Probing the high-redshift Universe (Cosmic Brunch)

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Outline

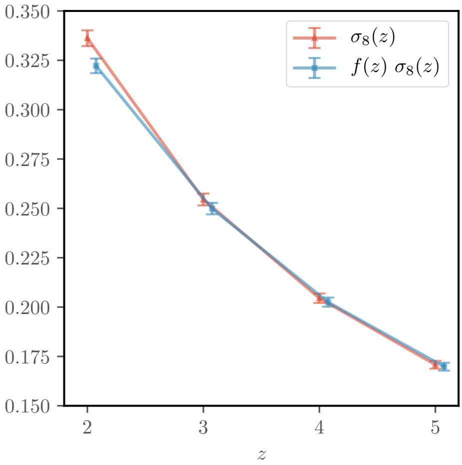
- Some reasons to go to high redshift.
- Upcoming observational opportunities/motivations.
- Lightening review of CMB lensing.
- Dropout selection of high z galaxies.
- Measuring the growth of large-scale structure.
- Bias, bias, bias, ...
- Future directions.

Searching under the lamppost?

- Increasing precision in cosmology is essentially a mode counting exercise – reduce sample variance by increasing the number of samples.
  - Inflation (f_{NL}, features, flatness, ...)
  - Neutrino masses (and other light relics)
  - Test General Relativity to the largest scales.
- In general non-linearity is not your friend, especially if you are after 'primordial' physics.
- Ideally maximize S/N of 'new physics' or 'new insights'
  - I don't have a crystal ball which tells me where/if new physics will show up, so I can't increase 'S'. How do I lower N?
- All else being equal, I'd like a problem with well controlled and interesting theory!

Going to high redshift gives me more volume, more modes and less non-linear structure ...

One example: growth rate

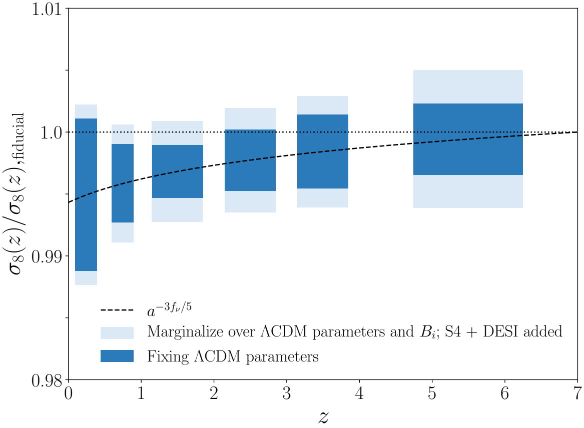


- Between $z \simeq 10^3$ and today, fluctuations grow by $\sim 10^3$.
- GR predicts growth very precisely.
- Marginalizing over unknown parameters, growth is predicted to 1.1% per bin (dominated by m_ν uncertainty).

Is GR right?

Light neutrinos

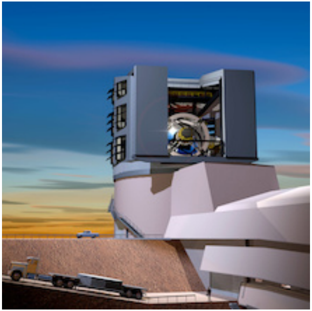
Since neutrinos free stream on small scales, $\delta_m \propto a^{1-3f_\nu/5}$ where f_ν is the ν mass fraction.



Yu+19

New facilities

We are about to “turn on” several new facilities representing billions of dollars and hundreds of person-years of investment ...



Optical surveys

Major new imaging and spectroscopic facilities ...

- Dark Energy Survey (DES)
- DECam Legacy Survey (DECaLS)
- Dark Energy Spectroscopic Instrument (DESI)
- Subaru Hyper Suprime-Cam (HSC)
- Prime Focus Spectrograph (PFS)
- Large Synoptic Survey Telescope (LSST)
- Euclid
- Wide-Field Infrared Survey Telescope (WFIRST)

These facilities can map large areas of sky to unprecedented depths!

Optical Surveys

Survey	u	g	r	i	z	y (Y)	Area [deg^2]
DES	–	25.4	24.9	25.0	24.7	21.7	5K
DECALS	–	24.0	23.5	–	22.5	–	14K
LSST-Y1	24.1	25.6	25.8	25.1	24.1	23.4	12K
LSST-Y10	25.3	26.8	27.0	26.4	25.2	24.5	14K

CMB Surveys

A similar revolution is happening at longer wavelengths ...

Survey	Map RMS [μK-arcmin]	Resolution [$'$]	Area [deg^2]
Planck	30.0	7.0	21K
Simons Observatory	6.0	1.0	27K
CMB-S4	1.0	1.4	17K
LiteBIRD	2.5	30.0	30K

A natural "by-product" of next generation CMB experiments to constrain primordial gravitational waves is high fidelity CMB lensing maps.

Lensing of the CMB

- The anisotropies we see in the CMB are the seeds of large-scale structure in the Universe.
- General Relativity makes precise predictions for the growth of this large-scale structure once the constituents are known.
- The gravitational potentials associated with this structure lens the CMB photons on their way to us ...
- ... imprinting a characteristic pattern which can be used to probe the structure itself.
- This provides an important consistency check *and* sensitivity to the low redshift Universe.

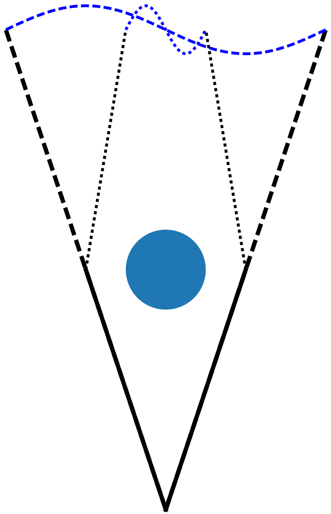
Characteristic scales

The lensing-induced deflections of CMB photons

- are $\mathcal{O}(2' - 3')$ in size
- are coherent over $2^\circ - 3^\circ$
- arise from structures over a wide redshift range ...
- ... but are most sensitive to $z \sim 2 - 3$.

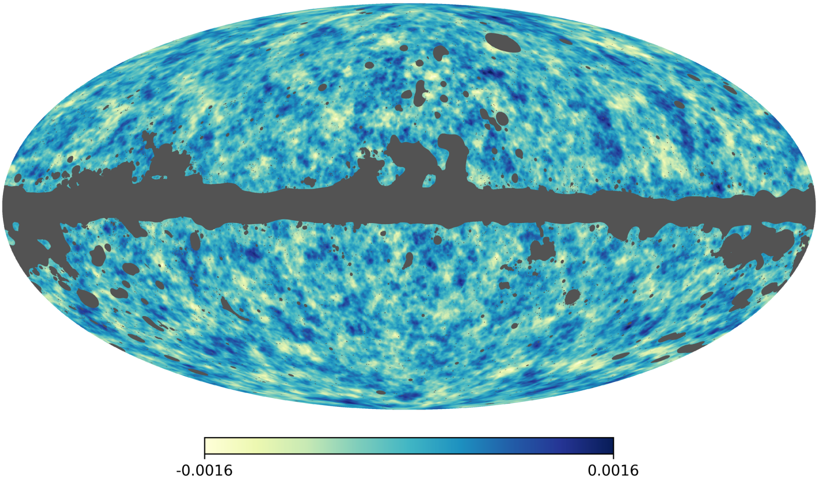
The CMB is 14 Gpc away.
$\delta\Phi$ nearly scale invariant on large scales, damped below horizon size at equality ($\sim 300\,\mathrm{Mpc}$).
There are $\sim 14000/300 \sim 50$ lenses along the line of sight, each with $\delta\Phi \sim 3 \times 10^{-5}$ or deflection $\alpha \sim 10^{-4}$ so $\alpha_{\mathrm{tot}} \sim 50^{1/2} \times 10^{-4} \sim 2'$.
Half-way to the surface of last scattering 300 Mpc subtends $300/7000 \sim 2^\circ$.

