Cosmology with CMB lensing-galaxy cross-correlations

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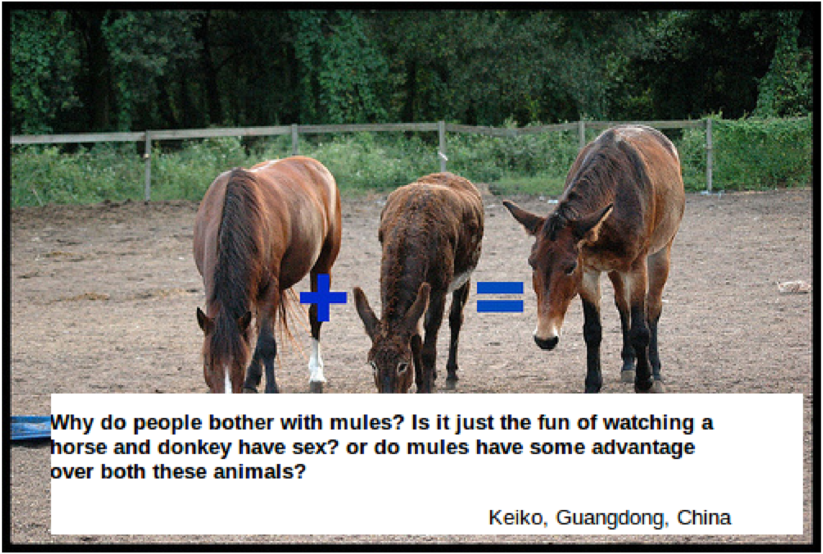
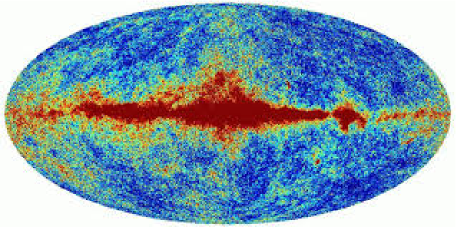
Why bother with mules?



Current situation

Precision cosmology data from CMB and large-scale structure (LSS):

CMB (Horse)



- Probes linear/quasilinear scales
- Systematics: astrophysical and instrumental
- Cannot do tomography

LSS (Donkey)

- Probes out to very small scales
- Systematics: photo-z, baryonic effects, intrinsic alignment...
- Can do tomography

Need

Q: **What do we want?**

A: We want a new offspring from CMB and LSS data which can:

- Beat systematics
- Construct new estimators $\rightarrow$ additional constraining power
- Enhance low amplitude signals $\rightarrow$ optimise use of data
- Probe interesting physics (fundamental and non)

Solution: cross-correlations

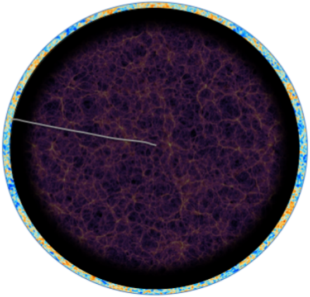
CMB (Horse) $\times$ LSS tracer (Donkey) =

[Primary CMB + Secondary CMB (lensing, kSZ, tSZ) + Foregrounds (CIB, galaxy) + Noise] $\times$ LSS tracer (Mule)

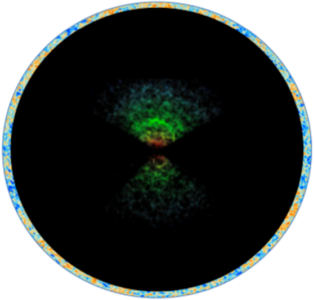
- Different datasets $\rightarrow$ different/uncorrelated systematics
- Both related to gravitational potential $\rightarrow$ probe density perturbations
- Can construct several new estimators which probe a lot of interesting physics

Solution: cross-correlations!

$C_\ell^{\kappa g}$: cross-correlation of CMB lensing and galaxy density



x



Note: lensing convergence $\kappa \equiv -\nabla \cdot \mathbf{d}(\hat{\mathbf{n}})$, where $\mathbf{d}(\hat{\mathbf{n}})$ deflection field such that $T(\hat{\mathbf{n}})_{\text{lensed}} = T(\hat{\mathbf{n}} + \mathbf{d}(\hat{\mathbf{n}}))_{\text{unlensed}}$

Conclusions: what can we study with $C_\ell^{\kappa g}$?

