Cosmological Correlators

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Cosmological Correlators

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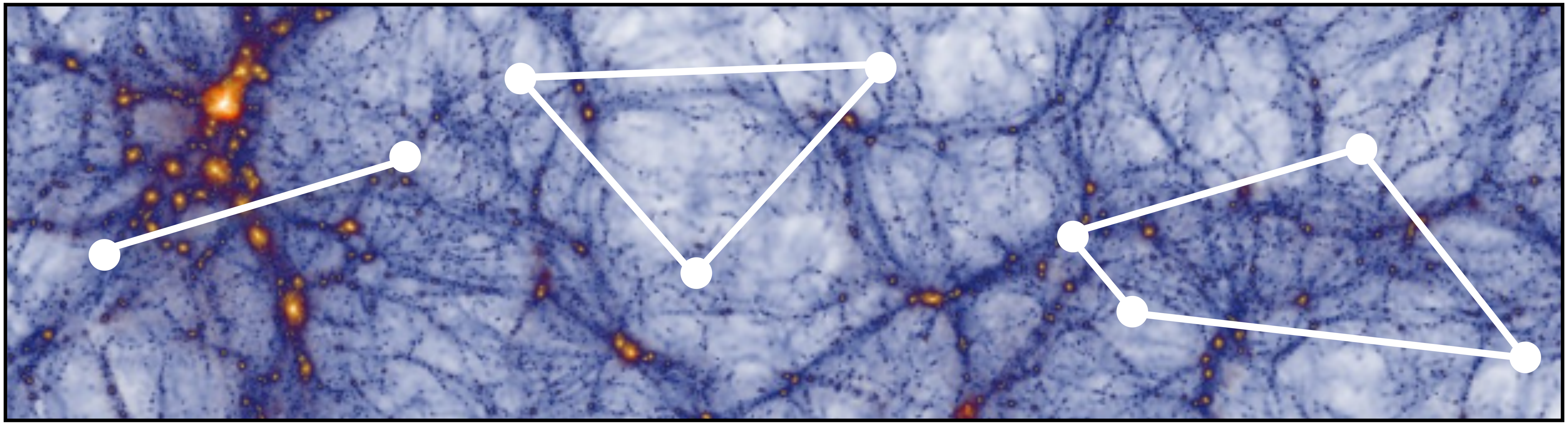
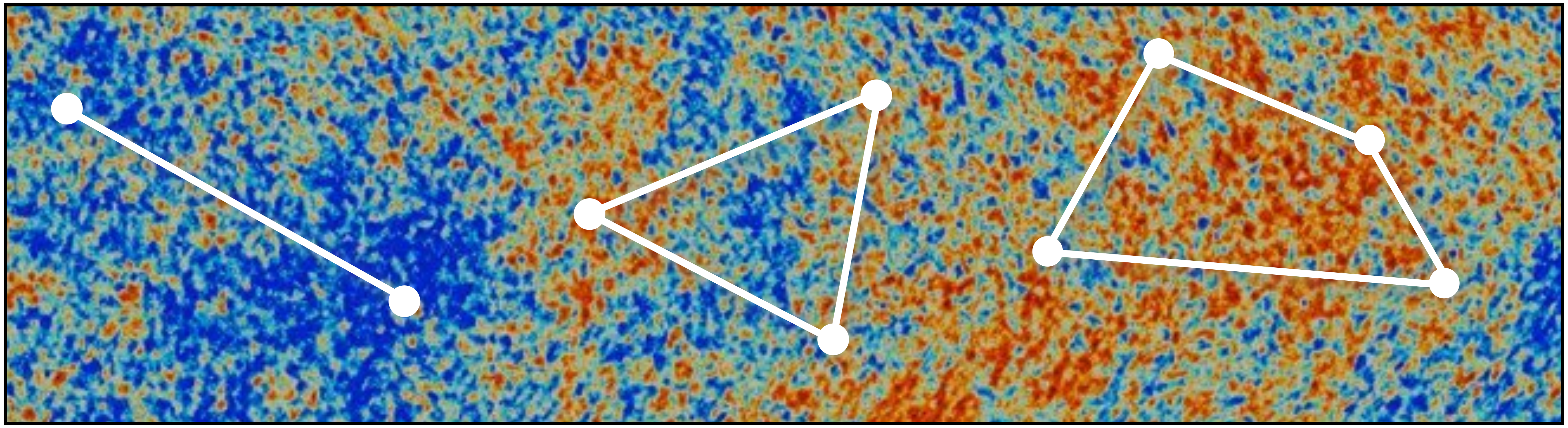
What is the origin of structure in the universe?

Cosmological Correlators



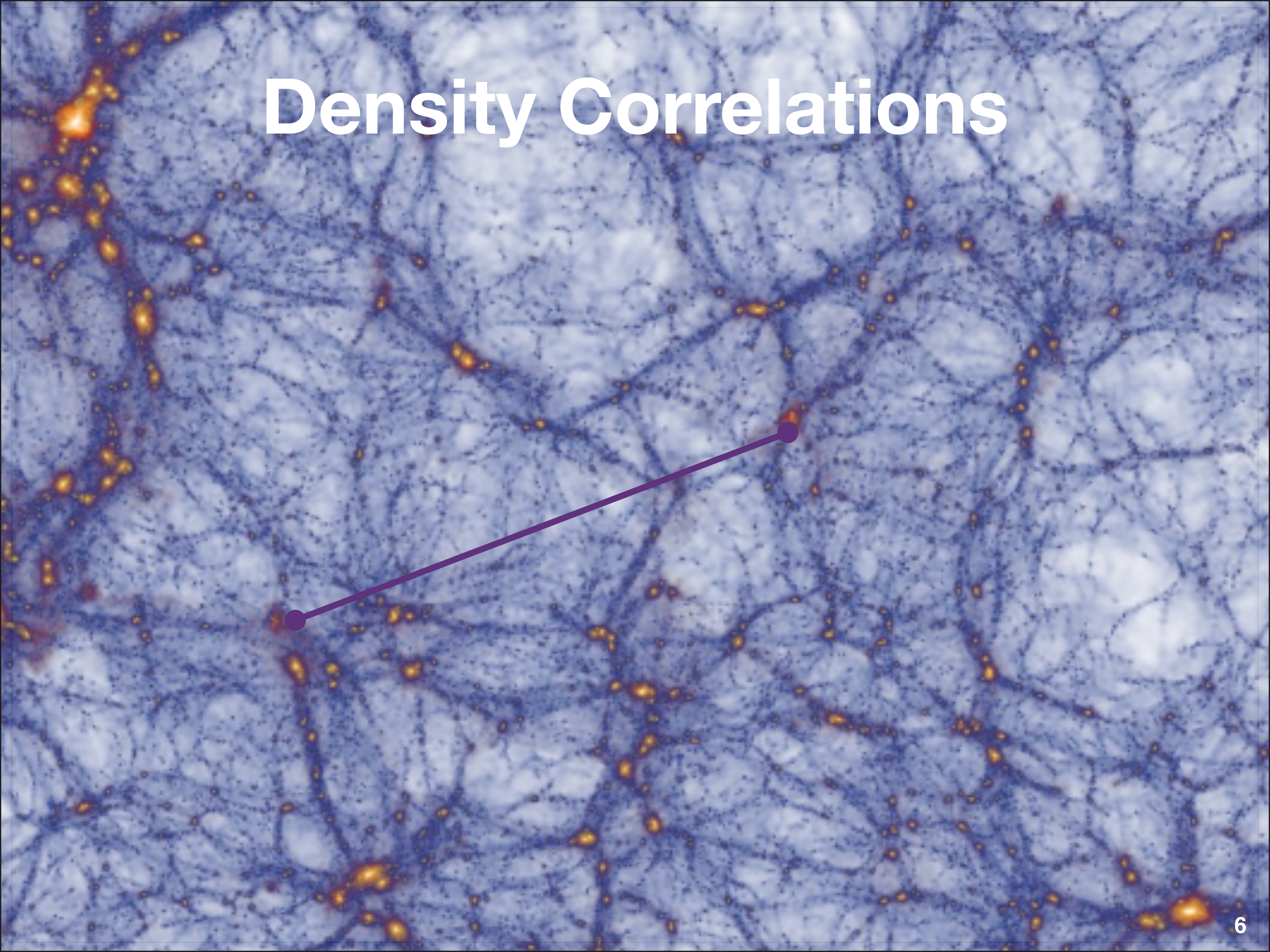


All of the information about the **origin of structure** and the dynamics of the early universe is encoded in cosmological correlations!

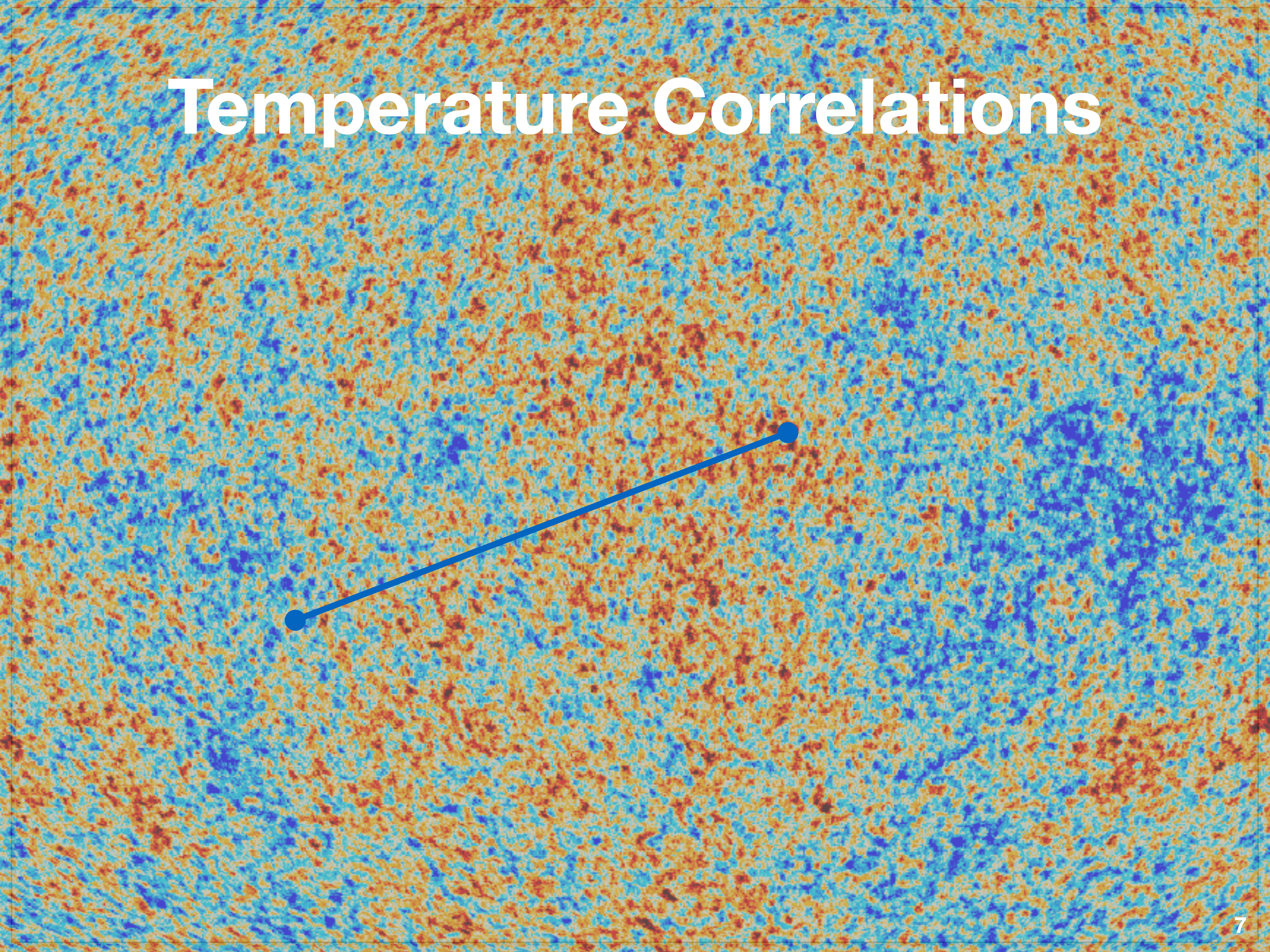
I will show that the early universe is a collider experiment run at enormous energies.

Cosmological correlators are the scattering amplitudes of this experiment.

