Cosmology at high redshift: a probe of fundamental physics

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Wither cosmology?

We are cursed/blessed with a "standard model" of cosmology:

- "The 6-parameter ΛCDM model continues to provide an excellent fit to the cosmic microwave background data at high and low redshift, describing the cosmological information in over a billion map pixels with just six parameters." Planck18-I
- Despite its incredible success, at a fundamental level ΛCDM "makes no sense". It has 'strange constituents' (Λ and CDM!) and poorly understood epochs (e.g. inflation).
- It's surely (?) only a phenomenological model ... that will be replaced by a more complete understanding.
- **Stress testing this model, and seeing what breaks, is a primary focus of current research!**
- One bright spot – we are entering the golden era of cosmological surveys, and are nowhere near exhausting the information we can access.

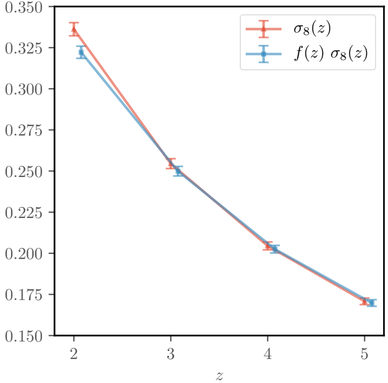
Tensions in the current model

Not everything is rosy in the land of ΛCDM – "tensions" (Hubble tension, S_8/growth tension, ...)

- These tensions are the focus of a lot of effort in the field!
- The evidence is not as robust as we'd like, but they resist 'easy' solution.
- They have only arisen as we've shrunk the error bars: "precision" cosmology.
  - 'Hubble tension' and 'growth tension' represent $\mathcal{O}(10\%)$ shifts in parameters.
  - Seeing such things at $> 5\,\sigma$ requires $\sigma \simeq 1 - 2\%$

Since the model is working "pretty well" any signatures of BSM physics or deviations from ΛCDM are likely to be subtle ...

Firm prediction of ΛCDM: growth of LSS



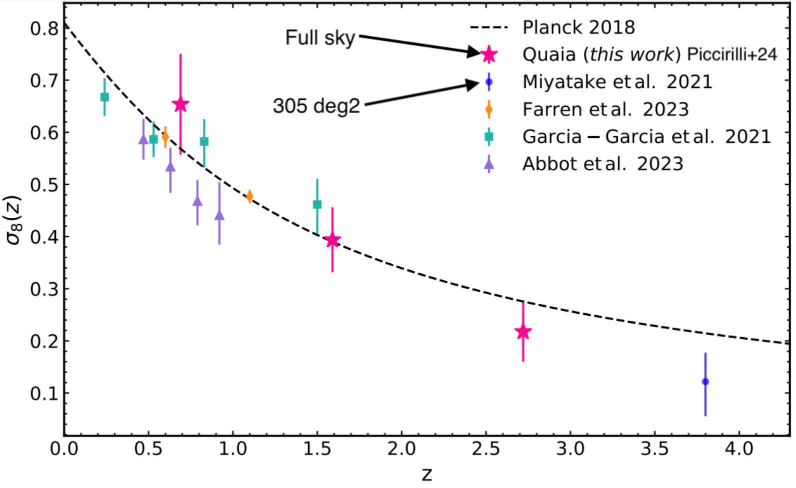
- Between $z \simeq 10^3$ and today, fluctuations grow by $\sim 10^3$.
- GR+ΛCDM predicts growth very precisely when conditioned on the CMB.
- Marginalizing over unknown parameters, growth is predicted to 1.1% vs. z (dominated by m_ν uncertainty).

Is GR+ΛCDM right?

[Along the way test gravity model, expansion history, contents, ...]

Structure at high z!

Proof of principle that we can trace large-scale structure at high z with galaxies and lensing – and $\approx 300\,\mathrm{deg}^2$ of galaxy data from Subaru is worth a "full sky" QSO catalog!



Opportunity

To really move into the precision era, however, we need to move to 3D, i.e. a spectroscopic survey!

- Recent advances in detectors and experimental techniques have made it feasible to dramatically extend spectroscopic surveys with 'modest' cost.
- This opens the possibility that spectroscopic galaxy surveys could surpass even the CMB as a probe of fundamental physics.
- Reorients spectroscopic surveys away from "DE FOM".
  - inflation, non-Gaussianity, parity violation, cosmological collider, primordial features, axions, light relics, dark radiation, neutrino masses and interactions, dark matter, ...

