Title: Holographic cosmology: status report

Speakers: Kostas Skenderis

Series: Quantum Fields and Strings

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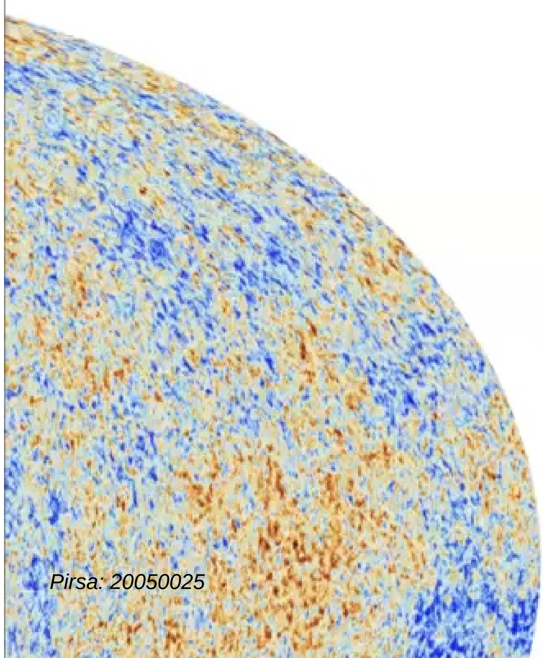
Abstract: I will give an overview of holographic cosmology and discuss recent results and work in progress.

In holographic cosmology time evolution is mapped to inverse RG flow of the dual QFT. As such this framework naturally explains the arrow of time via the

monotonicity of RG flows. Properties of the RG flow are also responsible for the holographic resolution of the classic puzzles of hot big bang cosmology, such as the horizon problem, the flatness problem and the relic problem.

The holographic framework includes qualitatively new models describing a non-geometric very early Universe, and such models provide an excellent fit to CMB data. In the last part of the talk I will present on-going work with lattice gauge theorists aiming to compute on the lattice the QFT observables(the 2-point function of stress energy tensor) needed to compute holographically the cosmological power spectrum in the regime where the dual QFT is non-perturbative.

Holographic cosmology: status report



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Holography Cosmology

Holographic cosmology is a new framework for cosmology

- In holographic cosmology our 4-dimensional Universe is described by providing:
- a three dimensional QFT (with no gravity)
- a dictionary that related QFT observables to 4-dimensional observables

- The new framework includes:

Why holographic cosmology

- Models are fully consistent with quantum mechanics
- General relativity emerges when the QFT dynamics becomes strongly interacting
- Models are well-defined when traditional GR breaks down
- ... including at the initial singularity

- From a more general perspective it bring to scientific domain questions such as:

☞ what were the laws of physics before time and space the way we

Outline

- This is a work in progress

and not everything is understood.

- Very early Universe cosmology, the period usually associated with inflation, is the part which is best understood and it will be the focus of this talk.

- I will start by outlining general, model independent, implications of this framework

Outline

1. Gauge/gravity duality
2. General implications
3. Holographic dictionary
4. Models for non-geometric Universe
5. Holographic cosmology and Hot Big Bang puzzles

References

- A holographic framework for cosmology was put forward in works with Paul McFadden and Adam Bzowski (2009 - 2013).
- Related work:
  [Witten (2001)] [Strominger (2001)] ... (dS/CFT correspondence)
  [Maldacena (2002)] ... (wavefunction of the universe)

  [Trivedi et al][Garriga et al] [Maldacena, Pimentel] ....
  [Arkani-Hamed, Maldacena] .... [Baumann et al] ...

References

In this talk I will give an overview of the earlier work and discuss more recent and on-going work:

- N. Afshordi, C. Coriano, L. Delle Rose, E. Gould, KS, PRL(2017), E. Gould, N. Afshordi, KS, PRD(2017).
- Horatiu Nastate, KS, Holography for the very early Universe and the classic puzzles of Hot Big Bang cosmology, Phys.Rev.D 101 (2020) 2, 021901 (rapid communication) and on-going.
- LatCos Collaboration: G. Cossu, L. Del Debbio, E. Gould, A. Jüttner, B. Kitching-Morley, J. Lee, A. Portelli, H. Rocha, KS, P. Vranas on-going.

J. Lee, L. Del Debbio, A. Jüttner, A. Portelli, KS, Towards a holographic

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Gauge/gravity duality: a primer

A conjectured equivalence:

> Gravity in $(d+1)$ dimensions $\Leftrightarrow$ QFT in d dimensions

- In this talk we will focus exclusive on $d = 3$: a 4-dimensional universe and its dual $3d$ QFT.
- The idea of "holography" has its origins in black holes physics.

Gauge/gravity duality in a nutshell

Gauge/gravity duality provides a way to

- obtain QFT correlation functions of gauge invariant operators by doing a gravitational computation, or conversely
- obtain the behaviour of a gravitational system using correlation functions of gauge invariant operators.

Weak/strong duality

- An important feature of the duality is that it is a weak/strong duality.

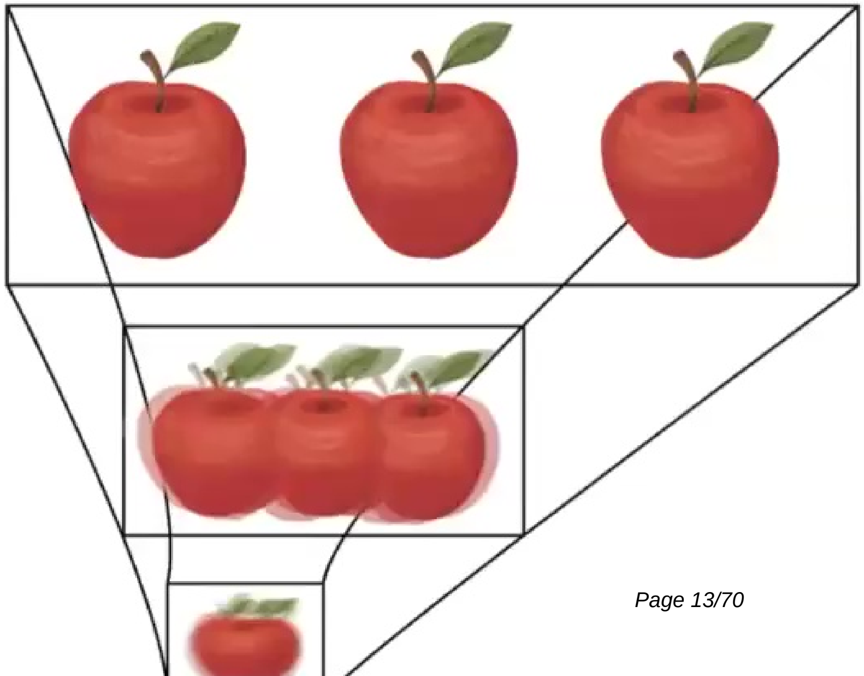
weakly coupled gravity $\Leftrightarrow$ strongly coupled QFT

- One can obtain QFT correlation functions of gauge invariant operators at strong coupling by solving Einstein equations.

Strongly coupled gravity $\Leftrightarrow$ weakly coupled QFT

What is the additional dimension?

- QFT observables depend on what scale we probe the theory.
- This is captured by Renormalization Group (RG) flows.
- As we go from higher energies (UV) to lower (IR) there is a monotonic coarse-graining of the degrees of freedom.

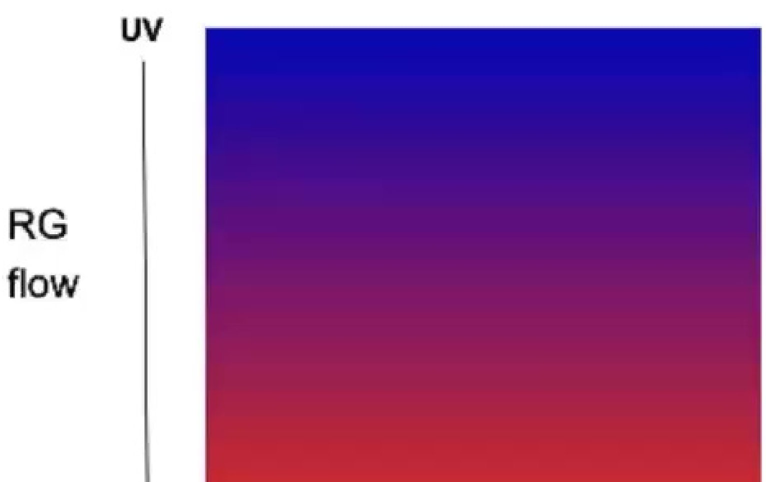


- The RG scale corresponds to the

Time and RG-flow

➢ In holographic cosmology:

Cosmological evolution = inverse RG flow



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Gauge/gravity duality

General implications

Holographic dictionary

Models for non-geometric Universe

Holographic cosmology and Hot Big Bang puzzles

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RG flow and cosmological evolution

The RG flow of the QFT should reflect the cosmological evolution:

- Current dark energy era:
  - a strongly coupled UV fixed point (corresponding to a positive cosmological constant), or
  - strongly coupled superrenormalizable QFT (corresponding to quintessence)
- In the IR the theory should either flow to:
  - an IR fixed point (corresponding to de Sitter inflation), or
  - a phase governed by a super-renormalizable theory (corresponding to power law inflation)

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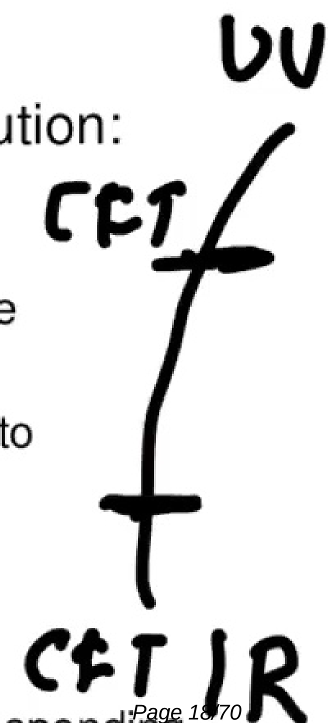

