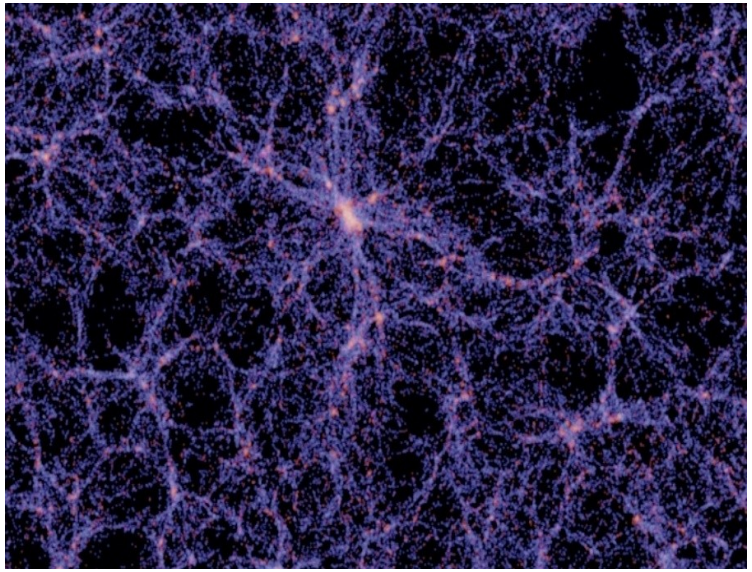
Constructing the density field of the Universe based on DESI observation

Xiaohu Yang (Shanghai Jiao Tong University)

With: F. Shi, H. Y. Wang, Y. Zhang, W.S. Hong, H.J. Mo, W.G. Cui, Y. Jing, X. Kang, etc

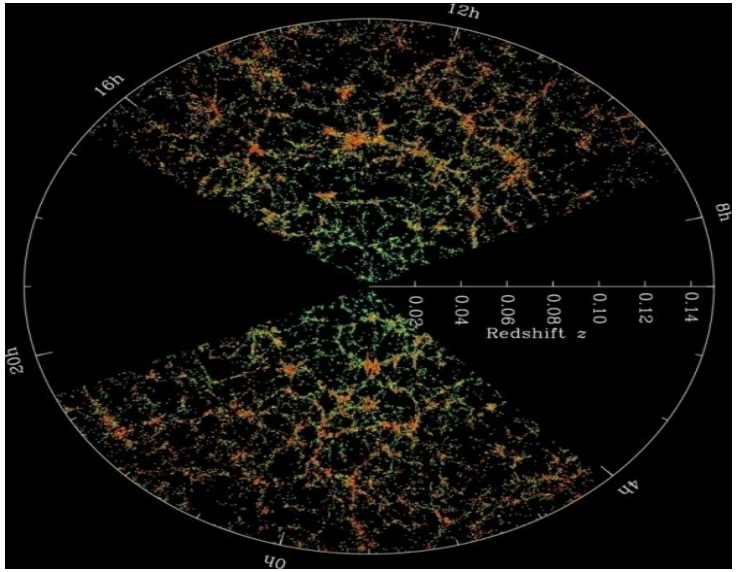
2024/10/31, KIAS 11th workshop on Cosmology & Structure Fo

Motivation

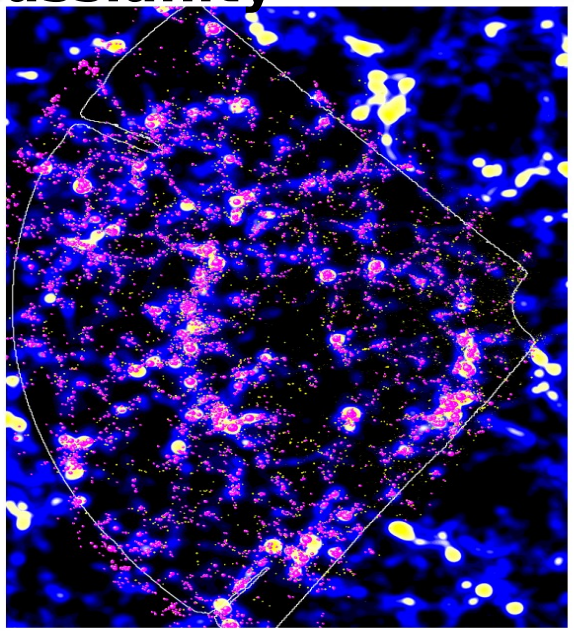


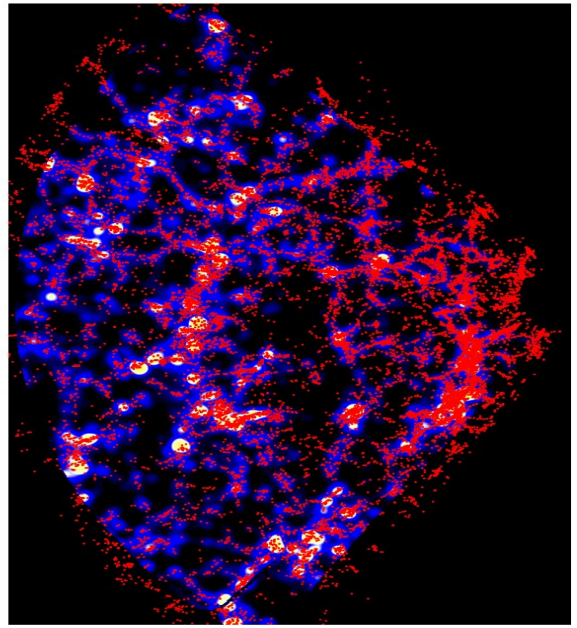
Usually, theoretical results are compared with observational data in a statistical way.

-----Power spectra and Gaussianity



If we can accurately reconstruct the initial condition of local Universe, we can compare the data and theory 'directly'.
-----Power spectra, Gaussianity and Phase

