Baryon Acoustic Oscillations with Galaxy Surveys

Present State and Some Future Prospects

Nikhil Padmanabhan

Berkeley Cosmology Seminar
Oct 17, 2023

w/ The DESI collaboration
Xinyi Chen
Farnik Nikakhtar

My Plan

- What can we expect from the upcoming BAO measurements?
  - Early results from DESI
  - A flavor of the Y1 BAO analyses
- What new directions might we extend reconstruction in?
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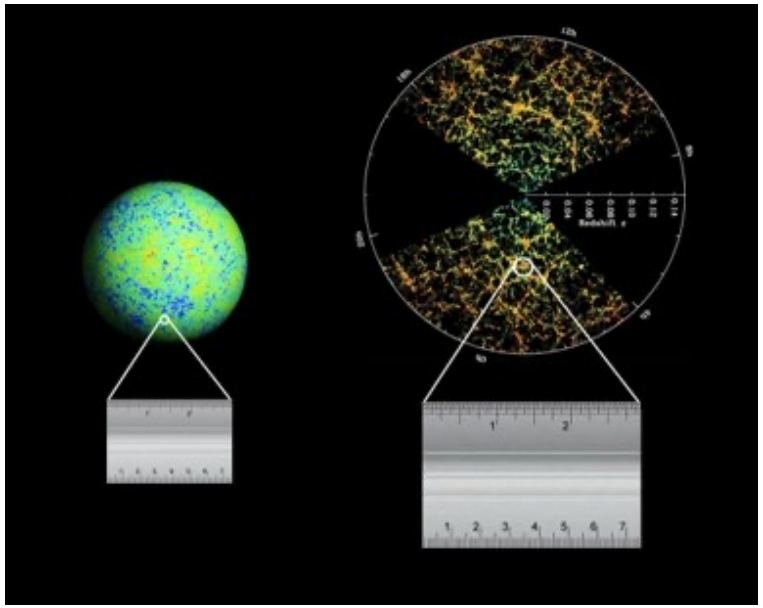
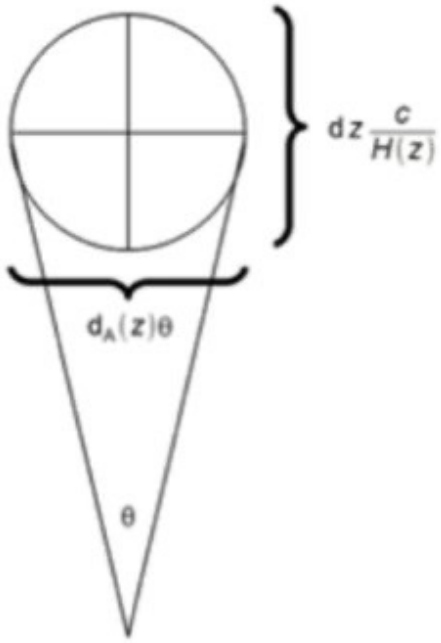
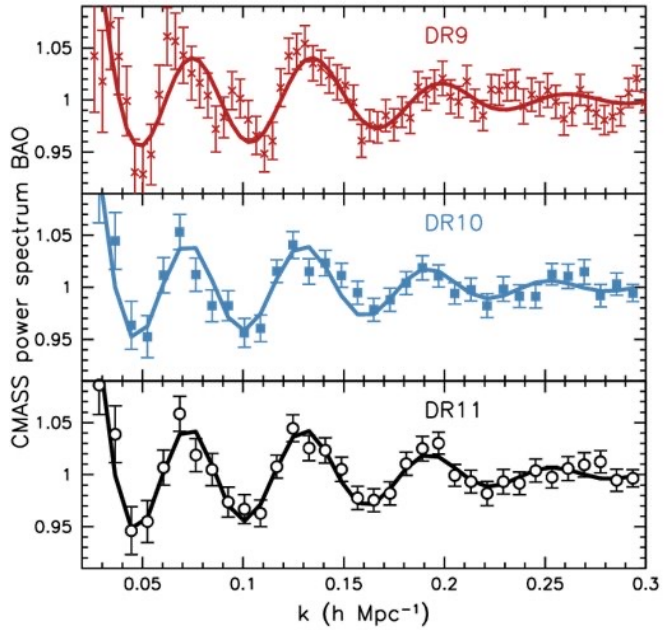
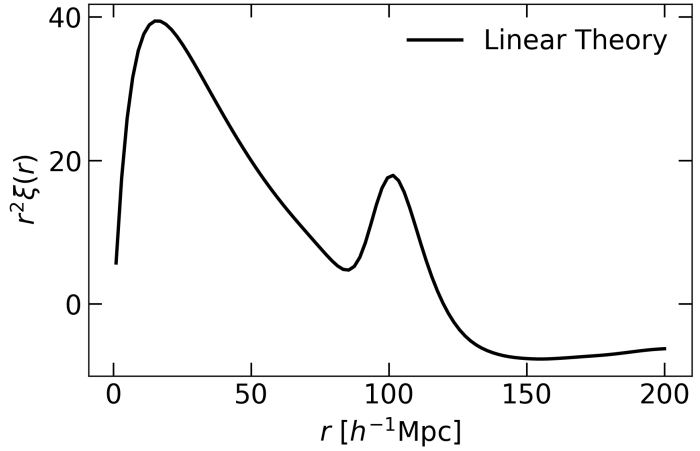
A Standard Ruler : Baryon Acoustic Oscillations



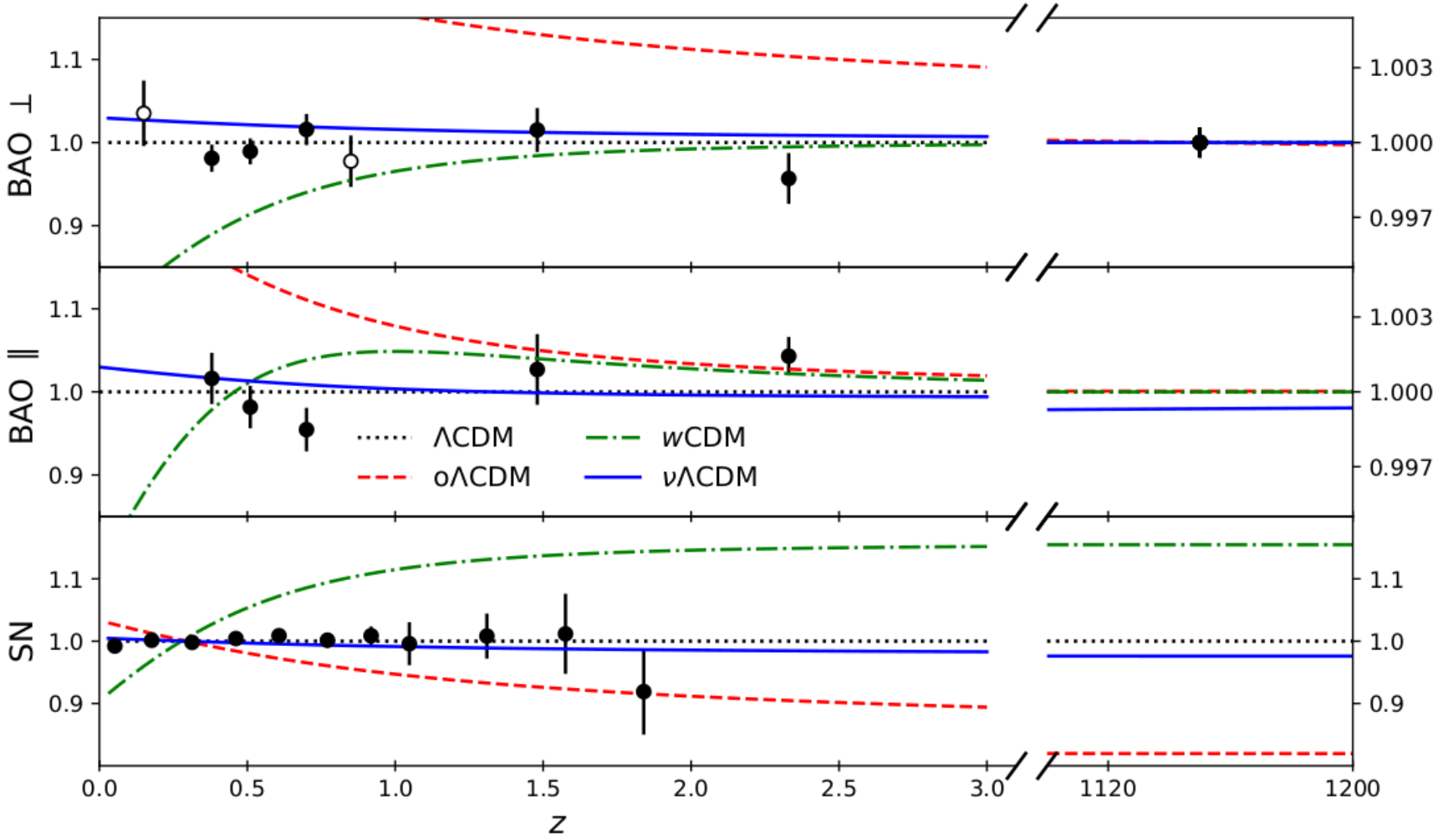






Figures from lbl.gov,
Elisa Ferreira et al
BOSS CMASS measurements

The expansion history : BAO and SNe

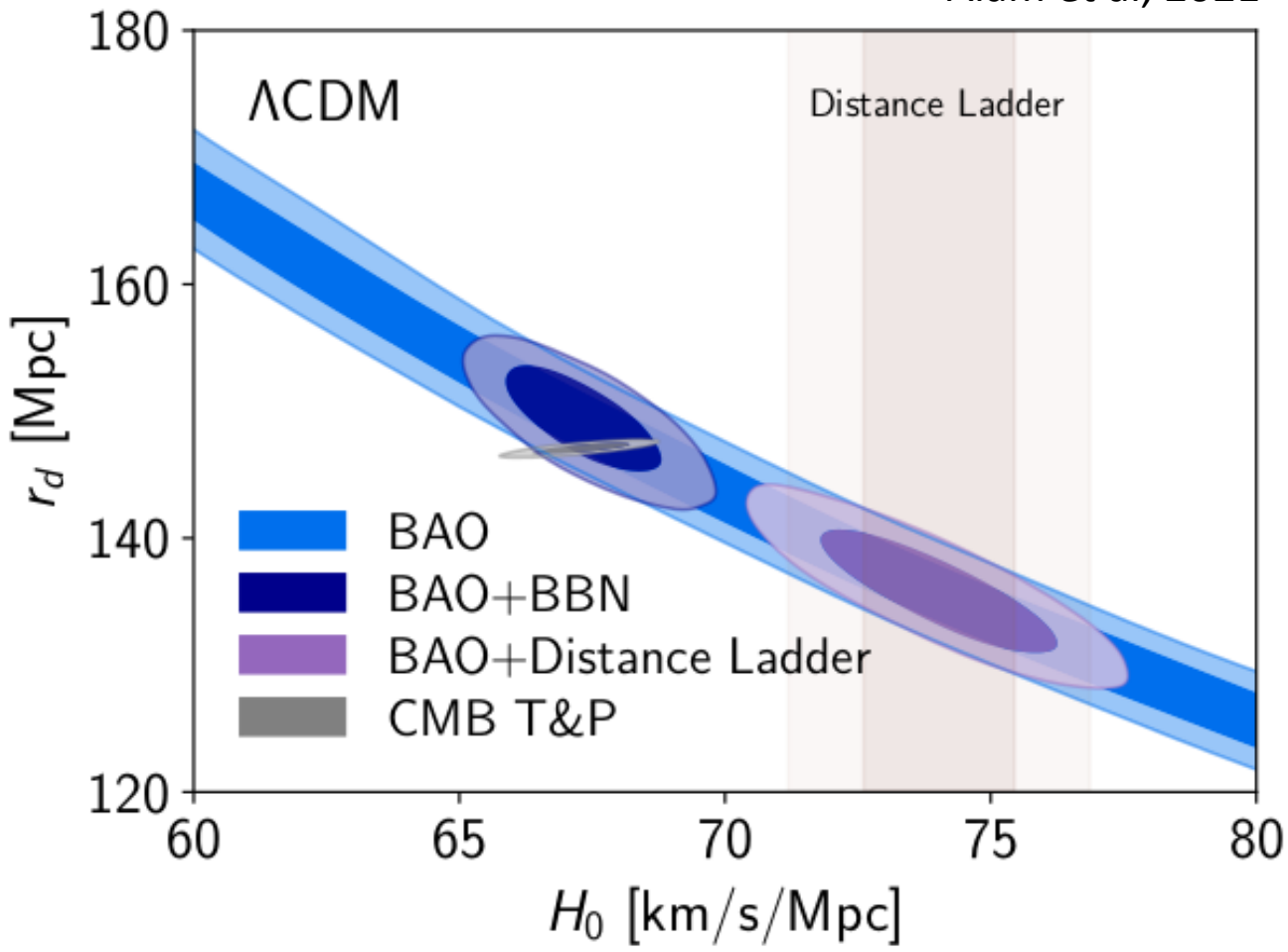


Alam et al, 2021

A different version of the H0 tension

Use the BAO + local measurements to measure the sound horizon

Alam et al, 2021



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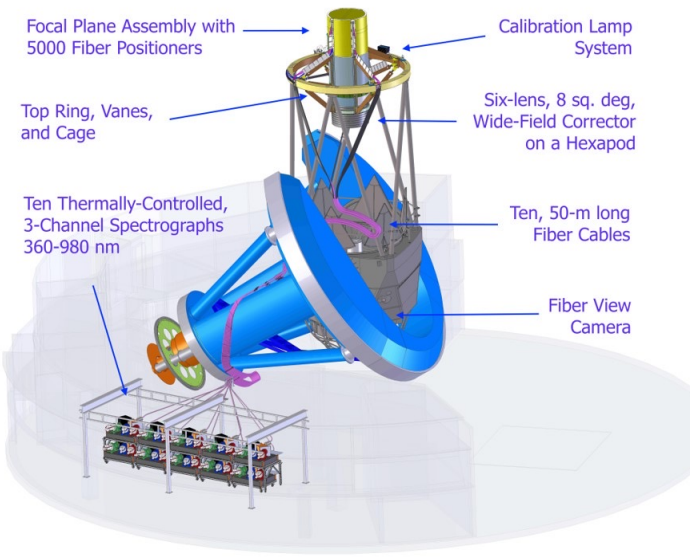
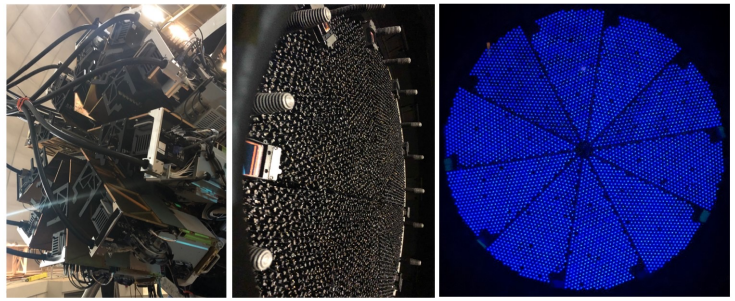
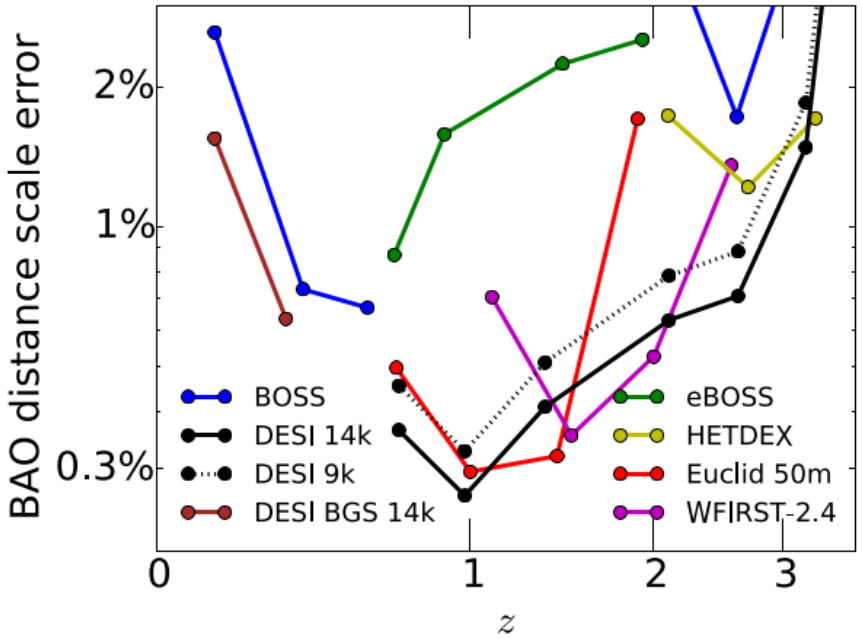
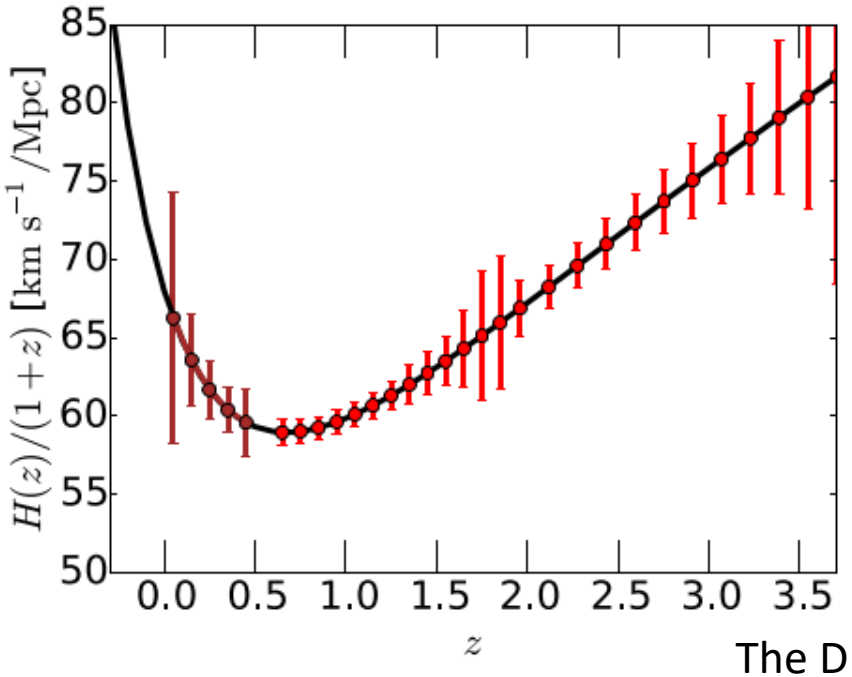
DESI : The Stage IV Spectro DE