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Arrow of time

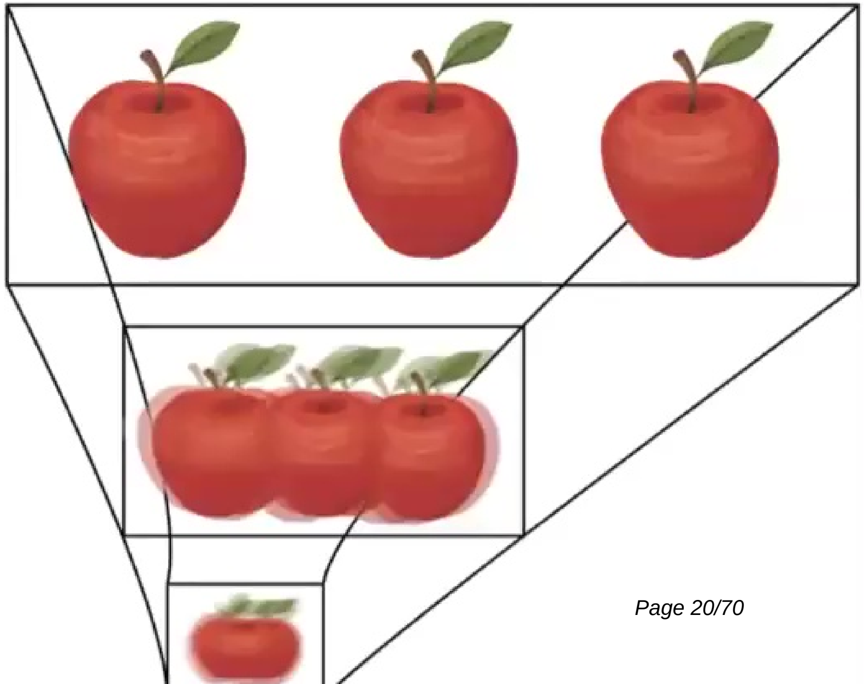
- Why is there an arrow of time, when the microscopic laws of physics are time symmetric?

- A common view is that this has a thermodynamic origin:
  - We are moving towards the state of maximum entropy.
  - The Universe must have started from a very low entropic state.

- But why would the initial state be a low entropic state?

Arrow of time via holography

- Monotonicity of RG flow explains the arrow of time.
- Entropy increase: more degrees of freedom in the UV
- Universality of the IR dynamics: initial conditions are natural.



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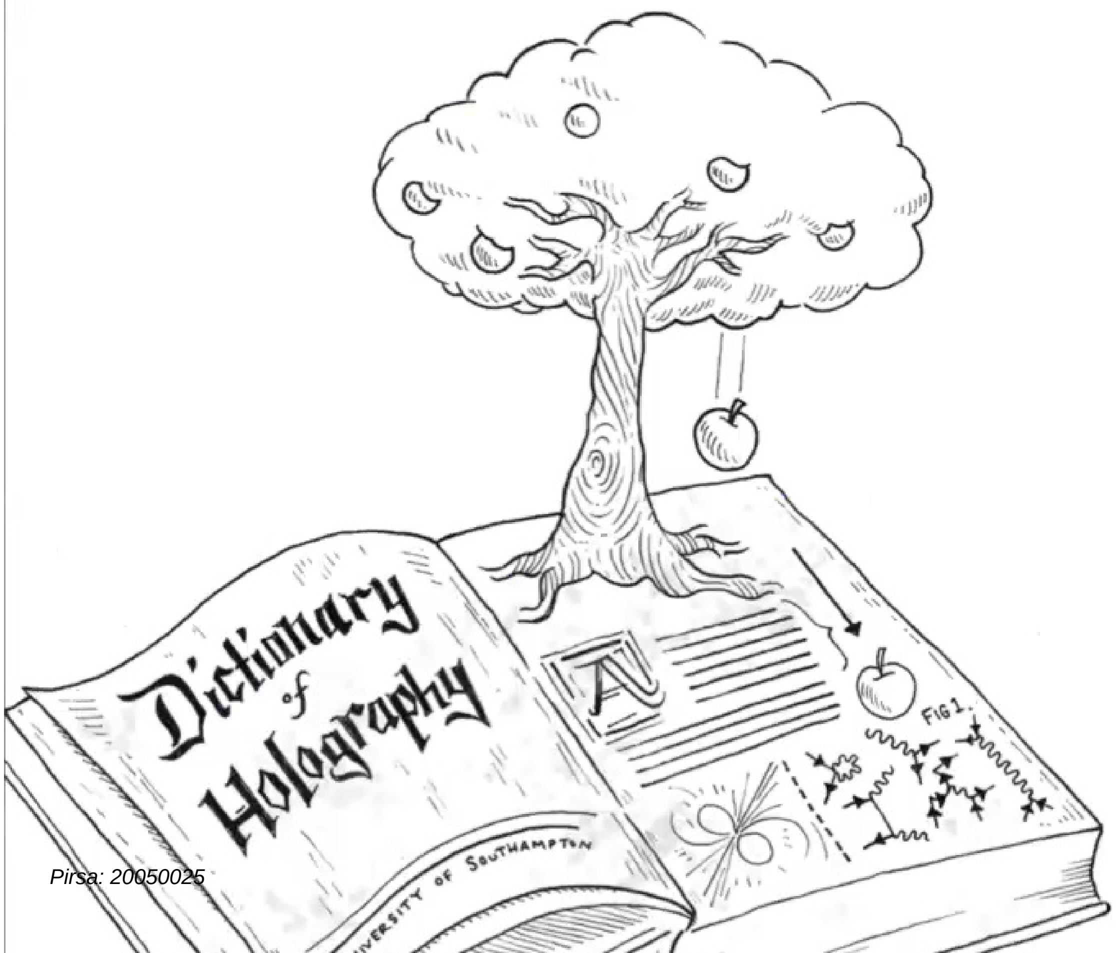

- We need formulae that relate cosmological observables with QFT correlation functions.
- There are explicit holographic formulas for power spectra and non-Gaussianities.
- Here I will present the ones for the power spectra.

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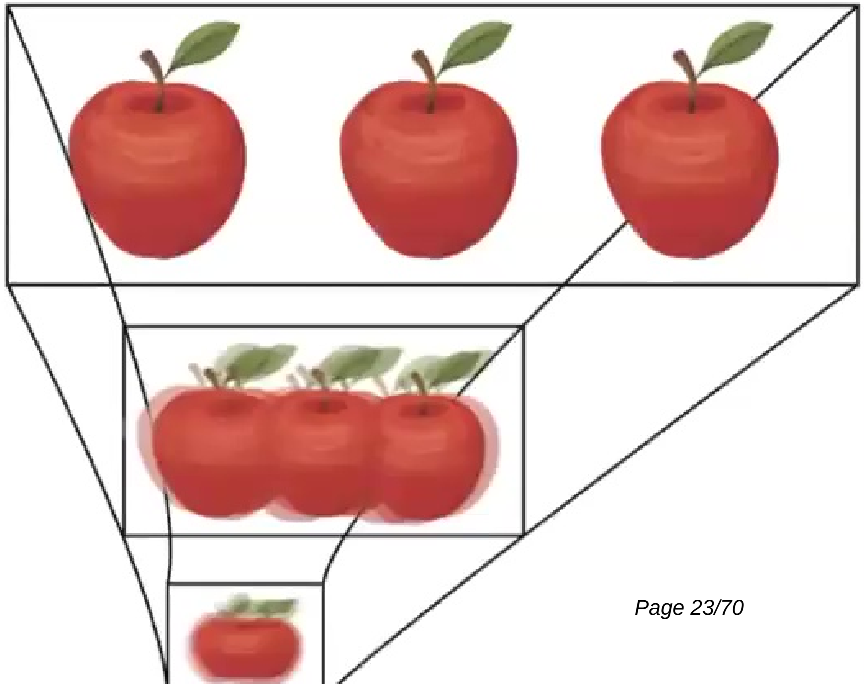

Holographic formulae for power spectra [McFadden, KS]

- The 2-point function of the energy momentum tensor T_{ij} in momentum space has the form

$$\langle T_{ij}(q) T_{kl}(-q) \rangle = A(q^2) \Pi_{ijkl} + B(q^2) \pi_{ij} \pi_{kl},$$

where $\Pi_{ijkl} = \frac{1}{2}(\pi_{ik}\pi_{lj} + \pi_{il}\pi_{kj} - \pi_{ij}\pi_{kl}), \quad \pi_{ij} = \delta_{ij} - q_i q_j / q^2.$

- The power spectra are given by

$$\Delta^2_{\mathcal{R}}(q) = -\frac{q^3}{16\pi^2} \frac{1}{\mathrm{Im}\, B}, \quad \Delta^2_{T}(q) = -\frac{2q^3}{\pi^2} \frac{1}{\mathrm{Im}\, A},$$

Wavefunction of the Universe

- The partition function of the dual QFT computes the wavefunction of the Universe [Maldacena (2002)]:

$$\psi[\Phi] = Z_{QFT}[\Phi]$$

- Cosmological observables are computed as

$$\langle \Phi(x_1) \cdots \Phi(x_n) \rangle = \int D\Phi |\psi|^2 \Phi(x_1) \cdots \Phi(x_n)$$

- The partition has an expansion in correlation functions:

$$Z_{QFT}[\Phi] = \exp\left(\sum \langle O(x_1) \cdots O(x_n) \rangle \Phi(x_1) \cdots \Phi(x_n) \right)$$

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Outline

Dual QFT

- There is currently no *first principles* derivation of the dual QFT.
- A class of QFTs which is linked with holographic dualities is:

$$S = \frac{1}{g_{YM}^2} \int d^3x \mathrm{tr} \Big[\frac{1}{2} F_{ij}F^{ij} + \frac{1}{2}(D\phi^J)^2 + \bar{\psi}^K \not{D} \psi^K + \lambda_{J_1J_2J_3J_4} \phi^{J_1}\phi^{J_2}\phi^{J_3}\phi^{J_4} + \mu_{JL_1L_2}\phi^J\psi^{L_1}\psi^{L_2}\Big].$$

All fields are massless and in the adjoint of $SU(N)$, $\lambda_{J_1J_2J_3J_4}$, $\mu_{JL_1L_2}$ are dimensionless couplings while g_{YM}^2 has mass dimension 1.

