Loop Quantum Cosmology and the CMB

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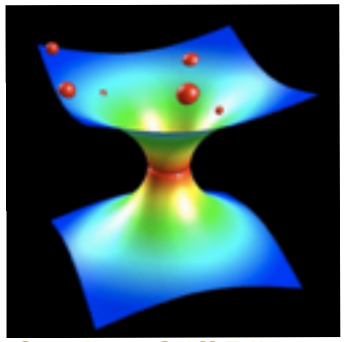
NSF

Recent advances in LQG: Concrete physical systems

- Black hole spacetimes: see previous talks
- This talk: LQC and its phenomenology

Regarding the background spacetime, a couple of important results:

- Bounce replacing the Big Bang singularity



Credits: Cliff Pikover

- If $(\phi, V(\phi))$ in the matter sector: Inflation appears at some time after the bounce

Arena to construct a Quantum Gravity extension of the inflationary scenario

Strategy for phenomenology

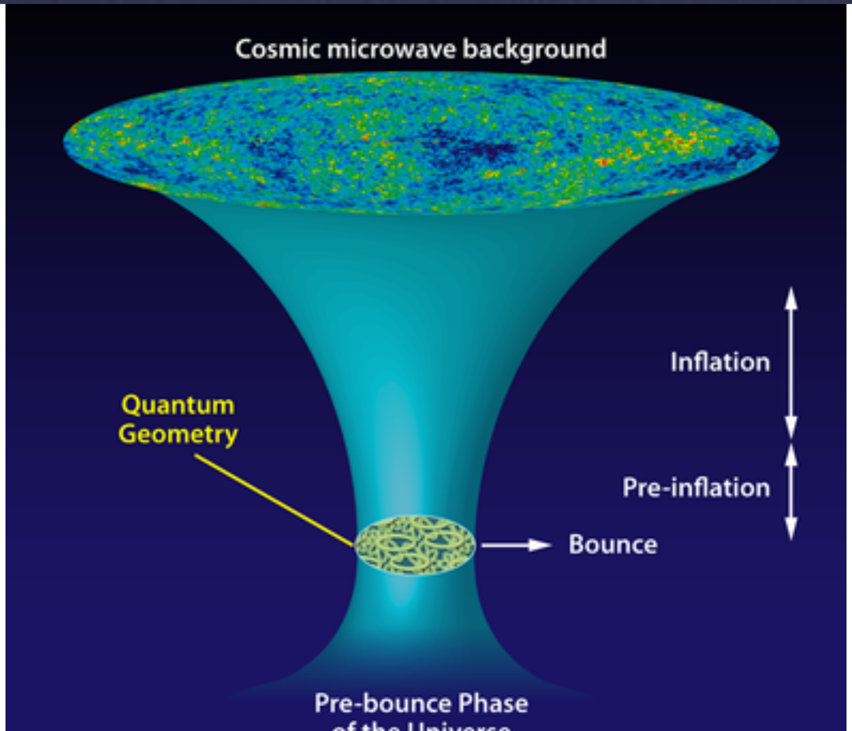


Fig. Credits:
P. Singh, Physics 5, 142 (2012)

- **Background space-time:** LQC $\Psi_{\mathrm{FRW}}(a, \phi)$

- **Cosmological perturbations** (scalar and tensor): QFT in Quantum space-times

  I.A., Ashtekar, Nelson: PRL 109 251301 (2012); PRD 87 043507 (2013); CQG 30 085014 (2013)