See Haruki Ebina's talk for detailed forecasts ...

A spectroscopic roadmap

This opportunity has been recognized by the community, who are supportive of a roadmap towards a "Stage V" spectroscopic survey that includes a pathfinder (DESI-2) and a future facility:

> Spec-S5, holds great promise to advance our understanding and reach key theoretical benchmarks in several areas: inflationary physics via the statistical properties of primordial fluctuations, late-time cosmic acceleration, light relics, neutrino masses, and dark matter – *P5 report (Murayama)*.

Open the precision frontier!

Science case for Stage V

The details of this science case have been discussed in a number of meetings, white papers and published papers. I can also highly recommend the talks linked from the websites of recent conferences on this topic:

- New Physics from Galaxy Clustering I
  https://indico.cern.ch/event/1192722/
- New Physics from Galaxy Clustering II
  https://indico.cern.ch/event/1308028/
- Fundamental Physics from Future Spectroscopic Surveys
  https://indico.physics.lbl.gov/event/2769
- New Physics from Galaxy Clustering III
  https://indico.cern.ch/event/1375290

Opportunity

What should Stage V look like?

In the interests of time, I will focus on one of the science cases that a future spectroscopic survey could enable. Such a facility will be uniquely powerful though, and a complete program would include other science cases as well, in cosmology and elsewhere.

Maximizing S/N

Want to maximize the S/N for new, BSM, physics

- There are many possible extensions to our SM (ΛCDM+GR).
  - See e.g. "New physics from galaxy clustering" workshop series.
- None are more compelling than others.
- If theory can't give us guidance, maybe phenomenology can?
  1. Work where inference is clean.
  2. If you don't know how to maximize S, then minimize N!
- **Design an experiment that is capable of investigating proposed solutions to existing anomalies while being sensitive to a broad range of BSM physics.**

Push to higher redshift, in the epochs before cosmic noon ($z \simeq 2$)!

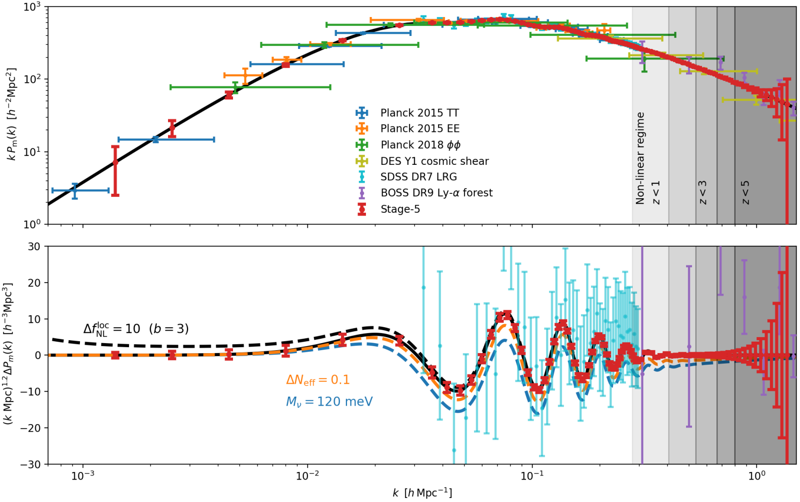
Standard ~~ruler~~ spectrum

Moving to higher z gives us:

1. Fundamental mode moves to lower k (larger volume).
2. Non-linear scale moves to higher k (less evolved).
   - Get "unprocessed" information from the early Universe.
3. Longer lever arm in time.
4. Large dynamic range in scale where we have highly precise measurements of $\delta(k)$.
5. **We're sensitive to anything that deviates from "boring" spectra (could be primordial, could be bias, could be evolution, could be new interactions, ...)**

LSS at high-z offers many of the advantages of CMB anisotropy!

The big picture – standard ~~ruler~~ spectrum!



Tracers of LSS at $2 < z < 6$

How can we trace large-scale structure at $z > 2$?

- CMB lensing (plus tSZ, kSZ, ...).
  - A natural biproduct of surveys aimed at r.
  - By probing the matter field we get an "unbiased" tracer.
  - By using relativistic particles we probe both metric potentials.
  - Next-generation CMB experiments capable of dramatically improving on the current state of the art are **already funded and in construction** with even better instruments proposed!
- **Hi-z galaxies (LBGs and LAEs)**
  - Dropout, or Lyman Break Galaxy (LBG) selection targets the steep 912Å break in an otherwise 'flat' spectrum.
  - Selects massive, star-forming galaxies (tend to have high b).
  - Some of these have bright emission lines (e.g. LAEs), allowing very efficient redshifting. Tend to have lower b.
- The IGM ... in galaxy spectra (Lyα tomography).

