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QuaRT: A toolkit for the exploration of quantum methods for radiation transport

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Summary

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

The source code for QuaRT is available on GitHub. It can be installed via pip from the pypi index. Its documentation is hosted publicly.

Statement of need

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 following Moore's law. Numerous codes (Brummel-Smith et al., 2019; Bryan et al., 2014; Davis et al., 2012; Hayes & Norman, 2003; Ilian T. Iliev et al., 2006; Ilian T. Iliev et al., 2009; Jiang et al., 2014; Rahul Kannan et al., 2019; R. Kannan et al., 2021; O'Shea et al., 2015) have 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 computing hardware is slowly approaching the fundamental quantum limit where electronics cannot be scaled down any further (Powell, 2008). Quantum computers present a potential path for further scaling of physical simulations by taking advantage of quantum phenomena such as superposition and entanglement which enable new models of computation. Many quantum algorithms have already been developed for the simulation of cosmological problems (Joseph et al., 2021, 2022; Kaufman et al., 2019; Liu & Li, 2021; Mocz & Szasz, 2021; Wang & Wu, 2024; Yamazaki et al., 2025). Such simulations must model physical processes such as radiation transport from stars, magnetohydrodynamics of matter, gravitation between massive particles, gas chemistry, and the formation of structures such as stars, black holes, halos, and galaxies (e.g., Brummel-Smith et al., 2019; Hopkins et al., 2023). Of these, radiation transport tends to be one of the most expensive steps due to the high dimensionality of the problem, but it also the most difficult to develop because of the lack of problems with analytical solutions (Ilian T. Iliev et al., 2006; Ilian T. Iliev et al., 2009). Quantum algorithms have been formulated for radiation transport, such as those based on ray tracing (Lu & Lin, 2022a, 2022b, 2023; Mosier, 2023; Santos et al., 2025), random walks (Lee et al., 2025), and other novel differential equations solvers (Gaitan et al., 2024). Classical lattice Boltzmann methods (LBMs), which track the distribution of a quantity on a grid with discretized propagation directions (McNamara & Zanetti, 1988), have already been applied extensively to study radiation transport (Bindra & Patil, 2012; McCulloch & Bindra, 2016; Mink et al., 2020; Olsen & Rezzolla, 2025; Weih et al., 2020) and radiation hydrodynamics (Asahina et al., 2020). Quantum LBMs have also been constructed to study hydrodynamics (Budinski, 2021; Ljubomir, 2022; Wawrzyniak, Winter, Schmidt, Indiniger, et al., 2025; Wawrzyniak, Winter, Schmidt, Indinger, et al., 2025) and radiation transport (Igarashi et al., 2024). These quantum LBMs reduce the memory constraints of classical simulations by storing information in quantum state amplitudes, the number of which grows exponentially with the number of qubits, enabling the storage of data with only logarithmic scaling with problem size. Individual simulation steps can thus be made very high resolution and only the necessary amount of data needs to be stored classically. However, existing quantum LBMs are not suited for cosmological problems because such simulations are typically non-scattering, but isotropic sources under stars are not accurately resolved angularly by LBMs due to their discretized angular structure. `QuaRT` features the first known implementation of a quantum LBM which accurately resolves isotropic sources in non-scattering media; it does so via a novel methodology which we refer to as "angular redistribution", where radiation is redistributed between angular directions based on the expected angular distribution. This can even be done globally for an entire simulation domain with no increase in computational complexity, enabling larger and more accurate simulations of the evolution of the universe than currently possible.

Functionality

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

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

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

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

There is also a set of demo notebooks including a fully-classical implementation for comparison with the quantum algorithm and some unit tests of experimental features.

Scholarly Work

`QuaRT` is currently being used to study lattice Boltzmann methods for radiative transfer (Devkota & Wise, 2025, in prep.).