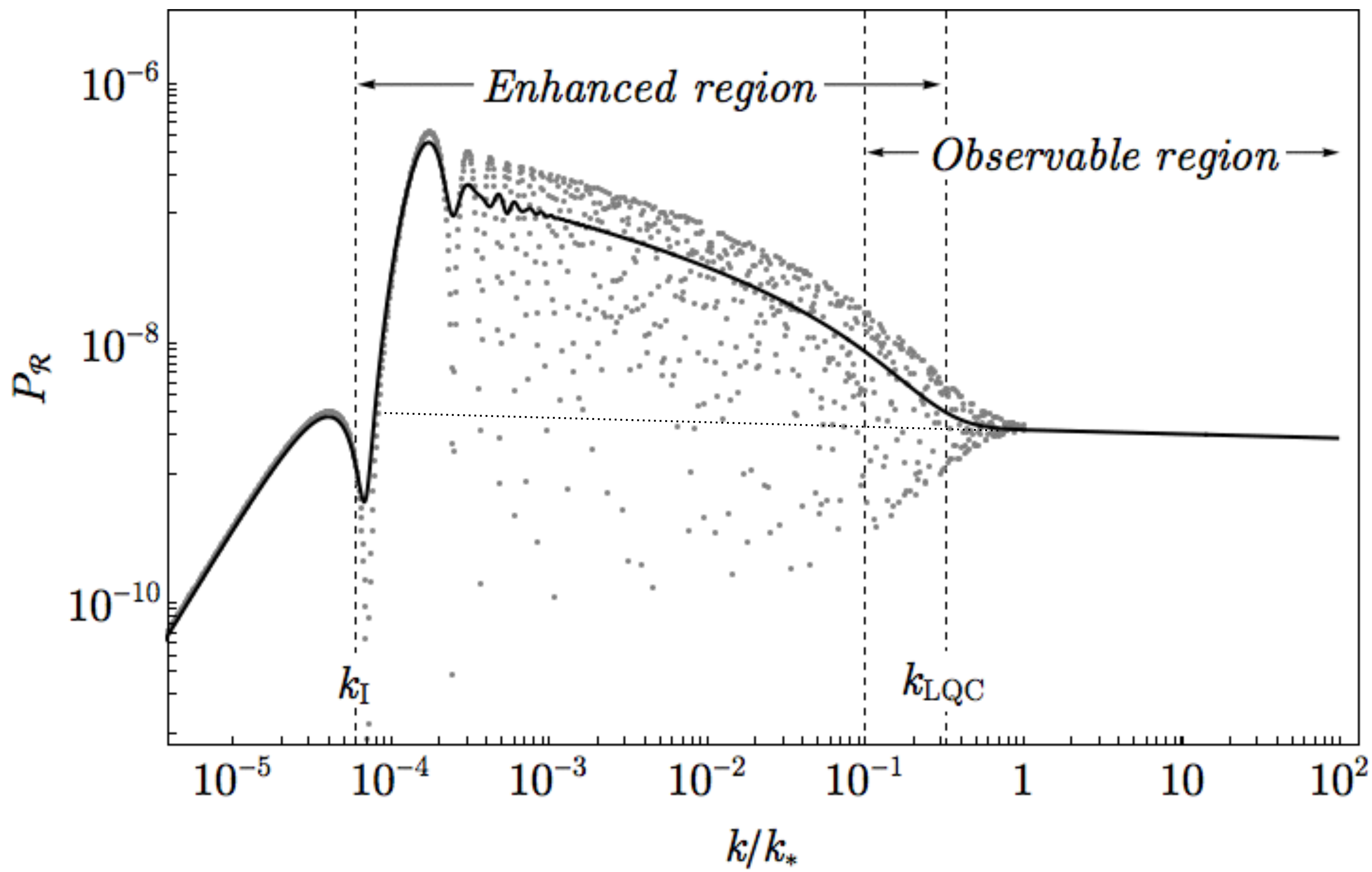
  - Perturbations start in the vacuum at early times
  - Evolution excites quanta of curvature perturbations for long wavelengths (compared to the space-time curvature scale)
  - Then standard inflation begins, but perturbations reach the onset of inflation in an excited state

Observational consequences

Results of numerical evolution

(I.A.-Ashtekar-Nelson 2012-13, I.A.-Morris 2015)

Scalar Power Spectrum



The LQC pre-inflationary evolution modifies the power for the lowest k-values (longest wavelengths) we can observe, and quite significantly for even longer wavelengths (super-Hubble modes)