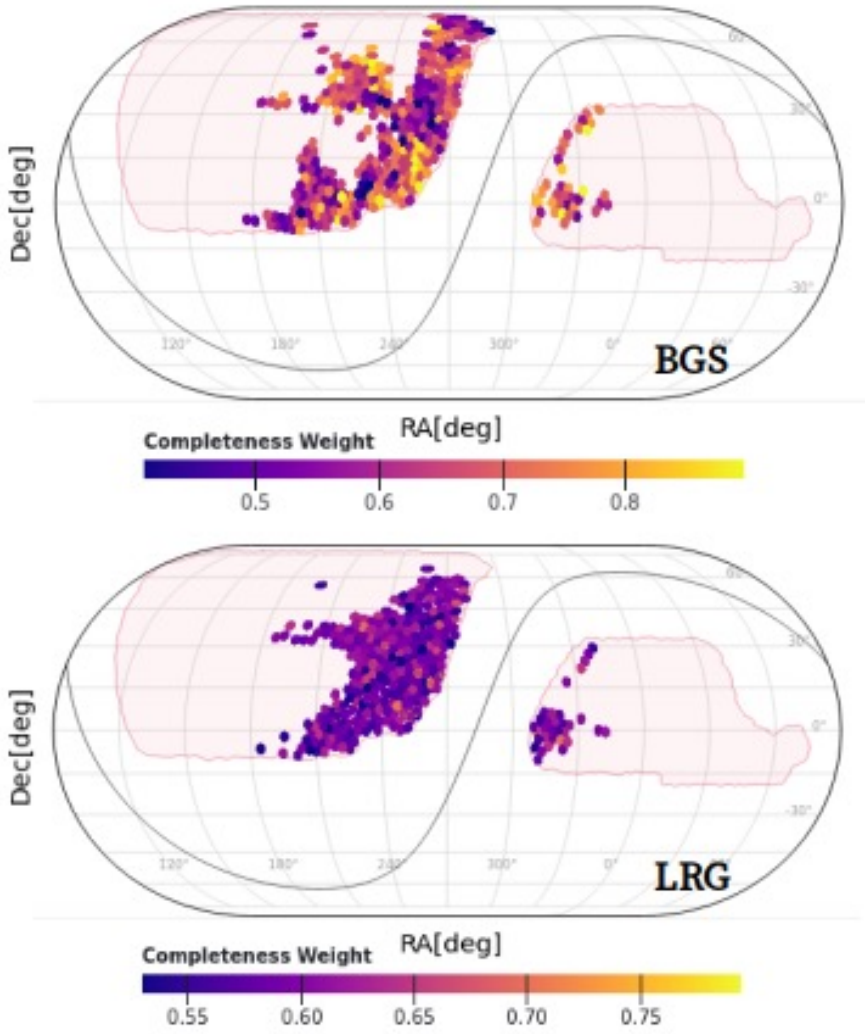


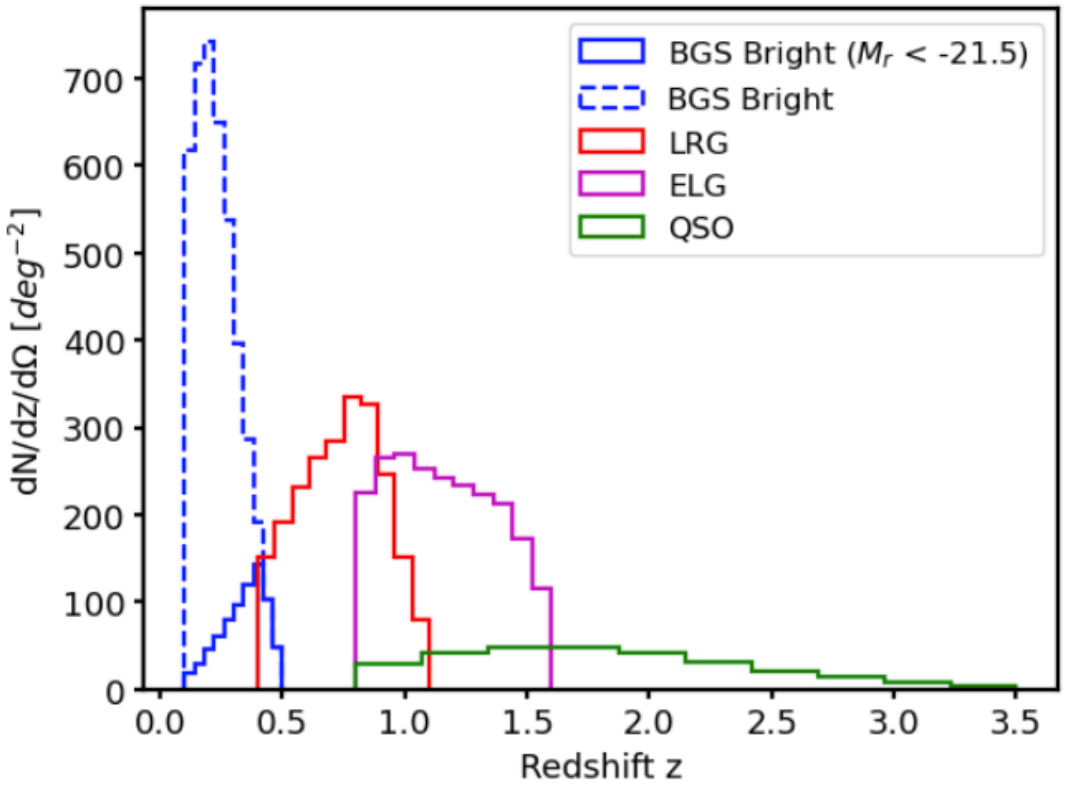


DESI Overview Paper, DESI collab.

The DESI Collaboration; 1611.00036

The first two months of DESI data, unblinded

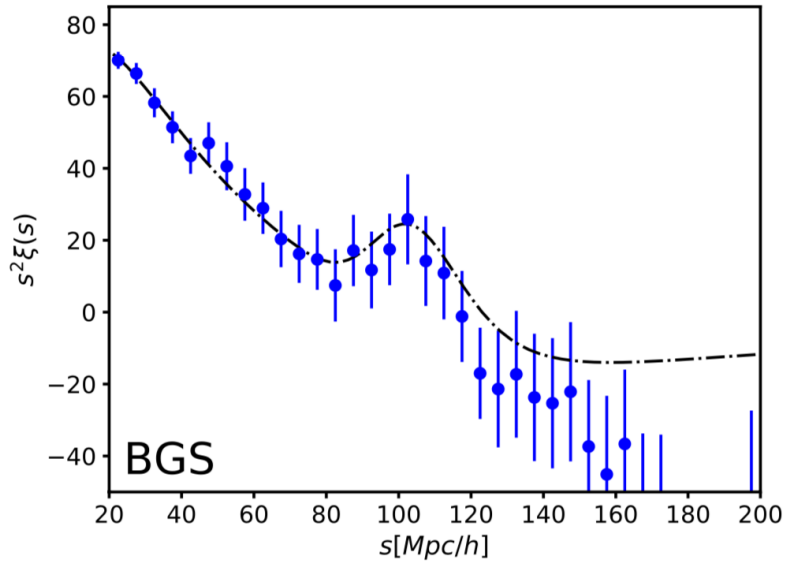


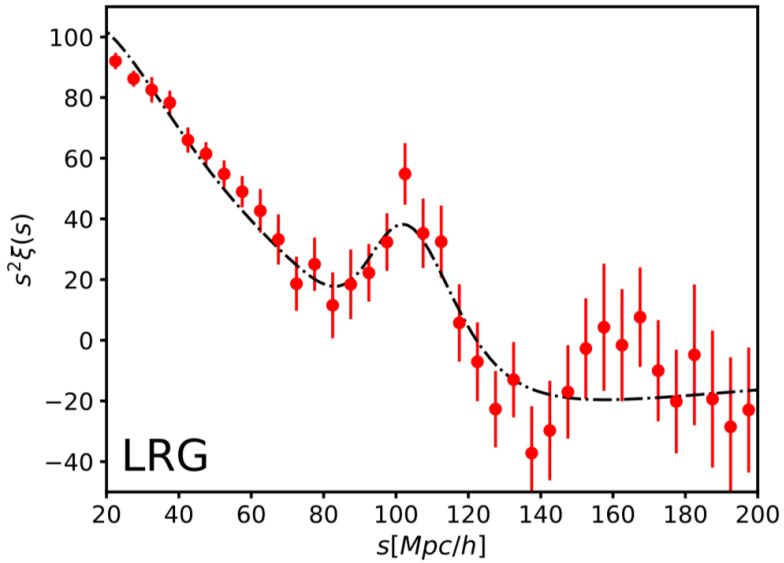


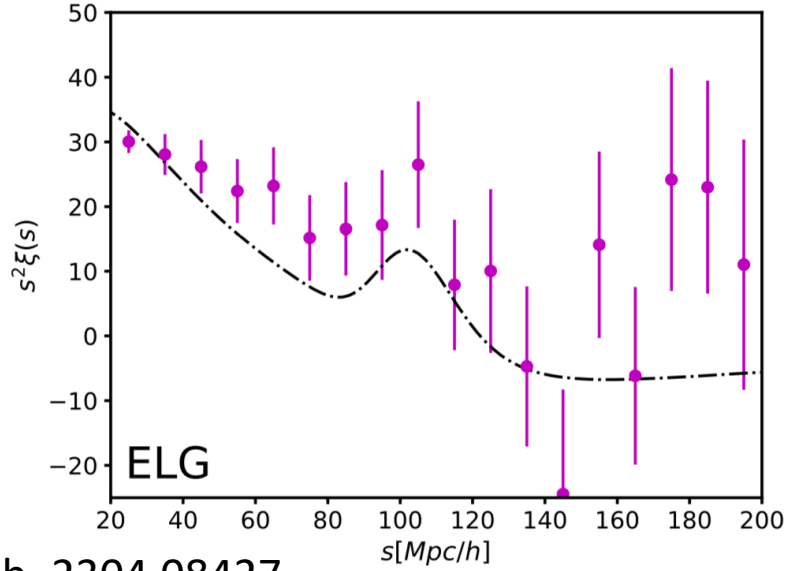
Target	$N_{\rm North}$	$N_{\rm South}$	$N_{\rm Total}$	z range	Area [deg^2]	Completeness
BGS Bright	239492	390988	630480	0.1 - 0.5	3677	0.500
BGS Bright, M_r < −21.5	38472	71051	109523	0.1 - 0.5	3677	0.500
LRG	80651	180640	261291	0.4 -1.1	1651	0.579
ELG	55383	117145	172528	0.8 - 1.6	976	0.297
QSO	70337	153453	223790	0.8 - 3.5	2906	0.778

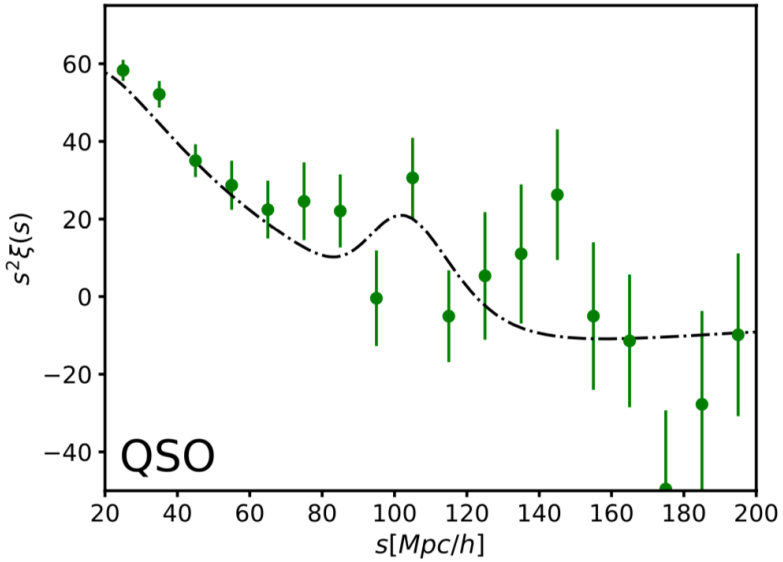
Moon et al, DESI collab.,2304.08427

Correlation functions in the first two months of DESI



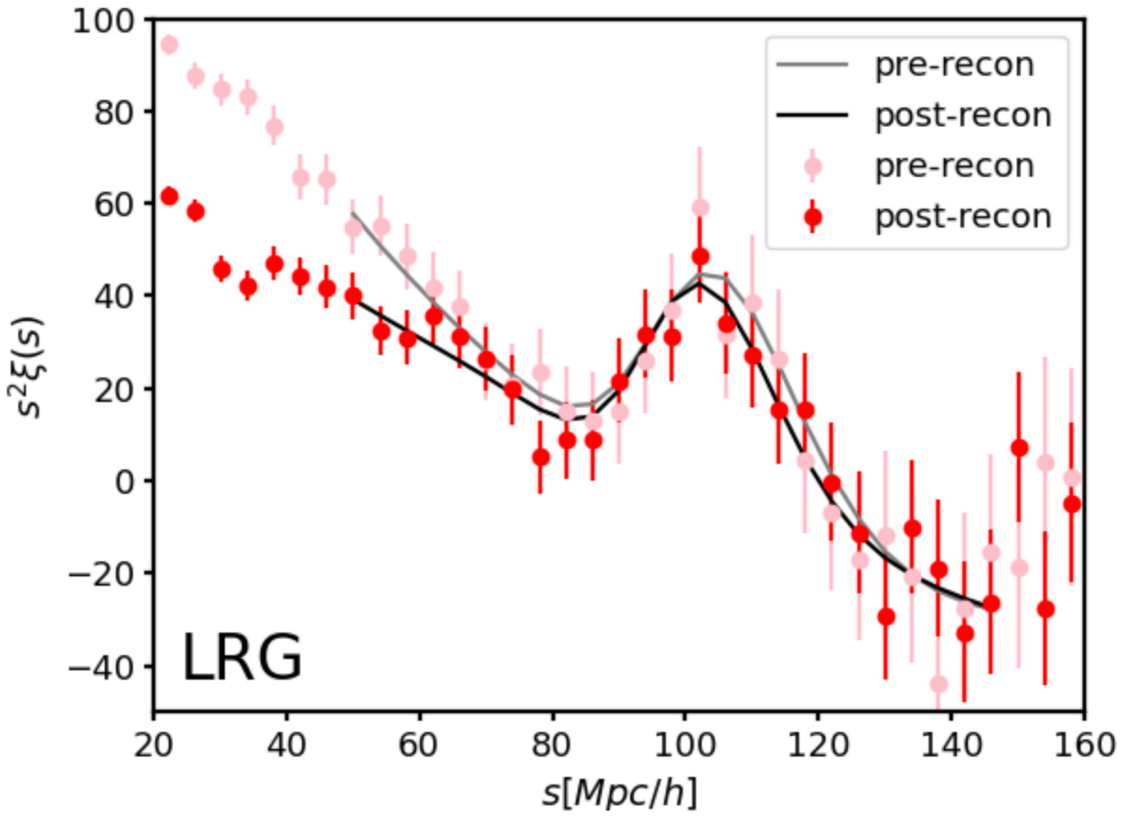


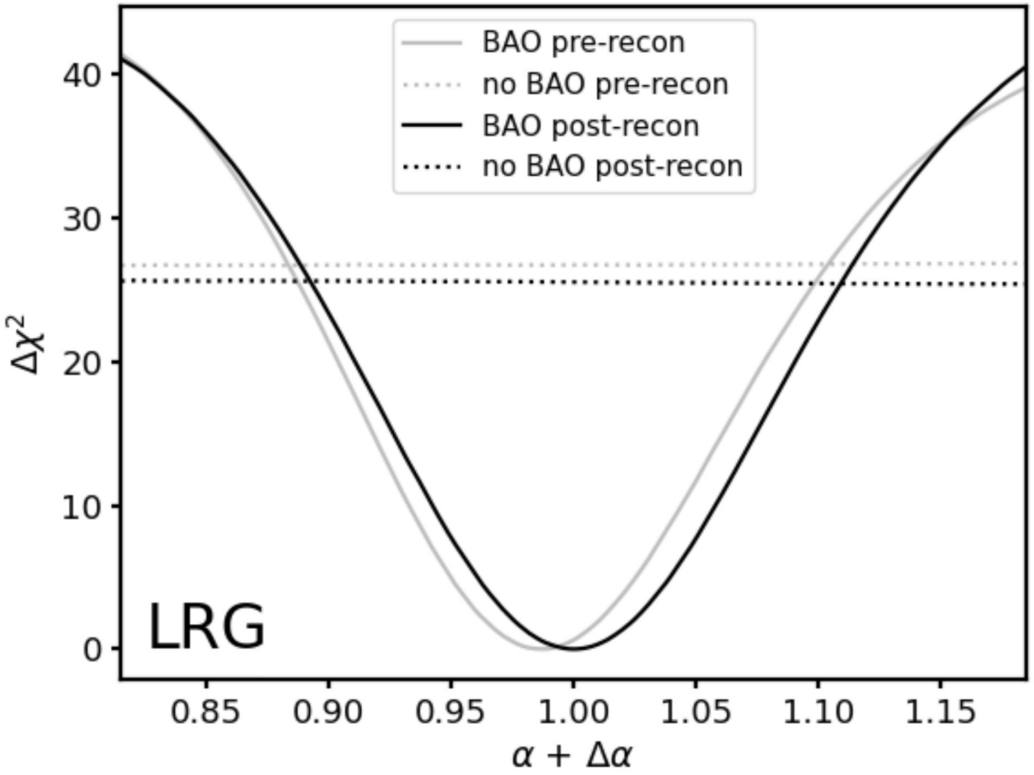




Moon et al, DESI collab.,2304.08427

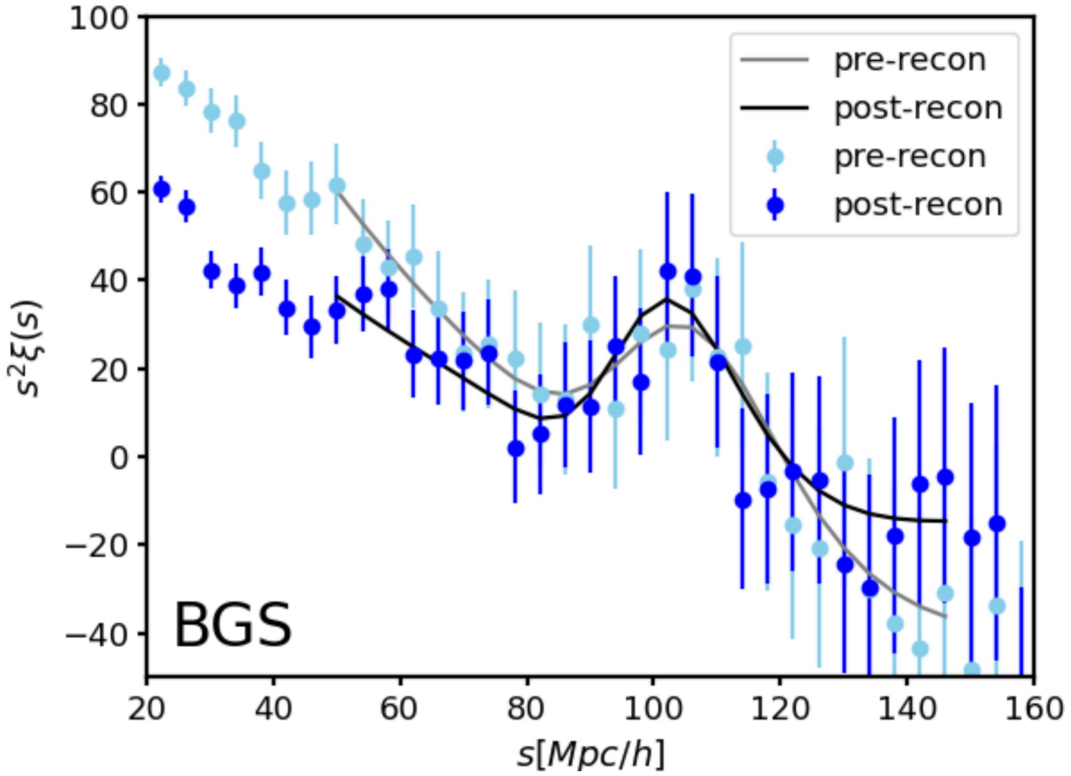
A 1.7% distance measurement in the LRG sample

