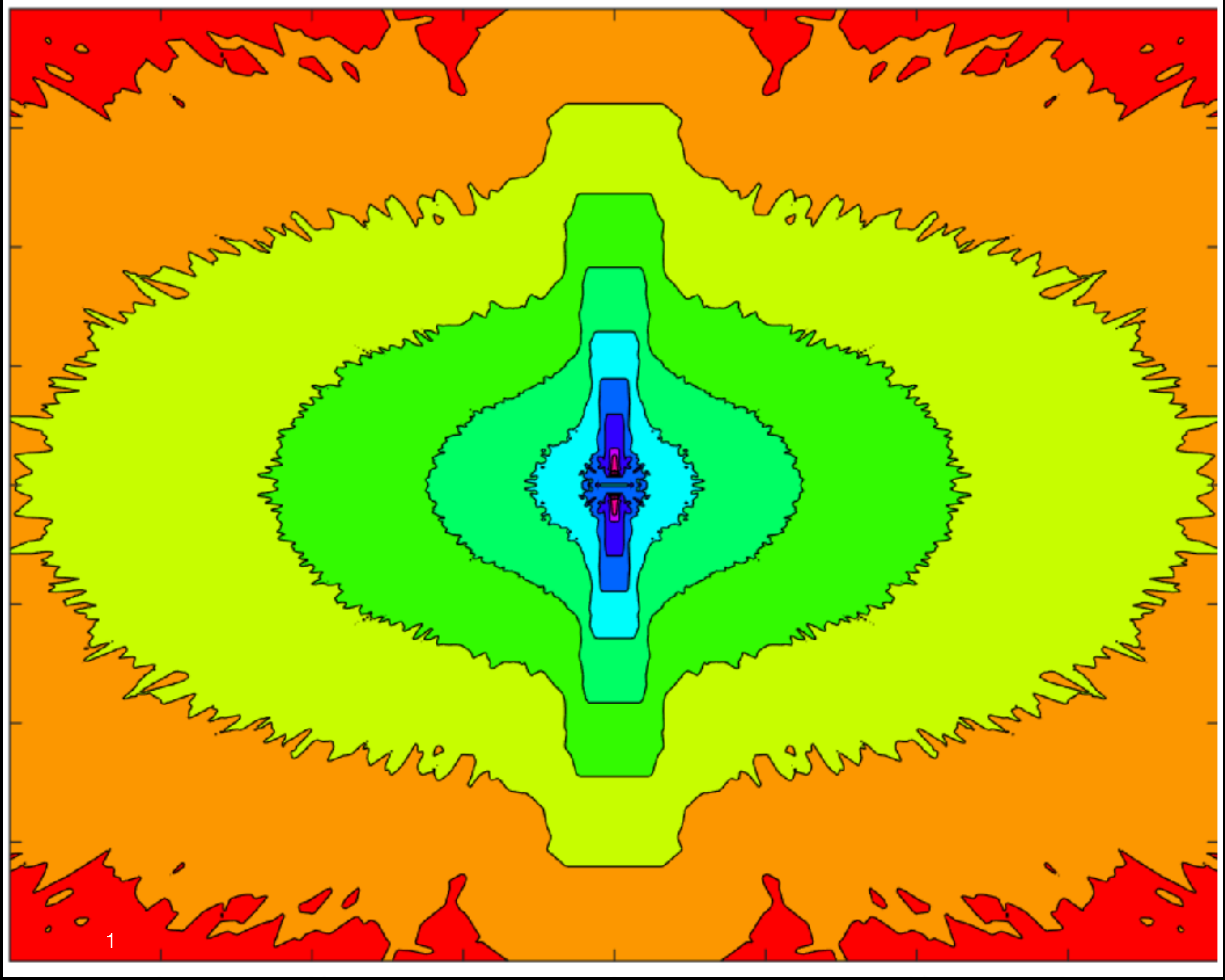
Challenges and Opportunities at non-linear scales of Large-Scale Structures

$$P_s^g(k,\mu) = P_m(k)(b+f\mu^2)^2$$



Shadab Alam
Institute for Astronomy,
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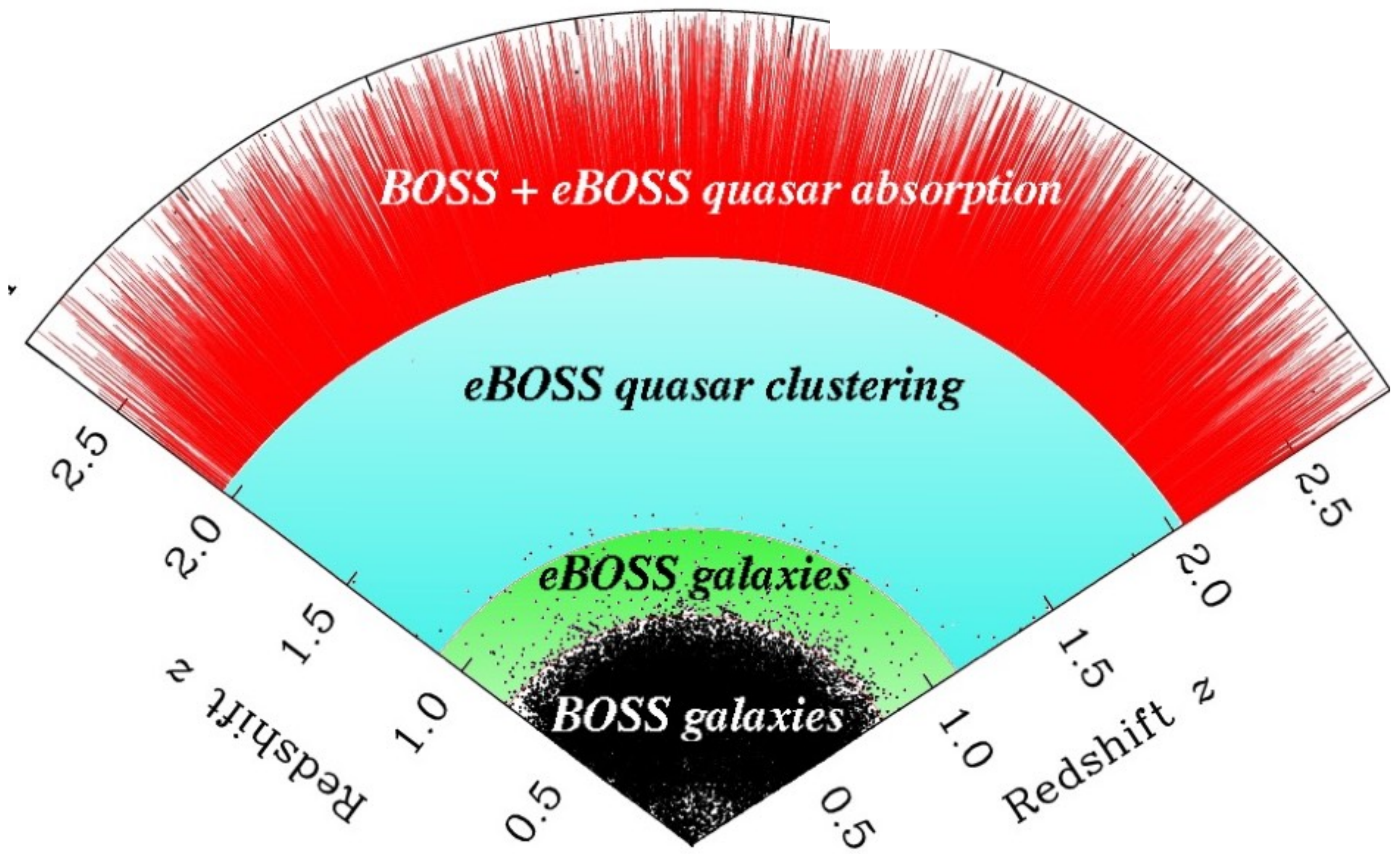
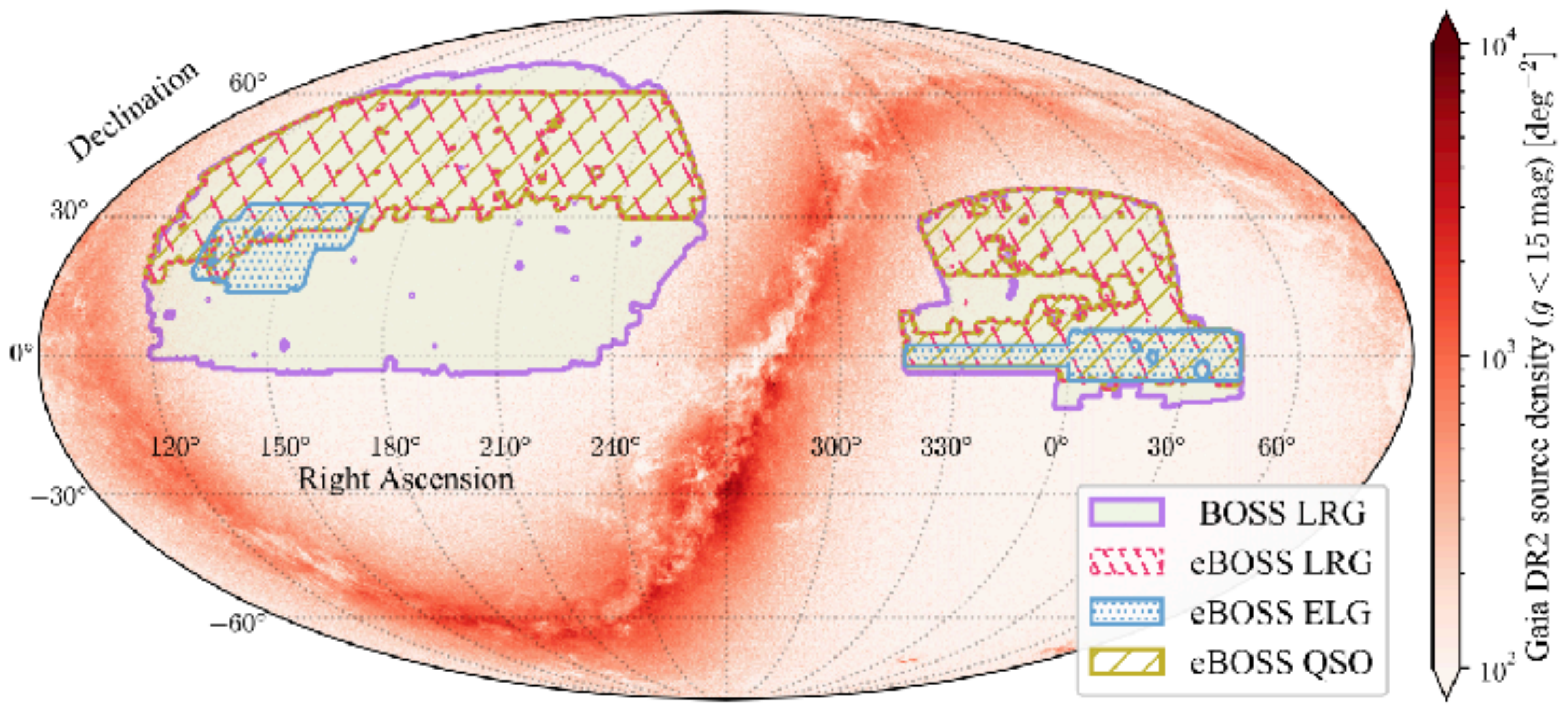
State of the Universe seminar
Tata Institute of Fundamental Research (TIFR), Mumbai
16th February 2022

Institute for Astronomy

THE UNIVERSITY of EDINBURGH

SDSS at a glance





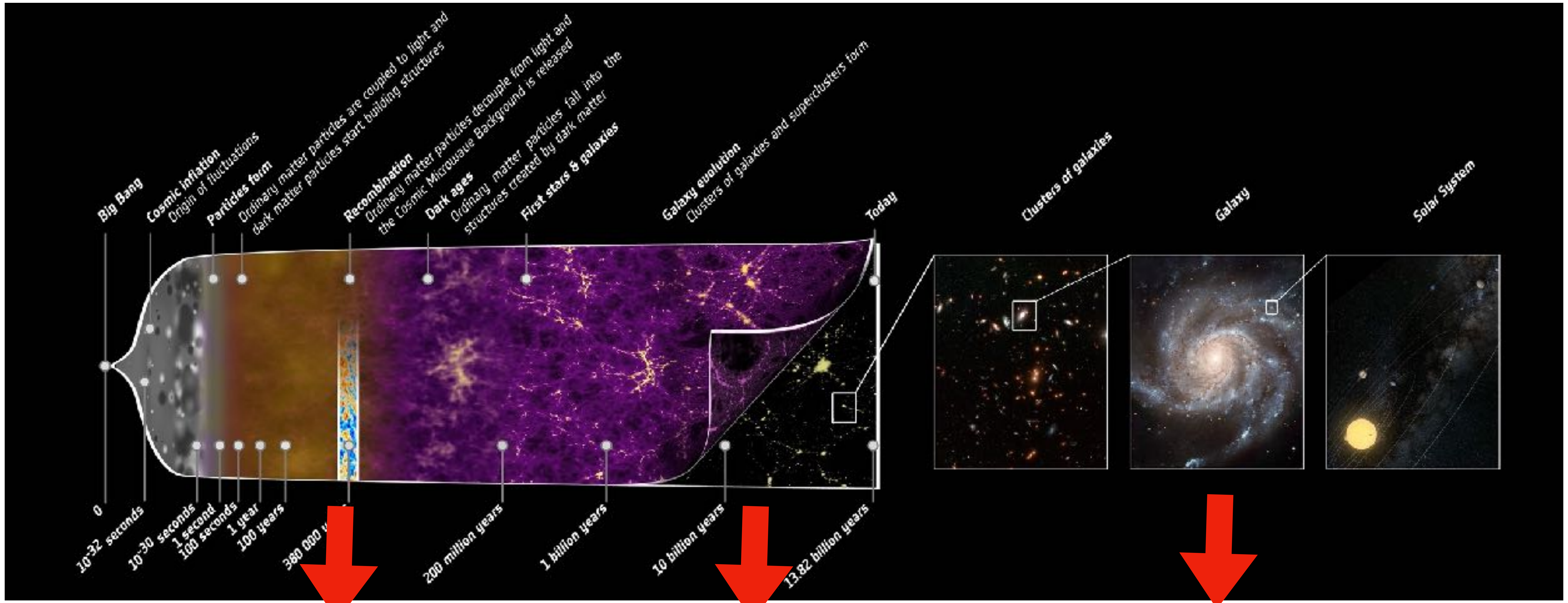
Zhao et. al. 2020; arxiv:2007.08997

Parameter	MGS	BOSS Galaxy	BOSS Galaxy	eBOSS LRG	eBOSS ELG	eBOSS Quasar	Lyα-Lyα	Lyα-Quasar
	<2007	**2008-2012**		**2014-2019**				
redshift range	$0.07 < z < 0.2$	$0.2 < z < 0.5$	$0.4 < z < 0.6$	$0.6 < z < 1.0$	$0.6 < z < 1.1$	$0.8 < z < 2.2$	$z > 2.1$	$z > 1.77$
$N_{\rm tracers}$	63,163	604,001	686,370	377,458	173,736	343,708	210,005	341,468
$z_{\rm eff}$	0.15	0.38	0.51	0.70	0.85	1.48	2.33	2.33
$V_{\rm eff}$ (Gpc^3)	0.24	3.7	4.2	2.7	0.6	0.6		

More than 2.5 Million spectra of galaxies

Alam* +eBOSS, PRD 103, 083533 (**2021**)
This is the only collaboration paper in this talk

Cosmology: *Physical Origin and evolution of the universe*



CMB | **SDSS (BAO+RSD)** | **SN**

Equation of state for dark energy? w=-1

Data	ΛCDM		oΛCDM	wCDM	νΛCDM
	$\Omega_{\rm DE}$	H_0 [km/s/Mpc]	Ω_k	w	Σm_ν [eV]
BAO	0.701 ± 0.016	–	$0.078^{+0.086}_{-0.099}$	-0.69 ± 0.15	–
CMB	0.6836 ± 0.0084	67.29 ± 0.61	$-0.044^{+0.019}_{-0.014}$	$-1.58^{+0.16}_{-0.35}$	< 0.268 (95%)
CMB + BAO	0.6881 ± 0.0059	67.61 ± 0.44	-0.0001 ± 0.0018	$-1.034^{+0.061}_{-0.053}$	< 0.134 (95%)
CMB + SN	0.6856 ± 0.0078	67.43 ± 0.57	$-0.0061^{+0.0062}_{-0.0054}$	-1.035 ± 0.037	< 0.174 (95%)
CMB + BAO + SN	0.6891 ± 0.0057	67.68 ± 0.42	-0.0001 ± 0.0018	-1.026 ± 0.033	< 0.125 (95%)

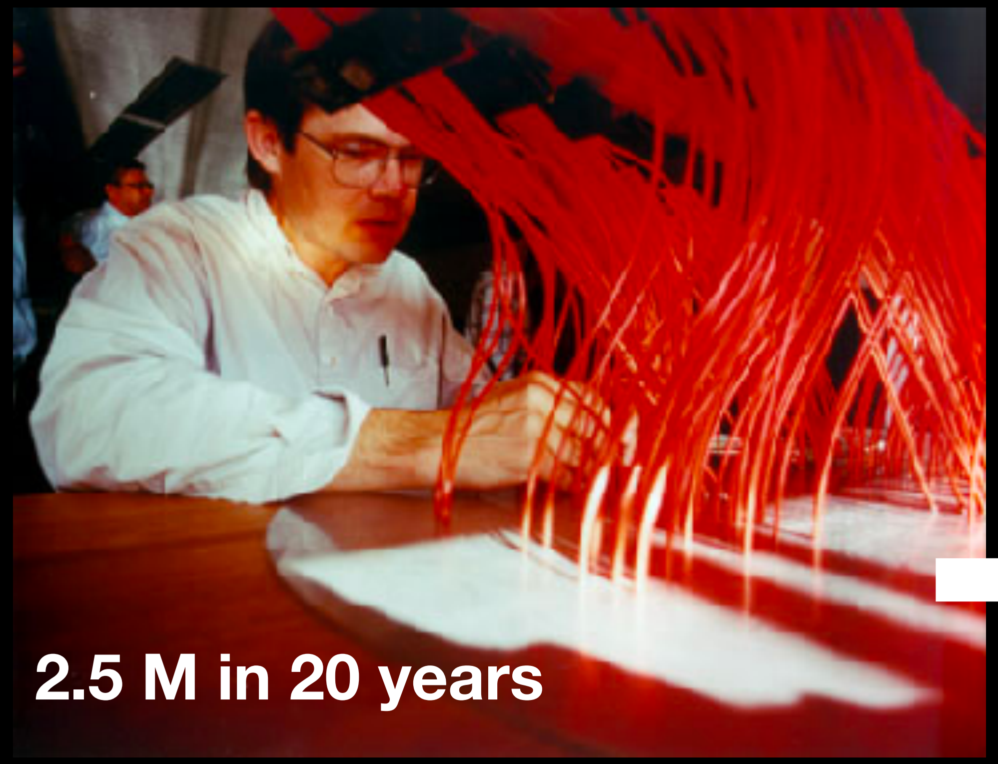
<u>Alam*</u> +eBOSS, PRD 103, 083533 (**2021**)

Dark Energy Spectroscopy Instrument (DESI)

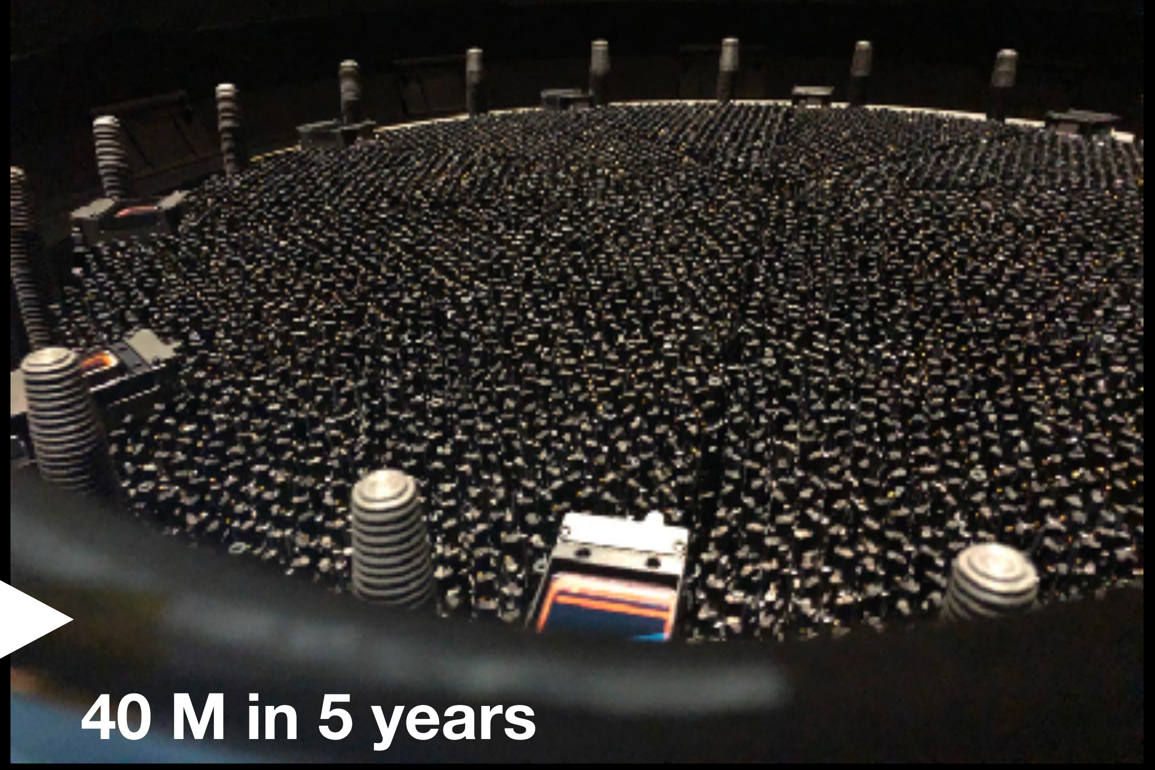
Ongoing : 2021-2026 (5 year program), overall cost~150 M $

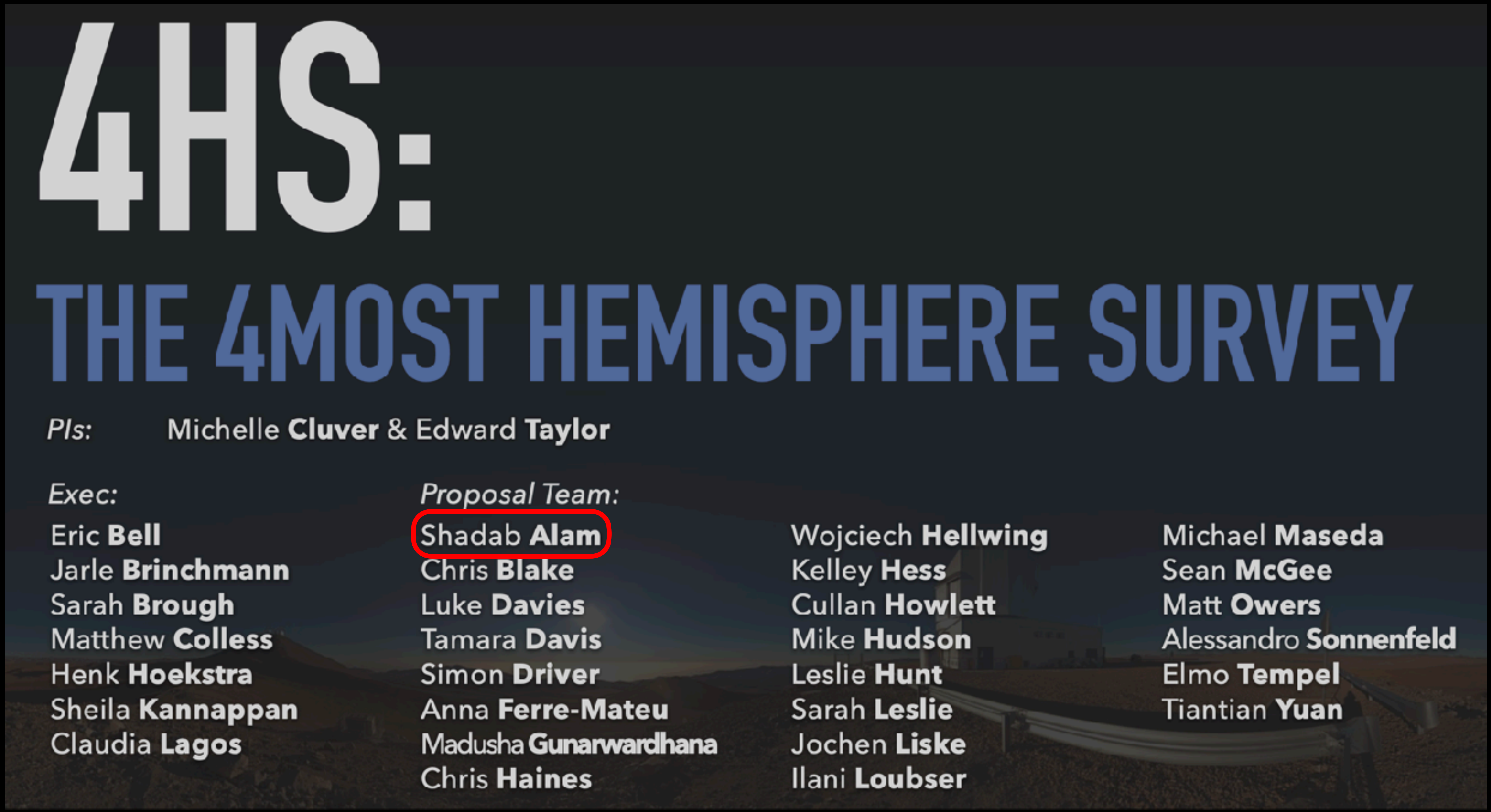
- 2021-2026 (5 years, Ongoing since May 2021)
- Instrument performs excellently (Survey Validation Completed-April 2021)
- **40 million** Galaxy Spectra by the end of 5 years

SDSS focal plane: HUMAN



DESI focal plane: 5000 ROBOTS





A spectroscopic redshift survey targeting z<0.15 galaxies covering 20,000 sq deg of sky.

