New Probes of Large Scale Structure

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Carnegie Mellon University
Copernicus Webinar Series
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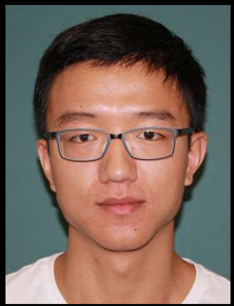
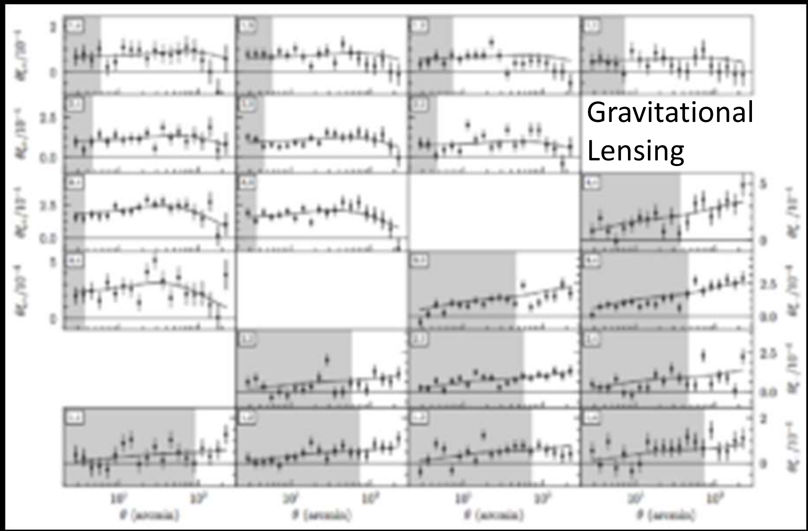
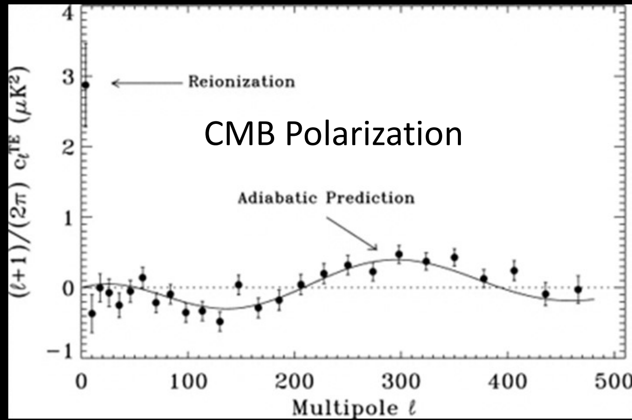
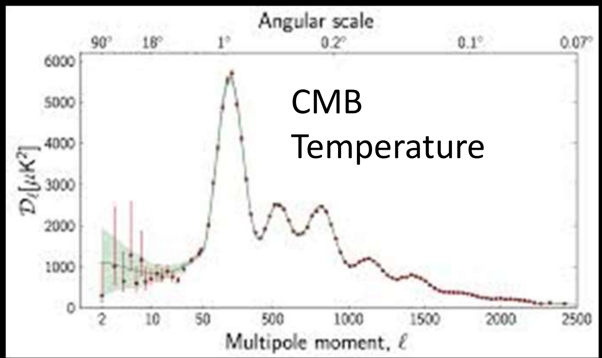


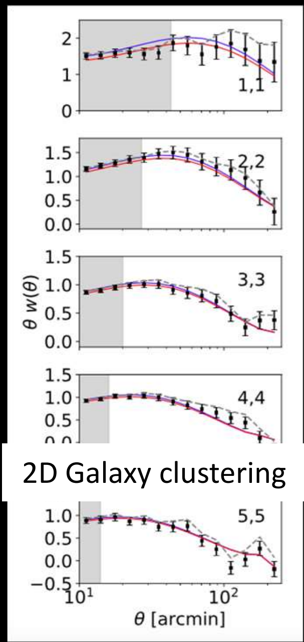
Peikai Li

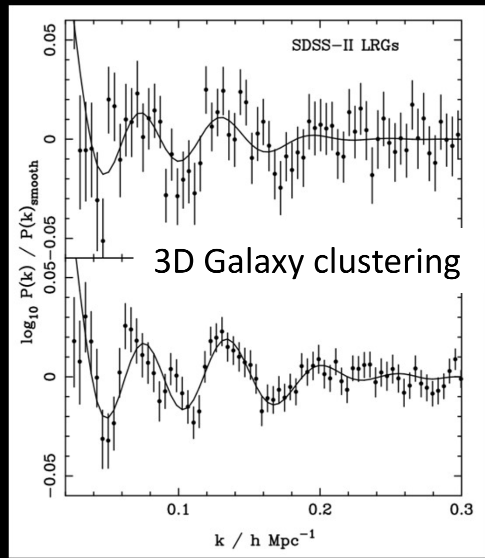
Fiducial Cosmological Model: Stunning Agreement with a wide variety of observations



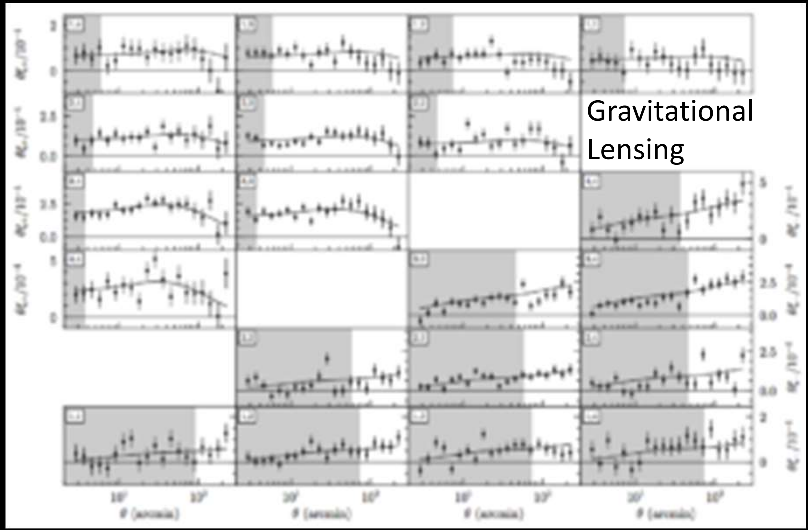


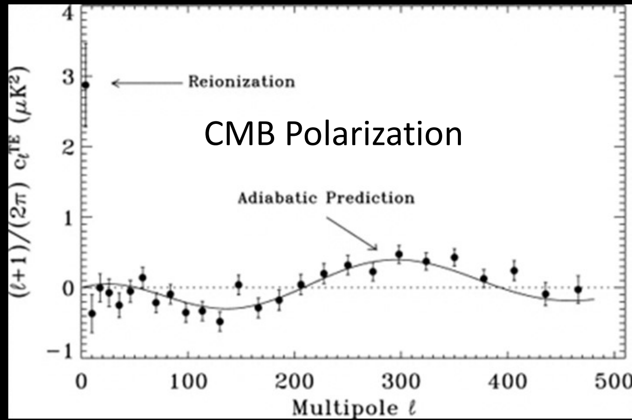


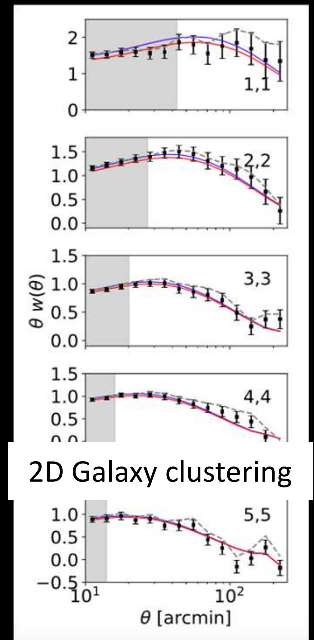


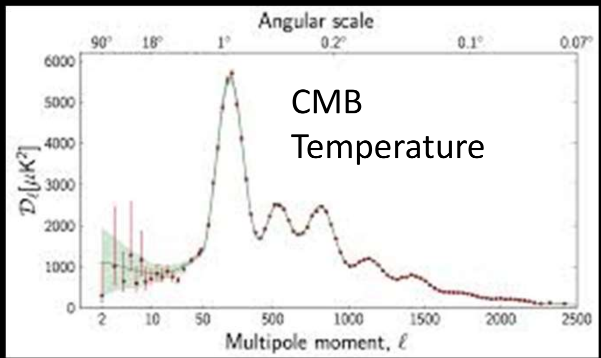


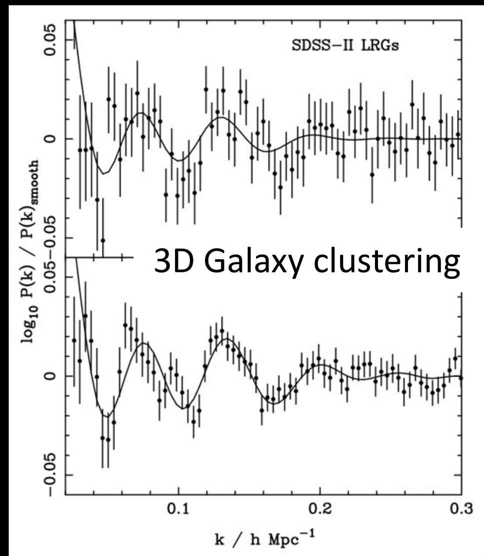
These are all correlation functions or Power spectra











What else?