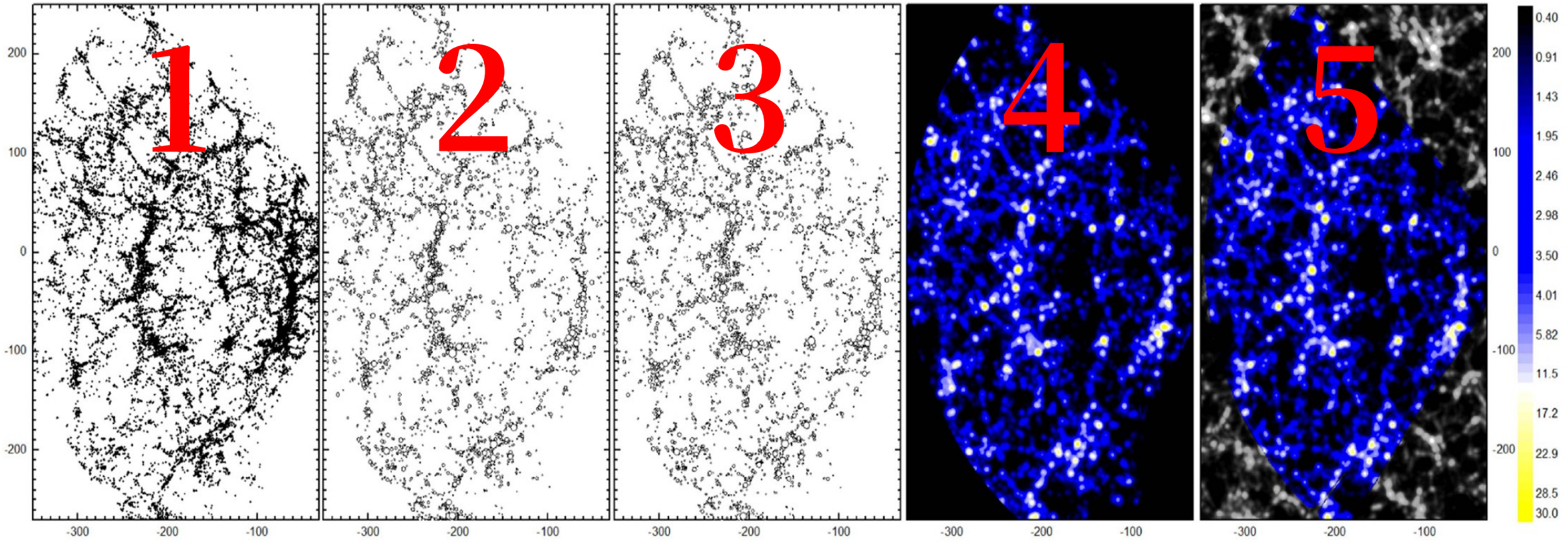




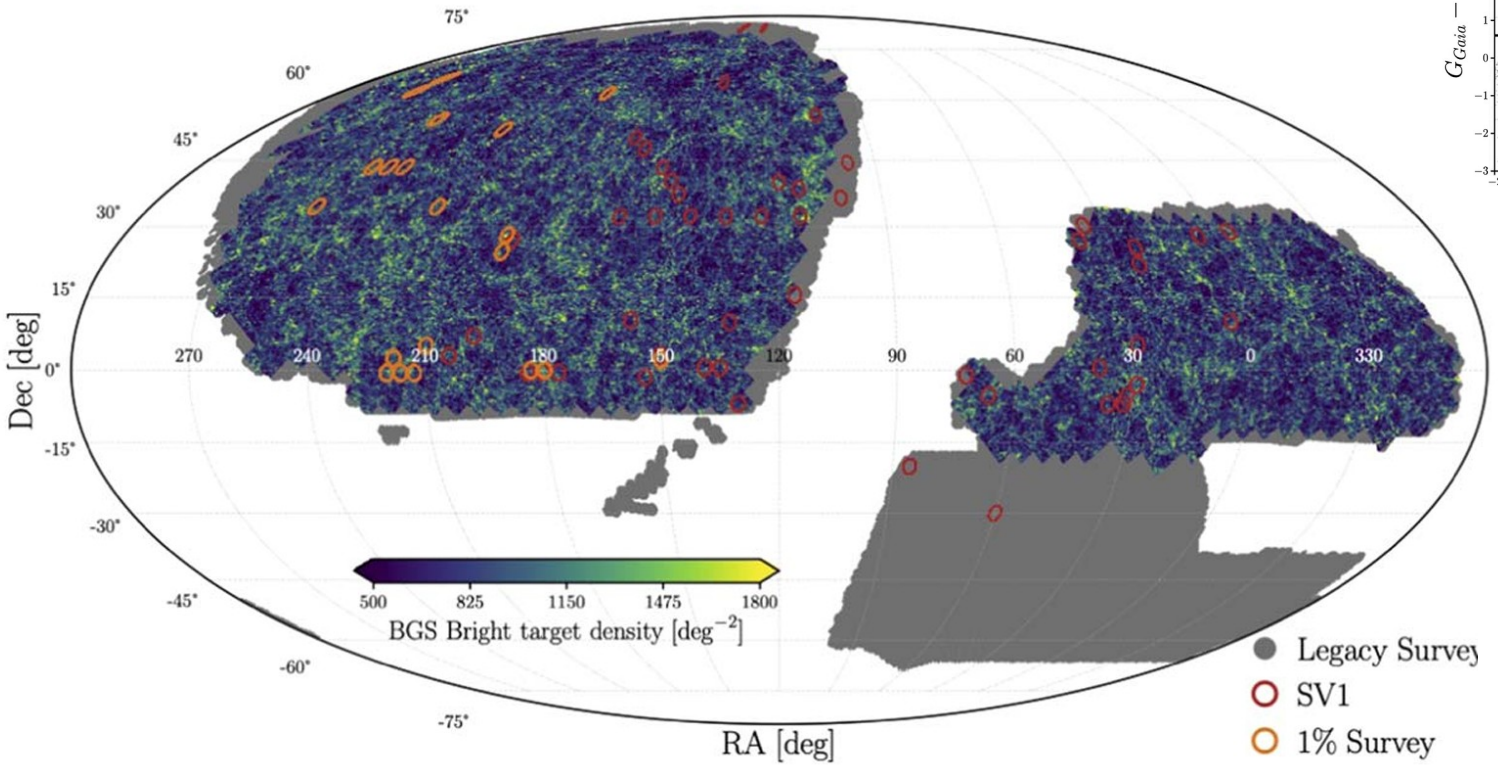
ELUCID : Exploring the Local

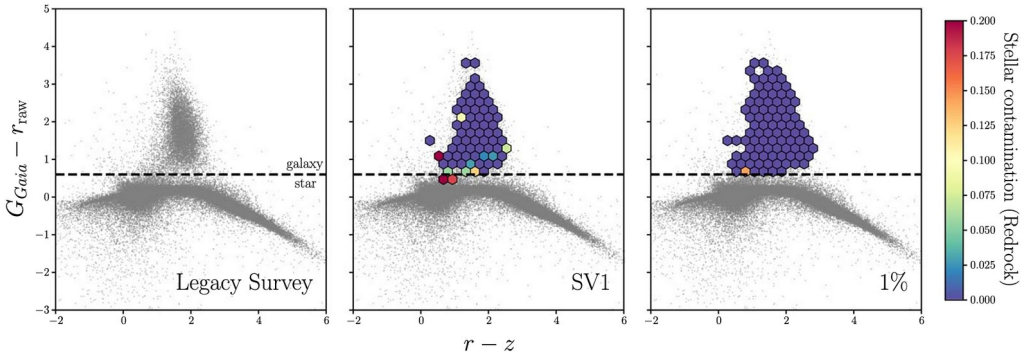
ELUCID based on SDSS observation

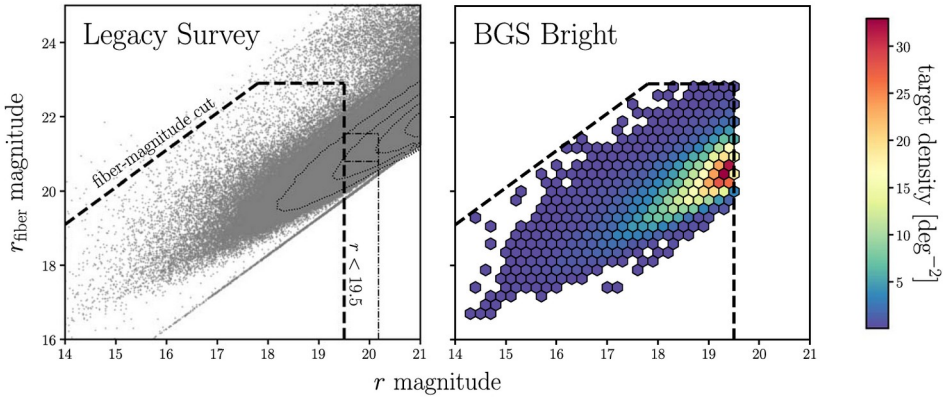
- (Wang et al. 2009,2012,2013,2014; Zhang et al. 2009,2013; ELUCID I--VIII)



1 Get the best flux limited sample of galaxies







Hahn et al. 2023

DESI: 2021-2026

DESI probably will be complete at the end of 2025

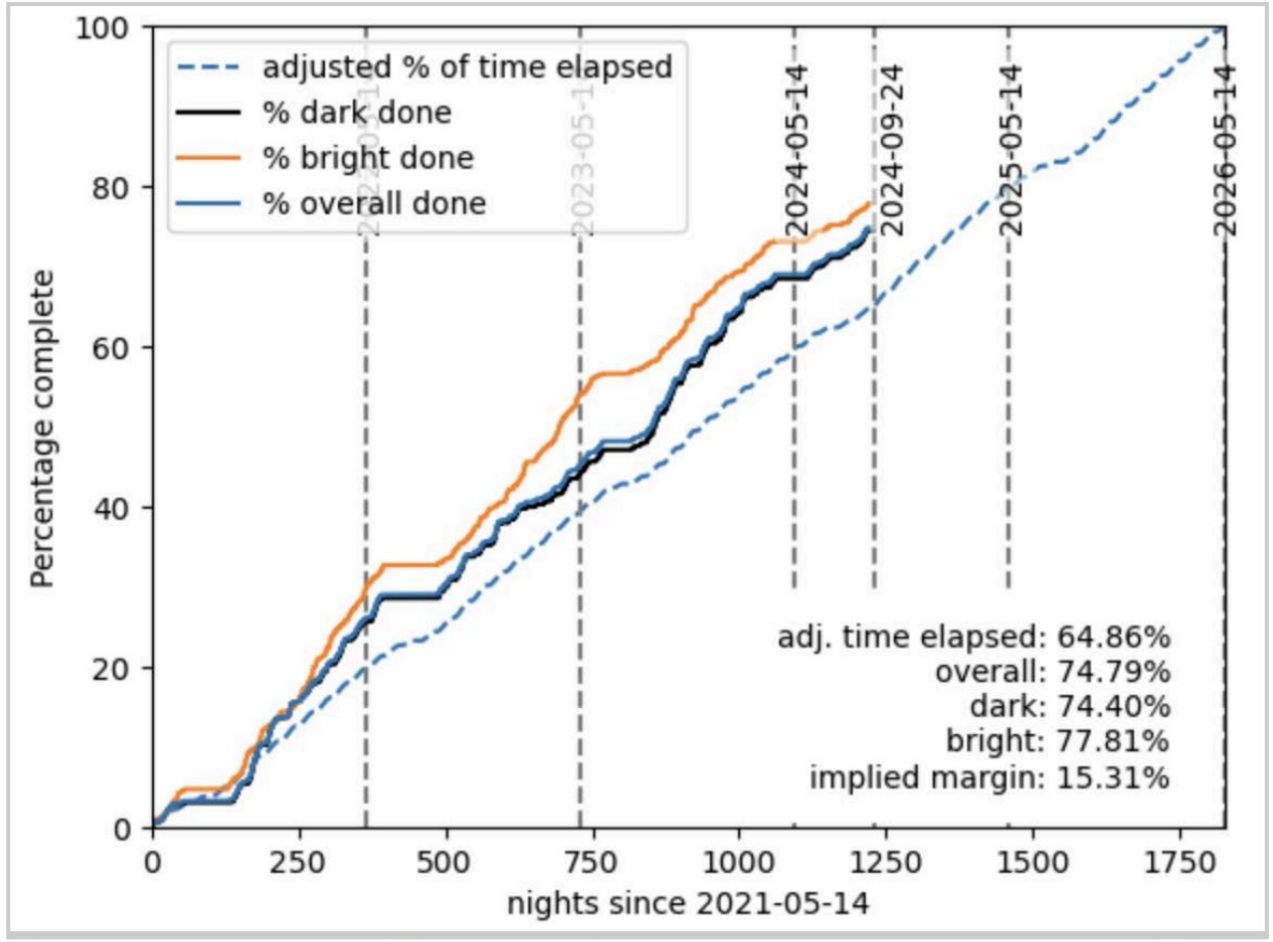


Figure 1. Survey progress. Solid curves give the survey progress as a function of time in different programs. The dashed curve shows the weather-adjusted fraction of the five-year survey elapsed.

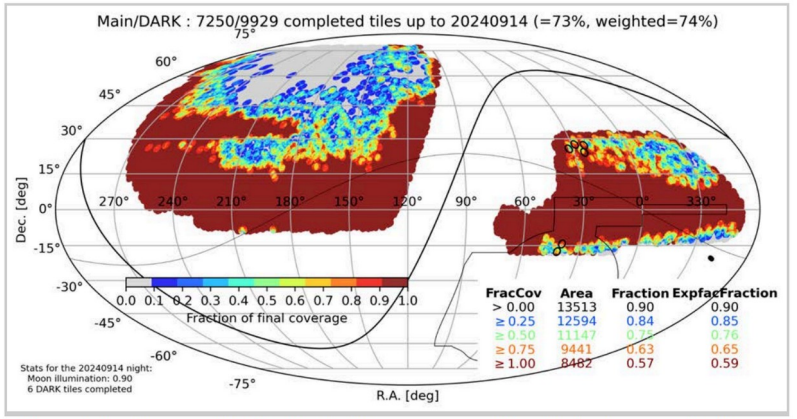


Figure 5. Fraction completed for the dark-time program, with red indicating areas that have achieved full coverage. Note that this plot is only through Sept. 14.

