Can we prove the quantum origin of cosmic inhomogeneities ?

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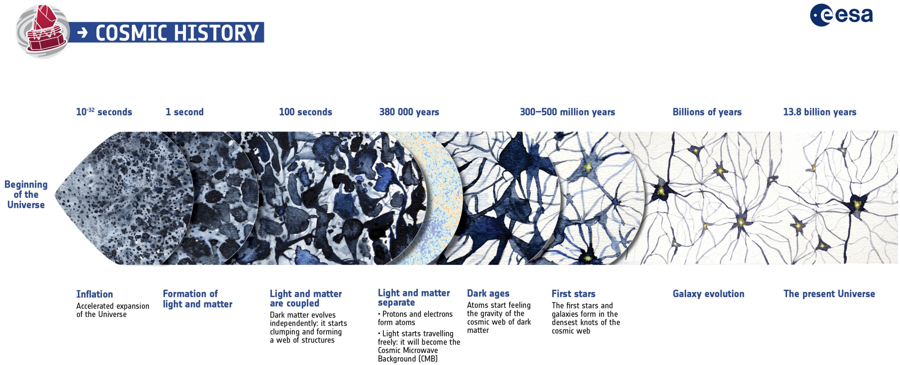
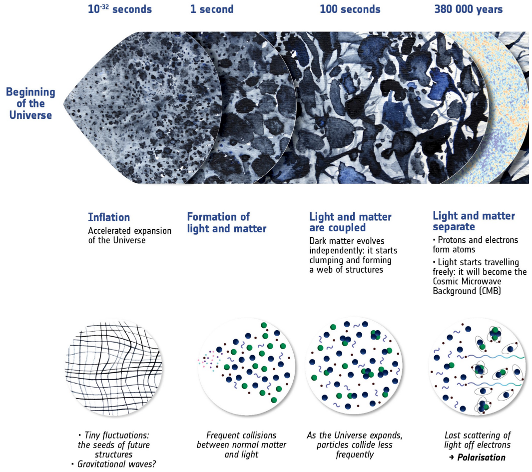
The standard model of cosmology



Origins of the Cosmic Microwave Background (CMB)



The quantum origin of structures

Why proving the quantum origin of structures ?

- Direct experimental proof of inflation or alternatives based on quantum fluctuations.
- Direct experimental proof that gravity is consistent with quantization in perturbative expansions.

Can we prove the quantum origin of structures ?

Outline

1 Quantumness

2 Decoherence

3 Cosmic OQS

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How do we prove that something is quantum ?

Bell test experiment :

- If Bell's inequality is violated, then fluctuations cannot be reproduced by a classical stochastic theory.

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ON THE EINSTEIN PODOLSKY ROSEN PARADOX*

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Bell test experiments

Bell's inequality violation in quantum optical systems :

- Pioneering works : Freedman and Clauser (1972), Aspect *et al.* (1981);

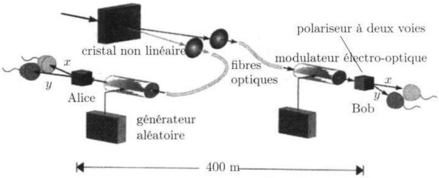

Figure: "Two channel" Bell test experiment, from Le Bellac (2003).

- Last loopholes addressed recently: Hensen *et al.* (2015), Giustina *et al.* (2015), Shalm *et al.* (2015).

Toward cosmic Bell test experiments ?

Choice of measurement directions using :

- Milky Way stars [Handsteiner *et al.* (2017)];
- High redshift quasars [Rauch *et al.* (2018)].

Could we observe Bell's inequality violation in the CMB ?

- Theoretically : YES ! [Kanno and Soda (2017), Martin and Vennin (2019)];
- Experimentally : maybe, but a lot of possible obstructions [Martin and Vennin (2019)].

$\Rightarrow$ We now focus on one of them.

