Aspects of Holographic Cosmology

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IAP

Fundamental .be Interactions

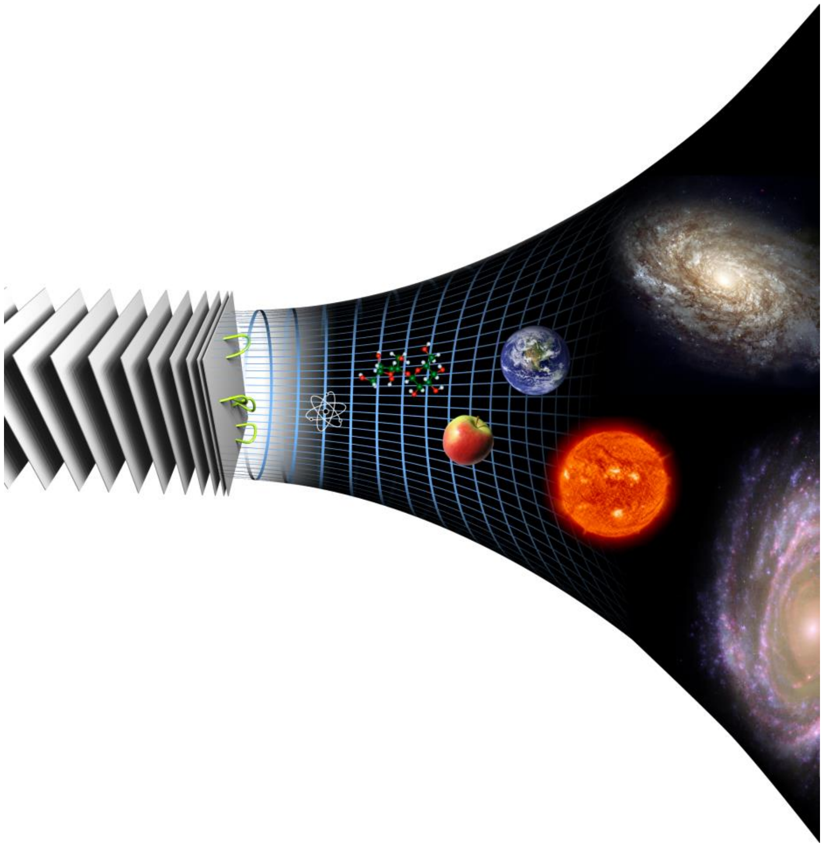
Collaborations

- AB, P. McFadden, K. Skenderis, *Holographic predictions for cosmological 3-point functions*, JHEP 1203 (2012) 91,
- AB, P. McFadden, K. Skenderis, *Holography for inflation using conformal perturbation theory*, JHEP 1304 (2013) 47.