Part of 4MOST, starting by late 2024

- Establish the local benchmark for galaxy/AGN demographic in the era of LSST/EUCLID/SKA.
- Test gravity in the local Universe
- Provides an excellent resource for gravitational wave counter-part studies.
- Many more science case of interest. Potentially shed light on aspects of Hubble tension.

Time Frame

DESI 2021-2025: 40 M spectra, finalised analysis probably by 2027!

4HS: 2024-2029 (20k, z<0.15)

LSST: 2023 -2033 (survey)

EUCLID: 2022 -2028 (survey), final science by 2030?

- To achieve this we need to model upto k=0.2

Dark Energy Equation of state $w(z) = w_p + (a_p - a)w'$

Surveys	FoM	a_p	σ_{w_p}	σ_{Ω_k}
BOSS BAO	37	0.65	0.055	0.0026
DESI 14k galaxy BAO	133	0.69	0.023	0.0013
DESI 14k galaxy and Ly-α forest BAO	169	0.71	0.022	0.0011
DESI 14k BAO + gal. broadband to $k < 0.1\ h\ \mathrm{Mpc}^{-1}$	332	0.74	0.015	0.0009
DESI 14k BAO + gal. broadband to $k < 0.2\ h\ \mathrm{Mpc}^{-1}$	704	0.73	0.011	0.0007
DESI 9k galaxy BAO	95	0.69	0.027	0.0015
DESI 9k galaxy and Ly-α forest BAO	121	0.71	0.026	0.0012
DESI 9k BAO + gal. broadband to $k < 0.1\ h\ \mathrm{Mpc}^{-1}$	229	0.73	0.018	0.0011
DESI 9k BAO + gal. broadband to $k < 0.2\ h\ \mathrm{Mpc}^{-1}$	502	0.73	0.013	0.0009

Bit more details on Neutrino

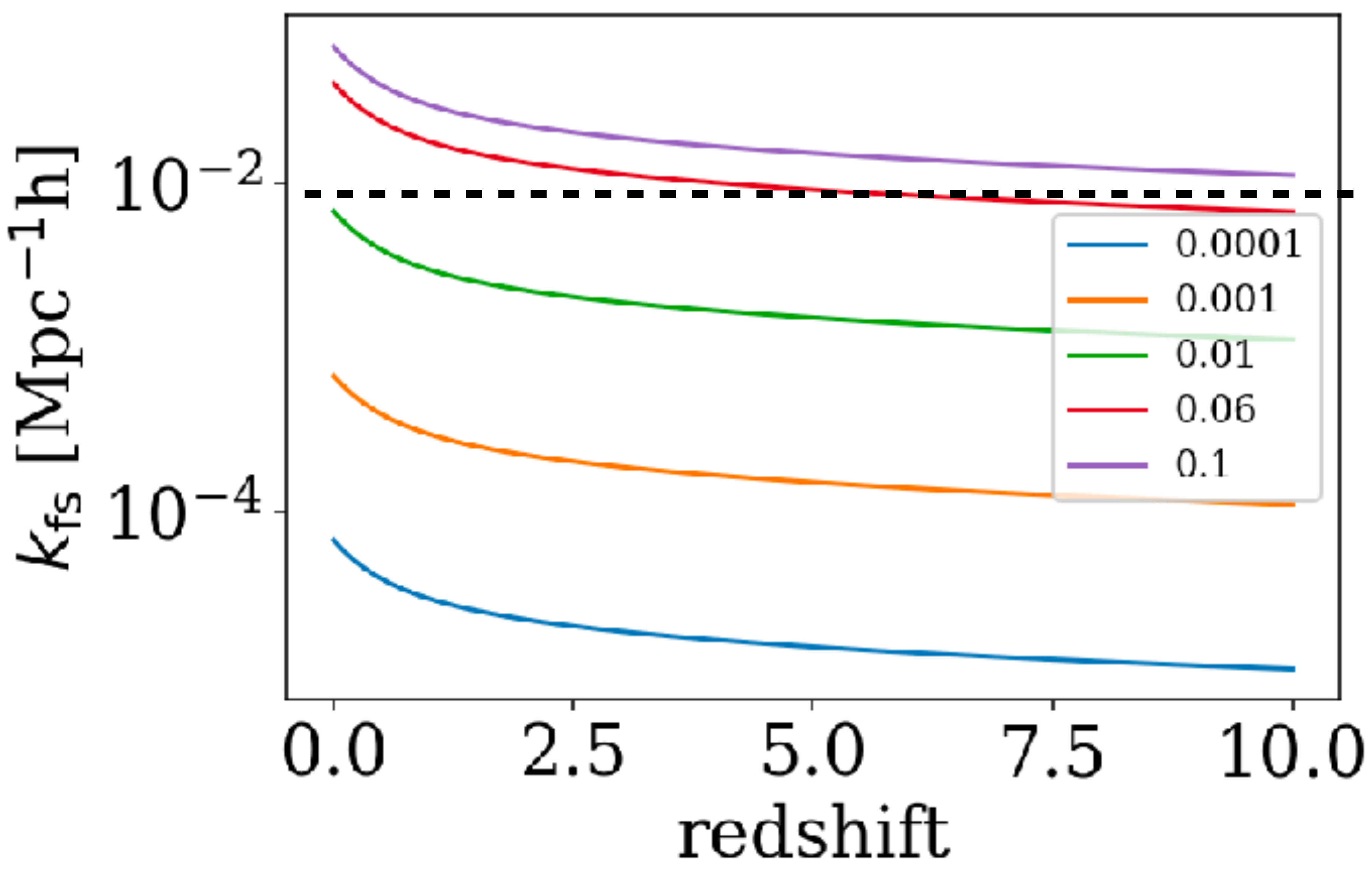
- In principle difference in mass separates free streaming scales will be imprinted in power spectrum

- **Good thing:** linear scale simpler to model from theory

- **Complications:** more physics and limited data
  1) Not completely covered by LSS and noisy (DESI-2) is being proposed to focus on these scales
  2) CMB probes these scales but the calibration depends on knowledge of reionisation era (τ)
  3) Sensitive to wide angle effects, relativist effects
  4) Same scale will get affected by non-gaussianity

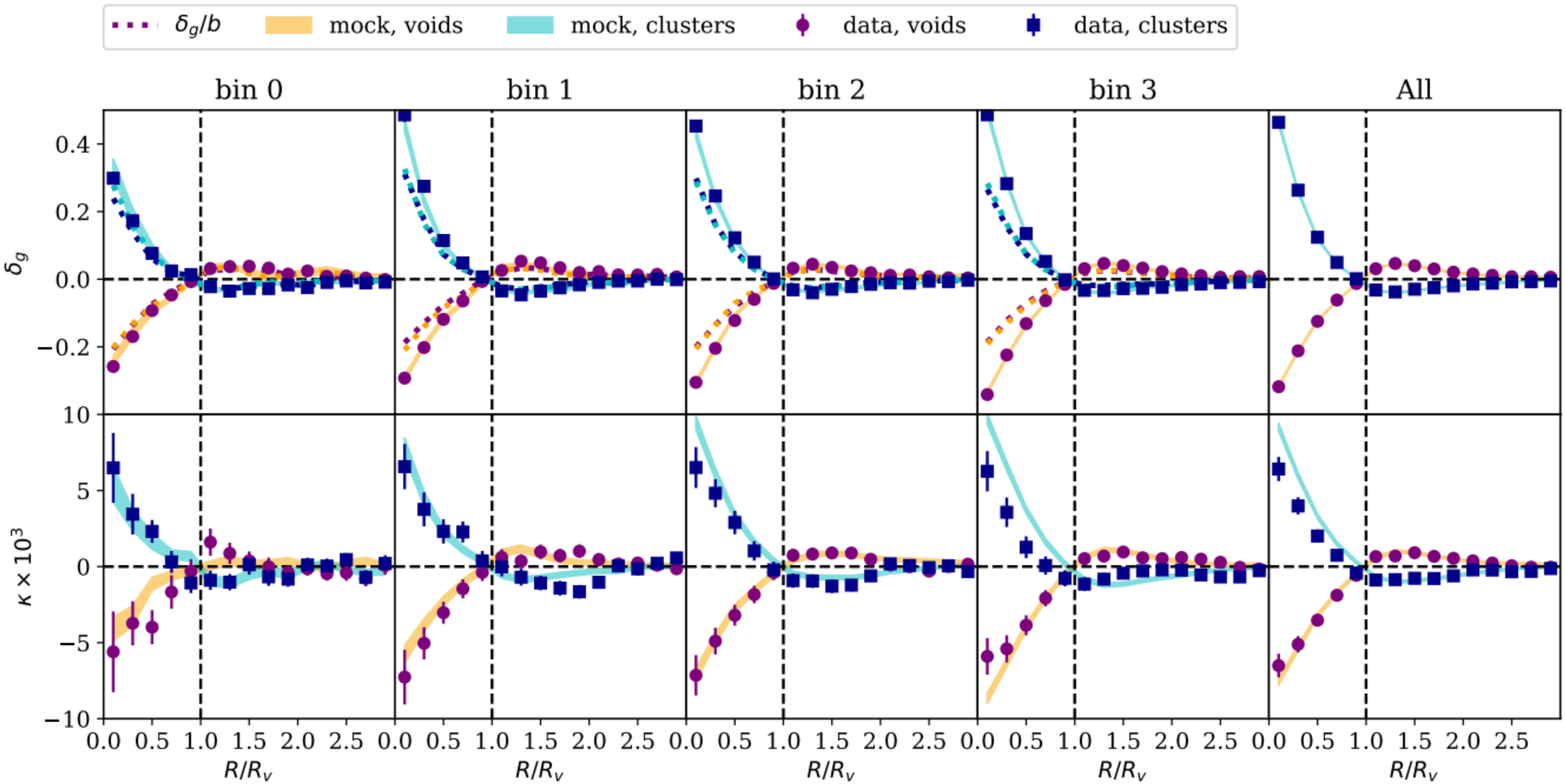
$$k_{fs} \approx \sqrt{3/2}\mathcal{H}(z)/\sigma_v^i$$

Assumes fermi-dirac distribution, 3 neutrinos and sounds speed is same as velocity dispersion



Shoji and Komatsu PRD 81:123516,2010; https://arxiv.org/abs/1003.0942

Thinking beyond galaxy for neutrino



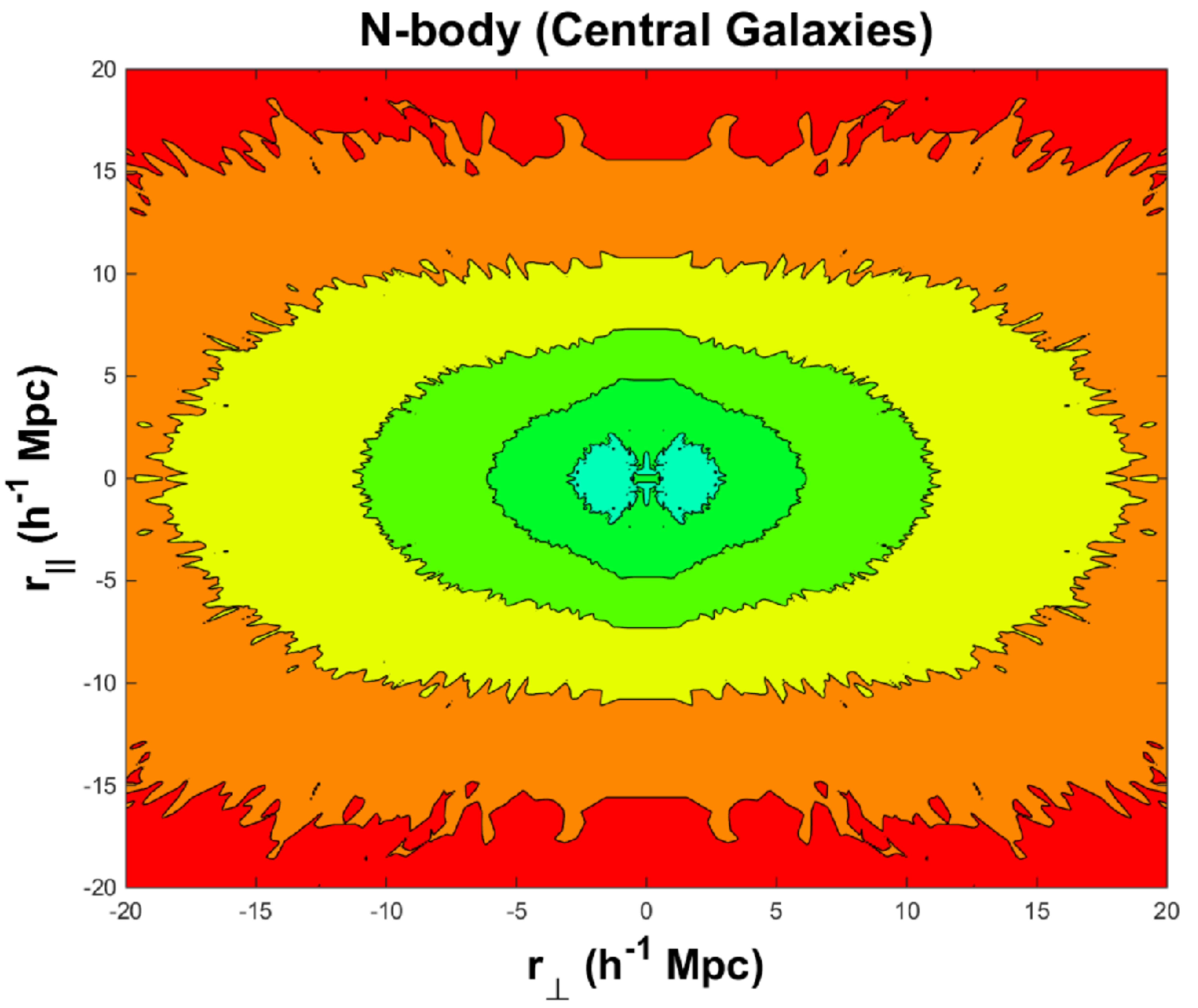
Hang, **Alam**, Cai, Peacock, MNRAS 507, 1, 2021

Things to discuss

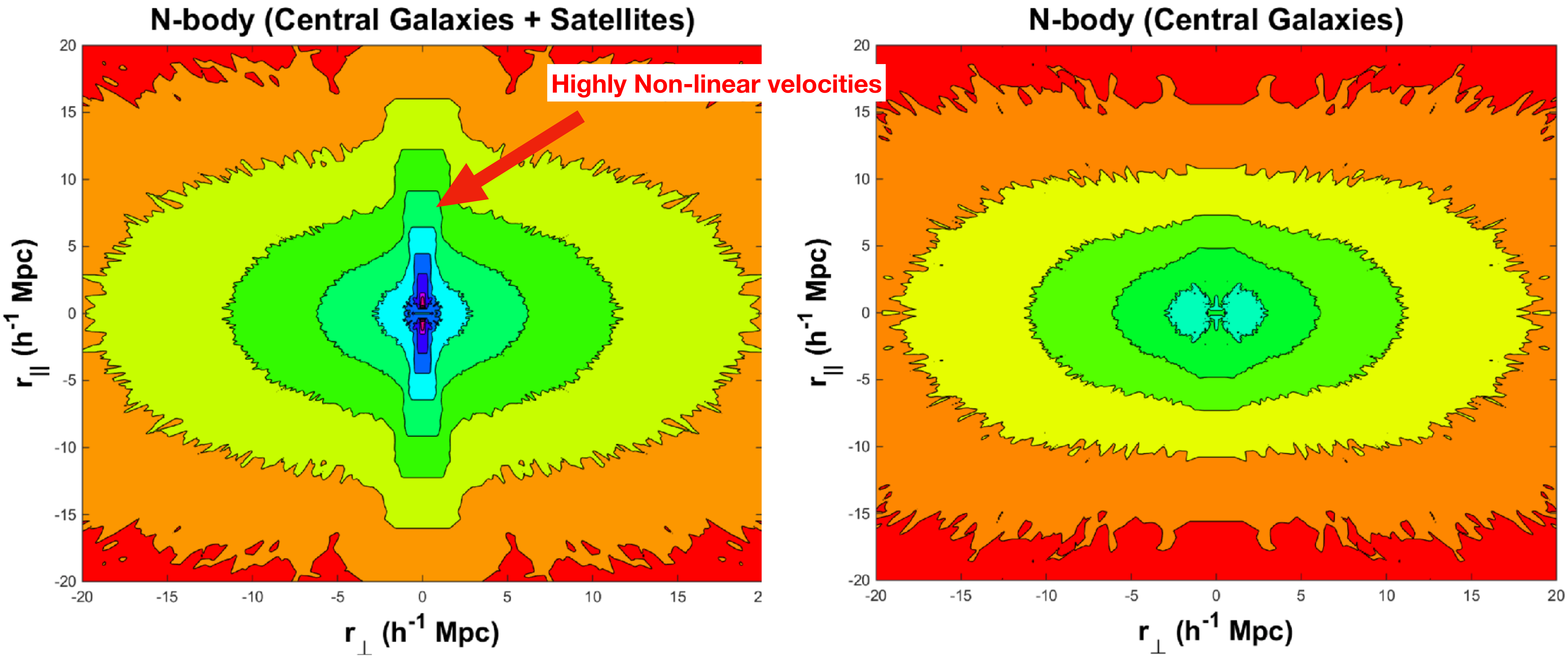
- Challenges
- Closer to observation
- Closer to theory
- Theory meets Observations
- Marginalising over galaxy physics

Challenges

Galaxy in galaxy clustering



Galaxy in galaxy clustering



Quantifying the clustering

$$\rho(\vec{r}) = \bar{\rho}(1 + \delta(\vec{r}))$$

$$P(k) = \left\langle \delta(\vec{k})\delta^*(\vec{k}) \right\rangle$$

$$\delta(\vec{r}) = \int \delta(\vec{k}) e^{-i\vec{k}\cdot\vec{r}} d\vec{k}$$

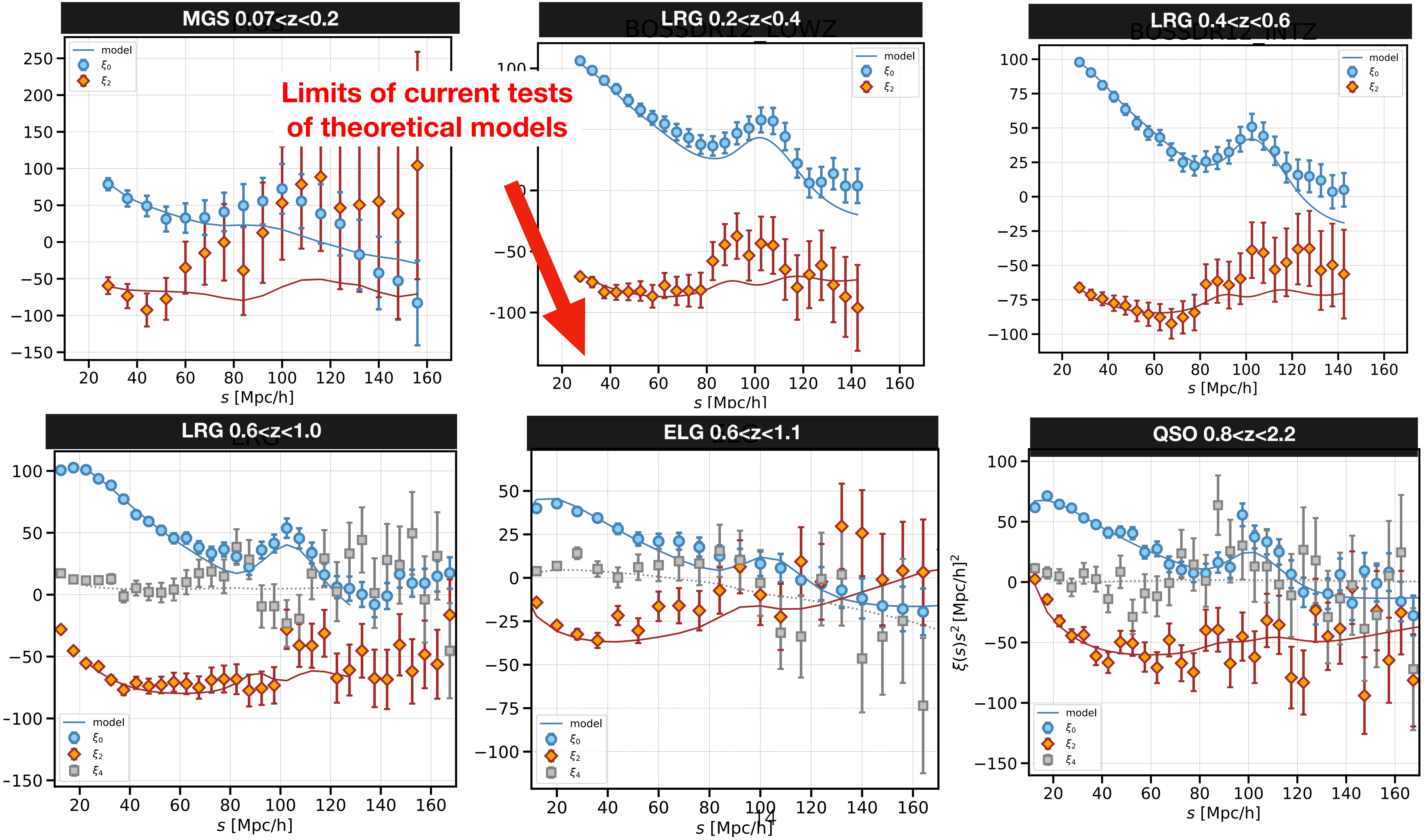
$$\xi(r) = \langle \delta(\vec{x})\delta(\vec{x} + \vec{r}) \rangle$$

Legendre Decomposition

$$P_\ell(k) = \frac{2\ell + 1}{2} \int_{-1}^{1} P(k, \mu)\mathcal{L}_\ell(\mu) d\mu \qquad \xi_\ell(s) = \frac{2\ell + 1}{2} \int_{-1}^{1} \xi(s, \mu)\mathcal{L}_\ell(\mu) d\mu$$

- In linear theory we only expect 0,2 and 4th order multipoles
- All higher order multipoles are typically ignored as it is noisy and model bias is large
- For this talk I will mostly show monopole(l=0) and quadrupole (l=2) moments of clustering.

Current Status of 3d clustering measurement



The exact need?

- Accurate description of redshift space galaxy clustering for cosmology.

Non-linear density velocity coupling
Perturbative approach fails (at what k?)

