Probabilistic cartography of the large-scale structure

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August 21st, 2015
How did structure appear in the Universe?

A joint problem!

• How did the Universe begin?
  • What are the statistical properties of the initial conditions?
  • Usually these problems are addressed in isolation.
• How did the large-scale structure take shape?
  • What is the physics of dark matter and dark energy?

This talk:
  • A case for physical inference of four-dimensional dynamic states
  • A description of methodology and progress towards enriching the standard for the analysis of galaxy surveys (upcoming, but also existing)

(see talks on eBOSS by Julian Bautista, on SPHEREx by Olivier Doré, on Euclid by Martin Kunz)
**BOR** **G:** *Bayesian Origin Reconstruction from Galaxies*

What if we could just fit the entire survey?

The challenge: \(d \approx 10^7\)!

What makes the problem tractable:

- **Sampler**: Hamiltonian Markov Chain Monte Carlo method
- **Physical model**: Second-order Lagrangian perturbation theory (2LPT) – Gaussian prior – Poisson likelihood

(and also: luminosity-dependent galaxy bias, automatic noise level calibration)

**Observations**

(galaxy catalog + meta-data: selection functions, completeness...)

**Samples of possible 4D states**

Jasche & Wandelt 2013, arXiv:1203.3639
Chrono-Cosmography
BORG at work – chronocosmography

The BORG SDSS run:
463,230 galaxies, ≈ 17 millions parameters, 12,000 samples, 3 TB, 10 months on 32 cores

Jasche, FL & Wandelt 2015, arXiv:1409.6308
Bayesian chronocosmography from SDSS DR7

Data

Jasche, FL & Wandelt 2015, arXiv:1409.6308
Bayesian chronocosmography from SDSS DR7

Jasche, FL & Wandelt 2015, arXiv:1409.6308
Bayesian chronocosmography from SDSS DR7

Jasche, FL & Wandelt 2015, arXiv:1409.6308

Posterior mean (initial conditions)

Posterior mean (final conditions)
Uncertainty quantification is crucial!
Can we propagate uncertainties to other physical quantities or observables?

Two examples: cosmic web classification and CMB secondary effects.
HOW IS THE COSMIC WEB WOVEN?
Cosmic web classification procedures

• **The T-web**: uses the sign of $\mu_1, \mu_2, \mu_3$: eigenvalues of the tidal field tensor, Hessian of the gravitational potential:

$$T_{ij}(x) = \partial_i \partial_j \Phi(x)$$

**Hahn et al. 2007, arXiv:astro-ph/0610280**

• **DIVA**: uses the sign of $\lambda_1, \lambda_2, \lambda_3$: eigenvalues of the shear of the Lagrangian displacement field:

$$R_{\ell m}(q) = \partial_m \Psi_\ell(q)$$

**Lavaux & Wandelt 2010, arXiv:0906.4101**

• **ORIGAMI**: uses the dark matter “phase-space sheet” (number of orthogonal axes along which there is shell-crossing)

**Falck, Neyrinck & Szalay 2012, arXiv:1201.2353**

Lagrangian classifiers now usable in real data!
T-web structures inferred by BORG

Final conditions

FL, Jasche & Wandelt 2015, arXiv:1502.02690
T-web structures inferred by BORG

Initial conditions

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FL, Jasche & Wandelt 2015, arXiv:1502.02690
Comparing classifiers and making a decision

FL, Jasche, Lavaux & Wandelt, in prep.  (comparing classifiers, with quantitative arguments using information gain)

FL, Jasche & Wandelt 2015, arXiv:1503.00730  (selecting structures via Bayesian decision theory)
TEMPLATES FOR CMB SECONDARY EFFECTS
Producing LSS-CMB observables

2M++ catalog
Lavaux & Hudson 2011, arXiv:1105.6107, Lavaux & Jasche 2015, submitted

Initial conditions from BORG

Resimulations with COLA
Tassev, Zaldarriaga & Eisenstein, arXiv:1301.0322

Constrained realizations with hard-to-compute non-linear dynamics

Gravitational potential
Integrated Sachs-Wolfe (iSW) and Rees-Sciama (RS) effects

Momentum field
kinetic Sunyaev-Zel’dovich (kSZ) effect

Gas profiles in clusters
thermal Sunyaev-Zel’dovich (tSZ) effect

Raytracing algorithm
Cai et al. 2010, arXiv:1003.0974

kSZ/tSZ model
Lavaux, Afshordi & Hudson 2012, arXiv:1207.1721

Better modeling yields higher Signal/Noise ratio

Cai et al. 2010, arXiv:1003.0974
Lavaux, Afshordi & Hudson 2012, arXiv:1207.1721
Lavaux & Jasche 2015, submitted
Templates for secondary effects in the CMB

with G. Lavaux, J. Jasche, B. Wandelt

kSZ

iSW

iSWRS

Only non-linear effects (iSWRS – iSW)

• Simulations in ONE BORG sample, raytraced from 0 to 100 Mpc/h
• The full posterior is available for Hierarchichal Bayesian analysis
Summary & Conclusions

• A new method for the analysis of galaxy surveys: Bayesian large-scale structure inference
  • Uncertainty quantification (noise, survey geometry, selection effects and biases)
  • Non-linear and non-Gaussian inference with improving techniques

• Application to data: four-dimensional chronocosmography
  • Simultaneous analysis of the morphology and formation history of the large-scale structure
  • Physical reconstruction of the initial conditions
  • Characterization of the dynamic cosmic web underlying galaxies
  • Cross-correlation of galaxy surveys and CMB data through kSZ/iSW/RS effects

PhD defense on Thursday, September 24th in the IAP amphitheater – Much more about all these ideas – There will be champagne – Everybody is welcome!