Measuring lensing from the CMB



- CMB fluctuations have a characteristic scale.
- Lensing "reconstruction" finds κ by measuring a local stretching of the power spectrum.
- Magnified regions shift power to larger scales (smaller ℓ).
- Demagnified regions shift power to smaller scales (higher ℓ).

Planck lensing map



Planck Collaboration (2018)

Coming of age

Planck was definitely not the first experiment to

- to measure lensing,
- … by large scale structure,
- … of the CMB

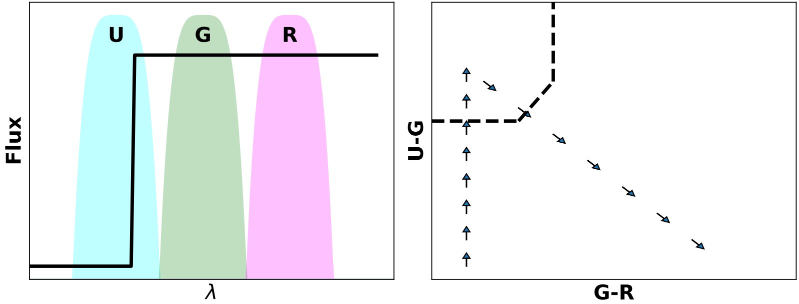
however it was the first experiment to measure CMB lensing by large scale structure over a significant fraction of the sky and with enough signal to noise that it provided a sharp test of the theory and could drive fits.

In some sense *Planck* was a "coming of age" for CMB lensing, and a taste of things to come – much of the science from future CMB surveys will come from lensing …

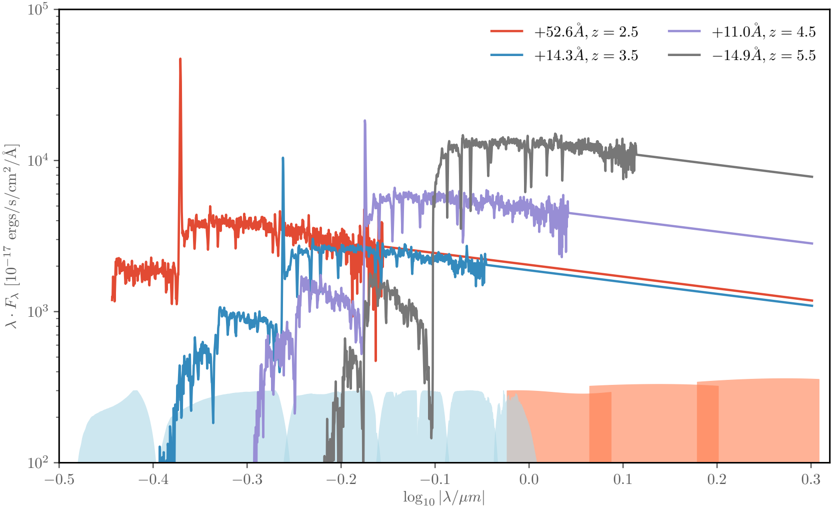
in combination with …

Dropout or Lyman-Break Galaxy (LBG) selection

Dropout color-color selection targets the steep break in an otherwise shallow F_ν spectrum bluewards of the 912Å Lyman limit due to absorption by the neutral hydrogen rich stellar atmospheres and interstellar photoelectric absorption. Lyman-series blanketing along the line-of-sight further suppresses flux short-ward of 1216Å for $z > 2$ sources



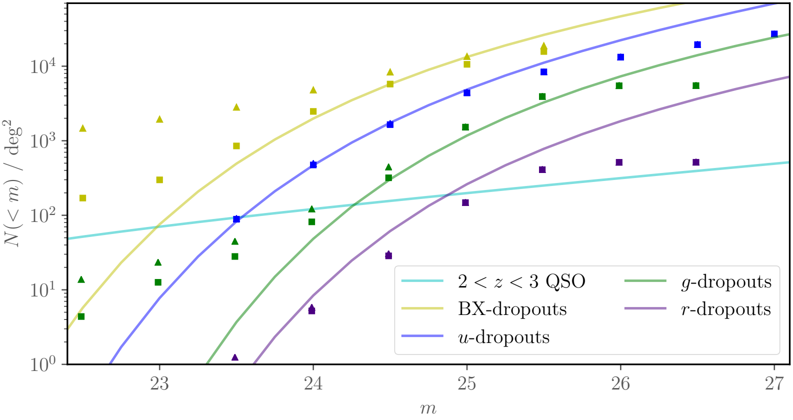
Composite spectra



Dropout or Lyman-Break Galaxy (LBG) selection

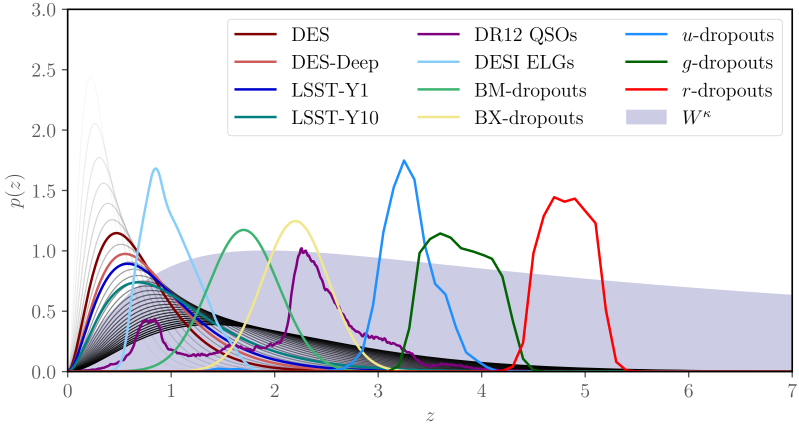
- Dropout selection requires only 3 filters, so is observationally efficient.
  - Easier to model selection than a photo-z based case.
- These objects have been extensively studied (for decades!) over the range $2 < z < 7$.
- Selects massive, actively star-forming galaxies – and a similar population over a wide redshift range.
- Rest-frame UV spectra dominated by O5 and B star emission with $M > 10\,M_\odot$ and $T > 2.5 \times 10^4$ K.
- LBGs lie on the main sequence of star formation and UV luminosity is approximately proportional to stellar mass.
- Galaxies of interest have $M_\star \sim 10^{10-11}\,M_\odot$,

Large numbers of galaxies



Tomographic lensing

The combination of galaxies with known redshifts and CMB lensing with its long lever arm can be particularly powerful ...