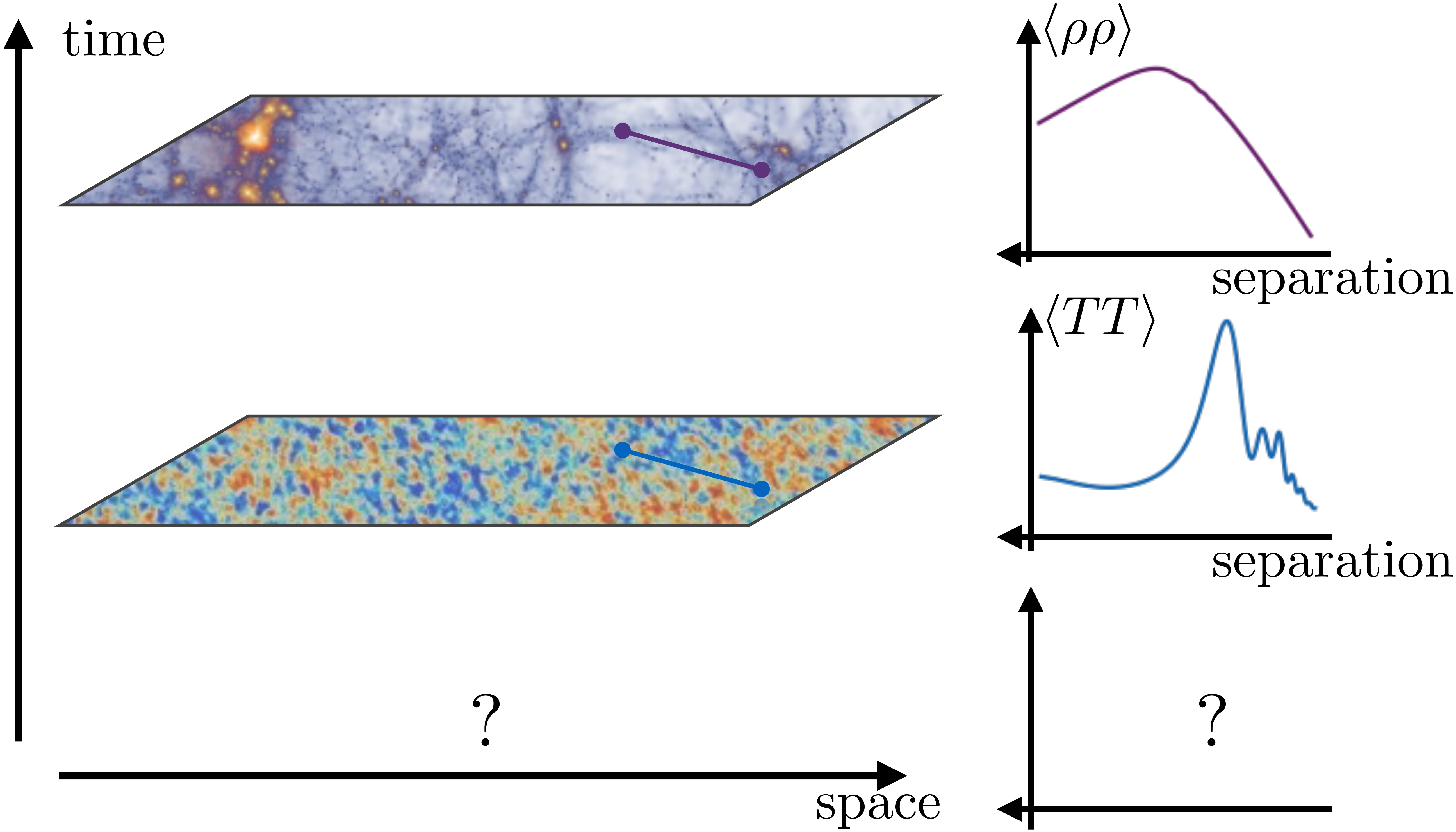
Density Correlations



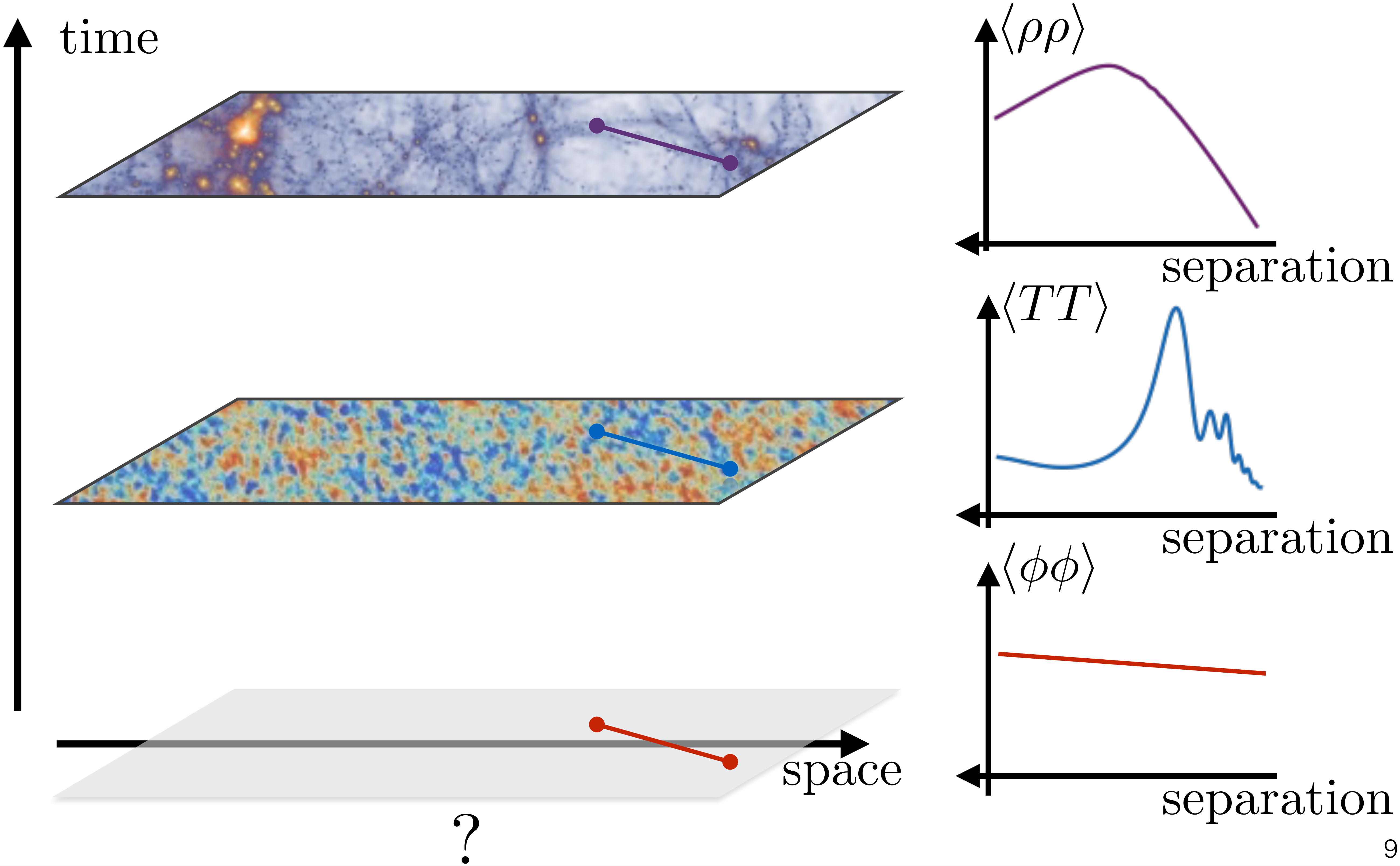
Temperature Correlations



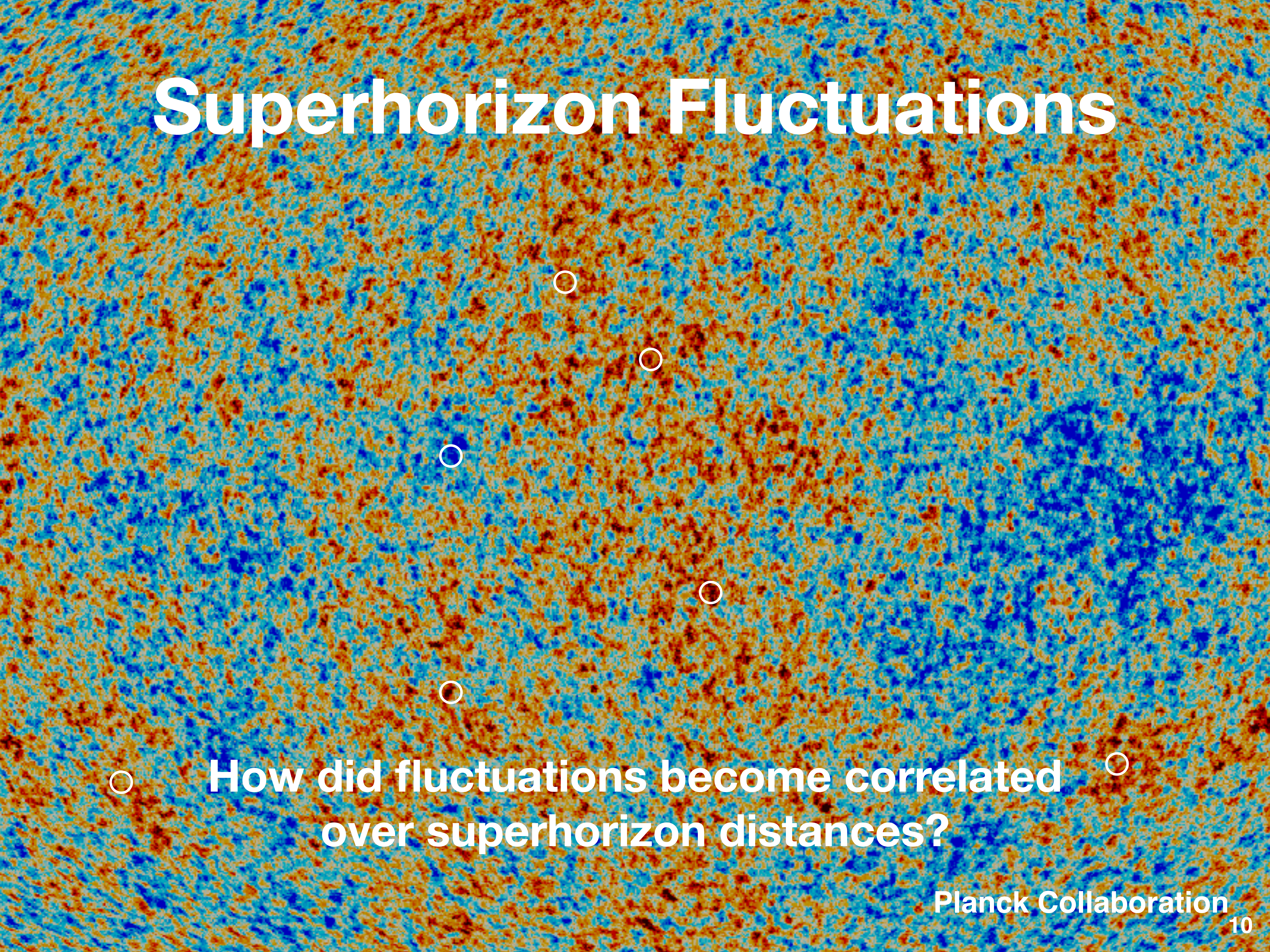
Inference


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

Primordial Fluctuations



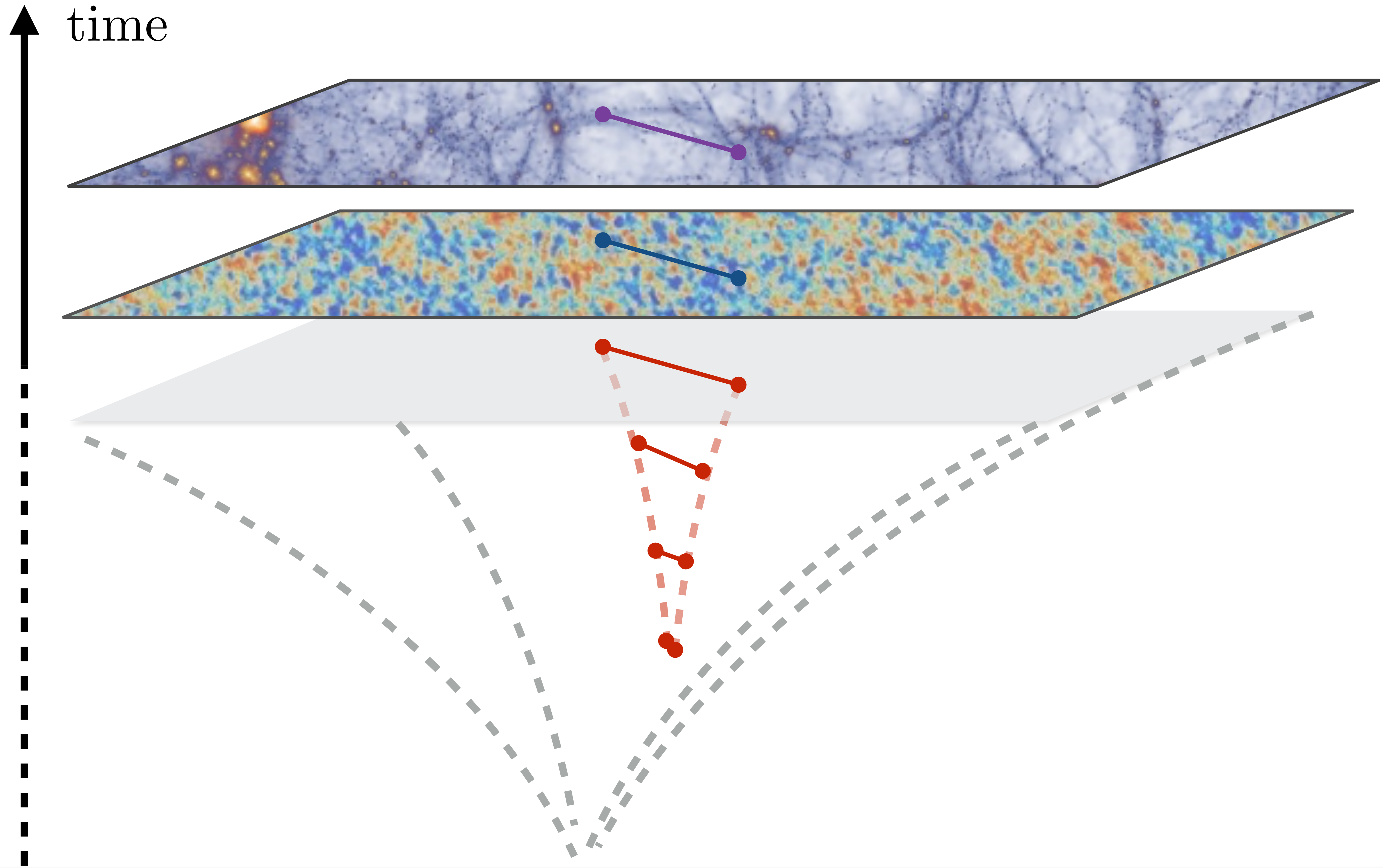
Superhorizon Fluctuations



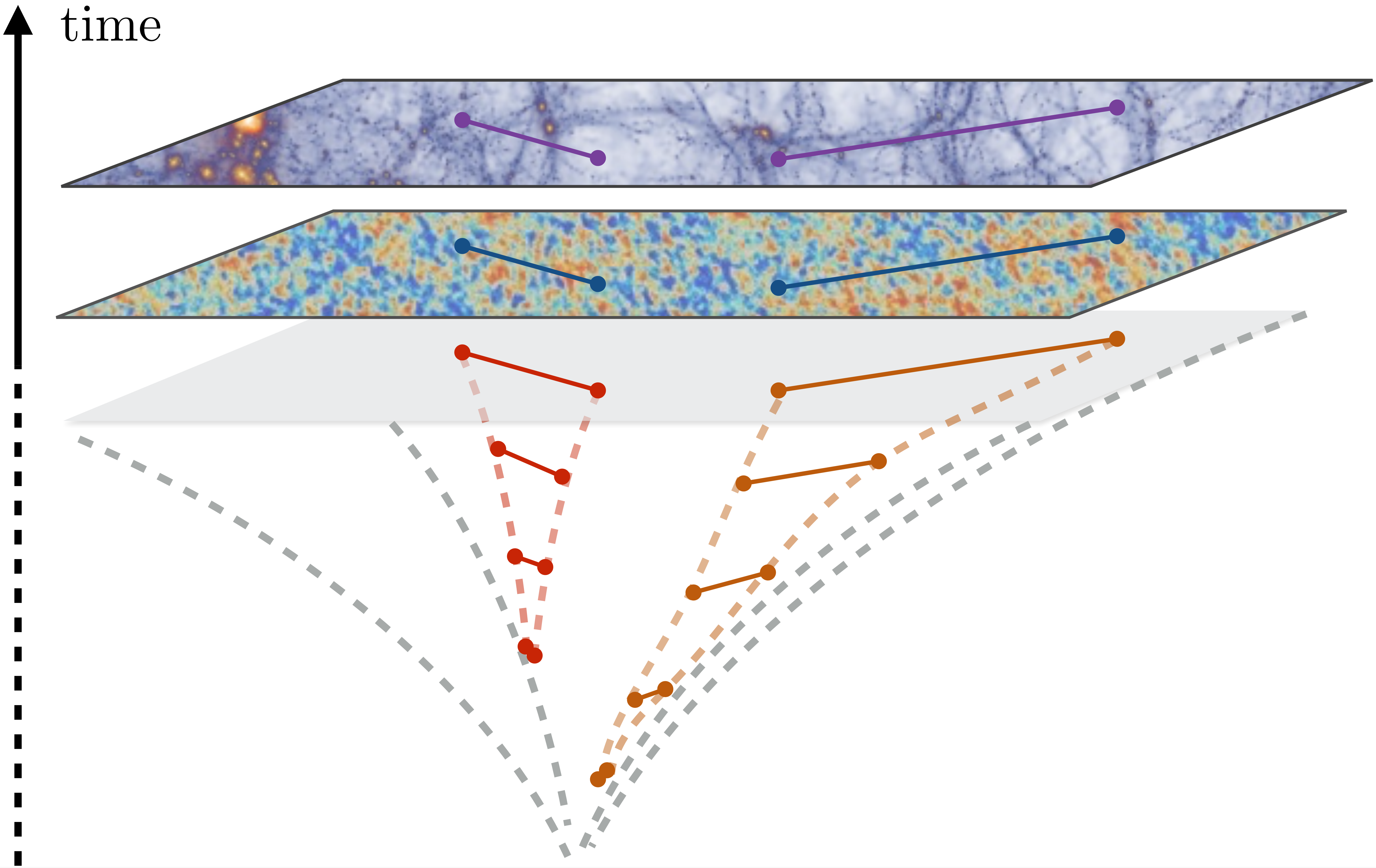
How did fluctuations become correlated over superhorizon distances?

