Connection with Observations

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LQC

Main ingredients

Summary of work done by many researchers:

Alesci, Ashtekar, Barrau, Benitez-Martinez, Bojowald, Bonga, Bolliet, Brizuela, Cailleteau, Cianfrani, Corichi, Campiglia, Castelló-Gomar, de Blas, Dapor, Diener, Elizaga-Navascues, Engle, Freishhack, Garay, Grain, Gupt, Hanusch, Hernandez, Joe, Karami, Kranas, Martin-Benito, Martin de Blas, Mena-Marugan, Megevan, Mielczarek, Montoya, Lewandowski, Li, Linsefors, Nelson, Pawlowski, Payli, Putchta, Olmedo, Oriti, Singh, Rovelli, Taveras, Thiemann, Vandersloot, Vidoto, Vijayakumar, Wang, Wilson-Ewing,…)

(1) Symmetry reduction: drastic simplification. Physics can be missed. But it has been proven useful to allow progress in many areas of physics.

(2) LQG: no canonical hom+isotrop sector. Not even Hamiltonian we all agree on.

(3) Physicist viewpoint has been adopted in LQC:

- **build a model using symmetry reduction;**
- **simple matter sector;**
- **make choices when needed using existing knowledge and physical intuition.**

Goal: Build a self-consistent model…

- **Able to make contact with well-established theories (e.g. standard cosmological model)**
- **Able to make predictions (aim at a data-driven approach)**
- **Providing the foundations for further scrutiny and improvement**

What we have learned so far

(1) Singularity resolution. First for flat FLRW. Extended to other models (spatial curvature, anisotropies, Gowdy). Robust.

⟶ **Detailed understanding (within LQC) of mathematical and physical origin of singularity resolution.**

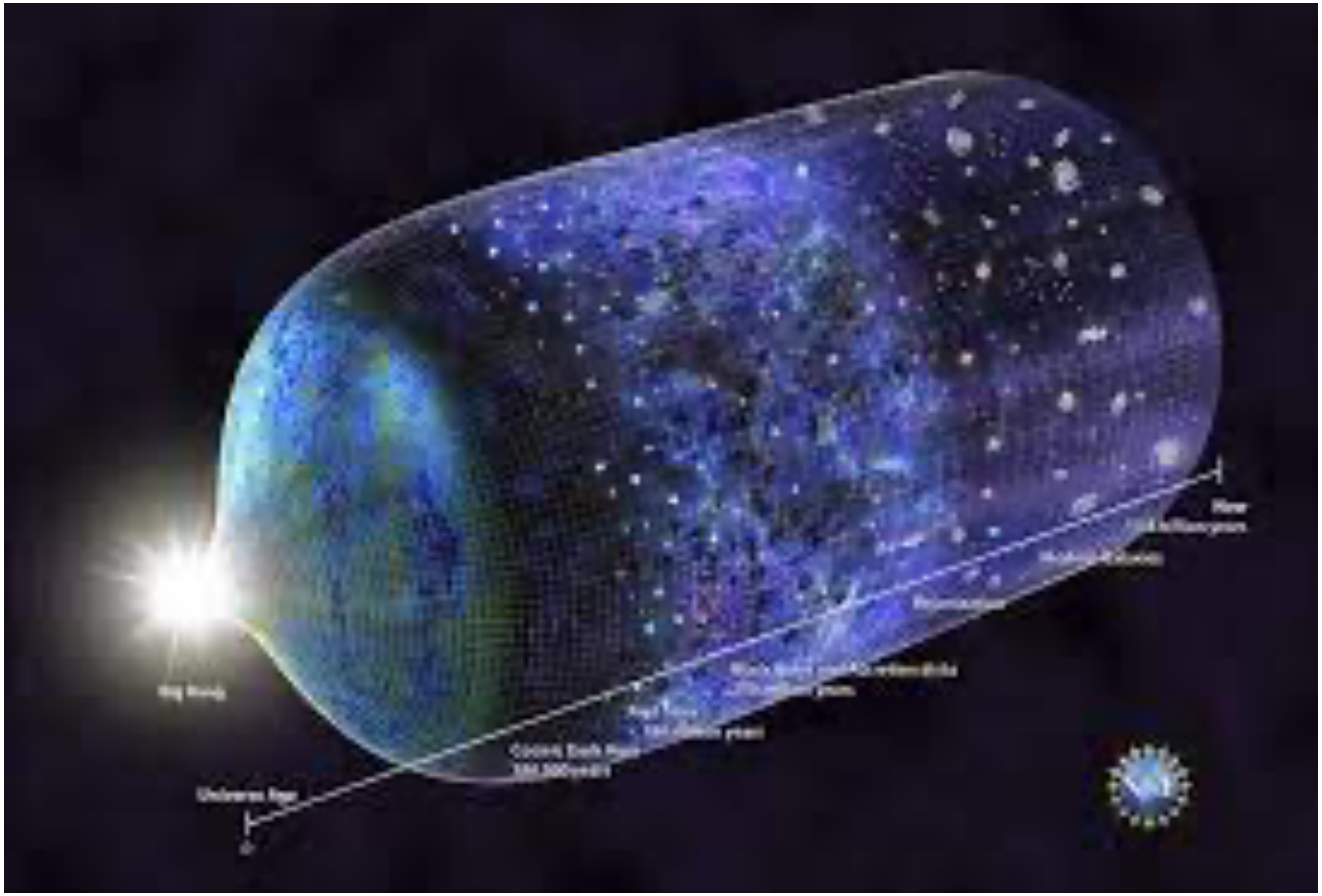
(2) Many choices made on the way: ϕ-clock, Hamiltonian constraint, Fock quantization for perturbations, etc.