Dr. Marjorie Schillo

Prof. Thomas Hertog

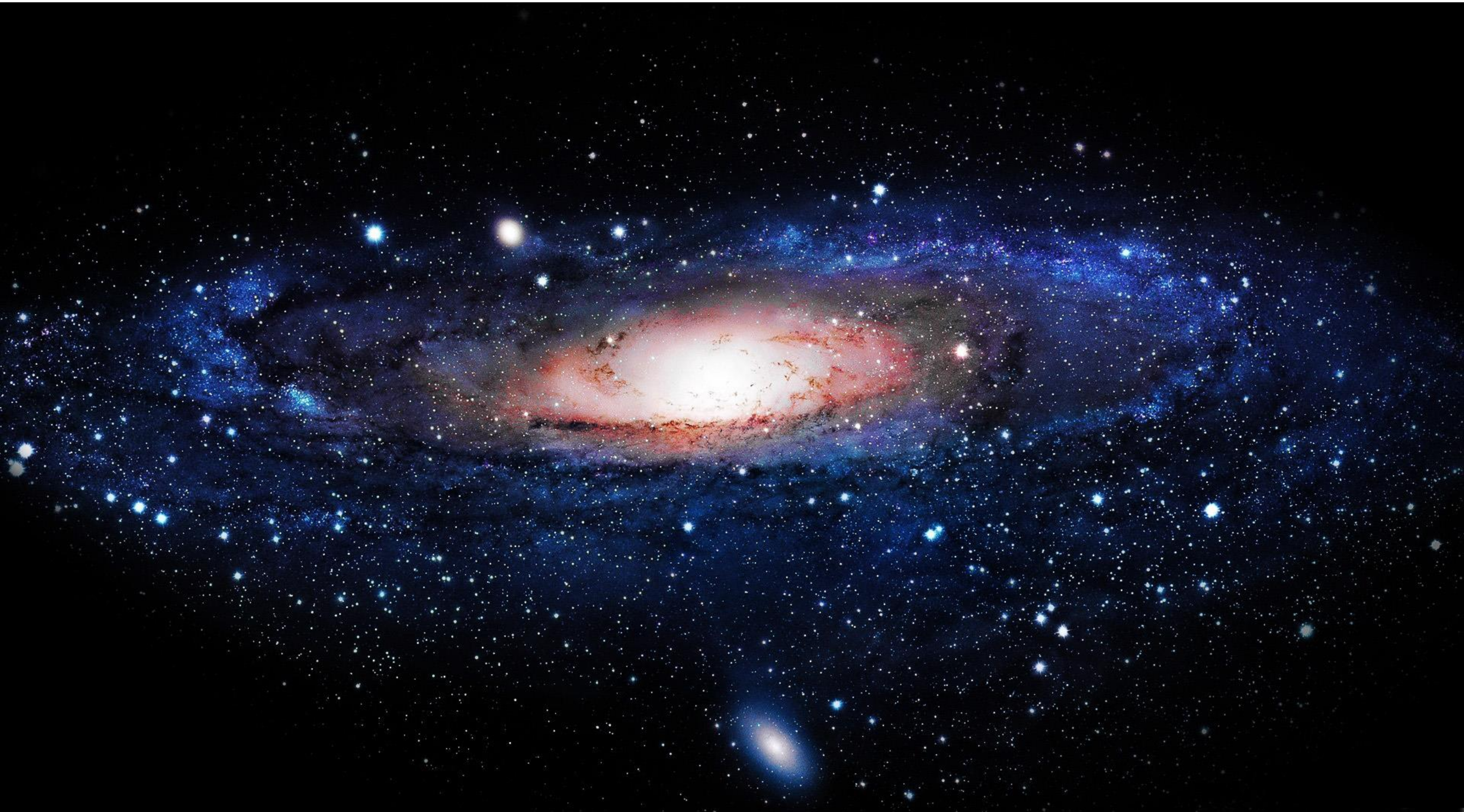
Outline



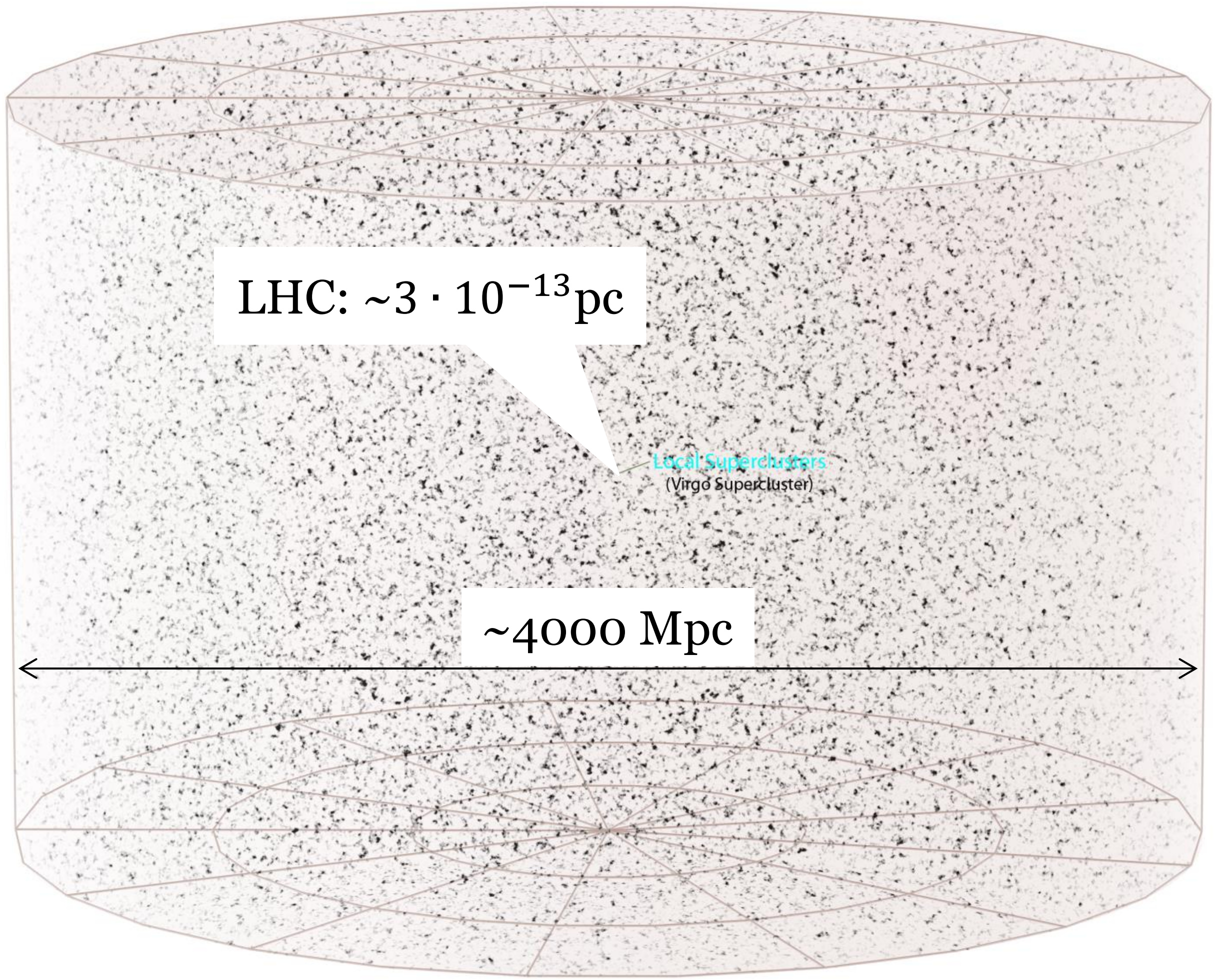
1) Standard inflationary cosmology.
2) The full power of the gauge/gravity correspondence.
3) Basic ideas and results of holographic cosmology.
4) Cosmological singularities and holography.
5) Conclusions.