Planck Collaboration

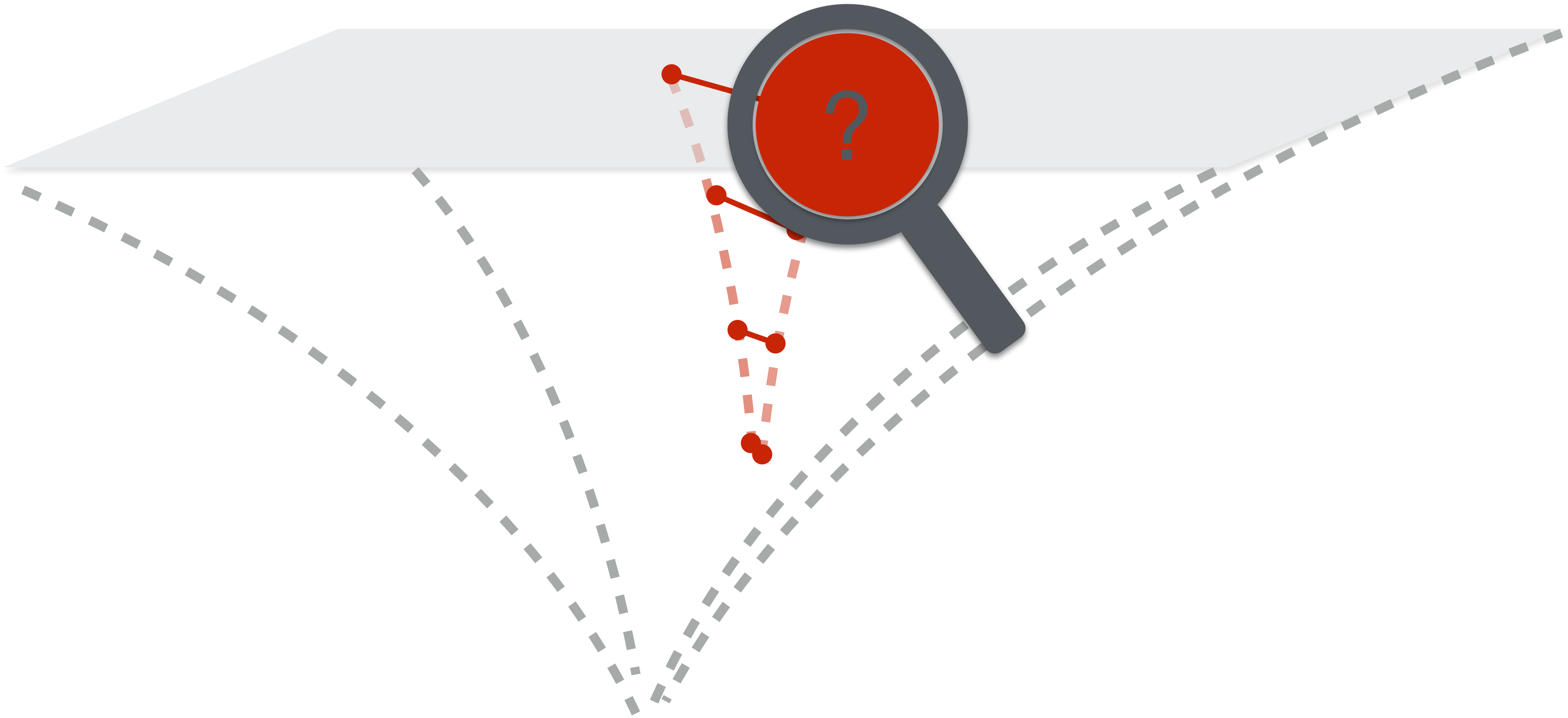
Inflation



Time without Time



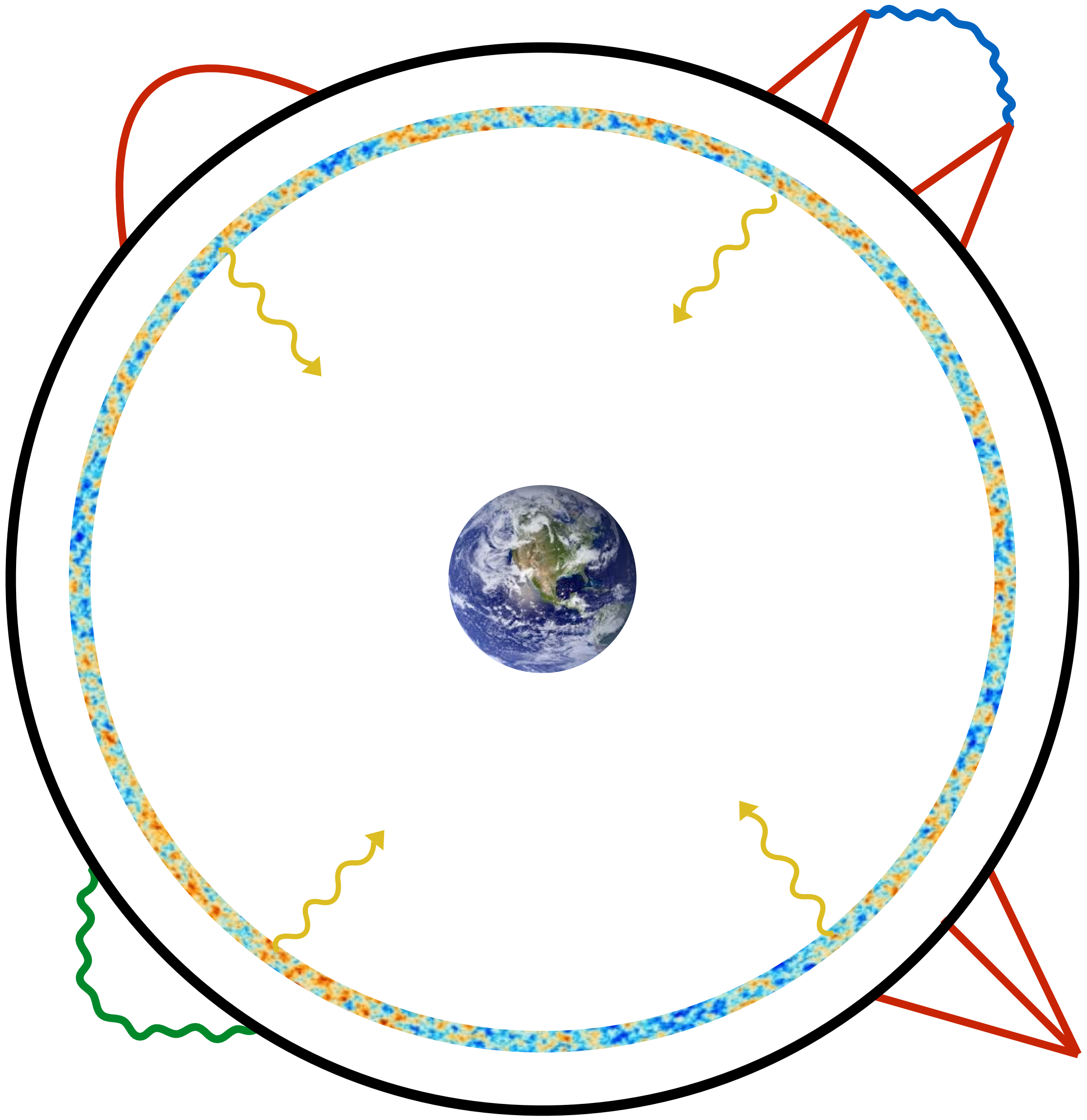
Inflaton ?

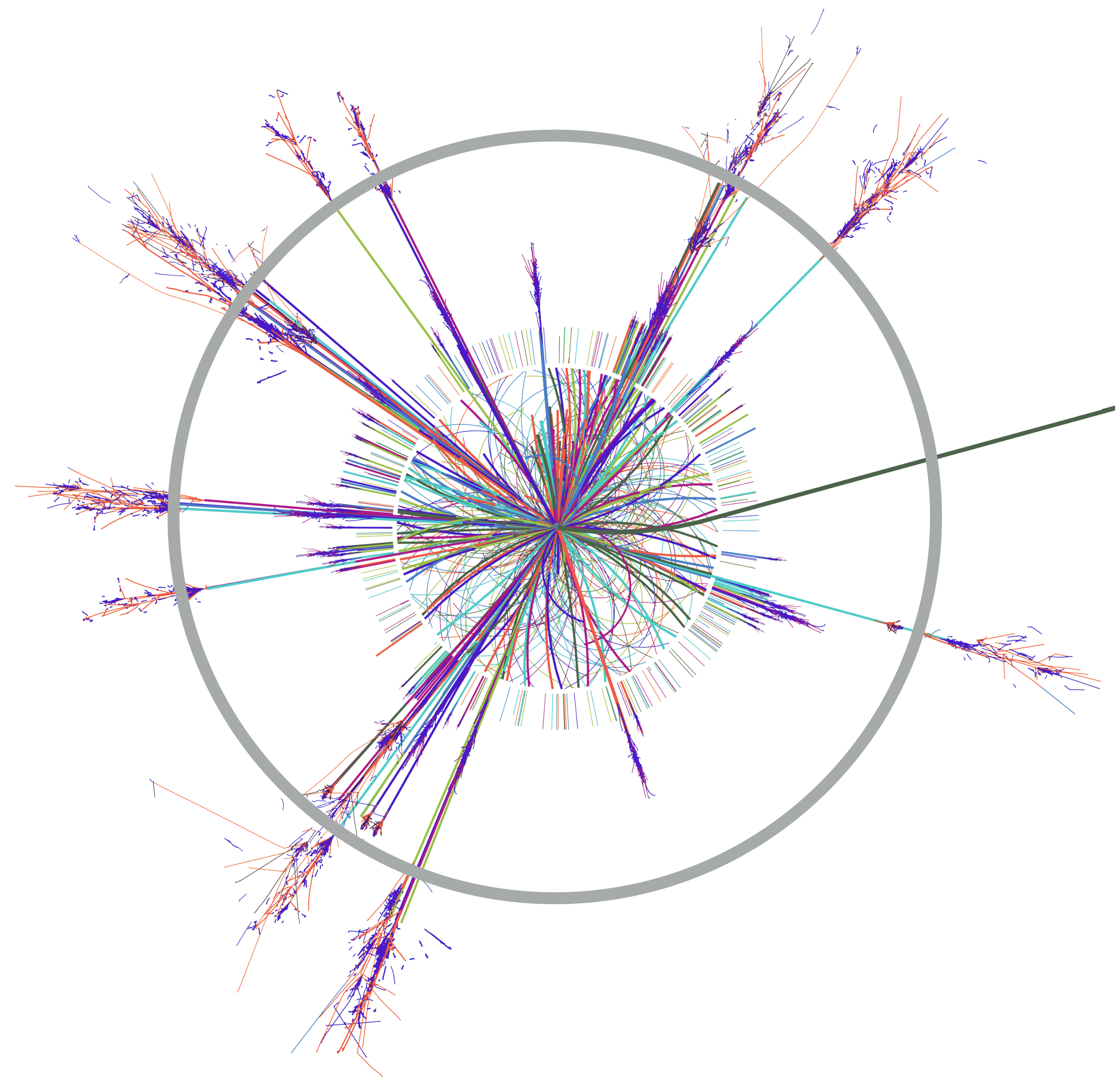


Inflationary Microscopy

Inflation as a Collider

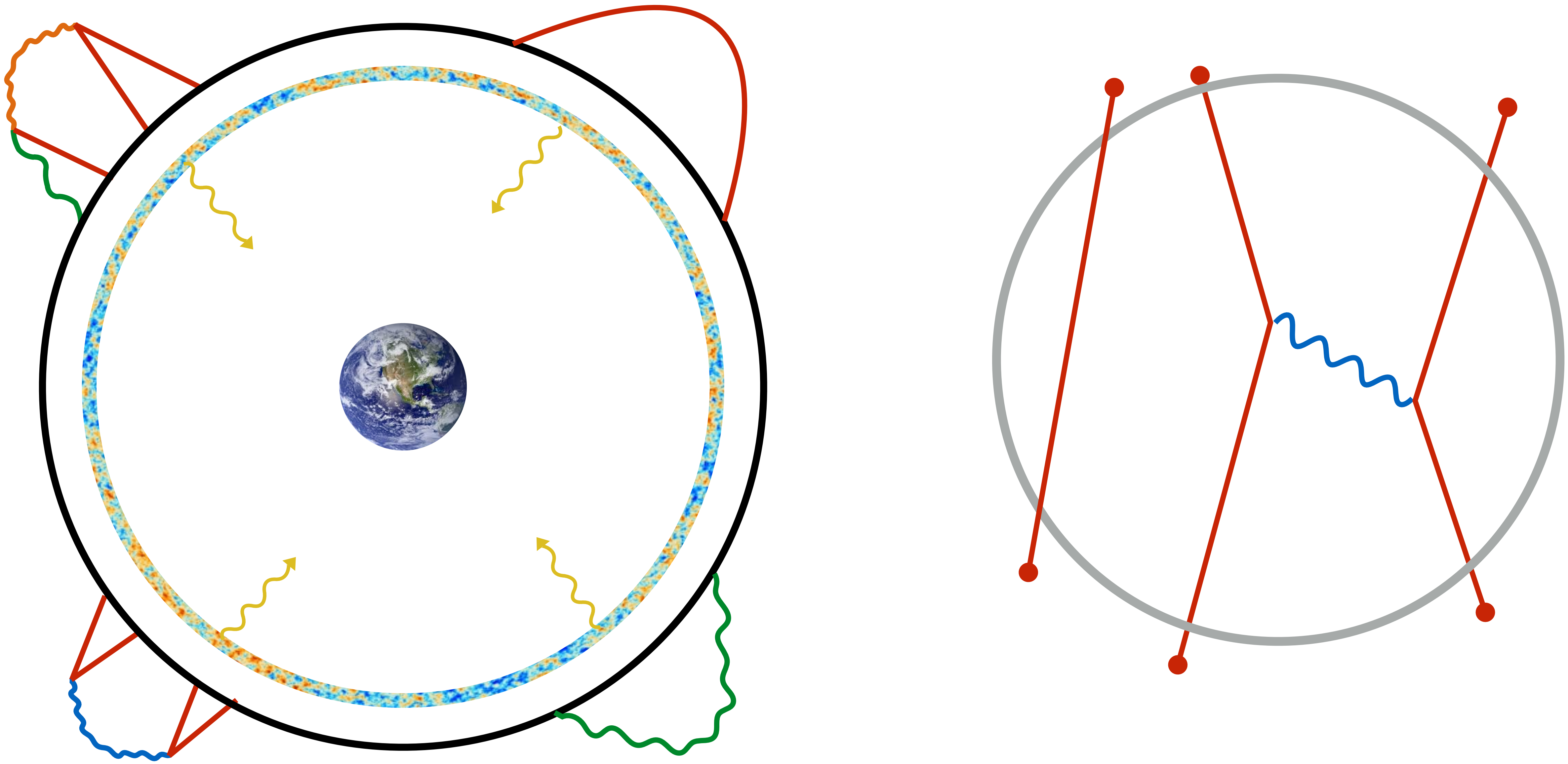
Inflation is most energetic event in nature, perhaps (LHC x billions)!





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

What collides? How?

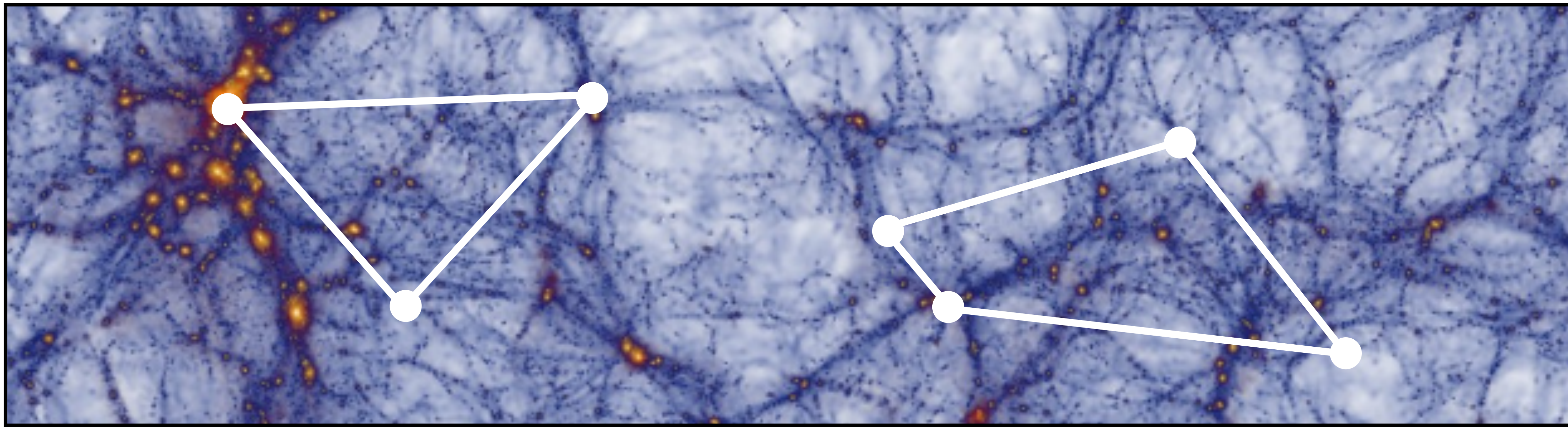


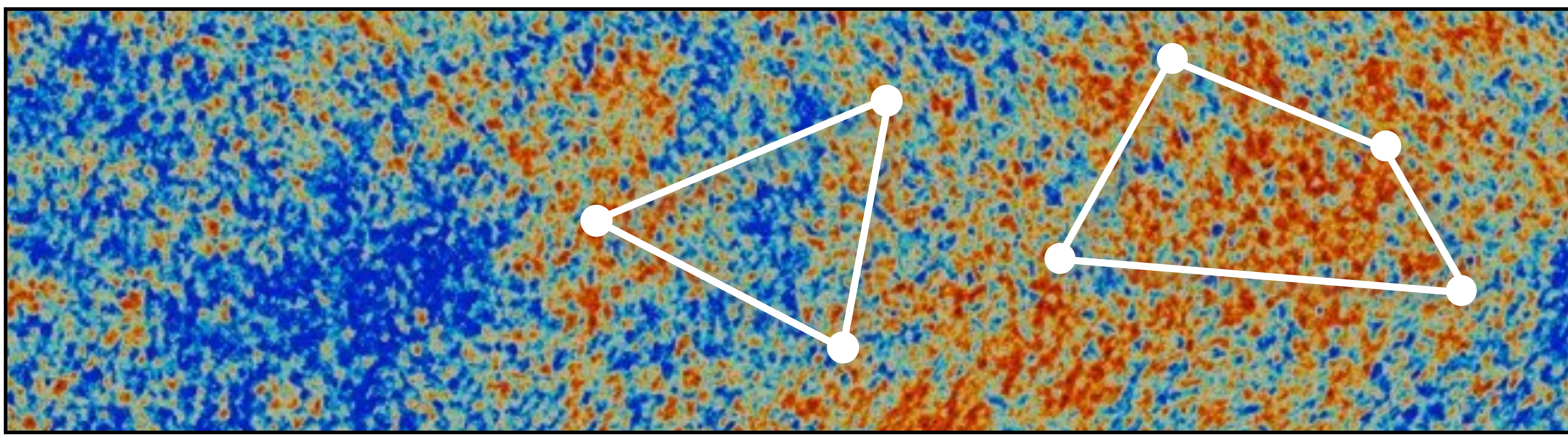
What — large two-point functions!