Supernova

CMB blackbody

Time Delays (H_0)

Strong Gravitational Lensing

Clusters: Hard

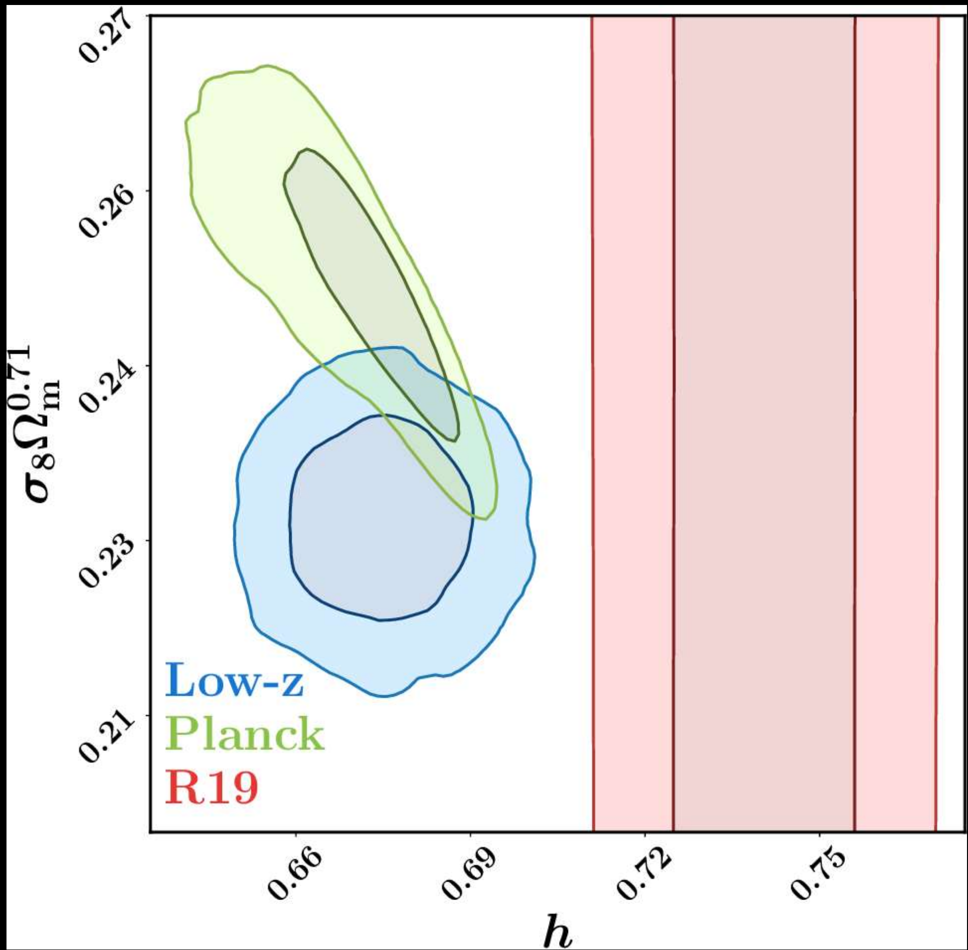
Galaxy Morphology at high-z

Voids

Nice to see: Anomalies or non-gaussianities

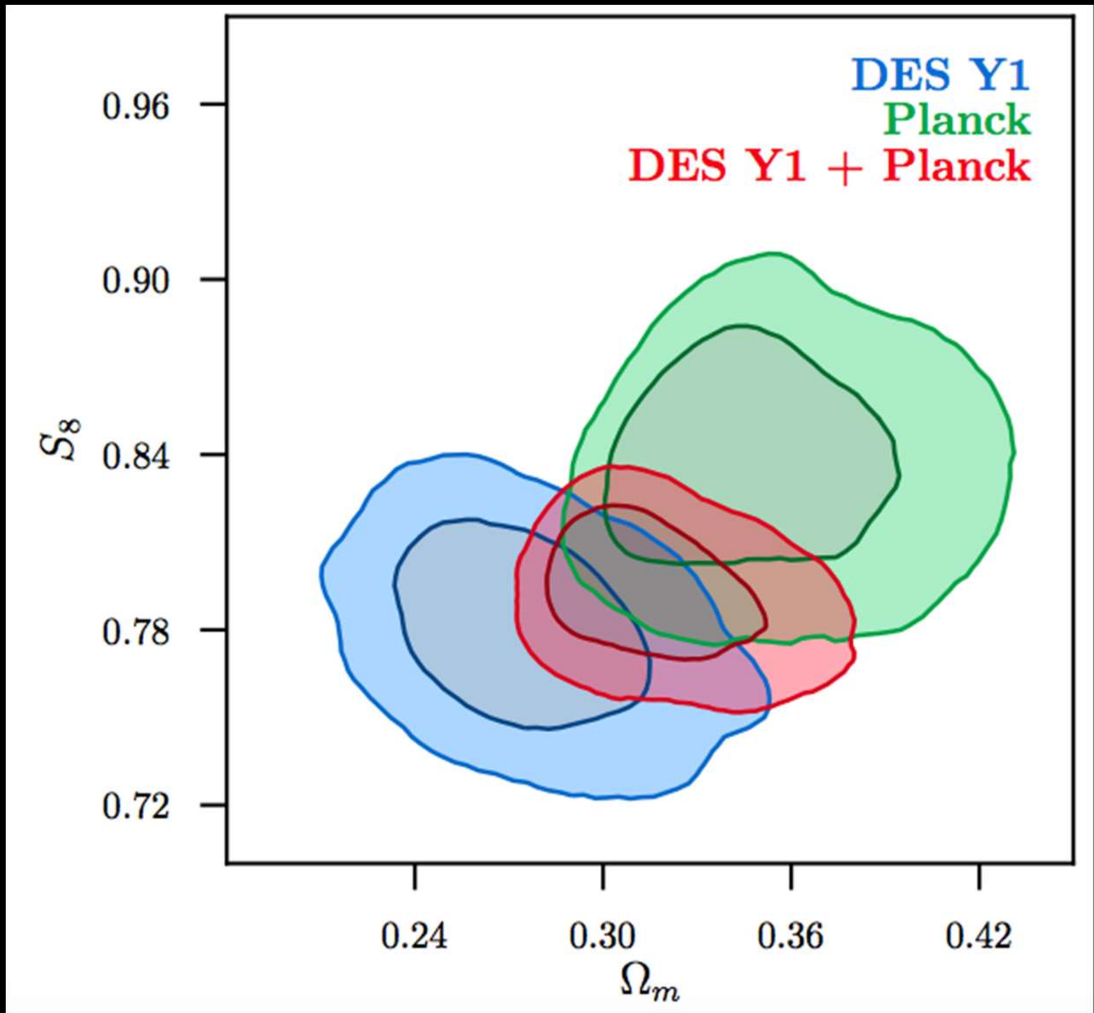
Gravitational Waves from primordial origin

Possible Tensions



Park and Rozo 2019

Stay Tuned for DES Y3 Results in N weeks



Correlation Functions & Power Spectra

$$\tilde{\delta}(\vec{k}) = \int d^3x\, \delta(\vec{x})\, e^{-i\vec{k}\cdot\vec{x}}$$

$$\langle \tilde{\delta}(\vec{k})\, \tilde{\delta}(\vec{k}')\rangle = \int d^3x e^{-i\vec{k}\cdot\vec{x}} \int d^3y e^{-i\vec{k}'\cdot\vec{y}}\, \xi(\vec{x} - \vec{y})$$

since the correlation function depends only on the distance between two regions, **not** on where those regions are. Then,

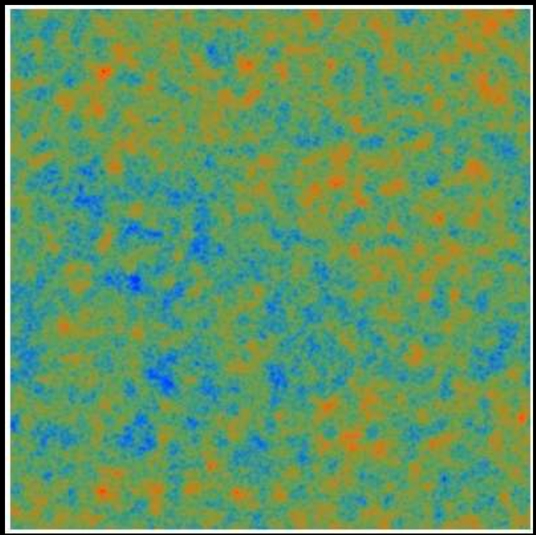
$$\langle \tilde{\delta}(\vec{k})\, \tilde{\delta}(\vec{k}')\rangle = \int d^3x e^{-i(\vec{k}+\vec{k}')\cdot\vec{x}} \int d^3x_- e^{i\vec{k}'\cdot\vec{x}_-}\, \xi(\vec{x}_-)$$