(3) Beyond LQC (relation with full theory): post-bounce phase robust. Difference in pre-bounce phase.

Phenomenology

Motivation

The Planck era is within our past light cone!



What we have learned so far

(1) Out of the abstract quantum geometry $\Psi_{\rm LQC}(a,\phi)$

Perturbations governed buy hyperbolic wave equations, on an emergent metric:

$\longrightarrow$ effective causal structure out of $\Psi_{\rm LQC}(a,\phi)$

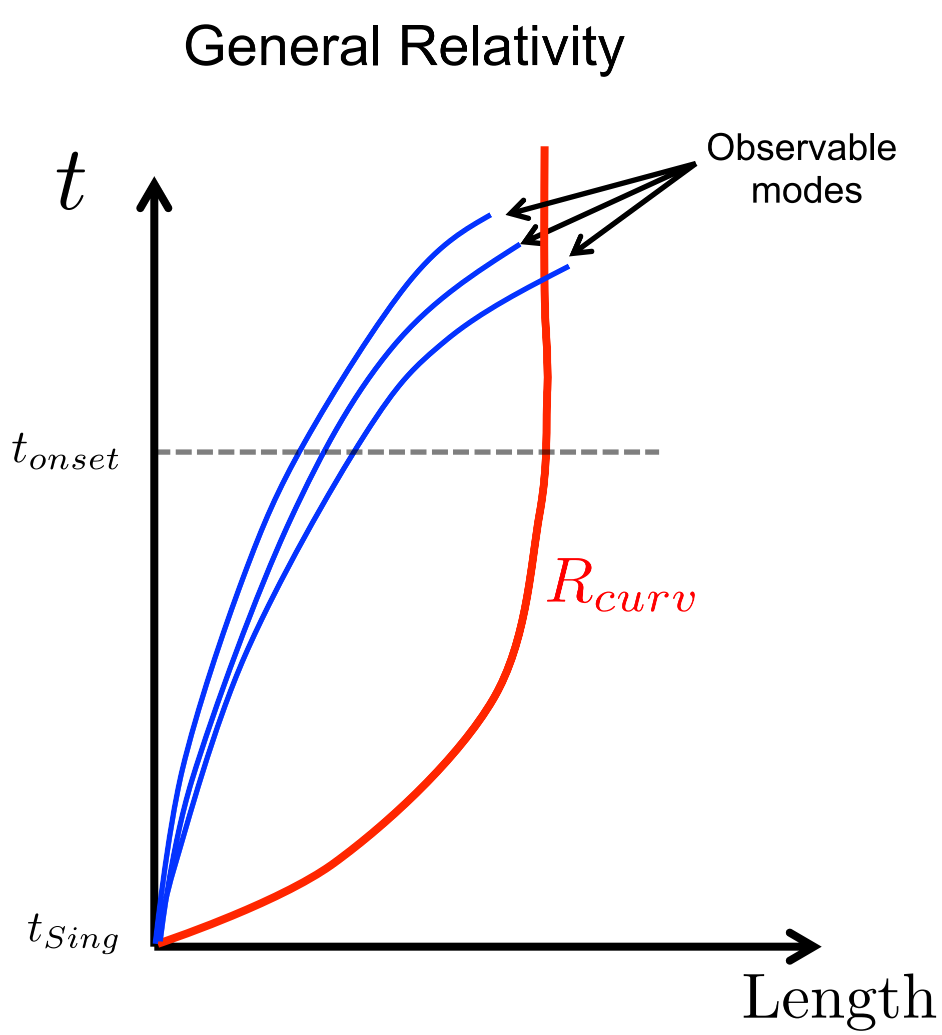
(2) Mechanism to generate primordial perturbations? No.