Spoiler: lots of exciting stuff! For example:

- Neutrinos mass and hierarchy
- Primordial non-Gaussianity: initial conditions of the Universe
- Models of galaxy formation
- Models of gravity on ultra-large scales
- Models of dark energy
- Calibration of systematics, e.g. photo-zs (boring but necessary)

Some background: cross-correlations

Cross-correlate two projected 2D fields $X(\hat{n})$ and $Y(\hat{n})$:

$$X(\hat{n}) = \int dz\ W^X(z)\delta(\chi(z)\hat{n}, z)\,, \quad Y(\hat{n}) = \int dz\ W^Y(z)\delta(\chi(z)\hat{n}, z)$$

On small angular scales (large ℓ), making Limber approximation:

$$C_\ell^{XY} = \int_0^{z^\star} dz\ \frac{H^2(z)}{\chi^2(z)} W^X(z) W^Y(z) P\left(k = \frac{\ell}{\chi(z)}, z\right)$$

So cross-correlation expresses the "overlap" between two projected fields that at least in part probe the same underlying signal

Lensing convergence-galaxy density cross-correlation

CMB lensing convergence and galaxy density kernels:

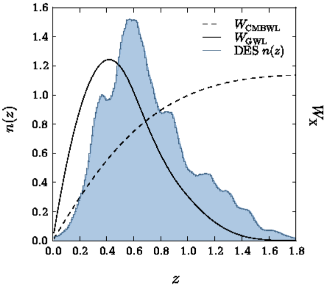
$$W^{\kappa}(z) = \frac{3}{2H(z)}\Omega_m H_0^2 (1+z)\chi(z)\frac{\chi^\star - \chi(z)}{\chi^\star}\,, \quad W^g(z) = \frac{b\frac{dN}{dz}}{\int dz' \frac{dN}{dz'}}$$

Cross-correlation:

$$C_\ell^{\kappa g} = \frac{3\Omega_m H_0^2}{2\int dz'\ \frac{dN}{dz'}} \int_{z_{\rm min}}^{z_{\rm max}} dz\ (1+z)\frac{\chi^\star - \chi(z)}{\chi^\star \chi(z)}\frac{dN}{dz} b\left(\frac{\ell}{\chi(z)}\right) P\left(\frac{\ell}{\chi(z)}, z\right)$$

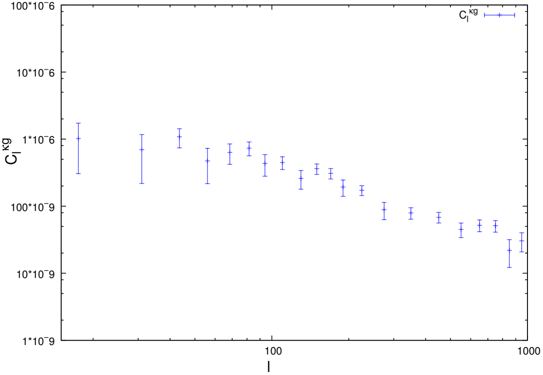
Lensing convergence-galaxy density cross-correlation

Kernels



Credits: Kirk et al., MNRAS 459 (2016) 1, 21

Cross-correlation of Planck lensing and SDSS-III BOSS DR12 CMASS



What is $C_\ell^{\kappa g}$ sensitive to?

- CMB lensing: weighted integral of matter power spectrum, so...
- $C_\ell^{\kappa g}$ sensitive to any parameter which affects the growth of structure, for example:
  - Massive ν
  - Dark energy
  - Modifications of gravity
  - Alternative dark matter models
- ...but it's not as sensitive to these parameters as many other probes we have (e.g. $P(k)$)!

So why do we care?

What is $C_\ell^{\kappa g}$ sensitive to?

- Real power of $C_\ell^{\kappa g}$ is ability to break degeneracies between parameters:
  - Galaxy clustering amplitude $\propto b^2\sigma_8^2$
  - $C_\ell^{\kappa g} \propto b\sigma_8^2$
  - $\rightarrow$ can use $C_\ell^{\kappa g}$ to reconstruct "true" matter power spectrum!
  - (studying b is extremely interesting in its own right)

- Can do tomography, i.e. evolution of CMB lensing as a function of z...

