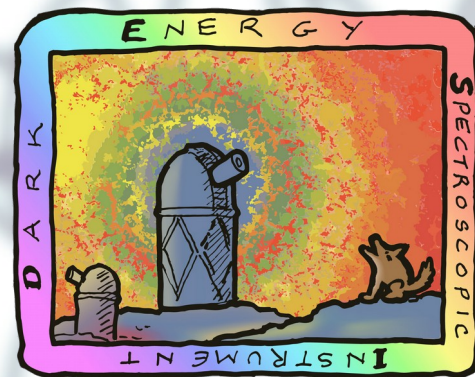


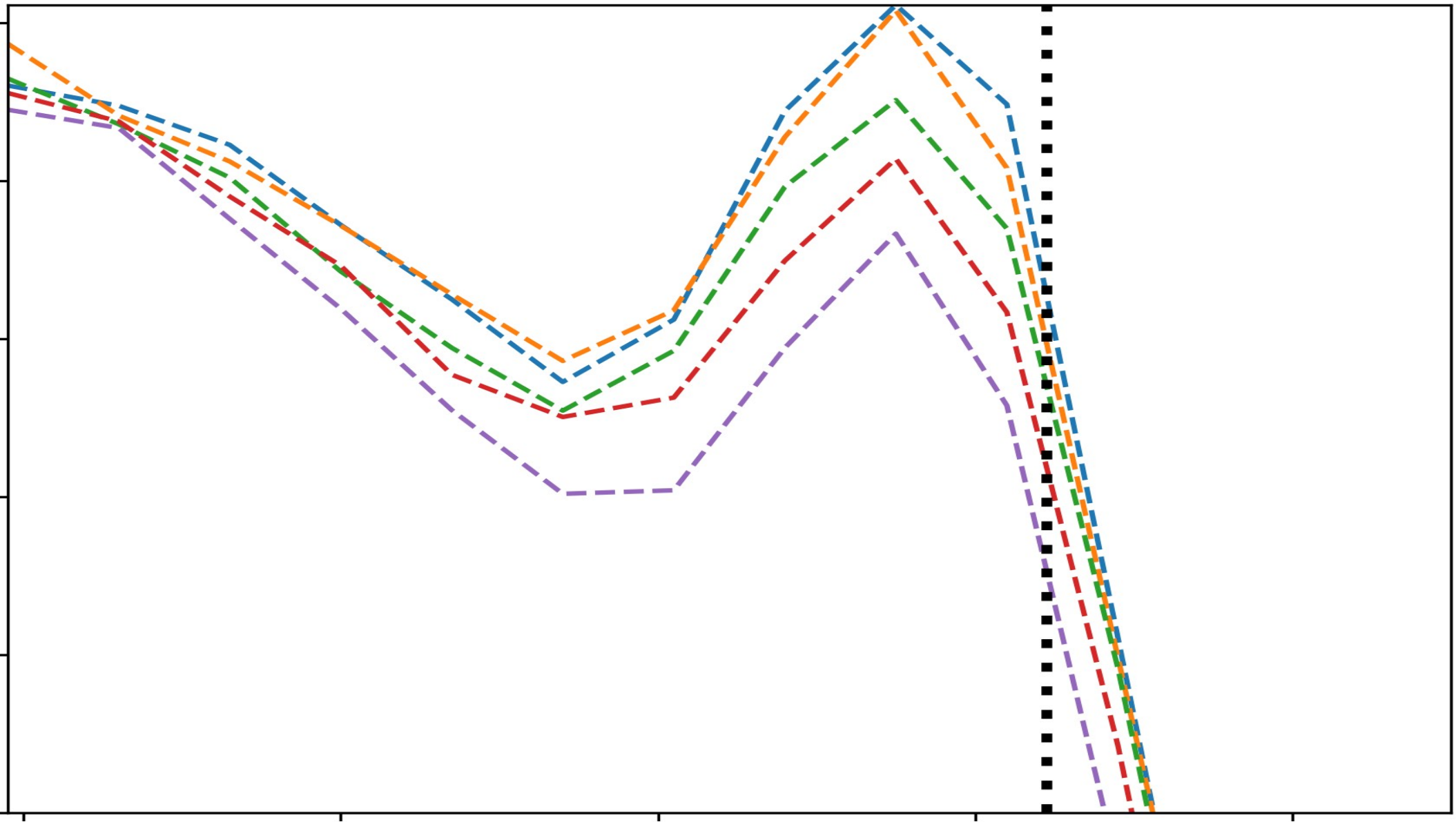
# Studying the BAO peak with more than just spectroscopic data

by  
**Christoph Saulder**



**한국천문연구원**  
Korea Astronomy & Space Science Institute







# Collaborators



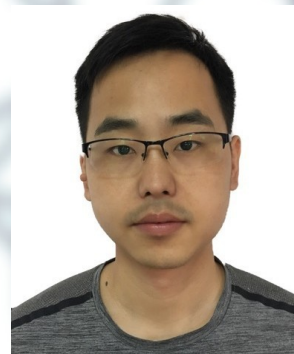
**Yong-seon  
Song**  
(KASI)



**Minji Oh**  
(Chosun  
University)



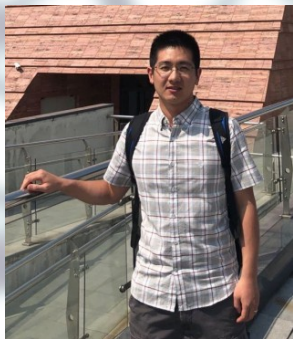
**Yi Zheng**  
(SYSU)



**Feng Shi**  
(Xidian  
University)



**Srivatsan  
Sridhar**  
(formerly KASI)



**Zhijie Ding**  
(SJTU)



**Rongpu Zhou**  
(University of  
Pittsburgh)



**Ashley Ross**  
(Ohio State  
University)



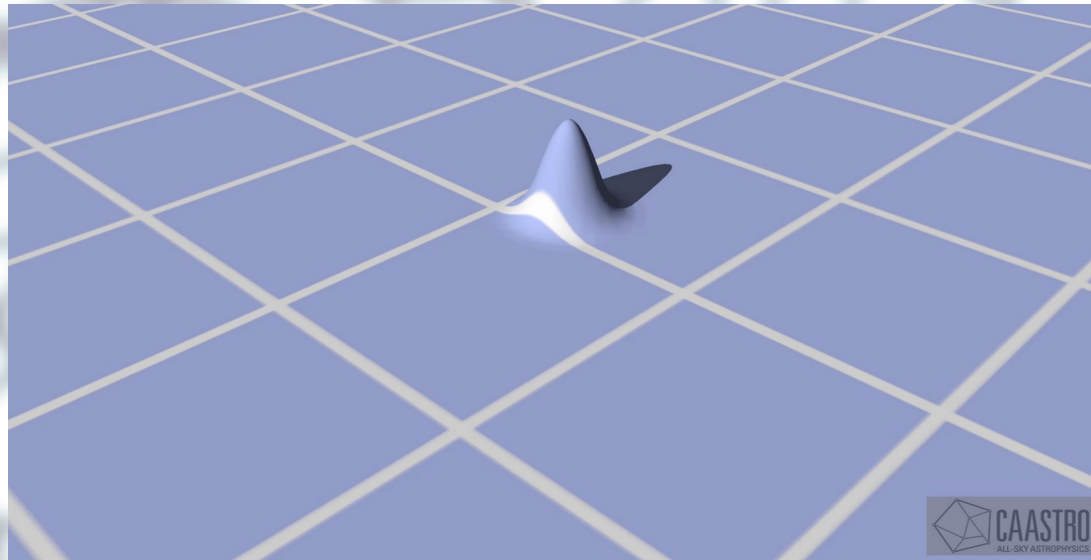
**Jeffrey Newman**  
(University of  
Pittsburgh)



**Chia-Hsun Chuang**  
(Stanford  
University)

# What is the BAO (peak)?

- Baryonic Acoustic Oscillations





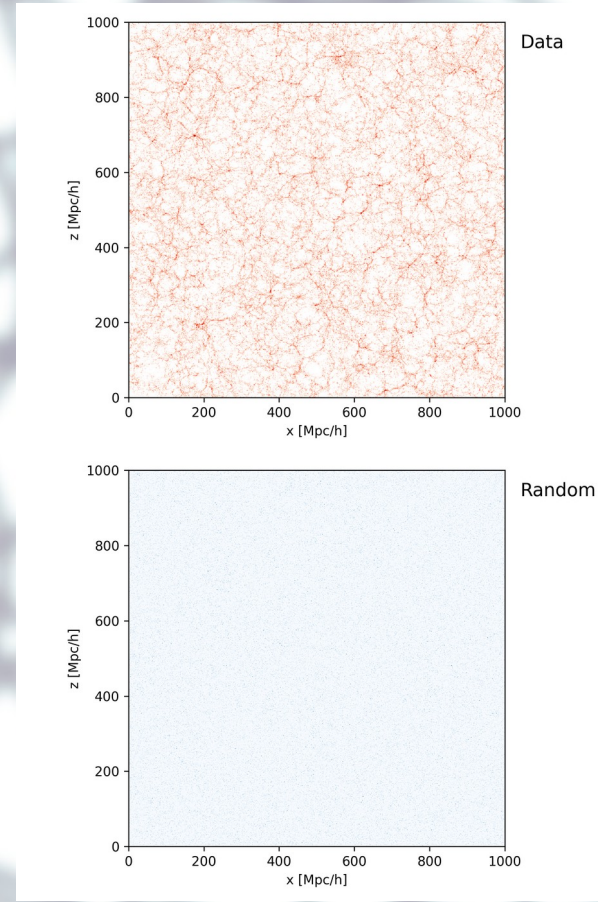
# Measuring the BAO in configuration space

- Fast codes like corrfunc
- → number counts DD, DR, RR as a function of separation

- Estimator for correlation function:

$$\xi_{LS} = (\text{DD} - 2 * \text{DR} + \text{RR}) / \text{RR}$$

(Landy-Szalay estimator)



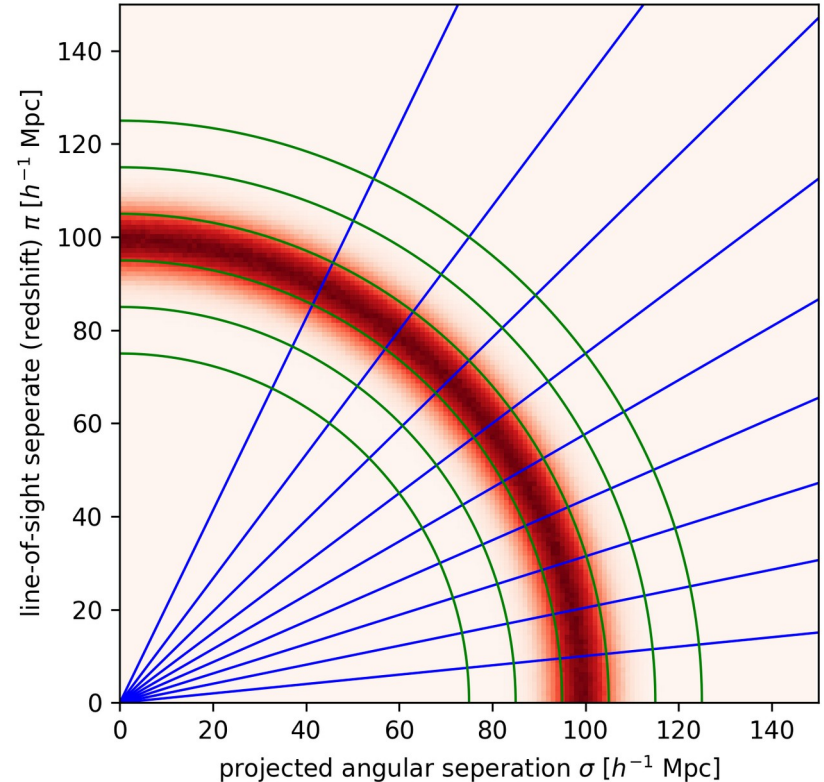
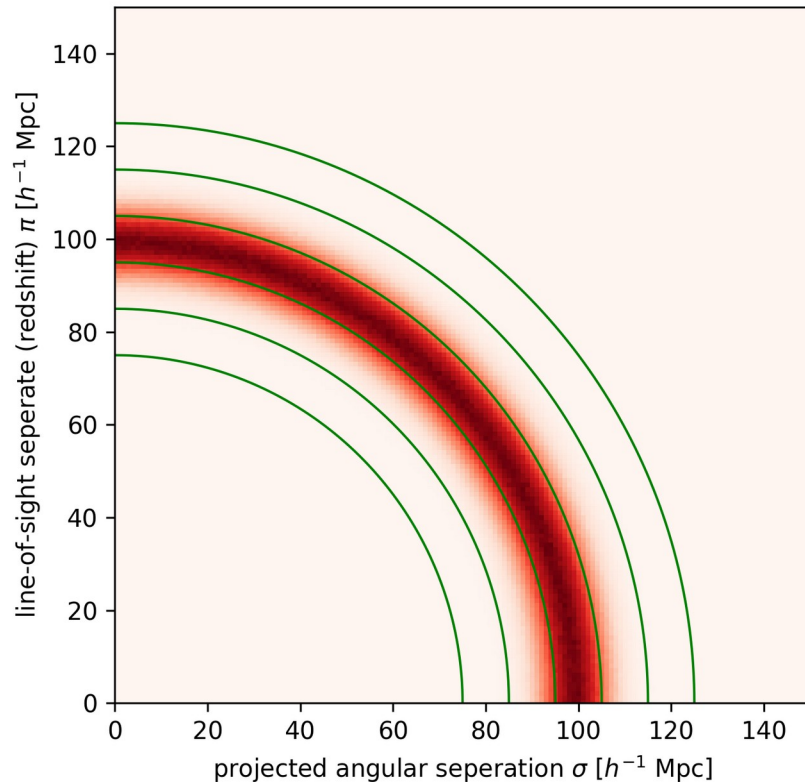


# Anisotropic correlation function

isotropic  $\xi(s)$

$$s^2 = \pi^2 + \sigma^2$$
$$\mu = \pi/s$$

anisotropic  $\xi(s, \mu)$

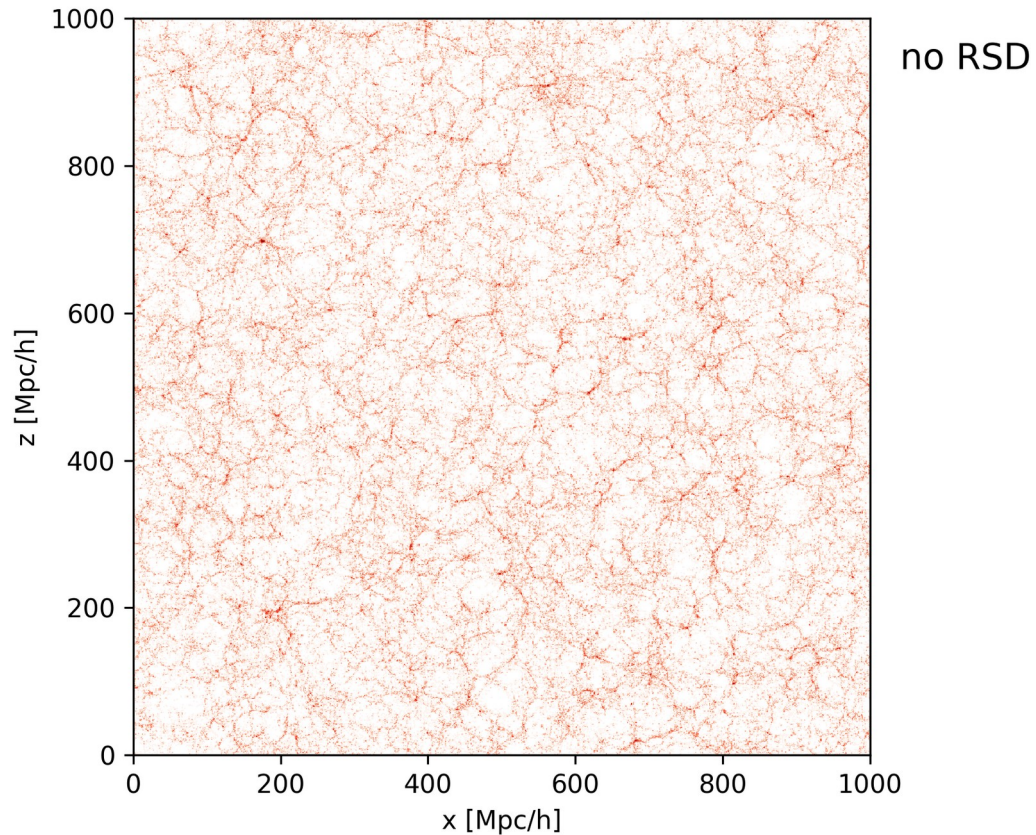


# Redshift distance relation

- Ideally: perfect correlation between redshift and distance
- In practice:
  - Redshift space distortions due to peculiar motions
  - Uncertainty of redshift measurements
    - Relatively small for spectroscopic redshifts
    - **But huge for photometric redshifts (!)**

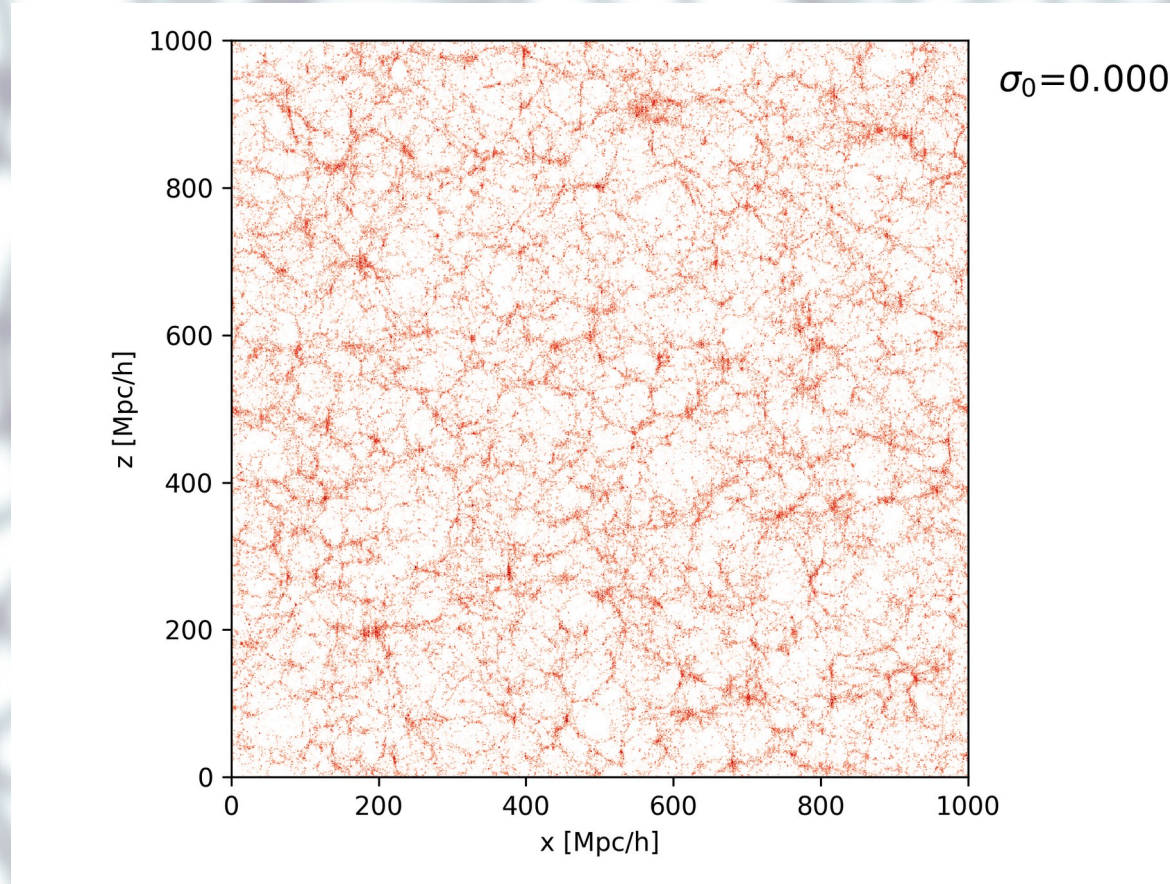


# Photometric redshifts washes out clustering features

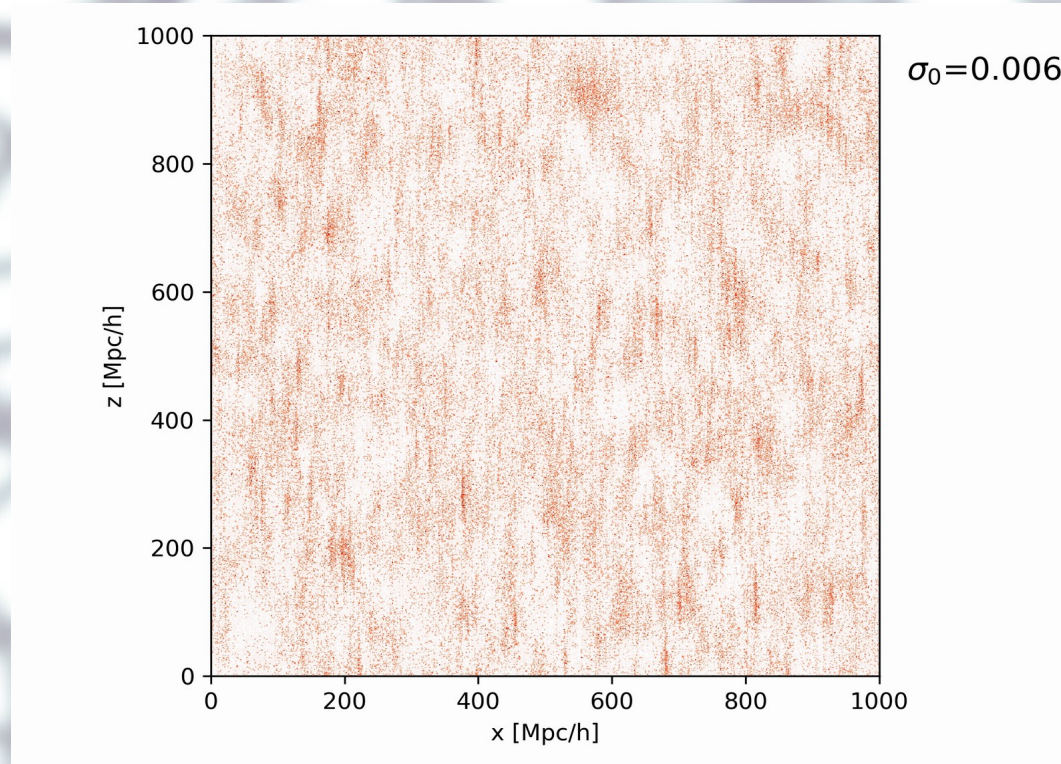




# Photometric redshifts washes out clustering features

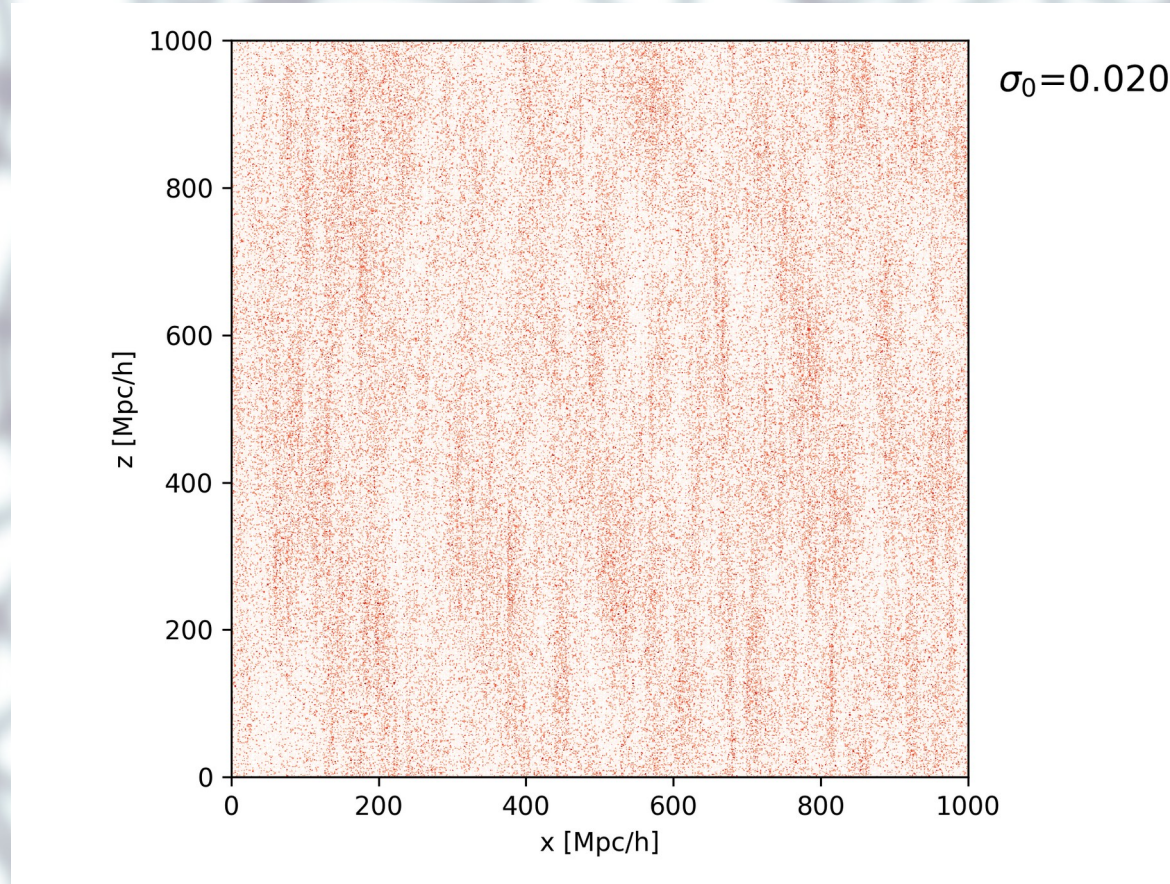


# Photometric redshifts washes out clustering features





# Photometric redshifts washes out clustering features





# Simulations

- 100 Cubic box dark matter only simulation with 1890 Mpc/h and a mass resolution of  $5.5 \times 10^{11} M_{\odot}$
- Populated using an HOD model corresponding to the DESI LRG at  $z=0.7$
- Used for basic tests of our methods
- Additionally, cut-sky easy-mocks matching the DESI footprint for the covariance matrix of the observational data

# Observational data

- Dark Energy Spectroscopic Instrument survey
- Ongoing spectroscopic survey
- Data from the first few months is already internally available
- Photometric survey for target selection: DESI Legacy survey DR9



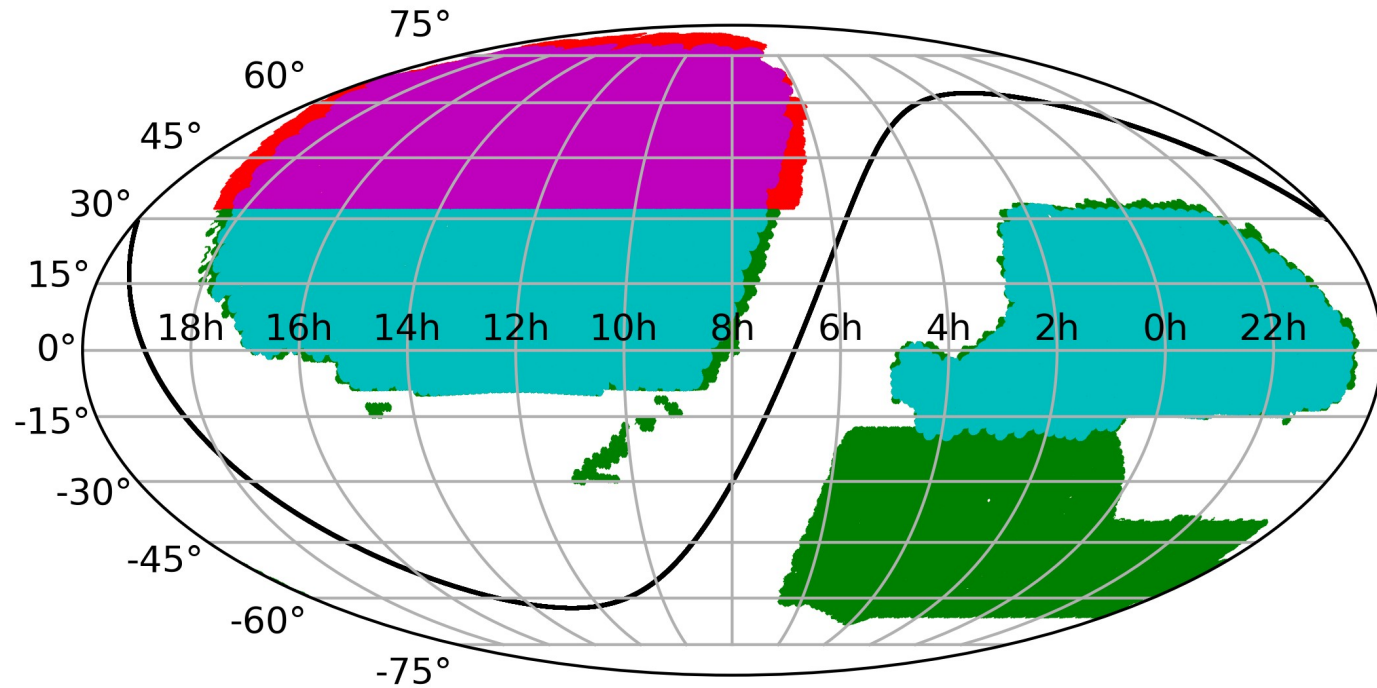
# Target classes

- MWS: not for cosmology
- BGS:  $z < 0.5$
- **LRG:  $0.4 < z < 1.1$**
- ELG:  $0.6 < z < 1.5$
- QSO:  $0.8 < z < 3.5$
- Focus on LRG: balance between photometric redshift uncertainty and sample size



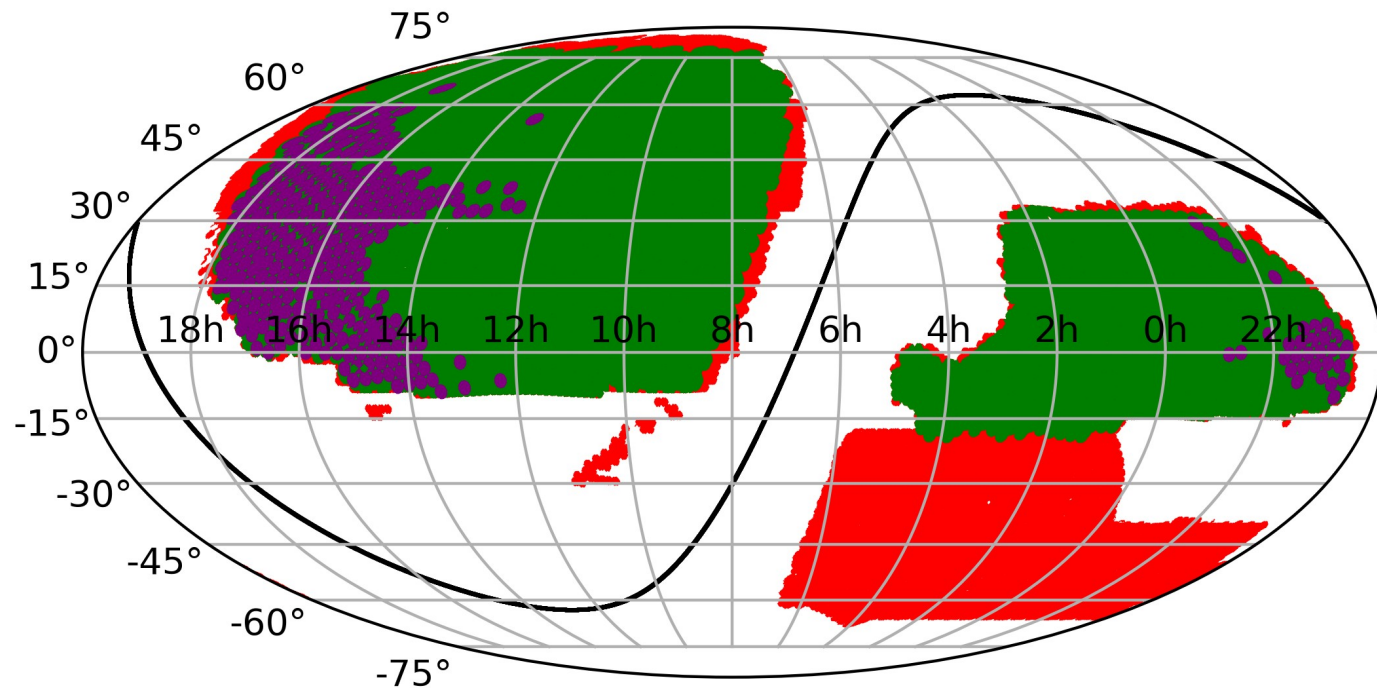
# Footprint

- LRG DR9 North photometric
- LRG DR9 North spectroscopic
- LRG DR9 South photometric
- LRG DR9 South spectroscopic



