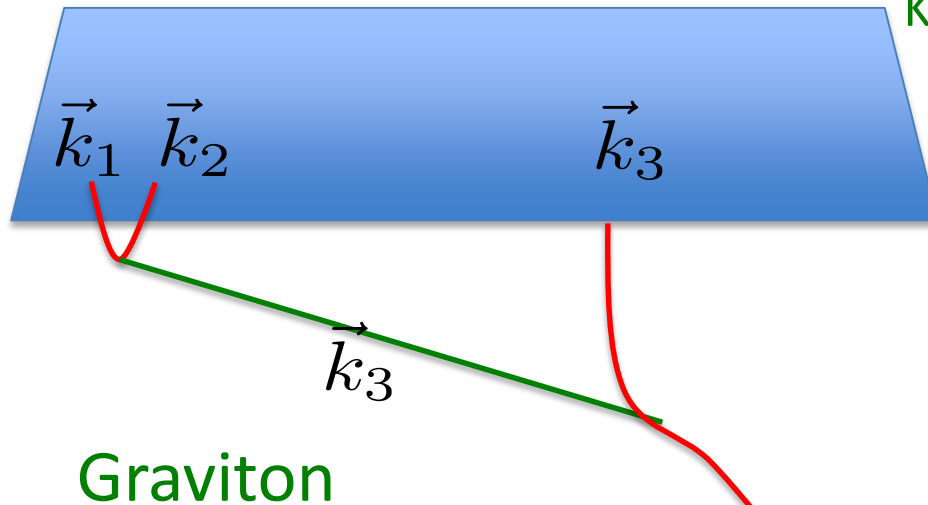
Very

How difficult is it to detect ?

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

JM, Creminelli, Norena, Simonovic,
Seery, Sloth, Vernizzi
Kundu, Shukla, Trivedi, Raju,

Talk by Trivedi



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

How difficult is it to detect ?

$$\left| \langle 3pt \rangle_{\text{squeezed}}^{\text{experimental}} \right| \lesssim 5,$$

Planck

$$\left| \langle 3pt \rangle_{\text{squeezed}}^{\text{graviton}} \right| \sim |n_s - 1| \sim 0.04$$

How difficult is it to detect ?

$$\left| \langle 3pt \rangle_{\text{squeezed}}^{\text{massive}} \right| \sim \underbrace{\epsilon e^{-\pi\mu} \left(\frac{k_3}{k_1} \right)^{3/2}}_{\text{small factors}} \frac{\lambda^2}{M_{pl}^2}$$

- Assuming gravitational strength couplings \rightarrow extra small factors.
- Cosmic variance \rightarrow the number of modes has to grow like the square of the above factor.
- The interactions could be larger than gravitational !

How difficult is it to detect ?

Futuristic + luck

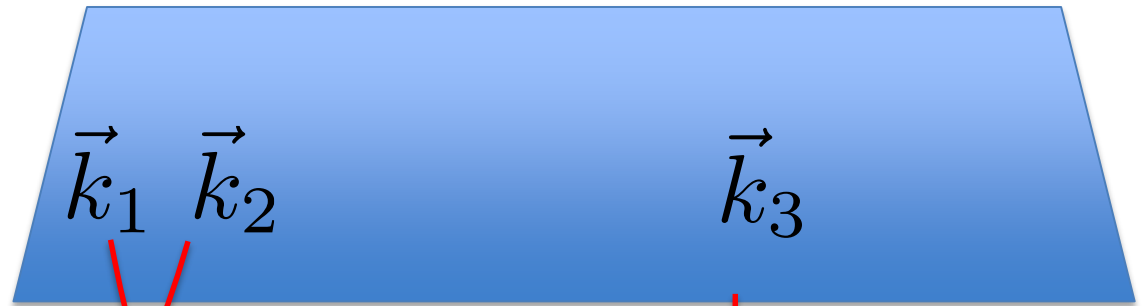
Theory with a large H and M_s similar to H .

Ability to detect vastly more primordial fluctuation modes.
e.g. Cosmological 21cm tomography.

Loeb & Zaldarriaga

First non-gaussianity → Then squeezed limit and spectrum of particles.