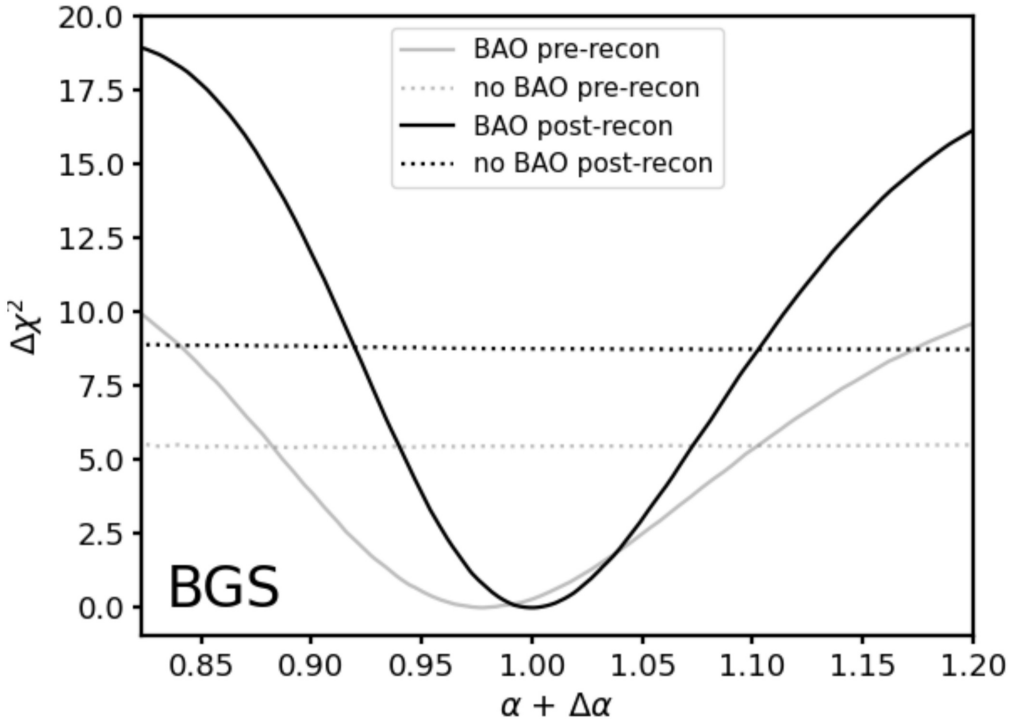




Moon et al, DESI collab.,2304.08427

A 2.6% distance measurement in the BGS sample





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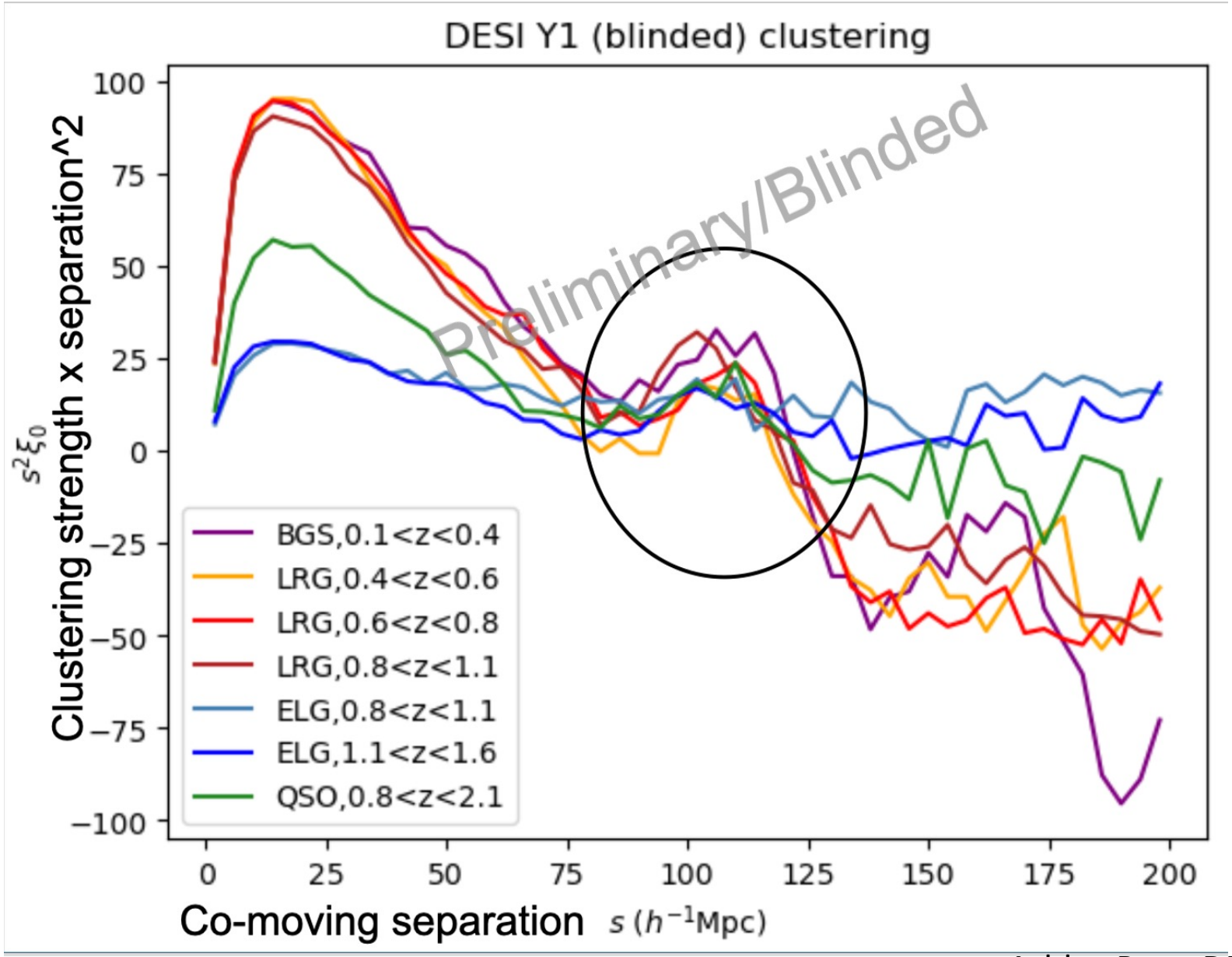
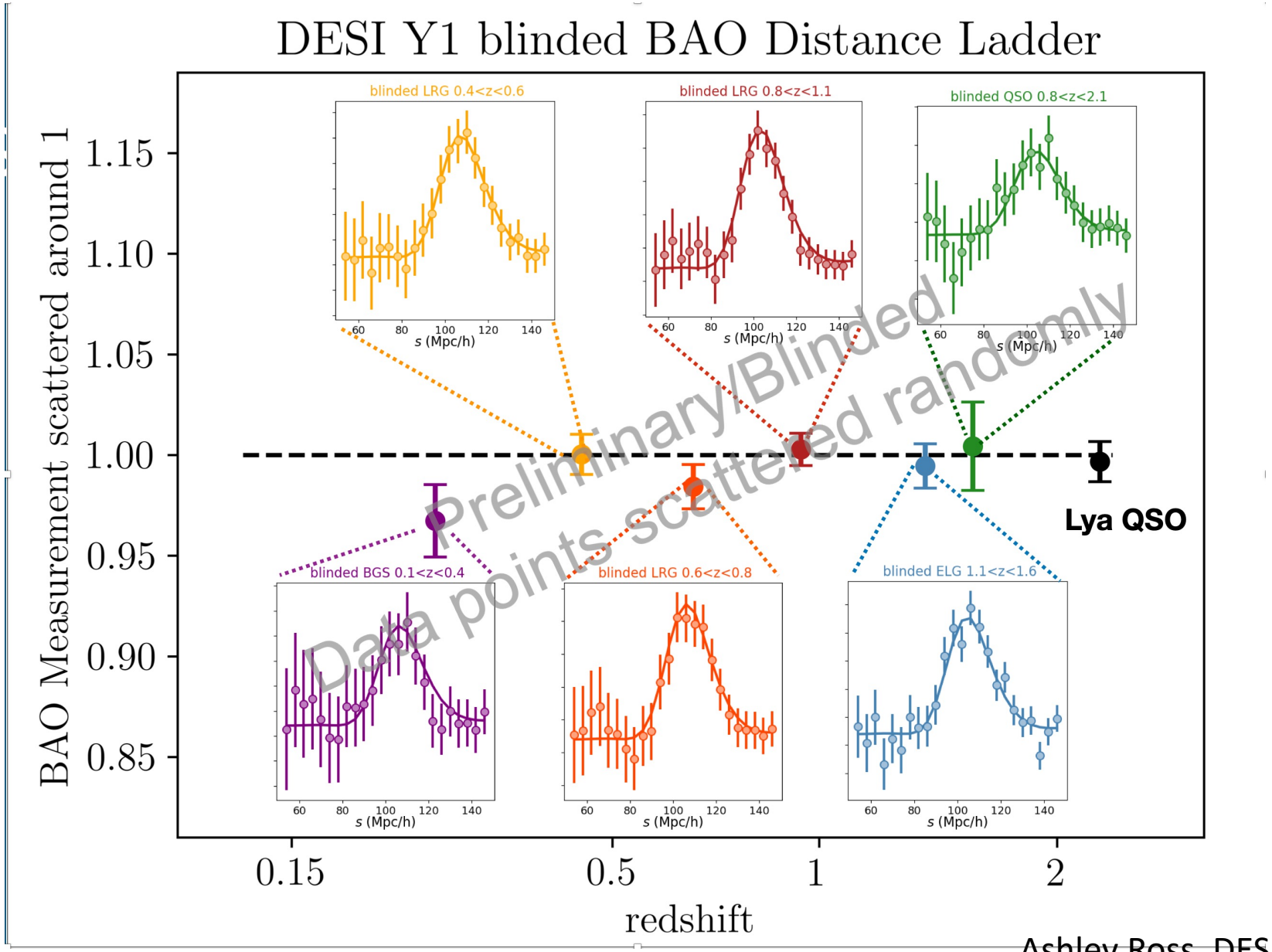
Y1 DESI Correlation functions



Ashley Ross, DESI KP3, and DESI collab

Building a Y1 Hubble diagram



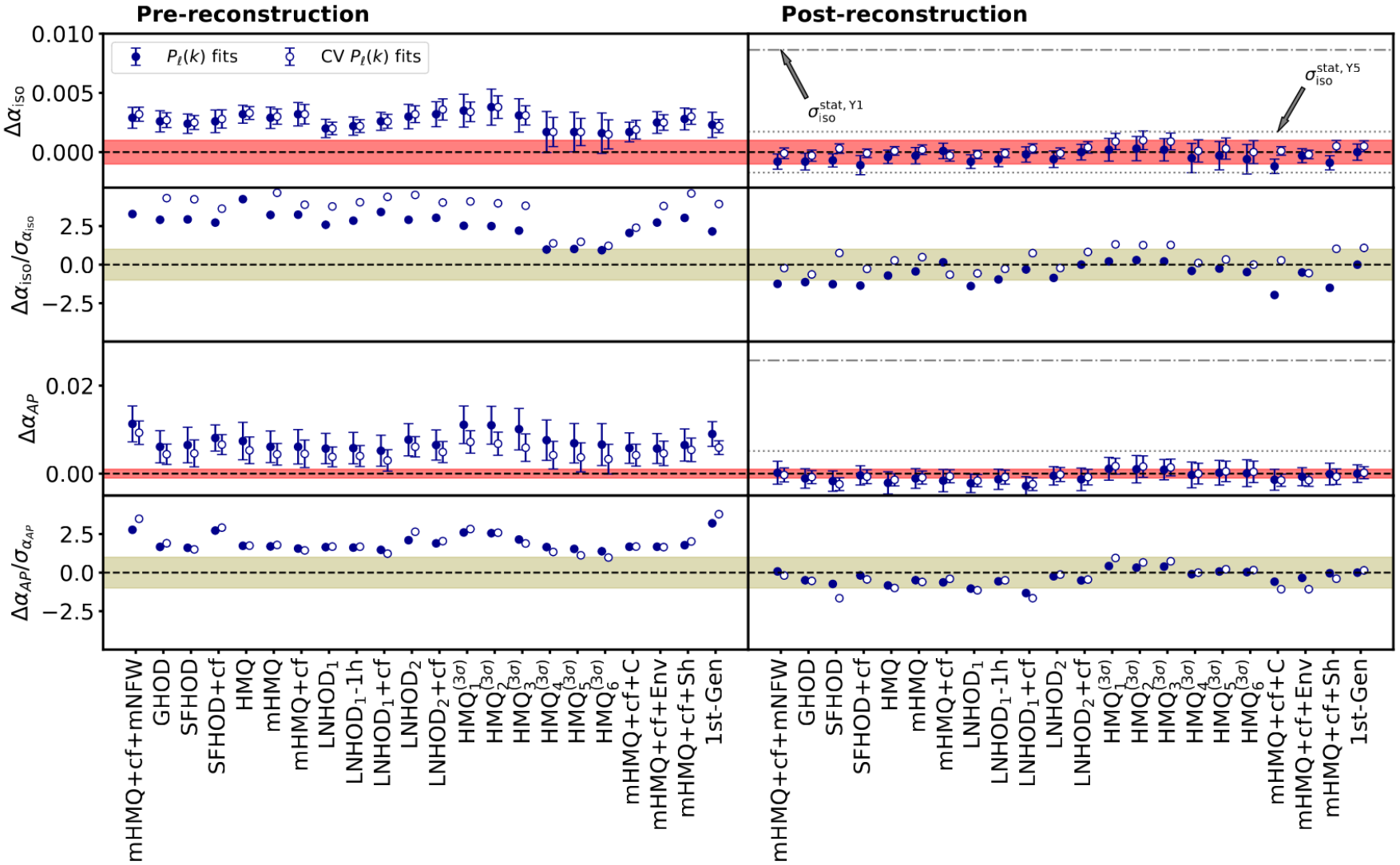
Ashley Ross, DESI KP3, and DESI collab

Preparing for the DESI Y1 analyses

- BAO theoretical systematics (Stephen Chen, Cullan Howlett)
- Optimizing reconstruction (*Xinyi Chen*, Zhejie Ding, *Enrique Paillas*)
- Testing robustness to HOD models (Juan Mena, *Cristhian Garcia-Quintero*)
- Fiducial cosmology assumptions (Alejandro Perez-Fernandez, Rossana Ruggeri, Leonel Medina Varela)
- Observational systematics (Alberto Rosado Marin, *Jiaxi Yu*, Mathilde Pinon, …)
- Covariances (Otavio Alves, Daniel Forero-Sanchez, Misha Rashkovetskyi)
- Overlapping tracers (David Valcin)

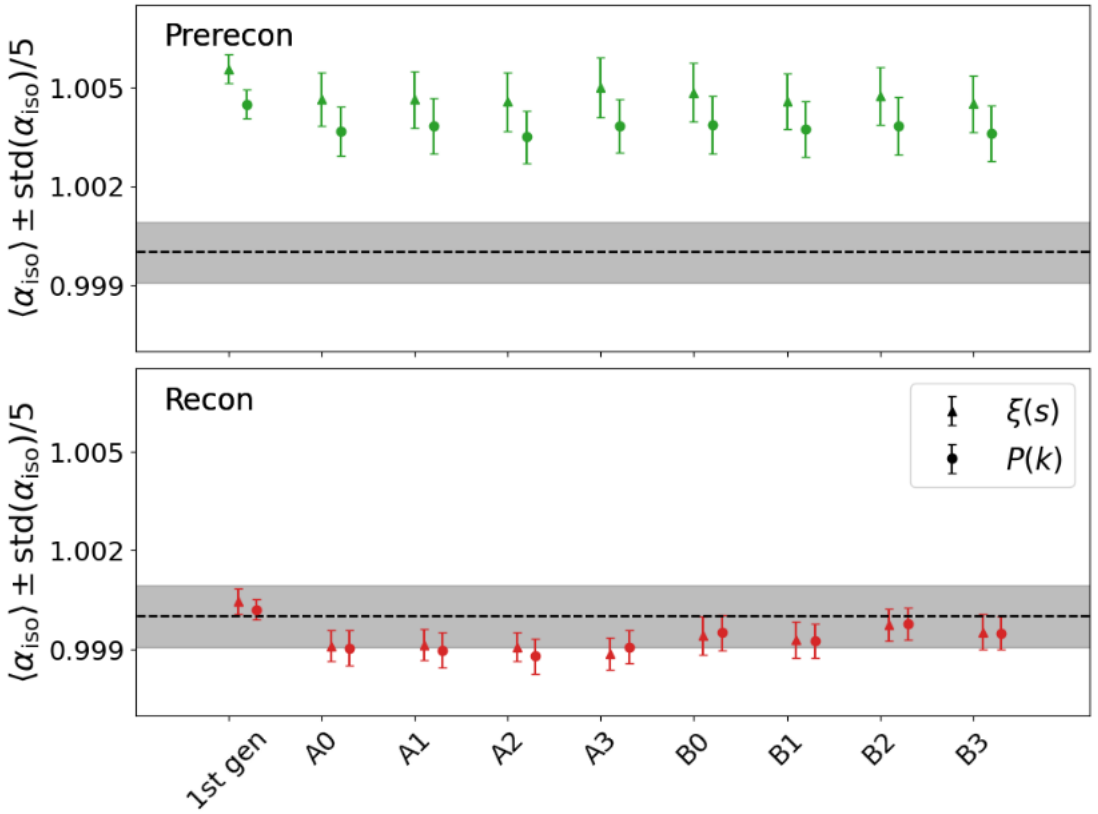
w/ Hee-Jong Seo, and many others

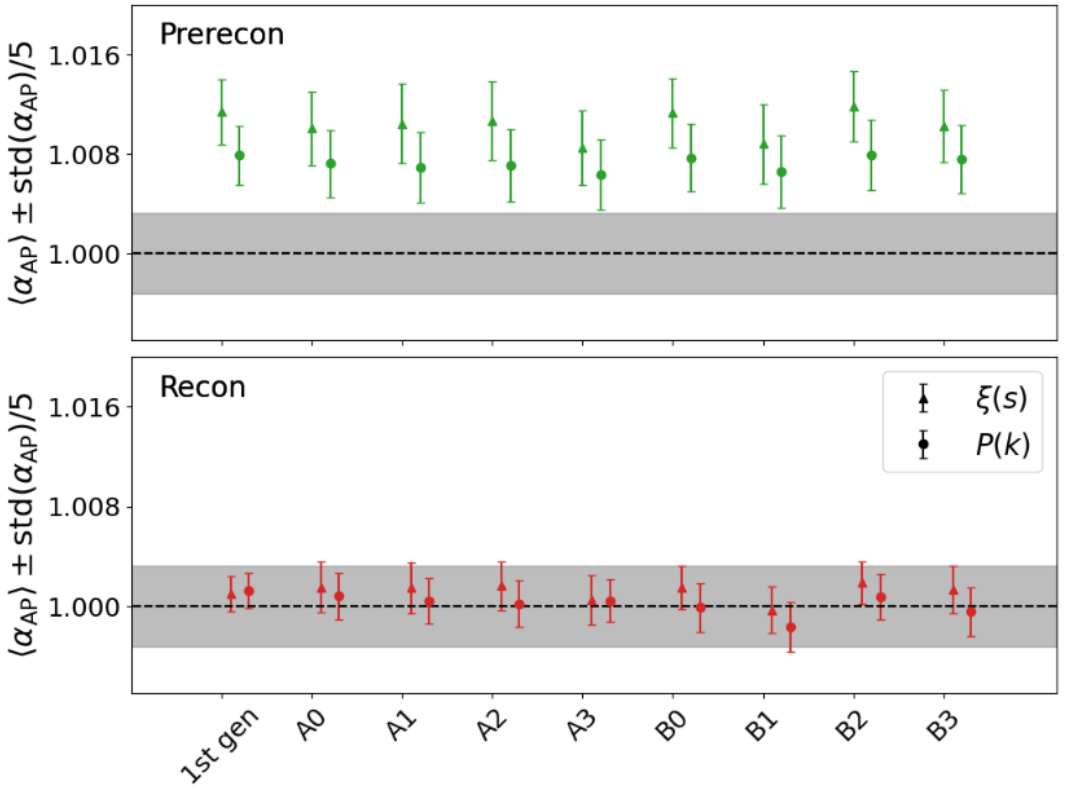
Exploring the ELG HOD space



C. Garcia-Quintero, J. Mena, et al, in prep

Exploring the LRG HOD space





J. Mena, C. Garcia-Quintero, et al, in prep

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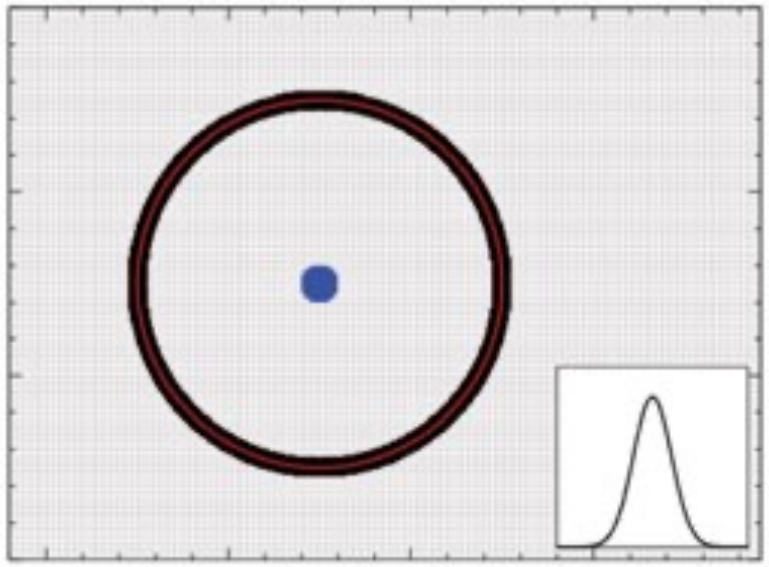
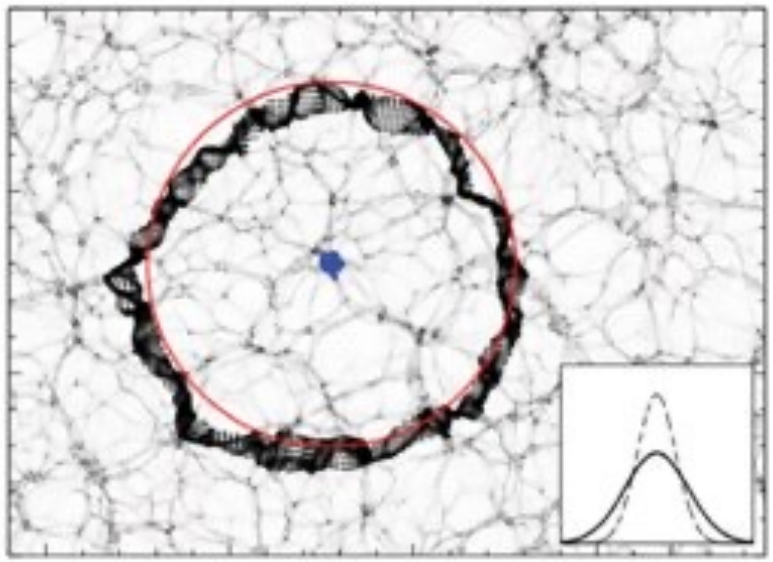
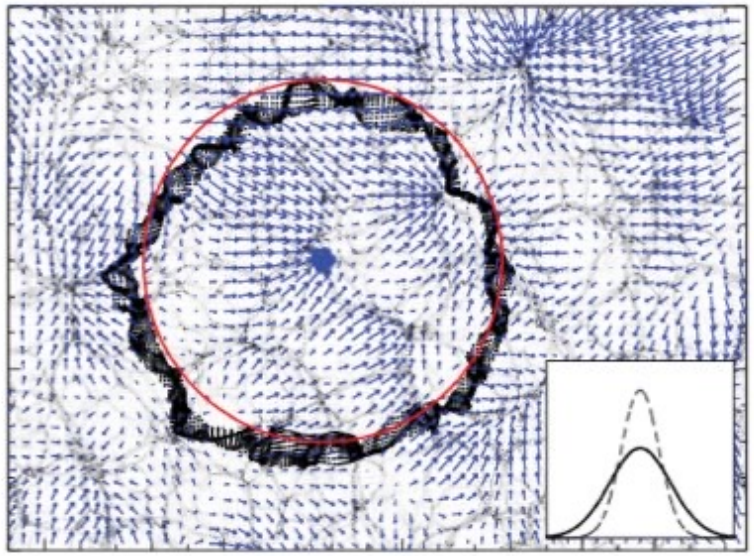
Many ideas here :
- Schmittfull et al 2015, Feng et al, 2019, Ota et al, 2021, Liu et al, 2021, Bayer et al, 2023

