Precision cosmology all scales with DESI brightest galaxies

Pauline Zarrouk (LPNHE, Sorbonne Université, Paris)

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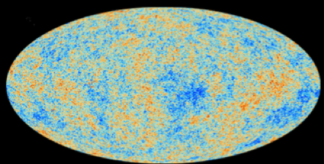
DESI will create 3D maps of the structures of the universe

Which physics governs the very first moments of the universe?

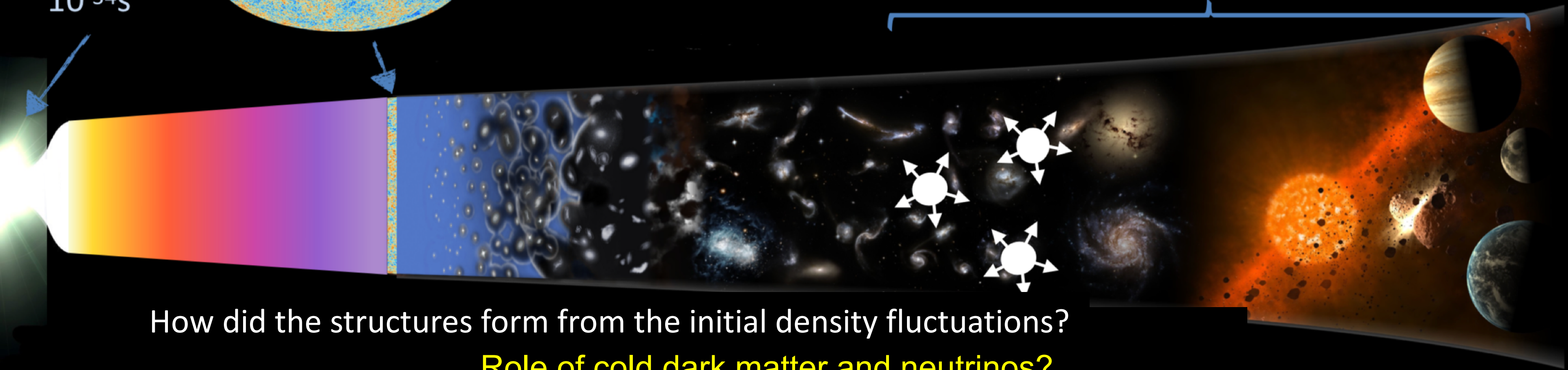
Inflation?

10^{-34}s



What drives the acceleration of the expansion of the universe?

Dark energy?



How did the structures form from the initial density fluctuations?

Role of cold dark matter and neutrinos?

Time

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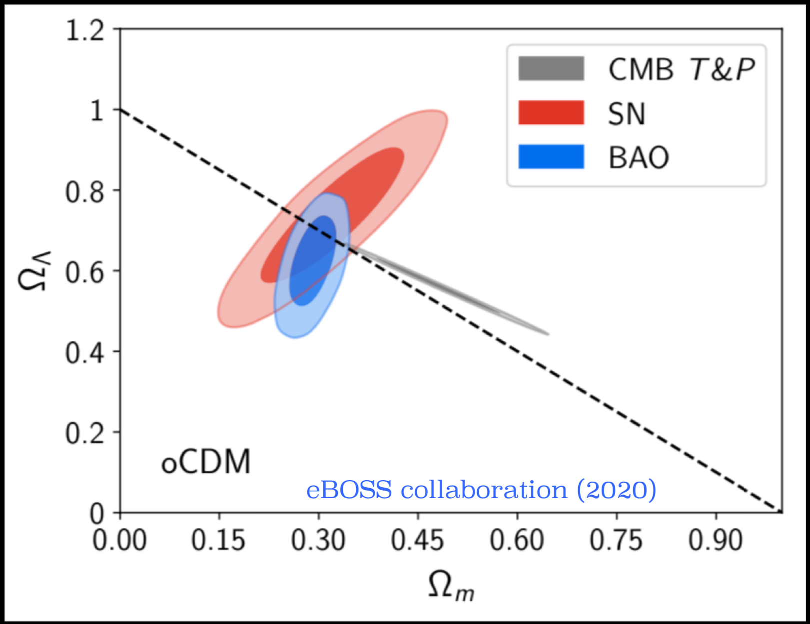
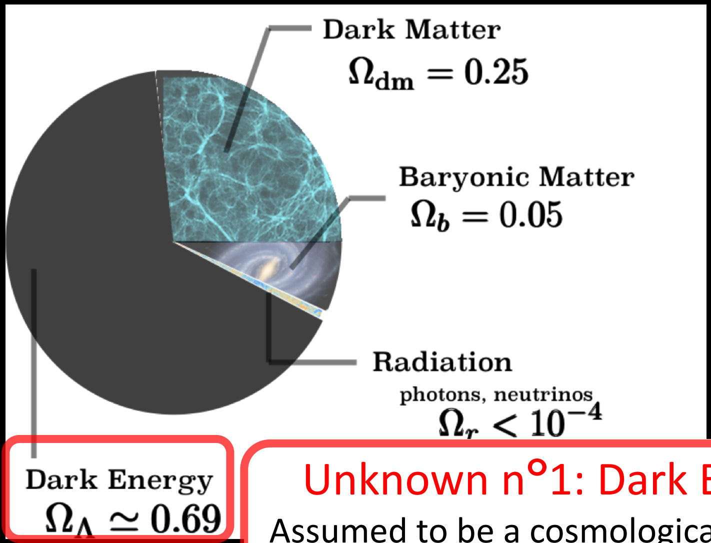
The concordance model
ΛCDM

Different cosmological probes



Today's energy content



Unknown n°1: Dark Energy
Assumed to be a cosmological constant
Equation of state: $w = \frac{p_{DE}}{\rho_{DE}} = -1$

'Dark Energy' approach

What are the properties of dark energy?
→ Measure the evolution of distances across time

'Modified Gravity' approach

Is GR still valid at cosmological scales?
→ Measure the rate at which structures grow by gravitational collapse

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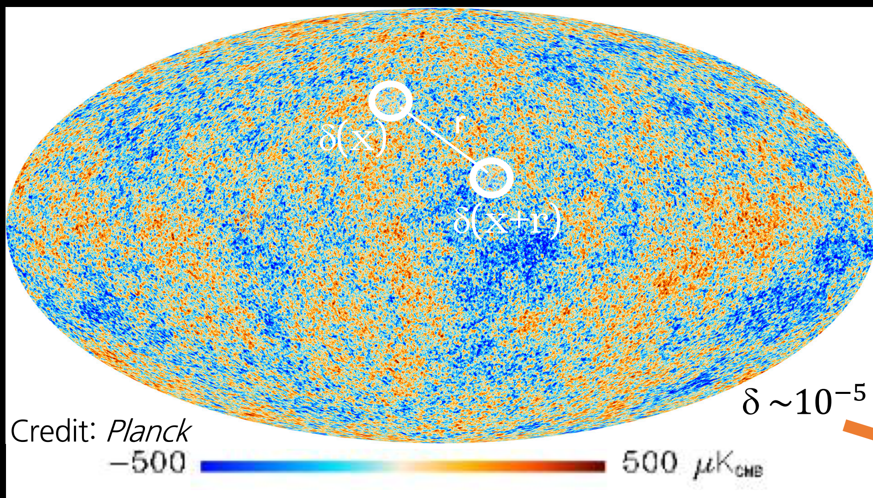
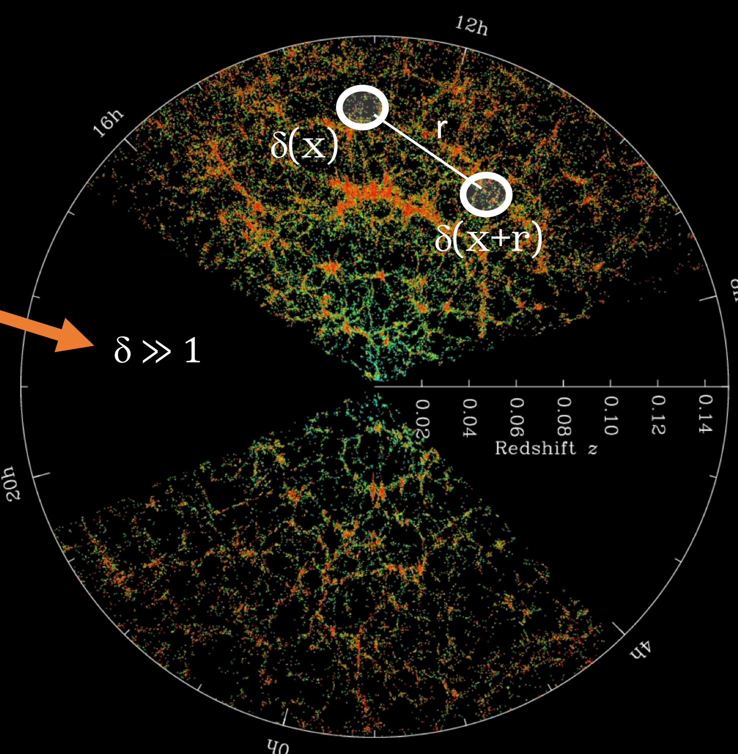
Large-scale structures (LSS)
Clustering analysis



Credit: *Planck*

- Primordial inhomogeneities (CMB)
- Gravitational collapse in an expanding universe



Credit: SDSS I/II

2-point clustering statistics: $\xi(r) = \langle \delta(x)\delta(x+r) \rangle$

→ Statistical tool to quantify the clustering strength

Standard analysis: single-tracer 2pt-statistics up to quasi-linear regime

But there is also a wealth of information:

- in the non-linear regime
- beyond standard single-tracer 2pt-statistics

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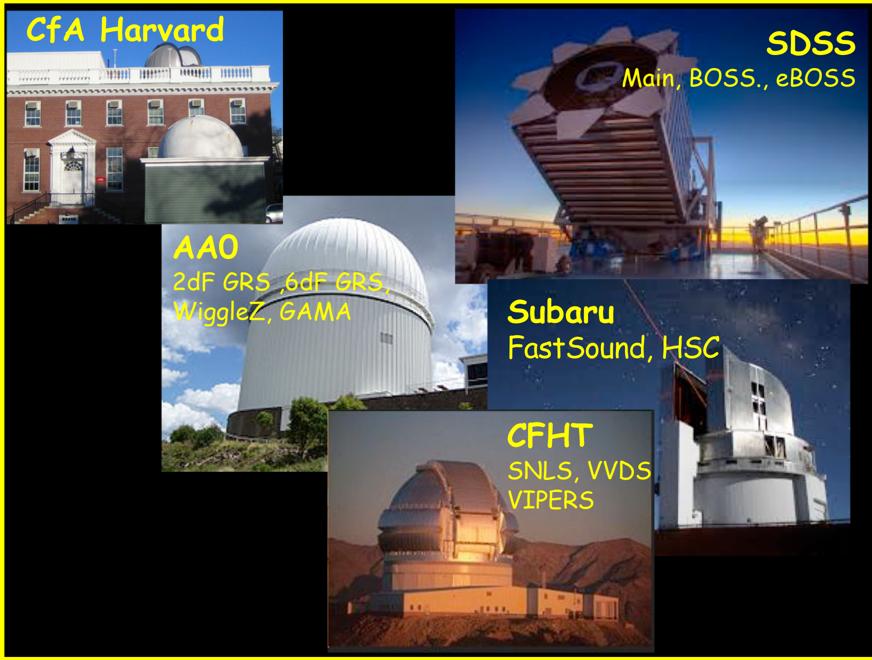
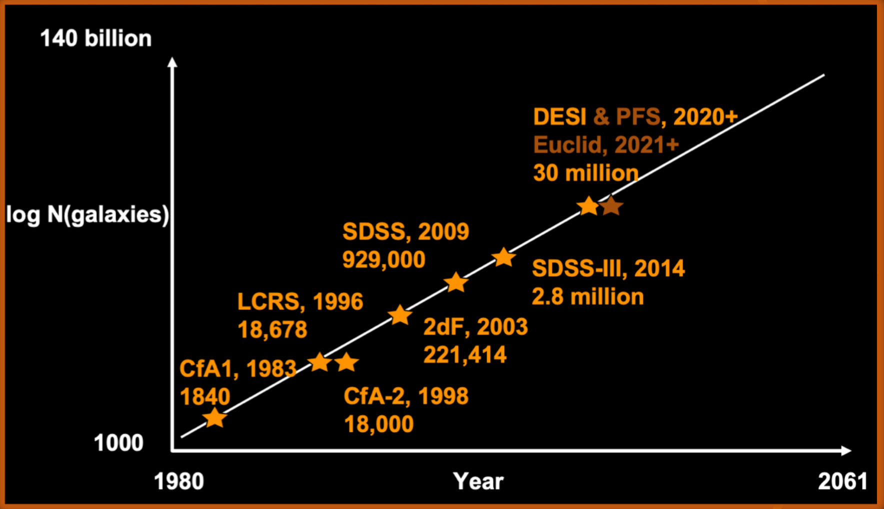
Dark energy experiments
Galaxy surveys