High energy collider physics

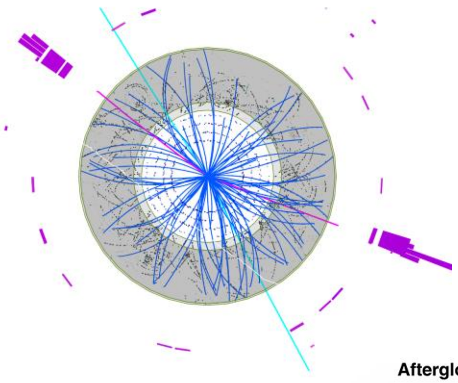
High energy collider physics



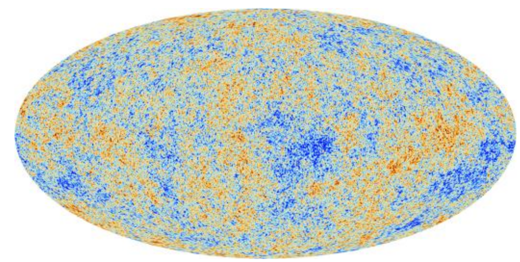
High energy collider physics

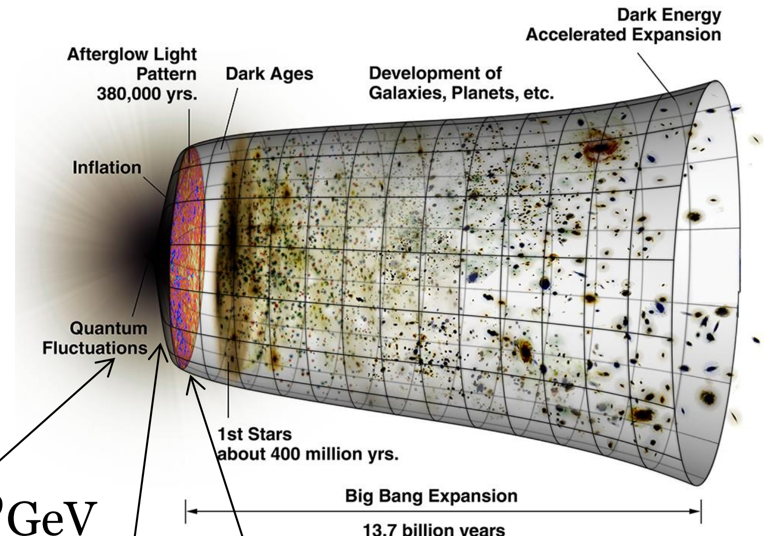


High energy collider physics



detected photons =
= a snapshot of
Cosmic Microwave
Background





[Arkani-Hamed, Maldacena, Cosmological Collider Physics, 1502.08043]

$> 10^{19}$GeV

$\sim 10^{17}$GeV

$\sim$10 eV

$\sim$0.2 meV

Primordial perturbations

- Fundamental observables are perturbations of the metric on top of the rapidly expanding inflationary universe,

$$ds^2 = -dt^2 + a^2(t)\left(\delta_{ij} + e^{2\zeta}[e^{\gamma}]_{ij}\right)dx^i dx^j$$

- The Friedman – Lemaître background is determined by the scale factor $a(t)$.
- For example: rapidly expanding de Sitter space, $a(t) = e^{Ht}$. De Sitter space is a space of a constant positive curvature.
- Perturbations are divided into:
  - scalar perturbations ζ
  - tensor perturbations (gravitational waves) γ_{ij}
- The observables are correlation functions. 2-point functions are known as power spectra and 3-point functions as non-gaussianities.

$$\Delta_S{}^2(p) = \frac{p^3}{(2\pi)^2}\langle\zeta(p)\zeta(-p)\rangle \qquad \Delta_T{}^2(p) = \frac{p^3}{(2\pi)^2}\langle\gamma_{ij}(p)\gamma_{ij}(-p)\rangle$$

