Holographic Cosmology and the Dark Matter Phenomenon

The HoloCosmo Project

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Abstract

This document explores holographic cosmology as a framework for addressing the dark matter phenomenon. We summarize how the holographic principle, inspired by black hole thermodynamics and quantum gravity, can be applied to cosmology, potentially explaining phenomena often attributed to dark matter through emergent gravity effects or holographically guided matter candidates. We discuss successes, challenges, and the interplay between holographic models, standard cosmological observations (galaxy rotation curves, gravitational lensing, clusters, and CMB structure), as well as possible hybrid or "best-of-both-worlds" scenarios.

1 Introduction: Holographic Principle as a Framework in Cosmology

The holographic principle posits that our universe has a *finite* number of degrees of freedom, proportional to the area of its cosmological horizon in Planck units, rather than its volume. This insight stems from black hole thermodynamics and quantum gravity, where the entropy of a black hole is proportional to the horizon *area*. Applied to cosmology, this suggests that conventional field-theoretic approaches might overcount gravitational degrees of freedom, leading to inflated predictions for the vacuum energy. Imposing a holographic cap on cosmic degrees of freedom can thereby mitigate the cosmological constant problem.

Banks and Fischler were among the pioneers of *holographic cosmology*, introducing a perspective wherein the universe is described in terms of causal diamonds. Each causal diamond is associated with a Hilbert space whose dimension is set by the maximal horizon area. This self-consistent framework eschews assuming an infinite phase space, raising the question of whether phenomena traditionally ascribed to dark matter might emerge from holographic degrees of freedom or boundary constraints, rather than requiring new, undiscovered particle species.

2 Dark Matter Phenomenology and Holographic Models

Observations supporting the existence of dark matter include:

- **Flat galaxy rotation curves**: Stars at large galactic radii rotate faster than Keplerian decline would suggest.
- **Gravitational lensing**: Clusters exhibit larger inferred masses than visible matter can account for.
- **CMB acoustic peaks**: Data on the early universe (e.g. Planck) is well-fit by a ΛCDM model with a dark matter component.

- **Large-scale structure formation**: Simulations require cold dark matter to seed early clumps and match observed galaxy distributions.

A holographic approach *must* reproduce these phenomena by either *(a)* modifying gravity so that no new particle is required, *or (b)* providing a viable *dark matter* candidate (e.g. primordial black holes) consistent with horizon-based constraints.

2.1 Explaining Galaxy Rotation Curves Without Particle Dark Matter

One of the main triumphs of any alternative to conventional dark matter is its explanation of the flat rotation curves in galaxies. In ΛCDM, these are explained by extended halos of collisionless dark matter. Holographic or *emergent gravity* theories aim to produce a similar extra gravitational pull *without* unseen mass, linking it instead to changes in horizon entropy or entanglement.

Erik Verlinde's *Emergent Gravity (EG)* [**?**] is a prime example:

- Gravity is treated as an *entropic force* resulting from the reconfiguration of holographic degrees of freedom.
- A positive cosmological constant (dark energy) sets a horizon scale with temperature and entropy; baryonic mass displaces some of this entropy, leading to an additional "dark" force.
- On galaxy scales, this emergent force can mimic the empirical Tully–Fisher relation, produce approximately flat rotation curves, and do so with minimal free parameters.

EG and similar approaches (like MOND, though not explicitly holographic) show notable success in reproducing many observed galaxy relations.

Nonetheless, extending this success to **dwarf galaxies** can be tricky. Analyses such as that by Pardo (2020) [**?**] show that while EG often matches moderate dwarfs, it can over- or under-predict certain rotation velocities, suggesting that environmental effects or residual dark matter might still be required.

2.2 Gravitational Lensing and Cluster Scales

Gravitational lensing is a powerful probe of the mass distribution, independent of the motion of luminous matter. In standard GR, lensing directly traces mass/energy. For a holographic or modified-gravity theory to succeed, it must reproduce lensing observations:

- **Galaxy–galaxy lensing**: Some tests have shown that emergent gravity matches average lensing profiles around galaxies (e.g. Brouwer *et al.* 2017).
- **Galaxy clusters**: Observations typically require large dark matter fractions. EG and MOND-like theories tend to fail here if no additional mass is introduced. Studies of the Coma cluster and stacked cluster data indicate tension [**?**].
- **Bullet Cluster (1E0657–56)**: Cited frequently as "direct" evidence of collisionless dark matter, since the lensing center of mass is offset from the bulk of luminous X-ray plasma. In emergent gravity, it is unclear how a purely entropic effect would detach from the baryonic mass distribution.

Hence, *clusters and lensing* remain a big challenge for purely modified/holographic gravity without a genuine matter component.

2.3 Early-Universe Structure and CMB Constraints

The standard picture has non-interacting dark matter clumping gravitationally long before ordinary matter decouples from radiation, thereby seeding cosmic structure and shaping the cosmic microwave background acoustic peaks. Purely modified gravity approaches (like MOND or EG alone) have historically struggled to replicate the correct pattern of CMB peaks, particularly the amplitude of the third peak. Some attempt to add massive neutrinos or additional fields to fix this, but it becomes less *pure* as a dark-matter-eliminating solution.

Holographic approaches can offer alternative solutions:

- **Holographic Space-Time (HST) theory by Banks and Fischler**: Proposes finite inflation with discrete horizon degrees of freedom leading to *primordial black holes (PBHs)* that act as dark matter.
- The challenge is to produce the observed DM abundance without overclosing the universe or violating nucleosynthesis constraints.
- Mergers of tiny black holes are invoked, or stable Planck-mass relics after evaporation.

