

# **Cosmology and String Theory**

Discussion Session at STRINGS 2021

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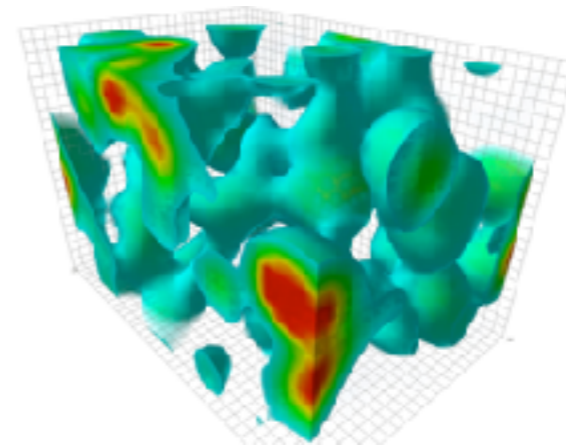
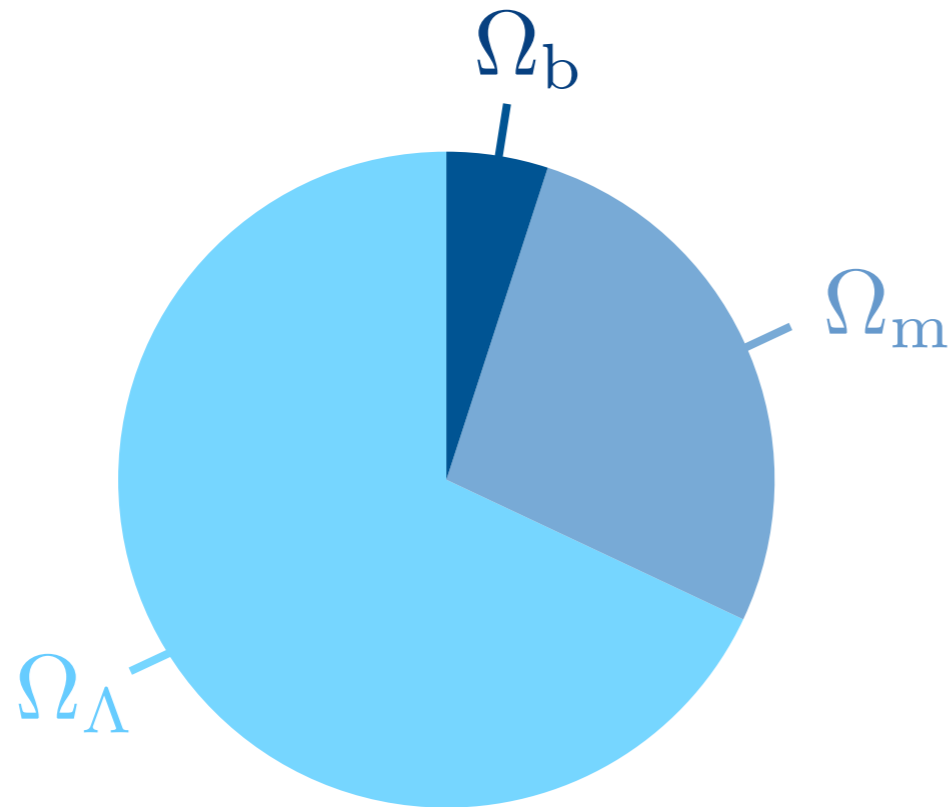
- Requires de Sitter vacua
- Time as an emergent dimension
- Precision data: CMB, LSS

- Inflationary models are UV sensitive
- String theory motivates novel EFTs
- Signatures: B-modes, non-Gaussianity

# The Standard Model

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A **simple** 5 parameter model fits all observations:



$A_s, n_s$

It is a **strange** model because none of these parameters are well understood.

- Dark energy and inflation are UV sensitive (see de Sitter discussion).
- Quantum gravity is the conceptual foundation of cosmology.


→ An opportunity for string theory.

# The Hubble Tension


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There is a persistent disagreement in measurements of the Hubble constant:

CMB


$$H_0 = 67.4 \pm 0.5$$

Supernovae


$$74.0 \pm 1.4$$

New physics or systematic errors?



