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

$$H \lesssim 10^{14}\,\mathrm{Gev}$$

- 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

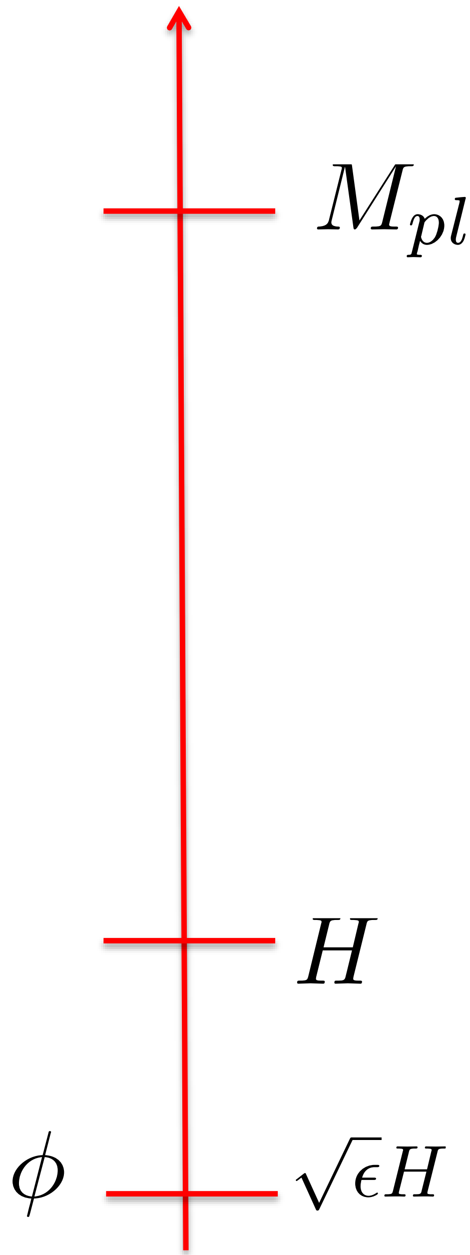
- There are terms in the effective theory that can only arise in string theory.

- 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: $g_{eff} \sim \dfrac{H}{M_{pl}}$