The opportunity

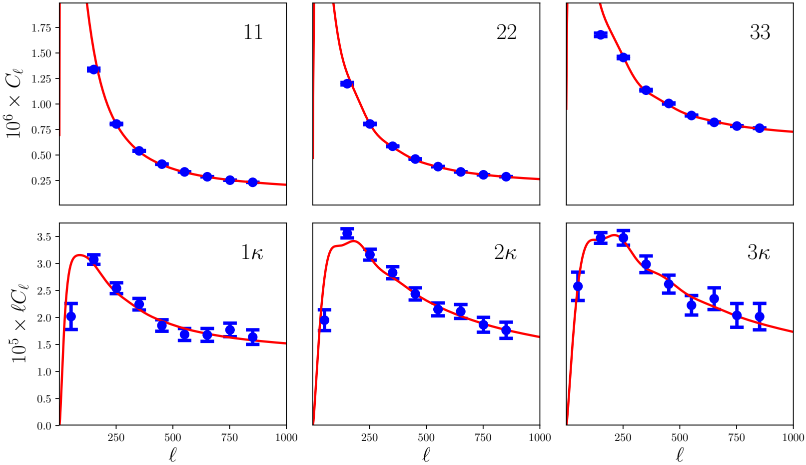
A new generation of deep imaging surveys and CMB experiments offers the possibility of using cross-correlations to

- constrain the early Universe
- investigate light particles
- test General Relativity
- probe the galaxy-halo connection
- measure the growth of large-scale structure

The combination can be more than the sum of its parts!
In particular we can use the optical survey to isolate the κ contribution from narrow z slices, increase S/N and downweight systematics.

Signal to noise: now

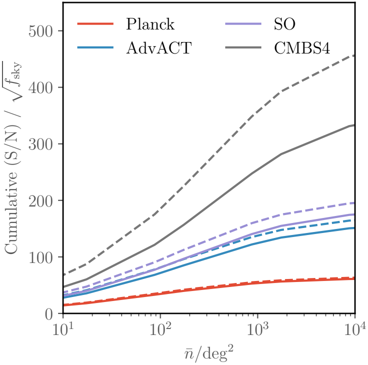
unWISE galaxies crossed with Planck lensing ...

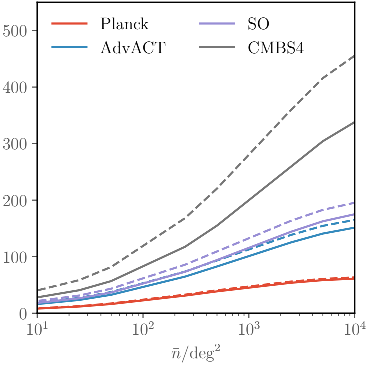


Krolewski+19

Signal to noise: the future

We could achieve $S/N \gtrsim 10^2$ at $z \simeq 3$ and at 4, larger than or comparable to S/N we can achieve in one bin at low z at present.

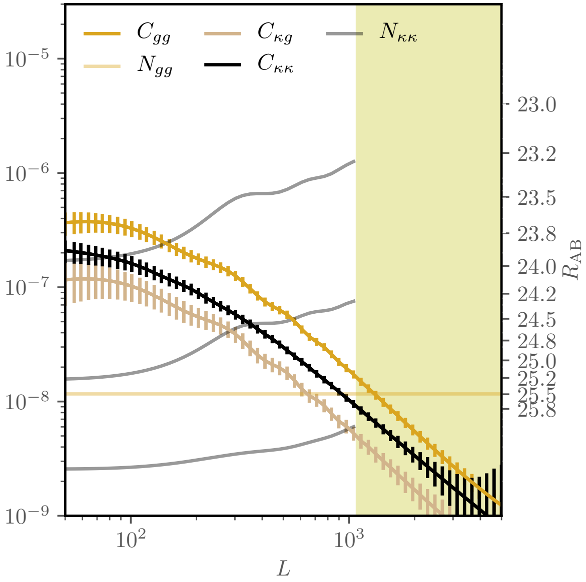




Fiducial samples

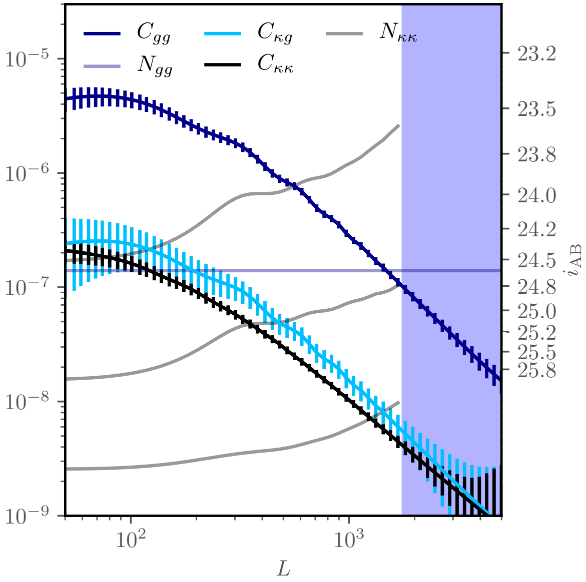
Sample	Band	$m_{\rm lim}$	$\log_{10} \bar{n}$	n_θ	b
BX	R	25.5	-2.06	26300	–
u-dropouts	i	24.6	-3.15	2220	4.0
g-dropouts	i	25.8	-2.45	5250	3.2
r-dropouts	z	25.8	-3.00	1300	5.4

Signal-to-noise: BX galaxies ($z \sim 2$)



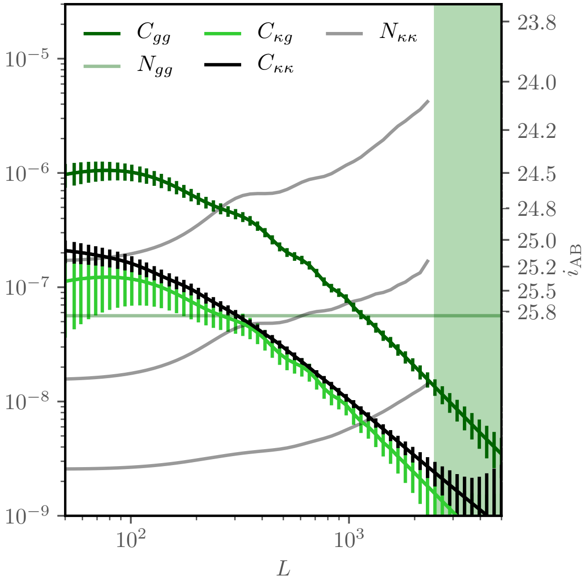
- C_ℓ^{gg}, $C_\ell^{\kappa g}$ and $C_\ell^{\kappa\kappa}$.
- Grey lines: noise levels (per ℓ) for AdvACT, SO and S4.
- Horizontal line: shot noise
- Band at L_{nl}.

Signal-to-noise: u-dropouts ($z \sim 3$)



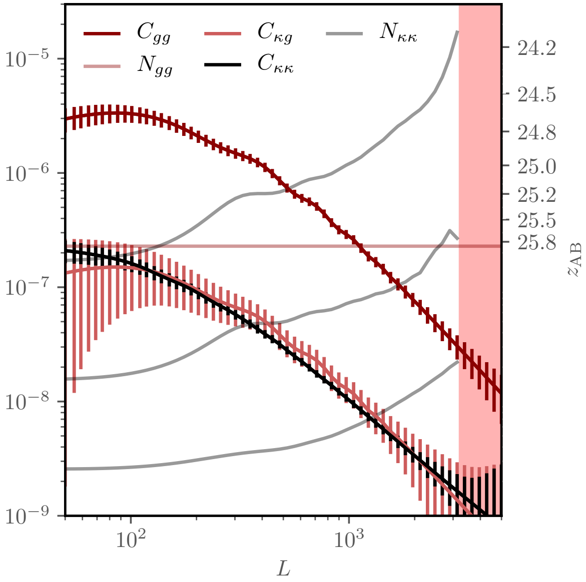
- C_ℓ^{gg}, $C_\ell^{\kappa g}$ and $C_\ell^{\kappa\kappa}$.
- Grey lines: noise levels (per ℓ) for AdvACT, SO and S4.
- Horizontal line: shot noise
- Band at $L_{\rm nl}$.

