Dark Energy, Large Scale Structure, Cosmological Computing

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Dark Energy

Constraining DE and Modified Gravity w/ Combined Surveys

- Imaging surveys (2D) constrain DE and MG via weak lensing: DES, LSST
- Redshift surveys (3D) constrain DE/MG via Redshift Space Distortions (RSD) and BAO: eBOSS, DESI
- Overlapping 2D and 3D surveys provide stronger constraints
- Quantified these “same sky” benefits
- Optimized spectroscopic target selection from imaging surveys
- Results impact design of cosmic surveys

Kirk, etal 2014, Jouvel, etal 2014 (including Frieman)
Dark Energy

Improving Supernova Constraints on Dark Energy

• Improve & rigorously test (via simulations) method for turning SN light curves into distance estimates
• Control dominant SN distance systematic via improved cross-calibration of SN surveys: JLA combines SDSS-II SN [led by Frieman] and SNLS survey data
• Results in tightest & robust DE constraints to date
• Relieves previous tension with Planck CMB results
• Plan: apply these techniques to DES SN data and develop for LSST

Dark Energy

Improving Galaxy Photometric Redshift Estimates

- Dark Energy constraints from imaging surveys (DES, LSST) rely on galaxy photometric redshifts: $z = f(\text{galaxy color})$
- Calibration of photo-z estimators limited by incomplete spectroscopic training sets
- Photo-z errors dominant source of DE systematics
- Using new, deep spectroscopy to develop improved photo-z estimates
- Developing recent method of angular cross-correlations to improve redshift estimates for DES and LSST

Frieman, Lin, U. Chicago student Helsby
Dark Energy

Weak Lensing: Systematics

- Information in lensing (constraining power) moves to small scales (where it is harder to extract) due to gravity.
- By analyzing the spectrum of the log of the relevant field (convergence $\kappa$), re-capture this “lost” information,
- “Figure of Merit” quantifies information in the 8D parameter space: do a factor of 10 better with the log transform,

Seo, Sato, Takada, & Dodelson 2011
Dark Energy

Gravitational Lensing: Baryonic Effects

• “Baryonic effects” is a major systematic error. They cannot be simulated directly yet with enough precision, need to be mitigated by other means.

• **Adaptive Refinement Tree** (ART) code is the state-of-the-art cosmological hydro code; it can model a wide range of relevant physical processes.

• We use the ART code to explore the “phase space” of baryonic physics (gas cooling, star formation, stellar feedback, etc).

• Plan: complete simulations for all physical limits.
Dark Energy

GravitationaL Lensing: Baryonic Effects

- Baryonic effects bias cosmological constraints.
- Standard method: parameterize and marginalize.
- Novel, Principal Component Analysis (PCA) based method removes almost all of the bias – a significant improvement over the standard method.

Eifler, etal 2014 (including Dodelson, Gnedin)
Dark Energy

Future Probes

- A promising technique for a “Stage V” experiment is 21cm intensity mapping redshift surveys.
- Pathfinder projects are under way: CHIME, Tianlai,…
- New foreground removal techniques have been developed.

Shaw, et al 2014 (including Stebbins)
Dark Energy

WYSIWYG Cosmology

• Developed very simple observational form of space-time geometry.
• Plan: Develop techniques to use proper motions redshift drift to determine curvature w/o assumption.

\[ ds^2 = -c^2 dT^2 + c^2 \left( dT - \frac{dt}{1+z} \right)^2 + (ds - v dt) \cdot (ds - v dt) \]

\[ dT = T dt + \delta_z T dz + \delta_\theta^a T d\theta^a \]

\[ ds \cdot ds = d\theta^a D_{ab} d\theta^b \]

\[ v \cdot ds = \partial^a D_{ab} \partial^b \]

\[ v \cdot v = \partial^a D_{ab} \partial^b \]

Stebbins 2012

t - time of observation
z - measured redshift
\( \theta^a \) - angle on sky
metric variables:
D_{ab} - 2x2 symmetric tensor gives angular diameter distance / shear
\( \theta' \) - proper motions
T - universal time defined by matter flow (related to redshift drift)
Effect of Cosmic Reionization on the CMB

- Cosmic Reionization is an ionized screen in front of the CMB.
- Highlighted by Snowmass working group as one of the few areas of simulation work in which significant progress can be expected in the near term.
- Numerical work has started; bias in cosmological constraints has been investigated.
- Plan: explore reionization constraints on dark matter annihilation, continue numerical work.

Dizgah, et al. 2014 (including Gnedin)
Large Scale Structure

Plan: Constraining Dark Matter with Cosmic Reionization

- Dark Matter models that reproduce the observed gamma-ray emission from the center of our Galaxy also predict sub-dominant, but not negligible contribution to cosmic reionization.
- Using our latest simulations, we can now reliably model that contribution at all cosmic times.
- Plan: explore the effect of DM annihilation on reionization; conversely, constraint DM models from the existing observations of high redshift universe.
Large Scale Structure

Growth of LSS as a Probe of Dark Matter

- The growth of large-scale structure also serves as a probe of the nature of dark matter and dark energy/modified gravity.
- There exist observational hints that the number of relativistic degrees of freedom is different from the canonical value $N_\nu = 3$.
- We explored the properties of decaying dark matter that mimic extra relativistic degrees of freedom, and placed new constraints on them.

*Change in the Hubble constant*

Hooper, et al 2012 (including Gnedin)
Large Scale Structure

Testing Nonlocal Gravity Models

- The Deser-Woodard model of nonlocal gravity is an attractive explanation for the current epoch of acceleration.
- It introduces no new mass scale, while all other modified gravity models introduce a new, tiny mass scale of order the current Hubble parameter.
- Dodelson & Park solved for the evolution of linear perturbations in this model and then compared them to the observational constraints.

GR+DE favored over Nonlocal Models

*Park & Dodelson 2012
Dodelson & Park 2013*
Cosmological Computing

Cosmological Numerical Simulations

- Numerical simulation is a main tool for making cosmological predictions.
- We designed and produced several simulation sets for weak lensing and CMB modeling:
  - Specifically designed to explore extreme limits of baryonic effects
  - Largest volume, multiple independent realizations
  - Publicly available
- Plan: extend existing simulation sets; investigate numerical convergence requirements for each simulated problem.
Cosmological Computing

Organizational Efforts

- Multi-lab national initiative (ANL, FNAL, SLAC, LBL, BNL) since 2011 – Cosmic Frontier Computational Collaboration (CFCC).
- Successful Scientific Discovery with Advanced Computing (SciDAC) Program proposal (2012) [Supports code development, porting, etc]
- Effective collaboration with Fermilab Computing Division.

Virgo Consortium (Germany+UK) [30+ FTE]
Project Horizon (France+Spain) [20+ FTE]
Cosmological Computing

**CosmoSIS: Cosmological Survey Inference System**

- Designed by Theory & Combined Probes Working Group in Dark Energy Survey (Dodelson, co-convener) to help the collaboration work together to extract tightest constrains on dark energy.
- Software Framework empowers multiple users to develop and share code, combine analyses, and produce robust cosmological parameter constraints.
- Already in use in DES, likely to become the community tool for DESI, LSST.
- Use software development expertise of Fermilab Computing Division.
Summary

We do a wide range of scientific work, from pure theory to experiment/theory interface.

- **Dark Energy**: theory/analysis support for DES, weak lensing, Baryonic Acoustic Oscillations, supernovae
- **Large Scale Structure**: numerical simulations for weak lensing and CMB, dark matter constraints
- **Cosmological Computing**: simulation code development and design, modern analysis framework, CFCC has formed