

¹ QuaRT: a toolkit for the exploration of quantum methods for radiation transport

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⁷ Summary

⁸ QuaRT is a Python library for quantum simulation of radiative transfer in astrophysical and ⁹ cosmological problems.

¹⁰ The source code for QuaRT is available on [GitHub](#). It can be installed via pip from the [pypi](#) ¹¹ index. Its [documentation](#) is hosted publicly.

¹² Statement of need

¹³ Computational cosmology, the use of simulations to study the evolution of the universe, is a rapidly-growing field of research, driven largely by the exponential increase in computing power ¹⁴ following Moore's law. Numerous codes ([Iliev et al., 2006](#), pp. [Iliev2009](#), [Bryan2014](#), [Brummel-Smith2019](#), [OShea2015](#), [Kannan2019](#), [Kannan2021](#), [Davis2012](#), [Jiang2014](#), [Hayes2003](#)) have ¹⁵ been written to study questions about the early universe and to obtain a better understanding of the plethora of observational results which have come with new telescopes such as the James Webb Space Telescope ([Adams et al., 2024](#)). However, classical high-performance ¹⁶ computing hardware is slowly approaching the fundamental quantum limit where electronics cannot be scaled down any further ([Powell, 2008](#)). Quantum computers presents a potential ¹⁷ path for further scaling of physical simulations by taking advantage of quantum phenomena ¹⁸ such as superposition and entanglement which enable new models of computation. Many ¹⁹ quantum algorithms have already been developed for the simulation of cosmological problems ²⁰ ([Mocz & Szasz, 2021](#), pp. [Yamazaki2025](#), [Kaufman2019](#), [Joseph2021](#), [Joseph2022](#), [Wang2024](#), ²¹ [Liu2021](#)). Such simulations must model physical processes such as radiation transport from ²² stars, magnetohydrodynamics of matter, gravitation between massive particles, gas chemistry, ²³ and the formation of structures such as stars, black holes, halos, and galaxies ([Brummel-Smith ²⁴ et al., 2019](#)). Of these, radiation transport tends to be one of the most expensive steps due to ²⁵ the high dimensionality of the problem, but it also the most difficult to develop because of the ²⁶ lack of problems with analytical solutions ([Iliev et al., 2006](#), p. [Iliev2009](#)). Quantum algorithms ²⁷ have been formulated for radiation transport, such as those based on ray tracing ([Lu & Lin, ²⁸ 2022](#), pp. [Lu2022](#), [Lu2023](#), [Mosier2023](#), [Santos2025](#)), random walks ([Lee et al., 2025](#)), and ²⁹ other novel differential equations solvers ([Gaitan et al., 2024](#)). Classical lattice Boltzmann ³⁰ methods (LBMs), which track the distribution of a quantity on a grid with discretized propagation ³¹ directions ([McNamara & Zanetti, 1988](#)), have already been applied extensively to study ³² radiation transport ([McCulloch & Bindra, 2016](#), pp. [BindraPatil2012](#), [Mink2020](#), [Olsen2025](#), ³³ [Weih2020](#)) and radiation hydrodynamics ([Asahina et al., 2020](#)). Quantum LBMs have also been ³⁴ constructed to study hydrodynamics ([Budinski, 2021](#), pp. [Budinski2022](#), [Wawrzyniak20251](#), ³⁵ [Wawrzyniak20252](#)) and radiation transport ([Igarashi et al., 2024](#)). These quantum LBMs ³⁶ reduce the memory constraints of classical simulations by storing information in quantum state ³⁷ amplitudes, the number of which grows exponentially with the number of qubits, enabling the ³⁸ ³⁹ ⁴⁰ ⁴¹ ⁴²

43 storage of data with only logarithmic scaling with problem size. Individual simulation steps
44 can thus be made very high resolution and only the necessary amount of data needs to be be
45 stored classically. However, existing quantum LBMs are not suited for cosmological problems
46 because such simulations are typically non-scattering, but isotropic sources under stars are
47 not accurately resolved angularly by LBMs due to their discretized angular structure. QuaRT
48 features the first known implementation of a quantum LBM which accurately resolves isotropic
49 sources in non-scattering media; it does so via a novel methodology which we refer to as
50 “angular redistribution”, where radiation is redistributed between angular directions based on
51 the expected angular distribution. This can even be done globally for an entire simulation
52 domain with no increase in computational complexity, enabling larger and more accurate
53 simulations of the evolution of the universe than currently possible.

54 **Functionality**

55 The qlbm_rt module features the simulate method which is called to perform simulations
56 with the lattice Boltzmann method. This method constructs the full quantum circuit for each
57 timestep of the simulation and returns the lattice data.

58 The qlbm_circuits module features constructors for the necessary circuits for radiative transfer
59 simulation in 1D, 2D, and 3D, including a constructor for the novel angular redistribution step.
60 These constructors are called by the simulate method which composes them to construct the
61 full quantum circuit.

62 QuaRT features a variety of utility methods for both general and quantum lattice Boltzmann
63 methods in lbm_utils and qlbm_utils, respectively. It also features analysis utilities in the
64 analysis module. These utilities are used by the simulate method for problem setup and
65 analysis.

66 The test module features a variety of common test cases used for radiative transfer codes,
67 including the isotropic source, opaque cloud shadow, and crossing radiation beams tests. These
68 tests demonstrate the general correctness of the codebase, with a particular emphasis on the
69 performance of the angular redistribution methodology.

70 **Scholarly Work**

71 QuaRT is currently being used to study lattice Boltzmann methods for radiative transfer (see
72 upcoming ([Devkota & Wise, 2025](#))).

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76 Institute of Technology, Atlanta, Georgia, USA ([PACE, 2017](#)).

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