Planck 2015 results. XVI. Isotropy and statistics of the CMB

Planck Collaboration: P. A. R. Ade[89], N. Aghanim[60], Y. Akrami[65, 103], P. K. Aluri[55], M. Arnaud[75], M. Ashdown[72, 6], J. Aumont[60], C. Baccigalupi[88], A. J. Banday[100, 9 *], R. B. Barreiro[67], N. Bartolo[32, 68], S. Basak[88], E. Battaner[101, 102], K. Benabed[61, 99], A. Benoît[58], A. Benoit-Lévy[26, 61, 99], J.-P. Bernard[100, 9], M. Bersanelli[35, 49], P. Bielewicz[85, 9, 88], J. J. Bock[69, 11], A. Bonaldi[70], L. Bonavera[67], J. R. Bond[8], J. Borrill[14, 94], F. R. Bouchet[61, 92], F. Boulanger[60], M. Bucher[1], C. Burigana[48, 33, 50], R. C. Butler[48], E. Calabrese[97], J.-F. Cardoso[76, 1, 61], B. Casaponsa[67], A. Catalano[77, 74], A. Challinor[64, 72, 12],

ABSTRACT

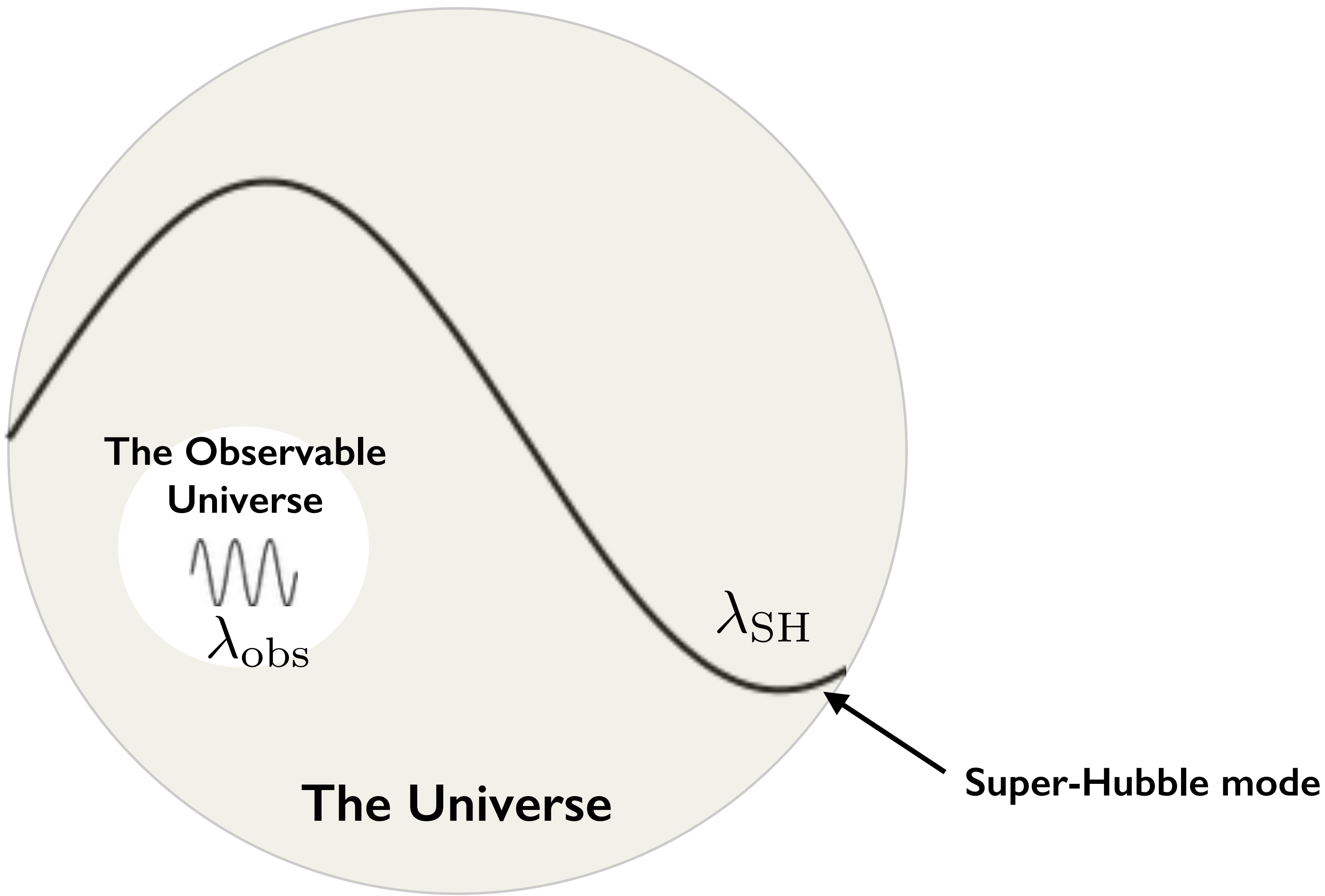
We test the statistical isotropy and Gaussianity of the cosmic microwave background (CMB) anisotropies using observations made by the *Planck* satellite. Our results are based mainly on the full *Planck* mission for temperature, but also include some polarization measurements. In particular, we consider the CMB anisotropy maps derived from the multi-frequency *Planck* data by several component-separation methods. For the temperature anisotropies, we find excellent agreement between results based on these sky maps over both a very large fraction of the sky and a broad range of angular scales, establishing that potential foreground residuals do not affect our studies. Tests of skewness, kurtosis, multi-normality, N-point functions, and Minkowski functionals indicate consistency with Gaussianity, while a power deficit at large angular scales is manifested in several ways, for example low map variance. The results of a peak statistics analysis are consistent with the expectations of a Gaussian random field. The "Cold Spot" is detected with several methods, including map kurtosis, peak statistics, and mean temperature profile. We thoroughly probe the large-scale dipolar power asymmetry, detecting it with several independent tests, and address the subject of a posteriori correction. Tests of directionality suggest the presence of angular clustering from large to small scales, but at a significance that is dependent on the details of the approach. We perform the first examination of polarization data, finding the morphology of stacked peaks to be consistent with the expectations of statistically isotropic simulations. Where they overlap, these results are consistent with the *Planck* 2013 analysis based on the nominal mission data and provide our most thorough view of the statistics of the CMB fluctuations to date.