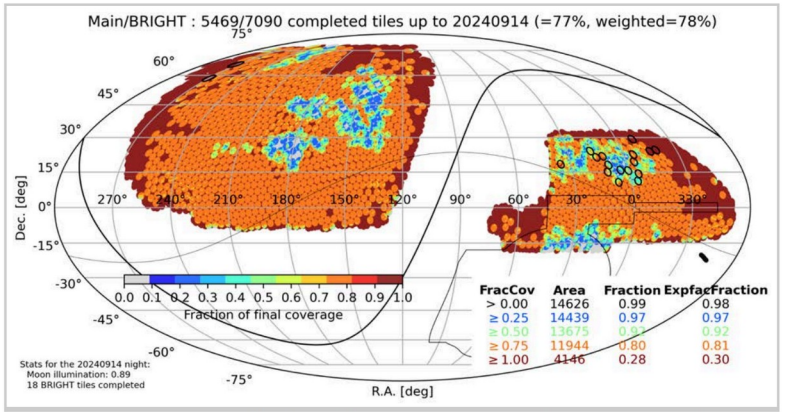
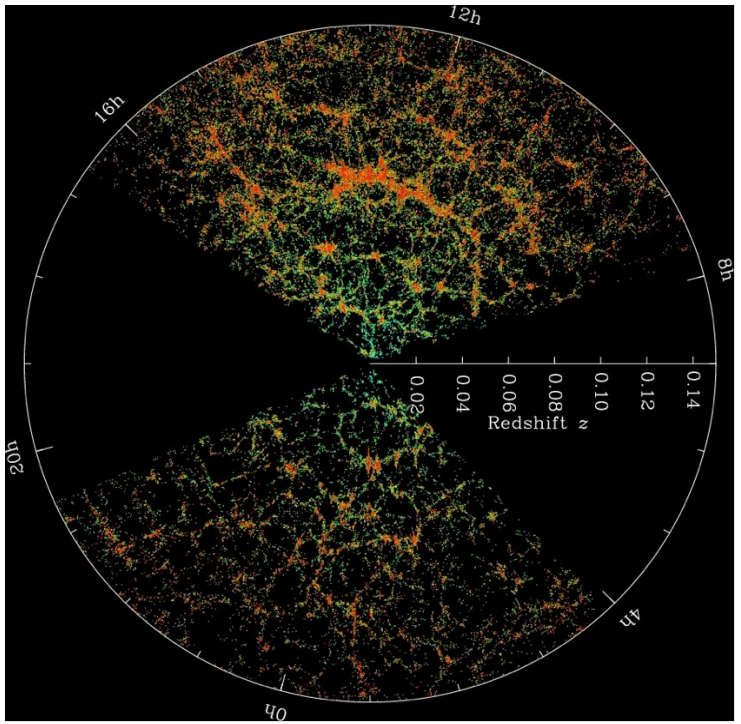


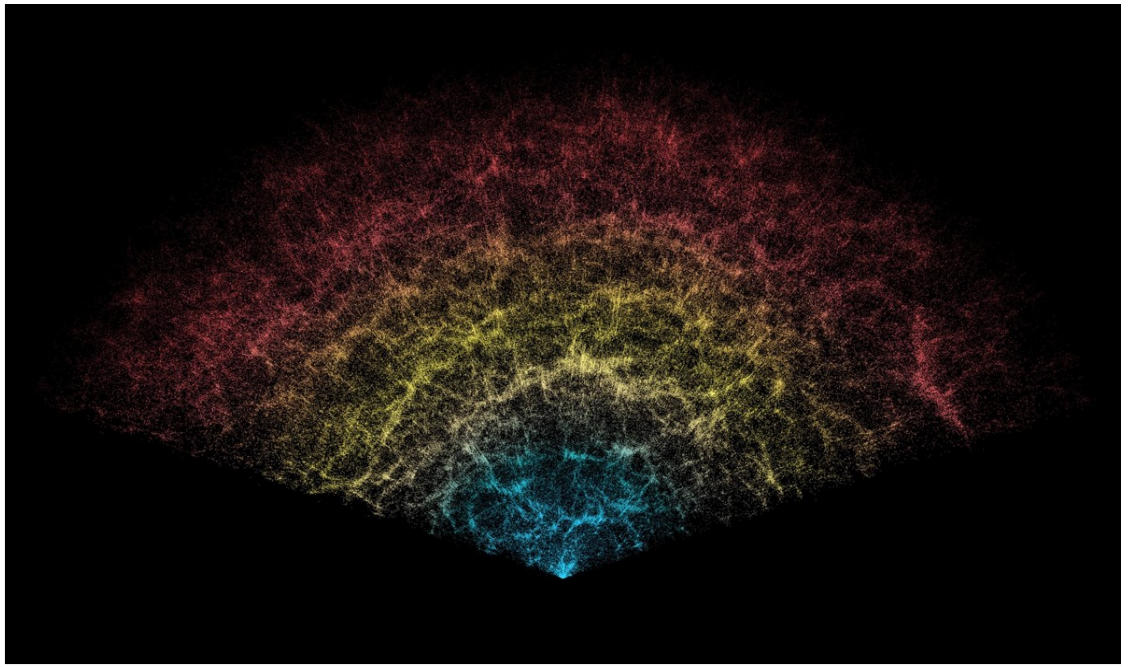
Figure 6. Fraction completed for the bright-time program, with red indicating areas that have achieved full coverage. Note that this plot is only through Sept. 14.

DESI Operations Monthly report
(Michael Levi)

Compare to SDSS main, DESI BGS is much larger



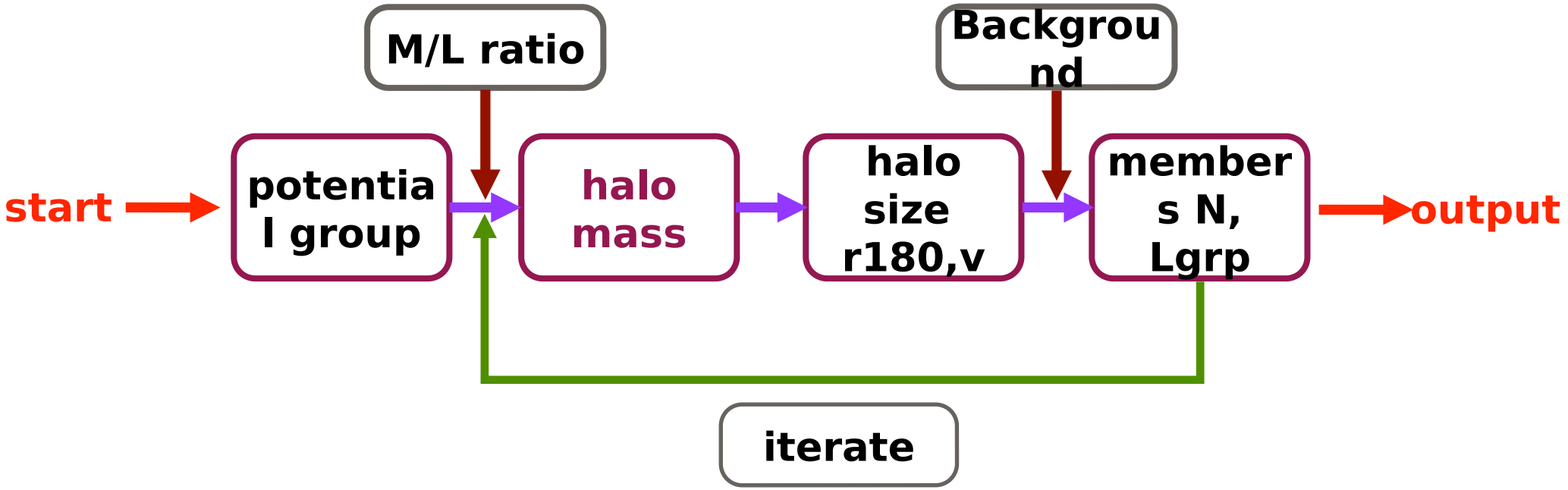
SDSS: 2000-2020



DESI: 2021-

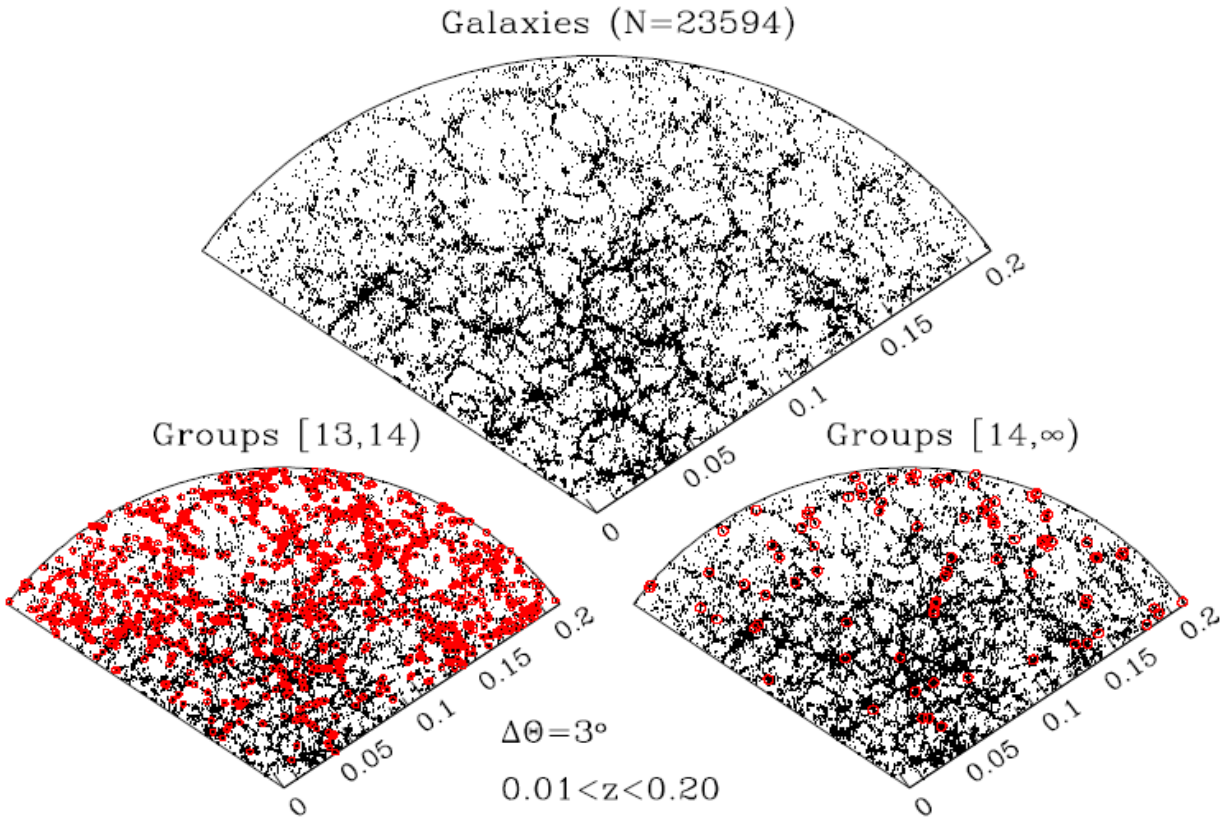
2 Get the halo distributions from the galaxy observation

- A halo-based group finder (**Yang et al. 2005a; 2007**)



- **We refer a `group' as a system of galaxies regardless of its richness, including isolated galaxy to rich clusters of galaxies.**