Signal-to-noise: g-dropouts ($z \sim 4$)



- C_ℓ^{gg}, $C_\ell^{\kappa g}$ and $C_\ell^{\kappa\kappa}$.
- Grey lines: noise levels (per ℓ) for AdvACT, SO and S4.
- Horizontal line: shot noise
- Band at L_{nl}.

Signal-to-noise: r-dropouts ($z \sim 5$)



- C_ℓ^{gg}, $C_\ell^{\kappa g}$ and $C_\ell^{\kappa\kappa}$.
- Grey lines: noise levels (per ℓ) for AdvACT, SO and S4.
- Horizontal line: shot noise
- Band at $L_{\rm nl}$.

Example: Measuring $P_{mm}(k,z)$

- A proper accounting of the growth of large scale structure through time is one of the main goals of observational cosmology – key quantity is $P_{mm}(k,z)$.
- Schematically we can measure $P_{mm}(k,z)$ by picking galaxies at z and

$$P_{mm}(k) \sim \frac{[bP_{mm}(k)]^2}{b^2 P_{mm}(k)} \sim \frac{[P_{mh}(k)]^2}{P_{hh}(k)} \sim \frac{\left[C^{\kappa g}_{\ell=k\chi}\right]^2}{C^{gg}_{\ell=k\chi}}$$

- Operationally we perform a joint fit to the combined data set.
  - With only the auto-spectrum there is a strong degeneracy between the amplitude (σ_8) and the bias parameters (b).
  - However the matter-halo cross-spectrum has a different dependence on these parameters and this allows us to break the degeneracy and measure σ_8 (and b).
- Need a model for the auto- and cross-spectra of biased tracers.

As always ...

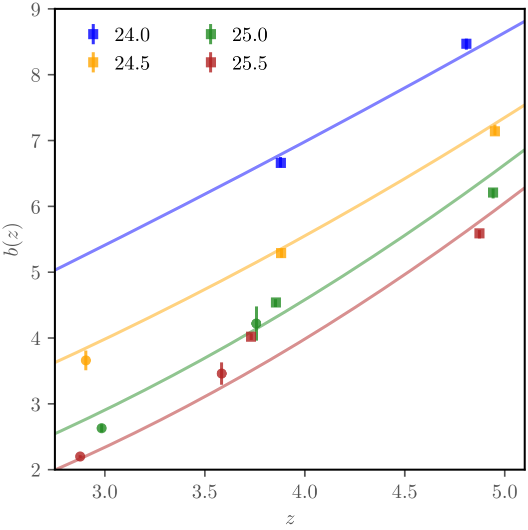
Improvements in data require concurrent improvements in the theoretical modeling in order to reap the promised science.

What is the right framework for analyzing such data?

We need a model which can predict the auto- and cross-spectra of biased tracers at large and intermediate scales.

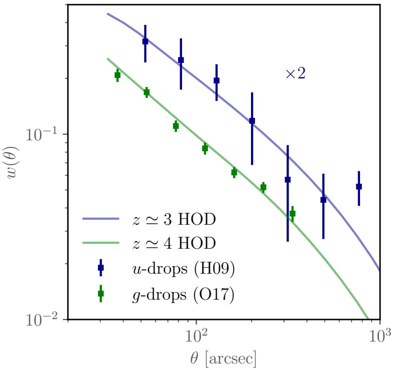
- Even though we are at high z and "large" scales it turns out that linear perturbation theory isn't good enough.
- Need to include non-linear corrections – and as soon as you do that you need to worry about scale-dependent bias, stochasticity and a whole host of other evils.

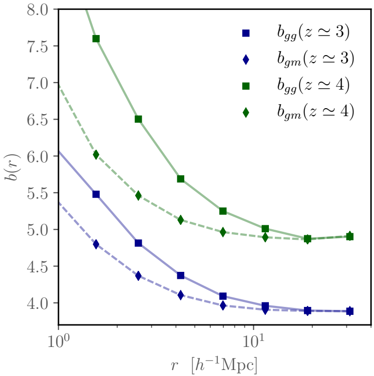
Highly biased objects



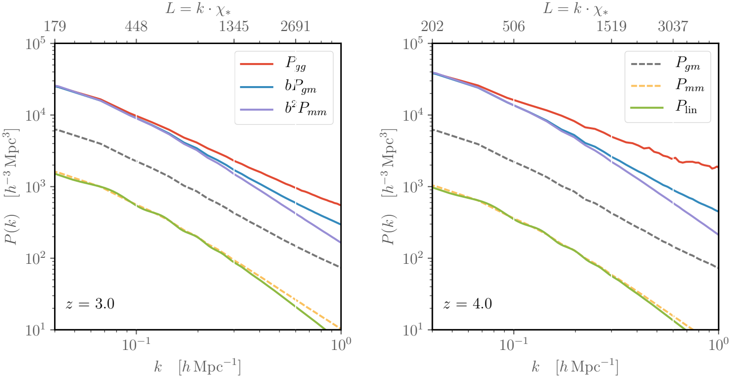
- From existing surveys we can estimate† the bias.
- Even at faint magnitudes, these are highly biased objects.

Scale-dependent bias





Scale-dependent bias



“Standard” model

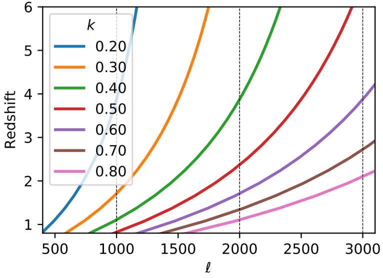
- The most widely used model to date is based on the HaloFit fitting function for $P_{mm}(k)$ (auto-magically computed by CAMB and CLASS).
- Most analyses assume scale-independent bias (but this is barely sufficient even “now”).
- One extension, motivated by peaks theory, is to use $b(k) = b^E_{10} + b^E_{11}k^2$.
- We will find we need to augment this with a phenomenological linear (k) term

$$P_{mh}(k) = \left[b^E_{10} + b^E_{1\frac{1}{2}}k + b^E_{11}k^2\right] P_{HF}(k)$$

$$P_{hh}(k) = \left[b^E_{10} + b^E_{1\frac{1}{2}}k + b^E_{11}k^2\right]^2 P_{HF}(k)$$

Note the (necessary) assumption that $b_{hh} = b_{mh}$!

Our approach



- Much of the information available from combining galaxy and CMB surveys lies at high z and low k.
- This is the regime where PT excels!
- Less sensitive to baryonic effects, galaxy formation physics, etc.

Extend the highly successful linear perturbation theory analysis of primary CMB anisotropies which has proven so impactful!

[Formalism in PT similar to CMB lensing formalism]

Perturbation theory

- As surveys get larger and more powerful more of the modes we measure well are "quasi-linear" $\Rightarrow$ analytic models.
- Over the last several decades, cosmological perturbation theory has developed steadily.
  - New ideas from particle physics and condensed matter.
  - Advances in modeling bias.
  - Generalizations beyond ΛCDM.
- At Berkeley we have been developing analytic models based on Lagrangian perturbation theory.
- Our original goal was baryon acoustic oscillations (BAO) and redshift-space distortions (RSD). But I will argue these tools (and others like them) are "perfect" for the coming world of survey cross-correlations...

