Time without Time

Inflationary Correlators from the Boundary

Daniel Baumann

based on work in progress with

Nima Arkani-Hamed, Hayden Lee and Guilherme Pimentel based on work in progress with

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Outline

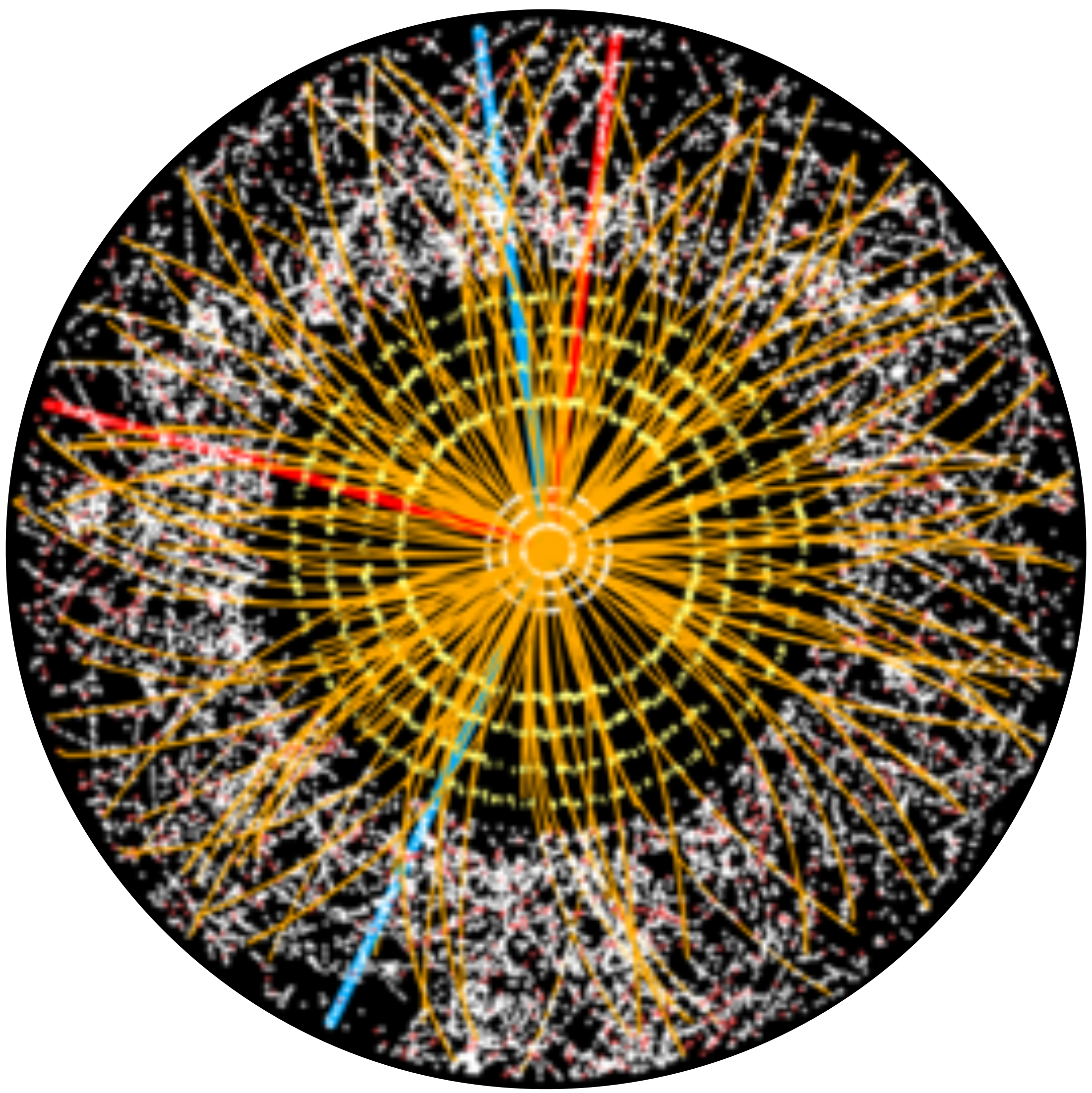
1. Motivation

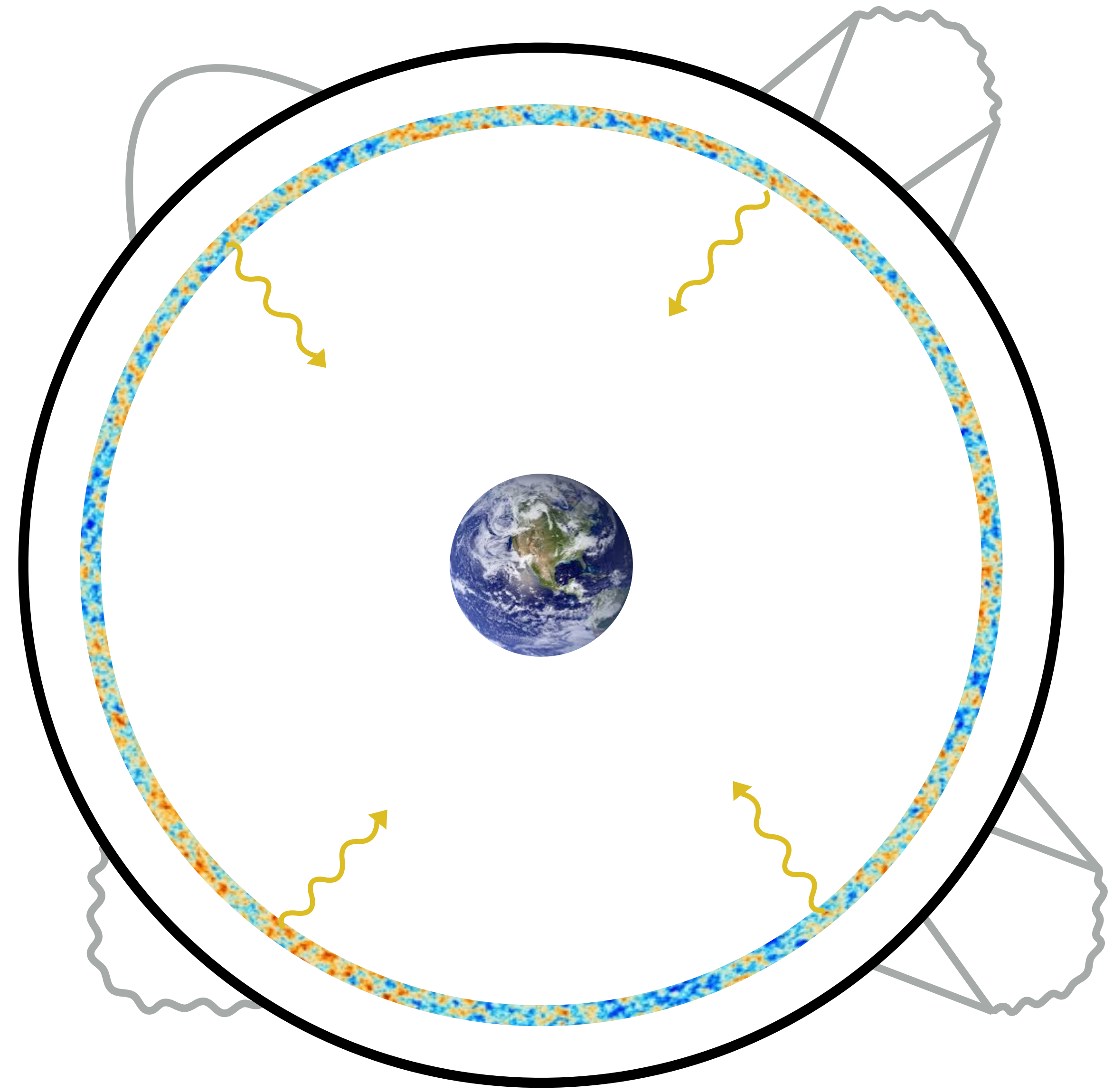
2. Method and Results

3. Summary and Outlook

Motivation

Cosmological Collider Physics

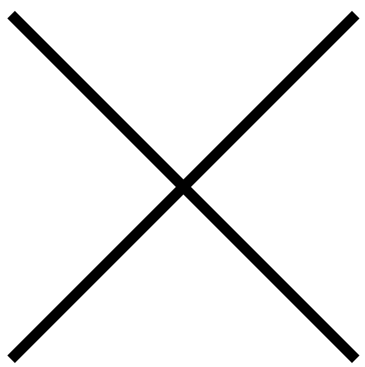




Goal: Obtain an analytic understanding of cosmological correlators that parallels our understanding of flat-space scattering amplitudes.

Scattering Amplitudes

At low energies, amplitudes are described by an **EFT expansion**:

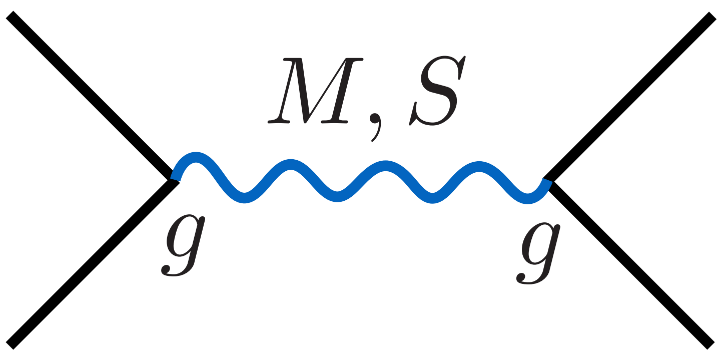


contact interactions

$$A(s,t) = \underset{\substack{\uparrow \\ \phi^4}}{a_0} + \underset{\substack{\uparrow \\ (\partial\phi)^4}}{a_2 s^2} + \cdots$$

Scattering Amplitudes

At higher energies, new particles can be excited in **resonances**:

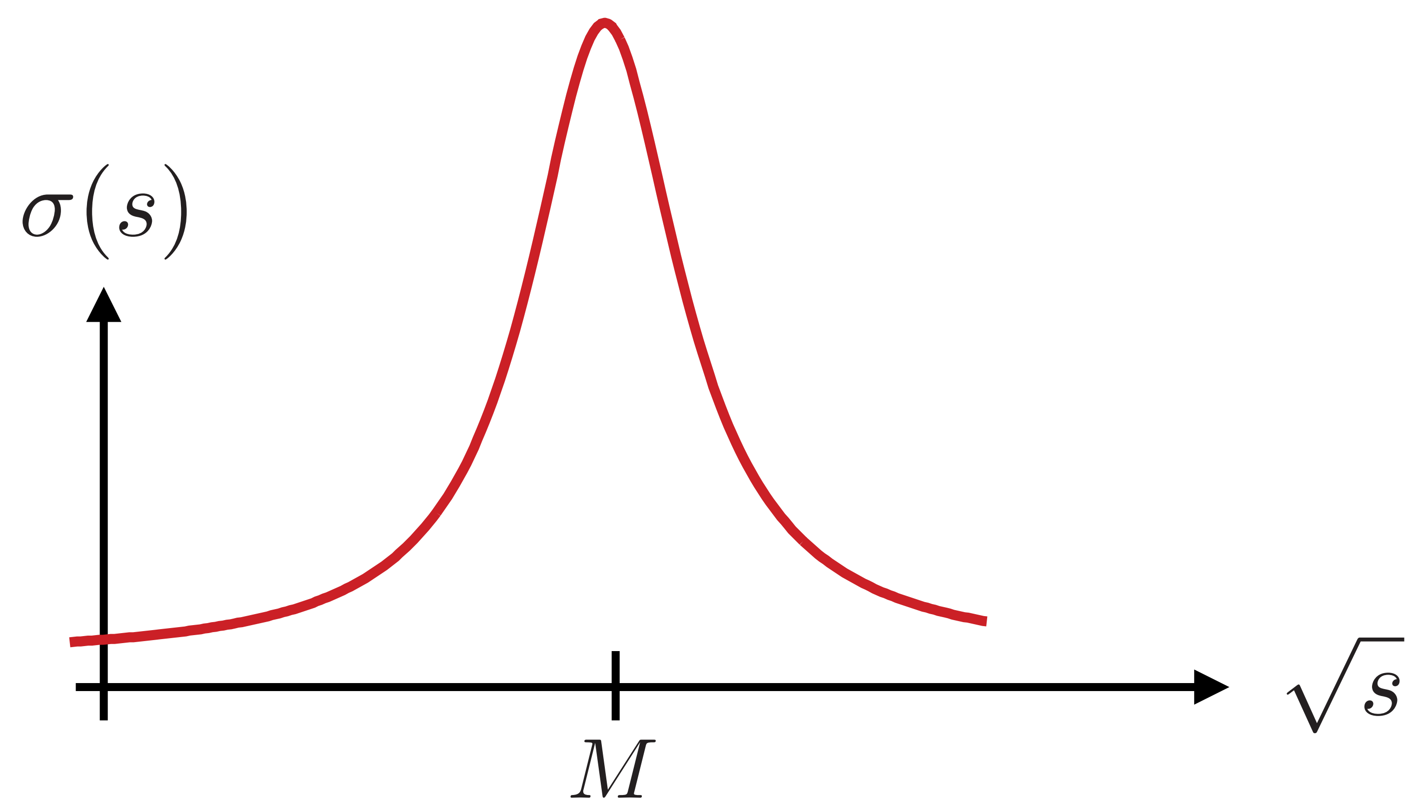


exchange interactions

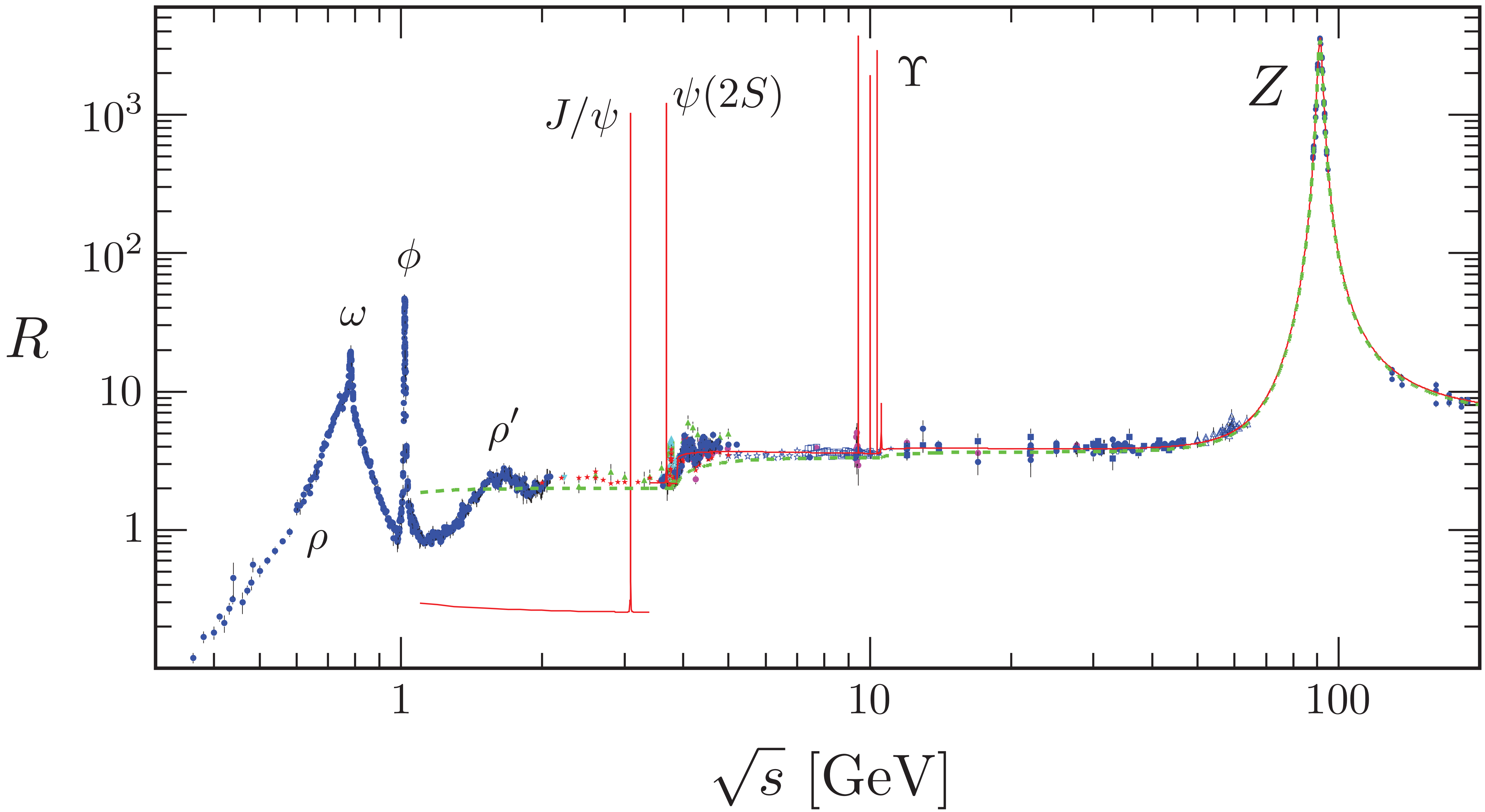
$$A(s,t) = \frac{g^2 P_S(\cos\theta)}{s - M^2} \longleftarrow$$

locality

unitarity



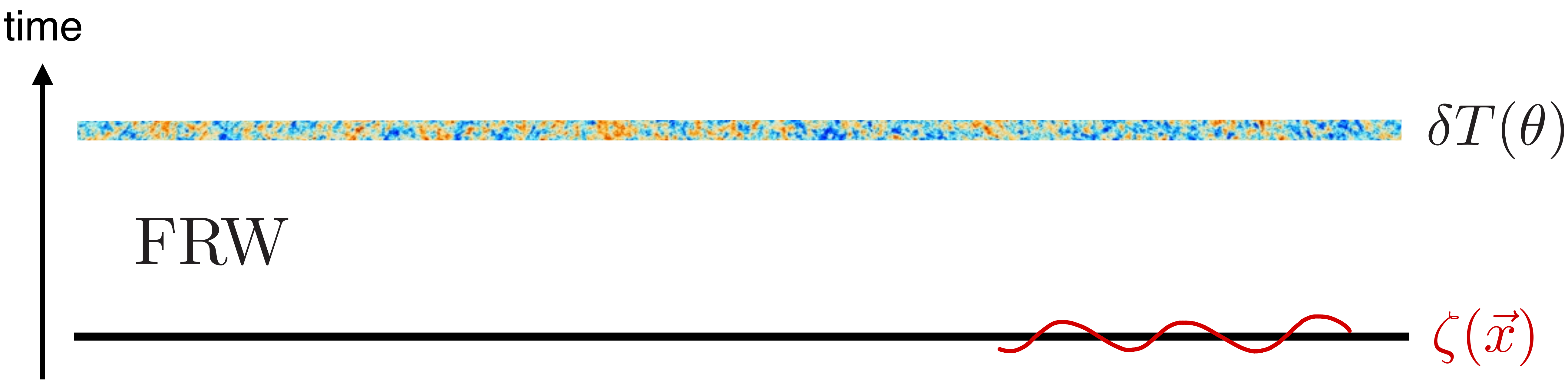
Scattering Amplitudes



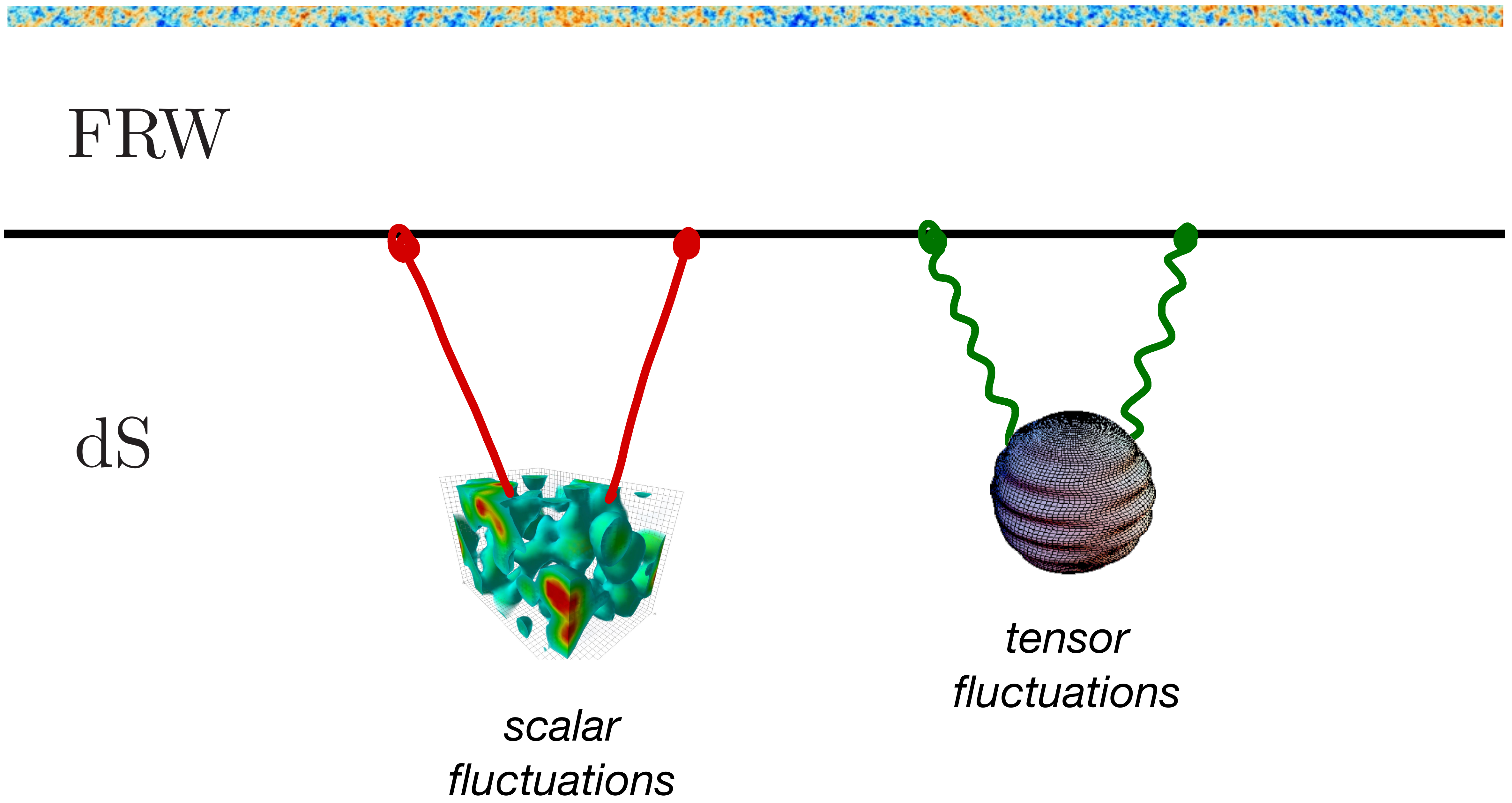
Particle Data Group [2018]

What is the analogous story in cosmology?