How — Higher-point functions!

The dynamics is encoded in those correlations.

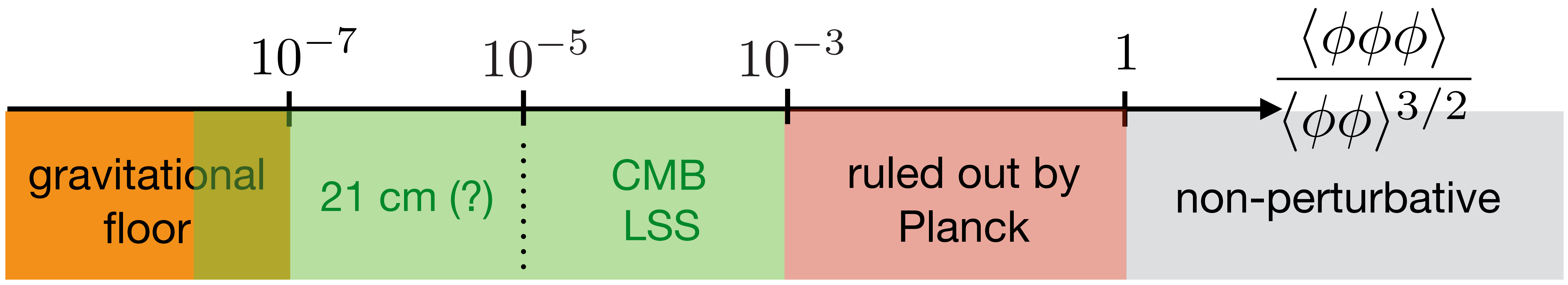
Cosmological Correlators





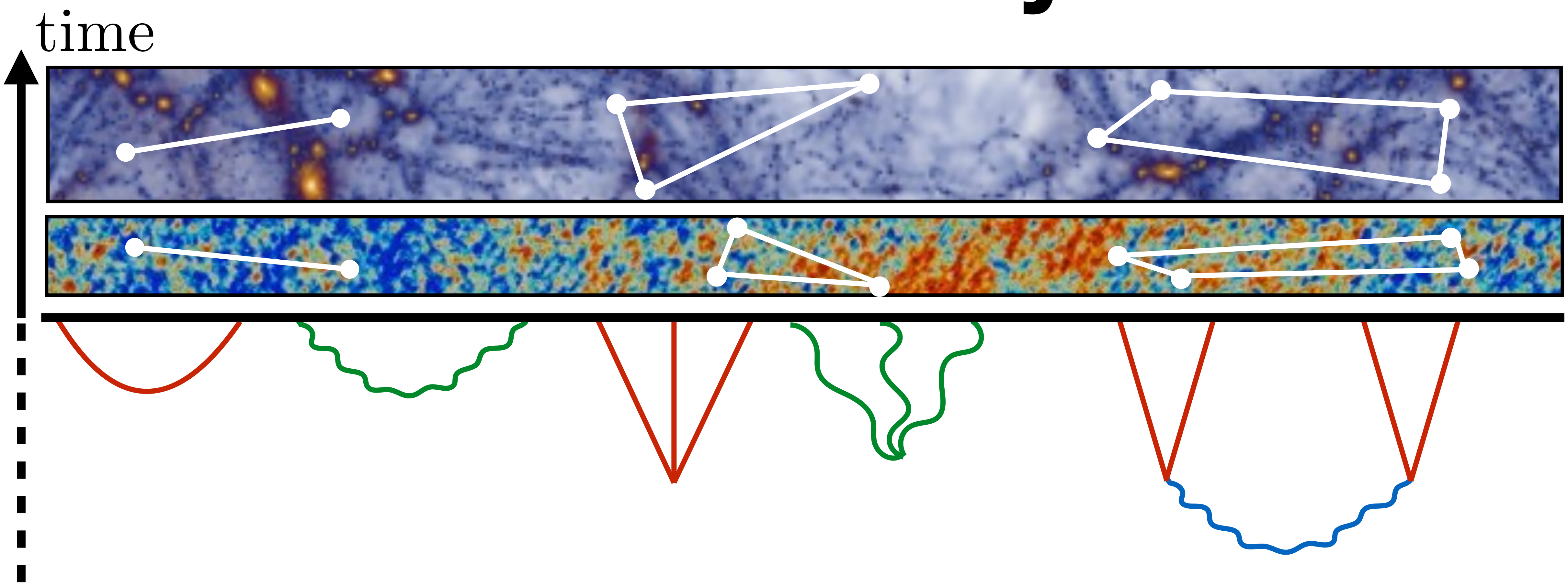
Scattering amplitudes in the sky!

How big is the signal?



We need <u>precise measurements</u>
& <u>precise theoretical predictions</u>!

Take Away

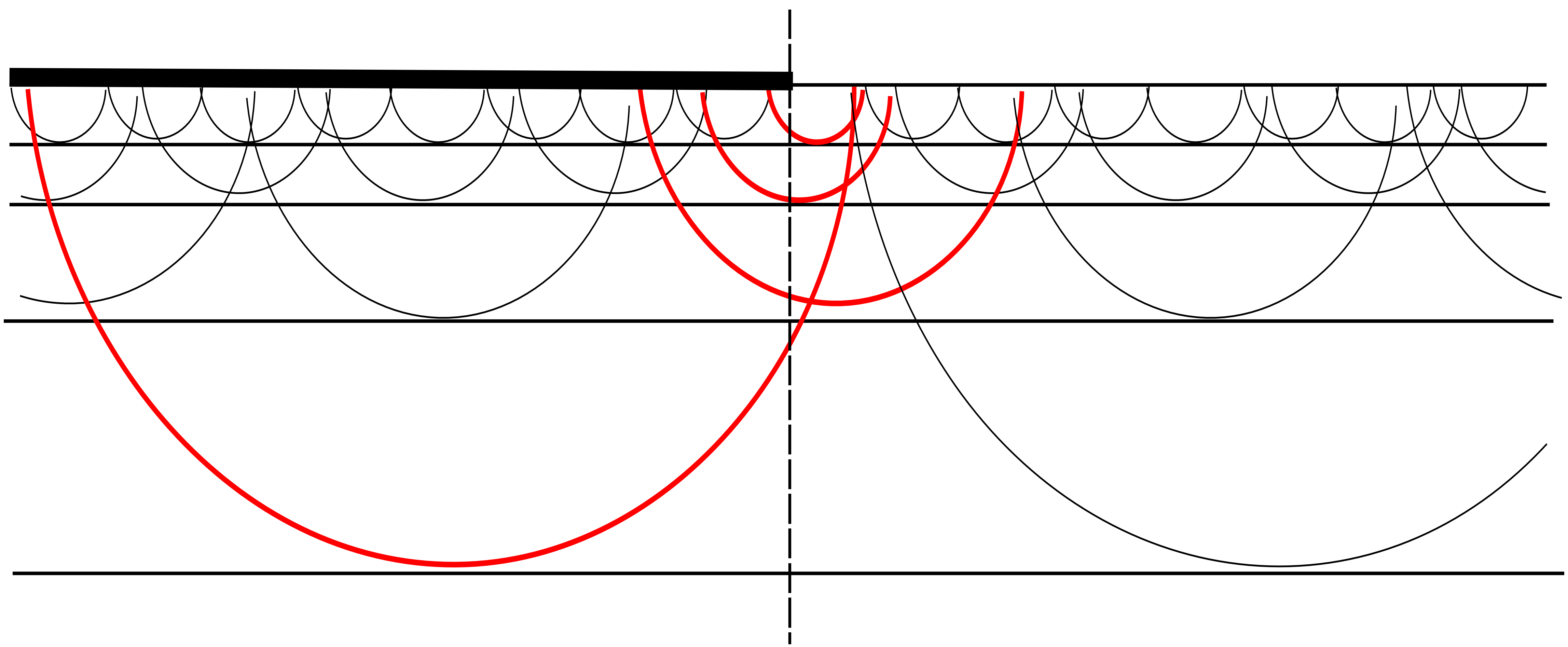


Fossils from the early universe
can be used as a unique particle detector.

These particles produce cosmological correlators
which <u>**encode**</u> the dynamics of the early universe.

Interlude

Entanglement



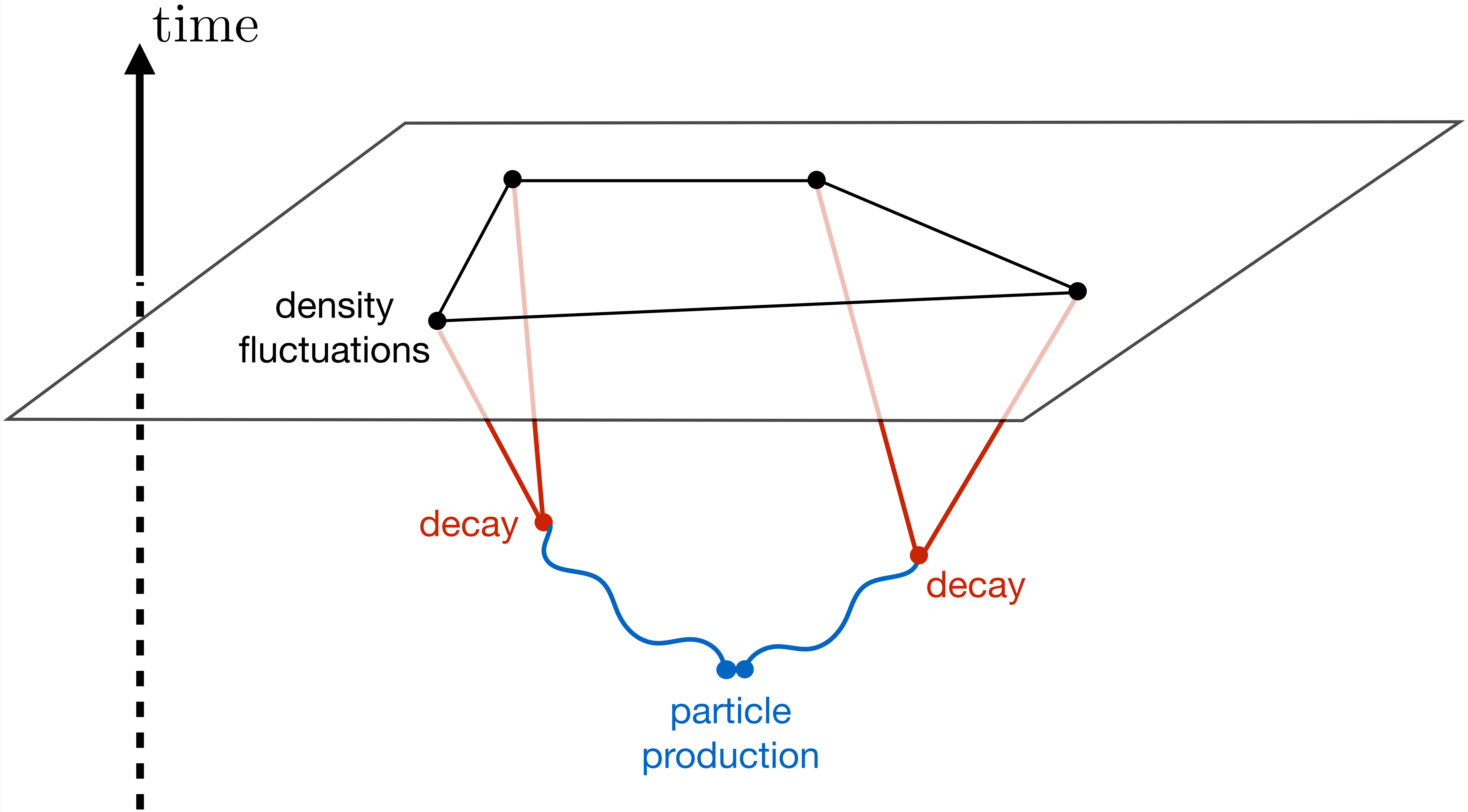
Neither thermal, nor like flat space vacuum.
I don't know how to probe it experimentally…

The Cosmological Bootstrap

Olena Shmahalo (*Quanta* magazine)

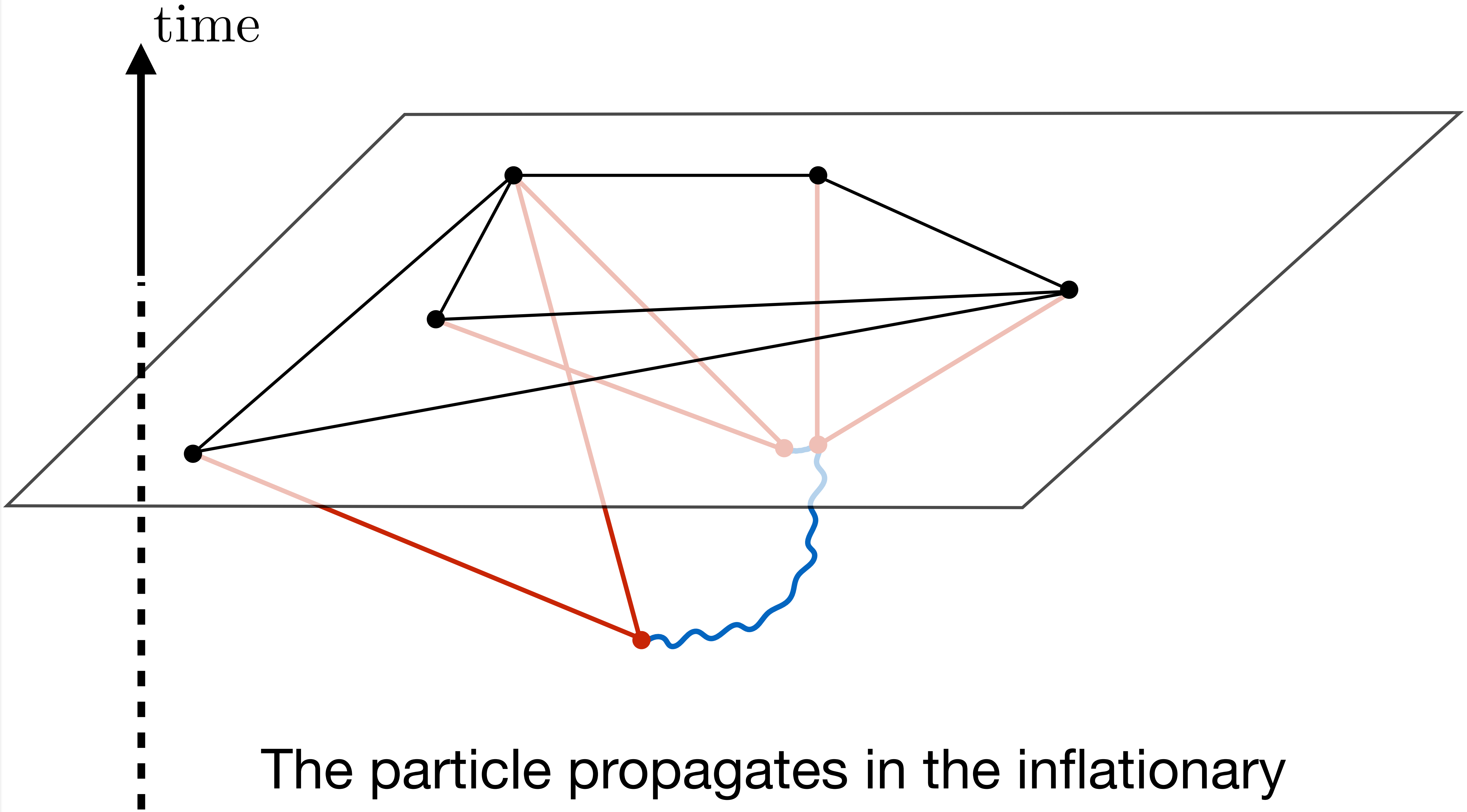
What are all the possible correlators?