# Processed spectroscopic data

- DESI photometric footprint
- DESI spectroscopic footprint
- DESI spectroscopy by July 2021
- galactic equator





# Our possibilities right now:

- Just use the photometric data collected by the DESI Legacy Imaging Survey DR9
- Use the already available spectroscopic data and use cross-correlation with the photometric data to account for the incompleteness of the current spectroscopic survey footprint

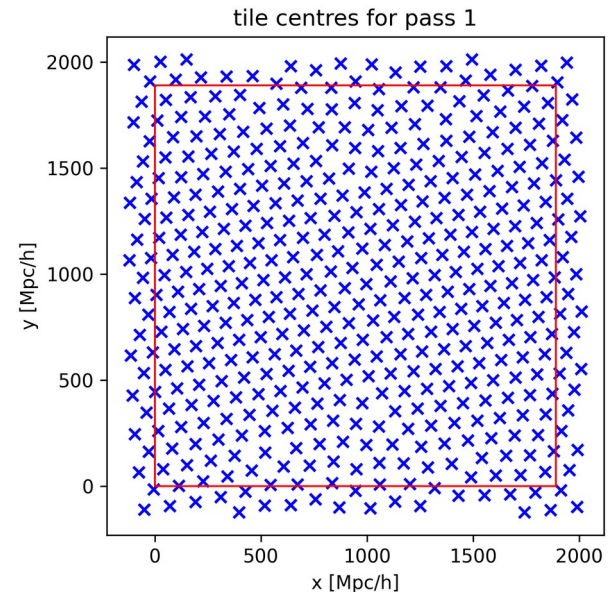
# Cross-correlations

- Cross-correlations between the spectroscopic data of DESI (after about one pass) and the photometric data of the same area (and surroundings)
- Tests on simulations
- First tests with observations using the internal DESI DA0.2 data release



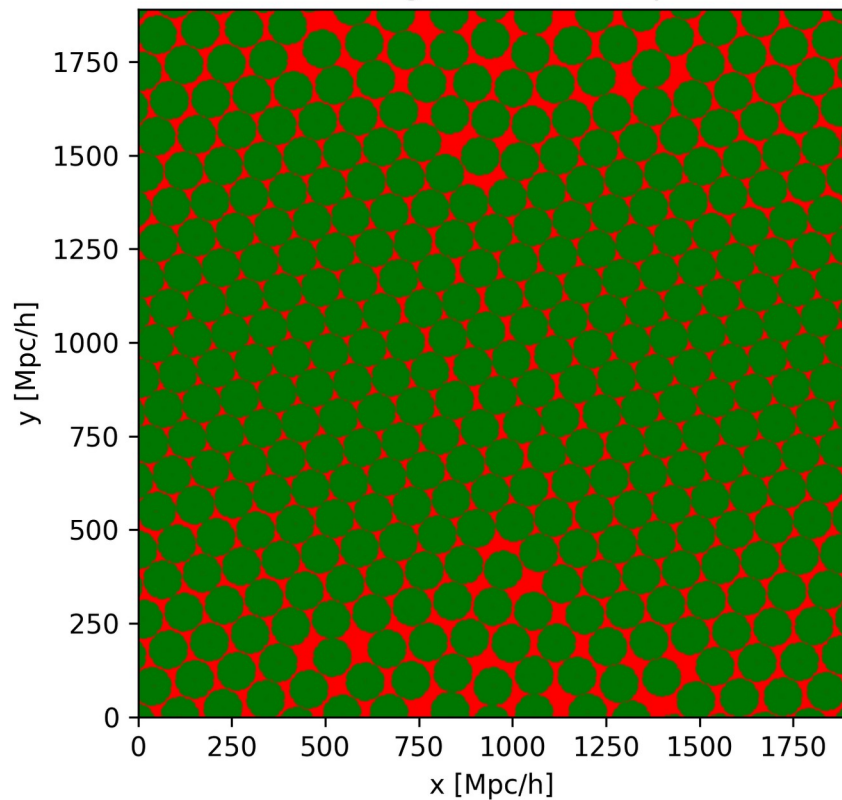
# Fibre assignment

- Tiling strategy of DESI
- Comparing 1-pass with many passes
- Impact of fibre placements and completeness of the spectroscopic data