Measurements

- Experimental results are parametrized as

$$\Delta_S{}^2(p) = \Delta_S{}^2(p_0)\left(\frac{p}{p_0}\right)^{n_S-1}$$

where the pivot scale is $p_0 = 0.002\text{Mpc}^{-1}$

- Current data gives [Planck Collaboration, 2015]

$$\Delta_S{}^2(p_0) = (2.441 \pm 0.092) \cdot 10^{-9}$$

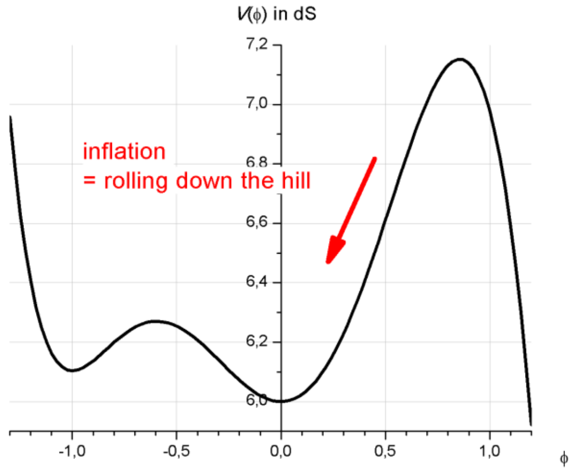
$$n_S - 1 = -0.033 \pm 0.004 \qquad r = \frac{\Delta_S{}^2(p_0)}{\Delta_T{}^2(p_0)} < 0.24 \quad (2\sigma \text{ bound})$$

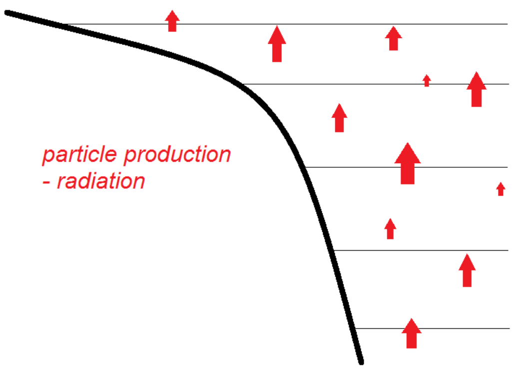
- Scalar power spectrum has small amplitude and is almost scale invariant.
- In principle, 3-point functions were measured, but uncertainties exceed the measured value.

Models

- The simplest model of inflation requires a single scalar – inflaton – coupled to gravity and a special form of the potential.

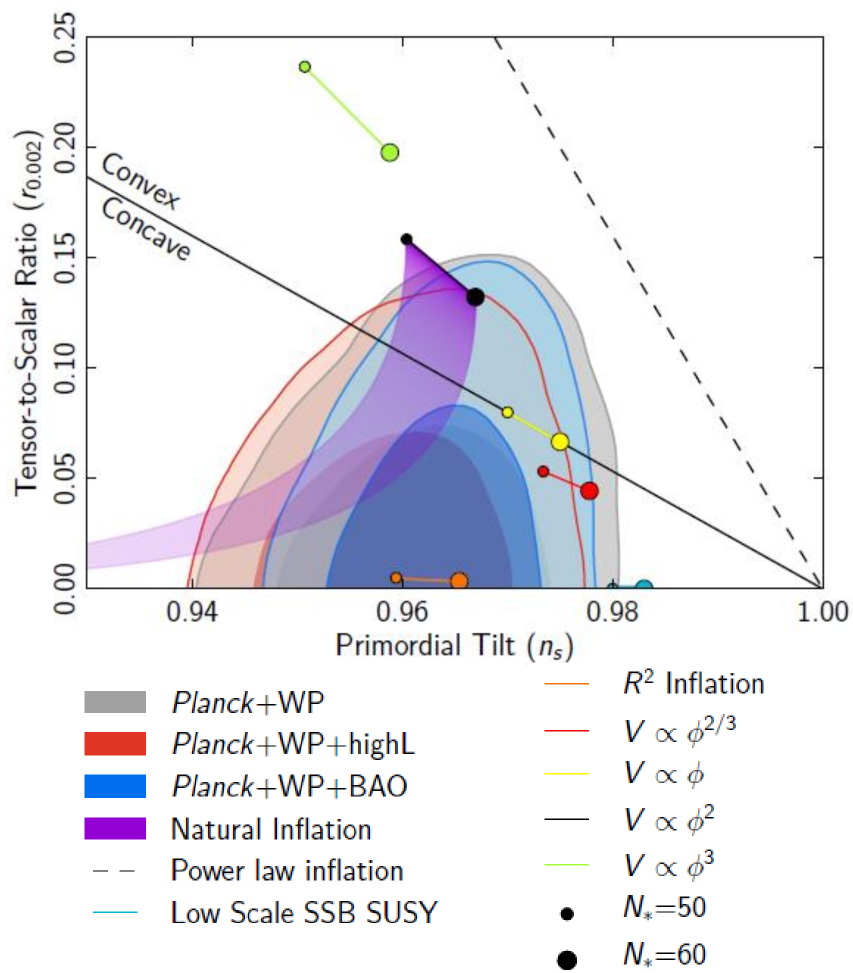
$$S = \int d^4x\sqrt{-g}\left[\frac{R}{2\kappa^2} - \frac{1}{2}\partial_\mu\Phi\partial^\mu\Phi - V(\Phi)\right]$$





- The field rolls slowly down the potetial and the universe grows. Finally, the inflaton reaches the de Sitter vacuum we live in now and decays into a zoo of particles.