Structure of Correlator



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

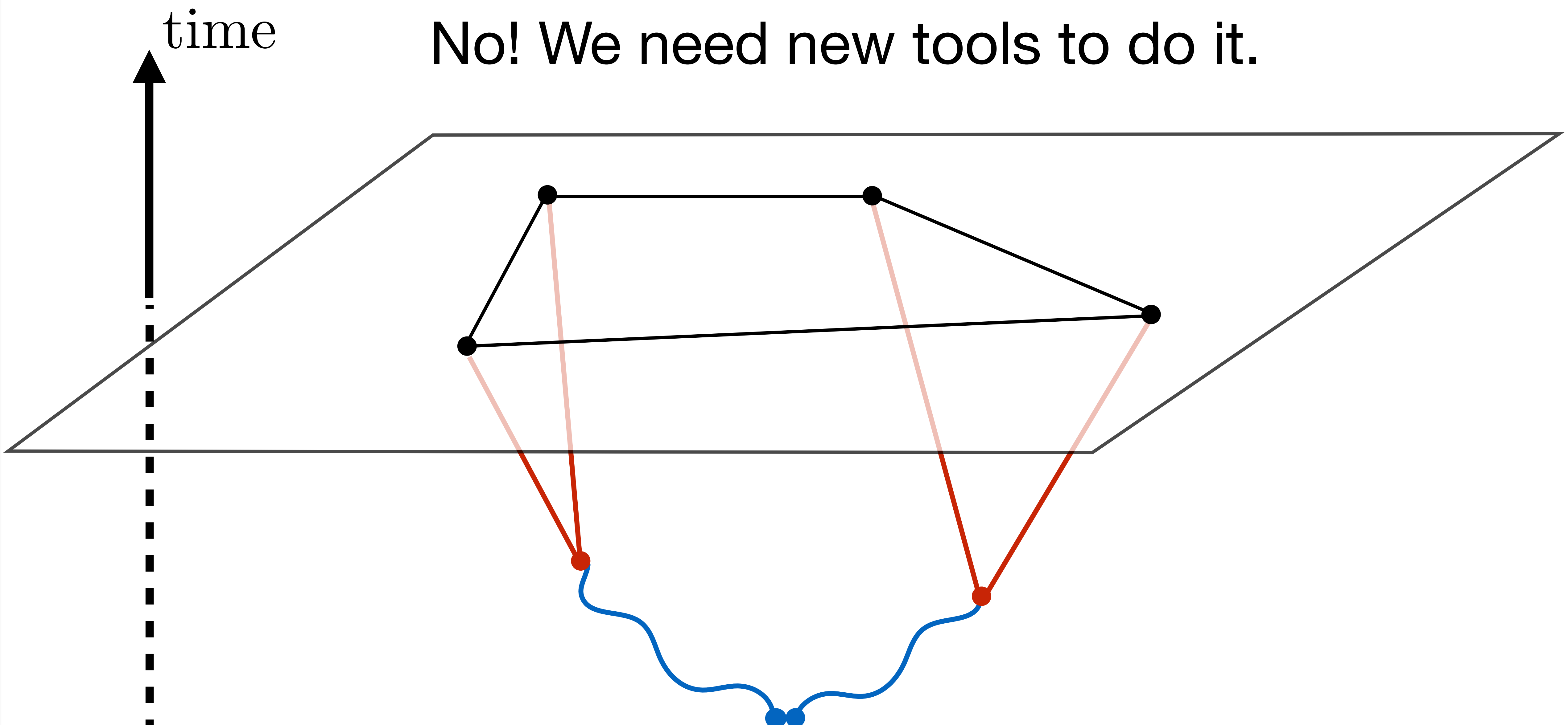
Particles as Tracers



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

Easy to Calculate?

No! We need new tools to do it.



$$\int \mathrm{d}t\,\mathrm{d}t'\; e^{i(k_1+k_2)t} e^{i(k_3+k_4)t'}\; G(|k_1+k_2|, t, t')$$

External Mode Functions

Lots of special (Hankel) functions

Bootstrap

Physical Principles
(Symmetry, Locality, Unitarity) → ~~Lagrangian~~ / ~~equations of motion~~ / ~~spacetime evolution~~ / ~~Feynman diagrams~~ → **Observables**

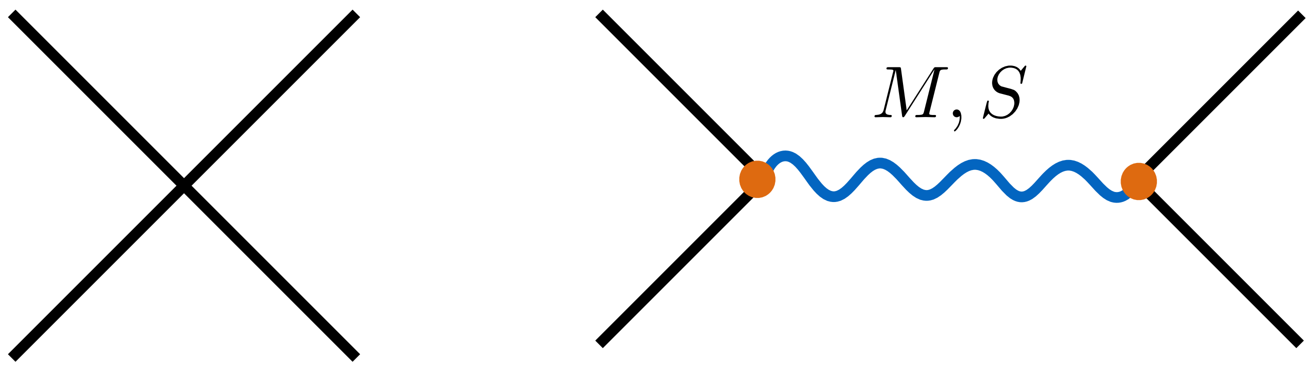
Bootstrap

- **Scattering amplitudes,**
- **Conformal field theories,**
- **Cosmological correlators?**

The S-matrix Bootstrap

Weakly coupled four-particle amplitude:

$$A(s,t) = \sum a_{nm} s^n t^m + \frac{g^2}{s - M^2} P_S\left(1 + \frac{2t}{M^2}\right)$$

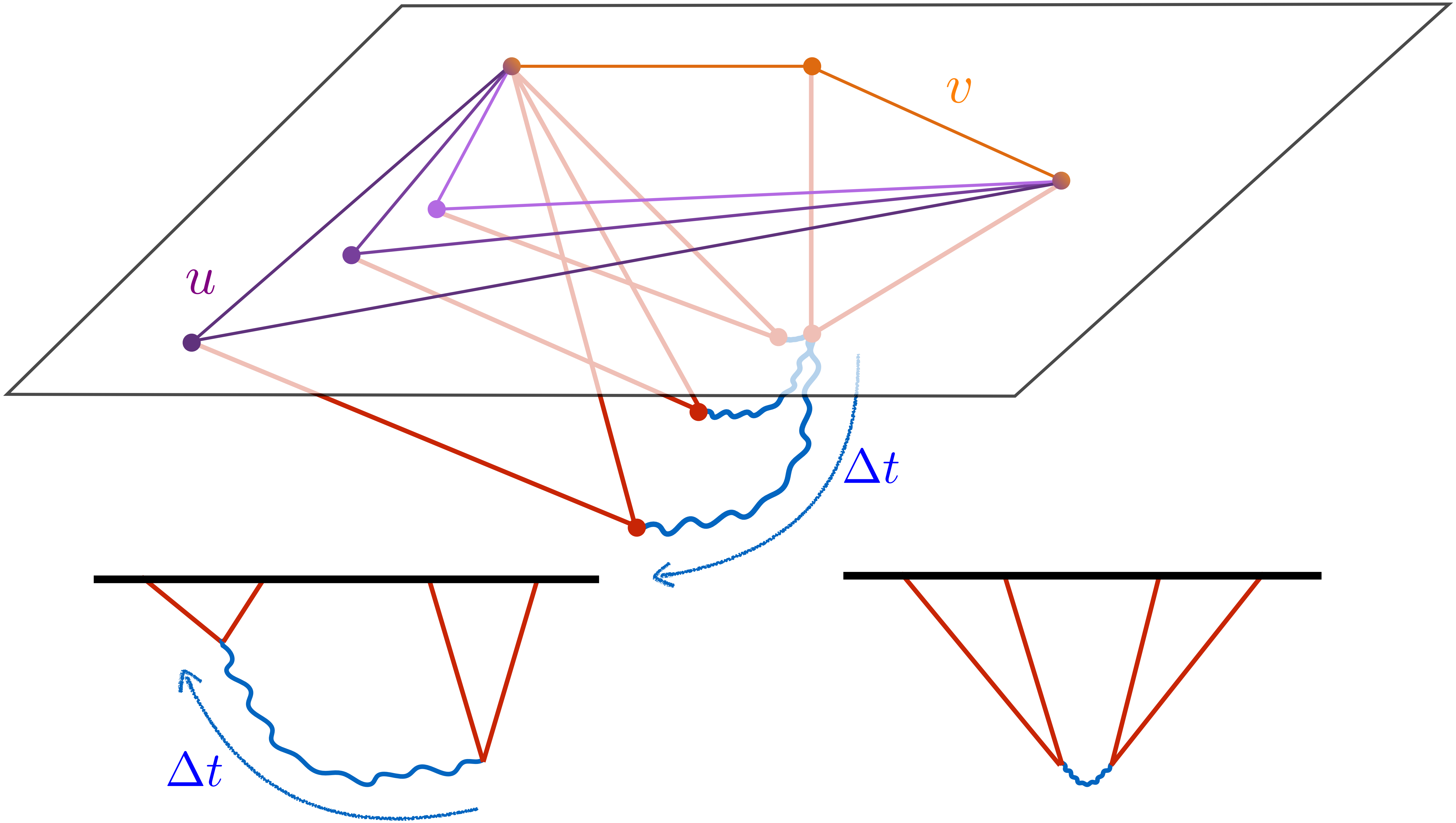


contact interactions

exchange interactions

No Lagrangian or Feynman diagrams.
Basic principles (symmetry, locality, unitarity)
allow only a small menu of possibilities.

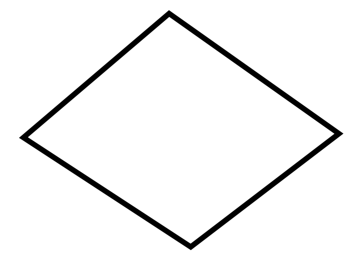
Time without Time

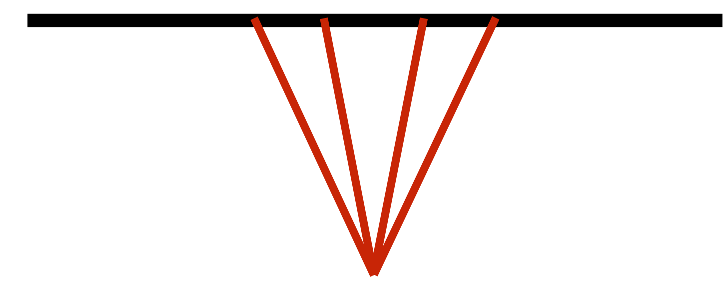


Particle Production

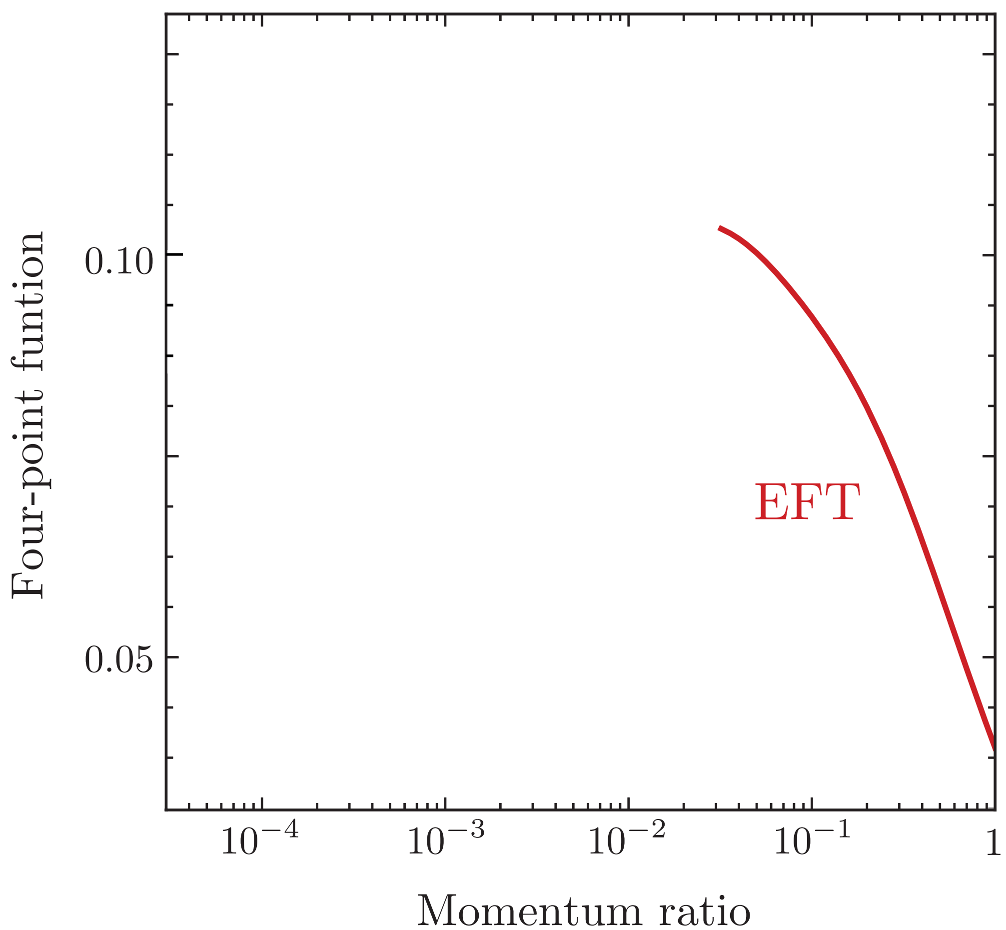
Contact Interaction

Cosmological Collider Physics

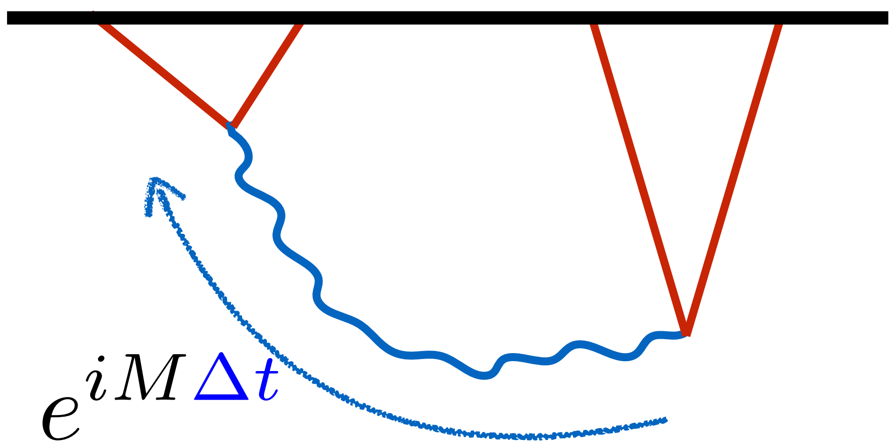


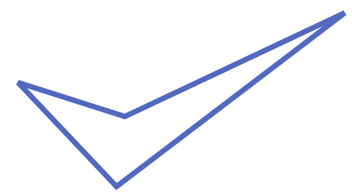


Equilateral
(EFT)