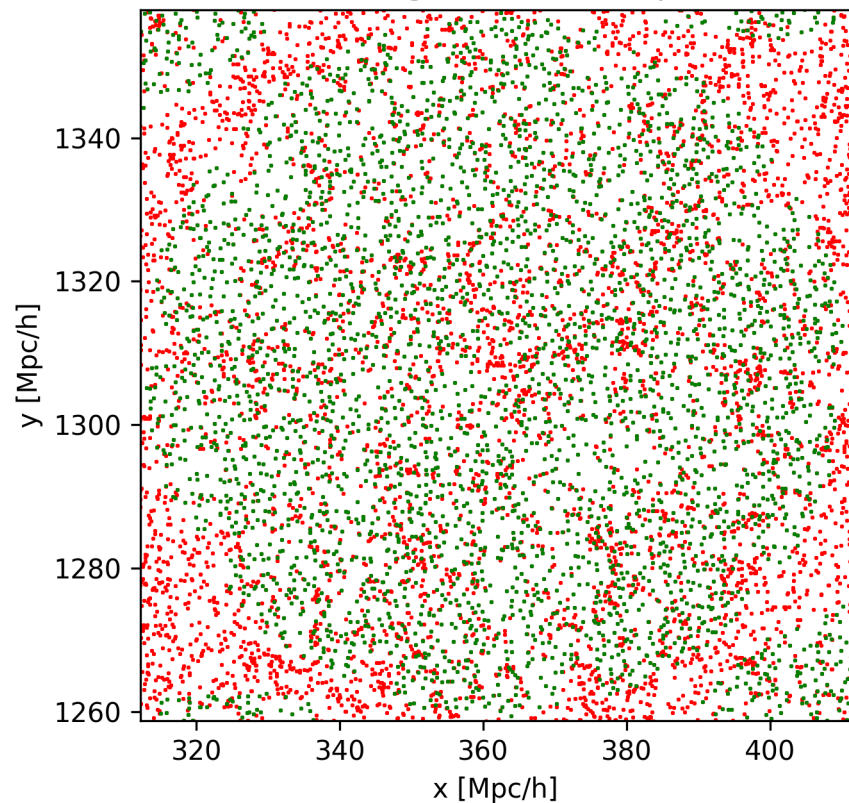


# First pass

fibre assignment after 1 pass

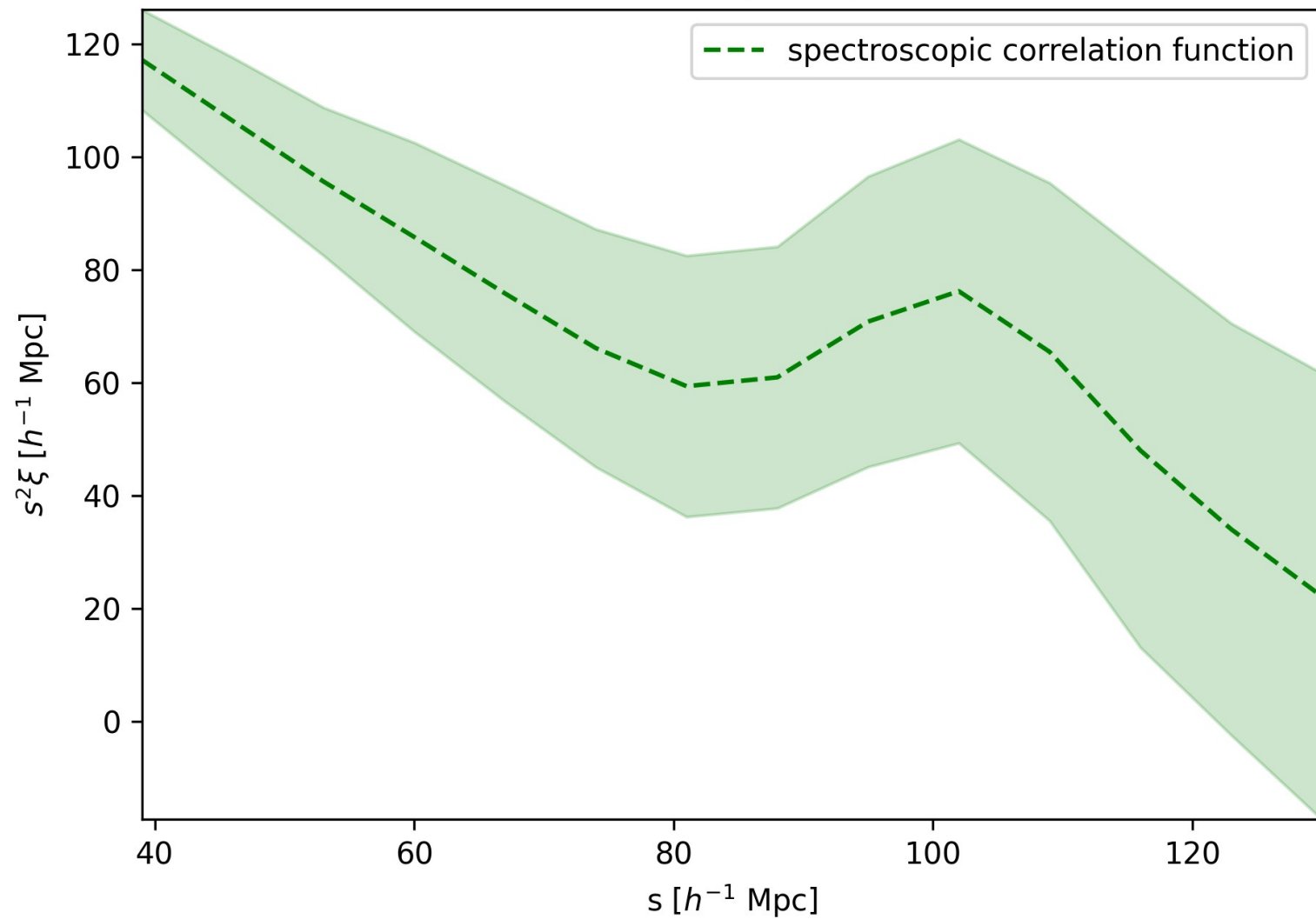


fibre assignment after 1 pass

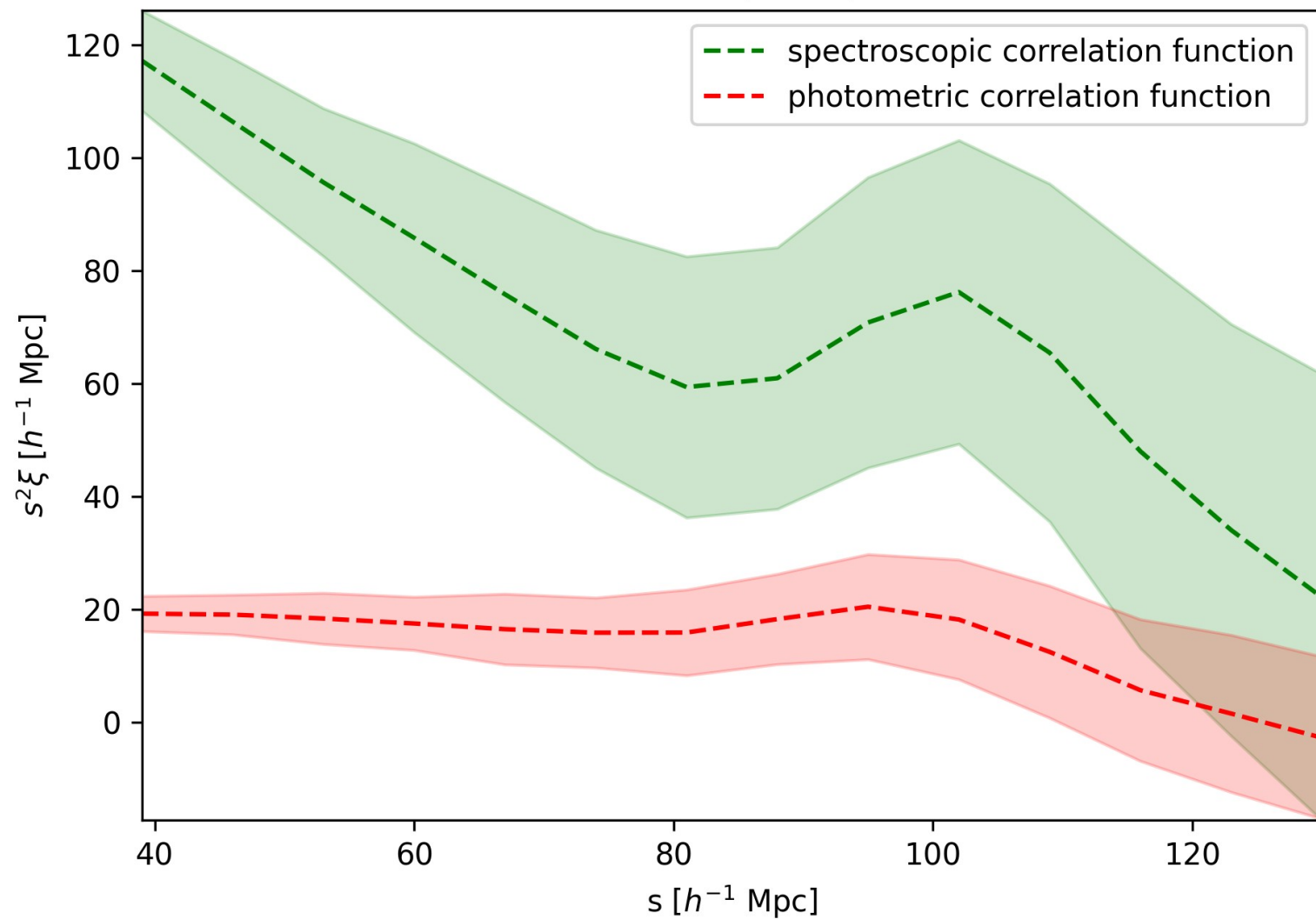




LRGs 0.02, 1st pass:  $\bar{\mu} = 0.05$

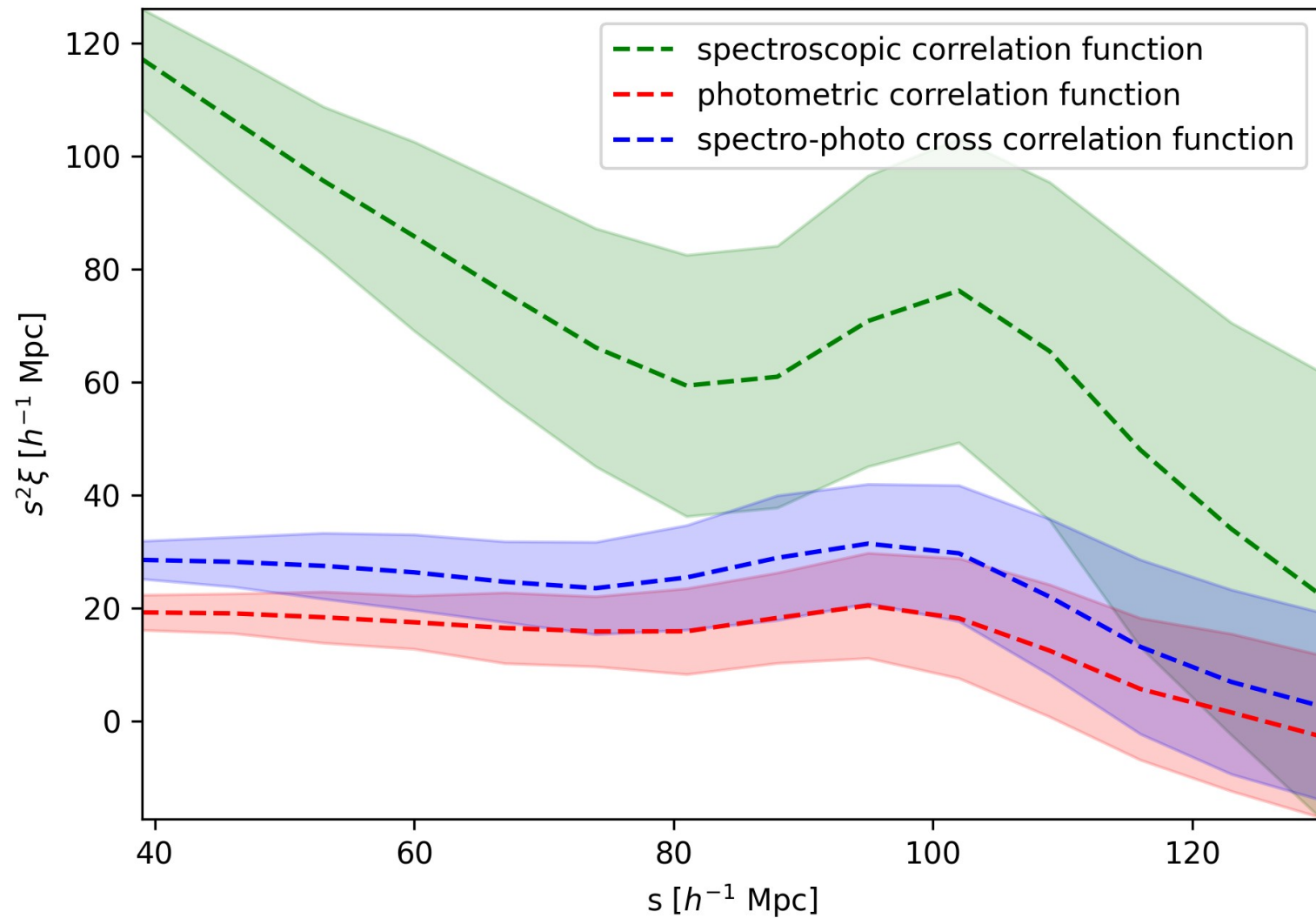


LRGs 0.02, 1st pass:  $\bar{\mu} = 0.05$

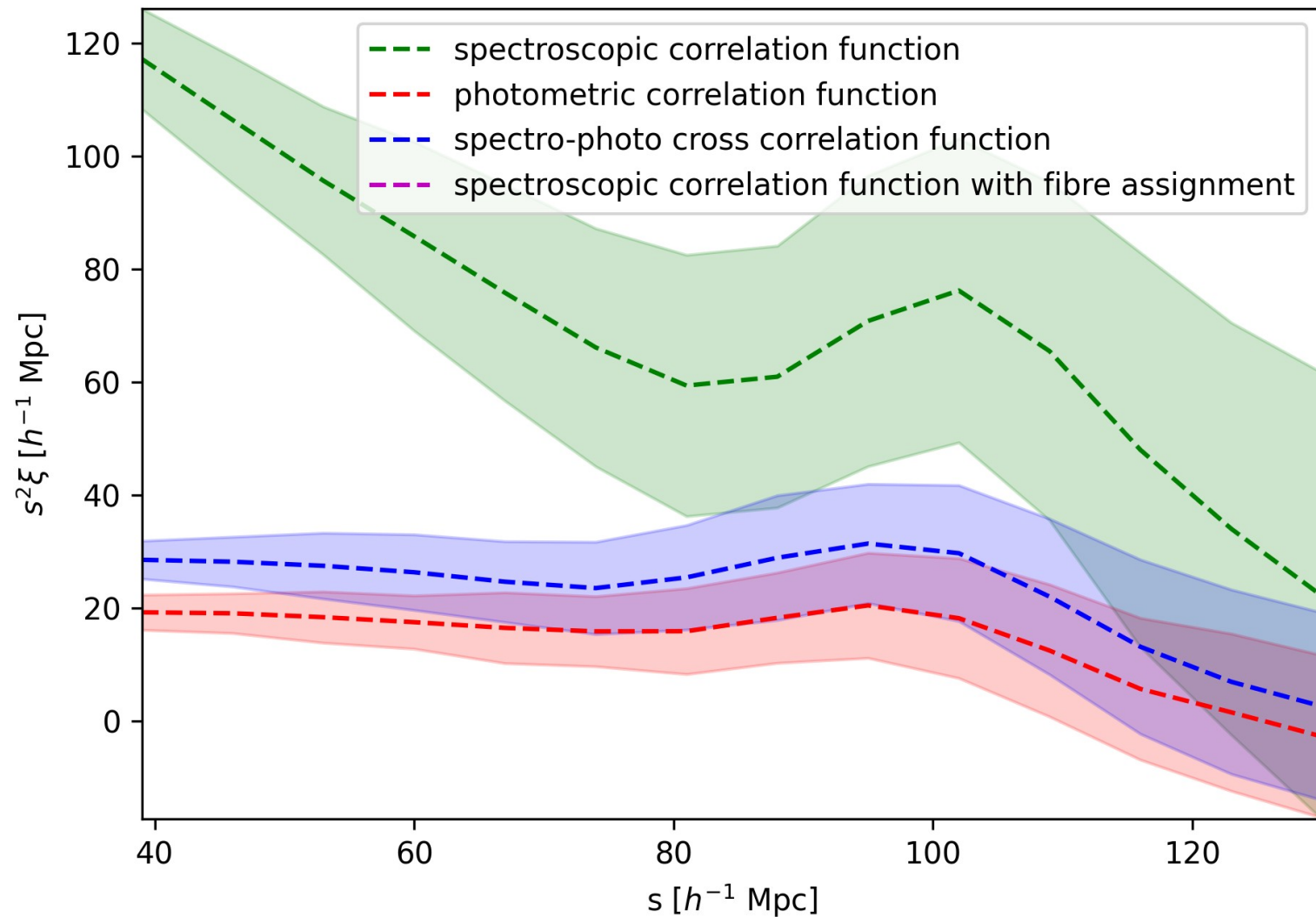




LRGs 0.02, 1st pass:  $\bar{\mu} = 0.05$

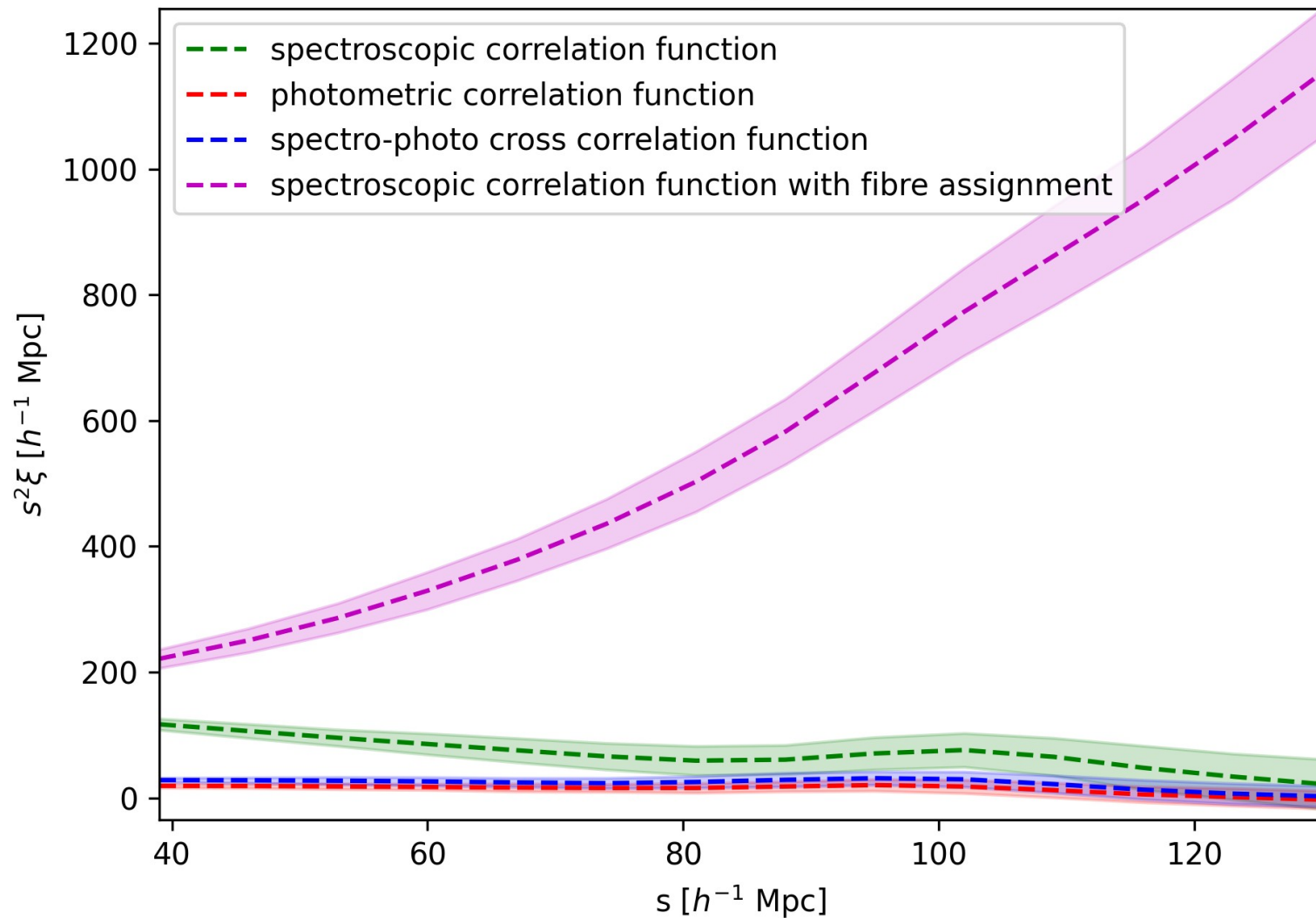


LRGs 0.02, 1st pass:  $\bar{\mu} = 0.05$

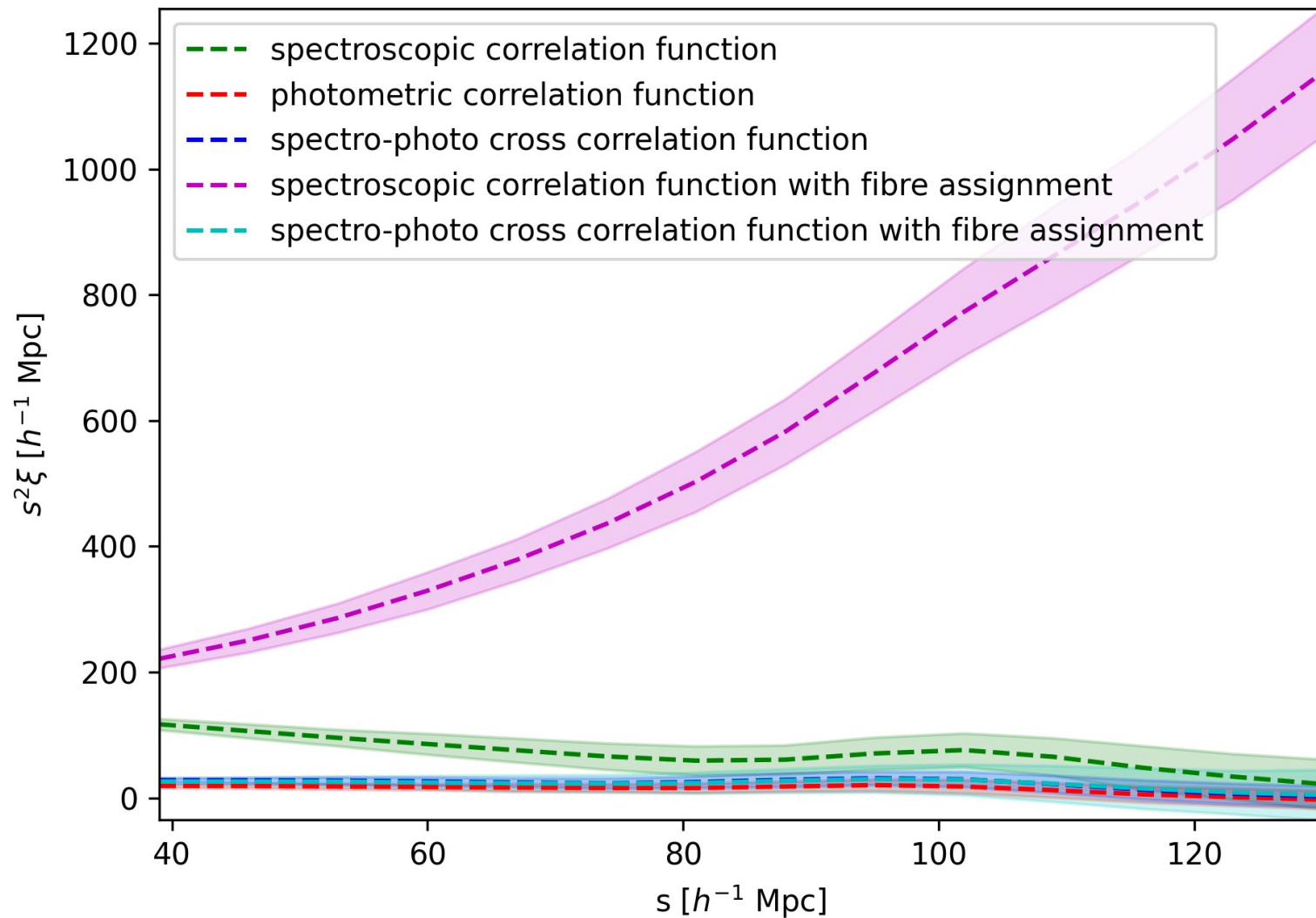




LRGs 0.02, 1st pass:  $\bar{\mu} = 0.05$

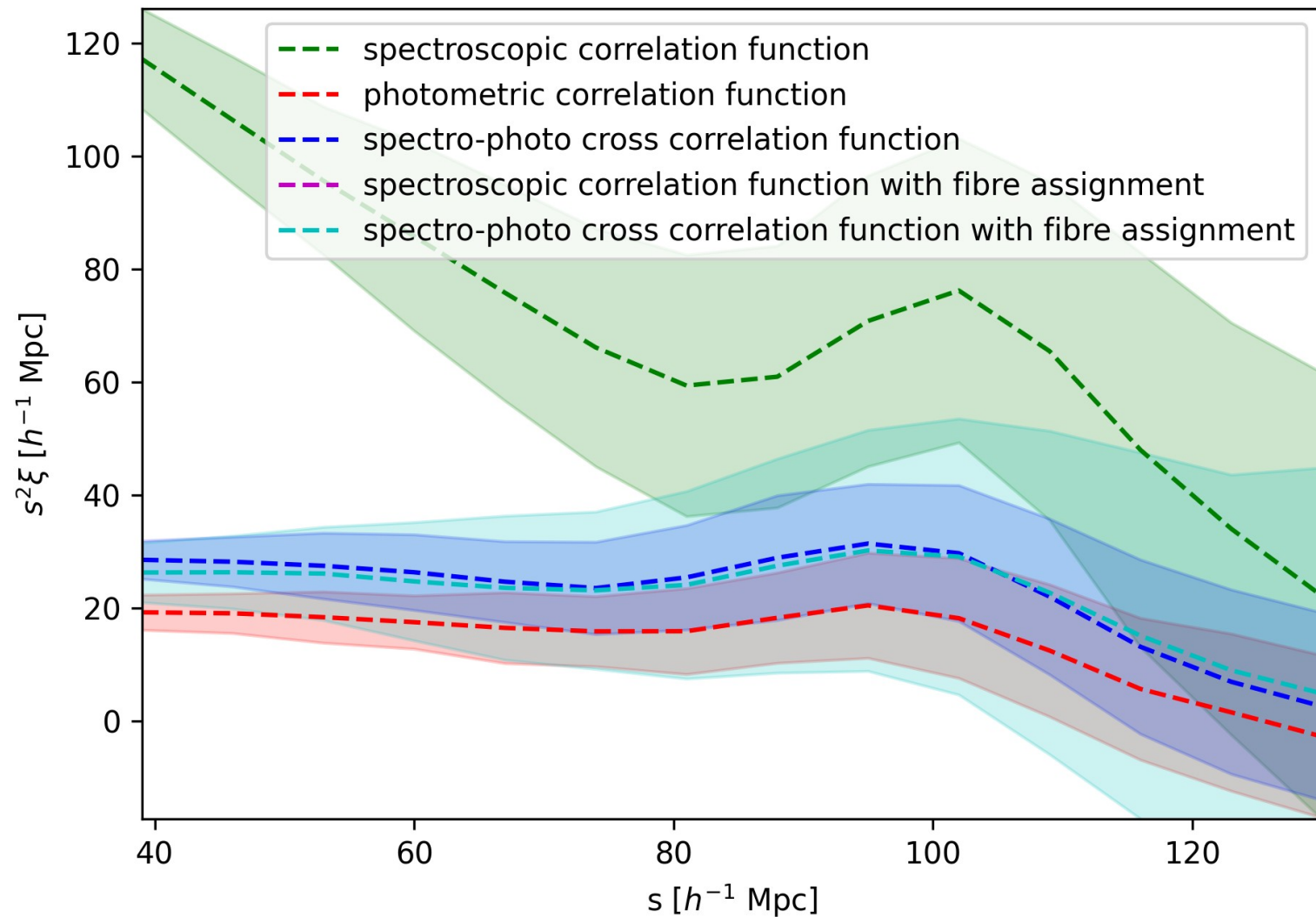


LRGs 0.02, 1st pass:  $\bar{\mu} = 0.05$

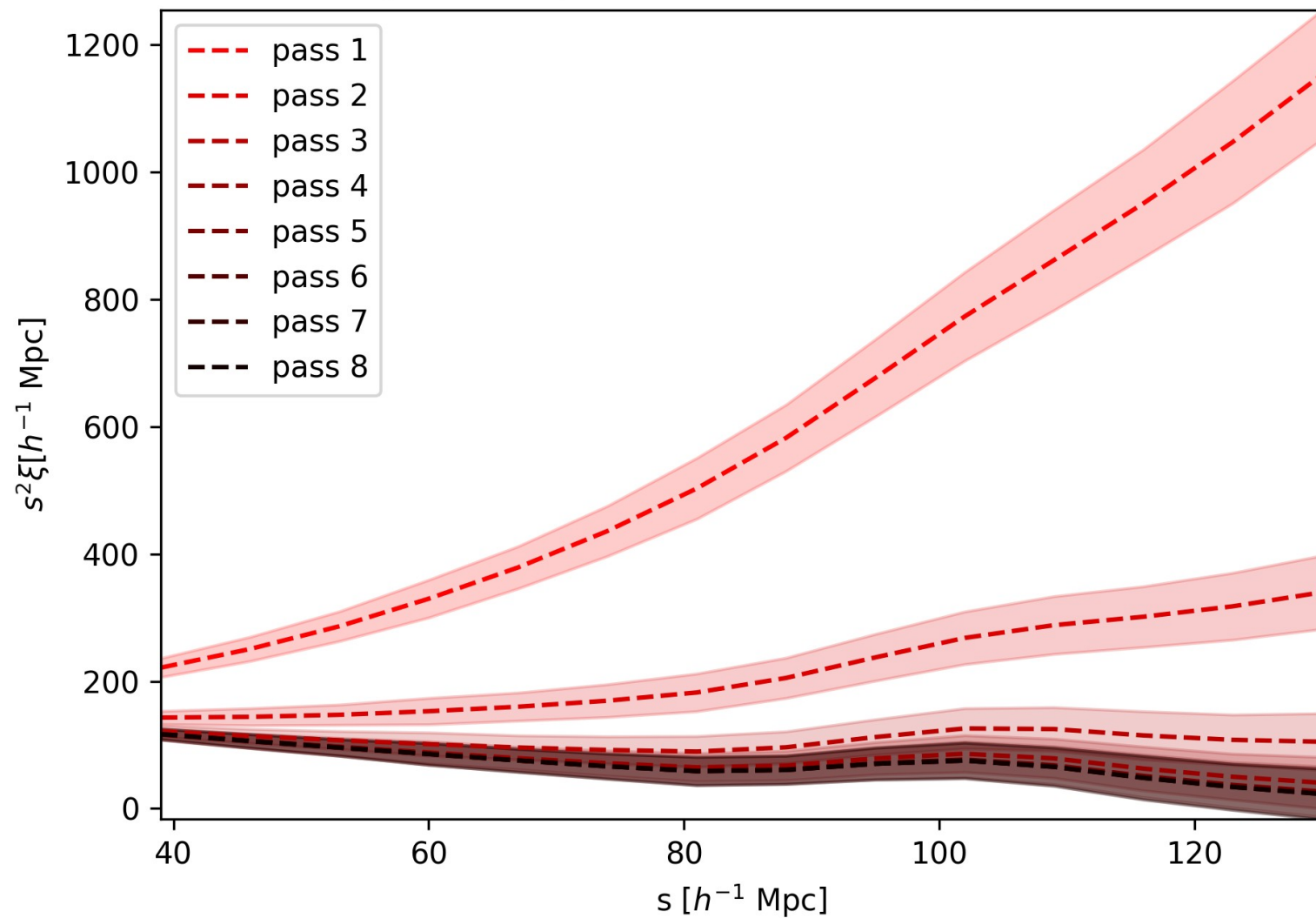




LRGs 0.02, 1st pass:  $\bar{\mu} = 0.05$

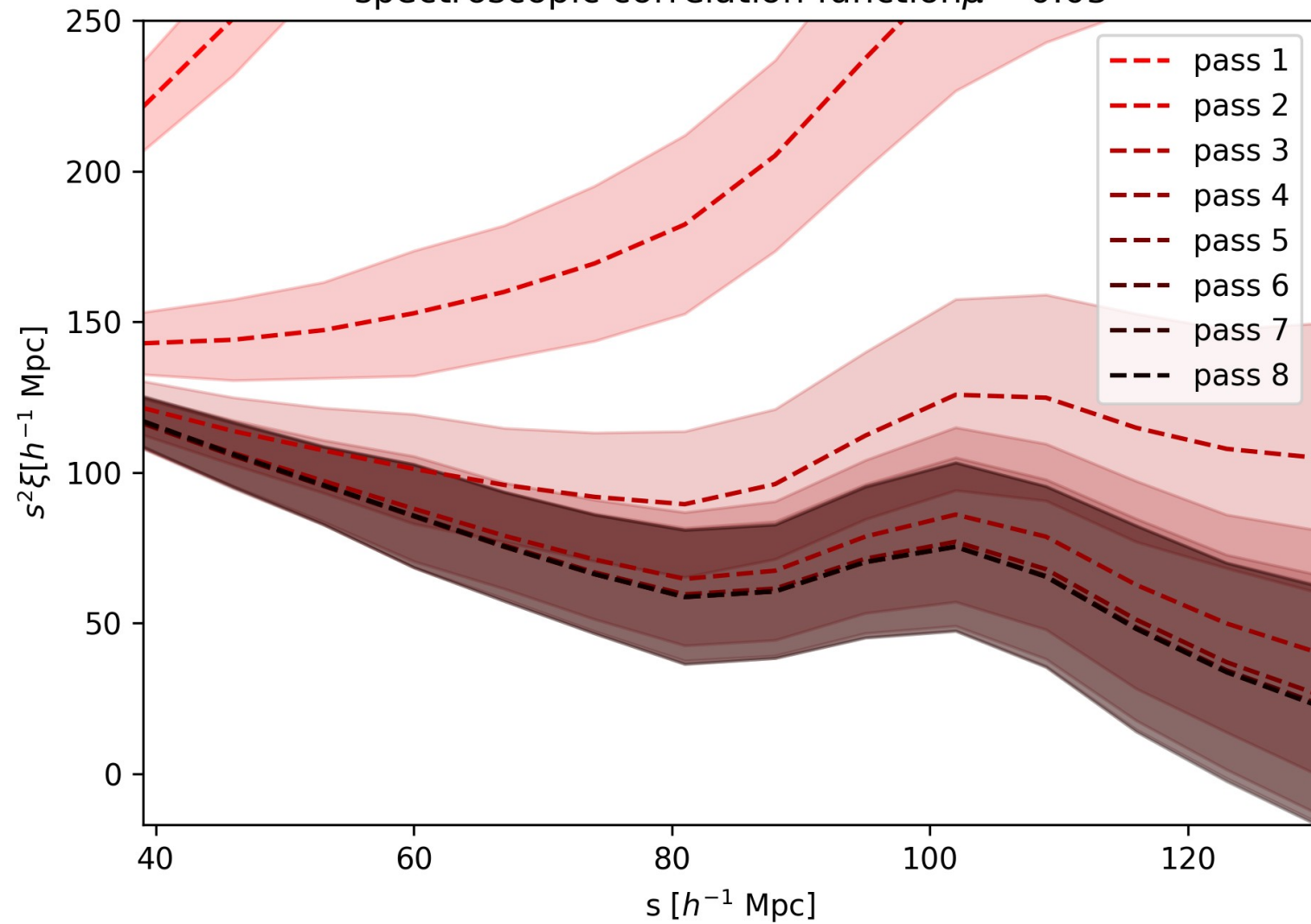


spectroscopic correlation function  $\bar{\mu} = 0.05$





spectroscopic correlation function  $\bar{\mu} = 0.05$

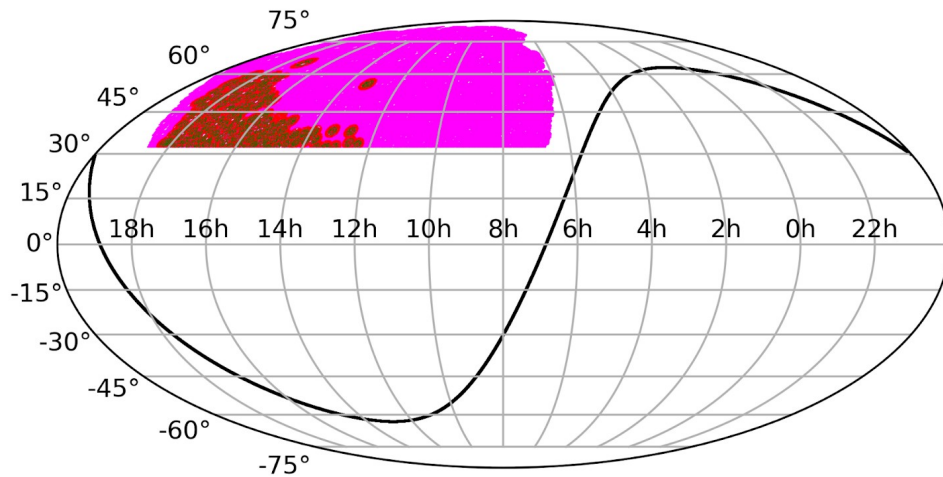




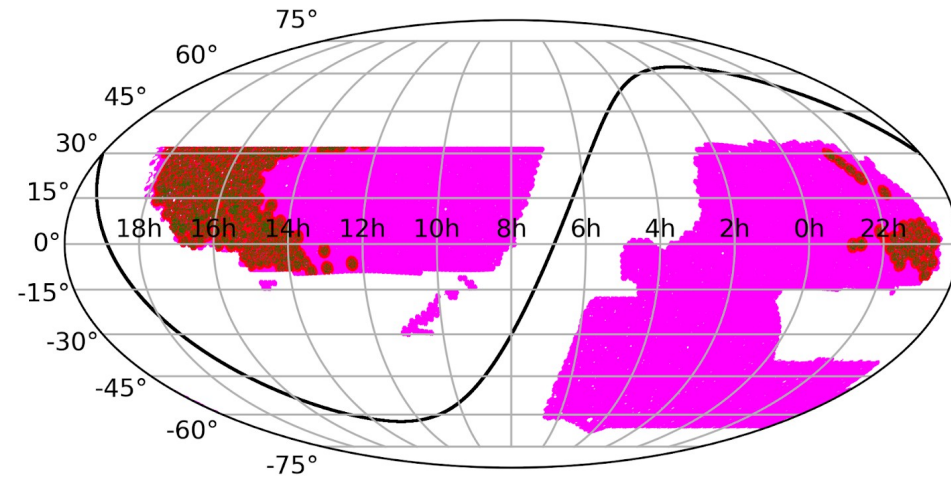


# DESI DA0.2 data

- DESI photometric footprint
- photometric data used
- spectroscopic data used
- galactic equator



- DESI photometric footprint
- photometric data used
- spectroscopic data used
- galactic equator



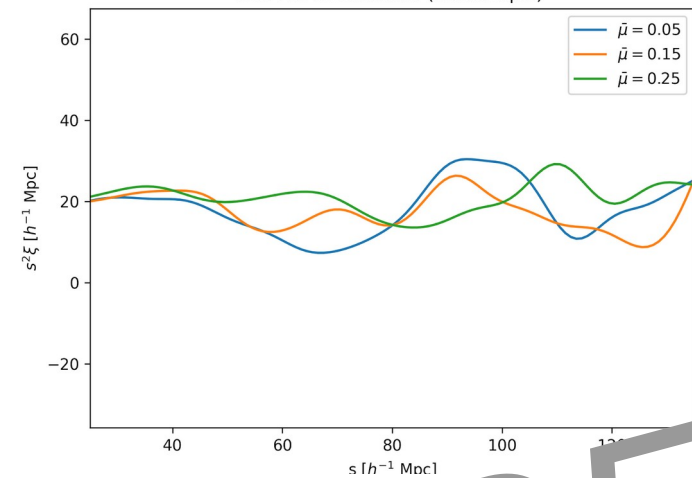
Differences in the photometric selection

→ North and South are treated separately

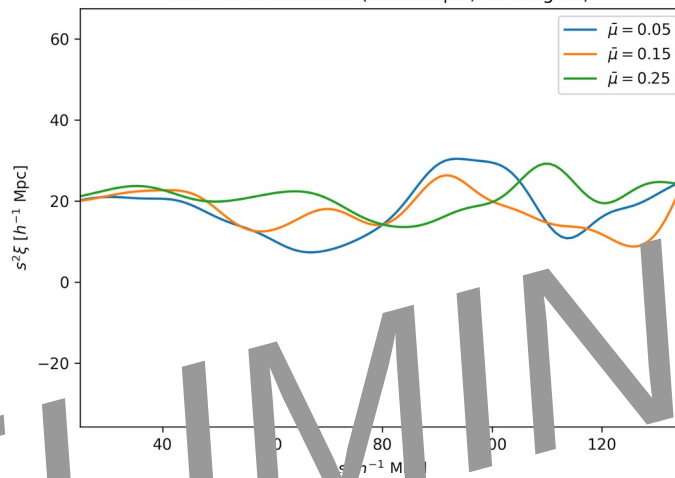
Photometric data used in a  $2^\circ$  radius around spectroscopic tile centres

# DESI DA0.2 data

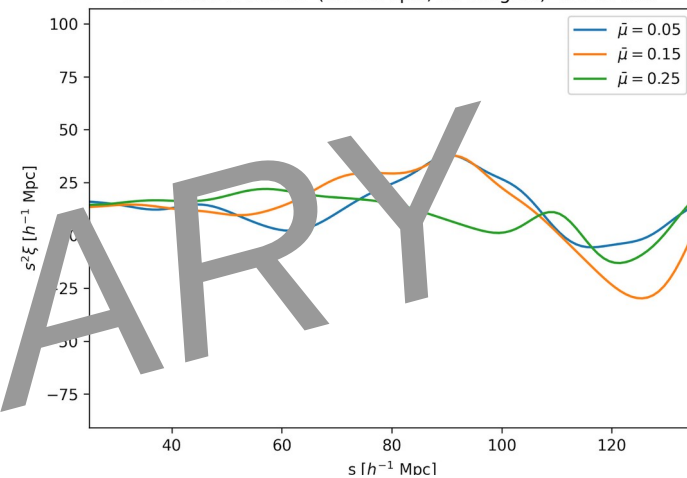
LRG North crosscorr (anisotropic)



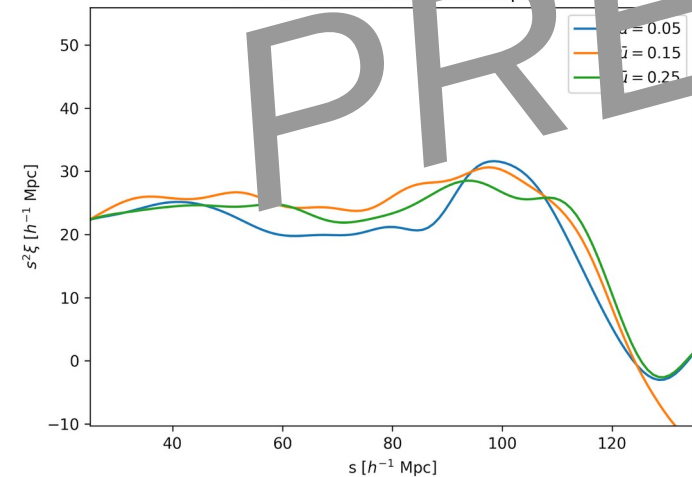
LRG North crosscorr (anisotropic, no weights)



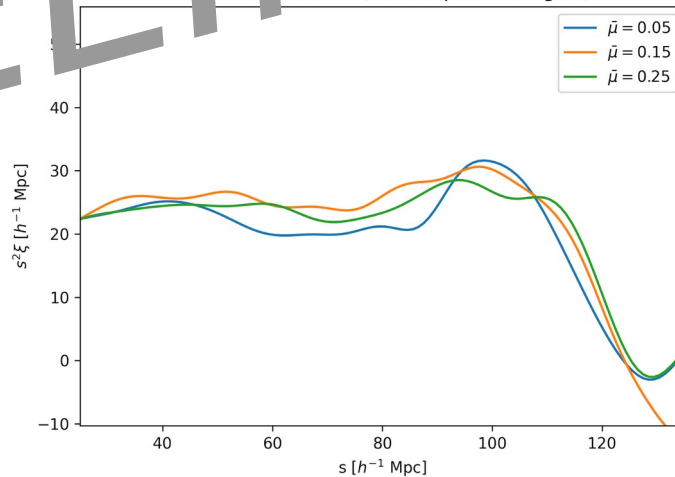
LRG North crosscorr (anisotropic, no weights)  $0.6 < z < 0.8$



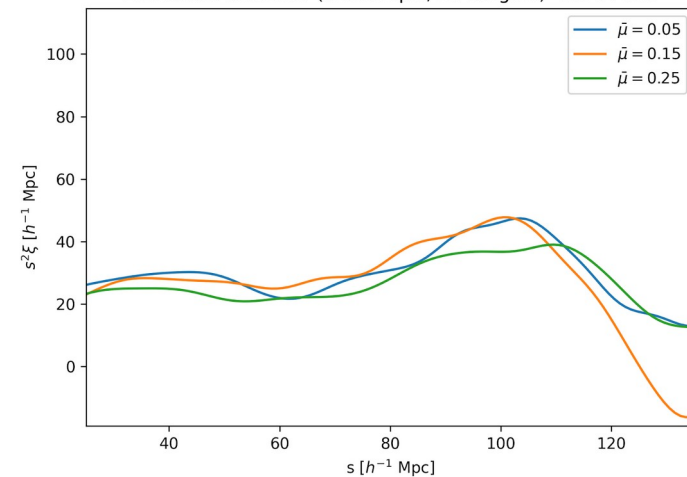
LRG South crosscorr (anisotropic)



LRG South crosscorr (anisotropic, no weights)



LRG South crosscorr (anisotropic, no weights)  $0.6 < z < 0.8$





# Advantages of cross-correlations

- Cross-correlation naturally recovers features, even if the spectroscopic data set is incomplete and biased due to fibre assignment
- Complimentary to the other methods such as PIP weights (combining both doesn't improve the data)
- Perfectly suited for early DESI data (single pass or few passes) such as DA0.2 and the year 1 data.

# Disadvantages of cross-correlations

- Only the lower  $\mu$ -bins of the anisotropic correlation function can be used.
- Any improvements over the photometric correlation function alone will be ultimately outdone by the spectroscopic correlation once the survey is more complete.
- Dominated by the photometric correlation function
  - **Suffers from the same systematic biases as it!**



# Photometric data only

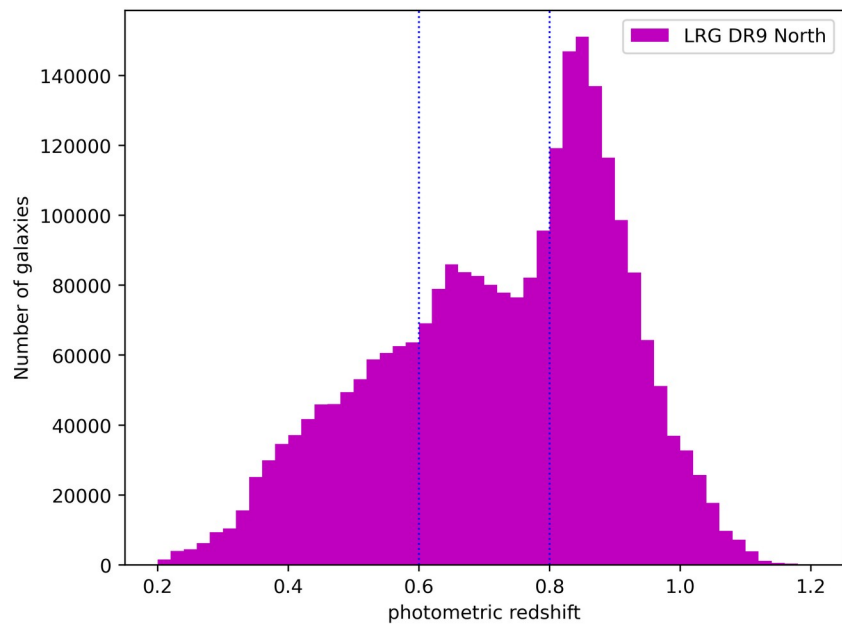
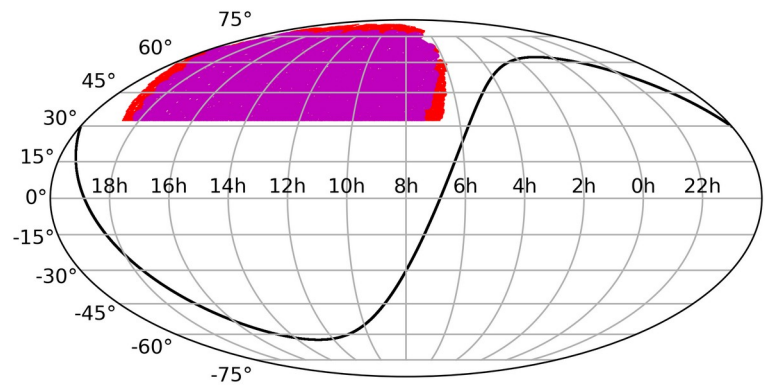
- Observational data from the DESI Legacy Imaging survey DR9
- Sridhar+ 2020 already did the Southern photometric footprint with DR8
- Original plan: update with DR9 and also include the Northern photometric footprint
- Improved LRG target selection



# Photometric data only

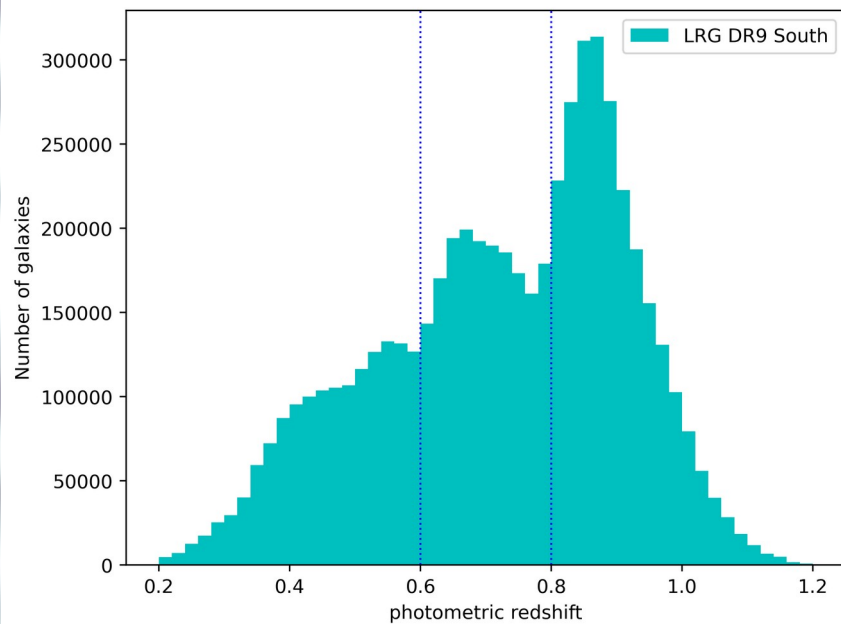
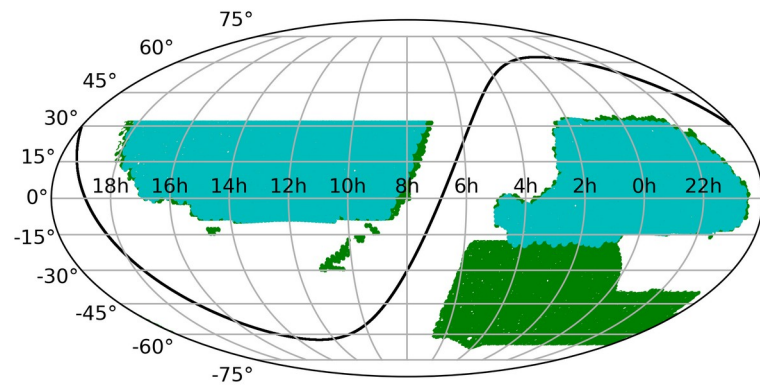
- Observational data from the DESI Legacy Imaging survey DR9
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- Original plan: update with DR9 and also include the Northern photometric footprint
- Improved LRG target selection

