Title: A Theory for All Seasons: Combining Full-Shape and BAO information in BOSS

Speakers: Shi-Fan Chen

Series: Cosmology & Gravitation

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Abstract: Spectroscopic surveys are a powerful cosmological probe, encoding information about structure formation and the geometry of the universe in the 3D distribution of galaxies. Upcoming surveys like DESI, which will increase the number of measured galaxy redshifts by an order of magnitude, will test our ability to use this information while providing opportunities to test fundamental physics in unprecedented ways. In this talk I will discuss our recent work on a new method to combine the two main prongs of these surveys--redshift-space distortions and BAO--within the framework of Lagrangian perturbation theory. As an illustrative example, I will discuss the application of this method to data from the BOSS survey, obtaining cosmological constraints that are competitive but consistent with primary CMB and lensing measurements. I will also discuss future prospects for perturbation theory analyses of large-scale structure, for example by jointly analyzing spectroscopic and lensing surveys.

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COSMOLOGICAL PHYSICS

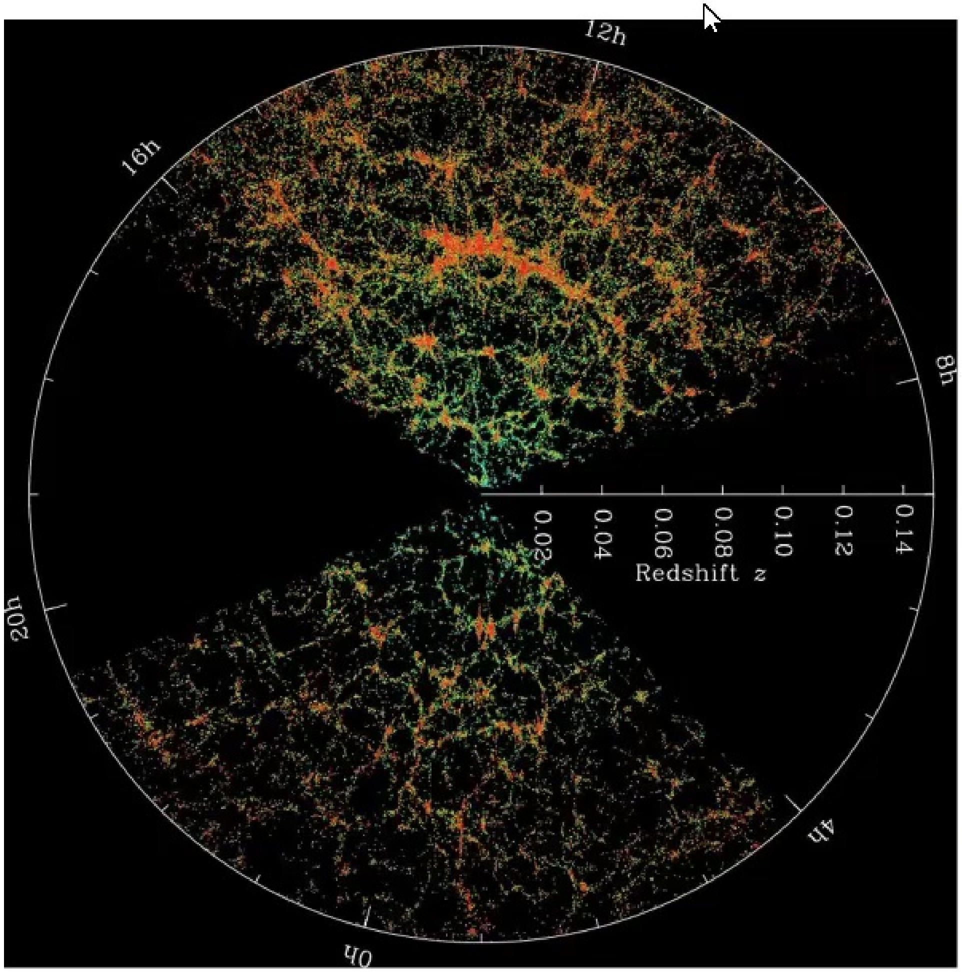
A Theory for All Seasons: Combining Full-Shape and BAO information in BOSS

Stephen Chen (w/ Martin White and Zvonimir Vlah)

Outline

1. Forward Models for Spectroscopic Surveys: from Cosmology to Data
2. Comparison to Previous Approaches: Template Fits
3. Why (Lagrangian) Perturbation Theory?
4. Application to BOSS
5. Conclusions

Forward Models of Spectroscopic Surveys

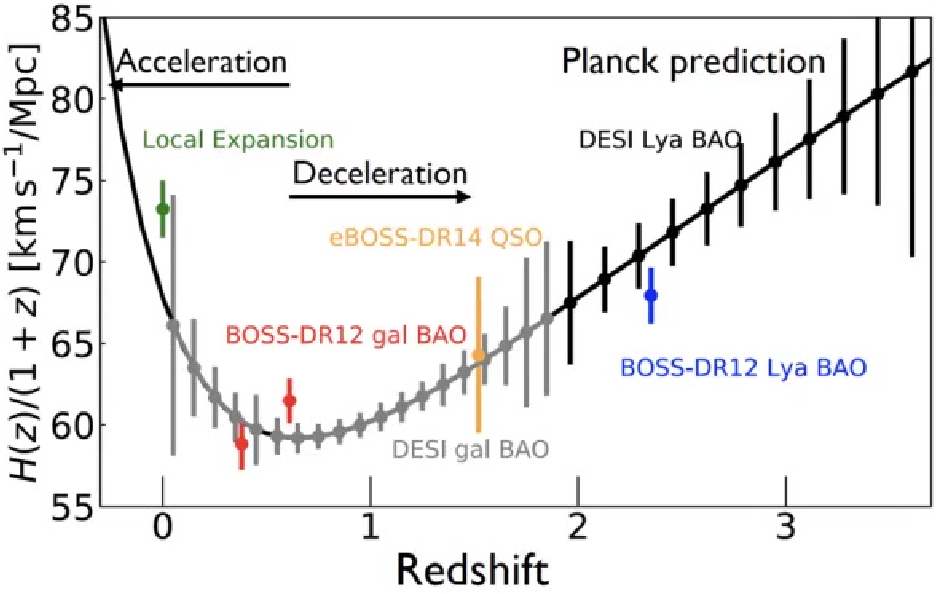


Spectroscopic Surveys

Spectroscopic surveys are a unique, 3D probe of large-scale structure.