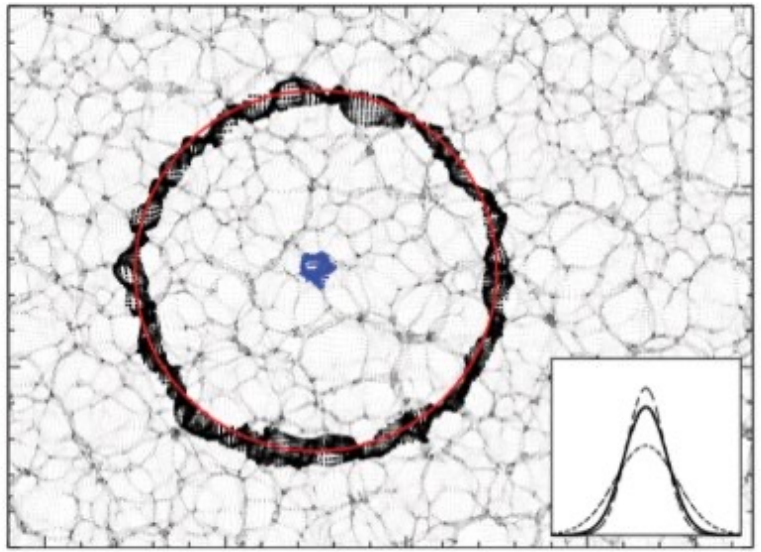
Reconstructing the BAO feature





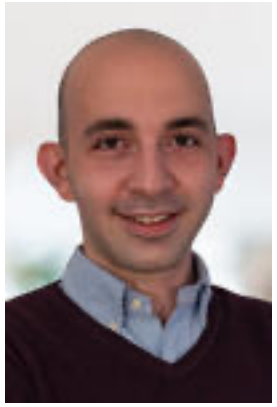
$$\nabla \cdot \Psi = -\delta$$





Eisenstein et al, 2006
NP et al, 2012

Back to simple flows : Optimal Transport



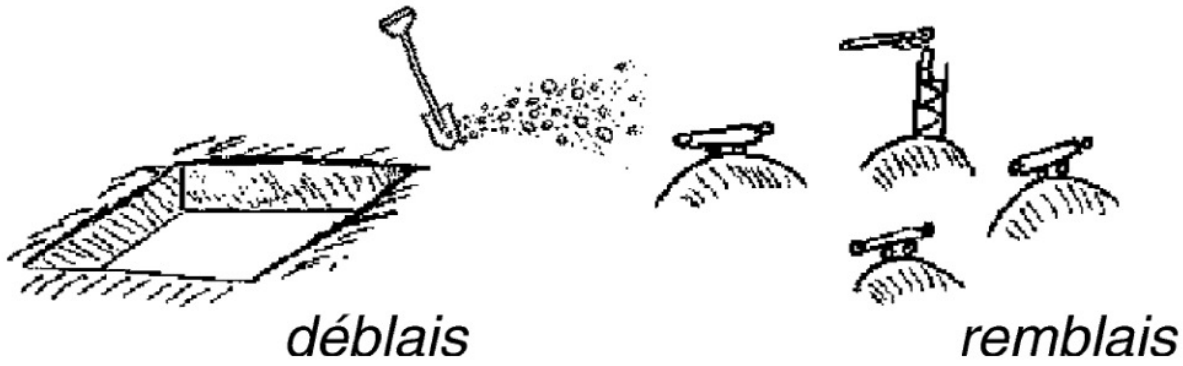
Optimal Transport Reconstruction of Biased Tracers in Redshift Space

Farnik Nikakhtar,[1,*] Nikhil Padmanabhan,[1,2] Roya Mohayaee,[3,4] Bruno Lévy,[5] and Ravi K. Sheth[6,7]

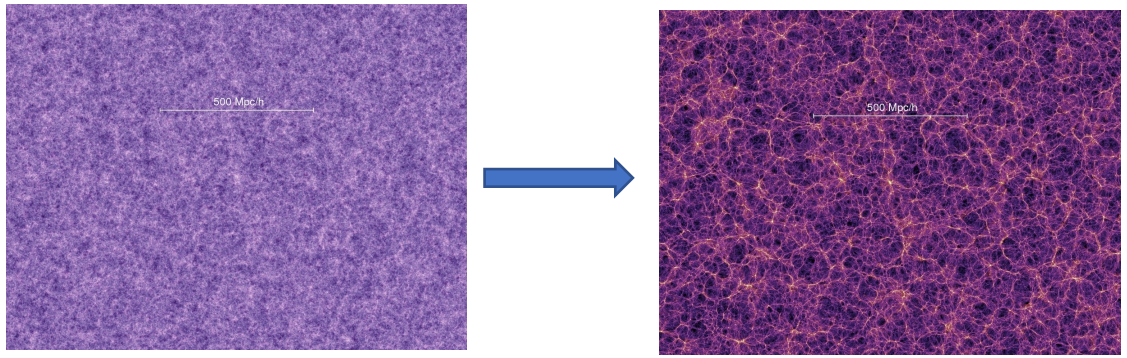
w/ Farnik Nikakhtar,
Ravi Sheth
Roya Moyahee
Bruno Levy

Old ideas meet new data
(Zeldovich, Peebles, Weinberg+Croft, …)

The Optimal Transport Problem



Brenier et al, 2003



Ideas trace back to Monge, Kantorovich

How to translate one distribution into another, minimizing a cost

Ideas now becoming very popular in machine learning, biology etc.

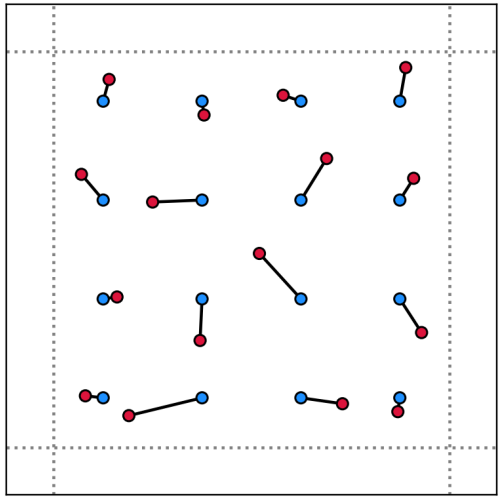
$$\rho(\mathbf{x})d^3x = \rho(\mathbf{q})d^3q = d^3q$$

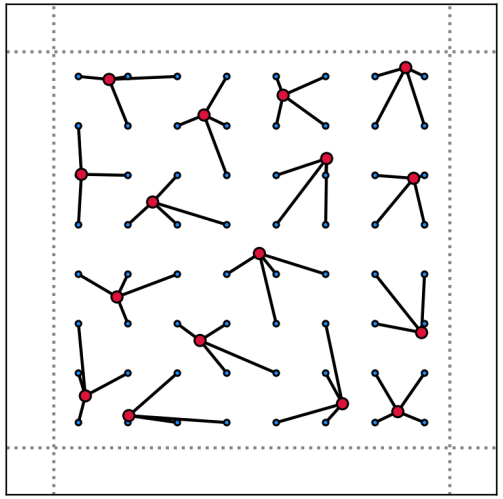
$$\mathbf{q} = \mathbf{x} + \nabla\phi$$

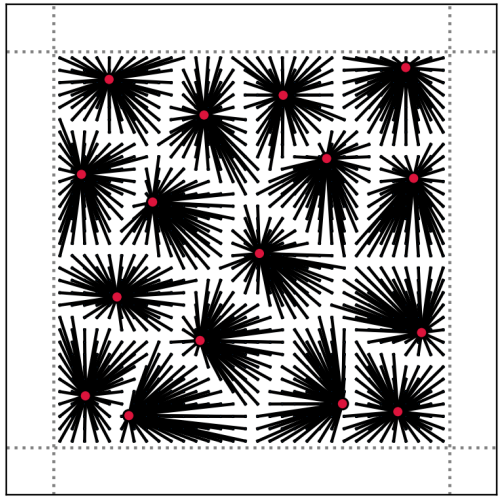
$$\det(1 + \partial_{xy}\phi) = \rho(\mathbf{x})$$

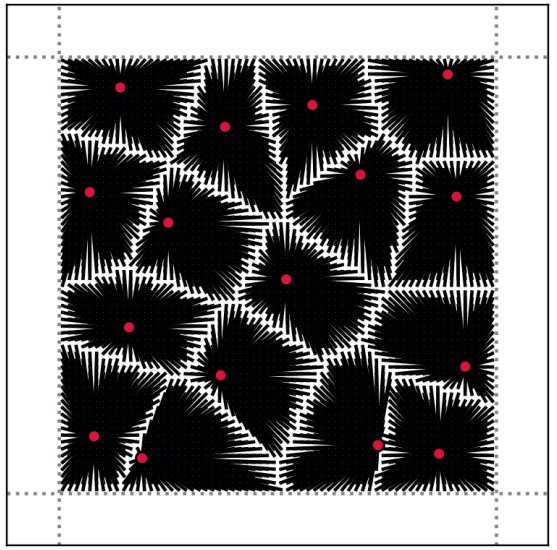
Equivalent to OT with quadratic cost

The Assignment Problem



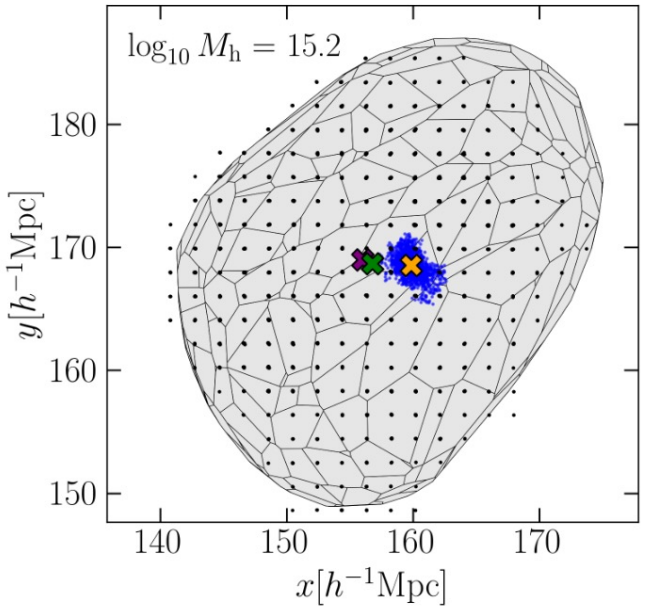


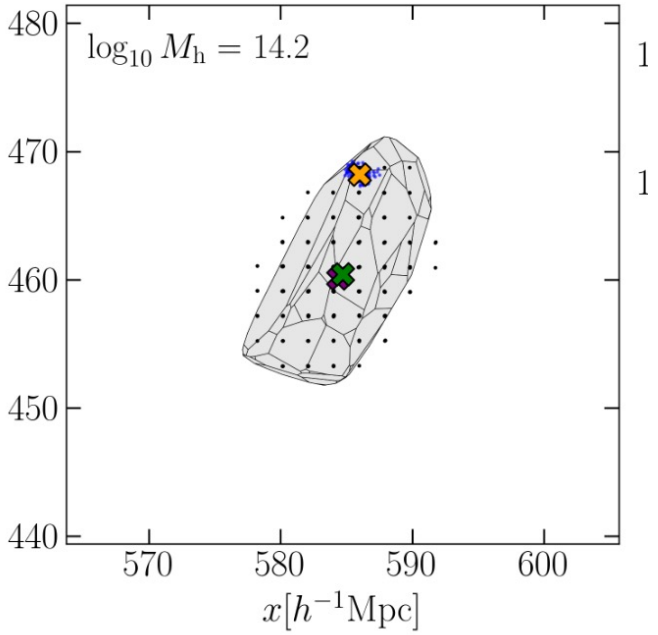


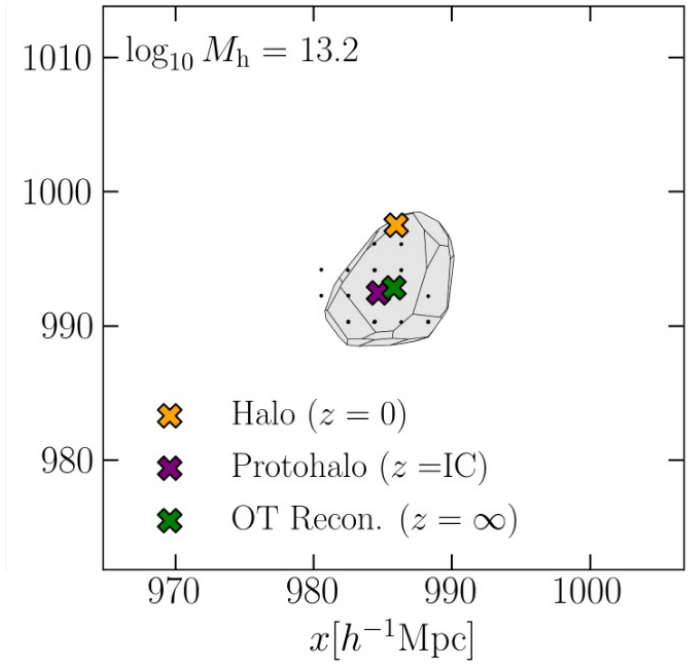


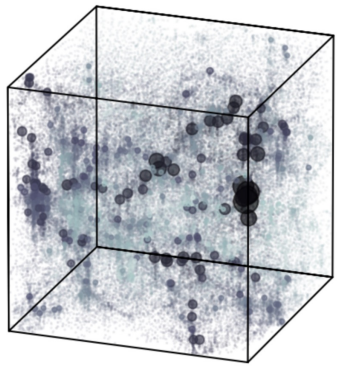
Partition space into Laguerre cells

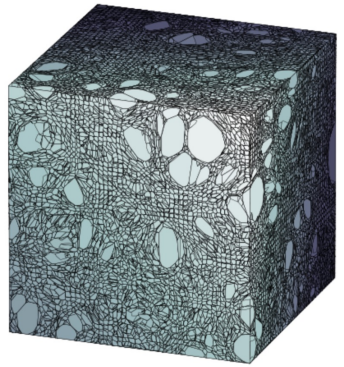
Reconstructing protohalo shapes







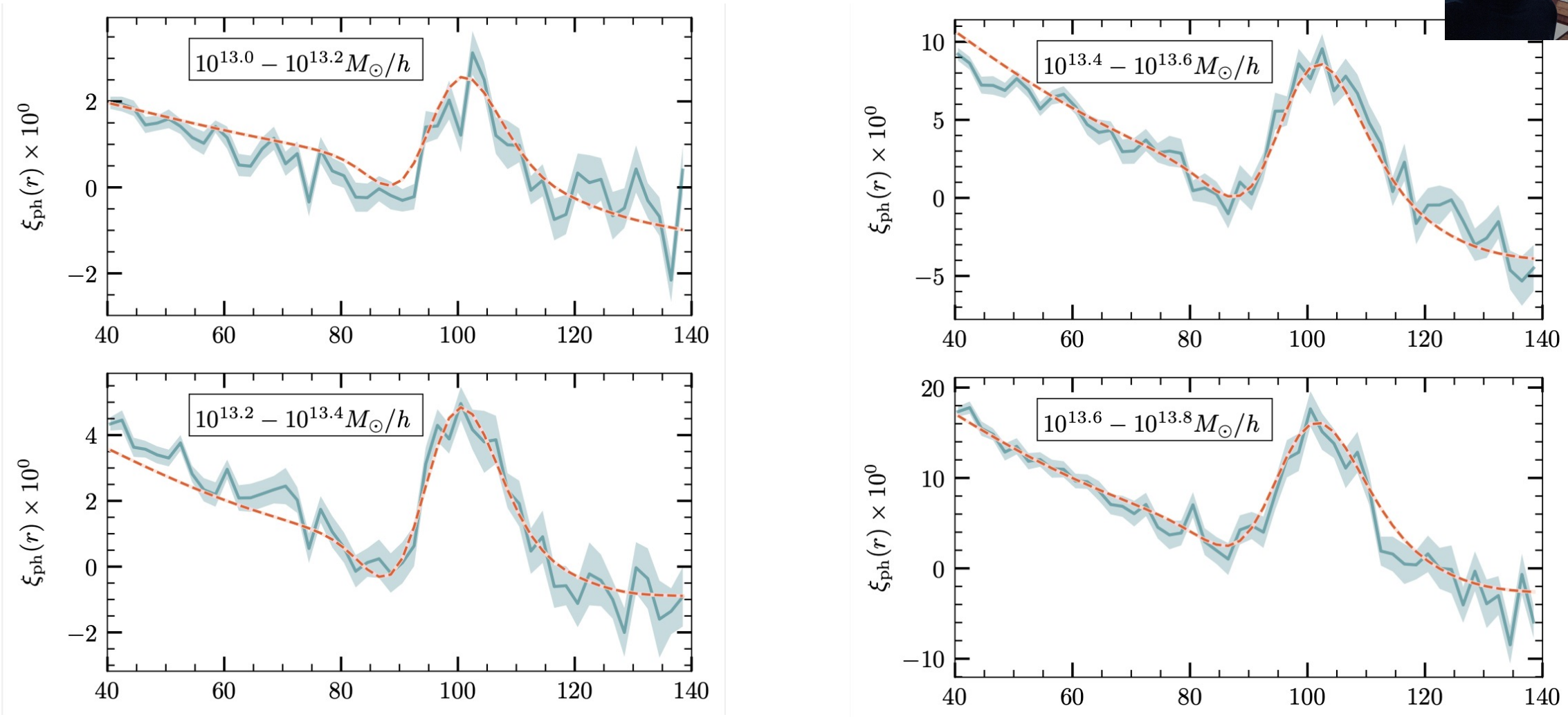




Nikakhtar et al, 2021

BAO in the protohalos

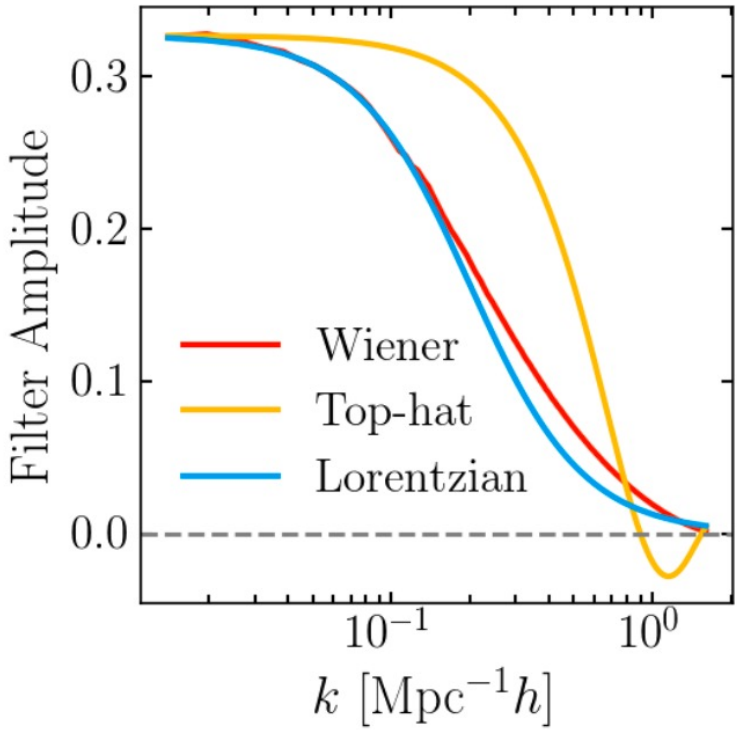
$$\delta_{\rm ph}(\vec{k}) = \left(b_{10} + b_{01} R_v^2 k^2\right) \delta_{\rm m}(\vec{k}) \tilde{W}(\vec{k} R_f)$$