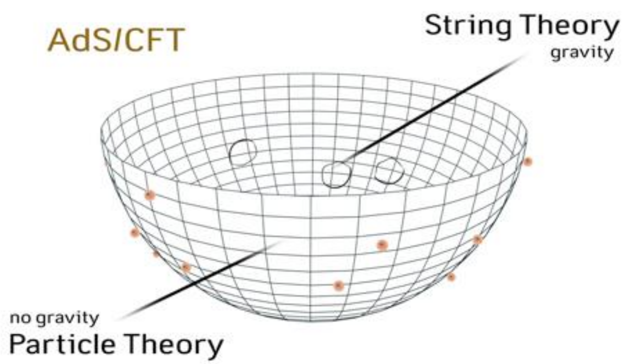
Questions

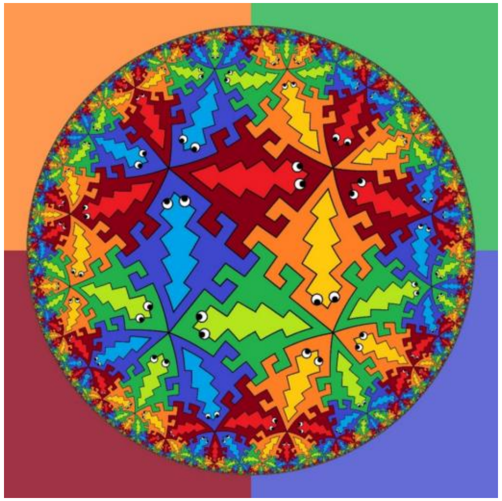


[Planck Collaboration, 2015]

- Inflation does not resolve singularity.
- Is the big bang a real singularity or is it solved by quantum gravity corrections?
- What are the pre-inflationary initial conditions?
- How random the universe is?
- Lyth bound: the inflaton must traverse trans-Planckian distances.
- Is inflation consistent with quantum gravity (QG)?
- Is QG necessary?

Gauge/gravity duality (AdS/CFT)

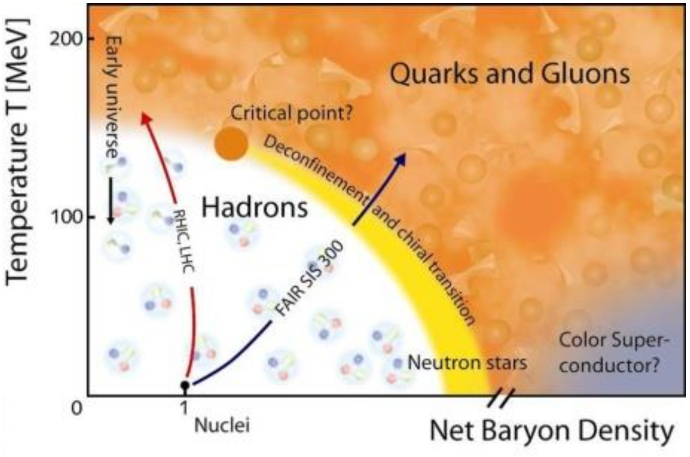


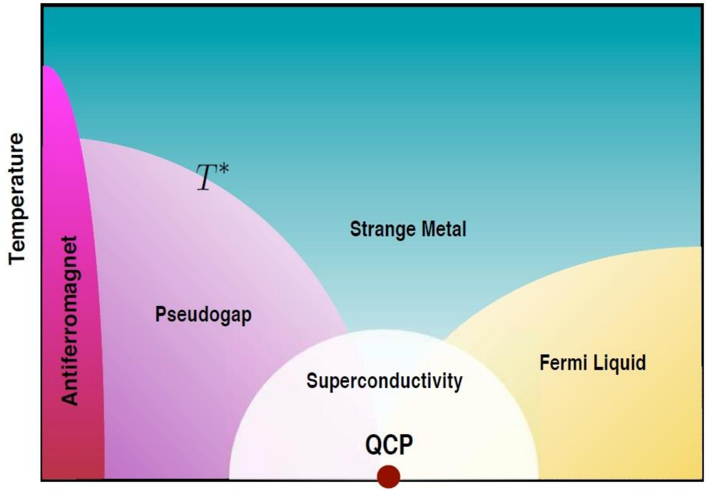


- Quantum gravity (string theory) on asymptotically anti-de Sitter (AdS) background is equivalent to a certain QFT ($\mathcal{N}$=4 SYM) in one spacetime dimension less. [Maldacena, 1997]
- Two parameters of the dual QFT: the rank of the gauge group SU(N) and the coupling constant g.
- Strong/weak type of duality: stronlgy coupled QFT corresponds to weakly coupled gravity and *vice versa*.
- AdS is a space of constant negative curvature (opposite to de Sitter space).