- ...and thus study amplitude of growth of structure as a function of z:

$$\ddot{\delta} + \mathbf{2H}\dot{\delta} - 4\pi G\rho_m\delta = 0$$

Cool stuff with $C_\ell^{\kappa g}$: scale-dependent bias

- Galaxy (or for that matter any tracer) bias:

$$\delta_g = b\delta_m\,, \quad \implies P_g(k) = b^2 P_m(k)$$

- Usually treated as scale-independent, however the simplest models of galaxy formation predict a scale-dependent bias: Desjacques, Jeong, Schmidt 2016

$$b(\mathbf{k}) = a + c\mathbf{k}^2$$

- Combining $C_\ell^{\kappa g}$ with $P(k)$ constrains the scale-dependence...

- ...and can “reconstruct” the “true” matter power spectrum!

Cool stuff with $C_\ell^{\kappa g}$: galaxy formation models

- Future data can probe more "realistic" bias parametrizations and constrain models of galaxy formation e.g. Modi, White, Vlah 2017

- Can constrain stochasticity $\epsilon(\mathbf{x}, z)$:

$$\delta_g(\mathbf{x}, z) = b\delta_m(\mathbf{x}, z) + \epsilon(\mathbf{x}, z)$$

- Stochastic component $\epsilon(\mathbf{x}, z)$ due to discrete sampling and physical processes affecting halo and galaxy formation

- Can be constrained by a mismatch between amplitude of $C_\ell^{gg} = b^2 C_\ell^{mm} + C_\ell^{\epsilon\epsilon}$ and $C_\ell^{\kappa g} = bC_\ell^{\kappa m}$

Cool stuff with $C_\ell^{\kappa g}$: neutrino masses

Massive neutrinos free-streaming suppress the growth of structure on small scales (large k), so:

- $C_\ell^{\kappa g}$ sensitive (but weakly) to M_ν
- M_ν is strongly degenerate with (scale-dependent) bias
- Corollary: $P(k)$ data to constrain M_ν + $C_\ell^{\kappa g}$ to constrain $b(\mathbf{k}) \rightarrow$ **great** bounds on M_ν
  [spoiler: it's true]

Cool stuff with $C_\ell^{\kappa g}$: neutrino masses

But there's more!

- Usually have to cut-off $P(k)$ data at $k \sim 0.1\, h\mathrm{Mpc}^{-1}$ due to non-linearities... Giusarma et al. 2016, Vagnozzi et al. 2017
- ...part of which is our ignorance of the scale-dependent bias
- $\implies$ $P(k)$ data is not as competitive as other large-scale structure data (e.g. BAO) when it comes to M_ν Hamann et al. 2010, Vagnozzi et al. 2017
- Corollary: $P(k)$ data to constrain M_ν + $C_\ell^{\kappa g}$ to constrain $b(\mathbf{k}) \rightarrow$ **awesome** bounds on M_ν because we can push $P(k)$ data to higher k and use many more modes!
  [spoiler: it's quite true]

Cool stuff with $C_\ell^{\kappa g}$: neutrino masses

Summary:

- $C_\ell^{\kappa g}+P(k)$ breaks degeneracy between M_ν and $b(\mathbf{k})$...
- ...and allows to exploit $P(k)$ at its full power!
- Gives great bounds on M_ν
- Could contribute to determining the neutrino hierarchy from cosmology

Cool stuff with $C_\ell^{\kappa g}$: primordial non-Gaussianity

Primordial non-Gaussianity: probes the **initial conditions** of our Universe

- Local primordial non-Gaussianity:

$$\Phi = \phi + f_{\mathrm{NL}}(\phi^2 - \langle \phi^2 \rangle)$$

- Mostly probes single-field vs multifield inflation

- Leaves an imprint in the large-scale-dependence of the bias: Dalal et al. 2008

$$\Delta b(k) = \frac{3(b_0 - 1) f_{\mathrm{NL}} \Omega_m H_0^2 \delta_c}{D(z) k^2 T(k)} \propto \frac{1}{k^2}$$

- Other types of non-Gaussianity (equilateral, orthogonal, etc.) also leave a less strong imprint on the bias

Cool stuff with $C_\ell^{\kappa g}$: primordial non-Gaussianity

- $C_\ell^{\kappa g}$ can constrain $b(k)$ as we have seen...
- ...thus constraining f_{NL} Takeuchi et al. 2010
- Expected errors depend a lot on tracer sample, realistically $\Delta f_{\mathrm{NL}} \sim 30 - 50$ but optimistically even $\Delta f_{\mathrm{NL}} \sim 1$ with future surveys
- Galaxies might not be the best tracer to cross-correlate, quasars are an excellent candidate (but suffer from many systematics)

