Cosmological Correlators

Theory and Phenomenology

Guilherme L. Pimentel

Scuola Normale Superiore and INFN

INFN PISA

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Collaborators

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Disclaimer

No references!

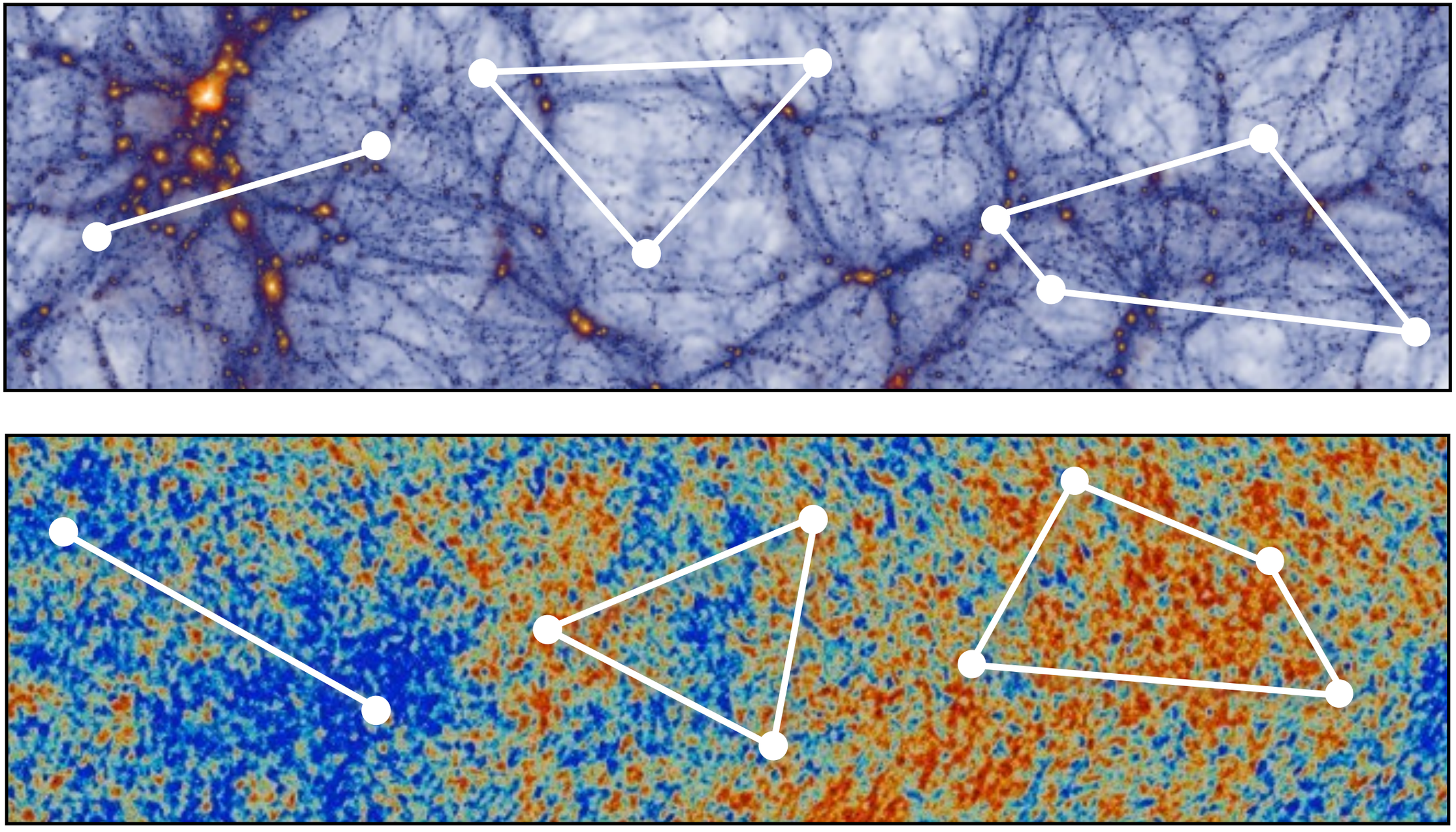
"I do not give many references in this book (…). The reason is that although to study the history of physics and to distribute credits is an interesting enterprise, I am not yet prepared for it." **Polyakov 87**

But for now…

Overview: Joy of Cosmological Correlators
Lectures: LACES 2024
Snowmass: Inflation, Cosmological Bootstrap

What is the origin of structure in the universe?

Cosmological Correlators



All of the information about the **origin of structure** and the dynamics of the early universe is encoded in cosmological correlations!

I will show that the early universe is a collider experiment run at enormous energies.

Cosmological correlators are the scattering amplitudes of this experiment.

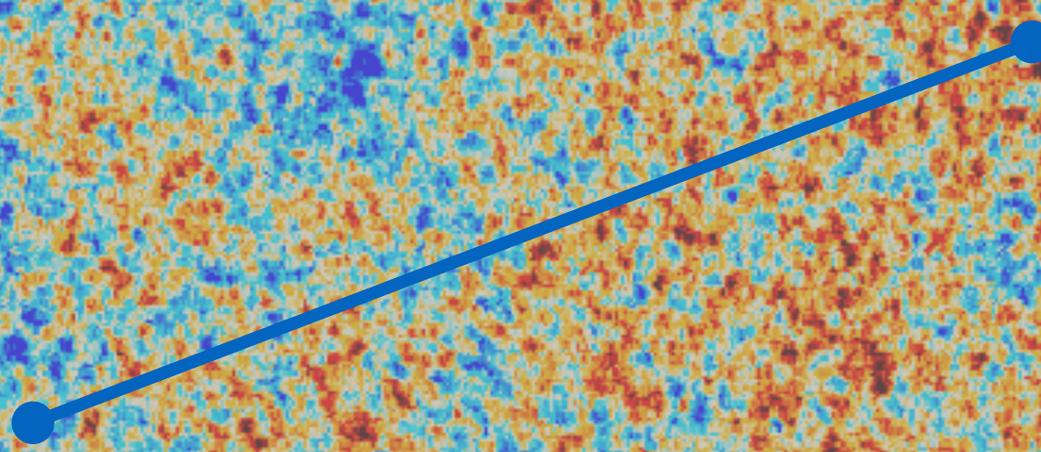
Many novel methods to compute and decode cosmological correlators are under development right now, drawing from other areas of physics.

These methods are practically useful, and conceptually necessary.

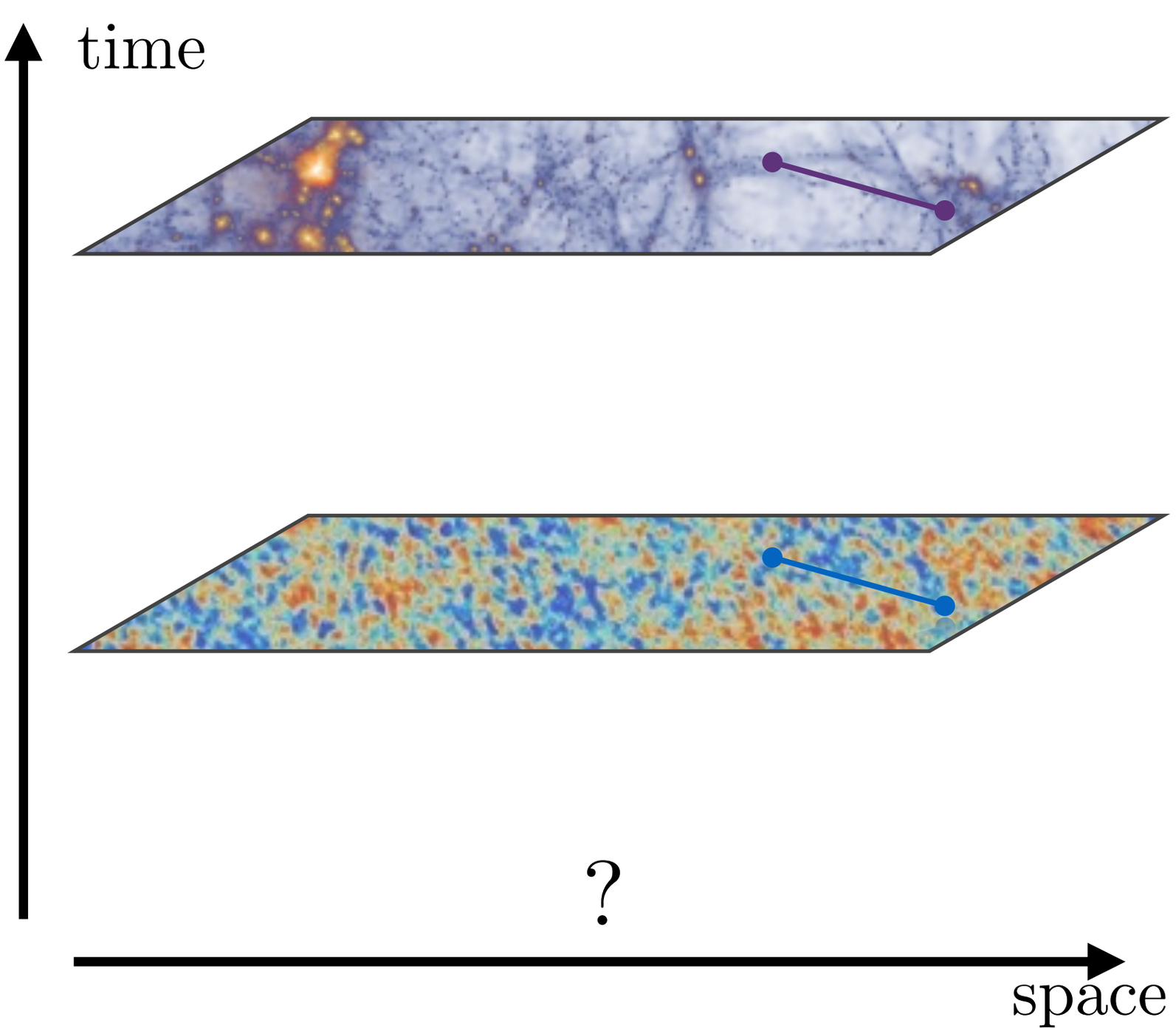
Speculation: there is a timeless description of the correlators within their kinematic space.

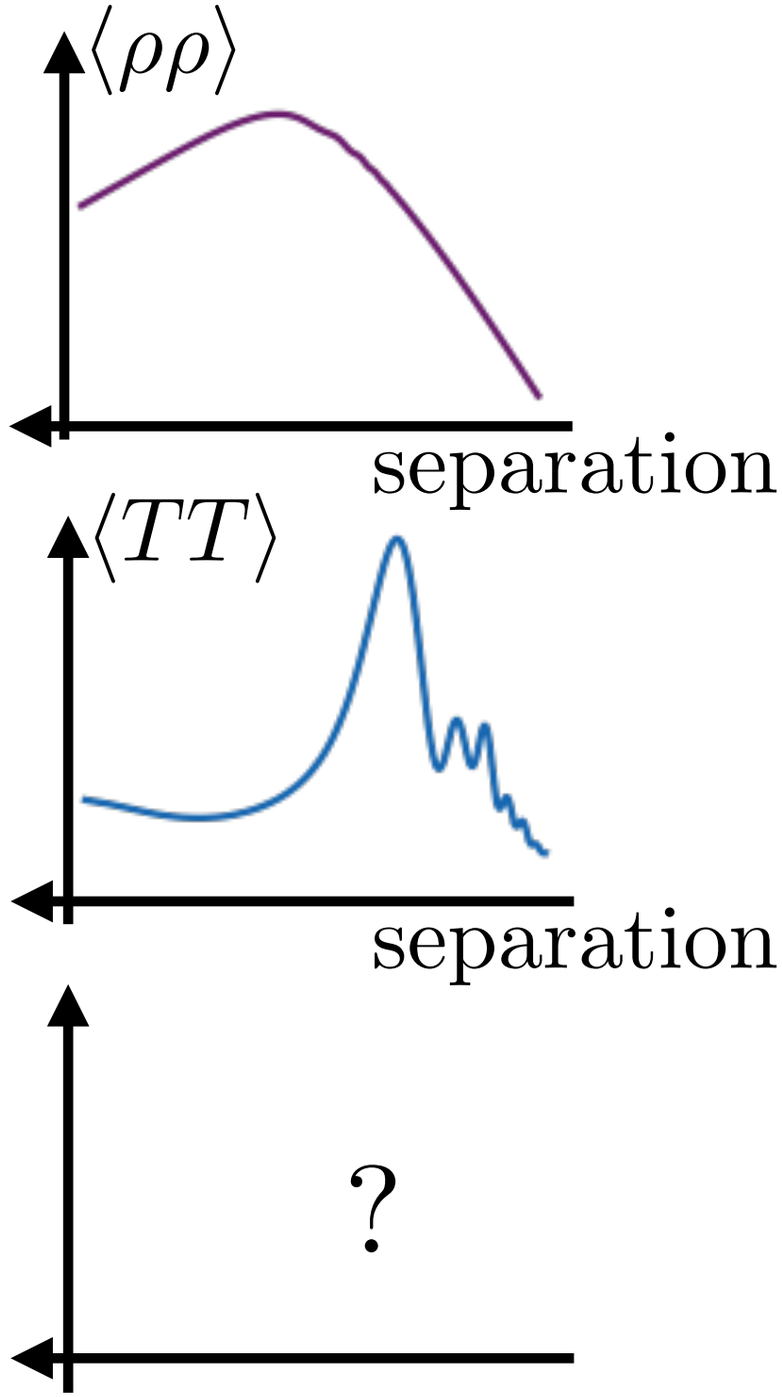
Density Correlations

Temperature Correlations

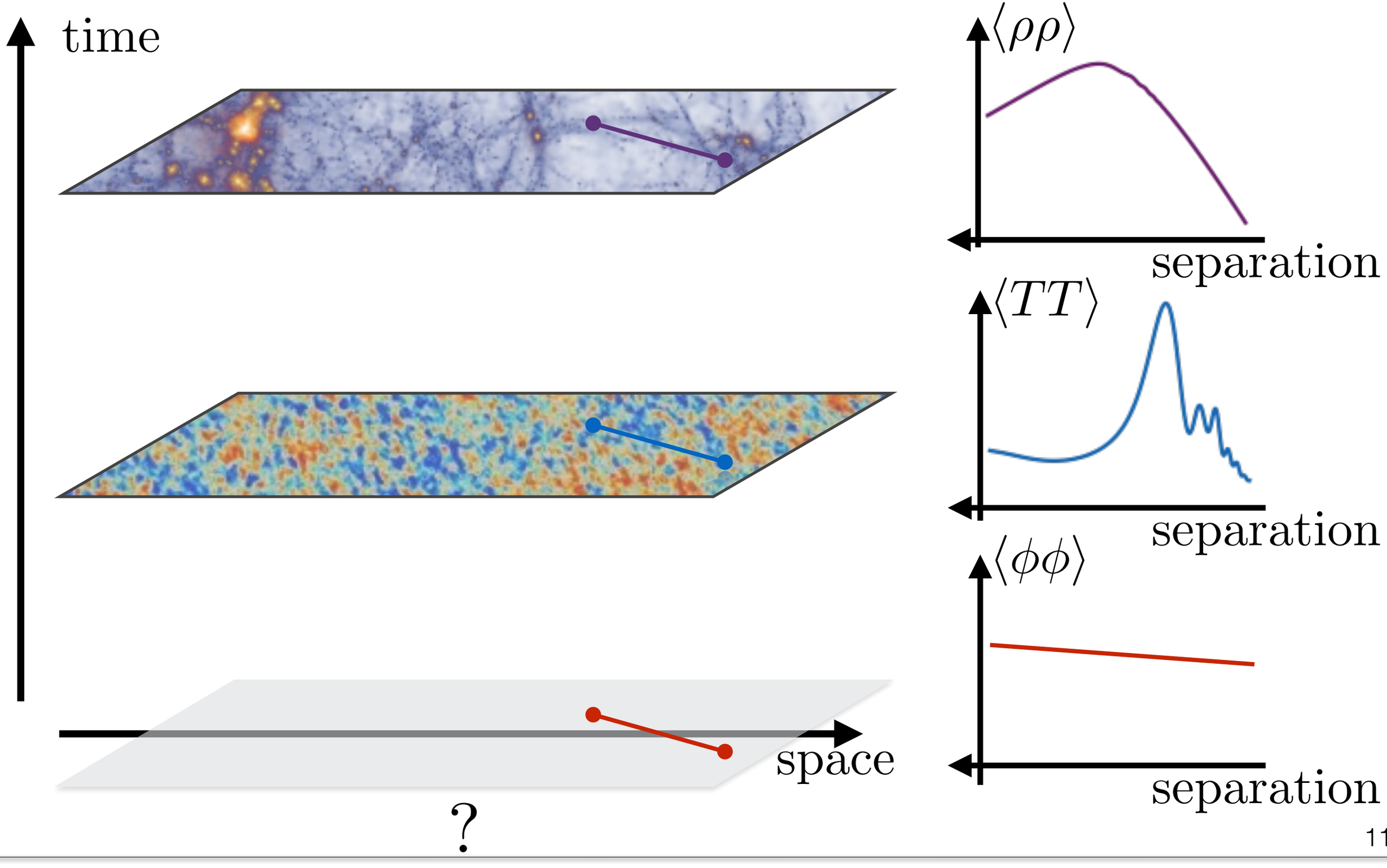


Inference


time
space
?


$\langle \rho\rho \rangle$
separation
$\langle TT \rangle$
separation
?