- An example of such theory is the maximally supersymmetric

Universal predictions

Using perturbation theory to 2-loops:

- The scalar power spectrum has the form

$$\Delta^2_{\mathcal{R}}(q) = \Delta_0 \frac{1}{1 + (gq_*/q)\ln|q/\beta g q_*|}$$

- The tensor power spectrum has the form

$$\Delta^2_{T}(q) = \Delta^T_0 \frac{1}{1 + (g_T q_*/q)\ln|q/\beta_T g_T q_*|}$$

- The scalar non-Guassianity is of exactly the factorisable

Universal predictions

Using perturbation theory to 2-loops:

- The scalar power spectrum has the form

$$\Delta^2_{\mathcal{R}}(q) = \Delta_0 \frac{1}{1 + (gq_*/q)\ln|q/\beta g q_*|}$$

$\delta_0 q^{n_s - 1}$

- The tensor power spectrum has the form

$$\Delta^2_{\mathcal{T}}(q) = \Delta_0^T \frac{1}{1 + (g_T q_*/q)\ln|q/\beta_T g_T q_*|}$$

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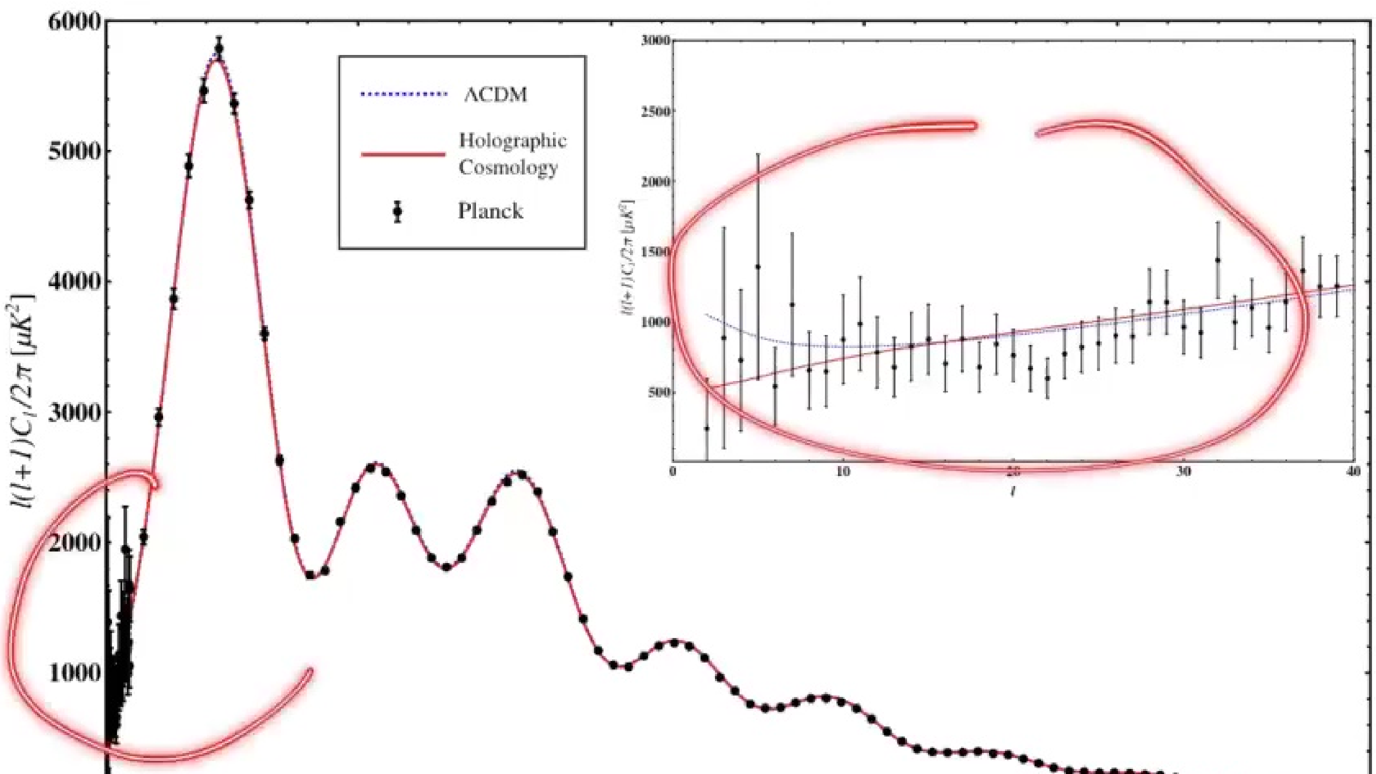
Planck 2015 vs ΛCDM vs holographic model (TT)



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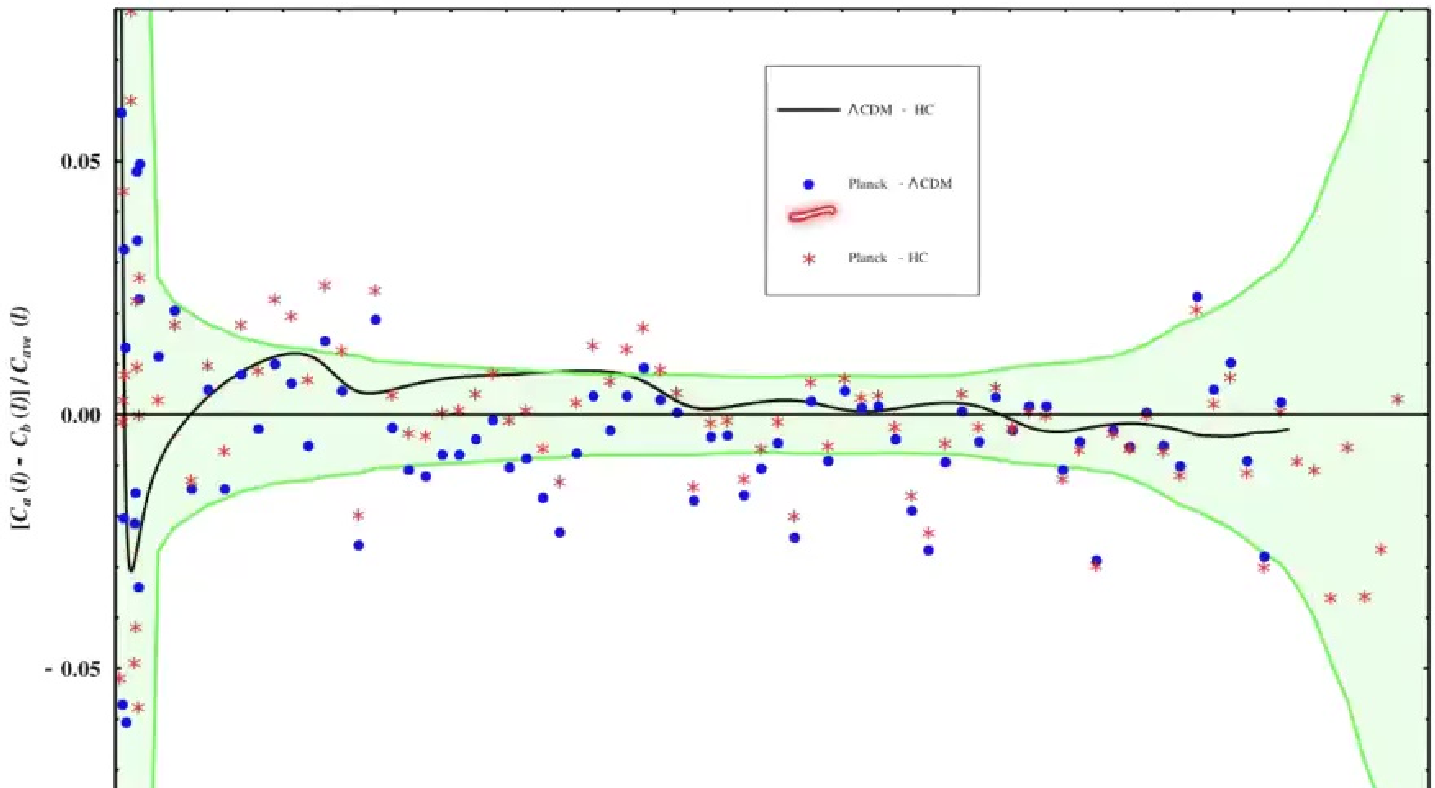

Results

- The fit to data implies that $g_{eff}^2 = g_{YM}^2 N/q$ is very small for all scales seen in CMB, except at very low multipoles, justifying *a posteriori* the use of perturbation theory.
- For $l < 30$ the model becomes non-perturbative and one cannot trust the perturbative prediction.
- Goodness of fit ($l > 30$)