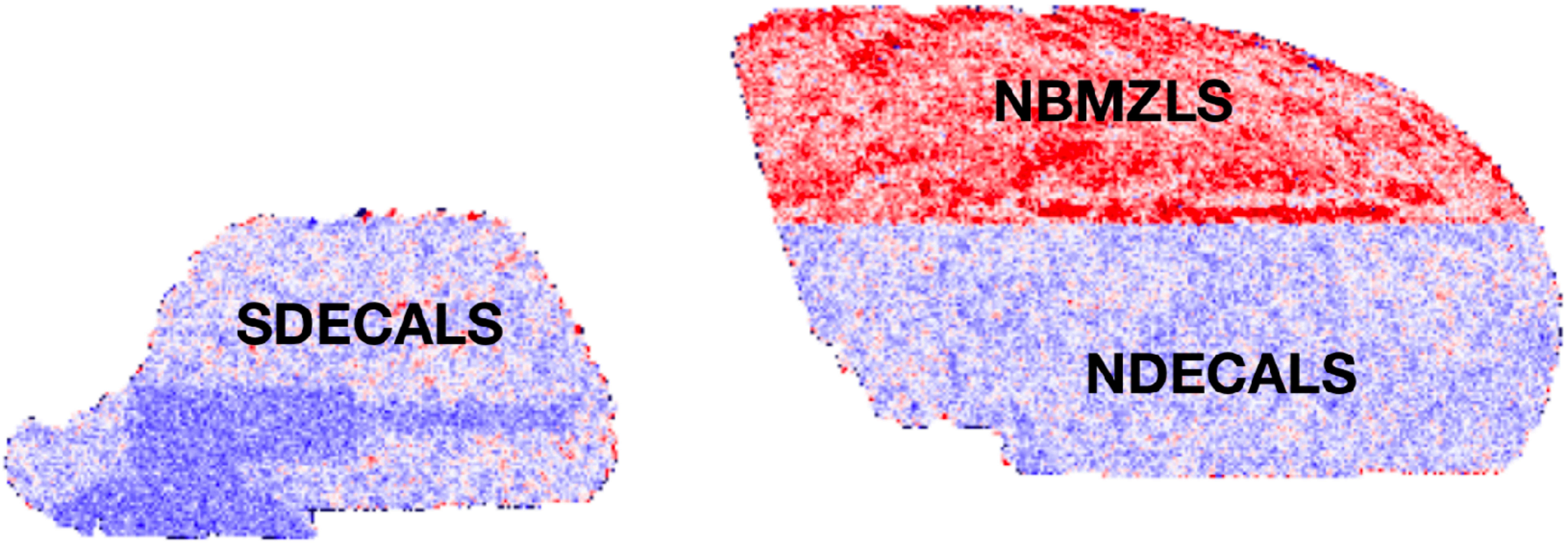
Galaxy formation and the non-linear physics.
Perturbative approach is only approximate at quasi-linear scale

We know our models are approximate.
We only need accuracy better than the experiments.
DESI promises 0.4% measurement of growth rate.
We need to test the models to 0.1% precision

Closer to Observations

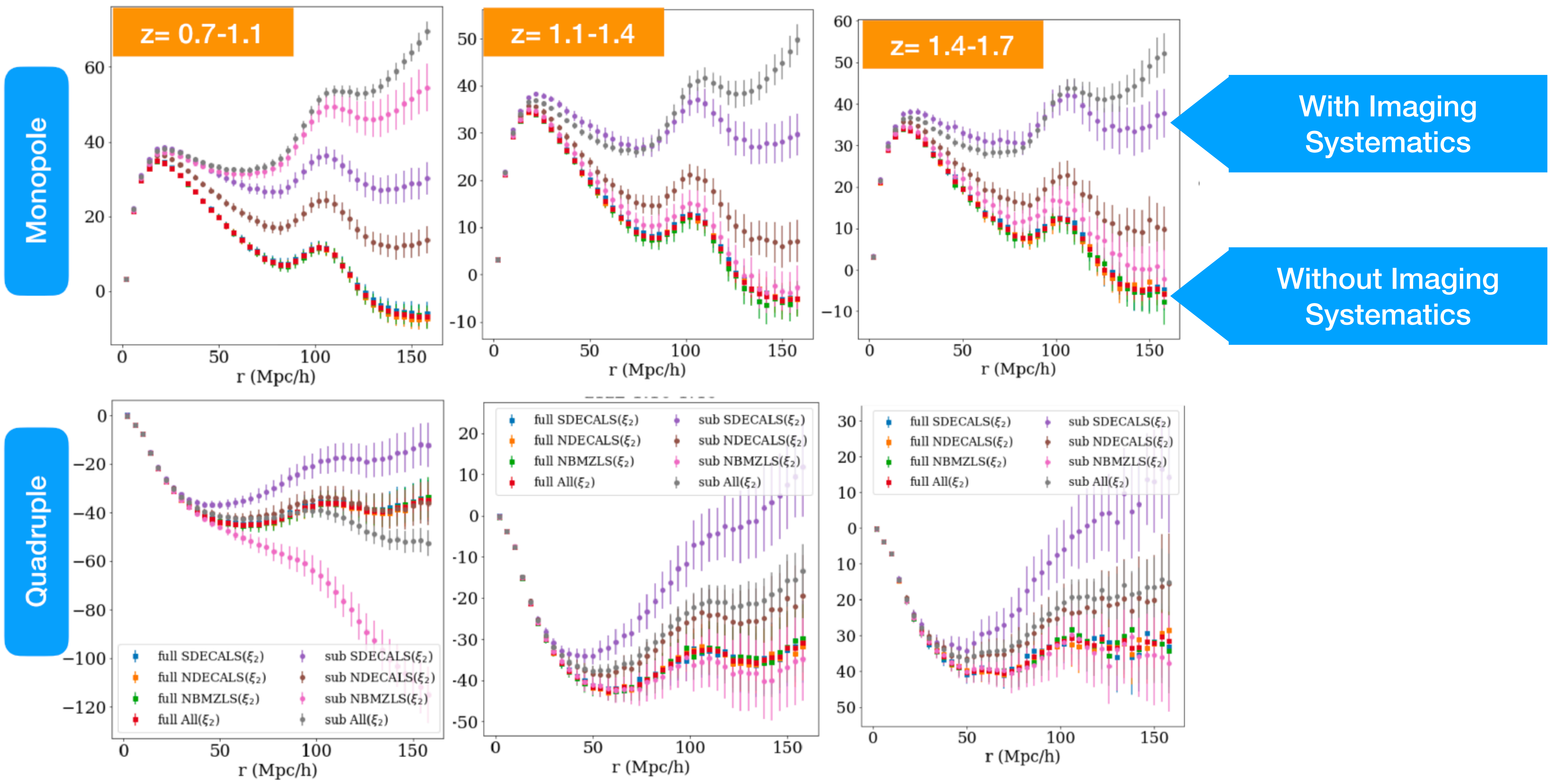
How to include terms in theory to marginalise around observational systematic

-



This is a simulate map of LSS with real inhomogeneity

Clustering with systematics



Alam et. al. in prep.

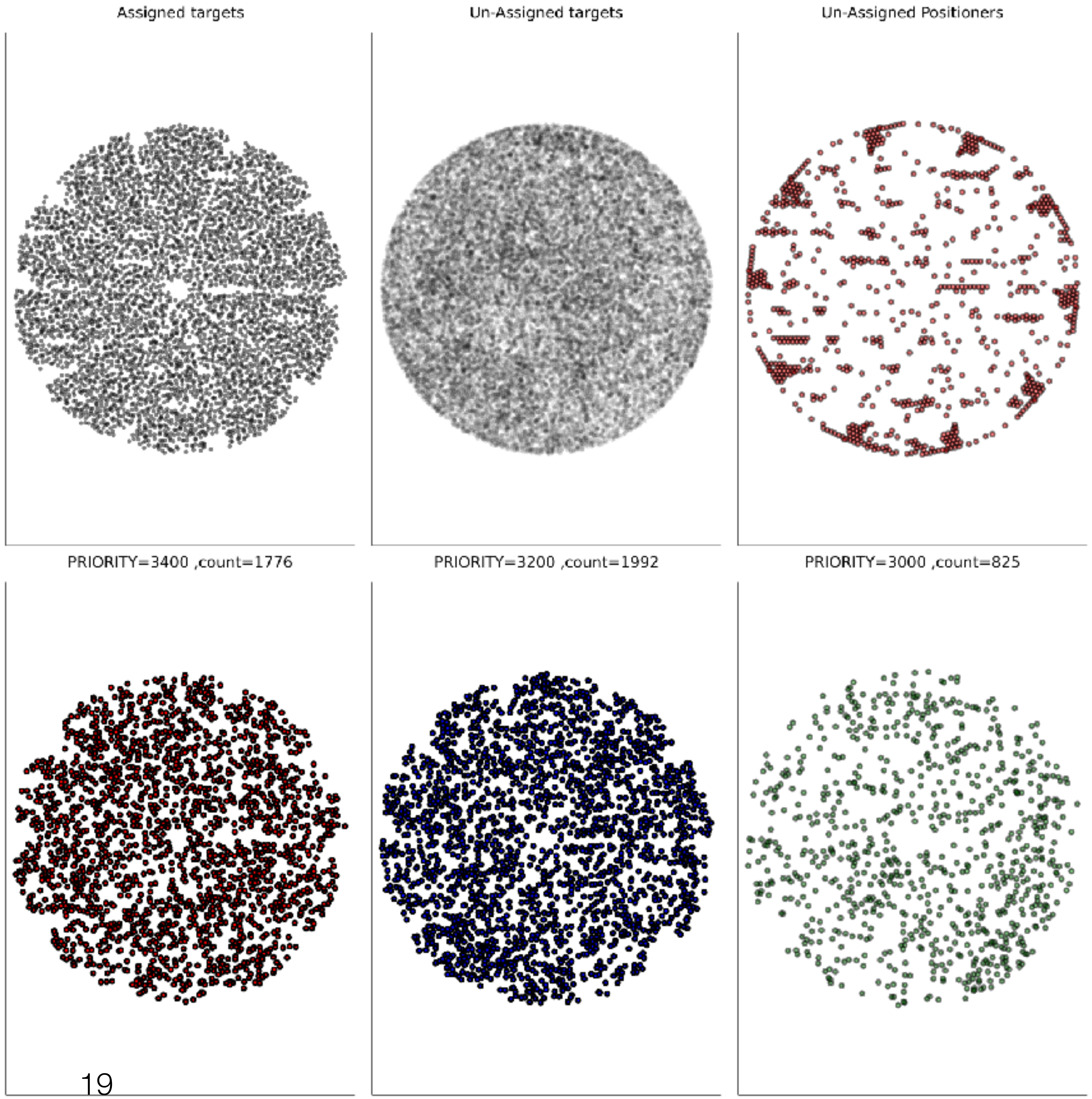
The curse of Spectroscopy

- Complicated selection function which theorist needs to model

- The advantage of robots: fast and cheap

- The problem with robots: Not very flexible

- Theorist responsibility to include them in the model.



Closer to Theory

LSS Challenges and Opportunity

Theoretical Challenges:

What: Show in presence of complex astrophysics that BAO is unbiased to 0.05% precision and RSD to 0.05% precision.

Ideal: We need to make realistic survey realisation with complex astrophysics covering 10 times the DESI volume? This is practically impossible with current computing resources and will require solving the galaxy/AGN physics.

Alternate/Approximate: Use empirical method to paint a range of complex astrophysics of galaxies and AGN on N-body gravity only simulation to test method and bias. This will require significantly large computing power but feasible.

Opportunity: Use the combination of small hydro sims, large gravity only sims and DESI data to drive progress in astrophysics and cosmology simultaneously. We must understand **all important physical effects** to do this robustly.

Cosmologist Dilemma

- **Extremely precise measurements:** We would love to use all the data
- **Galaxy formation is complex:** We do not have a fundamental theory
- **LSS models:** Perturbative in nature, breaks at non-linear scales but founded on fundamental theory. Very well understood physics

Two approaches

- Let us use only part of the data where we can trust the prediction of LSS clustering models. It will give less precise but robust results.
  (All forecasts I showed in colloquium uses this approach with some with kmax=0.2)

- Let us use everything, and try to augment the LSS clustering models with numerical/empirical models. Additional parameter at the cost of not well understood physics.

  - Potential gain in cosmology

  - Potential gain in galaxies and black-hole physics

Perturbative models:
Three challenge for LSS models

- **Non-linear growth:**
  Present day on order of 10 Mpc $\delta \gg 1$
  1) Assumptions breaks
  2) mode-coupling reduces information
  3) decorrelates from primordial field.

CMB- 1970-2018
Linear, direct, no-velocity coupling

LSS- 2000-2020
At least 30 more years of progress needed in the modelling side to extract all information in the data

- **Galaxy bias:**
  Different galaxies will connect to underlying matter differently
  This is likely to induce scale dependent term in clustering

- **Redshift Space Distortions:**
  Couples the matter distribution to the velocity field

Non-linearity: Two flavours of PT

- Eulerian
  Pressure-less single component Newtonian fluid

$$\partial_\tau \delta + \nabla \cdot [(1+\delta)\mathbf{v}] = 0$$

$$\partial_\tau \mathbf{v} + \mathcal{H}\mathbf{v} + \mathbf{v} \cdot \nabla \mathbf{v} = -\nabla \phi$$

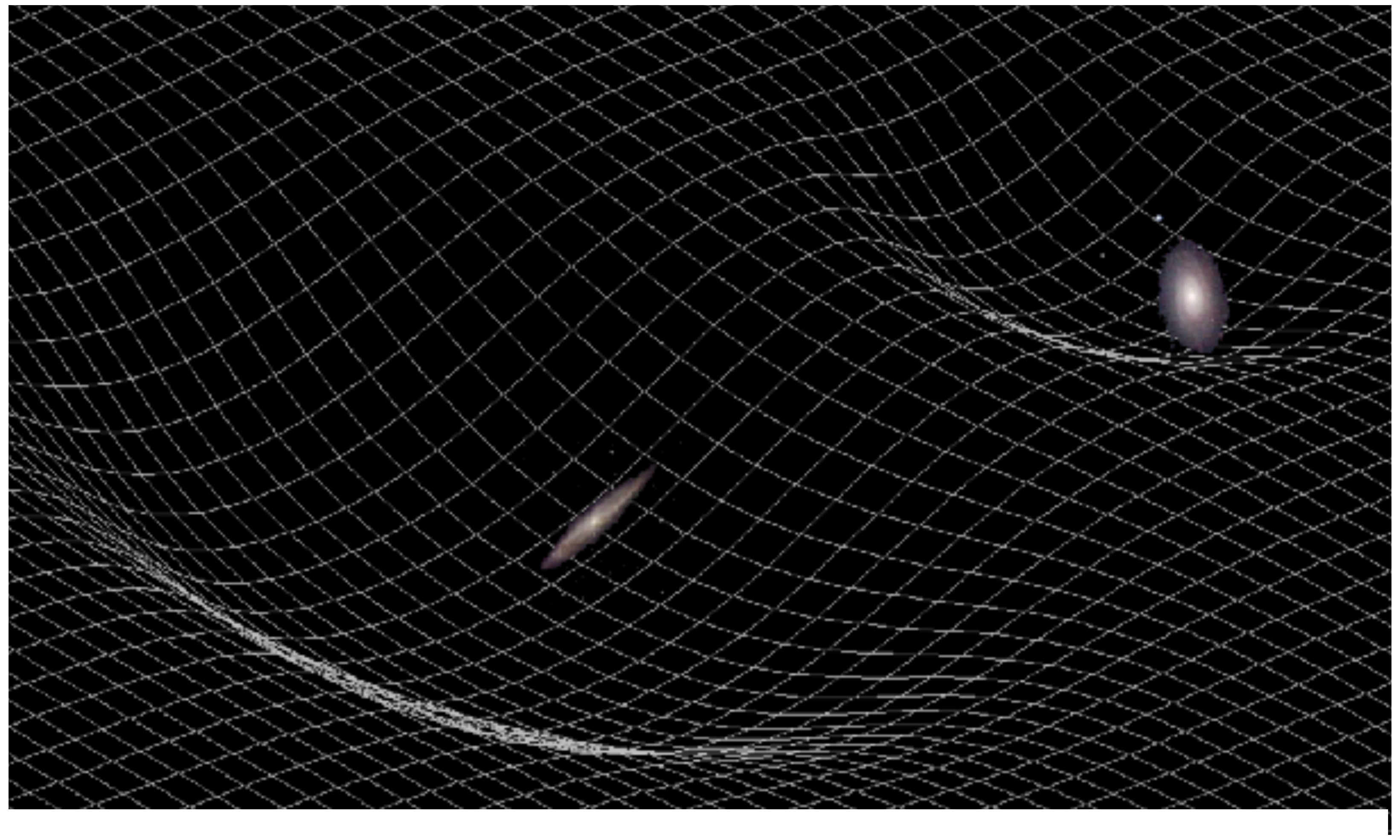
- Lagrangian
  Collision-less single component Newtonian fluid

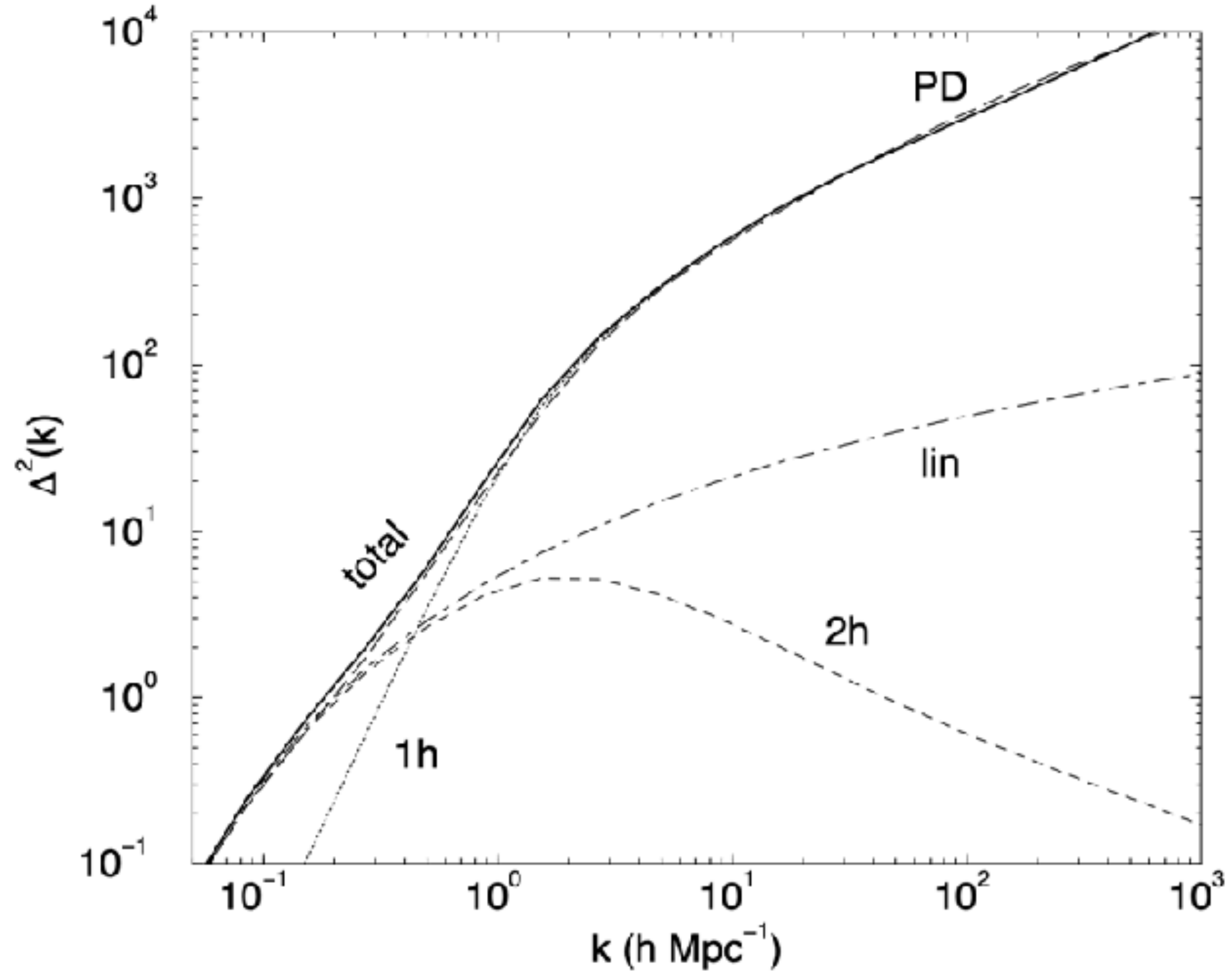
$$\mathbf{x}(\mathbf{q}) = \mathbf{q} + \mathbf{\Psi}(\mathbf{q}, \tau)$$

$$\partial_\tau^2 \Psi + \mathcal{H}\partial_\tau \Psi = -\nabla \Phi(q + \Psi(q))$$

Non-linearity: Analytic Halo model

- Description of Inhomogeneity
  - Matter density field: $\rho(x,t) = \bar{\rho}(t)[1 + \delta(x,t)]$
  - Fourier modes: $\delta_k = \frac{1}{V}\int \delta(x) e^{-i\vec{k}\cdot\vec{x}} d^3x$
- Two point functions
  - Power Spectrum: $P(k) = \left\langle |\delta_k| \right\rangle$
  - Dimensionless power spectrum: $\Delta^2 = 4\pi V \left(\frac{k}{2\pi}\right)^3 P(k)$
- Halo model power spectrum:
  - $\Delta^2(k) = \Delta^2_{\rm 1h} + \Delta^2_{\rm 2h}$
  - $\Delta^2_{\rm 1h} = 4\pi \left(\frac{k}{2\pi}\right)^3 \frac{1}{\bar{\rho}^2} \int_0^\infty M_h W^2(k, M_h) F(M_h) dM_h$
  - $\Delta^2_{2h} = \Delta^2_{\rm lin}$





Cooray and Sheth 2002, Physics Reports . 372, 1

Galaxy Bias

How the galaxy clustering is related to the underlying matter clustering?

