Title: Prospects for CMB lensing-galaxy clustering cross-correlations and initial condition reconstruction

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Abstract: The lensing convergence measurable with future CMB experiments will be highly correlated with the clustering of galaxies that will be observed by imaging surveys such as LSST. I will discuss prospects for using that cross-correlation signal to constrain local primordial non-Gaussianity, the amplitude of matter fluctuations as a function of redshift, halo bias, and possibly the sum of neutrino masses. A key limitation for such analyses and large-scale structure analyses in general is that the mapping from initial conditions to observables is nonlinear for wavenumbers $k > 0.1 h/\text{Mpc}$. This can destroy cosmological information or move it to non-Gaussian tails of the probability distribution that are difficult to measure. I will describe how we can use recently developed initial condition reconstruction methods to help us recover some of that information in the nonlinear regime.
Prospects for
CMB lensing-galaxy clustering cross-correlations
& initial condition reconstruction

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With Tobias Baldauf, Uros Seljak, and Matias Zaldarriaga

Perimeter, April 24th 2018
CMB lensing

Oldest light we can observe: CMB

deflected by dark matter

Image credit: ESA
Lensed CMB

\[ T(\hat{n})_{\text{lensed}} = T(\hat{n} + d(\hat{n}))_{\text{unlensed}} \]

Slide credit: Blake Sherwin
Many unlensed patches

Image credit: cosmoplat.org
Many unlensed patches

Image credit: cosmoplot.org, ESA/Planck
Many unlensed patches

Local power spectrum

Local power spectrum

Local power spectrum is the same in each patch
Many lensed patches

Acoustic peaks of global power are smeared out
Many lensed patches

Local power spectrum

Local power spectrum

Local power is magnified or de-magnified
Many lensed patches

Acoustic peaks of global power are smeared out

Global power spectrum

Image credit: Smidt+ (2010)
Many lensed patches

Acoustic peaks of global power are smeared out

Global power spectrum

Image credit: Smidt+ (2010)
First detection: X-correl with galaxies

WMAP CMB lensing X NVSS galaxies

$\Delta^2 C_{l}^{\phi}$

Fiducial

Smith, Zahn & Doré (2007); Hirata, Ho et al. (2008)
Now these are $\sim$20-sigma signals

Planck CMB lensing X \{NVSS, MaxBCG, SDSS, WISE\}

**Fig. 17.** Cross-spectra of the *Planck* MV lensing potential with several galaxy catalogs, scaled by the signal-to-noise weighting factor $A^n_{\nu}$ defined in Eq. (52). Cross-correlations are detected at approximately 20$\sigma$ significance for the NVSS quasar catalog, 10$\sigma$ for SDSS LRGs, and 7$\sigma$ for both MaxBCG and WISE.
Future

CMB lensing maps will soon be signal-dominated (e.g. Simons Observatory & CMB-S4)

Galaxy surveys collect more galaxies at high redshift (e.g. DESI, Euclid & LSST)

=> Expect large cross-correlation signal
What can we learn?

Matter amplitude \( \sigma_8(z) \)

Expansion history / dark energy

Sum of neutrino masses

Primordial non-Gaussianity / inflation

Galaxy bias and galaxy formation

More?
The future is bright

CMB lensing
AdvACT
SPT-3G
Simons Observatory
CMB-S4

Galaxies
eBOSS
DESI
Hyper Suprime-Cam
HETDEX
Euclid
LSST
WFIRST
SPHEREx?
The future is bright

CMB lensing
AdvACT
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CMB-S4

Galaxies
eBOSS
DESI
Hyper Suprime-Cam
HETDEX
Euclid
LSST
WFIRST
SPHEREx
A forecast for CMB-S4 X LSST

Driving question:

If our models all work and we can mitigate all systematics, and if CMB-S4 and LSST will deliver, what can we hope for?
LSST number density

Following Gorecki et al. (2014), adding z>4 dropouts; MS & Seljak 1710.09465
Correlation of CMB lensing and galaxies

CMB lensing and galaxy maps are up to 95% correlated

\[ r_\ell = \frac{C^{\kappa g}_\ell}{\sqrt{C^{\kappa \kappa}_\ell C^{gg}_\ell}} \]
May cancel cosmic variance

\[ \frac{\hat{C}_\ell}{C_{\ell}^{\text{ref}}} \]