Primordial Fluctuations

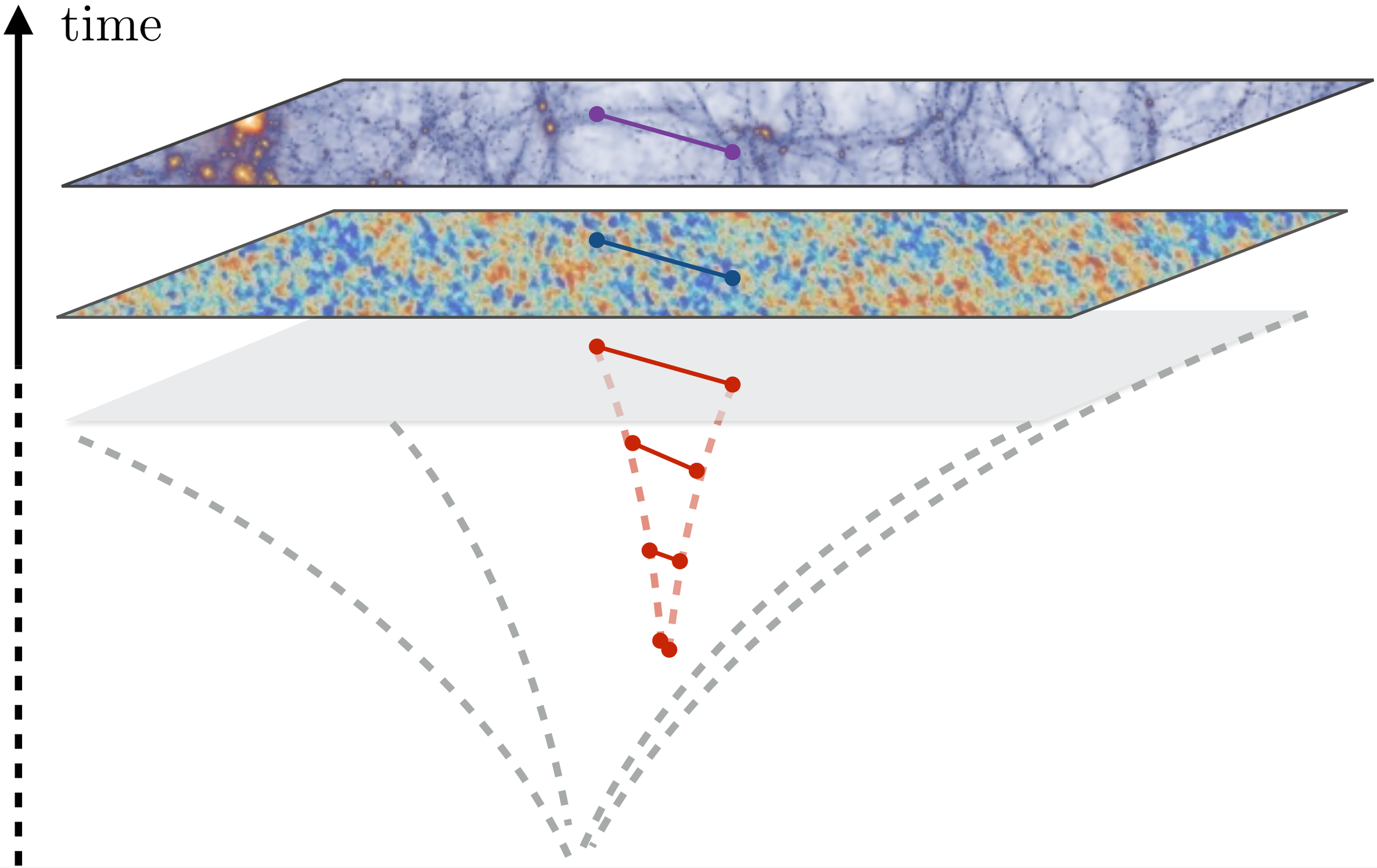


Superhorizon Fluctuations

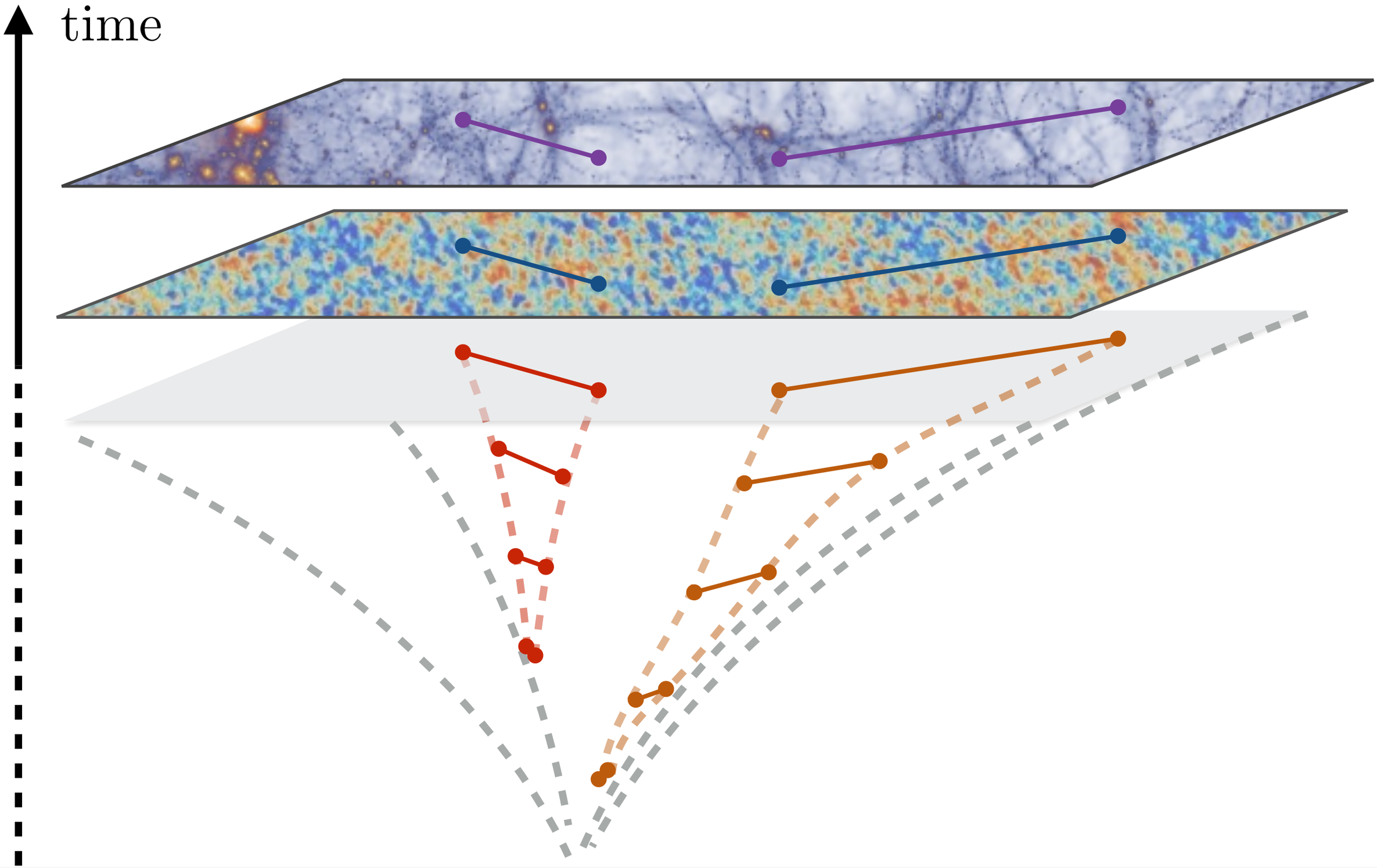
How did fluctuations become correlated over superhorizon distances?

Planck Collaboration

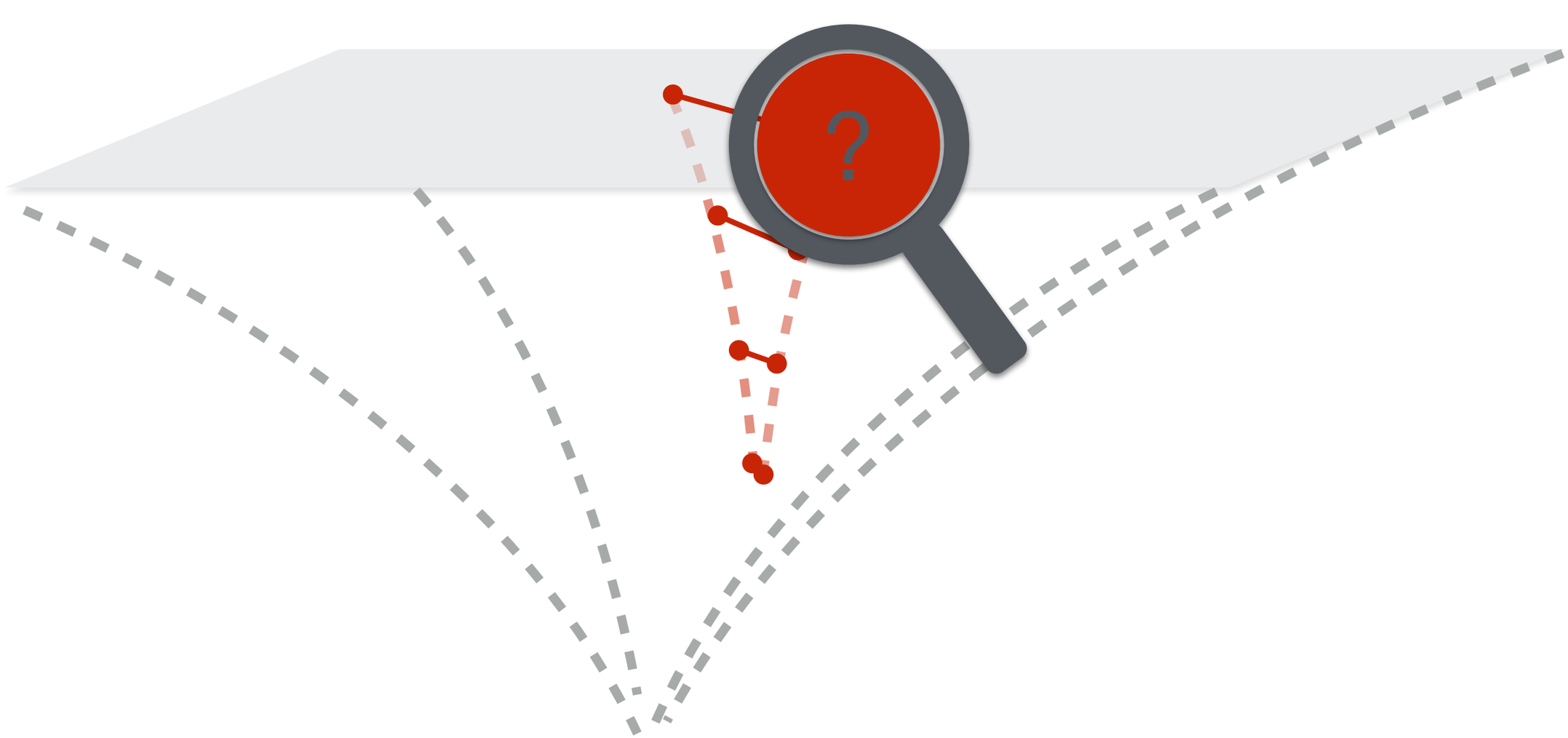
Inflation



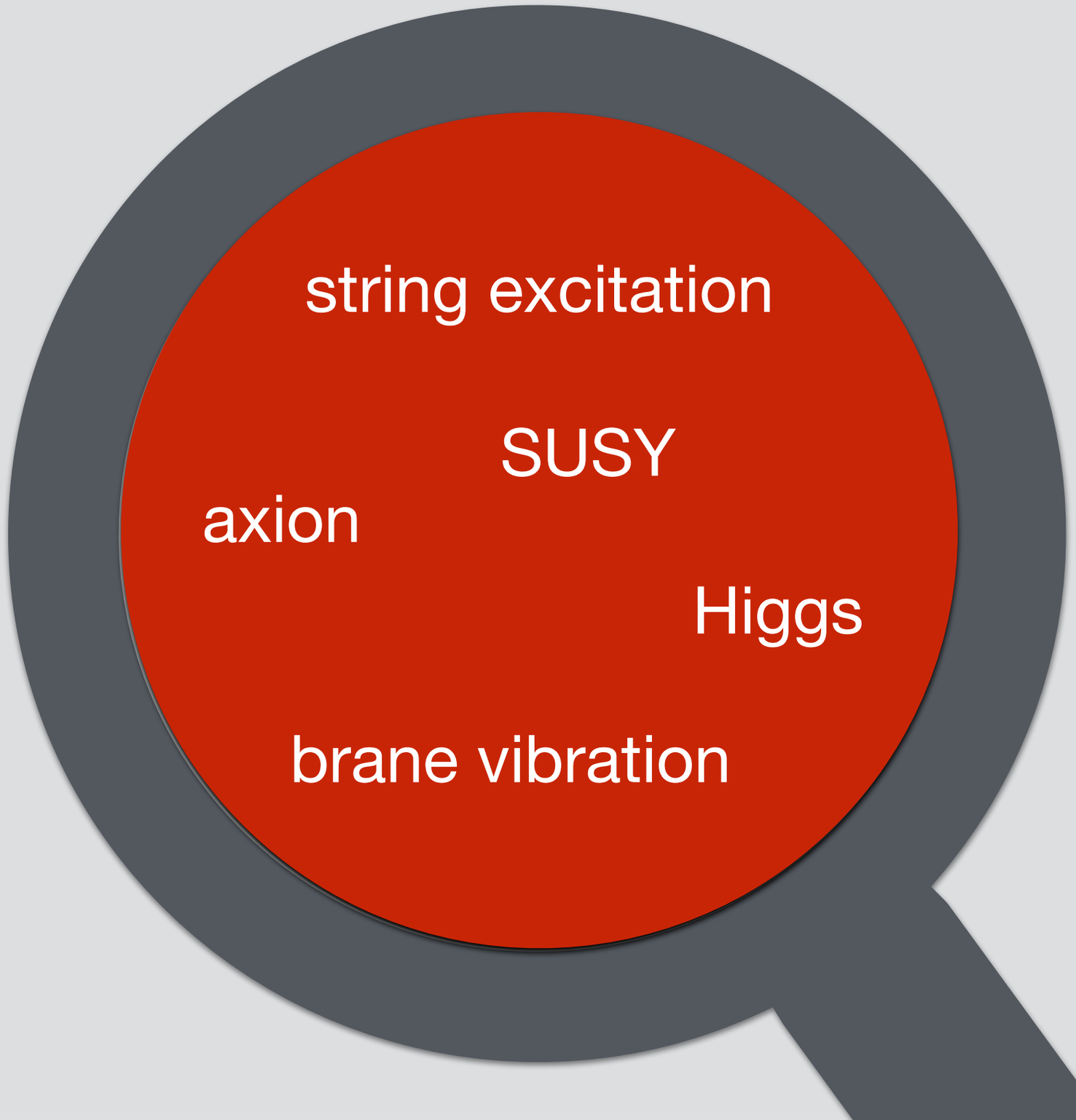
Time without Time



Inflaton ?