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References

Adams, N. J., Conselice, C. J., Austin, D., Harvey, T., Ferreira, L., Trussler, J., Juodžbalis, I., Li, Q., Windhorst, R., Cohen, S. H., Jansen, R. A., Summers, J., Tompkins, S., Driver, S. P., Robotham, A., D'Silva, J. C. J., Yan, H., Coe, D., Frye, B., … Zitrin, A. (2024). EPOCHS. II. The ultraviolet luminosity function from 7.5 < z < 13.5 using 180 arcmin2 of deep, blank fields from the PEARLS survey and public JWST data. *The Astrophysical Journal*, *965*(2), 169. https://doi.org/10.3847/1538-4357/ad2a7b

Asahina, Y., Takahashi, H. R., & Ohsuga, K. (2020). A numerical scheme for general relativistic radiation magnetohydrodynamics based on solving a grid-based boltzmann equation. *The Astrophysical Journal*, *901*(2), 96. https://doi.org/10.3847/1538-4357/abaf51

Bindra, H., & Patil, D. V. (2012). Radiative or neutron transport modeling using a lattice boltzmann equation framework. *Physical Review E*, *86*(1). https://doi.org/10.1103/physreve.86.016706

Brummel-Smith, C., Bryan, G., Butsky, I., Corlies, L., Emerick, A., Forbes, J., Fujimoto, Y., Goldbaum, N., Grete, P., Hummels, C., Kim, J., Koh, D., Li, M., Li, Y., Li, X., O'Shea, B., Peeples, M., Regan, J., Salem, M., … Zhao, F. (2019). ENZO: An adaptive mesh refinement code for astrophysics (version 2.6). *Journal of Open Source Software*, *4*(42), 1636. https://doi.org/10.21105/joss.01636

Bryan, G. L., Norman, M. L., O'Shea, B. W., Abel, T., Wise, J. H., Turk, M. J., Reynolds, D. R., Collins, D. C., Wang, P., Skillman, S. W., Smith, B., Harkness, R. P., Bordner, J., Kim, J., Kuhlen, M., Xu, H., Goldbaum, N., Hummels, C., Kritsuk, A. G., … Li, Y. (2014). ENZO: AN ADAPTIVE MESH REFINEMENT CODE FOR ASTROPHYSICS. *The Astrophysical Journal Supplement Series*, *211*(2), 19. https://doi.org/10.1088/0067-0049/211/2/19

Budinski, L. (2021). Quantum algorithm for the advection–diffusion equation simulated with the lattice boltzmann method. *Quantum Information Processing*, *20*(2). https://doi.org/10.1007/s11128-021-02996-3

Davis, S. W., Stone, J. M., & Jiang, Y.-F. (2012). A RADIATION TRANSFER SOLVER FOR ATHENA USING SHORT CHARACTERISTICS. *The Astrophysical Journal Supplement Series*, *199*(1), 9. https://doi.org/10.1088/0067-0049/199/1/9

Devkota, R., & Wise, J. H. (2025). A novel quantum lattice Boltzmann methodology for cosmological radiation transport. *Phys. Rev. D*.

Gaitan, F., Graziani, F., & Porter, M. D. (2024). Simulating nonlinear radiation diffusion through quantum computing. *International Journal of Theoretical Physics*, *63*(10). https://doi.org/10.1007/s10773-024-05800-x

Hayes, J. C., & Norman, M. L. (2003). Beyond flux-limited diffusion: Parallel algorithms for multidimensional radiation hydrodynamics. *The Astrophysical Journal Supplement Series*, *147*(1), 197–220. https://doi.org/10.1086/374658

Hopkins, P. F., Wetzel, A., Wheeler, C., Sanderson, R., Grudić, M. Y., Sameie, O., Boylan-Kolchin, M., Orr, M., Ma, X., Faucher-Giguère, C.-A., Kereš, D., Quataert, E., Su, K.-Y., Moreno, J., Feldmann, R., Bullock, J. S., Loebman, S. R., Anglés-Alcázar, D., Stern, J., … Hayward, C. C. (2023). FIRE-3: updated stellar evolution models, yields, and microphysics and fitting functions for applications in galaxy simulations. *519*(2), 3154–3181. https://doi.org/10.1093/mnras/stac3489

Igarashi, A., Kadowaki, T., & Kawabata, S. (2024). Quantum algorithm for the radiative-transfer equation. *Physical Review Applied*, *21*(3).