● LRG DR9 North photometric    ● LRG DR9 North spectroscopic



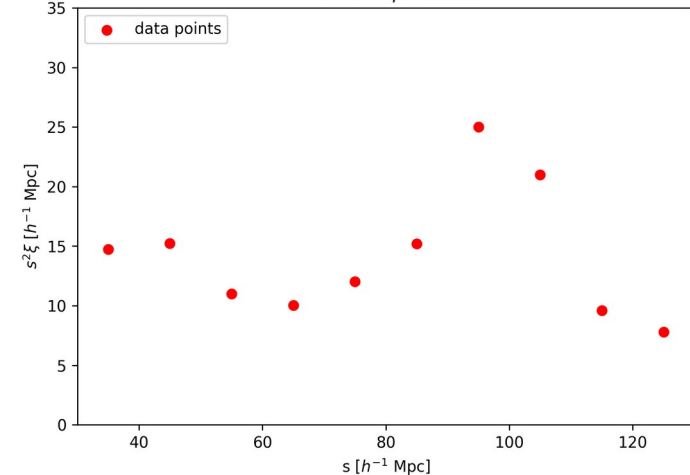
**LRGs**  
 **$0.6 < z < 0.8$**

● LRG DR9 South photometric    ● LRG DR9 South spectroscopic

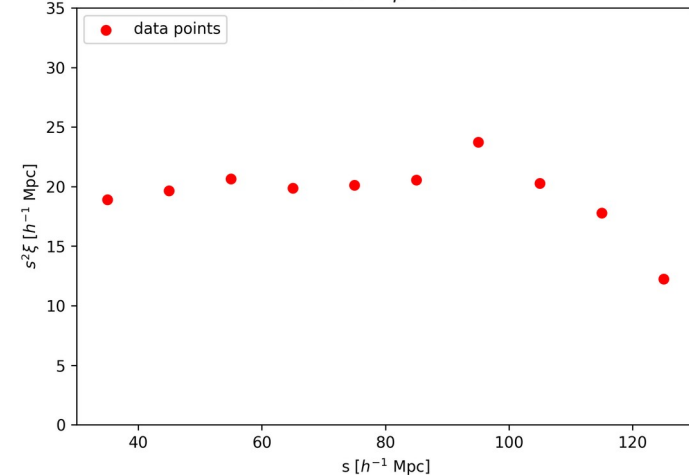


# BAO peak measurements

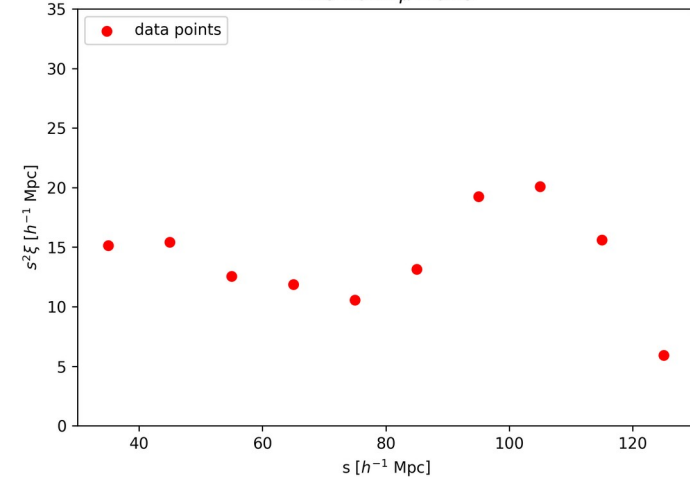
LRG North  $\bar{\mu} = 0.083$



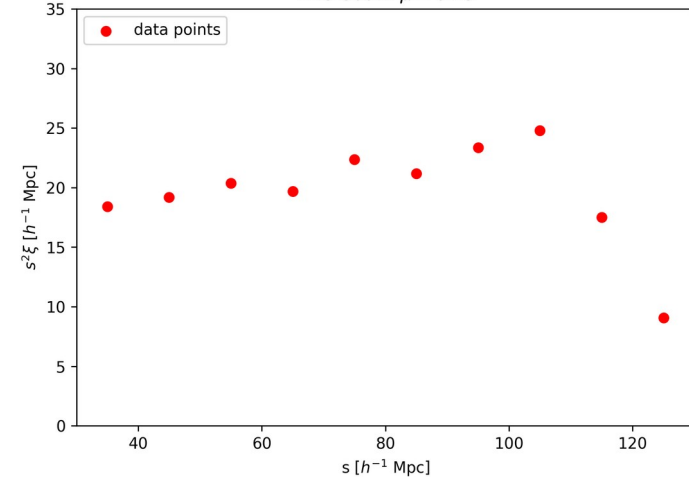
LRG South  $\bar{\mu} = 0.083$



LRG North  $\bar{\mu} = 0.25$



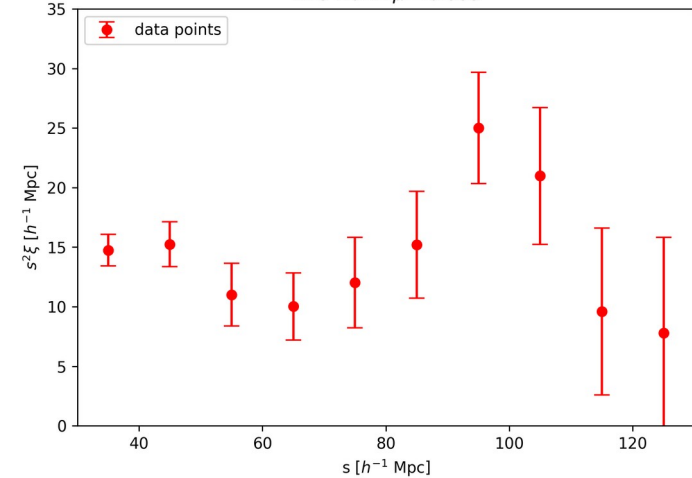
LRG South  $\bar{\mu} = 0.25$



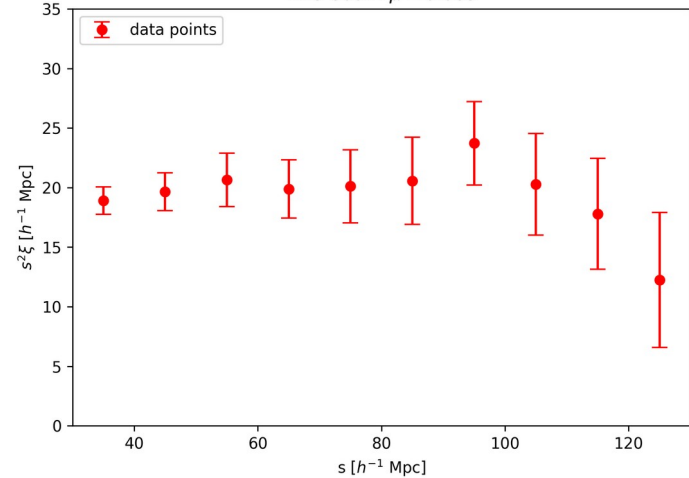


# BAO peak measurements

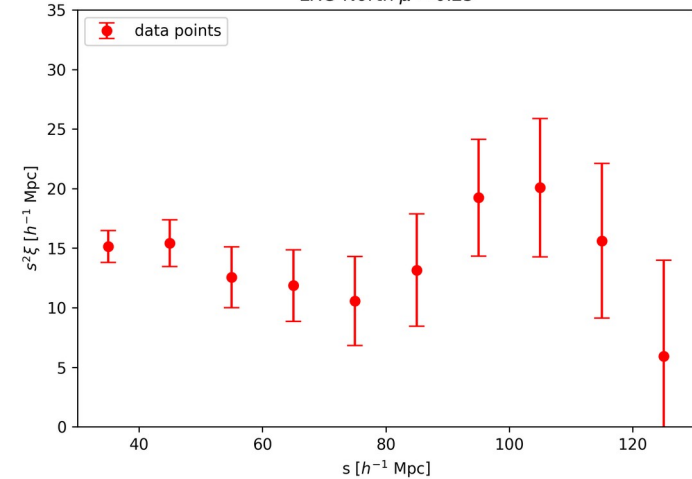
LRG North  $\bar{\mu} = 0.083$



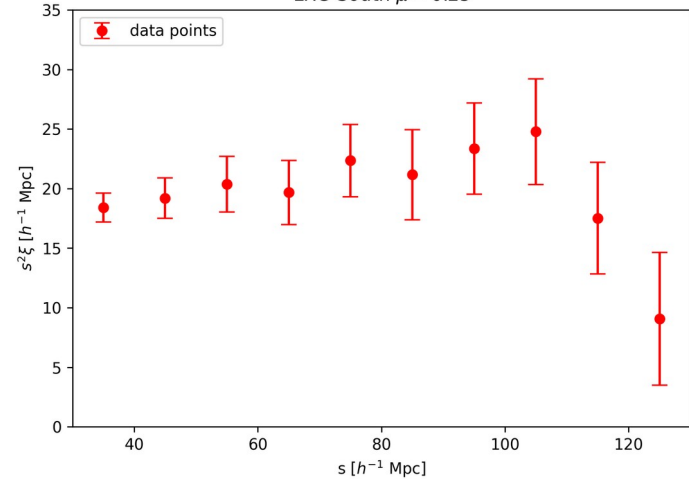
LRG South  $\bar{\mu} = 0.083$



LRG North  $\bar{\mu} = 0.25$

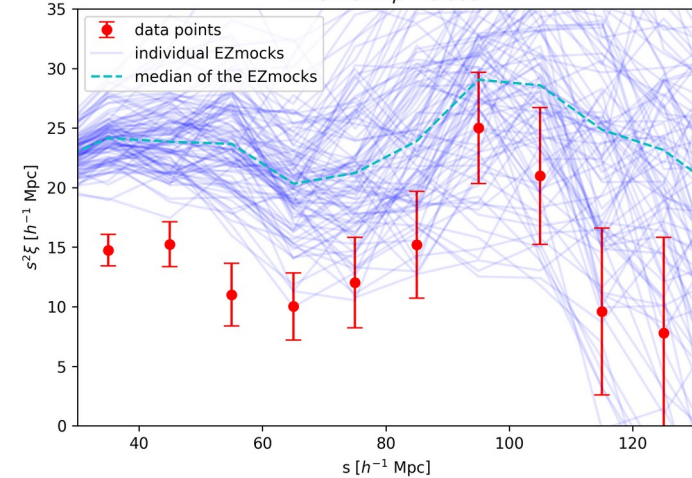


LRG South  $\bar{\mu} = 0.25$

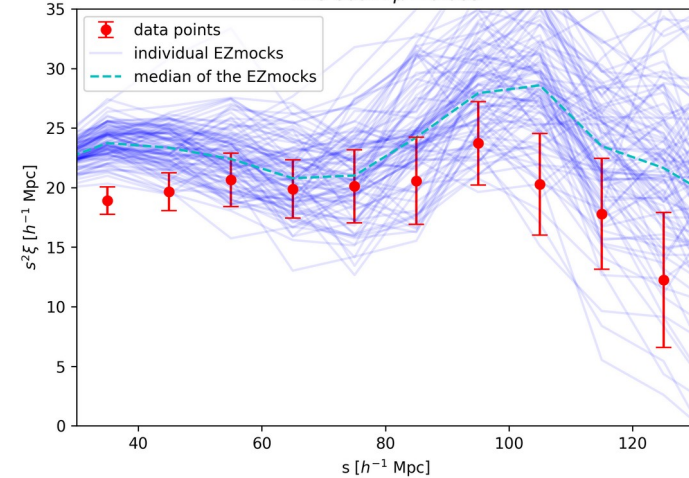


# BAO peak measurements

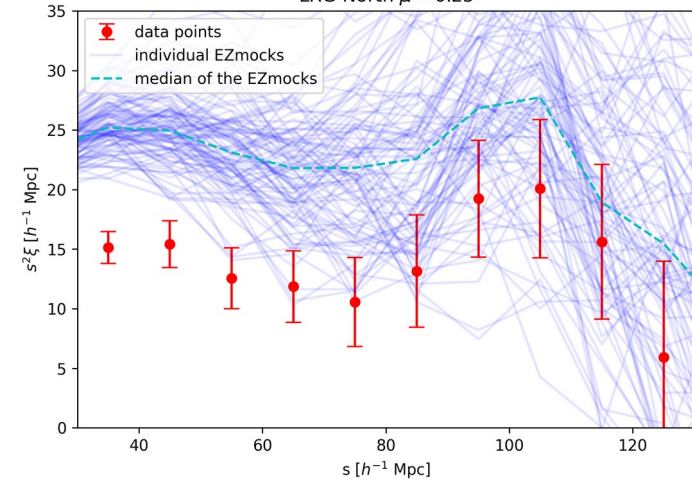
LRG North  $\bar{\mu} = 0.083$



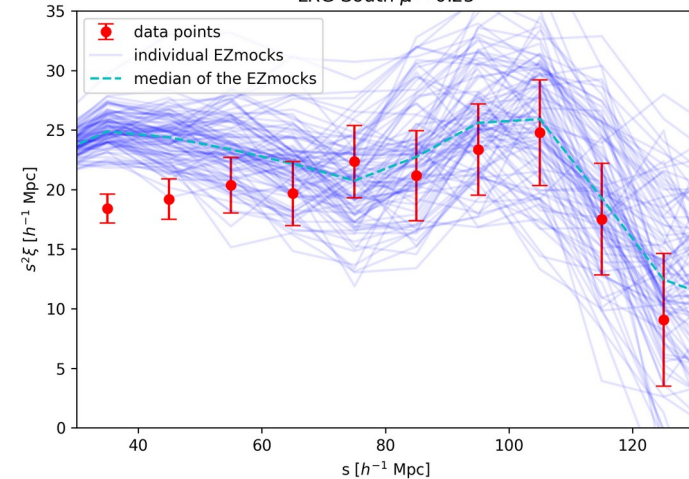
LRG South  $\bar{\mu} = 0.083$



LRG North  $\bar{\mu} = 0.25$



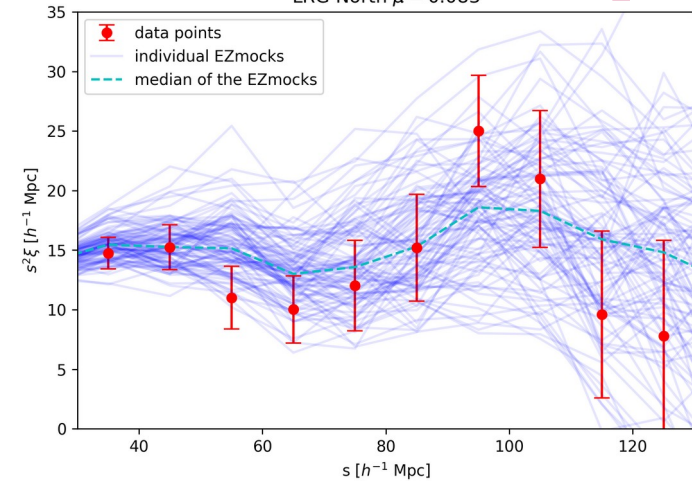
LRG South  $\bar{\mu} = 0.25$



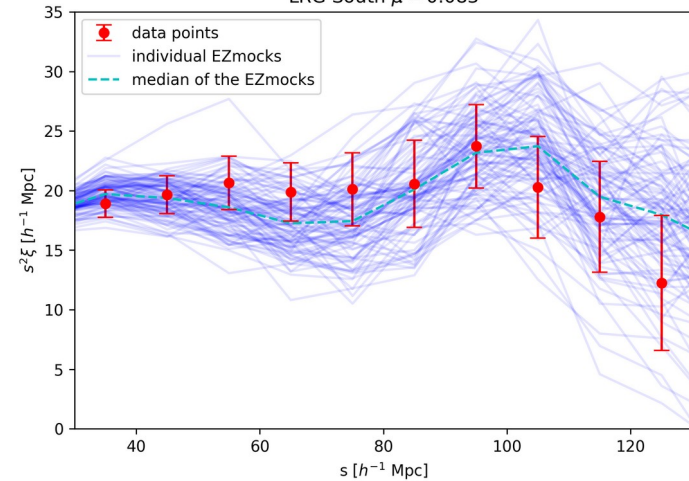


# BAO peak measurements

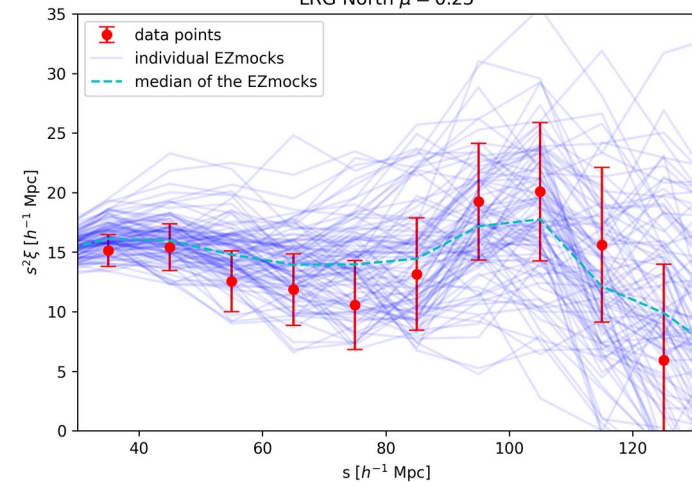
LRG North  $\bar{\mu} = 0.083$



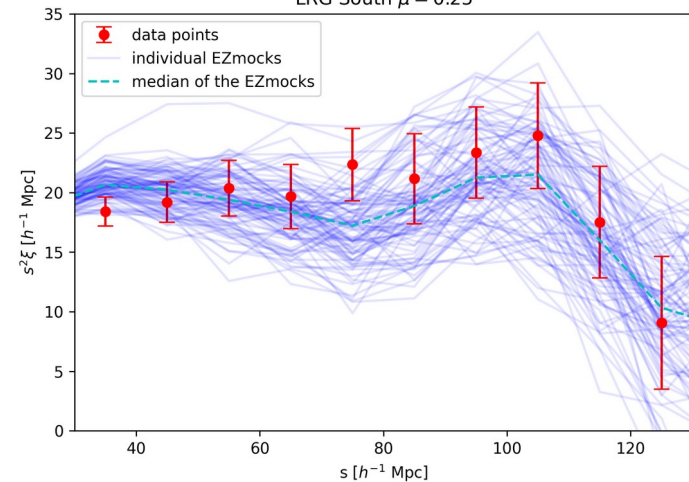
LRG South  $\bar{\mu} = 0.083$



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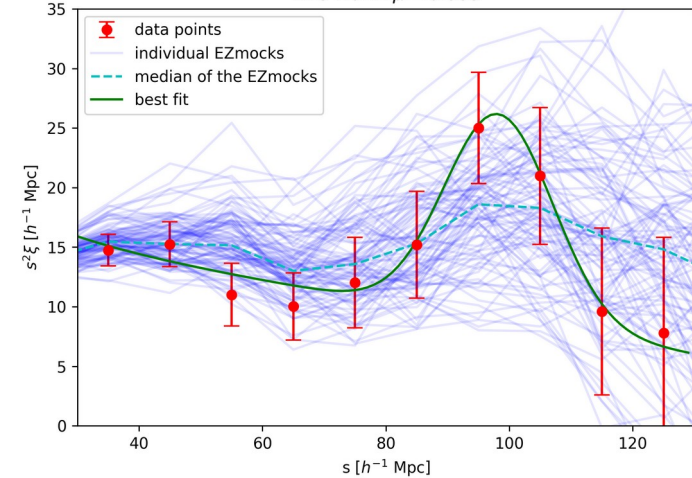
LRG South  $\bar{\mu} = 0.25$



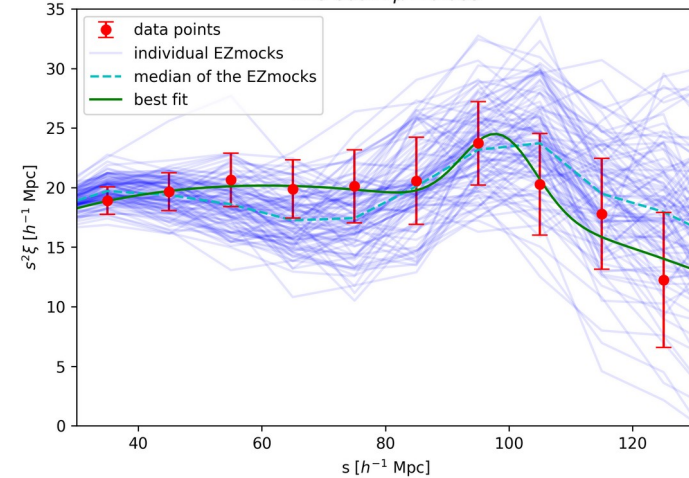


# BAO peak measurements

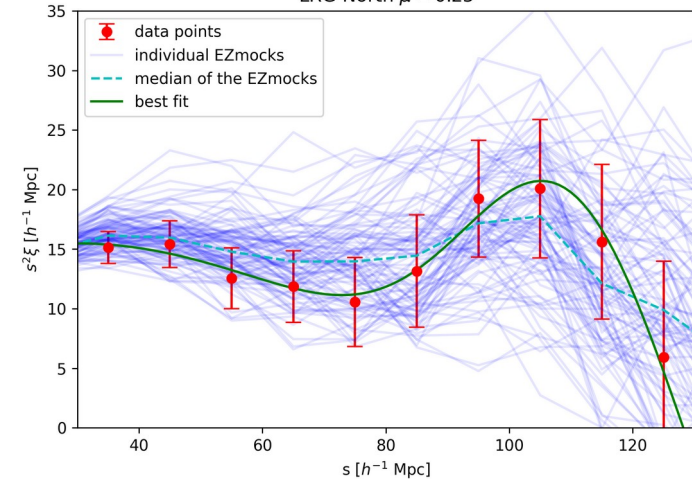
LRG North  $\bar{\mu} = 0.083$



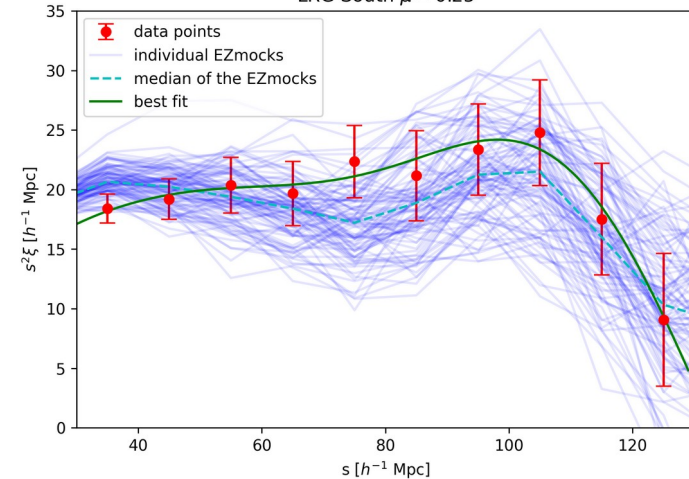
LRG South  $\bar{\mu} = 0.083$



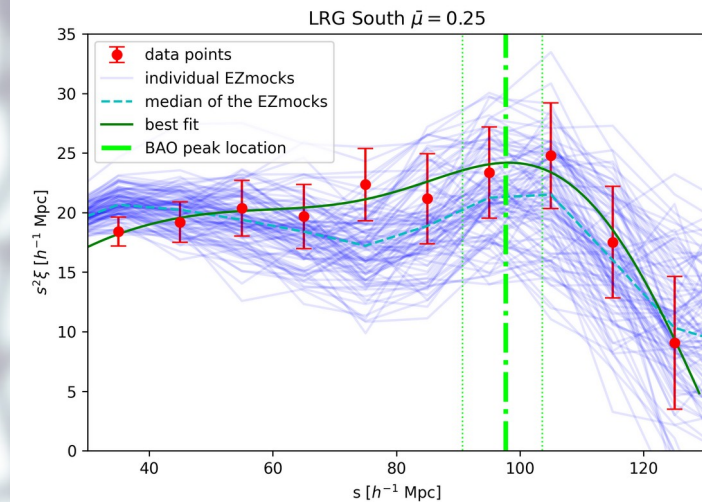
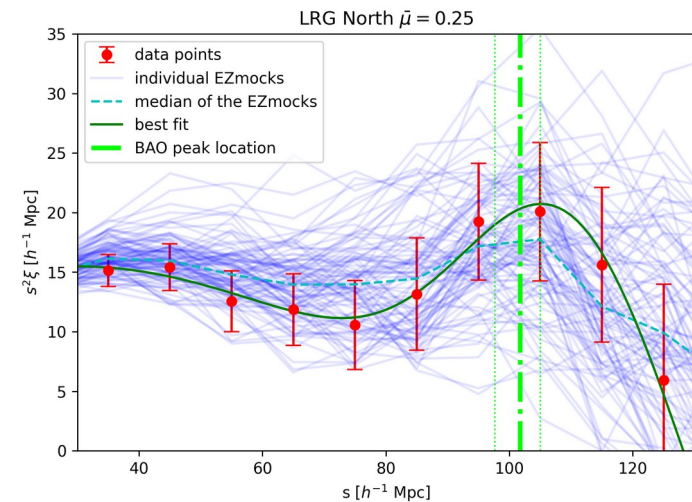
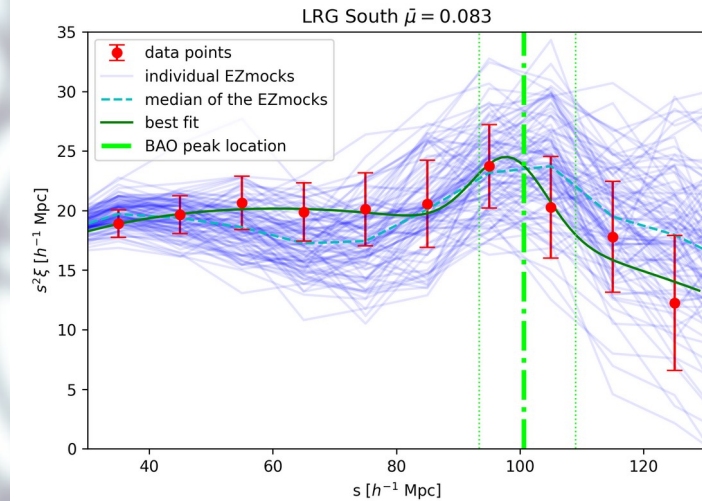
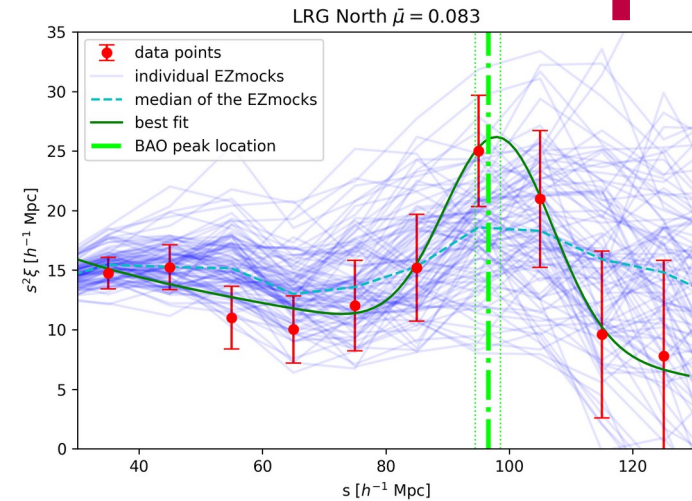
LRG North  $\bar{\mu} = 0.25$



LRG South  $\bar{\mu} = 0.25$



# BAO peak measurements

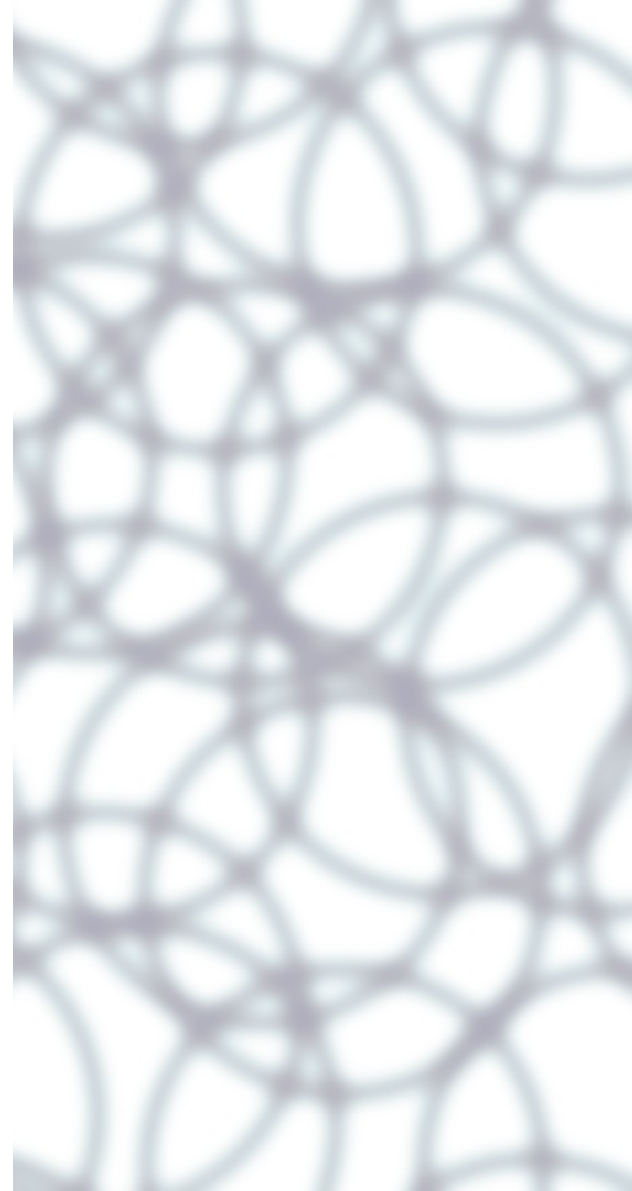
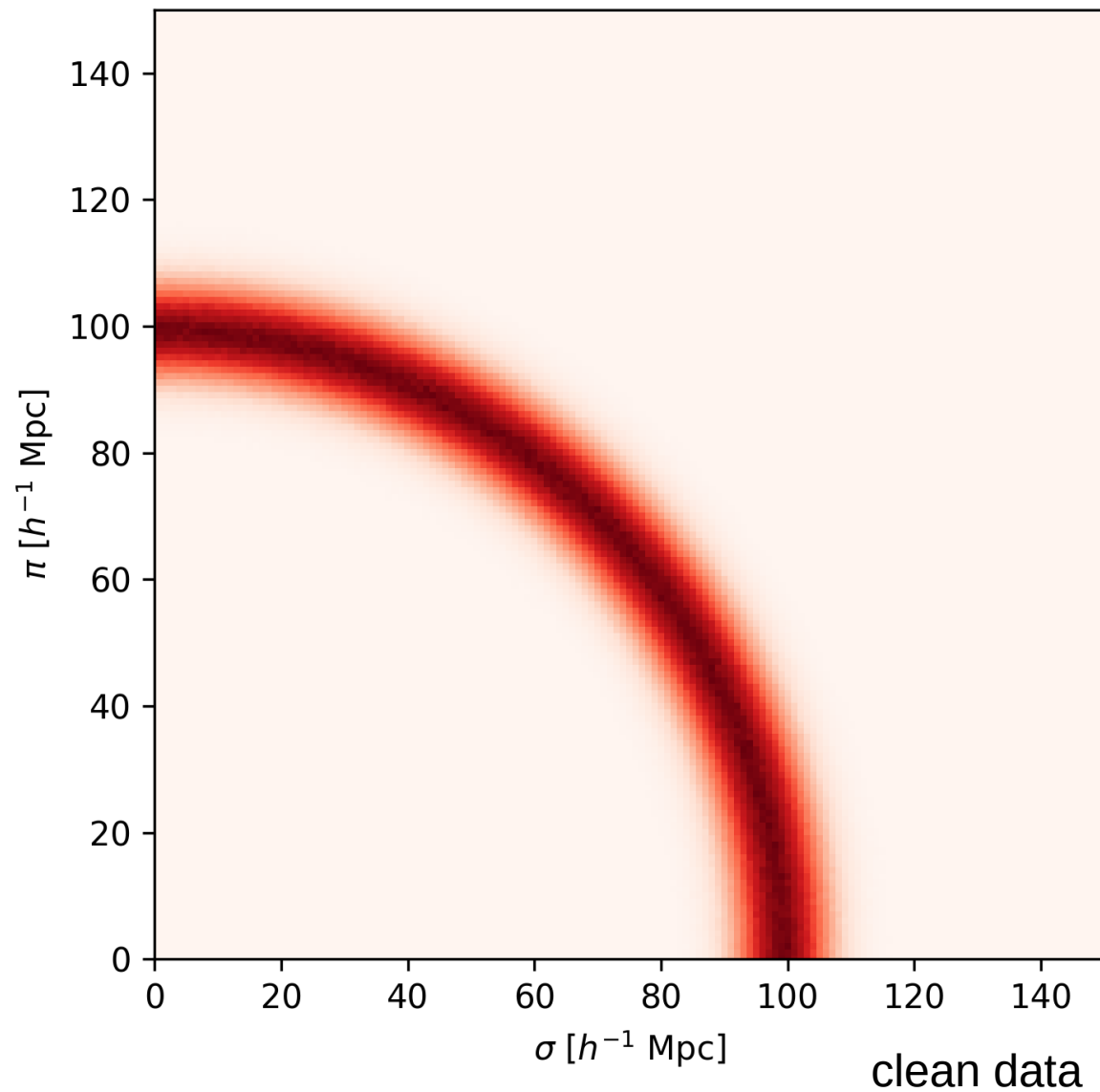