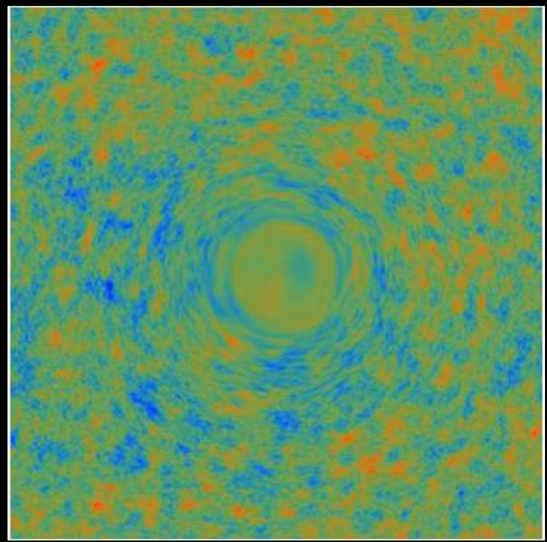
$$= (2\pi)^3\, \delta_D^3(\vec{k} + \vec{k}')\, P(k)$$

As long as the universe is homogenous, only Fourier modes with equal and opposite wave vectors are correlated.

Lensing of the CMB

CMB photons from the last scattering surface are deflected (~few arcminutes) by coherent large scale structure (~few degrees)





Effect is not as dramatic in real maps, but estimators of non-Gaussianity extract projected gravitational potential

Hu 2002

Gravitational Lensing of the Primordial CMB

Primordial *unlensed* temperature Θ^u is re-mapped to

$$\Theta(\vec{\theta}) = \Theta^u(\vec{\theta} + \vec{\delta\theta})$$

where the deflection angle is a weighted integral of the gravitational potential along the line of sight

$$\begin{aligned} \vec{\delta\theta}(\vec{\theta}) &= -\nabla\phi(\vec{\theta}) \\ &\equiv -\int_0^{\chi_*} d\chi W(\chi) \nabla\Psi(\chi\vec{\theta}, \chi) \end{aligned}$$

Taylor expand …

$$\Theta(\vec{\theta}) \simeq \Theta^u(\vec{\theta}) + \frac{\partial \Theta^u}{\partial \vec{\theta}} \cdot \delta\vec{\theta}$$

or using the deflection angle

$$\Theta(\vec{\theta}) \simeq \Theta^u(\vec{\theta}) - \frac{\partial \Theta^u}{\partial \vec{\theta}} \cdot \nabla\phi(\vec{\theta})$$

and then taking the Fourier transform

$$\tilde{\Theta}(\vec{l}) = \tilde{\Theta}^u(\vec{l}) + \int d^2l' \left(\vec{l'} \cdot [\vec{l} - \vec{l'}]\right) \tilde{\Theta}^u(\vec{l'})\tilde{\phi}(\vec{l} - \vec{l'})$$

The two-point function is no longer diagonal!

$$\tilde{\Theta}(\vec{l}) = \tilde{\Theta}^u(\vec{l}) + \int d^2l' \left(\vec{l'} \cdot [\vec{l} - \vec{l'}]\right) \tilde{\Theta}^u(\vec{l'})\tilde{\phi}(\vec{l} - \vec{l'})$$

Recall that $\langle \tilde{\Theta}^u(\vec{l})\tilde{\Theta}^u(\vec{l'})\rangle = (2\pi)^2\delta^2(\vec{l} + \vec{l'})C_l$

Now though different Fourier modes are coupled!

$$\langle \tilde{\Theta}(\vec{l})\tilde{\Theta}(\vec{l'})\rangle\Big|_{\vec{l}+\vec{l'}\neq 0} = \int d^2l_1 \left(\vec{l_1} \cdot [\vec{l} - \vec{l_1}]\right) \langle \tilde{\Theta}^u(\vec{l_1})\tilde{\phi}(\vec{l} - \vec{l_1})\tilde{\Theta}^u(\vec{l'})\rangle$$

Normally, 3-point functions of Gaussian fields vanish

Off-Diagonal Two-Point Functions

$$\langle\tilde\Theta(\vec l)\tilde\Theta(\vec l')\rangle\Big|_{\vec l+\vec l'\neq 0} = \int d^2l_1\left(\vec l_1\cdot[\vec l-\vec l_1]\right)\langle\tilde\Theta^u(\vec l_1)\tilde\phi(\vec l-\vec l_1)\tilde\Theta^u(\vec l')\rangle$$

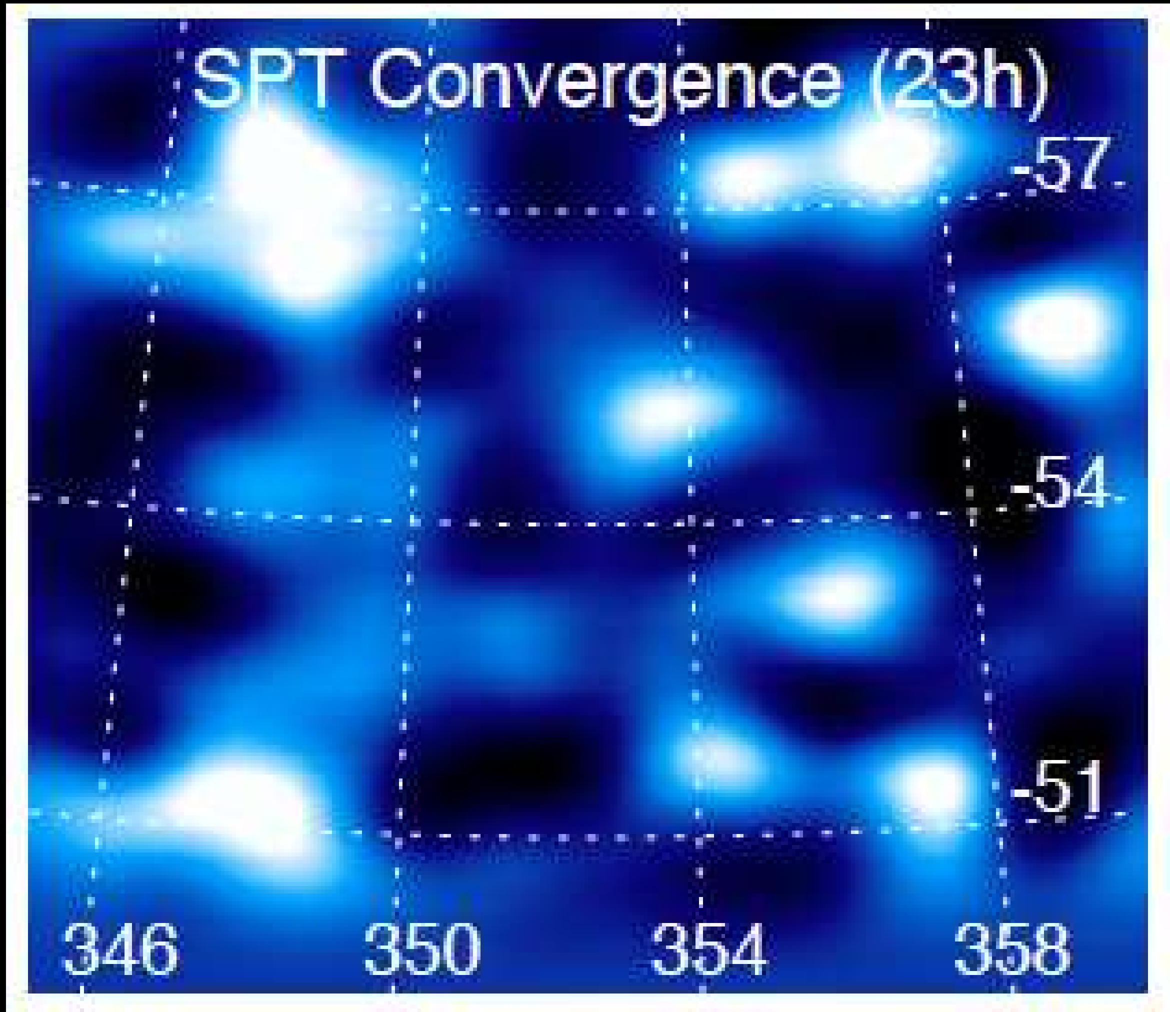
But think of the lensing field as external to the CMB, so the angular brackets mean averaging over all realizations of the CMB for fixed lensing field. In terms of field theory, think of doing a functional integral over the CMB fields while treating the potential field as fixed, external.

