Anisotropic Galaxy Clustering in the Isotropic Universe

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University of Utah
Adam Bolton
Associate Professor
Ph.D., MIT, 2005
structure, dynamics, and evolution of galaxies; observational cosmology; gravitational lensing; precision algorithms for astronomical spectroscopy

Ben Bromley
Professor
Ph.D., Dartmouth College, 1994
planet formation; formation and evolution of black holes; galactic dynamics; large-scale structure of the universe; computational and statistical method in astrophysics

Kyle Dawson
Associate Professor
Ph.D., Cornell Univ., 2004
observational cosmology; astronomical instrumentation; supernovae; large-scale structure; spectroscopic surveys

Paolo Gondolo
Professor
Ph.D., UCLA, 1991
nature of dark matter and dark energy; high-energy cosmic neutrinos

Inese Ivans
Assistant Professor
Ph.D., Univ. of Texas at Austin, 2002
stellar spectroscopy; origins of chemical elements; stellar populations; formation and evolution of galaxies, including the Milky Way

David Kieda
Professor
Ph.D., Univ. of Pennsylvania, 1989
experimental high energy astrophysics; energetic phenomena in compact objects; gamma ray astronomy; cosmic ray physics

Pearl Sandick
Assistant Professor
Ph.D., Univ. of Minnesota, 2008
dark matter; particle astrophysics and cosmology; supersymmetry phenomenology; physics beyond the standard model

Wayne Springer
Associate Professor
Ph.D., Univ. of Maryland, 1991
ultra high energy cosmic ray physics; cosmic ray detectors; astroparticle physics; observational astronomy

Anil Seth
Assistant Professor
Ph.D., Univ. of Washington, 2006
observations of nearby galaxies; formation of galaxy nuclei and black holes; galaxy histories from resolved stellar populations & star clusters

Zheng Zheng
Associate Professor
Ph.D., Ohio State University, 2004
cosmology, large-scale structure, and galaxy clustering; galaxy formation and evolution; high-redshift star forming galaxies; radiative transfer of Lyman-alpha photons and application in astrophysics

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Anisotropic Galaxy Clustering in the Isotropic Universe

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13.8 billion years

Inflation
Quantum Fluctuations

Reionization
First Stars and Galaxies

Dark Energy
Accelerated Expansion

Dark Matter
26.8%

Ordinary Matter
4.9%

Dark Energy
68.3%

13.8 billion years
Dark Matter Halo Formation

image courtesy: V. Springel
Galaxy Formation

- accretion
- heating
- cooling
- star formation
- star formation feedback
- supermassive black hole growth
- supermassive black hole feedback
- mergers
- ...
Observation: Bright Side

Theory: Dark Side

Galaxy Formation
Gastrophysics
gas cooling, gas dynamics,
star formation, feedback, ...

Dark Matter Halo Formation
Gravity
Cosmology

Dark Matter Halo Population

Halo Occupation Distribution (HOD)

Galaxy Formation Physics

Gas dynamics

Star formation

Known knowns

Known unknowns

Unknown unknowns
Two-point Correlation Function (2PCF) of Galaxies

Excess probability w.r.t. random distribution of finding **galaxy pairs** at a given separation
Two-point Correlation Function (2PCF) of Galaxies

Baryon Accoustic Oscillation (BAO), standard ruler
Small-scale shape, neutrino mass
Broad-band shape, cosmological parameters

Small- and intermediate-scale shape and amplitude, galaxy-halo connection

Anderson et al. (2012)
Zehavi, ZZ, et al. (2011)

Guo, ZZ, et al. (2015a)

3D Two-point Correlation Function of Galaxies
Galaxy comoving with the expansion
Distance $\leftrightarrow$ Cosmological Redshift

Observed Redshift: Cosmological Redshift + Doppler Redshift

Distance inference: distorted by the Doppler redshift from galaxy peculiar motion

Peculiar velocity of the galaxy
velocity w.r.t. the comoving frame
$\Rightarrow$ Doppler redshift
Large-Scale Linear Redshift-Space Distortion (Kaiser 1987)

\[ \dot{\delta} + \frac{1}{a} \nabla \cdot \mathbf{v} = 0 \]  
(continuity)

Probe combination of structure growth rate and fluctuation amplitude (gravity, dark energy)
Small-Scale Nonlinear Redshift-Space Distortion (Finger-of-God Effect)

Probe galaxy kinematics inside dark matter halos (galaxy formation and evolution)
Redshift-Space Distortion
(Gravitational Distortion)