- Linear model $\delta_g = b_{\rm lin}\delta_m$
- Perturbative models $\delta_g = b_1\delta(x) + b_2\delta^2(x) + \ldots + \text{stochastic terms}$
- Based on halo model (proposed in Hang, **Alam**, Peacock and Cai 2020)
  $P_g(k) = b_1 P_m^{\rm lin}(k) + b_2 P_m^{\rm nl}(k)$

Redshift Space Distortions

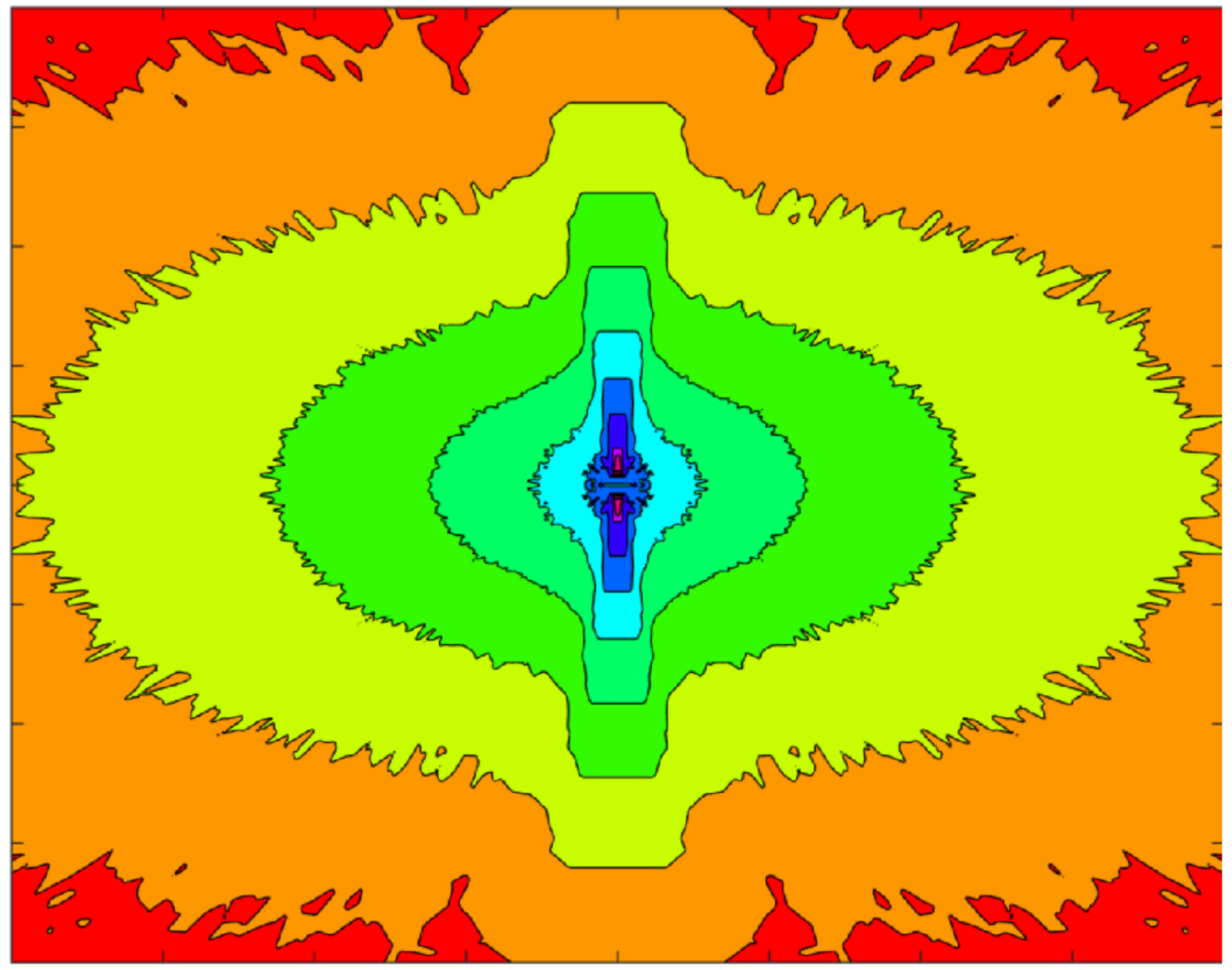
- In general this require knowledge of non-linear evolution particularly $\xi_m^{\mathrm{nl}}(r), v_{12}(r), \sigma_{12}(r)$

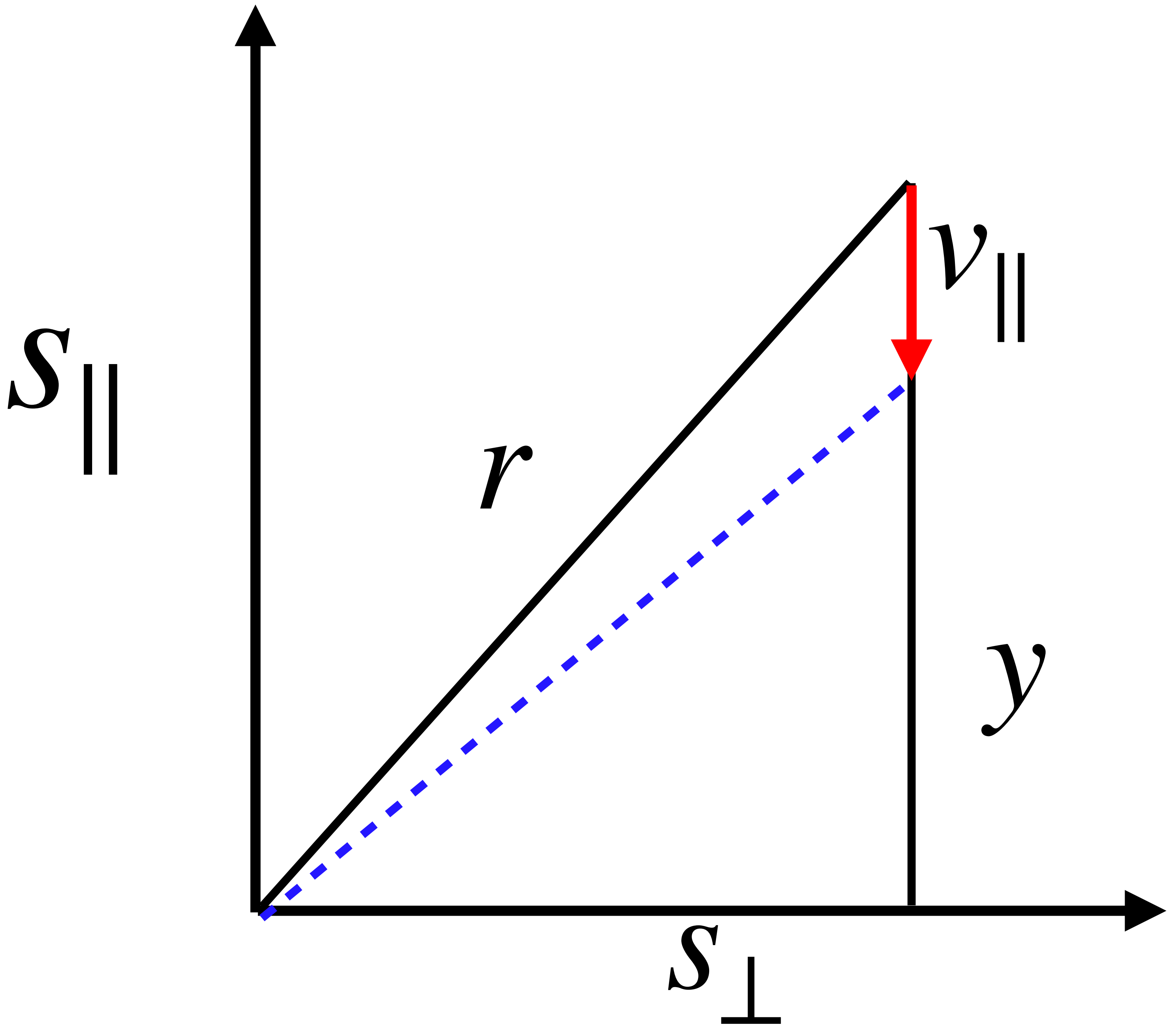
- These components can be solved for using a number of methods e.g: linear theory, PT, Halo model etc. and are part of standard tools.

- For illustration purposes lets look at Gaussian Streaming Model (GSM)

Gaussian Streaming model

- Redshift space: $s = r + \overrightarrow{v} \cdot \hat{r}$
- $$1 + \xi^s(s_\perp, s_\|) = \int \frac{dy}{\sqrt{2\pi\sigma_{12}}}[1 + \xi(r)]\, e^{-\frac{(s_\| - (y + \mu v_{12}(r)))^2}{2\sigma_{12}^2}}$$
- Finger-of-god term: $\sigma_{12}^2(r) + \sigma_{\rm FOG}^2$





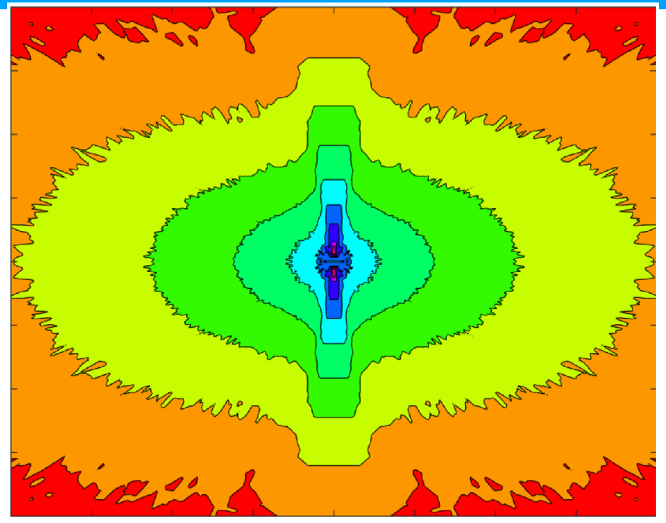
Reid and White MNRAS 417, 3, 2011
Alam et. al. MNRAS 453, 1754 (2015) (my very first paper)
Satpathy, **Alam** et. al. MNRAS 469, 1369-1382 (2017)

Non-linear matter clustering
One of many PT
or
HM

Include galaxy bias
Linear model
PT based biasing
HM based biasing

Include RSD
PT based
PT+GSM

Observed, redshift space clustering of galaxies



Infer Physics, eg: is growth consistent with GR?

Each step has multiple approximations.
How to test these approximations in the model: i.e. non-linearity, bias and redshift space distortions?

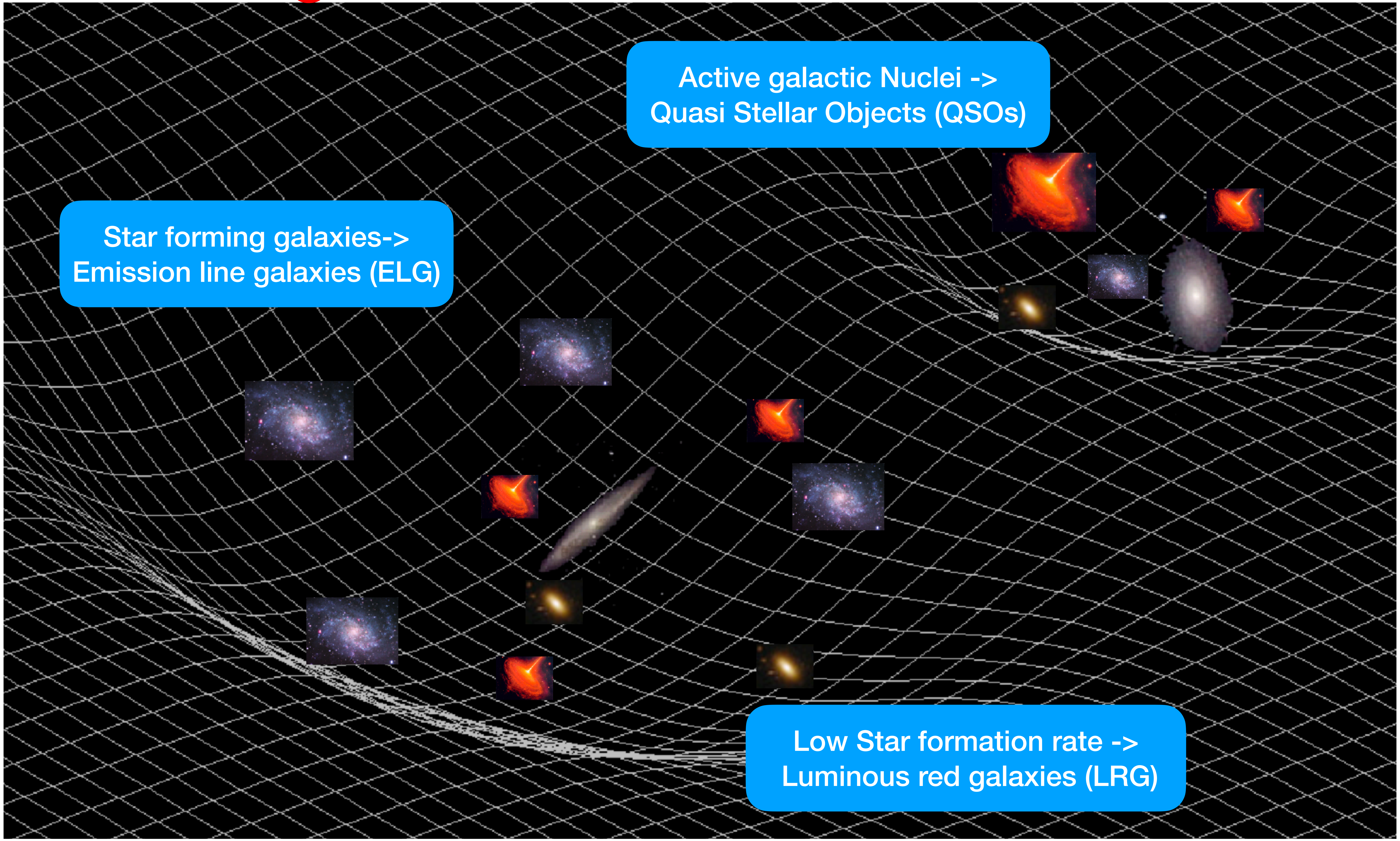
- Using Simulations
    - Simulations of galaxy formation: limited in predictive power and accuracy
    - N-body dark matter only
        - Do not predict galaxies only have dark matter halos
        - Need empirical models of galaxy formation

Halo Occupation Distribution (HOD)

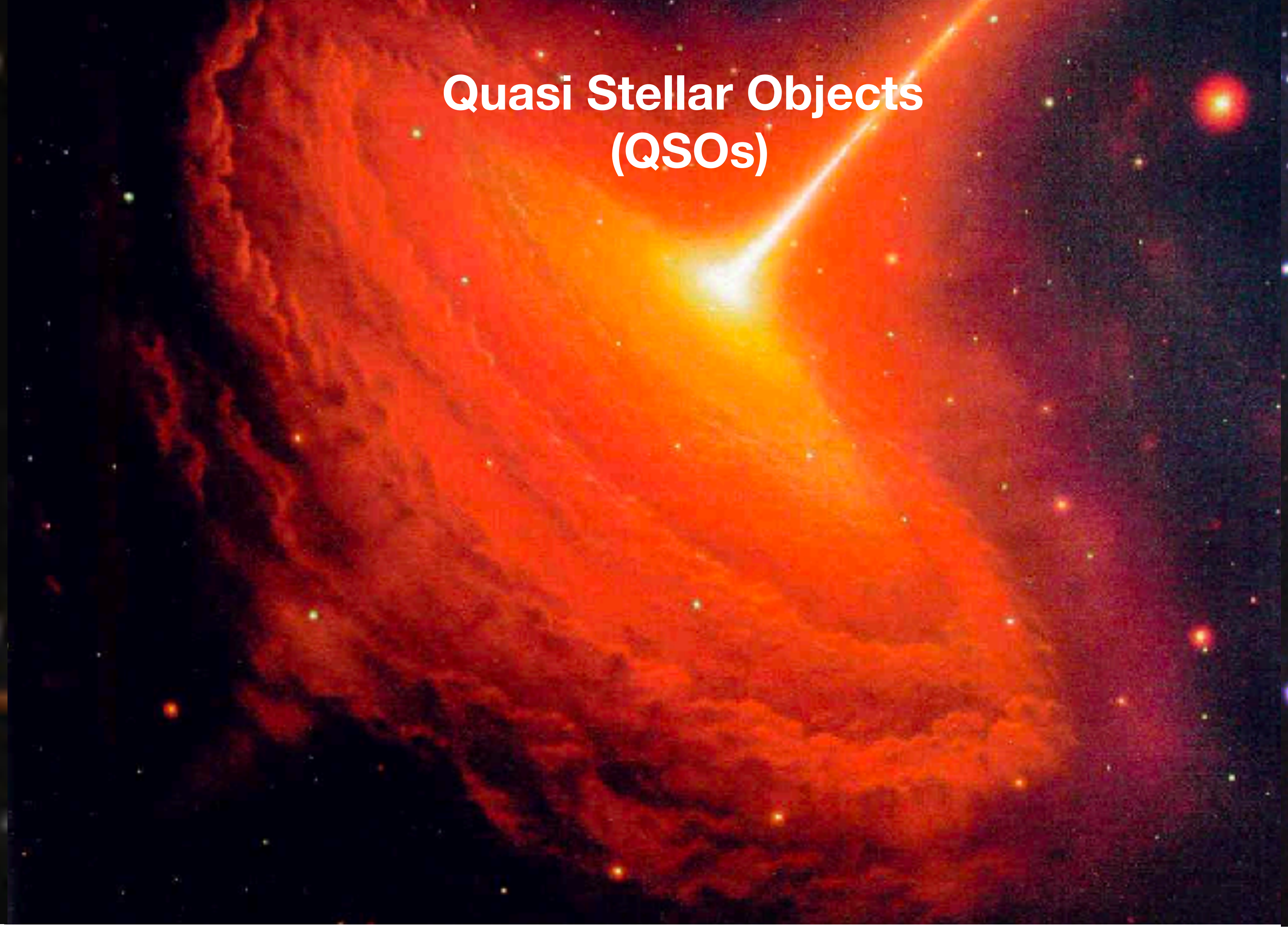
- $P_{\rm gal}(k) = P^{\rm 1h}_{\rm gal}(k) + P^{\rm 2h}_{\rm gal}(k)$
- $P^{\rm 1h}_{\rm gal}(k) = \int dM_h n(M_h) n_{\rm g}(n_{\rm g} - 1)\,|\,u_{\rm gal}(k\,|\,M_h)\,|^2$
- $P^{\rm 2h}_{\rm gal}(k) = P^{\rm lin}(k) \left[\int dM_h n(M_h) b_1(M_h) n_g(M_h) u_{\rm gal}(k\,|\,M_h) \right]^2$
- Numerical HOD -> split central satellite
  $p_{\rm cen}(M_h), n_{\rm sat}(M_h)$

Cooray and Sheth 2002

Challenges: Non-linearity and Galaxy Formation



$p_{\rm cen}(M_h), n_{\rm sat}(M_h)$



Multi-Tracer HOD

Alam et. al. , MNRAS 497, 1, 2020

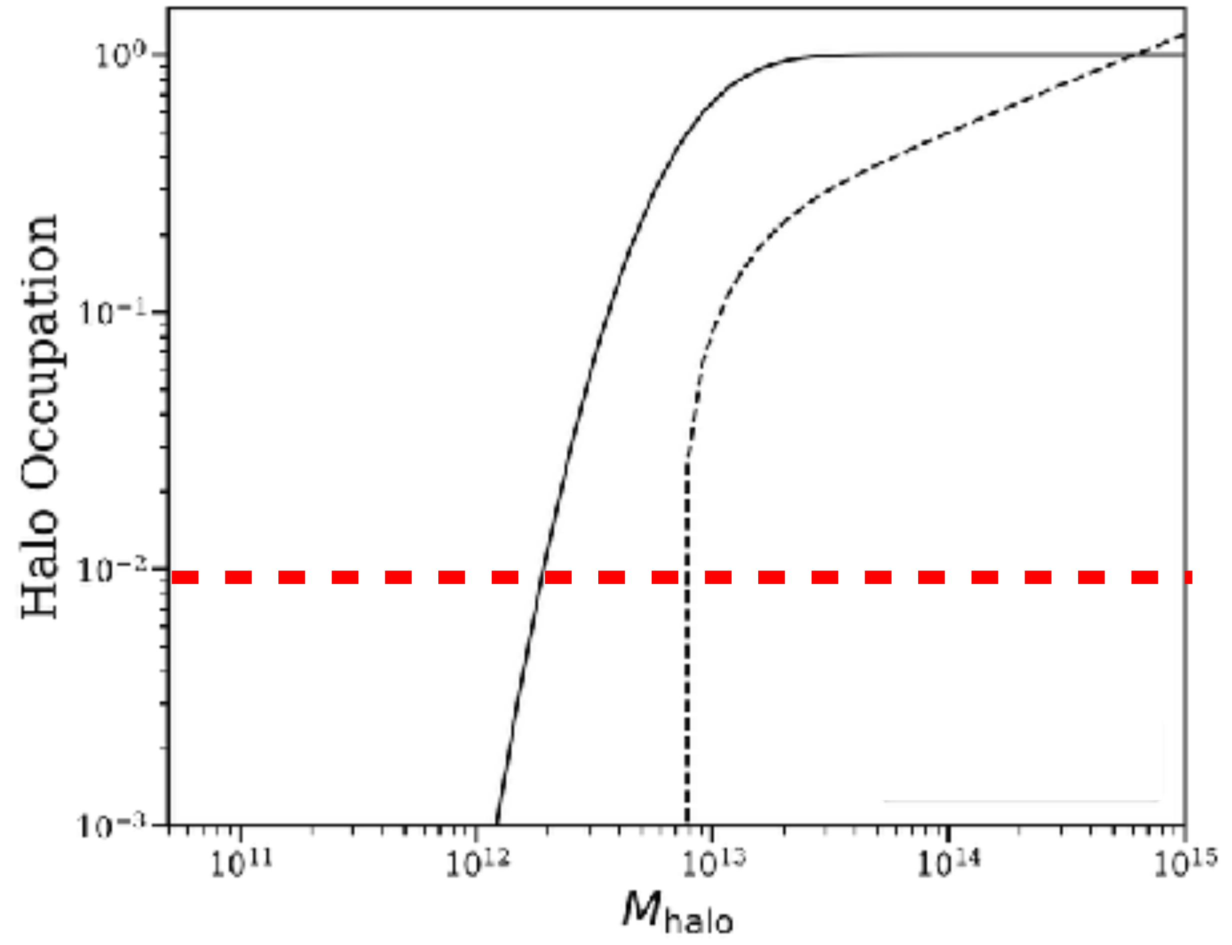
- Key Idea 1:

  $p_{\mathrm{cen}}(M_h) = \Sigma_{\mathrm{tracer}} p_{\mathrm{cen}}^{\mathrm{tracer}}(M_h)$ with $p_{\mathrm{cen}}(M_h) \leq 1$

Standard HOD model

$$N_{\mathrm{central}} = \frac{1}{2} erfc\left(\frac{\log_{10} M_c - \log_{10} M_h}{\sqrt{2}\sigma_M}\right)$$

$$N_{\mathrm{sat}} = N_{\mathrm{central}}\left(\frac{\log_{10} M_h - \kappa \log_{10} M_c}{M_1}\right)^{\alpha}$$



New HMQ HOD model

Alam et. al. , MNRAS 497, 1, 2020

$$N_{\mathrm{central}} = 2A\phi(x)\Phi(\gamma x) + B$$

Where:

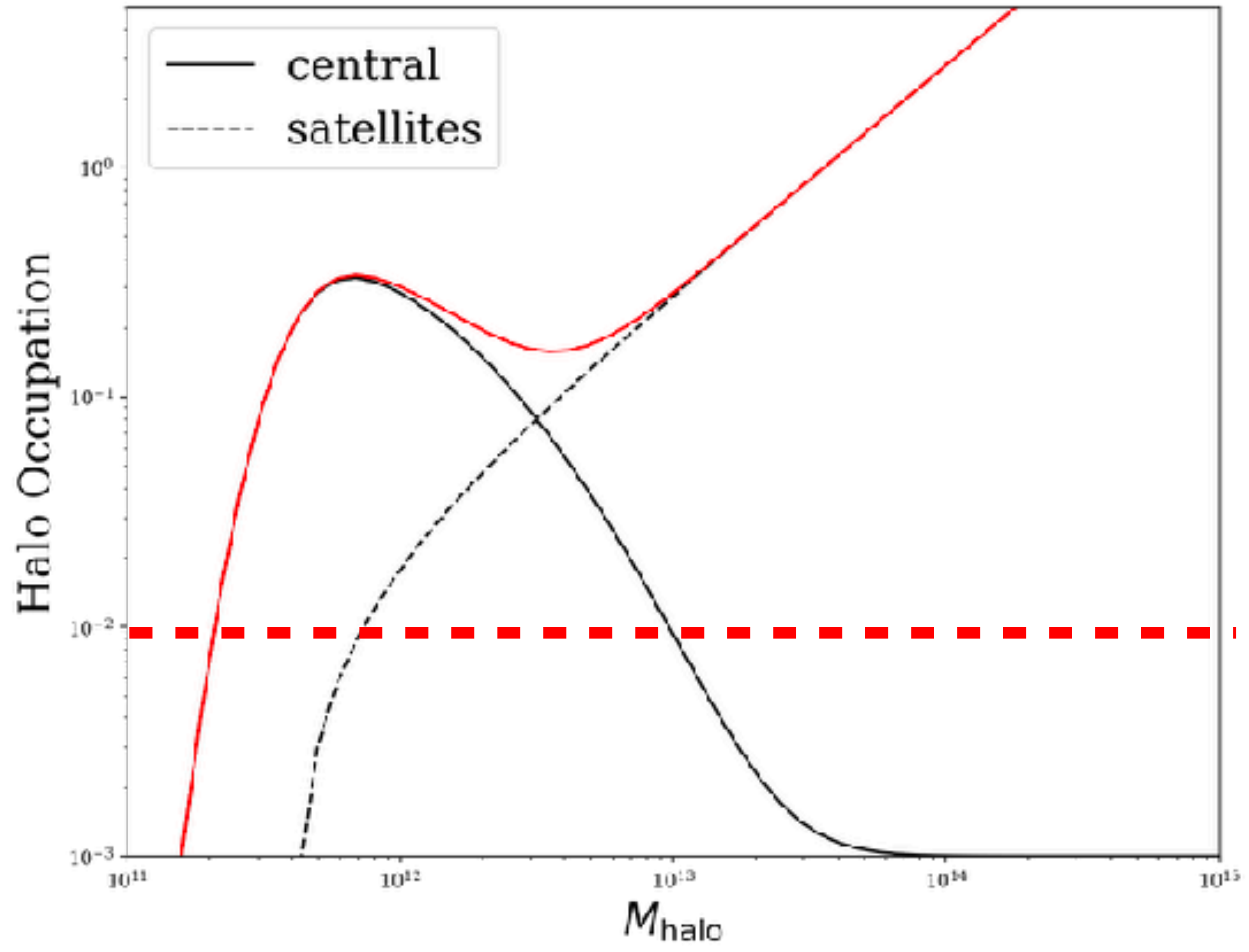
$$\phi(x) = \mathcal{N}(\log_{10} M_c, \sigma_M)$$

$$\Phi(\gamma x) \text{ is pdf of } \phi(\gamma x)$$

$$A = \frac{p_{\max} - \kappa}{\max(2\phi(x)\Phi(\gamma x))}$$

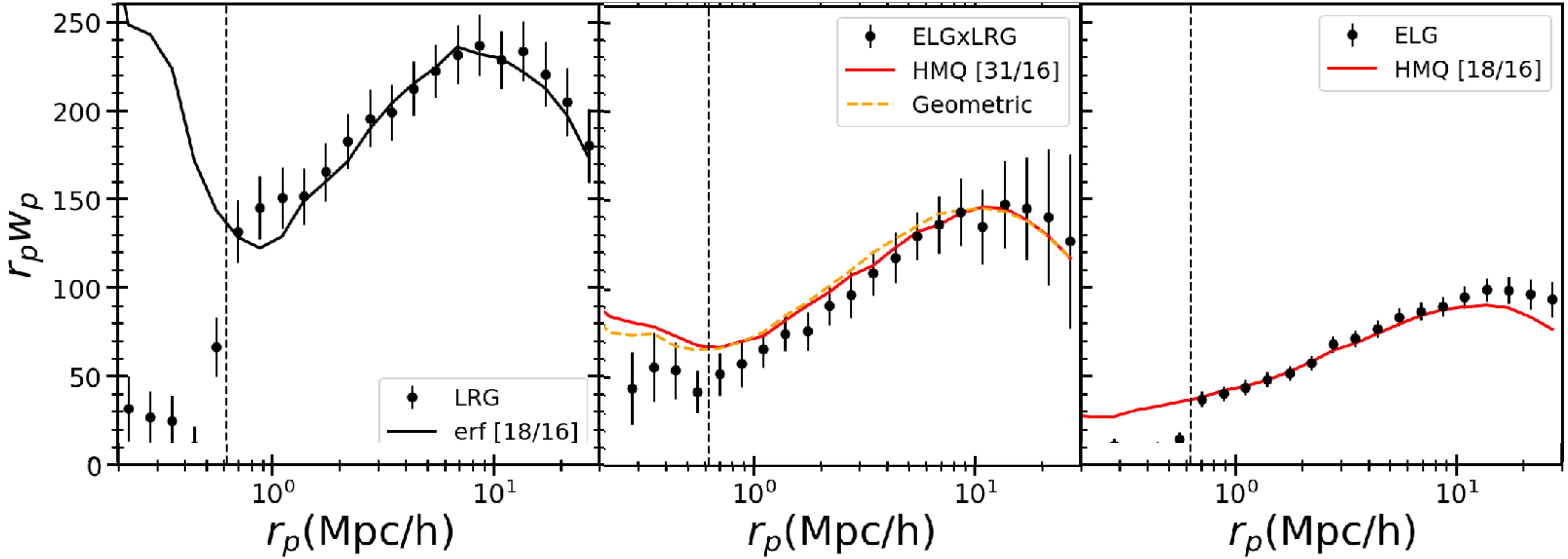
$$B = \frac{\kappa}{2}\left[1 + erf\left(\frac{\log_{10} M_h - log_{10} M_c}{0.01}\right)\right]$$

$$N_{\mathrm{sat}} = N_{\mathrm{central}}\left(\frac{\log_{10} M_h - \log_{10} M_c}{M_1}\right)^{\alpha}$$



