Vision/discussion session: Cosmological Bootstrap

Enrico Pajer
University of Cambridge

Primordial Cosmo = QFT in curved spacetime / Quantum Gravity

- On large scales (>> Mpc) cosmological surveys measure QFT correlators of metric fluctuation

$$\langle \prod_a^n \delta(\mathbf{k}_a) \rangle \sim \left[\prod_b^n \Delta(k_b) \right] \langle \prod_c^n \zeta(\mathbf{k}_c) \rangle$$

CMB temperature
density of galaxies
dark matter, …

QFT / QG
in de Sitter

- Gravitational floor of non-Gaussianity in single-clock inflation: $\dfrac{\langle \zeta^3 \rangle}{\langle \zeta^2 \rangle^2} \sim f_{NL}^{eq} \gtrsim 10^{-2}$
- The goal of primordial cosmology is to understand QFT and QG in (approximately, asymptotically) de Sitter

State of the art

- Brute force calculations in *perturbation theory*:
  - *Tree-level:* Well established machinery. Many 2-,3- and 4 point functions for massless (realistic, rational functions) and conformally coupled (toy model, related to massless in flat space) fields.
  - General masses; results are available but increasingly formal. The answer is intrinsically complicated. Beyond elementary functions.
  - Mostly equal time (as observed) correlators.
  - Coordinates: cosmologists want correlators in Fourier space. CFT's technology mostly in position space. AdS in Mellin space (see talks by Sleight & McFadden)

Constraints from fundamental principles

- Unitarity:
  - Non-perturbative *spectral decomposition* of 2- & 4-point correlators. Positive spectral densities
  - Non-perturbative optical theorem of "*de Sitter amplitudes*", with associated positivity
  - Perturbative constraints to all loop orders in any FLRW from *Cosmological Optical Theorem*. Formulated in term of more primitive *wavefunction* ($\frac{\text{wavefunction}}{\text{correlator}} \sim \frac{\text{amplitude}}{\text{cross section}}$)
- Locality/Causality/analyticity:
  - Singularity structure in perturbation theory for massless and conf. coupled scalars
  - *Manifestly Local Test* in perturbation theory
  - Analyticity of retarded correlators
  - Theories without Lorentz invariance (realistic for cosmo)

Outlook 1: Loops & renormalisation

- Why loops:
  - Ensure we have a consistent framework to compute observables to any desired order
  - Parity-odd correlators of a massless scalar in de Sitter vanishes at tree level, so 1-loop is the leading term!
  - Special kinematic limits can overcome loop suppression (squeezed, collinear limits)
- Renormalization schemes: explicit cutoff, dim reg, mass&dim reg, η-regulators, Mellin-Barnes regulators. Very active. Universality results, regularisation independence.
- 3 distinct types of divergences: UV divergences ($q \to \infty$, see Pajer's talk), IR divergences ($q \to 0$) and late-time ($\eta \to 0$, see McFadden's talk).
- Renormalization group: re-sum large logs using RG.

Outlook 2: positivity bounds

- What Effective Field Theories admit a consistent UV-completion? Constraints from UV unitarity, causality, locality, quantum gravity, …
- For Lorentz invariant EFTs in flat spacetime we have many constraints leading to *positivity bounds* on effective couplings. In AdS similar bounds can be derived from CFT dual. In de Sitter such bounds are not yet known.
- Ongoing promising directions & challenges:
  - Use fundamental constraints, e.g. non-perturbative cosmo bootstrap, or de Sitter amplitudes.
  - Investigate Lorentz breaking constraints (in Mink and dS)
  - Holographic bounds?

Outlook 3: open system effects

- Unlike for collider phenomenology, in cosmology we always have a spacetime filling medium with unknown microscopic (inflaton, dark matter, dark energy, …). We need an open system approach

- Important & studied for late-time divergences, superHubble physics (e.g. secular growth)

- Important for all models: in single field there is a thermal bath at the dS temperature. More generally other fields can have non-zero occupation numbers

- Completely different “open QFTs”. Density matrices and non-Hamiltonian evolution

Outlook 4: everything else

- Still very little interplay/cross contamination between advances in cosmo correlators and ideas in *de Sitter holography*

- Yet no clear variables to make spinning correlators of gauge fields “simple” (see Skinner’s talk)

- Alternative *boundary* formulation of perturbation theory (polytopes (see Benincasa’s vision), differential equations, …)