Then, the 3-point function in the integrand becomes a 2-point function that requires l_1 and l' to be equal and opposite.

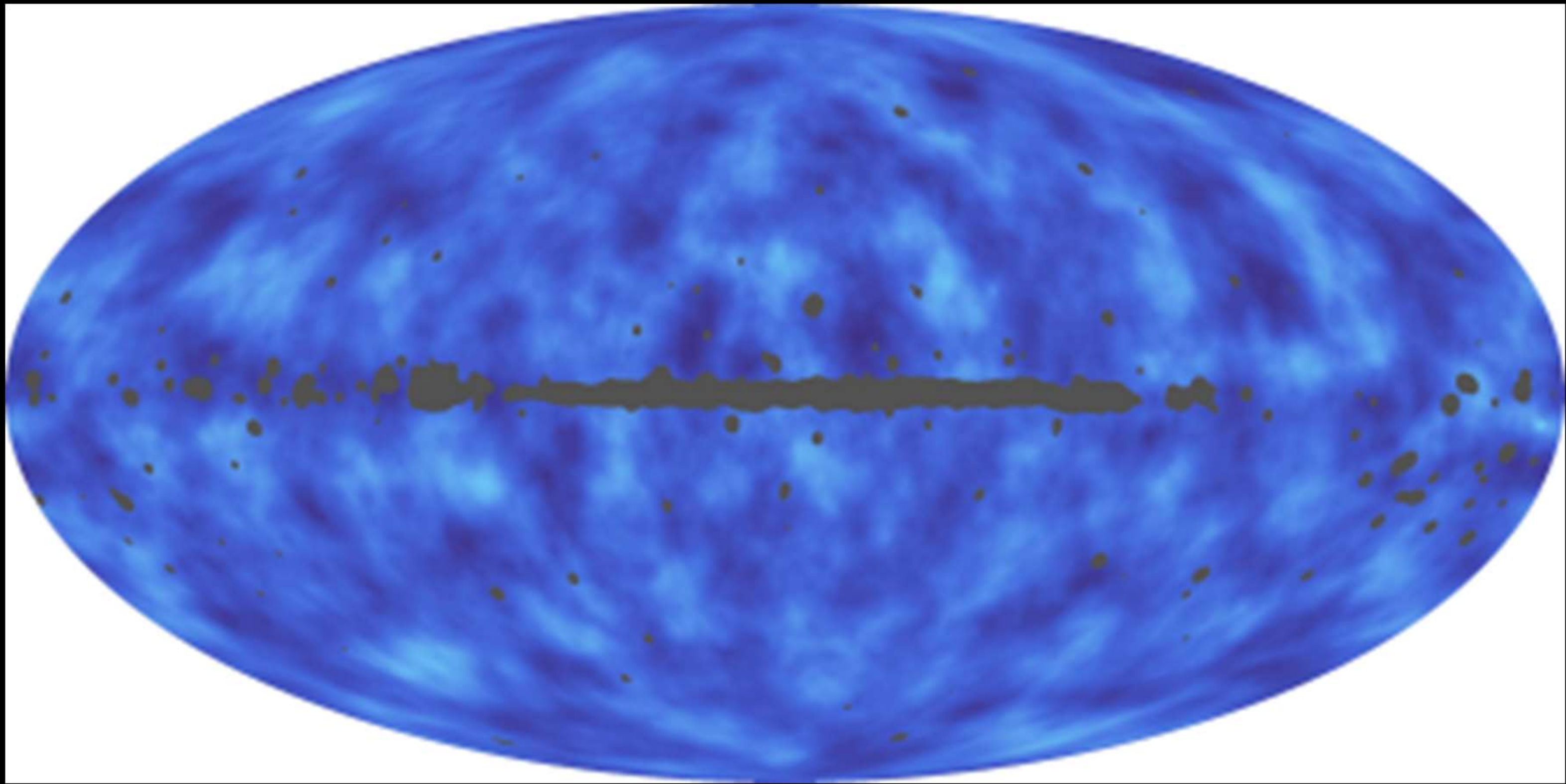
$$\langle\tilde\Theta(\vec l)\tilde\Theta(\vec l')\rangle\Big|_{\vec l+\vec l'\neq 0} = (2\pi)^2 C_{l'}\left(-\vec l'\cdot[\vec l+\vec l']\right)\,\tilde\phi(\vec l+\vec l')$$

The off-diagonal part of the 2-point function then gives an estimate of the thing that is making the universe inhomogeneous: the gravitational potential

CMB Lensing is hot!

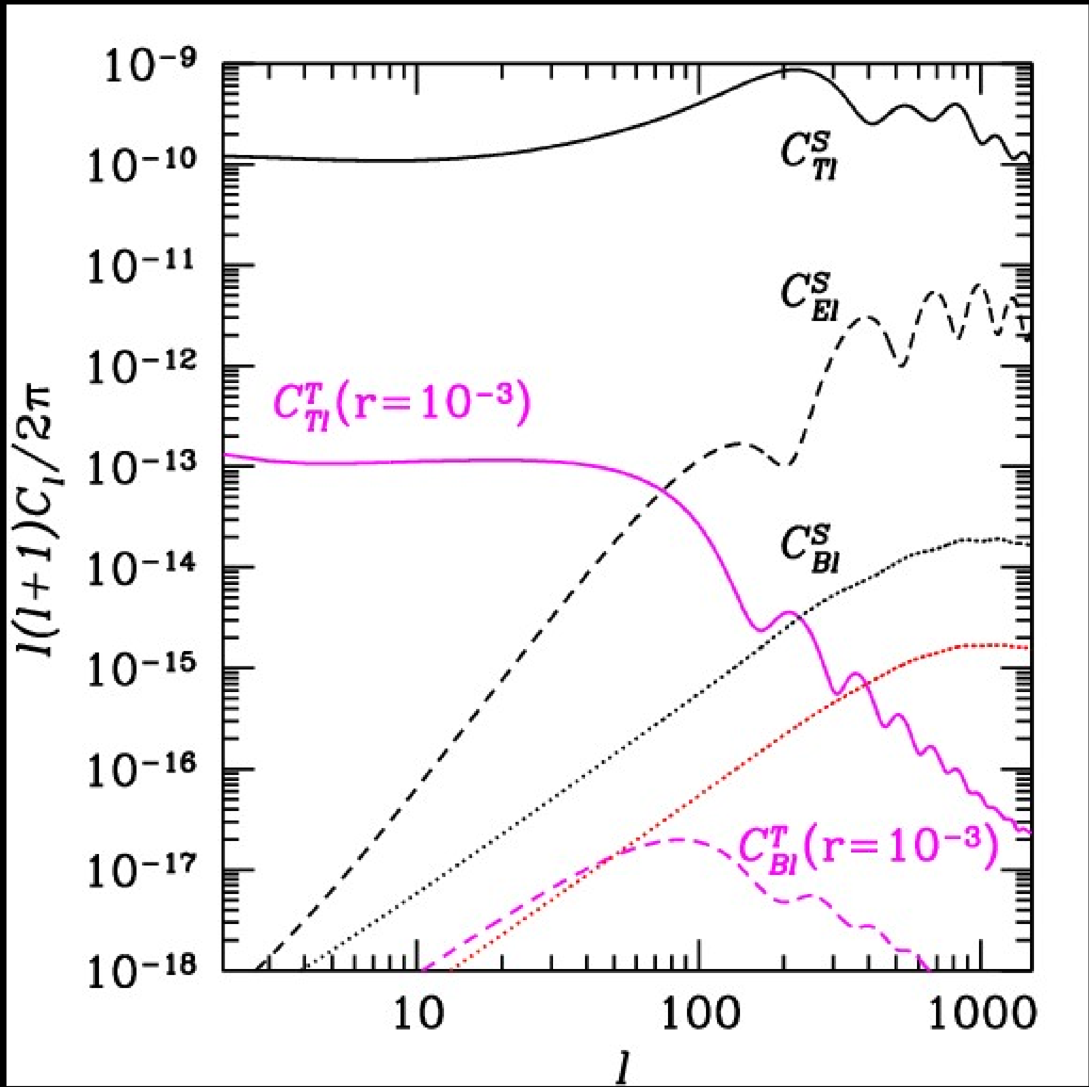


Planck has all-sky maps of the projected potential!



