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The case of Quantum Gravity with Spontaneous Collapse of the Wave Function

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Abstract. When about half a century ago the concept of universal spontaneous collapse of the wave function was conceived it was an attempt to alter standard non-relativistic quantum physics. As such, it was largely ignored by relativistic field theory and quantum gravity communities. A central motivation of spontaneous collapse community has been to replace the standard collapse-by-measurement that annoyed many. With few exceptions, it did not annoy the field theory and quantum gravity communities. Concept of certain general-relativity-related universal irreversibility in quantum field theory had been initiated very long ago by Wheeler, Hawking and a few others independently from the concept of spontaneous collapse. Lately the two concepts started to converge and support each other.

1. Introduction

Allow the author to introduce the topics in a self-quotation from 2015 [1]. 'The inception of a universal gravity-related irreversibility took place originally in quantum cosmology but it turned out soon that a universal non-unitary dynamics is problematic itself. Independent investigations of the quantum measurement postulate clarified that a non-unitary dynamics is of interest already in the non-relativistic context. An intricate relationship between Newton gravity and quantized bulk matter might result in universal non-relativistic violation of unitarity - also called spontaneous decoherence. The corresponding gravity-related spontaneous decoherence model is now on the verge of detectability in optomechanical experiments. It is also a toy-model of cosmic quantum gravitational non-unitarity, illuminating that the bottle-neck of quantum gravity is the quantum measurement postulate instead of quantum cosmology.'

We want to build our message around the appearance of the concept of fundamental irreversibility in two separate fields of foundational theoretical physics. One is quantum cosmology. It has no consistent theory valid down towards the Planck scale, despite various efforts using various advanced mathematical models. At the same time, semiclassical and heuristic approaches imply that fundamental irreversibilities may be part of quantum cosmology. But quantum irreversibility itself, especially when universal, happens to be non-trivial both technically and conceptually. And here another research field gains importance. Its tasks seem opaque compared to quantum cosmology's. They include, e.g., the measurement problem, the dynamics of wave function collapse, the quantum-classical transition and hybrid dynamics, but the relevant task is the quantum theory of macroscopia, coined as the Schrödinger cat problem. You should discuss the options of macroobjects' quantum behavior, and you can do it non-relativistically, before you go for quantum cosmology! The hypothesis of spontaneous universal

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Table 1. Comparison of the two research fields and the status of fundamental irreversibility.

QUANTUM COSMOLOGISTS	SCHRÖDINGER CAT KILLERS*
field-string-membrane theorists, for full relativistic quantum gravity of the Universe within standard quantum theory unitary (reversible)	quantum foundation experts, for non-relativistic spontaneous wave function collapse of macroscopic bodies with modified quantum theory non-unitary (irreversible)
Fundamental Irreversibility? Possible: foamy vacuum, black holes	Fundamental Irreversibility? Mandatory: wave function collapse

*Measurement Problem Solvers

collapse in massive degrees of freedom, assuming a fundamental gravity-related irreverisibility, may have perspectives for quantum cosmology as well, especially if fundamental irreversibility remains part of it.

2. Fundamental irreversibility? — Two Communities

The two fundamental issues in question are the following: unified theory of space-time with quantized matter (cf. quantum gravity, quantum cosmology) and the physics of quantum measurement (cf. wave function collapse, quantum-classical transition). These problems were considered unrelated for long time, studied by two separate research communities. We refer to the first one as quantum cosmologists and to other as measurement problem solvers or, with a spectacular touch, as Schrödinger cat killers. Quantum cosmology has always been part of main stream physics, using heavy artillery of mathematics, while Schrödinger cat killers used light weapons and sometimes whimsical identification of their problems.

2.1. Irreversible Quantum Gravity/Cosmology at the Planck Scale

Emergence of irreversibility *within standard physics* was not derived by exact derivations but by *heuristic arguments*. A selection of earliest theoretical signatures could be the following. In 1936, Bronstein [2] was the first to point out that space-time metric must have an ambiguity δg_{ab} of different nature from the dictum of Heisenberg uncertainty relationships. Much later in 1962, Wheeler [3] proposed that space-time has a certain foamy structure at the Planckian scale. After another decade, Bekenstein [4] proved that black-holes behave thermodynamically, they have entropy:

$$S_{BH} = \frac{A}{4}, \tag{1}$$

where A is the surface aera of the black-hole in Planck units (Boltzmann's constant $k_B = 1$). Then Hawking [5] showed that, yes, in accordance with the above entropy, black-holes emit thermal radiation of temperature

$$T_{BH} = \frac{1}{8\pi M}, \tag{2}$$

where M is the black-hole mass. Later, Hawking [6] went deeper and conjectured that unitarity of standard quantum theory is lost due to the instanton mechanism. The scattering processes must be non-unitary, the non-unitary super-scattering operator \$ acts on the density operator $\widehat{\rho}$:

$$\widehat{\rho} \to \$\widehat{\rho} \tag{3}$$

where the r.h.s. does not factorize into $\widehat{S}\widehat{\rho}\widehat{S}^\dagger$ with any unitary scattering operator $\widehat{S}$. Instead of Hawking's scattering process, Banks, Susskind and Peskin [7] considered a detailed dynamical equation

$$\frac{d\widehat{\rho}}{dt} = -i[\widehat{H},\widehat{\rho}] - \int\!\!\int [\widehat{Q}(x),[\widehat{Q}(y),\widehat{\rho}\,]]h(x-y)d^3xd^3y, \tag{4}$$

where $\widehat{H}$ is the Hamiltonian, $\widehat{Q}$ is a relativistic quantum field and h is a positive kernel. The authors show that the irreversible term on the r.h.s. violates the energy-momentum conservation which cannot be restored in local field theories.

2.2. Irreversible Quantum Mechanics for Massive Objects

Among diverse incentives, including a metaphysical discontent about von Neumann's quantum measurement theory, the only relevant motivation is the problematic extendibility of quantum theory for massive degrees of freedom. This led to *heuristic modifications of standard quantum physics.* According to that, the unitarity is violated in massive degrees of freedom so that macroscopically different superpositions, aka Schrödinger cat states like

$$|\Psi\rangle = \frac{|f_1\rangle + |f_2\rangle}{\sqrt{2}}, \tag{5}$$

collapse spontaneously into one of the components. Milestones of the consept could be the following.

In 1966, Károlyházy [15] proposed that, due to a conjectured spectrum of space-time metric fluctuations δg_{ab} at the Planck scale, Schrödinger cat states collapse before they get too large. He outlined a naive qualitative model of when and how the collapse happens. Independently and much later in 1986, Ghirardi, Rimini and Weber [18] constructed a simple model of universal spontaneous collapse in exact mathematical terms. They postulated extreme rare and weak spontaneous collapses for the elementary constituents' wave functions which in turn yield robust localization of the macrosopic center-of-mass, i.e., the collapse of the Schrödinger cat state. The GRW model has no reference to gravity. However, the present author [19, 20] proposed gravity-related universal spontaneous collapse of massive superpositions, like Schrödinger cats, based on a master equation:

$$\frac{d\widehat{\rho}}{dt} = -\frac{i}{\hbar}[\widehat{H},\widehat{\rho}] - \frac{G}{2\hbar}\int\!\!\int [\widehat{f}(x),[\widehat{f}(y),\widehat{\rho}\,]]\frac{1}{|x-y|}d^3xd^3y, \tag{6}$$

where $\widehat{f}$ is the non-relativistic quantized mass density field and G is Newton's constant. The master equation corresponds to a certain ambiguity $\delta\Phi = \frac{1}{2}c^2\delta g_{00}$ of the Newton potential.

2.3. Fundamental irreversibility? — Parallel pursuits

Thus, the desired quantum gravity and the unwanted Schrödinger cats led both the heavy-armed relativistic and light-horse non-relativistic studies to the same structure of heuristic master equations. And they suffer of the same problem of spontaneous creation of energy and momentum. This coincidence is a spectacular instance to illustrate that the two, apparently distant theoretical tasks, share similar proposals and problems. Another instance has been the surprising coincidence between the Schrödinger cat's collapse rate predicted by the non-relativistic master equation [19] and by the general relativistic arguments of Penrose [10]. For possible reasons of coincidence, see ref. [25].

Mention should be made of Gell-Mann and Hartle [9] who were perhaps the only ones at the time to recognize that quantum cosmology needed a more general measurement theory than von Neumann's. For the relationship of their theory of decoherent histories to spontaneous collapse theories, see [26]. Most recently, hybrid quantum-classical master equations have been tested in semiclassical cosmology by Oppenheim et al. [14], with numerous references to spontaneous collapse models which are, in fact, the alternative formalism, see [27].

Table 2. A selection of parallel concepts related to fundamental irreversibility.

	QUANTUM COSMOLOGISTS	SCHRÖDINGER CAT KILLERS
1936	Bronstein [2]: ambiguity δg_{ab}	
1962	Wheeler [3]: space-time foam	
1966		Károlyh. [15]: ambiguity δg_{ab} collapses Ψ
1973	Bekenstein [4]: black hole entropy	
1975	Hawking [5]: black holes radiate	
1976		Pearle [16]: searching collapse dynamics
1983	Hawking [6]: instantons break unitarity	
1984	BPS [7]: energy non-conservation	Gisin [17]: prototype collapse dynamics
1986		GRW [18]: universal collapse
1987		D. [19]: G-related decoherence
1989	Ellis & al. [8]: wormholes collapse Ψ	D. [20]: G-related collapse
1990	G-M&H [9]: decoherent histories	GRP [21]: G-unrelated collapse
1996	Penrose [10]: ambiguity δg_{ab} collapses Ψ	
2014		Bedingham & al. [22]: relativisation
2016	Kwon&Hogan [11]: holographic noise	Tilloy&D [23]: semiclassical G & collapse
2017		Bassi & al. [24]: review of G-collapse
2021	Sudarsky [12]: cosmology & collapse	
2022	Anastopoulos&Hu [13]: G-decoherence	
	Oppenheim & al. [14]: hybrid dynamics	