CLEFT model

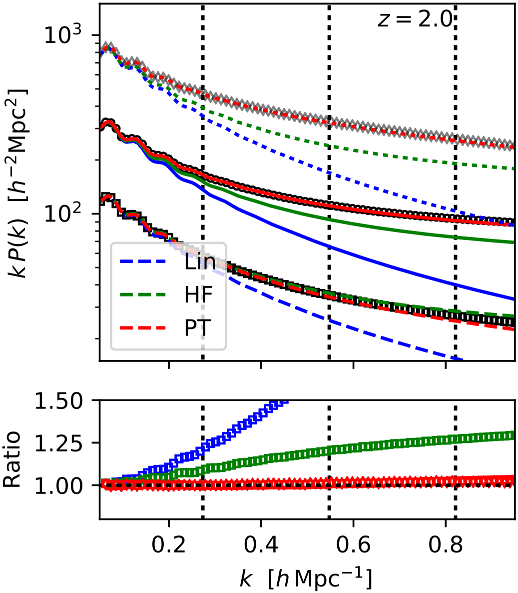
(Large scales, high z, it sounds like a job for ...)

The Lagrangian PT framework we have been developing for many years naturally handles auto- and cross-correlations in real and redshift space for Fourier or configuration space statistics. For example:

$$P_{mg}(k) = \left(1 - \frac{\alpha\, k^2}{2}\right) P_Z + P_{1-\mathrm{loop}} + \frac{b_1}{2} P_{b_1} + \frac{b_2}{2} P_{b_2} + \cdots$$

where P_Z and $P_{1-\mathrm{loop}}$ are the Zeldovich and 1-loop matter terms, the b_i are Lagrangian bias parameters for the biased tracer, and α is a free parameter which accounts for k^2 bias and small-scale physics not modeled by PT.

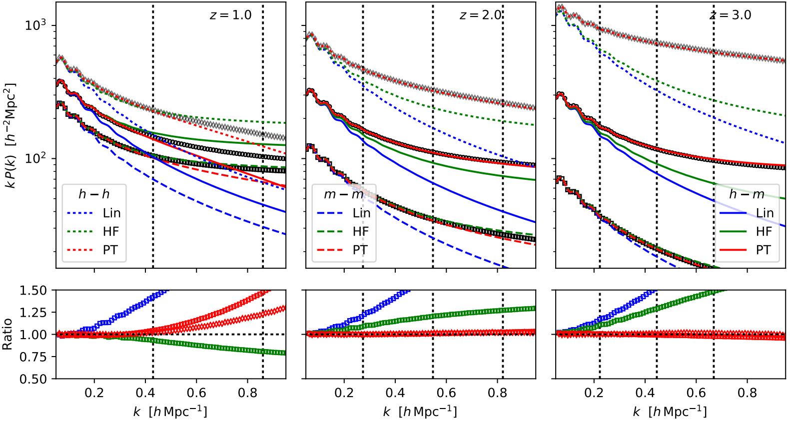
Comparison with N-body



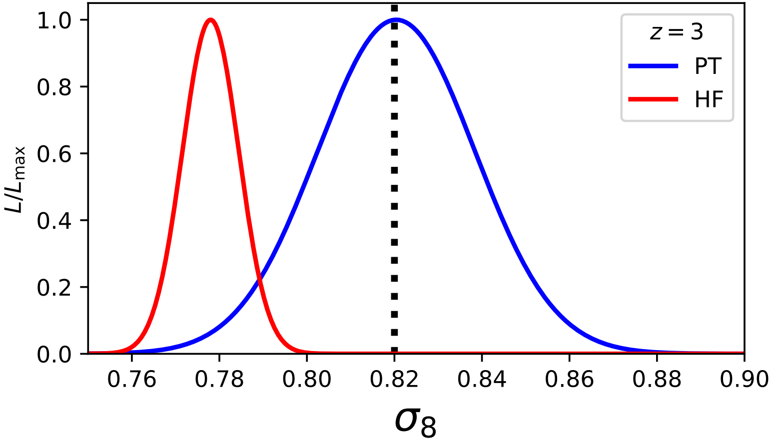
Let's look at the ingredients going into the prediction of C_ℓ^{XY}, for three cases:

- Linear theory, constant bias.
- HaloFit, constant bias (for now!).
- PT, $b_1 - b_2$.

Comparison with N-body



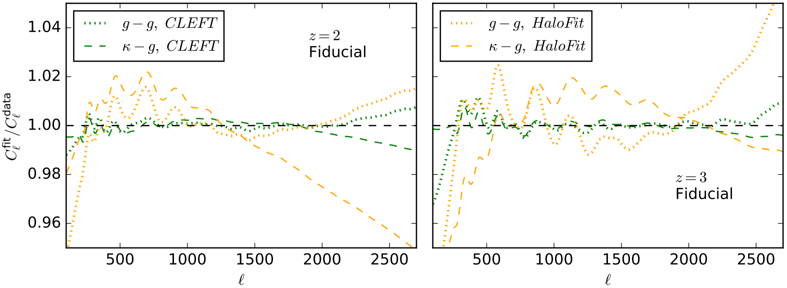
Model fit



1.0
0.8
0.6
0.4
0.2
0.0
$L/L_{\rm max}$
0.76
0.78
0.80
0.82
0.84
0.86
0.88
0.90
σ_8
$z = 3$
PT
HF

Model fit

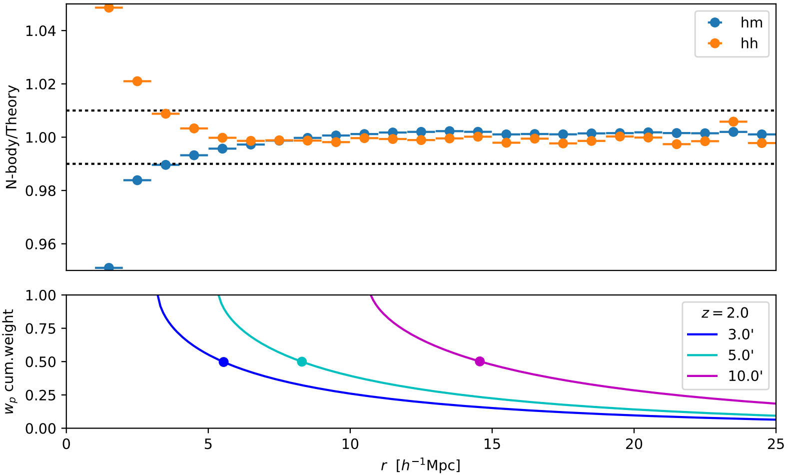
The likelihoods hide a lot of information about how the fit is performing. If we look at the best fit models:



Model fit

- Part of the issue with HALOFIT is with the fit to P_{mm}, much of it is with the $b(k)$ assumption.
  - Fitting functions for P_{mm} are good to $\mathcal{O}(5-15\%)$, but the error bars will be smaller than this.
  - Once b is large it is not a constant and $b_{hh} \neq b_{mh}$.
- At high z, modeling bias is at least as important as modeling non-linear structure formation.
- In the EFT language: k_{NL} shifts to higher k at higher z, but the scale associated with halo formation (the Lagrangian radius) remains constant for fixed halo mass.
- In general there is a "sweet spot", where b is not *too* scale dependent but non-linearity is not *too* pronounced.
- How $b_{ij}(k)$ depends upon complex tracer selection is unknown.

Model fit: configuration space



Future directions

- There are good reasons to work in configuration space, not Fourier space ... (with compensated filters?)
- Go to 2-loop, so we can work to lower z and higher ℓ.
- Add $m_\nu > 0$ or MG, v_{bc}, ...
- More explicit modeling of lensing.
- Inclusion of baryonic effects using EFT techniques.
- Look at non-Gaussianity from inflation (low ℓ).
- Combining 3D surveys with 2D surveys. More modes to a fixed ℓ, but more difficult to model.
- Clean low z. Can model $C_\ell^{\kappa\kappa}(> z_{\rm min})$ and the decorrelations using PT.
- Simultaneously fitting dN/dz and σ_8 using clustering redshifts.
- Multi-tracer techniques (Schmitfull & Seljak 2017).