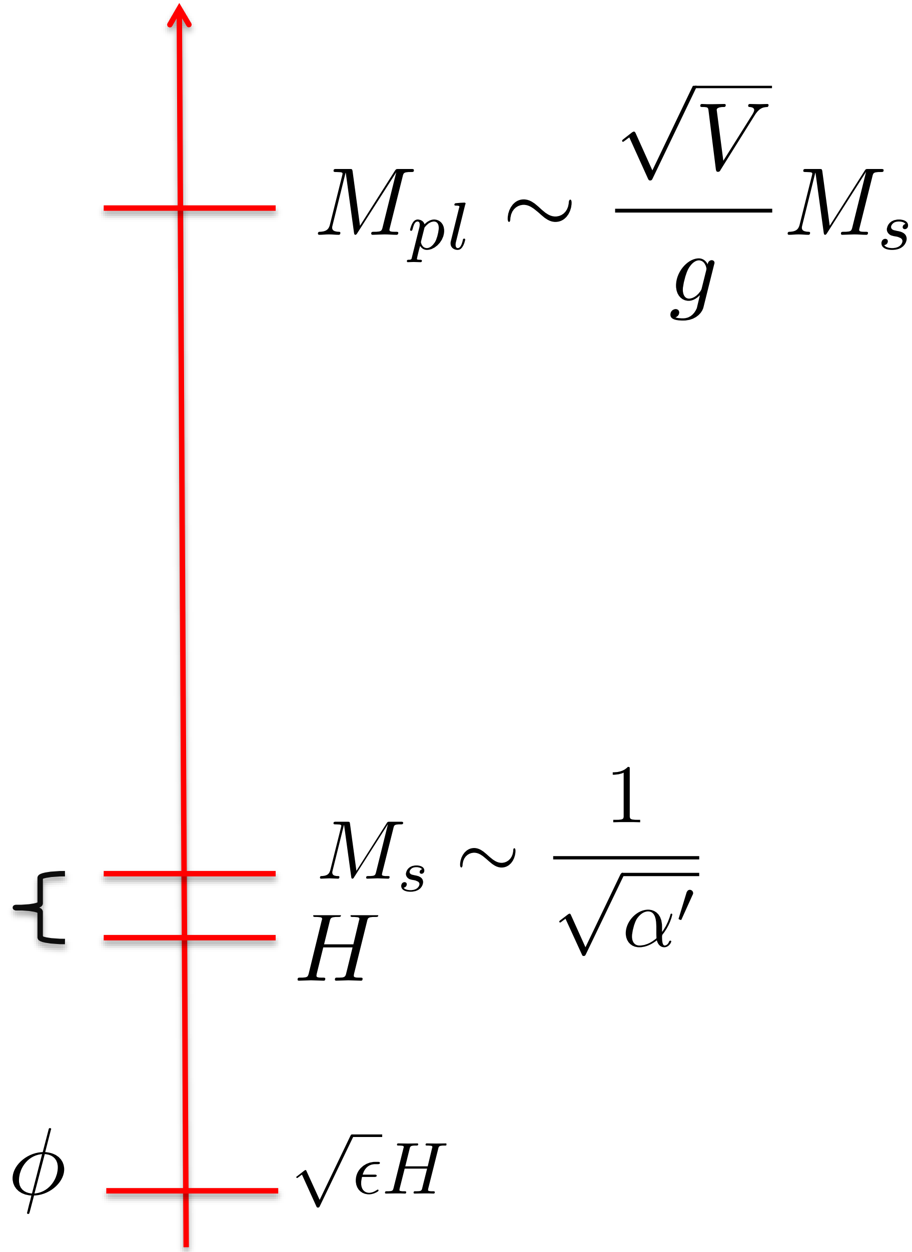
Energy scales



Energy scales

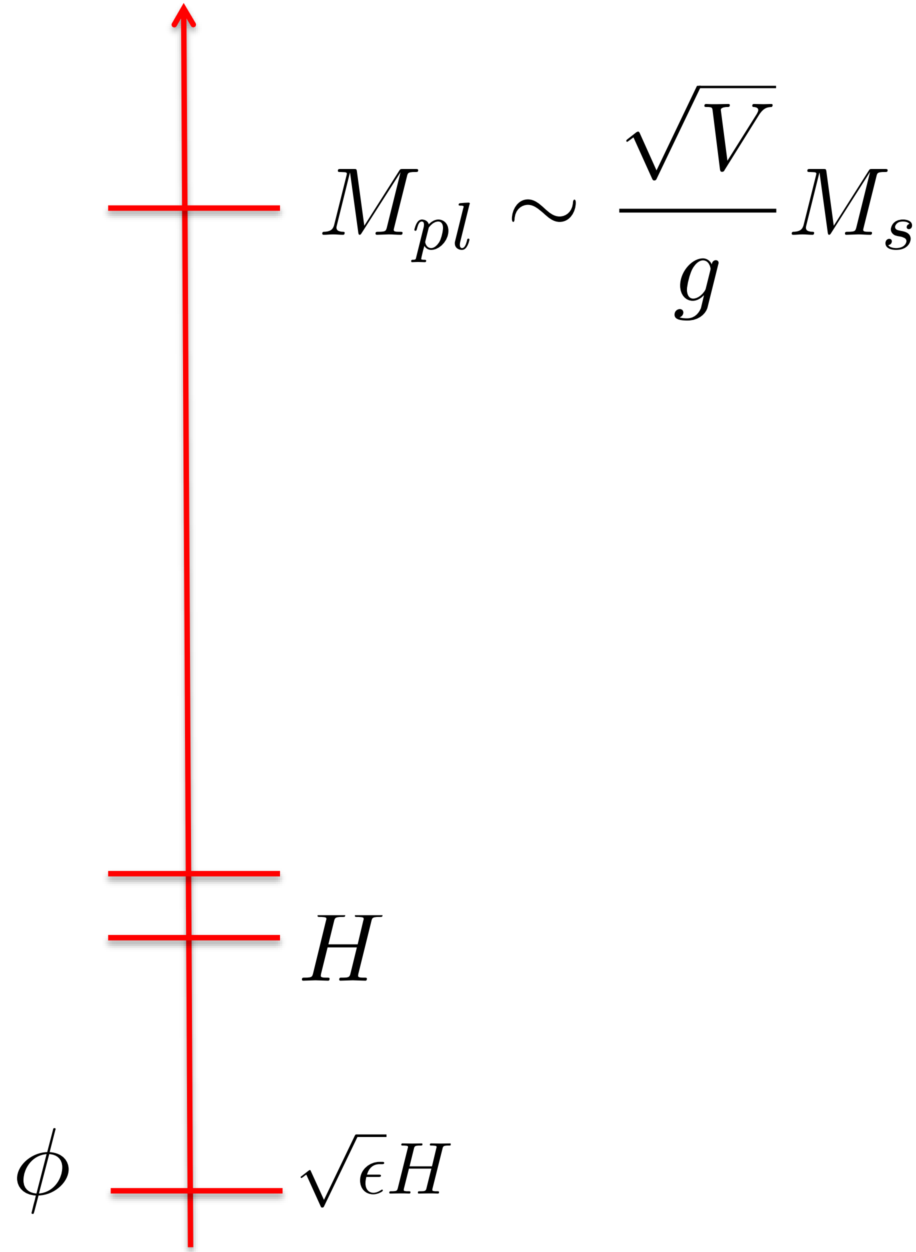
$$T = \frac{H}{2\pi} < T_{\text{Hagedorn}}$$

Stringy inflation



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

Energy scales



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

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

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

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

Larger than expected from gravity as an effective theory

$$M_s \to M_{pl}$$

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

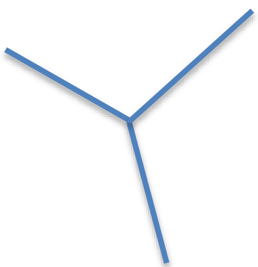
$$\exp\left(-\frac{M_s^2}{H^2}\right)$$

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.



$$\mathcal{A}_{grav} \sim \epsilon^3 k^2 \ , \qquad \int R$$

$$\mathcal{A}_{other} \sim \epsilon^3 k^6 \ , \qquad \int R^3 \qquad o(H^4/M_s^4)$$

Why is R^3 a signature of strings?

- In flat space → This leads to an asyptotic 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 → Regge behavior of amplitudes.

Observability

- The gravity two point function has not yet been observed.

- The three point function is <u>much</u> 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

  Enqvist, Sloth, Wands, Lyth, Moroi, Takahashi

  - Non gaussianities in the squeezed limit.

  - None observed so far…

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

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
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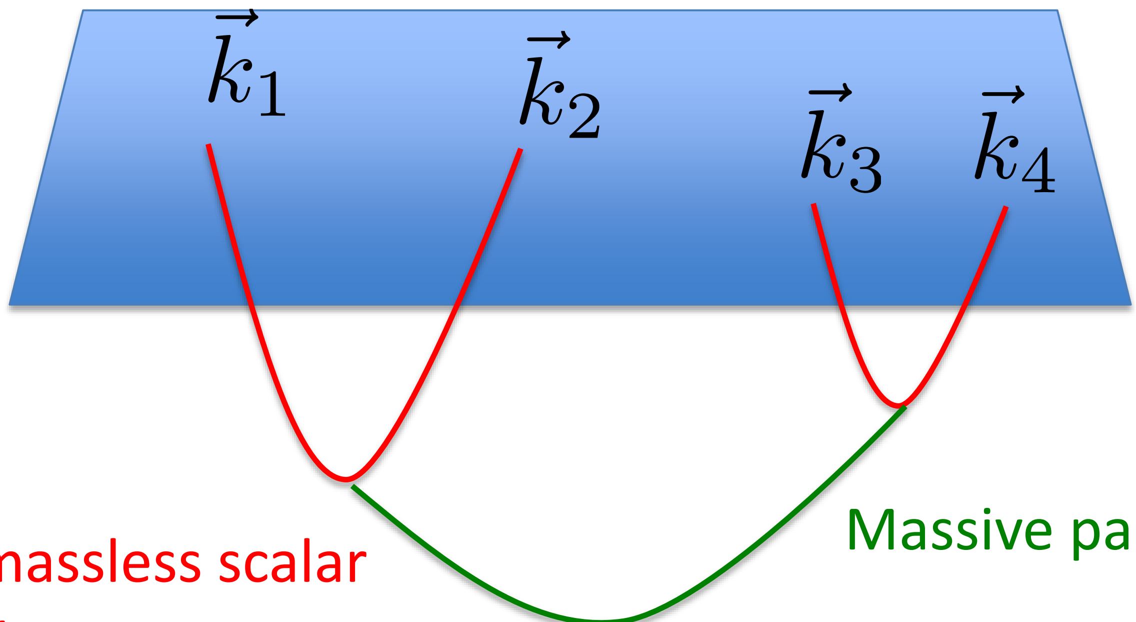
Four point function in de Sitter

