Can cosmological simulations of vHDM ease the large-scale tensions in cosmology?

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Introduction

Motivation for a new cosmological model

- Overview of the vHDM model
- My Simulations
- Preliminary results

Motivation: Cracks in the Cosmological Model



Enhanced early structure formation

- High local bulk flows
- High velocity cluster mergers
- Fast growing super massive black holes
- High redshift galaxies

Motivation: Cracks in the Cosmological Model



Supervoids on 100s Mpc scales

- "Local Hole" with 120 Mpc radius observed in near-IR, Xray and radio
- Overproduction of ~100 Mpc inferred from Integrated Sachs-Wolfe effect

Motivation: Cracks in the Cosmological Model

The Hubble Tension Abdalla et al. 2022 SNIa-Cenheir Direct Riess et al. (2022). R22: 73.04 ± 1.04 Early-time and late-time Kiess et al. (2022), R22: 73.04 ± 1.04 amarena, Marra (2021): 74.30 ± 1.45 Riess et al. (2020), R20: 73.2 ± 1.3 Breuval et al. (2020): 72.8 ± 2.7 Riess et al. (2019), R19: 74.03 ± 1.42 Camarena, Marra (2019): 75.4 ± 1.7 lacksquareSNI9-TRGI SNIa-TRCB Dhawan et al. (2022): 76.94 ± 6.4 Jones et al. (2022): 76.94 ± 6.4 Jones et al. (2022): 71.54 ± 1.8 Freedman (2021): 69.8 ± 1.7 Kim, Kang, Lee, Jang (2021): 69.5 ± 4.2 Solisis, Casertano, Rises (2020): 72.1 ± 2.0 Freedman et al. (2020): 69.6 ± 1.9 Yuan et al. (2019): 72.4 ± 2.0 measurements of H_0 disagree! SNIa-Miras Huang et al. (2019): 73.3 ± 4.0 Balkenhol et al. (2021), Planck 2018+SPT+ACT : 67.49 ± 0.5 Pogosian et al. (2020), eBOSS+Planck mH2: 69.6 ± 1.8 Blakeslee et al. (2021) IR–SBF w/ HST: 73.3 ± 2.5 Khetan et al. (2020) w/ LMC DEB: 71.1 ± 4.1 Cantiello et al. (2018): 71.9 ± 7.1 Aghanim et al. (2020). Planck 2018: 67.27 ± 0.60 Aghanim et al. (2020). Planck 2018+CMB lensing: 67.36 ± 0.54 Ade et al. (2016), Planck 2015, H0 = 67.27 ± 0.66 de Jaeger et al. (2022): 75.4+3-8 de Jaeger et al. (2020): 75.8+3-3 **CMB** without Planc Dutcher et al. (2021), SPT: 68.8 ± 1.5 H_{θ} [km s⁻¹ Mpc⁻¹] Masers Pesce et al. (2020): 73.9 ± 3.0 Aiola et al. (2020). ACT: 67.9 + 1.4 Aiola et al. (2020). WMAP9+ACT: 67.6 + 1. **Tully Fisher** Zhang, Huang (2019), WMAP9+BAO: 68.36+0.53 Kourkchi et al. (2020): 76.0 ± 2.0 Schombert, McGaugh, Lelli (2020): 75.1 ± 2.8 Henning et al. (2018), SPT: 71.3 ± 2.1 Hinshaw et al. (2013), WMAP9: 70.0 ± 2.2 HII galaxy Fernandez Arenas et al. (2018): 71.0 ± 3.5 Wang, Meng (2017): 76.12+3.42 No CMR with RRN Zhang et al. (2021), BOSS correlation function+BAO+BBN: 68.19±0.99 Lensing related, mass model depender Chen et al. (2021), P+BAO+BBN: 69.23±0.77 Denzel et al. (2021): 71.8⁺ Birrer et al. (2020), TDCOSMO: 74.5⁺ rrer et al. (2020), TDCOSMO+SLACS: 67.4⁺ Philcox et al. (2021), P+Bispectrum+BAO+BBN: 68.31+0.83 D' Amico et al. (2020). BOSS DR12+BBN: 68.5 + 2.2 Yang, Birrer, Hu (2020): 73.65+1-22 Millon et al. (2020), TDCOSMO: 74.2 ± 1. Colas et al. (2020), BOSS DR12+BBN: 68.7 ± 1.5 Qi et al. (2020): 73.6⁺ Liao et al. (2020): 72.8⁺ Liao et al. (2019): 72.2 ± Ivanov et al. (2020), BOSS+BBN: 67.9 ± 1.1 Alam et al. (2020), BOSS+eBOSS+BBN: 67.35 ± 0.97 Shajib et al. (2019), STRIDES: 74.2⁺² Wong et al. (2019), H0LiCOW 2019: 73.3⁺ CMB lensing GW r Baxter et al. (2020): 73.5 ± 5. Mukherjee et al. (2022), GW170817+GWTC-3: 67±2 Abbott et al. (2021), GWTC-3: 68±2 Palmese et al. (2021), GW170817: 72.77±4 Philcox et al. (2020), Pl(k)+CMB lensing: 70.6+3.7 LSS teg standard ruler Gavathri et al. (2020). GW190521+GW170817: 73.4+6 terice et al. (2020). GW170817+ZTF: 67.6 Farren et al. (2021): 69.5+3.0 Mukherjee et al. (2019), GW170817+VLBI: 68.3+ Indirect Hotokezaka et al. (2019): 70.3+2 Cosmic chronometer Moresco et al. (2022), flat ACDM with systematics: 66.5 ± 5. Moresco et al. (2022), open wCDM with systematics: 67.8+8-60 65 70 75 80 85 80 60 65 70 75