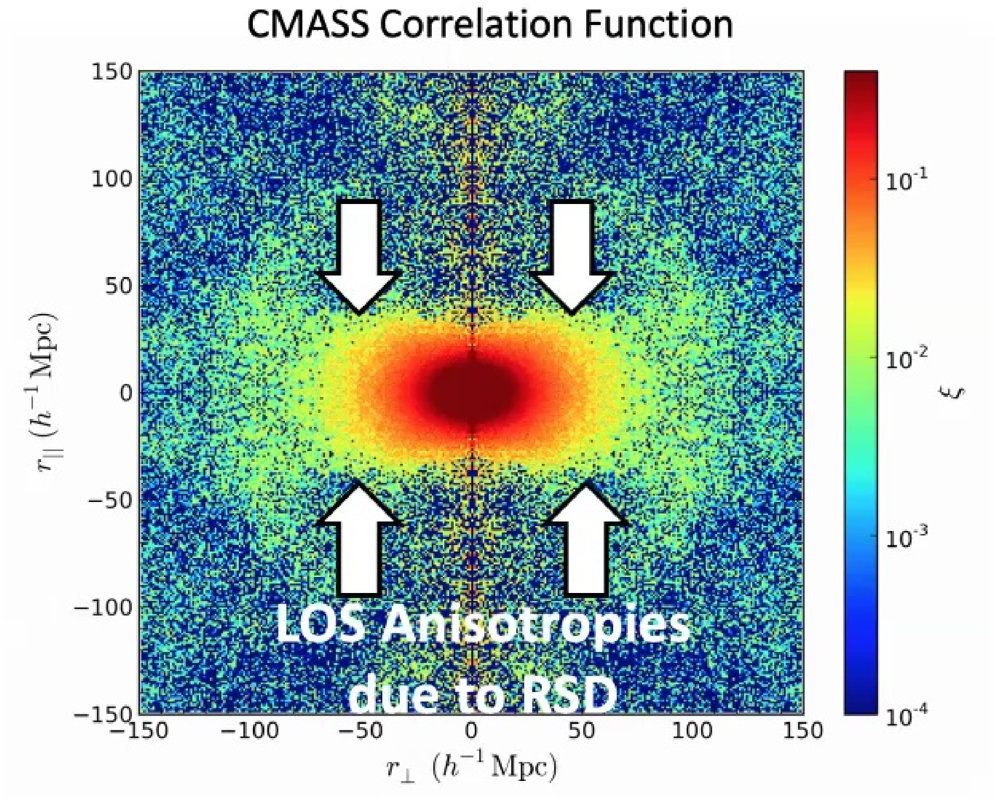
Improvements in coming years will be dramatic: 1.5 million galaxies (BOSS) → 35 million galaxies (DESI)!

Need to come up with optimal/flexible ways to use this data.



(Fig. Credit Hector Gil-Marin)

Spectroscopic Surveys: What are they good for?



Credit: Samushia et al. (2013)

Two (traditional) prongs:

1. **Redshift-Space Distortions** (RSD)
   - Physics: Cosmic velocities, matter clustering amplitude, growth of structure, general relativity
2. **Baryon Acoustic Oscillations** (BAO)
   - Physics: Cosmological distances (Alcock-Paczynski effect), geometry, expansion history, initial conditions at recombination

Of course, can also do neutrino masses, non-Gaussianities, etc.

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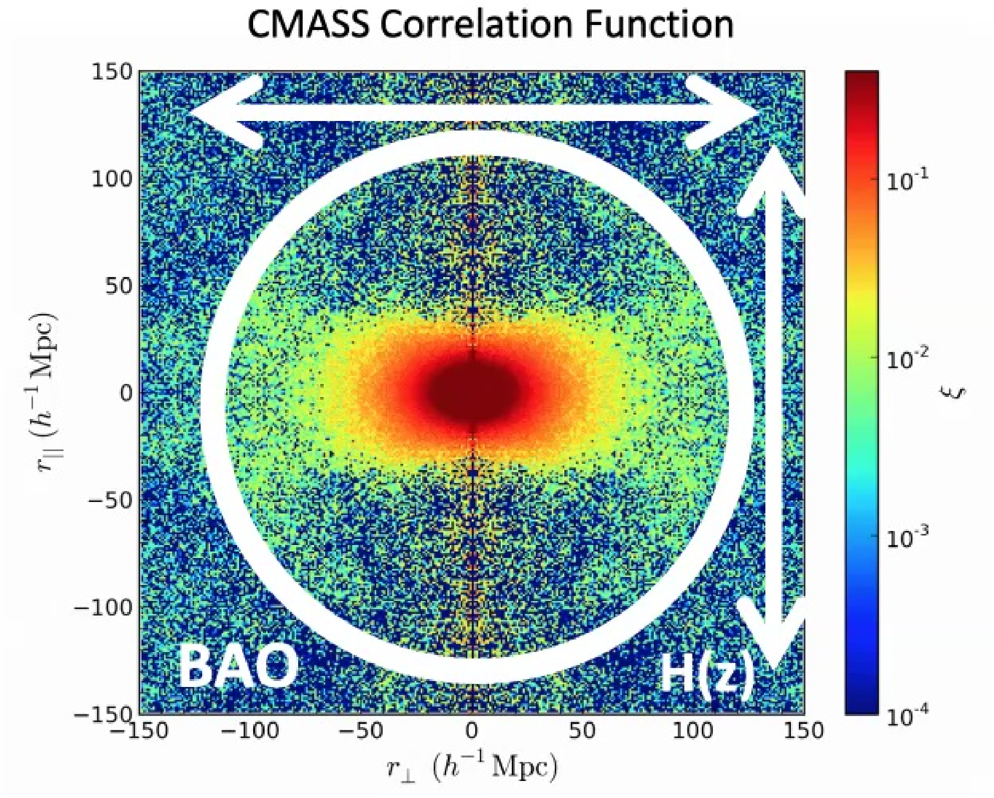

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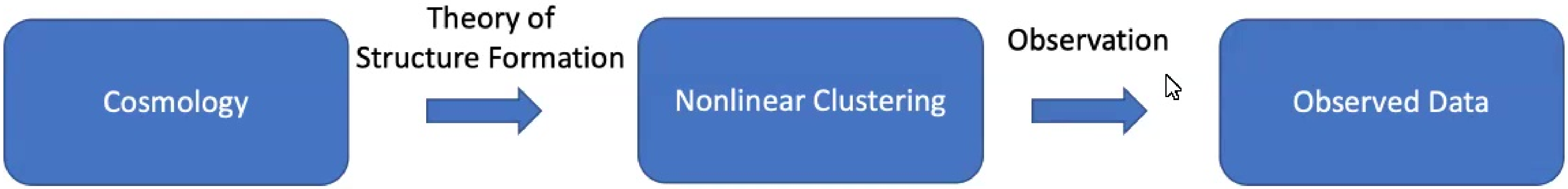
Forward Models from Cosmology to Data



Cosmology

Theory of Structure Formation

Nonlinear Clustering

Observation

Observed Data

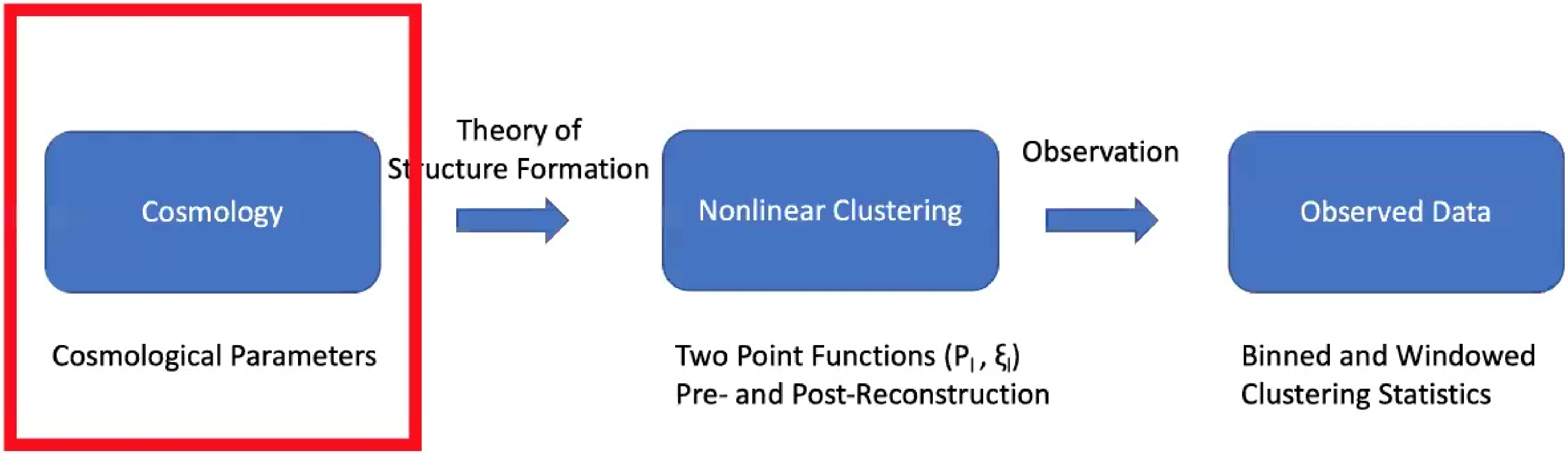
Cosmological Parameters

Two Point Functions (P_l, ξ_l)
Pre- and Post-Reconstruction

Binned and Windowed
Clustering Statistics

Rough idea: Perturbation Theory predicts many observables of cosmological interest within a consistent framework → Operate directly at level of data to constrain cosmology.

$$\mathcal{L} \propto \exp\left\{(m(\Theta) - \hat{d})^T \underbrace{C^{-1}}_{\text{Data Covariance}} (\underbrace{m(\Theta)}_{\text{Model}} - \underbrace{\hat{d})}_{\text{Data}}\right\}, \quad \hat{d} = (P_\ell, \xi_\ell^{\text{recon}}, ...)$$



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Isn’t That What We’ve Always Done?