“Any theory that can account for all the facts is wrong, because some of the facts are always wrong.” Francis Crick

# The Hubble Tension

Hard to explain with new physics:

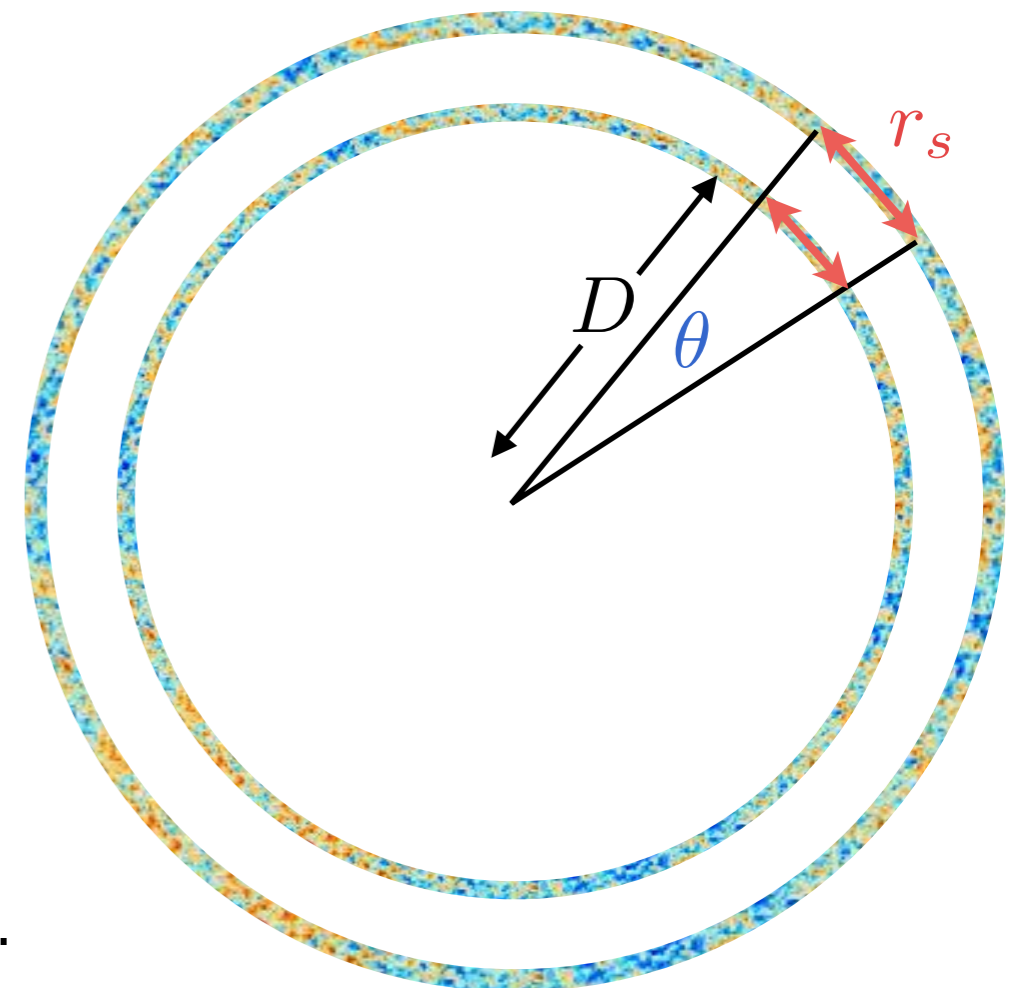
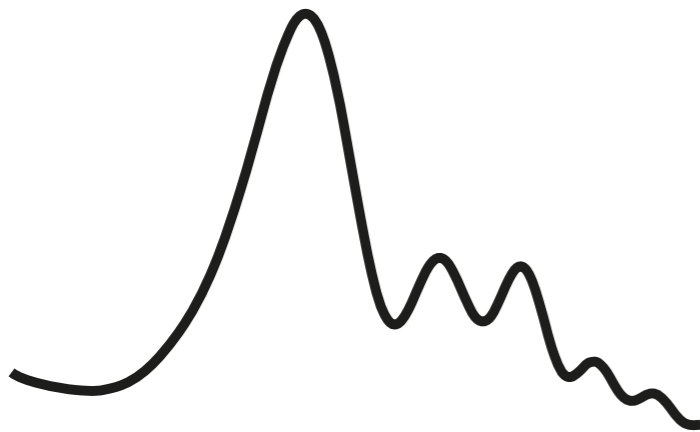
$$\theta = \frac{r_s}{D}$$