Galaxy groups in spectroscopic redshift surveys



https://gax.sjtu.edu.cn/data/Group.html

1. 2dFGRS: Yang et al. 2005
2. SDSS DR4: Yang et al. 2007
3. SDSS DR7: Yang et al. 2012

- **Galaxies are grouped according to their common halos**
- **Halo mass is assigned for each group**
- **The most massive galaxy is defined as the central**

DESI imaging legacy surveys DR9



https://www.legacysurvey.org/viewer
https://www.legacysurvey.org/

Extended version of the halo-based group finder

$$P_M(R, \Delta z) = \frac{H_0}{c} \frac{\Sigma(R)}{\bar{\rho}} p(\Delta z)\,, \tag{9}$$

where c is the speed of light, $\Delta z = z - z_{\rm cluster}$, $\bar{\rho}$ is the average density of Universe, and $\Sigma(R)$ is the projected surface density of a (spherical) NFW (Navarro et al. 1997) halo:

$$\Sigma(R) = 2\, r_s\, \bar{\delta}\, \bar{\rho}\, f(R/r_s)\,, \tag{10}$$

with r_s the scale radius,

$$f(x) = \begin{cases} \frac{1}{x^2-1}\left(1 - \frac{\ln \frac{1+\sqrt{1-x^2}}{x}}{\sqrt{1-x^2}}\right) & \text{if } x < 1 \\ \frac{1}{3} & \text{if } x = 1 \\ \frac{1}{x^2-1}\left(1 - \frac{\operatorname{atan}\sqrt{x^2-1}}{\sqrt{x^2-1}}\right) & \text{if } x > 1 \end{cases}, \tag{11}$$

and

$$\bar{\delta} = \frac{180}{3} \frac{c_{180}^3}{\ln(1+c_{180}) - c_{180}/(1+c_{180})} \tag{12}$$

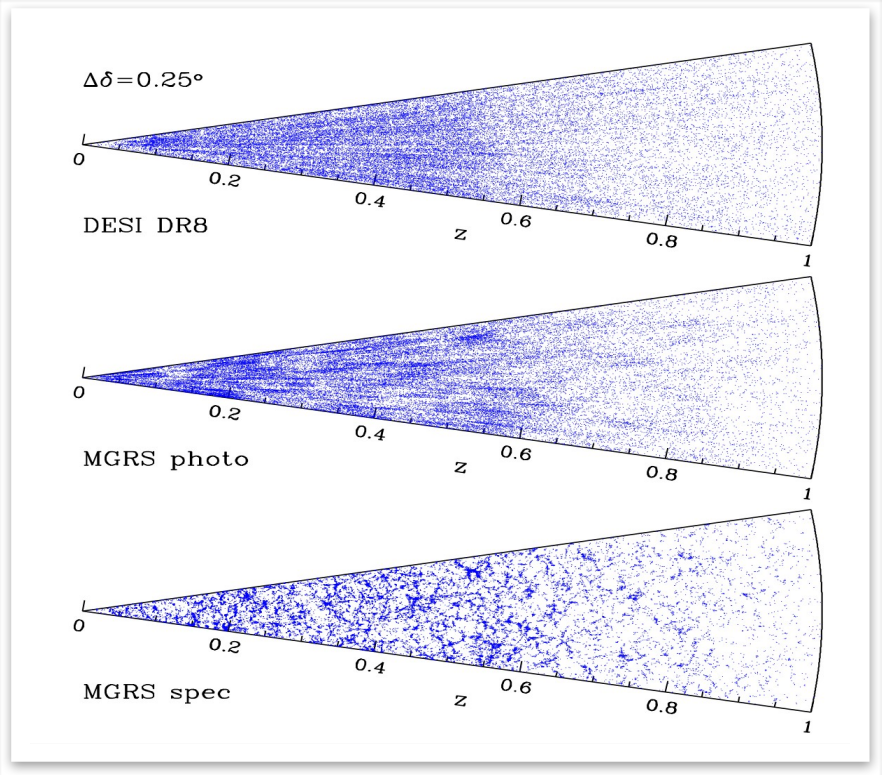
with $c_{180} = r_{180}/r_s$. The function $p(\Delta z)\mathrm{d}\Delta z$ describes the redshift distribution of galaxies within the halo, and is assumed to have a Gaussian form,

$$p(\Delta z) = \frac{1}{\sqrt{2\pi}} \frac{c}{\sigma(1+z_{\rm group})} \exp\left[\frac{-(c\Delta z)^2}{2\sigma^2(1+z_{\rm group})^2}\right].$$

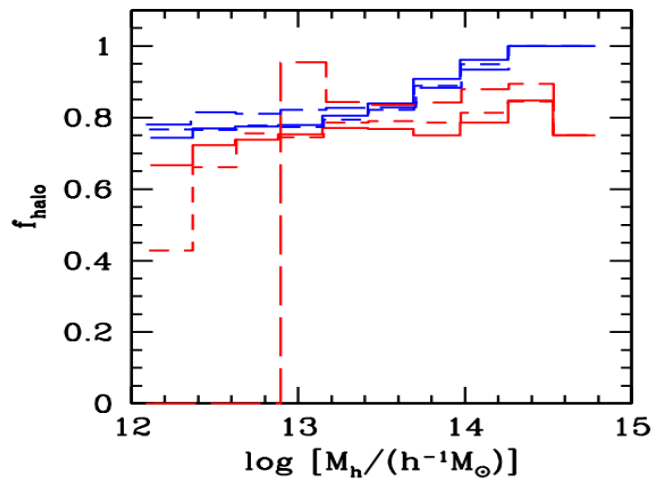
is assumed to have a Gaussian form,

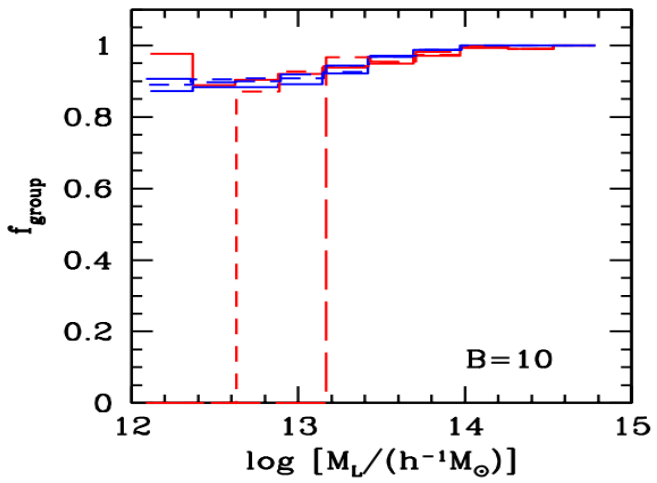
$$p(\Delta z) = \frac{1}{\sqrt{2\pi}} \frac{c}{\sigma(1+z_{\rm group})} \exp\left[\frac{-(c\Delta z)^2}{2\sigma^2(1+z_{\rm group})^2}\right]. \tag{13}$$

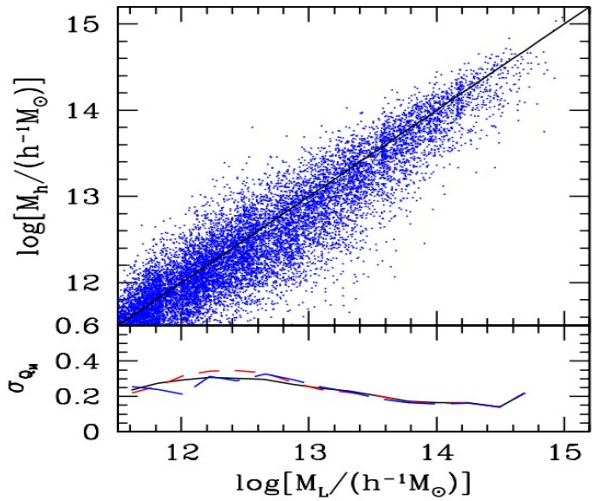
Here $\sigma = \max(\sigma_{180}, \sigma_{\rm photo})$ where $\sigma_{\rm photo}$ is the photometric redshift error in unit of $\mathrm{km\,s^{-1}}$. Thus defined,