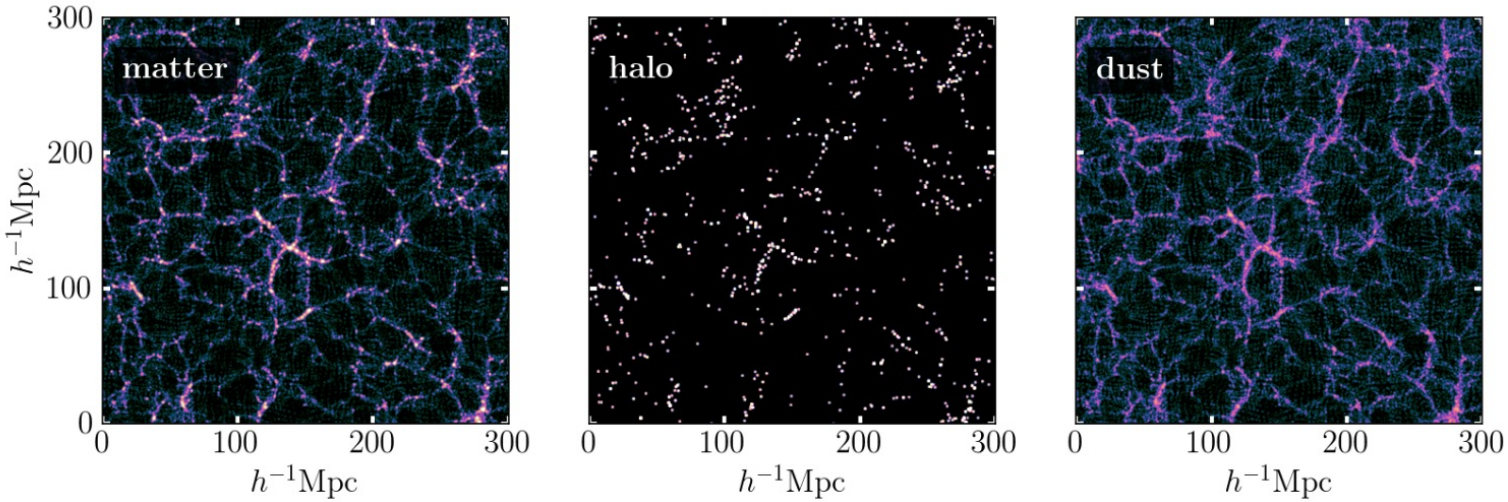


This simple model works well and produces an unbiased BAO scale

S. Gaines, et al, in prep

Filling in the dust



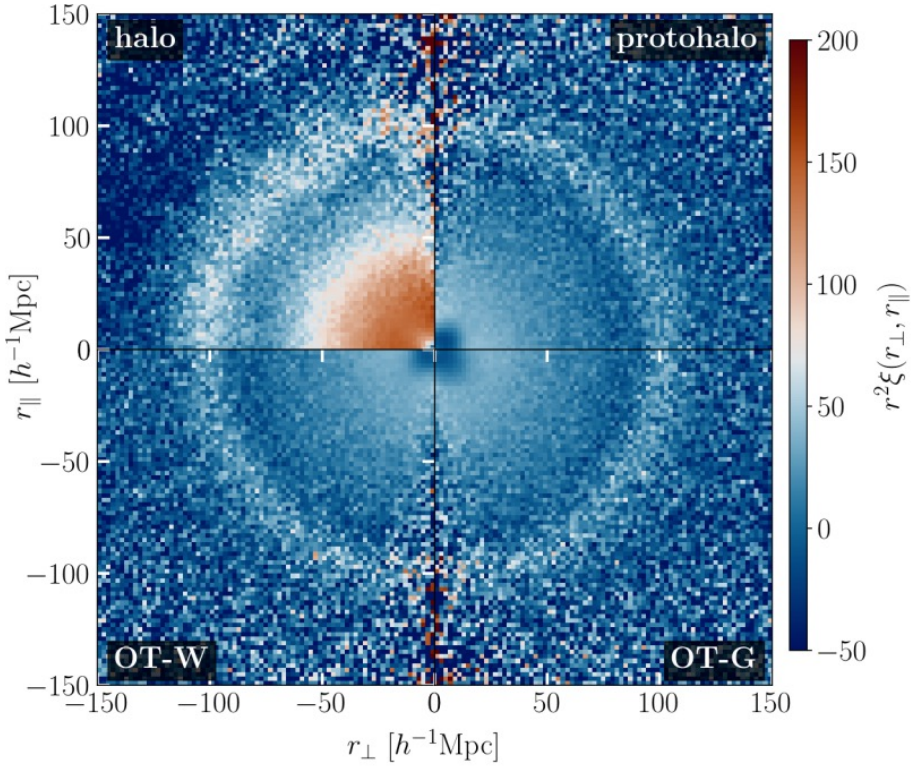


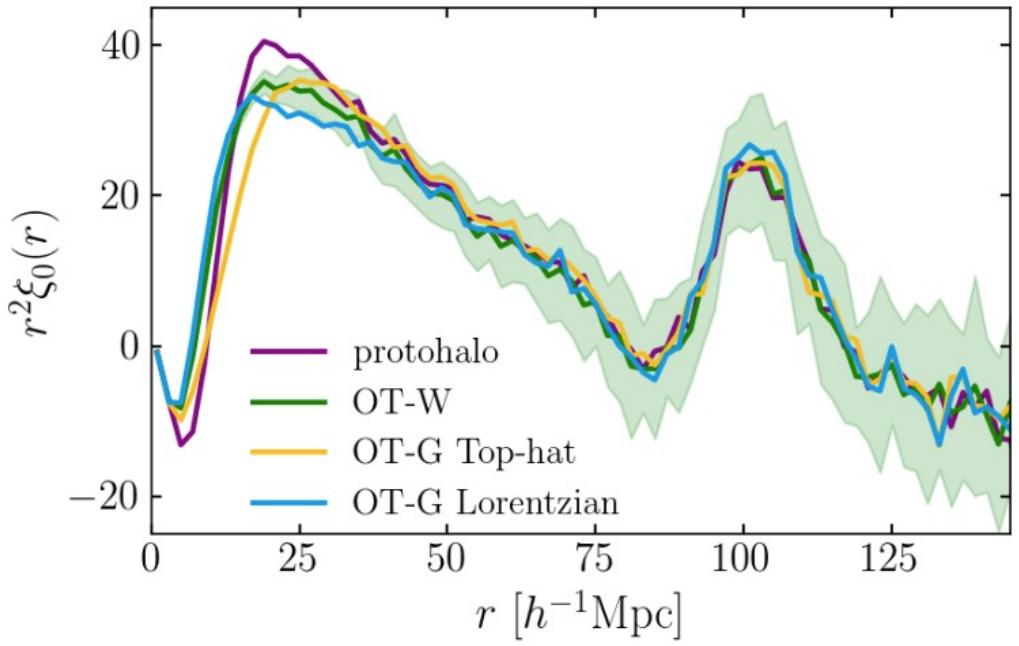
$$pb_h + (1-p)b_d = 1$$

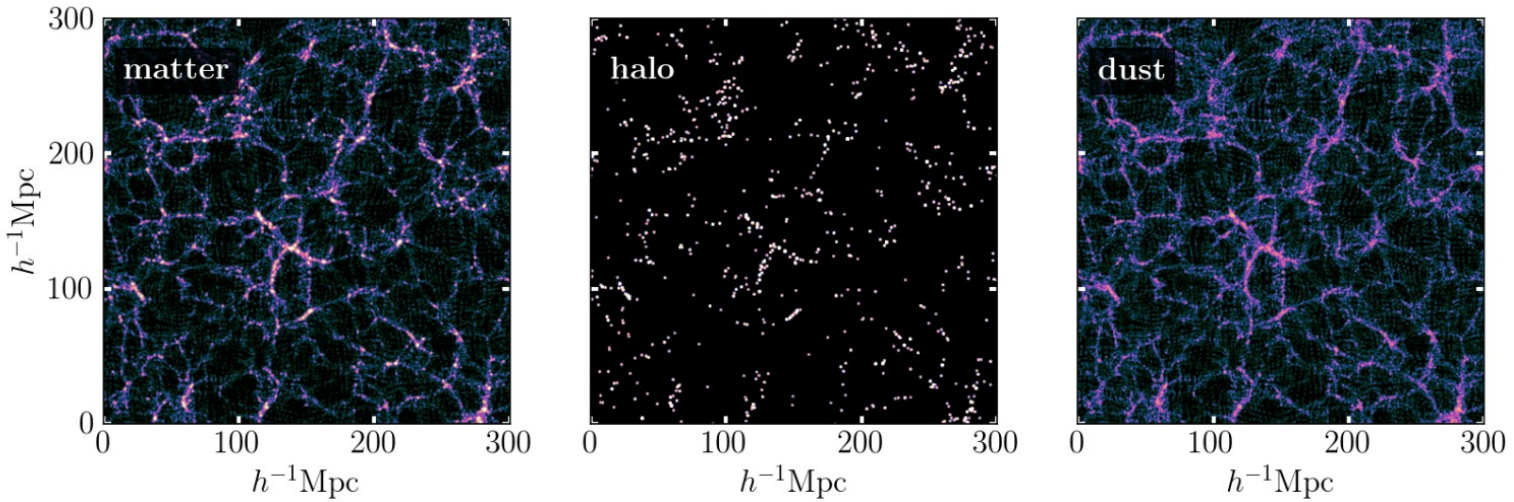
$$w_h = \frac{(b_d/b_h)\, n_h b_h^2\, P_{mm}(k)}{1 + \sum_h n_h b_h^2\, P_{mm}(k)}$$