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



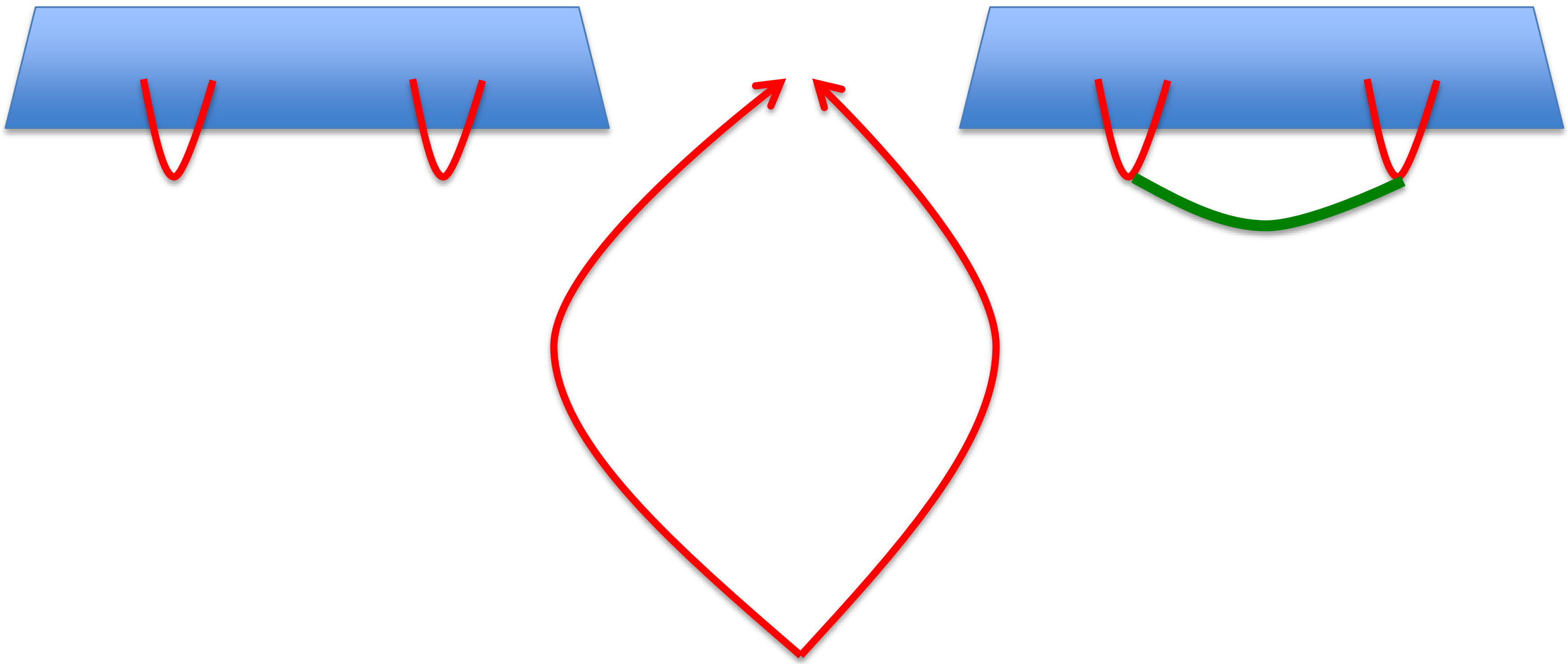
Massive particle

Inflaton → massless scalar field in de-Sitter.