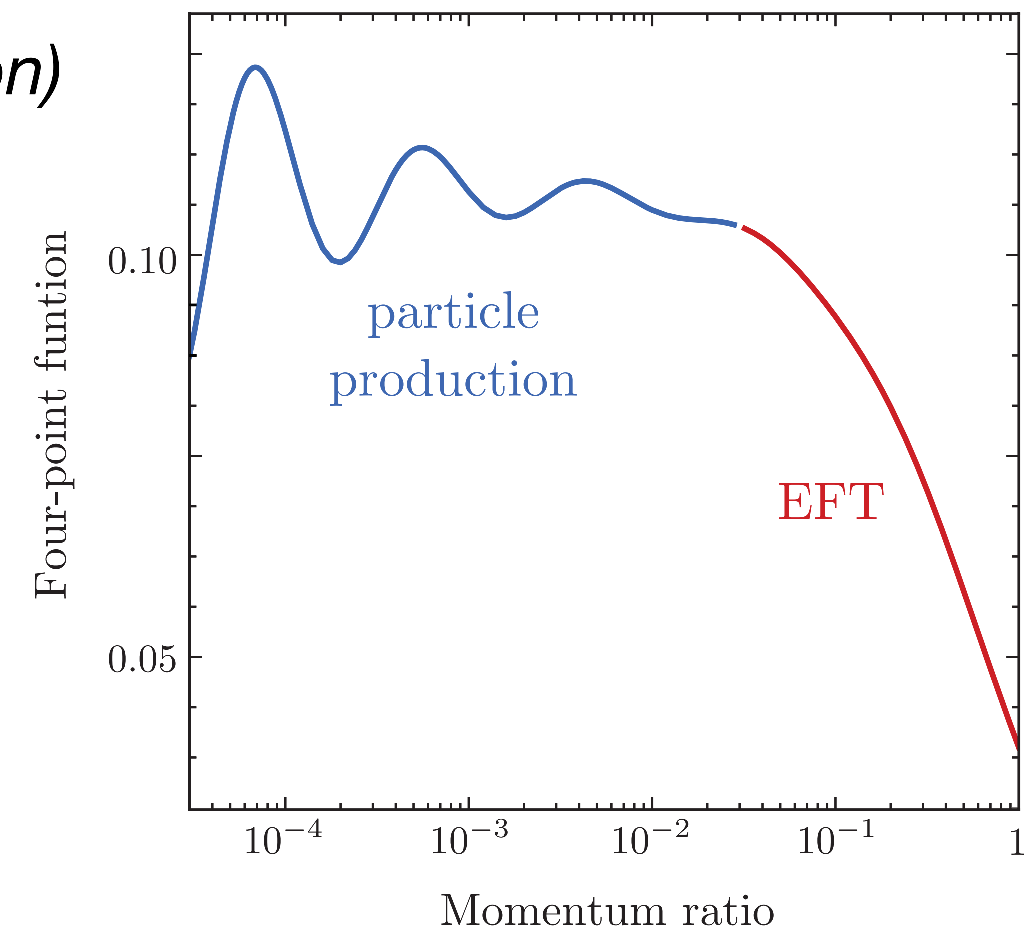


Cosmological Collider Physics





Collapsed
(particle production)



Particle Production

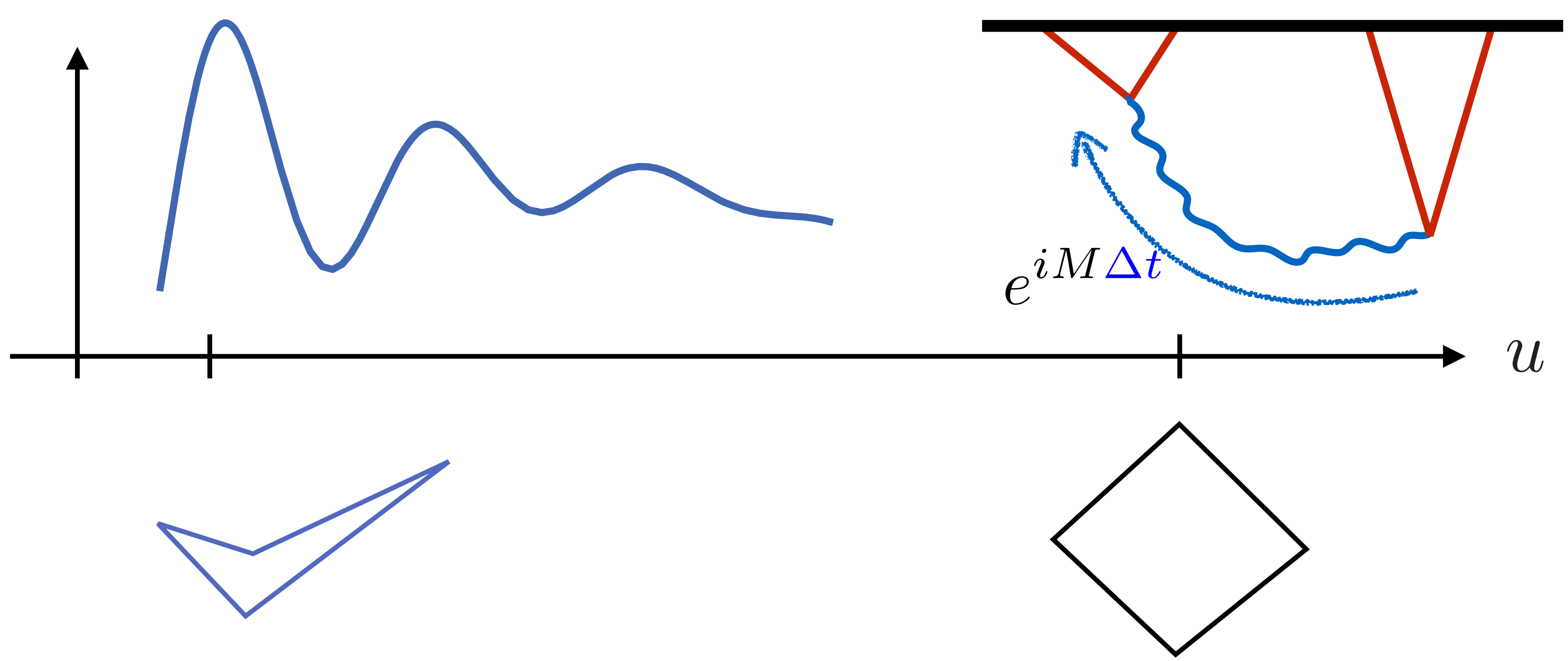
In the collapsed limit, dependence in **spatial** momenta is the same as **time evolution** of a harmonic oscillator

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

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

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

$F =$



Concrete Answer

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

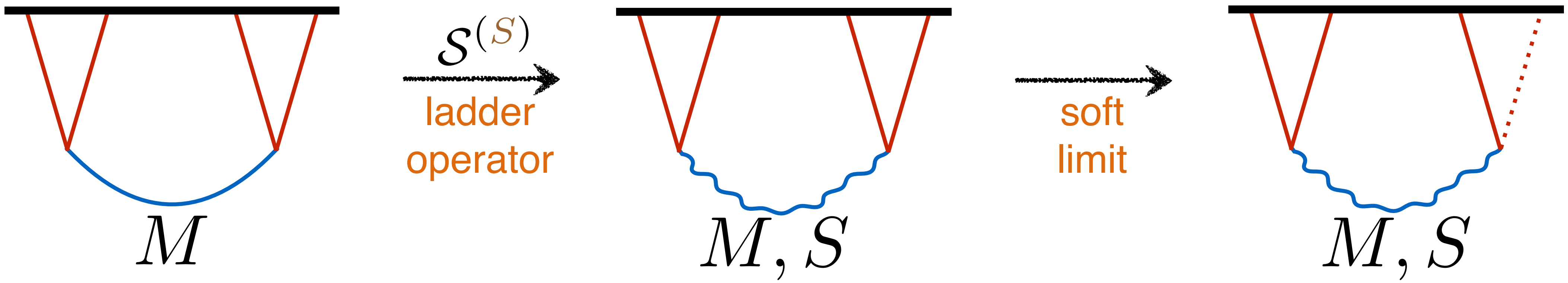
particle production

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

EFT

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

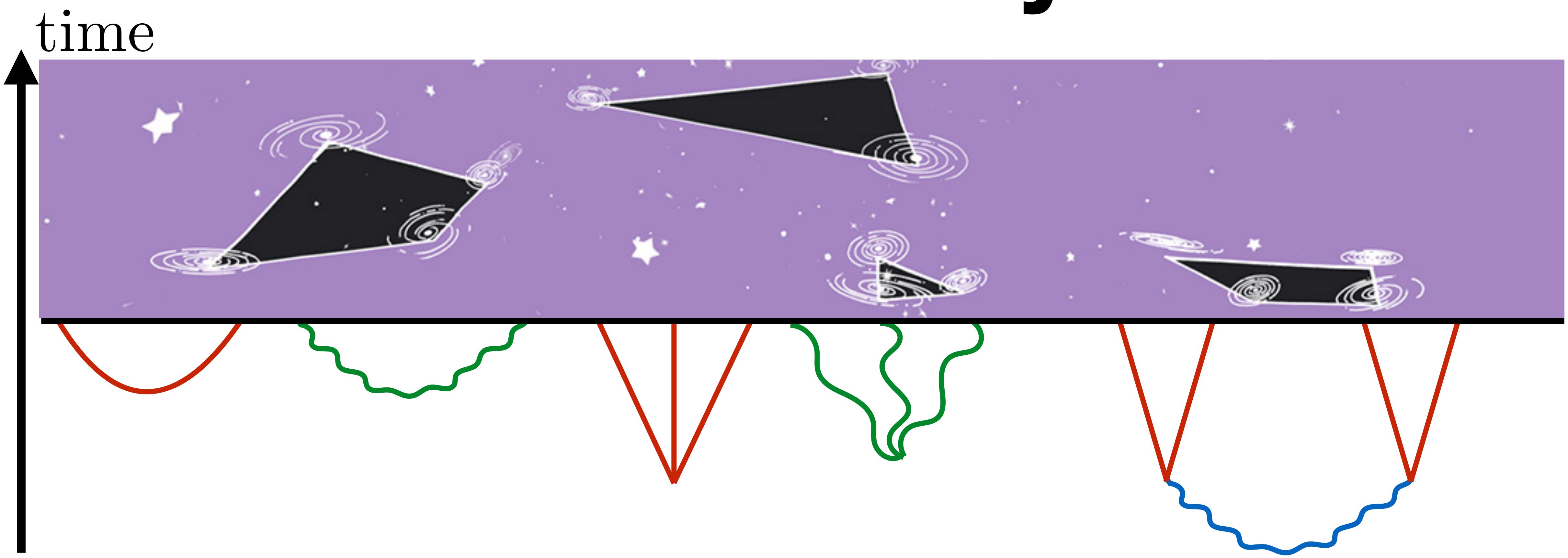
General Result



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

Parametrized by mass, spin, & coupling.

Take Away



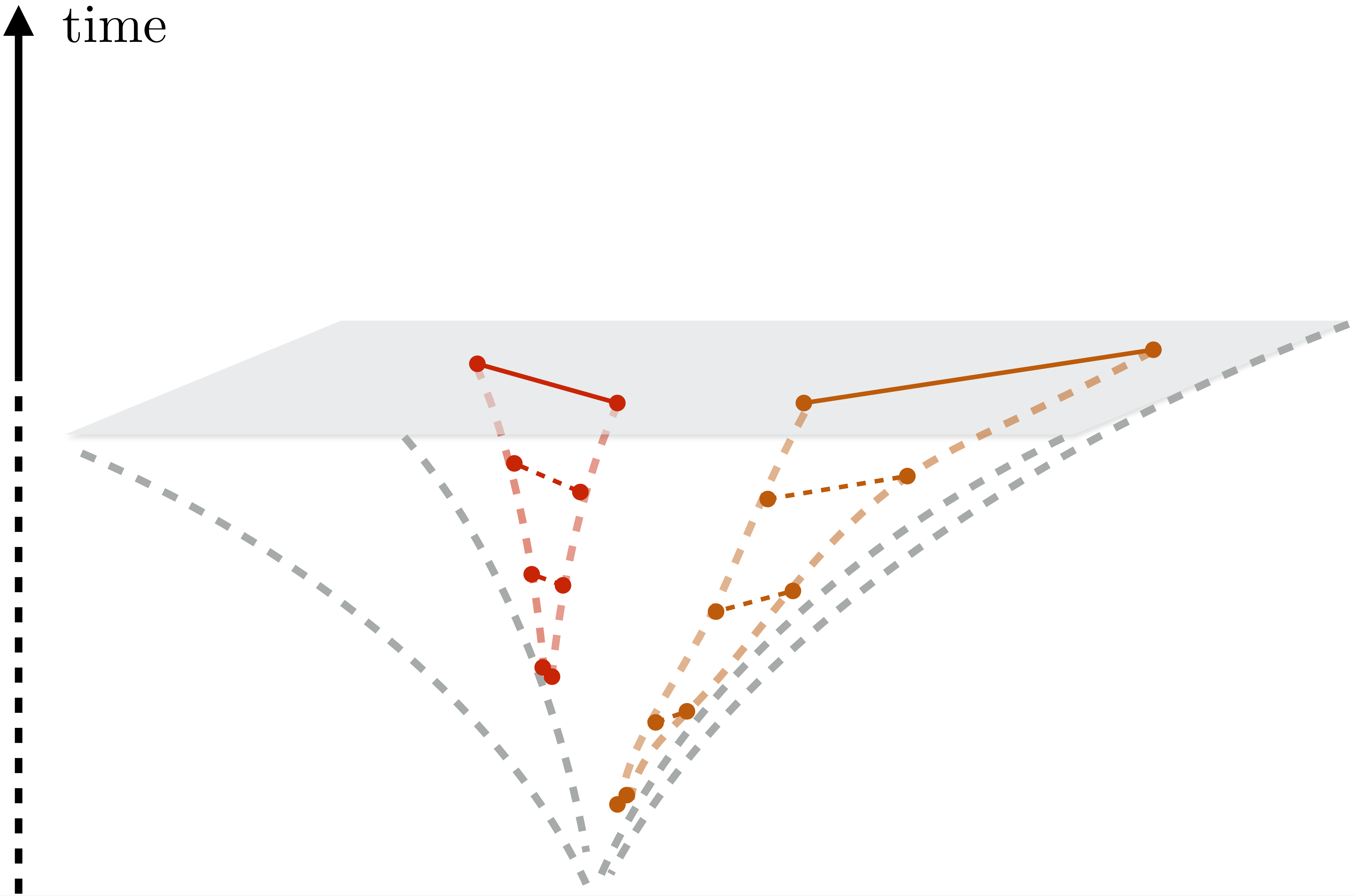
Small menu of cosmological correlators! Amazingly, highly constrained by **locality**, **unitarity** and **symmetry**.