Learning on the job

One of the advantages of large spectroscopic surveys is that the same instrument can take spectra of many kinds of targets – optimize the science return.

- Different science cases have different drivers.
- For cosmology, we have accurate forecasts allowing survey optimization.
- High and low bias tracers (LBGs and LAEs) are good for different science (e.g. $f_{NL}^{\rm loc}$, x-correlation vs. RSD) – the combination allows new approaches to clustering analysis (multi-tracer, density split statistics, h.o. moments, ...).

Need data to allow efficient target selection!

See Anand Raichoor's talk for more details ...

Conclusions

We are in the midst of the “golden age of cosmological surveys”.

- DESI, Euclid, SPHEREx, PFS, Rubin, Roman, ..., Simons, S4, ... will keep us busy for some time!
- The case for future spectroscopic surveys targeting “high z” is strong.
  - Long lever arms in scale and time where errors are small.
- We need to be planning for this now!
- We can optimize our spectroscopy for our science case.
- We need to be able to efficiently select targets.
- These same data allow a ‘downpayment’ on DESI-2 or Stage V science through projected clustering and cross-correlations – if calibrated with a small amount of spectroscopc follow-up.

The End!

Implications of "special selections"

Redshifts > 2 are a long way away, and we're planning to select special sub-populations of objects.

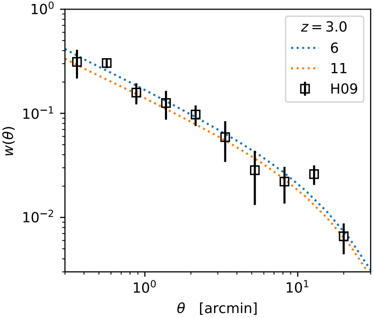
- Within the context of PT, all objects are just biased tracers of the matter field. Special selection $\Rightarrow$ implications for bias.
- 'Break' in the halo mass function, $M_{h,\star}$, shifts to smaller masses at high z.
- Large d_L means even faint galaxies are very luminous, e.g. high $M_\star$ or SFR.
- Bias tends to be large, and therefore scale-dependent.
- Satellite fractions tend to be low (we're on the steeply falling part of the halo mass function), suggesting smaller FoG.
- Stochastic terms smaller than we're used to at lower z for fixed b (since $\bar{n} \propto \bar{\rho}/M_{h,\star}$).

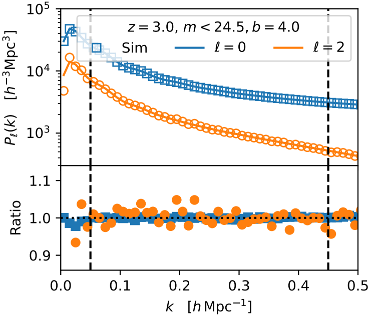
Bias expansion

What implications does this have?

- High bias can be a boon or a curse
  - Higher S/N in the monopole, more sensitive to $f_{NL}^{\rm loc}$, x-correlations, ...
  - Smaller RSD, so one important "protected by symmetry" signal is "lost"
- There's no problem, in principle, in going to higher order in the bias expansion – but we need to worry about degeneracies, projection effects, loss of constraining power.
  - Would we need simulation-based priors?
  - What measurements would we use to validate them?