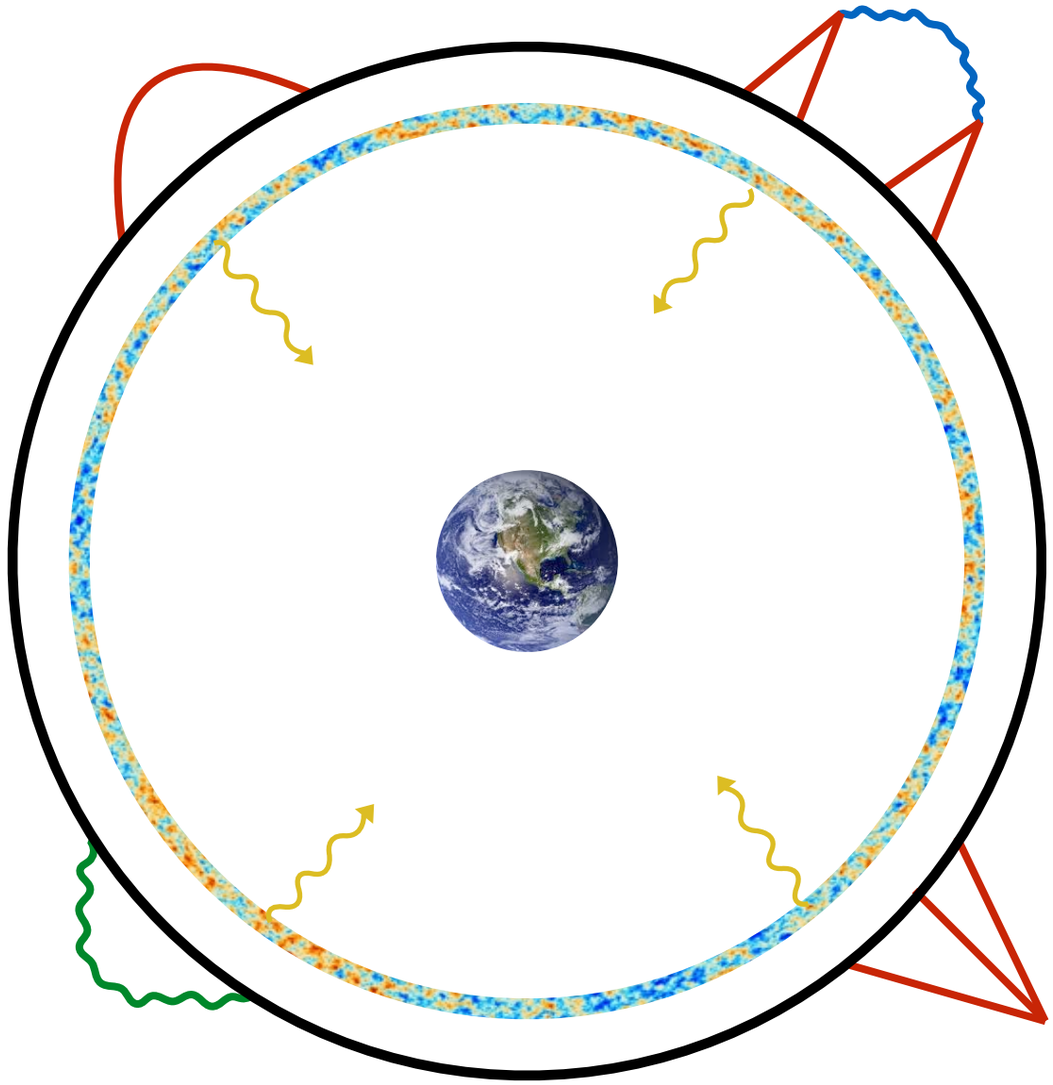


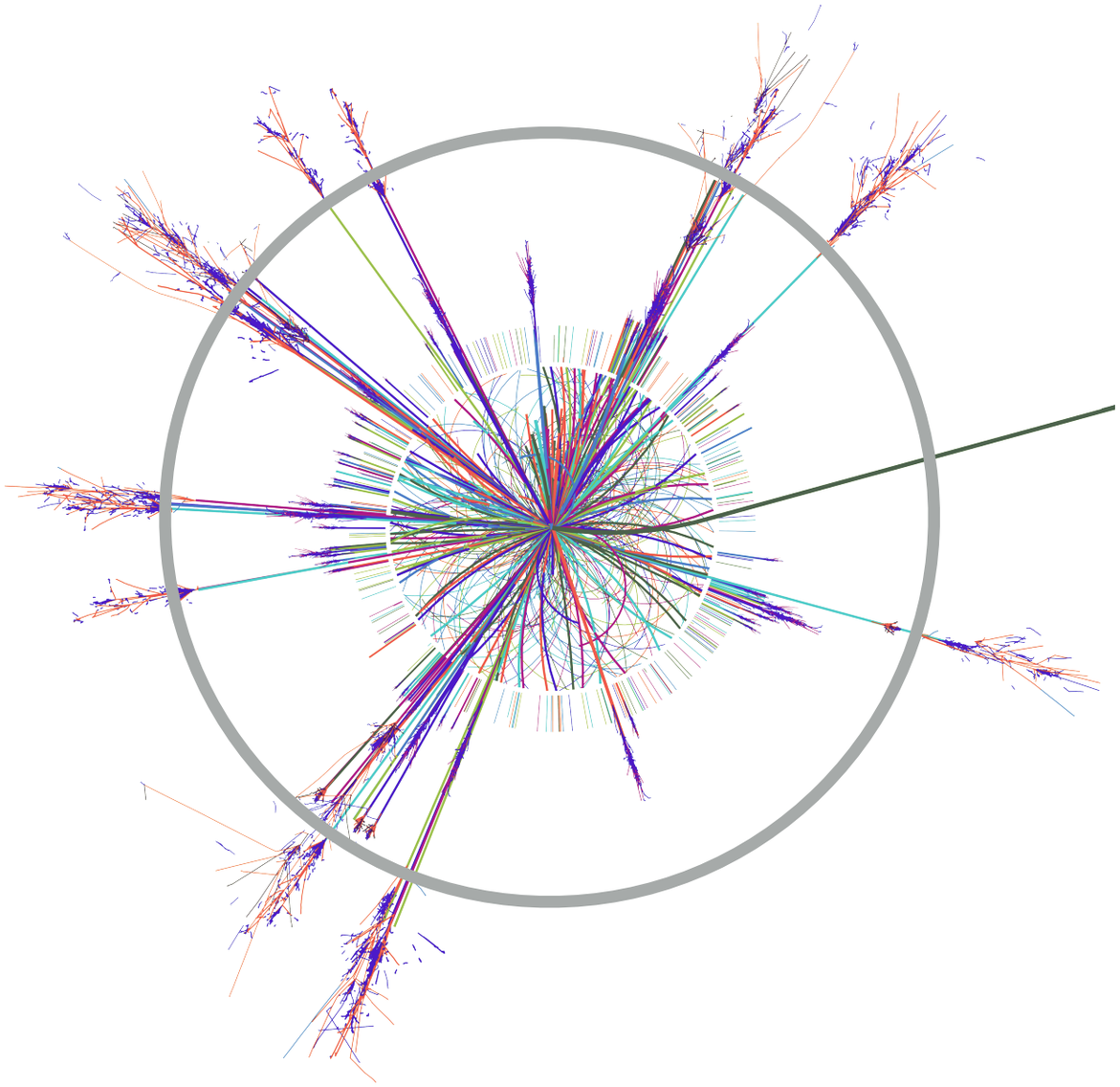
Inflationary Microscopy



Inflation as a Collider

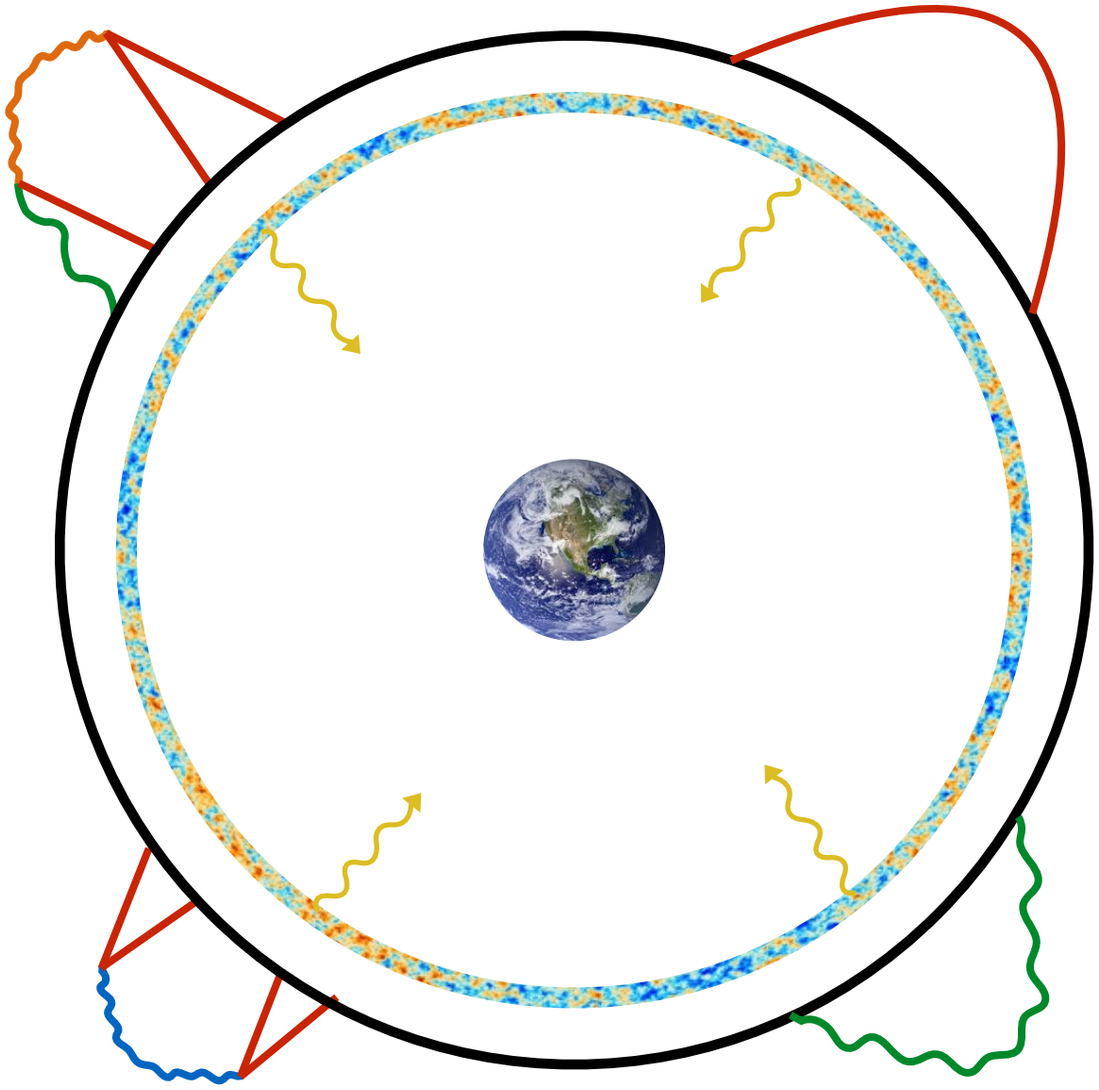
Inflation is most energetic event in nature, perhaps (LHC x billions)!

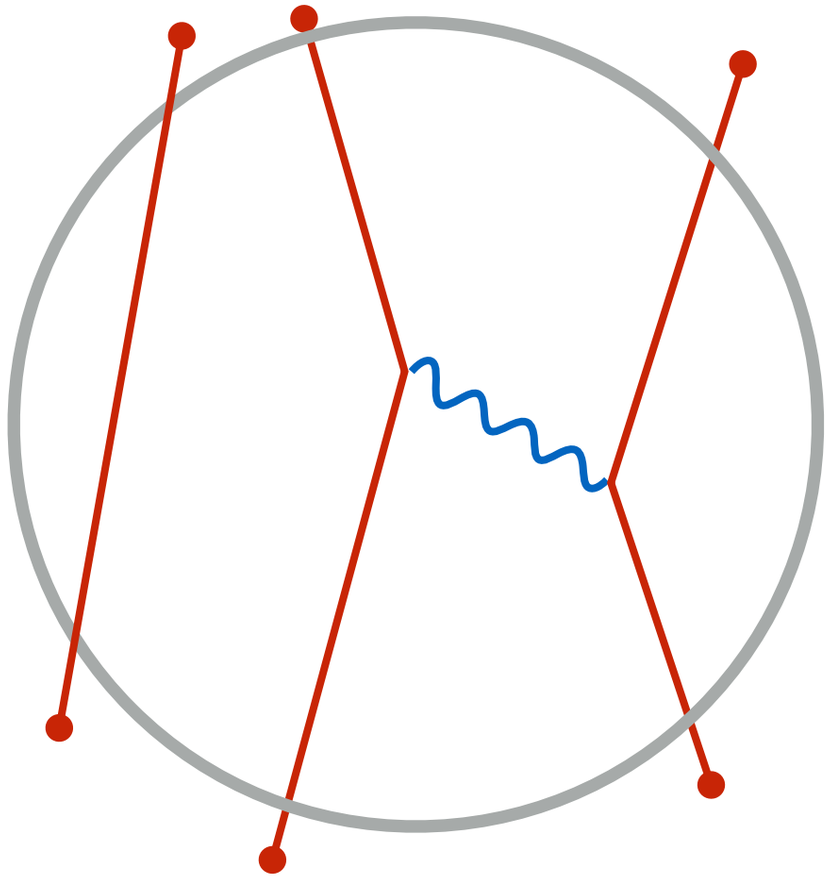




The early universe acts as a **particle accelerator**!

What collides? How?



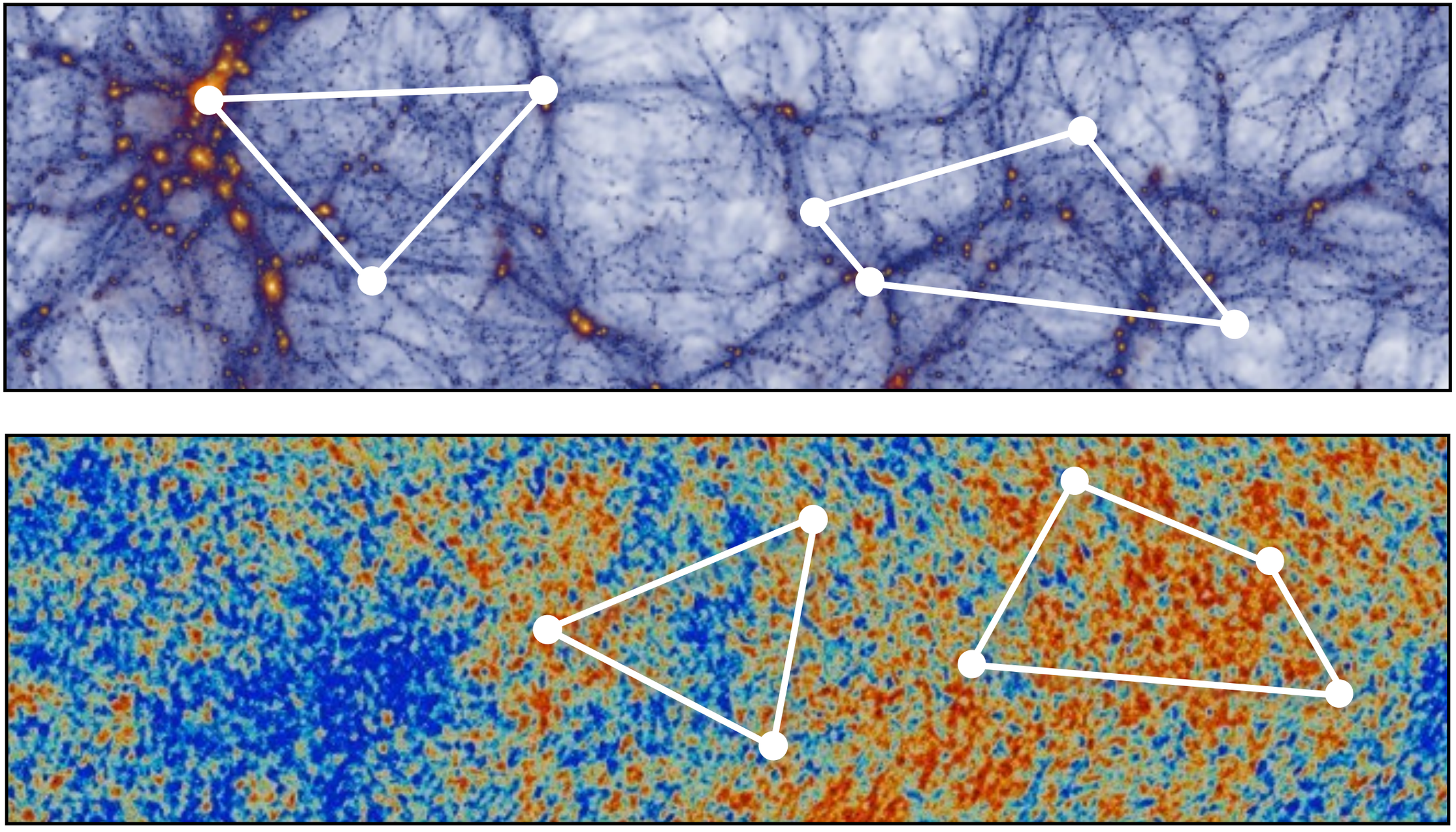


What — large two-point functions!

How — Higher-point functions!

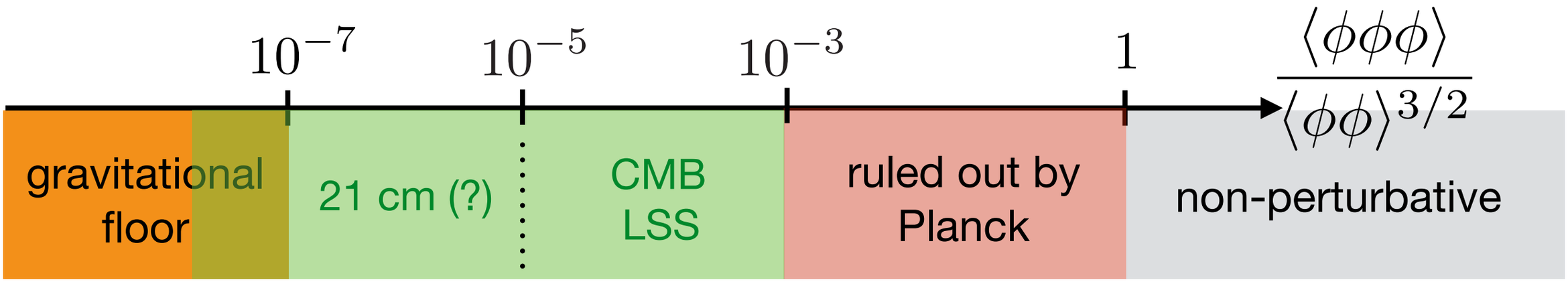
The dynamics is encoded in those correlations.

Cosmological Correlators



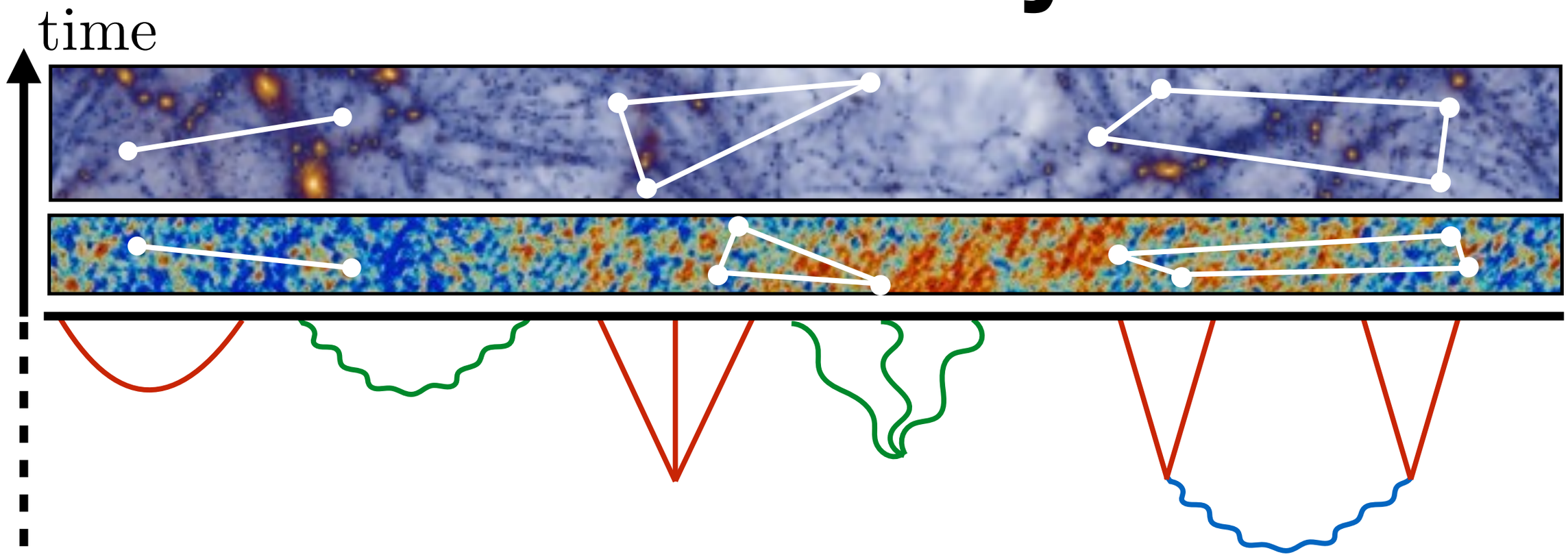
Scattering amplitudes in the sky!

How big is the signal?



We need **precise measurements**
& **precise theoretical predictions**!

Take Away



Fossils from the early universe
can be used as a unique particle detector.

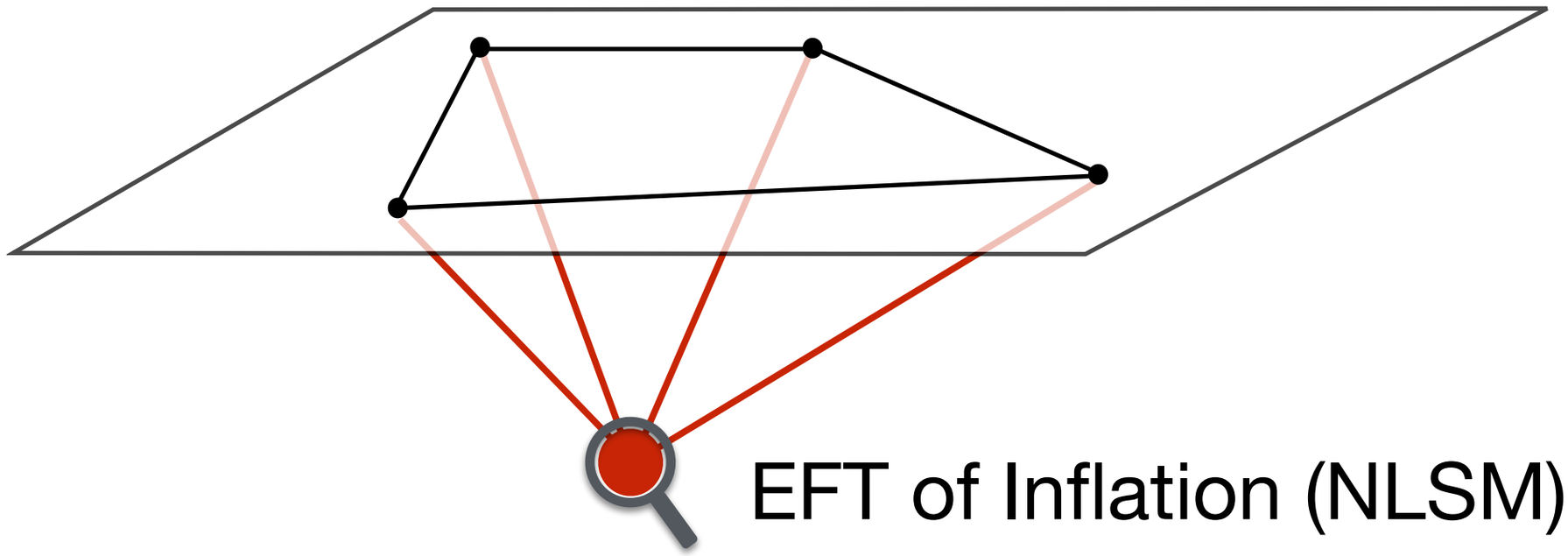
These particles produce cosmological correlators
which **encode** the dynamics of the early universe.