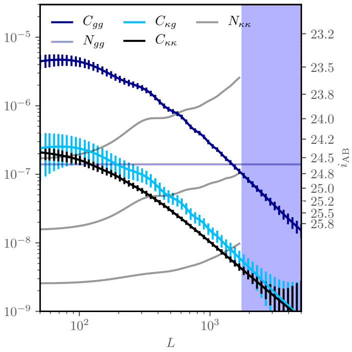
Conclusions

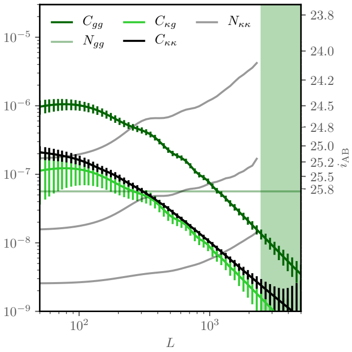
- We are on the cusp of a dramatic increase in the quality and quantity of both CMB and optical data. The combination can be more than the sum of its parts.
- As always, better data requires "better" modeling.
  - With primary anisotropies, linear theory is 99% of the story.
  - At lower redshift this is no longer the case.
- We need to model both non-linear matter clustering *and* bias.
- The fields of LSS and CMB have grown apart, but now are recoupling.
- The combination of high redshift and "large" scales makes this an attractive problem for analytic/perturbative attack.
- Generalizes to other high-z probes, in real- and redshift-space (e.g. LIM).

The End

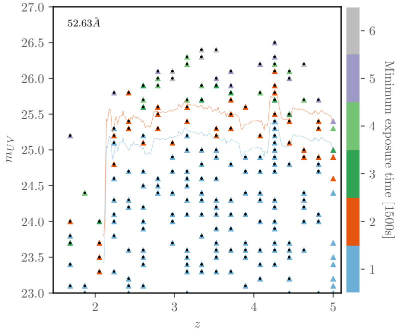
Ancillary material

Signal to noise





Exposure time



- Exposure time needed to get a redshift of a high-EW dropout with PFS.
- Using the highest EW quartile of Shapley et al.
- Lines show 1- and 2-hour exposure limiting magnitudes.

The landscape

A natural "by-product" of next generation CMB experiments to constrain primordial gravitational waves is high fidelity CMB lensing maps.

- CMB lensing is sensitive to the matter field and to the space-space metric perturbation, over a broad redshift range.
- CMB lensing has radically different systematics than cosmic shear (and measures[†] κ and γ).
- CMB redshift is very well known (but can't change it)!
- CMB lensing surveys tend to have large $f_{\rm sky}$, but relatively poor resolution.
- The lensing kernel peaks at $z \sim 2-3$ and has power to $z \gg 1$, where galaxy lensing becomes increasingly difficult.
- The CMB is behind "everything" ... but projection is a big issue.

Noise model I

The noise in our measurements goes as

$$\mathrm{Var}\left[C_\ell^{\kappa g}\right] = \frac{1}{(2\ell+1)f_{\rm sky}}\left\{\left(C_\ell^{\kappa\kappa}+N_\ell^{\kappa\kappa}\right)\left(C_\ell^{gg}+N_\ell^{gg}\right)+\left(C_\ell^{\kappa g}\right)^2\right\}$$

where $f_{\rm sky}$ is the sky fraction, C_ℓ^{ii} represent the signal and N_ℓ^{ii} the noise in the auto-spectra.

Similarly

$$\mathrm{Var}\left[C_\ell^{gg}\right] = \frac{2}{(2\ell+1)f_{\rm sky}}\left(C_\ell^{gg}+N_\ell^{gg}\right)^2$$

At low ℓ we are *sample variance* limited, and at high ℓ we are *noise* limited. For future experiments the transition will be $\ell \sim 10^3$.

Noise model II

For the galaxies the noise is simply shot-noise: $N_\ell^{gg} = 1/\bar{n}$
For the lensing we approximate the noise as

$$N_L^{\kappa\kappa} = \left[\frac{\ell(\ell+1)}{2}\right]^2 \left[\int \frac{d^2\ell}{(2\pi)^2} \sum_{(XY)} K^{XY}(\vec{\ell}, \vec{L})\right]^{-1}$$

with e.g.

$$K^{EB}(\ell, L) = \frac{[(\vec{L} - \vec{\ell}) \cdot \vec{L} C^B_{\ell - L} + \vec{\ell} \cdot \vec{L} C^E_\ell]^2}{C_\ell^{\mathrm{tot},E} C_{\ell-L}^{\mathrm{tot},B}} \sin^2(2\phi_\ell)$$

and similar expressions for TT, TE and EE.
(Ignore foregrounds *and* iterative methods.)

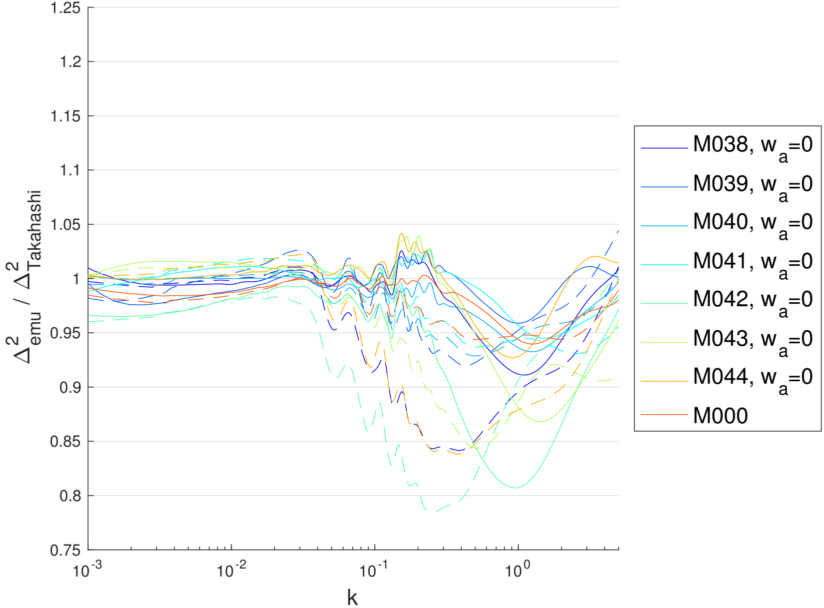
Effective redshift

- It is often the case that we wish to interpret the C_ℓ, which involve integrals across cosmic time, as measurements of the clustering strength at a single, "effective", epoch or redshift.
- Define

$$z_{\rm eff}^{XY} = \frac{\int d\chi\ \left[W^X(\chi)W^Y(\chi)/\chi^2\right]\ z}{\int d\chi\ [W^X(\chi)W^Y(\chi)/\chi^2]}$$