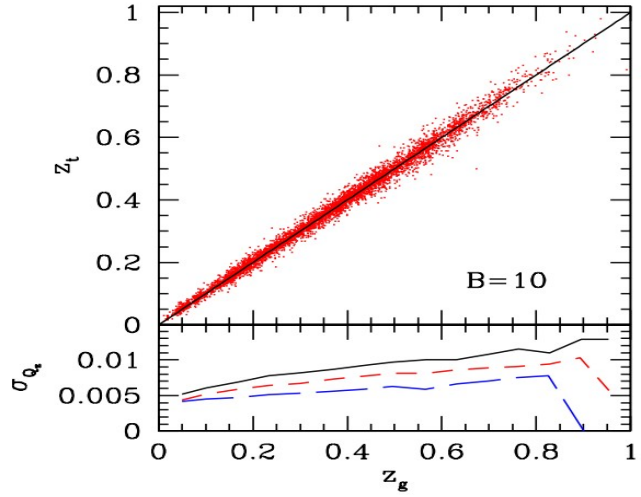


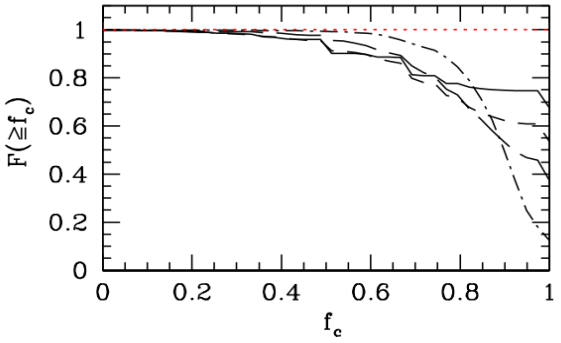
The group/cluster properties

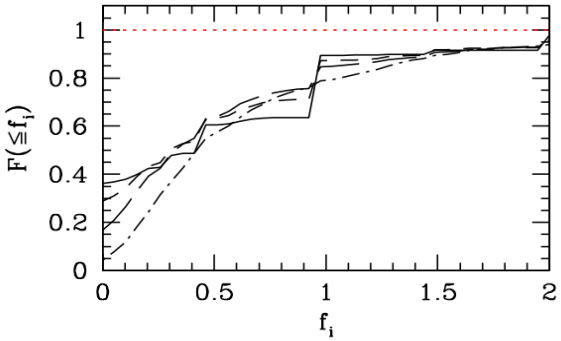


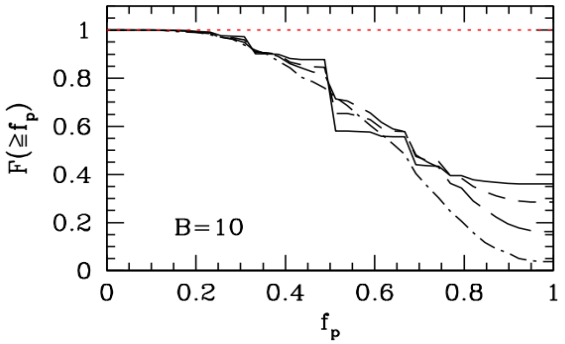






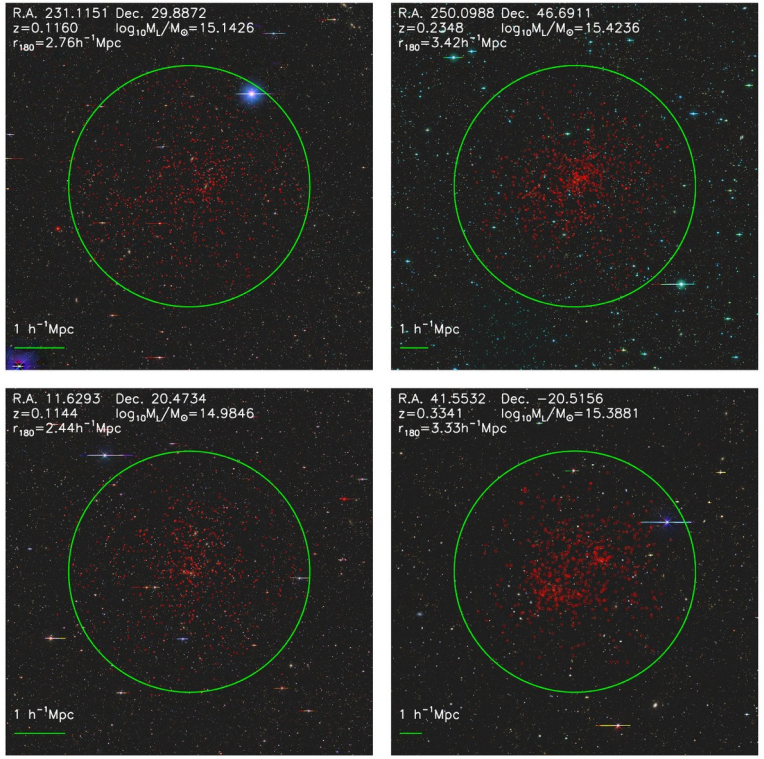






Take groups with f_c>0.5 as true halo detection

https://gax.sjtu.edu.cn/data/DESI.html

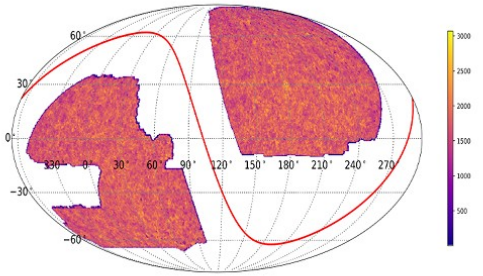


Yang et al. 2021, ApJ

https://gax.sjtu.edu.cn/data/DESI.html

DESI Image Legacy Surveys DR9

Shown in the following plot is the projected galaxy distribution in terms of sky coverage in the the Legacy Surveys DR9. The sky coverage are drawn from two contiguous areas: the south galactic cap (~8601 square degrees with 59.95 million galaxies) and the north galactic cap (~9622 square degrees with 67.20 million galaxies). The color code is the galaxy number counts per 0.25 square degrees.



Legacy Surveys DR9

Readme

Galaxy catalogue

Group catalogue

Member ID

Region	Galaxies	Sky coverage	Groups Ng>=1	Ng>=3	Ng>=5	Ng>=10
NGC	67197600	9622	51440885	2626797	835349	193254
SGC	59958088	8601	45416930	2406873	793217	187310

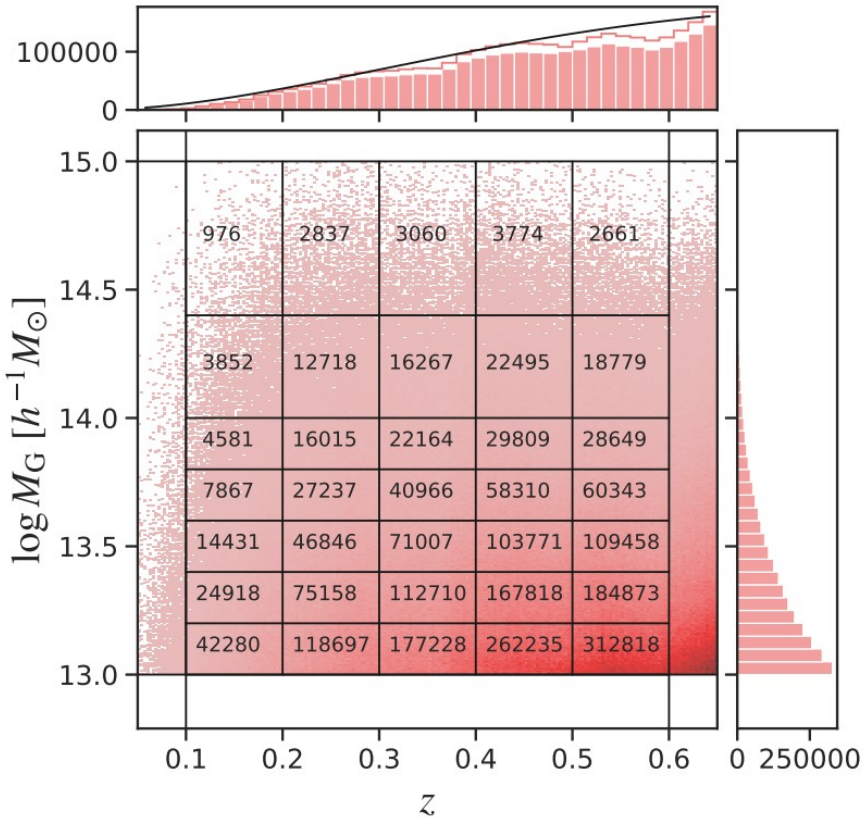
With DESI 1% spectroscopic redshifts -- available for those DESI collaborators upon request.

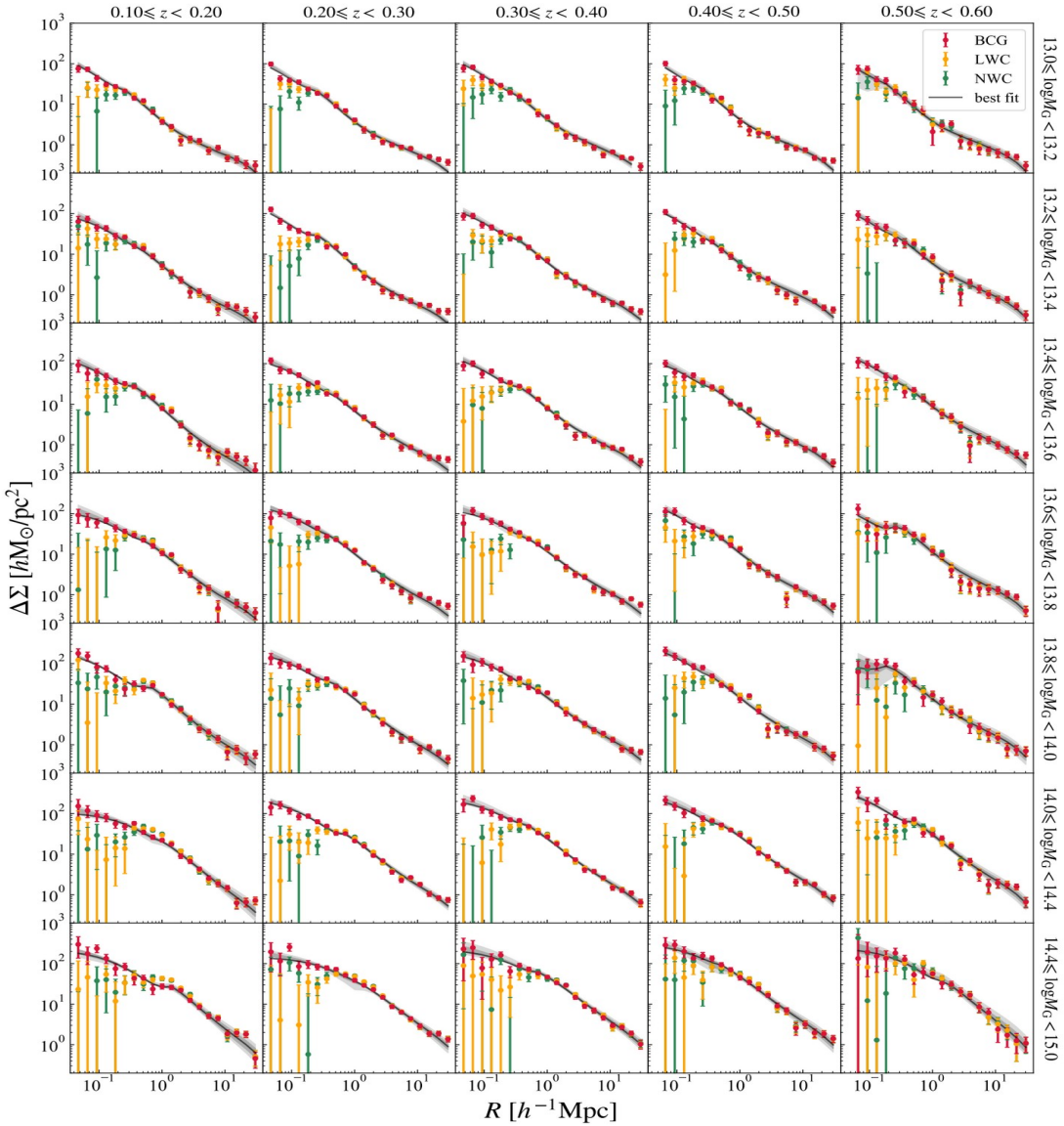
... Will be public once the DESI redshifts are made public.

In this version, we have incorporated the 1% DESI spectroscopic redshifts into our galaxy sample and updated the related group catalogs.