Stage IV: era of precision cosmology





Stage I Stage II ~2008: Stage III

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Dark energy experiments

Galaxy surveys

Stage IV: era of precision cosmology

Stage I Stage II ~2008: Stage III ~2020: Stage IV ~2030: Stage V

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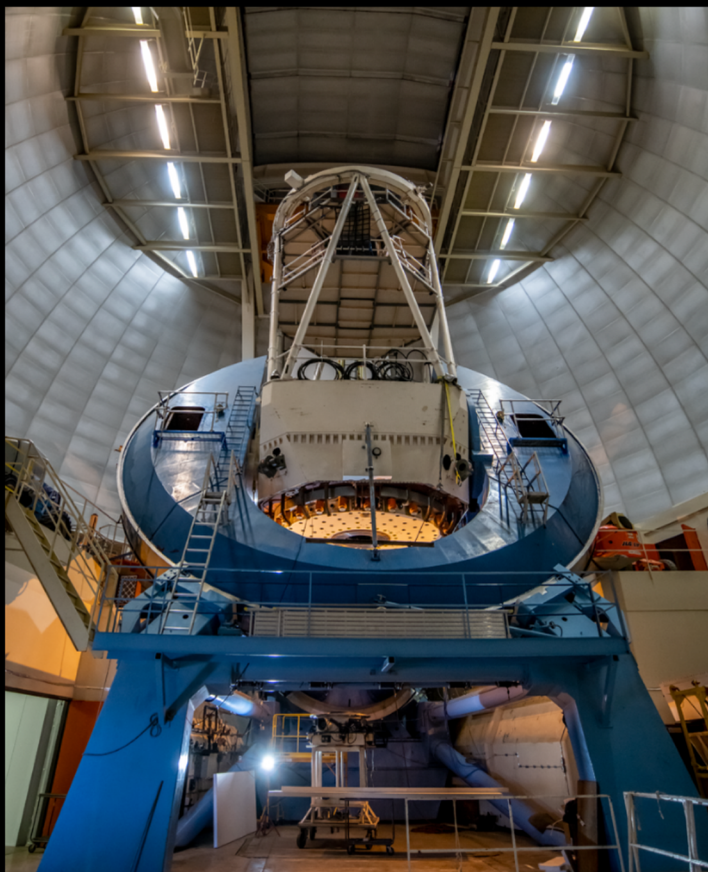
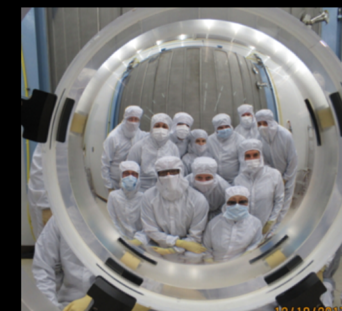
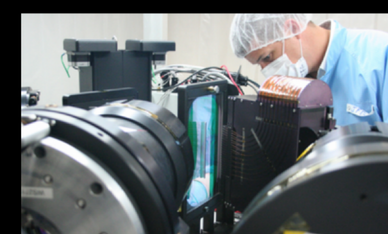
DESI installed on Mayall telescope at Kitt Peak



- Mayall 4m Telescope at Kitt Peak National Observatory
- 6 lens optical corrector with Hexapod
  - ~8 deg^2 FOV
- 5,000 robotic positioners and optical fibers
  - 40m fibers continuous
  - Positioners accuracy ~5μm
- 10 Spectrographs with 3 arms each
  - Wavelength Range: 3600-9800Å
  - Resolution: 2000-5500





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The DESI survey

35 million spectra in 5 years

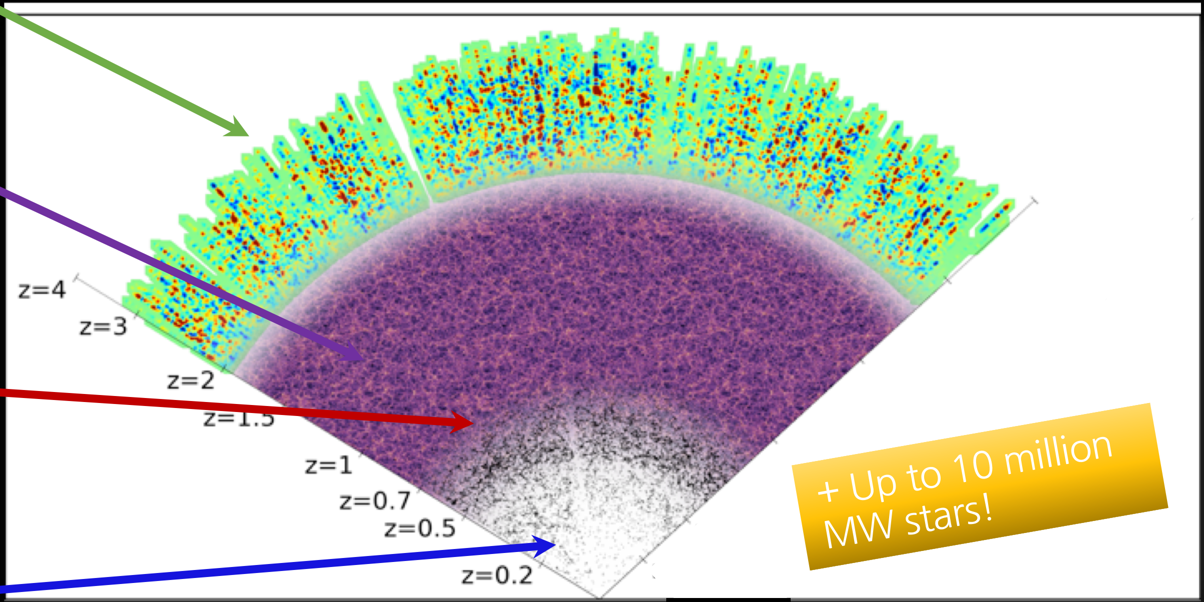
2.5 million quasars/Ly-a forest (1 < z < 3.5)

17 million Emission Line Galaxies (0.6 < z < 1.6)

4 million Luminous Red Galaxies (0.4 < z < 1)

10 million Bright Galaxy Survey (0 < z < 0.5)

DESI survey covers over 14,000 deg^2 in 5 years!



+ Up to 10 million MW stars!

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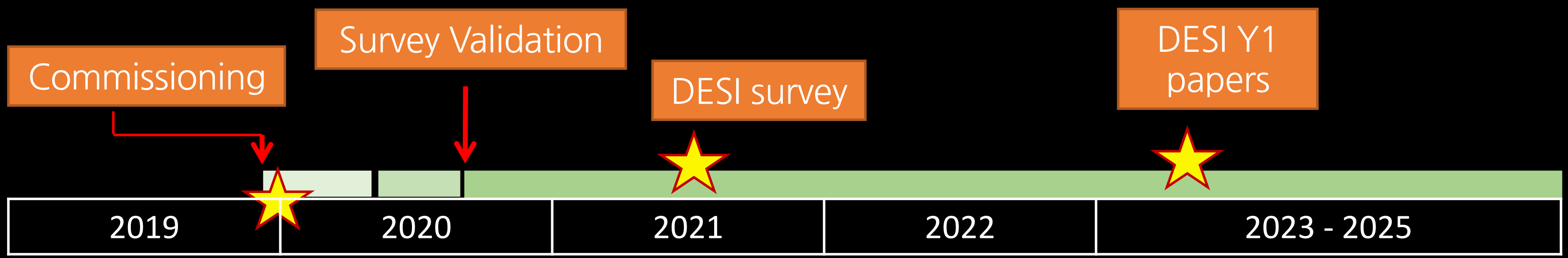
DESI timescale

Scientific data taking ongoing!



- **Start of DESI main survey in May 2021**
- **Key projects using DESI Y1**
  - KP1 and 2: Data release SV and Y1
  - KP3: Large-scale structure catalogues
  - KP4: BAO analysis
  - KP5: Full-shape analysis (co-convenor)
  - KP6: Ly-alpha forest analysis
  - KP7: Cosmological implications

Standard 2pt statistics up to quasi-linear regime

→ **2023: DESI Y1 papers**

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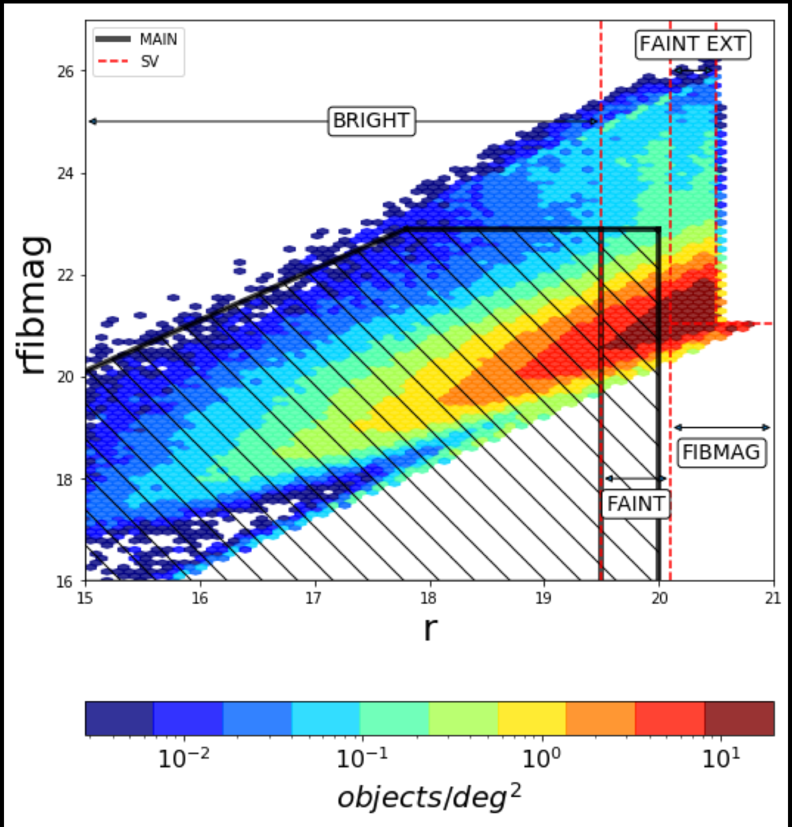
The DESI Bright Galaxy Survey
Overview