No! And…. it’s also not necessarily what you always want to do.

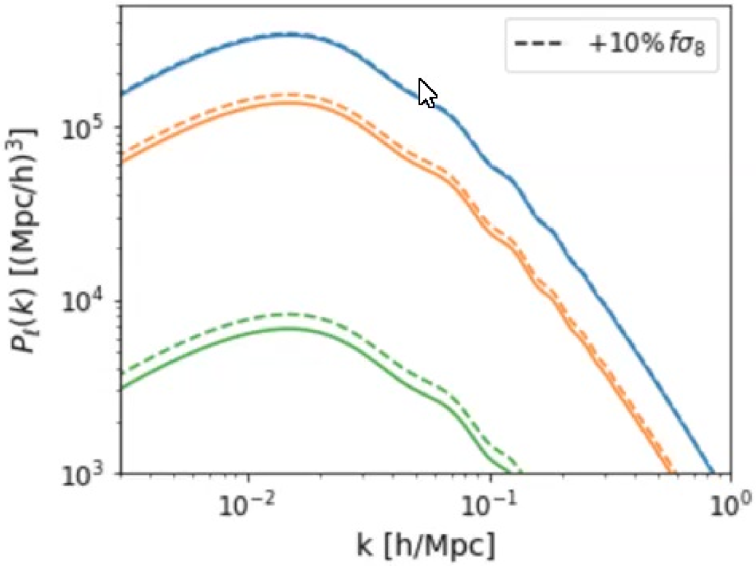
Traditional approach: recognize *physically* that spectroscopic surveys mostly measure two things:

- RSD: measure fσ_8(z) from anisotropic clustering
- BAO: distances/Alcock-Paczynski effect (α’s) from peak, modulo r_s (often with help of reconstruction)

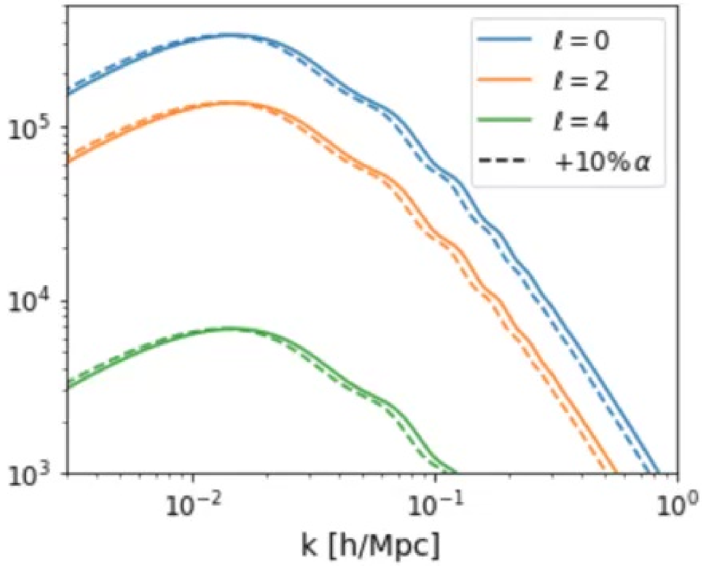
Advantage: easy-to-understand likelihood for broader community.

Disadvantage: not really probing same degrees of freedom as LCDM, assumes terms beyond fσ_8, α marginalized away properly

Intuitive at a phenomenological level:



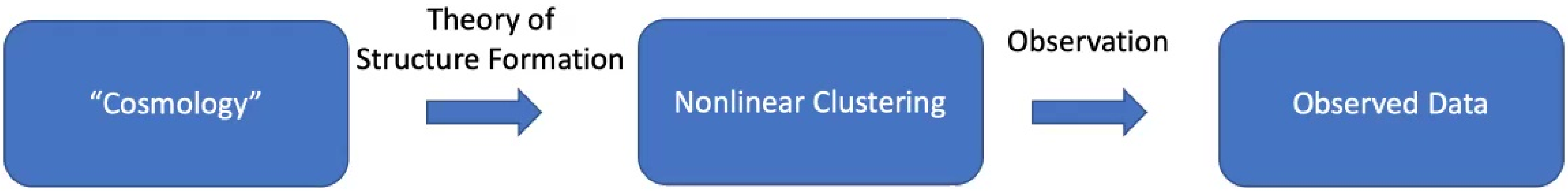
$f\sigma_8$: Scales Anisotropic Power



α's: Sets distance scale of spectra.

So, what *did* we do in the past?

Basic Approach: **Take the initial conditions to be mostly fixed** (because… Planck) but allow for differences in late-time physics, i.e. expansion rate or growth of structure.



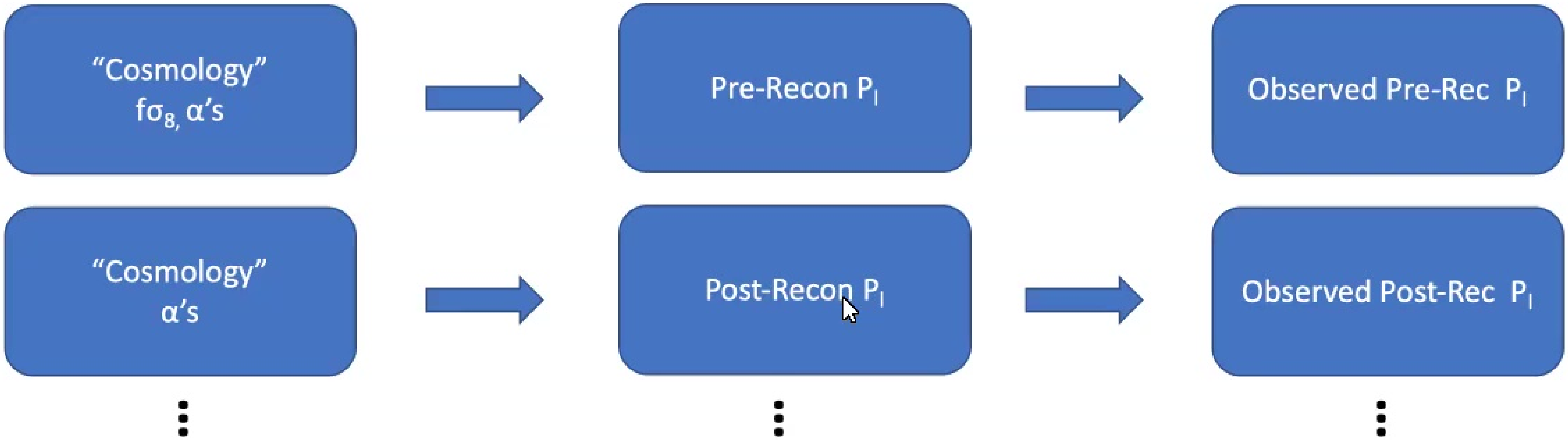
Linear Power **Template** Fixed to CMB
Free: summary statistics $f\sigma_8(z)$, α's

Two Point Functions (P_l , ξ_l)
Pre- and Post-Reconstruction

Binned and Windowed
Clustering Statistics

But, combining data was decidedly non-trivial.