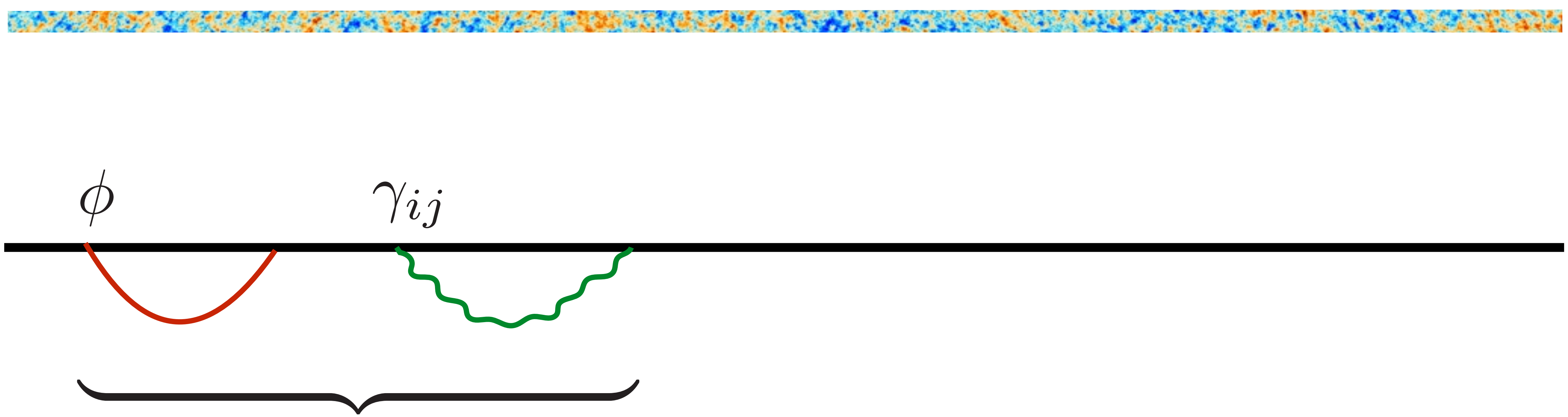
Cosmological Correlators



Cosmological Correlators

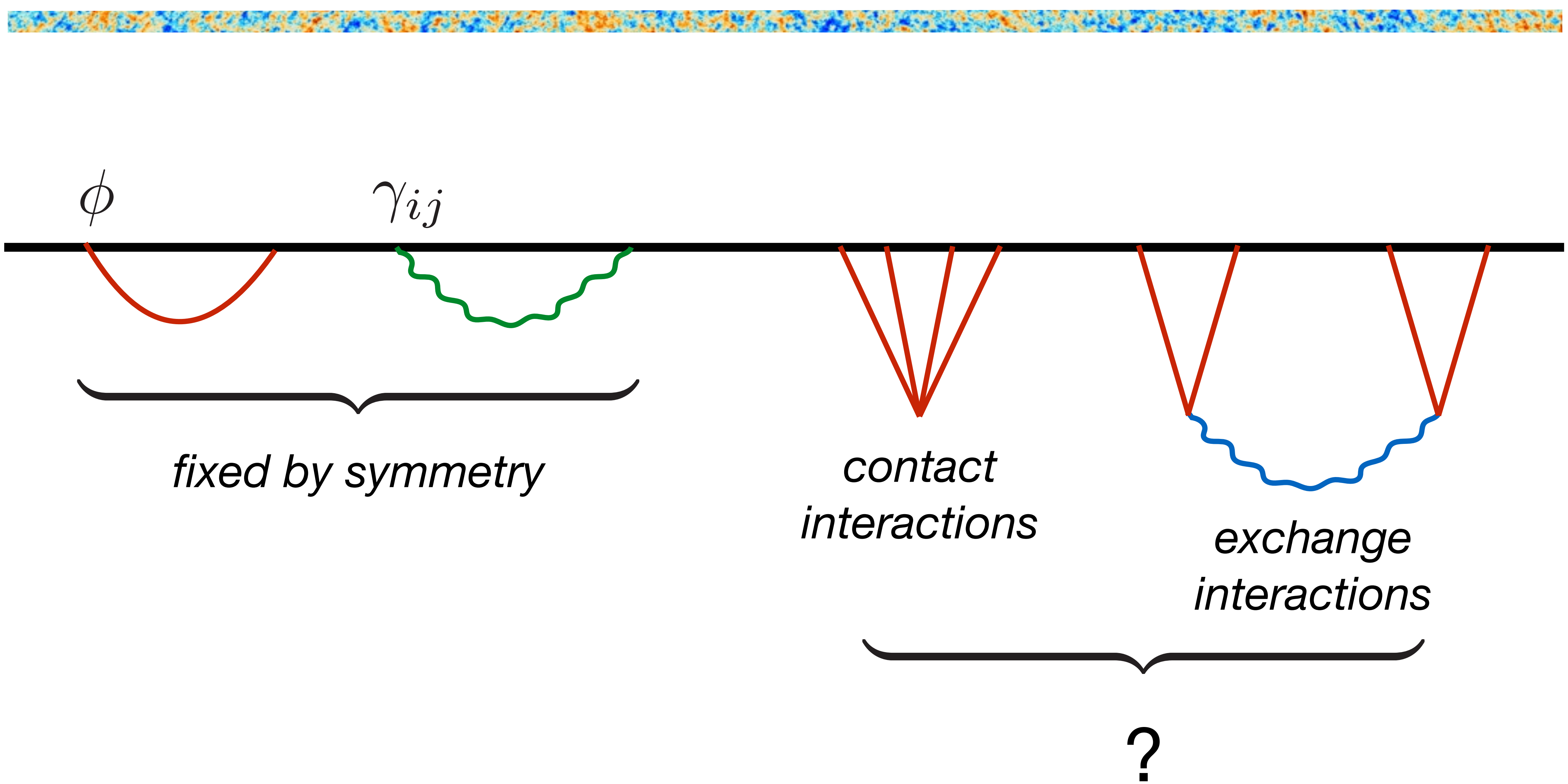


Cosmological Correlators

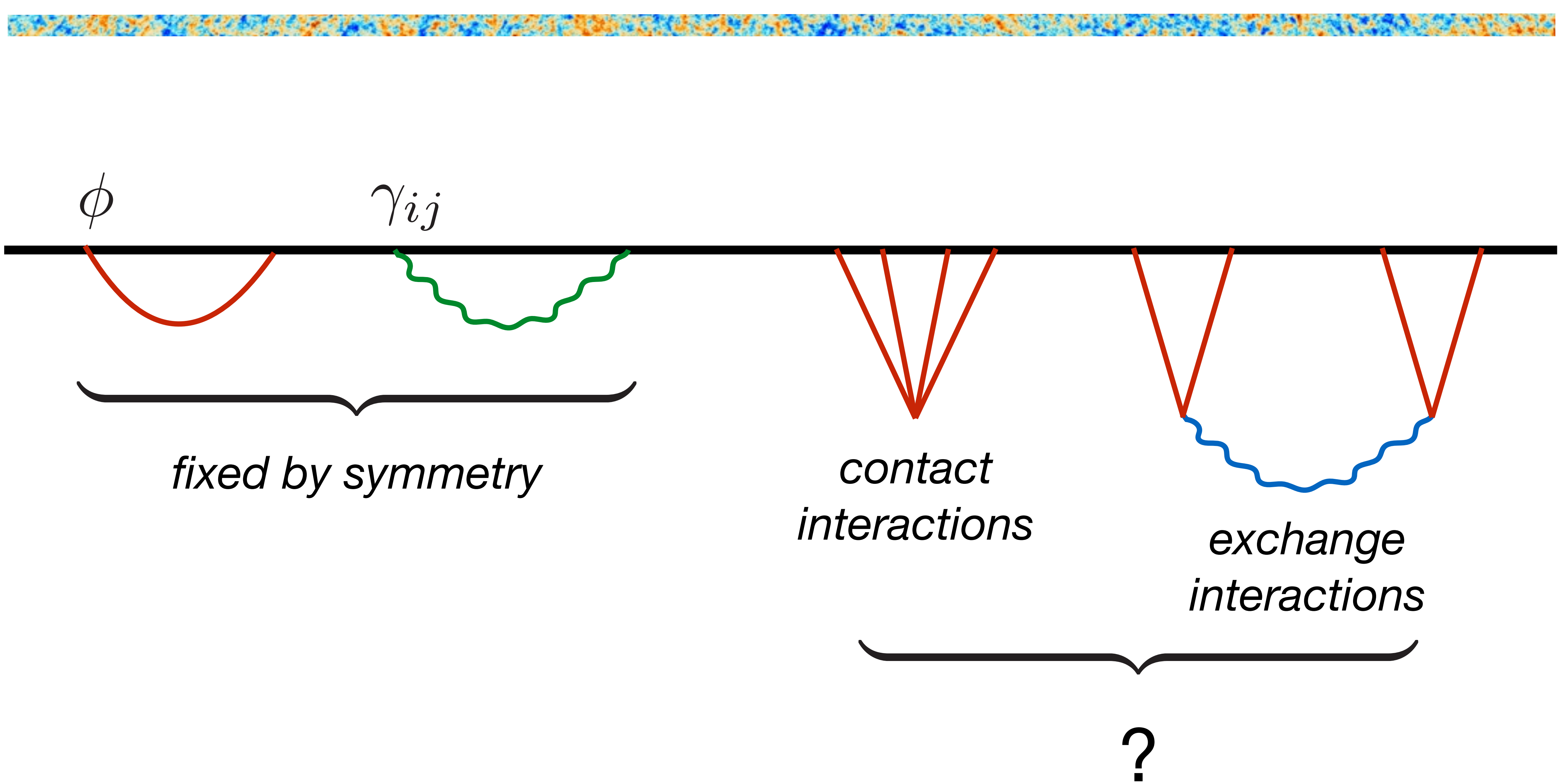


fixed by symmetry

Cosmological Correlators

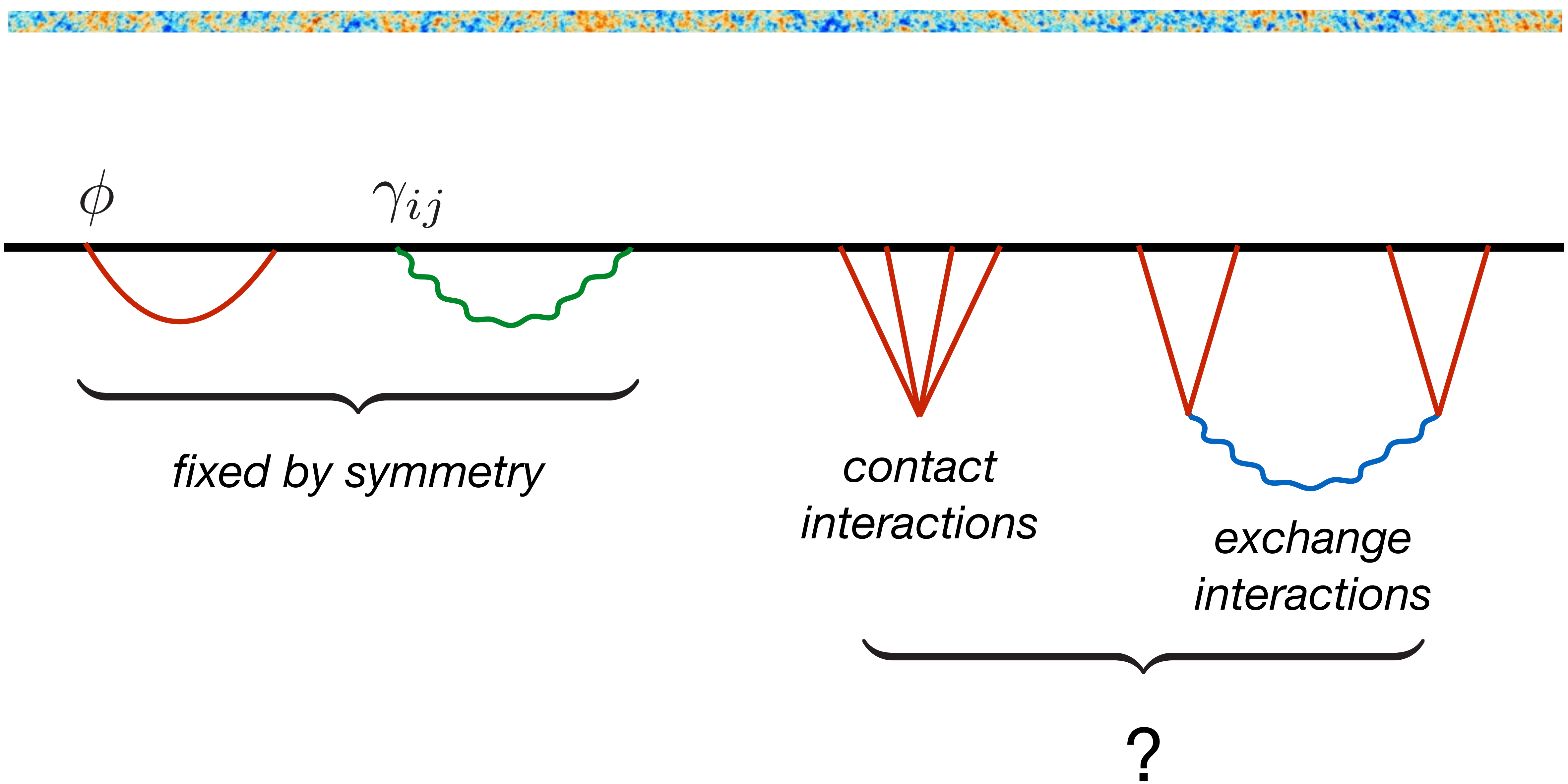


Cosmological Correlators



What is the analytic structure of inflationary correlators?

