Measuring the Neutrino Mass with Non-Linear Cosmological Structure

Neutrinos are the last particles in the standard model of particle physics whose mass remains undetermined. The best chance for measuring the neutrino mass comes from observing the effect of massive neutrinos on the growth of small scale non-linear cosmological structure. My research will provide the theoretical understanding necessary to successfully perform this measurement.

Introduction

Neutrinos created during the early universe make up a part of the dark matter today and significantly affect the growth of cosmic structure. These neutrinos are known to be massive (Fukuda *et al.*, 1998) but their total mass, which could motivate new models of particle physics, is still to be determined.

The large thermal energy of relic massive neutrinos distinguishes them from cold dark matter (CDM) and prevents them from clustering on scales smaller than their thermal free-streaming length (Lesgourgues and Pastor, 2006). The reduced clustering due to neutrino free-streaming affects the growth of dark matter structures, and so allows astrophysical measurements of this clustering to infer the mass of the neutrino. Figure 1 shows that the best detection potential comes from measuring small scales where the effect of neutrino mass is maximized. Matter on these scales has formed non-linear collapsed structures and thus must be understood using cosmological simulations.

I will constrain the neutrino mass by characterizing its effects on structure formation. I will focus on four probes; the matter power spectrum, especially from weak lensing, galaxy cluster abundances, the correlation between Lyman-α forest absorption, and the first galaxies. Each of these experiments probes structure formation on different scales and thus provides complementary information.

My research will improve understanding of the massive neutrino effect on the formation of cosmological structure from the clumping of dark matter, one of the central aims of the cosmic origins program. As the impact of massive neutrinos on structure growth is larger at lower redshift, my research will help explain differences in the formation of galaxies at $z = 0$ and early times.

Measuring the Neutrino Mass with the Matter Power Spectrum

Measurements of the matter power spectrum, from galaxy clustering or weak lensing, can be used to constrain the neutrino mass. Weak lensing experiments such as the current Dark Energy Survey and the future Euclid satellite will measure the matter power spectrum at the 1% level (Audren *et al.*, 2013). These measurements of the matter power spectrum will provide the ability to constrain neutrino masses close to 0.05 eV, the lower limit allowed by current neutrino oscillation experiments (Abe *et al.*, 2014). However, realizing this ability requires understanding the effect of the neutrino mass on the matter power spectrum at 1% accuracy.

As shown in Figure 1, the effect of massive neutrinos on the scales probed by weak lensing must be understood using cosmological N-body simulations. The cosmological simulations in **Bird** *et al.* (2012) probed the effect of massive neutrinos accurate to 10%. To reach an accuracy of 1% I will use the new method I developed in Ali-Haïmoud and **Bird** (2013), which treats massive neutrinos analytically as part of a numerical CDM simulation. It includes both relativistic effects and the mass splitting between neutrino species, required to accurately simulate neutrinos with a mass less than 0.15 eV. **I will thus characterize the effect of massive neutrinos on the matter power spectrum to the 1% accuracy required for future observations.**

Measuring the Neutrino Mass with Galaxy Clusters

Galaxy clusters are the largest collapsed structures in the $z \approx 0$ universe. One way of observing galaxy clusters is by measuring the change in energy of CMB photons due to interaction with high temperature electrons within the intra-cluster gas, known as the thermal Sunyaev-Zeldovich (tSZ) effect. The tSZ effect power spectrum scales as σ_8^8 and is thus extremely sensitive to changes in the dark matter clustering caused by massive neutrinos, as shown by Figure 2.

However, observations of clusters are also extremely sensitive to the distribution of hot gas within the galaxy cluster. This in turn is affected by the uncertain physical process of AGN feedback, energy injection from the central black holes of the cluster's constituent galaxies. Models for the effect of AGN feedback are constrained by comparing the output of cosmological simulations to observations of cluster X-ray luminosity and temperature, entropy and density profiles (Battaglia *et al.*, 2012; Le Brun *et al.*, 2014). However, considerable freedom in AGN feedback models remains. To extract robust neutrino mass constraints it is necessary to distinguish the effects of neutrino mass from those of AGN feedback.

I will produce robust neutrino mass constraints by quantifying the uncertainty from AGN feedback models in cosmological simulations. As shown in Figure 2, I have already simulated the effect of massive neutrinos on the tSZ power spectrum with one choice of AGN feedback model. I will be able to expand this to other models of AGN feedback, as I have already examined a range of feedback models in my work on Damped Lyman-α absorbers in **Bird** *et al.* (2014). I will compare model predictions to observations of cluster X-ray properties and the tSZ effect power spectrum. I will then quantify the freedom allowed by X-ray observations in AGN feedback models, and how much uncertainty this introduces into the tSZ effect power spectrum, allowing me to place robust constraints on the neutrino mass. I will help show how supermassive black holes affect the growth of dark matter structures surrounding them, work which is highly relevant to cosmic origins science.