\( f_{NL} = 0 \)

Galaxies

CMB lensing

\( f_{NL} = 1 \)

Dalal+ (2008), Seljak (2009), McDonald & Seljak (2009), MS & Seljak 1710.09465
May cancel cosmic variance

Ratio galaxies / CMB lensing has no cosmic variance if the two are perfectly correlated \((r=1)\)

SNR per mode is

\[
[\text{SNR}(f_{NL})]^2 \approx \frac{2 - r_{\ell}^2}{1 - r_{\ell}^2} \left( \frac{\partial \ln C_{\ell}^{kg}}{\partial f_{NL}} \right)^2
\]

\[
\propto \frac{1}{1 - r_{\ell}^2} \quad \text{for} \quad r \to 1
\]

Seljak (2009), McDonald & Seljak (2009), MS & Seljak 1710.09465
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Ratio galaxies / CMB lensing has no cosmic variance if the two are perfectly correlated ($r=1$)

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$$\propto \frac{1}{1 - r_{\ell}^2} \quad \text{for } r \to 1$$
Power spectra: CMB-S4 & LSST

Low ell: $C_{\ell}^{XX'} = \frac{2}{n} \int_0^\infty \frac{dk}{k} \Delta_{X,k}(k) \Delta_{X',k}(k) k^3 P_{\delta_X \delta_X}(k, z = 0)$.

High ell: $C_{\ell}^{XX'} = \int_0^\infty P_{\delta_X \delta_X}(k = \ell/\chi(z), z) \times W_X(z) b_X(z) W_{X'}(z) b_{X'}(z)$. 
### SNR of auto-power spectra

<table>
<thead>
<tr>
<th>SNR of $C^{XX}$</th>
<th>$\ell_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$$\kappa_{\text{CMB}}$$</td>
<td>233</td>
</tr>
<tr>
<td>BOSS LRG $z=0.0-0.9$</td>
<td>140 187 230</td>
</tr>
<tr>
<td>SDSS $r &lt; 22$ $z=0.0.5$</td>
<td>247 487 936</td>
</tr>
<tr>
<td>SDSS $r &lt; 22$ $z=0.5-0.8$</td>
<td>247 487 936</td>
</tr>
<tr>
<td>DESI BGS $z=0.0.5$</td>
<td>230 417 665</td>
</tr>
<tr>
<td>DESI ELG $z=0.6-0.8$</td>
<td>158 210 256</td>
</tr>
<tr>
<td>DESI ELG $z=0.8-1.7$</td>
<td>150 194 225</td>
</tr>
<tr>
<td>DESI LRG $z=0.6-1.2$</td>
<td>184 267 349</td>
</tr>
<tr>
<td>DESI QSO $z=0.6-1.9$</td>
<td>44.8 48.8 50.8</td>
</tr>
<tr>
<td>LSST $i &lt; 27$ (3yr) $z=0.0-0.5$</td>
<td>250 496 982</td>
</tr>
<tr>
<td>LSST $i &lt; 27$ (3yr) $z=0.5-1$</td>
<td>250 496 979</td>
</tr>
<tr>
<td>LSST $i &lt; 27$ (3yr) $z=1-2$</td>
<td>249 492 956</td>
</tr>
<tr>
<td>LSST $i &lt; 27$ (3yr) $z=2-3$</td>
<td>245 469 830</td>
</tr>
<tr>
<td>LSST $i &lt; 27$ (3yr) $z=3-4$</td>
<td>239 444 724</td>
</tr>
<tr>
<td>LSST $i &lt; 27$ (3yr) $z=4-7$</td>
<td>224 387 555</td>
</tr>
</tbody>
</table>
Fisher analysis setup

Include all kk, kg, gg power spectra \( d_\ell = (C_{\ell}^{11}, C_{\ell}^{12}, \ldots, C_{\ell}^{N,N}) \)

For Gaussian covariance, different ell are uncorrelated, so Fisher matrix is

\[
F_{ab} = \sum_{\ell=\ell_{\text{min}}}^{\ell_{\text{max}}} \frac{\partial d_\ell}{\partial \theta_a} [\text{cov}(d_\ell, d_\ell)]^{-1} \frac{\partial d_\ell}{\partial \theta_b}.
\]

\( N \times N \) matrix at every ell
Prospects for local $f_{NL}$

- dashed: no sky overlap, $f_{sky} = 0.5$, $\ell_{max} = 500$, no Limber

Graph showing the relationship between $\sigma(f_{NL})$ and $\ell_{min}$.