← Sound horizon at recombination

← Distance to last-scattering

$$D = \int_0^{z_*} \frac{dz}{H_0 \sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}}$$

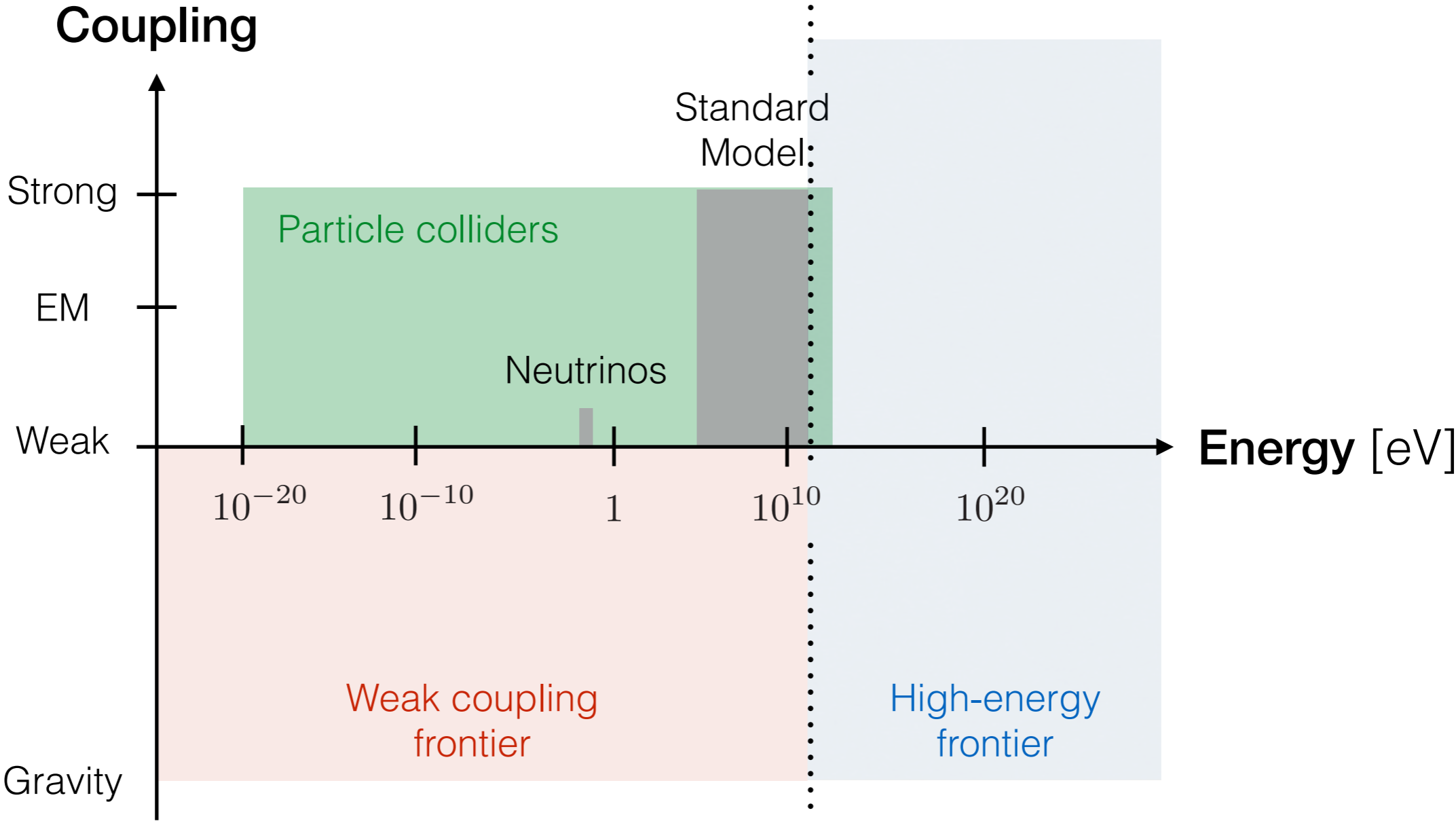
Angular separation of peaks  
in the CMB spectrum