You can think about the DESI BGS as SDSS main sample with 2 magnitudes deeper (but lower S/N) and GAMA with 50x the area (but less complete in dense regions)

Goals:

- **Completeness**: > 80% of r < 19.5 galaxies and > 95% redshift success
- **Density**: > 700/deg2 at r < 19.5
- **Footprint**: 14,000 deg^2 (> 9,000) with 3 passes

→ 10 million bright galaxies with r_{mag} < 19.5 in 0 < z < 0.5 with z_{mean} ~ 0.2



Ruiz-Macias, Zarrouk, Cole, Baugh, Norberg et al. 2021

What we tested during SV:

- Exposure time to ensure redshift success rate
- Density, completeness and redshift efficiency and accuracy
- Clustering properties with SV 1%

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The DESI Bright Galaxy Survey

Target selection pipeline

Omar Ruiz-Macias (Former PhD at ICC Durham with S. Cole, P. Norberg, C. Baugh and P. Zarrouk)

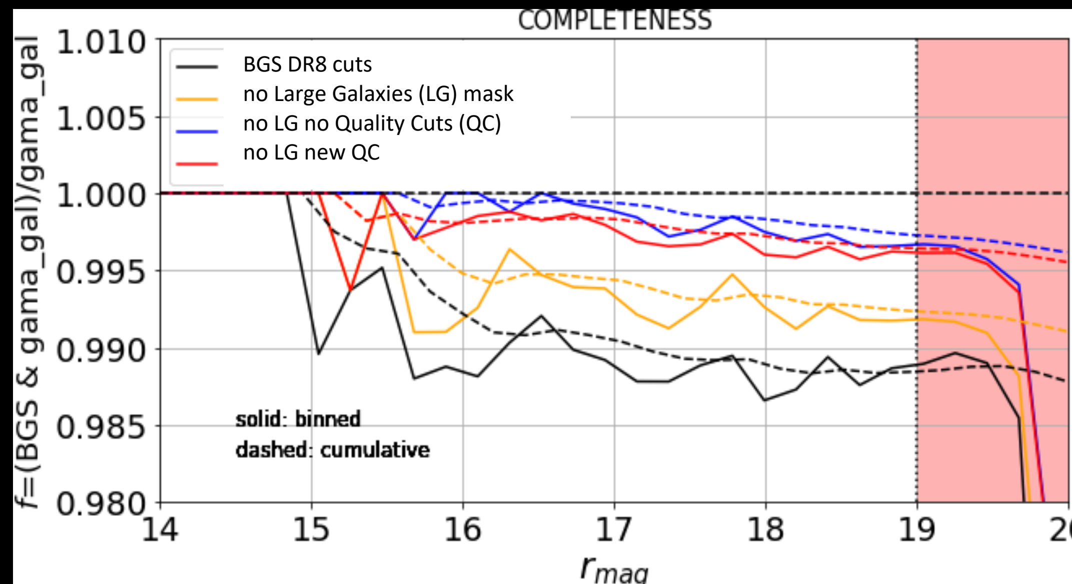
DR9 Legacy Imaging Surveys

↓

Star-Galaxy separation → Spatial masking → Photometric cuts → Quality cuts

↓

BGS Bright (r < 19.5) : 800 /deg^2
BGS Faint (19.5 < r < 20): 600 /deg^2



→ More than 99% complete w.r.t. GAMA on 14 < r_{mag} < 19

Ruiz-Macias, Zarrouk, Cole, Baugh, Norberg et al. 2020
Ruiz-Macias, Zarrouk, Cole, Baugh, Norberg et al. 2021

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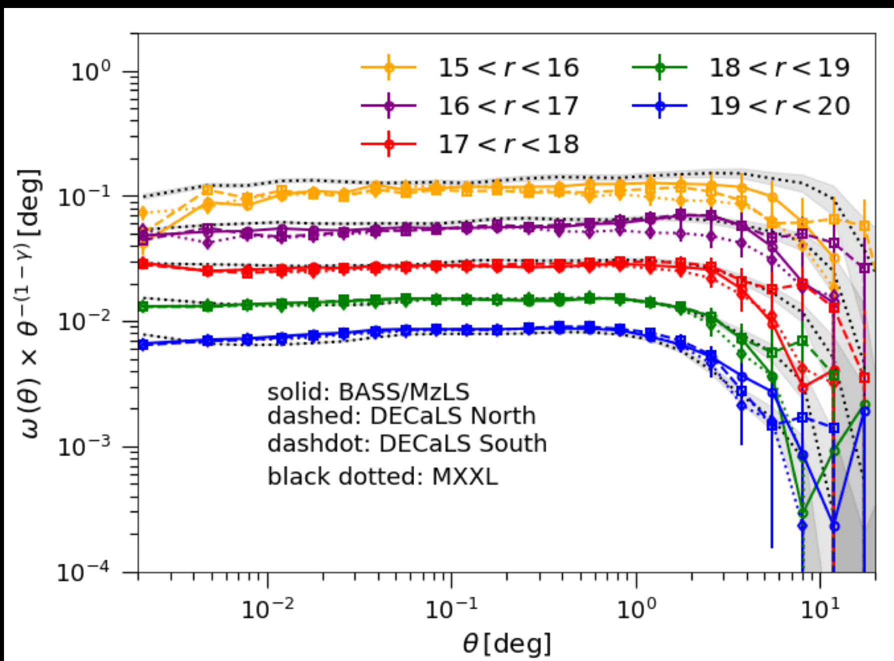
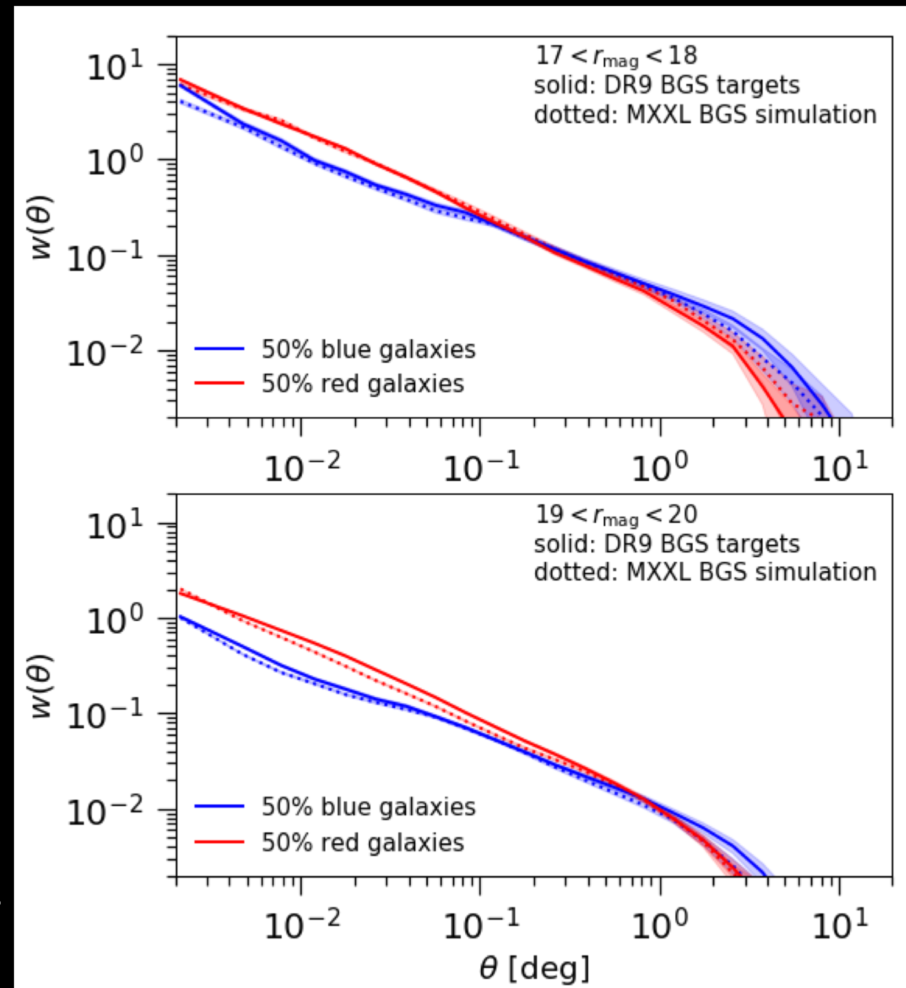
The DESI Bright Galaxy Survey
First clustering properties

As a function of apparent magnitude (left) and colour (right)



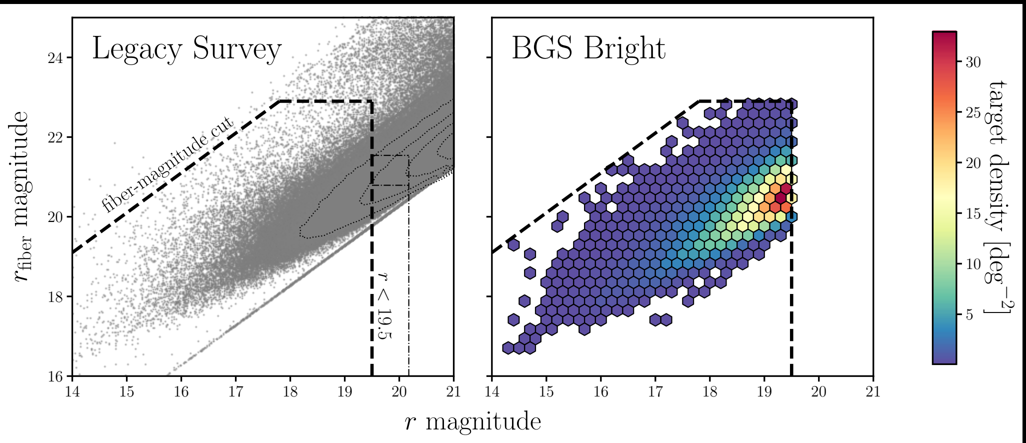


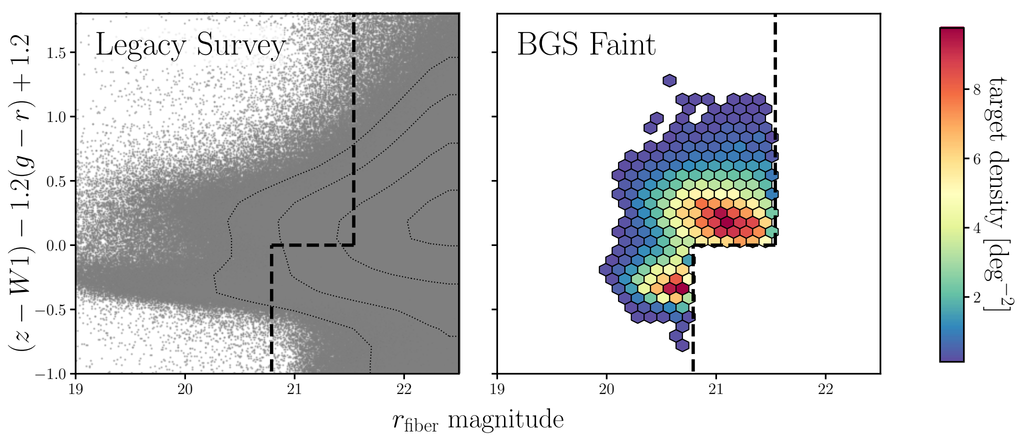
Galaxies with red colours trace an old stellar population while bluer galaxies exhibit higher star formation rates