Cosmological Correlators



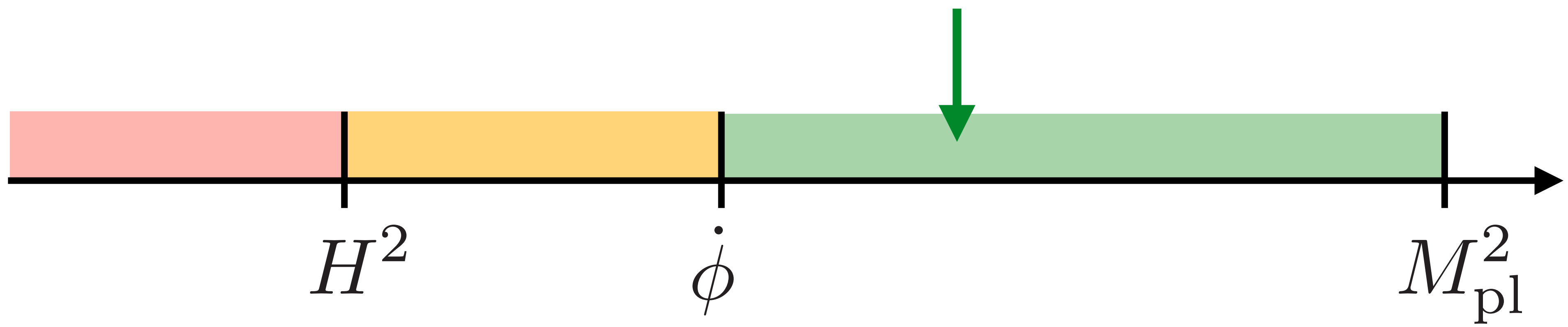
What particles exist up to 10^{14} GeV?

Method and Results

Arkani-Hamed, DB, Lee and Pimentel, *in progress*.

Symmetries

Consider slow-roll inflation with **weak couplings** to massive fields.

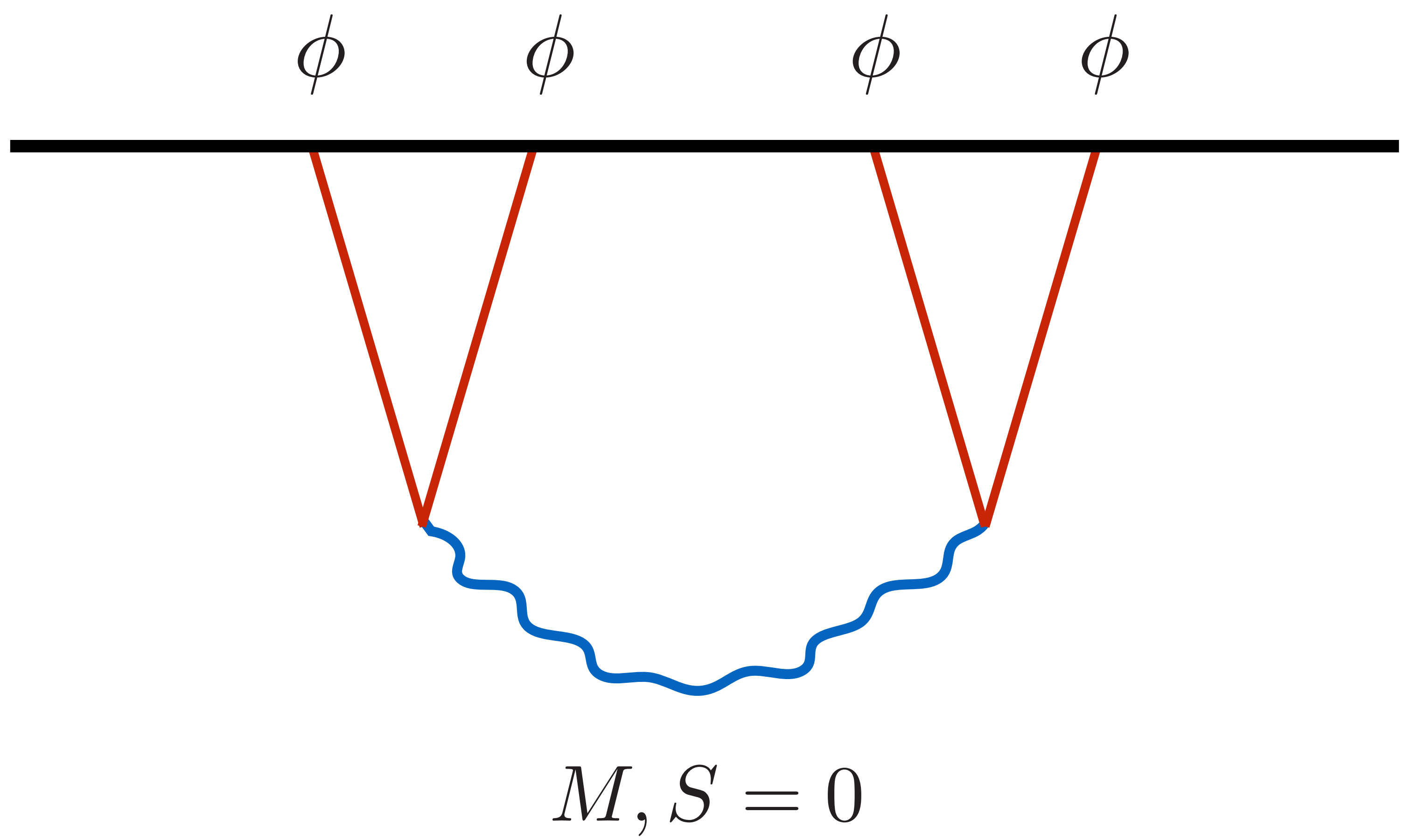


- Correlators are then determined by the approximate **conformal symmetry** on the boundary of the spacetime.

- The absence of unphysical **singularities** (and the correct normalization of physical ones) completely fixes the correlators.

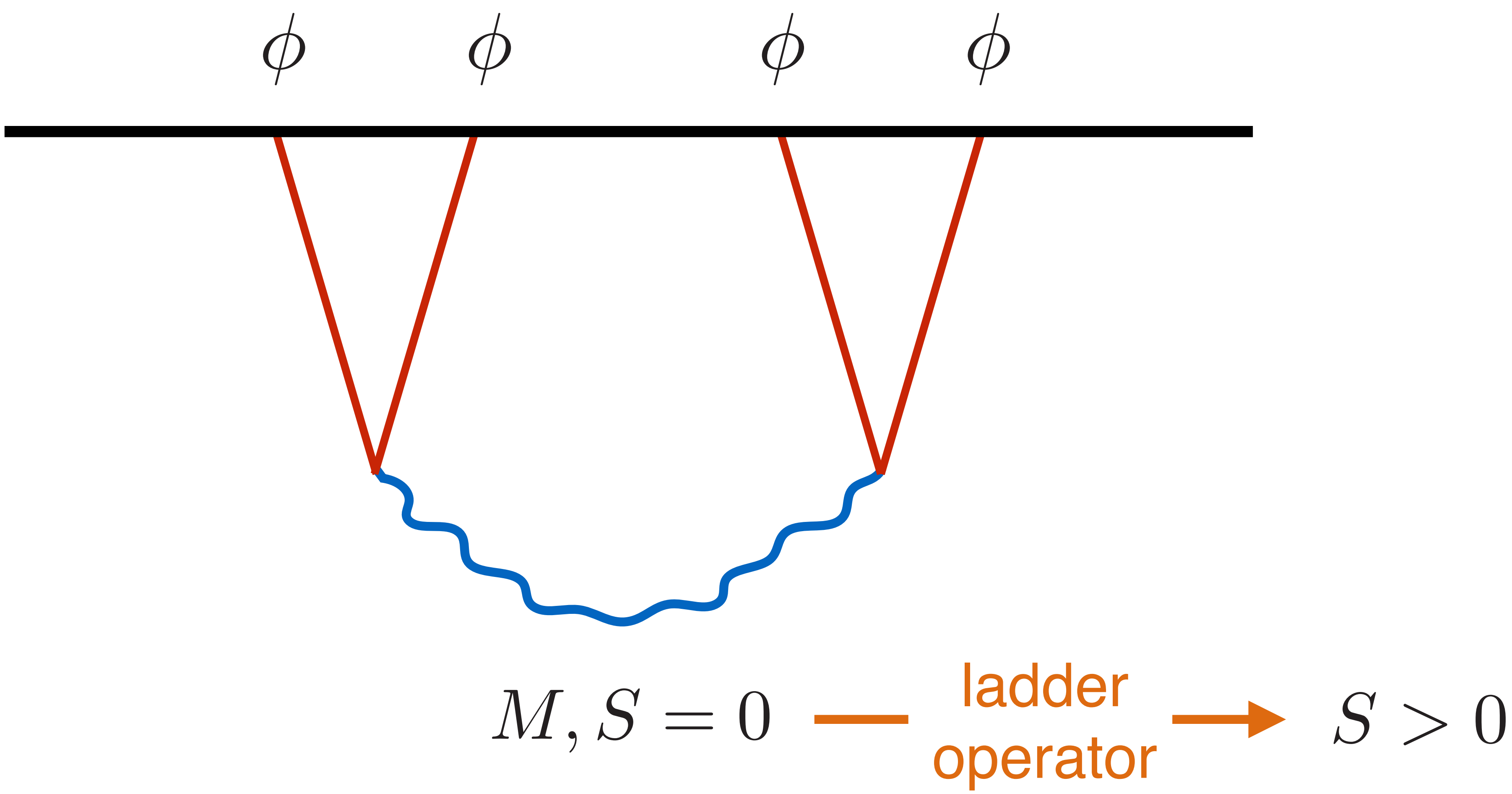
Arkani-Hamed and Maldacena [2015]
Arkani-Hamed, DB, Lee and Pimentel [2018]

Road Map



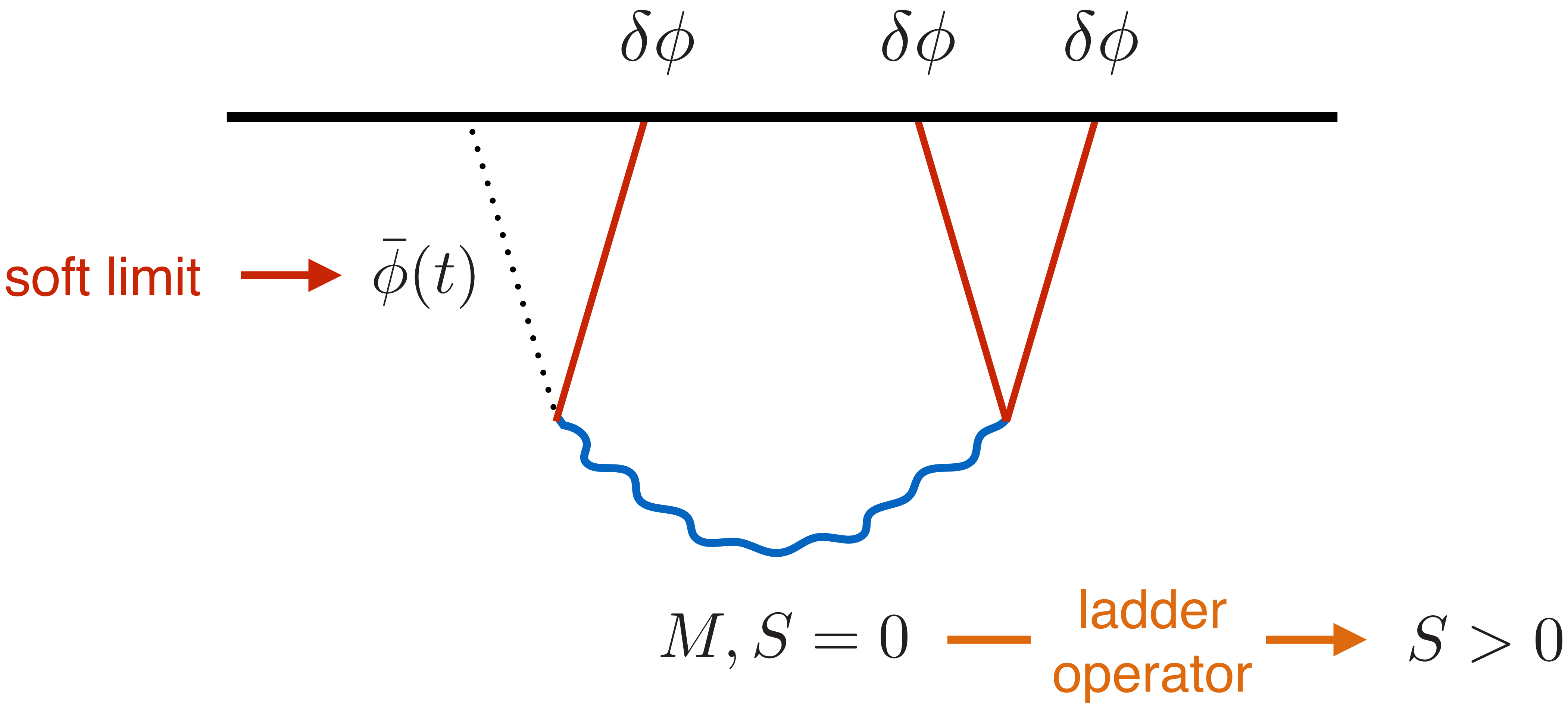
Using this symmetry-based approach, we will determine the four-point function of scalar exchange in de Sitter space.