The Cosmological Bootstrap

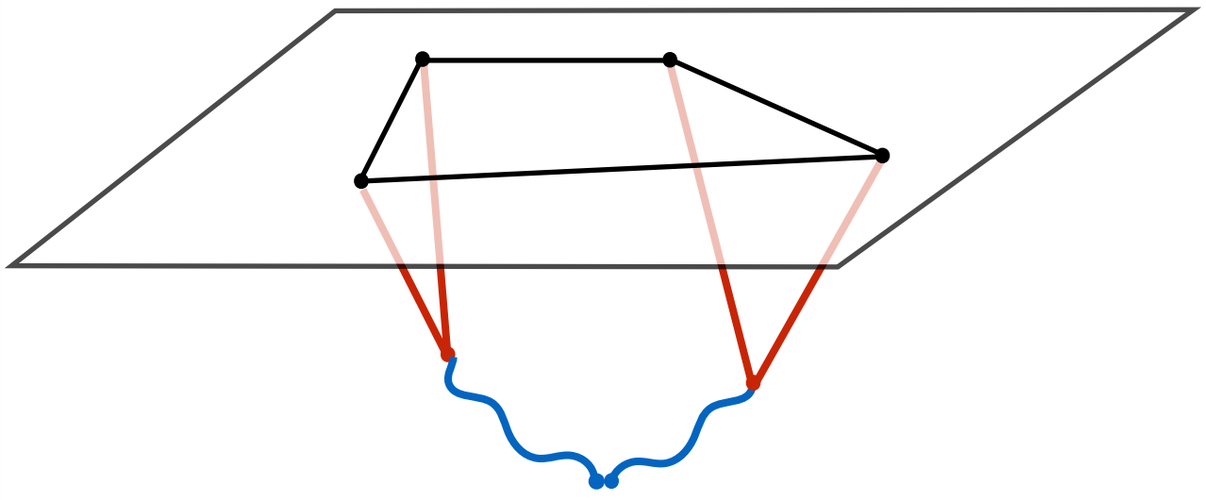
What are the possible correlators?

What do we learn about inflation?

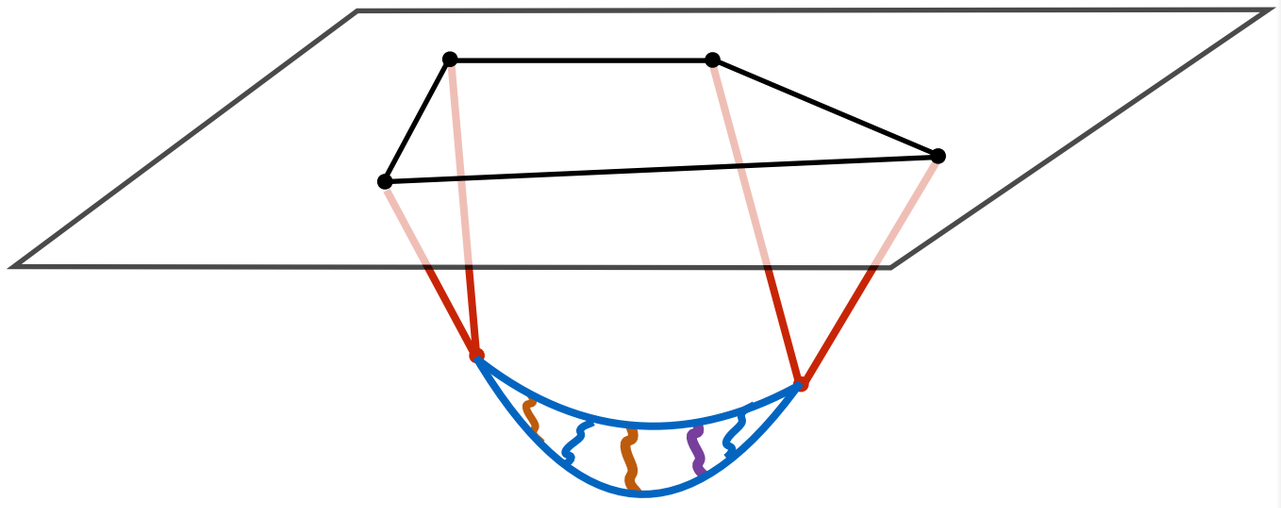
Under the Microscope



EFT of Inflation (NLSM)

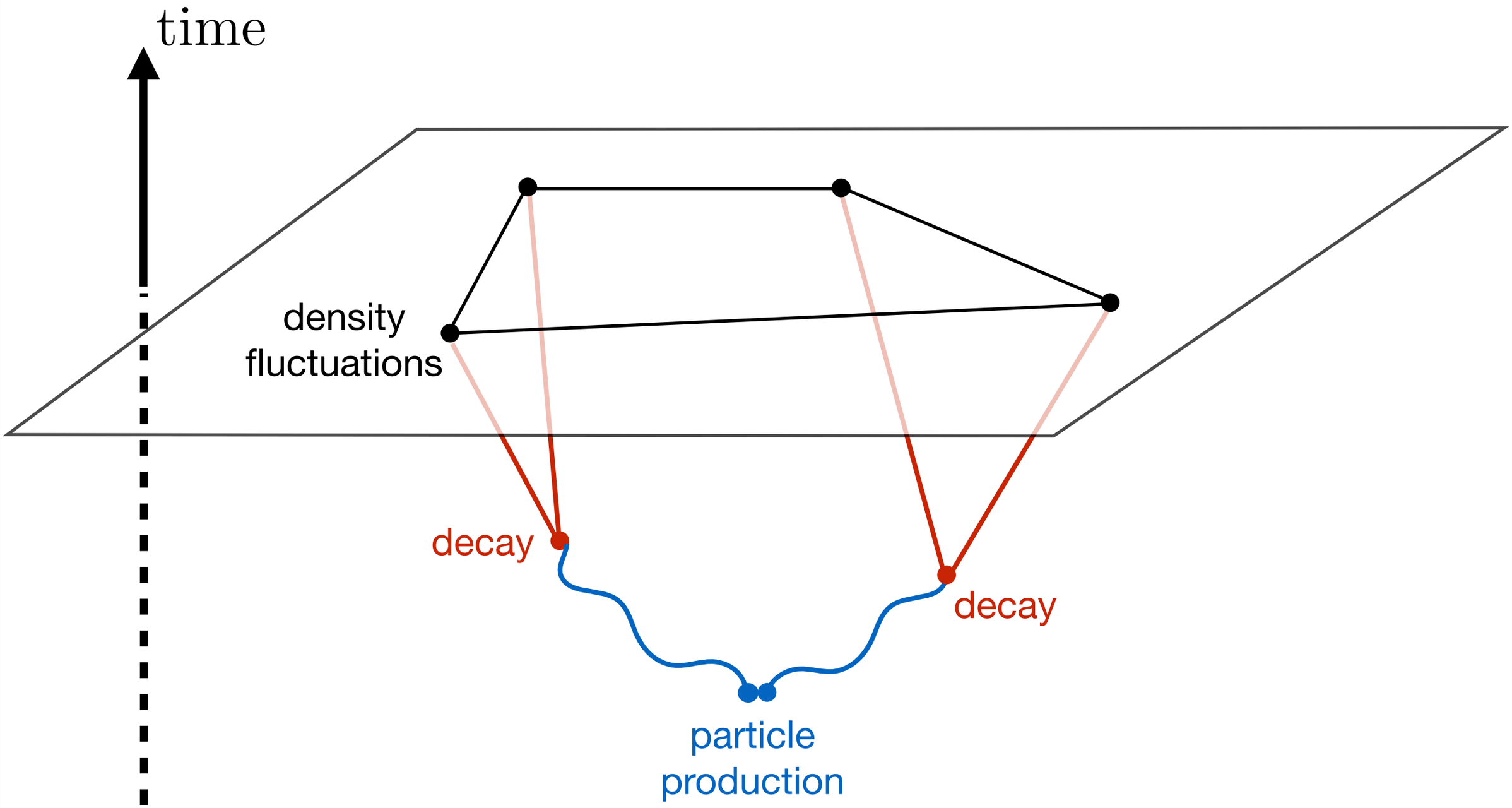


Weakly Coupled (EW)



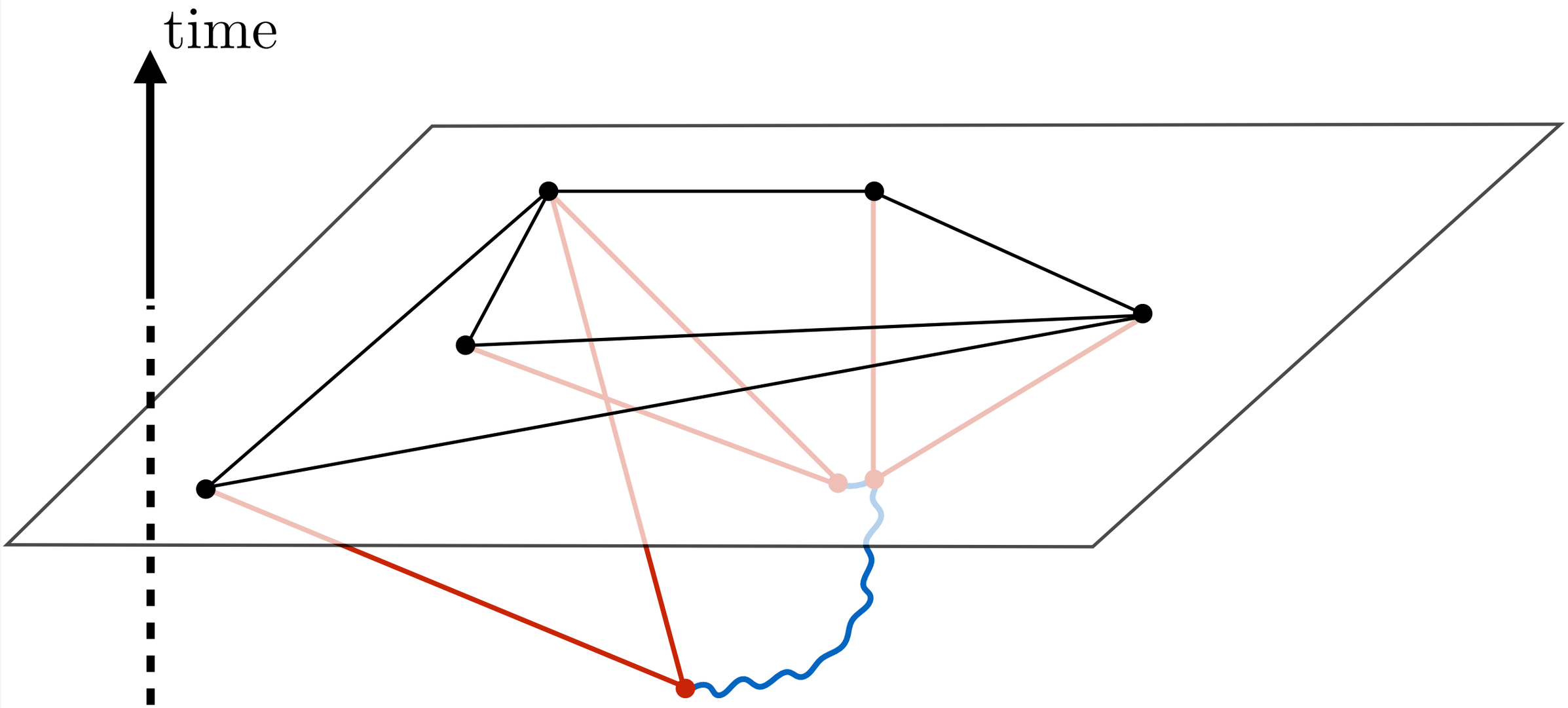
Strongly Coupled (QCD)

Structure of Correlator



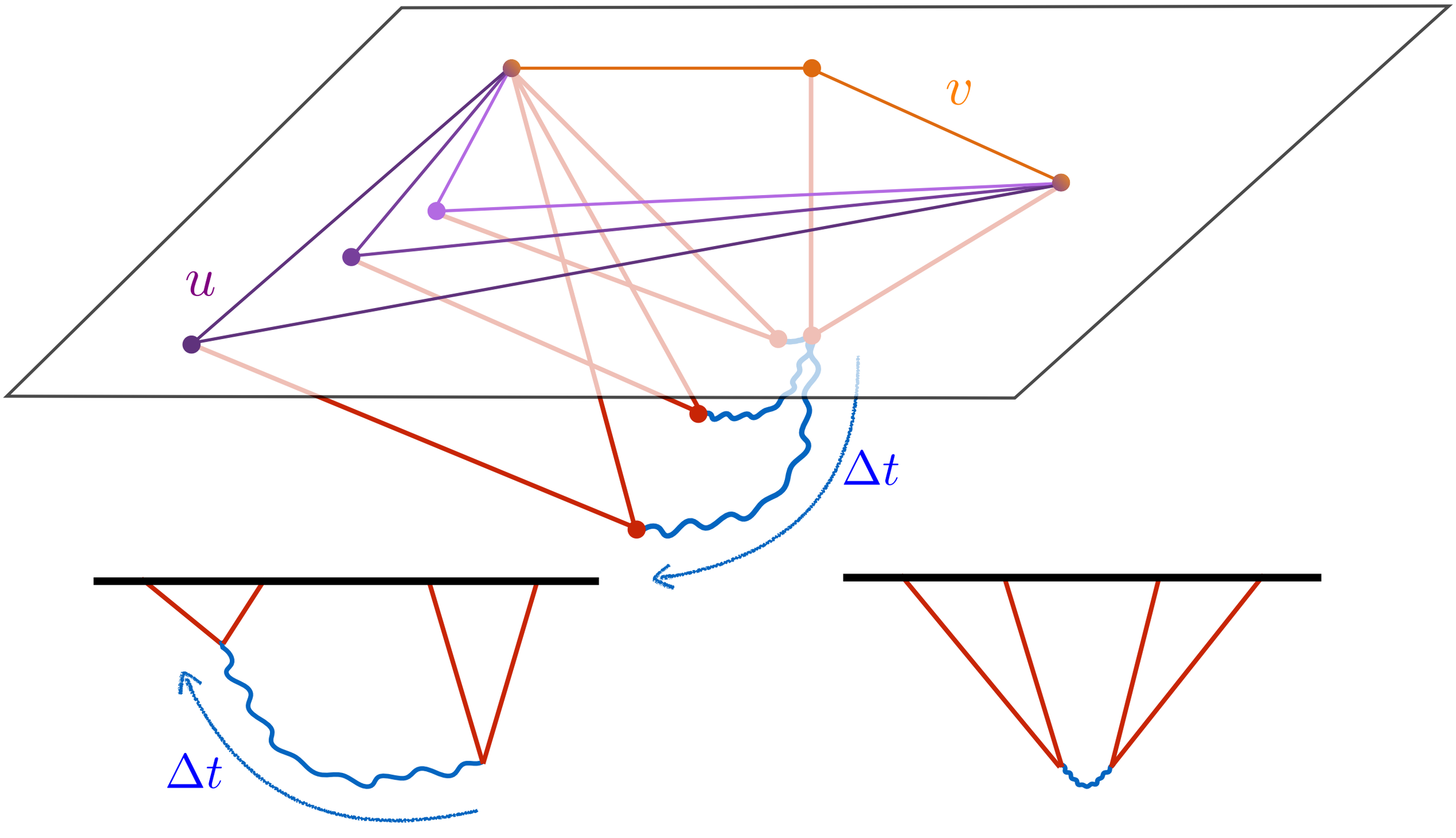
Inferring which particles are created
will tell us about the microphysics of inflation.

Particles as Tracers



The particle propagates in the inflationary background, tracing and imprinting it in the correlator, as we change the shape in the sky.

Kinematics



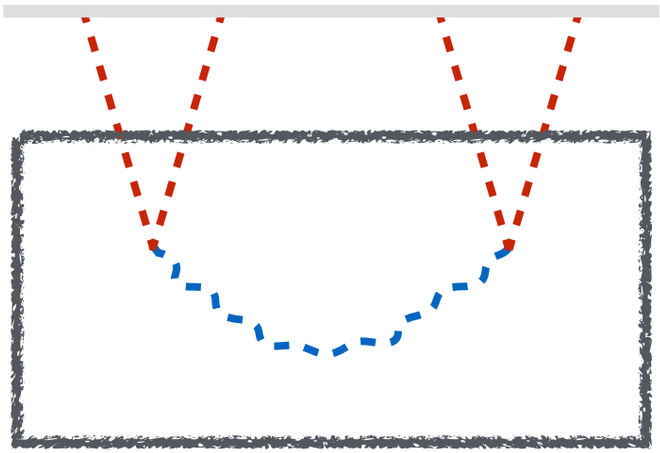
Particle Production

Contact Interaction

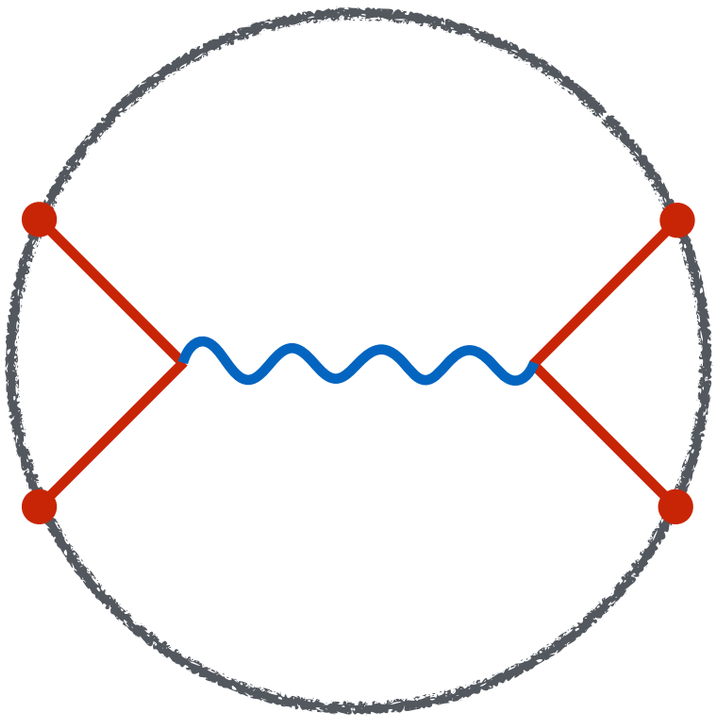
Singularities

$$u + v = E$$

$$\lim_{E \to 0}$$

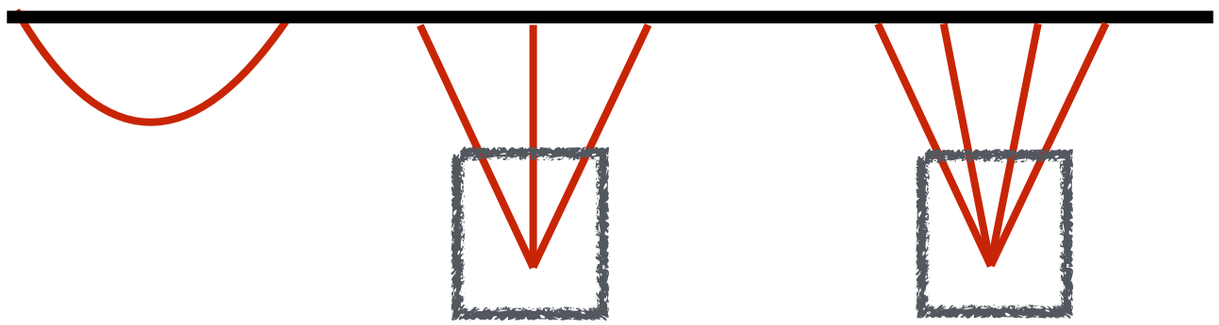


$$= \frac{1}{E\#}$$

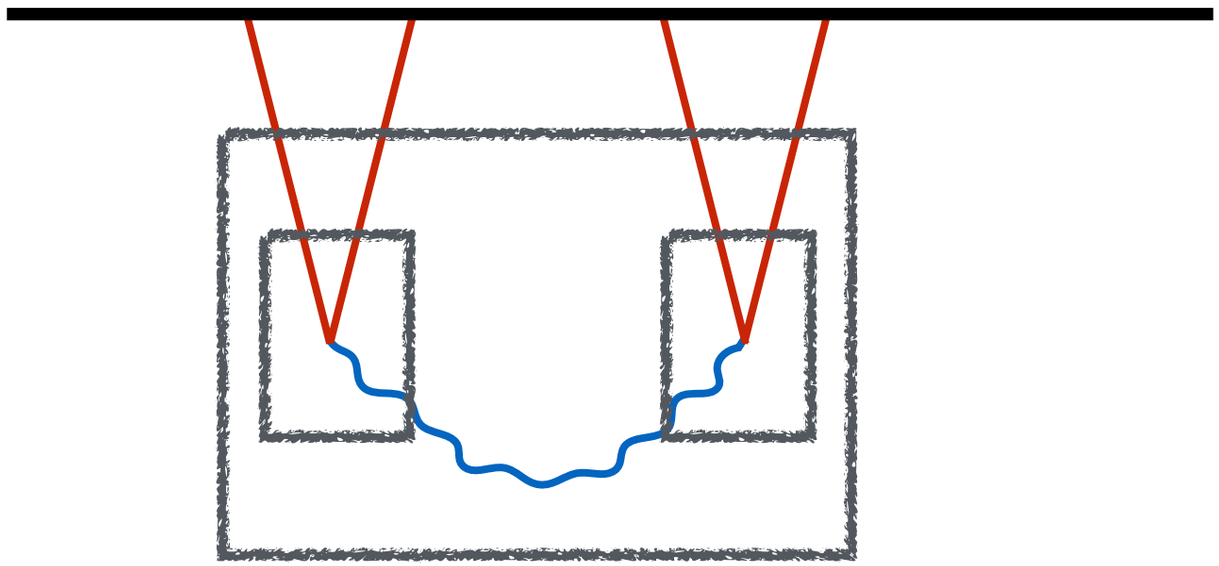


The S-matrix is **contained** in the
analytic structure of Cosmological Correlators!