Excluded by Planck

Multi-field inflation

Single-field inflation

- $\kappa_{S4}$+SDSS+DESI
- +LSST $i < 25$, $z < 4$
- +LSST $i < 27$, $3yr$, $z < 4$
- +LSST $i < 27$, $3yr$, $z < 7$

Dalal+ (2008), Jeong, Komatsu & Jain (2009), Ginnantonio & Percival (2014), MS & Seljak 1710.09465
Prospects for local $f_{\text{NL}}$

$S4 + \text{LSST}$ is sensitive to $f_{\text{NL}}=0.4 \ (L_{\text{min}}=2) - f_{\text{NL}}=1 \ (L_{\text{min}}=20)$

Without CMB lensing, degrade by factor 10-20

Without sky-overlap, degrade by factor 1.5-2 (SV cancellation)

Without low-L $C_{gg}$, degrade by factor 2-3

Without $z>4$ dropout galaxies, degrade by factor 2

MS & Seljak 1710.09465
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MS & Seljak 1710.09465
Challenges for local $f_{NL}$

Need to measure CMB lensing and galaxy clustering on large scales ($L<20$)

Star contamination affects low-$L$ $gg$, potentially mimicking $f_{NL}$
- Not relevant when just getting upper bound on $f_{NL}$
- Know direction of our galaxy so could project out modes as in Leistedt et al. (2014)
- Even without low-$L$ $gg$, $f_{NL}=1$ is possible

Catastrophic redshift errors
- Hope to calibrate using spec-z surveys
- If global $dn/dz$ known, data can determine outlier fraction so that catastrophic errors don’t degrade $f_{NL}$
Challenges for local $f_{\text{NL}}$

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Catastrophic redshift errors
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don’t degrade $f_{\text{NL}}$
Prospects for matter amplitude $\sigma_8(z)$

\[
\begin{align*}
C^{KK} &\propto \sigma_8^2 \\
C^{Kg} &\propto b_1 \sigma_8^2 \\
C^{gg} &\propto b_1^2 \sigma_8^2
\end{align*}
\]
Prospects for $\sigma_8(z)$

Marginalize over one linear bias parameter per redshift bin; fixed cosmology; halofit $P_{mm}(k,z)$; $f_{sky}=0.5$ for CMB-S4 & LSST

MS & Seljak 1710.09465, see Modi+ (2017) for impact of nonlinear bias
Challenges for $\sigma_8(z)$

- Nonlinear halo bias $b_2, b_{s2}$  
  \[ \text{Modi, White & Vlah (2017)} \]
  \[ \rightarrow \text{Hope for priors from theory, sims, and 3PCF/bispectrum} \]

- Modeling all power spectra to high $L_{\text{max}}$
Conclusions: Part I

CMB-S4 lensing X LSST clustering very promising for measuring primordial non-Gaussianity and growth of structure

Joint analysis is crucial (factor 10 improvement)

For $f_{\text{NL}}$, need rather low $L_{\text{min}}$ and large $f_{\text{sky}}$

Growth measurement is limited by modeling small, nonlinear scales
-> Part II of the talk

Stay tuned for Simons Observatory forecasts
Part II
Initial condition reconstruction
Acoustic scale is also imprinted in galaxies: BAO

Galaxies more likely separated by 150 rather than 140 or 160 Mpc

\[
\text{Distance} \sim \frac{150 \text{ Mpc}}{\text{angle}} \sim \int_0^z \frac{dz'}{H(z')}
\]

This measures Hubble parameter (=expansion rate)
Acoustic scale is also imprinted in galaxies: BAO

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Distance \sim \frac{150 \text{ Mpc}}{\text{angle}} \sim \int_0^z \frac{dz'}{H(z')}

This measures Hubble parameter (=expansion rate)
Preferred clustering at separation of 150 Mpc

How many galaxies...