Scale-dependent bias: LBGs





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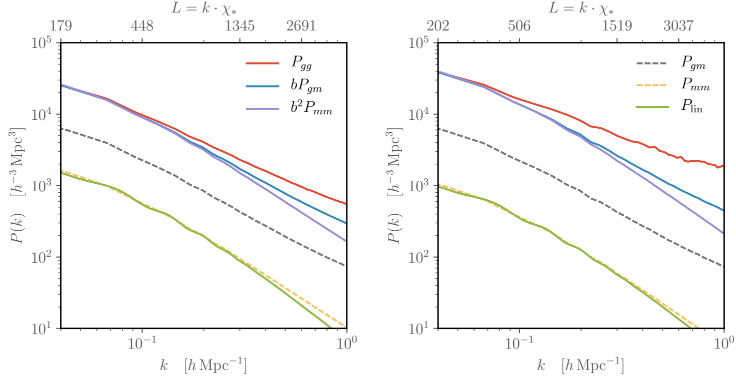
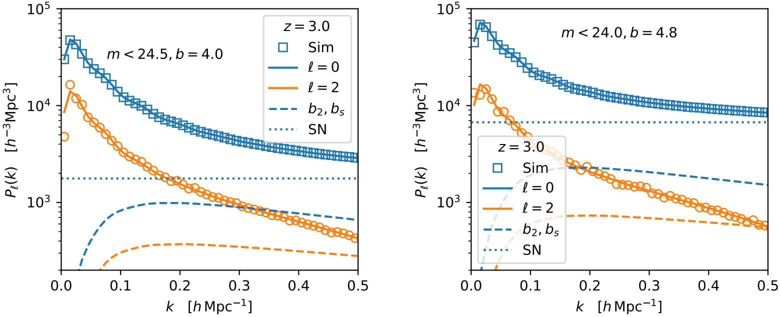
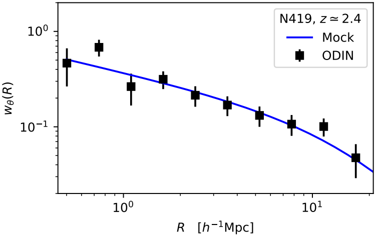


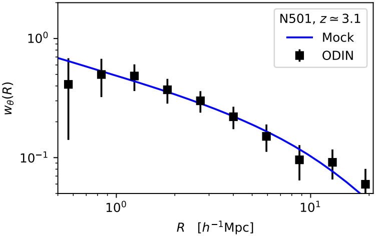
Wilson+19

Scale-dependent bias: LBGs



Lyman-α emitters (LAEs)

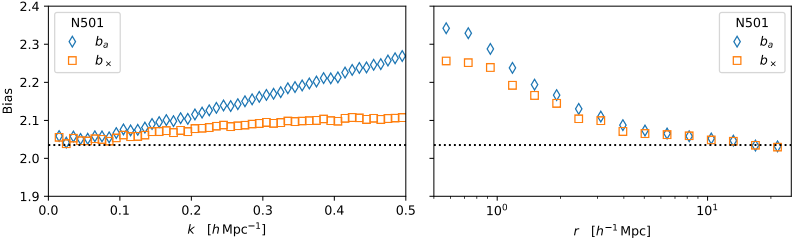




White+24

Scale-dependent bias: LAEs

For the LAEs, with lower bias, these effects are much reduced.



White+24

Line-of-sight and RT

If we want low bias, that's probably faint galaxies so we need 'strong' lines to have decent redshift success rate.

- Lyα is a resonant line, so strongly affected by radiative transfer (RT).
- RT modulates the galaxy selection depending upon local density and (line-of-sight) velocity divergence.
  - These are key signals for us!
- How strongly is currently under debate
  - Zheng+11 argue for a large effect.
  - Behrens+18 claim that this is due to poor resolution in the older simulation. (If gas very dense where Lyα is emitted, random walks more in frequency space before leaving the galaxy.)
- This plays havoc with our ability to constrain some parameters (Ebina+24)
- We know the physics – can we "break this degeneracy" using other measurements?

Lots of volume!

For a highly biased sample (neglect RSD)

$$\frac{\Delta P(k)}{P(k)} \approx \sqrt{\frac{2}{N_k}} \left[1 + \frac{1}{\bar{n}P}\right] = \frac{2\pi}{\sqrt{Vk^3 \ \Delta \ln k}} \left[1 + \frac{1}{\bar{n}P}\right]$$

For 18K sq.deg. from $3.0 < z < 3.5$ we have $V = 34.5\, h^{-3}\mathrm{Gpc}^3$.

Assuming 50% success for $m_{UV} < 24.5$ u-dropouts,
$\bar{n}P(k = 0.1) \simeq 3$, $\bar{n}P(k = 0.3) = 0.5$ and $\bar{n}P(k = 0.5) = 0.1$.
This implies:

$$\frac{\Delta P}{P} = 0.2\% \quad \text{at} \quad k \simeq 0.3\, h\,\mathrm{Mpc}^{-1} \quad \text{with} \quad \Delta \ln k = 0.1$$

and $< 1\%$ over more than 1.5 dex in scale (per $\Delta \ln k = 0.1$).