Why we've got the cosmological constant all wrong

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Effective field theory incorrectly predicts the value of the cosmological constant, Λ, as well as the value of an analogous term in an analogous gravity model in the form of a BEC. BECs are correctly described only by quantum models, and a quantum theory of gravity may be required to correctly predict Λ. Image credit: Finazzi, et al. ©2012 American Physical Society

(PhysOrg.com) -- Some scientists call the cosmological constant the "worst prediction of physics." And when today's theories give an estimated value that is about 120 orders of magnitude larger than the measured value, it's hard to argue with that title. In a new study, a team of physicists has taken a different view of the cosmological constant, Λ, which drives the accelerated expansion of the universe. While the cosmological constant is usually interpreted as a vacuum energy, here the physicists provide evidence to support the possibility that the mysterious force instead emerges from a microscopic quantum theory of gravity, which is currently beyond physicists' reach.

The scientists, Stefano Finazzi, currently of the University of Trento in Povo-Trento, Italy; Stefano Liberati at SISSA, INFN in Trieste, Italy; and Lorenzo Sindoni from the Albert Einstein Institute in Golm, Germany, have published their study in a recent issue of Physical Review Letters.

The authors are far from the first who are dissatisfied with the cosmological constant. Previously, other scientists have suggested that the huge discrepancy between the observed and estimated values is due to the use of semi-classical effective field theory (EFT) calculations for estimating a quantity that can be computed only using a full quantum theory of gravity. Although no one can show what value a quantum theory of gravity would give without having such a theory, physicists have shown that EFT calculations fail at estimating similar values in analogue gravity models.

Here, the physicists consider an analogue gravity model in the form of a Bose-Einstein condensate (BEC), a group of atoms that behave as a single quantum system when cooled to temperatures near absolute zero. While a BEC may seem to have nothing in common with the expanding universe, the physicists showed in a previous paper that a BEC can be described by the same Poisson equation that describes nonrelativistic (Newtonian) gravity. This framework includes a term that is analogous to the cosmological constant; this term describes the part of a BEC's ground-state energy that corresponds to the condensate's quantum depletion.

Since BECs are accurately described by other (quantum) equations, the physicists decided to test how well EFT calculations could compute the

BEC's analogous cosmological constant term. They found that EFT calculations do not give the correct result. The finding confirms the earlier studies that showed that EFT calculations produce an incorrect result when used to compute the ground-state energy of other analogue gravity models.

"We have shown how conceptually subtle could be the computation of the cosmological constant, by considering an analogue gravity model," Finazzi told *PhysOrg.com*. "This simple example shows that the knowledge of the microscopic structure of spacetime might be an essential guide for a correct interpretation of the nature of the cosmological constant, and hence for a correct estimate of it. We then reinterpret the large discrepancy between the naive computation and the observed value as a basic misunderstanding on this point. Interestingly, this reasoning might also be a guide to the selection of the correct quantum gravity theory."

As the physicists explain, the BEC model described by Poisson equations is too simple to completely describe the complex features of the universe's accelerating expansion. However, the failure of the EFT framework to describe BECs' analogue cosmological constant supports the possibility that the EFT framework also fails at describing the cosmological constant.

The details have further implications. For one thing, the results suggest that there may be no a priori reason to describe the cosmological constant as vacuum energy. Instead, the cosmological constant may emerge from the underlying quantum theory of gravity describing spacetime. As the physicists explain, a quantum theory of gravity differs from various modified theories of gravity that have been proposed recently in that a quantum theory describes spacetime at the most fundamental level.

“In a modified gravity theory, one is just postulating a different gravitational dynamics that might show accelerated expansion also for a universe filled with standard matter (i.e., without the so-called dark energy component),” Liberati said. “We instead consider the case where a gravitational dynamics is emergent from a microscopic quantum theory, i.e., a theory describing the fundamental constituents, whatever they are, of our spacetime. From such a theory one would be able to derive a theory of gravity (general relativity or any form of modified gravity) in some appropriate limit (possibly similar in nature to the hydrodynamic limit of a gas of interacting atoms). Our point is that it is only throughout this derivation/emergence of the gravitational dynamics that in the end one can determine what is the gravitating ‘energy of the vacuum.’ We have proven this explicitly in our toy model where it is clearly shown that the use of the macroscopic constituents (and corresponding energy scales) of the emergent physics might lead to a completely wrong estimate.

“We can try to explain this issue with a simple analogy,” he said. “Water is made by molecules. At a microscopic level molecular dynamics is properly described by quantum mechanics. However, no one would use quantum mechanics to describe a flowing river, but rather one would use fluid mechanics laws. Of course, fluid dynamics must be compatible with quantum mechanics, i.e., it must be possible to derive it from the microscopic quantum theory of molecules. Finally, the choice of the most appropriate equations for the description of any phenomenon depends on the scale at which one observes the physical system. We hence can say that the microscopic quantum theory of gravity corresponds in the analogy to the quantum mechanics of molecules, a theory of gravity corresponds to fluid mechanics, and the evolution of the universe to the flow of the river.”

Continuing the analogy, Liberati adds that there might be a quantity in macroscopic fluid dynamics that cannot be calculated using macroscopic parameters alone. Instead, a microscopic model is necessary to calculate the correct value.

"We argue that, in the case of the calculation of the cosmological constant, this is exactly what happens: the reason of the 'worst prediction of theoretical physics' might ultimately be due to the attempt to compute a quantity that is sensitive to the microphysics only in terms of macroscopic quantities," he said.

In the future, the physicists hope to further investigate how the BEC analogue model of gravity could possibly lead to the development of a quantum theory of gravity, since many proposed theories of gravity have features in common with the new model.

"We believe that this model can help to change the way how people usually think about the cosmological constant," Sindoni said. "In recent years, the idea that spacetime is a form of condensate is gaining momentum. Of course, to be able to get to theories as close as possible to general relativity, the microscopic models have to be considerably more complex than BECs. However, it can be conjectured that spacetime is the final outcome of a phase transition for a large number of suitable microscopic constituents, and that the determination of the resulting macroscopic dynamics might be essentially the same, at the conceptual level, of the determination of the dynamics of a BEC from the knowledge of effective molecular or atomic dynamics, near a phase transition. The translation of the language and ideas of BECs to quantum gravity models might be a key in the understanding of the physical content of the latter."

Sindoni adds that the cosmological constant will provide a vital test of any proposed quantum theory of gravity.

"We think that the comparison of the observational value of the cosmological constant against its theoretical value, predicted by any theory of quantum gravity, can be a very good (if not the unique) test to validate such theories," he said.

More information: Stefano Finazzi, et al. "Cosmological Constant: A Lesson from Bose-Einstein Condensates." *PRL* 108, 071101 (2012). DOI: 10.1103/PhysRevLett.108.071101