... separated by 150 Mpc

Anderson+ (2013) / Sloan Digital Sky Survey
BAO scale is set in the early (linear) Universe

- Hot sea of baryons & photons
- Driven by photon pressure

- Electrons cool,
  form hydrogen,
  decouple from photons,
  & remain in place

---

Big bang
[-13.8bn yrs]

Decoupling
[-13.7996bn yrs]

Sound wave travels 150 Mpc:
Baryon-acoustic-oscillation (BAO) scale
At early times, acoustic scale is the same everywhere

Padmanabhan++ (2012)
Displacements on ~10-150 Mpc modulate this

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Padmanabhan++ (2012)
Reduce nonlinear dynamics with reconstruction

Estimate potentials and move galaxies back

Eisenstein++ (2007)

Padmanabhan++ (2012)
Reconstruction works great in practice

For BOSS DR11 data, signal-to-noise of the distance scale improved by 50%, achieving sub-percent level precision

Nonlinear dynamics: What can we do?

1. Better analytical models
2. Simulate it all and infer cosmology
3. Transform data to reduce nonlinear dynamics
4. Exploit non-Gaussian tails of galaxy distribution
Paradigm 1: Backward reconstruction
Estimate velocities, move galaxies back
Paradigm 1: Backward reconstruction
Estimate velocities, move galaxies back

Paradigm 2: Forward model & sample
Sample ICs, evolve forward, compare vs observations, iterate

Eisenstein, Padmanabhan, Pen+group, Tassev, Zaldarriaga, MS, ...

Jasche, Wandelt, Leclercq, Kitaura, ...

Paradigm 1: Backward reconstruction
Estimate velocities, move galaxies back

Paradigm 2: Forward model & sample
Sample ICs, evolve forward, compare vs observations, iterate

Paradigm 3: Forward model & optimize
Maximum-likelihood solution by solving optimization problem
Paradigm 1: Backward reconstruction
Estimate velocities, move galaxies back

Paradigm 2: Forward model & sample
Sample ICs, evolve forward, compare vs observations, iterate
What nonlinearities are we fighting?

Initial

Final
(1) Displacement field is a nonlinear functional of the linear initial density

\[ \psi(k) = \frac{k}{k^2} \delta_0(k) \]

\[ + \int_{k_1} L^{(2)}(k_1, k - k_1) \delta_0(k_1) \delta_0(k - k_1) \]

\[ + \ldots \]
(1) Displacement field is a nonlinear functional of the linear initial density

- Nonlinear terms are small, so displacement is quite linear
- Perturbative modeling works well

e.g. Baldauf+ (2016)
(2) Shell crossing: Trajectories cross each other

- Strongly nonlinear & difficult to model
- Seems like we cannot tell initial from final position (How many crossings happened?)
- Expect to lose memory of initial conditions
Standard reconstruction

Final

 Undo 1st order (Zeldovich) displacement by estimating the potential of the particle distribution

Eisenstein, Seo, Sirko & Spergel (2007)
Alternatively: Estimate displacement if there was no shell crossing

- This displacement is pretty linear, so can estimate linear density as

\[ \delta_{\text{lin}} = \nabla \cdot \chi \]
Algorithm 1: Isobaric/nonlinear reconstruction

Get $\chi$ by continuously distorting mesh until $\delta=0$
using a moving mesh code

Several more papers with X. Wang, Q. Pan & D. Inman (2017)
Algorithm 2: Iterative reconstruction

Same idea, but get displacement by iteratively applying Zeldovich displacements

Start with large smoothing scale to achieve coherence on large scales; then decrease smoothing scale in iteration

MS, Baldauf & Zaldarriaga (2017)
MS, Baldauf & Zaldarriaga (2017)

2D slices of 3D density smoothed with R=2 Mpc/h Gaussian
1% subsample of 2048$^3$ DM particles in 500 Mpc/h per-side box
MS, Baldauf & Zaldarriaga (2017)

2D slices of 3D density smoothed with R=2 Mpc/h Gaussian
1% subsample of 2048³ DM particles in 500 Mpc/h per-side box

1st order reconstruction
Initial conditions

Reconstructed, 5 steps

MS, Baldauf & Zaldarriaga (2017)

2D slices of 3D density smoothed with R=2 Mpc/h Gaussian
1% subsample of 2048³ DM particles in 500 Mpc/h per-side box

1st order reconstruction
Correlation coefficient with initial conditions

Perfect correl.