3. Summary

The failures of quantum gravity models may not be due to the inadequacy of the quantization methods tried so far, but the inadequacy of standard quantum theory for macroobjects, e.g., the spontaneous decay of massive superpositions, aka Schrödinger-cats. We recalled that the idea of fundamental irreversibility has also been raised in quantum cosmology. The roots of irreversibility may be common in quantum cosmology and in speculative models of spontaneous collapse of the wave function. This may be so despite the fact that one is predicted at the Planck scale while the other comes from non-relativistic discussion of massive superpositions [28]. Considerations of quantum cosmologists and advocates of spontaneous collapse (referred here extravagantly as Schrödinger cat killers) will have to come closer to each other. To support this suggestion, here are two quotes. The author (cat killer) claimed 'the measurement problem culminates in quantum cosmology" [29]. The cosmologist claims 'the principles of general relativity must influence, and actually change, the very formalism of quantum mechanics' [30].

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References

[1] Diósi L 2015 *Gravity related spontaneous decoherence: from Wheeler-Bekenstein-Hawking to optomechanics* (talk given in Erice) www.wigner.hu/∼diosi/slides/erice2015.pdf
[2] Bronstein M 1936 *Phys. Z. Sowjetunion* **9** 140
[3] Wheeler J A 1962 *Geometrodynamics* (New York: Academic Press)
[4] Bekenstein J D 1973 *Phys. Rev. D* **7** 2333
[5] Hawking S W 1975 *Commun. Math. Phys.* **43** 199
[6] Hawking S W 1982 *Commun. Math. Phys.* **87** 395
[7] Banks T, Susskind L and Peskin M E 1984 *Nucl. Phys. B* **244** 125
[8] Ellis J, Mohanty S and Nanopoulos D V 1989 *Phys. Lett. B* **221** 113
[9] Gell-Mann M and Hartle J B 1993 *Phys. Rev. D* **47** 3345
[10] Penrose R 1996 *Gen. Relativ. Gravit.* **28** 581
[11] Kwon O and Hogan C J 2016 *Class. Quantum Grav.* **33** 105004
[12] Sudarsky D 2021 *Do Wave Functions Jump? Perspectives of the Work of GianCarlo Ghirardi*, ed V Allori, A Bassi, D Dürr, N Zanghi (Cham: Springer Nature Switzerland) p 291
[13] Anastopoulos C and Hu B L 2021 *AVS Quantum Science* **4** 015602
[14] Oppenheim J and Weller-Davies 2022 *J. High Energ. Phys.* **2022** 80; Oppenheim J, Sparaciari C, Šoda B and Weller-Davies Z 2022 *Preprint* arXiv:2203.01982
[15] Karolyhazy F 1966 *Nuovo Cim.* **42** 390
[16] Pearl P 1976 *Phys. Rev. D* **13** 857
[17] Gisin N 1984 *Phys. Rev. Lett.* **52** 1657
[18] Ghirardi G C, Rimini A and Weber T 1986 *Phys. Rev. D* **34** 470
[19] Diósi L 1987 *Phys. Lett. A* **120** 377
[20] Diósi L 1989 *Phys. Rev. A* **40** 1165
[21] Ghirardi G C, Rimini A and Pearl P 1990 *Phys. Rev. A* **42** 78
[22] Bedingham D, Dürr D, Ghirardi G, Goldstein S, Tumulka R and Zanghi N 2014 *J. Stat. Phys.* **154** 623
[23] Tilloy A and Diósi L 2016 *Phys. Rev. D* **93** 024026
[24] Bassi A, Grossardt A and Ulbricht H 2017 *Class. Quantum Grav.* **34** 193002
[25] Diósi L 2022 *AVS Quantum Sci.* **4** 015605
[26] Diósi L, Gisin N, Halliwell J and Percival I C 1995 *Phys. Rev. Lett.* **74** 203
[27] Diósi L 2023 *Preprint* arXiv::2302.13418
[28] Diósi L 2018 *Entropy* **20** 496; 2019 *J. Phys. Conf. Ser.* **1275**
[29] Diósi L 1992 *Quantum Chaos—Quantum Measurement* (Springer) p 299
[30] Penrose R 2014 *Found. Phys.* **44** 557