Coding the Cosmos: A New Generation of Superstring Simulations

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According to the standard fundamental cosmology paradigm, the universe started 13.8 billion years ago, in a hot, dense and highly symmetric state, and subsequently evolved by expanding and cooling down. One unavoidable consequence of this cooling is that its initial symmetry properties are gradually lost, not in a continuous way but rather at specific stages of its evolution, known as symmetry-breaking phase transitions (much in the same way that cooling down water vapor first leads to liquid water and then to ice).

Cosmic strings are the best motivated example of a class of physical objects called topological defects, which necessarily form at these phase transitions via a process called the Kibble mechanism. They can be thought of as fossil remnants of earlier phases of the Universe which can survive up to the present day, encoding information on fundamental physics regimes that would otherwise be entirely inaccessible to us. Searching for their observational imprints (in gravitational waves and the cosmic microwave background, among others) is a key goal of current and forthcoming observational facilities, including LIGO and the SKA on the ground and CORE and LISA in space.

Being highly non-linear objects, studying their dynamcs, evolution and consequences heavily relies on high-performance computing, complemented by analytic modelling. Current observational searches are bottlenecked by the lack of numerical simulations with sufficient spatial resolution and dynamical range to calibrate existing analytic models. These searches rely on simulations done on standard CPUs, but there are only around a dozen reasonably precise simulations (and 3 or 4 groups worldwide with know-how to do them), implying that all current analyses relying on them are statistics-limited, and the derived constraints unreliable.

We report on our solution to this bottleneck: a GPU-accelerated version of the standard cosmic strings evolution code, shown to weak-scale to thousands of GPUs at Piz Daint (Europe's largest supercomputer). This leads to speedups which, with state-of-the-art high GPU resources, for the first time enable hundreds or thousands of high-resolution simulations with sufficiently large dynamic range to be carried out in manageable amounts of time. For the largest achievable production runs, our code has been shown to be 30 times faster than the fastest previously available code. From this a full statistically robust calibration of the analytic models became possible. Ultimately, this will lead to significantly optimized observational searches with next-generation astrophysical facilities, and more stringent constraints on the underlying physics.

We will also present results from our visualisation analysis of these simulations, done in collaboration with Jean Favre at CSCS, which enables a deeper characterisation of key physical properties of these objects.

Our methods are also enabling the first numerical studies of more complex physical objects such as current-carrying (a.k.a. superconducting) strings and cosmic superstrings, which according to many extensions of the standard model (including string theory itself) must have formed in the early universe. Our work thus opens a new numerical/astrophysical way of probing fundamental physics, complementing and extending what is done in particle accelerators.

We acknowledge PRACE for awarding us access to Piz Daint at CSCS, Switzerland, in projects 2010PA4610, 2019204986 and 2020225448.