Iliev, Ilian T., Ciardi, B., Alvarez, M. A., Maselli, A., Ferrara, A., Gnedin, N. Y., Mellema, G., Nakamoto, T., Norman, M. L., Razoumov, A. O., Rijkhorst, E.-J., Ritzerveld, J., Shapiro, P. R., Susa, H., Umemura, M., & Whalen, D. J. (2006). Cosmological radiative transfer codes comparison project – i. The static density field tests. *Monthly Notices of the Royal Astronomical Society*, *371*(3), 1057–1086. https://doi.org/10.1111/j.1365-2966.2006.10775.x

Iliev, Ilian T., Whalen, D., Mellema, G., Ahn, K., Baek, S., Gnedin, N. Y., Kravtsov, A. V., Norman, M., Raicevic, M., Reynolds, D. R., Sato, D., Shapiro, P. R., Semelin, B., Smidt, J., Susa, H., Theuns, T., & Umemura, M. (2009). Cosmological radiative transfer comparison project II. The radiation-hydrodynamic tests. *Mon. Not. R. Astron. Soc.*, *400*(3).

Jiang, Y.-F., Stone, J. M., & Davis, S. W. (2014). AN ALGORITHM FOR RADIATION MAGNETOHYDRODYNAMICS BASED ON SOLVING THE TIME-DEPENDENT TRANSFER EQUATION. *The Astrophysical Journal Supplement Series*, *213*(1), 7. https://doi.org/10.1088/0067-0049/213/1/7

Joseph, A., Varela, J.-P., Watts, M. P., White, T., Feng, Y., Hassan, M., & McGuigan, M. (2021). *Quantum computing for inflationary, dark energy and dark matter cosmology*. arXiv. https://doi.org/10.48550/ARXIV.2105.13849

Joseph, A., White, T., Chandra, V., & McGuigan, M. (2022). *Quantum computing of schwarzschild-de sitter black holes and kantowski-sachs cosmology*. arXiv. https://doi.org/10.48550/ARXIV.2202.09906

Kannan, R., Garaldi, E., Smith, A., Pakmor, R., Springel, V., Vogelsberger, M., & Hernquist, L. (2021). Introducing the <scp>thesan</scp> project: Radiation-magnetohydrodynamic simulations of the epoch of reionization. *Monthly Notices of the Royal Astronomical Society*, *511*(3), 4005–4030. https://doi.org/10.1093/mnras/stab3710

Kannan, Rahul, Vogelsberger, M., Marinacci, F., McKinnon, R., Pakmor, R., & Springel, V. (2019). <Scp>arepo-rt</scp>: Radiation hydrodynamics on a moving mesh. *Monthly Notices of the Royal Astronomical Society*, *485*(1), 117–149. https://doi.org/10.1093/mnras/stz287

Kaufman, A., Sundy, D., & McGuigan, M. (2019). Quantum computation for early universe cosmology. *2019 New York Scientific Data Summit (NYSDS)*, 1–6. https://doi.org/10.1109/nysds.2019.8909801

Lee, E., Lee, S., & Kim, S. (2025). Quantum walk based monte carlo simulation for photon interaction cross sections. *Physical Review D*, *111*(11). https://doi.org/10.1103/physrevd.111.116001

Liu, J., & Li, Y.-Z. (2021). Quantum simulation of cosmic inflation. *Physical Review D*, *104*(8). https://doi.org/10.1103/physrevd.104.086013

Ljubomir, B. (2022). Quantum algorithm for the navier–stokes equations by using the streamfunction-vorticity formulation and the lattice boltzmann method. *International Journal of Quantum Information*, *20*(02). https://doi.org/10.1142/s0219749921500398

Lu, X., & Lin, H. (2022a). *A framework for quantum ray tracing*. https://doi.org/10.48550/ARXIV.2203.15451

Lu, X., & Lin, H. (2022b). Quantum ray tracing with simulation. *SPIN*, *12*(04). https://doi.org/10.1142/s2010324722500308