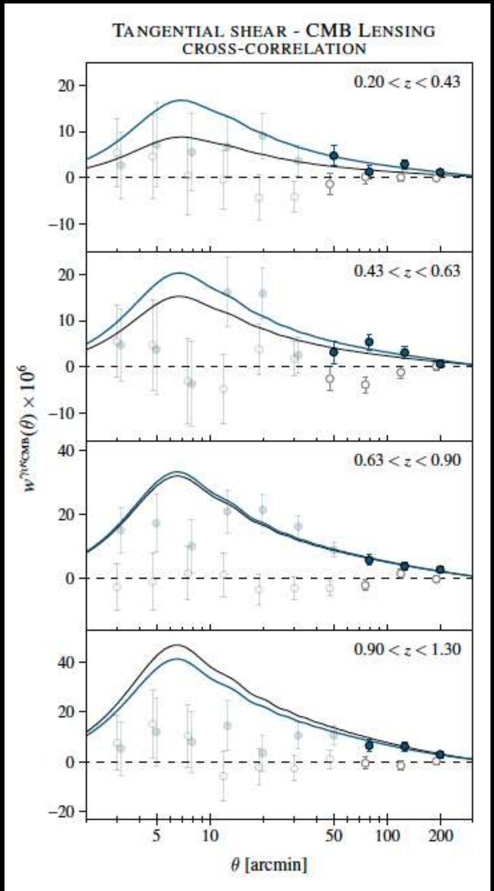
Can clean up B-mode contamination and measure even smaller tensor component

Probe inflation even if energy scale is low

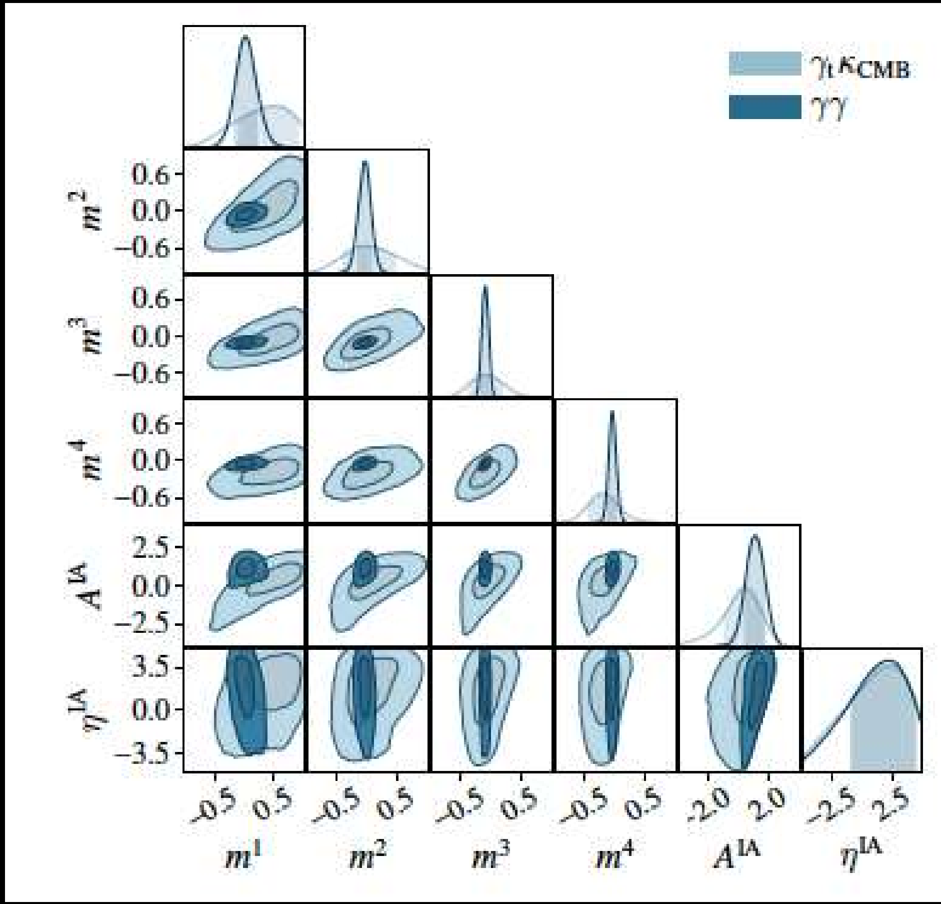


Knox & Song; Kesden, Cooray, & Kamionkowski 2002

Correlate SPT lensing map with DES



Omori et al 2019

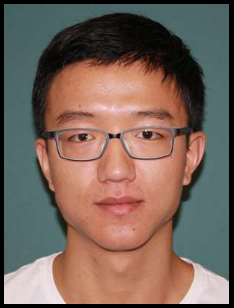


Consistency check on systematic effects

New Probes of Large Scale Structure

2001.02780

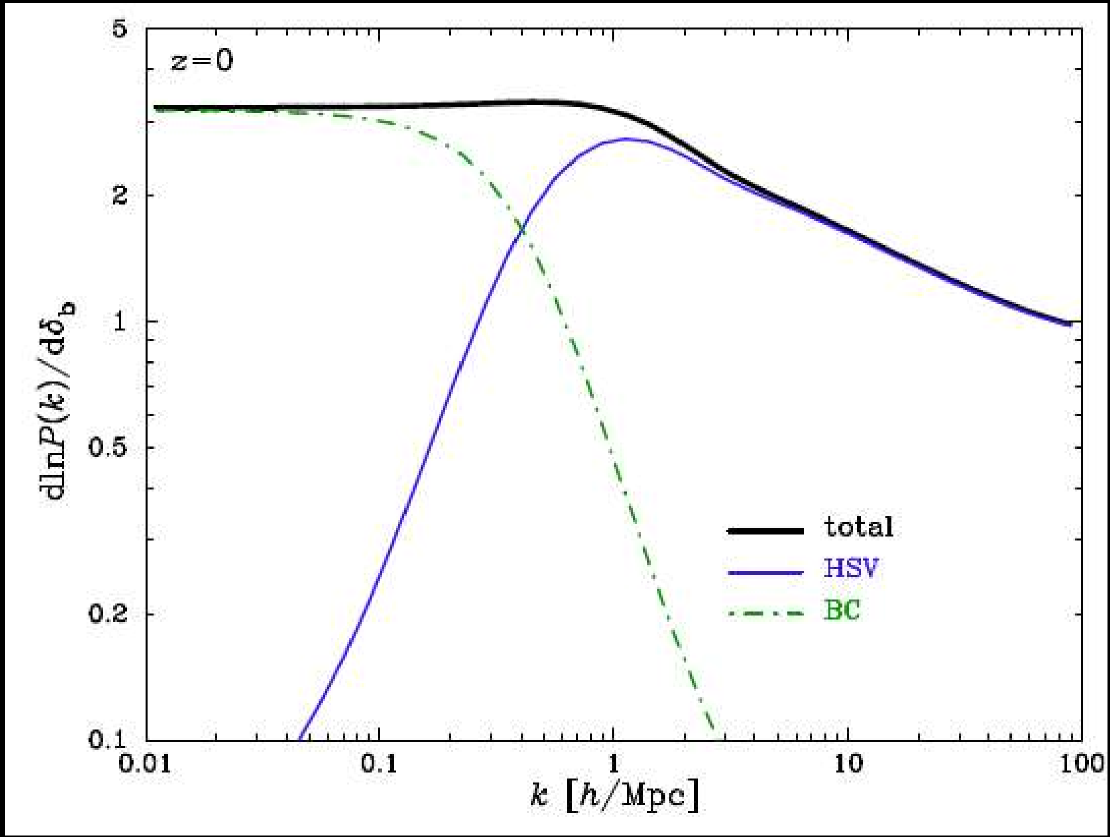
2007.00226



Peikai Li

Small Scale Structure grows faster in a region with a positive large-scale overdensity

Not surprising: the short wavelength modes are evolving in a region that has larger matter density than average → perturbations grow faster than average



Hu and Takada 2013

Perturbation Theory

$$\frac{\partial \delta(\vec{x},\tau)}{\partial \tau} + \vec{\nabla} \cdot [(1+\delta(\vec{x},\tau))\vec{v}(\vec{x},\tau)] = 0 \quad (1)$$

$$\left[\frac{\partial}{\partial \tau} + \vec{v}(\vec{x},\tau) \cdot \vec{\nabla}\right]\vec{v}(\vec{x},\tau) = -\frac{da}{d\tau}\frac{\vec{v}(\vec{x},\tau)}{a} - \vec{\nabla}\Phi \quad (2)$$

$$\nabla^2\Phi = 4\pi G a^2 \bar{\rho}_{\mathrm{m}} \delta(\vec{x},\tau). \quad (3)$$

Expand and solve order by order

$$\delta(\vec{k},\tau) = \sum_{n=1}^{\infty} \delta^{(n)}(\vec{k},\tau)$$

Linear Order

$$\langle \delta^{(1)}(\vec{k},\tau)\delta^{(1)}(\vec{k}',\tau)\rangle = (2\pi)^3\delta_{\rm D}(\vec{k}+\vec{k}')P_{\rm lin}(k,\tau)$$

with linear growth given by the growth function

$$\delta^{(1)}(\vec{k},\tau) = \delta^{L}(\vec{k},\tau) = \delta^{L}(\vec{k},\tau_0)D(\tau)$$

Second Order

$$\delta^{(2)}(\vec{k},\tau) = \int \frac{d^3\vec{k}_1}{(2\pi)^3} F_2(\vec{k}_1, \vec{k}-\vec{k}_1)\delta^{(1)}(\vec{k}_1,\tau)\delta^{(1)}(\vec{k}-\vec{k}_1,\tau)$$

with

$$F_2(\vec{k}_1,\vec{k}_2) = \frac{5}{7} + \frac{2}{7}\frac{(\vec{k}_1\cdot\vec{k}_2)^2}{k_1^2k_2^2} + \frac{\vec{k}_1\cdot\vec{k}_2}{2k_1k_2}\left[\frac{k_1}{k_2}+\frac{k_2}{k_1}\right]$$

Note: in the integrand if $k_1 << k$. then $F_2 \sim k/k_1$.
Large-scale mode $\delta(k_1)$ could couple to nearby small scale modes and feed power into $\delta(k)$

Key point: small scale structure is **not** homogeneous; it varies depending on the amplitude of the large scale modes.