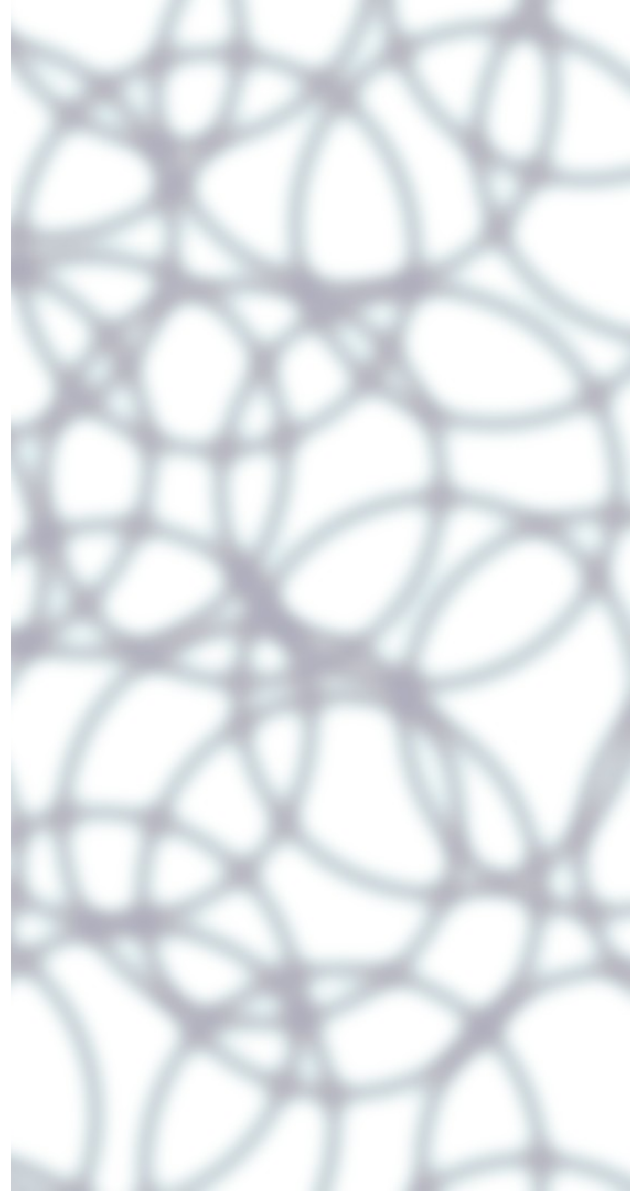
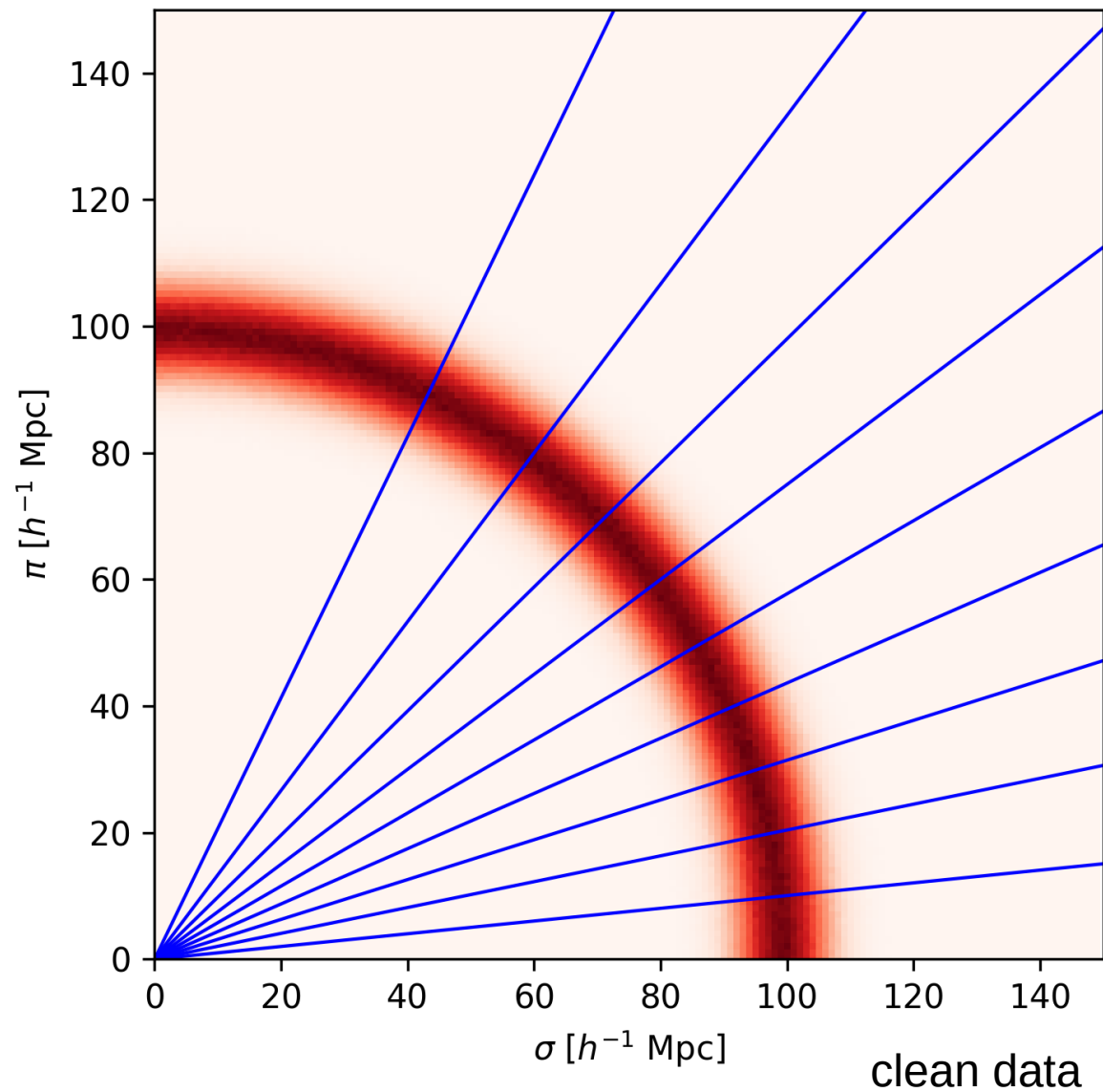


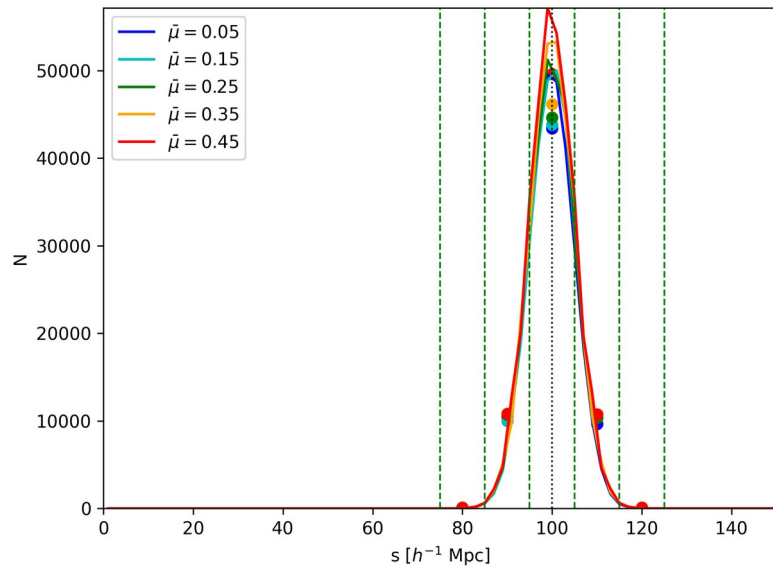
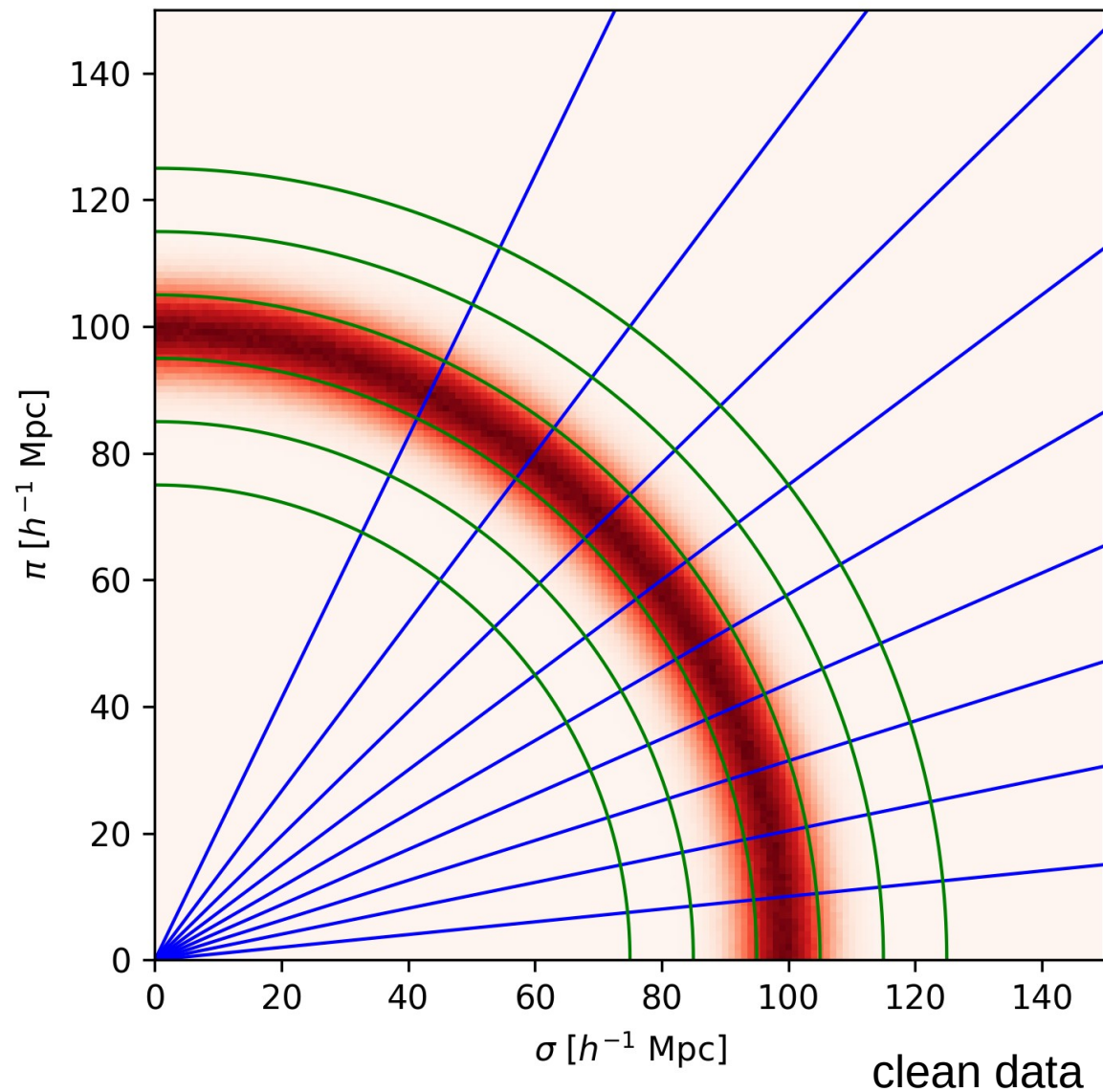
# So, what is the problem?

- Surprisingly well constraint value for the peak location in the North, but also relatively small value (tension with Planck).
- Additional tests: systematic shift of the photometric BAO as a function of  $\mu$ .
- Chan+2021 found a similar effect and also a possible solution, but there is more to it.

