Snowmass2021 - Letter of Interest

Cycle and symbiosis: AI and Cosmology intersect to produce new knowledge and tools

Topical Group(s): (check all that apply by copying/pasting ☐/☑)

☑ (CF3) Dark Matter: Cosmic Probes
☑ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
☑ (CF7) Cosmic Probes of Fundamental Physics
☑ (CompF3) Machine Learning
☑ (CommF1) Applications & Industry

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Cosmology and Artificial Intelligence (AI) research intersect in unique ways that can enable and accelerate discovery, such that the two fields may move forward faster together. AI is a recently matured and fast-evolving algorithmic paradigm that has significant potential to provide a new framing for modeling and interpreting large and complex data sets. Cosmological phenomena, problems, and data sets provide a complementary physics-based framework for applying and developing new algorithms. In this letter of interest, we explore the symbiosis of these fields.

Themes of AI applications for cosmology Observational data sets emerge from multiple current- and next-generation experiments that overlap in space, wavelength, and scientific goals (e.g., CMB-S4, DESI, DES, e-Rosita). The complexity of these data originates in the high-precision data-taking capability of sophisticated instruments. Simulators generate synthetic data with size and precision that rival and surpass that of observational data.

Fast algorithms for finding astronomical objects in these data are one of the most considered and experimented uses of AI. Without further development of algorithms (e.g., to address uncertainty quantification), this would remain a significant boon for reducing human intervention in searches. If error analysis can be integrated into AI algorithms, this would represent a significant milestone. Similarly, AI

has been demonstrated to speed up the simulations themselves. Simulation-based inference represents a new paradigm for statistical inference wherein deep neural networks play a key role in speeding up the computation. New horizons are emerging for applications of reinforcement learning in planning and executing cosmic surveys (i.e., self-driving telescopes).

Themes of cosmology utility for AI development AI and related statistical modeling algorithms have demonstrated versatility, power, and efficiency in modeling diverse data sets. However, there remain at least two key barriers for AI to be taken on as a high-impact everyday tool in science: models like neural networks a) lack explainability and interpretability, and b) don't have statistically robust methods for uncertainty quantification.

Symbiotic research cycle The challenges and features of cosmology and AI research are symbiotic, which we show with the description of a cycle of interaction between the two fields.

1. Large, multi-modal cosmological data sets are difficult to model both accurately and efficiently.
2. AI has been demonstrated to quickly produce relatively accurate models for complex data sets.
3. However, AI models typically lack both interpretability and the quantification of uncertainties.
4. Interpretable first principles-based models underpin cosmology data --- e.g., in simulations.
5. These phenomena and models can be used to design more explainable AI models, which can then be fed back into (2).

In this cycle, a cosmology challenge can be approached with AI models, which themselves still face challenges; the unique cosmological phenomena and data can themselves help address the issues with the AI models. The cycle presented here is also augmented by the wide availability of simulations that in many cases closely match real-world observations. Maximizing opportunities for science and AI will likely occur when simulation and observational data are co-located.

Cosmology-AI symbiosis in context We also see a similar cycle and symbiosis in other areas of high-energy physics (HEP) and other physical sciences. HEP data generally differs from many other kinds of data, because it is derived from first or fundamental physical principles. A key difference in cosmology is that many data sets are publicly available and unburdened of privacy concerns. Furthermore cosmology data is unlikely to be directly monetized in contrast to other public data sets.

Aspects of automated experimentation are being explored in many areas of science, including biology labs, nuclear fusion reactors, particle accelerators, telescopes. The DOE AI Town Halls resulted in a concept for an Automated Cosmic Experiment (ACE), which engages all the tools of AI in one loop of the scientific method.

The intention to develop powerful tools for benign ends affords no additional ability to avoid negative outcomes. While we may imagine that we are merely discovering new aspects of the universe, our work can be, has been, and will be used in other areas of society --- in some cases for purposes of oppression and violence. It's critical that we consider the ethical implications of our work at the outset of our research. The intersection of cosmology and AI is no different. Rather it is a clear example of a space where we should engage this framing. There are many avenues for immediately beginning to address this challenge, including clear descriptions and recommended uses of data sets and ethical reviews of algorithms in partnership with professional social scientists and ethicists.

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