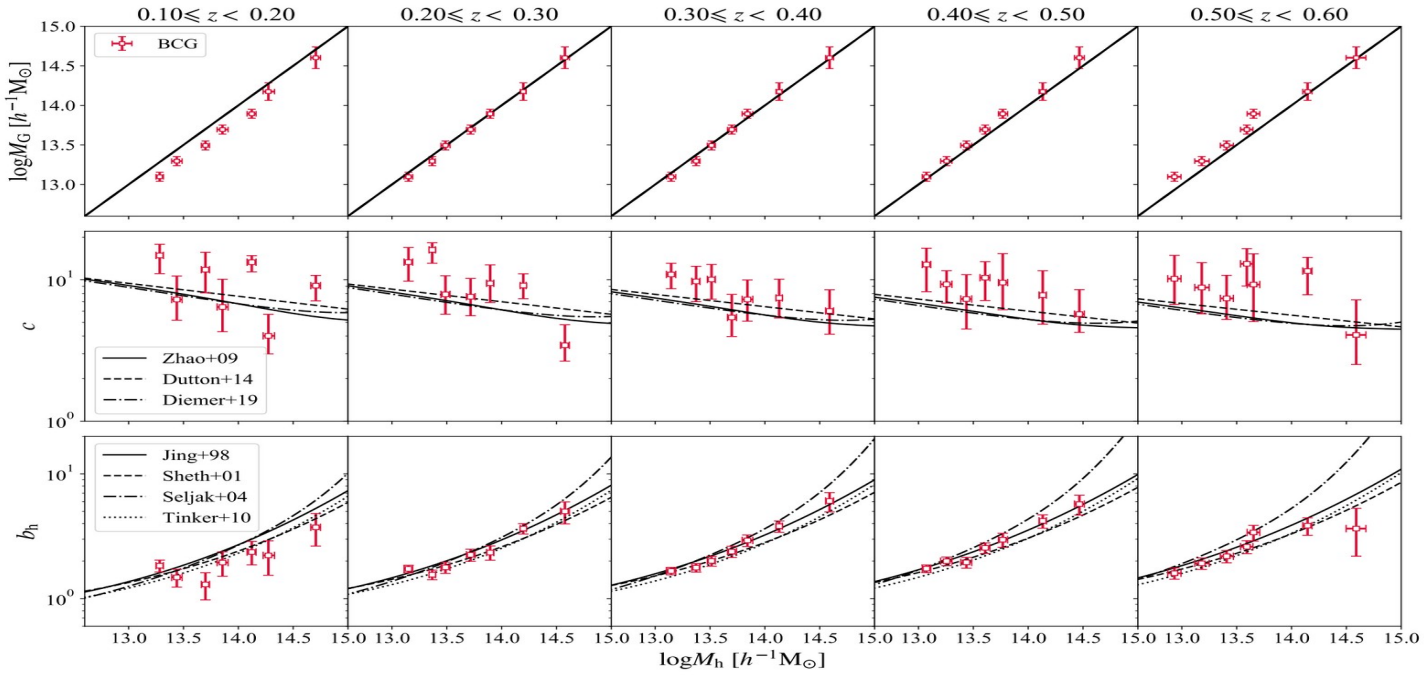
Shown in the following plot is the projected galaxy distribution in terms of sky coverage in the the Legacy Surveys DR9. The updated redshifts on the sky are marked with green color.

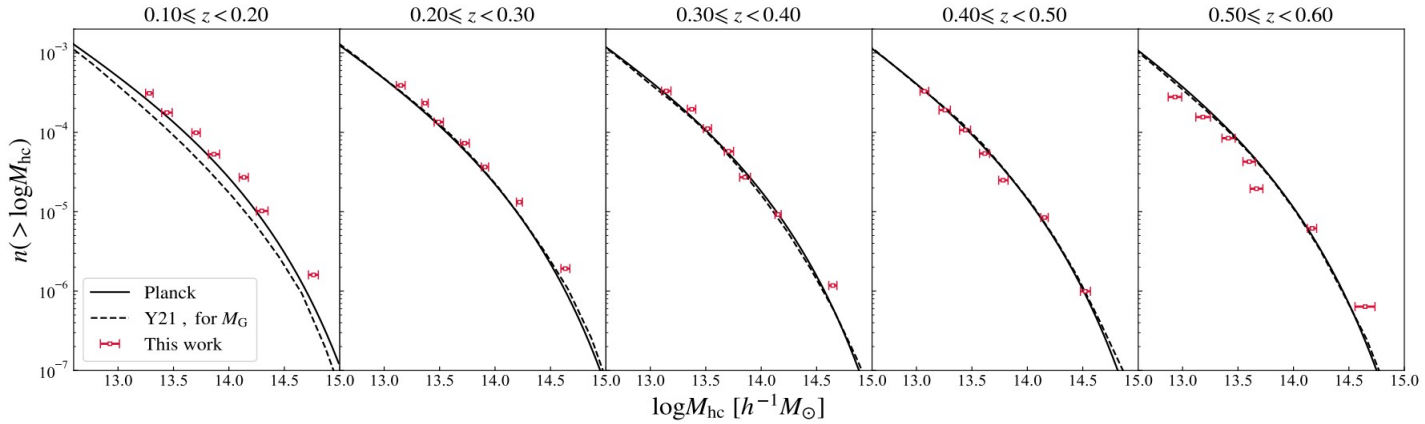
DESI： Group-Galaxy weak lensing ESD measurements





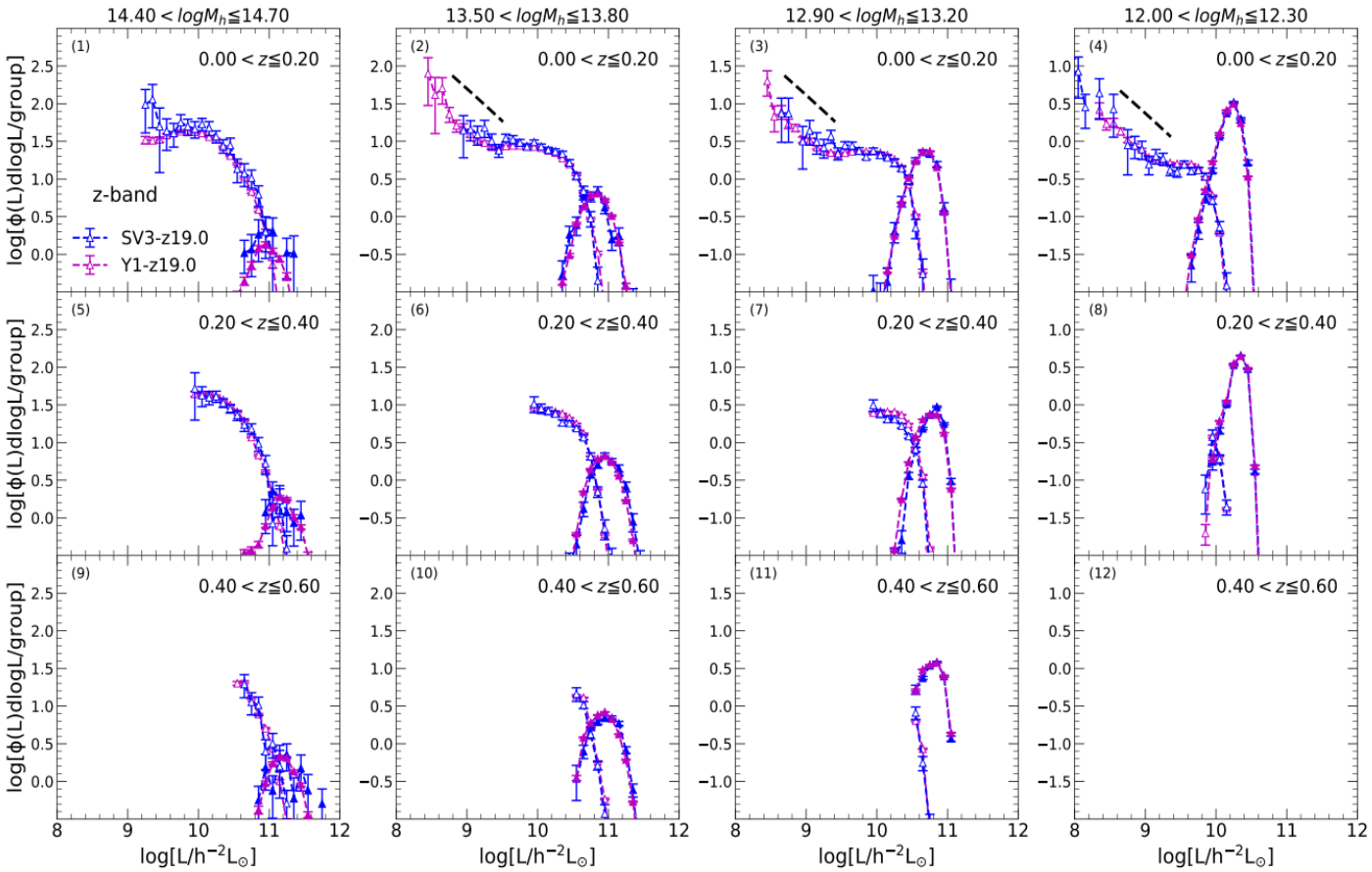
Cluster properties as function of halo mass