Predictions of AdS/CFT

- Explains hydrodynamic properties of quark-gluon plasma, $\eta/s = 1/4\pi$
  [Policastro, Son, Starinets, 2001]
- Produces a phase diagram of high-T superconductors and predicts their properties.
  [Hartnoll, Herzog, Horowitz, 2008]
- Explains the Bekenstein-Hawking formula for the entropy of black holes and "restores" their unitarity.
  [Suskind, 1994; 't Hooft, 1994; Witten, 1997]





AdS/CFT in cosmology

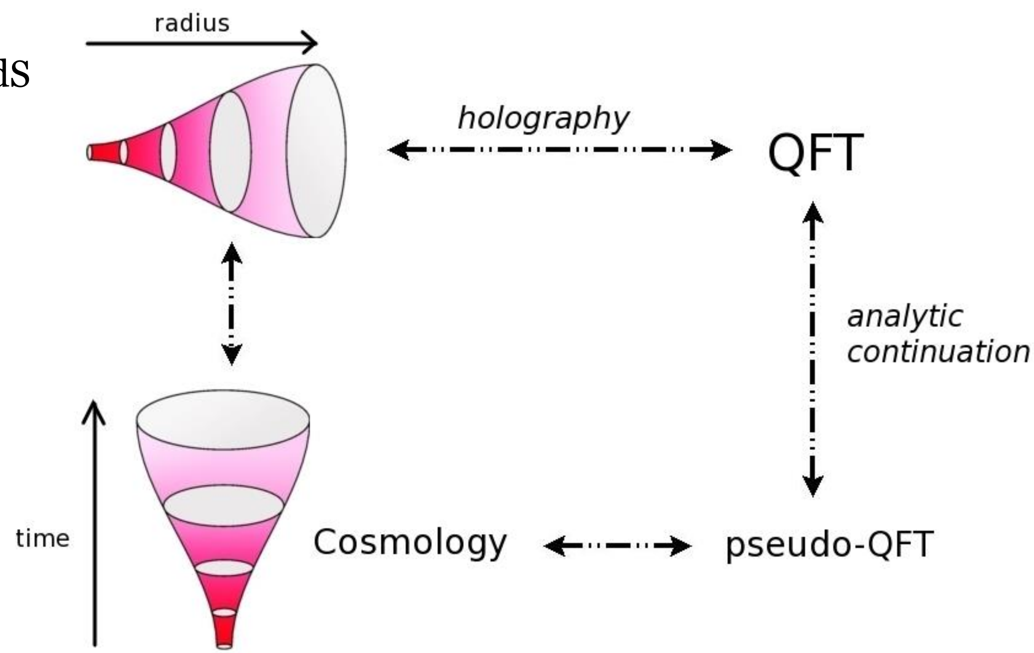
- Negative curvature of AdS is crucial for AdS/CFT.
- Rotate the universe: dS $\leftrightarrow$ AdS by specific continuations. [McFadden, Skenderis, 2010, 2011, 2011]

Asymptotically Euclidean AdS (hyperbolic space)