What is vHDM?

What is v?

vis MOND!!!

Simple Interpolation function

$$v(y) = \frac{1}{2} + \sqrt{\frac{1}{4} + \frac{1}{y}}$$

What is HDM?

HDM is Hot Dark Matter

• Hot Dark Matter particles have low mass and high thermal velocities at recombination

• Free-streaming suppresses small-scale structure

• 11 eV Sterile Neutrinos in vHDM (Angus 2009)

Key assumptions

Assume ACDM interpretation of Cosmic Microwave Background temperature anisotropies is (mostly) correct

Assume all Dark Matter is 11 eV sterile neutrinos

Assume background FRLW metric

Assume MOND effects are negligible in the early Universe

Why combine MOND and Dark Matter?

- •HDM means galaxies are purely baryonic and MONDian
- Dark Matter in clusters should ease large-scale issues faced by MOND
- CMB is easily explained
- Stronger MOND gravity will enhance structure formation

Why return to this model now?

- •Angus et al. 2013 produced Local Hole analogues **before** it was observed
- A local void solution to the Hubble Tension is possible (Haslbauer et al. 2020)
- The rate of El Gordo analogues in Katz et al. 2013 is observationally accurate (Asencio et al. 2021)

My Simulations

Cosmological collisionless N-body simulations using "Phantom of Ramses" code (Teyssier 2002; Lüghausen 2014)

$$\nabla^2 \Phi(\boldsymbol{r}) = 4\pi G \rho(\boldsymbol{r}) + \nabla \cdot \left[\tilde{\nu} \left(\frac{|\nabla \Phi_N|}{a_0} \right) \nabla \Phi_N(\boldsymbol{r}) \right]$$

Runs presented here have 800 cMpc/h box length and 256³ particles

Initialised at z=199 and initial conditions produced with CAMB and MUSIC (https://bitbucket.org/SrikanthTN/bonnpor/src/master/)

Consider Λ CDM, Λ HDM, ν CDM and ν HDM models for comparisons



Cumulative Halo Mass Function



Halos identified with Amiga Halo Finder

$$M_{180} \equiv 180 \rho_{crit} \left(\frac{4}{3} \pi R_{180}^3\right)$$

$$M_N = \nu \left(\frac{g_N}{a_0}\right) M_{180}$$





What next?

- Creating a more realistic model
- Heavier sterile neutrinos
- Smaller enhancement to gravity
- Analysis of Local Hole analogues
- What signals are imprinted onto mock observations?
- Can a Local Hole realistically solve the Hubble Tension?



Conclusions

The vHDM cosmology does not ease large-scale tensions, but instead overcorrects

- MOND gravity over-enhances large-scale structure formation
- Hot Dark Matter underproduces small-scale structure
- A more realistic cosmology will require less drastic modifications
- Supervoids produced in these self-consistent simulations can still provide insight into the real world
 - What observational signatures should a local void produce?
 - Do we observe these signatures and does the Local Hole really exist?
 - Is a local void solution to the Hubble Tension plausible?



Appendix: Warm Dark Matter



Appendix: Resolution