Correlation with initial conditions

Observed nonlinear

No correl.

Large scales

Small scales

$k [h/\text{Mpc}]$

MS, Baldauf, Zaldarriaga (2017): noise-free 4096$^3$ DM simulations at $z=0.6$; also see Zhu+ (2017)
Correlation coefficient with initial conditions

- **Perfect correl.**
- **No correl.**

**Correlation with initial conditions**

- **Observed nonlinear**
- **Standard reconstruction**

Large scales | Small scales

MS. Baldauf, Zaldarriaga (2017): noise-free $4096^3$ DM simulations at $z=0.6$; also see Zhu+ (2017)
Correlation coefficient with initial conditions

- Perfect correl.
- New reconstruction
- Standard reconstruction

Observed nonlinear

Correlation with initial conditions

Large scales

Small scales

$k \ [h/\text{Mpc}]$

MS. Baldauf, Zaldarriaga (2017): noise-free $4096^3$ DM simulations at $z=0.6$; also see Zhu+ (2017)
Size of fractional mistake (relative to linear)

Error / signal power

$k [h\text{Mpc}^{-1}]$

$z = 0.6$

Final conditions
Standard rec
New $\mathcal{O}(1)$ rec
New $\mathcal{O}(2)$ rec

MS, Baldauf, Zaldarriaga (2017)
BAO signal

Fractional BAO signal [%]

\[ k \ [h \text{Mpc}] \]

\[ z = 0 \]

MS, Baldauf, Zaldarriaga (2017); also see Wang, Yu, Zhu, Yu, Pan & Pen (2017)
Best-fit BAO scale in 10 simulations

MS, Baldauf, Zaldarriaga (2017); also see Wang, Yu, Zhu, Yu, Pan & Pen (2017)
Broadband power spectrum

Initial conditions
Final conditions
\mathcal{O}(1) \text{ rec}
\bar{t}_1(k) \times \mathcal{O}(1) \text{ rec}
\mathcal{O}(2) \text{ rec}

\frac{\hat{P}}{P_{\text{init}}}

k \ [h\text{Mpc}^{-1}]

z = 0

MS, Baldauf, Zaldarriaga (2017); also see Pan, Pen, Inman & Yu (2017)
Fractional error bar of BAO scale

$V = 2.6 \, h^{-3} \text{Gpc}^3$, $z = 0$

- Initial conditions
- Final conditions
- New $O(1)$ rec
- New $O(2)$ rec
- Standard rec

$\sigma(\hat{r}_{\text{BAO}})/r_{\text{BAO}}$

$k_{\text{max}}^{\text{fit}} \, [h \text{Mpc}^{-1}]$

MS, Baldauf, Zaldarriaga (2017); also see Wang, Yu, Zhu, Yu, Pan & Pen (2017)
Broadband power spectrum

\[ \frac{\tilde{P}}{P_{\text{init}}} \]

\( k \ [h\text{Mpc}^{-1}] \)

- Initial conditions
- Final conditions
- \( \mathcal{O}(1) \) rec
- \( t_1(k) \times \mathcal{O}(1) \) rec
- \( \mathcal{O}(2) \) rec

MS, Baldauf, Zaldarriaga (2017); also see Pan, Pen, Inman & Yu (2017)
Challenges

Add realism:

- Shot noise
- Halo/galaxy bias (doing right now)
- Redshift space distortions
- Survey mask & depth variation (inhomogeneous noise)
- What happens to primordial $f_{\text{NL}}$ after reconstruction?
Conclusions: Part II

Nonlinear physics limits science return of galaxy surveys

Reconstruction can reduce that degradation

At z=0, reconstruction achieves >95% correlation with linear density at $k<0.35 \, h\text{Mpc}^{-1}$

Improve BAO signal-to-noise by factor 2.7 ($z=0$) to 2.5 ($z=0.6$)

70%-30% improvement over standard BAO reconstruction

Can improve LSS survey science (dark energy, Hubble constant, early universe physics)