1. Introduction

foreground-cleaned CMB maps, it was generally considered that the case for anomalous features in the CMB had been strengthened. Hence, such anomalies have attracted considerable attention in the community, since they could be the visible traces of fundamental physical processes occurring in the early Universe.

However, the literature also supports an ongoing debate about the significance of these anomalies. The central issue in this discussion is connected with the role of a posteri-

Is there any way super-Hubble modes can affect observable ones???



The answer is yes, if modes $\lambda_{\rm SH}$ and $\lambda_{\rm obs}$ are correlated: Non-Gaussianity

(Adhikari, Brahma, Bartolo, Bramante, Byrnes, Carrol, Dai, Dimastrogiovanni, Erickcen, Hui, Jeong, Kamionkowski, LoVerde, Matarrese, Mota, Nelson, Nurmi, Peloso, Pullen, Ricciardone, Shandera, Schmidt, Tasinato, Thorsrud, Urban,...)

The statement:

If we only observe a small patch within a larger universe, correlations with super-Hubble modes will generically modify the observed power spectrum (change in power, anisotropies, etc.)

Another way of saying the same:

($Q_{\vec{k}} \equiv$ scalar curvature perturbations)

If $\langle Q_{\vec{k}_{\rm obs}} Q_{\vec{k}'_{\rm obs}} Q_{\vec{k}_{\rm SH}} \rangle$ **large, and we cannot observe** $\vec{k}_{\rm SH}$

$\longrightarrow$ **correlations between** $\vec{k}_{\rm obs}$ **and** $\vec{k}'_{\rm obs}$

$\longrightarrow$ **non-diagonal contribution to** $\langle Q_{\vec{k}_{\rm obs}} Q_{\vec{k}'_{\rm obs}} \rangle$

$\longrightarrow$ $\langle Q(\vec{x}) Q(\vec{x} + \Delta\vec{x}) \rangle$ **will depend on** $\vec{x}$ **and direction of** $\Delta\vec{x}$

$\longrightarrow$ **the observable patch of the universe will look more inhomogeneous and isotropic**

Non-Gaussian modulation of the power spectrum:

In k-space:

Non-Gaussianity

$$\langle Q_{\vec{k}_{\rm obs}} Q_{\vec{k}'_{\rm obs}} \rangle = P_Q(k) \Big[(2\pi)^3\, \delta(\vec{k}_{\rm obs} + \vec{k}'_{\rm obs}) + G(\vec{k}_{\rm obs}, \vec{k}_{\rm SH})\, Q_{\vec{k}_{\rm SH}} \Big]$$

In angular space:

Wigner 3j-symbols

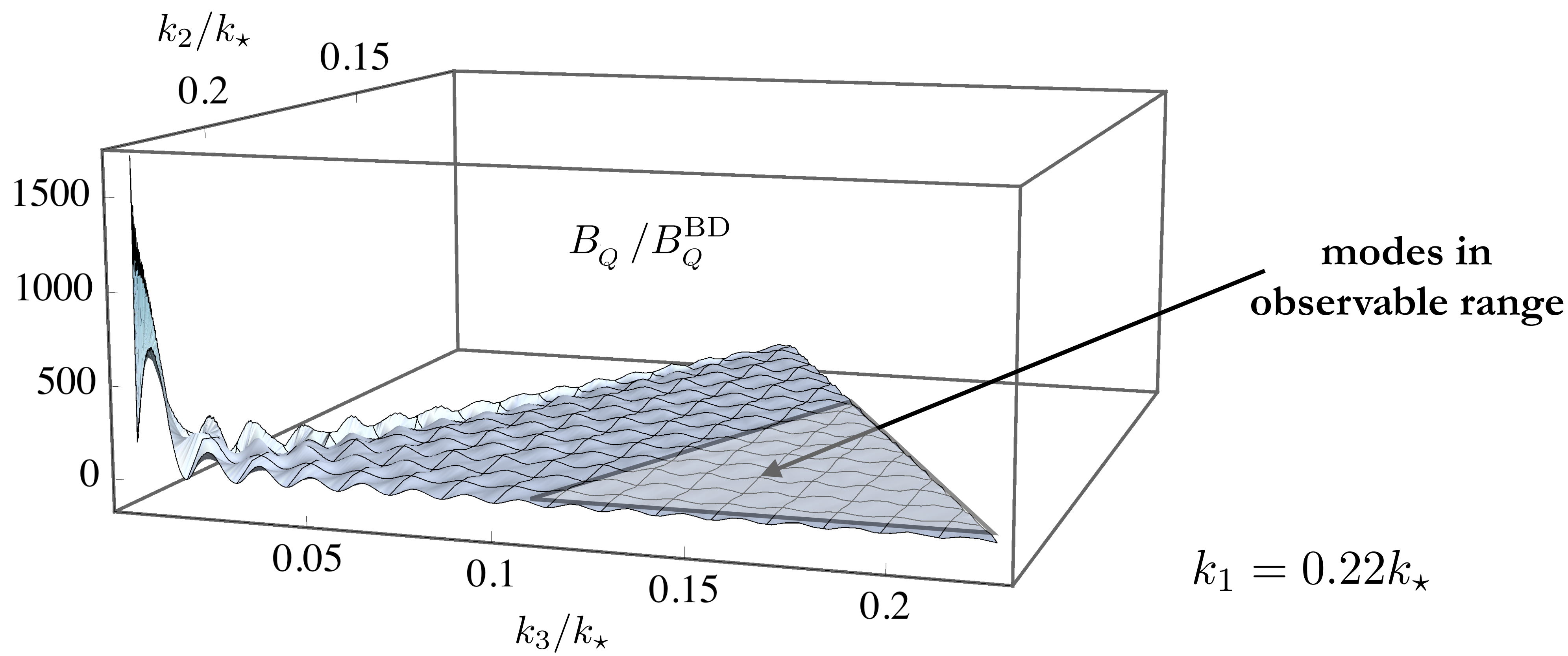
$$\boxed{\langle a_{\ell m} a^{\star}_{\ell' m'} \rangle = \delta_{\ell\ell'} \delta_{mm'}\, C_\ell + \sum_{LM} A_{LM}\, \mathcal{G}^{\ell\ell' L}_{-mm' M}\, (C_\ell + C_{\ell'})}$$