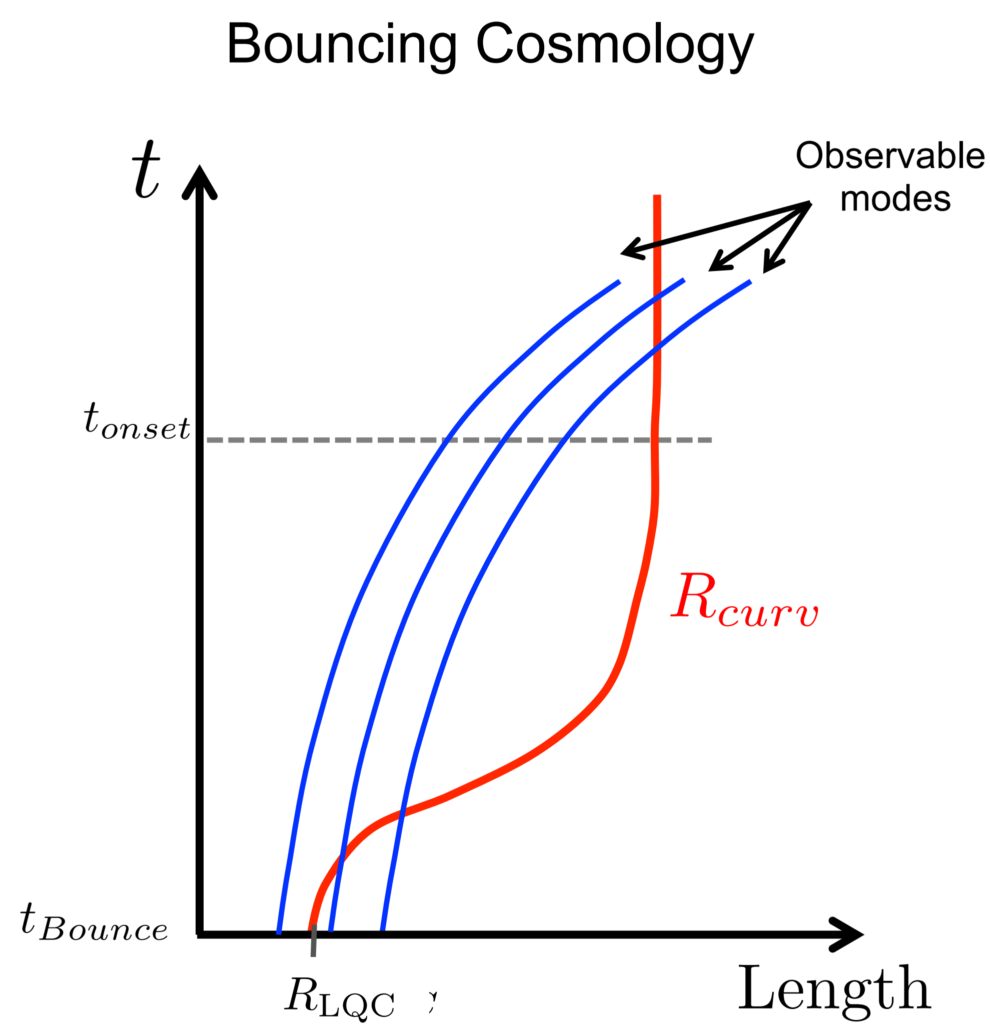
Problem: absence of other physical scales (only Planck scale)

Possible if we go beyond LQC? Message from GFT (Daniele's contribution to this panel)

(3) LQC used so far to complement other mechanisms (inflation, matter bounce, etc.)