Loops



Higgs, gauge fields, fermions

Faster decay

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

Different volume dilution factor

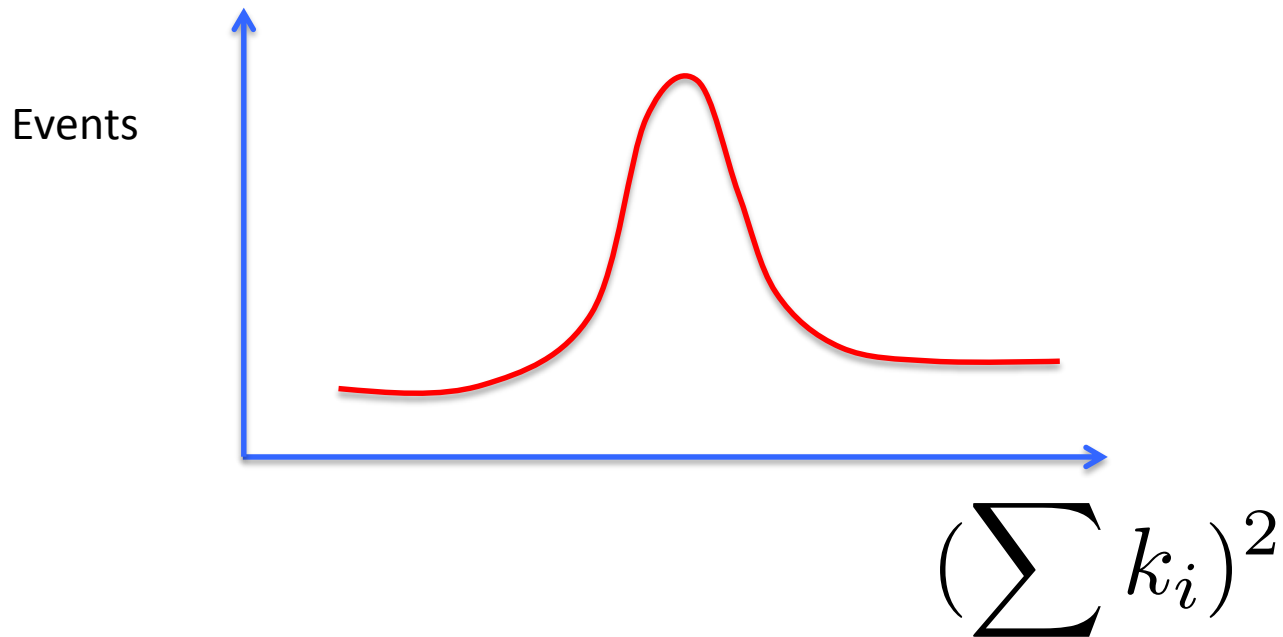
An extra factor of H^2/M_{pl}^2

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

Some conceptual aspects

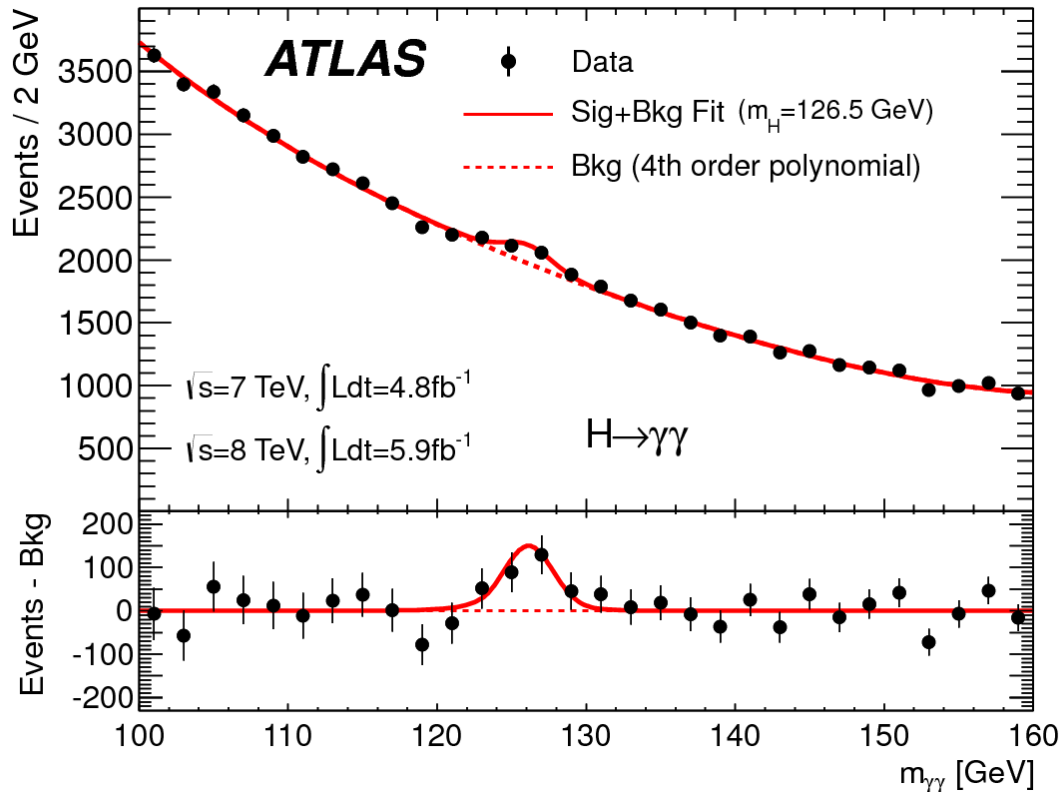
Finding new particles: collider physics

- Collider \rightarrow peaks in the invariant mass distribution.



Finding new particles collider physics

- Collider \rightarrow peaks in the invariant mass distribution.



Cosmological collider physics

- Cosmology \rightarrow peaks in the Fourier transform of the cosmological correlator as a function of

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

- Spin \rightarrow angular dependence.

De Sitter isometries and conformal symmetry

$$ds^2 = \frac{-d\eta^2 + dx^2}{\eta^2} \quad \langle O_4(\eta_1, \vec{x}_1) \cdots O_4(\eta_n, \vec{x}_n) \rangle$$

Invariant under de-Sitter isometries.