Ideally, use full-shape RSD + post-recon BAO for tighter constraints:



"Cosmology" $f\sigma_8$, α's → Pre-Recon P_l → Observed Pre-Rec P_l

"Cosmology" α's → Post-Recon P_l → Observed Post-Rec P_l

⋮

… not to mention Fourier vs. configuration space.

Analyze separately, so have to use *parameter* covariances implied by mocks.

Template Fit Caveats

Caveat: Not all clustering signal obeys $f\sigma_8(z)$ scaling.

At the linear theory level

$$P_{gg}(k,\mu) = (b_1\sigma_8 + f\sigma_8\mu^2)^2(\sigma_8^{-2}P_{\rm lin}(k))$$

but beyond this there are plenty of terms that scale like

$$\sigma_8^4, f\sigma_8^4, f^2\sigma_8^4, f^3\sigma_8^4, f^4\sigma_8^4, \ldots$$

and similarly bias terms have contributions with different scaling… though of course these are subdominant.

Template Fit Caveats Caveat

All of these caveats are ”ok” if the goal is to compare with CMB, in which case r_s and σ_8 are essentially known.

Not *inherent* issues of template fits: possible, with a little bit more trouble, to include $f\sigma_8(z)$ and $\sigma_8(z)$, AP and BAO scales as separate parameters.

Goal of this talk is to explain how to do “joint” fits of spectroscopic surveys when using “true” (e.g. ΛCDM) cosmological parameters.

What’s different in direct cosmology fits:

1. Don’t need to move around linear power spectrum
    - changes in BAO and growth rates inherent in how initial conditions/Boltzmann codes respond to cosmological parameters
    - ”straightforward” what the parameters mean
2. Maybe we can also streamline combining parameters!
    - If the theory model is good enough we can predict whatever data outputs we want within the theory and do everything “at once”
3. Of course, hybrid cosmology + template fits also possible (e.g Philcox et al. 2020).

Why (Lagrangian) Perturbation Theory?

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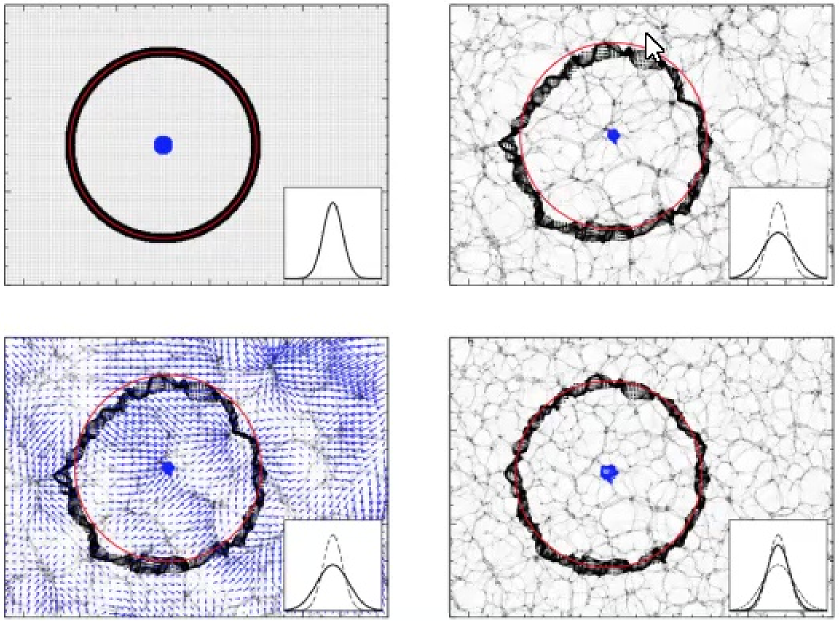
Two Necessary Ingredients

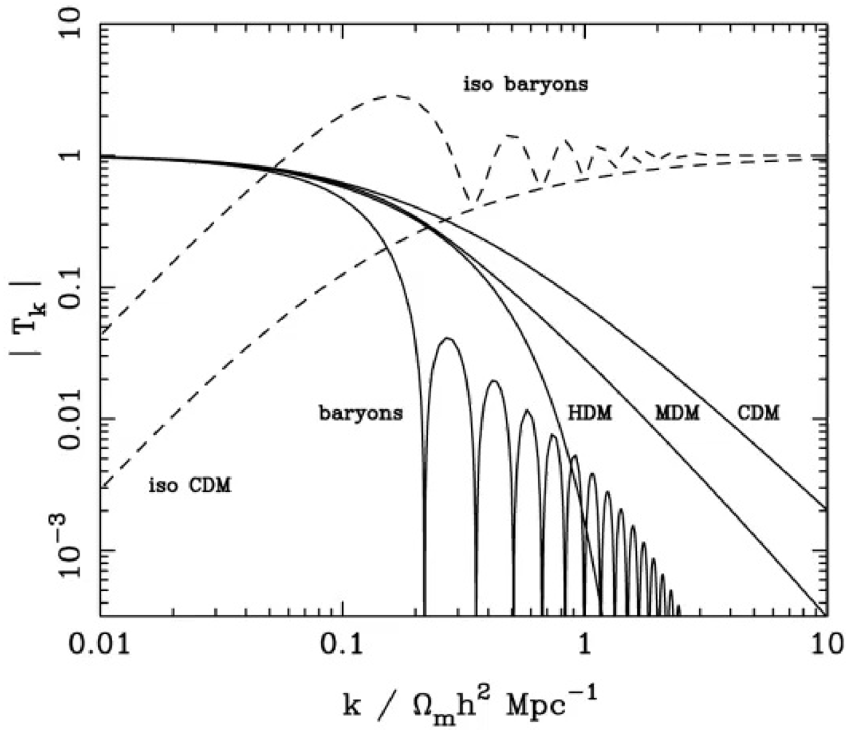


1. Accurate model of **redshift-space distortions** including nonlinear bias, fingers of god, etc.
2. Accurate model of nonlinear damping of **BAO** due to bulk (IR) displacements, and of reconstruction, which reverses *some* of the damping by reconstructing displacement field.

Both well-modeled by Lagrangian perturbation theory.

Figure Credit: Padmanabhan et al. 2012

No, not that perturbation theory:



But kind of!

(Effective) Perturbation Theory

Galaxies are complicated! Form via gravitational collapse, star formation, active galactic nuclei etc.

However, on large scales we can isolate the effect of long-wavelength modes on this small-scale astrophysics.

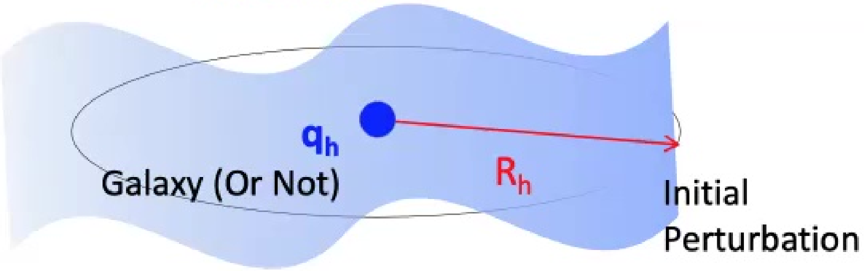
These responses can be perturbatively enumerated order-by-order—number of terms limited by fundamental symmetries.