F. Nikakhtar, NP, et al, 2023

Filling in the dust

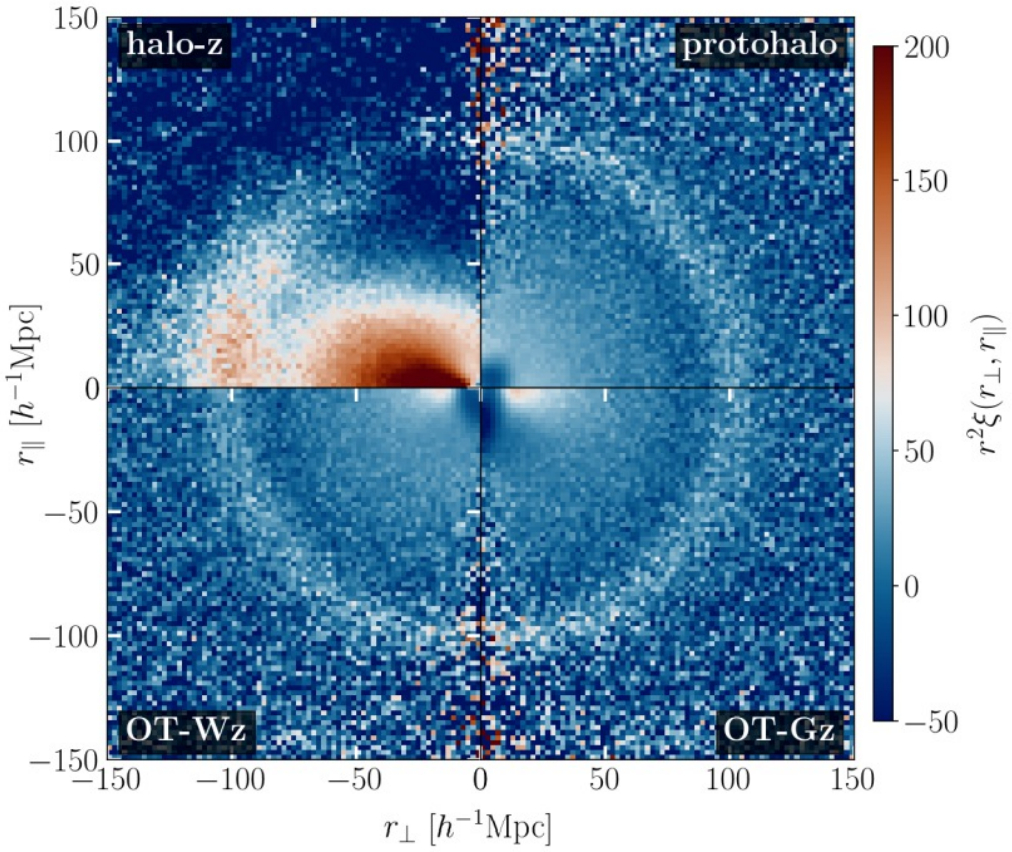




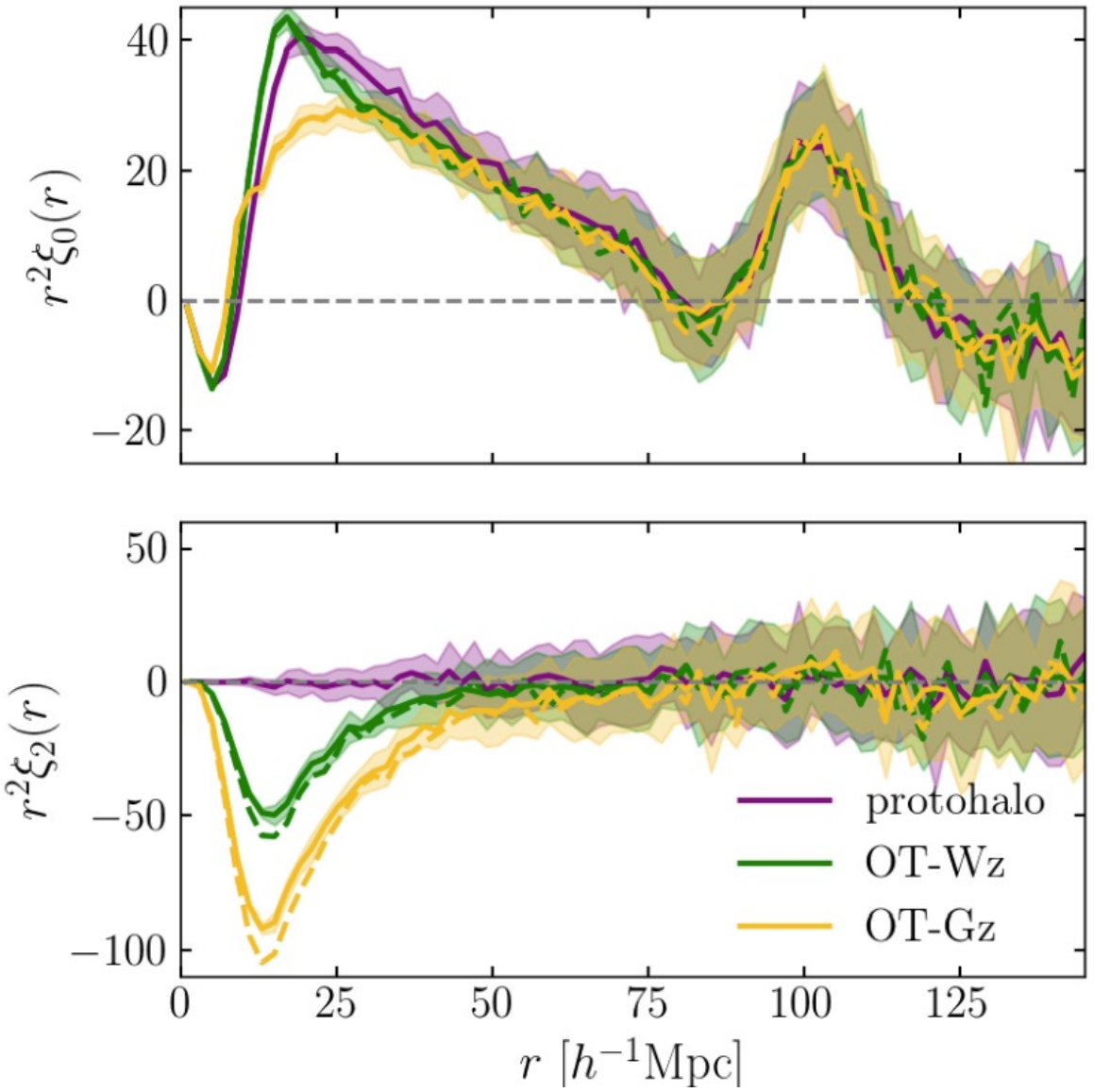


F. Nikakhtar, NP, et al, 2023

… and in redshift space

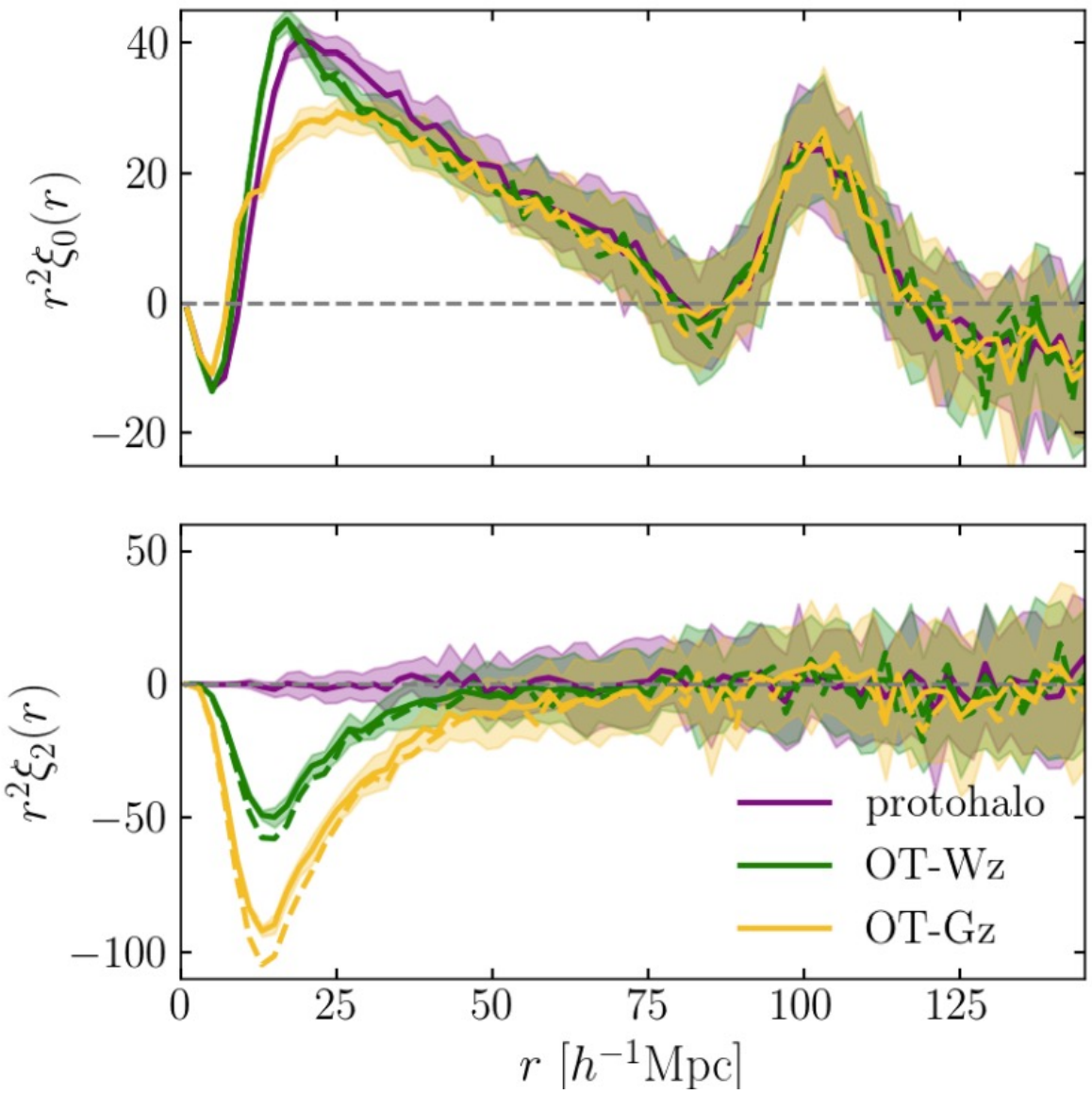


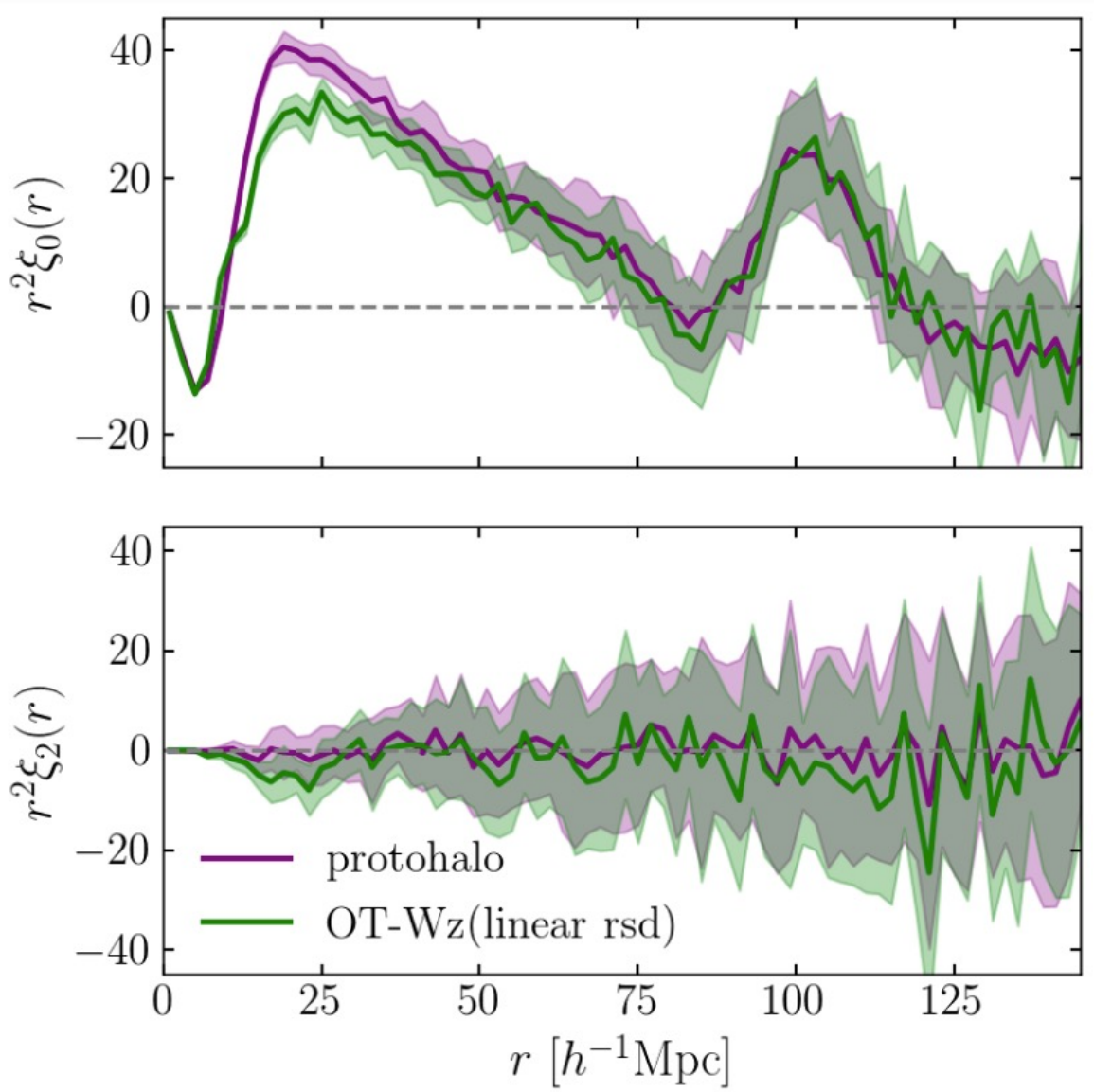
$$|\mathbf{S}|^2 = |\mathbf{S}_{\rm rsd}|^2 - \frac{f(2+f)}{(1+f)^2}\,(\hat{\mathbf{x}}\cdot\mathbf{S}_{\rm rsd})^2.$$



F. Nikakhtar, NP, et al, 2023

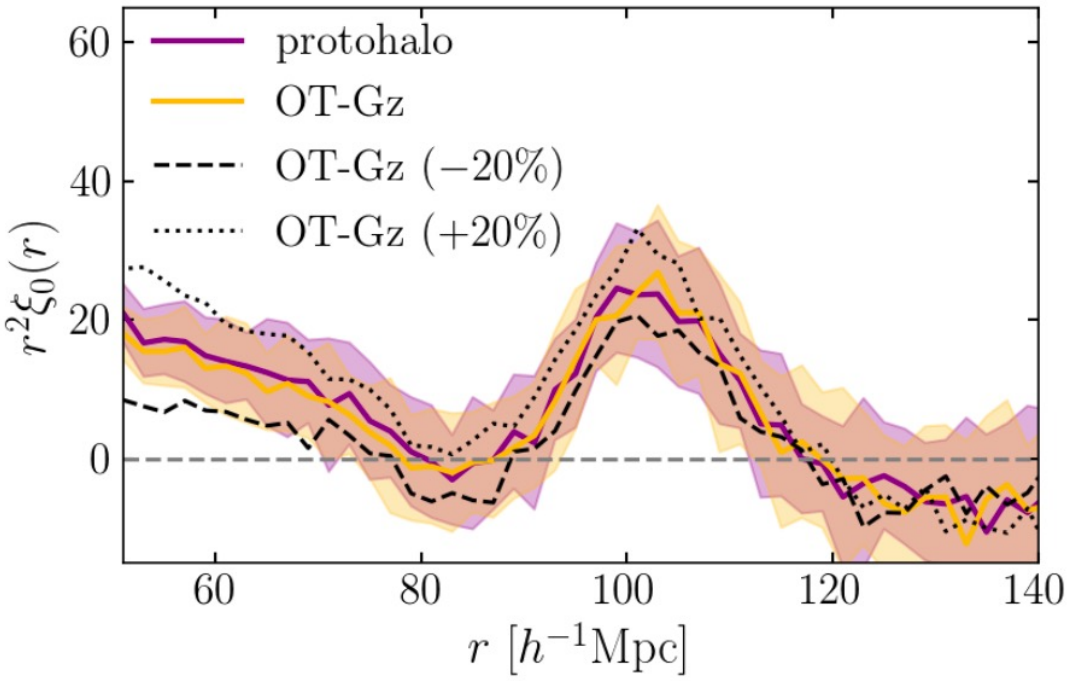
… and in redshift space



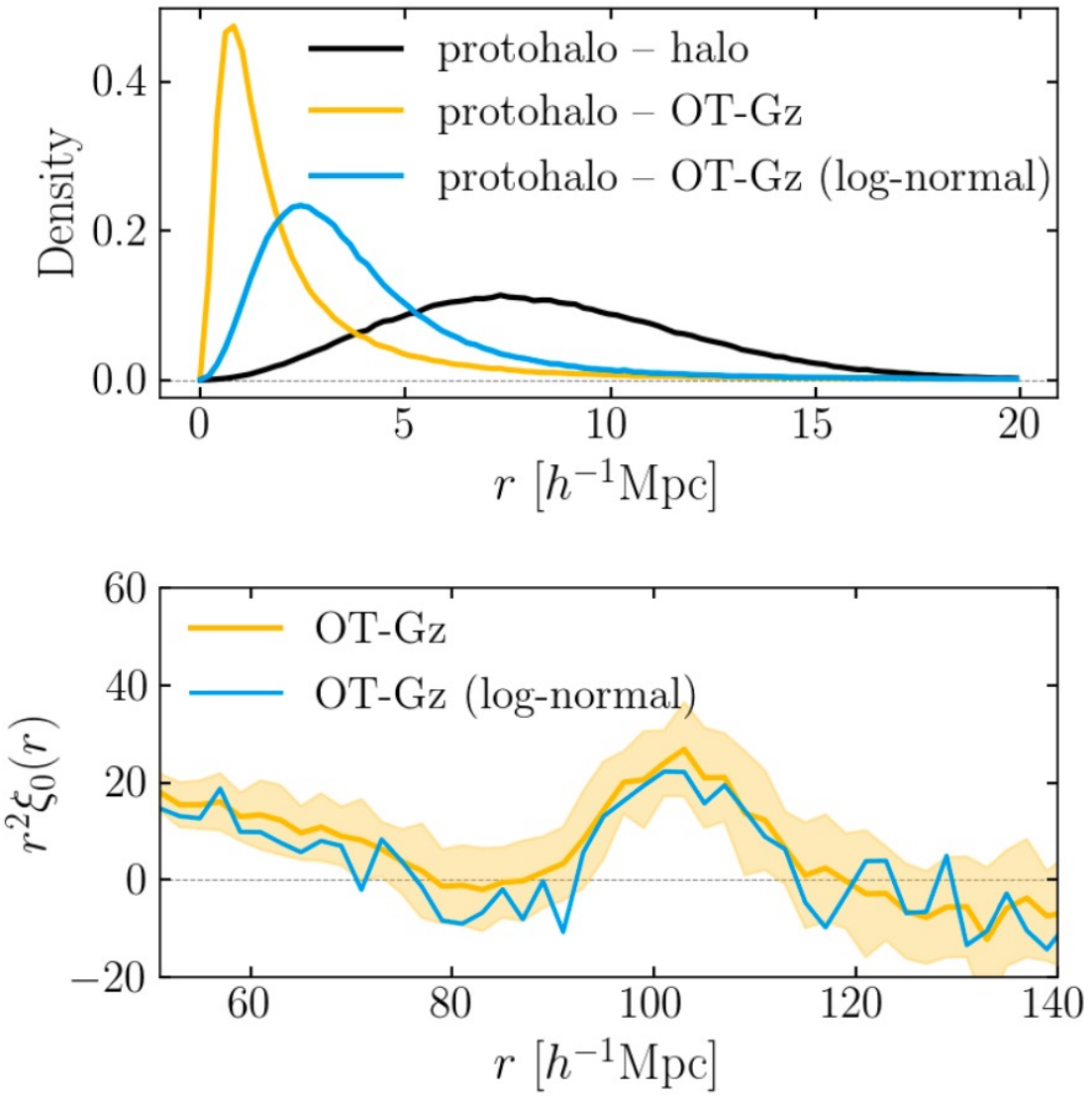


Robustness to assumptions

Incorrect galaxy bias



Incorrect masses



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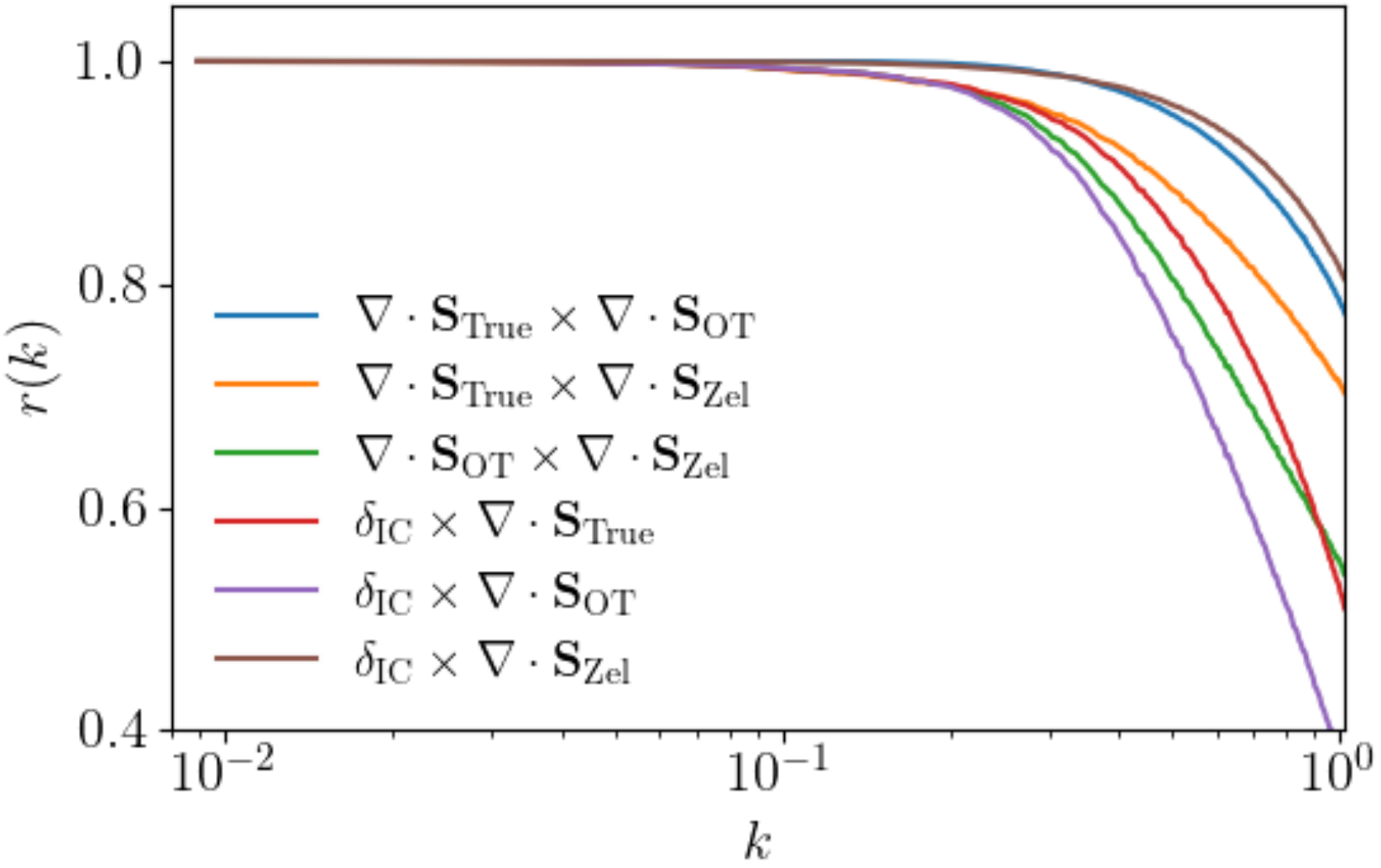
Reconstructing the matter field from displacements



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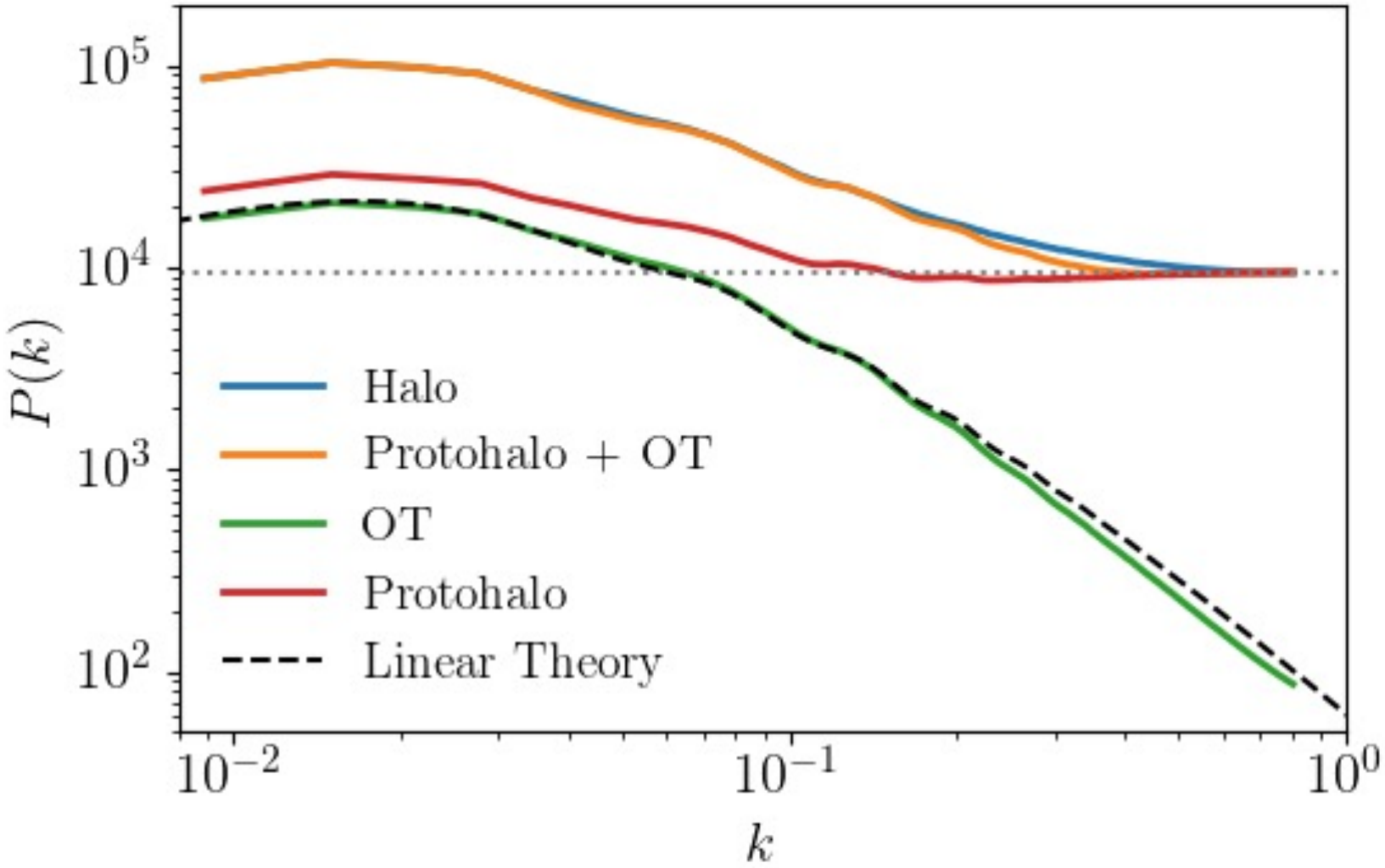
Boosting the protohalo clustering

Protohalo bias ~ (b-1), which suppresses clustering and S/N
Restore large scale power with the displacements (a la SS terms in standard reconstruction)



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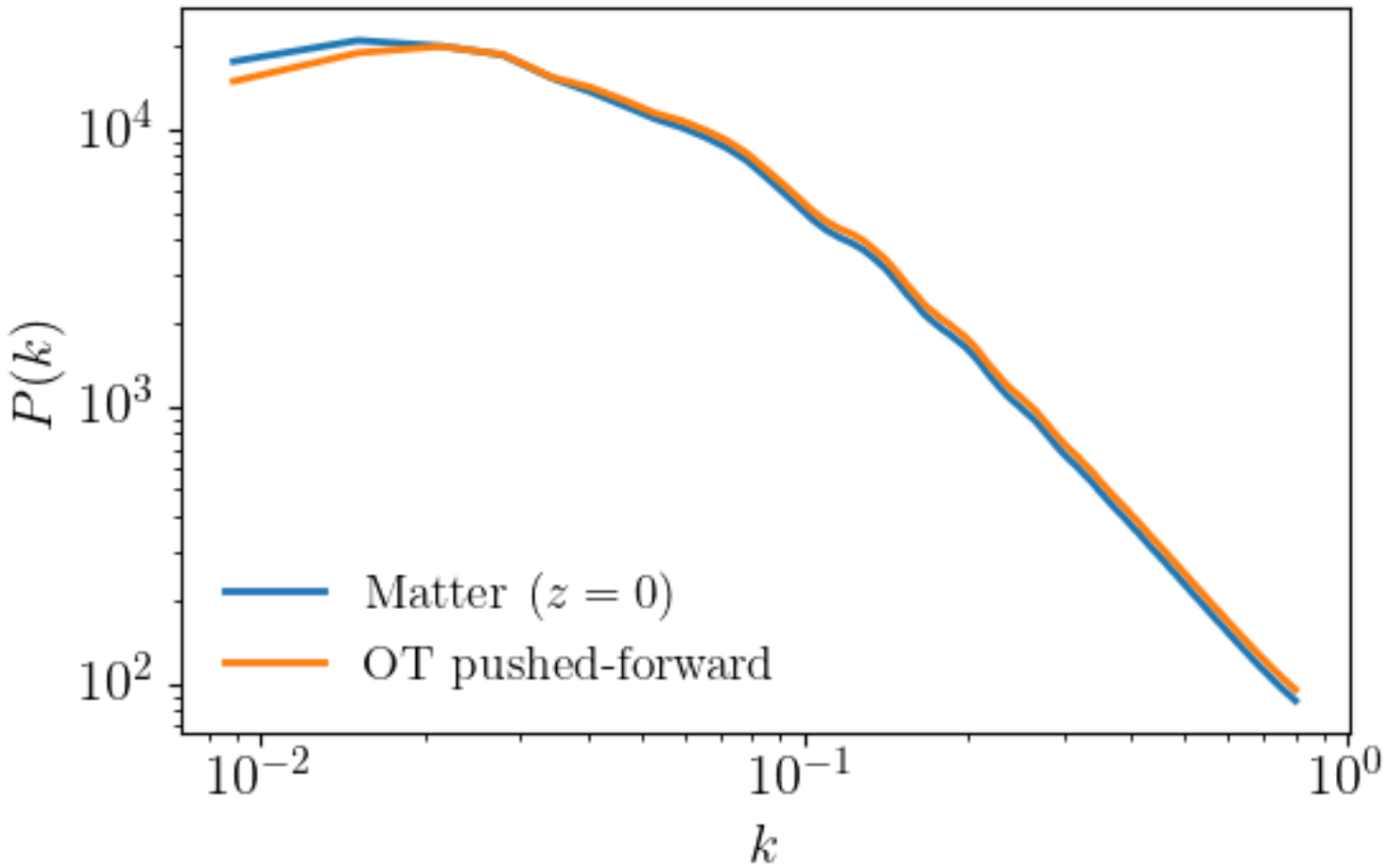
Revisiting "Zeldovich"