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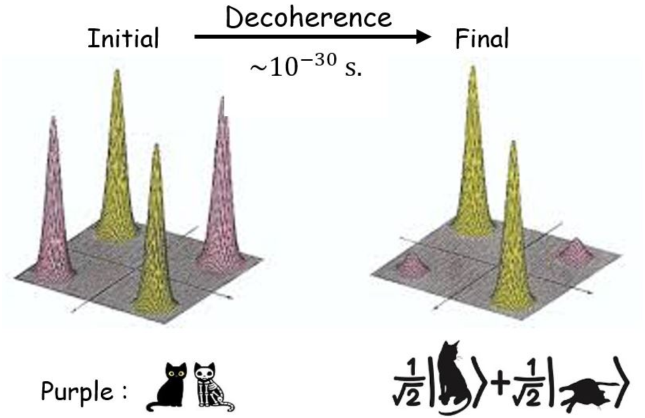
Why is it difficult to build a quantum computer ?

- Quantum features are extremelly sensible [Joos and Zeh (1985)]
  - Really challenging to maintain a quantum signal more than a few seconds because of quantum decoherence.
  - A system never lives in isolation but exists in a wider environment : Open Quantum System (OQS).
  - Environment/system interactions induce information leakage which washes away quantum correlations.
  - Only the states that have a classical outcome are robust to quantum decoherence.

Schrödinger's cat paradox resolution



Quantum-to-classical transition

- Cosmological perturbations are not immune to quantum decoherence.
- It induces a quantum-to-classical transition which explains why the universe look classical to us.
- To study the quantum origin of structure, need to assess quantum decoherence to tell if any quantum signal survived.

Is the level of decoherence low enough so that Bell's inequality violation can be obtained from CMB photons ?

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Two-field cosmology as a Cosmic OQS

We studied two-scalar fields in a homogeneous and isotropic background at linear order :

- *System* : one of the two fields (can be the inflaton, observable cosmological perturbations, ...) ;
- *Environment* : the other field (can be the Higgs field, unobservable cosmological perturbations, ...)
- *Interactions* : linear order in perturbation theory : only allowed couplings are quadratic

$$\phi_1\phi_2; \quad \pi_1\pi_2, ; \quad \phi_1\pi_2; \quad \pi_1\phi_2.$$

Implications of working at linear order

Main consequence of working at linear order :

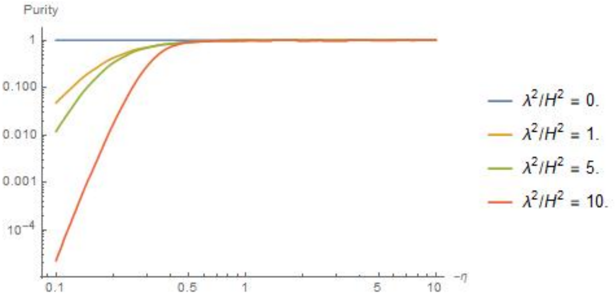
- Phase-space has extra symmetries : symplectic structure.

  $\Rightarrow$ All constituents of the dynamics (Green's functions, evolution operator, canonical transformations, ...) are given in a representation of the Lie group $\mathrm{Sp}(4,\mathbb{R})$

Strategy :

1. Study $\mathrm{Sp}(4,\mathbb{R})$;
2. Find evolution operator $\widehat{\mathcal{U}}(t,t_0)$.
3. Find final quantum state $|\Psi(t)\rangle = \widehat{\mathcal{U}}(t,t_0)\,|\Psi(t_0)\rangle$;
4. Look at how $|\Psi(t)\rangle$ decoheres.

Assessing decoherence : results on a toy model



- We can follow the level of decoherence at any time.
- Stronger coupling with the environment implies faster decoherence
  - If know coupling, can tell if can perform Bell CMB experiments.
  - If don't observe any quantum correlations : bounds on the coupling

    $\Rightarrow$ a new way to probe the unobservable sector.

Summary

- In the Standard Model of Cosmology, all structures originate from quantum fluctuations.
- Direct experimental proof of this statement would confort the current paradigm and pave the road to quantum gravity.
- In a foreseeable future, we may be able to perform Bell CMB experiment.
- To perform such experiment, the level of decoherence has to be low enough.
- We developed an open quantum system formalism to assess this level of decoherence.

Thank you for your attention !

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