(4) Given one such mechanism: LQC includes Planck scale physics + adds extra features to the predictions





Messages:

New scale from quantum gravity $R_{\rm LQC}$

Modifications for long wavelengths

(5) Are there freedoms? Yes

Number of e-folds, initial state for perturbations, etc.

(Compare with GR, Standard Model, Inflation, etc)

(6) Are there choices of the free parameter producing agreement with current data?

Yes!

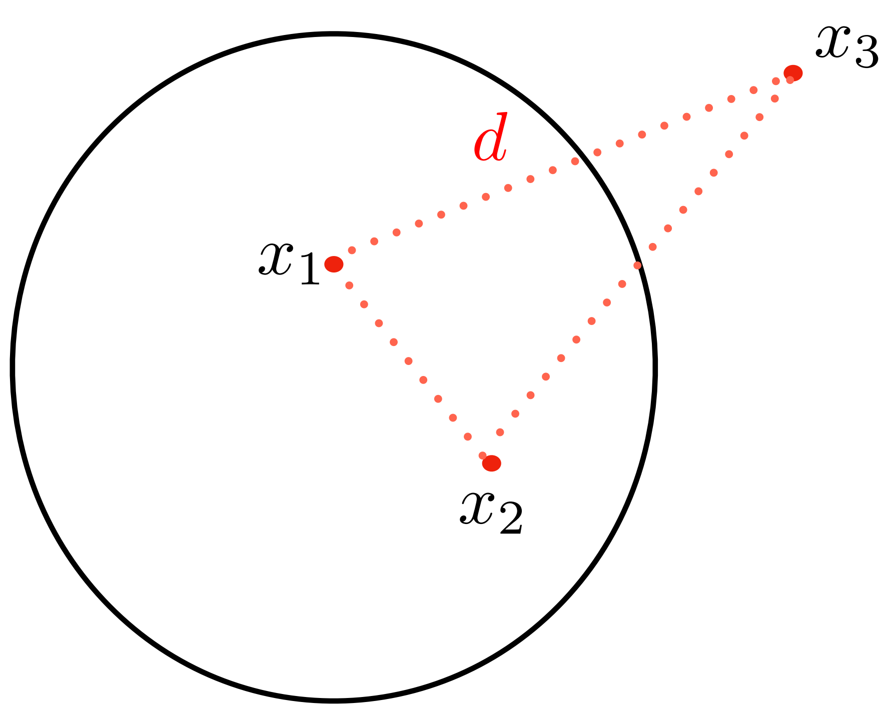
(7) Can we further constrain the freedoms using data?

Yes ⟶ Ambitious strategy: show that concrete choices allows LQC to account for unexplained features in the CMB (anomalies)

Example: Non-Gaussianities

(See Ashtekar-Gupt-Jeong-Sreenath, de Blas-Mena-Marugan-Martin-Benito-Elizaga-Navascues-Olmedo, Wang et. al, for other approaches based on arguments to choose the initial state. See also Guillermo's contribution to this panel)

Non-Gaussian correlations:



There exists a choice of parameters (number of e-folds) for which the non-Gaussian correlations produced by the bounce:

-Are small enough within our Hubble patch to be below observational upper bounds

-Are large enough to bias the statistics of the CMB (slightly)

-These modifications can explain the CMB anomalies:

-Power suppression
-Dipolar anomaly
-Parity anomaly

The CMB bispectrum from bouncing cosmologies

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Abstract. In this paper we compute the CMB bispectrum for bouncing models motivated by Loop Quantum Cosmology. Despite the fact that the primordial bispectrum of these models is decaying exponentially above a large pivot scale, we find that the cumulative signal-to-noise ratio of the bispectrum induced in the CMB from scales $\ell < 30$ is larger than 10 in all cases of interest and therefore can, in principle, be detected in the Planck data.