Can we build fast "straight line" simulations?
- the OT displacement is curl-free
- explore the connection between the Zeldovich potential and the OT potential



F. Nikakhtar, NP, et al, in prep

My Plan

- What can we expect from the upcoming BAO measurements?
  - Early results from DESI
  - A flavor of the Y1 BAO analyses
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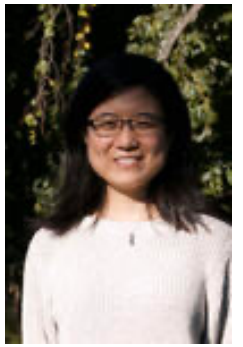
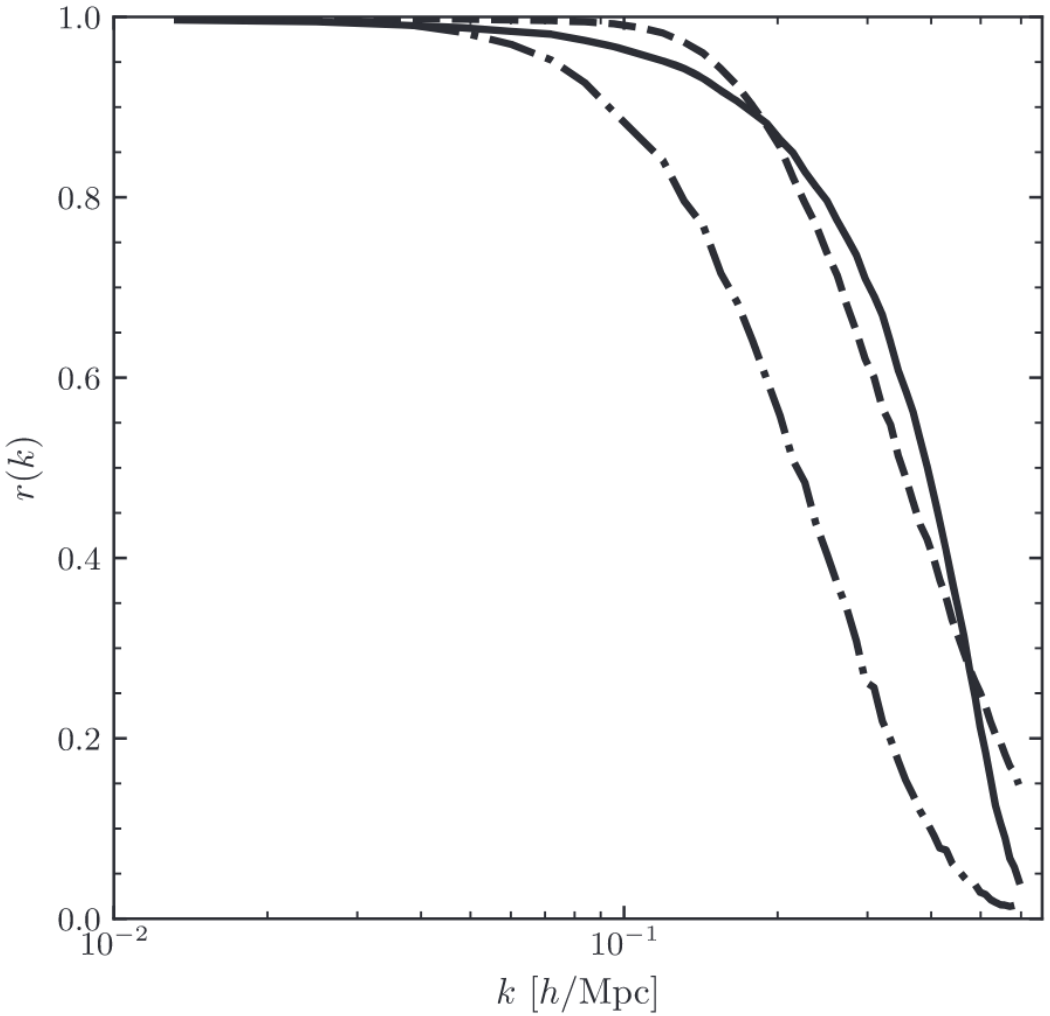
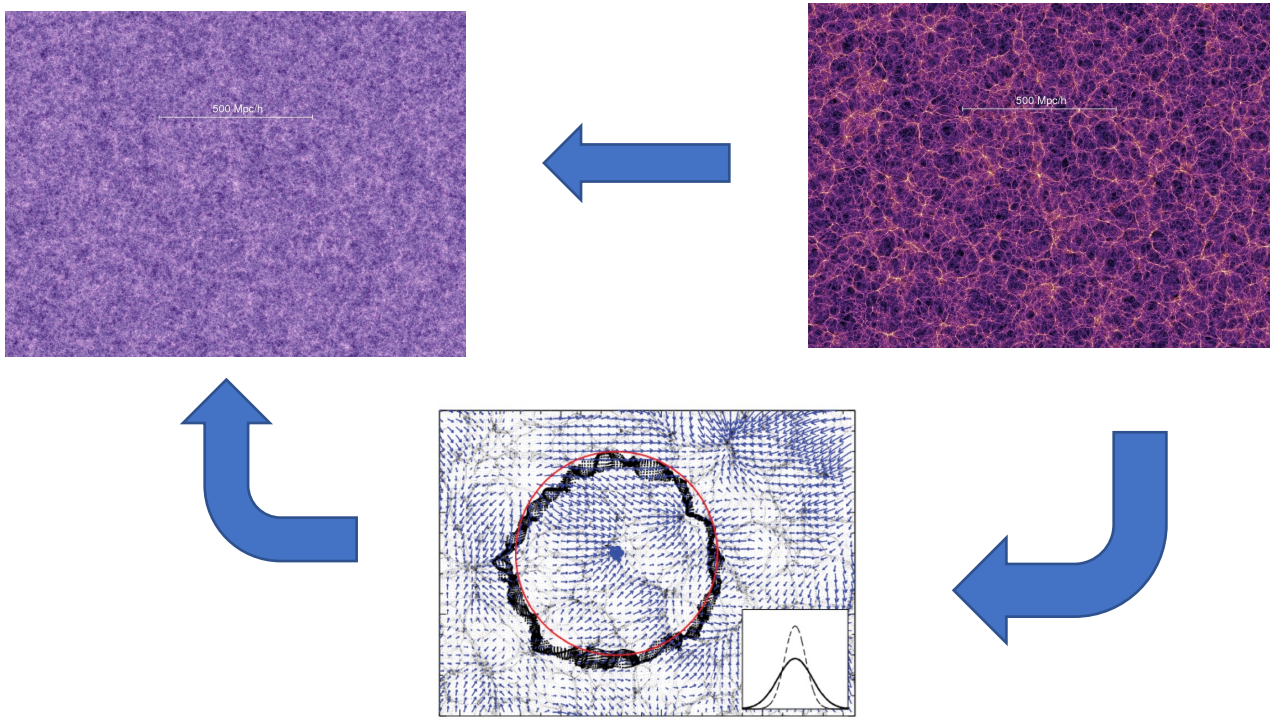
Going beyond a simple flow : CNNs

w/ Xinyi Chen







Hard to access large scales

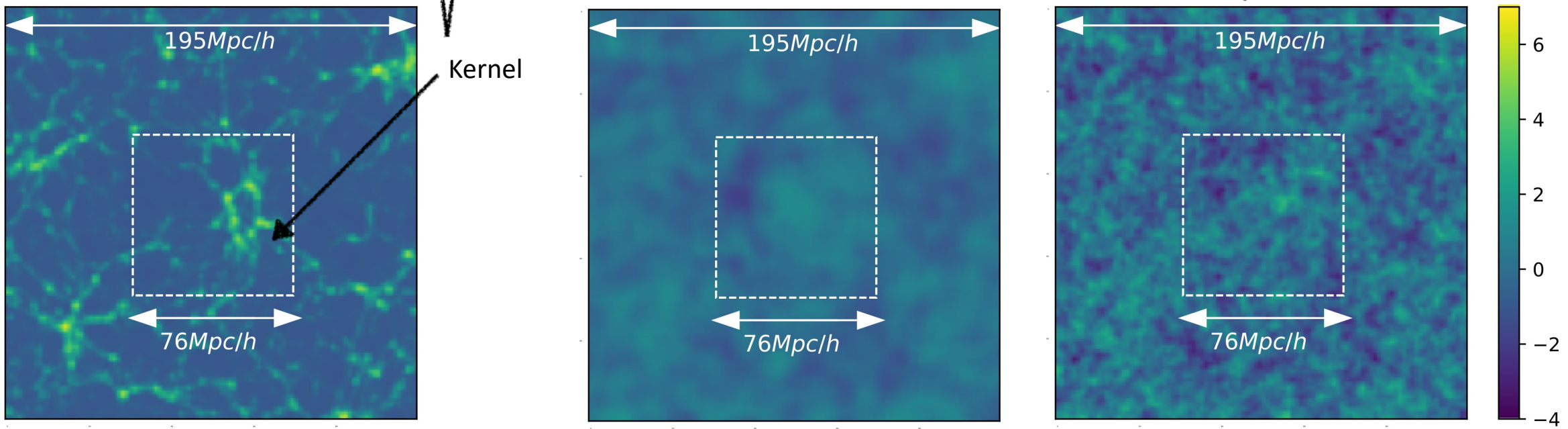
Use known behavior when possible

Mao et al, 2021
Shallue & Eisenstein, 2022
Chen et al, 2023

Using local information to enhance reconstruction

- Considers neighbor points by grouping them in a batch
- Trains with 8 simulations, normalized field, with initial density field the target

Extract information from this volume to determine the reconstructed density at the center



Late-time

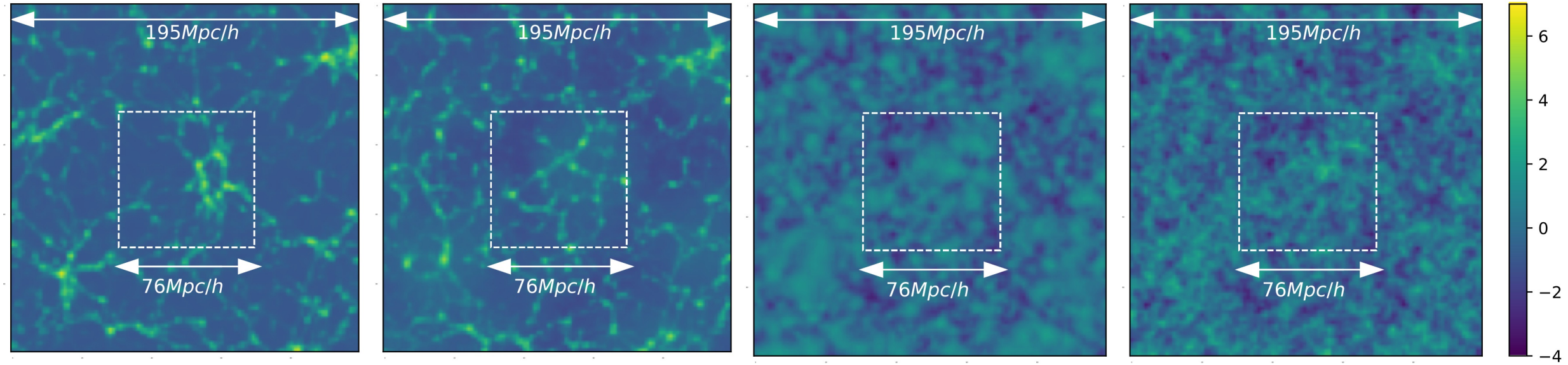
CNN trained w/ late-time field

Initial

Chen, et al, 2023

Training with reconstructed density field significantly improves performance

- The initial reconstruction provides a good approximation on large scales.
- CNN then reconstructs further on smaller scales.



Late-time

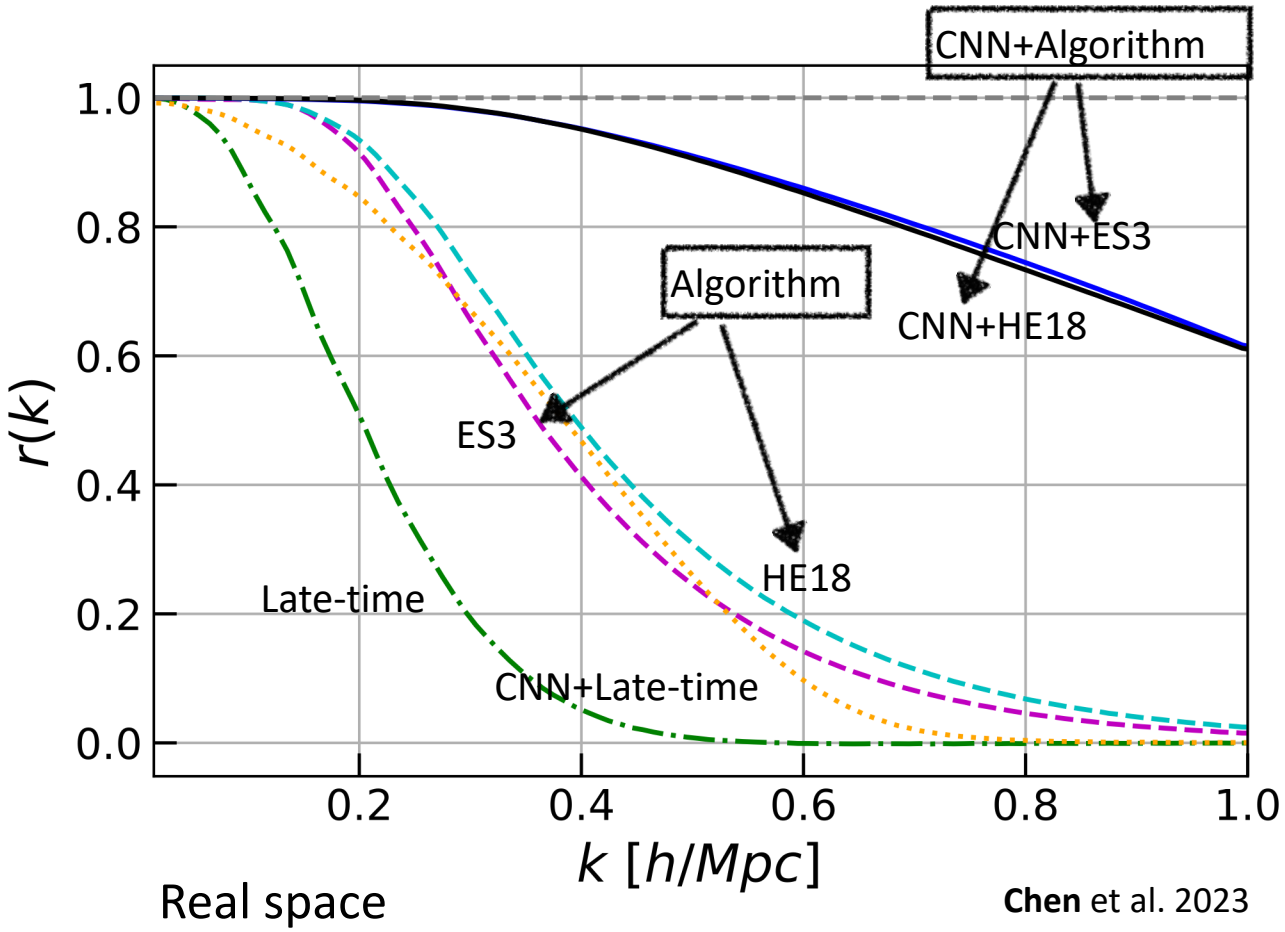
Standard recon

CNN trained w/ standard recon field

Initial

Chen, et al, 2023

CNN improves cross-correlation



Real space

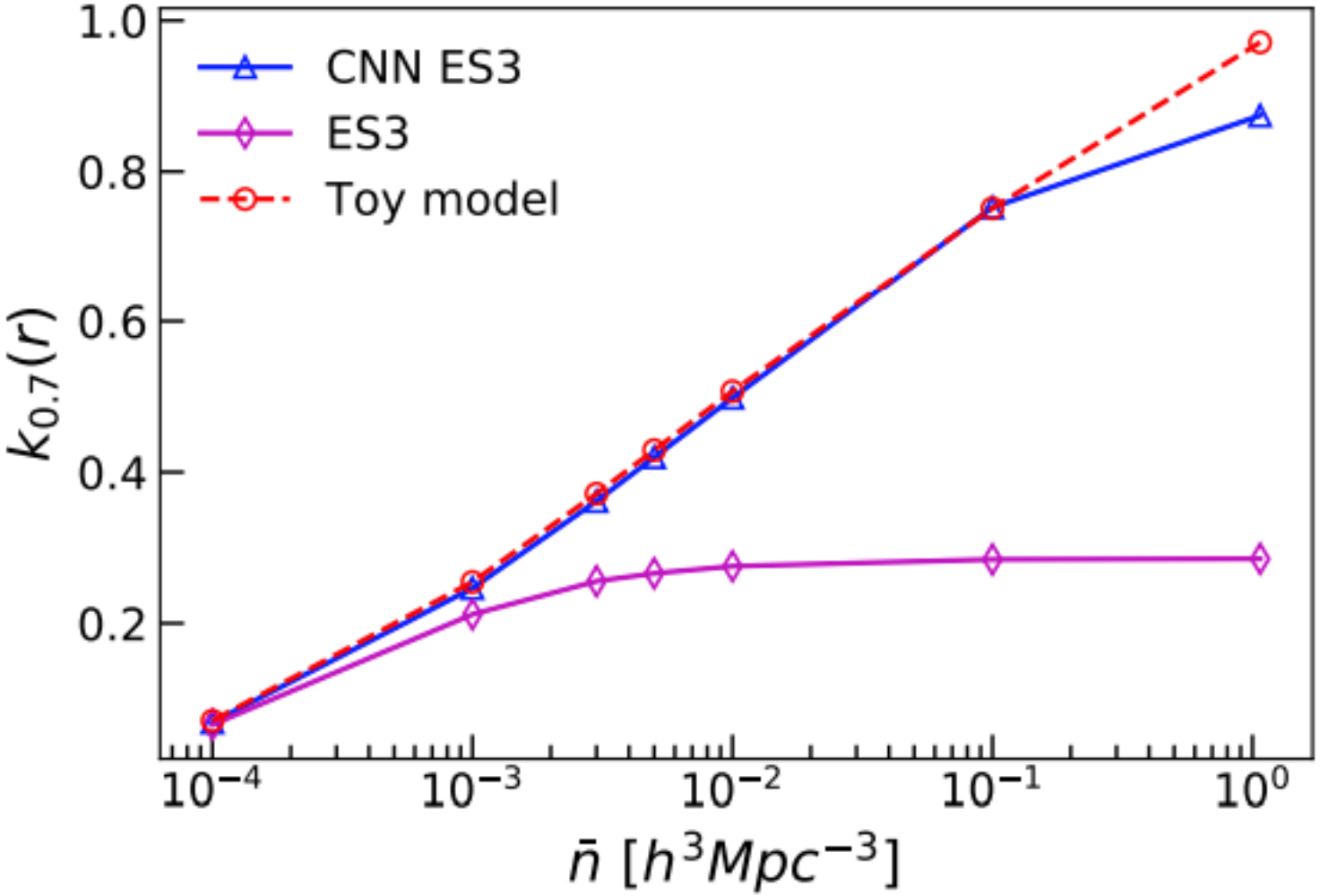
Chen et al. 2023

- CNN+Algorithm performs significantly better than algorithms alone and CNN+Late-time density field
- CNN+ES3 and CNN+HE18 are similar

Two reconstruction algorithms:

- Eisenstein et al. 2007, **ES3**, i.e., standard
- Hada & Eisenstein 2018, **HE18**

