a brief introduction to cosmology

what a cosmologist wants from string theory

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What a Cosmologist Wants from String Theory

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**Cosmology**
- General relativity
- Particle physics

**Initial State**

**Ideas Required**

**Observations**

**Final State?**

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**The Cosmological Standard Model**

Simple (+ special) initial state evolved (general relativity + particle physics) into observed distribution of matter

- Abundances of light elements (BBN)
- Anisotropies in cosmic microwave background sky (CMB)
- Line-of-sight distribution of pre-galactic hydrogen (Ly-alpha clouds)
- Abundance of galaxy clusters versus redshift
- Luminosity vs. redshift of supernovae
- Weak grav. lensing by foreground dark matter
- 3D distribution of galaxies
Standard model parameters

- $\Omega_k$: spatial curvature
- $\langle R^2 \rangle$: scalar metric perturbations
- $n_s$: spectral tilt
- $\langle T^2 \rangle$: tensor metric perturbations
- $\tau$: tensor tilt
- $\Omega_b$: baryon density
- $\Omega_r$: radiation density
- $\Omega_{cdm}$: cold dark matter
- $\Omega_\nu$: neutrino density
- $b$: bias light / mass
- $\tau$: optical depth to last
- $H_0$: present Hubble expansion
- $\Omega_\Lambda$: vacuum energy density
- $w_\Lambda$: "vacuum" equation of state

Initial conditions

- $\Omega_k$, $\langle R^2 \rangle$, $n_s$, $\langle T^2 \rangle$, $\tau$, $\Omega_b$, $\Omega_r$, $\Omega_{cdm}$, $\Omega_\nu$, $b$, $\tau$, $H_0$

Particle physics

- $\Omega_k$, $\langle R^2 \rangle$, $n_s$, $\langle T^2 \rangle$, $\tau$, $\Omega_b$, $\Omega_r$, $\Omega_{cdm}$, $\Omega_\nu$, $b$, $\tau$, $H_0$

Astrophysics

- $\Omega_k$, $\langle R^2 \rangle$, $n_s$, $\langle T^2 \rangle$, $\tau$, $\Omega_b$, $\Omega_r$, $\Omega_{cdm}$, $\Omega_\nu$, $b$, $\tau$, $H_0$

"Clock" - $H_0$

Vacuum gravity

- $\Omega_\Lambda$, $w_\Lambda$, "vacuum" equation of state
initial state

- (3+1) - dimensional spacetime
  statistically
  almost homogeneous & isotropic
  (perturbed FLRW spacetime)
- almost spatially flat ("ζ = 1")
- expanding \((H > 0)\)
- almost scale-invariant spectrum
  of Gaussian metric perturbations
  \((δg ∼ 10^{-5})\)

inflation in early universe

* constant vacuum energy
  de Sitter attractor (for \(H > 0\))
  - homogeneous & isotropic
  - \(Ω_k \rightarrow 0\) as \(t \rightarrow \infty\)

* slowly-rolling scalar fields
  almost constant vacuum energy
  - light fields \((m^2 ≪ H^2)\) acquire
    scale-invariant spectrum of perturbations
  - vacuum energy → radiation
    at reheating after inflation
  - scalar field perturbations
    → density perturbations
large-scale structure from scalar fields

small scale \( (k \gg aH) \)
quantum vacuum
under-damped oscillator

small scale, \( (k \ll aH) \)
large scale
perturbations
over-damped

\[ \delta x \propto e^{-i k \eta} \]
\[ \langle \delta x^2 \rangle_{k=ah} \approx \left( \frac{H}{2 \pi} \right)^2 \]

scalar metric perturbation
during inflation after inflation

\[ R = \frac{H \delta \phi}{\dot{\phi}} \]
\[ \rightarrow \]
\[ R = \frac{H \delta \phi}{\dot{\phi}} \]
\[ \text{inflaton, } \phi \]
\[ \text{density, } \rho \]

isocurvature field perturbations
\[ S_{ij} = H \left( \frac{\delta \phi_i}{\phi_i} - \frac{\delta \phi_j}{\phi_j} \right) \]
\[ \rightarrow \]
\[ S_{\phi} = H \left( \frac{\delta \phi_x}{\dot{\phi}_x} - \frac{\delta \phi_y}{\dot{\phi}_y} \right) \]
\[ \text{"entropy" perturbations.} \]
**stochastic inflation**

- Starobinsky, Linde, Vilenkin...

**classical evolution dominated by quantum fluctuations**

- "self-reproducing"
- inhomogeneous
- future eternal

Problems?

- non-linear gravitational back-reaction of quantum fluctuations
- past incomplete geodesics Vilenkin, Borde, Guth
- problem of measure

**pre big bang**

Gravitational instability of vacuum

\[ \rightarrow \text{cosmological collapse (similarities with inflation!)} \]

\[ \rightarrow \text{locally homogeneous attractor} \]

\[ \rightarrow \text{quantum vacuum} \]

\[ \rightarrow \text{large-scale perturbations} \]

Problems?

- approaches cosmological singularity
- does not (in general) produce scale-invariant perturbations (probably need "entropy" perturbations)
Q: what happens at a cosmological singularity?

big bang, big crunch, big rip...

- higher order string/loop corrections to avoid singularity?
- non-perturbative dual description that is non-singular?

Q: does time begin?

- e.g. quantum cosmology + no boundary proposal?
- or eternal stochastic inflation?
- or pre-big bang phase?
- or eternal cyclic model?
Q: What is quantum vacuum for gravitational fields?

- 2-point function for trans-Plankian fields in curved spacetime

- 3-point function for self-gravitating fields (non-Gaussianity of primordial perturbation spectra)

Q: is there a future asymptotic vacuum state?

- does $\Lambda \to 0$? ($\to M_+$)
- $\Lambda > 0$? ($\to dS_+$)
- $\Lambda < 0$? recollapse

Kallosh, Linde, et al

- why does present vacuum weigh so little? Dvali et al
Q:

why are there (only?)
3 large spatial dimensions?

- are hidden dimensions
  compact / infinite ?
  universal / gravitational ?.

- what is the topology
  of space ?. and time ?.

summary:

cosmology

successful standard model
seeks deep meaningful connection
with string theory
five questions:

1. what happens at a cosmological singularity?
2. does time begin?
3. what is the quantum vacuum for gravitational fields?
4. is there a future asymptotic vacuum state?
5. why only 3 large/visible spatial dimensions?