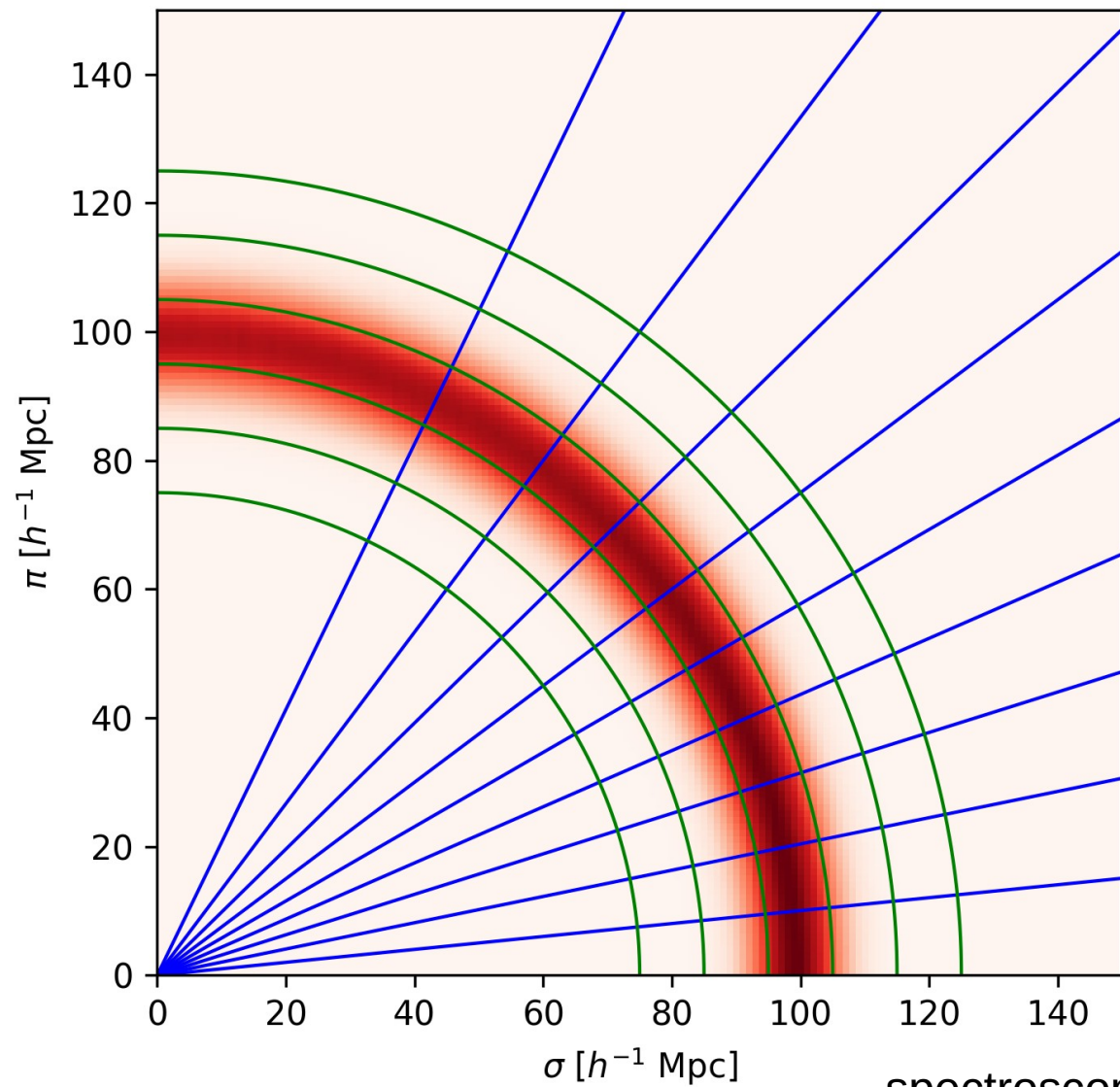




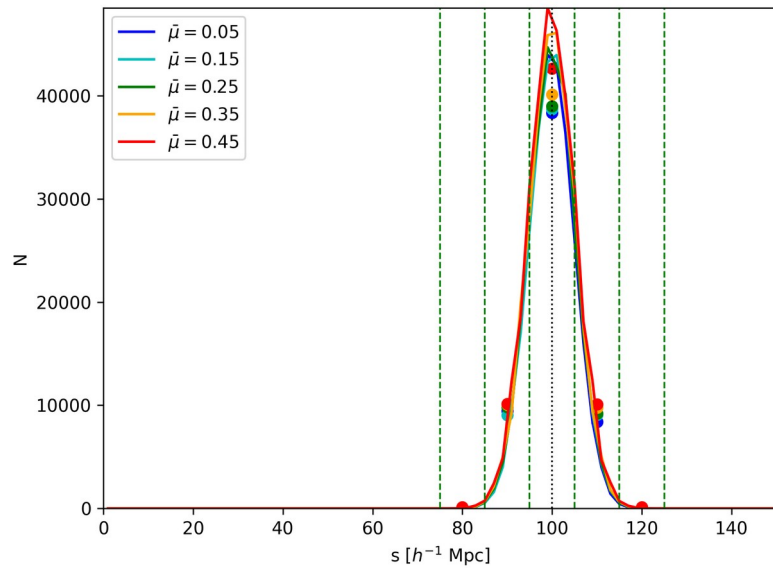


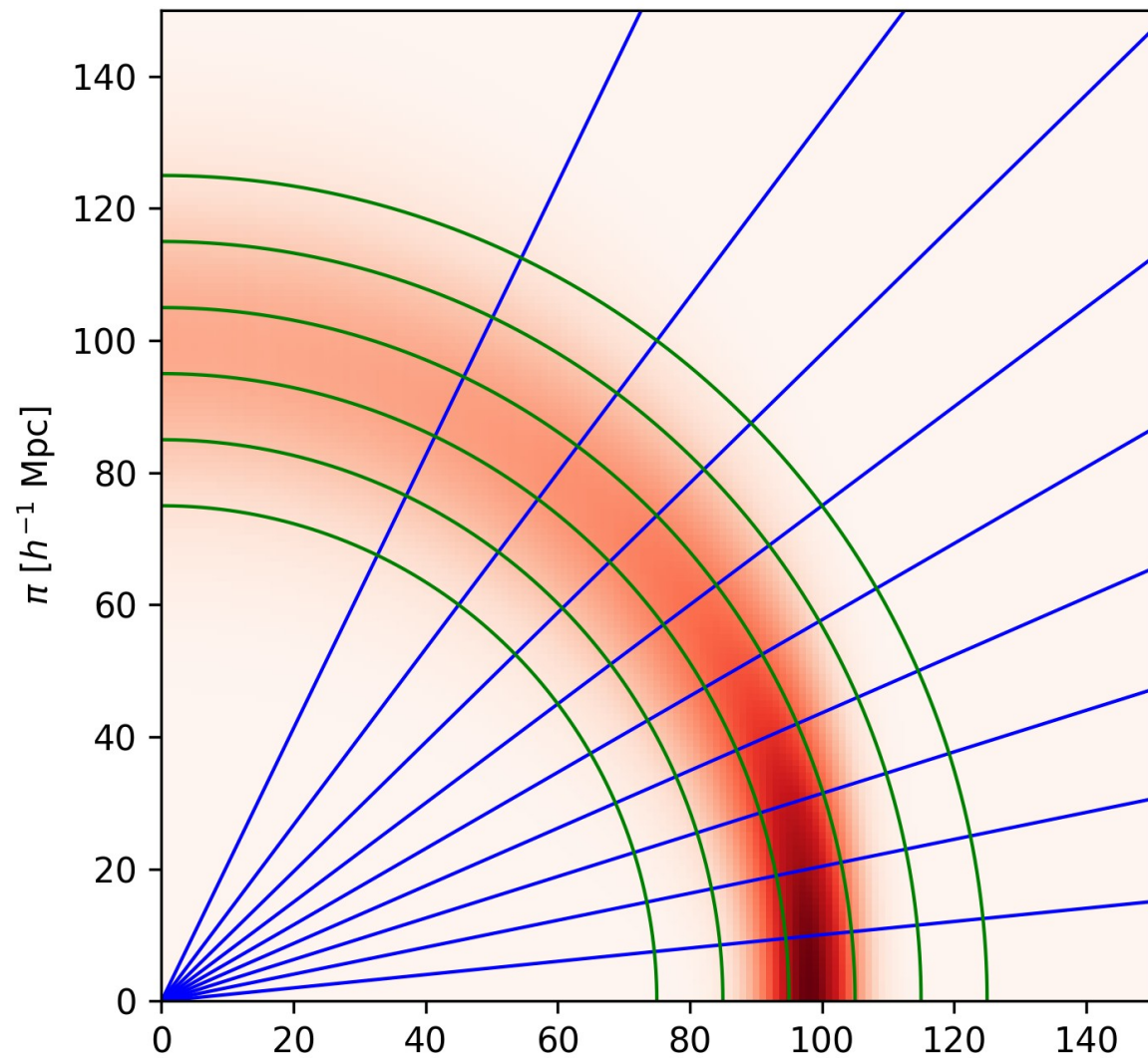




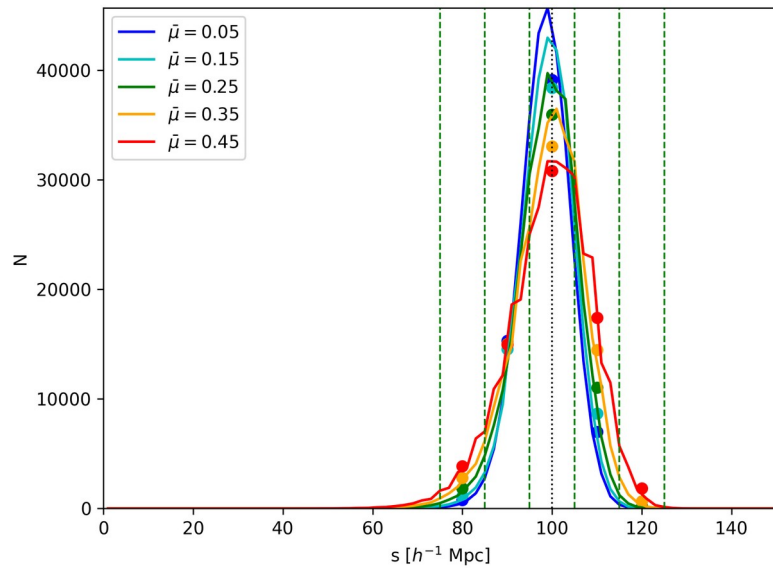


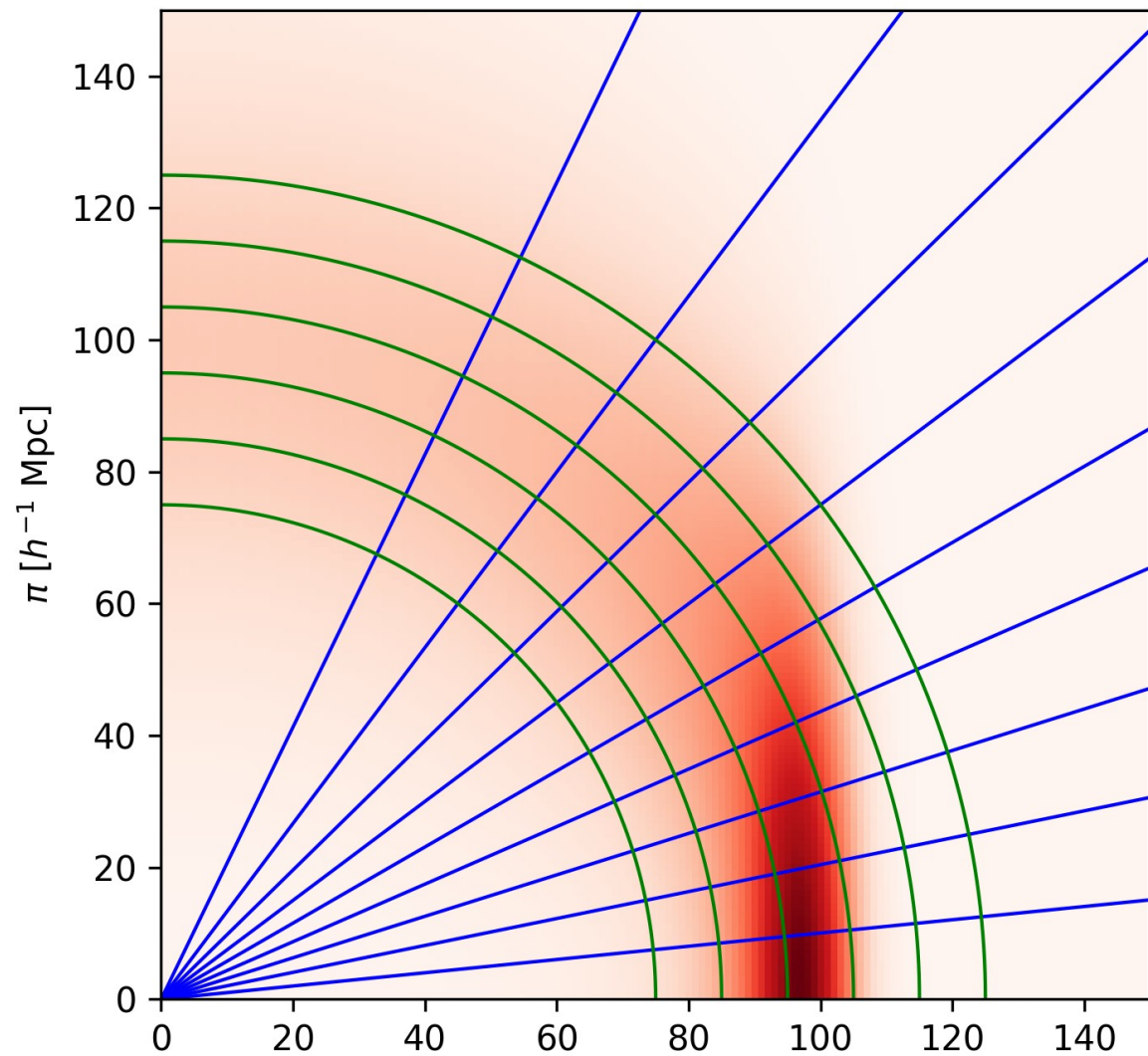
spectroscopic data



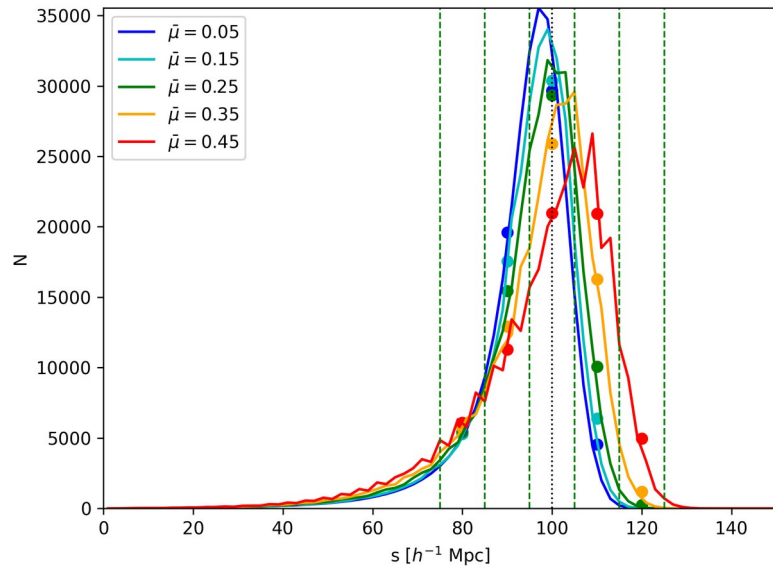


Photometric data  $\sigma_0=0.005$

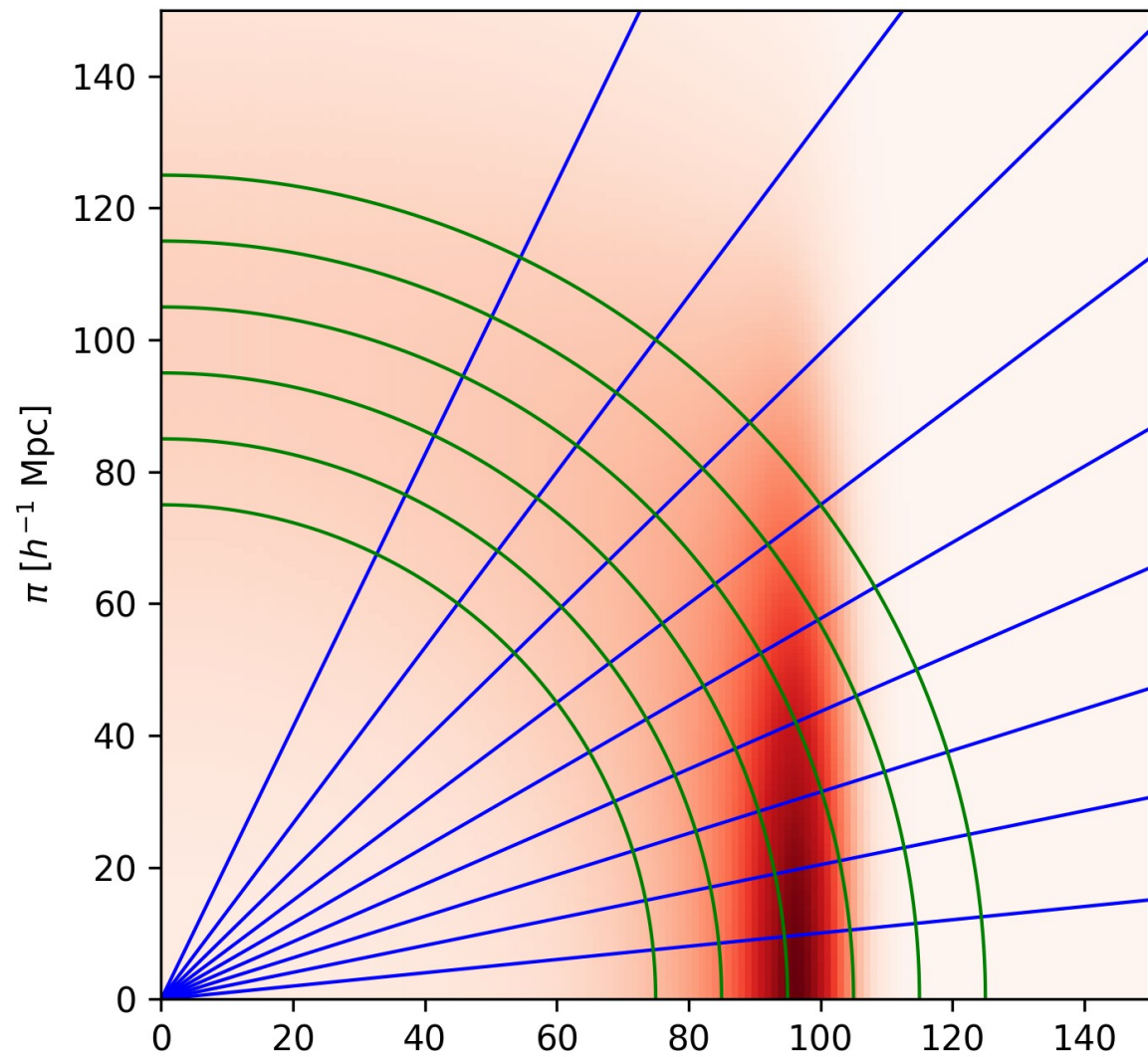




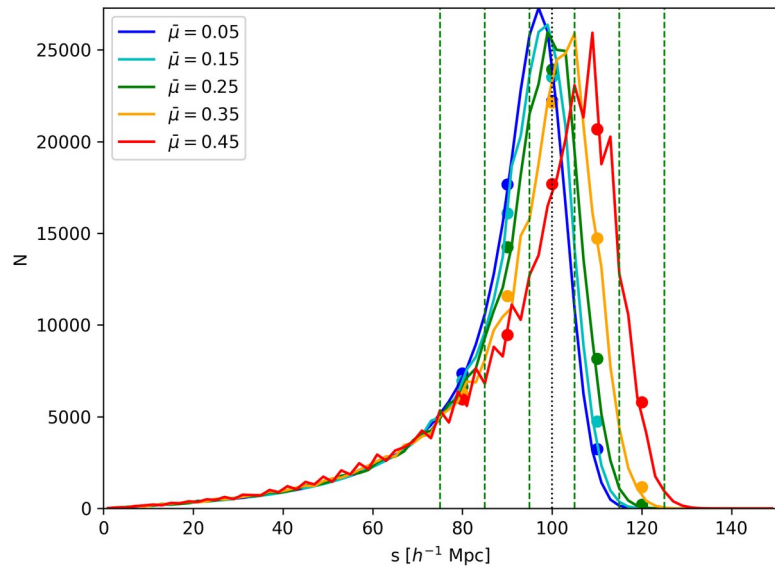
Photometric data  $\sigma_0=0.010$

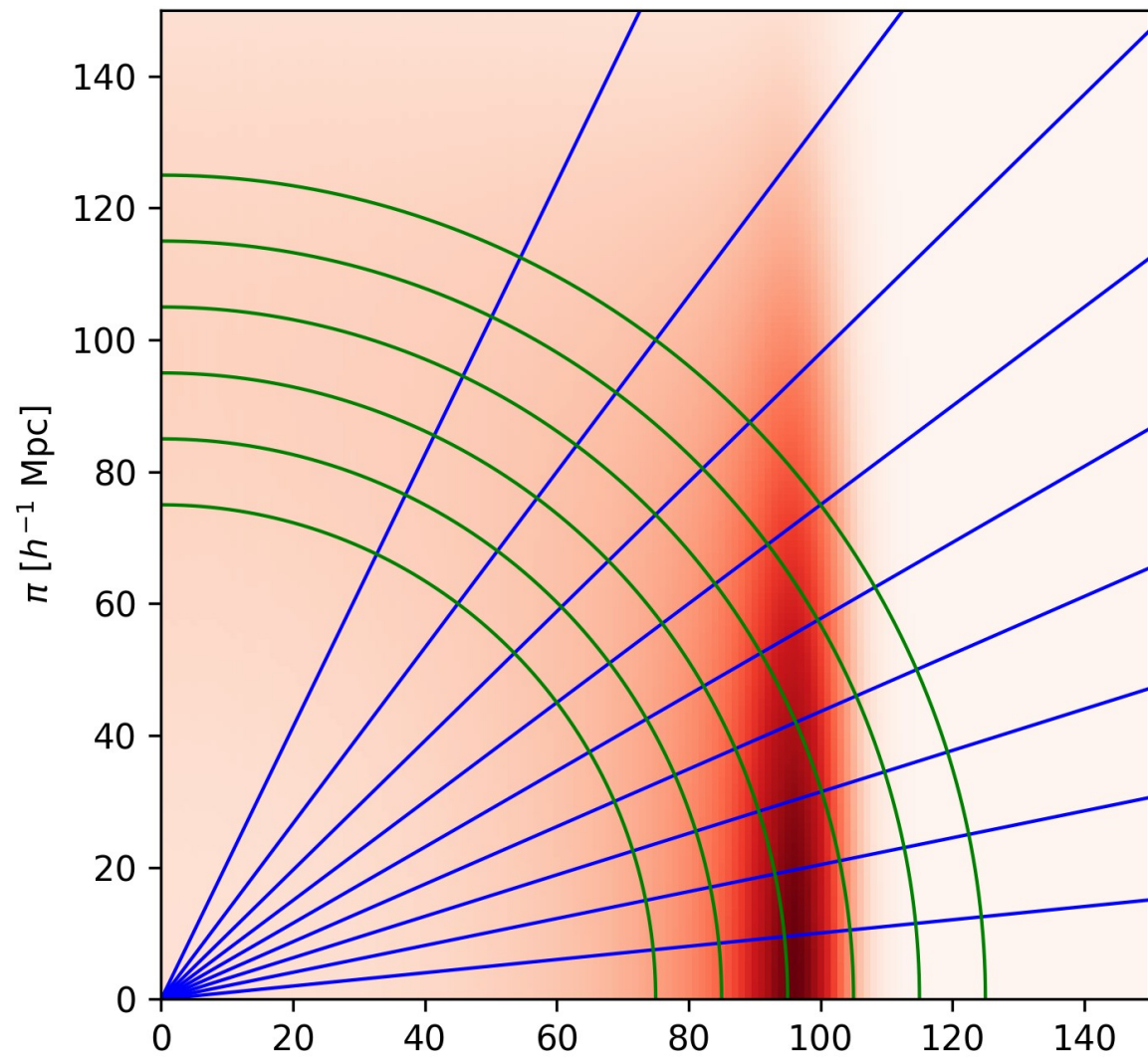




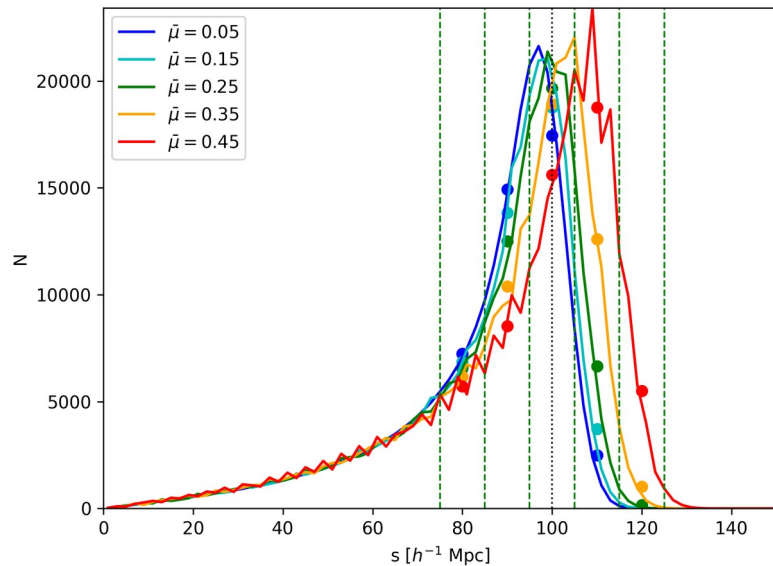


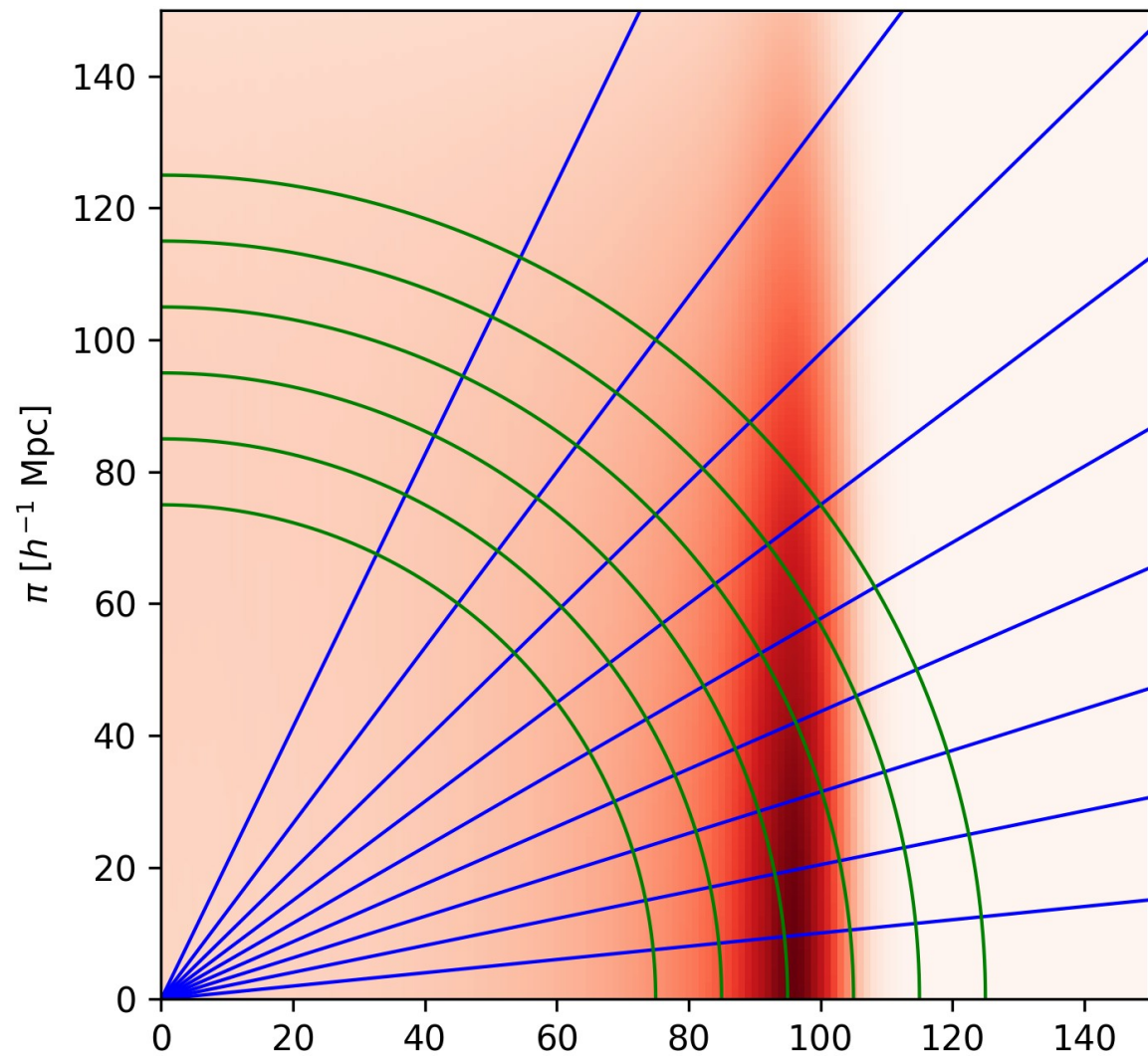
Photometric data  $\sigma_0=0.015$



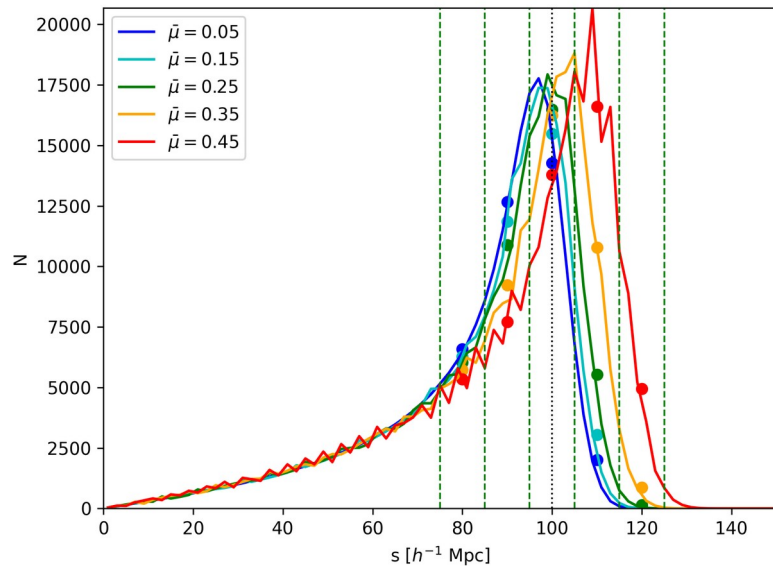


Photometric data  $\sigma_0=0.020$

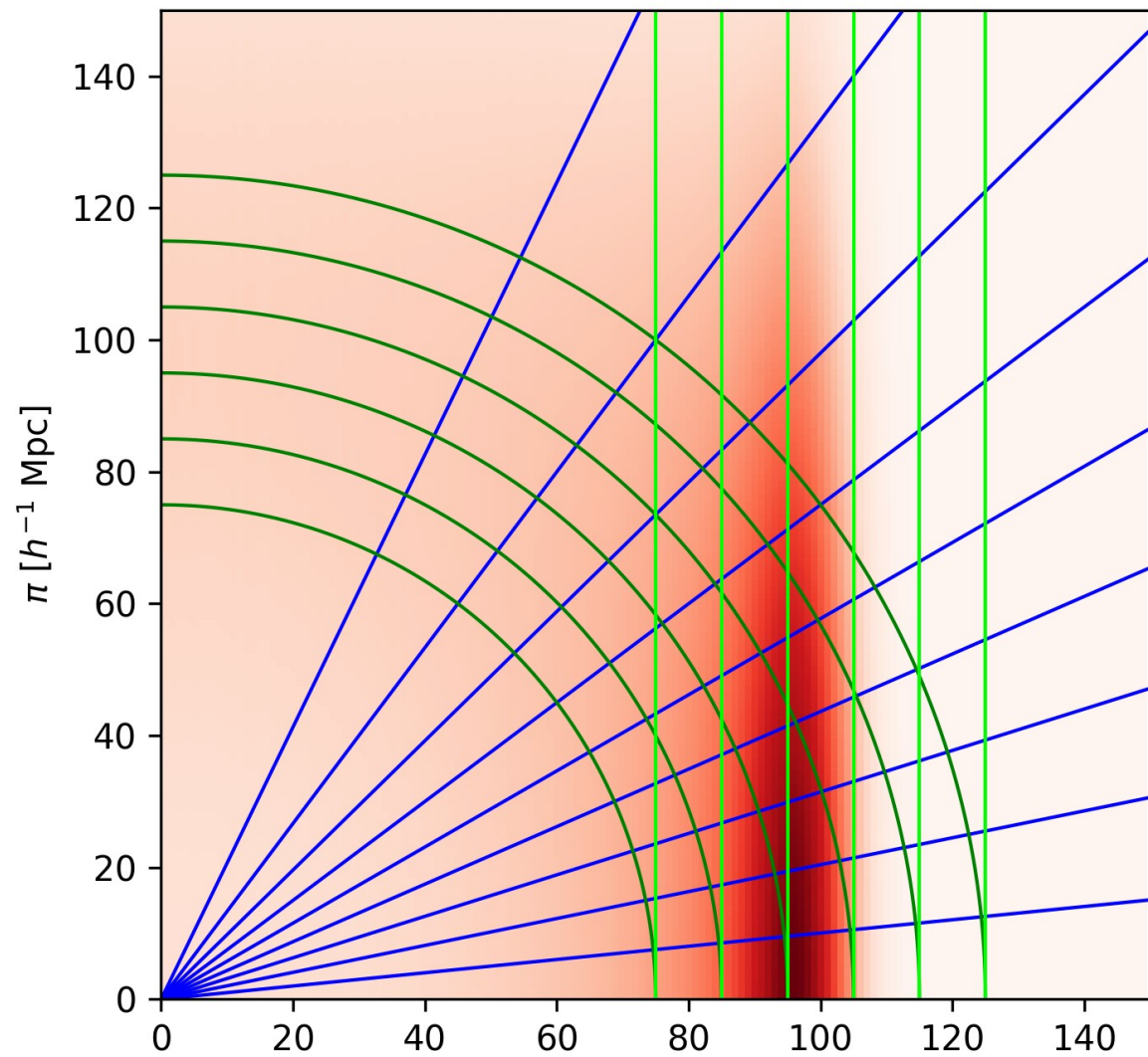




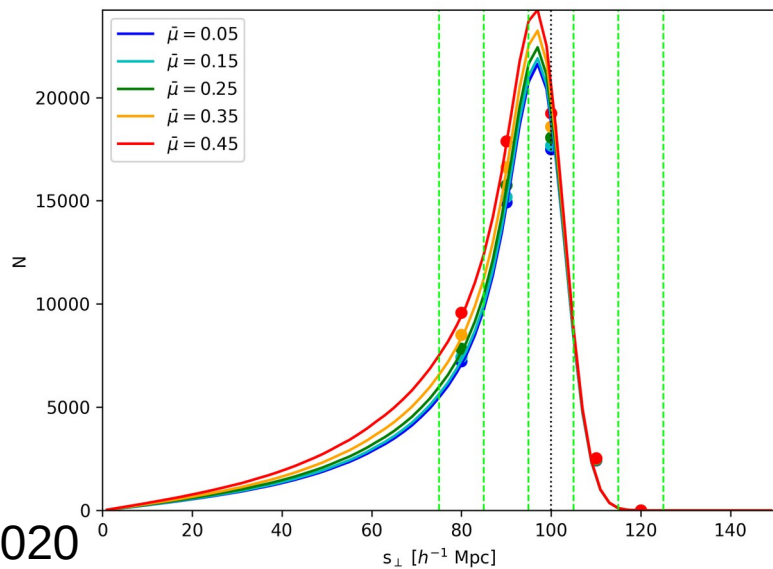
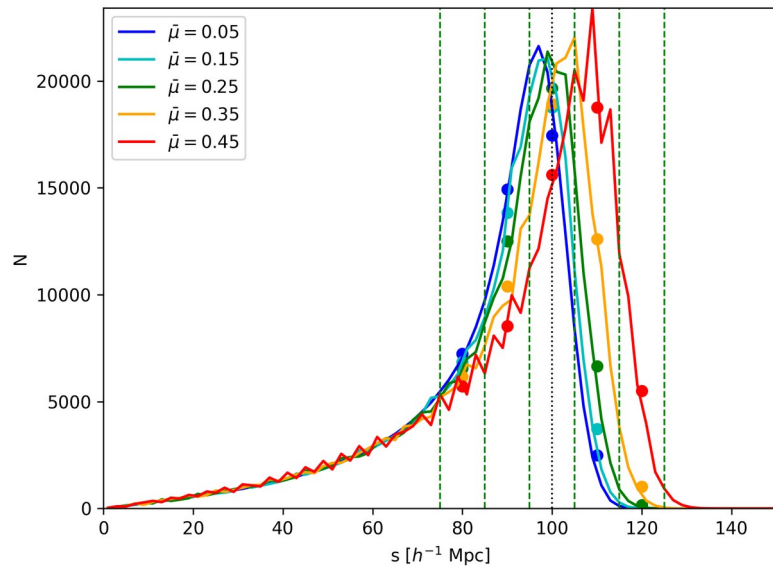
Photometric data  $\sigma_0=0.025$

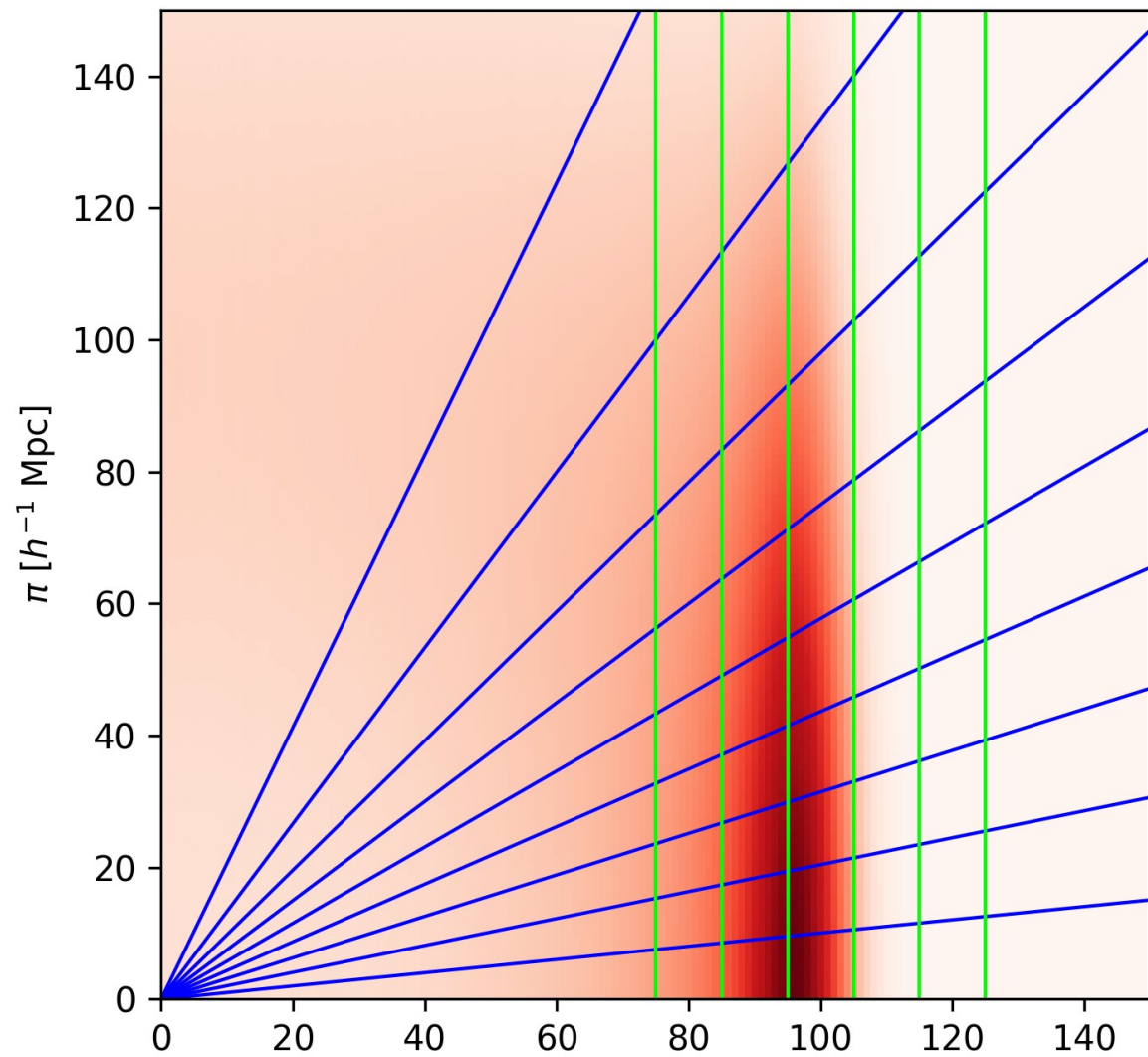




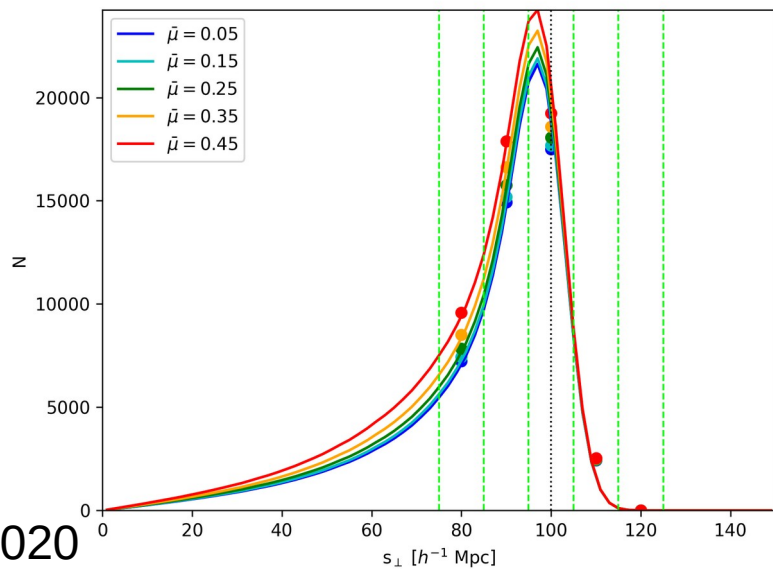
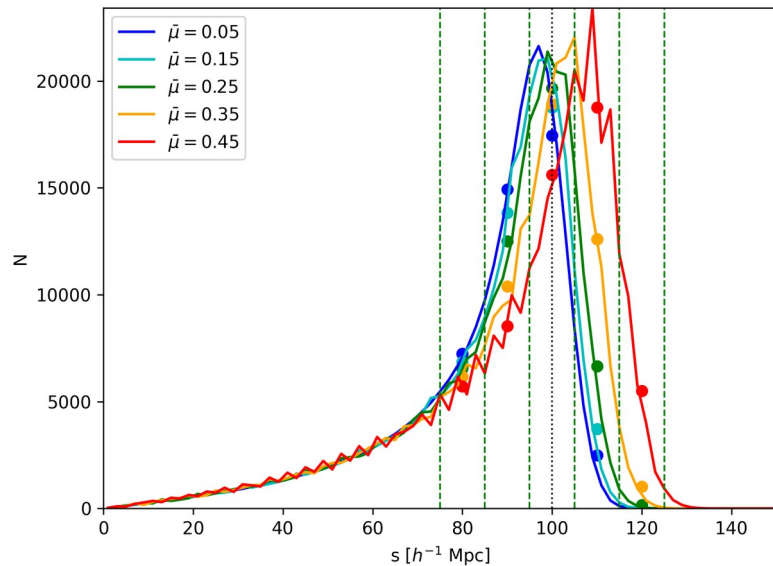


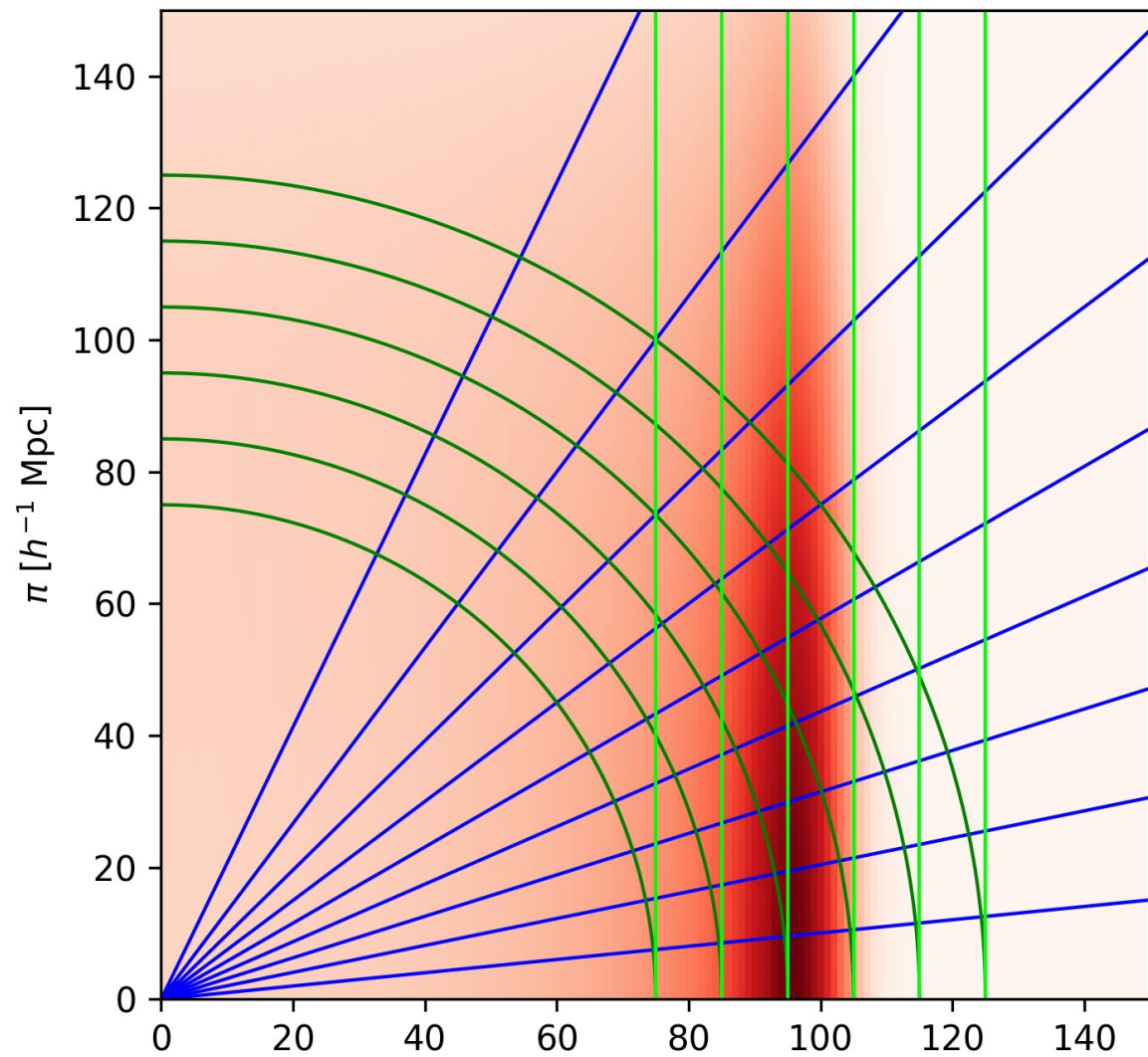
Photometric data  $\sigma_0=0.020$



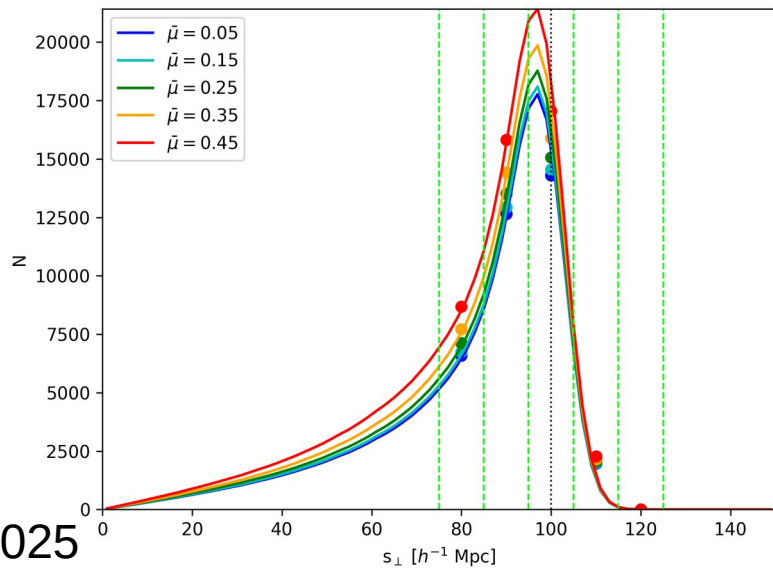
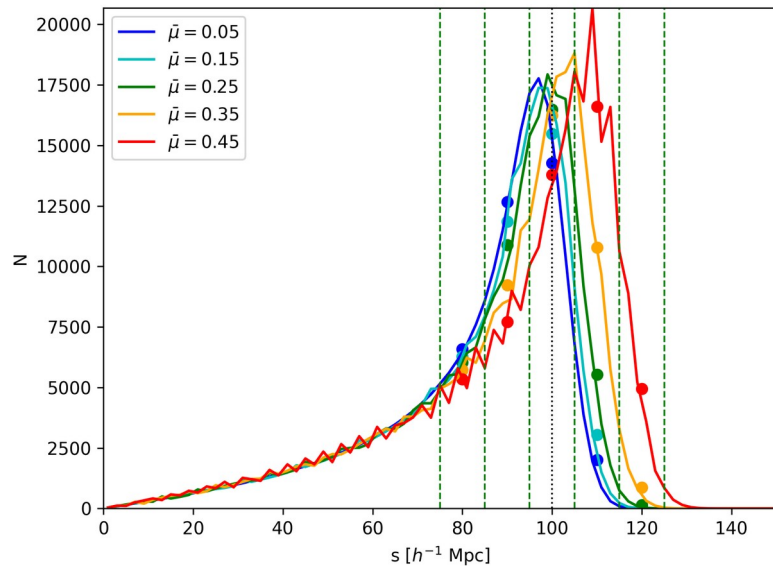