Challenges : Shot Noise



Chen, et al, 2023

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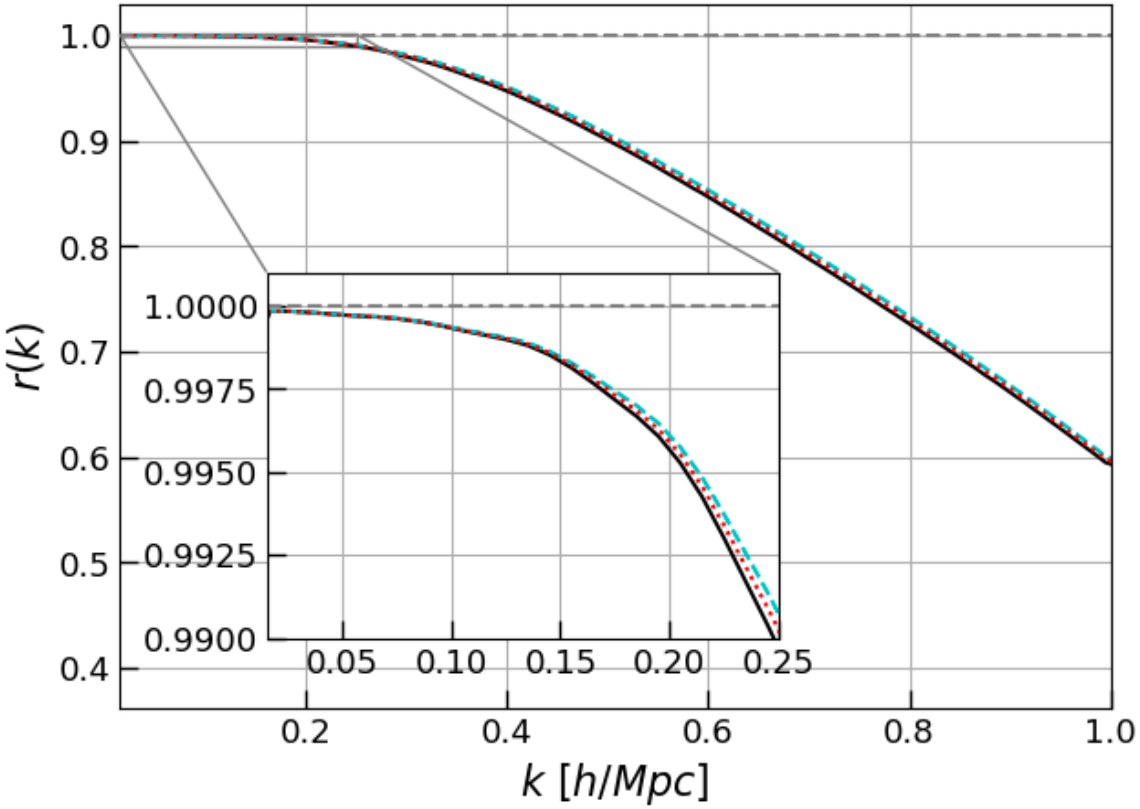
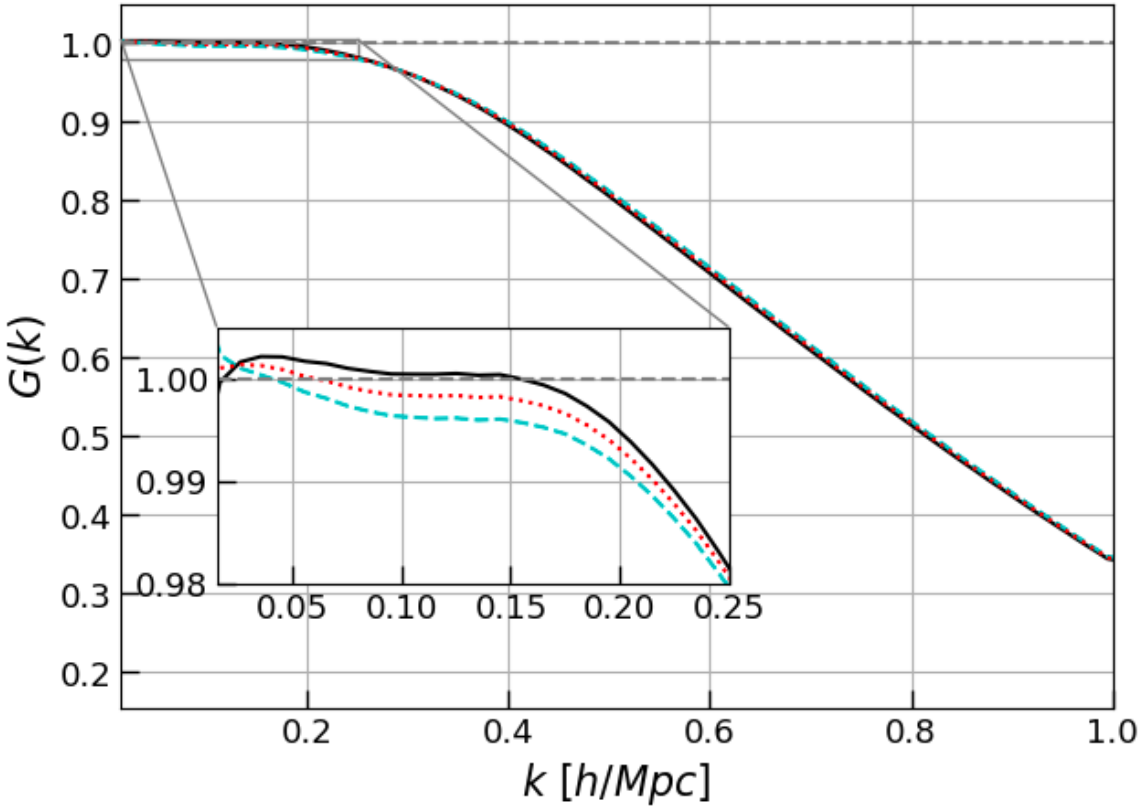
Model trained with no PNG works for PNG





– $f_{\mathrm{NL}} = +100$
... $f_{\mathrm{NL}} = 0$
- - $f_{\mathrm{NL}} = -100$

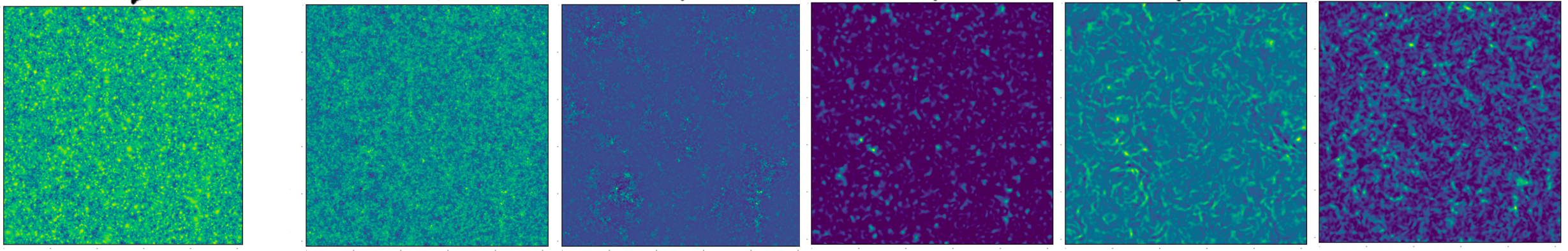
CNN+HE18

Templates for fitting f_{NL}

- δ_G=No PNG IC
- $\delta_{f_{\rm NL}} = \phi_G^2(k) M_\phi(k)$
- $\delta^2, \delta_{\nabla^2}, \delta_{s^2}$ all computed using δ_G

Gaussian Growth Shift Tidal

$$\delta_{\rm CNN} = b_G \delta_G + f_{\rm NL} \delta_{f_{\rm NL}} + b_2 \delta^2 + b_{\nabla^2} \delta_{\nabla^2} + b_{s^2} \delta_{s^2}$$



Templates for fitting f_{NL}

Gaussian Growth Shift Tidal

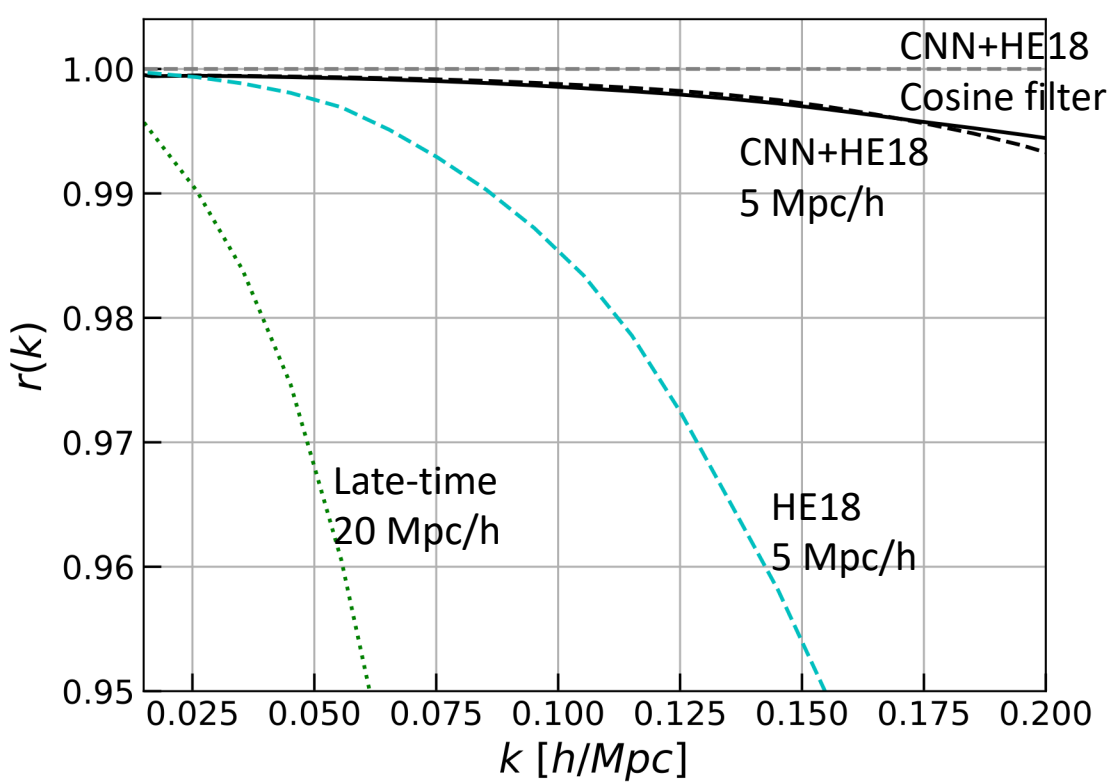
$$\delta_{\mathrm{CNN}} = b_G\delta_G + f_{\mathrm{NL}}\delta_{f_{\mathrm{NL}}} + b_2\delta^2 + b_{\nabla^2}\delta_{\nabla^2} + b_{s^2}\delta_{s^2} + \ldots$$

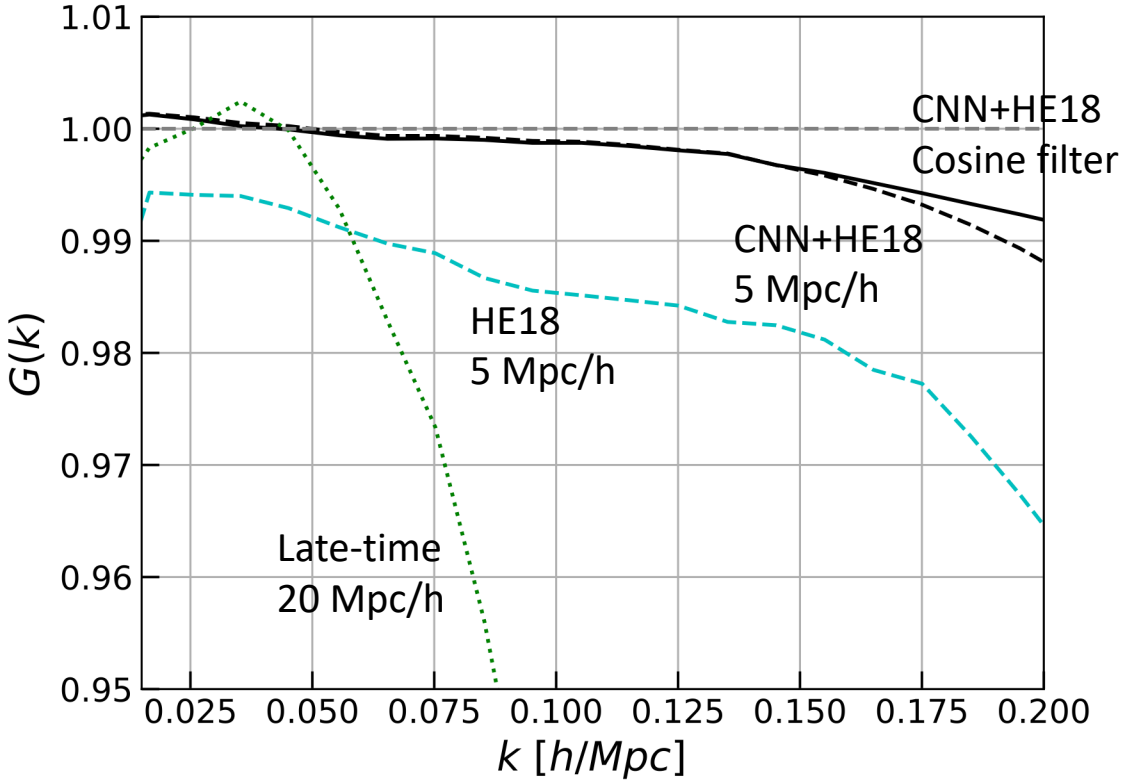
fnl value	Gaussian	fnl	growth	Shift	tidal
0	~1	-15+/-5	0.006	-0.014	0.014
+100	~1	77+/-5	0.005	-0.015	0.014
-100	~1	-107+/-5	0.007	-0.014	0.013

Perturbative values : growth = 17/21, shift = -1, tidal = 4/21

Reconstruction significantly reduces all the nonlinearities, while (mostly) preserving non-gaussianity

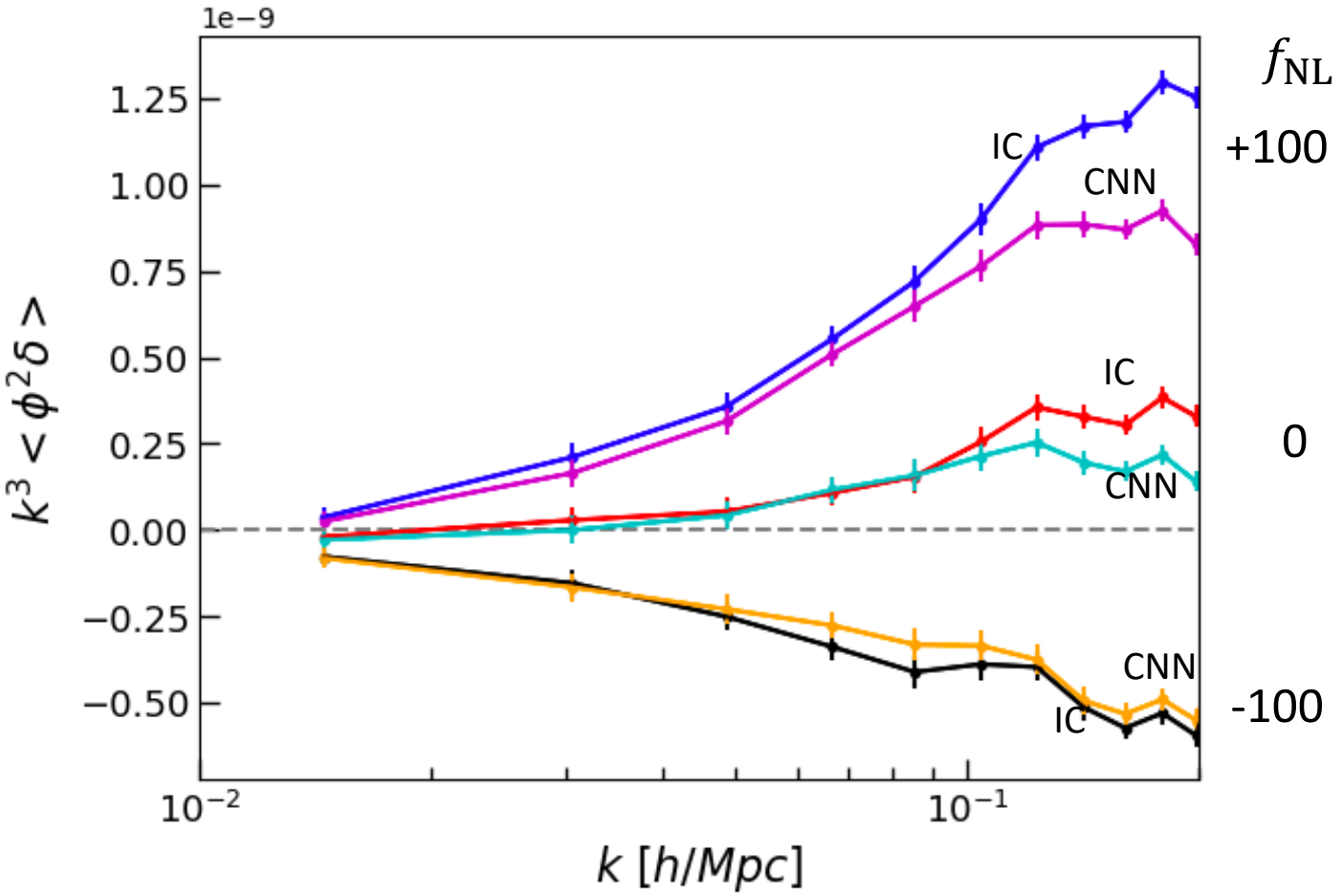
Constructing a template for the fnl contribution





Cosine filter: between k in 0.2-0.25 h/Mpc

Constructing a bispectrum estimator



- Does not fully recover the initial conditions, but consistent with template fits
- Can construct analogous estimators for other fields to constrain nuisance/nonlinear parameters
- In progress…

with cosine filter between
k=0.2-0.25 h/Mpc

Schmittfull, Baldauf, Seljak 2015

My Plan - reprised

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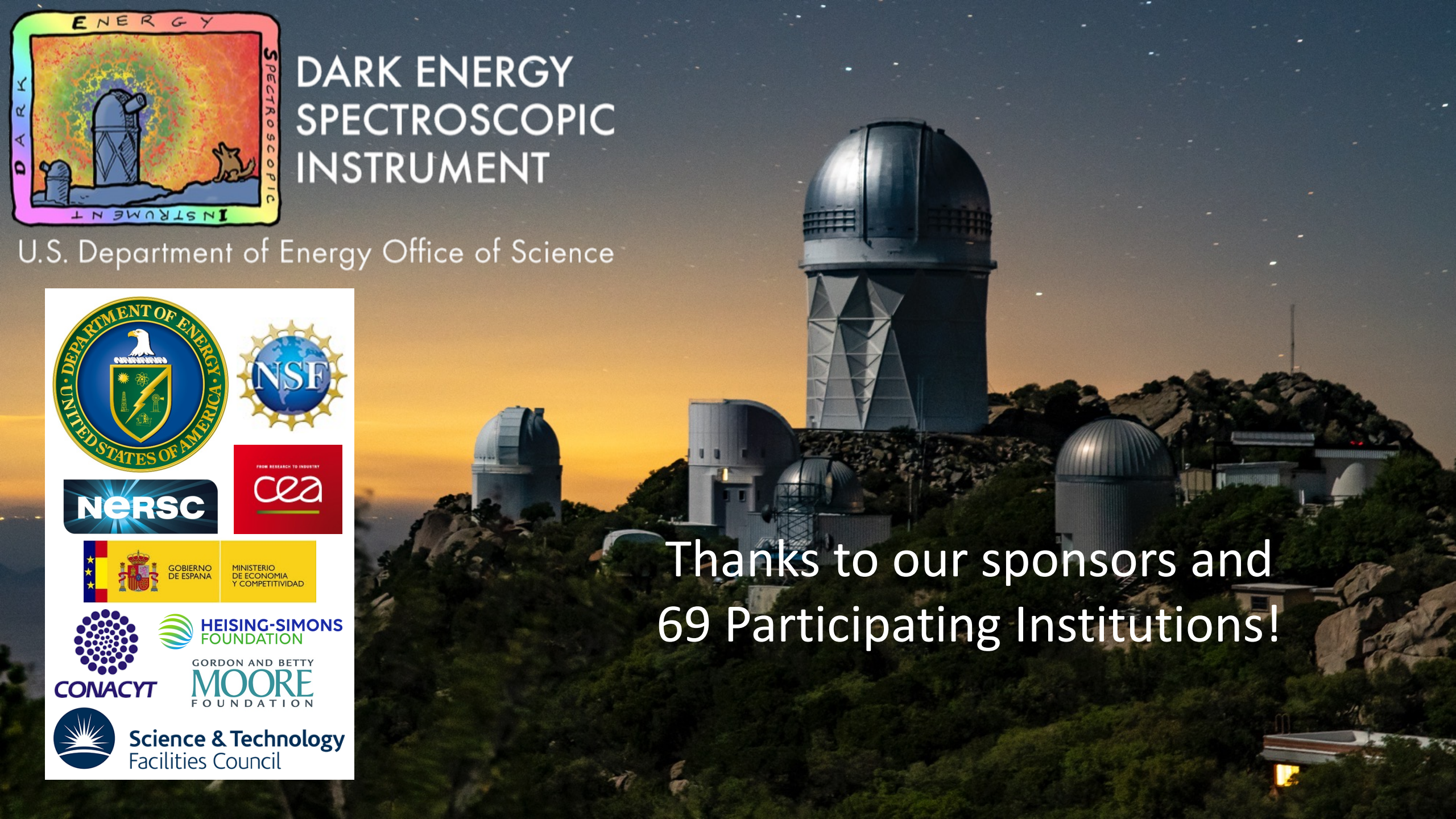
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