→ Constrain galaxy formation models

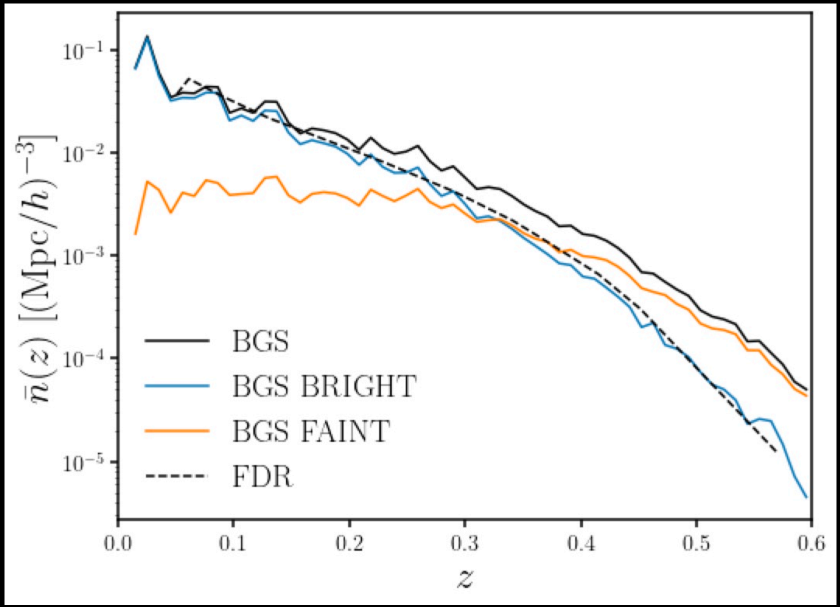
Zarrouk, Ruiz-Macias et al. 2021b

The DESI Bright Galaxy Survey
Final Target Selection





- BGS Bright
- BGS Faint (+ fiber-magnitude and colour cuts)



Hahn, Wilson and the DESI BGS WG (submitted)

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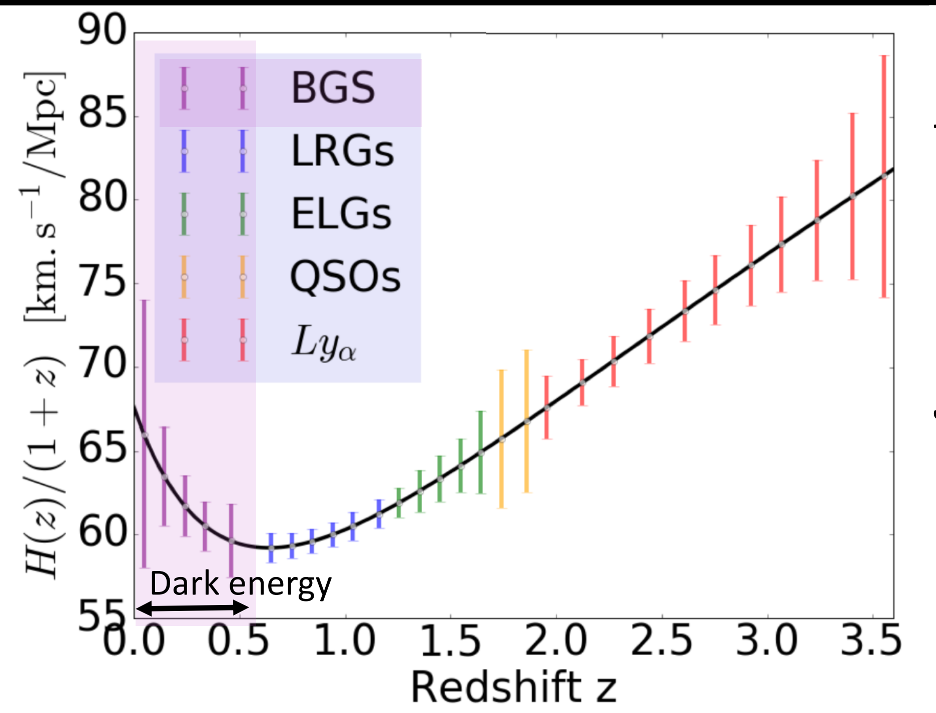
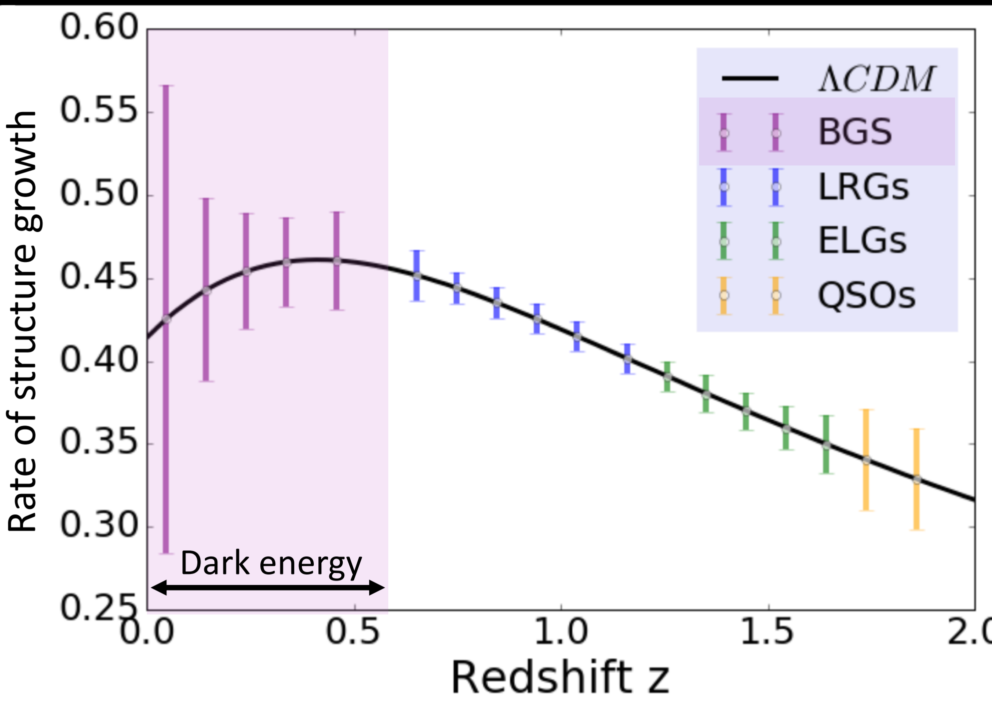
DESI Y5 forecasts

Expansion rate and structure growth





→ Sub-% measurements of cosmic distances

→ Few-% measurements of structure growth

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Key Project 5 (KP5)

Full-Shape 2pt analysis

1) Redshift space distortions (RSD)

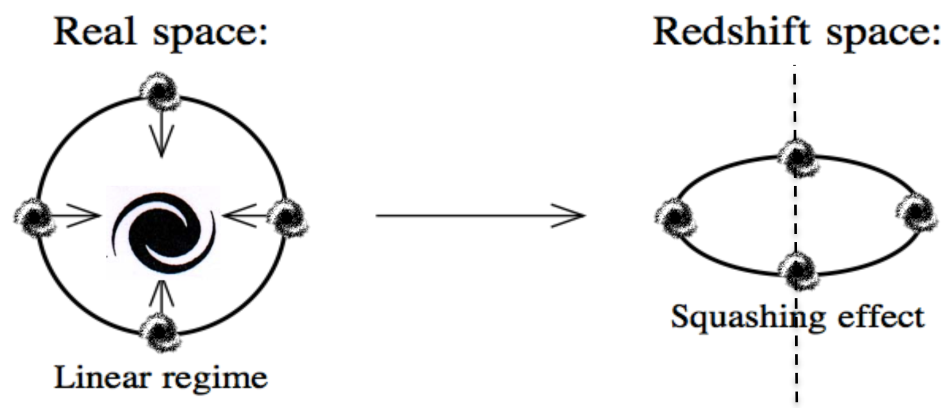
From « real » to « redshift » space

$$\boxed{\mathbf{s}} = \boxed{\mathbf{r}} + \boxed{u_z}(\mathbf{r})\hat{\mathbf{z}}$$

Sensitive to the **growth rate**

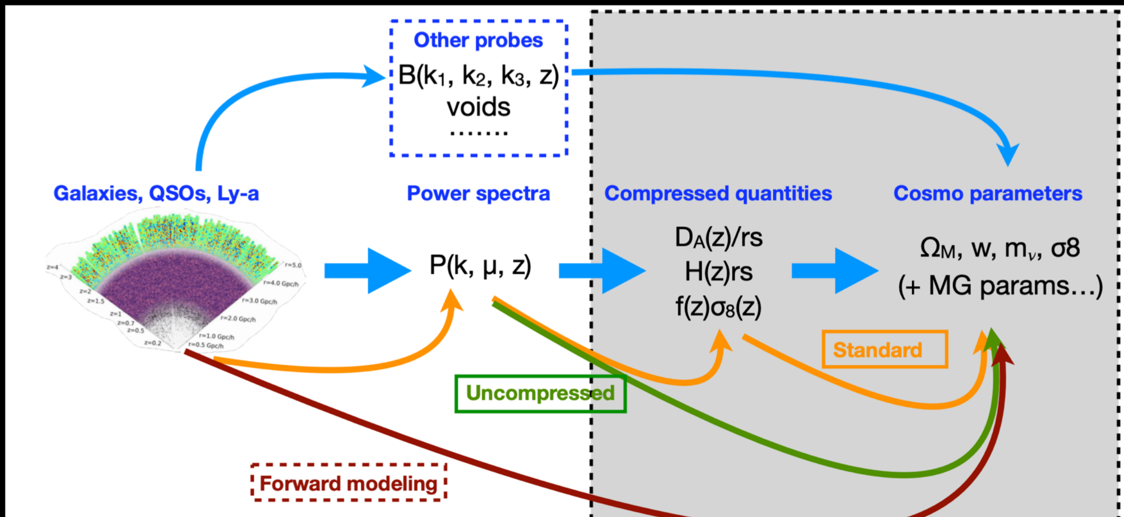
→ direct prediction of GR

$$f(a) = \Omega_m(a)^{\gamma=0.55}$$



2) Compression techniques

→ Can we find an optimal compression of the information contained in 3D galaxy surveys that yields similar constraints as from the uncompressed approach?