	HC	ΛCDM
χ^2	824.0	824.5

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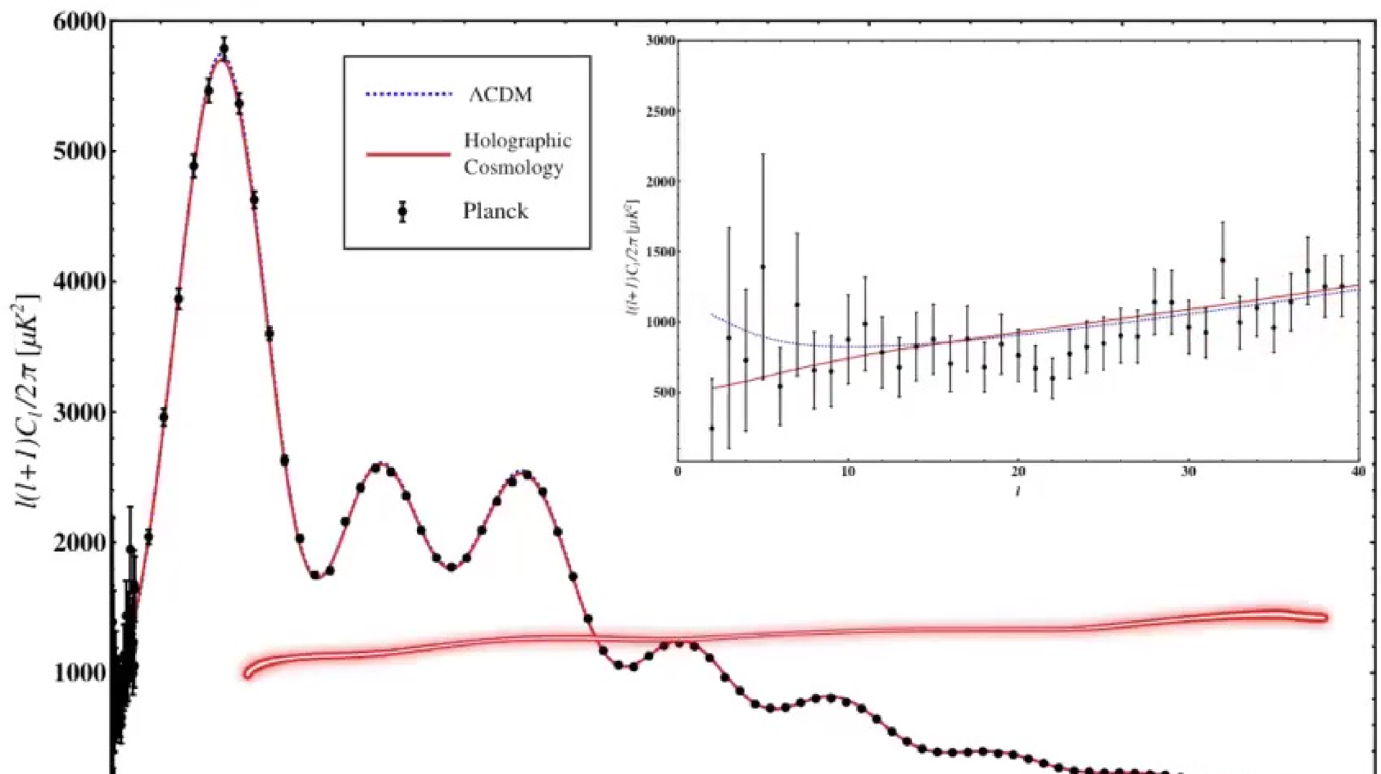

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Model selection

- $SU(N)$ gauge theory coupled to fermions only is ruled out.
- A model that satisfies all observational constraints is: $SU(N)$ gauge theory coupled to N_ϕ non-minimal scalars with ϕ^4 self-interaction.
- Non-minimal means that the energy momentum tensor contains an improvement term:

$$T_{ij} = T_{ij}(A) + \mathrm{Tr}\left(\partial_i\phi\partial_j\phi - \delta_{ij}(\frac{1}{2}(\partial\phi)^2 + \frac{1}{4!}\phi^4) + \xi(\delta_{ij}\Box - \partial_i\partial_j)\phi^2\right)$$

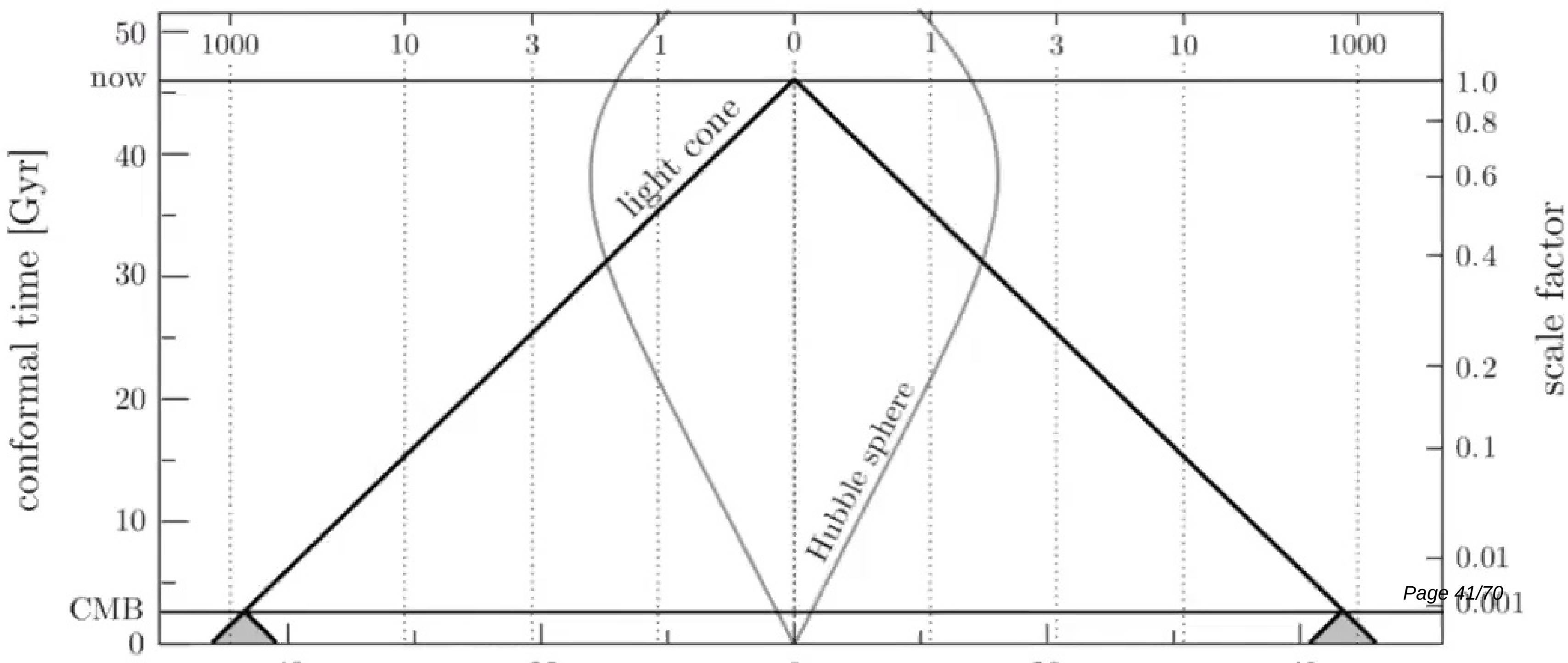
$\xi = 1/8$ yields conformal scalars.

Outline

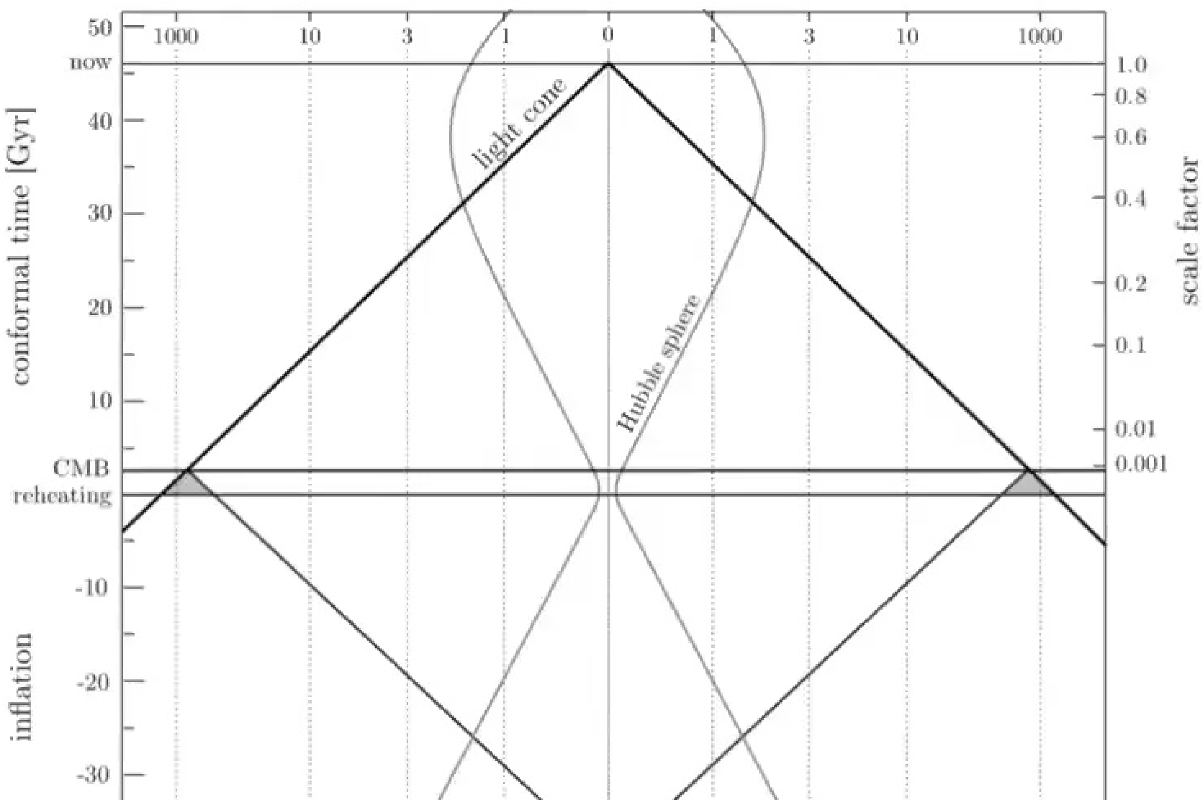
Hot Big Bang Cosmology puzzles

- Inflationary was originally introduced as an answer to three puzzles of the Hot Big Bang cosmology:
  - Why is the Universe uniform and isotropic?
  - Flatness problem
  - Relic (monopole) problem
- If the new holographic models are to replace conventional inflation must also resolve these puzzles.