Contact Dynamics



SYMMETRY +
ONLY E



SYMMETRY +
E, E_L, E_R

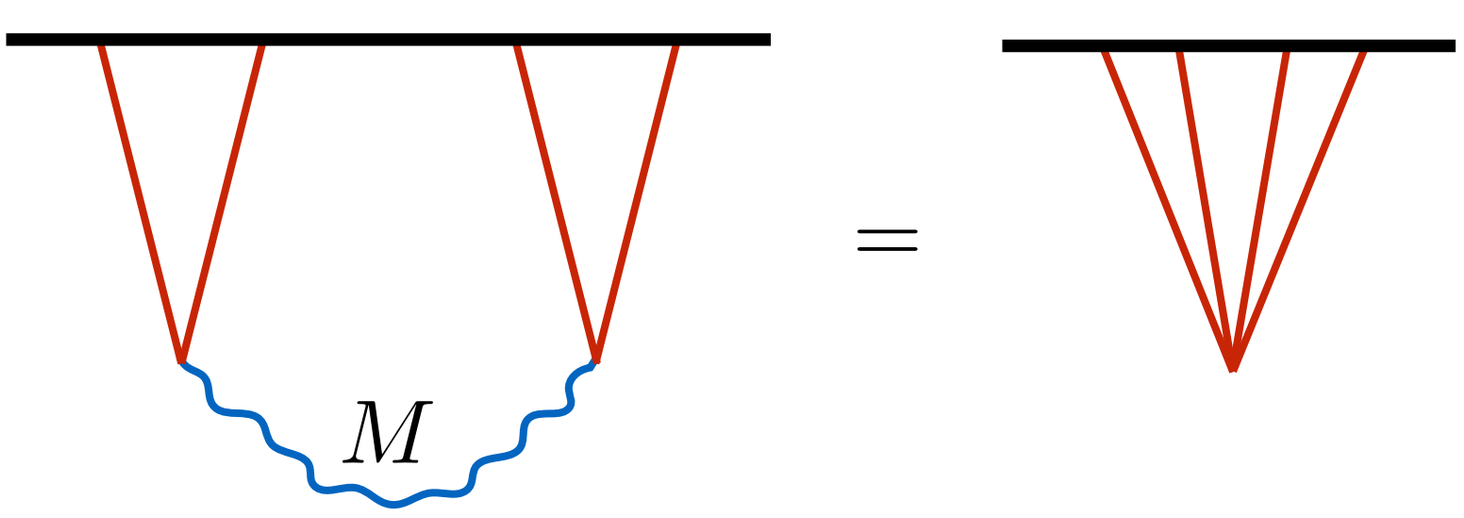
Exchange Dynamics

$$(\Delta_u + M^2)F = F_c$$

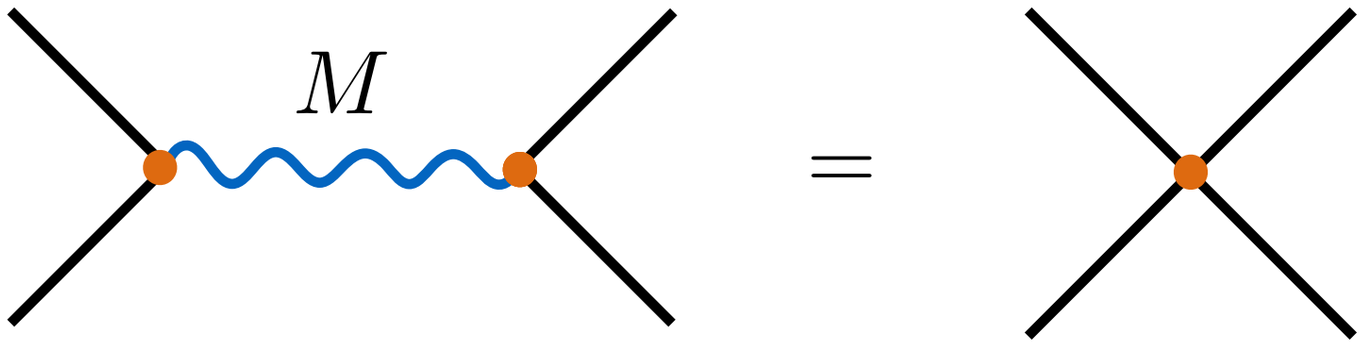
Contact correlator

Mass of exchanged particle

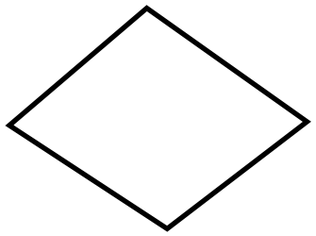
$(\Delta_u + M^2)$
$(\Delta_v + M^2)$

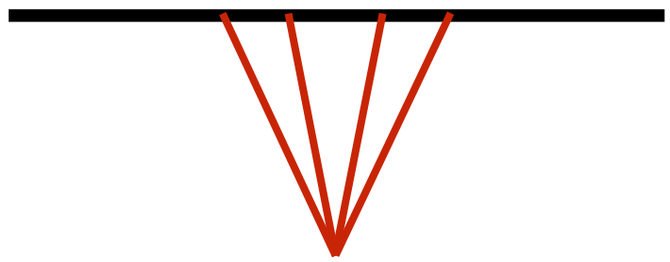


$(s - M^2)$

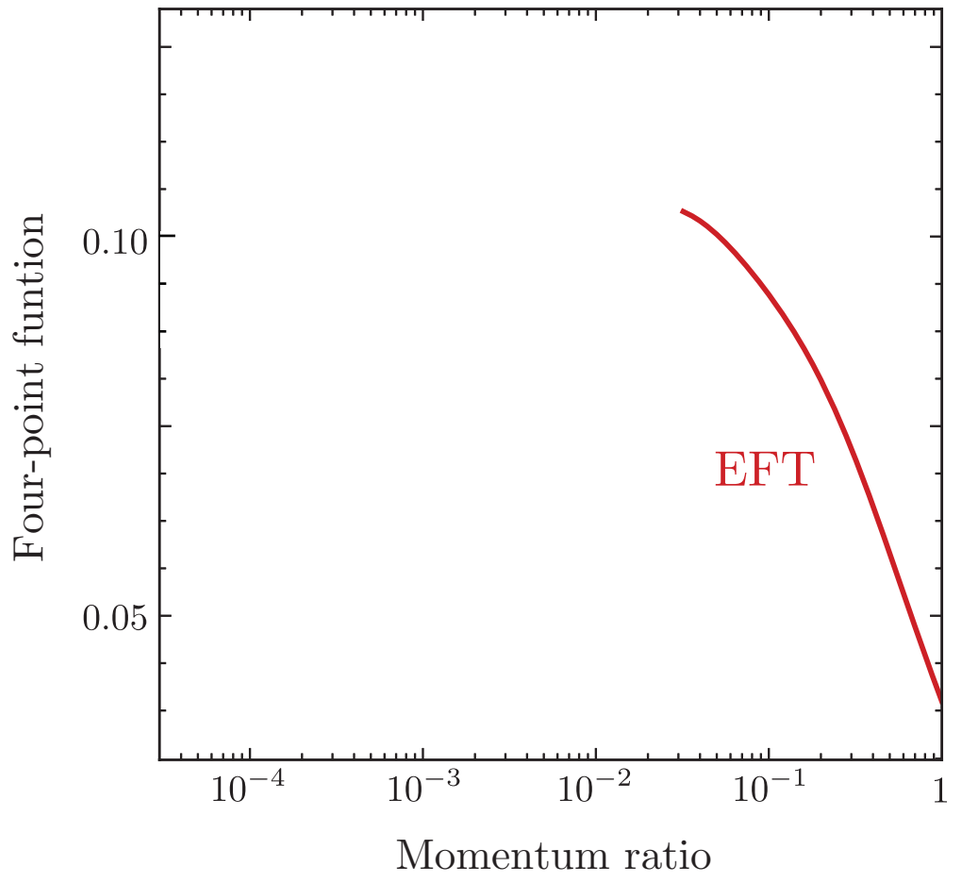


Cosmological Collider Physics

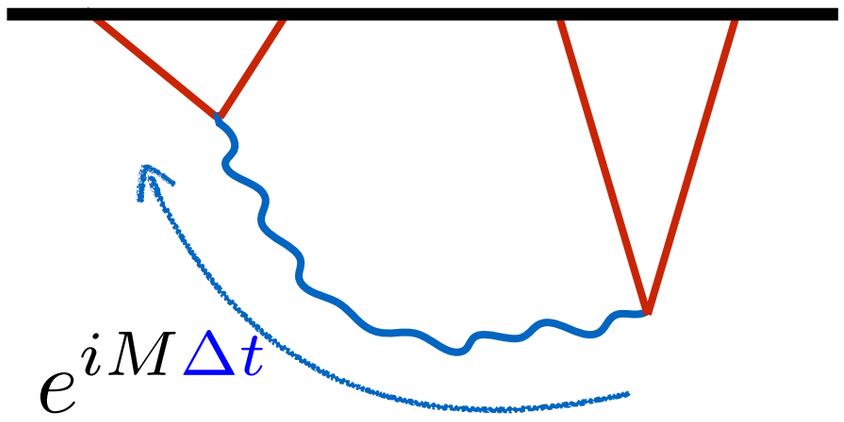


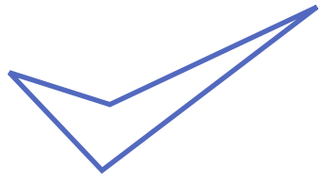


Equilateral (EFT)

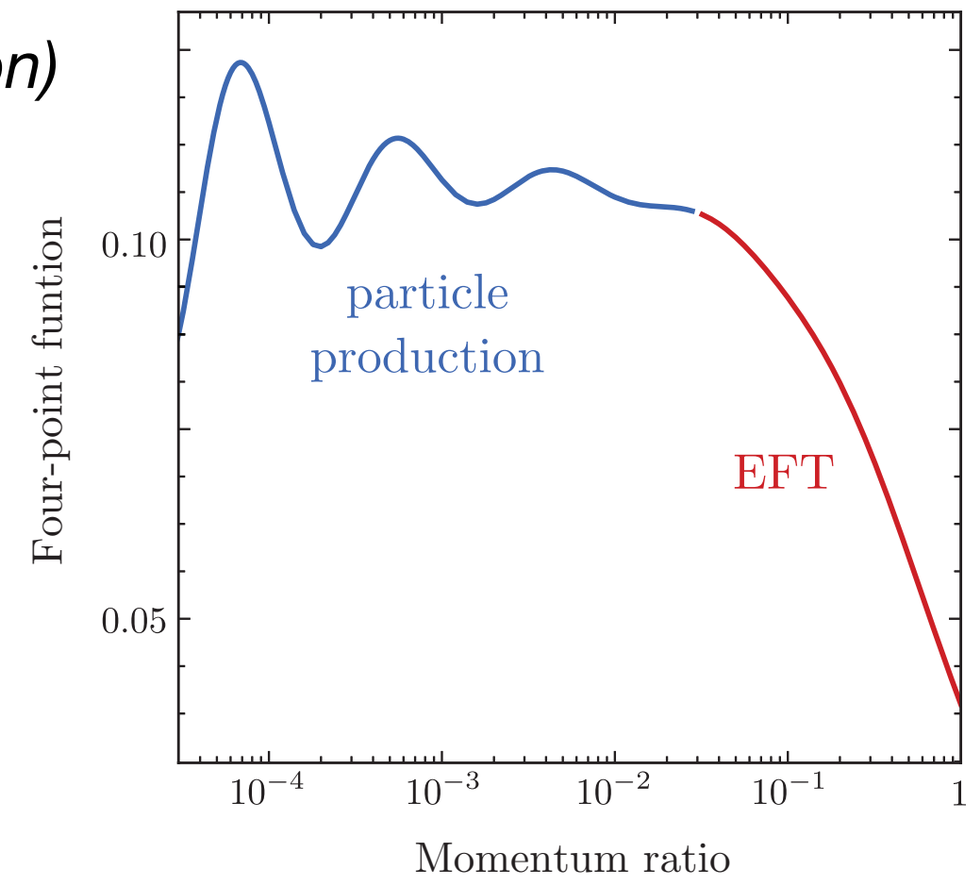


Cosmological Collider Physics





Collapsed
(particle production)



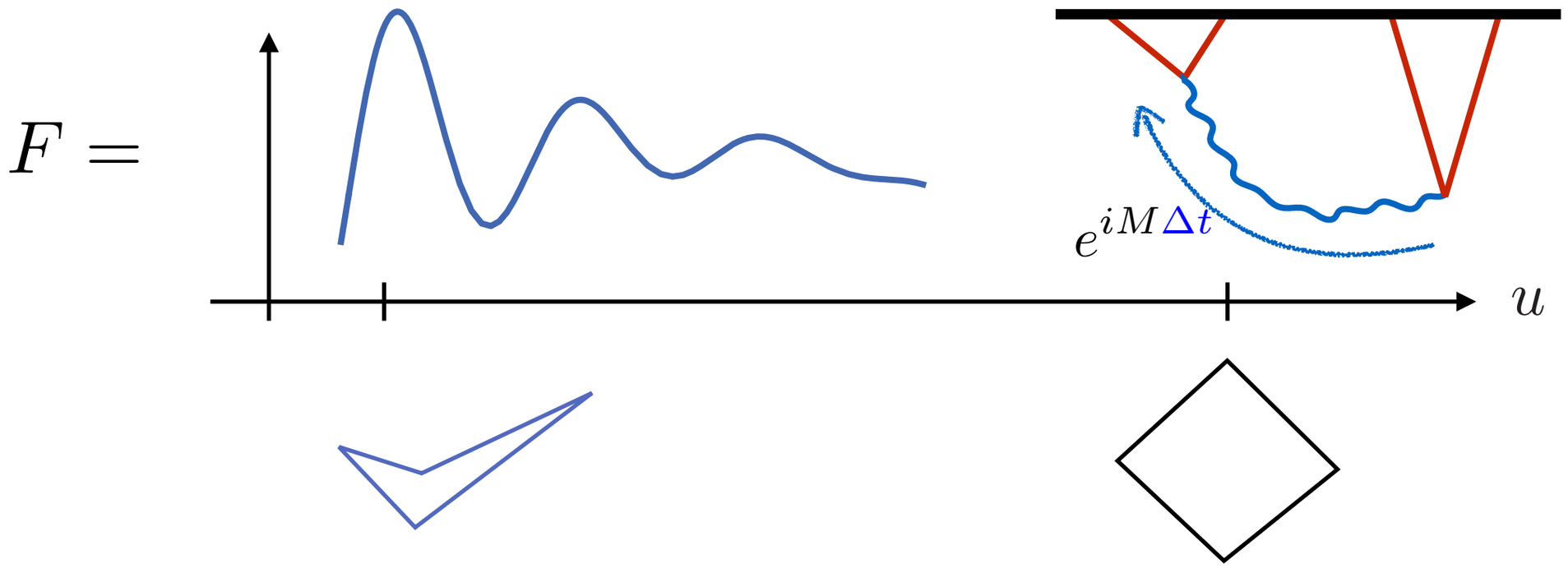
Particle Production

In the collapsed limit, dependence in **spatial** momenta
is the same as **time evolution** of a harmonic oscillator

$$\left[\frac{d^2}{dt^2} + M^2\right] f = \frac{1}{2\cosh(\frac{1}{2}t)}$$

$$e^t \equiv \frac{u}{v}$$

$$f \equiv (uv)^{-1/2} F$$



Concrete Answer

$$(uv)^{\frac{1}{2}\pm iM}\,{}_2F_1\left[\begin{matrix}\frac{1}{4}\pm iM,\,\frac{3}{4}\pm iM\\ 1\pm iM\end{matrix}\,\middle|\,u^2\right]\,{}_2F_1\left[\begin{matrix}\frac{1}{4}\pm iM,\,\frac{3}{4}\pm iM\\ 1\pm iM\end{matrix}\,\middle|\,v^2\right]$$