How well does this model work for real galaxies

LRG **LRGxELG** **ELG**

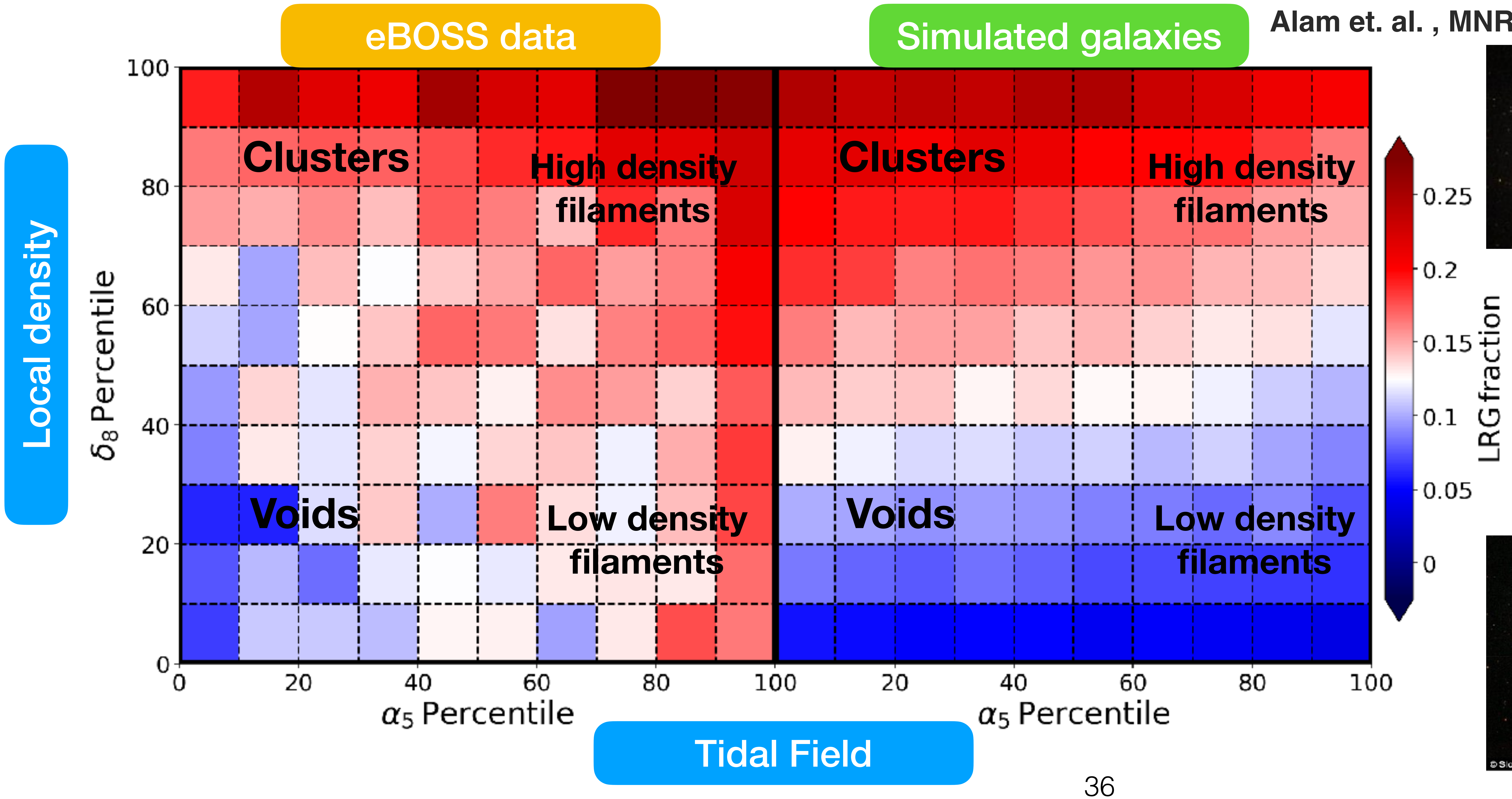


Projected Correlation function: $w_p(r_\perp) = \int_0^{r_\parallel} \xi(r_\perp, r_\parallel)\, dr_\parallel$

Application of MTHOD: Look for beyond halo mass effect

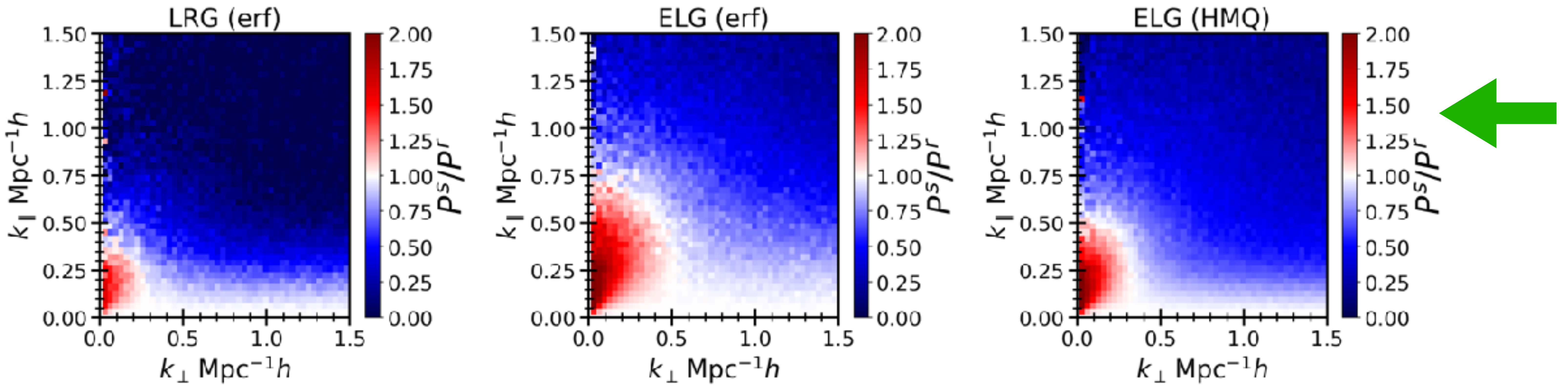
LRG fraction (fraction of quenched galaxies) is over-estimated in low-density filaments from MTHOD model.

Alam et. al. , MNRAS 497, 1, 2020



Application of MTHOD:
Study the non-linear scales for RSD

$$\frac{P_s(k,\mu)}{P_r(k,\mu)} = D_{nl}(k\mu)(1+\beta\mu^2)^2$$



$$\frac{P_s(k,\mu)}{P_r(k,\mu)}$$

Bases on Alam et. al. , MNRAS 497, 1, 2020

Application of MTHOD:
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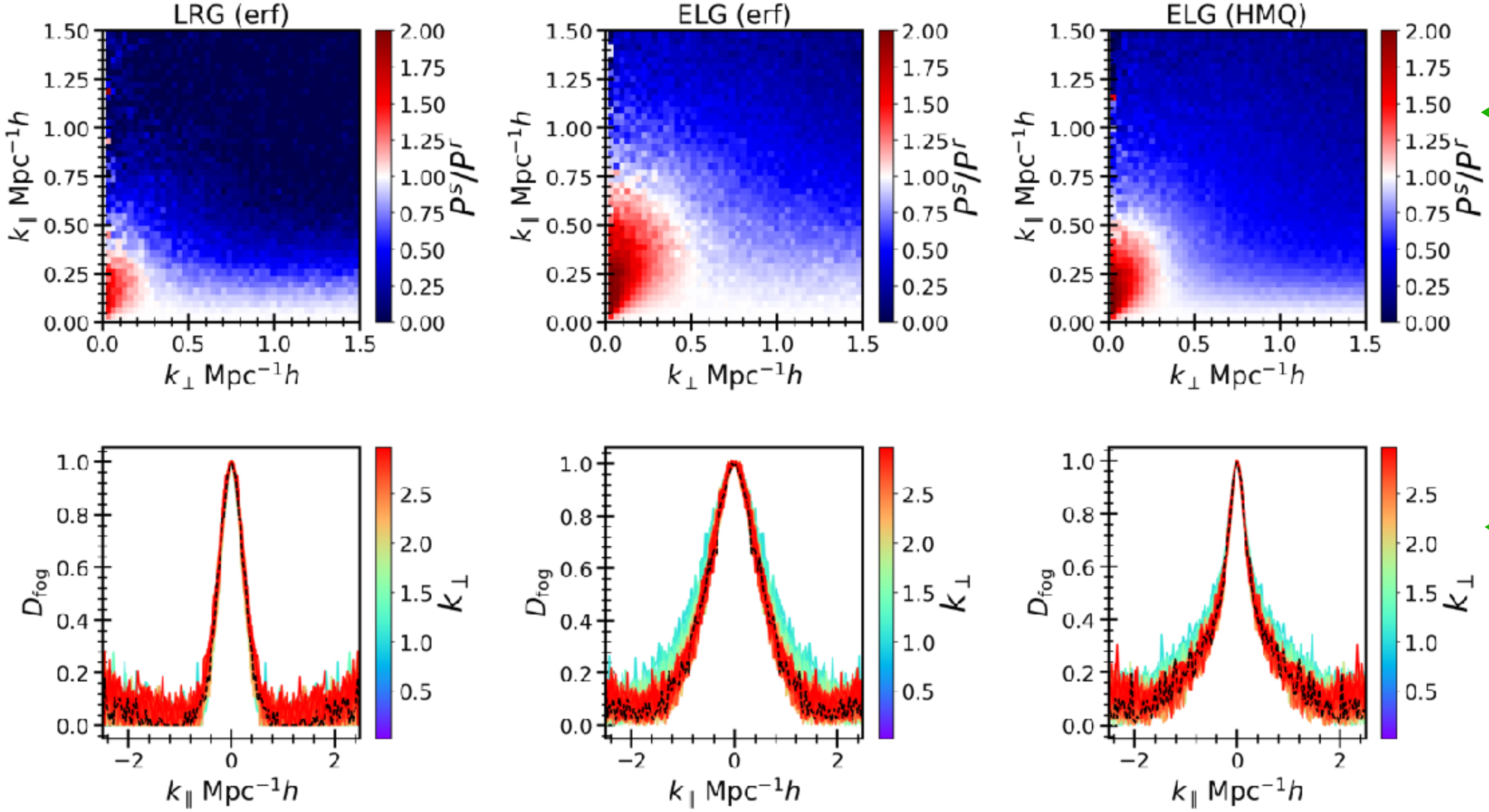
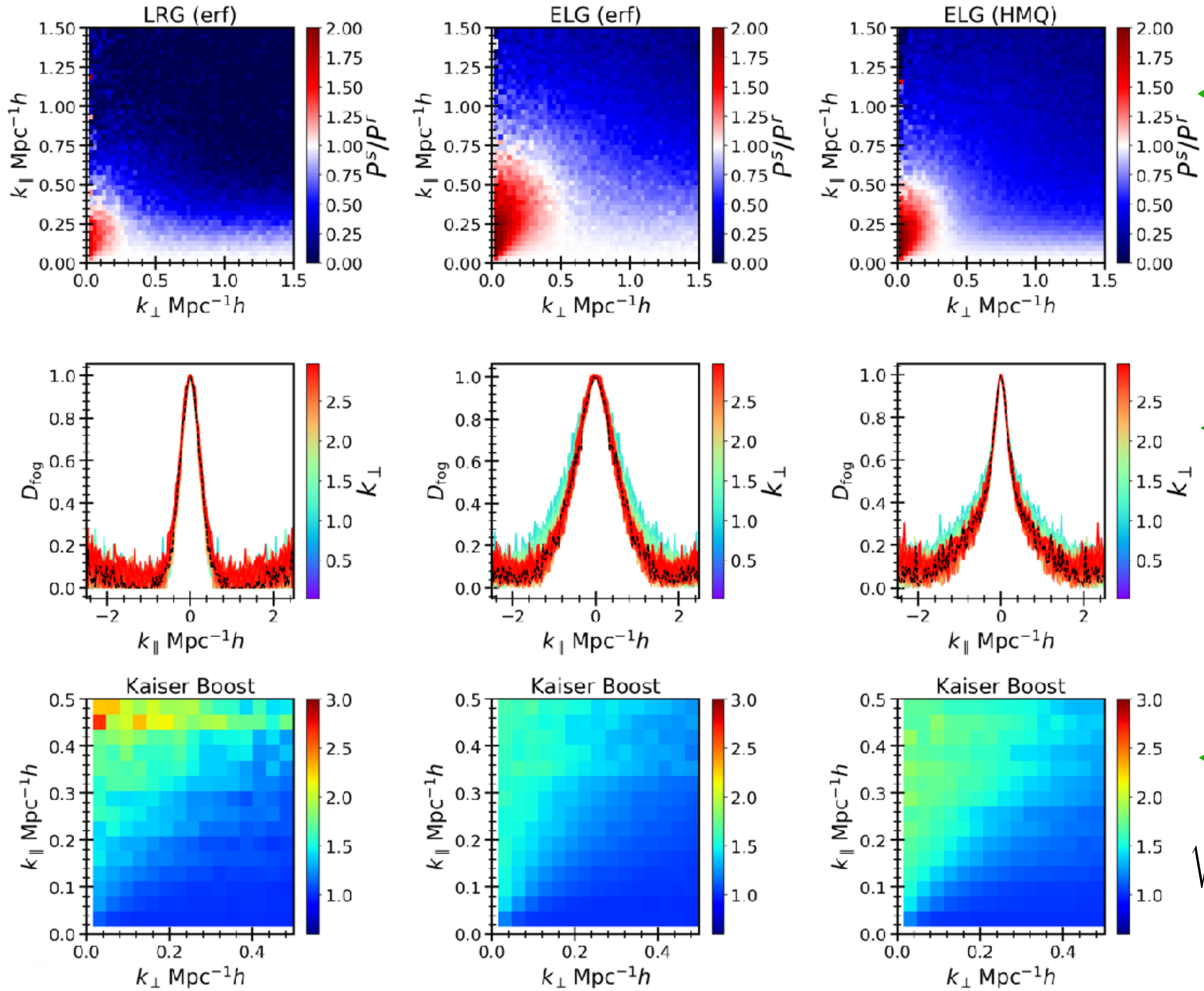


$$\frac{P_s(k,\mu)}{P_r(k,\mu)}$$

$$D_{nl}(k\mu)$$

Application of MTHOD: Study the non-linear scales for RSD

$$\frac{P_s(k,\mu)}{P_r(k,\mu)} = D_{nl}(k\mu)(1+\beta\mu^2)^2$$



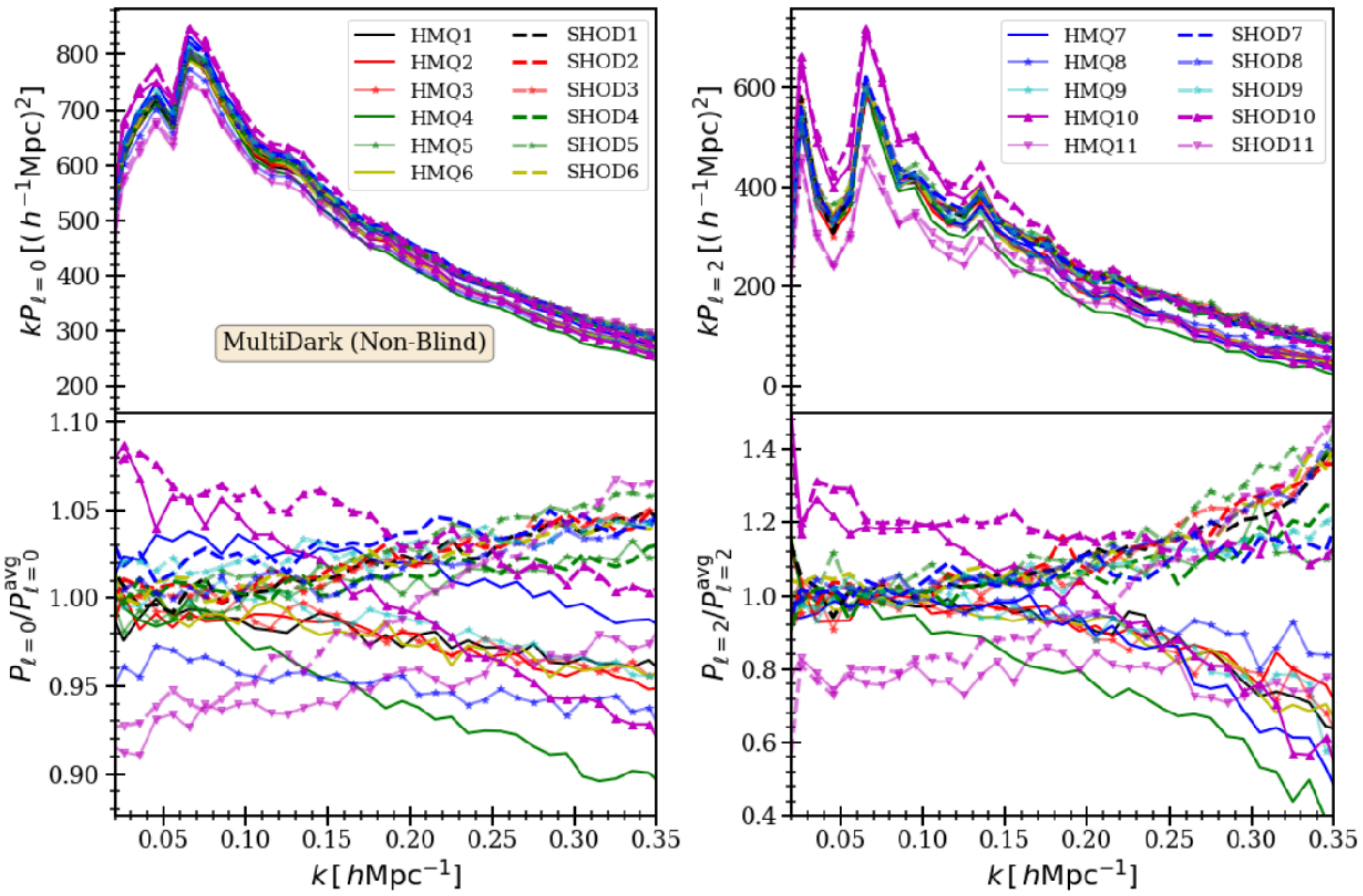
$$\frac{P_s(k,\mu)}{P_r(k,\mu)}$$

$$D_{nl}(k\mu)$$

$$\sqrt{\frac{1}{D_{nl}(k\mu, k_\perp = 2)} \frac{P_s(k,\mu)}{P_r(k,\mu)}}$$

Alam et. al. , MNRAS 497, 1, 2020

Fully non-linear calculation of galaxy power spectrum including models with beyond halo mass



Alam et. al. , MNRAS 504, 4, 2021

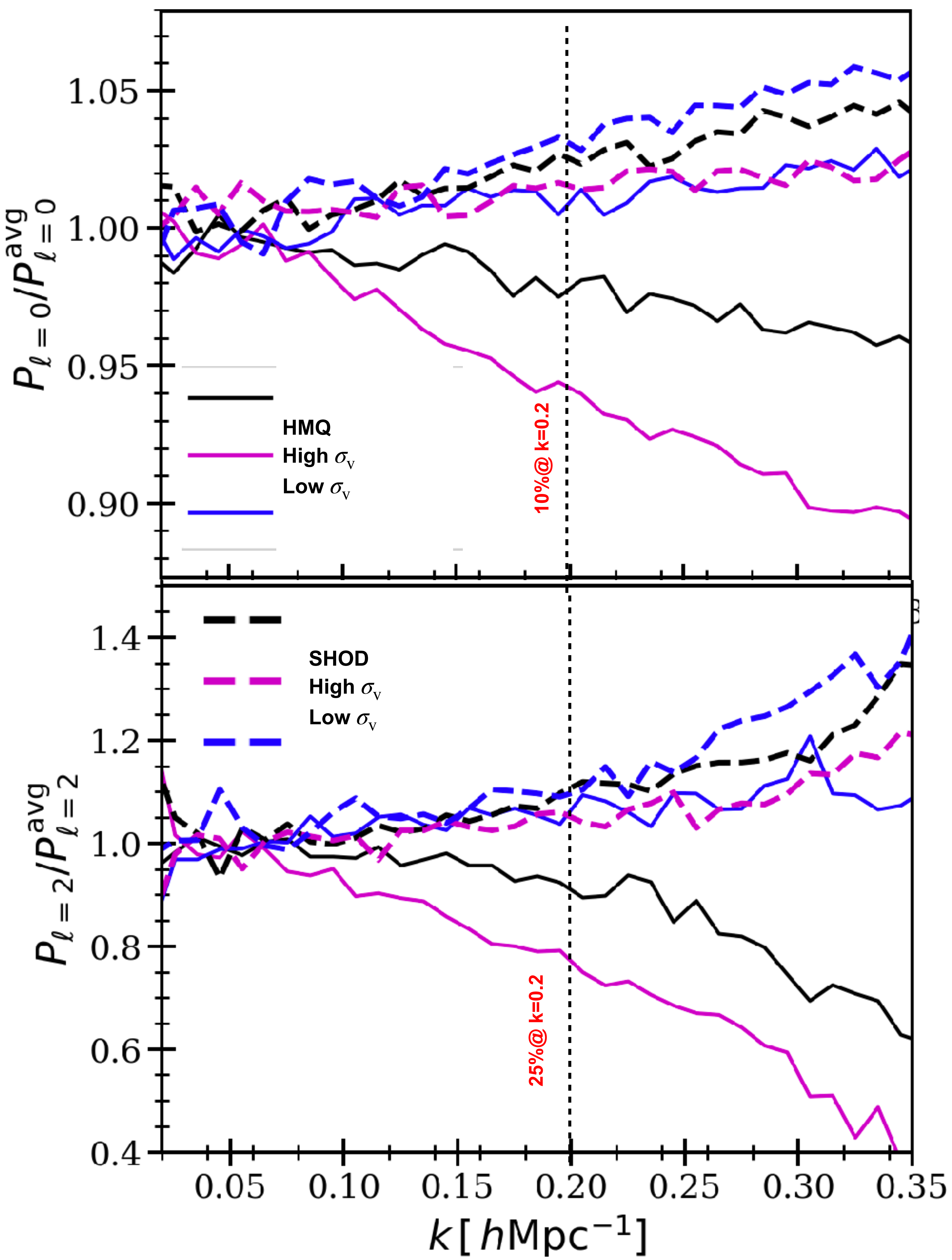
Detail description of the models

Table 3. List of SHOD and HMQ HOD models with their detailed description and simulations used. The basic HOD parameters used for these models are given in Table 2 with any additional degree of freedom described in this table.