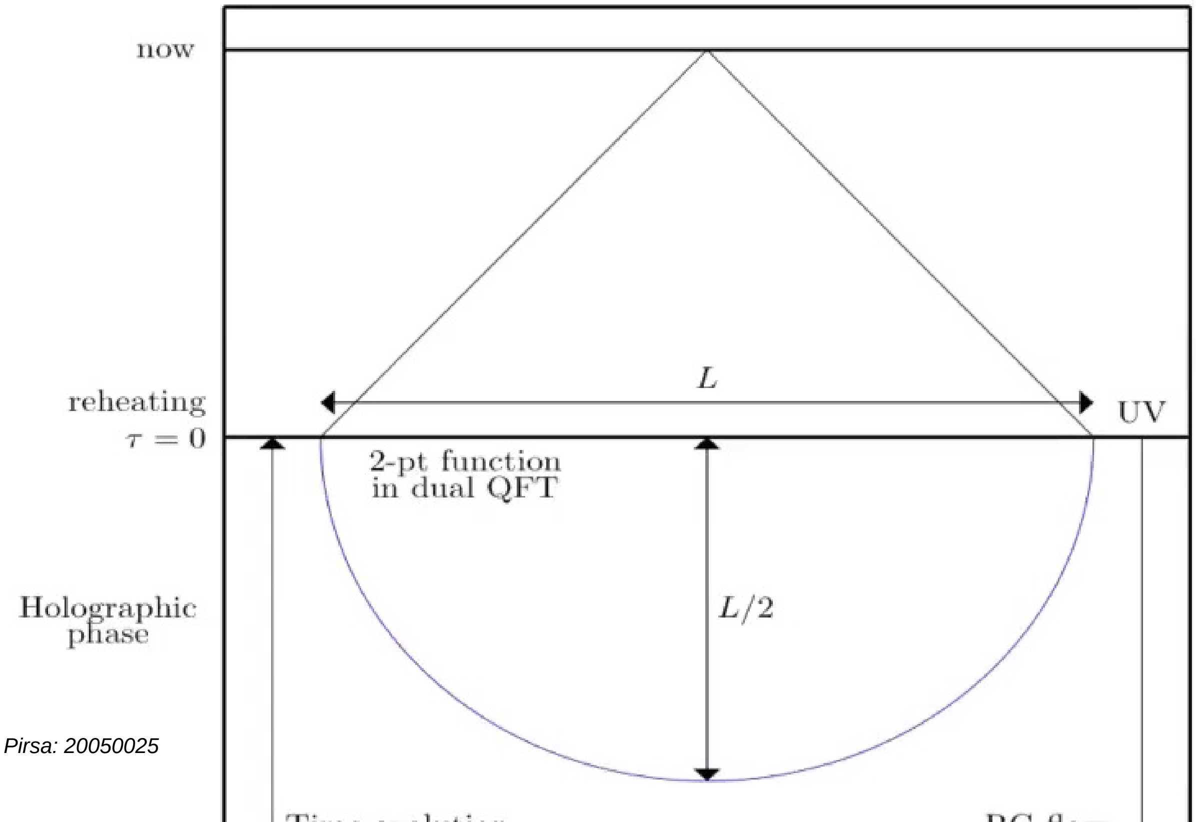
Why is the Universe uniform and isotropic?



Resolution via inflation

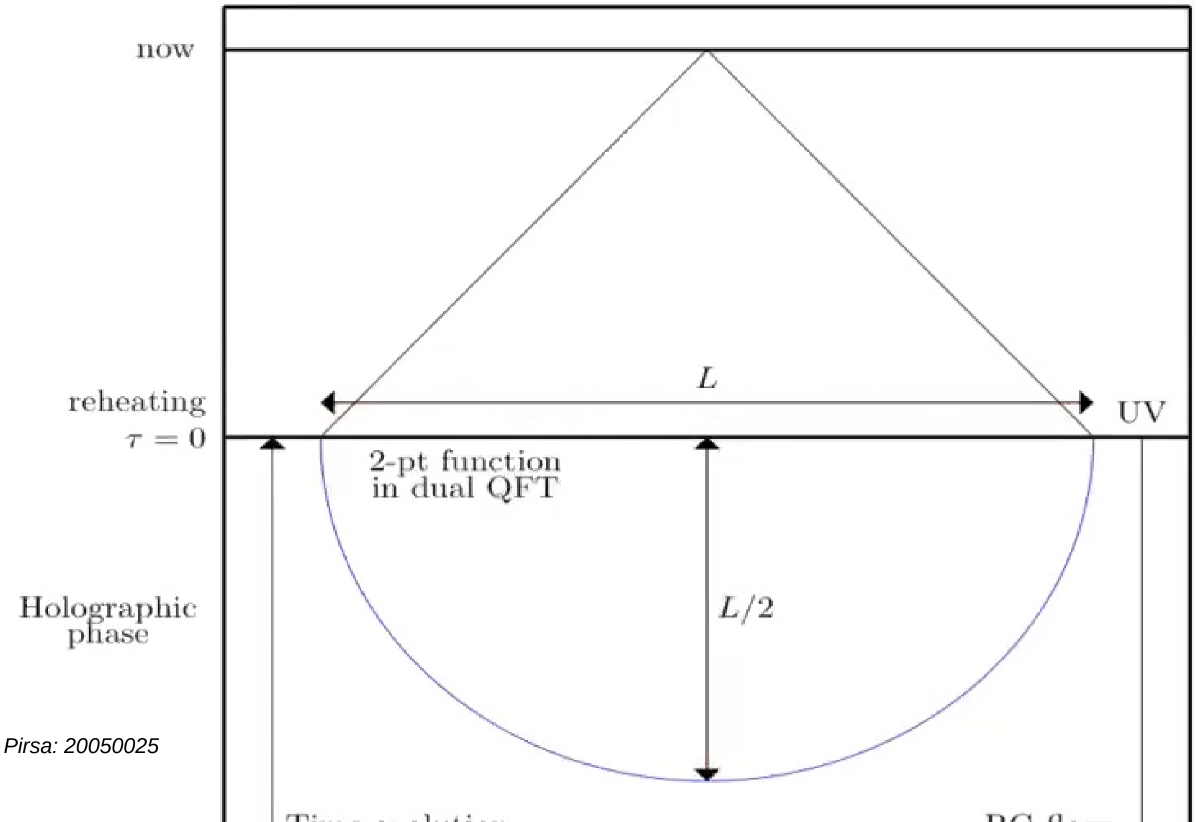


Resolution via holographic cosmology [Nastase, KS]



The RG flow puts all points in causal contact.

Resolution via holographic cosmology [Nastase, KS]



The RG flow puts all points in causal contact.

Flatness problem

- Observation tell us that the Universe is approximately flat today.
- If the Universe were exactly flat in the past, then cosmic evolution would preserve this property and it would be exactly flat today.
- If the Universe is only approximately flat today, $\Omega - 1 \neq 0$, it had to be extremely flat at initial times.
- ➠ Fine tuning.

- Inflation naturally drives Ω very close to one.

The flatness problem and holography [Nastase, KS]

- In holography, time evolution is RG flow.
- How does the space where the theory lives change under RG transformation?

- If we put a QFT on flat background, it will remain on a flat background under RG.
- This is the analogue of the statement that a flat Universe remains flat under cosmic evolution.

The flatness problem and holography

- What if we slightly curve the background: $g_{\mu\nu} = \delta_{\mu\nu} + h_{\mu\nu}$
- The action now changes as

$$S_{flat} \to S_{flat} + \int h^{\mu\nu} T_{\mu\nu}$$

i.e. relative to the original theory we introduce a new coupling that couples to an operator of the QFT, namely the energy momentum tensor.

- We now want to know what happens in the UV.
- This depends on whether the operator is marginal, relevant or irrelevant.

The anomalous dimension

- We need to work the anomalous dimension of $T_{\mu\nu}$.
- Near the UV, the theory is perturbative (it is asymptotically free), and the anomalous dimension can be worked out from its 2-point function.
- The result to 2-loops is

$$\langle T(q)T(-q)\rangle \sim q^3 f_0(1 - f_1 g_{\rm eff}^2 \log g_{\rm eff}^2 + f_2 g_{\rm eff}^2) \sim q^{3+\delta}$$

where

$$\delta = f_1 g_{eff}^2 < 0$$

since the fit to data implies $f_1 < 0$

Relics

- No relics from the early Universe, such as monopoles from GUT phase transitions, have been observed.
- Inflation dilutes them.
- Is there a mechanism to suppress them in holographic cosmology?

Monopoles in holography [Nastase, KS]

- We need to turn this into QFT problem and then analyze it.
- A monopole in the bulk implies that the QFT acquires a new coupling

$$S_{flat} \to S_{flat} + \int A_\mu j^\mu$$

  where j^μ is the magnetic current.
- The effect of the monopole will be washed out if j^μ has negative anomalous dimension.