Off-Diagonal Elements of the Two-Point Function

$$\langle \delta(\vec{k}_s)\delta(\vec{k}'_s)\rangle|_{\vec{k}_s+\vec{k}'_s=\vec{k}_l} = \langle \delta^{(1)}(\vec{k}_s)\delta^{(2)}(\vec{k}'_s)\rangle + \langle \delta^{(2)}(\vec{k}_s)\delta^{(1)}(\vec{k}'_s)\rangle$$

These appear to depend on 3-point functions (bispectra):

$$\langle \delta^{(1)}(\vec{k}_s)\delta^{(2)}(\vec{k}'_s)\rangle = \int \frac{d^3\vec{k}}{(2\pi)^3} F_2(\vec{k}, \vec{k}'_s - \vec{k}) \times \langle \delta^{(1)}(\vec{k}_s)\delta^{(1)}(\vec{k}'_s - \vec{k})\delta^{(1)}(\vec{k})\rangle$$

Each of those first order over-density are linear, Gaussian fields so we expect the 3-point function to vanish

Off-Diagonal Elements of the Two-Point Function

$$\langle \delta^{(1)}(\vec{k}_s)\delta^{(2)}(\vec{k}'_s)\rangle = \int \frac{d^3\vec{k}}{(2\pi)^3} F_2(\vec{k}, \vec{k}'_s - \vec{k}) \times \langle \delta^{(1)}(\vec{k}_s)\delta^{(1)}(\vec{k}'_s - \vec{k})\delta^{(1)}(\vec{k})\rangle$$

However, repeating the logic behind CMB Lensing, suppose the last δ here is a large-scale mode. Then this collapses to:

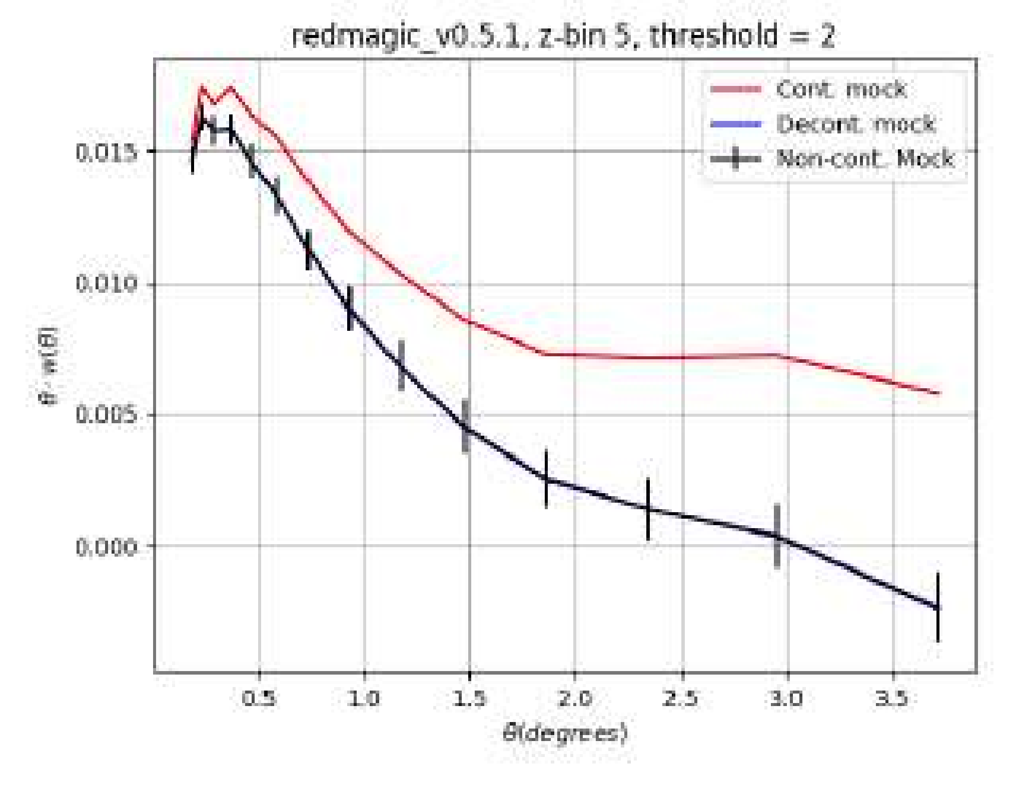
$$2F_2(-\vec{k}_s, \vec{k}_s + \vec{k}'_s)P_{\rm lin}(k_s)\delta^{(1)}(\vec{k}_s + \vec{k}'_s)$$

So, the observed off-diagonal 2-point function is non-zero and offers information about the large-scale modes. *By measuring small-scale structure, we can infer information about large scale structure.*

Why Does this Matter?

1. It is hard to measure large scale modes directly
2. There seems to be something weird going on at large scales

1. Hard to measure large-scale modes directly

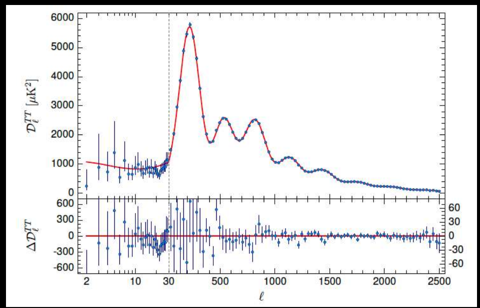


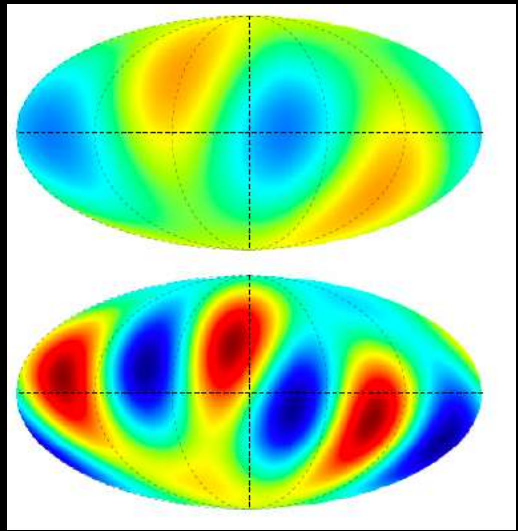
DES: Rodriguez Monroy, et al

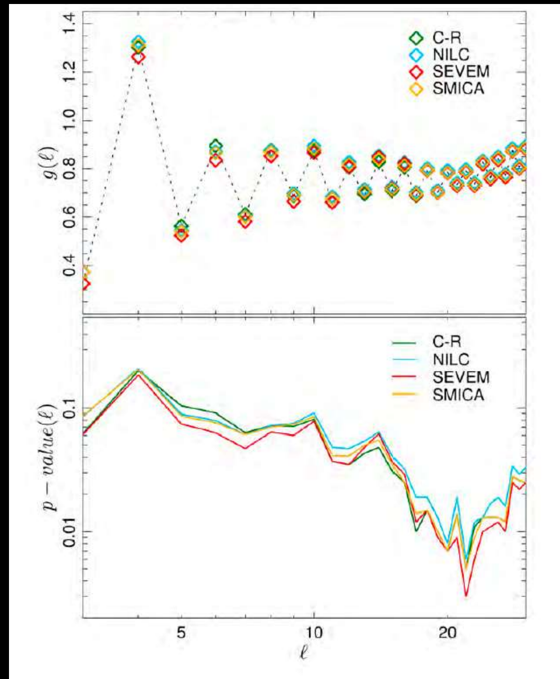
DES covers 5000 sq deg., so you might expect a reliable measurement out to ~10 deg

Angular correlation of galaxies fall off at large scales, but the contamination from survey properties does not …