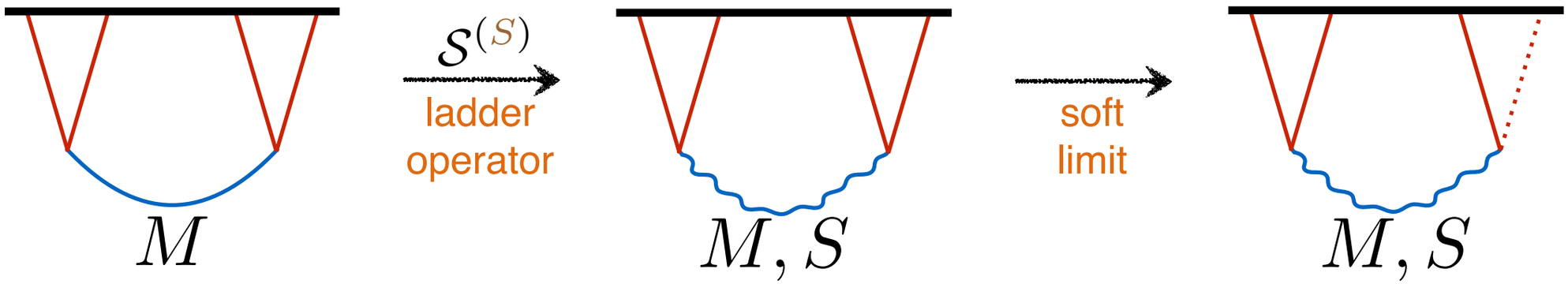
particle production

$$F = \sum_{m,n} c_{mn}(M)\, u^{2m+1} \left(\frac{u}{v}\right)^n + \frac{\pi}{\cosh(\pi M)}\, g(u,v)$$

EFT

$$F^{2|1|3}_{2|0|1}\left[\begin{matrix}\frac{1}{2},1\\ \frac{5+2iM}{4},\frac{5-2iM}{4}\end{matrix}\,\middle|\,\begin{matrix}1\\ -\end{matrix}\,\middle|\,\begin{matrix}\frac{5+2iM}{4},\frac{5-2iM}{4},\frac{1}{2}+iM\\ \frac{3}{2}+iM\end{matrix}\,\middle|\,u^2,\frac{u^2}{v^2}\right]$$

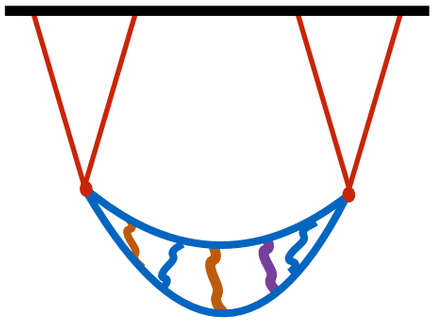
General Result



$$F_{M,S,g} = g^2\, \mathcal{S}^{(S)}\, F_{M,0}$$

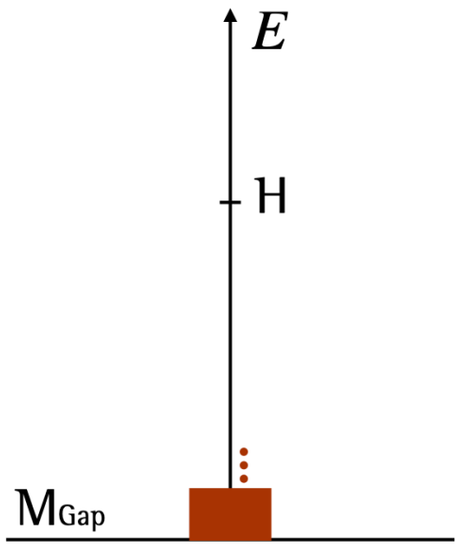
Parametrized by **mass**, **spin**, & **coupling**.

Strong Coupling

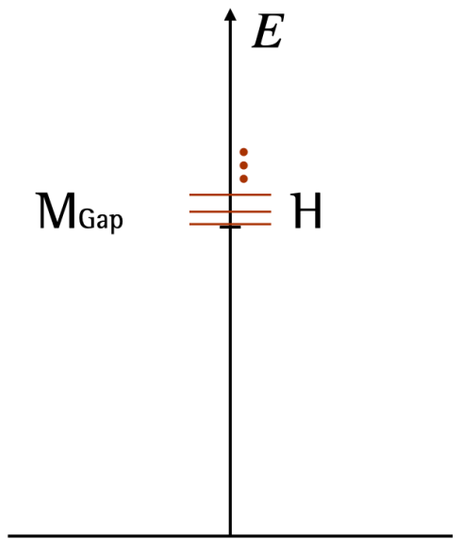


Organize by mass gap (very roughly)

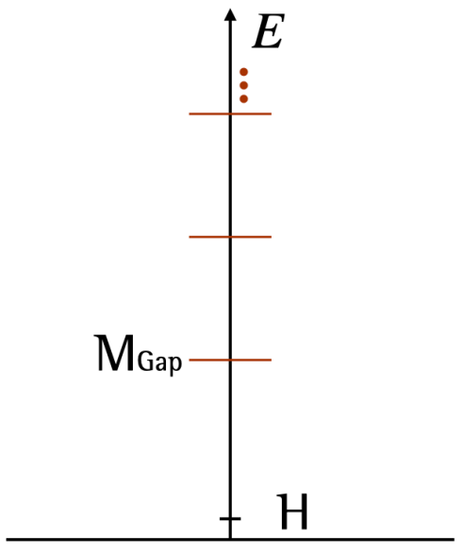
M=0
Unparticles



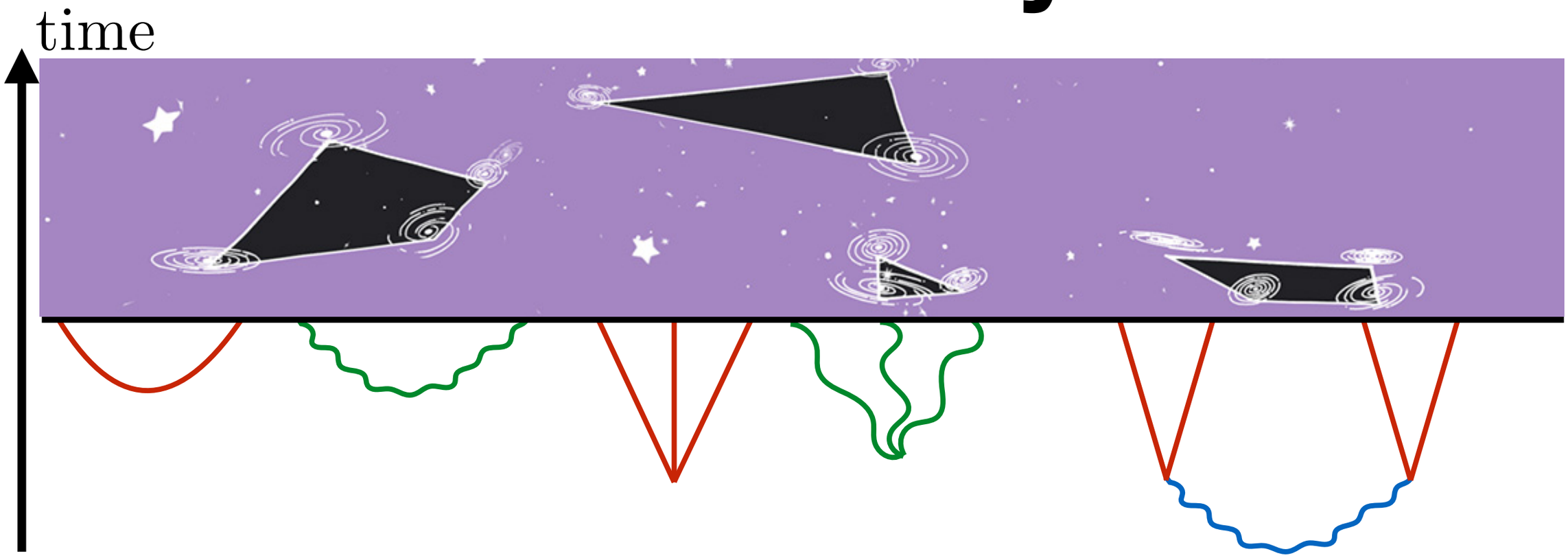
M~H
RS with
“fried IR brane”



M>>H
RS with
Hard wall



Take Away



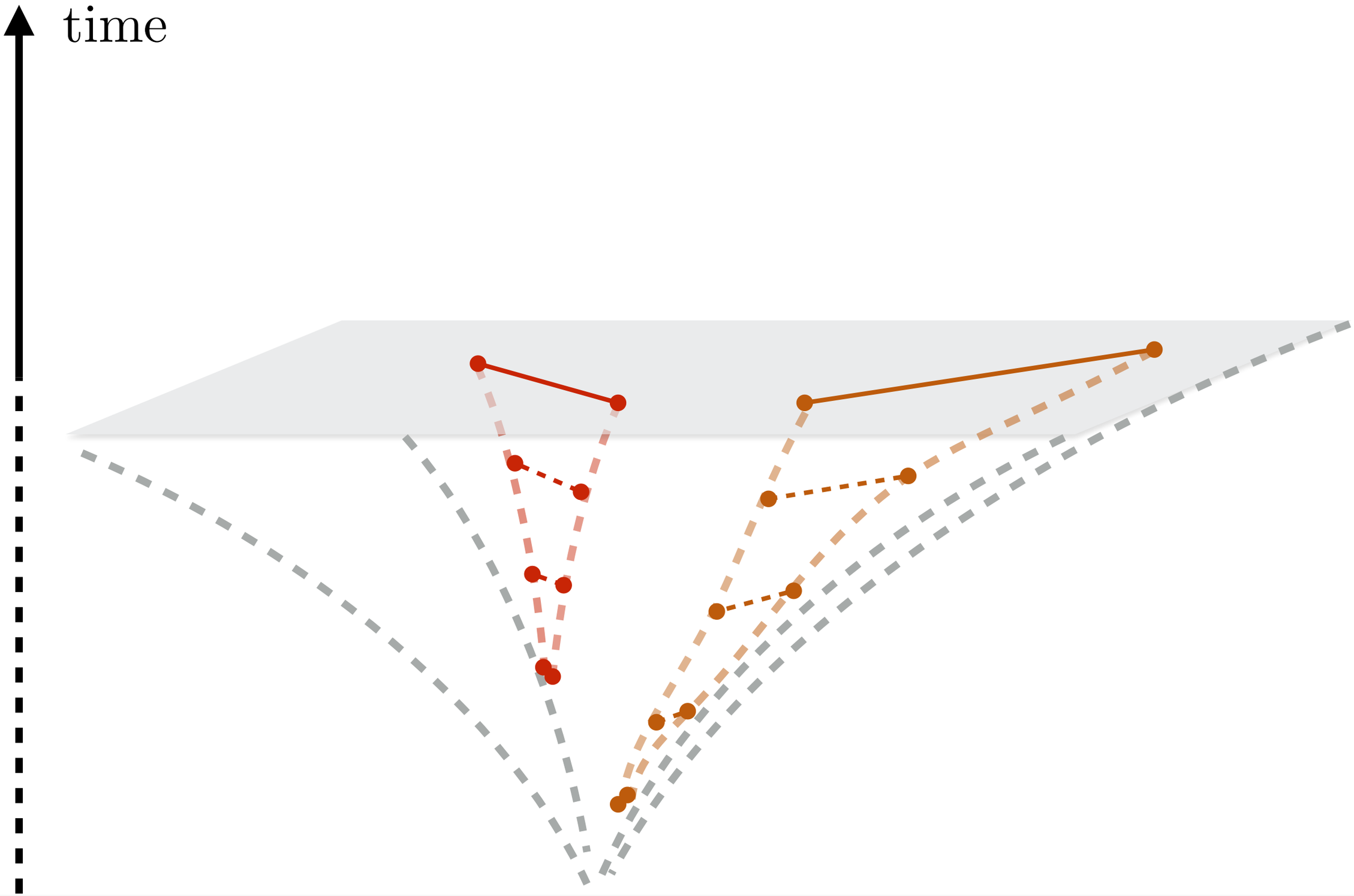
Small menu of cosmological correlators! Amazingly, highly constrained by **locality**, **unitarity** and **symmetry**.

The shapes are computed using **new methods**!

This will have profound implications for understanding fundamental physics and the universe at the earliest times.

Emergent Time

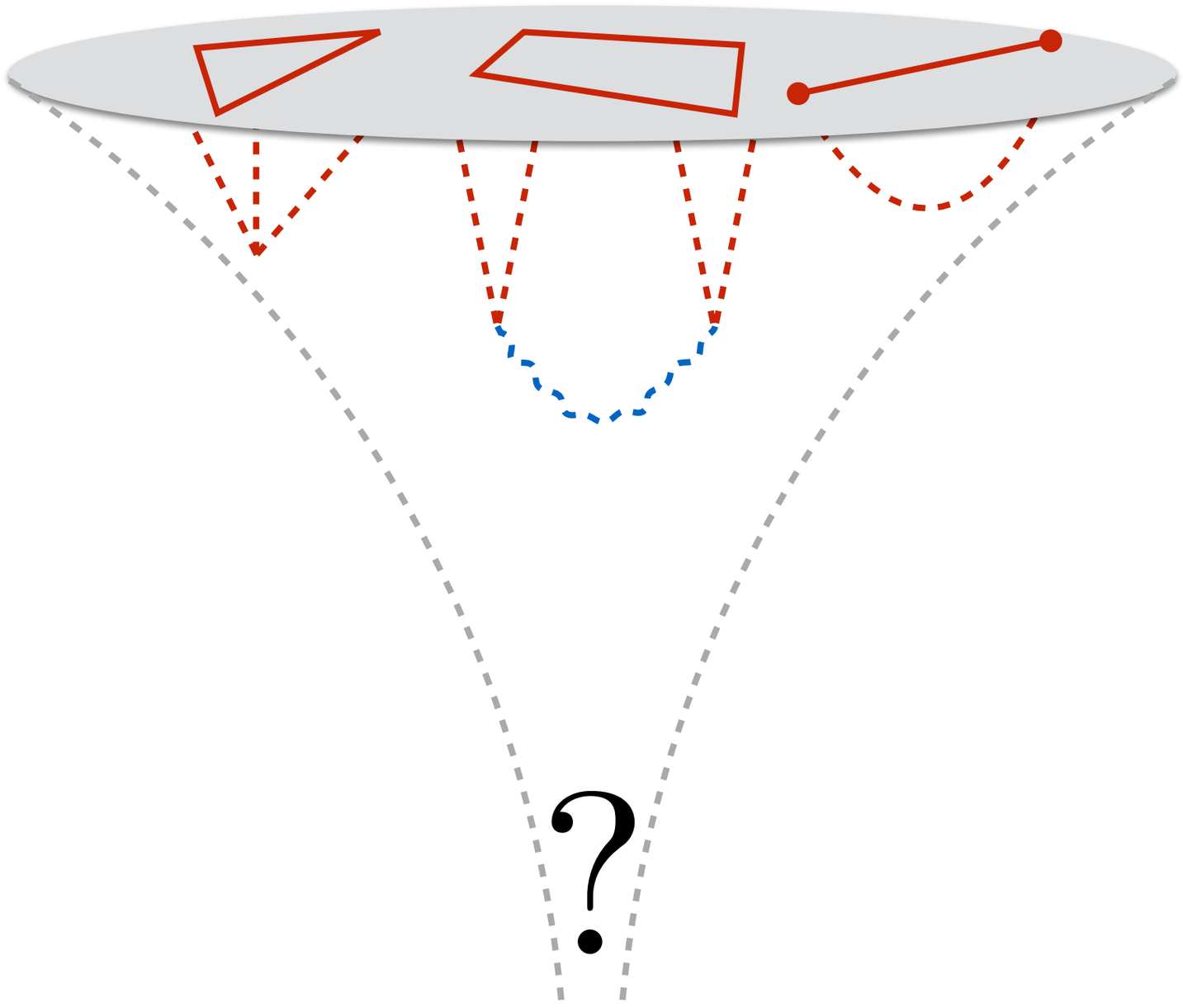
Time without Time



Hypothesis

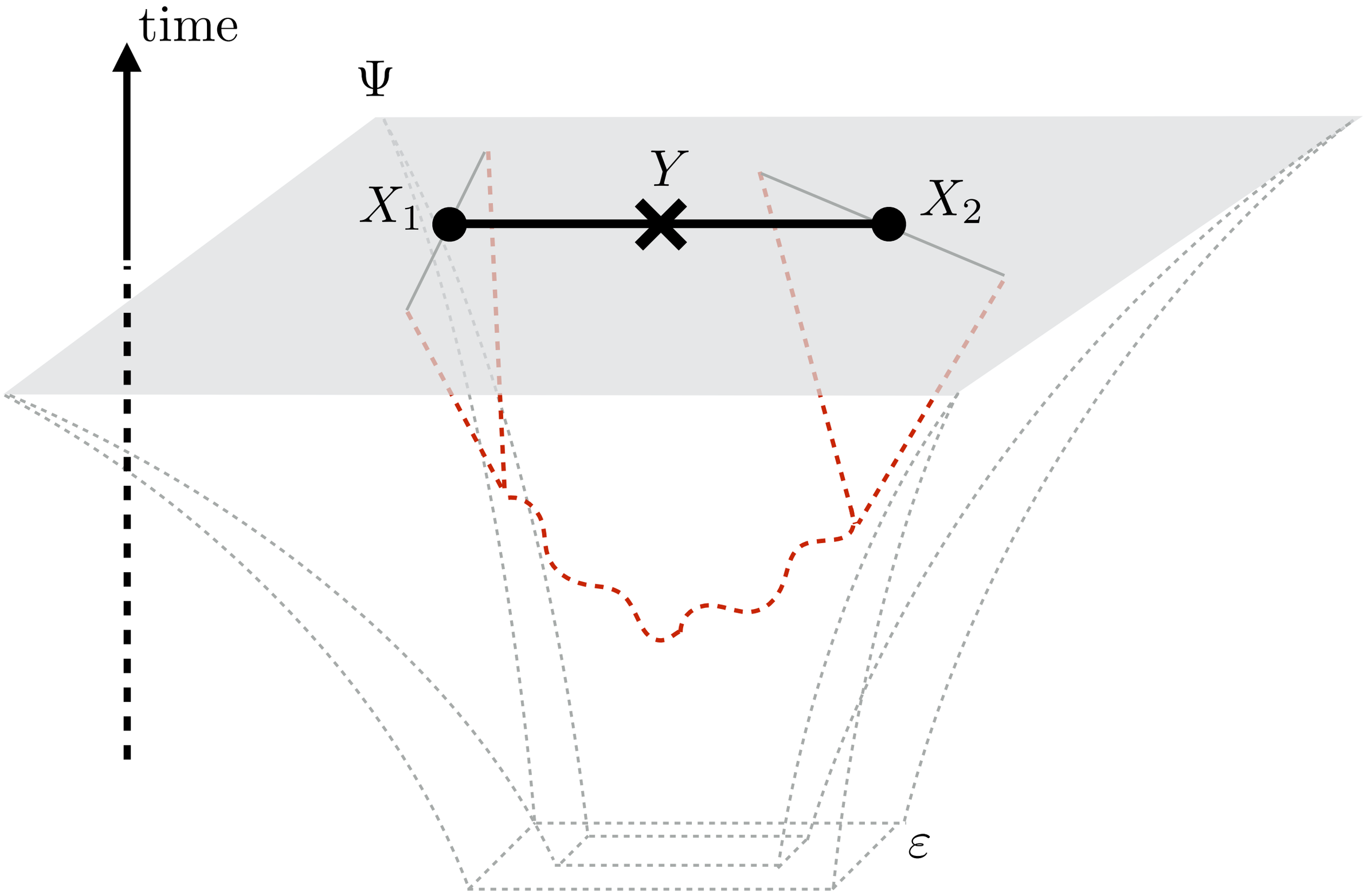
Time evolution emerges from **static differential equations**