Galaxy Formation and evolution: kinematics of galaxies inside halos
Cosmology: amplitude and growth rate of matter density fluctuation
Projected Two-point Correlation Function of Galaxies

redshift-space distortion effect removed essentially the real-space clustering

Galaxy Pair Counts

HOD (Galaxy-Halo Relation)
HOD Modeling of the SDSS Galaxy Clustering

z ~ 0.1

Luminosity Dependence

Zehavi, ZZ, et al. (2011)
An Accurate and Efficient Simulation-based Model for Redshift-Space Galaxy Two-Point Correlation Function
ZZ & Guo (1506.07523)
An Accurate and Efficient Simulation-based Model for Redshift-Space Galaxy Two-Point Correlation Function
BOSS (Baryon Oscillation Spectroscopic Survey) 
$z \sim 0.5$ massive galaxies
Measuring and Modeling the Redshift-Space Galaxy Clustering

Guo, ZZ, et al. (2015a)
The central galaxy in a halo is not at rest w.r.t. the halo.

Guo, ZZ, et al. (2015a)
Similar Results of Galaxy Motion from Redshift-Space 3-point Correlation Functions
SDSS Main Galaxy Sample (z~0)

Guo, ZZ, et al. (2015c)
Small- and intermediate-scale redshift-space distortions help tighten cosmological constraints.

\[ \dot{\delta} + \frac{1}{a} \nabla \cdot \mathbf{v} = 0 \quad \text{(continuity)} \]

- Probe structure growth rate
- Test theories of gravity
- Constrain dark energy

Redshift-Space Anisotropic Galaxy Clustering

Gravitational Distortion

- Constraints on the phase-space distribution of galaxies inside halos
- Relative relaxation between central galaxies and halos (offsets, external shear in gravitational lensing modeling)
- Dynamical friction effect on satellite galaxies
- Merging and dynamical evolution of galaxies
- Tests of galaxy formation models
- Tightening cosmological constraints (theories of gravity, dark energy)
Ly\(\alpha\) Emitting Galaxies / Ly\(\alpha\) Emitters (LAEs)

- studying young star-forming galaxies
- probing circum-galactic and intergalactic gas
- constraining the end of dark ages - reionization (the cosmic dawn)
- constraining cosmology

Lyman-alpha Emission from Star-forming Galaxies

\[ \text{Ly\(\alpha\)} \]

\[ \text{ionizing photons} \]

\[ \text{Ly\(\alpha\)} \]

Partridge & Peebles (1967)

\[ \frac{\Delta \nu}{\nu} = 5 \times 10^{12} \text{ c.p.s} \]

\[ F_{\nu} = 30 \]

\[ \text{Ly\(\alpha\)} \text{ photons} \]

~2/3 ionizing photons are converted to Ly\(\alpha\) photons
Lyα Radiative Transfer

Lyα line

$1s \rightarrow 2p$ transition

$\lambda_0 = 1216$ Å

lifetime $\sim 10^{-8}$ sec

scattering cross-section: large at line center
small at line wings

Circumgalactic/Intergalactic Media

atom rest frame

laboratory frame

- a large number of scatterings
- position/direction change from scattering
- frequency change after each scattering
Calculating the Lyα Radiative Transfer
A Key Result from Radiative Transfer Modeling of LAEs

Coupling between observed Lyman-alpha emission properties and circumgalactic and intergalactic environments

spatial and frequency diffusion
Anisotropic density and velocity distribution of circumgalactic and intergalactic gas leads to anisotropic Lyman-alpha escape.

ZZ et al. (2010)
ZZ & Wallace (2014)
Radiative Transfer Modeling of LAEs in a Large Cosmological Simulation

$z=5.7$  ZZ et al. (2010, 2011a, 2011b)

- first time, a realistic Ly$\alpha$ radiative transfer (RT) calculation in a cosmological volume to study Lyman-alpha emitters (LAEs).
- RT-induced coupling between the observed Ly$\alpha$ emission and CGM/IGM environment (density and velocity structures).
- natural explanations for an array of observed properties of LAEs
- predictions of new effects in the clustering of LAEs
Clustering of LAEs: Model Prediction

selection effect caused by environment dependent Lya RT

InterGalactic Medium

Hubble Flow

Peculiar Velocity
Clustering of LAEs: Model Prediction

enhancement in the transverse fluctuation

selection effect caused by environment dependent Lya RT

if the environment dependence of radiative transfer were eliminated

control sample
Clustering of LAEs: Model Prediction

Enhancement in the transverse fluctuation

Selection effect caused by environment dependent Lya RT

Suppression in the line-of-sight fluctuation

If the environment dependence of radiative transfer were eliminated
Clustering of LAEs: Model Prediction