- We analysed this and a 2-loop computation indeed yields a

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Outline

A very simple model

- A non-minimally coupled massless scalar field in the adjoint of $SU(N)$ with ϕ^4 self-interaction

$$S = \frac{1}{g_{YM}^2} \int d^3x \mathrm{Tr} \left(\frac{1}{2} (\partial_\mu \phi)^2 + \frac{\lambda}{4!} \phi^4 \right),$$

and energy momentum tensor

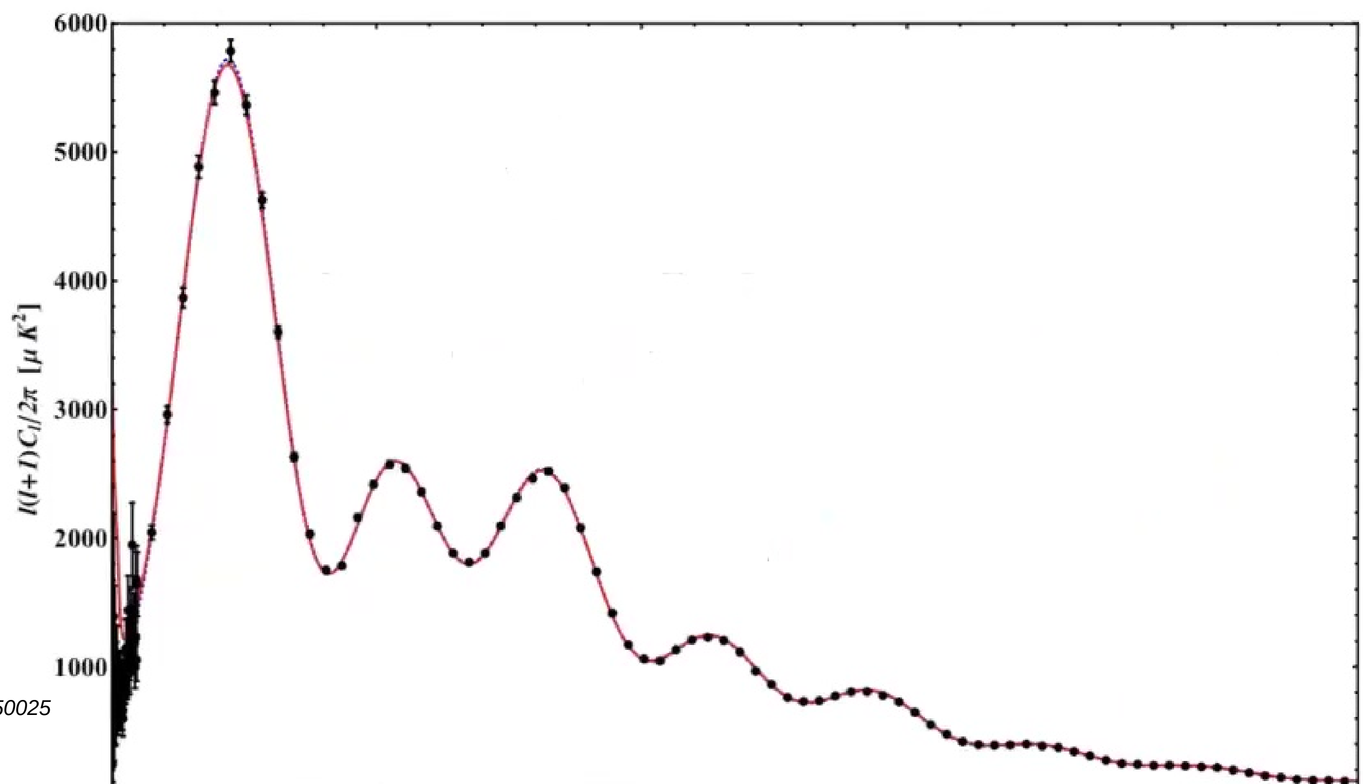
$$T_{ij} = \frac{1}{g_{YM}^2} \mathrm{Tr} \left(\partial_i \phi \partial_j \phi - \delta_{ij} (\frac{1}{2} (\partial \phi)^2 + \frac{\lambda}{4!} \phi^4) + \xi (\delta_{ij} \Box - \partial_i \partial_j) \phi^2 \right)$$

- The perturbative answer to 2-loops is [Coriano, Delle Rose, KS (to

Parameters

- λ can be scaled away, so the model contains two parameters: the rank of the gauge group N and the non-minimality parameter ξ.
- N is related with the smallness of the amplitude of the primordial perturbations.
- ξ is related with the tensor-to-scalar ratio.

Fit to Planck



Is this model perturbative?

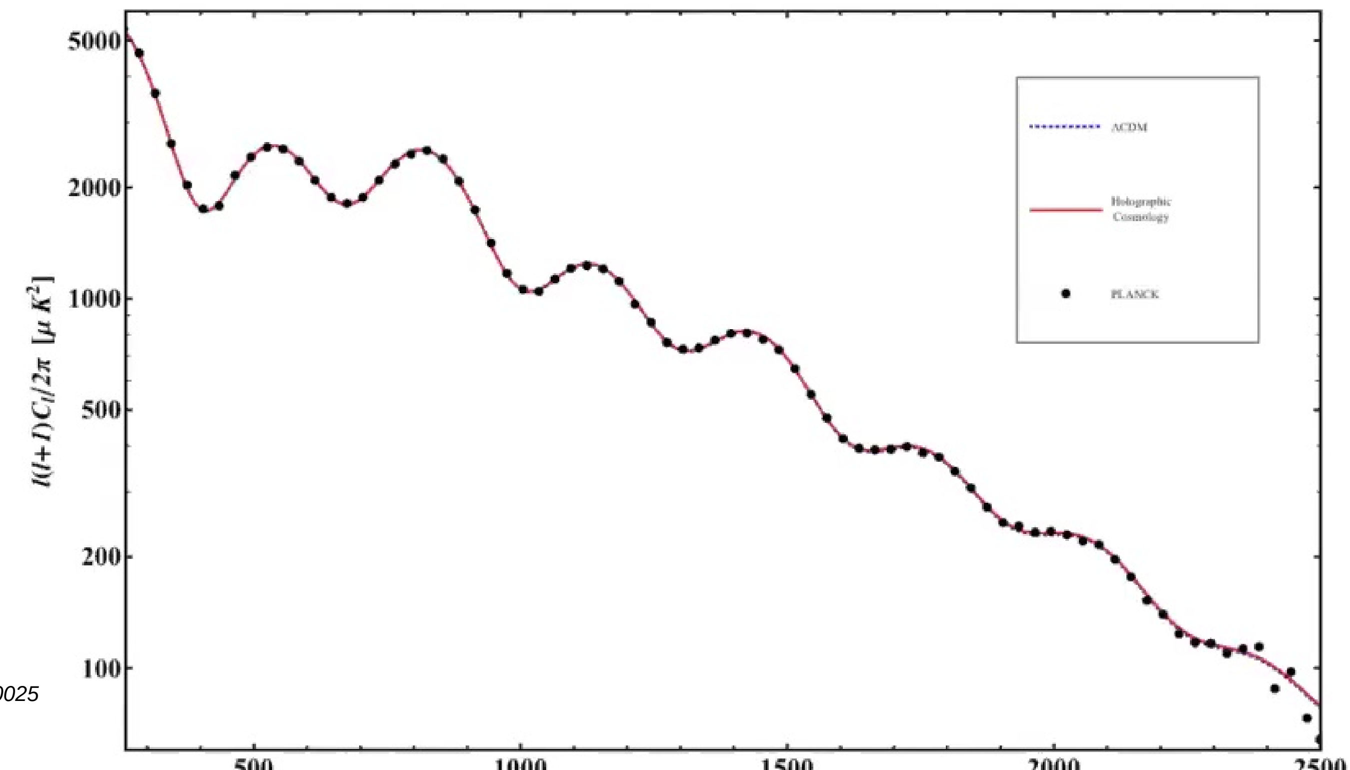
- Fit-to-data implies that perturbation theory breaks down at

$$g_{eff}^2 \geq 1 \qquad \Rightarrow \qquad l < 260$$

- We cannot trust the prediction of perturbation theory below $l = 260$.

Gauge/gravity duality
General implications
Holographic dictionary
Models for non-geometric Universe
Holographic cosmology and Hot Big Bang puzzles
A simple model and the resolution of initial singularity

Fit to Planck (l>260)



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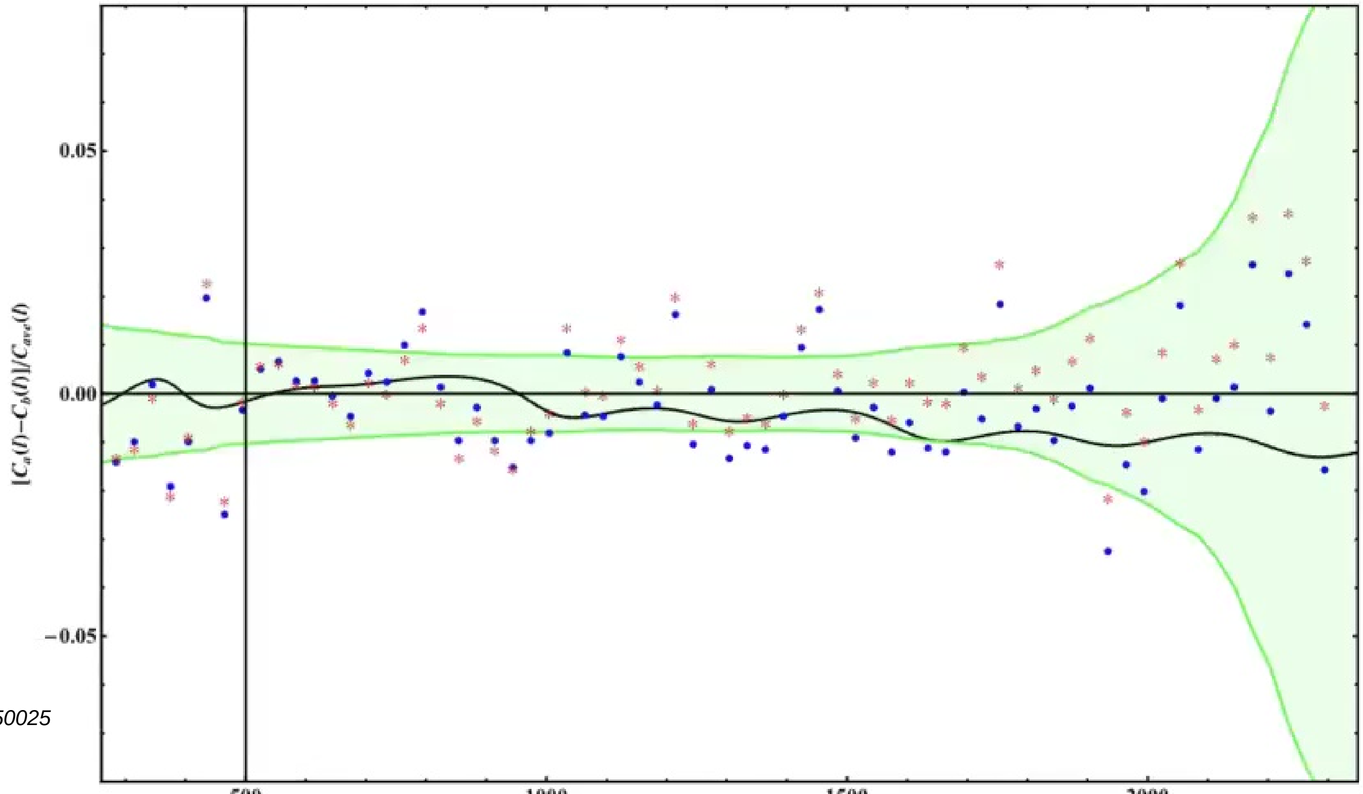