2. Weird things at large scales

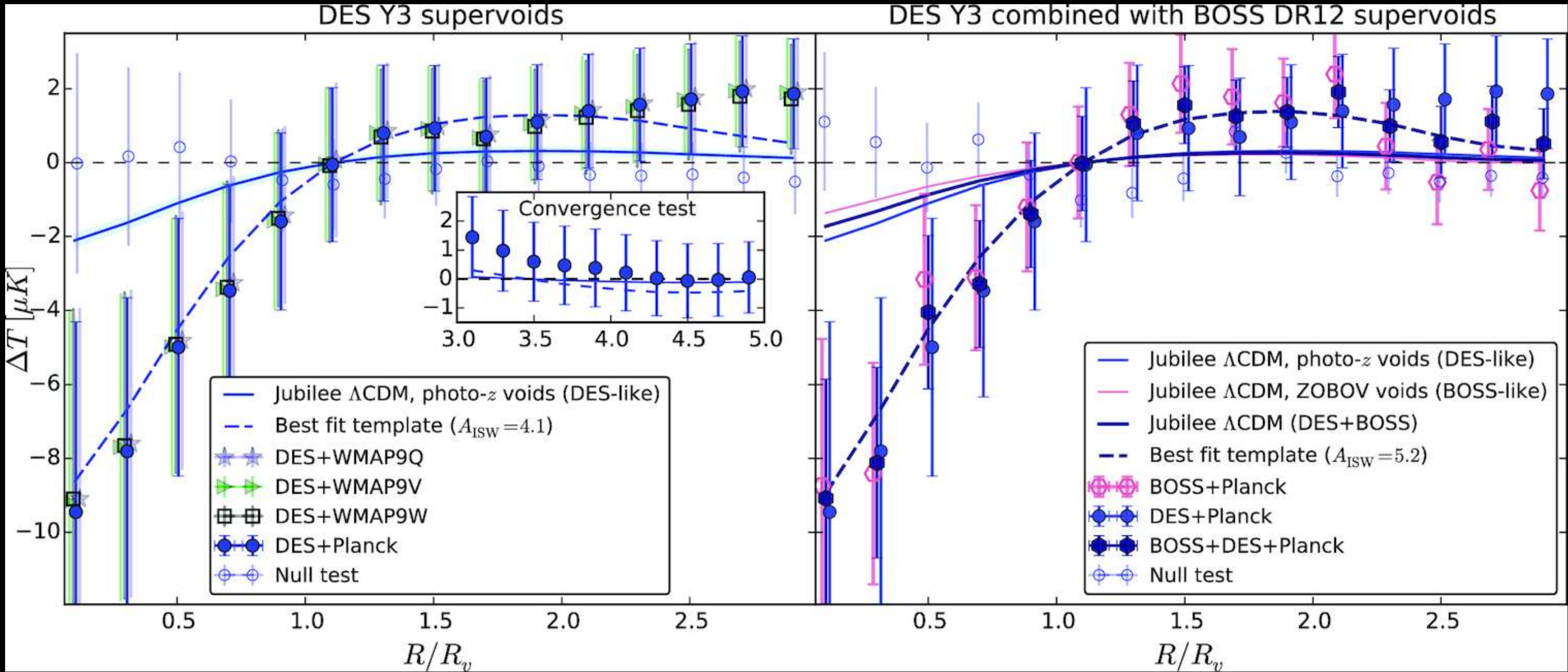






Thesis: Anne Mette Frejsel

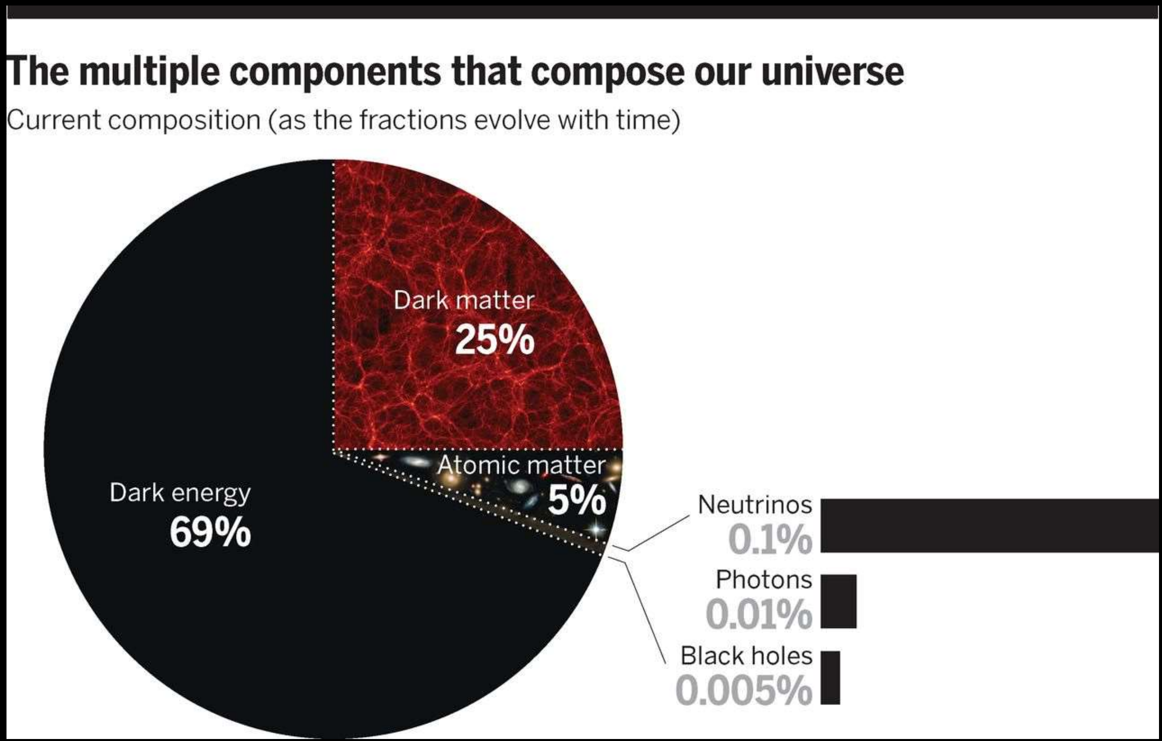
2. Weird things at large scales



Kovacs, Sanchez et al 2019

The measured Integrated Sachs Wolfe effect seems too big

2. Weird things at large scales

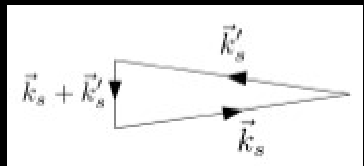


Dark energy – or whatever is driving the acceleration of the universe – is a large-scale phenomenon. Perhaps if we studied large scale structure more carefully, we could glean a clue as to what is going on

How to extract this information as efficiently as possible

$$2F_2(-\vec{k}_s, \vec{k}_s+\vec{k}'_s)P_{\rm lin}(k_s)\delta^{(1)}(\vec{k}_s+\vec{k}'_s)$$

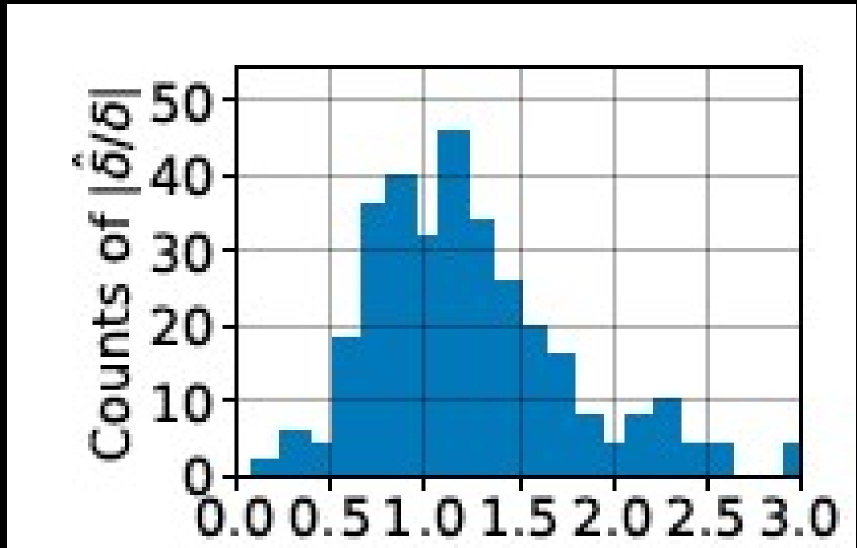
Sum over all small-scale quadratic pairs whose momenta sum to a given value of k_L



