Cross-correlations of CMB lensing as tools for cosmology and astrophysics

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Dark matter, large scales

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- ...starting from initial conditions consistent with CMB.

[Kravtsov, 2005]
Dark matter, large scales

- Structure forms through gravitational collapse...
- ... starting from initial conditions consistent with CMB.
- Simulations results are consistent with observational evidence from LSS surveys on large scales.
- We look at the universe through an inhomogeneous medium.

[Springel et al., 2005]
Dark matter, large scales

- Being dark, we cannot “see” DM.

- Two ways to probe its distribution in the universe:
  - Using “tracers”: intuitively, overdensities in the DM field should be matched by overdensities in other “visible” stuff
    - Galaxies, quasars and clusters
    - Neutral Hydrogen (Lyman-α, 21cm)
    - CMB temperature
  - Measuring the distortion of images by the DM grav. field.

- Different tracers allow to probe the DM field on different scales.

- Different tracers are “biased” in different ways.
CMB lensing correlations in brief

- The CMB convergence field depends only on the distribution of dark matter integrated along the los, all the way to the last scattering surface.
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- The ugly: **high resolution** CMB experiments are required to measure it.
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- Cross-correlations of CMB lensing with other tracers of the density field allows to extract two kinds of informations:
  - **Astrophysical** information: since we’re directly correlating a biased tracer with what it is supposed to trace, we can put constraints on the biasing relation.
  - **Cosmological** information: since both observables are sensitive to cosmological parameters.
- Applications: Lyman-α forest and 21-cm emission from neutral hydrogen...
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- Applications: Lyman-α forest and 21-cm emission from neutral hydrogen... from a theorist point of view!
Cross-correlation of CMB lensing and the Lyman-α forest
Lyman-\(\alpha\) forest and CMB lensing cross-correlation

- Quasar emits light which, as it travels through the universe, is redshifted.
- Whenever light travels through a gas cloud, a fraction of it (that at the cloud’s redshift has the appropriate frequency) is scattered through Lyman-\(\alpha\) transition in neutral hydrogen.
- The quasar spectra is then characterized by a “forest” of “absorption” lines.
- The forest is a map of neutral H along the los.
- Understanding the forest requires understanding and modeling the physics of the IGM.
- Fluctuations in the flux are related to overdensities
  \[ \mathcal{F} = \exp \left[ -A(1 + \delta)^\beta \right] \]
- On large scales (> 1 Mpc) the Lyman-\(\alpha\) forest can be used as a dark matter tracer [Viel et al. 2001]
  \[ \delta_{\text{IGM}} \approx \delta \]
- The flux-matter relation has many sources of uncertainty.

\[ \delta \mathcal{F}(\bar{n}) = \int_{\chi_i}^{\chi_q} d\chi \delta \mathcal{F}(\bar{n}, \chi) \approx \int_{\chi_i}^{\chi_q} d\chi (-A\beta)^r \delta^r(\bar{n}, \chi) \]
Lyman-α forest and CMB lensing cross-correlation

- Weak lensing depends to the distribution of matter between the observer and the source.
- Quadratic optimal estimators allow the reconstruction of the CMB lensing convergence field [Hu and Okamoto (2000), Hirata and Seljak (2003)].

\[
\kappa(\hat{n}, \chi_F) = \frac{3H_0^2\Omega_m}{2c^2} \int_0^{\chi_F} d\chi \, W_L(\chi, \chi_F) \frac{\delta(\hat{n}, \chi)}{a(\chi)}
\]

Original vs reconstructed deflection field  [Hirata and Seljak, 2003]
Physical meaning of the observables

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• Sensitive to mode coupling: the enhanced growth of structure in overdense regions [Zaldarriaga, Seljak, Hui, 2001].
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It is “just” a matter of evaluating a couple of integrals...

\[
\langle \delta F^r (\hat{n}) \kappa (\hat{n}) \rangle = \frac{3 H_0^2 \Omega_m}{2c^2} \int_0^{\chi_F} d\chi_c \frac{W_L(\chi_c, \chi_F)}{a(\chi_c)} \int_{\chi_i}^{\chi_Q} d\chi_q (-A\beta)^r \langle \delta^r (\hat{n}, \chi_q) \delta (\hat{n}, \chi_c) \rangle
\]
“Just” a couple of integrals...