Road Map



A ladder operator relates this to the exchange of spinning particles.

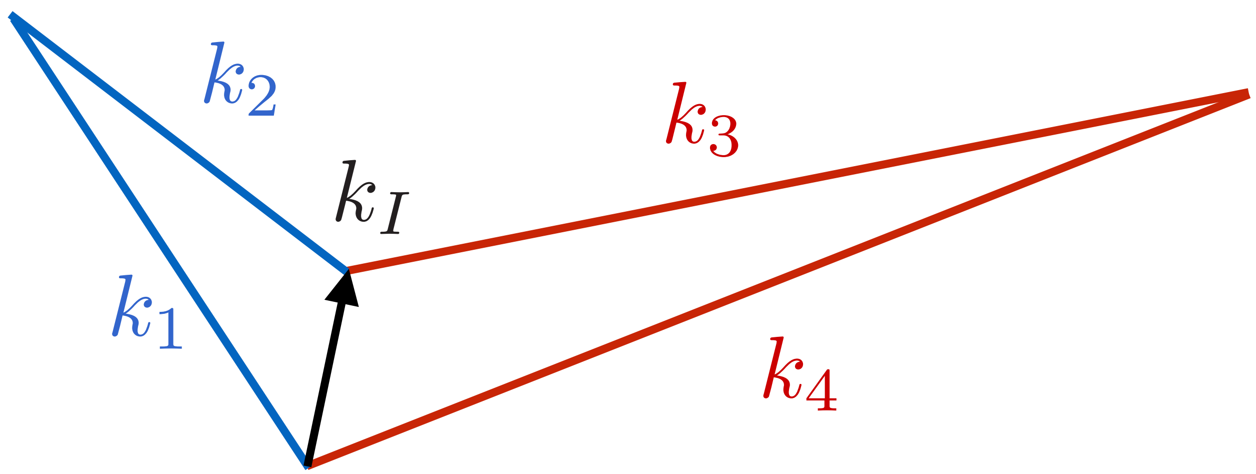
Road Map



Evaluating one leg on the background gives inflationary 3-pt functions.

Time without Time

Four-point functions in dS depend on only two variables:

$$F(k_i) \equiv$$ 

$$= k_I^{-1}\hat{F}(u, v) \qquad \text{where} \qquad u \equiv \frac{k_I}{k_1 + k_2} \qquad v \equiv \frac{k_I}{k_3 + k_4}$$

Time without Time

Conformal symmetry implies

$$\boxed{(\Delta_u - \Delta_v)\hat{F} = 0}$$

where $\Delta_u \equiv u^2(1-u^2)\partial_u^2 - 2u^3\partial_u$.

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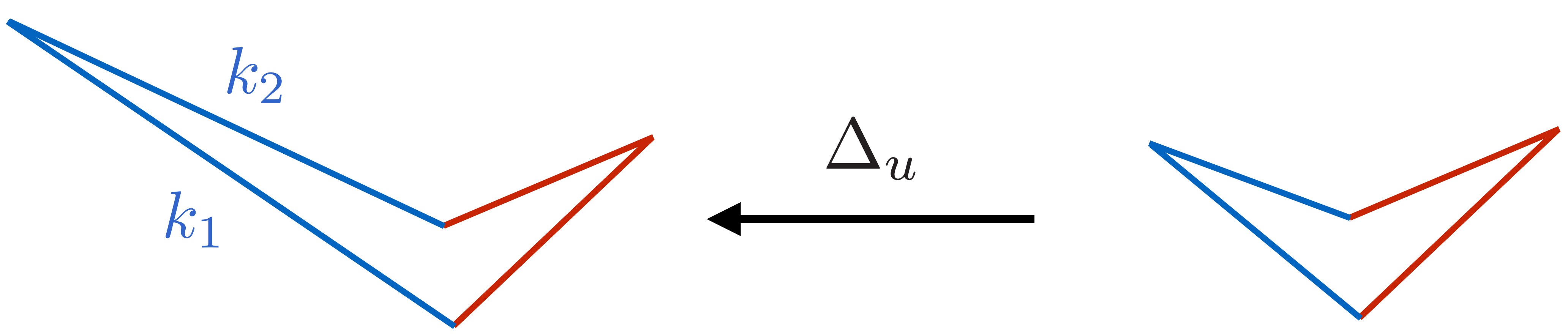
The momentum dependence of the boundary correlators encodes the time dependence of the bulk interactions:



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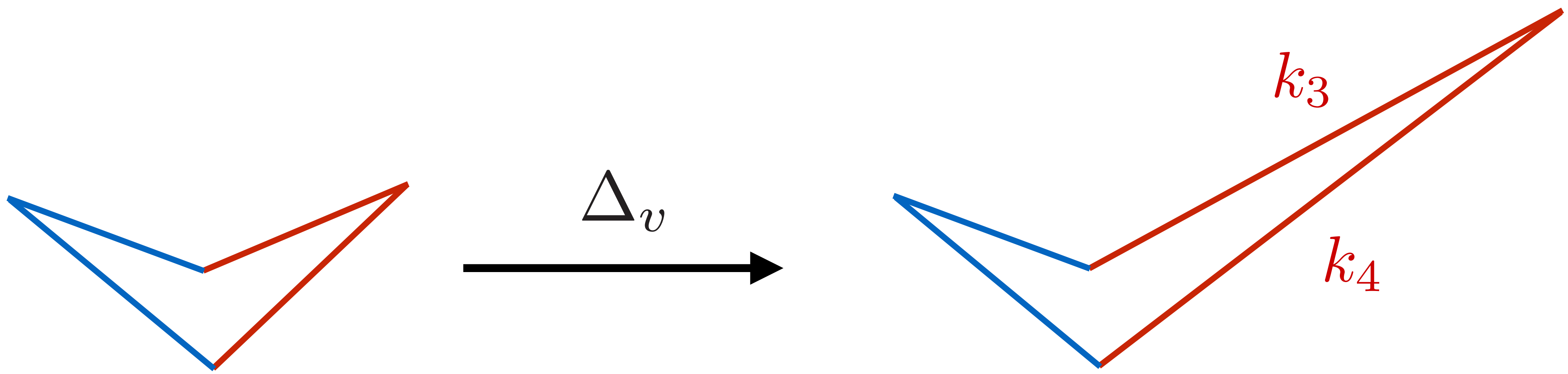

Time without Time

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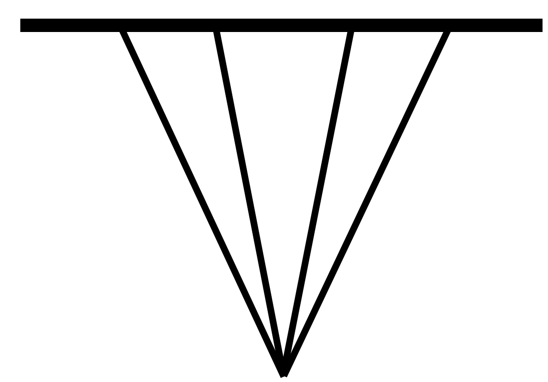
$$\boxed{(\Delta_u - \Delta_v)\hat{F} = 0}$$

where $\Delta_u \equiv u^2(1-u^2)\partial_u^2 - 2u^3\partial_u$.

In the rest of the talk, I will discuss the solutions of this equation.

Contact Interactions

The simplest solutions correspond to contact interactions

$$\hat{C}(u,v) \equiv$$ 

These are easy to classify

$$\hat{C}_0 \equiv \frac{uv}{u+v} \longleftarrow \phi^4$$

$$\hat{C}_n \equiv \Delta_u^n \hat{C}_0 \longleftarrow (\partial_\mu \phi)^4, \cdots$$

Arkani-Hamed, DB, Lee and Pimentel [2018]

Tree Exchange

For tree exchange, the conformal symmetry constraint reduces to

$$\boxed{\begin{aligned}(\Delta_u + M^2)\hat{F} &= \hat{C} \\ (\Delta_v + M^2)\hat{F} &= \hat{C}\end{aligned}}$$

contact interactions

cf. $(-s + M^2)A = C$

Given our classification of contact interactions, we can classify the solutions of these equations.

Arkani-Hamed, DB, Lee and Pimentel [2018]

EFT Expansion

A formal solution of the equation is

$$\hat{F}_p = \sum_n \left(-\frac{\Delta_u}{M^2} \right)^n \hat{C}(u,v) \quad \sim \left(\frac{H^2}{M^2} \right)^n$$

This is the EFT expansion of the correlation function.

EFT Expansion

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This is the EFT expansion of the correlation function.

However, this solution is still missing the effects of spontaneous particle production in the time-dependent background:

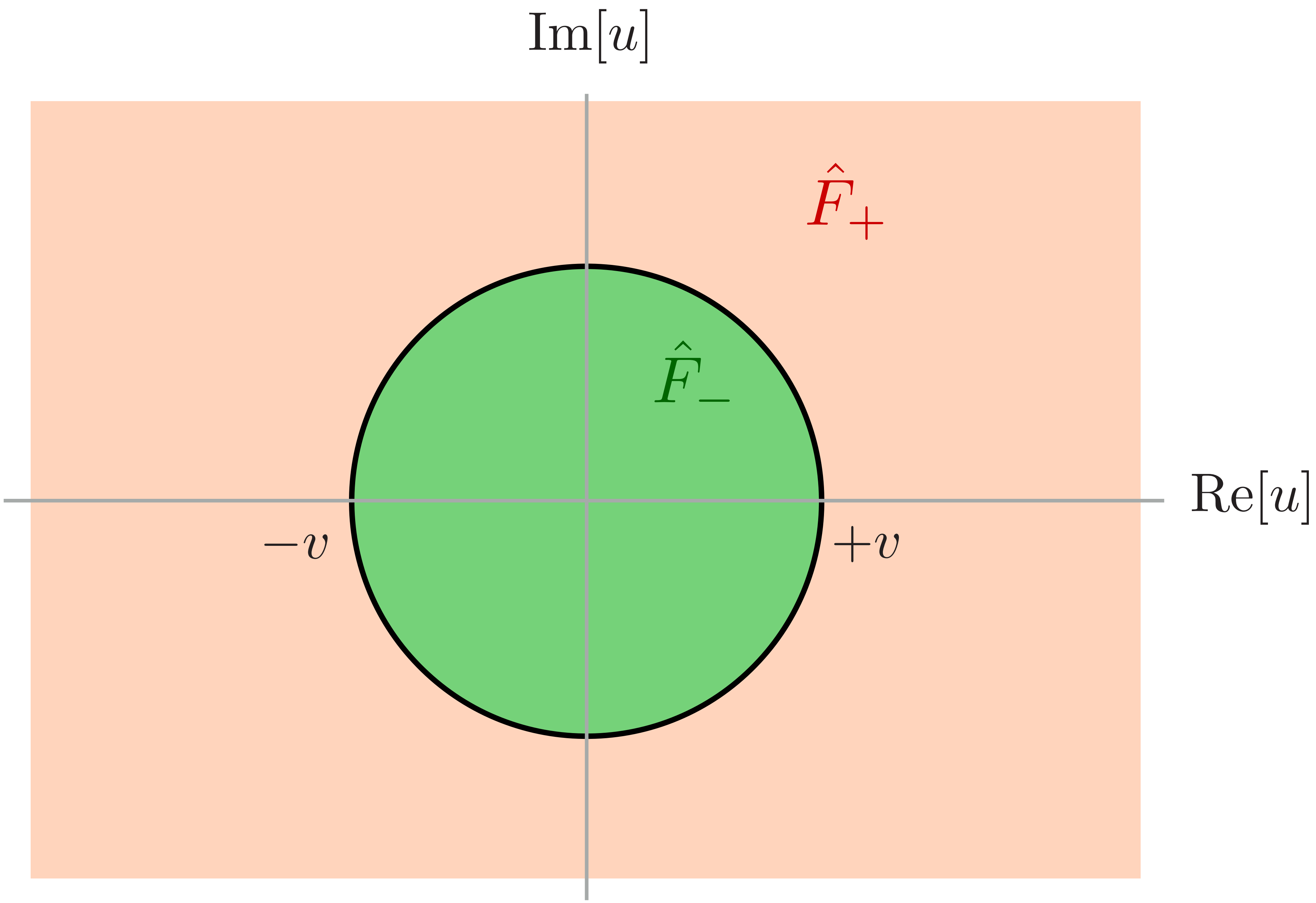
$$\hat{F} = \hat{F}_p + \hat{F}_h$$

$$\sim e^{-M/H}$$

Our equation knows about this!