Measuring the Neutrino Mass with the Lyman-alpha Forest

The majority of the baryons in the universe are found in the highly ionized hydrogen gas of the intergalactic medium. The small amount of neutral gas remaining scatters photons in quasar spectra, causing blended absorption features, the Lyman-α forest. The clustering of Lyman-α forest absorbers can be measured either by correlating absorption along the line of sight to the quasar, or correlating different quasar sight-lines in the direction perpendicular to the line of sight. The Baryon Oscillation Sky Survey (BOSS) (Busca *et al.*, 2013) will soon publicly release the first measurement of the correlation of Lyman-α forest absorbers between different quasar sight-lines. This correlation of Lyman-α forest absorbers probes the clustering of dark matter (Croft *et al.*, 1998) over a wide range of scales, shown in Figure 1.

The Lyman-α forest correlation function probes scales which include the peak effect of massive neutrinos on the matter power spectrum, making it an extremely powerful neutrino mass detector. **I will characterize the effect of massive neutrinos on the Lyman-α forest, using mock observations generated from cosmological hydrodynamic simulations.**

Simulations which resolve both the Jeans scale of individual absorbers (50 kpc) and the largest scales over which the Lyman-α absorber correlation is measured (300 Mpc) are computationally expensive. I will use multiple small simulations, each ~ 60 Mpc across, large enough only to resolve the Lyman-α forest in a single quasar. Each small simulation will be placed within a larger low-resolution dark matter simulation, allowing the inclusion of large scale correlations. The dynamical effect of larger scale modes will be included by altering the background cosmological parameters (Baldauf *et al.*, 2011). This will allow the Lyman-α correlation function between quasars to be modeled using the same methods I developed for the correlation along the line of sight to the quasar (**Bird** *et al.*, 2011) and estimate the effect of neutrino mass and other cosmological parameters on the Lyman-α forest without requiring large dynamic range simulations.

Measuring the Neutrino Mass with the First Galaxies

The effect of massive neutrinos on cosmological structure increases over time. By comparing measurements of the matter power spectrum on the same scales at two widely different redshifts, it may be possible to obtain a differential measurement of the neutrino mass, which would be free from degeneracies with other cosmological parameters.

JWST will increase the number of observed galaxies at $z = 8 - 15$ by over an order of magnitude. As these are the first collapsed objects to form, linear perturbation theory computations of cosmological structure are valid even on small scales. Galaxy clustering traces the matter power spectrum on linear scales, so a galaxy clustering survey at $z = 10$ can probe smaller scales than at $z = 0$, improving neutrino mass constraints. I will use semi-analytic models of these galaxies to forecast the potential constraints.

Early galaxies may also be observable indirectly. Their shallow potential wells allow outflows from stars within them to efficiently pollute the intergalactic medium with metals. Absorption lines in high redshift quasar spectra due to these metals can be observed by infrared spectrographs such as FIRE (Simcoe *et al.*, 2013) and JWST. Detecting these absorbers thus reveals the presence of galaxies too faint to be observed directly. The correlation function of these absorbers has the potential to be a measurement of dark matter clustering. I will use my existing cosmological simulations to investigate how early galaxies enrich the gas around them, thus determining their stellar and dark matter properties.

I will make forecasts for the ability of both direct and indirect observations of high redshift galaxies to constrain the matter power spectrum at $\mathbf{z = 8 - 15}$. I will combine these measurements with those at lower redshifts to constrain the neutrino mass. This portion of my research is particularly relevant to the cosmic origins program. I will motivate future JWST observations to probe the growth of structure at early times and investigate how the first galaxies enrich their surroundings.

Summary

I will improve constraints on the neutrino mass based on observations of cosmic structure. I will focus on small scales with the best prospects for detection. I will perform simulations to characterize the effect of massive neutrinos on the matter power spectrum to the 1% level required by future experiments. I will understand the uncertainty in models for galaxy cluster formation in order to use thermal Sunyaev-Zeldovich measurements as constraints on the neutrino mass. I will understand the effect of the neutrino mass on the correlation between Lyman-α forest absorbers on large scales. Finally I will investigate the possibilities for measurements of galaxies at high redshift to constrain the growth of structure and thus the neutrino mass.

Relation to Host Institution

The MIT Kavli Institute for Astrophysics (MKI) is the ideal setting to carry out this research, hosting experts in the theory and observations required. My simulation and model development will benefit from interaction with the Vogelsberger group, while understanding Lyman-α forest observations will benefit from interaction with the Simcoe group.