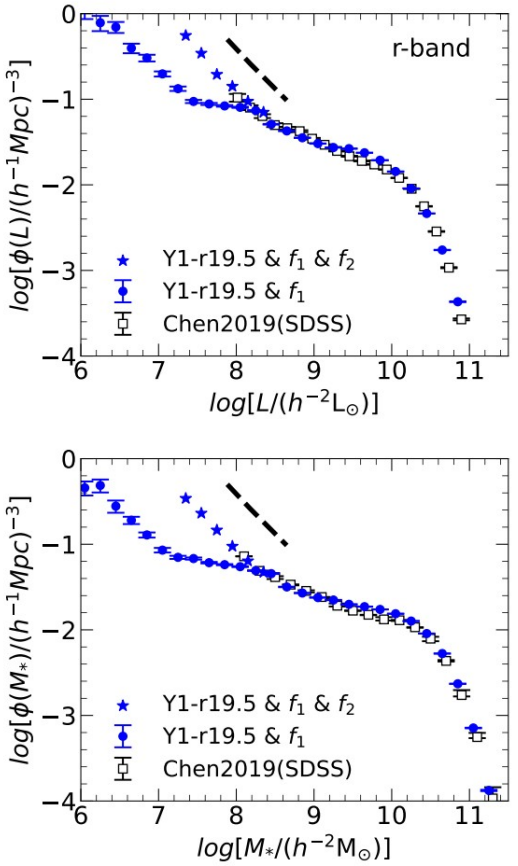




Wang et al. 2022, ApJ

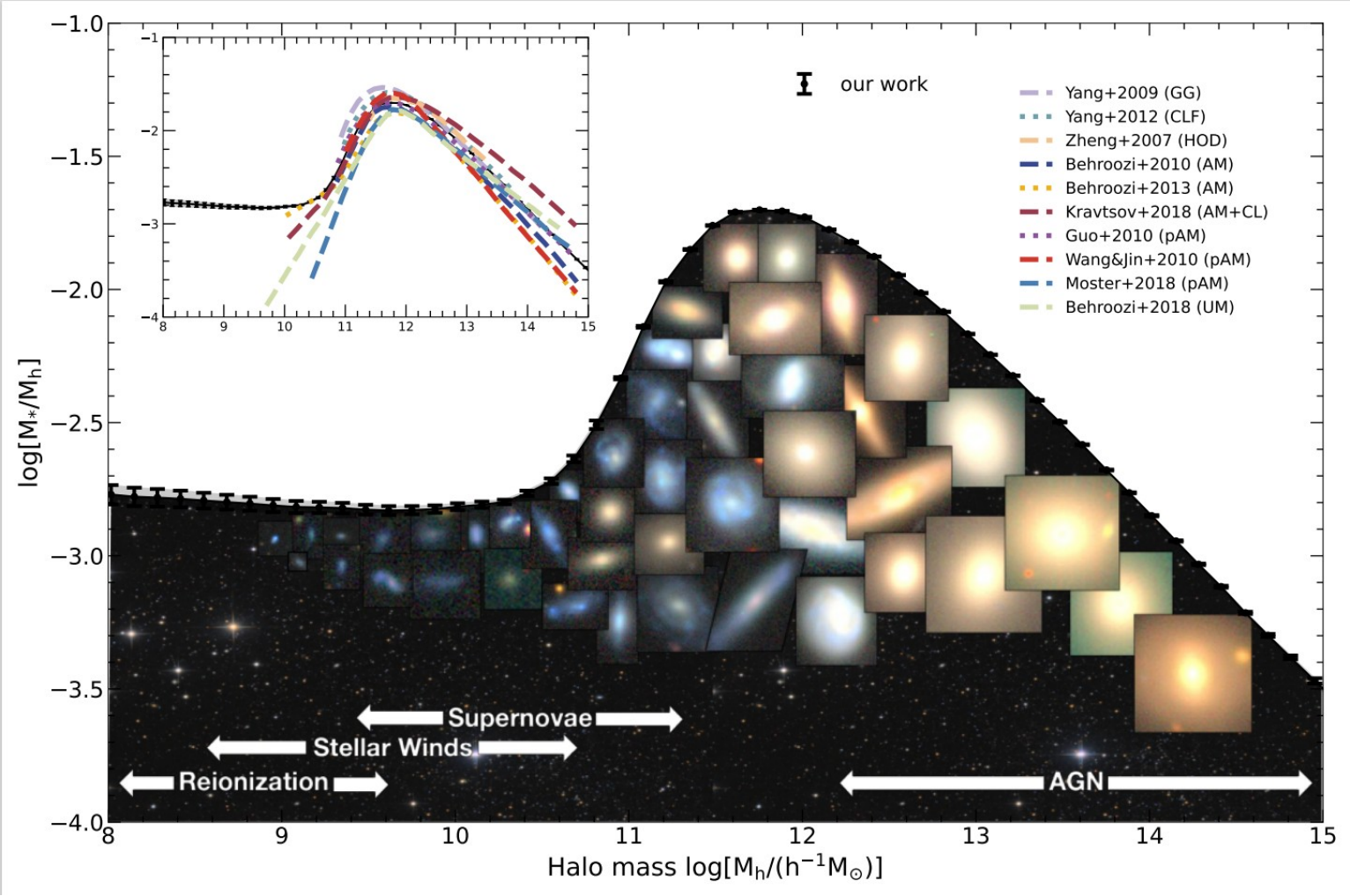
DESI: Measuring the CLFs from DESI groups/clusters





Wang et al 2024, ApJ

Halo-stellar mass ratios



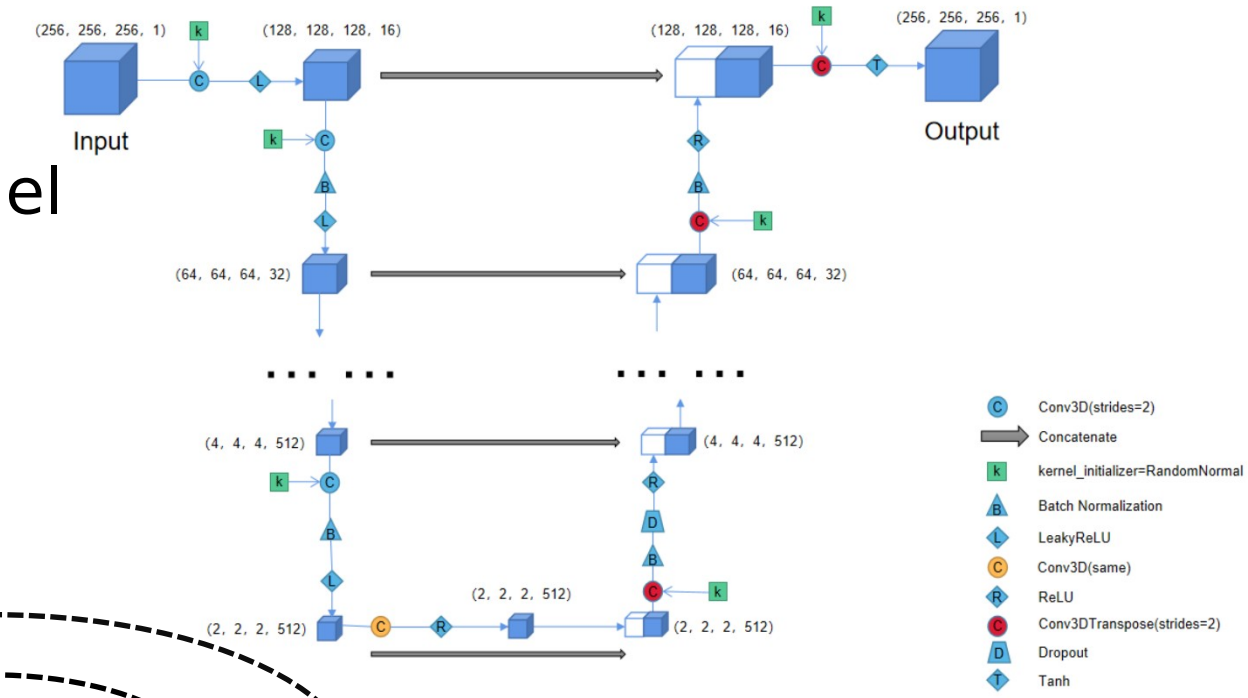
Wang et al 2024, ApJ

https://mp.weixin.qq.com/s/294hsyESfWzMkBx471CKDA

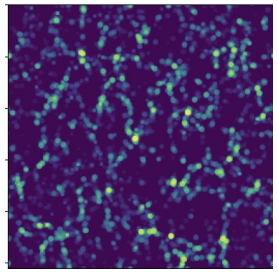
3 Get the velocity and density field from halo distribution

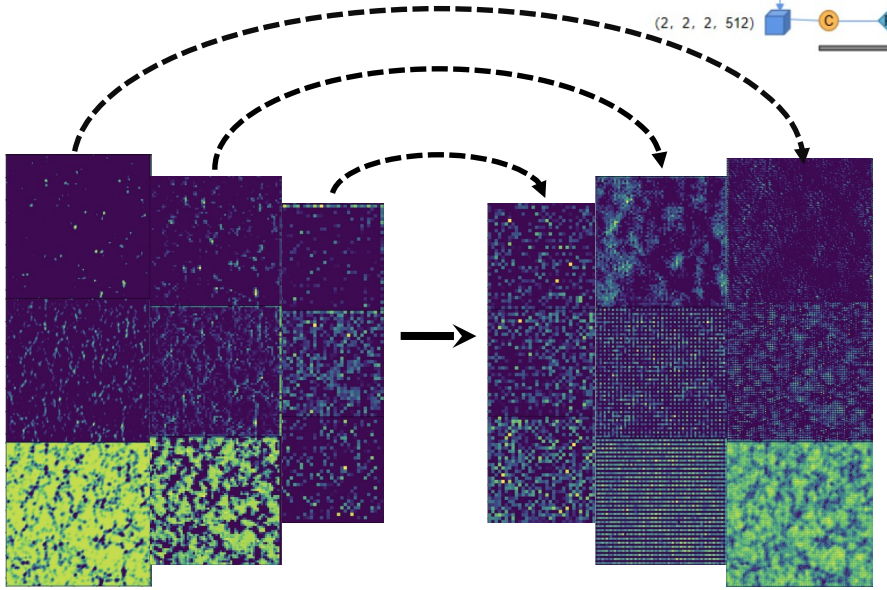
Deeping learning method: UNet model

Encoder-decoder with skip connections:

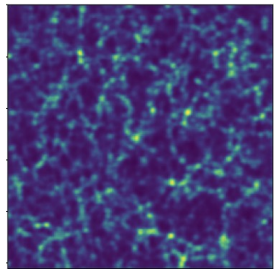


Halo field





Dark matter field



Generating training and testing data

1) Evolute the particles:

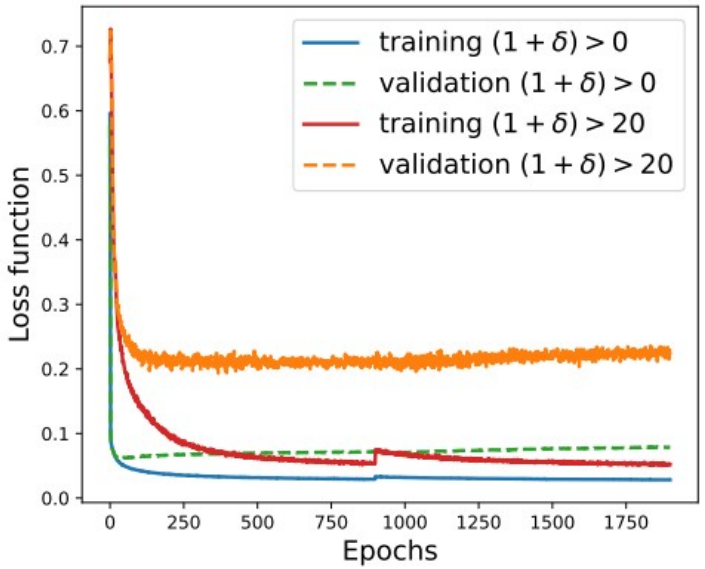
- **cola_halo code: COmoving Lagrangian Acceleration (COLA) fast simulation**
- **Generate 30 simulations: 15 training, 5 validation, and 10 testing samples**
- **Planck2018 cosmology, $\Omega_m = 0.3111$, $\Omega_\Lambda = 0.6889$, $h = 0.6766$, $\sigma_8 = 0.812$.**
- **512^3 particles, 500Mpc/h**
- **Add RSD along the z-axis for halos. Keep real space for dark matter.**