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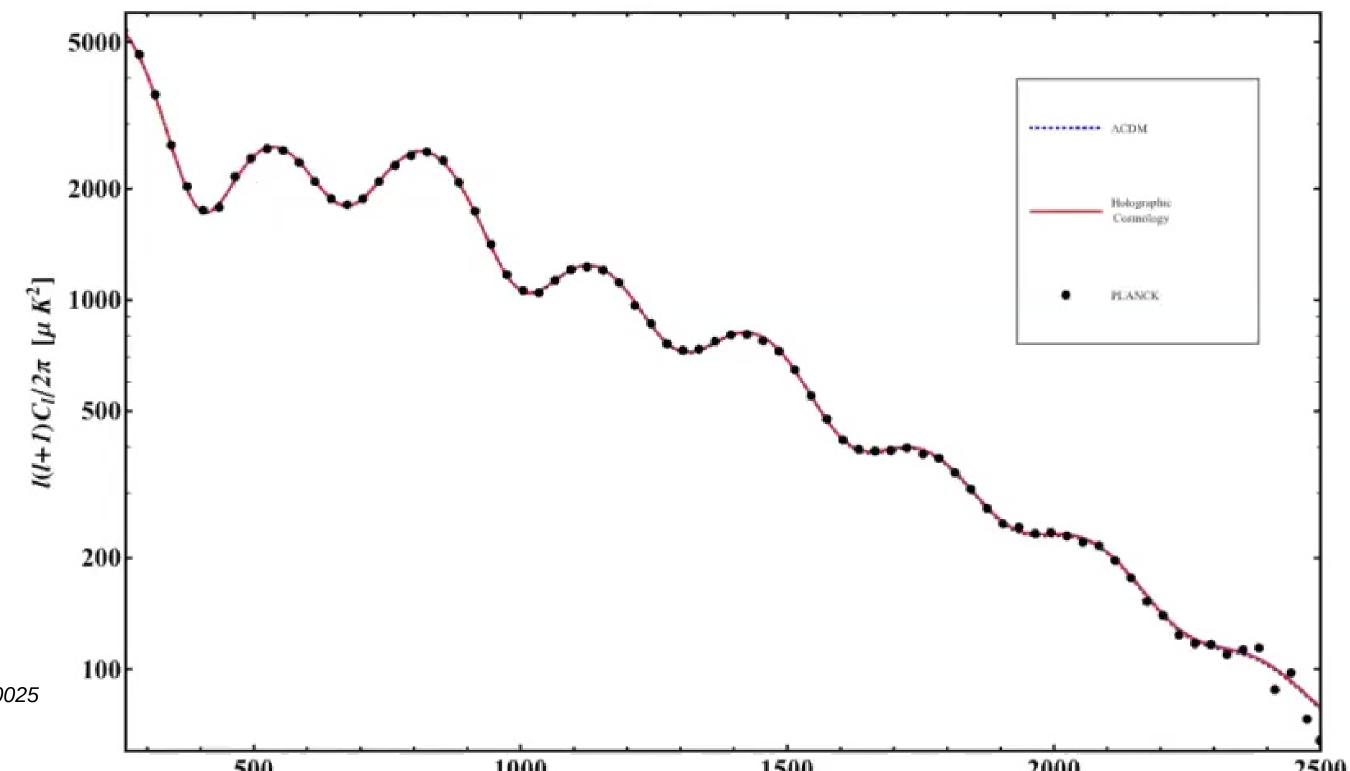


Using Lattice

- Use Lattice methods to compute the observables in the low-l region.

  Would this fit the data better or worse than ΛCDM? Large angle anomalies in the CMB sky?

- Resolution of the initial curvature singularity.

  In holographic cosmology, time evolution is inverse RG flow and the initial singularity is mapped to the IR of the QFT.

We need to ...

- Discretize the continuum model
- Find the massless point
- Find the energy-momentum tensor
- Compute its 2-point function

Massless point

- We need to simulate a massless theory.
- This requires introducing a bare mass δm^2 and fine tuning its value so that the theory becomes massless in the continuum limit.
- In perturbation theory δm^2 can be computed order by order:

$$\delta m^2 = -\lambda \frac{Z_0}{a}\left(2N - \frac{3}{N}\right) + \lambda^2 \left(N^2 - 6 + \frac{18}{N^2}\right) D + \mathcal{O}(\lambda^3)$$

where $Z_0 = 0.252728(6)$ and D is a 2-loop integral.

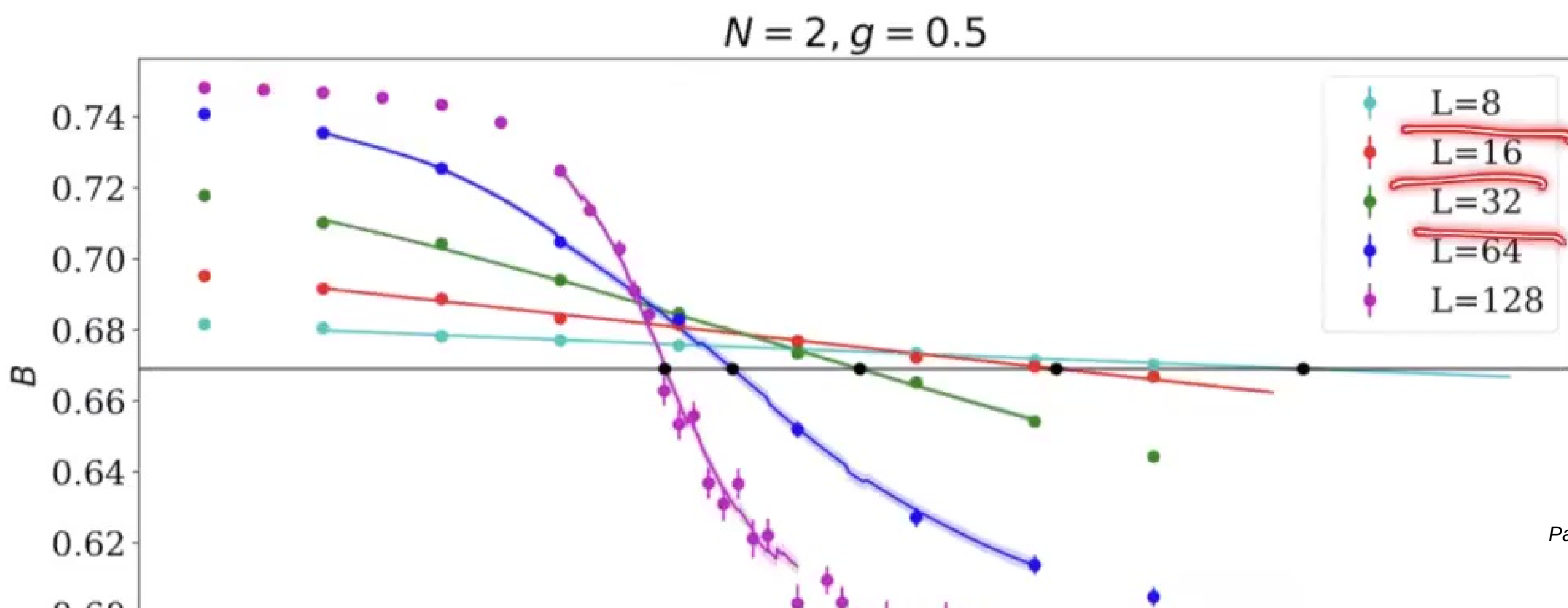
Singularity resolution

- Super-renormalizable theories have severe IR singularities in perturbation theory.
- If the IR singularities persist non-perturbatively the theory will be non-predictive.
- It was argued by JTAP [Jackiw,Templeton (1981)][Appelquist, Pisarski(1981)] that these type of theories are non-perturbative IR finite:
  g_{YM}^2 effectively acts as an IR regulator.
- As time evolution is inverse RG flow, this corresponds to the resolution of the initial singularity.

Massless point: non-perturbative

- If the mass in the continuum limit is positive then $\langle M^n \rangle = 0$ for any n, where $M = \frac{1}{V} \int d^3x \phi(x)$.
- If the mass in the continuum limit is negative we are in the spontaneously broken phase, $\langle \mathrm{Tr}\, M^n \rangle \neq 0$.
- To find the massless point one may compute the Binder Cumulant $B = \langle (TrM^2) \rangle^2 / \langle TrM^4 \rangle$ for different lattice sizes and find the intersection point.