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

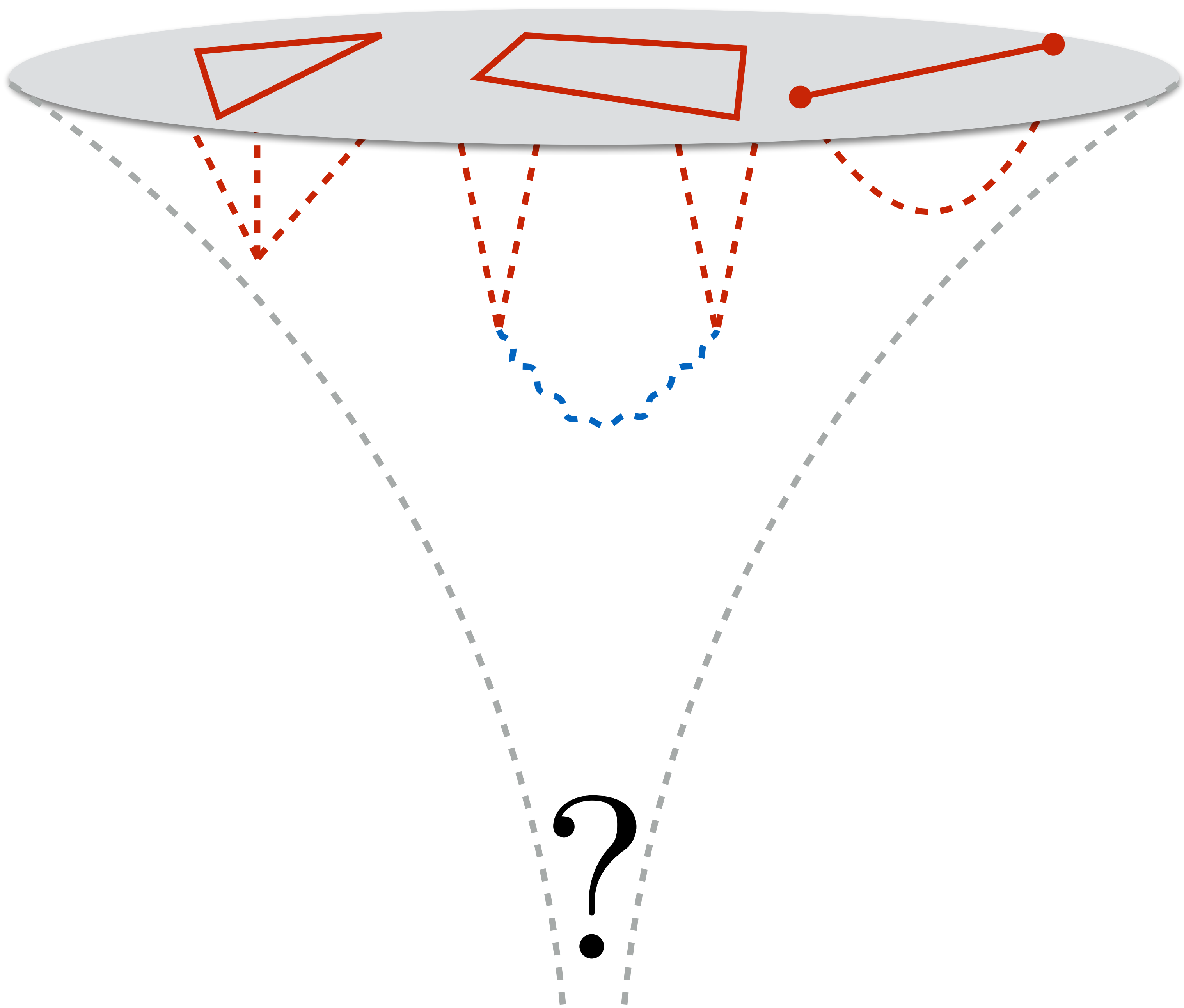
Time without Time



Hypothesis

Time evolution emerges from **static differential equations**

Cosmology & Holography

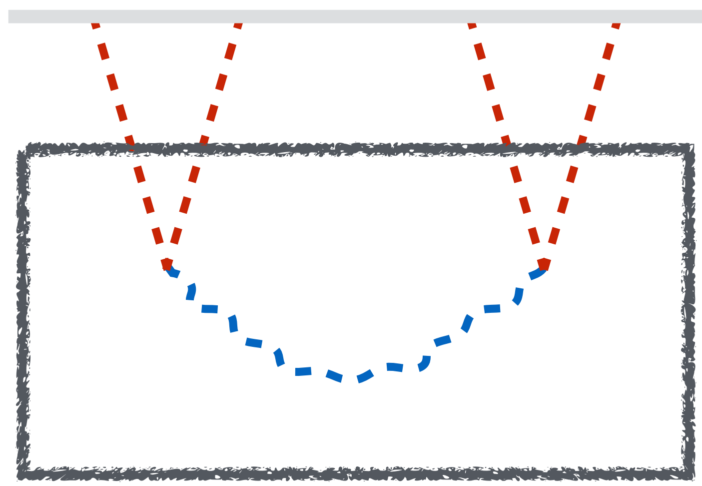


In quantum gravity, boundary observables are well-defined.

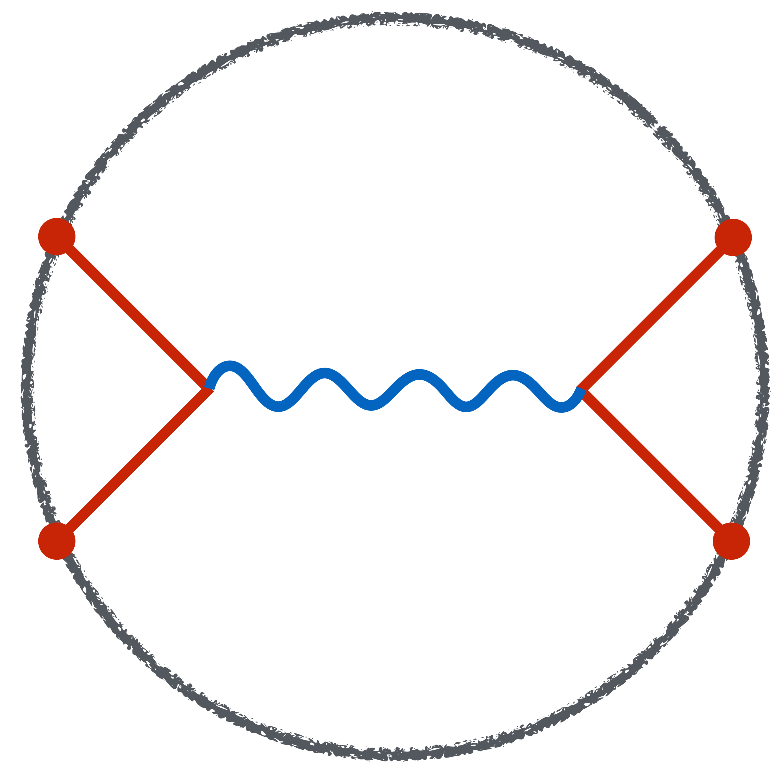
Cosmology & Scattering

$$\color{purple}{X_1} + \color{orange}{X_2} = E$$ ← "Total Energy"

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

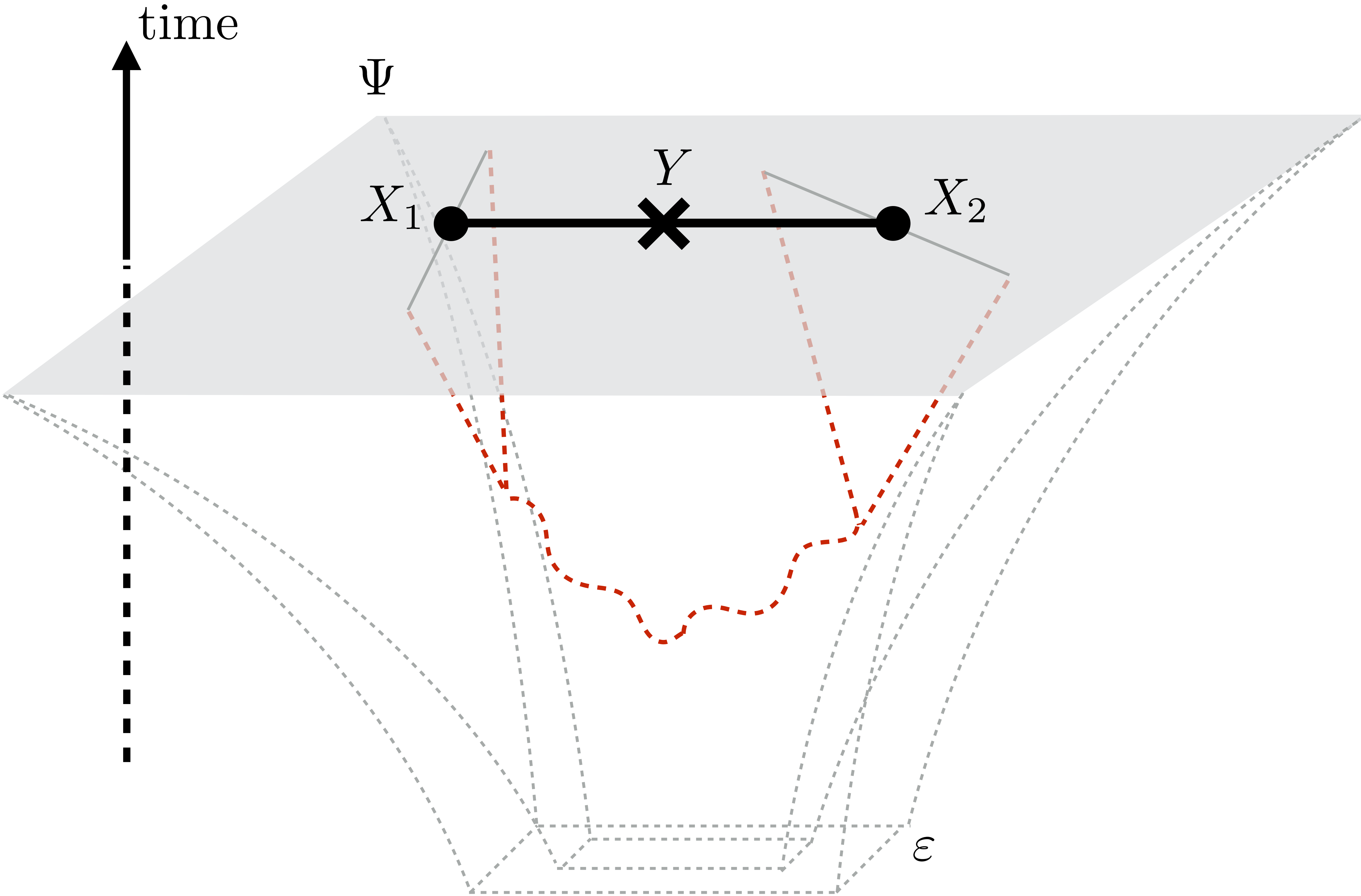


$$= \frac{1}{E^{\#}}$$

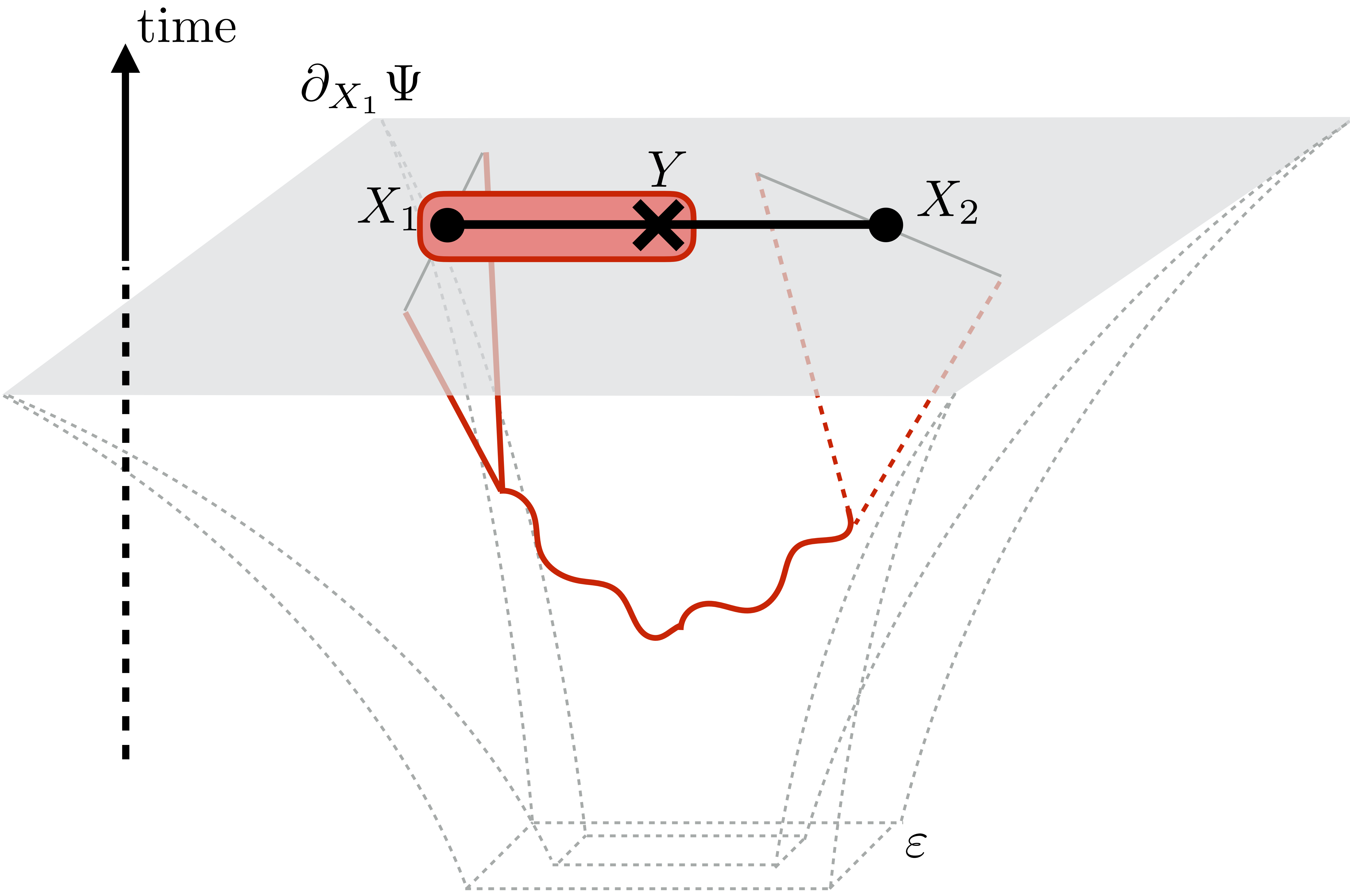


The S-matrix is <u>contained</u> in the
analytic structure of Cosmological Correlators!

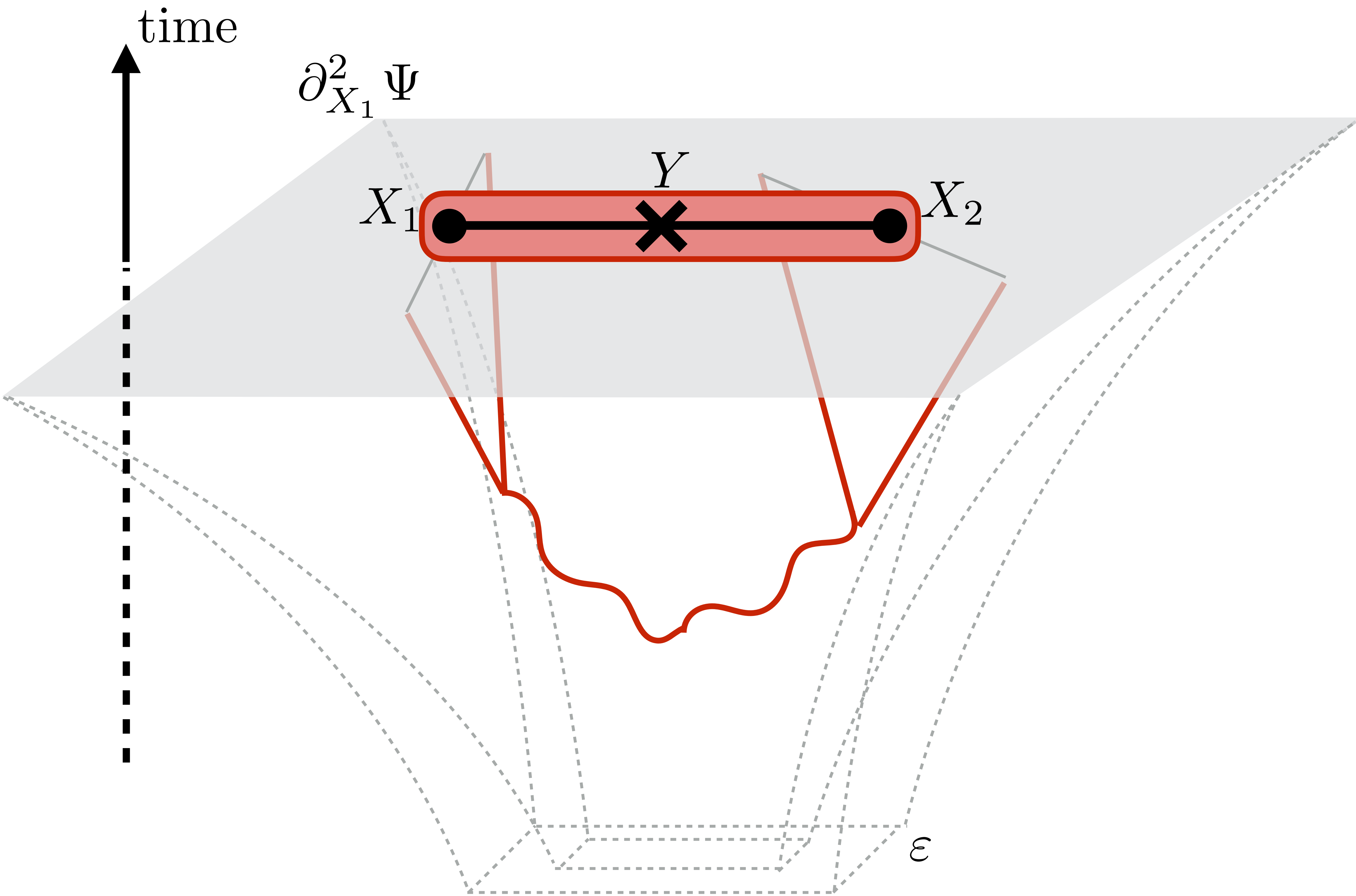
Kinematic Flow



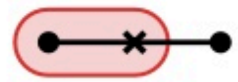
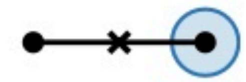
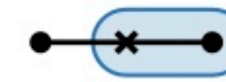
Kinematic Flow