These scenarios might simultaneously address early structure (e.g. early formation of supermassive black holes at $z > 10$) but face constraints from microlensing, cosmic gamma-ray backgrounds, etc.

3 Where the Holographic Approach Falls Short

Despite notable progress on galaxy dynamics, purely holographic or emergent gravity theories often fall short in the following arenas:

Galaxy Clusters Verlinde's EG underpredicts binding in cluster cores and overpredicts it at large radii. Similar problems plague MOND without supplementary dark matter.

Colliding Clusters The Bullet Cluster remains a key data point. The observed mass distribution (through lensing) is offset from the baryonic plasma, strongly suggesting a collisionless mass component that emergent gravity alone cannot mimic without additional degrees of freedom.

Early-Universe Constraints Obtaining the correct CMB acoustic structure and large-scale power spectrum is difficult if no real dark matter is present. Growth of fluctuations needs collisionless matter to form deep gravitational wells pre-recombination.

Overall, the purely *no-DM* variant of holography might *not* suffice. Hence, the interest in *hybrid* or *HST* frameworks that reintroduce dark matter (often PBHs or relics) in a holographic manner.

4 Contrasting Verlinde's Emergent Gravity vs. Banks–Fischler HST

It is helpful to separate two distinct uses of holography:

4.1 Emergent Gravity (EG)

- Essentially a *modified gravity* approach.
- Ties dark energy (de Sitter horizon) to an entropic force that explains the missing mass phenomenon in galaxies.
- Matches many galaxy observations but not cluster or early-universe data without extra components.
- No real new particle is introduced; dark matter is said to be "an elastic response of spacetime".

4.2 Holographic Space-Time (HST)

- A more radical cosmological framework by Banks and Fischler.
- Preserves *general relativity* on large scales but modifies early-universe conditions via a finite horizon Hilbert space.
- Dark matter is *real*, possibly PBHs or black hole remnants.
- Solves cluster/CMB issues (since it basically has genuine CDM) but might not directly explain galaxy-scale MOND-like laws.

Thus, EG tries to remove the need for dark matter *outright*, while HST replaces it with a distinctly holographic origin. They share the notion that dark energy and dark matter are intimately linked to the cosmic horizon (or inflationary horizon) but differ in *whether* new matter is introduced.

5 Hybrid Models: Holography *Plus* Some Dark Matter

One pragmatic compromise is to combine a mild emergent gravity effect for galaxies with a moderate amount of genuine dark matter for clusters and the early universe. Examples:

- MOND + neutrinos
- Superfluid dark matter (where the DM forms a superfluid in galaxy cores, reproducing MOND-like acceleration, yet acts like collisionless matter at large scales).

Such hybrids can unify galaxy-scale successes with cluster/cosmological requirements. However, critics note the potential ad-hoc feel of *two* separate solutions. A truly consistent hybrid would derive both phenomena (galaxy-scale emergent effects *and* large-scale collisionless matter) from a single principle, ideally something like a quantum gravitational or horizon-based argument.

6 Recent Perspectives and Future Directions

Null results in WIMP searches, intriguing new data from JWST (which found candidate massive galaxies at $z > 10$), and the persistent Bullet Cluster question drive ongoing research in emergent gravity and PBH dark matter. Key takeaways:

- **Galaxy phenomenology**: Both standard ΛCDM and emergent gravity must explain tight galactic scaling relations and the radial acceleration relation. MOND-like laws are empirically robust, so any new DM model or feedback mechanism must replicate them.

- **Clusters and lensing**: Observations continue to favor an actual mass component. Emergent gravity alone struggles without free-function additions.
- **CMB, large-scale structure**: Cold dark matter consistently fits the acoustic peak pattern. Modified gravity theories typically require extra tune-ups to match the CMB data. PBH-based holographic DM might also be tested via microlensing or gravitational wave signatures.
- **JWST & early structure**: Banks–Fischler's PBH approach could help with puzzlingly early galaxy and black hole formation, but it remains under scrutiny due to constraints on PBH abundance and mass distribution.

6.1 Data as the Final Arbiter

Future missions (Euclid, Roman Space Telescope, advanced IFU spectrographs, further JWST observations, *etc.*) will shed light on:

- **Precise galaxy rotation curves** across various morphologies, to test emergent gravity on small scales.
- **Weak lensing and cluster surveys** to see if any purely emergent approach can replicate mass profiles.
- **High-z structure** to ascertain whether a PBH-like dark matter or a simpler ΛCDM scenario better accounts for early massive galaxies.

Direct detection of WIMP-like particles or axions in the laboratory would strongly favor the CDM approach, but the possibility of PBHs or relics means that dark matter might remain gravitationally visible yet elusive to direct searches.

7 Conclusion

Holographic cosmology provides a fertile ground for rethinking dark matter. By imposing a finite horizon-based information budget, it can reduce the *overcounting* of vacuum energy and sometimes replicate galaxy-scale effects via emergent gravity. Yet, purely "no-DM" holographic approaches face serious empirical hurdles, particularly on cluster and early-universe scales. Hence, many researchers explore *hybrid* solutions or frameworks like Banks–Fischler HST, which incorporate actual dark matter—often in the form of primordial black holes—while preserving holographic ideas.

Ultimately, the interplay of theory and observation will determine whether a holographic principle can fully solve the dark matter puzzle. Verlinde's emergent gravity, though promising for galaxies, struggles with clusters; HST-based PBH dark matter might fit clusters and early structure but must still pass numerous astrophysical and microlensing constraints. The next generation of high-precision cosmological measurements will reveal whether these approaches can surpass the robust track record of ΛCDM with collisionless dark matter.

References

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