- Things become complicated when we take into account the finite resolution of the observational programs.

- The nature of the observables naturally breaks the spherical symmetry of the problem.

\[
W_\alpha = \exp \left[ -\frac{k_\parallel^2}{k_\perp^2} \right]
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W_\kappa = \exp \left[ -\frac{k_\perp^2}{k_\parallel^2} \right]
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A clever series solution yielding an efficient numerical computation scheme can actually be found for both the correlators and their variance.

\[
W_\alpha = \exp \left[ -\frac{k^2_{\parallel}}{k^2_L} \right]
\]

\[
W_\kappa = \exp \left[ -\frac{\vec{k}^2_{\perp}}{k^2_C} \right]
\]
Results: correlators (BOSS+Planck)

- Turn off IGM physics ($A=\beta=1$)
- $k_L = 4.8 \, h \, \text{Mpc}^{-1}$ (SDSS-III), $k_C = 0.021 \, h \, \text{Mpc}^{-1}$ (Planck)
- Signal decreases with increasing $z$: probing less collapsed regions
- Signal for $\langle \delta F \kappa \rangle$ is smaller than the one for $\langle \delta F^2 \kappa \rangle$.

[AV, Das, Spergel, Viel, 2009]
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Results: detectability (BOSS+Planck)

- S/N for single line-of-sight. $1.6 \cdot 10^5$ los for Boss, $\sim 10^6$ los for BigBoss.
- Estimates for total S/N are $\sim 30$ (75) for $\langle \delta F \kappa \rangle$ and $\sim 9.6$ (24) for $\langle \delta F^2 \kappa \rangle$ when Planck dataset is xcorrelated with Boss (BigBoss).
- The growth of structure enters twice for $\langle \delta F^2 \kappa \rangle$: once for the long-wavelengths and once for the short wavelengths. The variance is dominated by long wavelengths only.

[AV, Das, Spergel, Viel, 2009]
Results: detectability (BOSS+ActPol)

- S/N for single line-of-sight. $1.6 \cdot 10^5$ los for Boss, $\sim 10^6$ los for BigBoss.
- Estimates for total S/N are $\sim 50 (130)$ for $\langle \delta F_\kappa \rangle$ and $\sim 20 (50)$ for $\langle \delta F^2_\kappa \rangle$ when ActPol dataset is xcorrelated with Boss (BigBoss).
- S/N does not depend on the redshift evolution of $A$ and $\beta$.
Caveats

• **Numerical** results currently do not take into account non-linear effects due to gravitational collapse

• Extension is straightforward

• Signal is expected to increase, S/N is hard to say.

• **All** results do not take into account small scales (<1 Mpc) IGM physics and use “gaussian approximation” to evaluate the correlators’ variance
Cosmological application: neutrino masses

\[ \langle \delta F^2 \kappa \rangle \] is sensitive to intermediate to small scales and to the power spectrum normalization \( \sigma_8 \).
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$\sum m_\nu$ and $\sigma_8$ are not independent if they are to be consistent with CMB measurements.

[Komatsu et al., 2008]
Cosmological application: neutrino masses

\[ \langle \delta F^2 \kappa \rangle \] is sensitive to intermediate to small scales and to the power spectrum normalization \( \sigma_8 \).

\[ \sum m_\nu \text{ and } \sigma_8 \text{ are not independent if they are to be consistent with CMB measurements.} \]

We can use \( \langle \delta F^2 \kappa \rangle \) to put limits on the neutrino mass.