Lu, X., & Lin, H. (2023). Improved quantum supersampling for quantum ray tracing. *Quantum Information Processing*, *22*(10). https://doi.org/10.1007/s11128-023-04114-x

McCulloch, R., & Bindra, H. (2016). Coupled radiative and conjugate heat transfer in participating media using lattice boltzmann methods. *Computers &Amp; Fluids*, *124*, 261–269. https://doi.org/10.1016/j.compfluid.2015.05.024

McNamara, G. R., & Zanetti, G. (1988). Use of the boltzmann equation to simulate lattice-gas automata. *Phys. Rev. Lett.*, *61*, 2332–2335. https://doi.org/10.1103/PhysRevLett.61.

2332

Mink, A., McHardy, C., Bressel, L., Rauh, C., & Krause, M. J. (2020). Radiative transfer lattice boltzmann methods: 3D models and their performance in different regimes of radiative transfer. *Journal of Quantitative Spectroscopy and Radiative Transfer*, *243*, 106810. https://doi.org/10.1016/j.jqsrt.2019.106810

Mocz, P., & Szasz, A. (2021). Toward cosmological simulations of dark matter on quantum computers. *The Astrophysical Journal*, *910*(1), 29. https://doi.org/10.3847/1538-4357/abe6ac

Mosier, L. (2023). *Quantum ray marching: Reformulating light transport for quantum computers* [Master's Thesis]. University of Waterloo.

O'Shea, B. W., Wise, J. H., Xu, H., & Norman, M. L. (2015). PROBING THE ULTRAVIOLET LUMINOSITY FUNCTION OF THE EARLIEST GALAXIES WITH THE RENAISSANCE SIMULATIONS. *The Astrophysical Journal*, *807*(1), L12. https://doi.org/10.1088/2041-8205/807/1/l12

Olsen, T., & Rezzolla, L. (2025). General-relativistic lattice-boltzmann method for radiation transport. *Monthly Notices of the Royal Astronomical Society*, *541*(2), 1305–1328. https://doi.org/10.1093/mnras/staf992

PACE. (2017). *Partnership for an Advanced Computing Environment (PACE)*. http://www.pace.gatech.edu

Powell, J. R. (2008). The quantum limit to moore's law. *Proceedings of the IEEE*, *96*(8), 1247–1248. https://doi.org/10.1109/JPROC.2008.925411

Santos, L. P., Bashford-Rogers, T., Barbosa, J., & Navrátil, P. (2025). Towards quantum ray tracing. *IEEE Transactions on Visualization and Computer Graphics*, *31*(4), 2223–2234. https://doi.org/10.1109/tvcg.2024.3386103

Wang, C.-C. E., & Wu, J.-H. P. (2024). *Quantum cosmology on quantum computer*. https://doi.org/10.48550/ARXIV.2410.22485

Wawrzyniak, D., Winter, J., Schmidt, S., Indinger, T., Janßen, C. F., Schramm, U., & Adams, N. A. (2025). A quantum algorithm for the lattice-boltzmann method advection-diffusion equation. *Computer Physics Communications*, *306*, 109373. https://doi.org/10.1016/j.cpc.2024.109373

Wawrzyniak, D., Winter, J., Schmidt, S., Indiniger, T., Janßen, C. F., Schramm, U., & Adams, N. A. (2025). *Dynamic circuits for the quantum lattice-boltzmann method*. https://doi.org/10.48550/ARXIV.2502.02131

Weih, L. R., Gabbana, A., Simeoni, D., Rezzolla, L., Succi, S., & Tripiccione, R. (2020). Beyond moments: Relativistic lattice boltzmann methods for radiative transport in computational astrophysics. *Monthly Notices of the Royal Astronomical Society*, *498*(3), 3374–3394. https://doi.org/10.1093/mnras/staa2575

Yamazaki, S., Uchida, F., Fujisawa, K., Miyamoto, K., & Yoshida, N. (2025). Quantum algorithm for collisionless boltzmann simulation of self-gravitating systems. *Computers &Amp; Fluids*, *288*, 106527. https://doi.org/10.1016/j.compfluid.2024.106527