Cool stuff with $C_\ell^{\kappa g}$: modified gravity

- In GR lensing sensitive to $\nabla^2(\phi - \psi) \propto \nabla^2\phi \propto \delta$

- Idea: test whether "lensing = matter" comparing galaxy-lensing and galaxy-matter (-velocity) cross-correlations

- Use the following quantity: Zhang et al. 2007

$$E_G = \frac{\nabla^2(\phi - \psi)}{3H_0^2 a^{-1}\beta\delta}\,, \quad \beta = \frac{d\ln D}{d\ln a}$$

- In GR $E_G = \Omega_m/\beta$ is a constant

- In most modified gravity theories E_G is scale-dependent!

Cool stuff with $C_\ell^{\kappa g}$: modified gravity

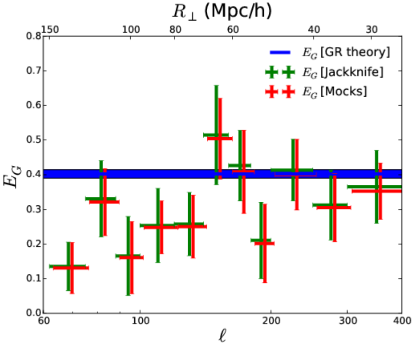
- Estimate E_G through:

$$E_G = \frac{2c}{3H_0^2} \frac{H(z) f_g(z)}{(1+z) W^\kappa(z)} \frac{C_\ell^{\kappa g}}{\beta C_\ell^{gg}}$$

- This estimator for E_G is independent of b (galaxy bias) and σ_8!

Cool stuff with $C_\ell^{\kappa g}$: modified gravity

Measurement of E_G using Planck lensing cross BOSS DR11 CMASS



GR prediction: $E_G(z = 0.57) = 0.402 \pm 0.012$

Measurement: $E_G(z = 0.57) = 0.243 \pm 0.060$ Pullen et al. 2016

$\sim$ **2.6σ tension** with GR! Could be systematics, but persists in similar measurements Alam et al. 2017

Cool stuff with $C_\ell^{\kappa g}$: evolving dark energy

- Can use $C_\ell^{\kappa g}$ tomography to test the evolution of dark energy as a function of redshift
- Example: can constrain the dark energy equation of state $w(z)$
- Will help addressing the question: is dark energy a cosmological constant Λ or something more complicated?
- Some work in this direction especially with DES galaxies cross Planck/SPT lensing Soergel et al. 2015; Giannantonio et al. 2016

Cool stuff with $C_\ell^{\kappa g}$: calibrating systematics

- Use $C_\ell^{\kappa g}$ to calibrate systematics such as photometric redshifts uncertainties. Actually use $w^{\kappa g}(\theta)$ given by:

$$w^{\kappa g}(\theta) = \sum_{\ell=0}^{\infty} \left(\frac{2\ell+1}{4\pi}\right) P_\ell(\cos\theta) C_\ell^{\kappa g}$$

- Combine $w^{\kappa g}(\theta)$ with $w^{\gamma_T g}(\theta)$[1] to simultaneously calibrate systematics in photo-z of tracer and source galaxies
- General idea (e.g. with DES $\times$ SPT lensing data): Baxter et al. 2016
  - Systematics in tracers photo-z affect both $w^{\gamma_T g}(\theta)$ and $w^{\kappa g}(\theta)$
  - Systematics in source photo-z affect only $w^{\gamma_T g}(\theta)$ but not $w^{\kappa g}(\theta)$
  - Joint measurement isolates effects of the two photo-z systematics

[1] γ_T: tangential shear i.e. component of shear perpendicular to the line connecting the image of a source galaxy and a tracer galaxy

Conclusions: part 1

What did we want? Something from CMB and LSS data which could:

- Beat systematics
- Create new estimators
- Enhance low amplitude signals
- Probe interesting physics (both fundamental and non)

Conclusions: part 2

What did we get? $C_\ell^{\kappa g}$, which can probe lots of interesting physics:

- Scale-dependent bias $\rightarrow$ galaxy formation models
- Stochasticity $\rightarrow$ galaxy formation models
- Neutrino masses (and in future hierarchy)
- Primordial non-Gaussianity $\rightarrow$ initial conditions of Universe
- Modified gravity $\rightarrow$ is GR valid on large scales?
- Evolving dark energy $\rightarrow$ simple cosmological constant or not?
- Calibration of systematics (e.g. photo-zs)

Mules again