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

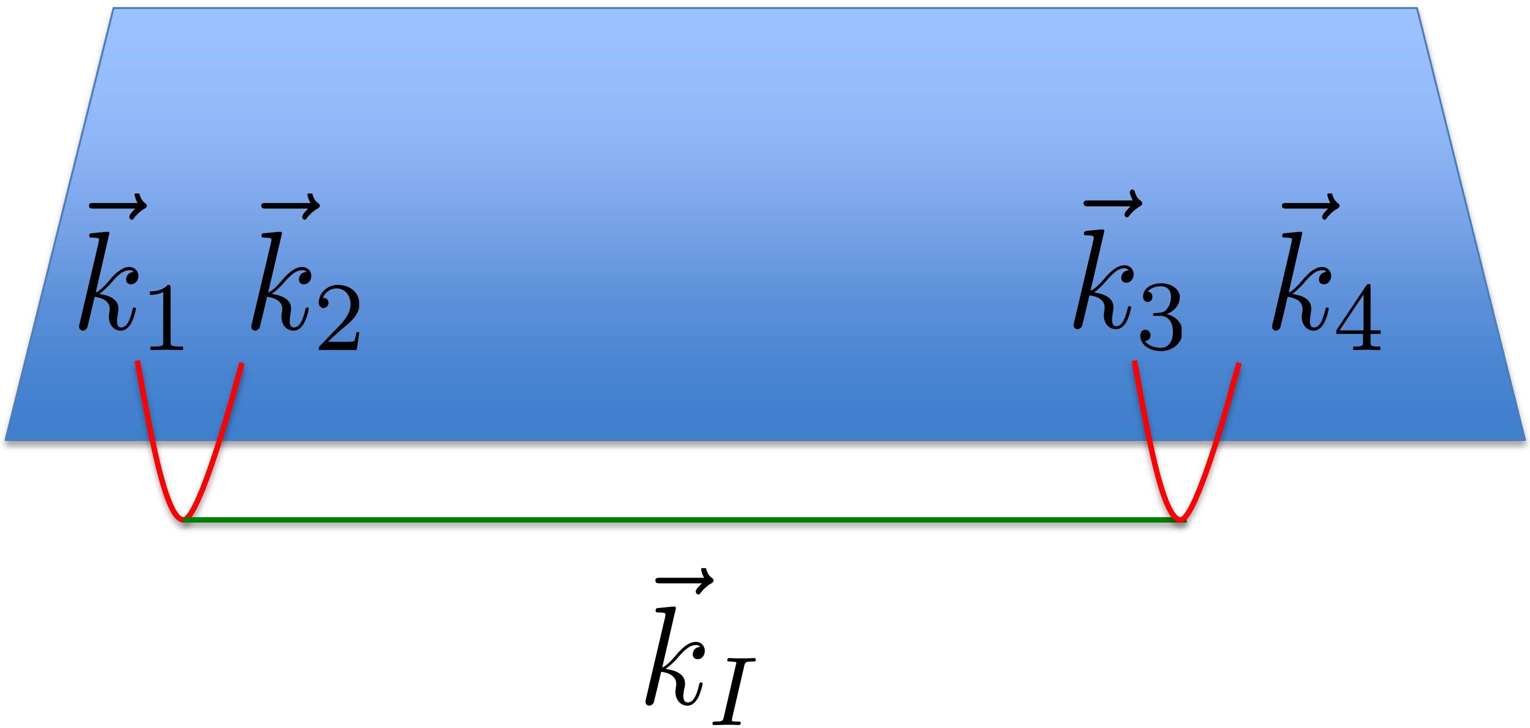
Cosmological double slit experiment

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



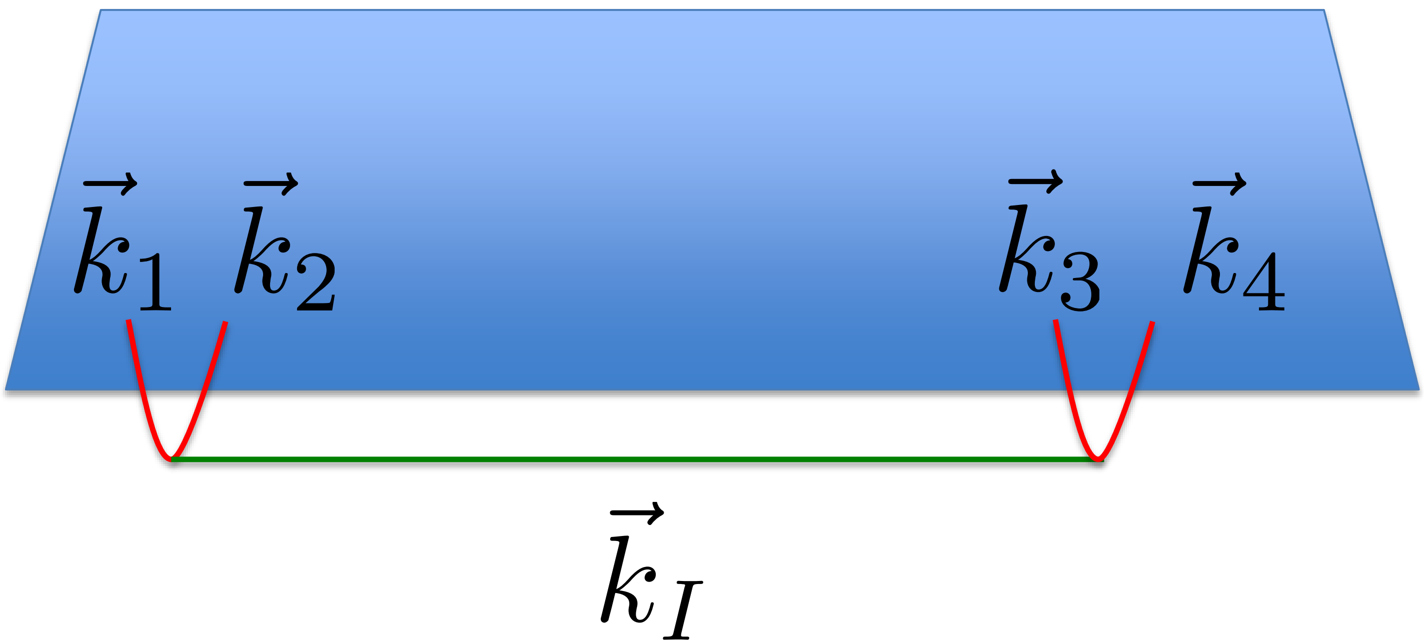
Interesting limit :

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



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

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

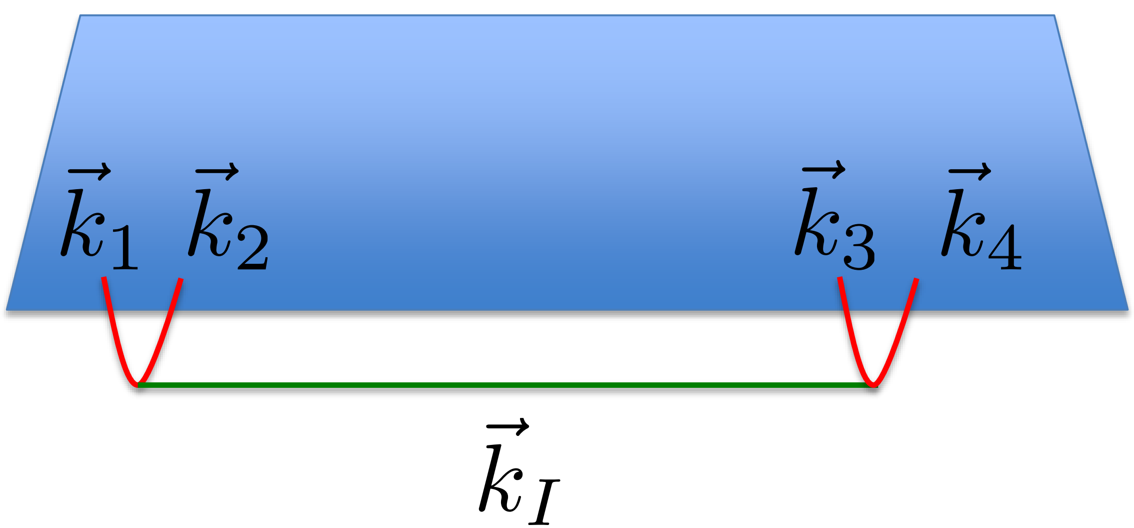


$$\langle 4pt \rangle \propto e^{-\pi\mu} \underbrace{\left[\left(\frac{k_I^2}{k_1 k_3} \right)^{\frac{3}{2}+i\mu} e^{i\delta} + \left(\frac{k_I^2}{k_1 k_3} \right)^{\frac{3}{2}-i\mu} e^{-i\delta} \right]}$$

Non trivial power law behavior in the ratio of scales.

Oscillatory for real μ → oscillations of the wavefunction

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



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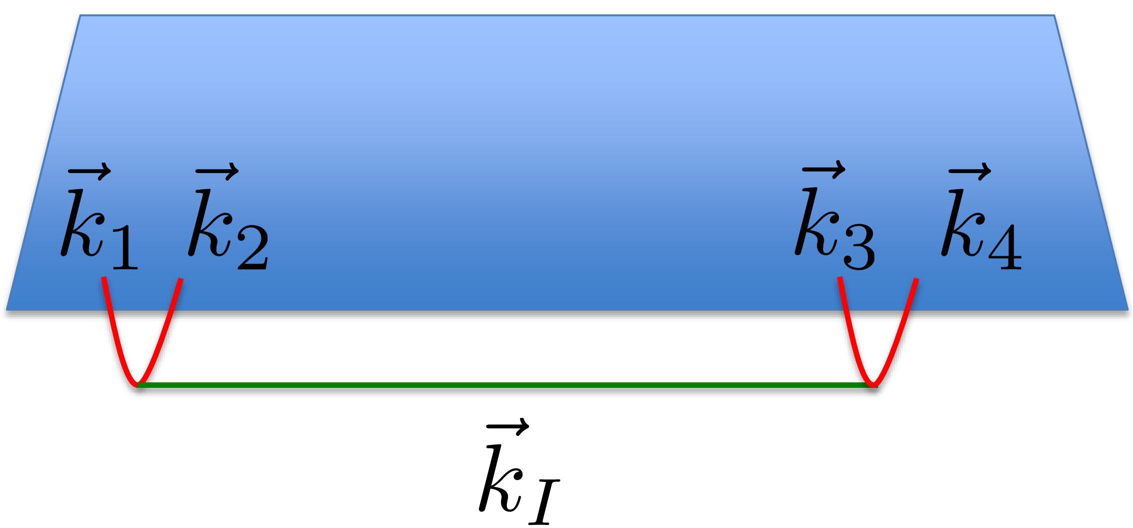

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Boltzman suppression $\quad e^{-\frac{m}{2T}}$