(Effective) Perturbation Theory: Bias Expansion

An important example is given by the *bias expansion* linking the distribution of galaxies to that of matter:

$$F_g(\mathbf{q}) = 1 + \underbrace{b_1\delta_0 + \frac{1}{2}b_2(\delta_0^2 - \langle\delta_0^2\rangle) + b_s(s^2 - \langle s^2\rangle)}_{\textbf{Local Response to IC's}} + \ldots$$

$$+ \underbrace{b_\nabla R_h^2 \nabla^2\delta_0 + \ldots}_{\textbf{Finite-Size (Effective) Correction}} + \underbrace{\epsilon_s}_{\textbf{Short Modes (Stochastic)}}$$

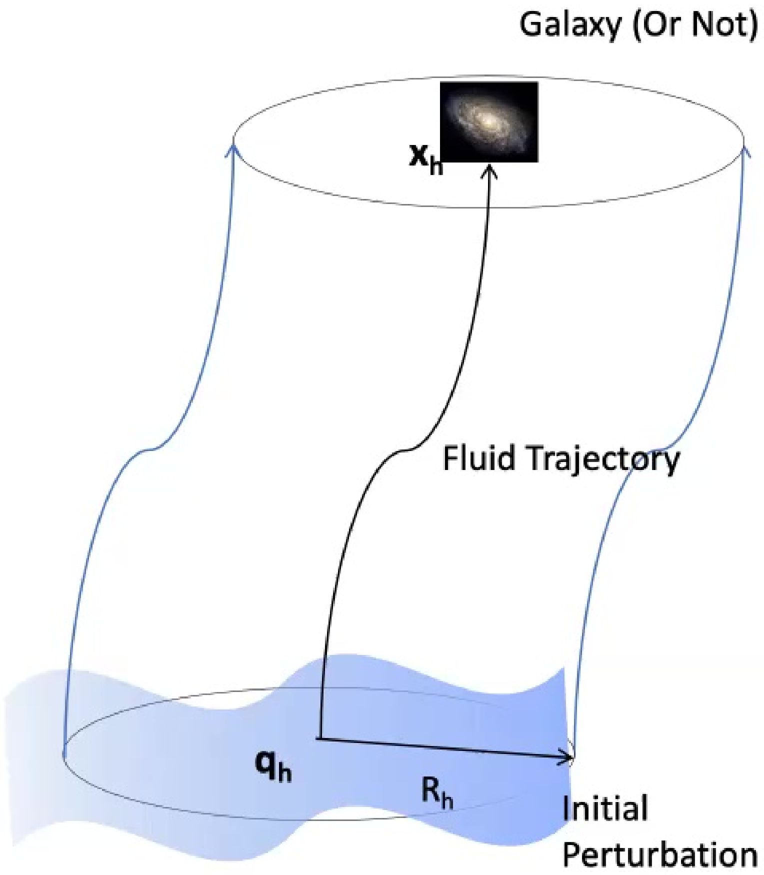


(Effective) Perturbation Theory: Dynamics

Caveat: galaxy clustering is nonlocal in time! Everything forms over ~ Hubble time.

However, these nonlocalities can be factored order-by-order as well.

Of course, need to marginalize over small scales here as well.



Why Perturbation Theory?

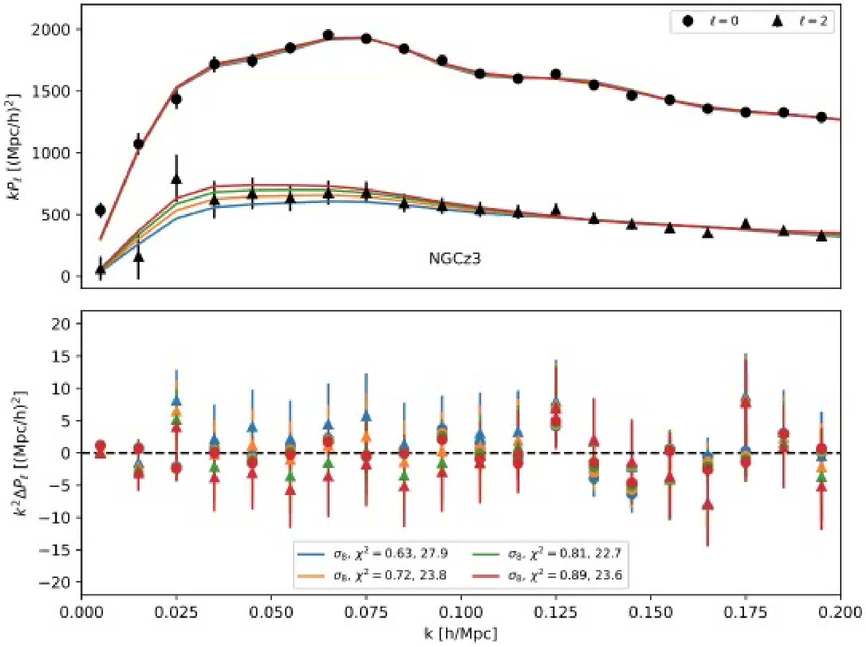
Perturbation theory provides clean predictions for redshift-space statistics, pre- and post-reconstruction.

As an effective theory, robust to any small-scale physics. No additional assumptions about galaxies, halos etc. needed.

Consistent predictions of power spectra and correlation functions on large scales using same model and parameters.

What about small scales?

A nice feature about effective perturbation theories is that they “know” where the large-scale cosmological information lives.



For example, amplitude (σ_8) constraints mostly come from large scales k < 0.1 h/Mpc.

This is because symmetries protect large scale velocity constraints but nonlinearities set in at small scales:

$P_{nl} \sim (1 + a_2 k^2 + \dots)\, P_{linear}$

Lagrangian Perturbation Theory

In our analysis we specifically use LPT:

- Pre-recon 2pt function from velocileptors (Chen, Vlah, Castorina and White 2021)
- Post-recon damping via Zeldovich (Chen, Vlah and White 2019)

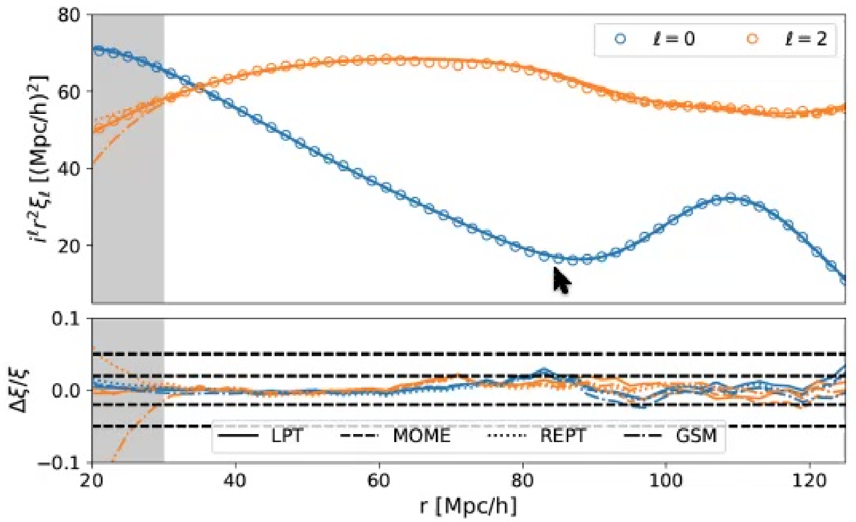
LPT models structure formation by following displacements, i.e. trajectories, of fluid elements. Useful for understanding:

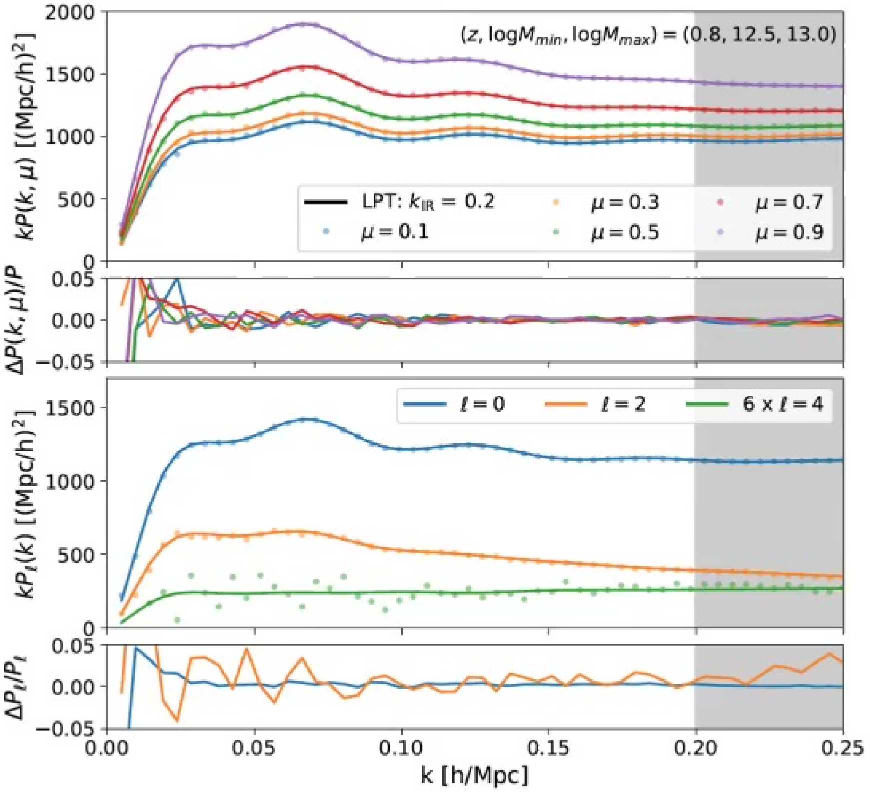
- RSD: velocities are just time derivatives
- BAO: nonlinear damping of BAO due to exactly these displacements

By the way: velocileptors also does velocity statistics, Eulerian EFT, etc. and is free! https://github.com/sfschen/velocileptors

Does it work…

… in both configuration and Fourier space vs. simulations?

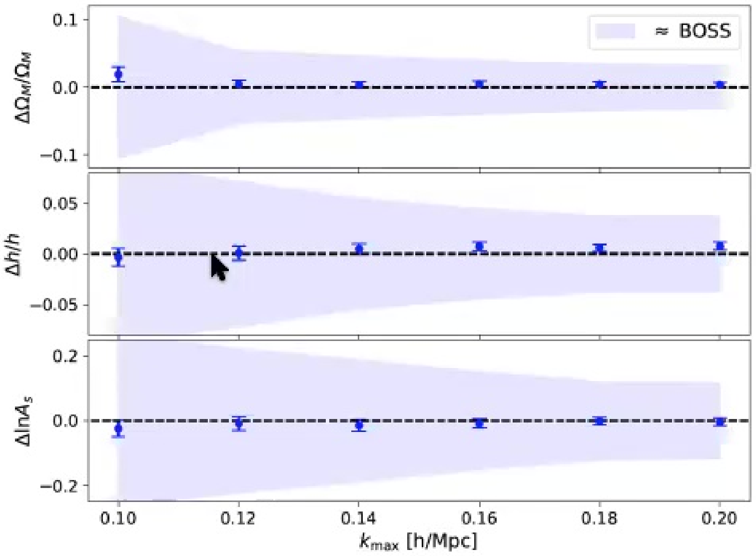


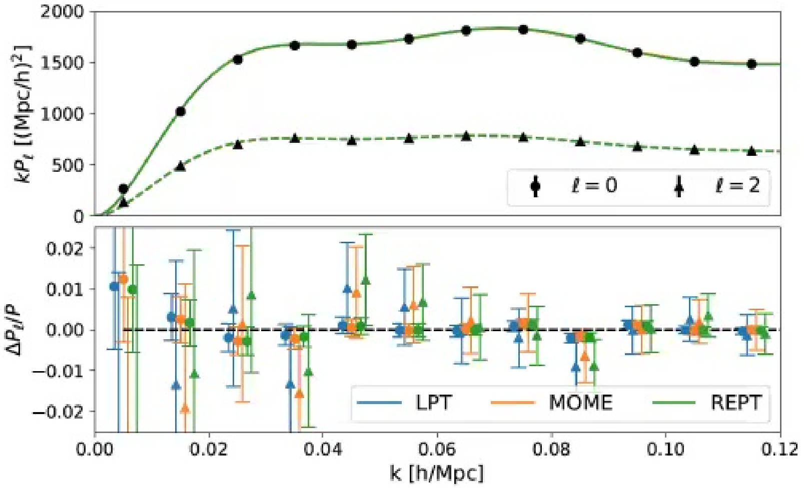


Chen, Vlah, Castorina and White 2021

Does it work…

… for cosmological constraints, e.g. in a blind challenge?





Reliable constraints on cosmological parameters out to high $k_{\max}$ using blind challenge data (volume = 100x BOSS) from Nishimichi (2020), comparable to CLASS-PT, PyBird.

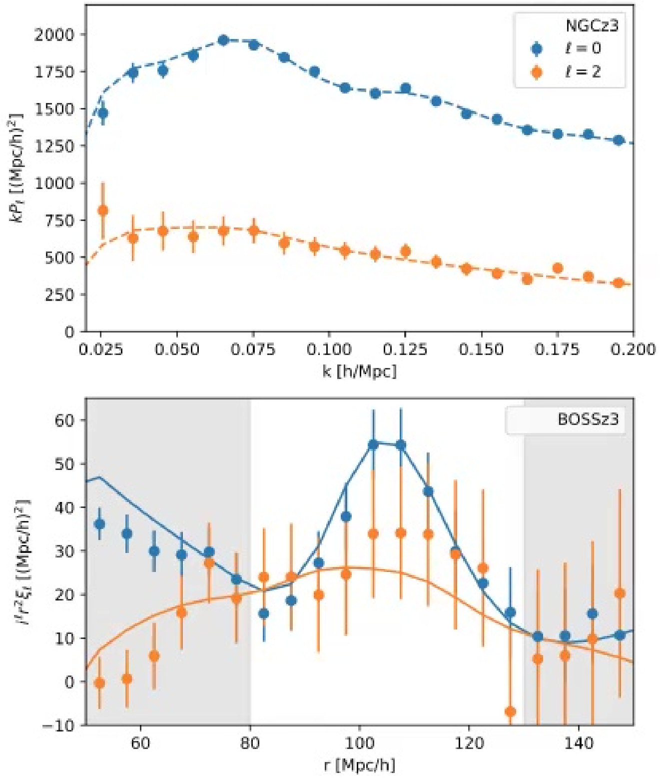
Application to BOSS

BAO live in configuration space (like us)

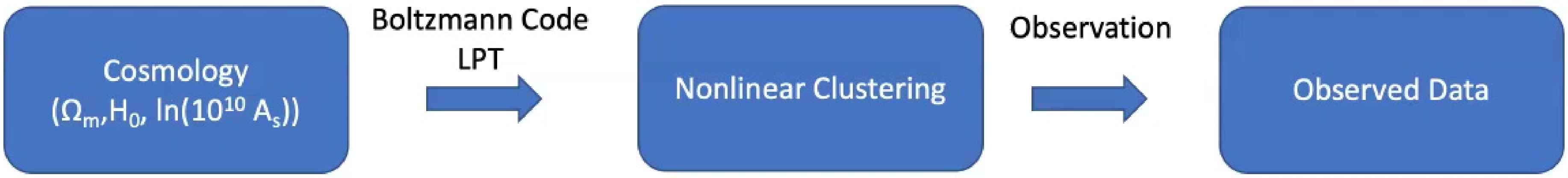
Issue: Pre- and post-reconstruction 2pt functions are highly correlated, especially at low k where nonlinearities are small—potential source of numerical issues.