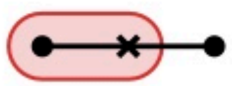
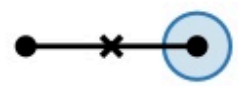
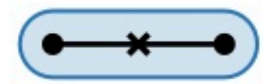


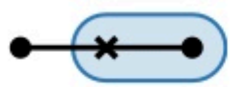
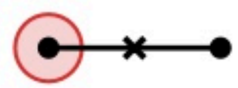
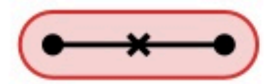
Kinematic Flow



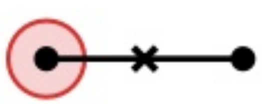
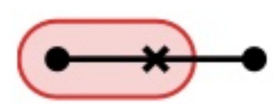
Kinematic Flow

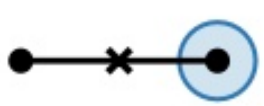
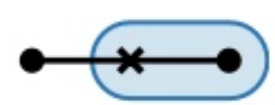
$\mathrm{d}\psi = \varepsilon\Big[(\psi - F)$  $+\ F$  $+\ (\psi - \tilde{F})$  $+\ \tilde{F}$  $\Big]$

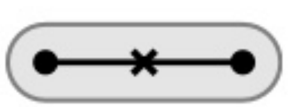
$\mathrm{d}F = \varepsilon\Big[F$  $+\ (F - Z)$  $+\ Z$  $\Big]$

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

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

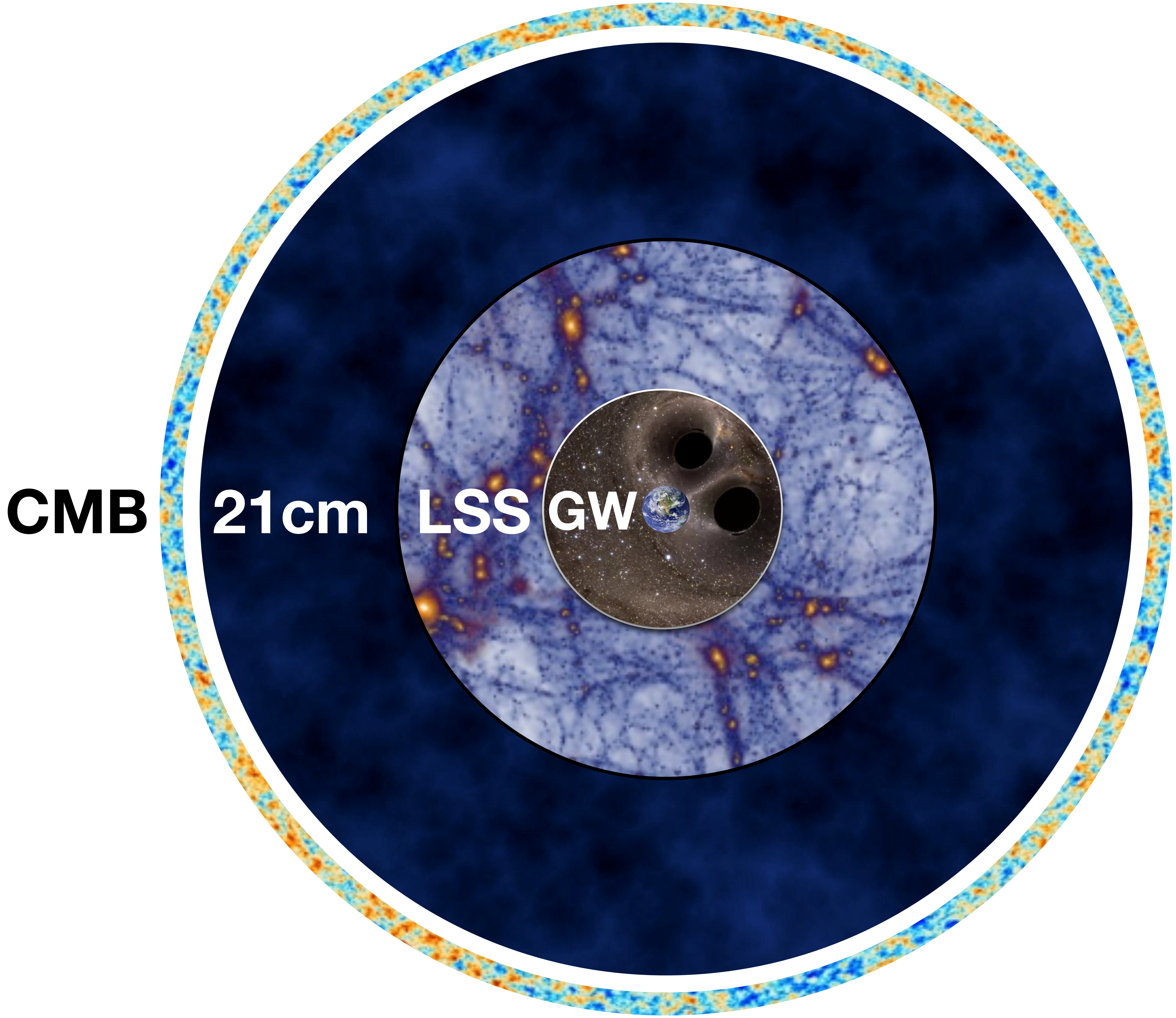
 $\equiv \mathrm{d}\log(X_1 + Y)\,,$  $\equiv \mathrm{d}\log(X_1 - Y)\,,$

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

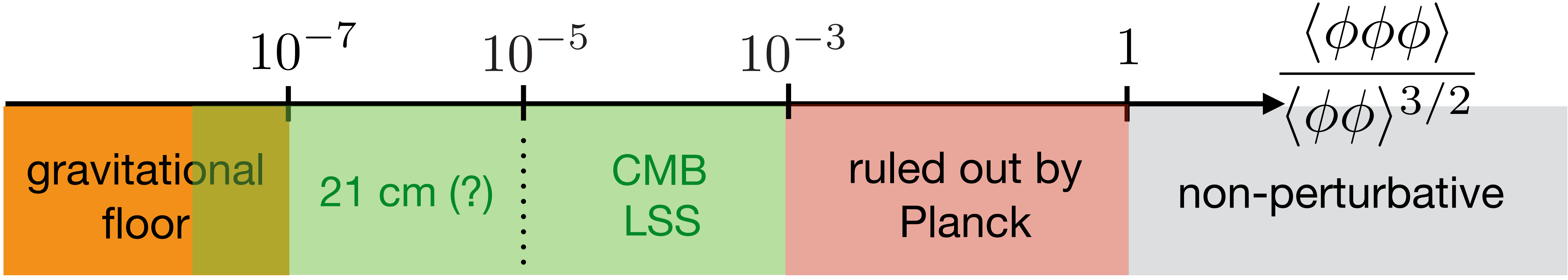
 $\equiv \mathrm{d}\log(X_1 + X_2)\,.$

Future

Observational Landscape

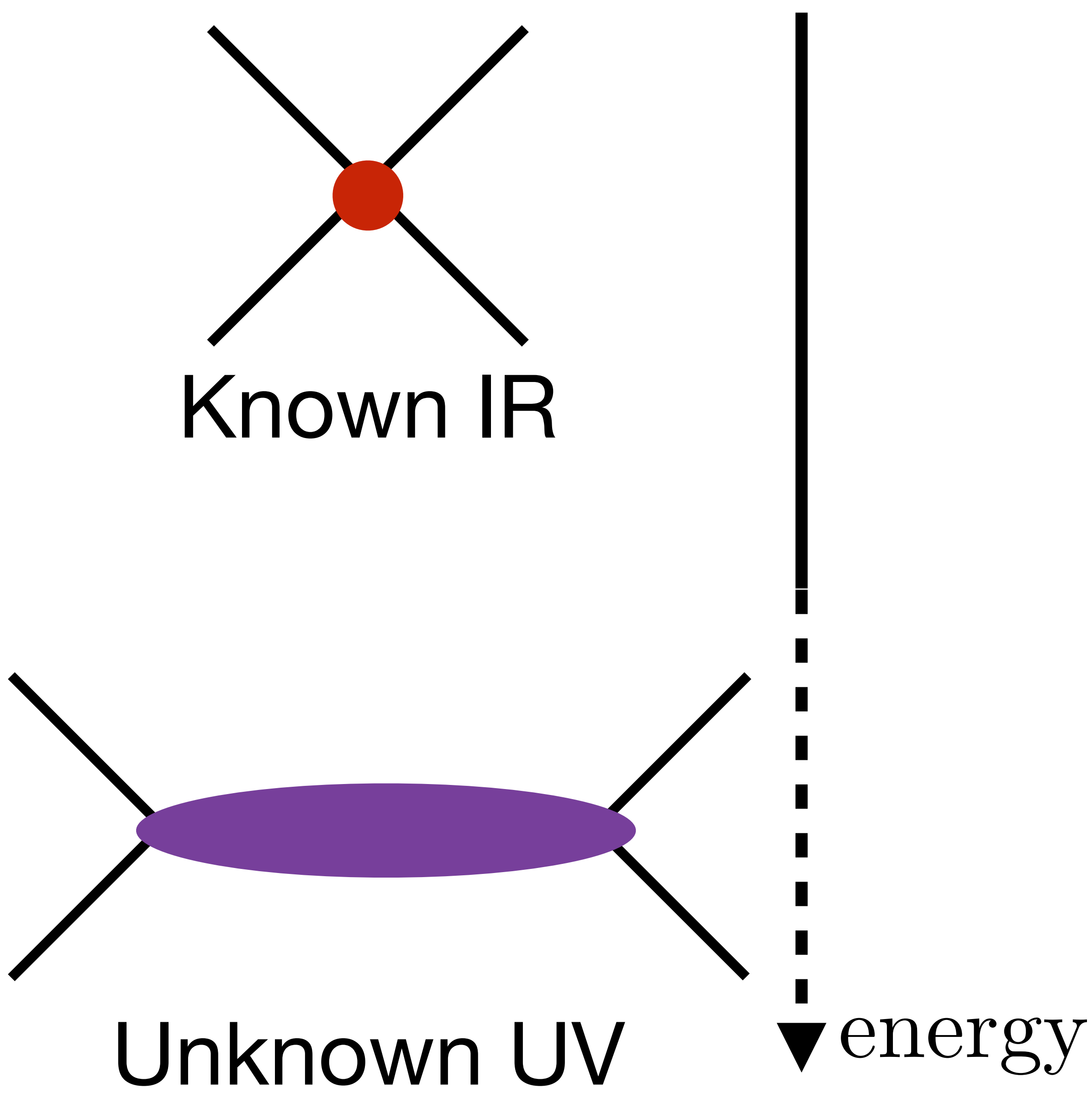


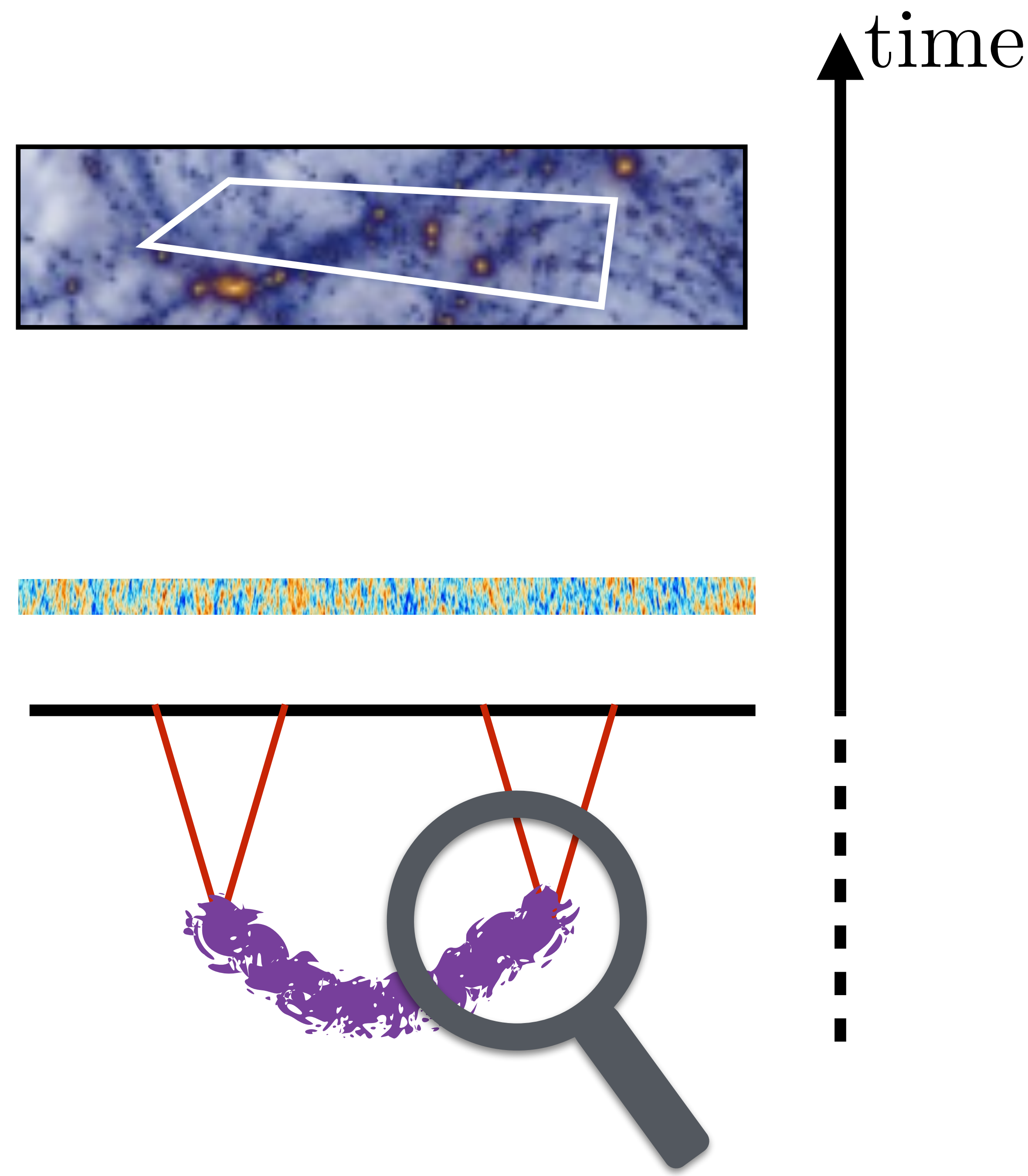
Targets



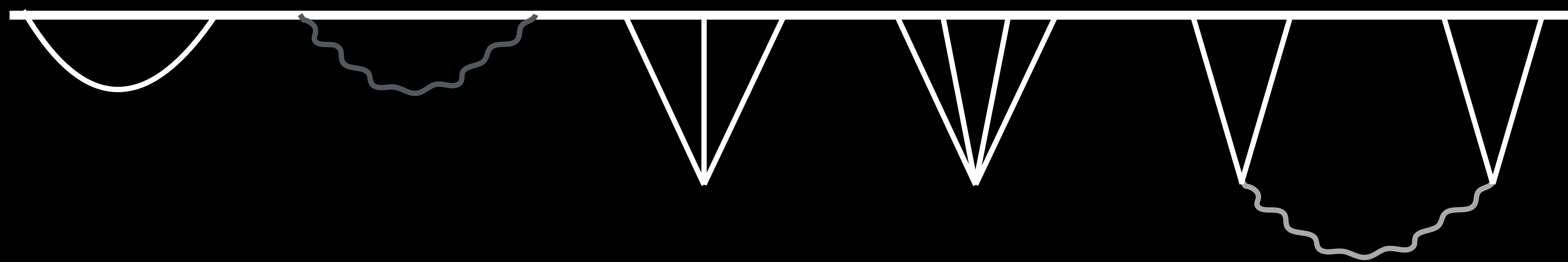
Probe	Modes
CMB	10^6
LSS	10^8
21 cm, ground	10^9
21 cm, moon	10^{12}

Microscopics





A detailed **theoretical understanding** of microscopic dynamics constrains **possible observations**



Cosmological correlators probe <u>particle collisions</u> in the sky at ultra high energies!

Bootstrap gives <u>new perspective</u> on cosmological correlators.

Time evolution is <u>encoded</u> in spatial patterns.

Differential equations <u>decode</u> these patterns.

We might be seeing glimpses of a <u>timeless</u> description of cosmology.