From Cosmology to the Formation of Galaxies

My recent work has focused on three areas; the effect of massive neutrinos on cosmic structure, cosmological interpretations of the Lyman-α forest, and the distribution of neutral gas around galaxies. I resolved the long-running problem of different observations giving differing indications for the host halo mass of Damped Lyman-α Absorbers. I simulated the effect of the neutrino mass on the matter power spectrum, and invented a new, optimal method for including massive neutrinos in simulations. I performed the first model-independent constraints on cosmology from the Lyman-α forest and showed how it can determine the sources of the ionising photon background. I have also worked on inflation, string theory, and signatures of the primordial gravitational wave background.

Galaxy Formation in Absorption

The processes by which galaxies form depend on the poorly understood way in which supernovae heat the gas surrounding them. My research into galaxy formation aims to characterise this process through studying absorption lines around galaxies, which directly measures the temperature and density of the gas. Part of this work took place as part of the Illustris collaboration (Vogelsberger et al., 2014), which produced one of the largest cosmological hydrodynamic simulations yet performed. More recently, I supervised a student on a project examining how the energy and temperature of galactic winds affects the structure of the gas around galaxies, especially their metallicity. This led to Suresh et al. (2014), where we were able to show that future measurements of this gas have the potential to strongly constrain the physics of galactic winds.

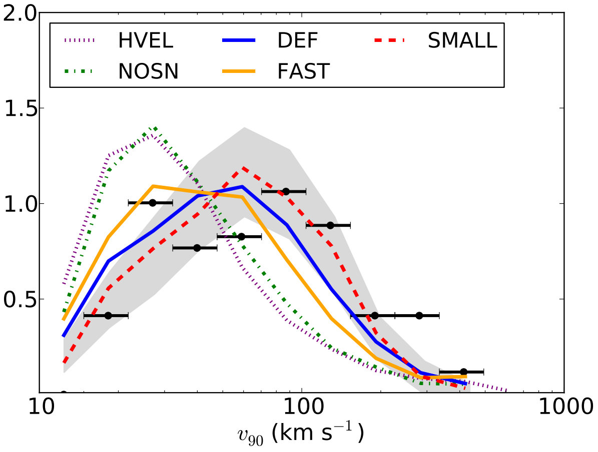

Figure 1: The grey band shows the expected velocity dispersion of Damped Lyman-α Absorbers (DLAs) from the preferred simulation in **Bird** et al. (2014a), compared to observed results from Neeleman et al. (2013), shown by the circles with error bars. Other dashed and solid lines show the results of simulations with different formulae for gas heating, demonstrating that the properties of DLAs contain information about this important physics.

Damped Lyman-α Absorbers (DLAs), strong neutral hydrogen absorbers, represent one particular important galactic absorption experiment. The nature of their host halos and the search for their stellar component is a decades-old problem in astronomy. Cosmological simulations have long indicated that they should form predominantly in small proto-galactic dwarfs. However, earlier simulations produced DLAs with too small a bias and velocity width. This has been interpreted to imply that these objects should instead form in larger, Milky Way sized, objects, which would suggest that dwarf galaxies are extremely efficient at removing their neutral gas. I showed instead that my simulations can reproduce all observed properties of DLAs with a population still residing in relatively small objects. The DLA bias is enhanced by the effects of non-linear growth (**Bird** et al., 2014b). The velocity width of DLAs was underestimated due to an insufficiently accurate treatment of the ionisation state of the metal ions from which it was measured (**Bird** et al., 2014a). With the resolution of these problems, I demonstrated that current models of galaxy formation can indeed reproduce all observed properties of DLAs, resolving a long-running problem in astrophysics.

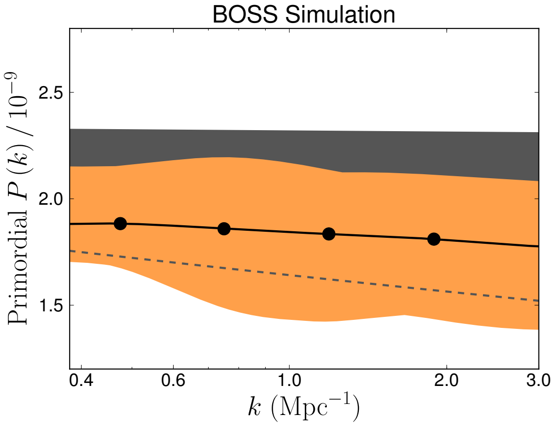

Figure 2: Forecast constraints on the shape of the matter power spectrum as measured by the Lyman-α forest component of the Baryon Oscillation Sky Survey (BOSS), from **Bird** et al. (2011). Orange regions show constraints without assuming a particular shape for the power spectrum, while grey regions show constraints extrapolated from the cosmic microwave background, assuming a nearly scale-independent shape for the power spectrum.