Model	Description	Simulations
1	Fiducial HOD model: Halo mass only with dark matter distribution and kinematics for satellite galaxies	MD, OR
2	Satellite galaxies have 50% higher concentration than dark matter	MD
3	Satellite galaxies have 50% lower concentration than dark matter	MD
4	Satellite galaxies have 50% higher velocity dispersion than dark matter	MD, OR
5	Satellite galaxies have 50% lower velocity dispersion than dark matter	MD, OR
6	The central galaxies are off-centred with a Gaussian distribution of width $0.1r_{200}$	MD, OR
7	Assembly Bias: Central galaxies occupation is correlated with halo concentration ($A_{\rm cen} = 0.3$)	MD
8	Assembly Bias: Satellite galaxies occupation is correlated with halo concentration ($A_{\rm sat} = 0.3$)	MD
9	Assembly Bias: Central and Satellite galaxies occupation is correlated with halo concentration ($A_{\rm cen} = A_{\rm sat} = 0.3$)	MD
10	Peculiar velocities of galaxies are scaled higher by 20%. This should increase the growth rate by 20% compared to the fiducial value.	MD, OR
11	Peculiar velocities of galaxies are scaled lower by 20%. This should decrease the growth rate by 20% compared to the fiducial value.	MD, OR

Alam et. al. , MNRAS 504, 4, 2021

Let us look at the physics a bit more carefully



Alam et. al. , MNRAS 504, 4, 2021

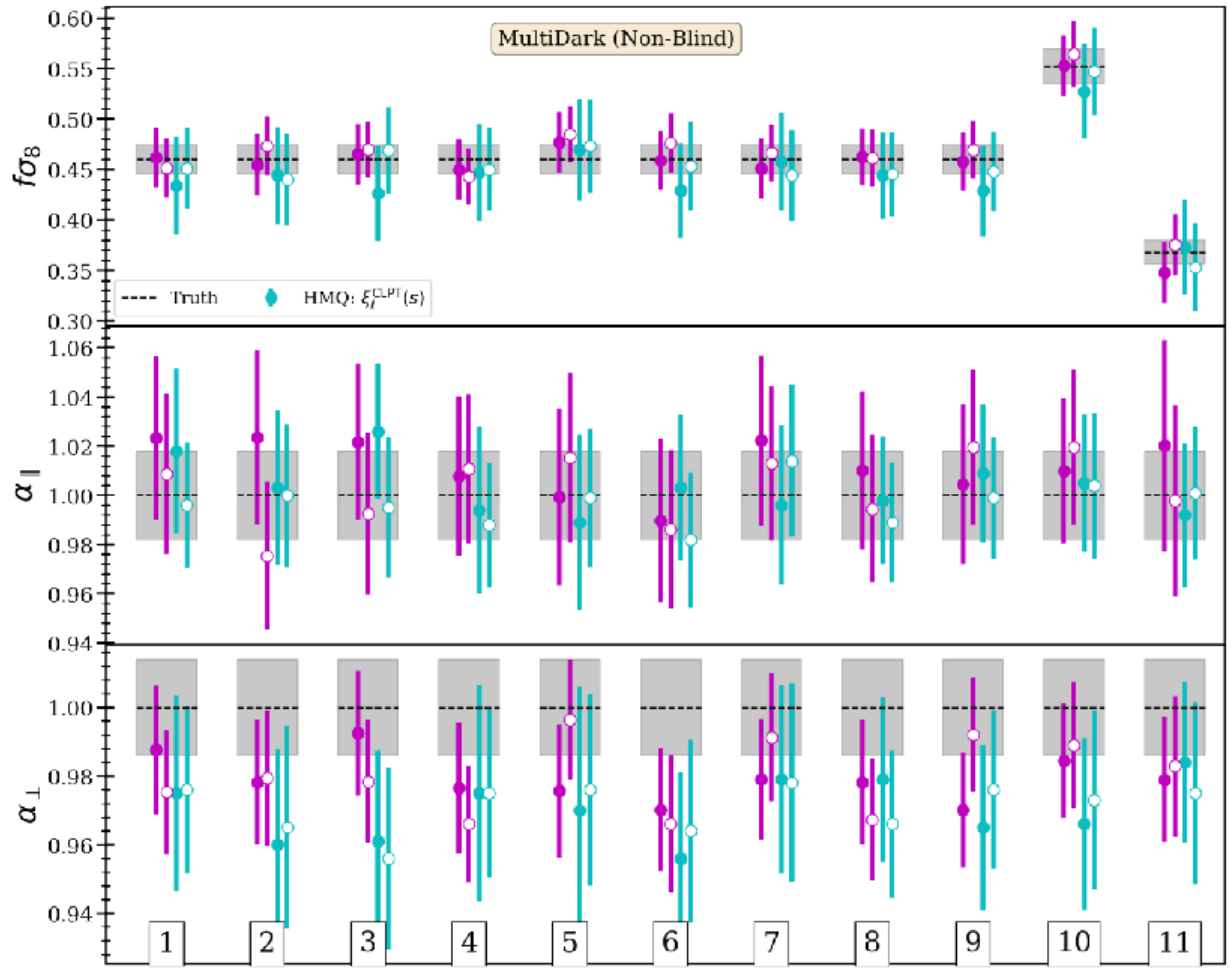
Can perturbation theory model work against such galaxy physics unknowns?

- 10% level these works well

- Why is it a 10% test?

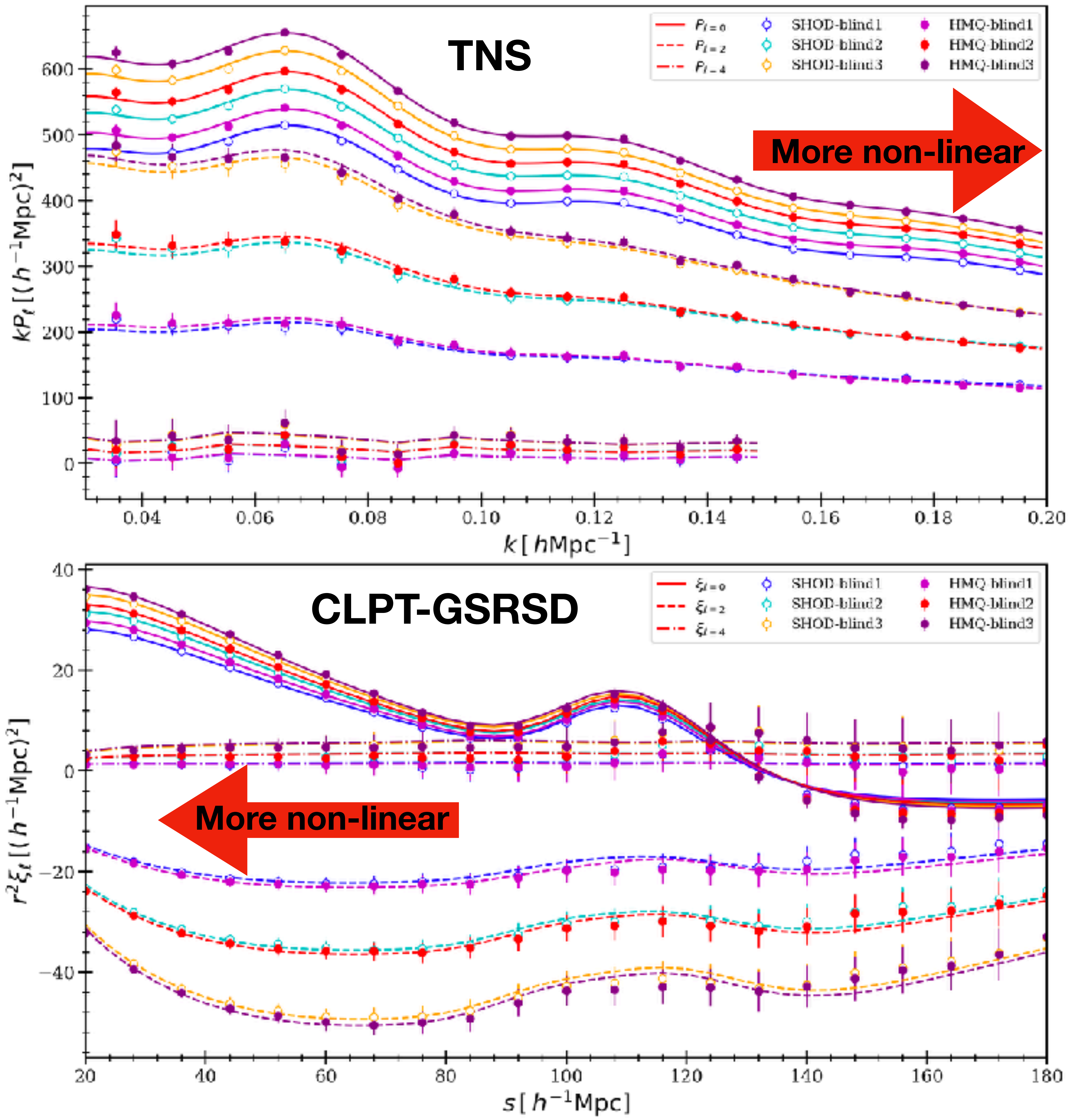
- TNS(Taruya A., Nishimichi T., Saito S., 2010, Phys. Rev. D, 82, 063522)
  $P_g(k,\mu) = P_{\mathrm{TNS}}(k) D_{\mathrm{FOG}}(k,\mu,\sigma_v)$
  $P_{\mathrm{TNS}}(k) = P^g_{\delta\delta}(k) + 2f\mu^2 P^g_{\delta\theta}(k) + f^2\mu^4 P^{(}_{\theta\theta}k) + C_b(b_1)$

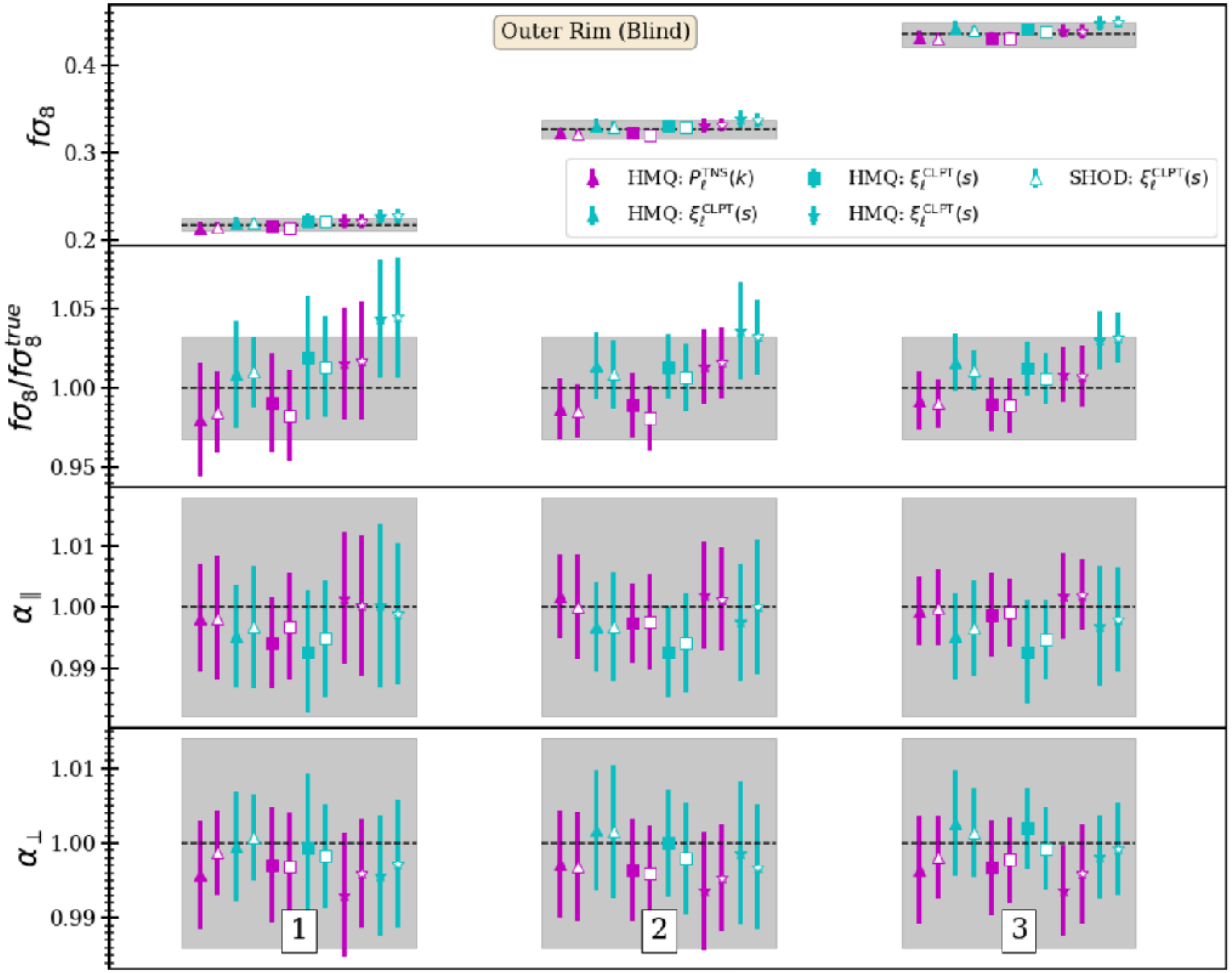
- CLPT-GSRSD: GSM + ingredient based on LPT proposed in
  Matsubara T., 2008c, Phys. Rev. D, 78, 109901
  later improve in
  Carlson J., Reid B., White M., 2013, MNRAS, 429, 1674



Alam et. al. , MNRAS 504, 4, 2021

A Blind test with 3% precision

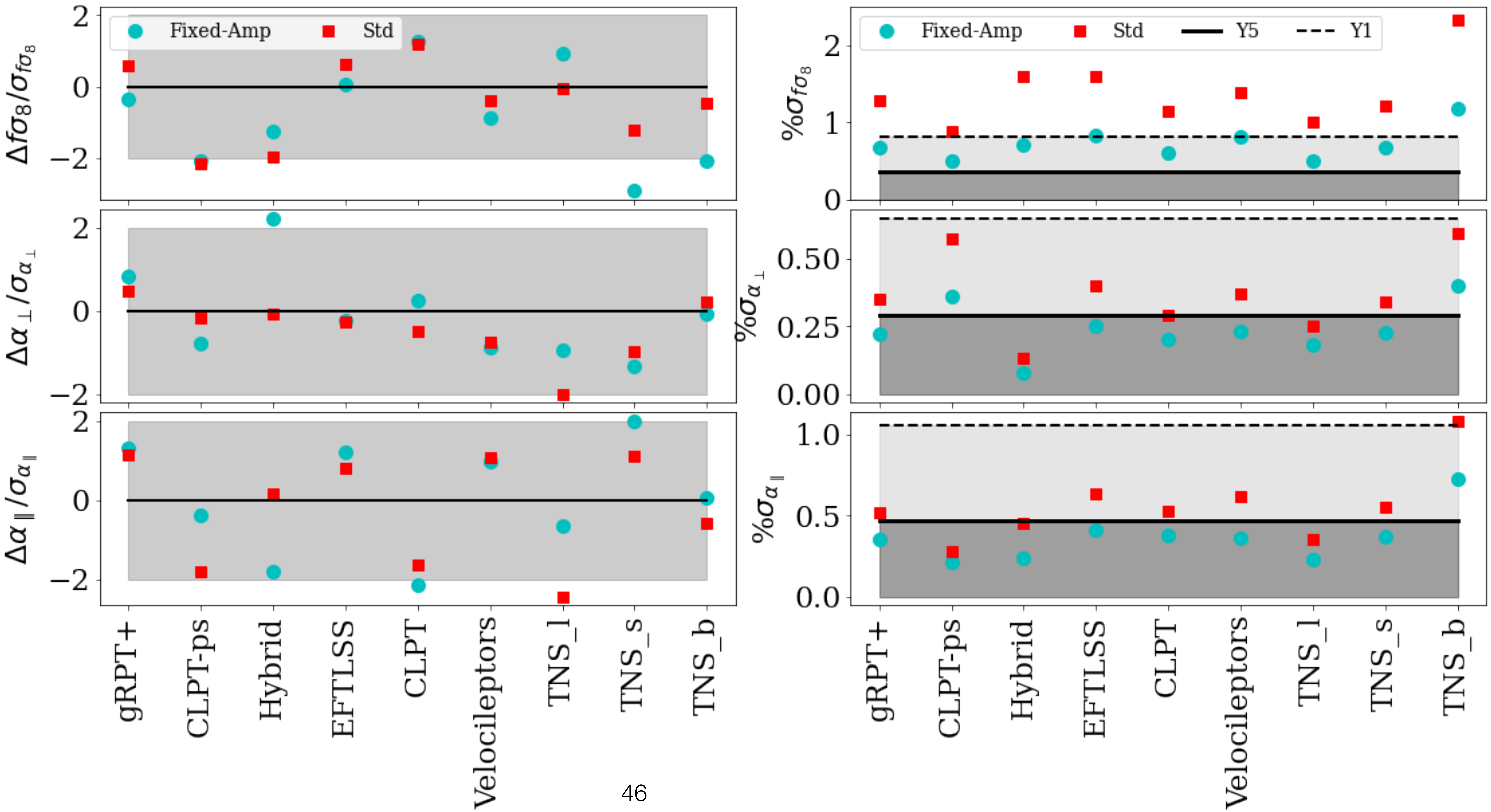




Alam et. al. , MNRAS 504, 4, 2021

DESI specific progress

Higher Precision more models



How to get to the 0.1% level test

Simulation	σ_{DESI}	H*rd	DA/rd	fs8
1 sigma for Y1	2.2	1.05%	0.69%	0.8%
1 sigma for Y5	1	0.47%	0.31%	0.36%
UNIT (MC)	0.5	0.25%	0.15%	0.5%
AbacusSummit	0.3	0.14%	0.087%	0.11%
DESI-FastPM	<0.1	< 0.05%	< 0.03%	< 0.04%
EZmock x 1000	0.05	0.025%	0.015%	0.02%

Final expected errors from DESI ← (1 sigma for Y5)

What I achieved so far in previous slides ← (UNIT (MC))

FirstGen galaxy simulation I produced for DESI ← (AbacusSummit)

FirstGen galaxy simulations (Alam et. al. in prep.)

FirstGen mocks in context

- Will achieve 0.1% precision test for RSD models
- 2Gpc/h side boxes, 25 realisation
- Total volume of 200 (Gpc/h)^3
- Resolves halos upto 2x10^11 needed for the ELG sample

<u>3% RSD test shown uses (Alam et. al.):</u>
Uses 3Gpc/h Outer Rim simulation (Run at LosAlamos by Habib S., et al., 2016, New Astron., 42, 49 and Heitmann K., et al., 2019, ApJS, 245, 16)
27 (Gpc/h)^3, with galaxy density ~2e-4, Total number of galaxies: 5.2e6 (for ELG)
Uses log-normal and gaussian covariance

<u>The current 0.5% RSD test I showed: (Alam et. al. in prep.)</u>
UNITSIM based ELG like sample matching eBOSS ELG with recalibration for DESI predicted linear-bias.
Volume is 3Gpc/h^3 and fixed amplitude can effectively give factor of 5 larger volume but those results have additional complication for interpretation.
27/(135 fixed**)** (Gpc/h)^3, with galaxy density ~**2.5e-3** , Total number of galaxies: **0.6e8** /(3.3e8 fixed)
Covariance Matrix using 1000 EZmocks

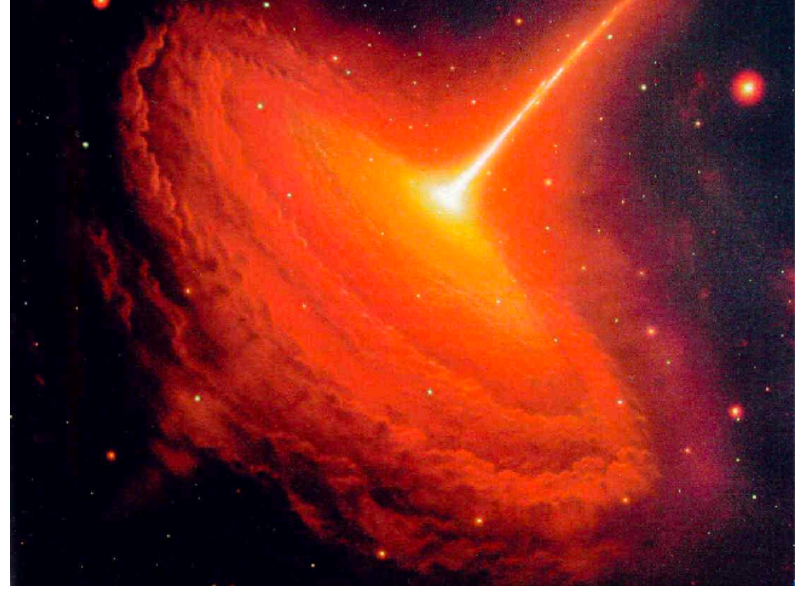
<u>Blind PT Challenge: (Nishimichi et. al. 2020, https://arxiv.org/abs/2003.08277)</u>
BOSS LRG like galaxy catalog , Much less non-linear
566 (Gpc/h)^3, with galaxy density ~**5e-4**, Total number of galaxies: **2.8e8**
Uses gaussian covariance matrix or diagonal

But it is not very physical to model QSOs in this framework of halos: At least we need to explore the possibilities

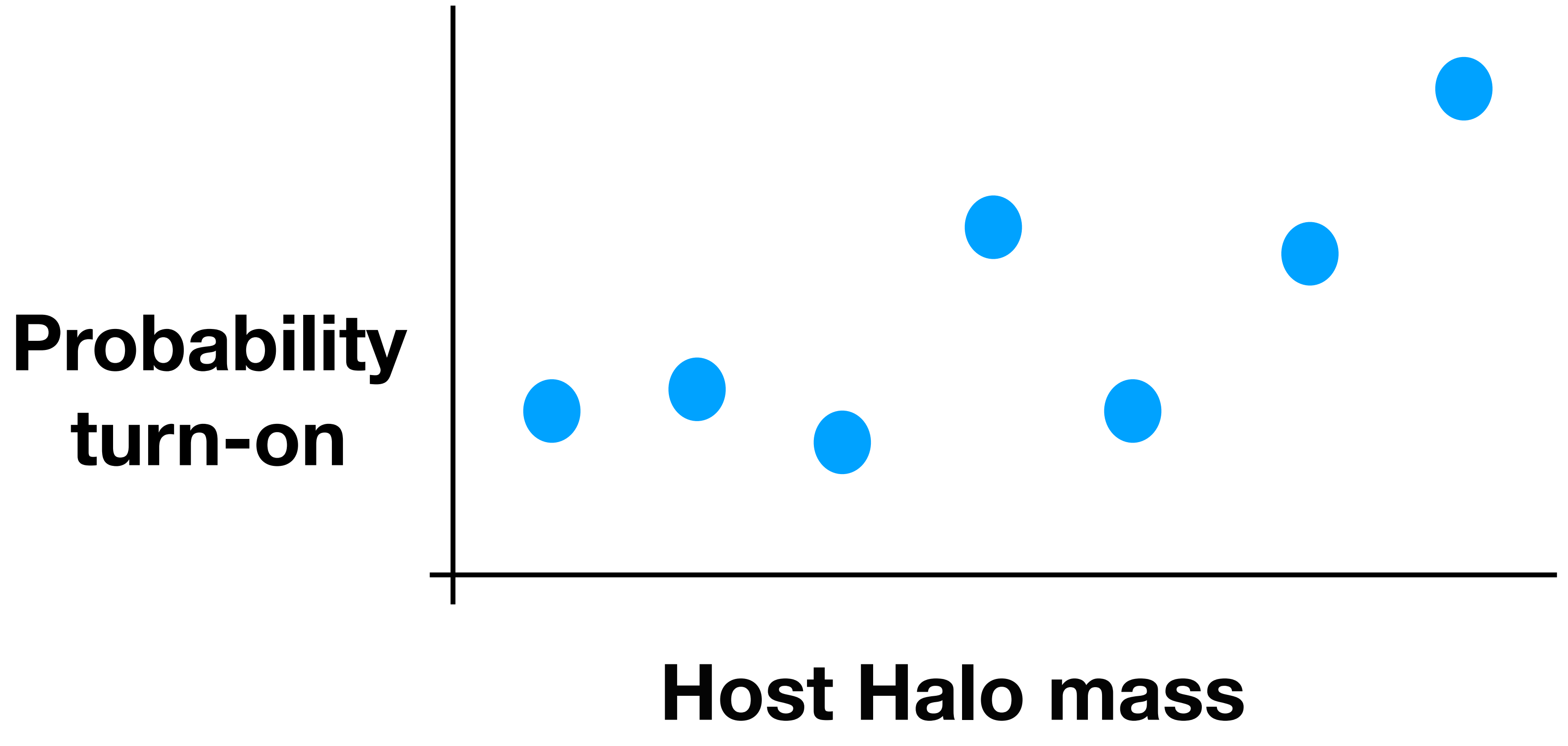
Galaxy
Occupation
Distribution

GOD

(Galaxy Occupation Distribution)