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

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

Volume dilution

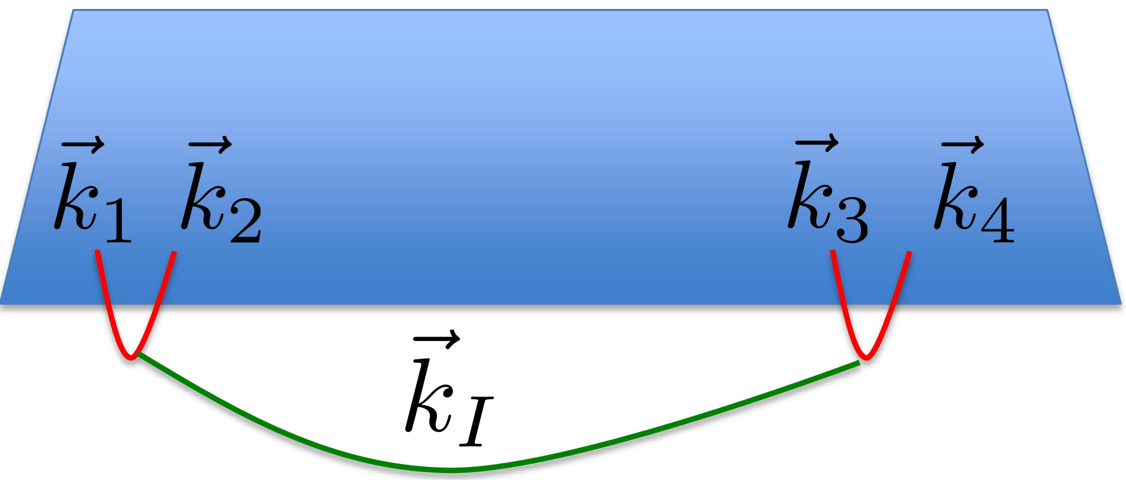
$$\langle 4pt \rangle \propto e^{-\pi\mu} \left[\left(\frac{k_I^2}{k_1 k_3} \right)^{\frac{3}{2}+i\mu} e^{i\delta} + c.c. \right]$$

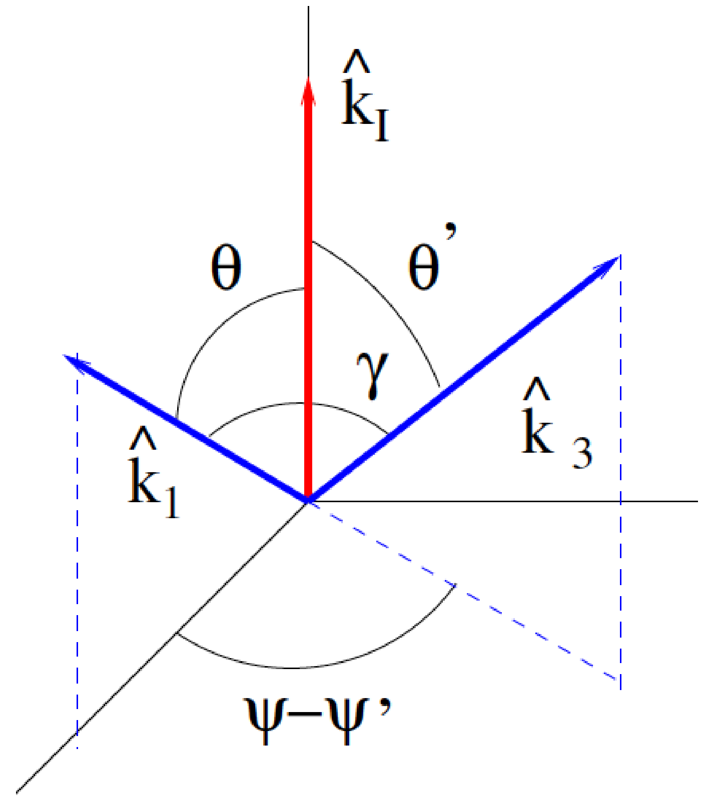
Explicit phase, function of μ

Test of quantum mechanics

Spin

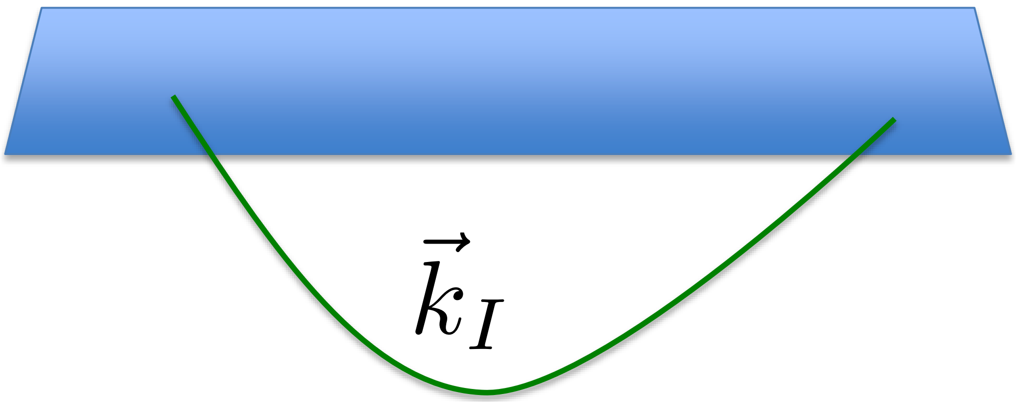
$$\langle 4pt \rangle \sim F(\gamma, \theta, \theta')$$





Further evidence of quantum mechanics ! →
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 → fixed by conformal symmetry

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

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

Overall size is small.

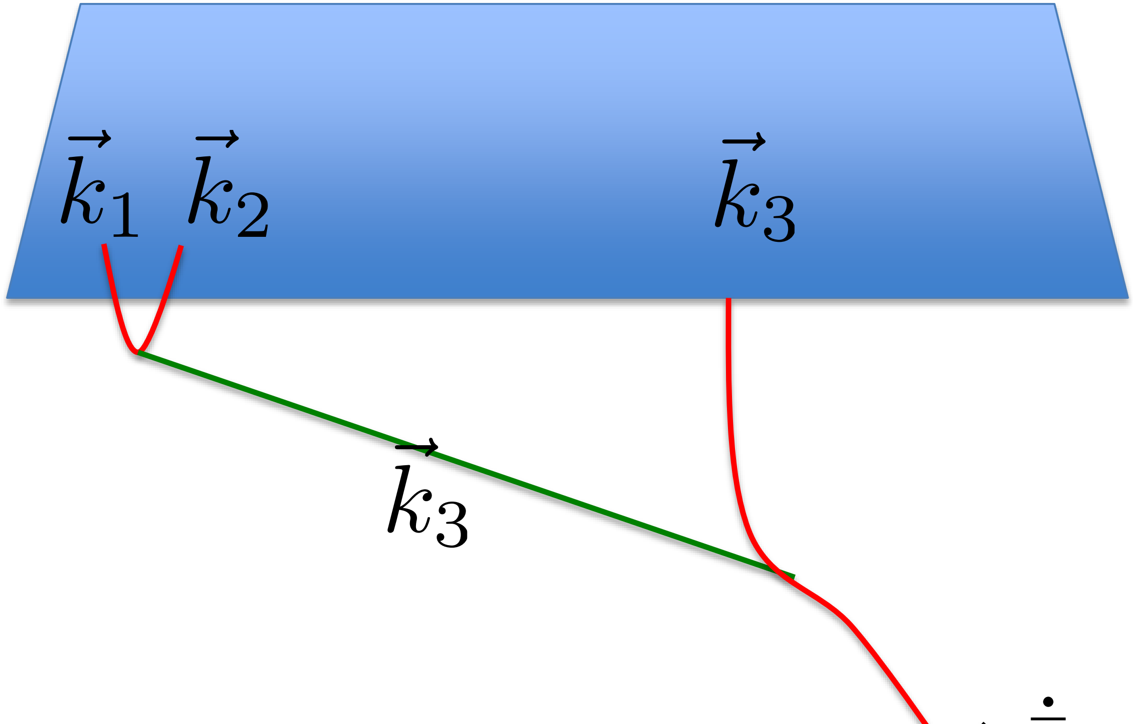
One factor of H/M from each interaction.