Goal: Compute the modulating amplitude $A_{\rm LM}$ using the LQC+inflation

First: Non-Gaussianity in LQC+inflation

I.A. 2015

Ratio (inflation+LQC)/inflation Bispectrum:

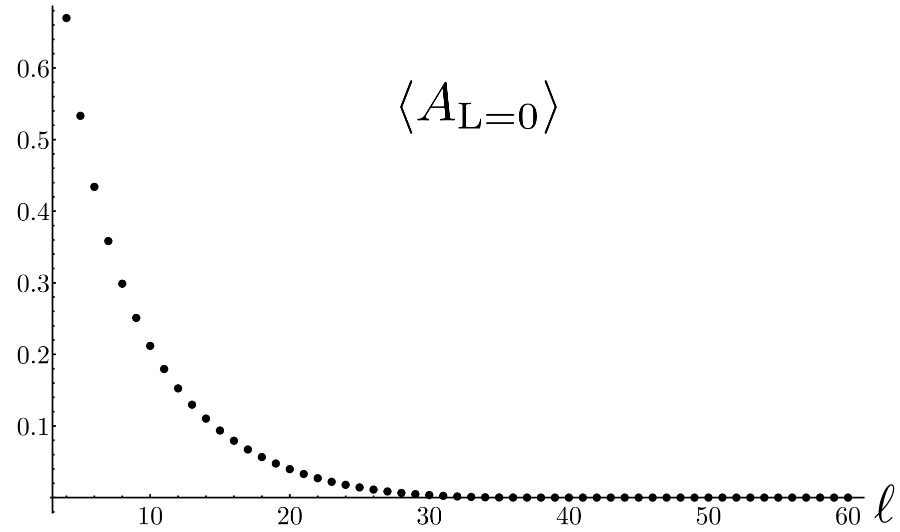


The plot tells us:

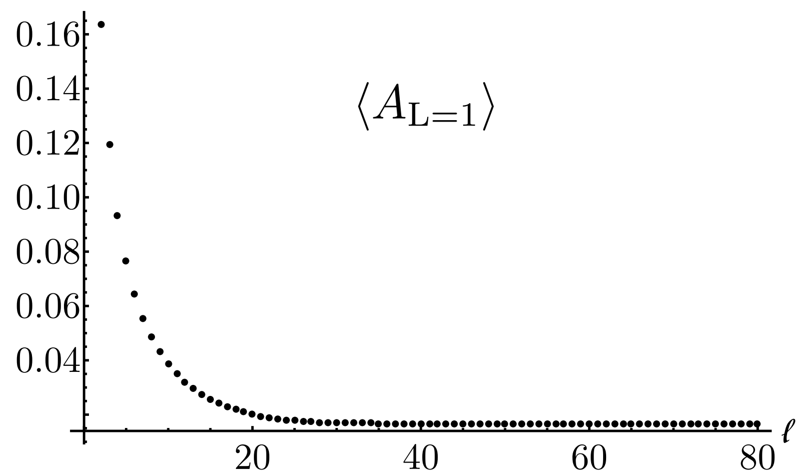
- **Observable modes are not correlated among themselves: ok with observations**
- **But the longest wavelengths we can observe are strongly correlated with super-Hubble modes (as expected)**