$\kappa^2 \to -\kappa^2$

$p \to -ip$

Cosmology

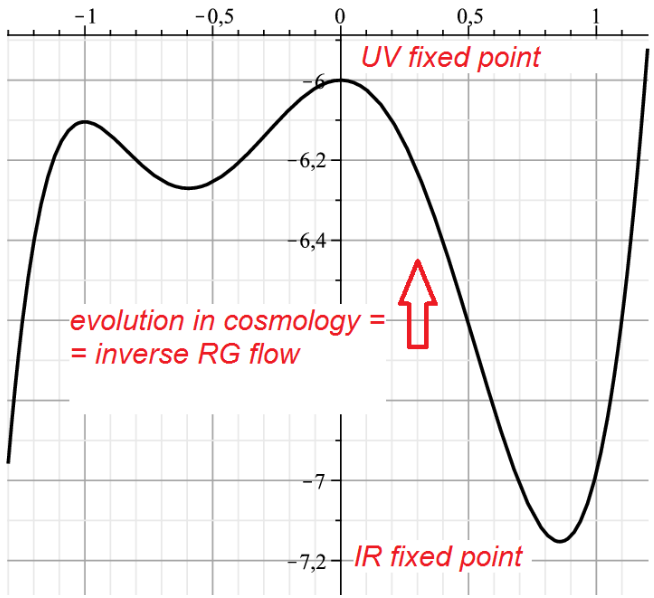


$N^2 \to -N^2$

$p \to -ip$

Holographic slow-roll inflation

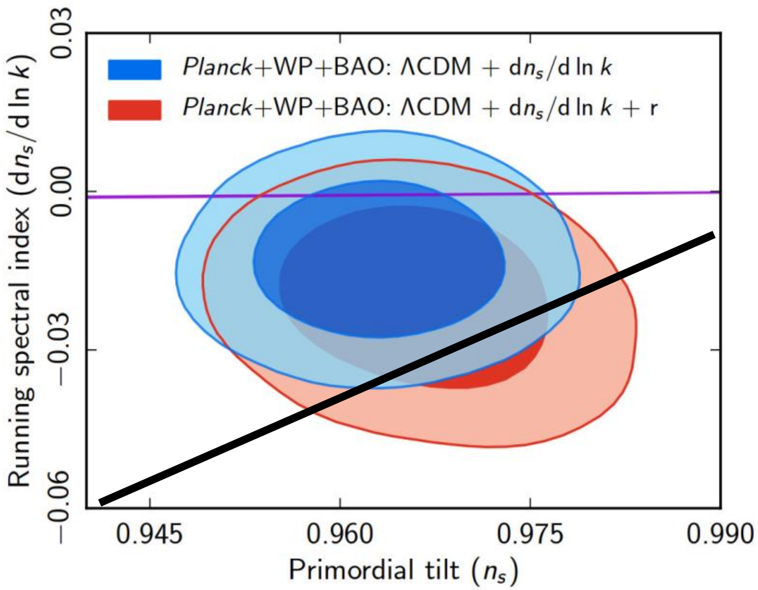
- Standard inflation is holographic.
  [AB, McFadden, Skenderis, 2013]
- Cosmological evolution in time corresponds to inverse RG flow of the dual QFT.
- Smallness of spectrum and near scale invariance follow from the simple structure of the dual QFT.



$$S = S_{CFT} + \frac{2\lambda}{c}\int d^3x\, O_{3-\lambda}(x)$$

- The dual QFT is a small deformation ($\lambda < 1$) of a (strongly coupled) CFT by a nearly-marginal operator $O_{3-\lambda}$
  - ➢ Smallness of deformation gives smallness of the power spectrum.
  - ➢ Near-marginality leads to near-scale invariance of the power spectrum.

Quantum gravity and inflation



In holographic models
with strongly coupled gravity

$$\frac{dn_S}{dlogk} = (n_S - 1) + \cdots$$

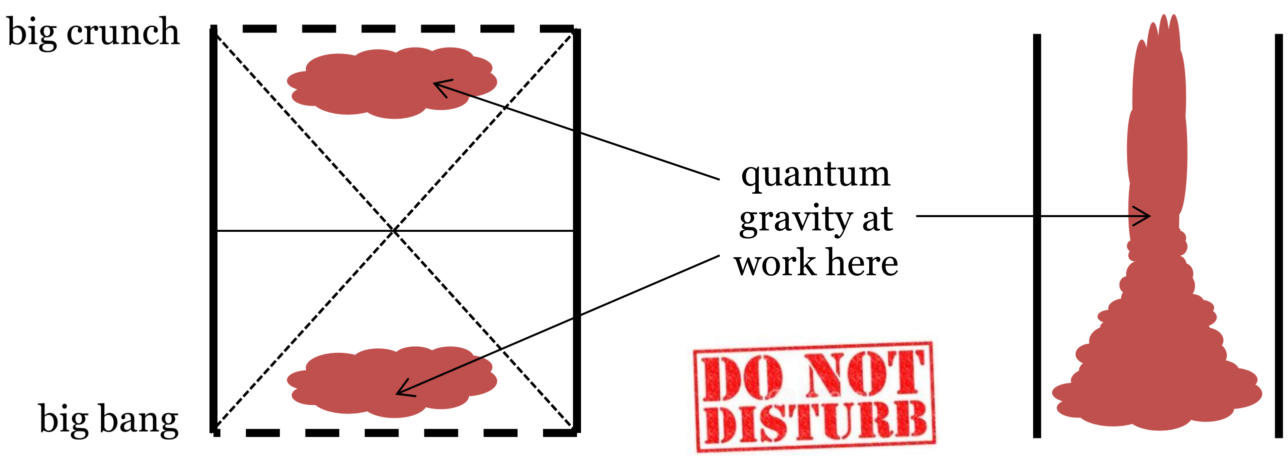
[Dias, 2011]

- AdS/CFT can be utilized to analyze quantum gravity effects on inflation.
- The simplest model
  [AB, McFadden, Skenderis, 2012]
  [Maldacena, Pimentel, 2012]
  contains a bunch of free fields in the boundary QFT:
  - minimal scalars,
  - conformal scalars,
  - fermions,
  - gauge fields.
- No statistically significant difference between this model and the standard ΛCDM model.
  [Easther *et al.*, 2011]

Towards the singularity

- Can we learn more about the nature of the singularity?
- Holography for de Sitter backgrounds is more difficult,
  so let us go back to the AdS setting:
  - Inflaton profile corresponds to a tunnelling between two AdS vacua.
  - We have a bubble geometry.
  - Big bang becomes a big crunch.