Lyman-α forest Cosmology

Hydrogen accounts for three quarters of the baryonic matter in the Universe, the bulk of it in the highly ionised gas of the intergalactic medium. Absorption of quasar spectra by this gas produces the Lyman-α forest, blended features which trace the gas density field over several Mpc. This gas falls into dark matter potential wells and so in turn traces structure formation on the smallest scales currently possible.

In **Bird** et al. (2011), I extracted robust cosmological information from the Lyman-α forest. Previous work had to extrapolate a power law shape for the initial perturbations from the larger scales probed by the cosmic microwave background. Instead I allowed the primordial power spectrum wide freedom in shape over the probed range of scales. I ran a suite of 70 cosmological hydrodynamic simulations designed to span the whole range of initial conditions, and compared synthetic Lyman-α forest spectra to observations in each case. To avoid over-fitting the data, I used cross-validation, a statistical technique which uses the principle that a successful theory should be predictive to avoid fitting to noise. My method paves the way for cosmological parameter estimation in an era where the most powerful data will come not from the cosmic microwave background but from small, non-linear scales.

More recently, in (Pontzen et al., 2014), we have shown that surveys such as BOSS are able to measure the clustering of sources contributing to the extragalactic UV background. This will allow us to infer directly what lights up the Universe; quasars or galaxies.

Finding The Neutrino Mass

Massive neutrinos are a component of dark matter and can be detected through their effect on the growth of cosmic structure. As illustrated in Figure 2, they possess significant thermal energy which prevents them from clustering on small scales. Measurement of this effect on the overall large scale structure will allow us to infer the neutrino mass. I have significantly improved all aspects of the modelling of massive neutrinos in large scale structure. In **Bird** et al. (2012), I used a suite of dark matter N-body simulations to precisely characterize for the first time the effect of massive neutrinos on the non-linear scales of the matter power spectrum. I showed that HALOFIT, the most widely used fitting formula for the matter power spectrum, was inaccurate by a factor of two, and produced an improved version, accurate to a few percent even at the smallest scales probed by weak lensing. I have since applied it to two measurements of the matter power spectrum. In Xia et al. (2012), we constrained the neutrino mass from CFHTLS, a large-scale galaxy survey, while in Audren et al. (2013) we forecast constraints from the EUCLID mission. In Villaescusa-Navarro et al. (2013), we used a second simulation suite to examine the effect of massive neutrinos on the halo mass function.

The simulations used in the work described above treated neutrinos as a second N-body particle species, like cold dark matter. This greatly increases the difficulty of running a simulation, especially since achieving full numerical convergence can requires ten times more particles for neutrinos than cold dark matter. In Ali-Haïmoud and **Bird** (2013) we developed and implemented a new method for including neutrinos in N-body simulations. Neutrinos can be described by linear perturbation theory even in the non-linear regime, provided the non-linear potential well of the cold dark matter is included. This approach is no more computationally expensive than a purely cold dark matter simulation. I demonstrated that our new method is as accurate as a fully converged particle based neutrino simulation, making it the optimal way to simulate massive neutrinos.

Inflationary Cosmology

The observed isotropy of the Universe is explained by inflation, a period of superluminal expansion in the early Universe. Inflation produces the initial perturbations which ultimately grow into galaxies, and simultaneously produces a large-scale background of gravitational waves. In **Bird** et al. (2008) I looked at the predicted amplitude of this background, and showed that simple inflationary models can produce very large or very small backgrounds, meaning that a non-detection cannot be used to rule out inflation, but will tell us the properties of the field which drove inflation. In Baumann et al. (2009) I helped to write a proposal for a dedicated microwave polarization satellite to measure the gravitational wave background. Finally, string theory has emerged as one of the best ways of describing inflation rigorously, and in **Bird**, **S.** et al. (2009) I examined the observational predictions for leading models of string theory inflation.

Summary

My recent work has focused on deriving cosmological information from non-linear scales, using cosmological structure simulations as an essential tool. My work on the neutrino mass has laid the groundwork for future detection of this important quantity. My work on the Lyman-α forest helps to turn it into a precision probe of cosmology and points the way to future work on strong neutral hydrogen absorbers.

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