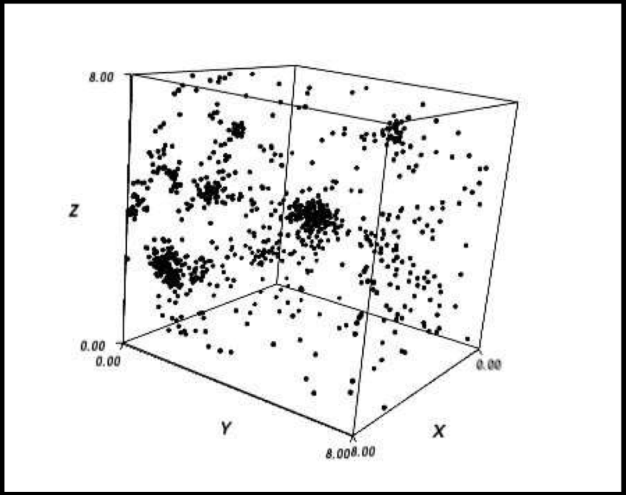


Courtesy: Eva-Maria Mueller / Dragan Huterer (KP7)

3) Primordial non-Gaussianities

Key Project 5 (KP5)
Full-Shape 2pt analysis

Accurate N-body simulations



- Systematics related to the modelling of the 2pt-statistics
- Systematics related to the galaxy-halo connection
- Systematics related to the choice of fiducial cosmology

+ specific issues to each tracer

Approximate simulations

- Systematics related to the observing condition -→ imaging systematics
- Systematics related to the instrument → spectroscopic systematics
- Estimate error bars → covariance matrix

+ specific issues to each tracer

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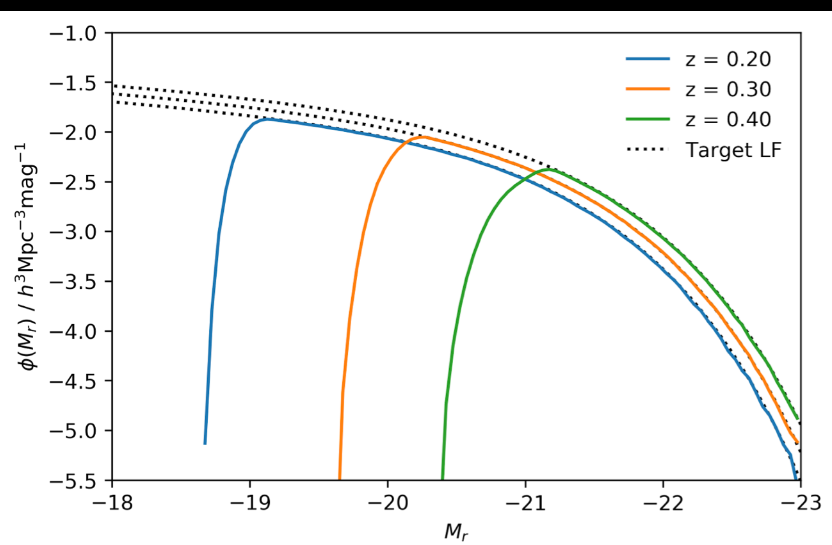
DESI BGS
N-body mocks

MXXL
WMAP1
3 Gpc/h
HOD + evolving LF
Smith et al. (2017, 2022 in prep)

UCHUU
Planck2015
2 Gpc/h
SHAM + evolving LF
Dong-Paez, Smith et al. (2022 in prep)

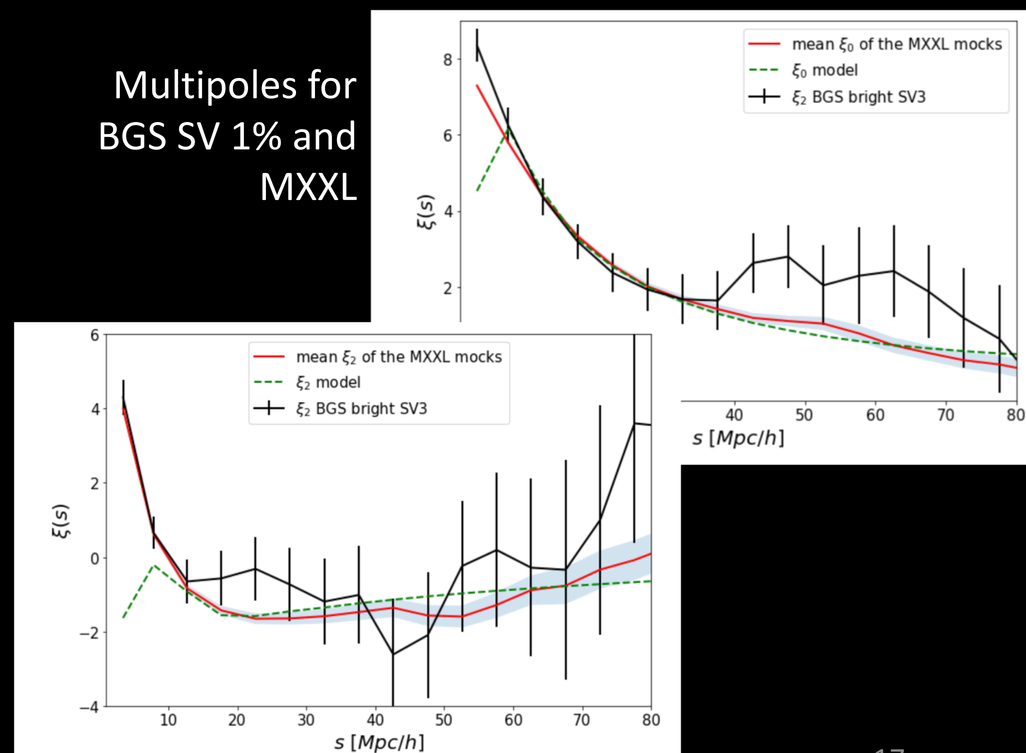
AbacusSummit
Planck2018
2 Gpc/h
HOD + evolving LF
Grove, Smith et al. (2022 in prep)

→ mocks with magnitude and colours



Redshift evolving HOD with target LF from SDSS a(z < 0.15) and Press-Schechter function fit to GAMA (z > 0.15)

Multipoles for BGS SV 1% and MXXL



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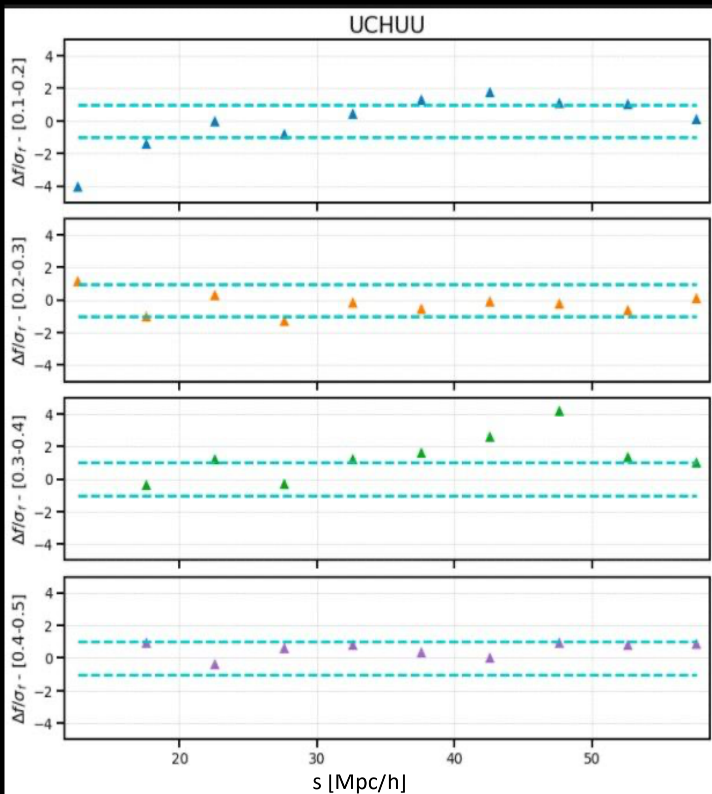
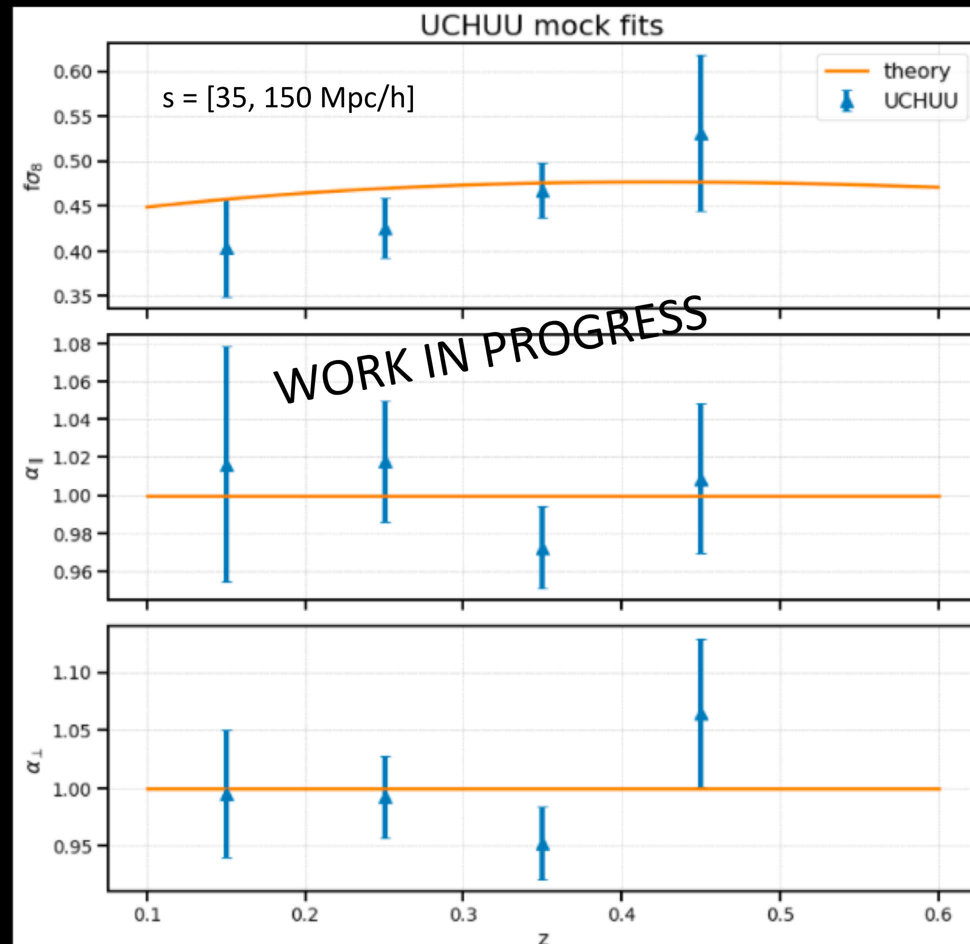
DESI BGS
Full-Shape 2pt analysis

with Svyatoslav Trusov, 1st year PhD student at LPNHE



PT model using velocileptors (*Chen, Vlah & White 2020*)



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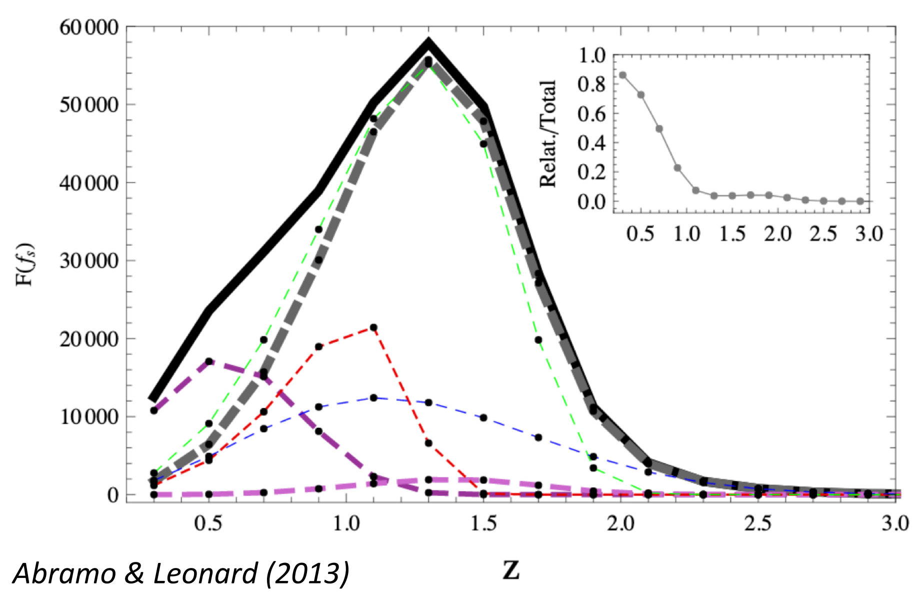
DESI BGS
Multi-tracer analysis