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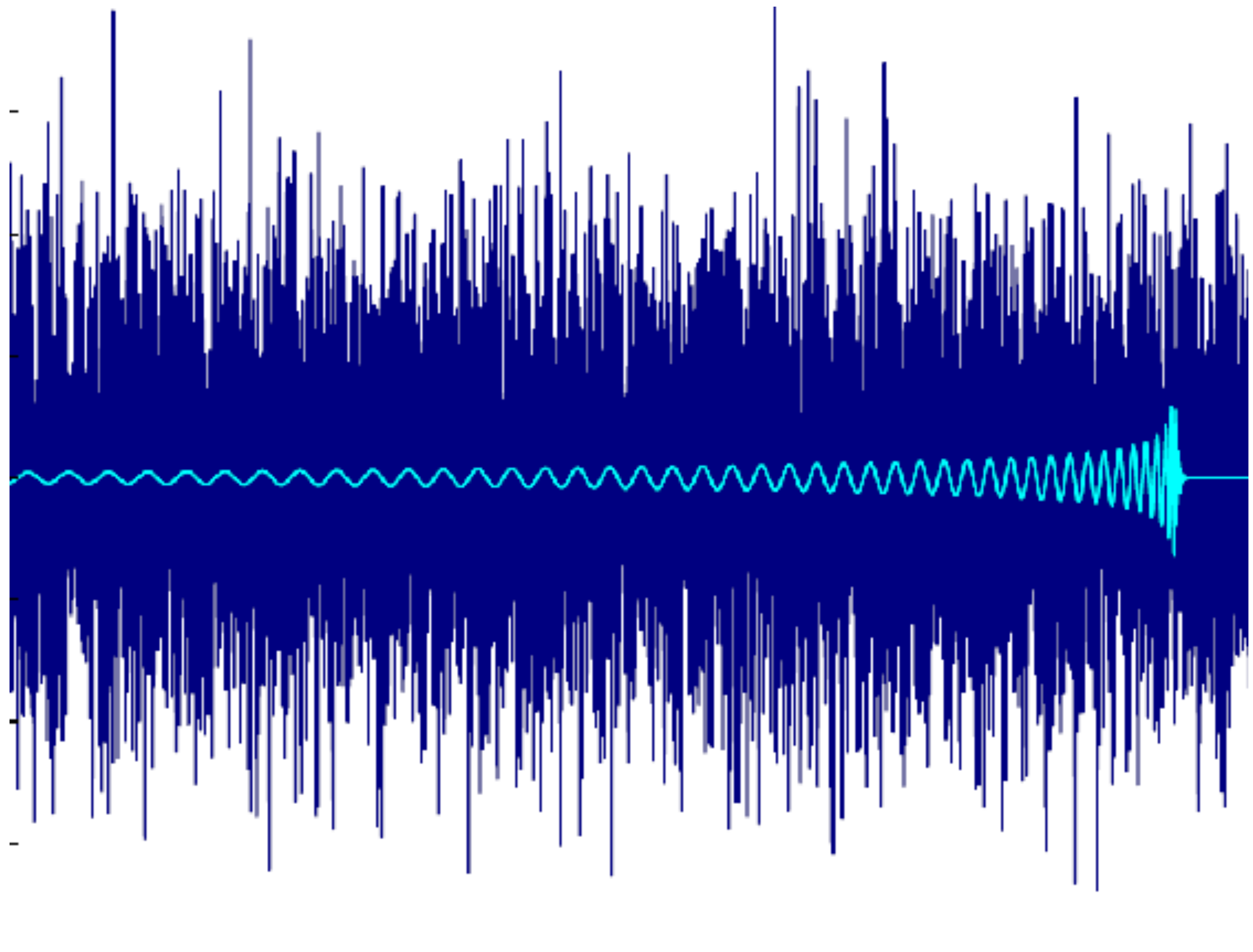
Example: signal and noise in LIGO



- **This and similar strategies come together with further predictions, e.g. tensor modes and optical depth.**

- **Forthcoming data will boots the interest of these predictions and analyses (compare with the revival of aspects of mathematical GR once gravitational waves were observed)**

- **Several other places were quantum cosmology could be useful: H0-tension, origin of cosmological constant (late or early universe), etc.**

Final Comments