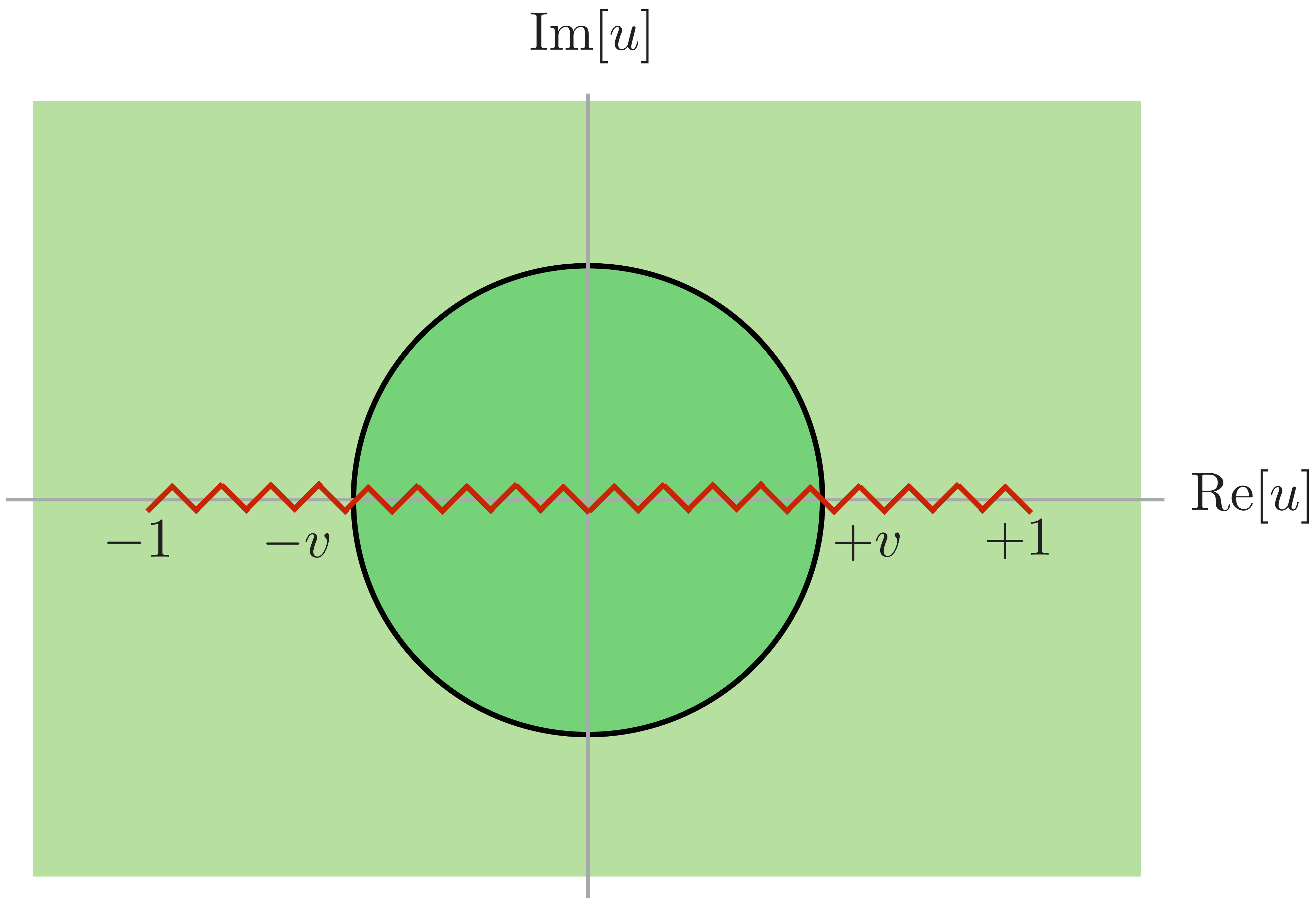
Particle Production

The EFT expansion has a finite range of convergence in the u-plane:



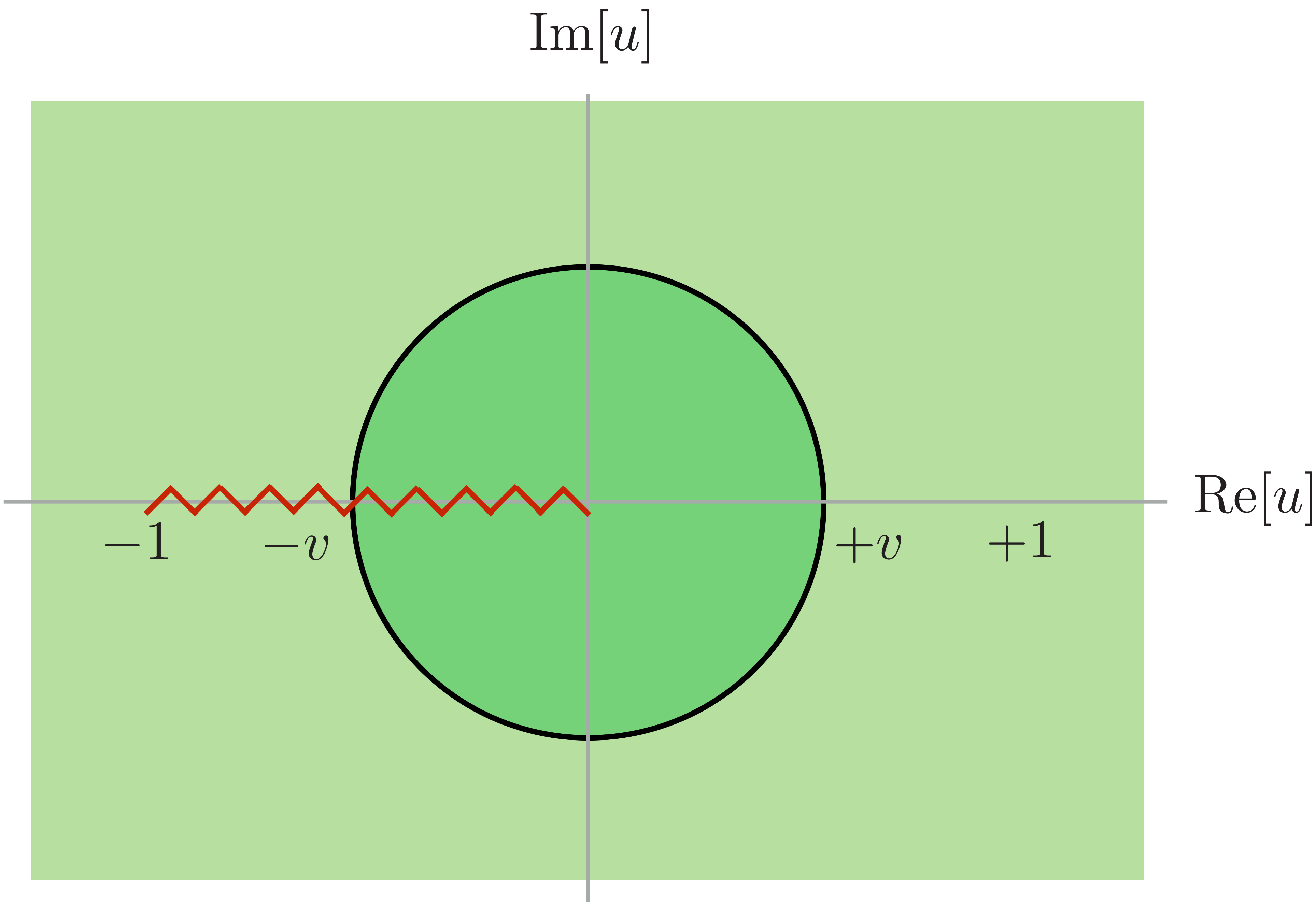
Particle Production

Extending the solution to the entire u-plane forces us to include a homogeneous solution corresponding to particle production:



Particle Production

Removing an unphysical singularity at u=1 and correctly normalising a physical singularity at u=-1 completely fixes the solution:



The Solution

Schematically, the final solution is

$$\boxed{\hat{F} = \underbrace{\hat{F}_p}_{\text{EFT}} + \underbrace{\hat{F}_h}_{\text{PP}}}$$

where

$$\hat{F}_p(u,v) = \sum c_{nm}(M)\, u^{2m+1}(u/v)^n \qquad |u| \leq |v|$$

$$\hat{F}_h(u,v) = e^{-M/H} g(u,v)$$

$\longmapsto$ unique combination of homogeneous solutions.

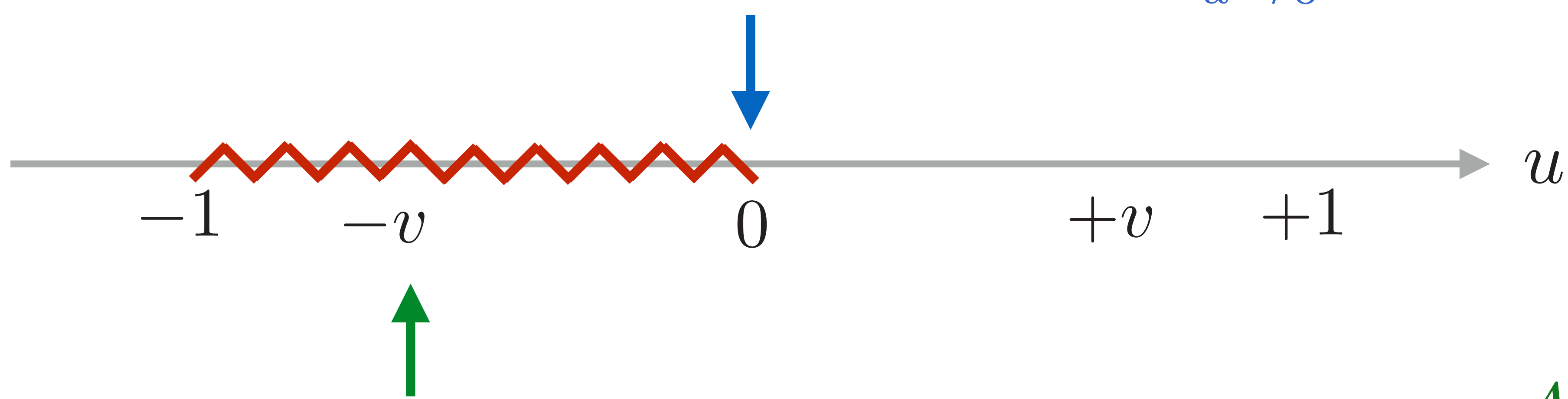
Arkani-Hamed, DB, Lee and Pimentel [2018]

The Solution

The solution has a number of interesting features:

It contains **particle production**

$$\lim_{u \to 0} \hat{F}_h \propto u^{iM/H}$$



It contains **flat-space scattering**

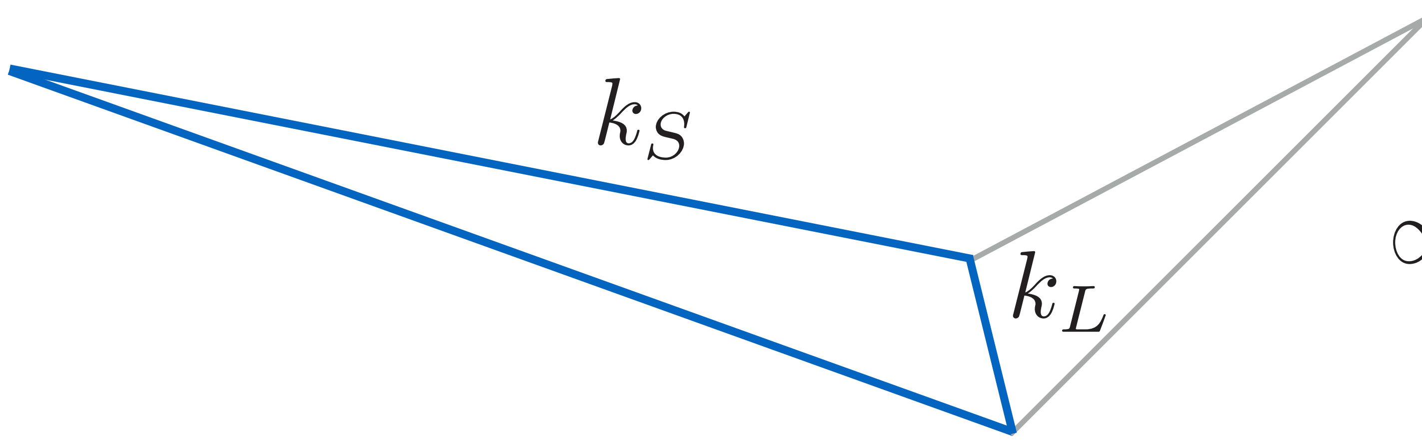
$$\lim_{u \to -v} \hat{F} \propto \frac{A_{\text{flat}}}{(u+v)^p}$$

These two features are closely related:

$$\boxed{A_{\text{flat}} \propto \lim_{u \to -v} \frac{\text{Disc}[\hat{F}_h^{(p)}(u,v)]}{2\pi i}}$$

Spectroscopy

The particle production piece dominates in the collapsed limit of the four-point function (or the squeezed limit of the three-point function):



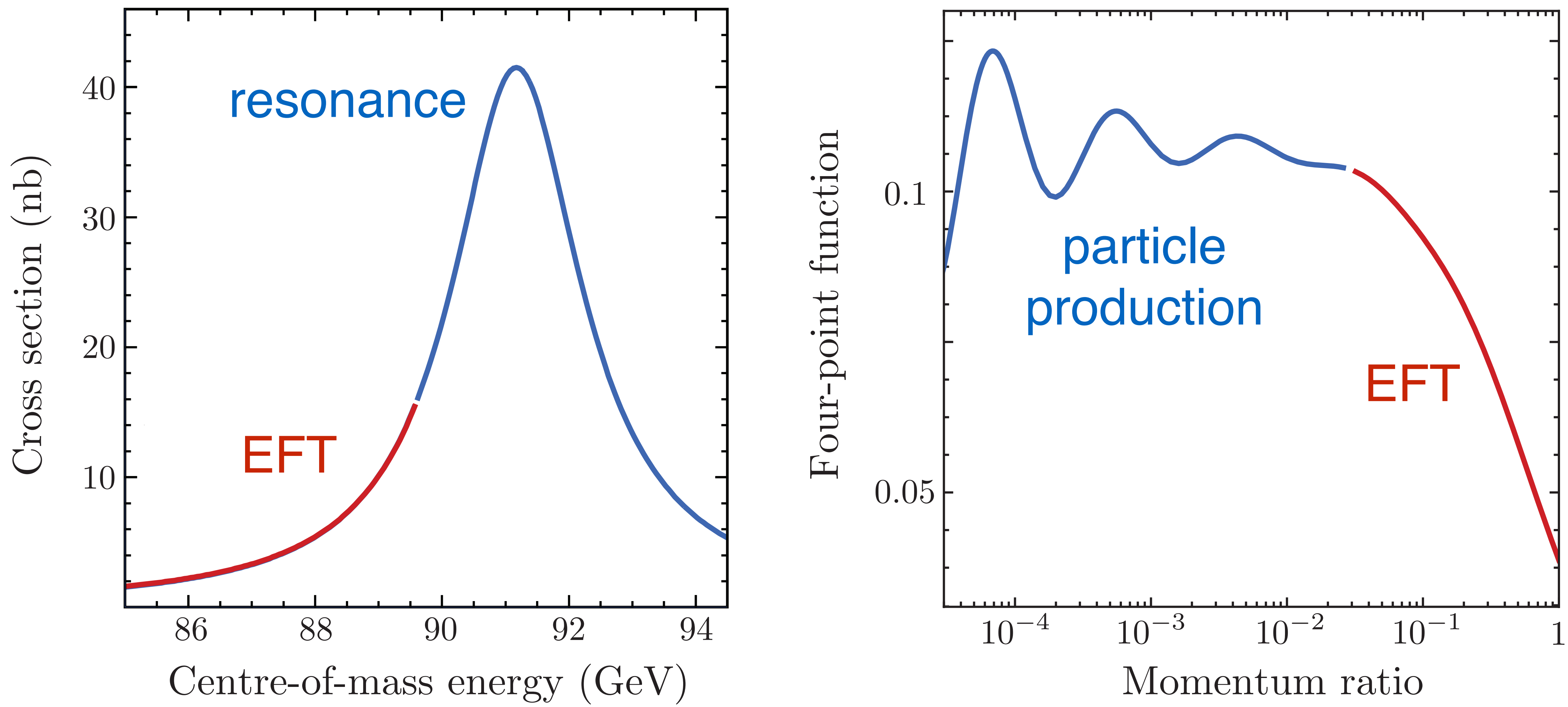
$$\propto \cos\left(\frac{M}{H}\ln(k_L/k_S)\right)$$

In this limit, the signal oscillates with a frequency given by the mass of the new particles.

This is the analog of the resonances in collider physics.

Arkani-Hamed and Maldacena [2015]
Arkani-Hamed, DB, Lee and Pimentel [2018]

Cosmological Collider Physics

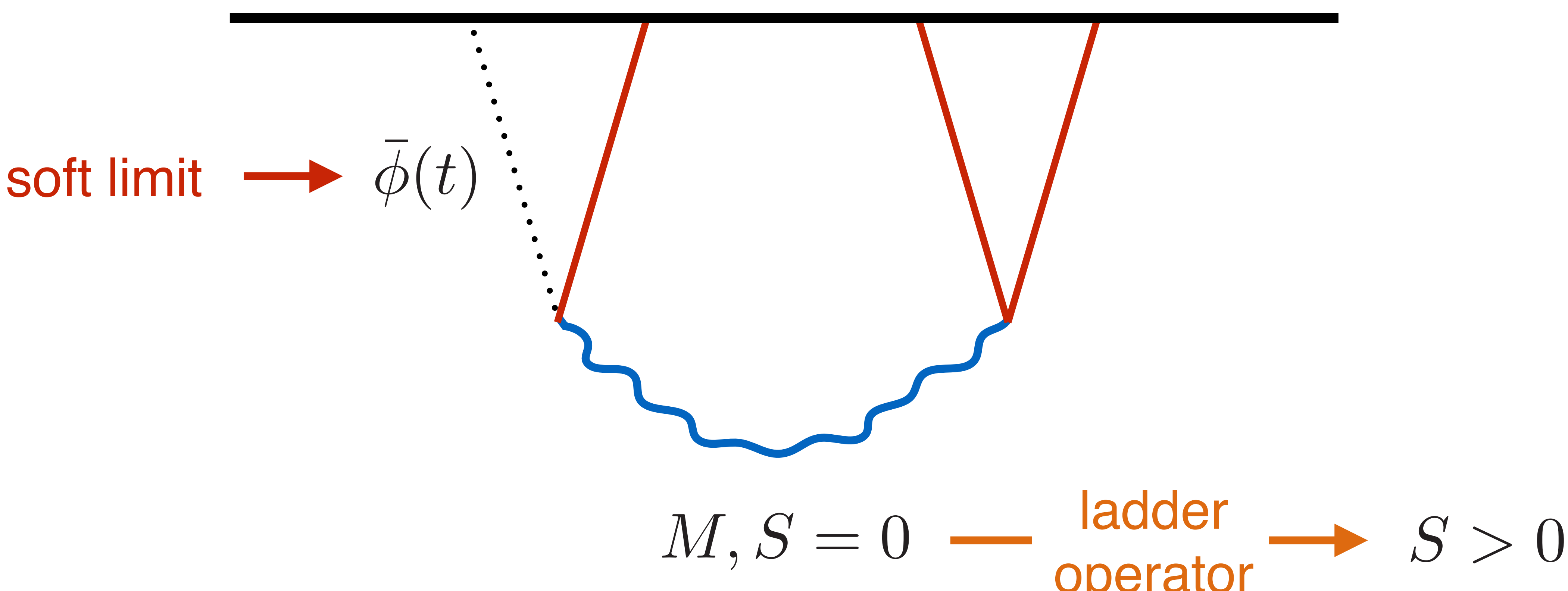


Arkani-Hamed, DB, Lee and Pimentel [2018]

Summary and Outlook

Summary

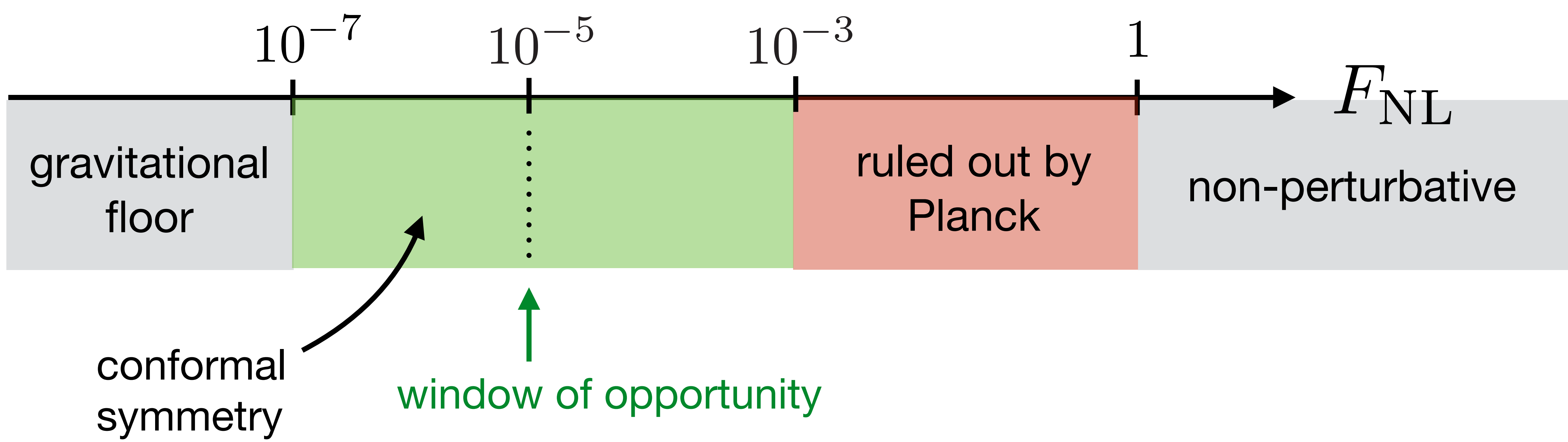
We derived the most general 3-pt and 4-pt functions arising from massive particle exchange in inflation:*



* In the regime of weakly broken conformal symmetry.

Summary

The signals described in this talk will be hard to observe:

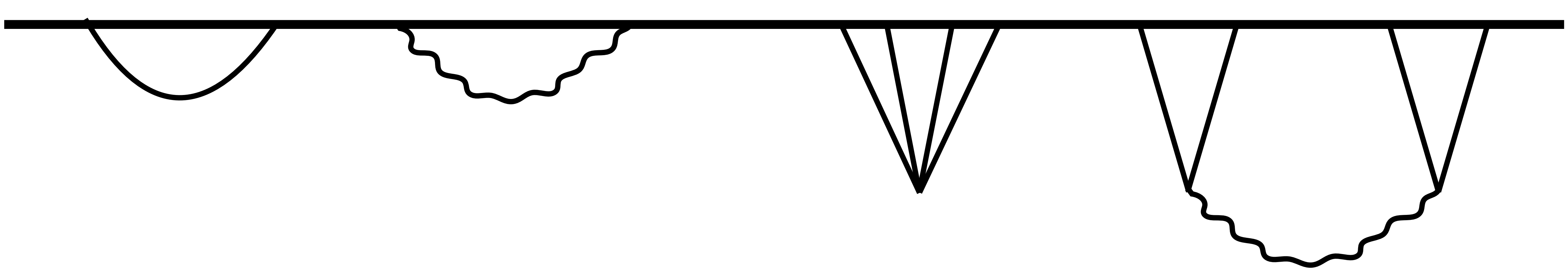


Having said that, their detection would be a **direct** probe of the UV completion of inflation (SUSY, strings, …)

Outlook

We hope that our improved analytic understanding of the inflationary correlators will allow us to answer questions like:

- How is **unitarity** of the bulk evolution encoded in the boundary?
- Does this lead to new **positivity** constraints on the EFT?
- What does this imply for the **ultraviolet completion** of inflation?