- Needed: 10% reduction of the sound horizon.
- Hard to achieve without messing up the CMB.

# High Energies and Weak Couplings

The early universe probes **high energies** and **weak couplings**:

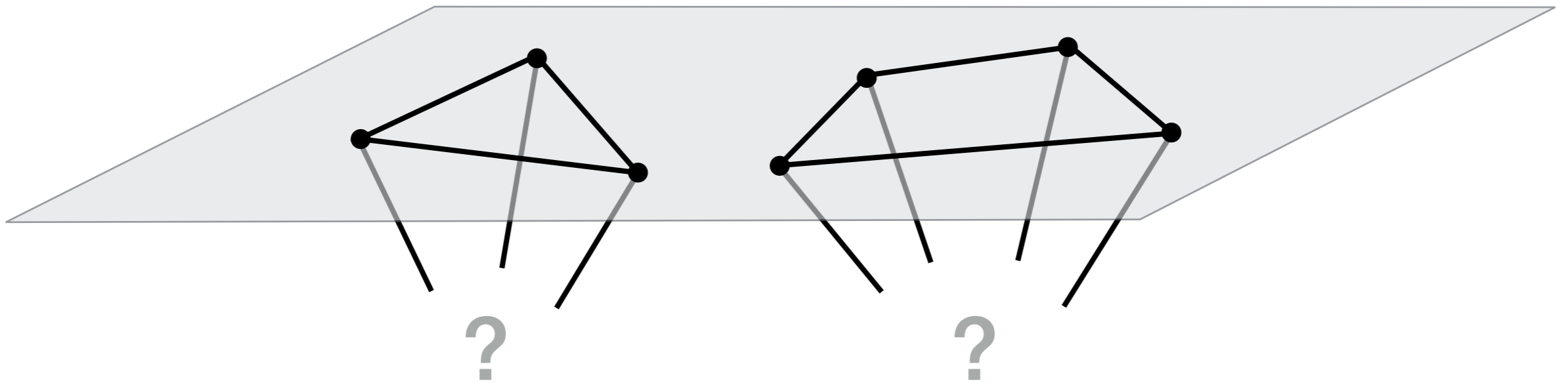
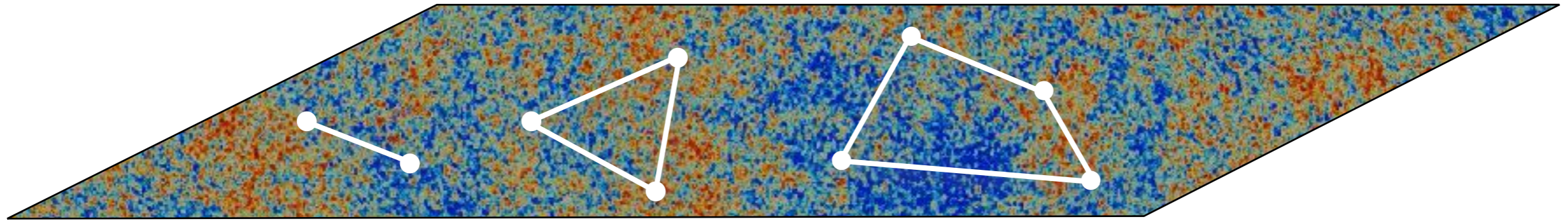


String theory is relevant in both regimes.