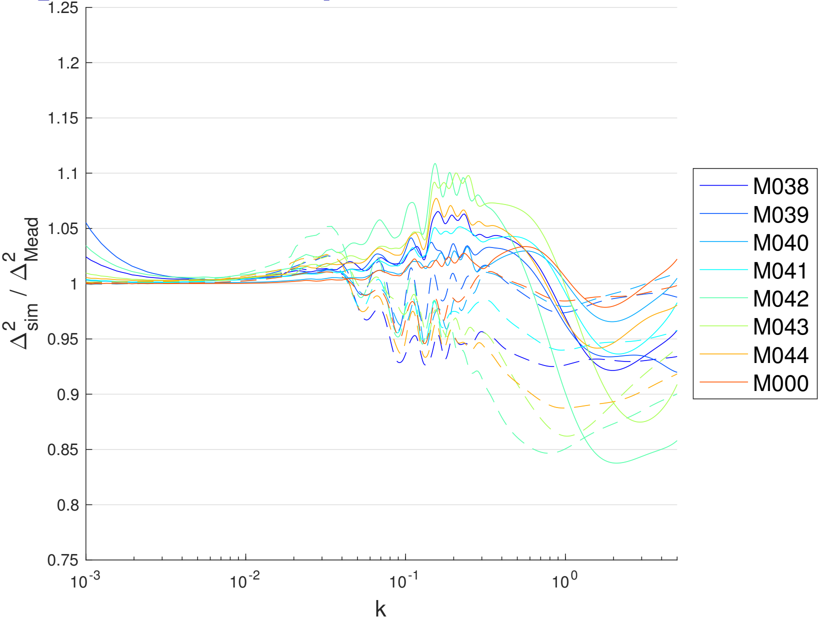
  such that the linear term in the expansion of $P(k,z)$ about $z_{\rm eff}^{XY}$ cancels in the computation of C_ℓ^{XY}.
- The C_ℓ computed with $P(k, z_{\rm eff})$ fixed are within 1.5% of the full result for $\Delta z \leq 0.5$ and $\ell > 10$ for $1 < z < 3$.

Fitting function accuracy



Lawrence et al. (2017)

Fitting function accuracy



Lawrence et al. (2017)

Perturbation theory

- CMB anisotropies are "everyone's favorite", linear, cosmological perturbation theory calculation ...
- Arguably, CMB anisotropies form the gold standard for cosmological inference and cosmological knowledge.
- A well controlled, analytic calculation which can be compared straightforwardly to observations.
- As we move to lower redshifts we need to start worrying about structure going non-linear and about the relation between the matter field and what we see (bias).

Lowest order I

$$
\begin{aligned}
P_{\rm tree} &= 4\pi \int q^2\, dq\ e^{-(1/2)k^2(X_L+Y_L)} \Bigg\{ \\
& \left[1 + b_1^2\left(\xi_L - k^2 U_L^2\right) - b_2\left(k^2 U_L^2\right) + \frac{b_2^2}{2}\xi_L^2\right] j_0(kq) \\
&+ \sum_{n=1}^{\infty} \left[1 - 2b_1 \frac{q\,U_L}{Y_L} + b_1^2\left(\xi_L + \left[\frac{2n}{Y_L} - k^2\right] U_L^2\right)\right. \\
& +b_2\left(\frac{2n}{Y_L} - k^2\right) U_L^2 \\
& \left. -2b_1 b_2 \frac{q\,U_L\,\xi_L}{Y_L} + \frac{b_2^2}{2}\xi_L^2\right] \left(\frac{k\,Y_L}{q}\right)^n j_n(kq) \Bigg\}
\end{aligned}
$$

For cross-correlations: $b_1 \to \frac{1}{2}\left(b_1^A + b_1^B\right)$, $b_1^2 \to b_1^A b_1^B$, etc.

Lowest order II

Where

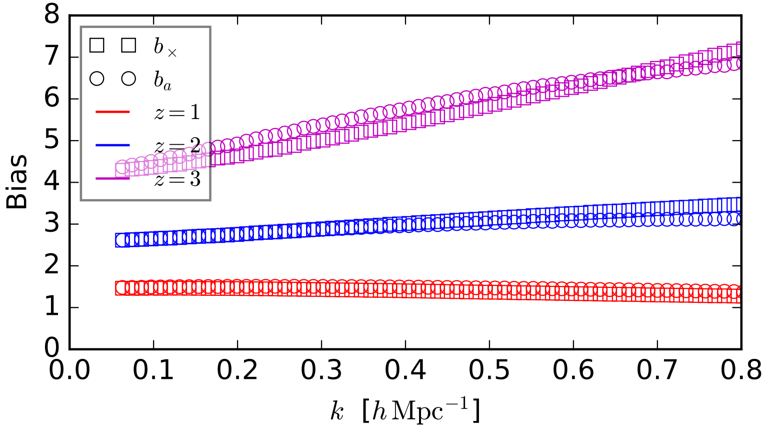
$$
\begin{aligned}
\xi_L(q) &= \frac{1}{2\pi^2}\int_0^\infty dk\; P_L(k)\left[k^2\, j_0(kq)\right] \\
X_L(q) &= \frac{1}{2\pi^2}\int_0^\infty dk\; P_L(k)\left[\frac{2}{3} - 2\frac{j_1(kq)}{kq}\right] \\
Y_L(q) &= \frac{1}{2\pi^2}\int_0^\infty dk\; P_L(k)\left[-2j_0(kq) + 6\frac{j_1(kq)}{kq}\right] \\
U_L(q) &= \frac{1}{2\pi^2}\int_0^\infty dk\; P_L(k)\left[-k\, j_1(kq)\right]
\end{aligned}
$$

The integrals over q can be done efficiently using fast Fourier transforms or other methods.

The full expressions contain "1-loop" terms which are integrals of P_L^2.

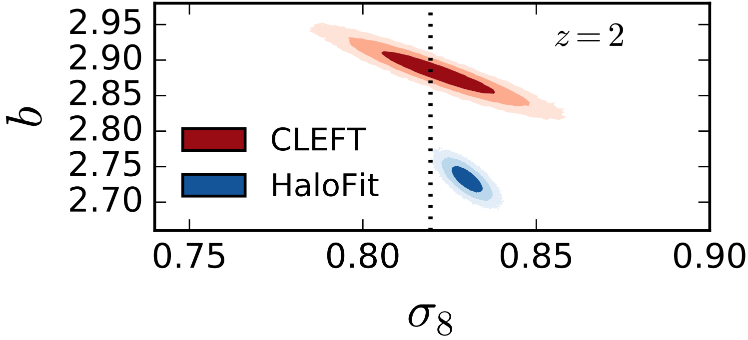
Scale-dependent bias

In detail P-S isn't right, but ...



Note the bias is scale-dependent, and the scale dependence is different for the auto- and cross-spectra.

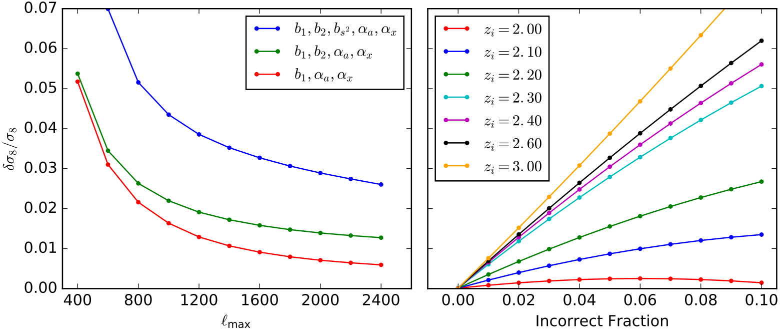
Model fit: galaxies



(b means something different in each theory)

Knowing dN/dz

We can use the Fisher forecasting formalism to investigate where the signal is coming from, degeneracies, and biases.