Photometric data  $\sigma_0=0.020$

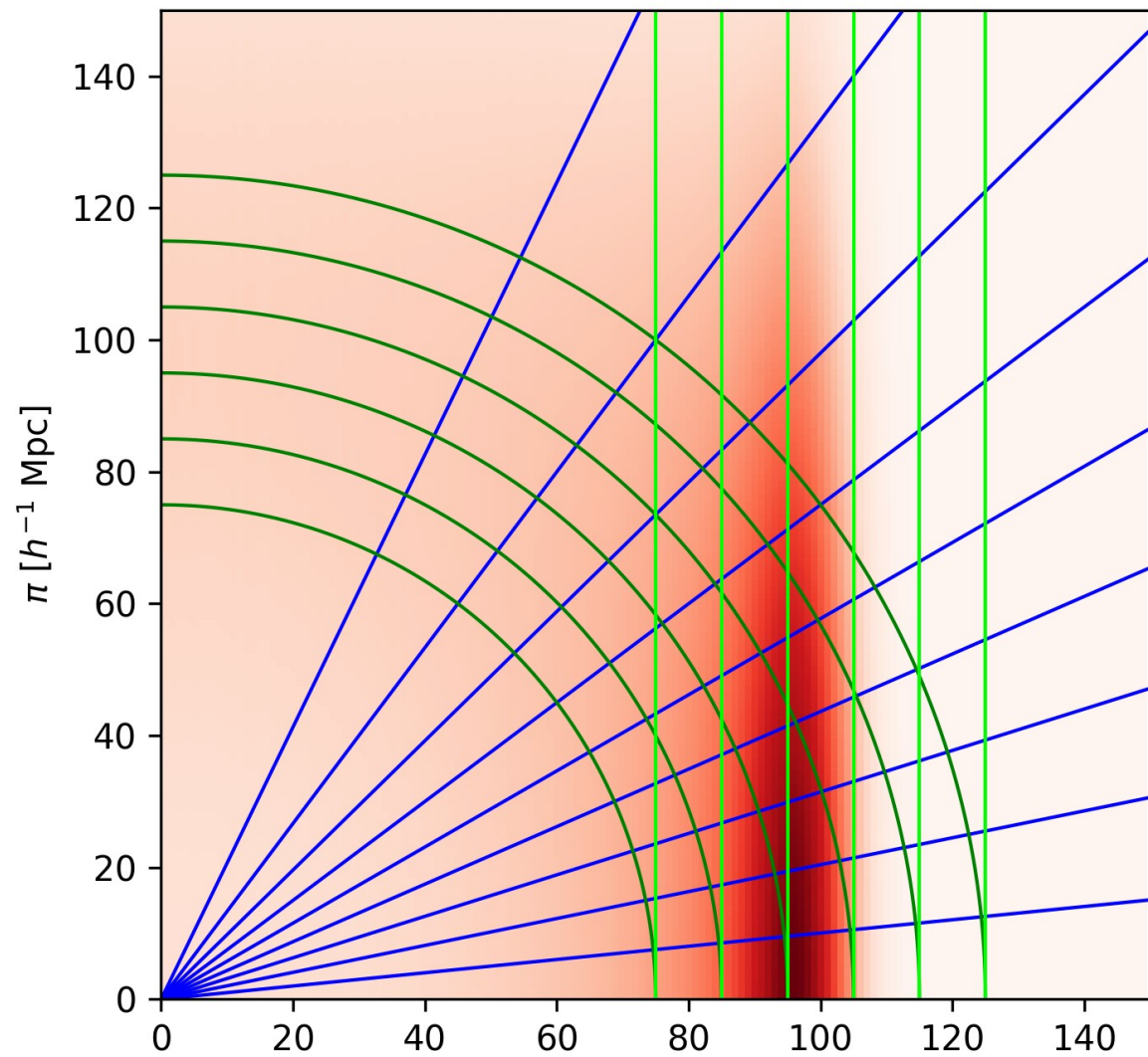




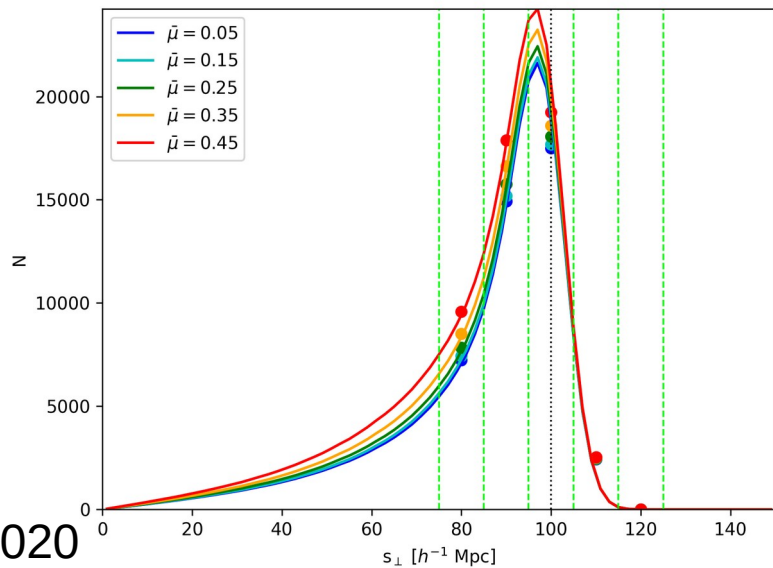
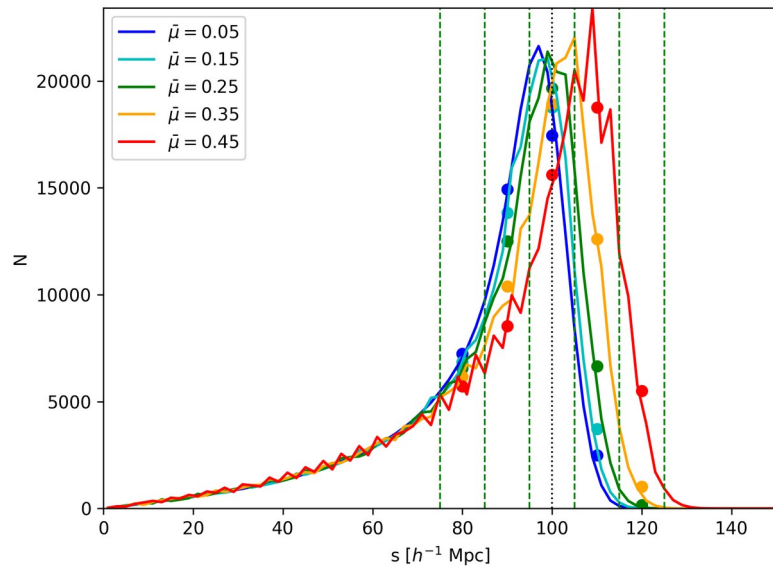
Photometric data  $\sigma_0=0.025$

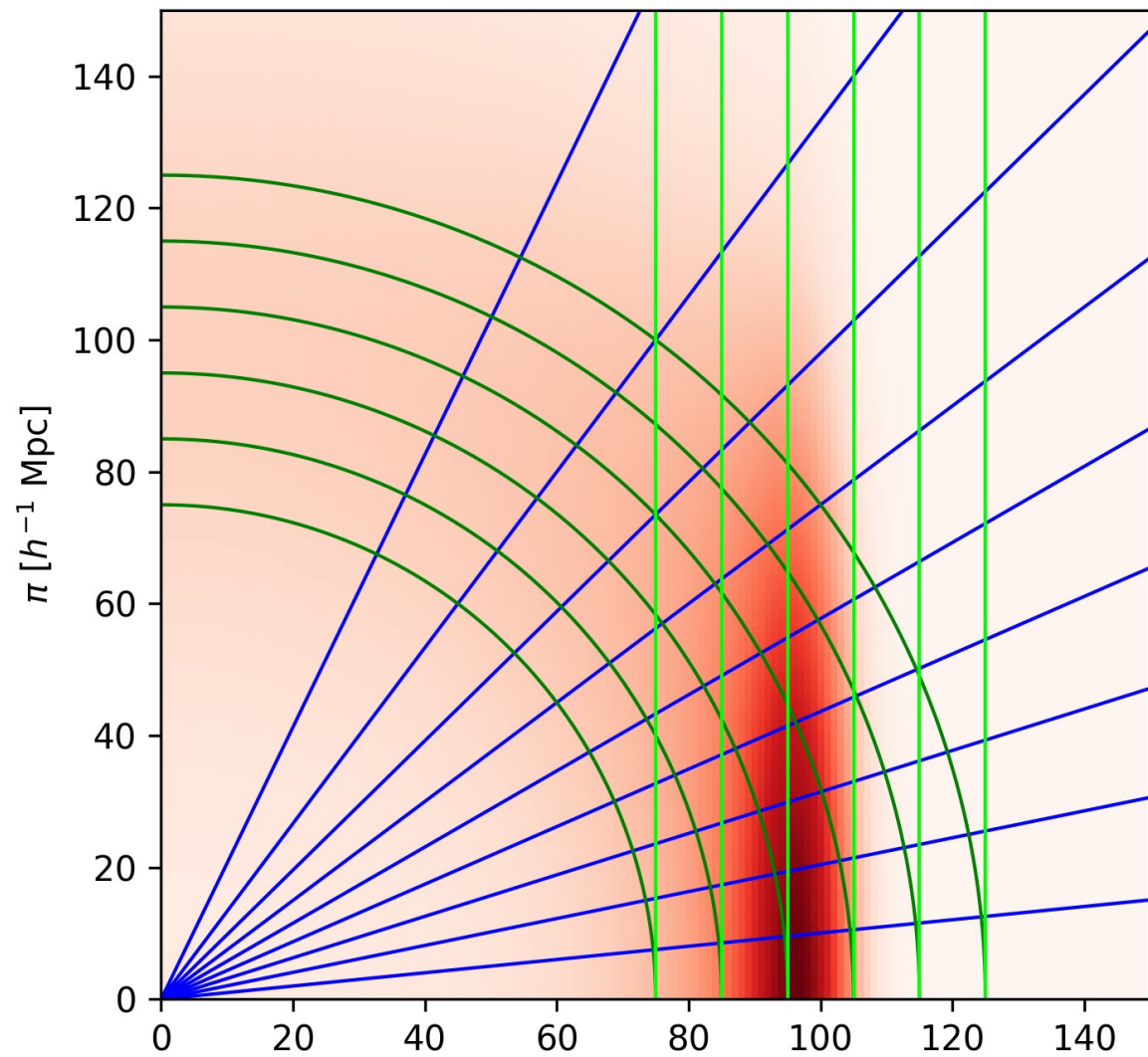




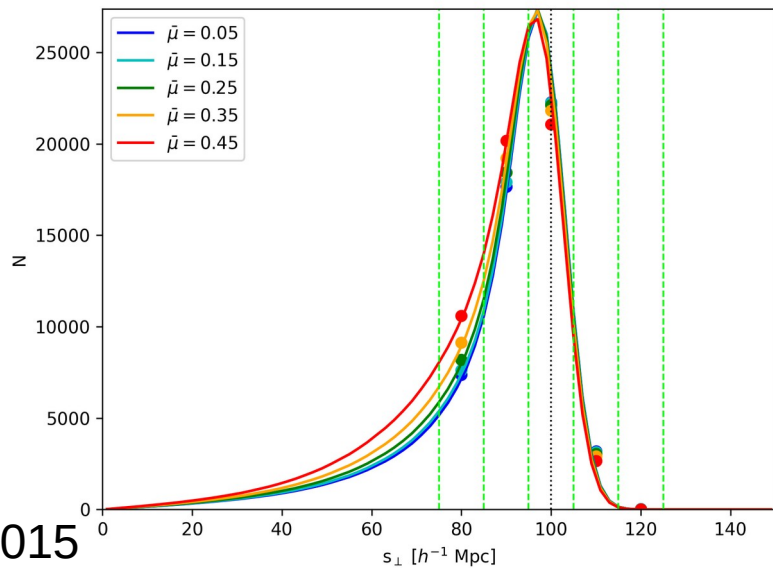
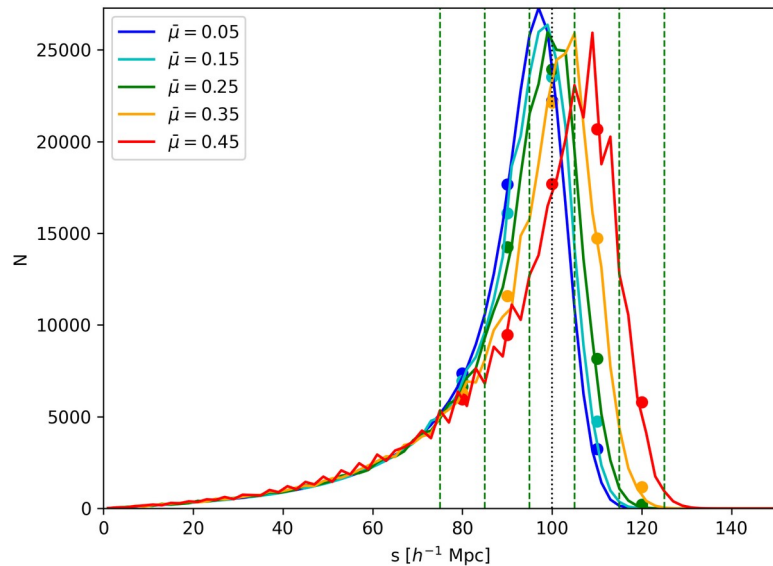


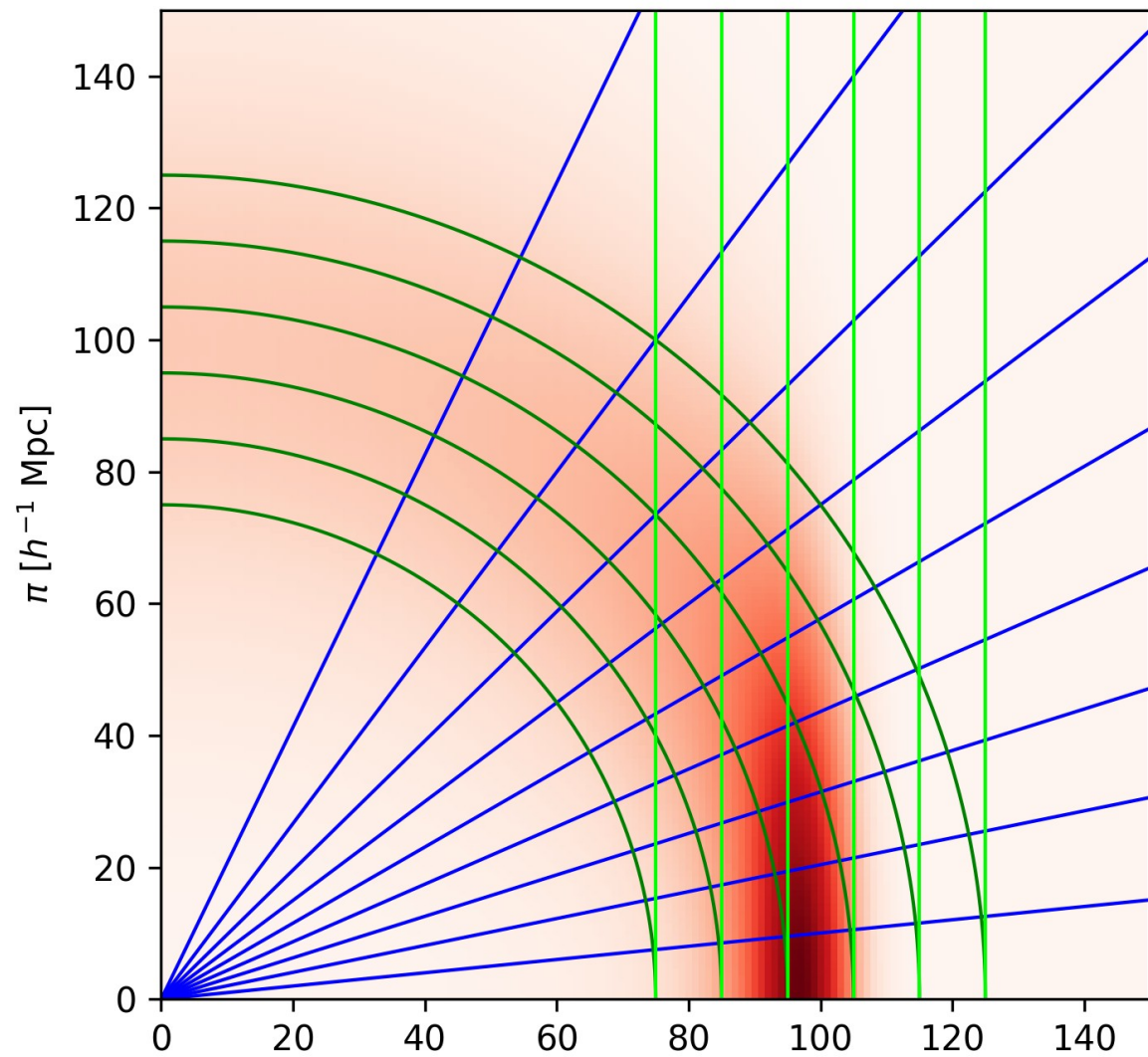
Photometric data  $\sigma_0=0.020$



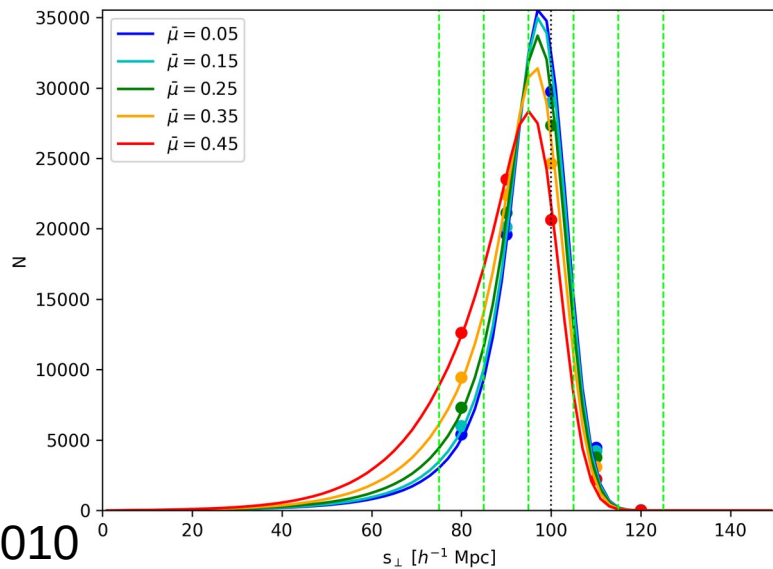
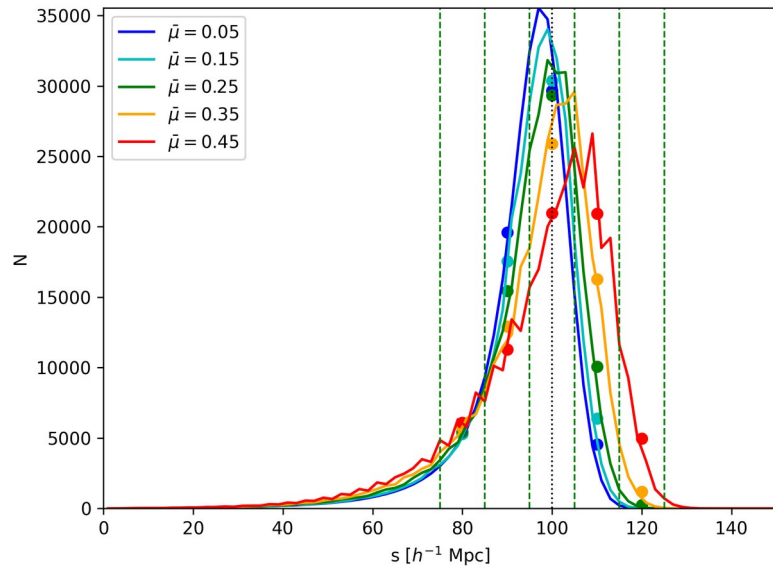


Photometric data  $\sigma_0=0.015$

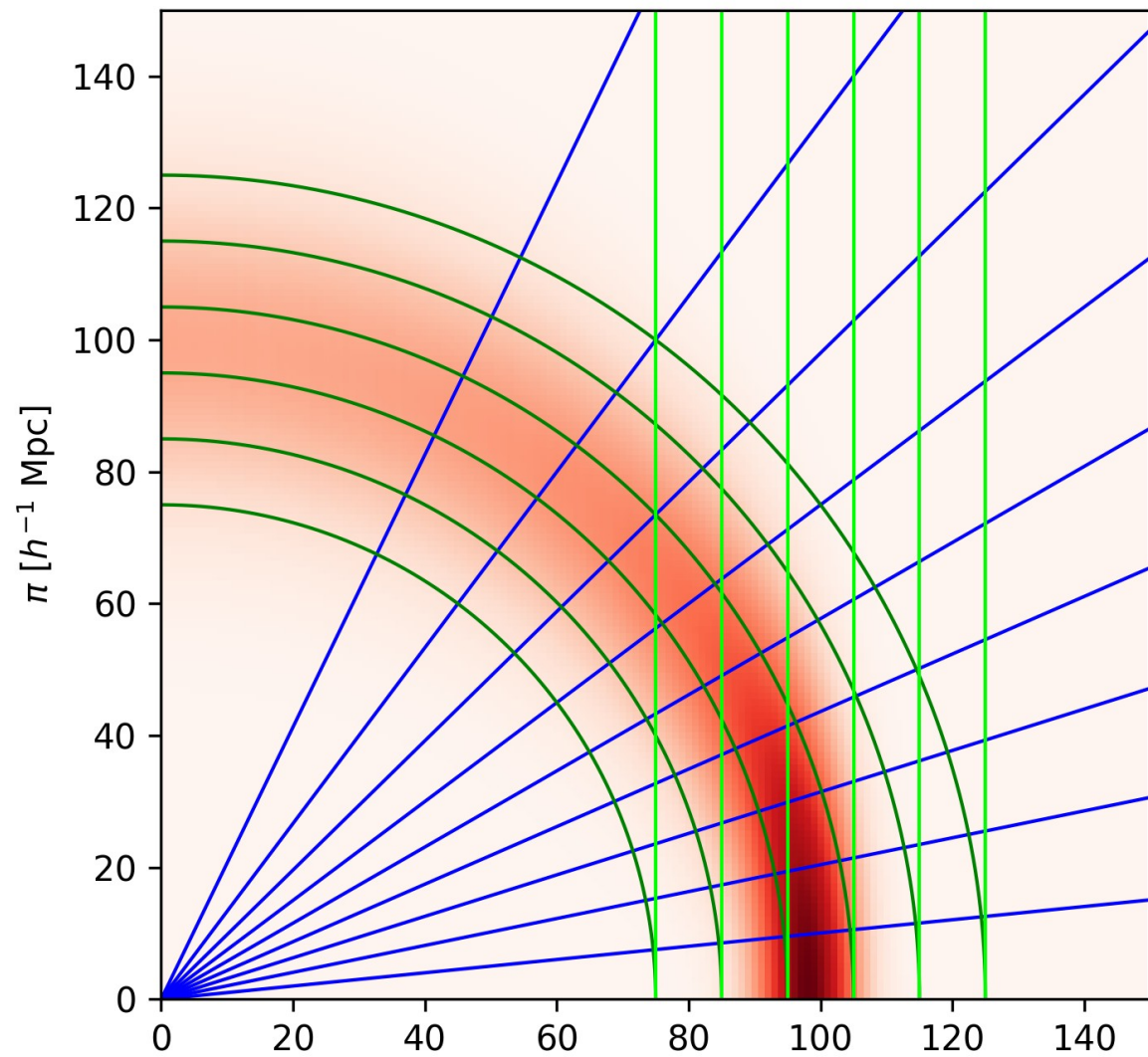




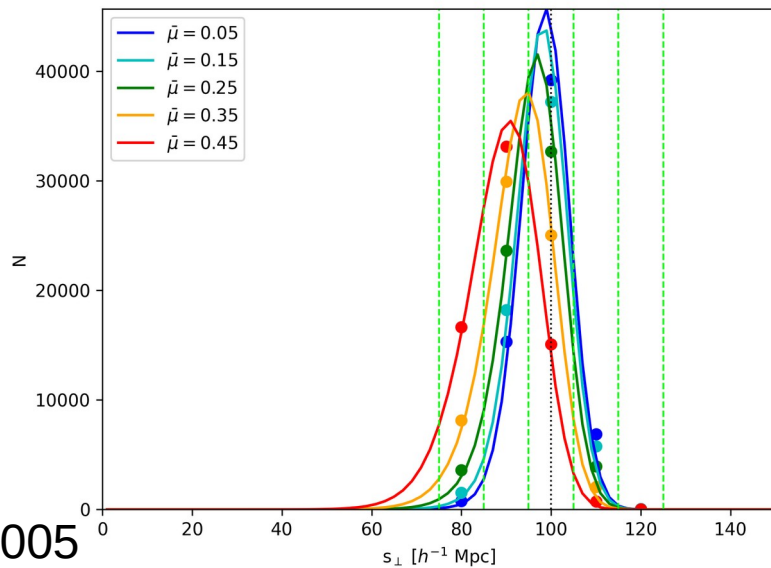
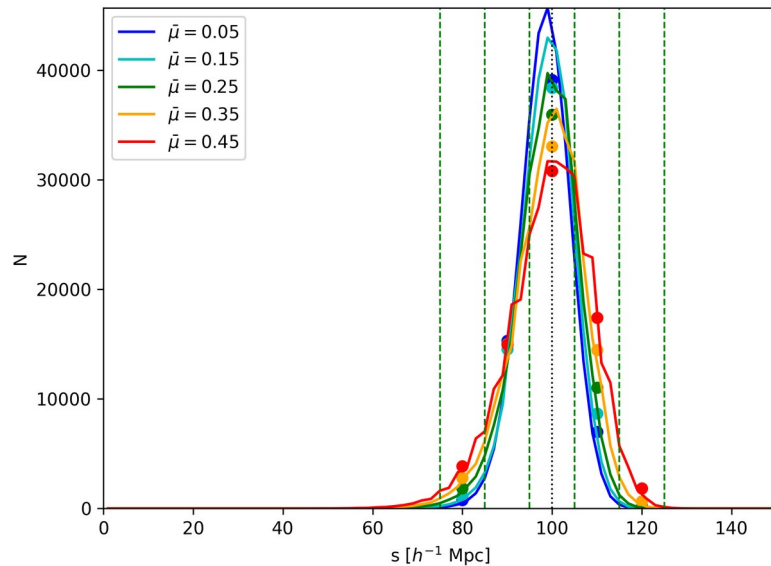
Photometric data  $\sigma_0=0.010$

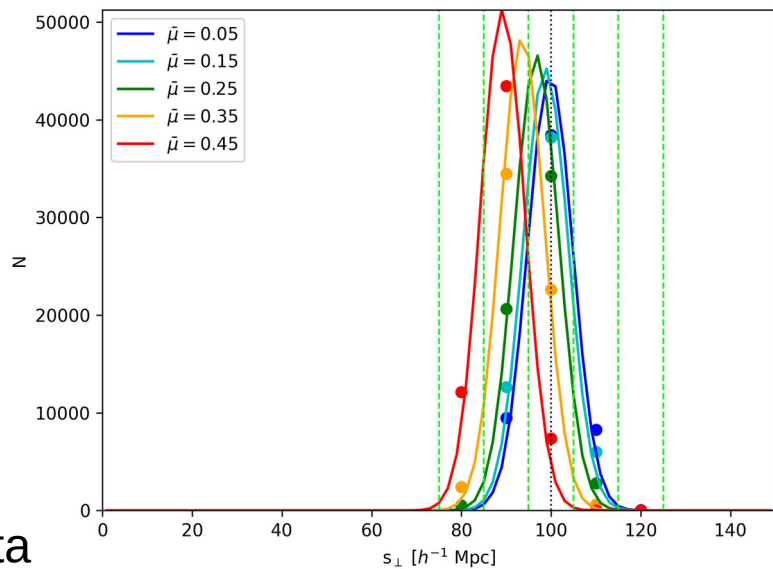
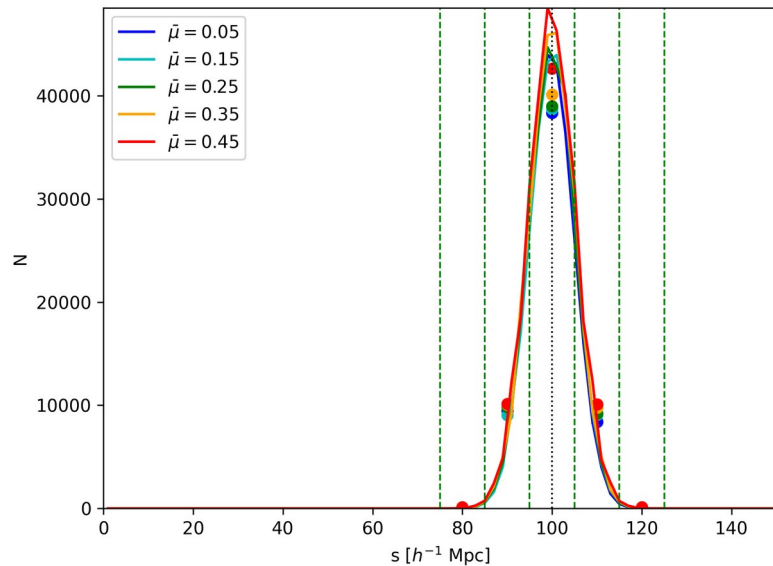
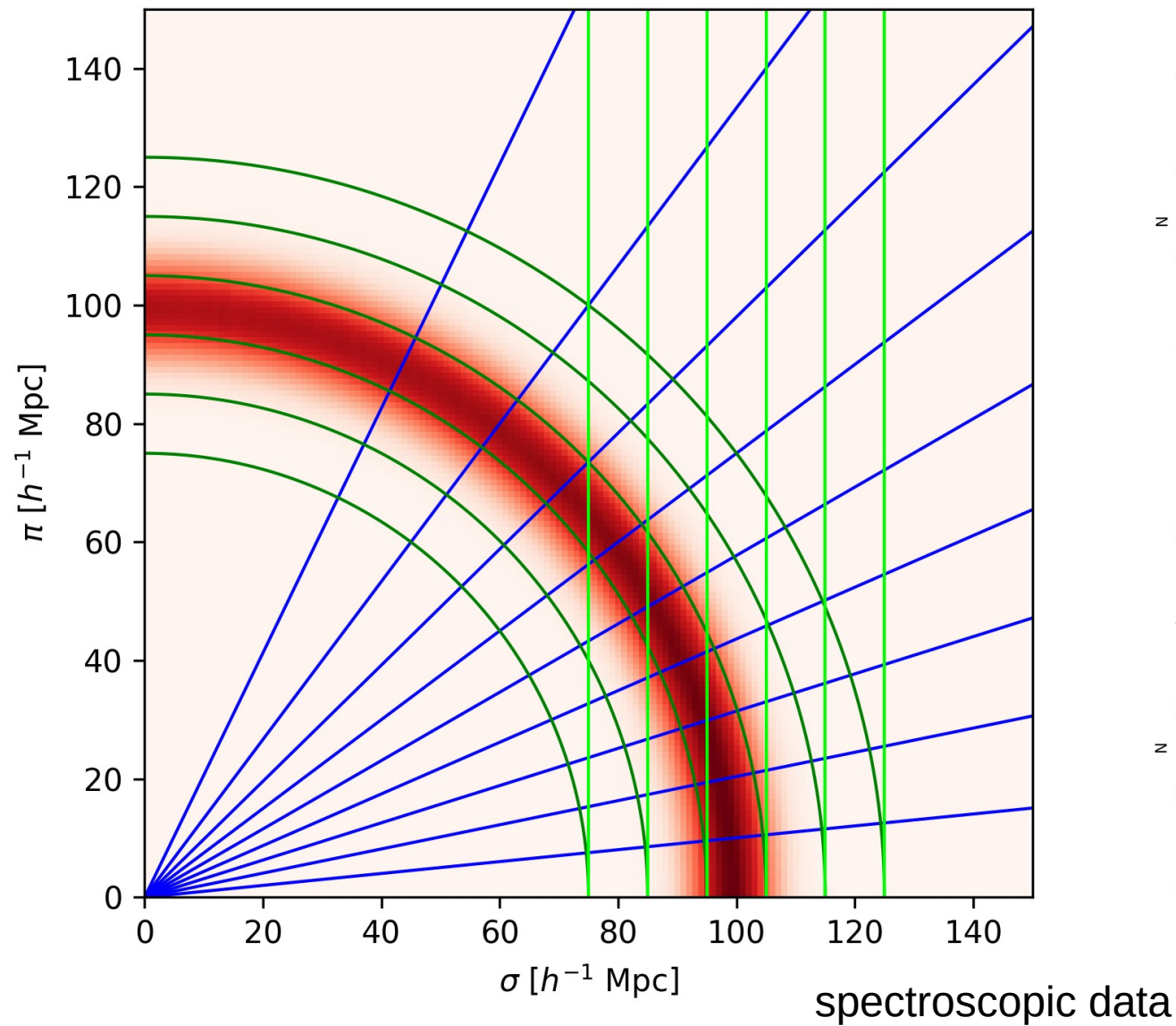