# Cosmological Correlations

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High-energy physics is encoded in cosmological correlations:

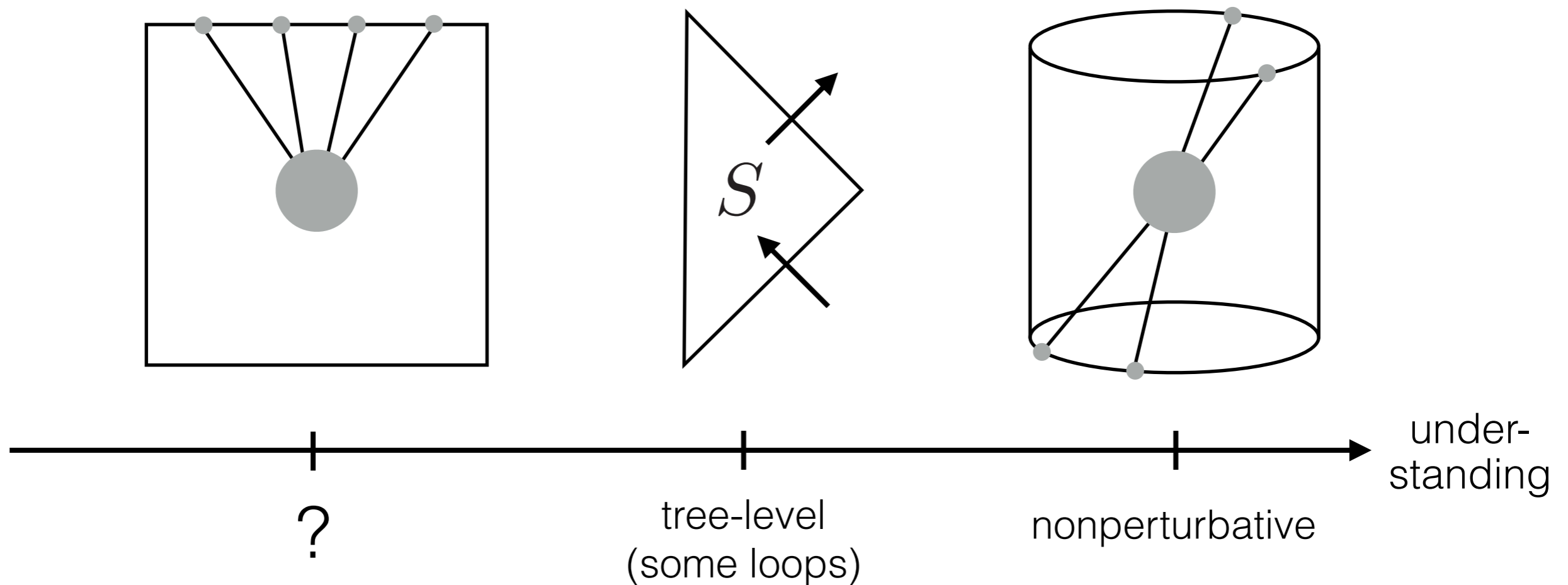


- What is the space of consistent correlations?
- What does string theory predict for these correlations?
- What is natural in string theory? (but maybe surprising in EFT?)

# Unique Challenges of Cosmology

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- Time (not space) may be emergent.
- Boundary theory is not Lorentz-invariant.
- Boundary theory is not unitary.
- Interactions are scale, but not conformally invariant.
- Lack of rigorous nonperturbative observables.





# Recent Progress

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Improved understanding of the analytic structure of cosmological correlators:

$$\begin{aligned} \lim_{E \rightarrow 0} & \text{ [Blue Parallelogram] } = \frac{\text{ [Scattering Amplitude Diagram] }}{E^p} \\ \lim_{E_L \rightarrow 0} & \text{ [Blue and Red Triangle] } = \frac{\text{ [Scattering Amplitude Diagram] } \times \text{ [Red Triangle] }}{E_L^q} \end{aligned}$$

- Correlators can be built from scattering amplitudes.
- Singularities are connected by differential equations and unitarity constraints.