We want to analyze: We have analyzed:



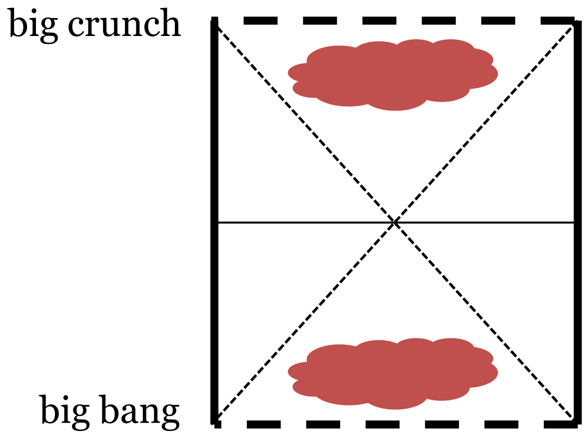
Towards the big crunch

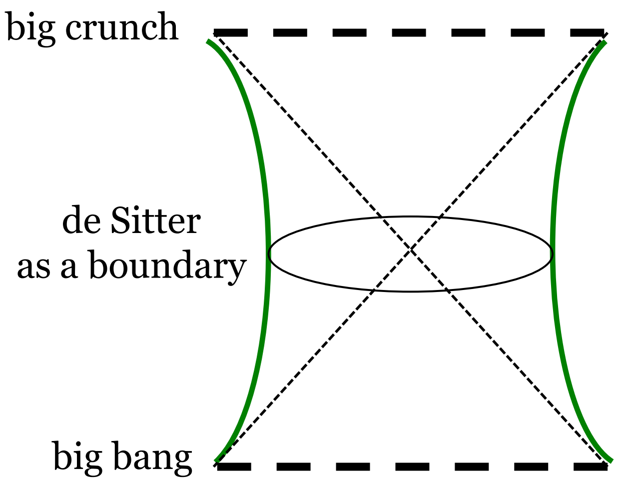
- Dual QFT becomes ill-defined after finite time.
- Resolution: consider the boundary QFT on de Sitter slices.
  [Hertog, Horowitz, 2004, 2005]
  [Maldacena, 2010]
- The boundary QFT is described as a massive deformation of a CFT

$$S = S_{CFT} + \alpha \int d^3x\, \Phi^2$$

- The bulk geometry contains gravity and a single scalar field of mass $m^2 = -2$.
- Its boundary conditions read

$$\phi \sim \frac{\alpha}{r} + \frac{\beta}{r^2}$$

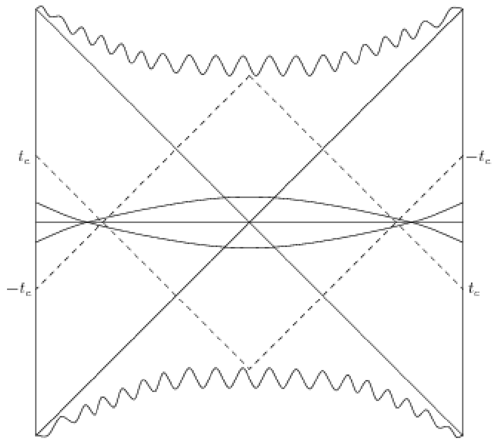




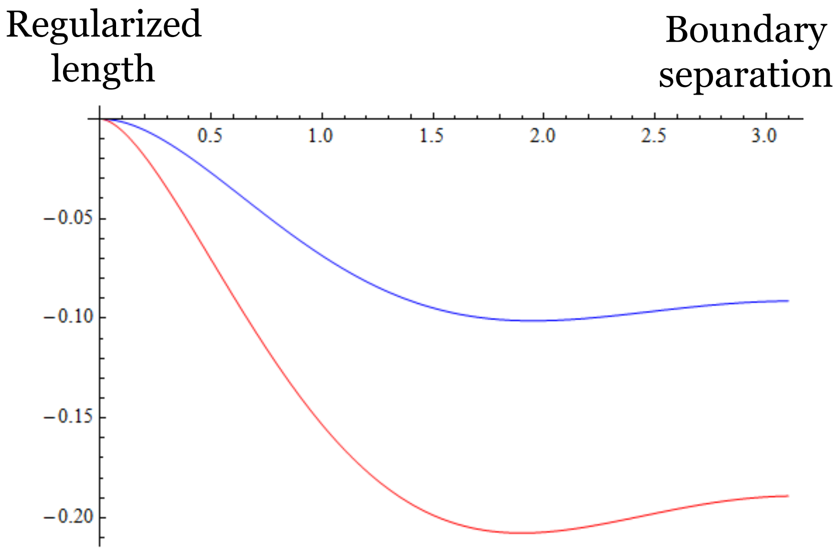
Features of the big crunch

- Two-point functions computed in two regimes:
  - ➢ weakly-coupled gravity,
  - ➢ massive bulk excitations; in this case

$$\langle\Psi|O(x_1)O(x_2)|\Psi\rangle \sim e^{-mL(x_1,x_2)}$$



[Hertog, Horowitz, 2004, 2005]



- Novel methods for generating bubble geometries.
- New, analytic results for bubble geometries.
- Work in progress.

Conclusions

- Cosmology is holographic. AdS/CFT correctly reproduces the semi-classical, inflationary regime of cosmology.
- Holography offers unprecedented opportunity for the analysis of cosmologies with strongly coupled (quantum) gravity at early times.
- New developments in holography allow for further investigations into the structure of big bang / big crunch singularities.
- Detailed analysis of AdS toy models is required for further advancements in the field.