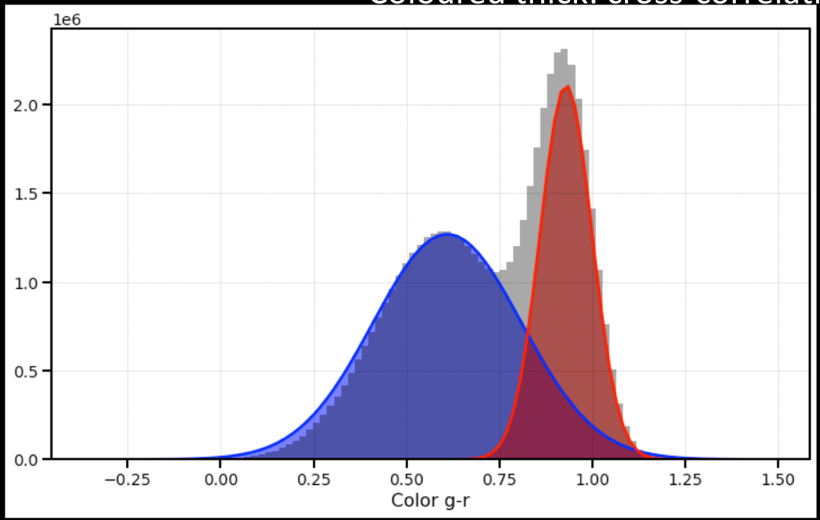
BGS constraints dominated by cosmic variance

→ Multi-tracer *(McDonald & Seljak 2008)* analysis to account for cross-correlations between two samples with different clustering properties and to bypass cosmic variance for the growth rate of structures f



Abramo & Leonard (2013)

Black: multi-tracer
Coloured-thin: single tracer
Coloured thick: cross-correlations



For BGS, split the sample between blue and red galaxies

- Red galaxies $^{0.1}(g-r) > 0.7$
(early-type galaxies at the bright end)
- Blue galaxies $^{0.1}(g-r) < 0.7$
(late-type galaxies at the faint end)

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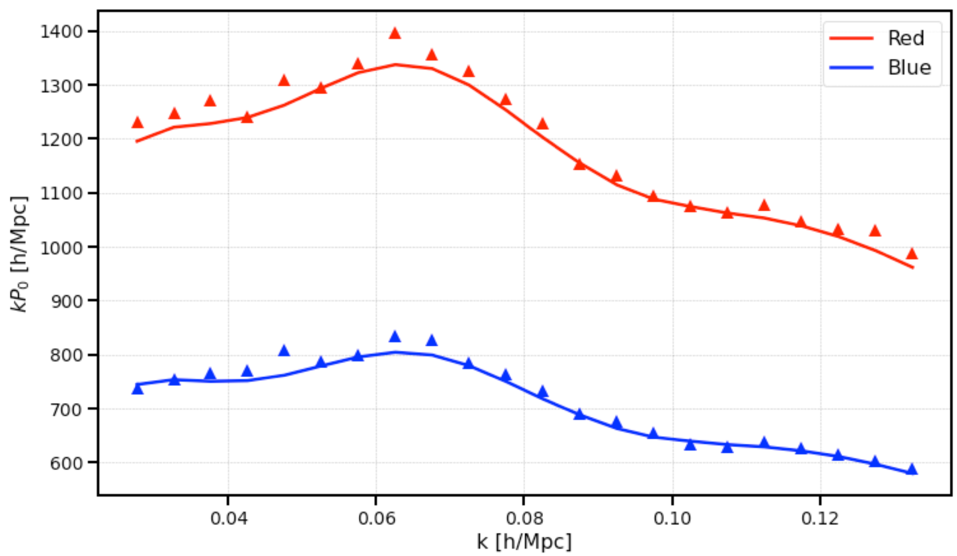
DESI BGS

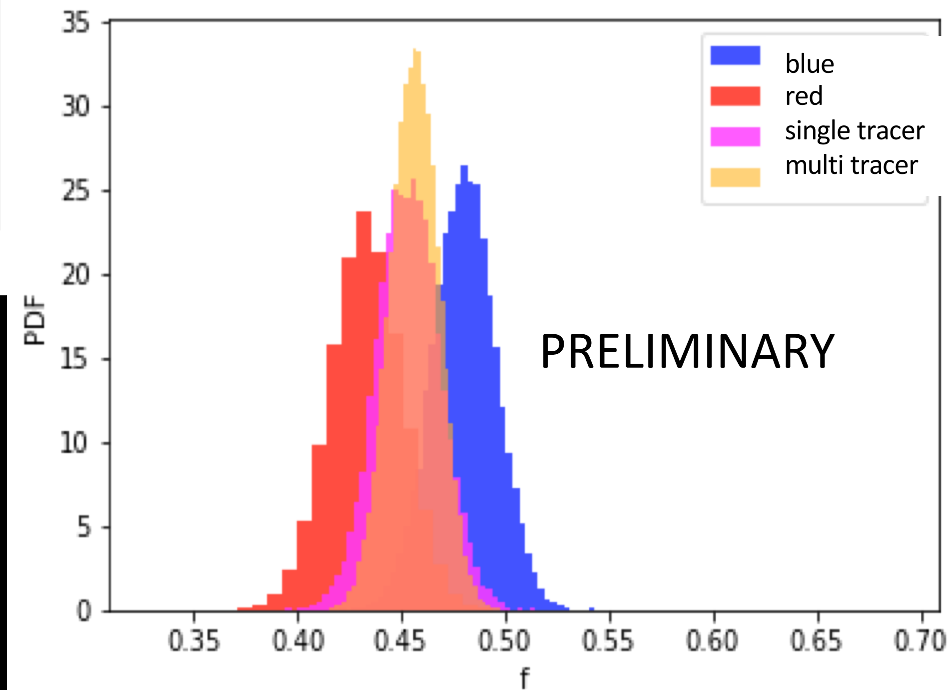
Multi-tracer analysis

Clustering of red and blue galaxies



The bigger the difference between the samples (clustering properties, or bias) - the better.

→ Preliminary tests on MXXL BGS DESI Y5 mock without systematics show 25% improvement on f for multi-tracer w.r.t. single tracer



Next steps:

- add cross CF/P(k) → done
- optimal splitting / weighting
- systematics

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DESI galaxies
Small-scale clustering

Streaming model for 2PCF:

Redshift space correlation function

Real space correlation function

Probability that a pair of galaxies separated by *r* appears to to be at a distance ***s***

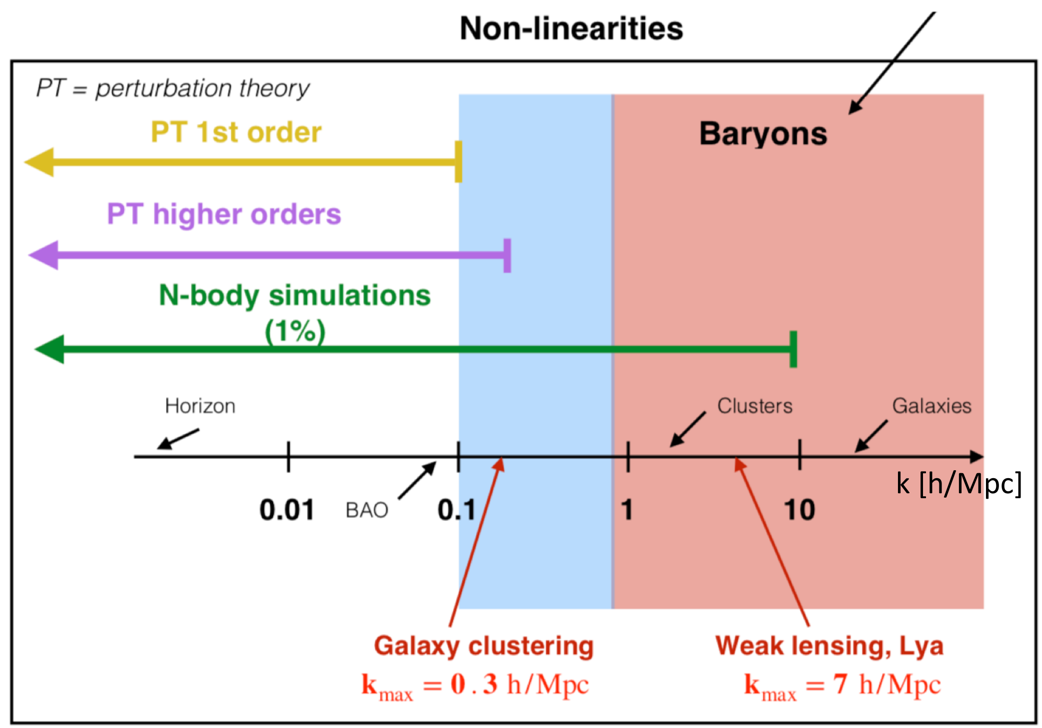
$$1+\xi^s(s_\perp, s_\parallel) = \int_{-\infty}^{\infty} dr_\parallel \, (1+\xi(r))\, \mathcal{P}(v_\parallel = s_\parallel - r_\parallel | r_\perp, r_\parallel)$$

Standard analysis (≥ 25 Mpc/h)

- Gaussian velocity PDF (only 2 moments)
- PT predictions for $\xi(r)$, $v_{12}(r)$, $\sigma_{12}(r,\mu)$
- HOD based on mass only ansatz

Small-scale clustering (1-20 Mpc/h)

- Beyond Gaussian velocity PDF (e.g. skew-t: Cuesta-Lazaro et al. 2020)
- Simulation-based model (neural network based emulator)
- Include assembly bias (secondary dependencies) in HOD



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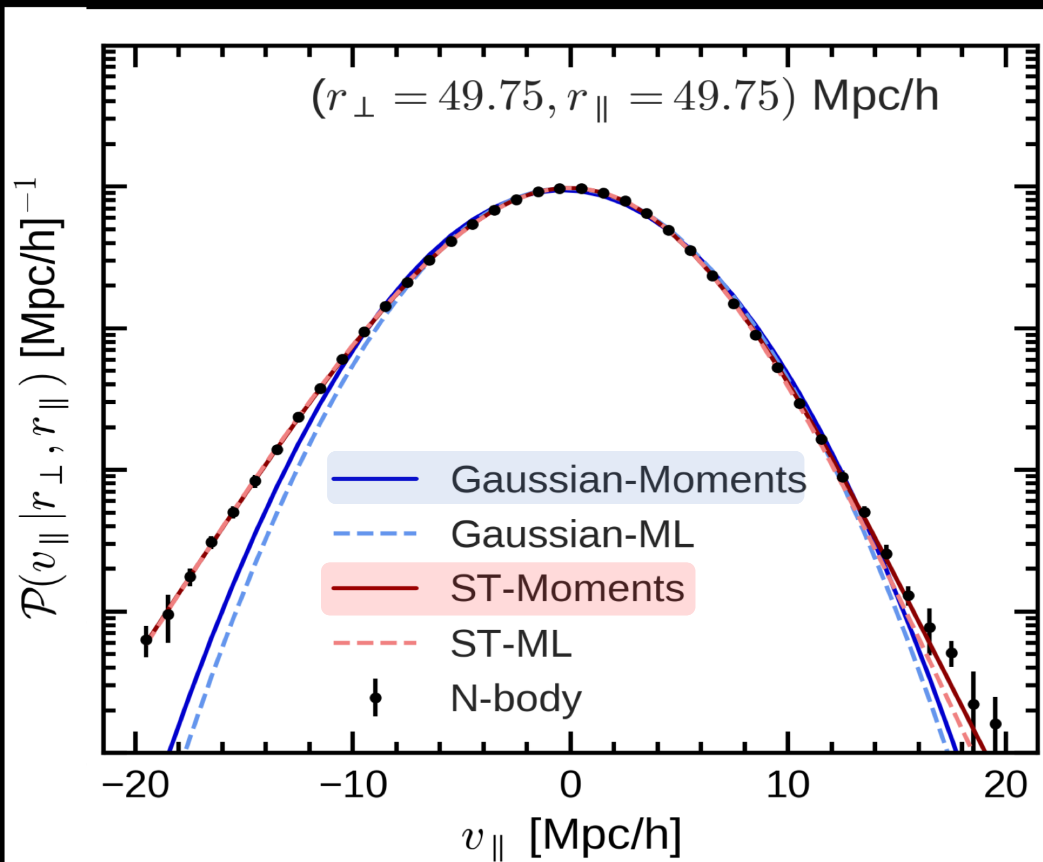
DESI galaxies