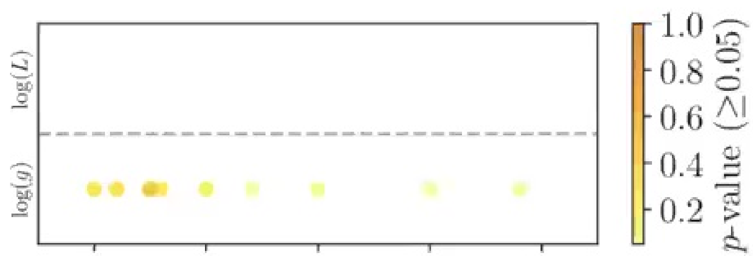
Binder Cumulant $SU(2)$ *[Preliminary]*

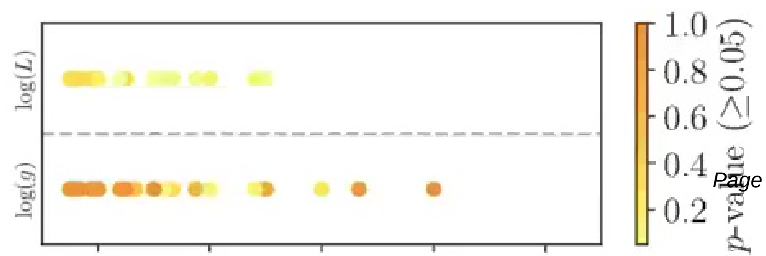


IR finiteness of critical mass *[Preliminary]*

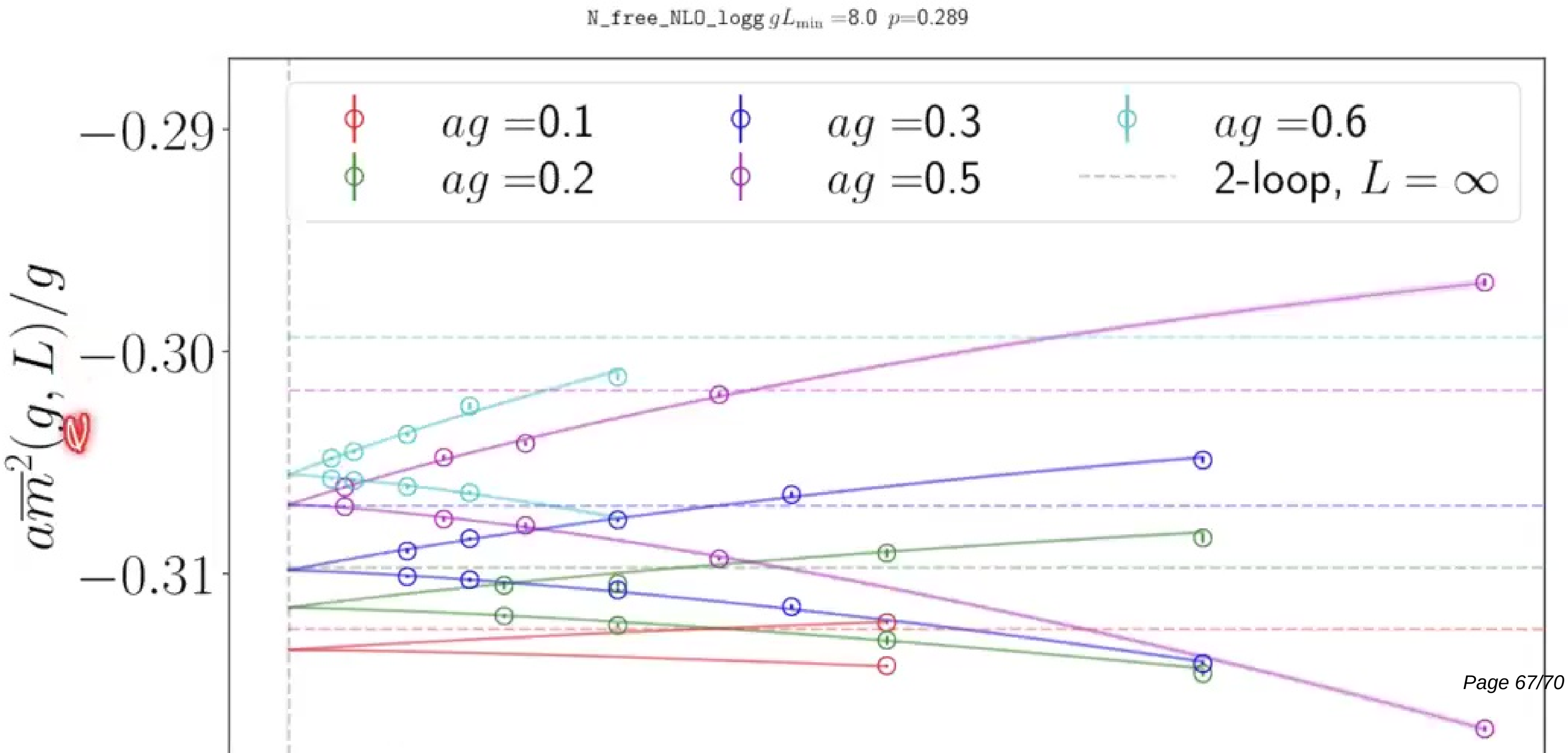
- On the lattice, the finite volume L^3 acts as an IR regulator.
- There are two relevant scales: g and $1/L$.
- The question is whether the finite critical mass determined by simulations are best fit by a function that contains
  - $\log L$, indicating IR divergence in the continuum limit
  - $\log g$, indicating IR finiteness as argued by JTAP.

$N = 2$ $\quad$ $N = 4$





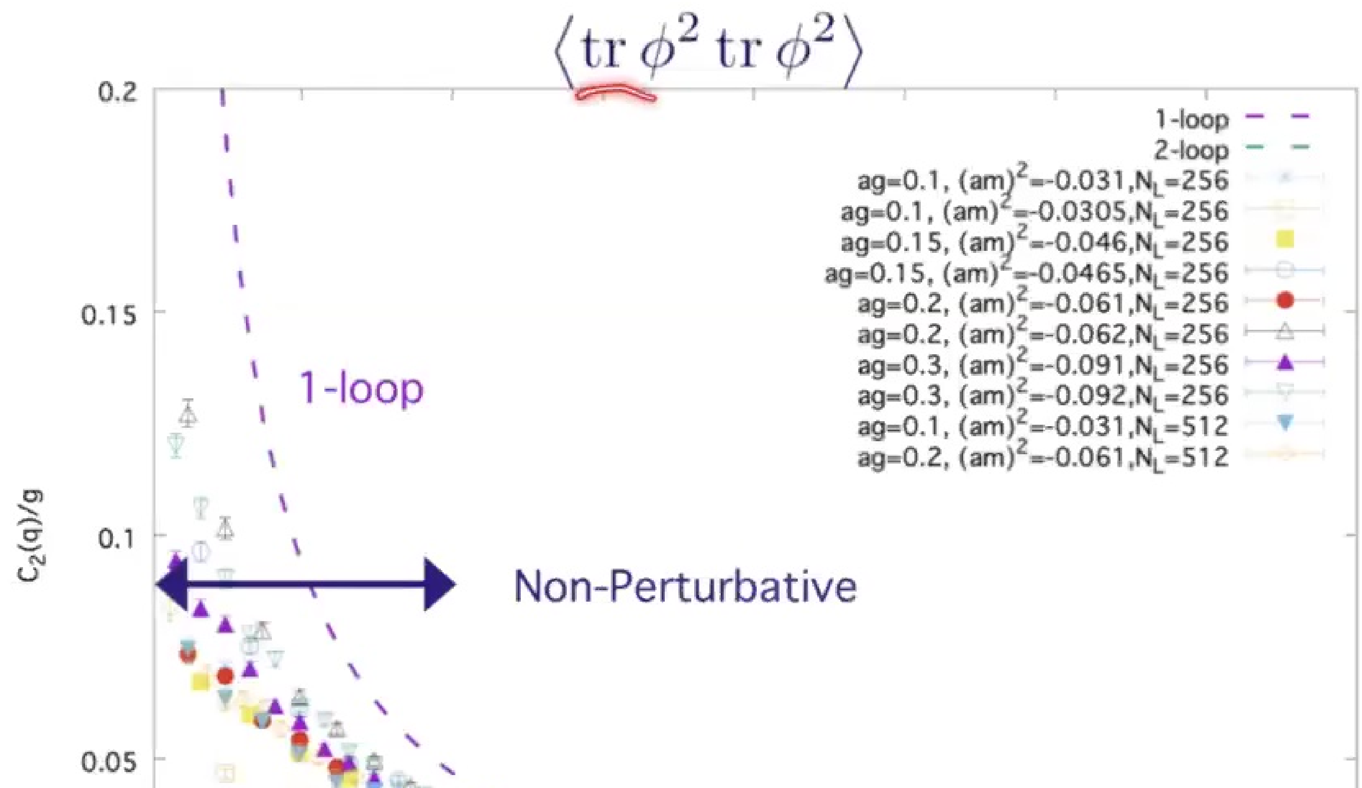
Scaling and IR finiteness of critical mass *[Preliminary]*



We need to ...

- Discretize the continuum model ✓
- Find the massless point ✓
- Find the energy-momentum tensor *almost done*
- Compute its 2-point function

2-point function [preliminary results]



Conclusions

- Holography offers a unified framework for discussing the very Early Universe:
  - Strongly couple QFT: conventional inflation.
  - Weak/intermediate coupling: new non-geometric models.
- Arrow of time via properties of RG of dual QFT.
- Resolution of Hot Big Bang puzzles via properties of RG flow of dual QFT.
- Resolution of initial singularity $\leftrightarrow$ IR finiteness of QFT