Weight them to get the maximum signal to noise

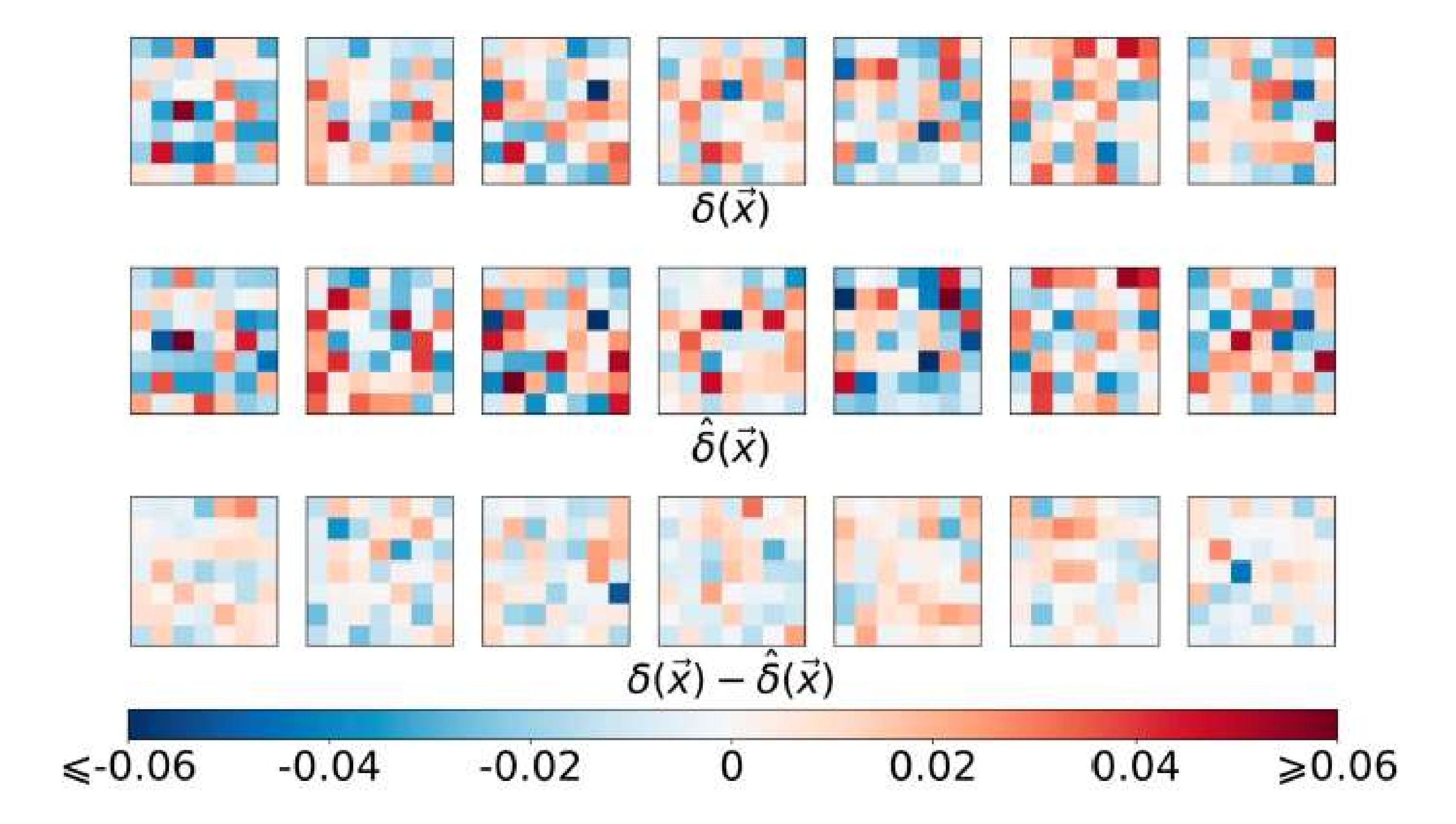
$$\hat{\delta}^{(1)}(\vec{k}_l) = A(\vec{k}_l)\int \frac{d^3\vec{k}_s}{(2\pi)^3} g(\vec{k}_s,\vec{k}'_s)\delta(\vec{k}_s)\delta(\vec{k}'_s)$$

Pretty good job in Recapturing the amplitude of the Fourier modes



Peikai applied this to one of the MultiDark cosmological simulations (box size 2.5 h^{-1} Gpc)

Looks good in Real Space

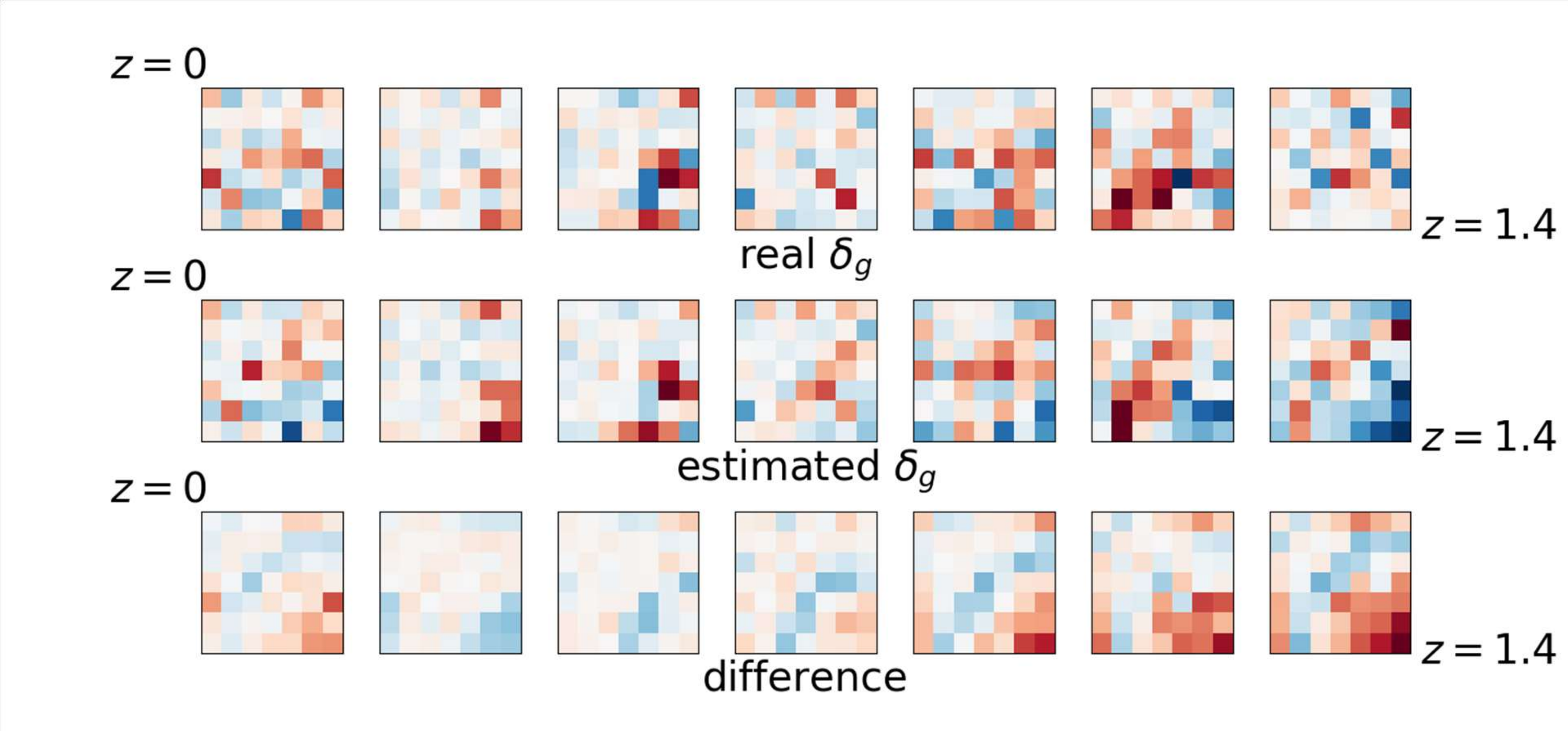


Each cell is a square with length ~400 Mpc

Before Applying to Data

- Light Cone: Requires window function and FKP weighting
- Halos, not dark matter particles: requires bias model
- Redshift Space Distortions

Preliminary Results



Next Steps

- Apply to BOSS QSO sample
- Generalize to 2D line of sight fields:

$$\langle \tilde{f}(\vec{l})\tilde{g}(\vec{l}')\rangle_{l\neq l'} = \int d\chi \frac{W_f(\chi)D(\chi)}{\chi^2} \int d\chi' \frac{W_g(\chi')D(\chi')}{\chi'^2} \int \frac{dk_z}{2\pi} \int \frac{dk'_z}{2\pi} e^{ik_z\chi + ik'_z\chi'} \tilde{\delta}^{(1)}(\vec{k}_1;\chi)F_2(\vec{k}_1,\vec{k}-\vec{k}_1)P(l'/\chi',k'_z)$$

Summary

- Modern cosmology is built on power spectra and correlation functions
- Even within the scope of 2-point functions, there is potentially much more information available for us to mine