Second: Computation of the modulation $A_{\rm LM}$

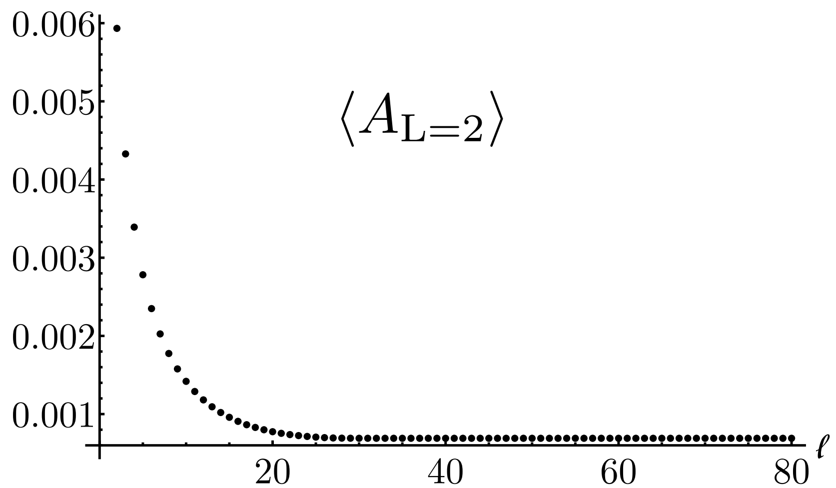
Monopole:



Dipole:



Quadrupole:



Etc.

Conclussions

There is a single choice of the parameters of the model for which:

- For the monopole: 1 every 6 simulated spectra show a suppression of at least 10% for $\ell < 30$
- A scale dependent dipole modulation in quantitative agreement with observations arises
- Negligible quadrupole, octopole, etc

In summary: the LQC bounce preceding inflation is a good candidate to account the CMB large scale anomalies

One more thing:

Can one predict something that hasn't been observed yet?

Answer: Yes

Recall:

If $\langle Q_{\vec{k}_{\rm obs}} Q_{\vec{k}'_{\rm obs}} Q_{\vec{k}_{\rm SH}} \rangle$ **large** $\longrightarrow$ **modulation in** $\langle Q_{\vec{k}_{\rm obs}} Q_{\vec{k}'_{\rm obs}} \rangle$

Same argument but now with tensor perturbations:

If $\langle \mathcal{T}_{\vec{k}_{\rm obs}} \mathcal{T}_{\vec{k}'_{\rm obs}} Q_{\vec{k}_{\rm SH}} \rangle$ **large** $\longrightarrow$ **modulation in** $\langle \mathcal{T}_{\vec{k}_{\rm obs}} \mathcal{T}_{\vec{k}'_{\rm obs}} \rangle$

Since both correlations are generated by the same $Q_{\vec{k}_{\rm SH}}$ **, they are correlated**

I've computed $\langle \mathcal{T}_{\vec{k}_{\rm obs}} \mathcal{T}_{\vec{k}'_{\rm obs}} Q_{\vec{k}_{\rm SH}} \rangle$ **and the results are very similar to** $\langle Q_{\vec{k}_{\rm obs}} Q_{\vec{k}'_{\rm obs}} Q_{\vec{k}_{\rm SH}} \rangle$

Values for $\langle A_{\rm L=0} \rangle$ $\langle A_{\rm L=1} \rangle$ $\langle A_{\rm L=2} \rangle$ $\langle A_{\rm L=3} \rangle$ **almost identical**

Prediction: if low ℓ's anomalies are originated from a the LQC bounce, then the tensor perturbations must also show the anomalies