However, we can use the fact that the BAO peak is cleanly isolated in configuration space at a peak at large scales and fit only a small piece of the correlation function.

Solution: Combine pre-recon P(k) and post-recon $\xi(r \sim r_{BAO})$



Final Plan:



Cosmology
$(\Omega_m, H_0, \ln(10^{10} A_s))$

Boltzmann Code
LPT

Nonlinear Clustering

Observation

Observed Data

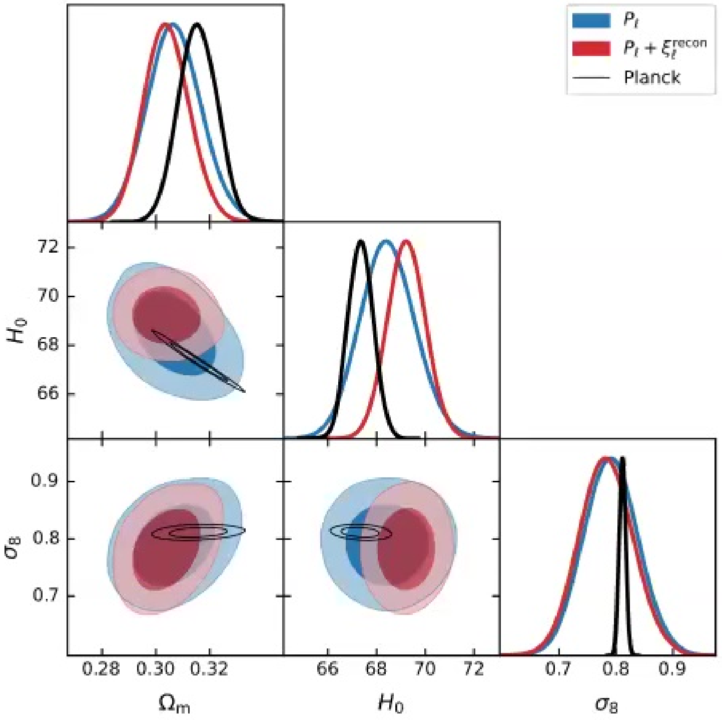
$\Omega_m, H_0, \ln(10^{10} A_s)$

Fixed spectral tilt, neutrino mass, baryon density

Two Point Functions:
Pre-Reconstruction P_l
Post-Reconstruction ξ_l

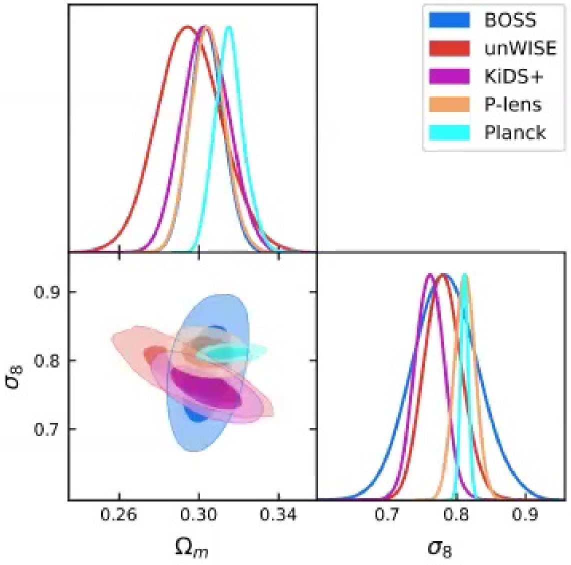
Binned and Windowed P_l
Binned ξ_l

Results with and without BAO



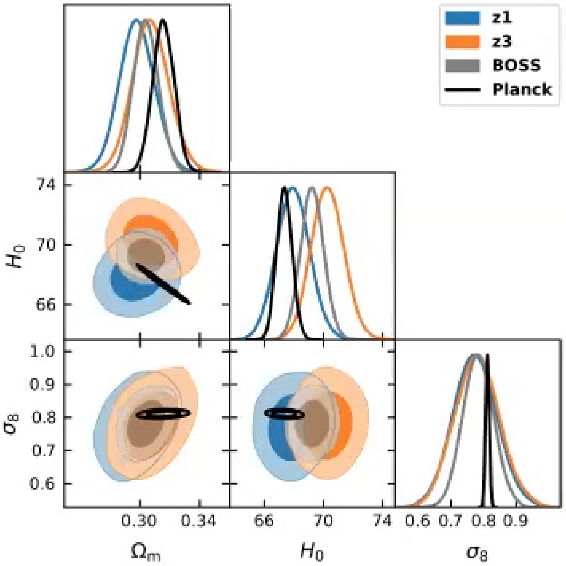
With/Without BAO

Not a particularly useful entrant in the discussion about “tensions”… but stick till the end!

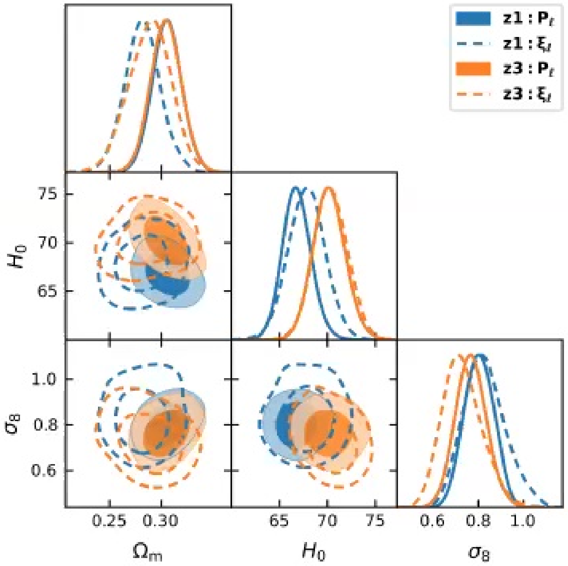


v.s. other surveys

Consistency Tests



High vs. Low Redshift (z_3=0.61, z_1=0.38)



Fourier vs. Configuration Space

A note about σ_8 and window functions

While this work was still in progress we noticed something odd:

The **consistency check between power spectra and correlation functions was failing**: power spectra consistently returned lower $\sigma_8 \approx 0.72$ in line with what other EFT-minded BOSS papers found (Ivanov et al. (2020), D'Amico et al. (2020)).

Coincidentally, Pat Mcdonald told us he had discovered a normalization inconsistency* in the published BOSS data at the 10% level → in linear theory this translates to a 5% difference in $f\sigma_8$!

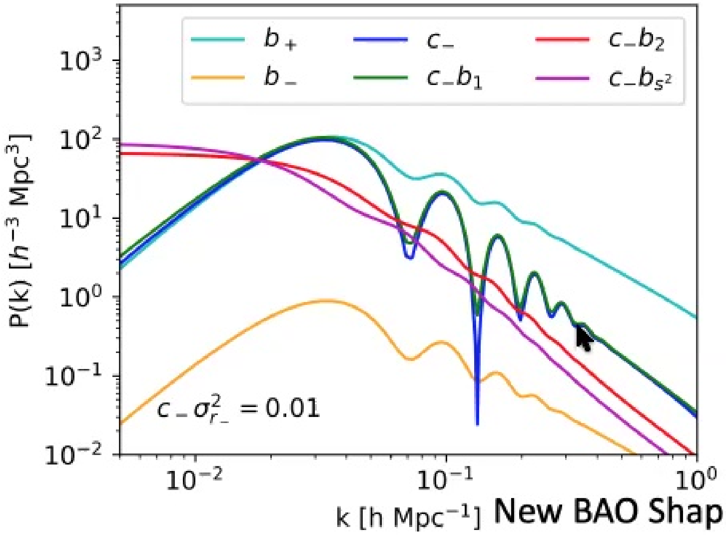
Recently confirmed by Zhang et. al. Eulerian EFT analysis of BOSS correlation functions.