An intuitive picture
Clustering of LAEs: 3D Clustering

Anisotropic 3D two-point correlation function of LAEs

Zheng, et al. (2011a)

Radiative Transfer Effect

Zehavi, Zheng, et al. (2011)

Finger-of-God Effect
nonlinear redshift distortion

Kaiser Effect
linear redshift distortion

SDSS Galaxies (continuum selected)

LAEs

Shuffled LAEs

environmental dependence of radiative transfer
New Effect in Galaxy Clustering
(induced by environment-dependent Ly$\alpha$ radiative transfer)

Non-gravitational Distortion

new window to probe the physical conditions in galaxies and surrounding gas

No Coupling
Kaiser effect dominated

Strong Coupling
RT effect dominated
Large Redshift Surveys of LAEs for Cosmological Study from Galaxy Clustering

unique data points from high redshifts accurate distance scales, growth rate, ... constraints on dark energy evolution constraints on gravity theory

important to understand the clustering of LAEs
A Tentative Observational Case from SDSS-III
BOSS Quasar-LAE Cross-Correlation

Croft, Miralda-Escude, ZZ, et al. (1504.04088)
Over the past century, we have unearthed problems in fundamental physics that can only be studied using astronomy. Hubble's first measurements of the relation between velocity and distance of galaxies revealed the expansion of the Universe. Today we know that the expansion is accelerating and is regulated by dark matter and dark energy, which comprise 96% of the Universe's energy density. The Nobel Prize in Physics in 2011 was granted for the definitive discovery in 1998 of this acceleration.

In the last decade, numerous theories have been advanced to explain the accelerated expansion, but its true nature is unknown. The goal of cosmologists is to precisely measure the contents of the Universe and to understand their behavior over time. Doing so requires understanding the onset of the era of dark energy around 6.5–11 billion years ago — the time that dark energy's influence over the Universe's dynamics started to become important.

This challenge motivates us to design a new survey with a larger reach. Its primary goal remains to measure the Hubble Law relating the distances of objects to their recession velocities. More distant objects recede more quickly, and because their light takes longer to reach us, exactly how much more quickly reveals the history of the Universe's expansion. In measuring the Hubble Law, the velocity is easy to determine from Doppler shifts and is quantified as a redshift $z$, ranging from $z \sim 0$ nearby to $z \sim 3$ at a distance of 12 billion light-years away. However, the exact distance is extremely difficult to measure.

SDSS has made fundamental contributions to studying the Hubble Law. Its signature accomplishment in this arena has been to establish the utility of the "Baryon Acoustic Oscillation" (BAO), the most accurate known measurement of absolute cosmological distance. For the first 400,000 years, the Universe was filled with a tightly coupled gas consisting of matter and light. Small perturbations drove pressure waves through this gas. As the Universe expanded, the matter became less dense and more transparent to the light, whereupon these waves stalled. Today, the remnant of these waves produces small features (the BAO) in the very large scale ($\sim 500$ million light-years) clustering of galaxies. The BAO is at a known physical scale, and can be detected in galaxy redshift surveys, so it can be used to measure the absolute physical distance to a particular redshift. Because the physics of the BAO is simple, there are few systematic uncertainties in this measurement, making it the most accurate cosmological distance indicator known to date.

### Future Work

- **SDSS-IV (2014-2020)**
  - Luminous Red Galaxies (LRGs)
  - Emission Line Galaxies (ELGs)
  - Quasars / Quasar Absorption Systems

- **Redshift-Space Distortion Modeling**
  - Cosmological Constraints with Redshift-Space Distortion
Future Work

Lyman-alpha Emitting Galaxies

**HETDEX**

(Hobby-Erberly Telescope Dark Energy Experiment)

$\sim 10^6$ Lyman-alpha Emitting Galaxies at $2 < z < 4$

LAE properties, Clustering, CGM/IGM probe

**Subaru HyperSuprimeCam Survey**

(Wide - 30 deg$^2$; Deep - a few deg$^2$)

$\sim 10,000$ Lyman-alpha Emitting Galaxies at $z > 6$

Reionization study
Summary

• **Redshift-space distortion** *(gravitational distortion)* in galaxy clustering is powerful to constrain the galaxy-halo connection, the phase-space distribution of galaxies inside halos, and the cosmic structure growth rate and fluctuation amplitude.

• Lyman-alpha **radiative transfer** induces **nongravitational distortion** in star-forming galaxy clustering - a new window to learn about physical conditions in galaxies and their surrounding gas, a potential probe for cosmic reionization, an important factor to be included for cosmological applications.