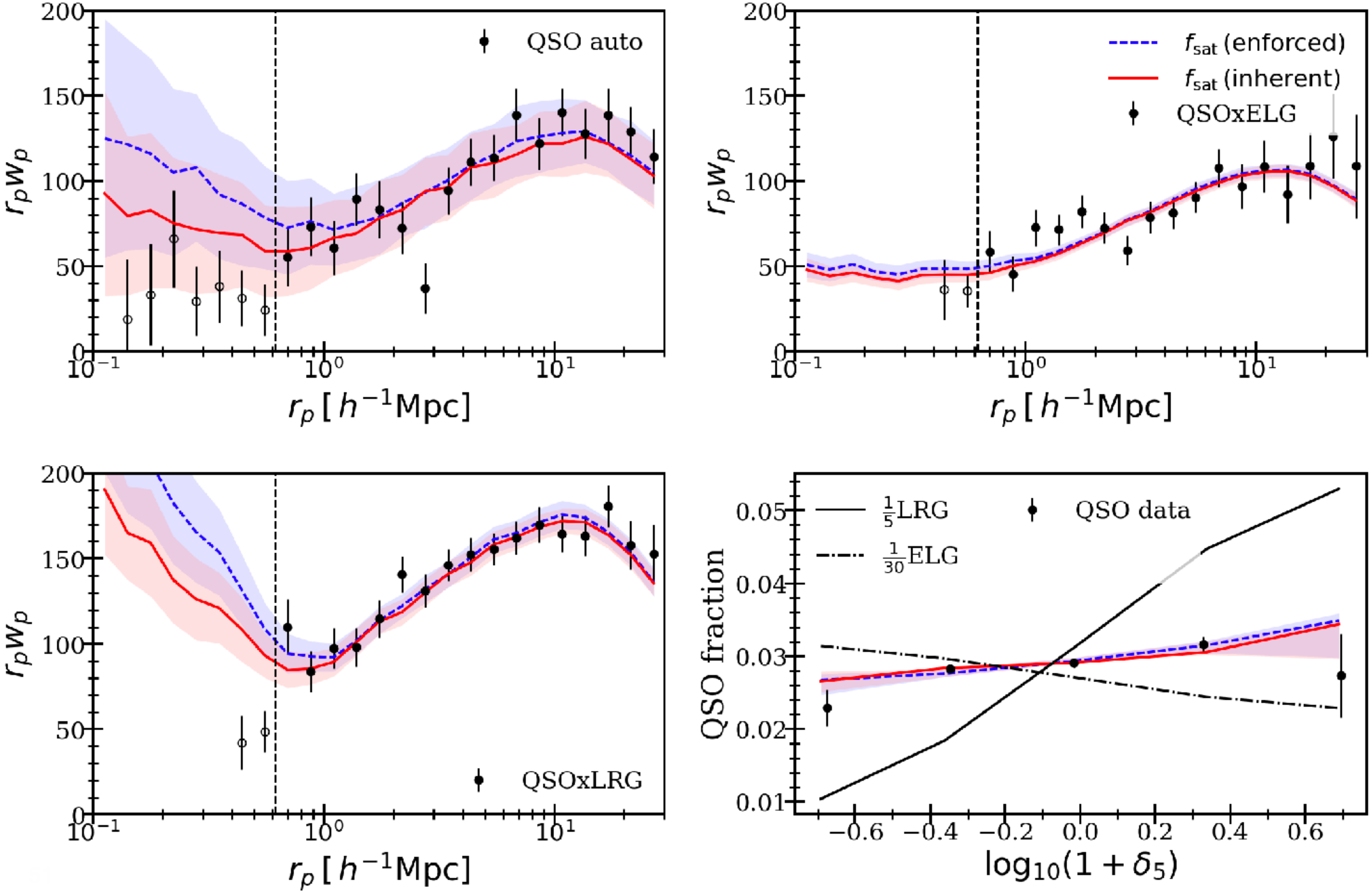
$$P_{\rm on}(M_{\rm halo}, G_{\rm type}, G_{\rm pos}) = f_{\rm on}(M_{\rm halo})p(G_{\rm type})p(G_{\rm pos})$$



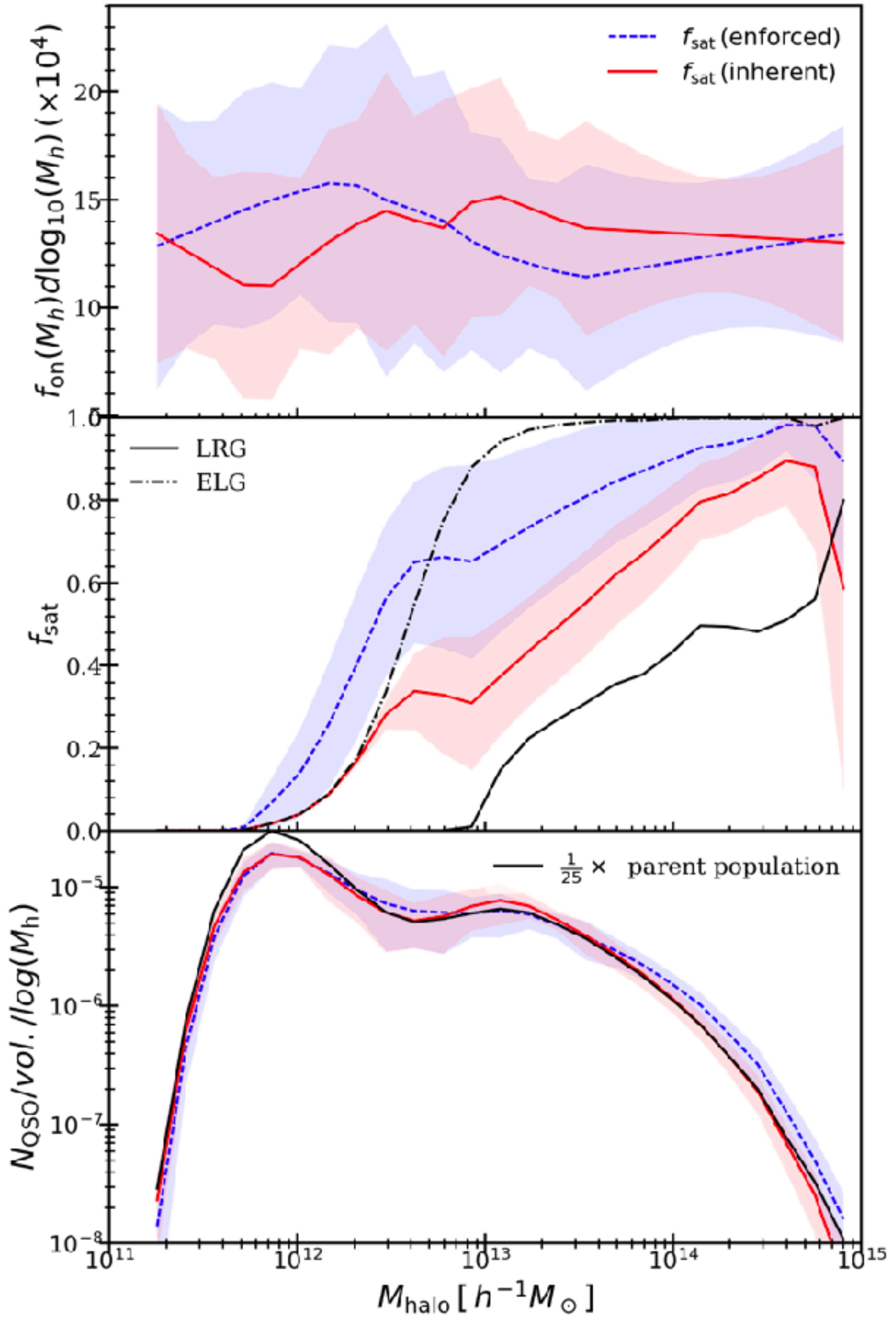
- Host halo mass
- Central/satellite
- star-forming/quenched

QSO probes largest volumes.
Plays dominant role in the PNG limits from LSS

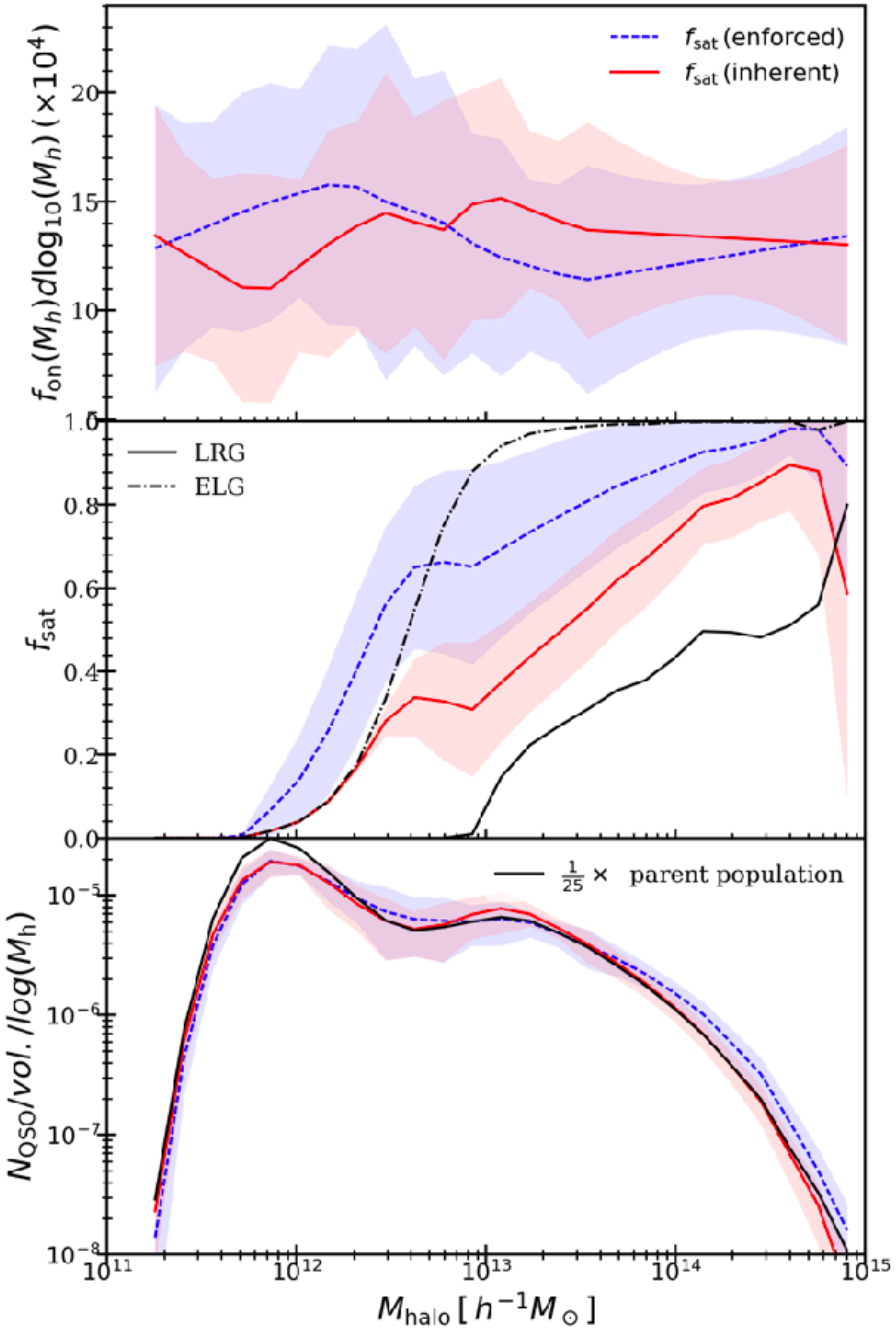
How well it works?

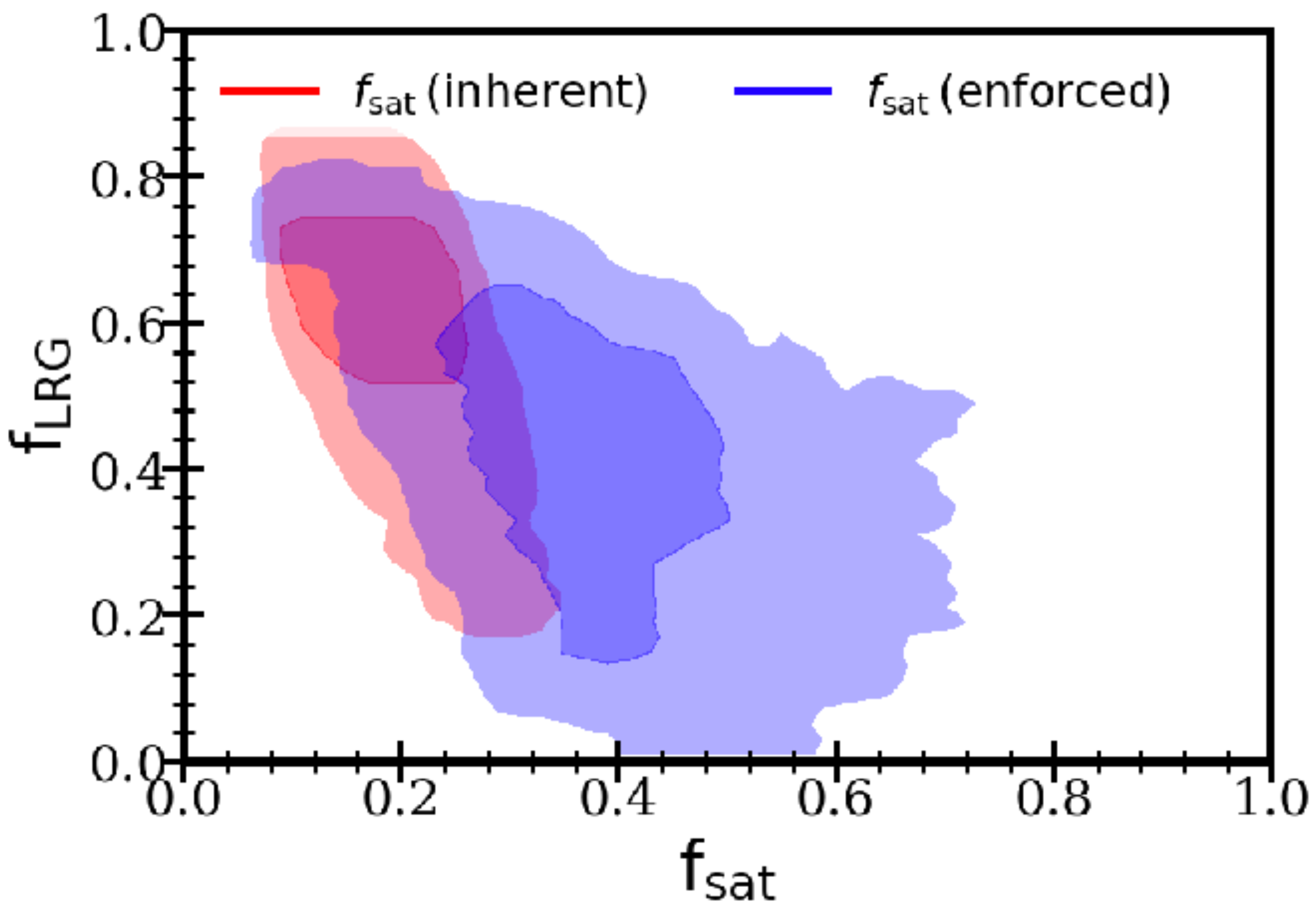


What are host galaxies of Optical QSO?

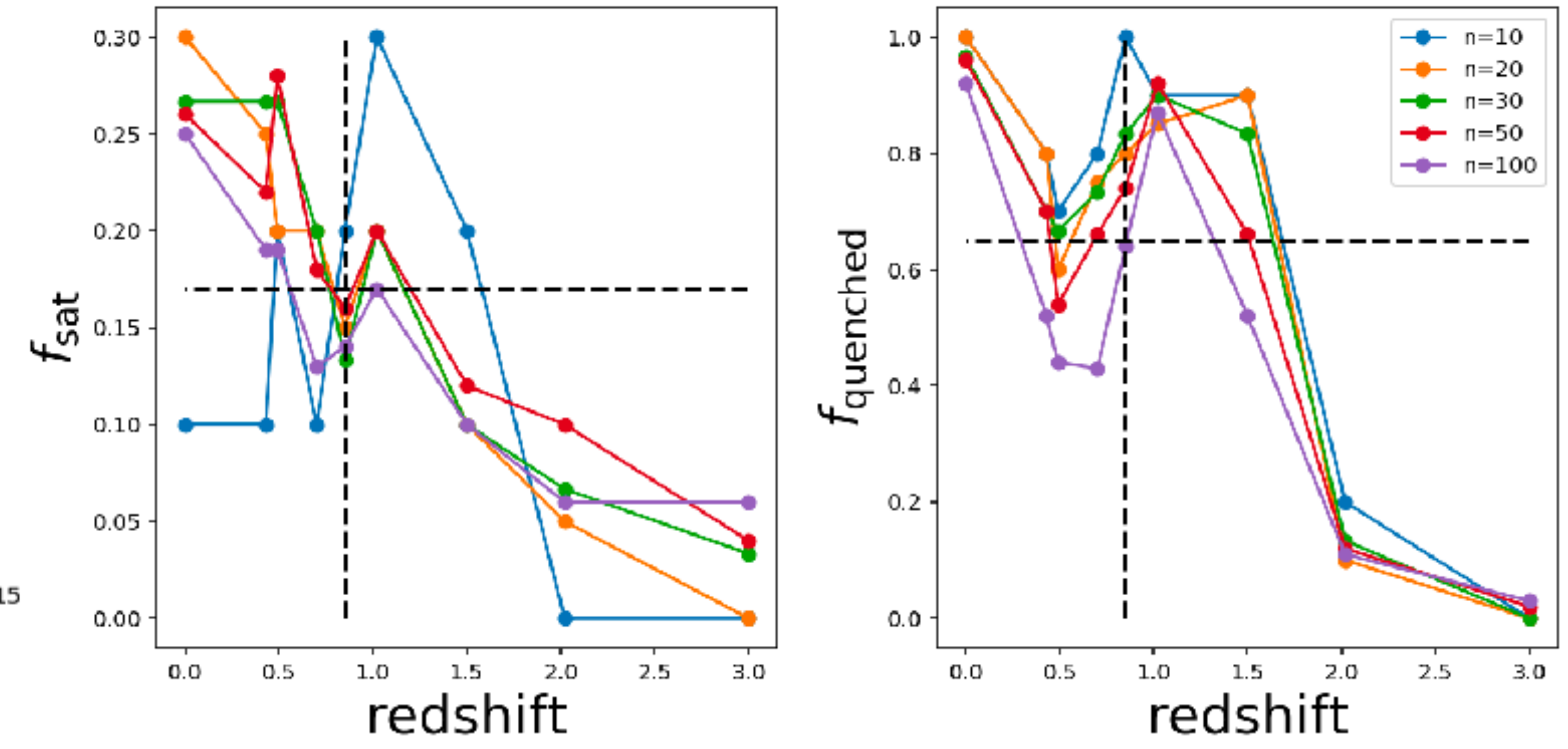


What are host galaxies of Optical QSO?





From SIMBA Dave R. et. al. (2019), (1901.10203)



Theory meets data

- Selection function
- Wide angle effects
- Covariance matrix
- Non-trivial terms in covariance matrix

Few Other topics of interest

- General Relativistic effects
- Full modelling vs robust physics feature
- Cross correlations of LSS with CMB
- Reconstruction for BAO/kSZ
- Beyond galaxies: Voids, cluster, filament the full cosmic web for cosmology.
- RSD around groups at low redshift

Summary

- Three challenges non-linearity, bias and RSD
- Marginalising over galaxy physics
- Precision test of model ingredients
  - To measure growth to 0.4% (as promised by DESI)
  - We need our approximate model under control below 0.1%
  - Current test shows this at 0.5% level, FirstGen mocks will achieve the needed limit of 0.1%.
- I have showed you results from following (non-alphabetical) papers today.

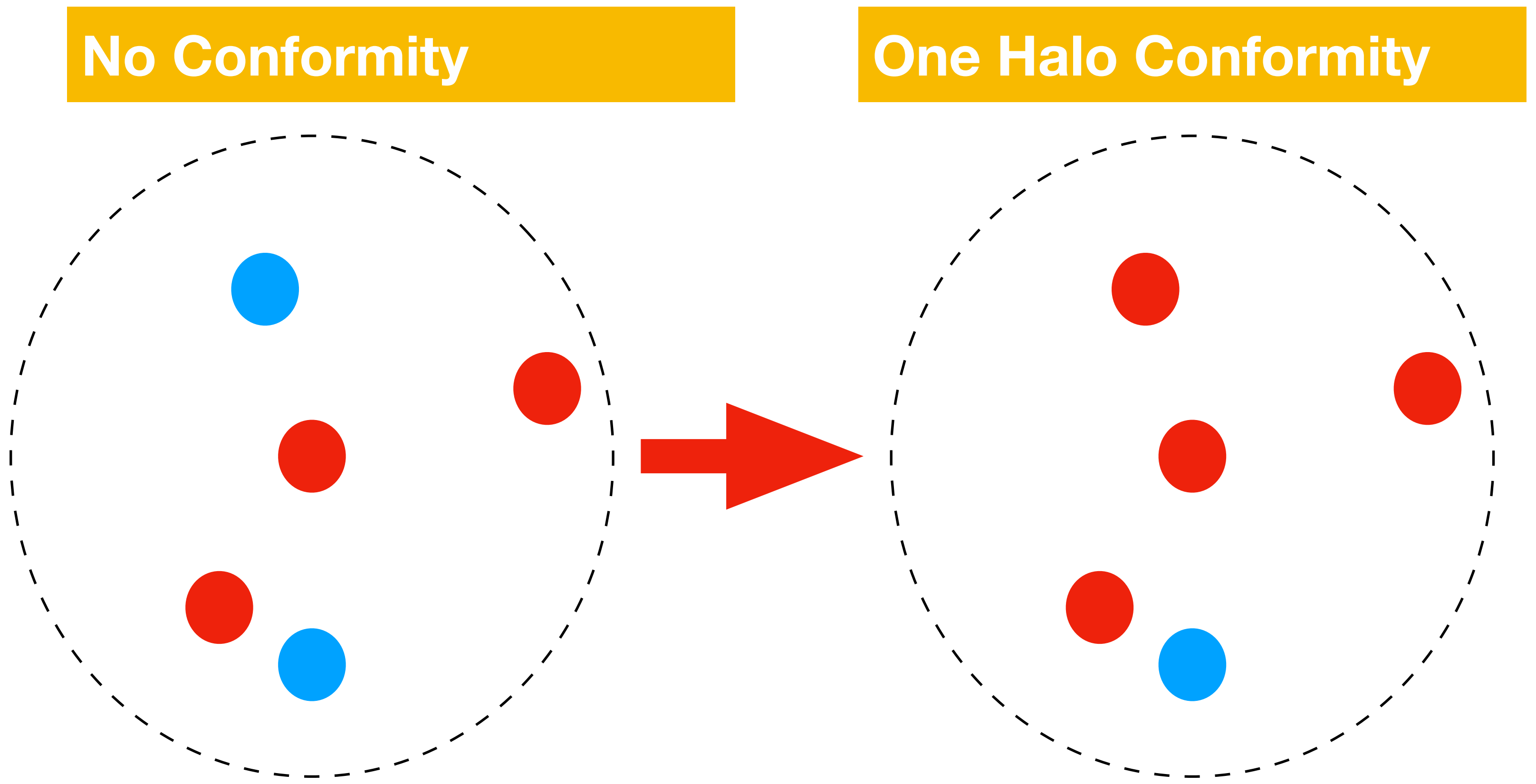
1) **Multi-tracer extension of the halo model: probing quenching and conformity in eBOSS**
Shadab Alam , John A. Peacock, Katarina Kraljic, Ashley J. Ross, Johan Comparat
MNRAS 497, 581-595 (2020),
2) **Quasars at intermediate redshift are not special; but they are often satellites**
Shadab Alam , Nicholas P. Ross, Sarah Eftekharzadeh, John A. Peacock, Johan Comparat, Adam D. Myers, Ashley J. Ross
MNRAS 504, 1, June 2021
3) **The Completed SDSS-IV extended Baryon Oscillation Spectroscopic Survey: N-body Mock Challenge for the eBOSS Emission Line Galaxy Sample**
Shadab Alam , et. al. MNRAS 504, 4, July 2021