Cosmology & Holography

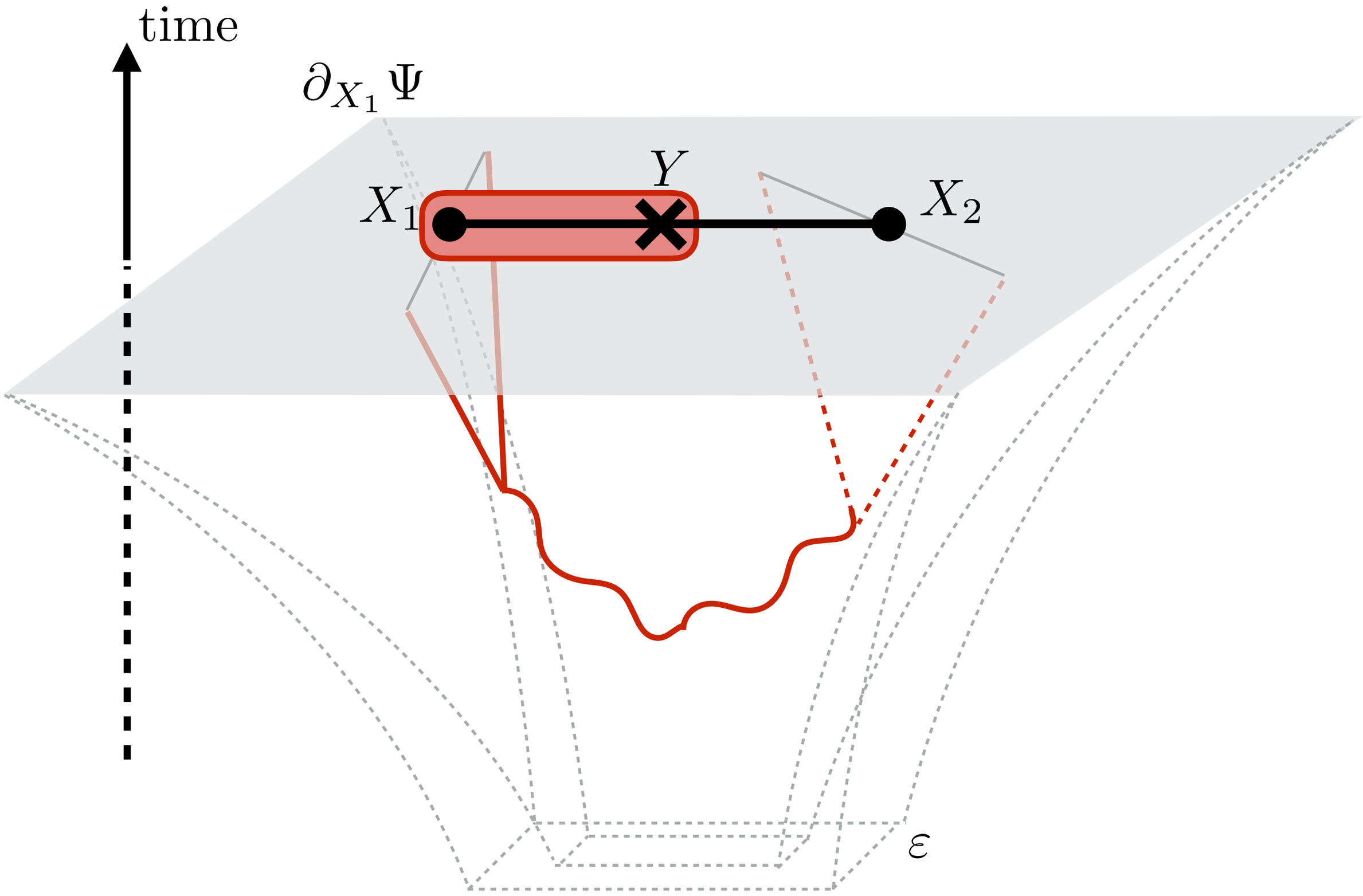


In quantum gravity, boundary observables are well-defined.

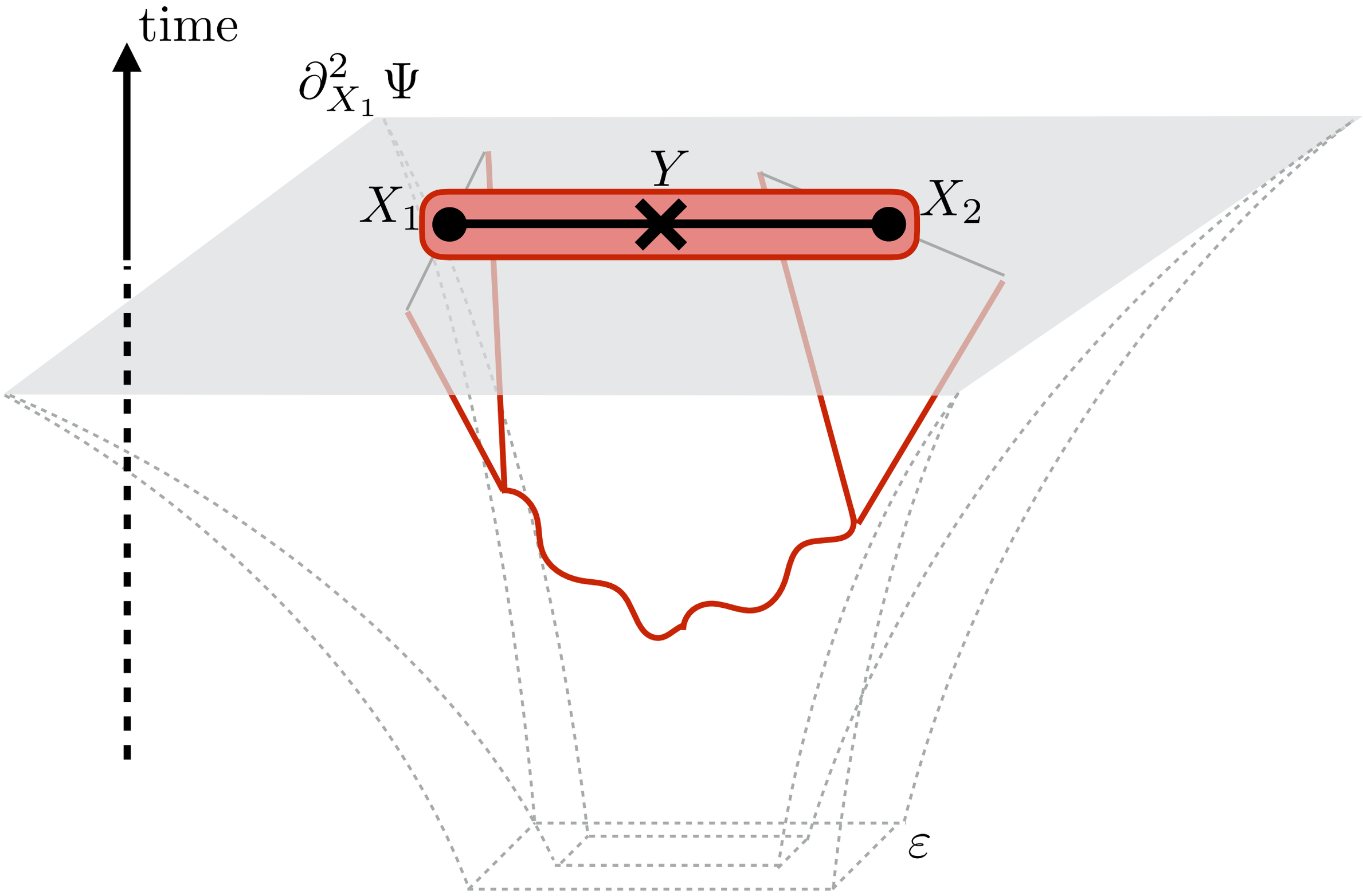
Kinematic Flow



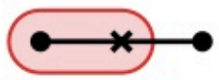
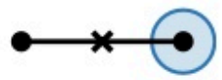
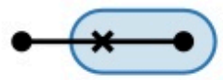
Kinematic Flow

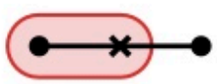
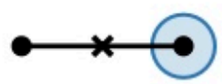
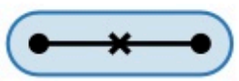


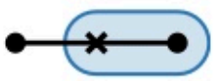
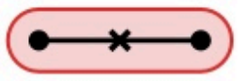
Kinematic Flow



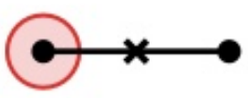
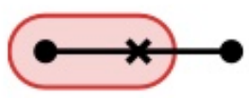
Kinematic Flow

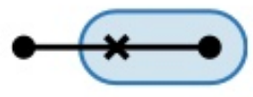
$$\mathrm{d}\psi \;=\; \varepsilon\Big[(\psi - F)$$ $$+\; F$$  $$+\; (\psi - \tilde{F})$$  $$+\; \tilde{F}$$  $$\Big]$$

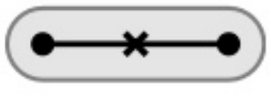
$$\mathrm{d}F \;=\; \varepsilon\Big[F$$  $$+\; (F - Z)$$  $$+\; Z$$  $$\Big]$$

$$\mathrm{d}\tilde{F} \;=\; \varepsilon\Big[\tilde{F}$$  $$+\; (\tilde{F} - Z)$$ $$+\; Z$$  $$\Big]$$

$$\mathrm{d}Z \;=\; 2\varepsilon\, Z$$

 $\equiv\; \mathrm{d}\log(X_1 + Y)\,,$  $\equiv\; \mathrm{d}\log(X_1 - Y)\,,$

$\equiv\; \mathrm{d}\log(X_2 + Y)\,,$  $\equiv\; \mathrm{d}\log(X_2 - Y)\,,$

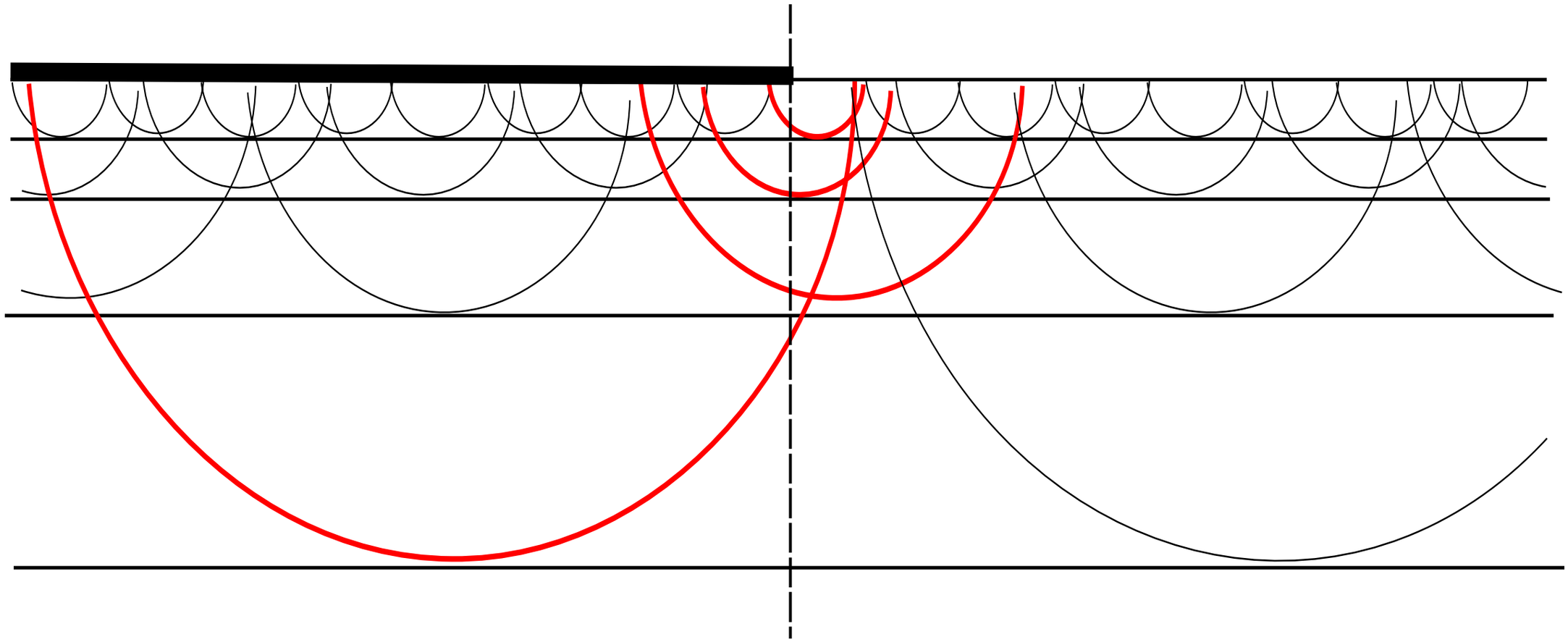
 $\equiv\; \mathrm{d}\log(X_1 + X_2)\,.$

Important Omissions

“there’s no time to kill today”

Unitarity
From AdS to dS
Stochastic Inflation
Loops
Soft Theorems
Graviton correlators
Twistors
Positive Geometries
Parity Violation
Stringy correlator?

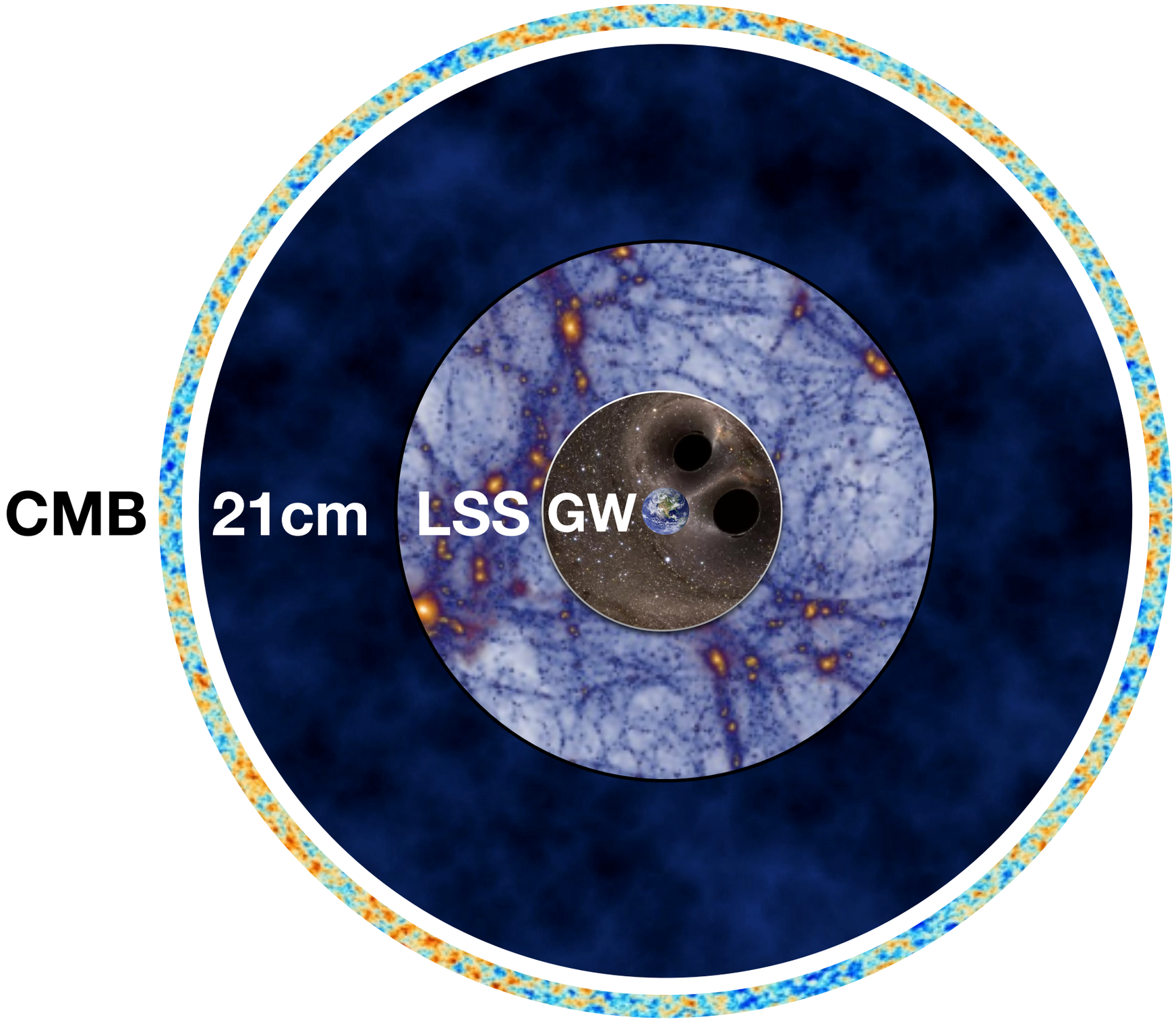
Entanglement



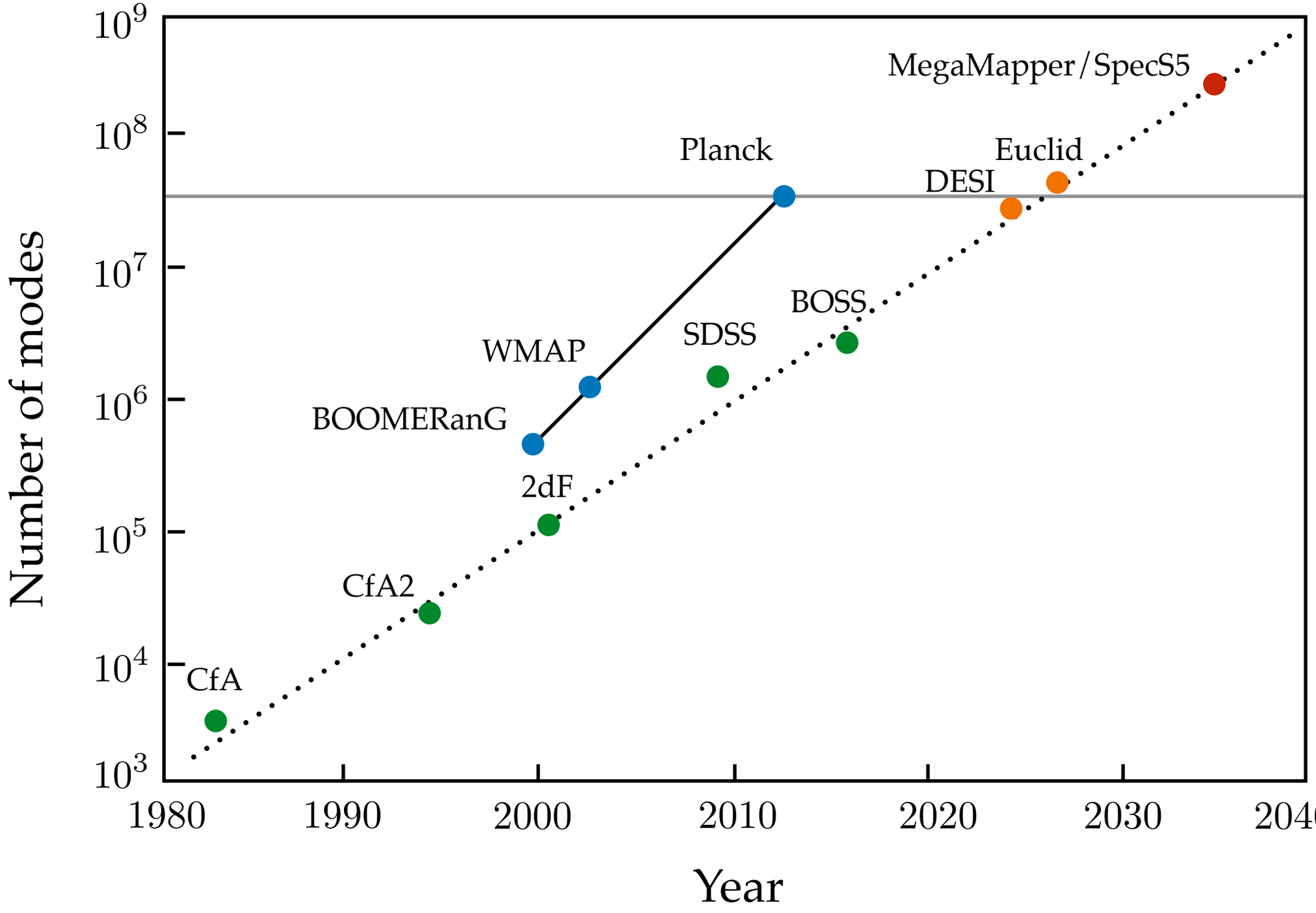
Neither thermal, nor like flat space vacuum.
I don’t know how to probe it experimentally…