Can we find a bigger effect ?

Three point functions

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

$$\phi(t)$$

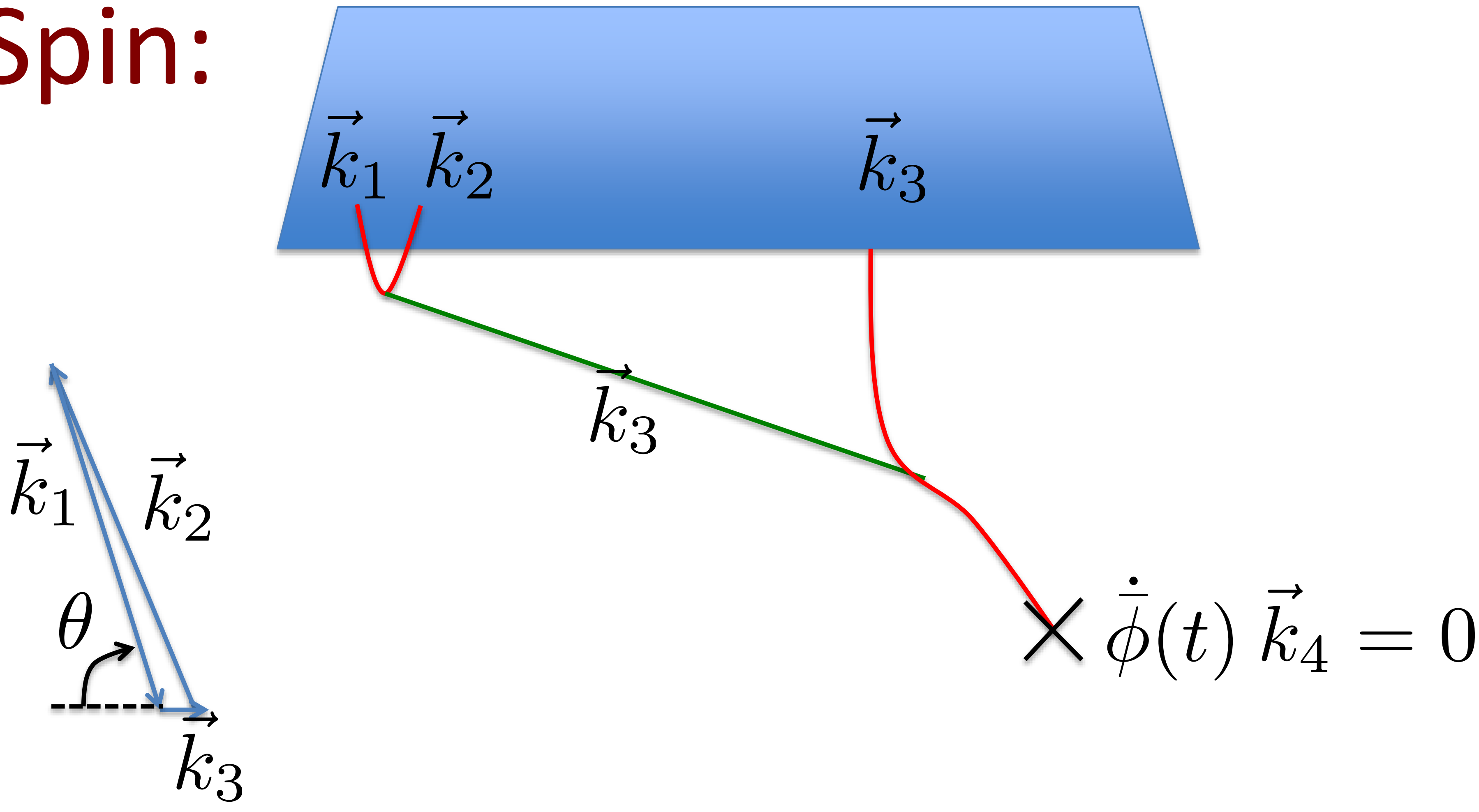


Only one very small coupling H/M$_{pl}$

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

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

Spin:



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

How difficult is it to detect ?

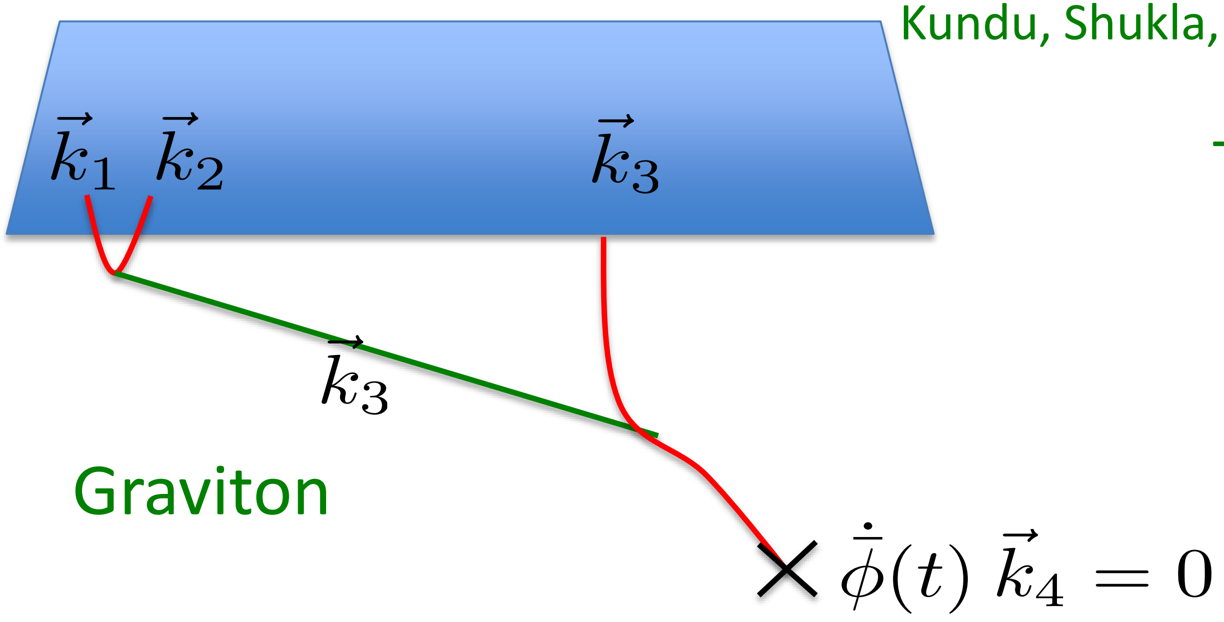
Very

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



How difficult is it to detect ?

$$\left| \langle 3pt \rangle^{\rm experimental}_{\rm squeezed} \right| \lesssim 5,$$

Planck

$$\left| \langle 3pt \rangle^{\rm graviton}_{\rm squeezed} \right| \sim |n_s - 1| \sim 0.04$$

How difficult is it to detect ?