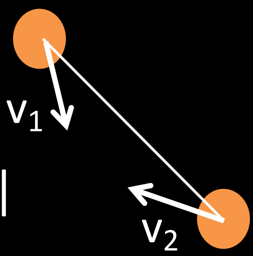
Small-scale clustering

Carolina Cuesta-Lazaro (PhD student at ICC Durham with B. Li, C. Baugh, A. Eggemeier and P. Zarrouk)



Cuesta-Lazaro, Li, Eggemeier, Zarrouk, Baugh et al. 2020

Pairwise infall velocity



$v_{12}(r) = (\mathbf{v_2} - \mathbf{v_1}) \,.\mathbf{r} \,/\, |\mathbf{r}|$

- **Gaussian**: the Gaussian case reproduces the multipoles within 1σ for s > 30 Mpc/h while it gives a very poor fit to the pairwise velocity PDF
- **Skew-t (with skewness and kurtosis)** correct and accurate predictions down to 10 Mpc/h

→ Extension of the validity of the Streaming Model to smaller scales

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DESI galaxies

Small-scale clustering

Step 1: Develop a simulation-based model (emulator) for galaxy 2PCF based on Neural Network using Dark Quest simulations - $N_{part}=2048^3$, L_{box}=2 Gpc/h (LR), 3 Gpc/h (HR) -

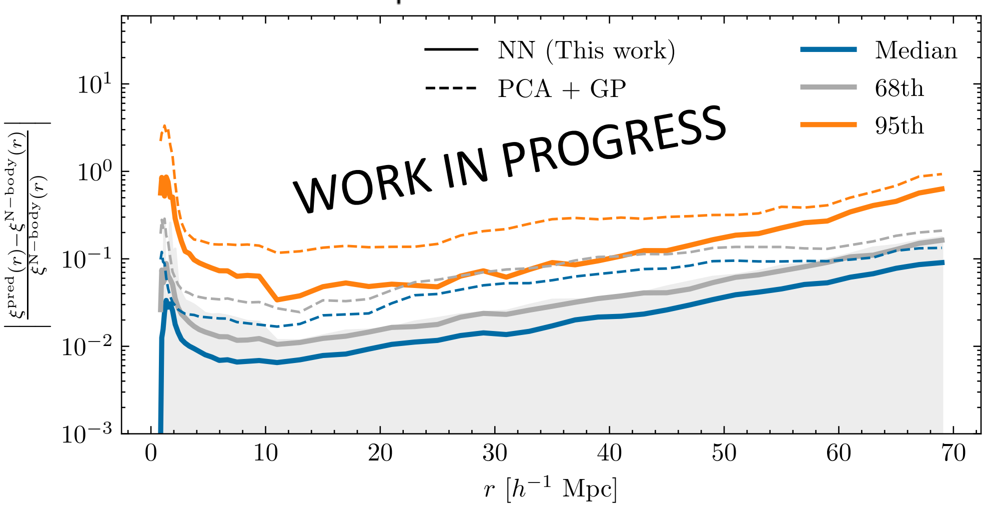
Step 2: Adjust / Apply this emulator on DESI Y1 data

$$1+\xi^S(s_\perp, s_\parallel) = \int dr_\parallel \left(1+\xi^{\mathrm{R}}(\mathbf{r})\right) \mathcal{P}(\mathbf{v}_\parallel = \mathbf{s}_\parallel - \mathbf{r}_\parallel | \mathbf{r}_\perp, \mathbf{r}_\parallel)$$

- Halo properties using low resolution simulations
- Halo mass function, c(M) using high resolution simulations

Described by **four** parameters

How do these vary with cosmological parameters on small scales?



- **Flexibility:** Vary galaxy tracers, and their cross-correlations. Marginalising over g requires flexible g!

Neural Net

$$\xi^S_{gg}(\vec{s}|\vec{c},\vec{g},z) = \mathcal{G}(\xi^S_{hh}(\vec{s}|\vec{c},z),\vec{g})$$

Analytical

- ~~1% accuracy~~ **1-sigma accuracy:**
  - Emulator only as good as data used for training
  - Simplify input/output relation through physical models

$$\xi^S_{hh} = F(\xi^R_{hh}(r|\vec{c}), v^i_{hh}(r|\vec{c}))$$

→ NN-based emulator for real space 2PCF performs better than previous Dark Quest emulator (Nishimichi et al. 2021) based on PCA and GP

Cuesta-Lazaro et al. 2022a in prep

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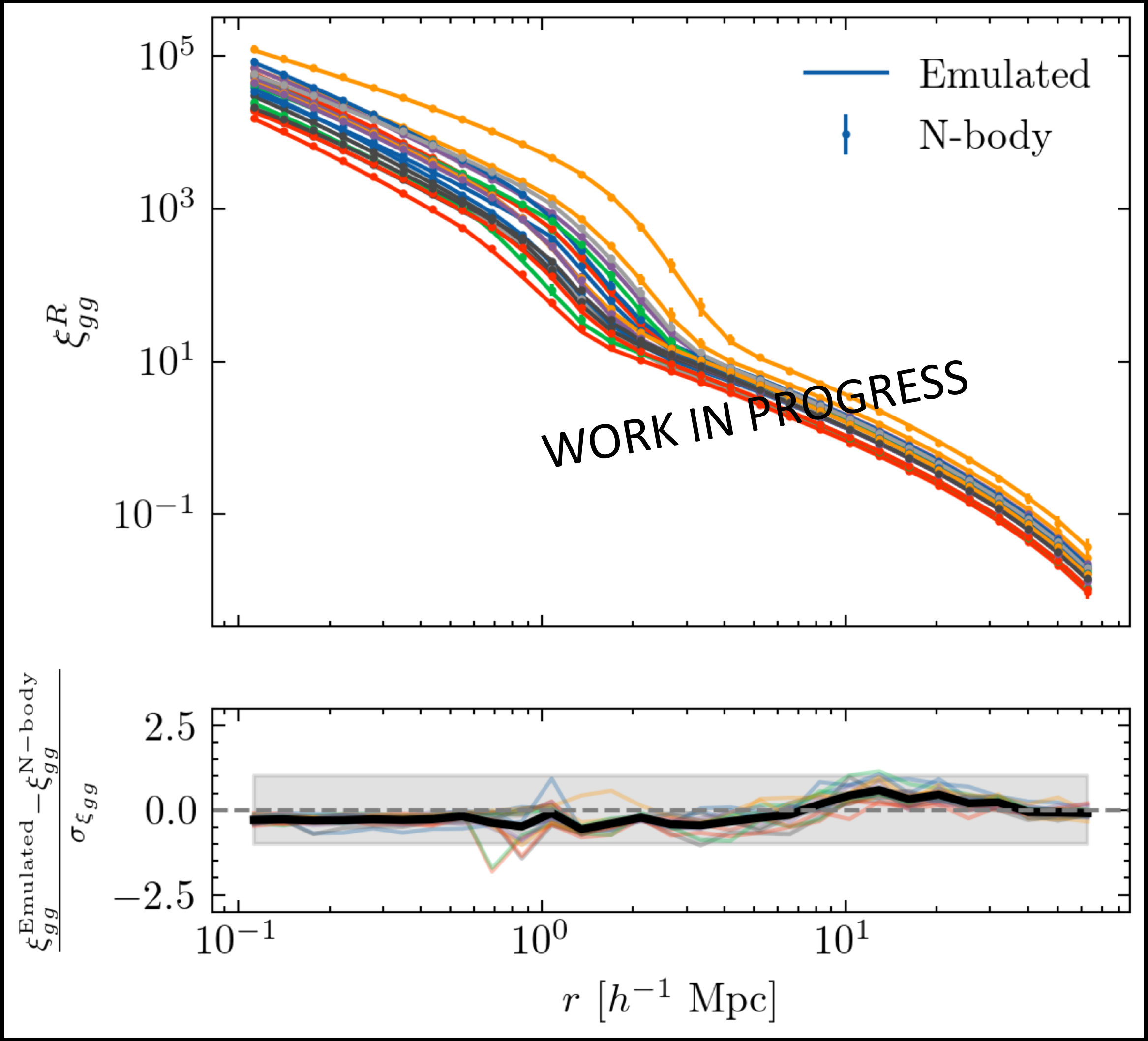
DESI galaxies
Small-scale clustering

Emulated real galaxy 2PCF compared to N-body results



Cuesta-Lazaro et al. 2022b in prep

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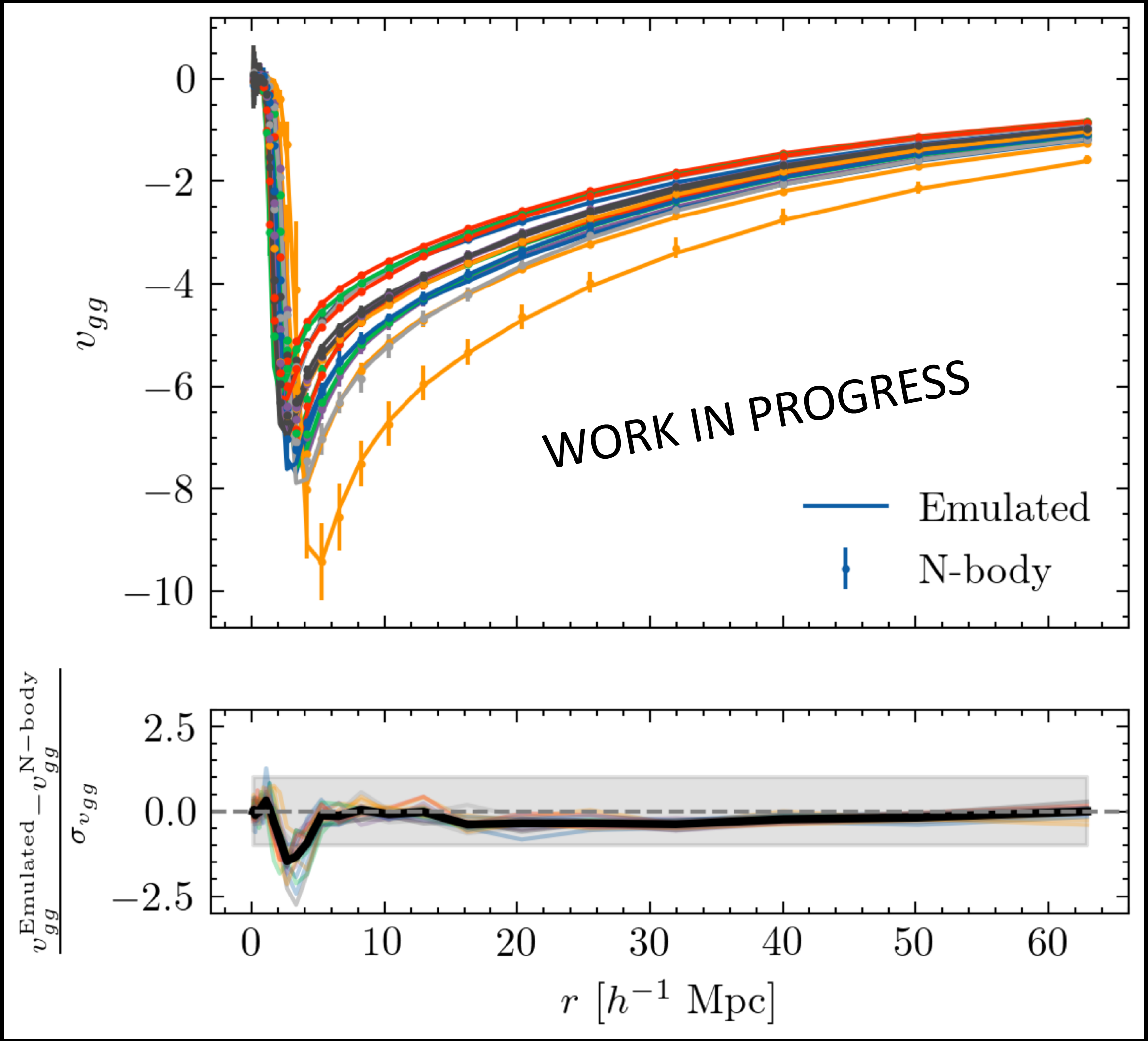
DESI galaxies
Small-scale clustering