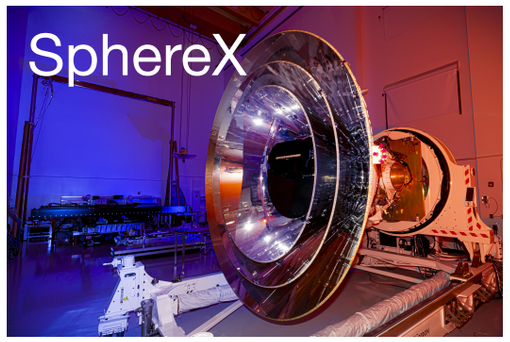
Near Future

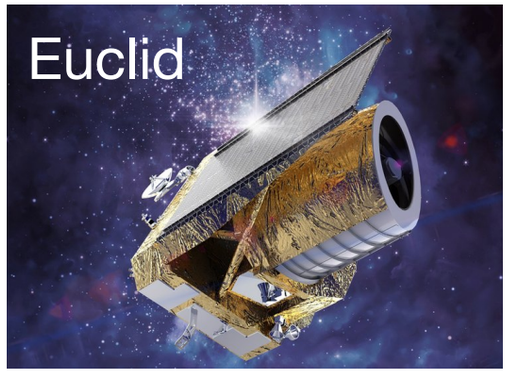
Observational Landscape



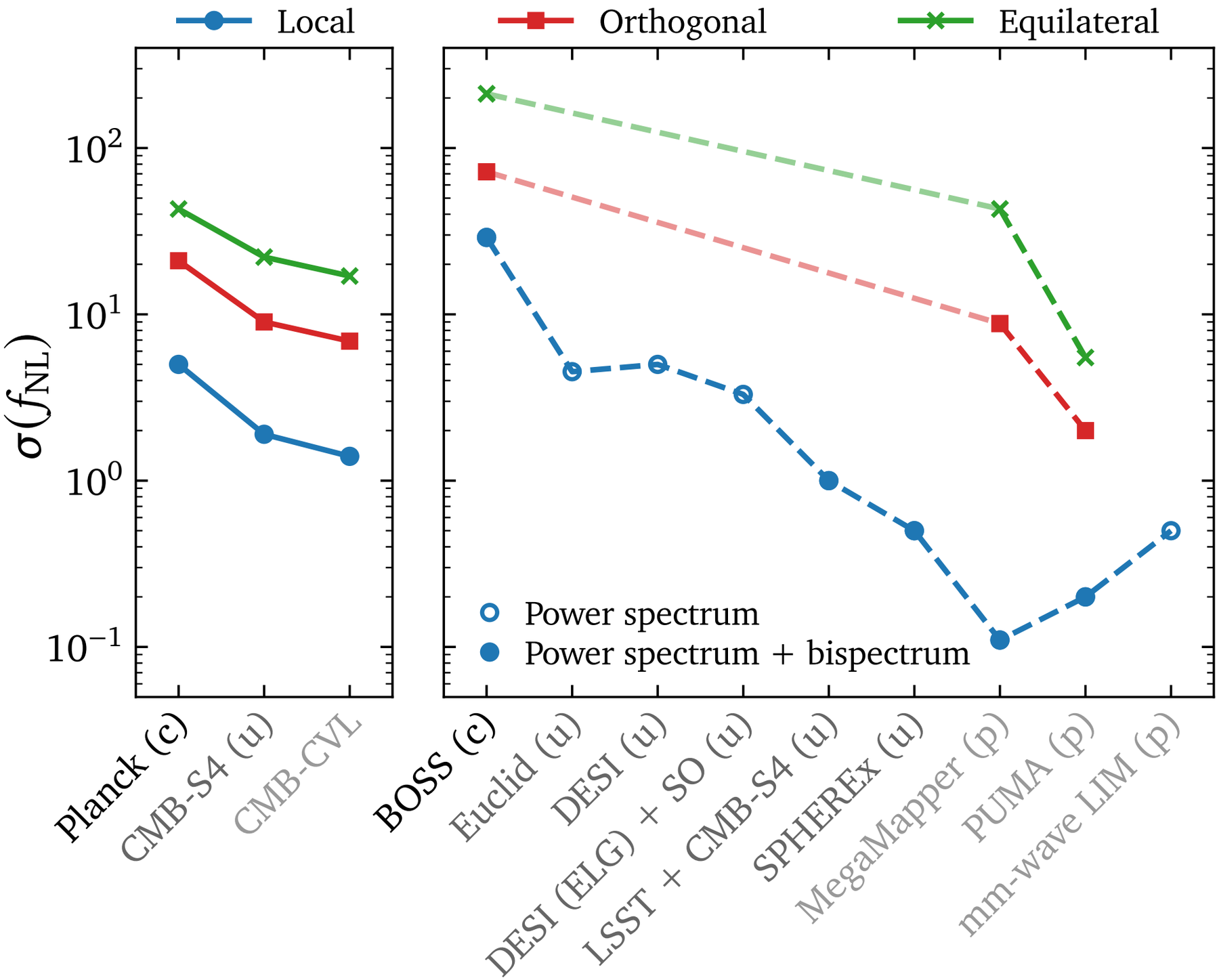
Observational Landscape

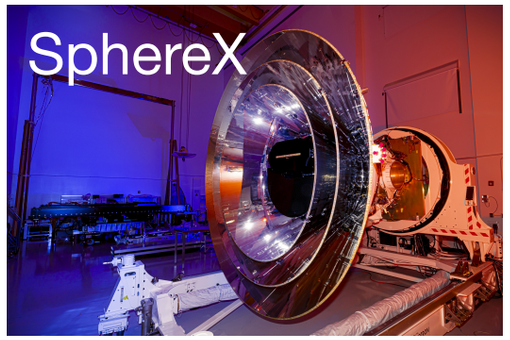


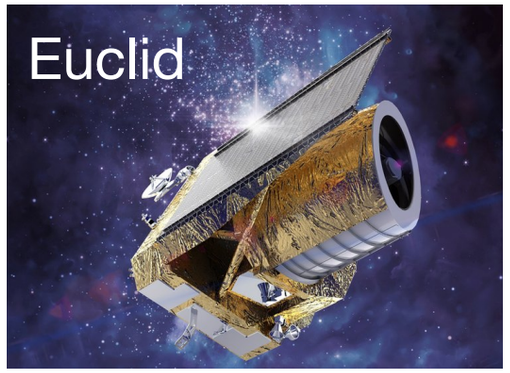




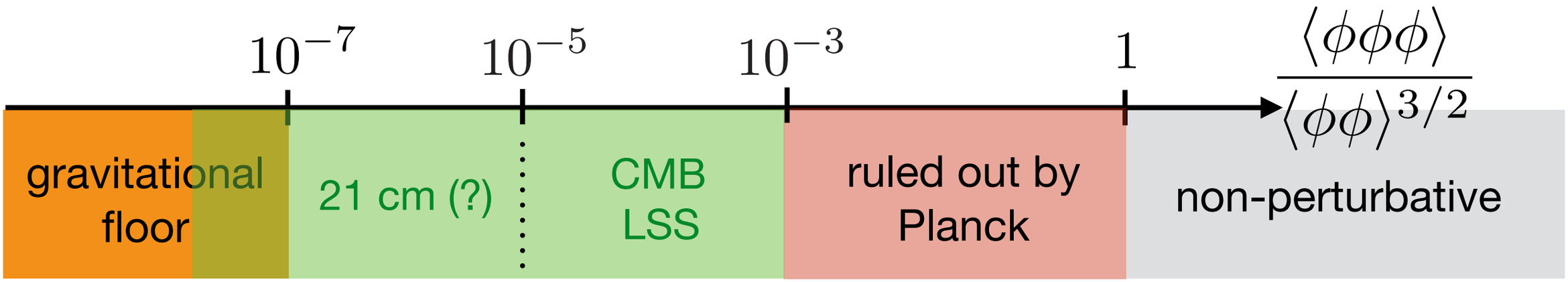
Observational Landscape





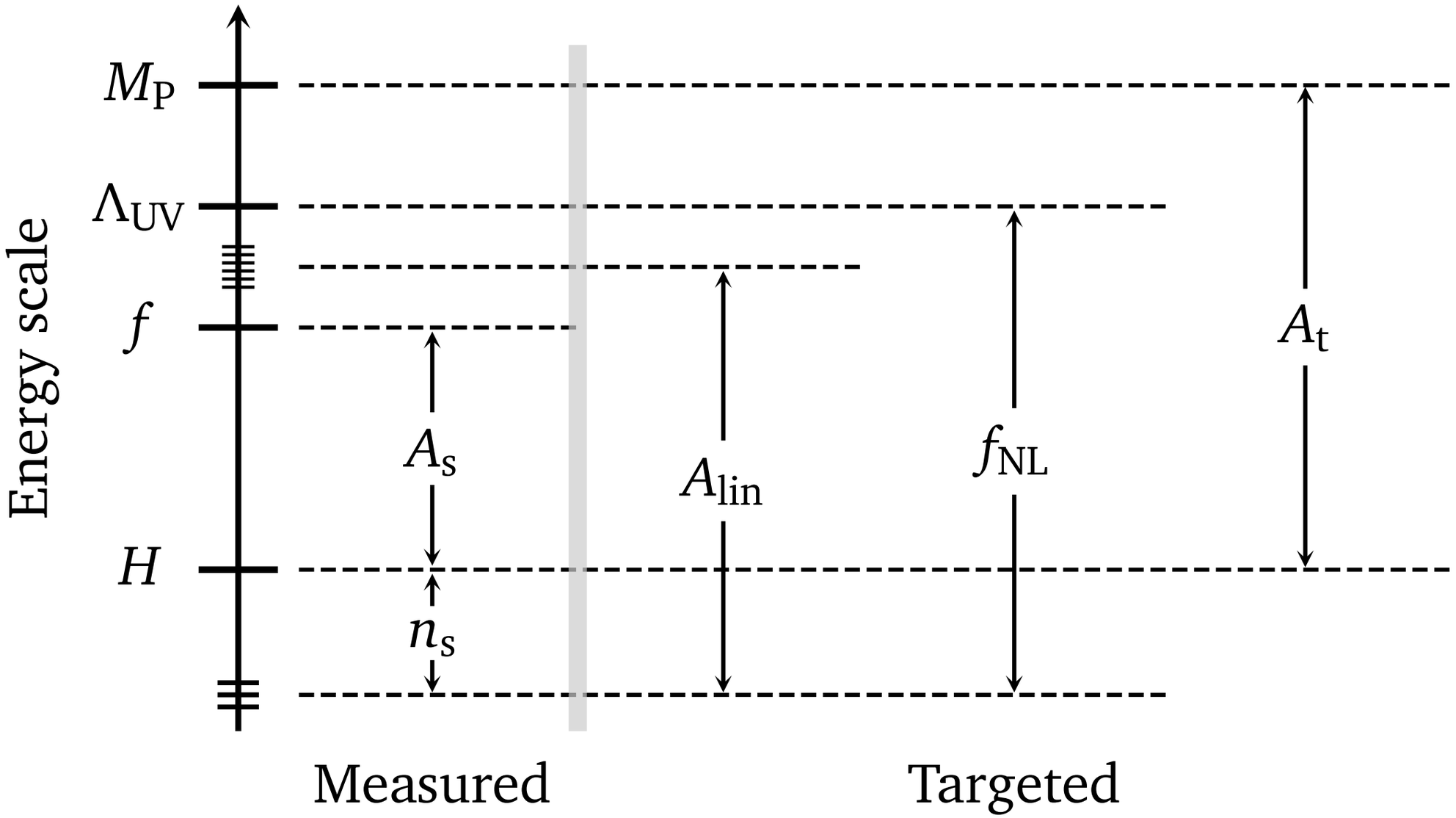


Targets

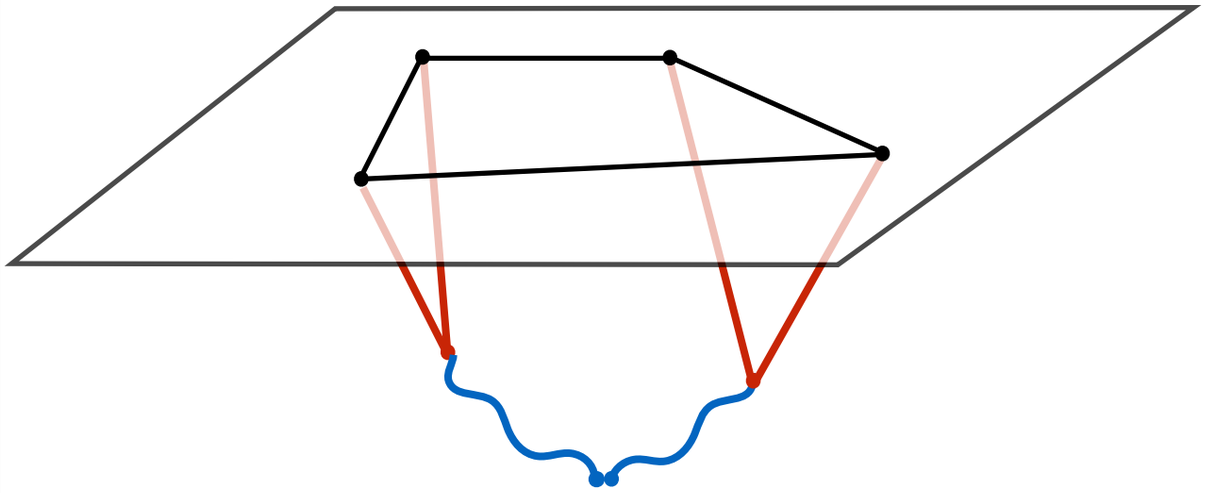


Probe	Modes
CMB	10^6
LSS	10^8
21 cm, ground	10^9
21 cm, moon	10^{12}

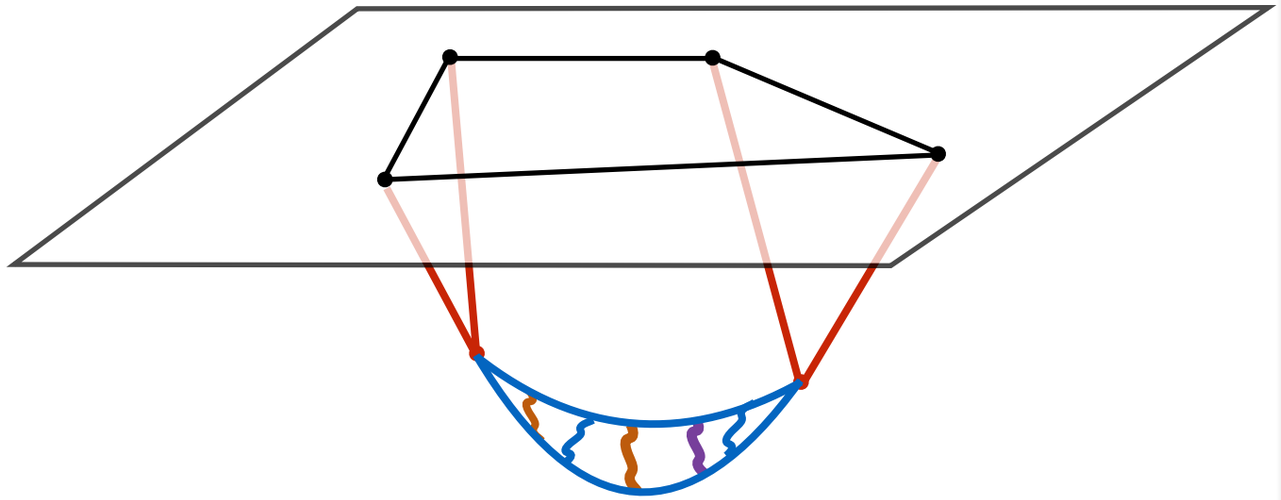
Scales


$M_{\rm P}$
$\Lambda_{\rm UV}$
f
H
Energy scale
$A_{\rm s}$
$n_{\rm s}$
$A_{\rm lin}$
$f_{\rm NL}$
$A_{\rm t}$
Measured
Targeted

Charting Possibilities



Loops



Unparticles

FLRW

Compositeness

Axions

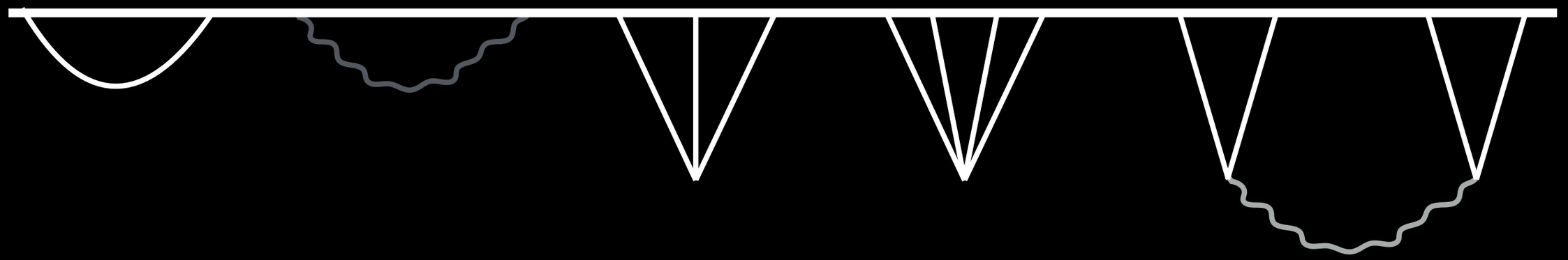
Spin

Holography

Stochastic Inflation

Twistors

Strings?



Cosmological correlators probe **particle collisions**
in the sky at ultra high energies!

Time evolution is **encoded** in spatial patterns.

We might be seeing glimpses of a **timeless**
description of cosmology.

Progress is fast and exciting,
from **theory** and **observations**!