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

QFT in a fixed de Sitter background.

Dimensions are quasinormal mode frequencies

$$ds^2 = \frac{-d\eta^2 + dx^2}{\eta^2} \quad \langle O_4(\eta_1, \vec{x}_1) \cdots O_4(\eta_n, \vec{x}_n) \rangle$$

At late times we can expand

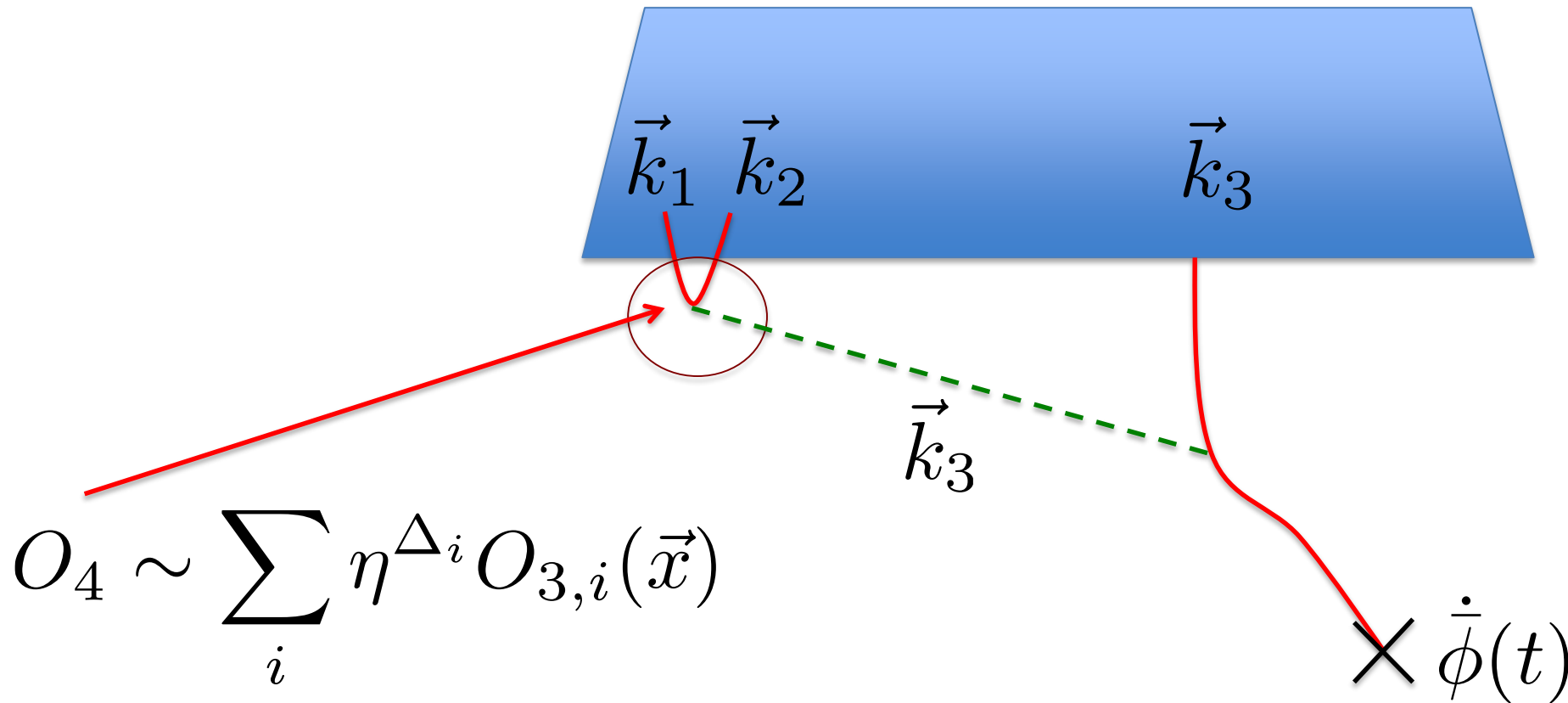
$$O_4 \sim \sum_i \eta^{\Delta_i} O_{3,i}(\vec{x})$$

Quasi-normal mode frequencies in the de-Sitter static patch.

3d operator of conformal dimension Δ_i

(Related to conformal dimensions of operator in dual CFT_3)

Squeezed limit = OPE expansion



Leads to $\langle 3pt \rangle \propto \sum_i \left(\frac{k_3}{k_1} \right)^{\Delta_i} c_i$

Conclusions

- If the string scale was similar to the Hubble scale, then there could be direct signals of string theory in the primordial fluctuations.
- Signals:
- Local effects \rightarrow terms in the classical lagrangian which are not field theoretic in origin.
- Non-local effects that correspond to real particle production (with spins > 2).

Conclusions

- Requires luck to be observable.
- There are interesting theoretical aspects in how the signal is encoded:
- Connection between quasinormal frequencies, the dimensions of operators and the squeezed limit of cosmological correlators.
- Small step towards decoding a cosmological hologram!.