*Correction to appear in Beutler and Mcdonald (2021), data already updated on website.

This method generalizes easily to nonstandard physics:

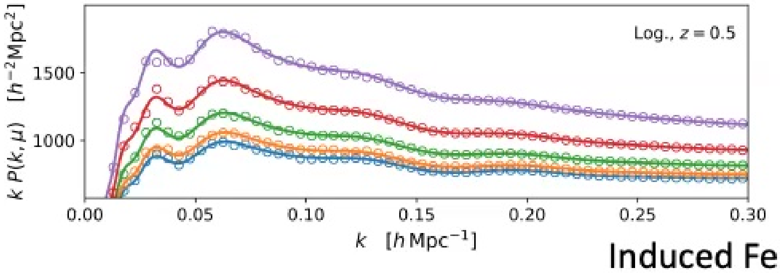
Examples:

1. "Relative velocity effect": features due to relative perturbations between baryons and dark matter (arXiv:1903.00437)



New BAO Shapes from Dark Matter-Baryon Perturbations

2. Inflationary Features/Early Dark Energy (arXiv:2007.00704)

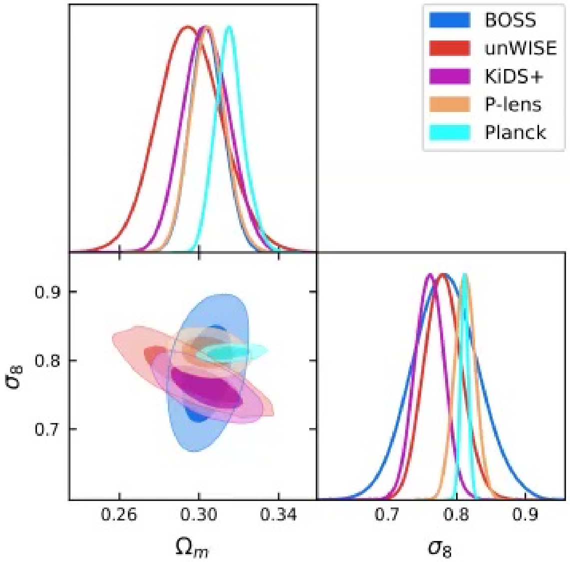


Induced Features from Beyond-LCDM Physics

The next frontier: RSD x Lensing!

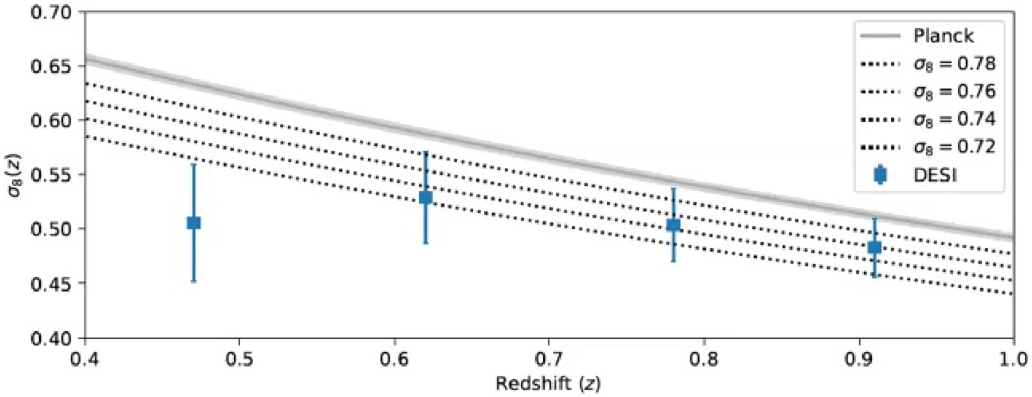
Flip side to earlier figure: RSD and lensing probe different degeneracies and will be powerful together!

Same LPT calculations also consistently predict lensing statistics, leading way to joint analysis of overlapping samples (e.g. recent MOU between ACT and DESI).



First step: DESI (Legacy Imaging Survey) LRGs x Planck

(with Martin White, Rongpu Zhou, Joe DeRose and Nick Kokron).



Stay tuned for supplemental sample, emulator and field-level papers!

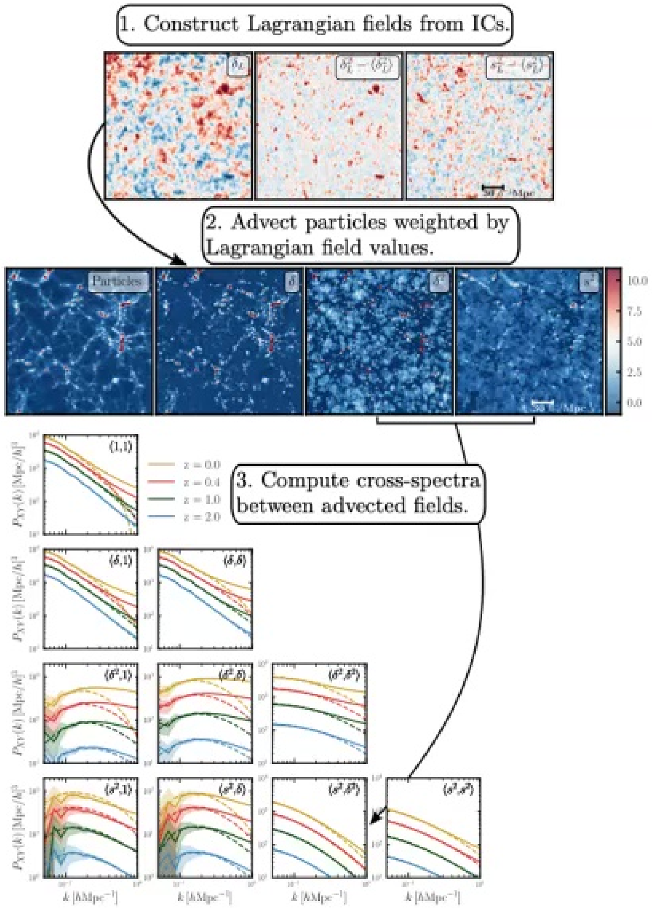
arXiv:2111.09898

What about small scales?

Lensing/imaging surveys often require theory well-behaved at smaller scales than PT.

Solution: combine symmetries-based biased expansion in LPT with exact dynamics of n-body simulations (Modi, **SC**, White 2019).

Scheme has *same free parameters* as LPT model, cosmology dependence with collaborators in Kokron et al. (2021), also Hadzhiyska et al. (2021), Zennaro et al. (2021)



1. Construct Lagrangian fields from ICs.

2. Advect particles weighted by Lagrangian field values.

3. Compute cross-spectra between advected fields.

https://github.com/kokron/anzu

Conclusions

- It's possible to forward model RSD + BAO without going through templates/computing covariances of model-dependent statistics.
- One benefit of having one model for everything is that it makes apples-to-apples comparisons and systematic checks easier…
- (Lagrangian) perturbation theory is a reliable tool to model large-scale clustering, including future analyses combining redshift and lensing surveys.