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

- Assuming gravitational strength couplings → extra small factors.
- Cosmic variance → 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

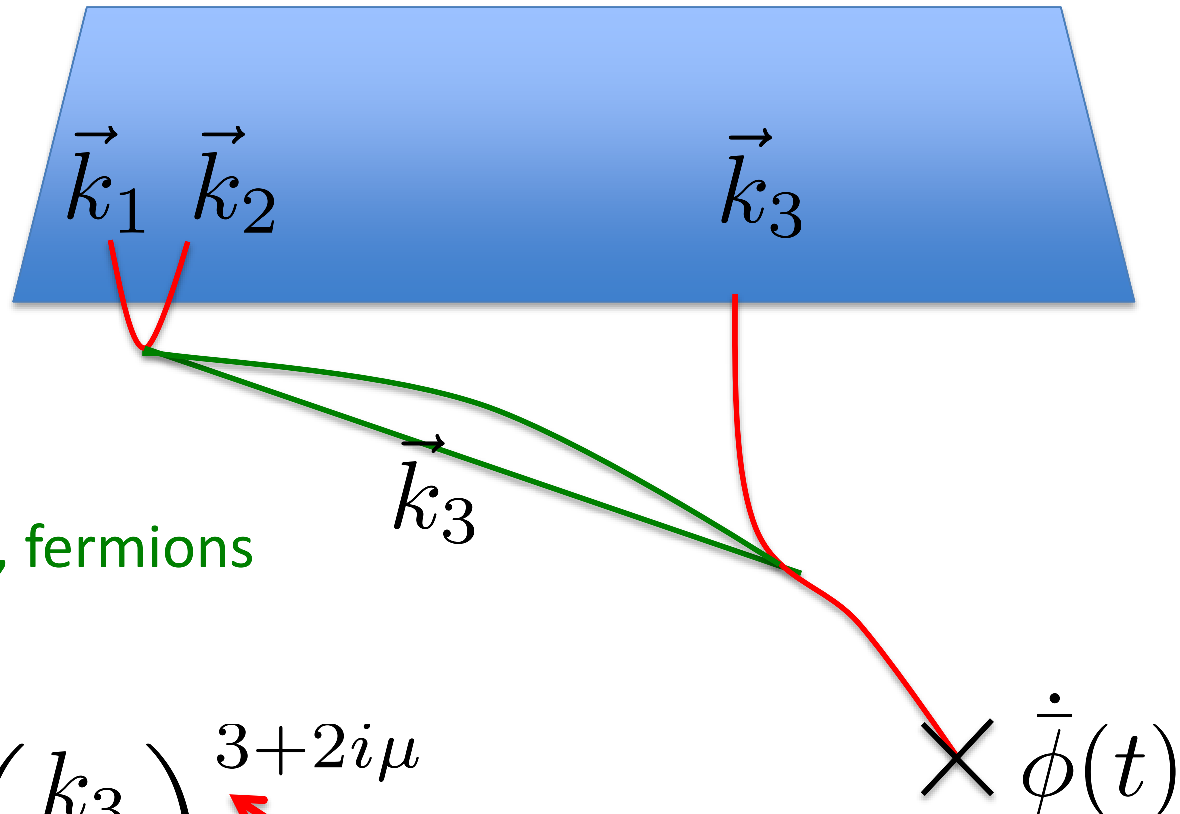
Theory with a large H and M_s similar to H.

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

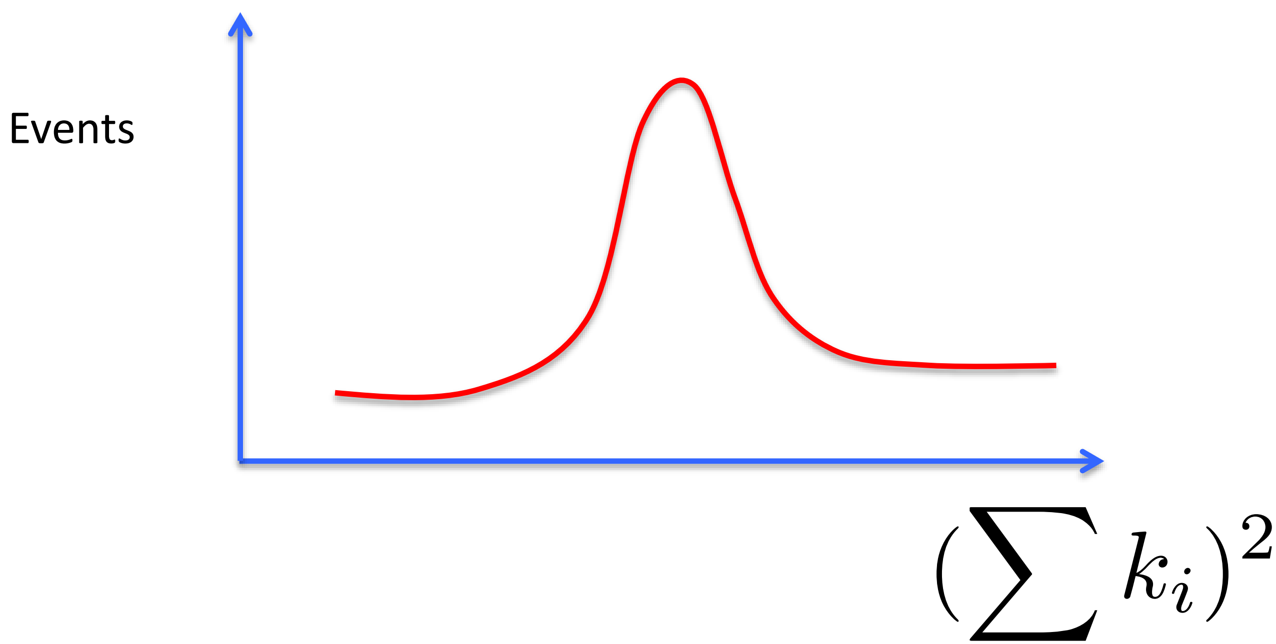
Different volume dilution factor

An extra factor of H^2/M^2_{pl}

Some conceptual aspects

Finding new particles: collider physics

- Collider → peaks in the invariant mass distribution.