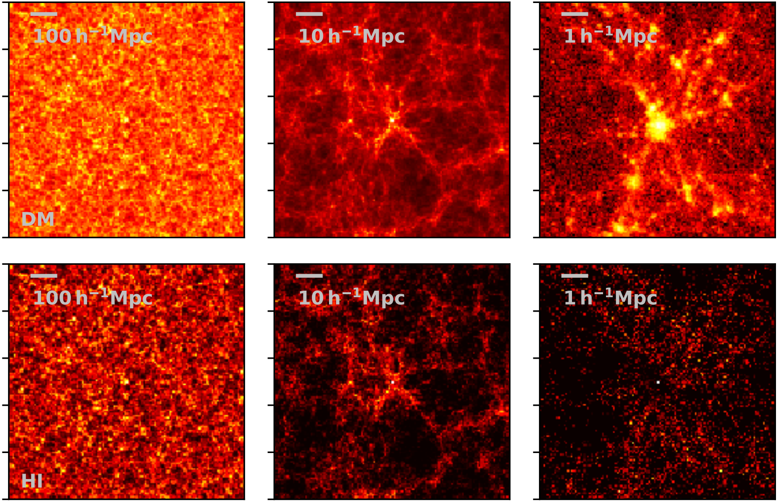
Can work at relatively low ℓ, but need to know dN/dz well.

Model fit

- Consider a future experiment, motivated by LSST and CMB-S4 but it could be a number of things.
- Imagine cross-correlating the CMB lensing map with the (gold sample) galaxies in a slice $\Delta z = 0.5$ at $z = 1$, 2 and 3.
  - $i_{\rm lim} = 25.3$.
  - $\theta_b = 1.5'$, $\Delta_T = 1\,\mu$K-arcmin.
- Compare two 'models':
  - HaloFit with $b(k) = b^E_{10} + b^E_{1\frac{1}{2}}\,k + b^E_{11}\,k^2$.
  - Perturbation theory with b_1, b_2 (and α_i).
- Concentrate on just measuring an amplitude of matter clustering, σ_8.
- Jointly fit $C_\ell^{\kappa g}$ and C_ℓ^{gg} ...

Hidden Valley

A set of $> 10^{12}$ particle N-body simulations directed at IM science ...



cyril.astro.berkeley.edu

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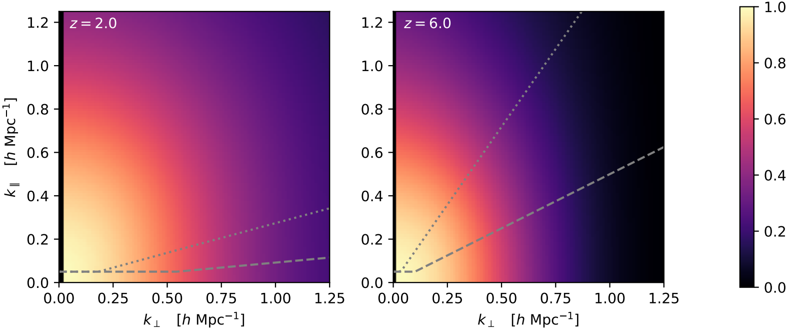

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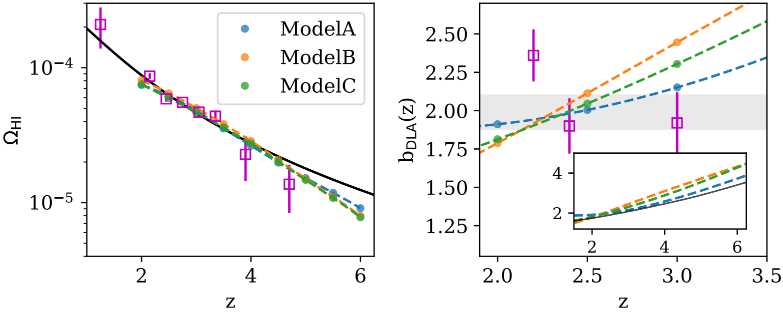

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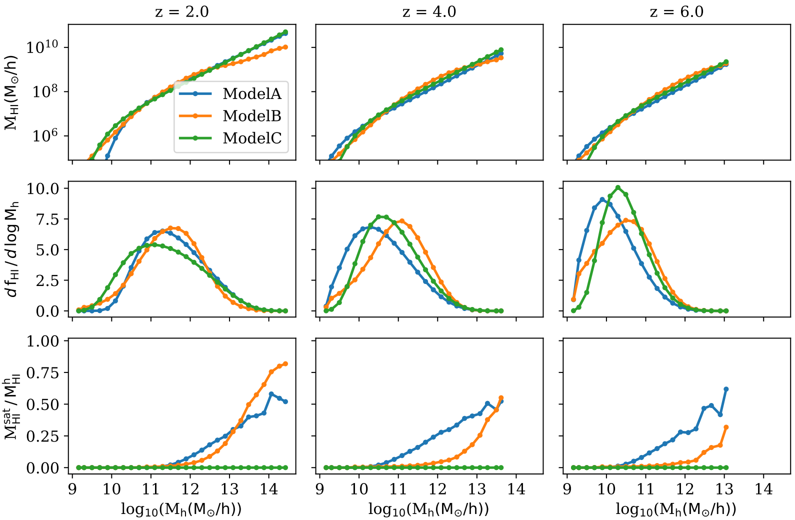

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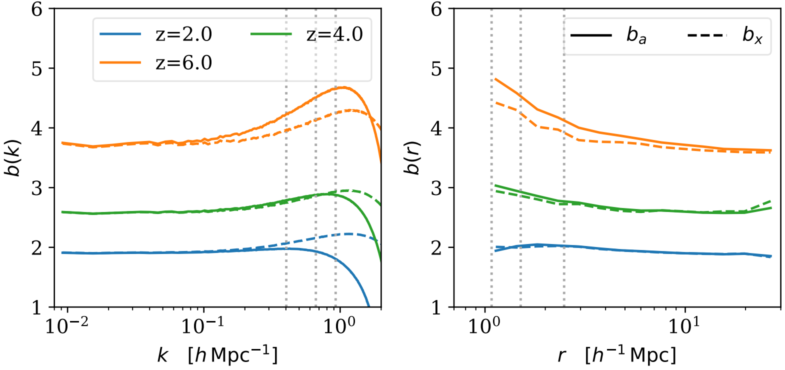

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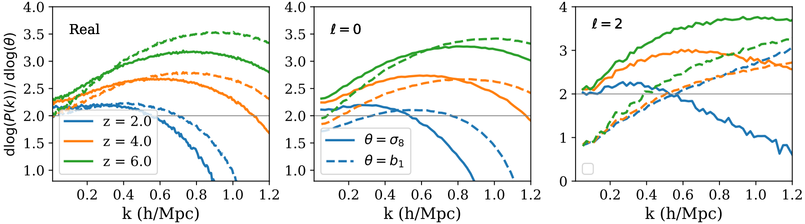

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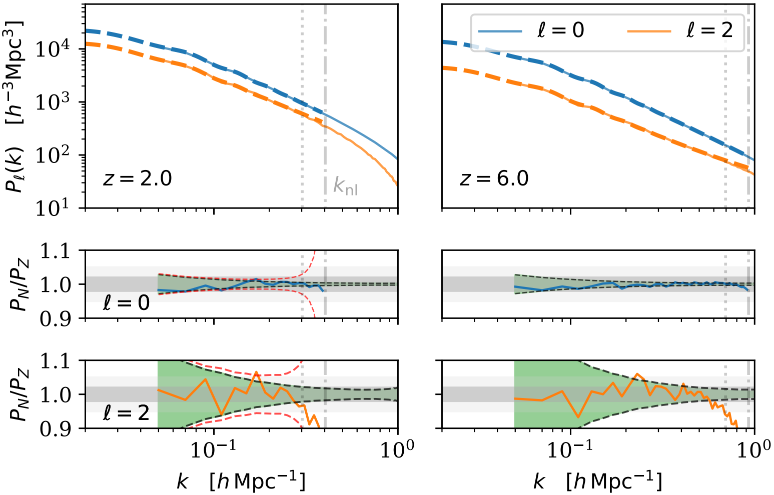

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