[Komatsu et al., 2008]
Cosmological application: neutrino masses

- **Caveat**: non-linear effects due to gravitational collapse need to be taken into account.

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[AV, Viel, Das, Spergel, 2010]
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Bottom line

- The xcorrelation between the Lyman-α forest and the CMB lensing convergence will be detectable with very near future data sets (Planck + BOSS).
- It allows to probe:
  - How well Lyman-α flux traces dark matter
  - Growth of structure at the Lyman-α redshifts
  - Matter power spectrum on intermediate-to-small scales
  - Scale dependent modifications of gravity
- Numerical simulations will be crucial for a better understanding (in progress at LANL).
Cross-correlation of CMB lensing and 21-cm radiation field from HI
Fun facts about 21-cm

• 21-cm radiation is emitted from the hyperfine transition of neutral hydrogen ground state.

• Up until reionization (z~10), hydrogen remains neutral (HI). UV background from star forming galaxies ionizes most of the HI between z~10 and z~6.

• Reionization is complicated astrophysical process. Most 21-cm experiments (GMRT, PAPER, LoFAR, MWA) target epoch of reionization.

• At low redshift (z ≤ 6) HI survives only in low density lyman-α absorbers and self shielded damped lyman-α systems.

• On large enough scales (~10 Mpc) it is still reasonable to assume that HI traces the DM overdensity field.

• Frequency dependence of the foregrounds should allow their subtraction like in the CMB case.
Large scales 21 cm surveys

- 21-cm intensity mapping survey at low redshift \((z=0-4)\) using a packed rectangular CRT array allows to image the large scale structure of the universe at low cost (and low resolution).

[Seo et al., 2009]
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- Cheap/competitive way to do dark energy measurements through BAO [Chang et al., 2008; Seo et al., 2009].
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- Intensity mapping technique has been recently applied using the GBT [Chang et al., Nature 2010].
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Very high future potential!

[Seo et al., 2009]
Large scales HI bias evolution

- With a prescription to evolve the HI mass function, we have been able to bracket the HI bias evolution.
- The (poorly measured) evolution of $\Omega_{HI}(z)$. We consider three limiting cases (A, B, C).
- Two limiting ways of assigning the total HI to halos:
  - Fix the number density (PME)
  - Fix the halo mass (PNE).
- Agrees reasonably well with measurements carried out on simulations.
- How to measure it? Cross-correlate with CMB lensing!

[Marin, Gnedin, Seo, AV, 2009]
CMB lensing and 21-cm

- Theoretical prediction of the correlation and its variance are similar to the Lyman-\(\alpha\) forest case. However, the resolution of the 21-cm experiment varies with redshift.

- Just need to evaluate this correlator and its variance...

\[
\langle \kappa(\bar{n})\delta_T(\bar{n}) \rangle = \frac{3H_0^2\Omega_m}{2c^2} g_{10} \int_0^{\chi_{\text{LSS}}} \frac{d\chi_c}{a(\chi_c)} W_L(\chi, \chi_{\text{LSS}}) \int_{\chi_i}^{\chi_f} d\chi_H \langle \delta(\bar{n}, \chi_c)\delta(\bar{n}, \chi_H) \rangle
\]
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- Theoretical prediction of the correlation and its variance are similar to the Lyman-α forest case. However, the resolution of the 21-cm experiment varies with redshift.

- Assume fiducial CRT design as in Seo et al., 2009 for the radio telescope.

- Aim: measuring the redshift evolution of large scale HI bias. For this I calculate the S/N for redshift slices of thickness $\Delta z$.

- Total S/N benefits from the large number of pixels.

[Vallinotto, 2011, in prep.]
Conclusions

- CMB lensing is the cleanest (albeit integrated) probe of the DM density field.
- X-correlations with density field tracers are expected to yield observable results.
- As probes of the DM density field, these x-correlations yield cosmological results.
- As probes of the biasing relation of the DM tracers, these x-correlations produce relevant astrophysical information.