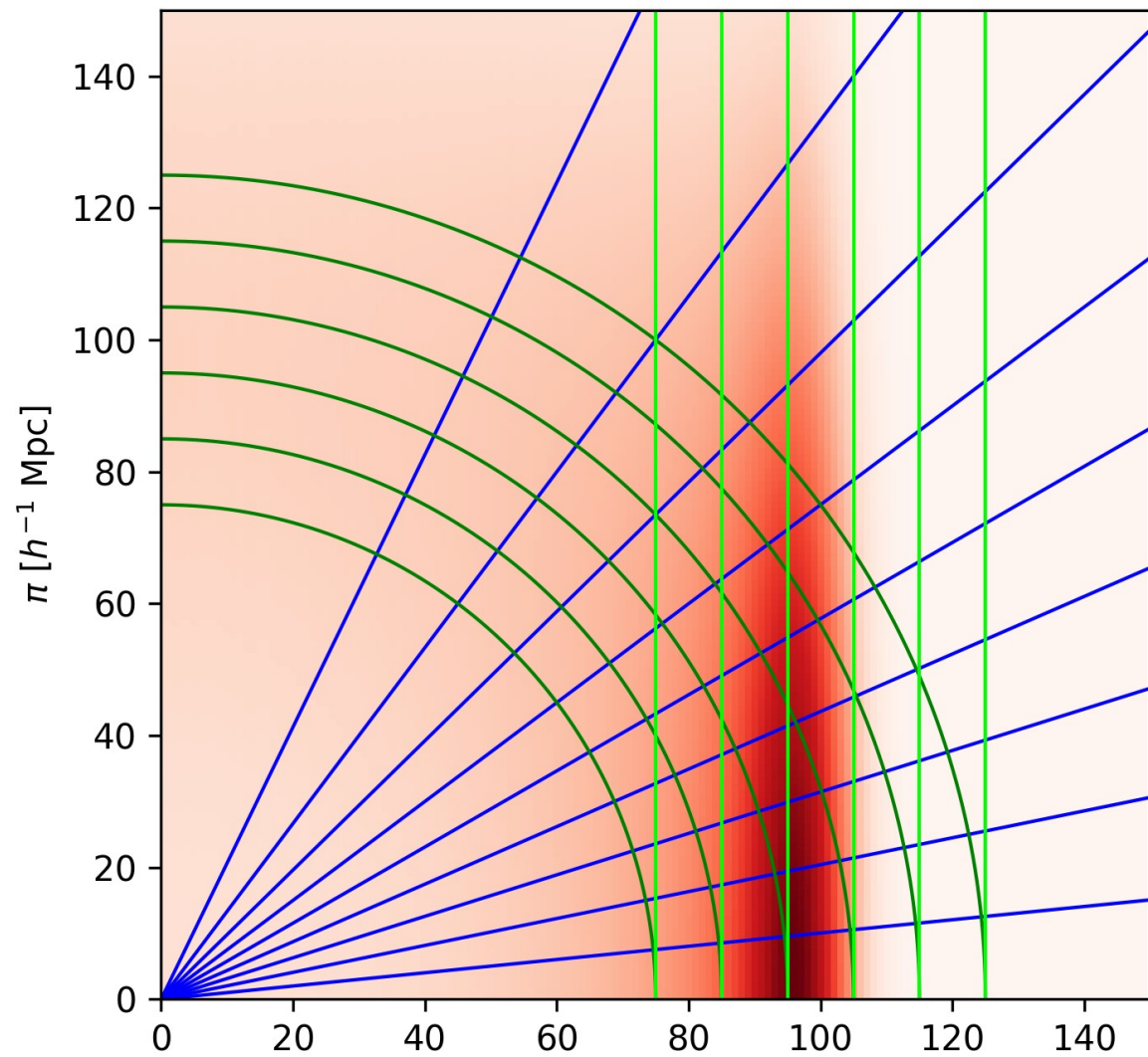




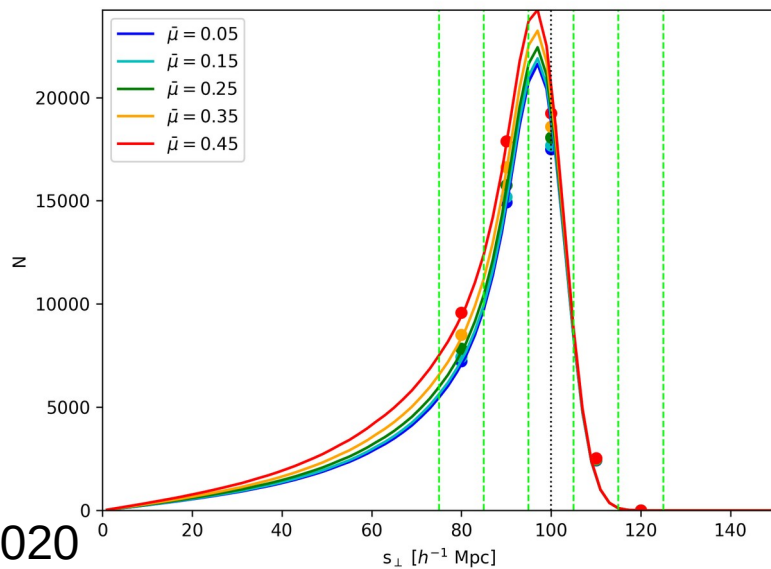
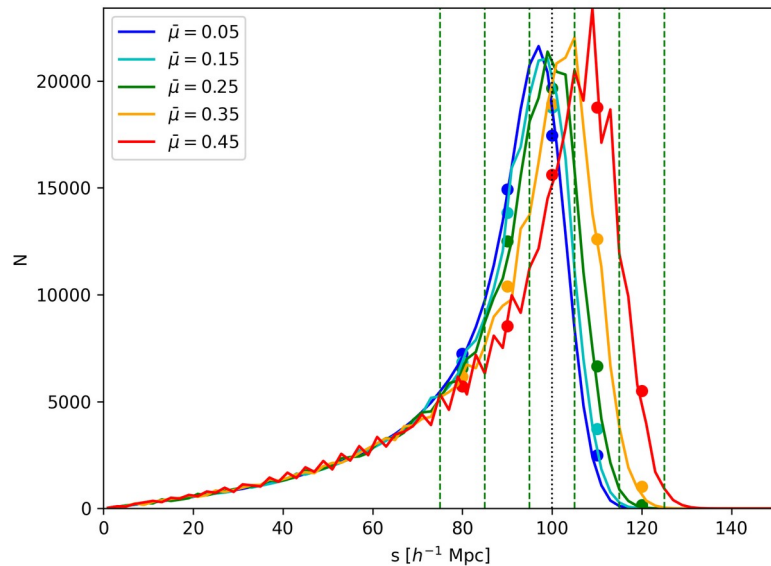
Photometric data  $\sigma_0=0.005$



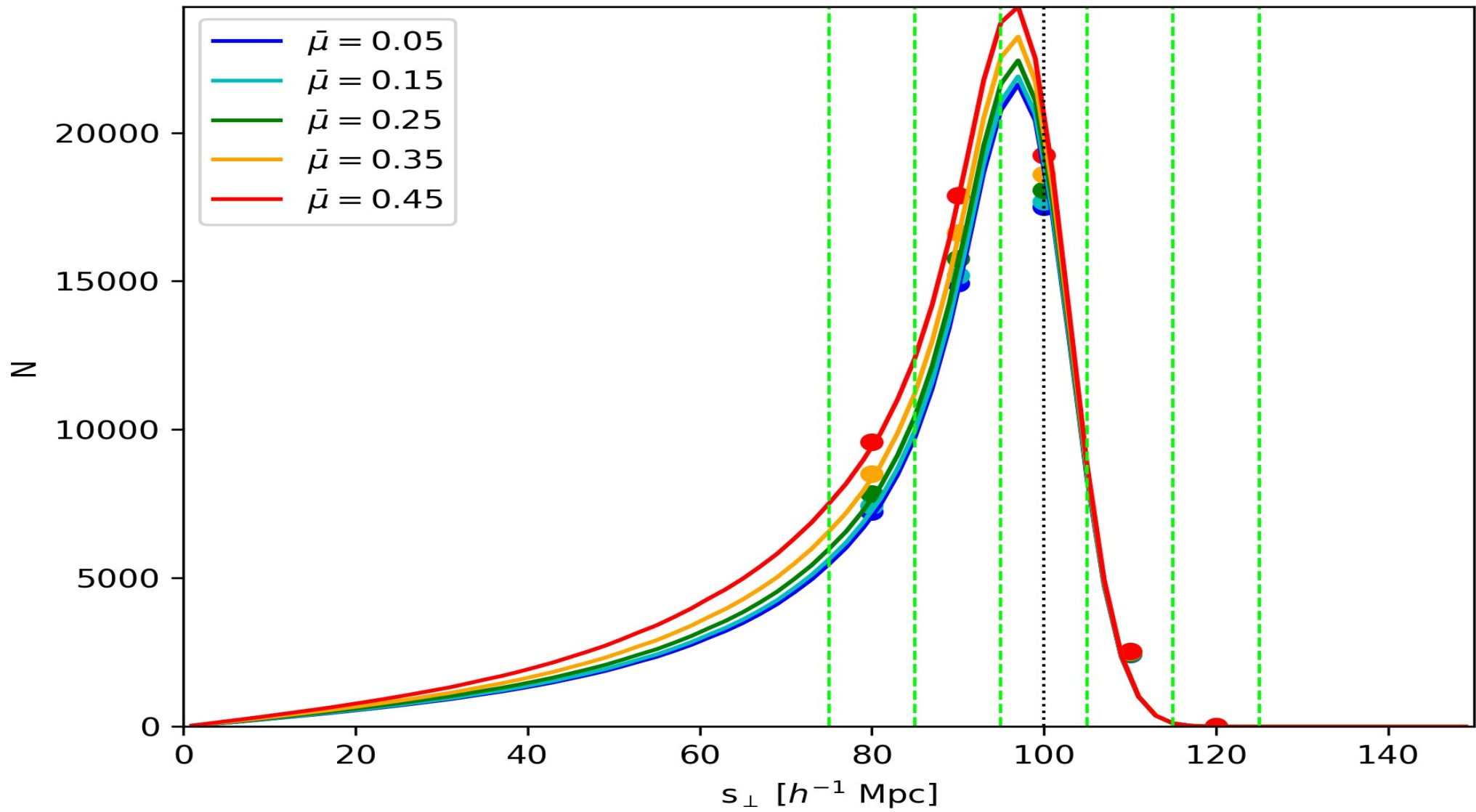




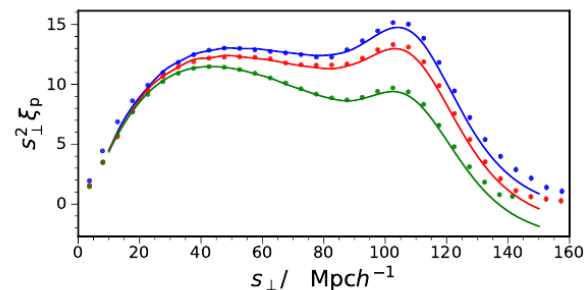
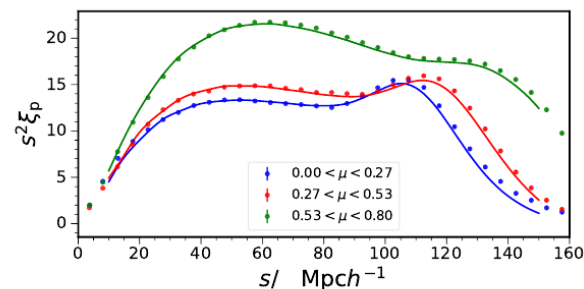
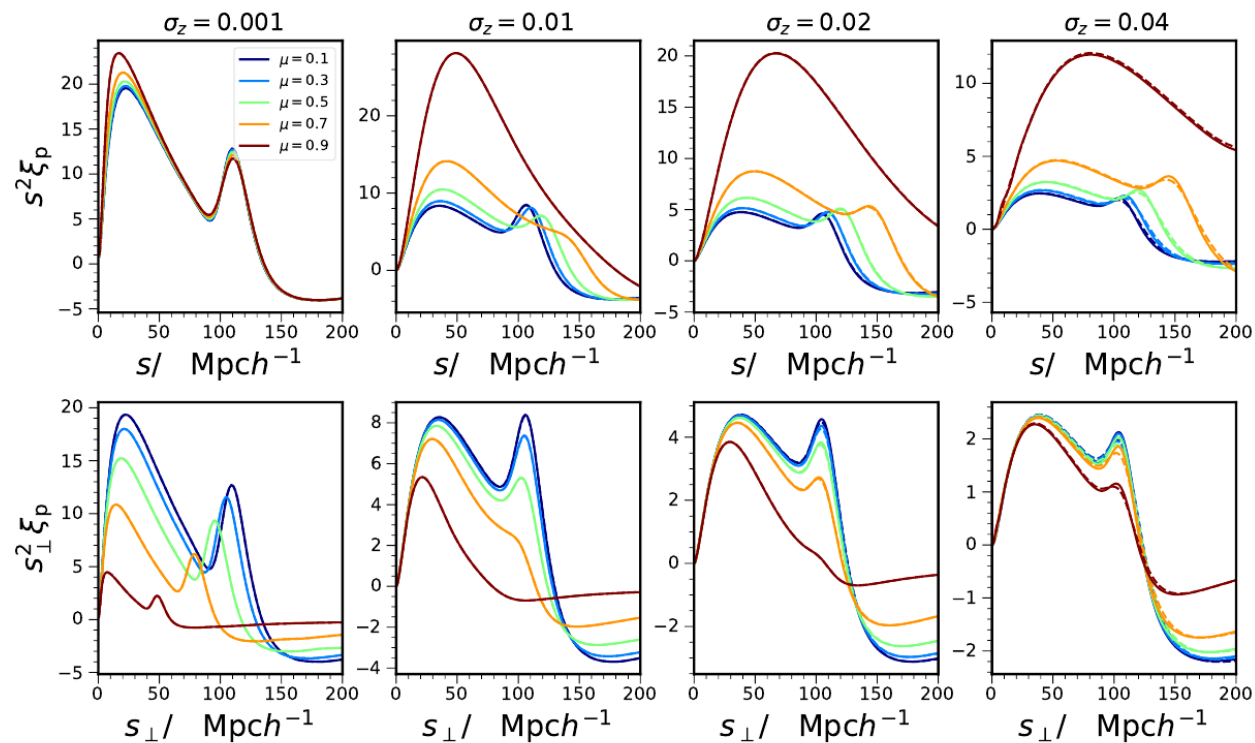
Photometric data  $\sigma_0=0.020$





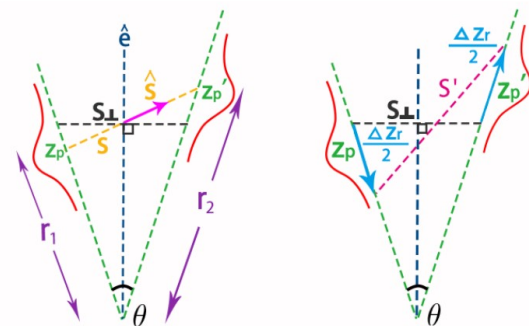


# Old news: shifting BAO peak

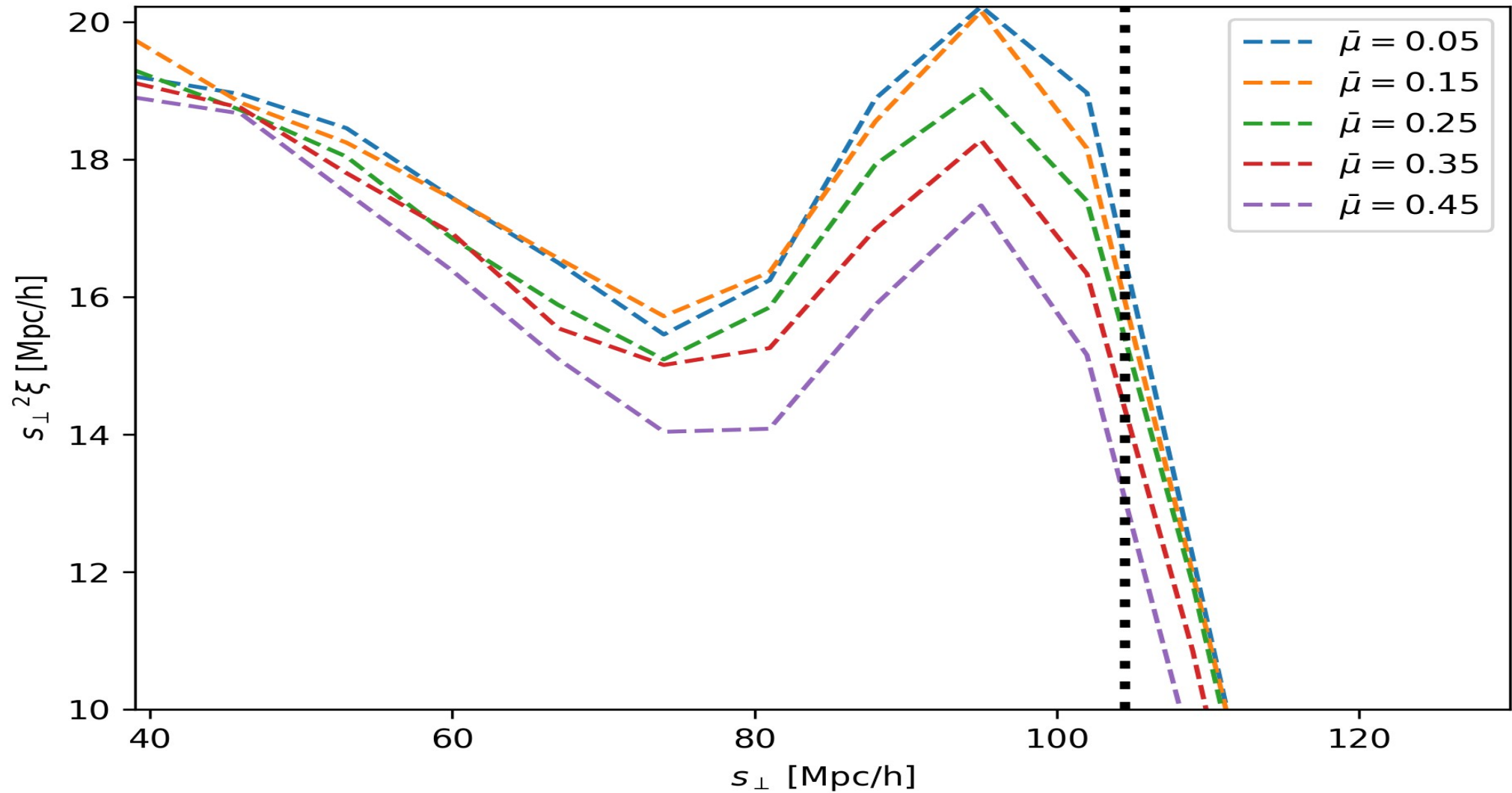


All figures on this slide  
are from Chan+2021  
(arXiv:2110.13332)

Solution:  $S \rightarrow S_{\perp}$



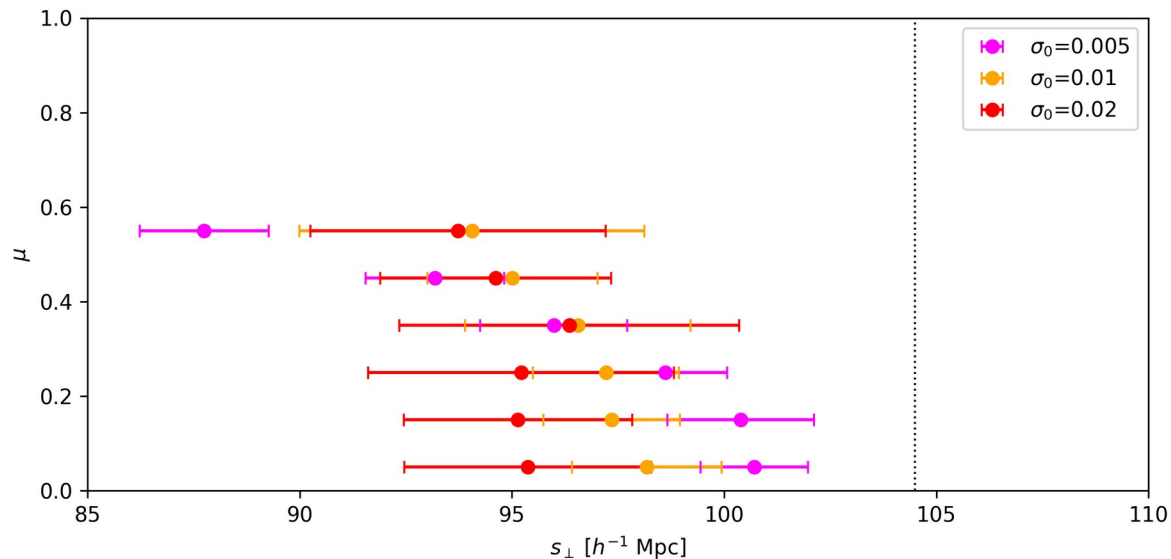
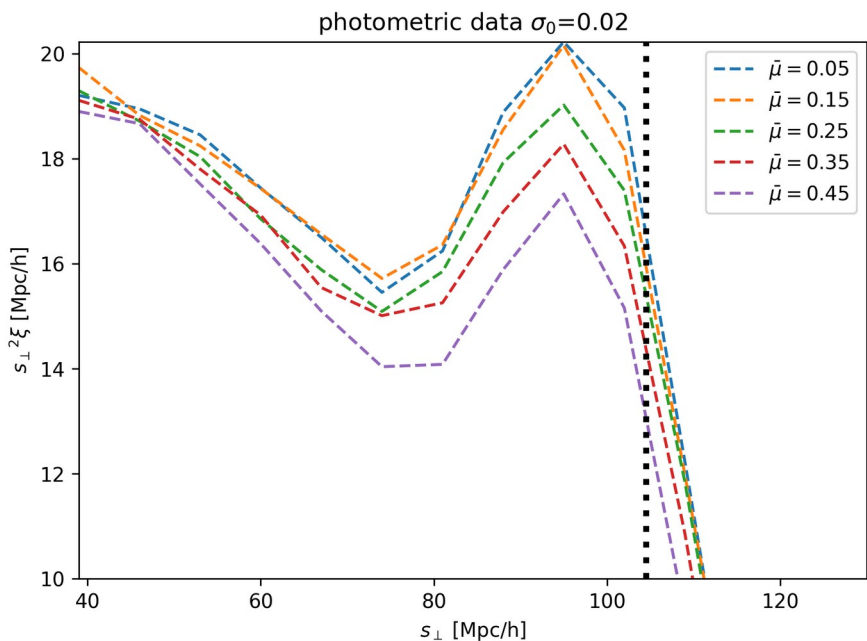
photometric data  $\sigma_0=0.02$





# Fresh news: BAO peak offset

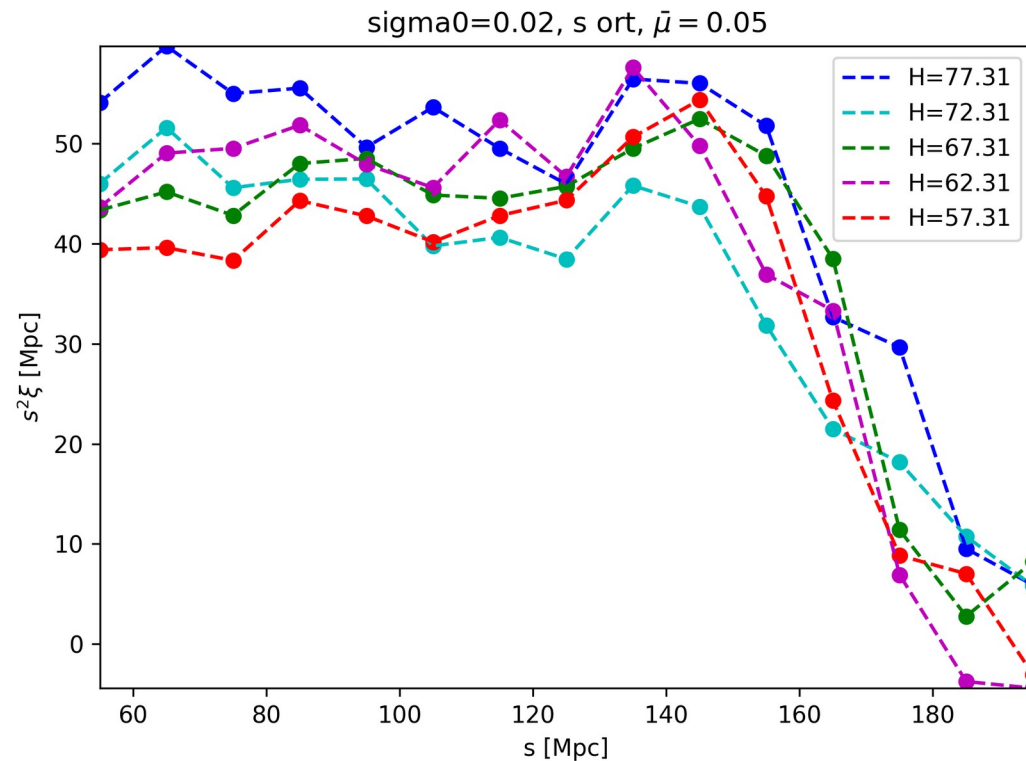
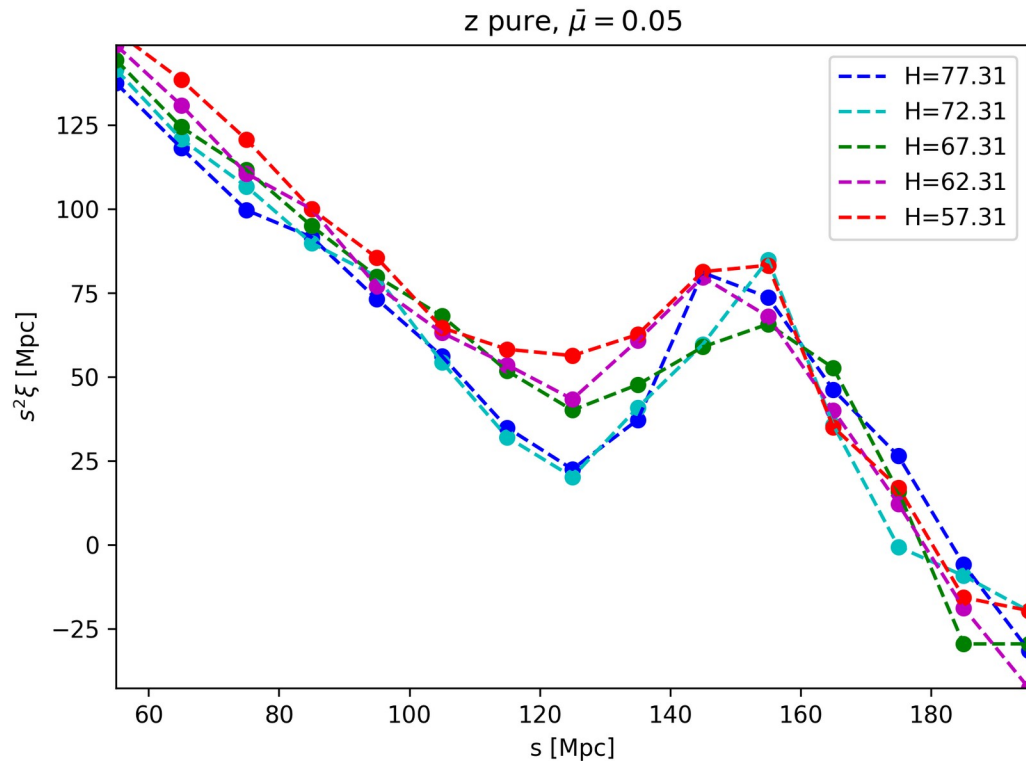
- One detail missed: the location of the **photometric BAO** is **systematically offset** from the spectroscopic BAO peak



# New findings, new problems

- Quantifying the offset
- Re-evaluating older papers (eg. Sridhar+ 2020)
- Also affects the photometric-spectroscopic cross-correlations
  - similar offset, but not exactly the same
- Cosmology dependence of the offset? →  
What can we still learn from the BAO peak?

# Testing for cosmological dependency of the offset



Challenge: cosmic variance  $\rightarrow$  more simulations



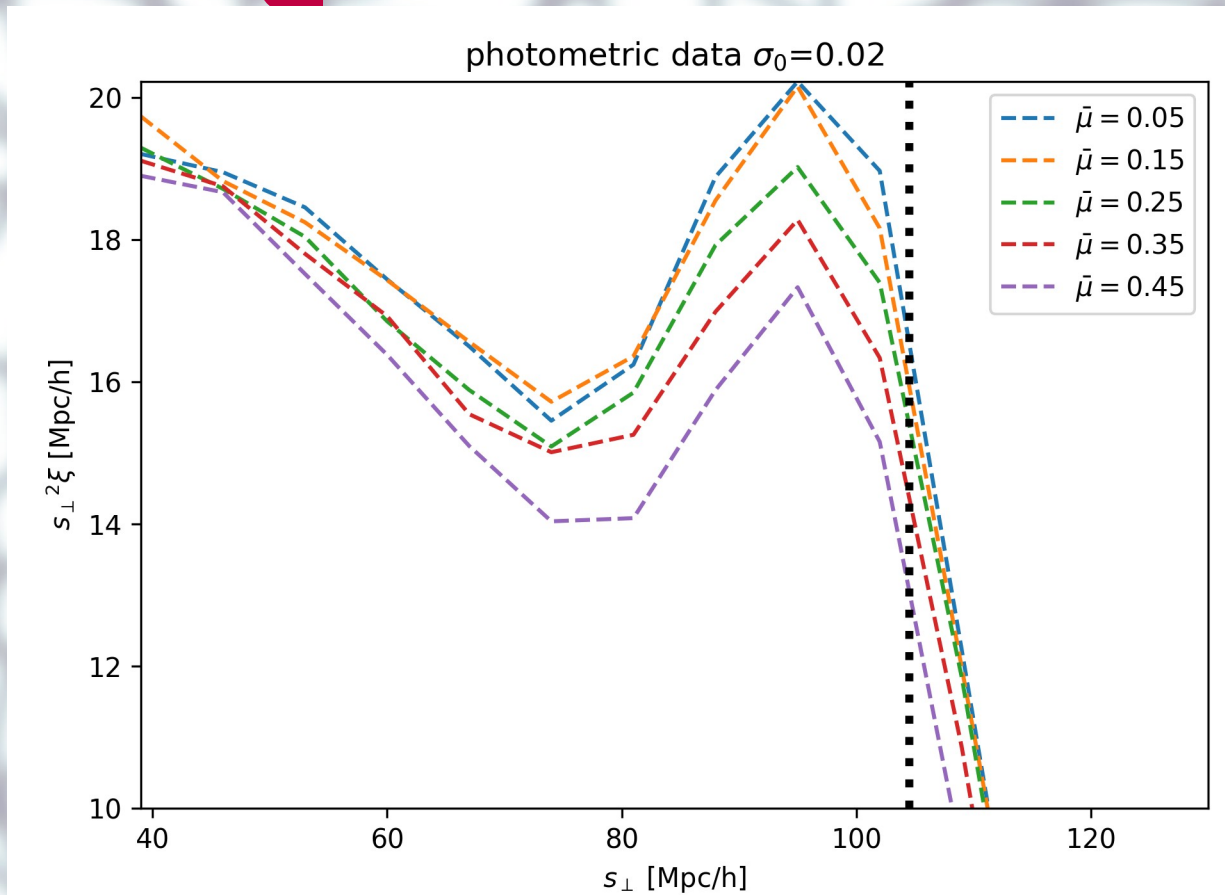
# Next steps

- Quantify shift of the photometric BAO peak
- Redo the photometric DR9 measurements in terms of  $\xi(s_{\perp}, \mu)$ 
  - publish the much delayed paper on them
- Adjust the method for the cross-correlations
- Apply cross-correlations to DESI DA0.2 and in the future to the DESI Y1 data

# Summary and Conclusion

- Photometric BAO peak is shifting between different  $\mu$ -bins as a function of  $s$
- Location of the photometric BAO peak is stable between different  $\mu$ -bins as a function of  $s_{\perp}$
- Location of the photometric BAO peak is systematically offset from the spectroscopic (true) location
- A challenge for all future BAO peak studies using photometric data (including the cross-correlations)

# ANY QUESTIONS?







# **Backup Slides**

# The fitting function

$$\xi_{\text{mod}}(s) = B + \left(\frac{s}{s_0}\right)^{-\gamma} + \frac{N}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(s - s_m)^2}{2\sigma^2}\right)$$