Professor Mark Vogelsberger and I have been collaborating for the past three years to develop and analyze the AREPO hydrodynamic cosmological simulations. As part of the collaboration I pioneered the use of AREPO to study the Lyman-α forest and Damped Lyman-α systems. I will continue this collaboration to further quantify the effect of AGN feedback on clusters and the effect of neutrinos on the matter power spectrum and the Lyman-α forest.

I will also continue my collaboration with Professor Rob Simcoe on high redshift absorbers. Together with a student, Daniel Miller, we have been working on a project to measure the effect of reionization on Carbon IV absorbers seen by FIRE. Professor Simcoe's expertise in absorption systems and quasar continuum fitting will be invaluable in simulating and interpreting the Lyman-α data needed to constrain the neutrino mass.

I plan to collaborate with Professor Paul Schechter on the internal structure of galaxy clusters for this research. The expertise of Professor Deepto Chakrabarty will also be helpful for interpreting X-ray measurements.

Simulations for the proposed research will be carried out both locally, using the computing resources available on the Odyssey cluster at MIT, or nationally using XSEDE time.

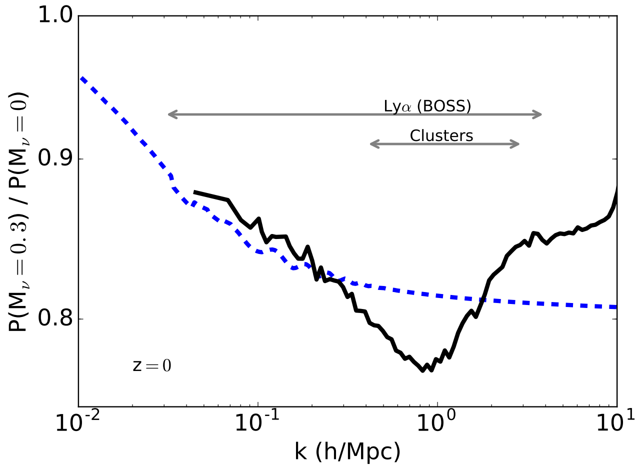

Figure 1: The ratio of the matter power spectrum including massive neutrinos (0.3 eV) to that assuming massless neutrinos, computed at $z = 0$. The results of cosmological N-body simulations from **Bird** *et al.* (2012) (solid line) are accurate even on the smallest scales, while linear perturbation theory (dashed line) is only accurate for large scales ($k < 0.1$ h/Mpc). Arrows show the approximate range of scales probed by various types of dataset. Real-space scales L are related to wavenumbers k by $L = 2\pi/k$.

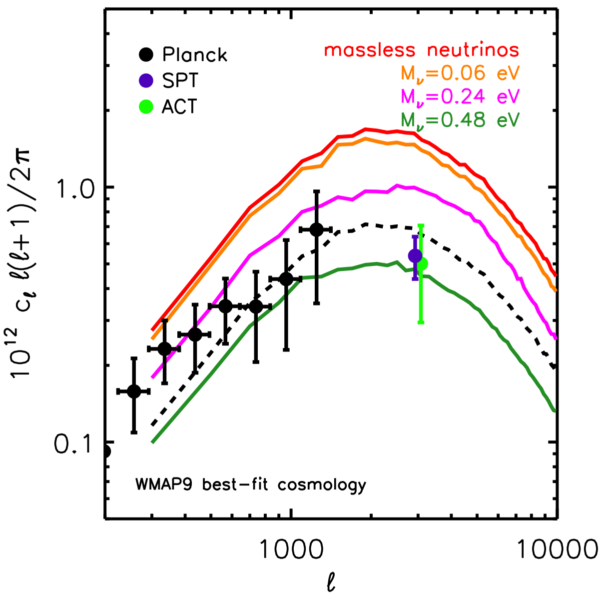

Figure 2: The effect of neutrino mass on the thermal SZ effect power spectrum, compared to observations from three CMB experiments. Each solid line shows a simulation with a different neutrino mass. The results of a cosmological simulation (McCarthy, **Bird** and Schaye, in preparation) including massive neutrinos using my implementation from Ali-Haïmoud and **Bird** (2013). AGN feedback is included following Le Brun *et al.* (2014), and the cosmological parameters are those from the WMAP satellite (Hinshaw *et al.*, 2013). The effect of massive neutrinos is significant compared to the experimental error bars. The best-fit neutrino mass (black dashed line) is 0.4 eV, but non-zero neutrino mass is preferred only because uncertainty in the AGN feedback model is not included.

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