Thank you for your attention!

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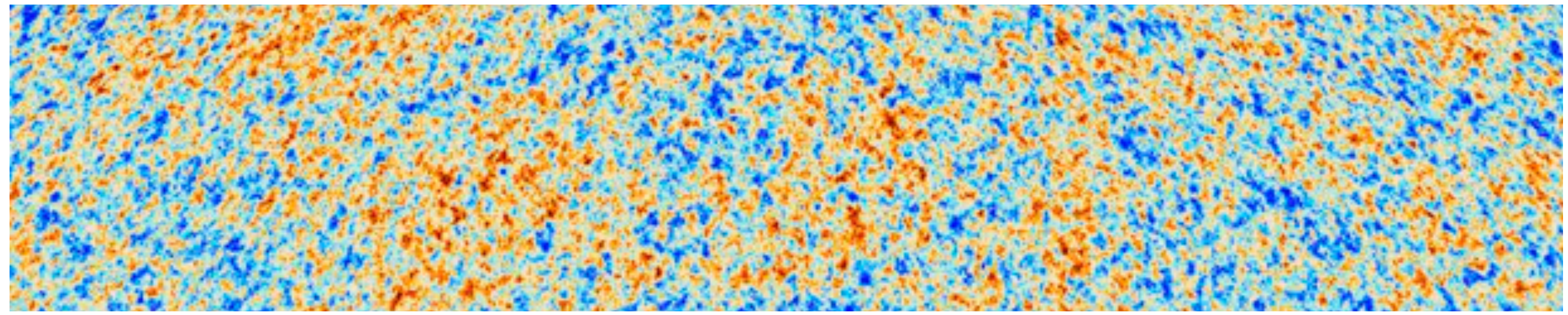
Lessons from the Past



“I did not continue with studying the CMB, because I had trouble imagining that such tiny disturbances to the CMB could be detected ...”

Jim Peebles

$$n_s = 0.960 \pm 0.007$$

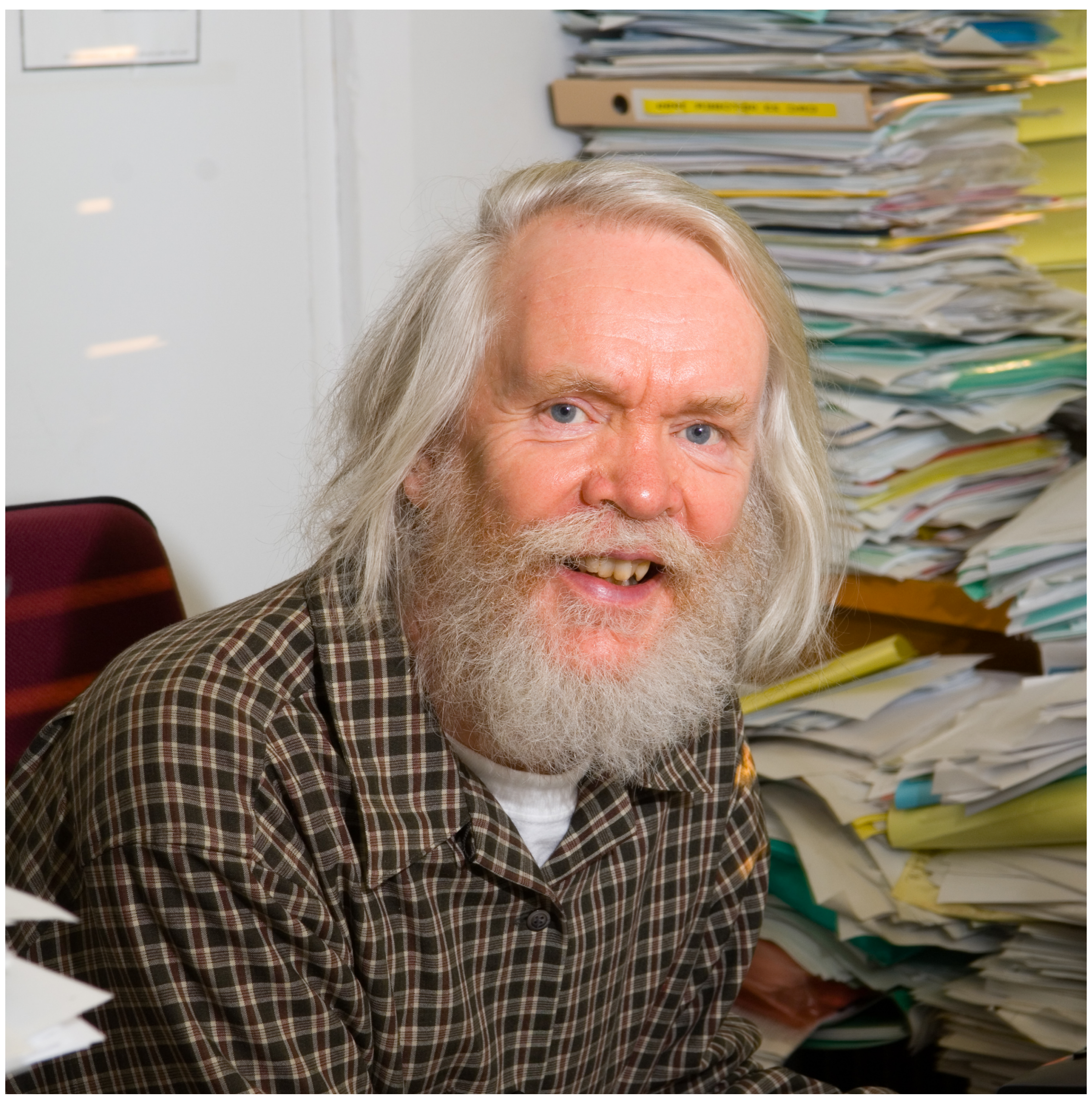
“I thought that it would take 1000 years to detect the logarithmic dependence of the power spectrum.”

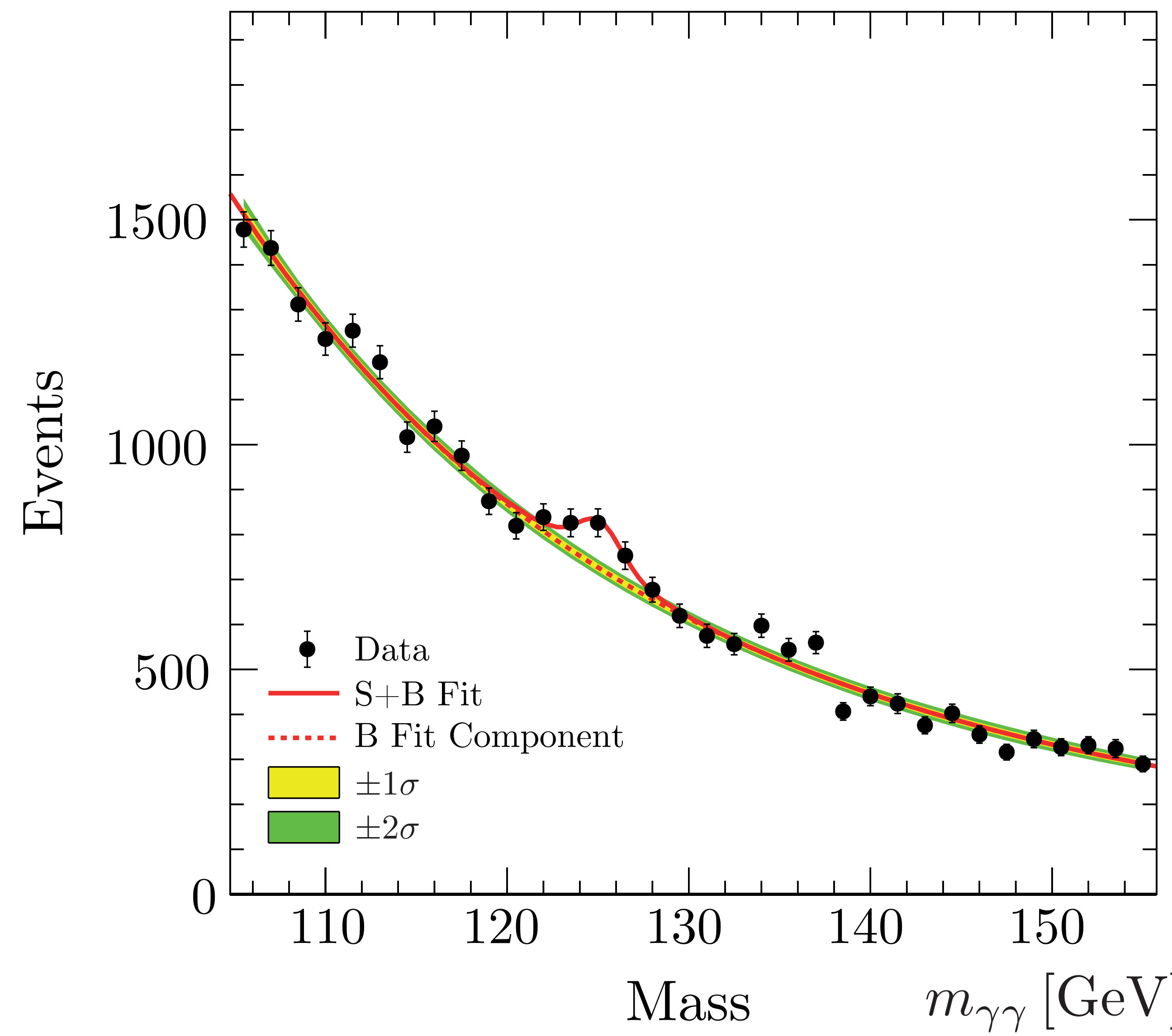
Slava Mukhanov

Lessons from the Past

"We apologise to experimentalists for having no idea what is the mass of the Higgs boson and for not being sure of its couplings to other particles. For these reasons we do not want to encourage big experimental searches for the Higgs boson, …"

Ellis, Gaillard and Nanopoulos





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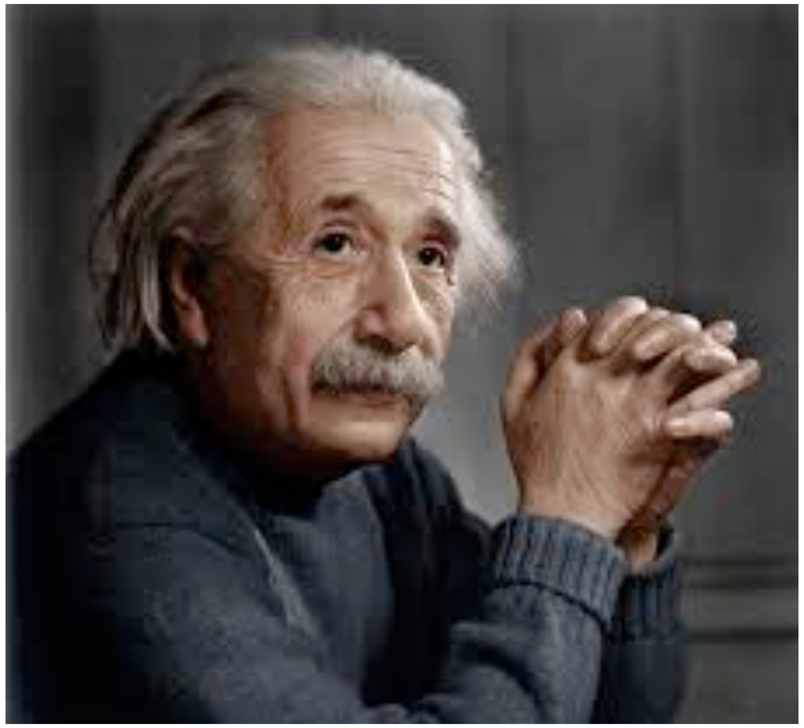

“I arrived at the interesting result that gravitational waves do not exist, …”

Einstein, in a letter to Born