Arkani-Hamed and Maldacena [2015]

Arkani-Hamed, Benincasa and Postnikov [2017]

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

Sleight and Taronna [2019]

Goodhew, Jazayeri and Pajer [2020]

DB, Chen, Duaso Pueyo, Joyce, Lee and Pimentel [2021]

# Unique Opportunities of Cosmology

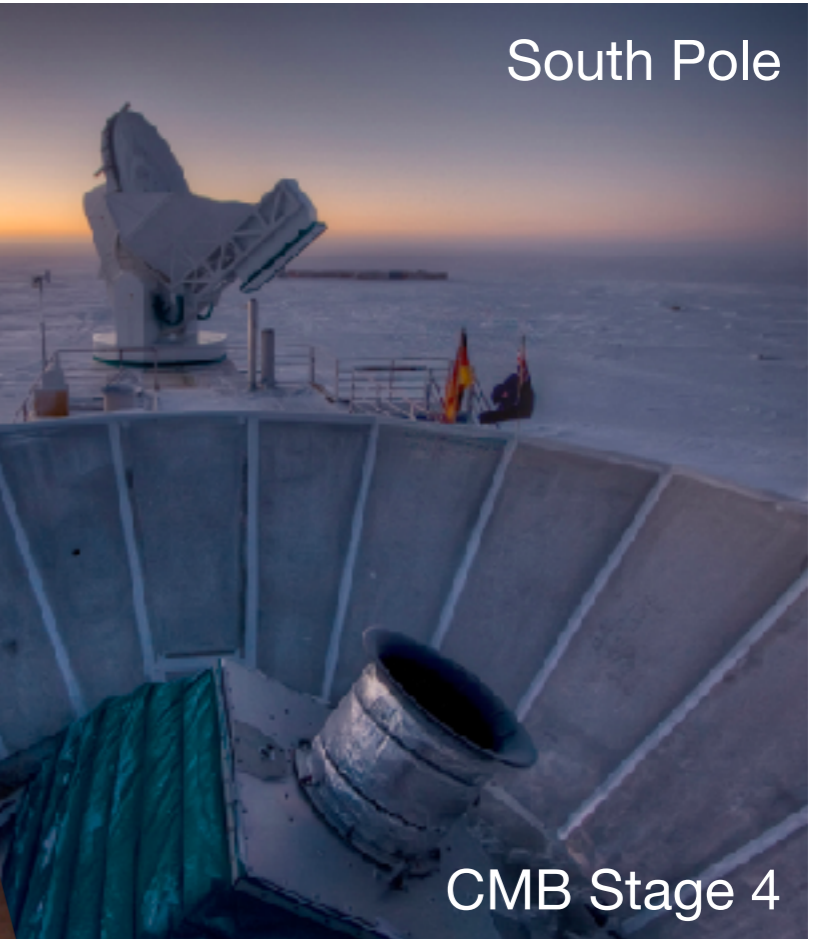
Many upcoming CMB and LSS observations:



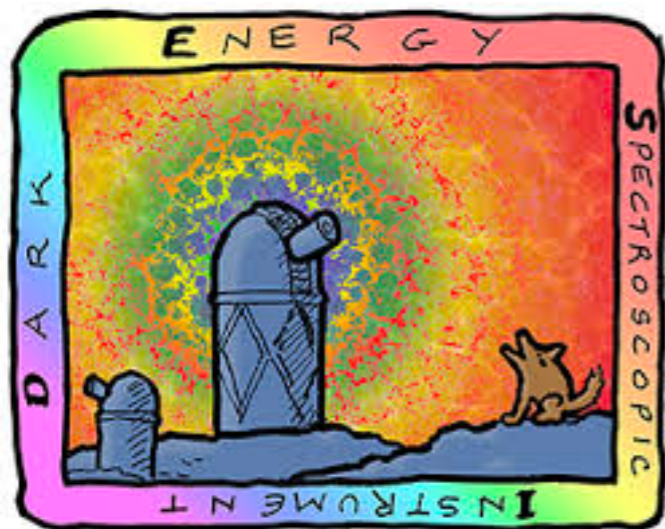
Atacama Desert



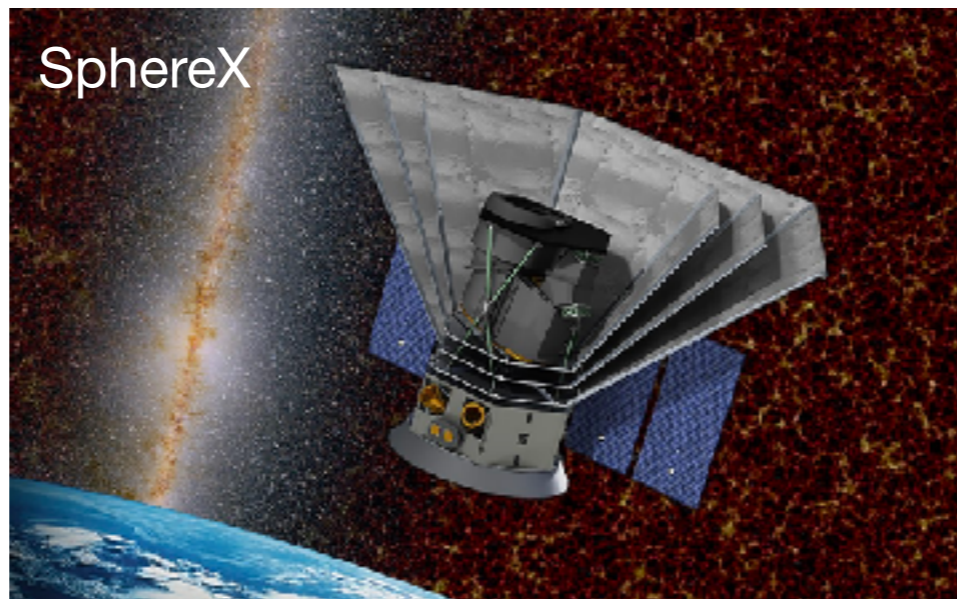
South Pole



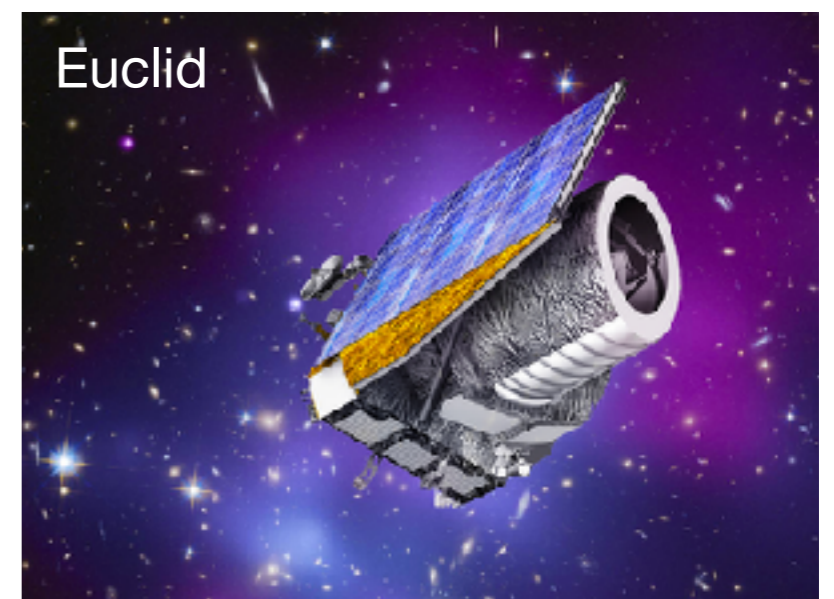
CMB Stage 4



SphereX



Euclid



# Questions and Discussion Topics

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## Observational

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- What are the prospects of future observations?
- What are the main observational challenges?  
Amenable to theoretical contributions (EFT, ML, ...)?
- What are key targets for future observations?
- Is the Hubble tension real?

## Phenomenological

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- What are important effects of the UV completion?
- How do we systematically study non-Gaussianity?
- How to make the most of B-mode measurements?
- How do we further test inflation?

## Conceptual

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- Do insights from the S-matrix / conformal bootstrap have implications for cosmology?
- How does string theory behave in generic (time-dependent) backgrounds?
- Can insights from cosmological holography impact real observables in cosmology?
- Do insights into the BH information paradox have implications for cosmology?
- ...