Emulated galaxy pairwise infall velocity compared to N-body results



Cuesta-Lazaro et al. 2022b in prep

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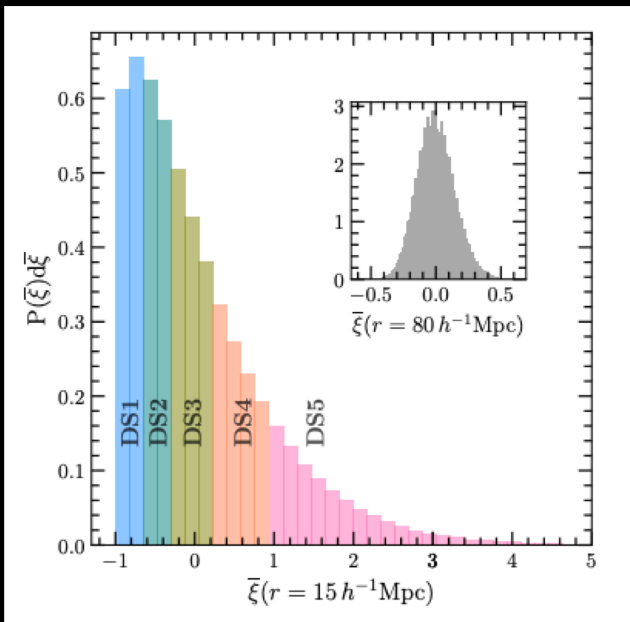
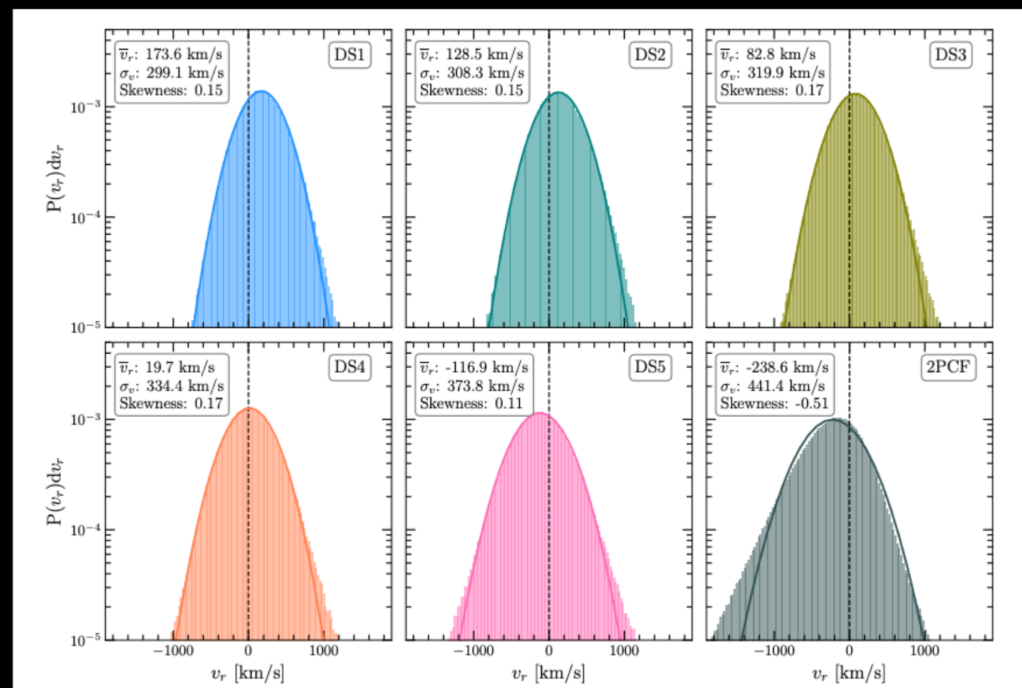
DESI galaxies
Density-split method



1. Split the galaxy field into multiple density environments, here 5 quantiles or density splits (DS)
2. Measure and model the cross-correlation function (CCF) between each density environment and the entire redshift-space galaxy field



- Method applied to mock galaxies with Gaussian Streaming model (GSM)

→ peculiar velocities PDF in each split density nearly Gaussian

→ GSM more accurate at all scales

Paillas et al. (2021)

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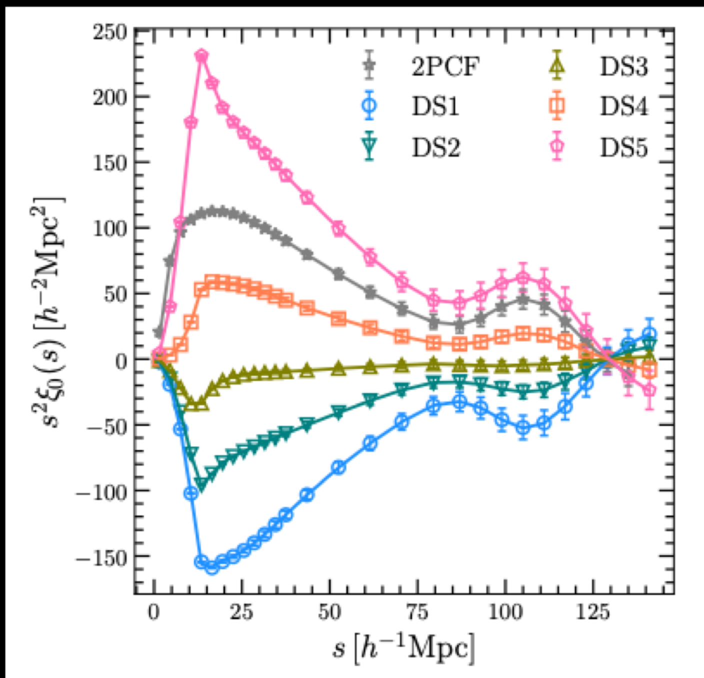
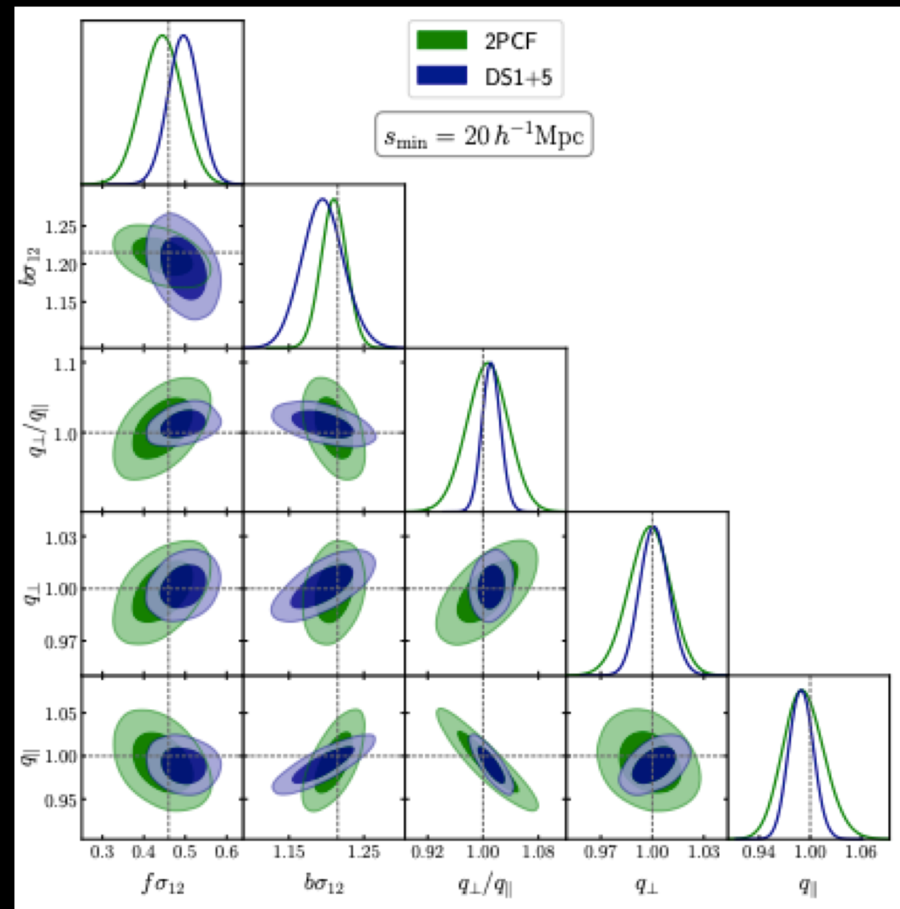
DESI galaxies
Density-split method

Monopole of the redshift space CFs



→ 30% improvement on the growth rate of structures over 2PCF

Paillas et al. (2021)



→ Ongoing DESI project: extend the emulator for the 2PCF to density-split CCF using AbacusSummit simulations and apply the method to DESI Y1 galaxies

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Conclusions

→ Exciting science opportunities with DESI

My particular interests: precision cosmology, tests of gravity, structure formation / galaxy-halo connection

- Bright Galaxy Survey (BGS): magnitude-limited sample of 10 million galaxies brighter than r=19.5, with $0 < z < 0.5$ and z_{mean} ~0.2
- BGS Target selection: star-galaxy separation + spatial masking + quality cuts

BGS DR8 *TS: Ruiz-Macias, Zarrouk et al. (2020, 2021)*

BGS DR9 TS and first clustering properties: Zarrouk et al. (2021)

BGS final TS paper (submitted)

- Scientific analyses with DESI Y1
    - Standard methods: BAO and Full-Shape 2-point statistics (KP4/5)
    - Multi-tracer analysis
    - Small-scale clustering
    - Environment-dependent clustering
    - But also forward-modelling approach with Bayesian inference

Thank you for the invitation again and for your attention!

Visiting Berkeley: June 13-25