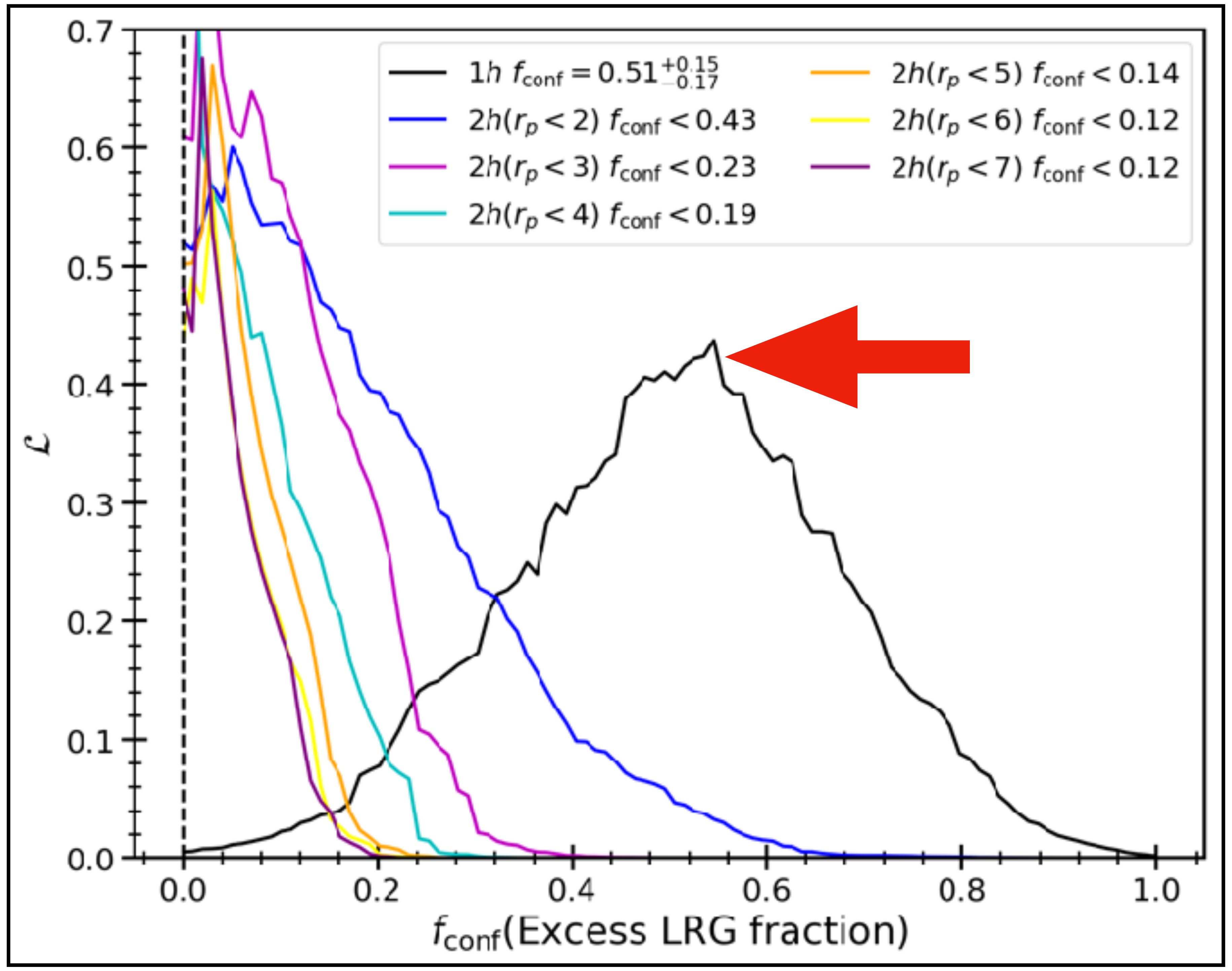
Extra Slides

One Halo Conformity

$$N_{\rm sat}^{\rm LRG}(g_{\rm cen}) = N_{\rm sat}^{\rm LRG} + f_{\rm conf} N_{\rm sat}^{\rm ELG} \quad \text{if } g_{\rm cen} = \text{LRG}$$
$$= N_{\rm sat}^{\rm LRG} \quad \text{otherwise}$$

$$N_{\rm sat}^{\rm ELG}(g_{\rm cen}) = (1 - f_{\rm conf}) N_{\rm sat}^{\rm ELG} \quad \text{if } g_{\rm cen} = \text{LRG}$$
$$= N_{\rm sat}^{\rm ELG} \quad \text{otherwise}$$

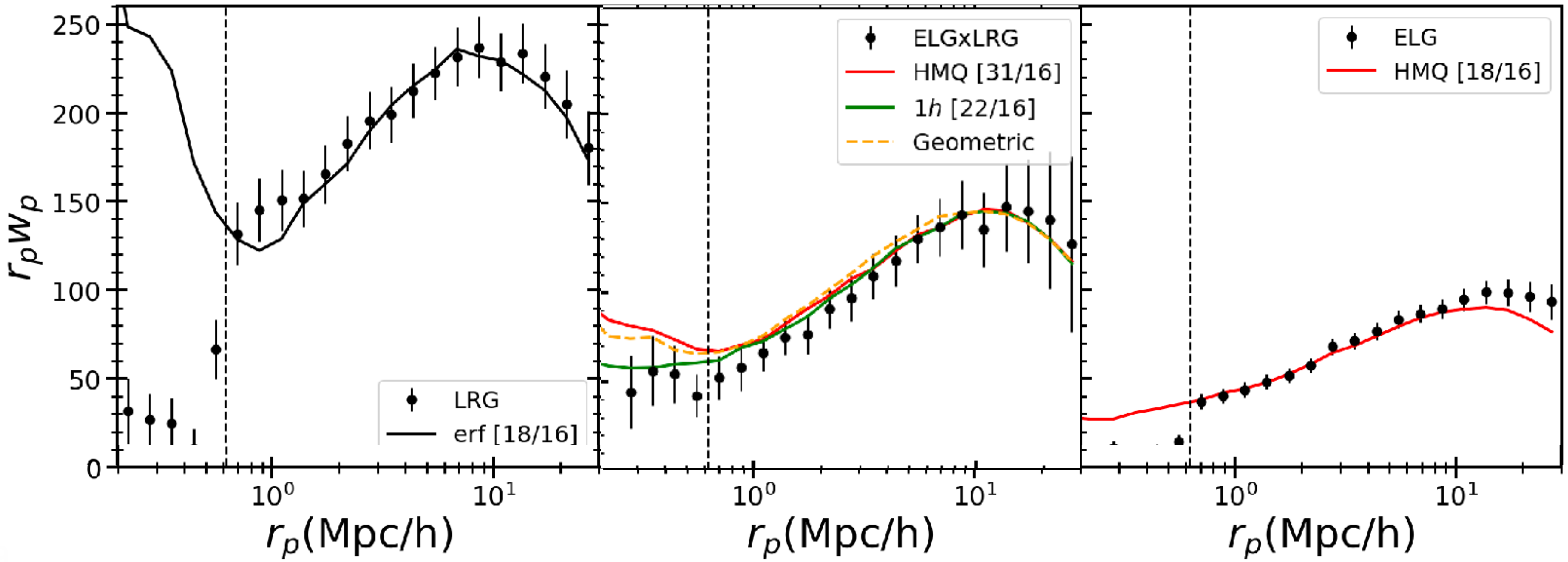


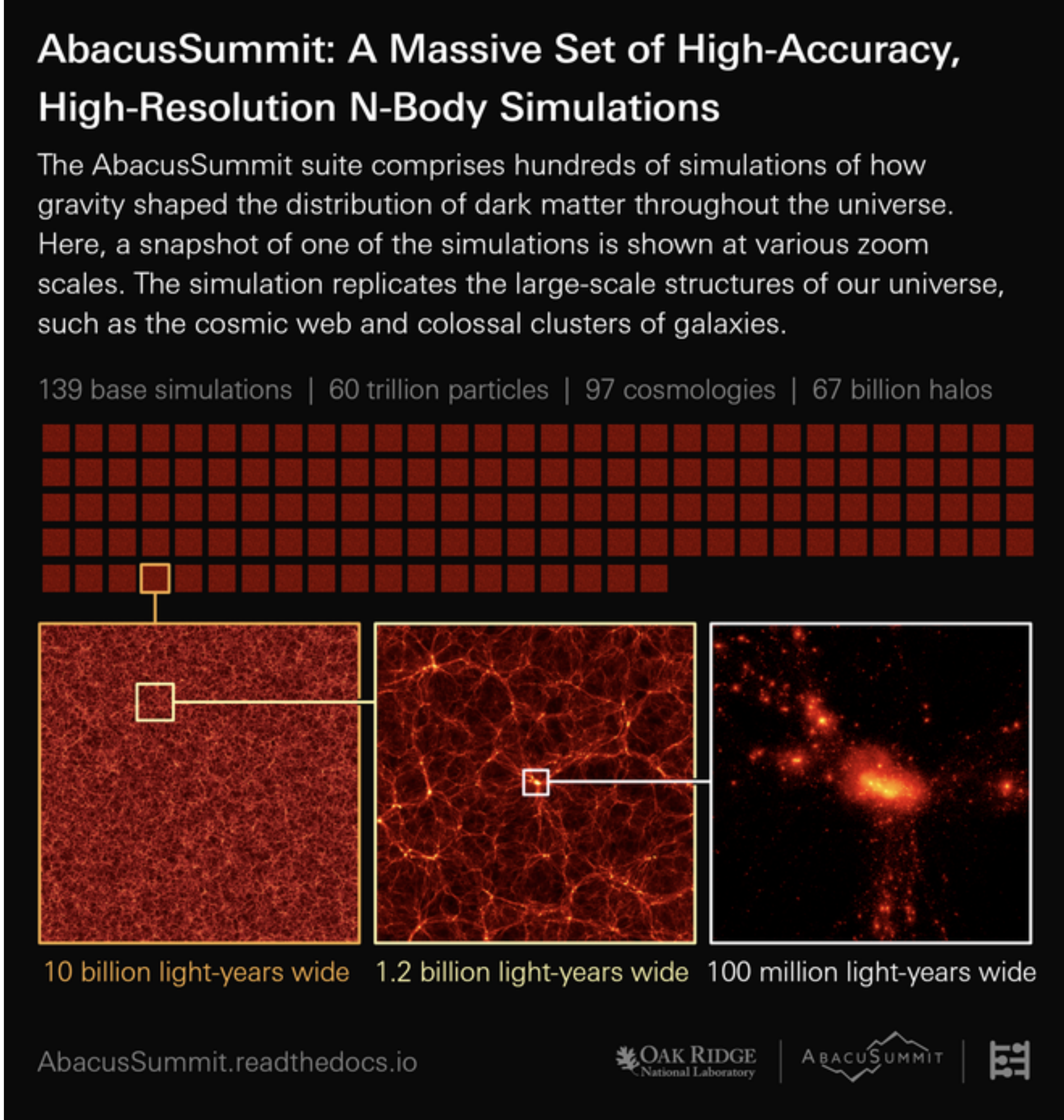


Multi tracer Halo Occupation Distribution (MHOD)

Cross correlation functions:

LRG LRGxELG ELG




AbacusSummit: A Massive Set of High-Accuracy, High-Resolution N-Body Simulations
The AbacusSummit suite comprises hundreds of simulations of how gravity shaped the distribution of dark matter throughout the universe. Here, a snapshot of one of the simulations is shown at various zoom scales. The simulation replicates the large-scale structures of our universe, such as the cosmic web and colossal clusters of galaxies.
139 base simulations | 60 trillion particles | 97 cosmologies | 67 billion halos
10 billion light-years wide
1.2 billion light-years wide
100 million light-years wide
AbacusSummit.readthedocs.io
OAK RIDGE National Laboratory
ABACUSUMMIT

PFS expected performance

https://arxiv.org/pdf/1206.0737.pdf

TABLE 4
COSMOLOGY SURVEY REQUIREMENTS

Science yield requirements	
Distance measurements	$\lesssim 3\%$ measurement of $D_A(z)$ and $H(z)$ in each of 6 redshift bins via BAO (0.8–1.0, 1.0–1.2, 1.2–1.4, 1.4–1.6, 1.6–2.0, and 2.0–2.4)
Dark energy reconstruction	$\lesssim 7\%$ measurement of $\Omega_{\rm de}(z)$ in each of 6 redshift bins via BAO
Curvature	Measure Ω_K to $\lesssim 0.3\%$ via BAO
Growth of structure	$\lesssim 6\%$ measurement of the growth rate of structure in each of 6 bins via RSD
Galaxy catalog requirements	
Redshift range	$0.8 \leq z \leq 2.4$ ($0.8 \leq z \leq 1.6$ minimum)
Number density of galaxies	≥ 2900 deg^{-2}
dN/dz of ELGs	$\bar{n}_g P_g > 1$ ($0.8 < z < 1.6$) or $\bar{n}_g P_g > 0.5$ ($1.6 < z < 2.4$) at $k = 0.1h$/Mpc
Total survey area	$\geq$1400 deg^2
Incorrect redshift fraction	$< 1\%$
Redshift precision, accuracy	$\Delta z/(1+z) < 0.0007$, 1σ ($\sigma_v < 200$ km/s)
Survey geometry	Width > 7.5 degrees; ≤ 4 contiguously-connected survey regions
Survey implementation requirements	
Total nights	$\simeq 100$ clear nights
Lunar phase	Dark (1 of 2 visits) or age < 7 days (other visit)
Imaging survey	HSC gri data to $\approx$ 26th magnitude AB (5σ)

Example of Galaxy selection

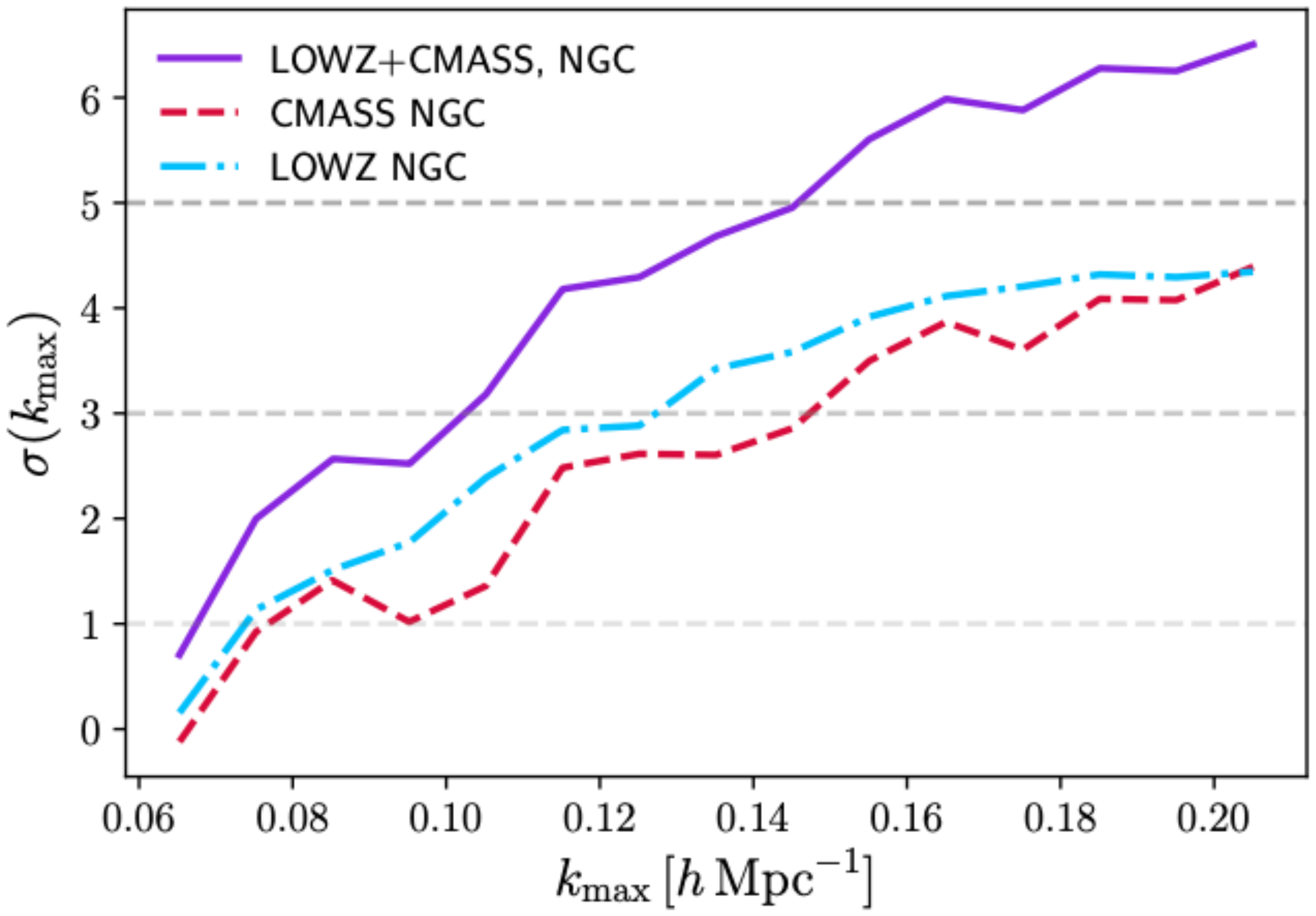
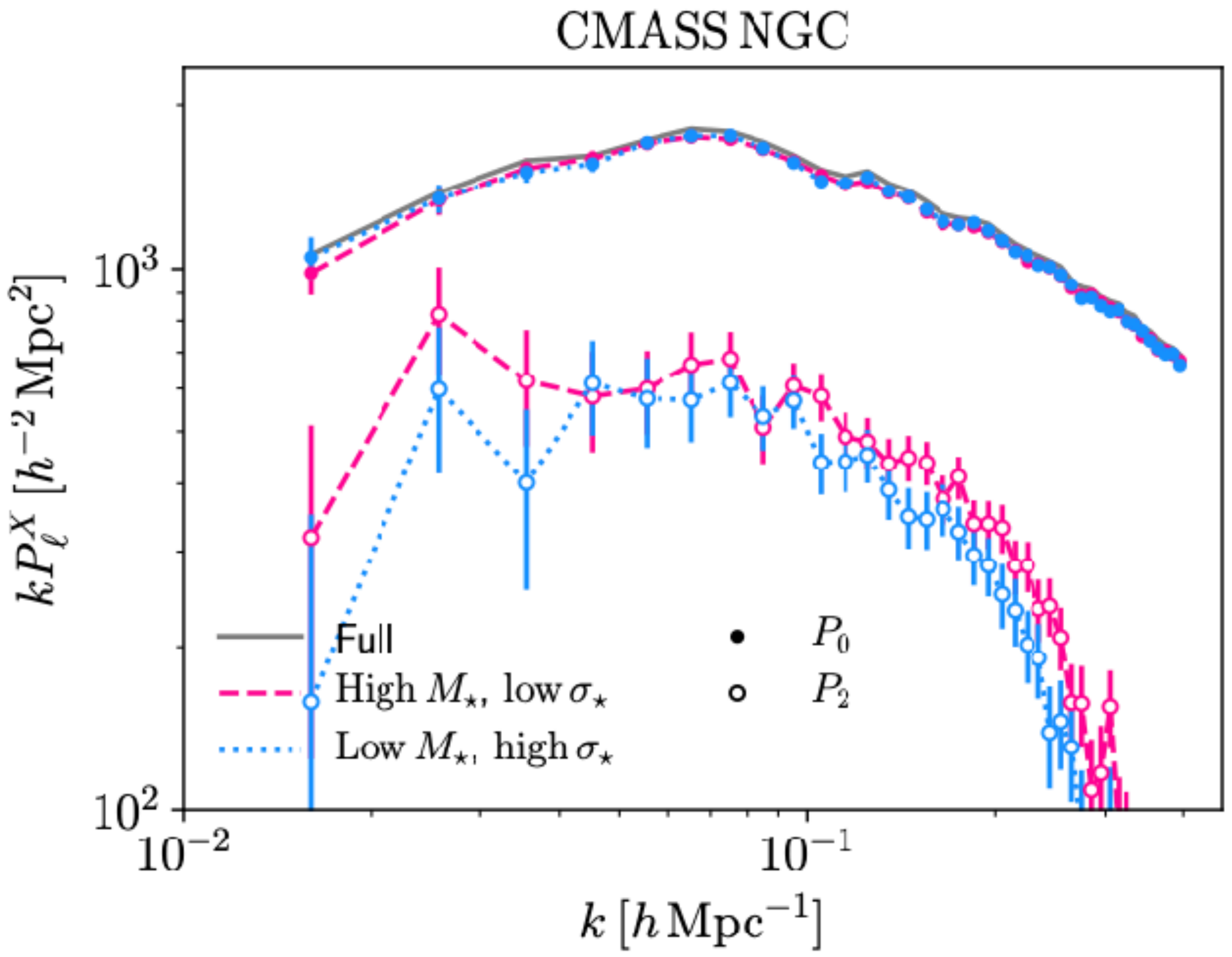
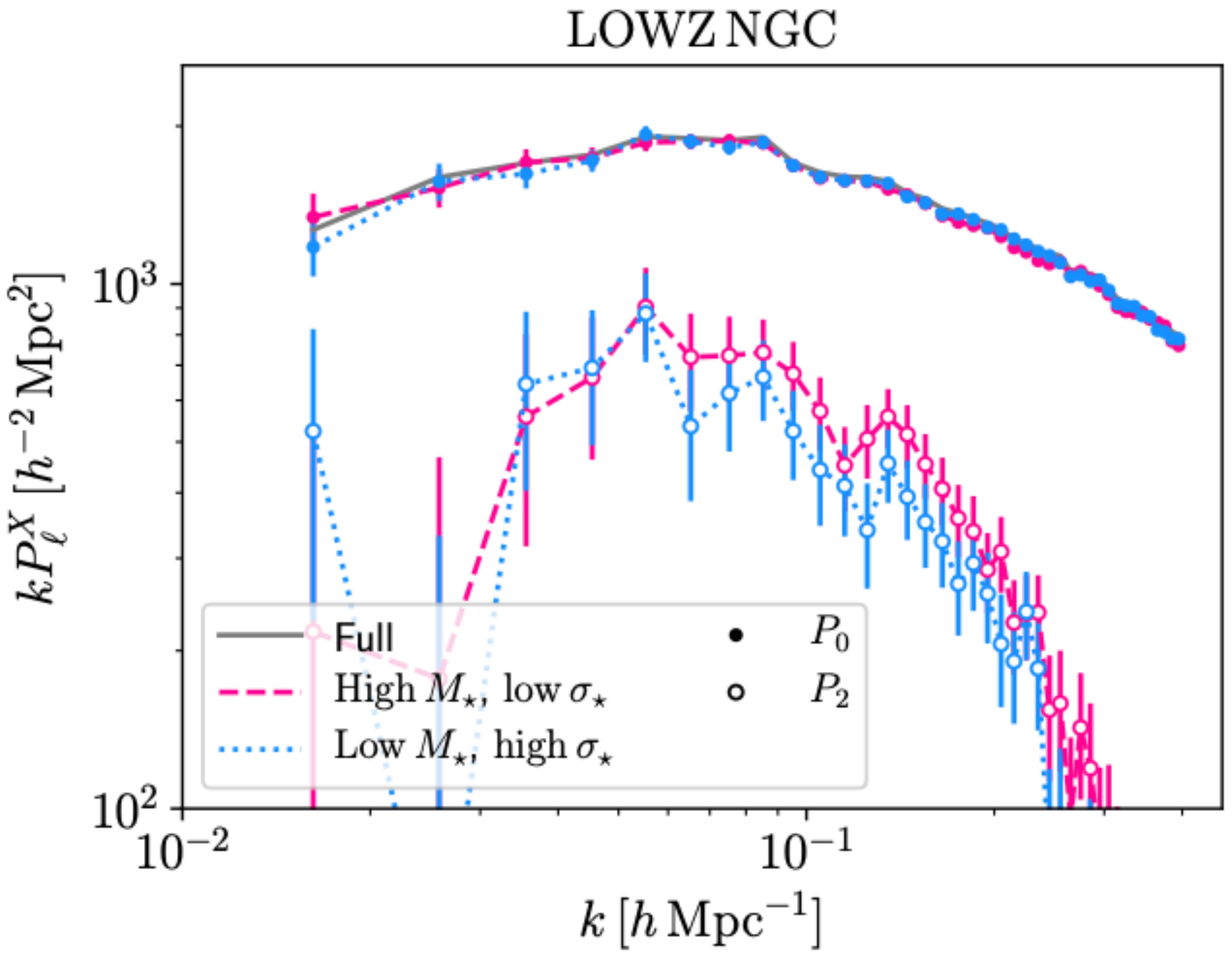


FIG. 8. Estimated significance of obtaining $a_2 \neq 1$ expressed in units of standard deviation, as a function of $k_{\max}$. Shown are the cases of using LOWZ and CMASS results individually (dot-dashed and dashed lines, respectively) and the combined significance (solid line).





https://arxiv.org/pdf/2004.07240.pdf