Finding new particles collider physics

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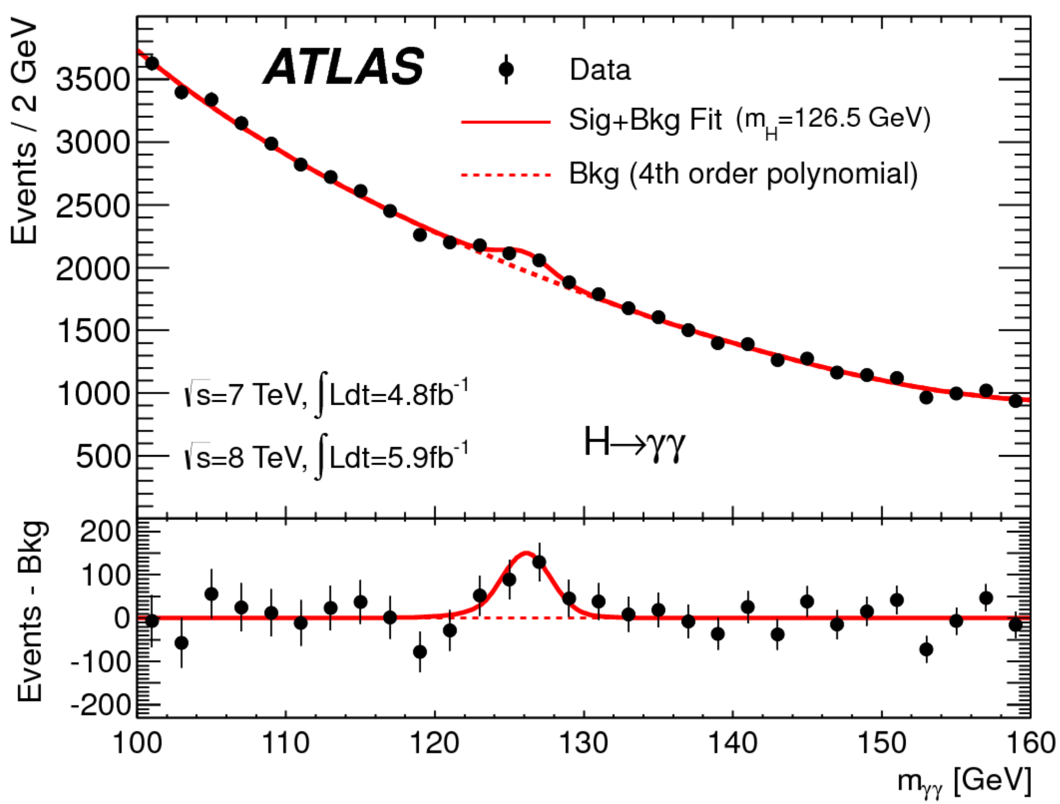


Cosmological collider physics

- 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

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

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

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

At late times we can expand

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

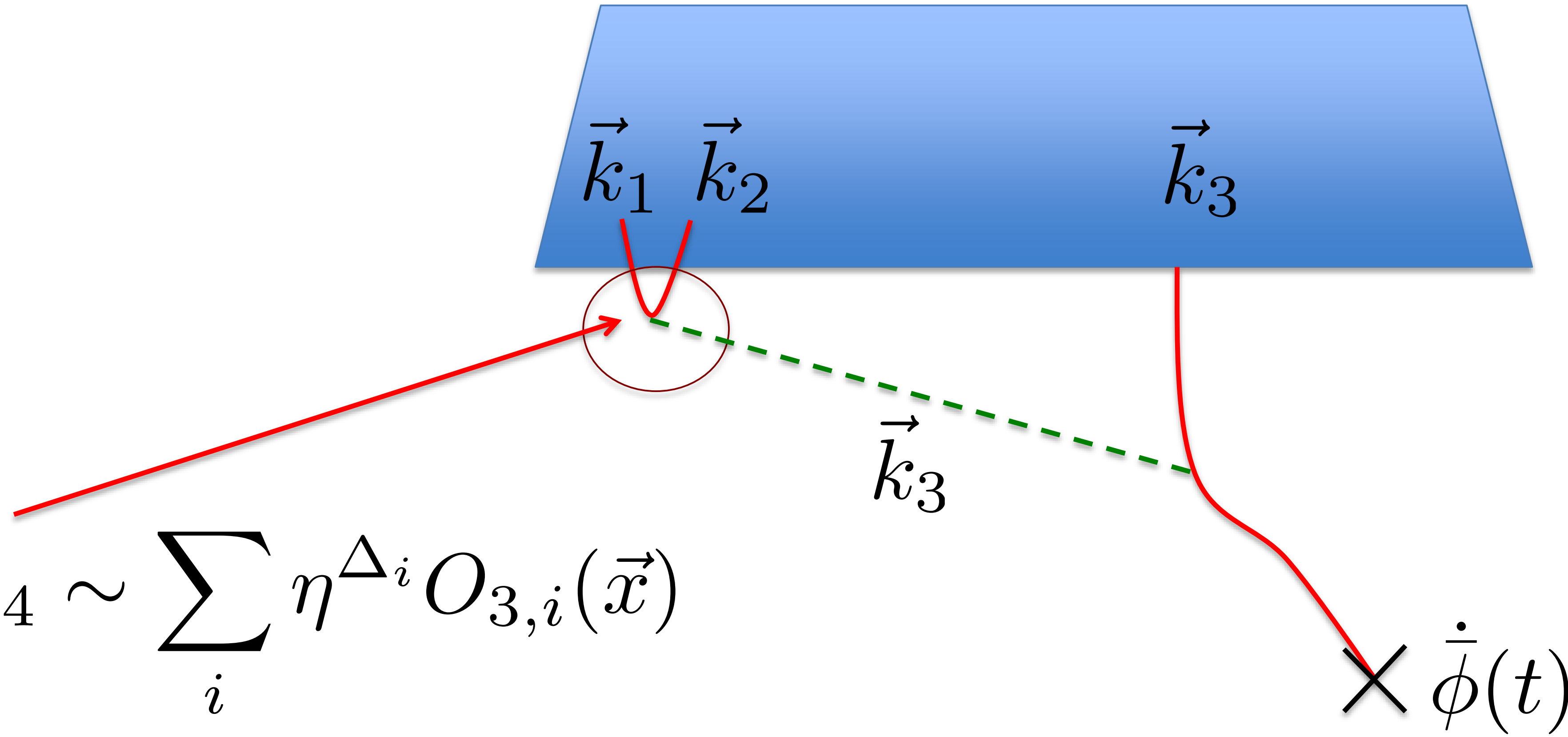
$$O_4 \sim \sum_i \eta^{\Delta_i} O_{3,i}(\vec{x})$$

3d operator of conformal dimension Δ_i

(Related to conformal dimensions of operator in dual CFT_3)

Strominger, Witten

Squeezed limit = OPE expansion



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

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 → terms in the <u>classical</u> 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!.