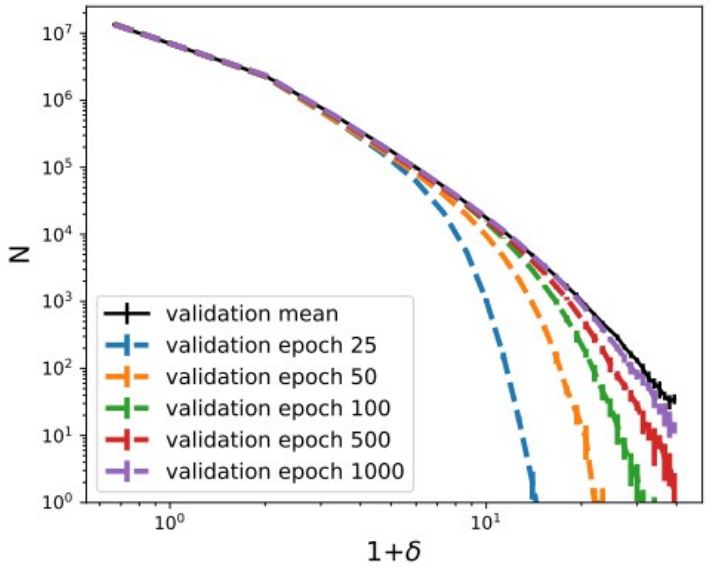
2) Construct the density fields:

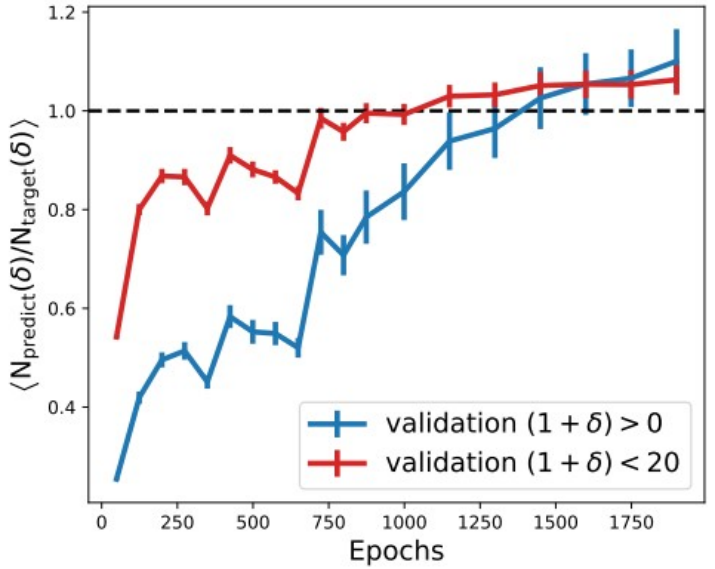
- **CIC scheme, 256^3 voxels,Top-hat smoothing with $R_s = 5\ h^{-1}$Mpc**
- **Halo mass weighting**
- **Rescaled the overdensity values to lie in the interval [−1, 1]**

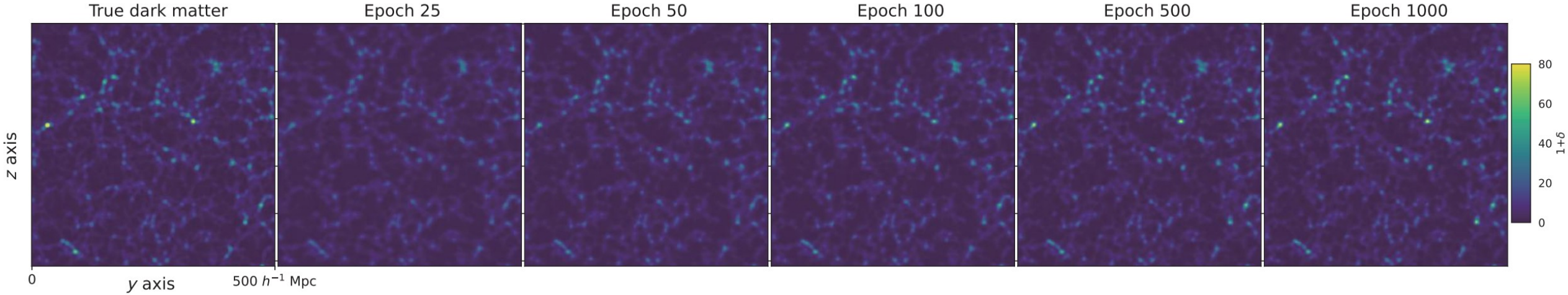
$$s(x) = 2x/(x+a) - 1,\ \text{a=5}$$

Training process

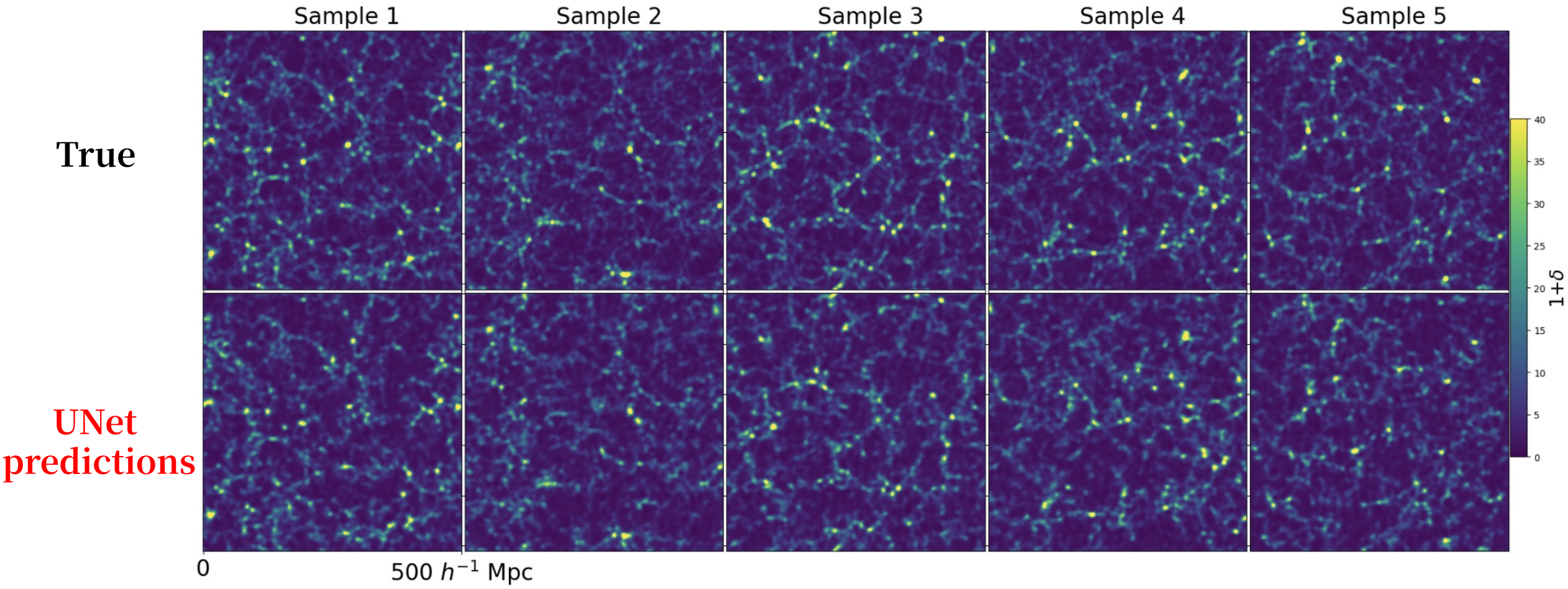




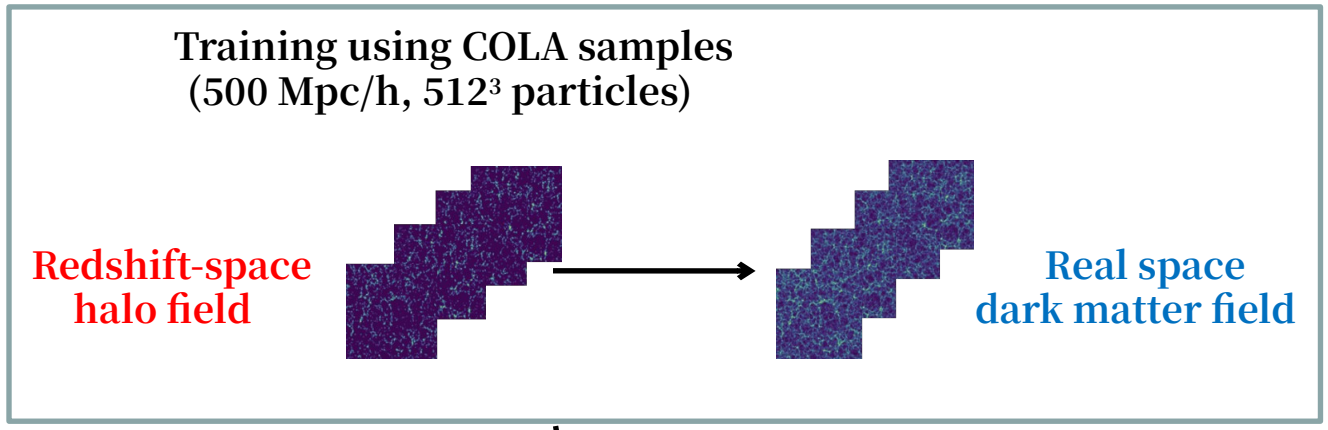




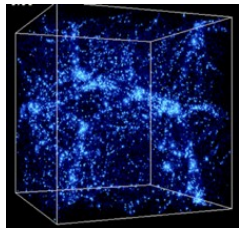
1) Comparisons of the projected density



Application to Jiutian

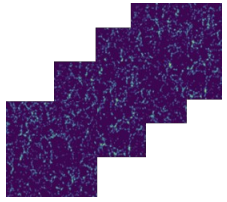


Apply model

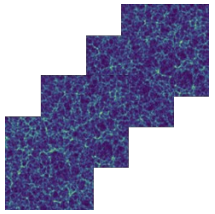


Jiutian halo:
(1000 Mpc/h, 6144³ particles)

Divided into 8 boxes

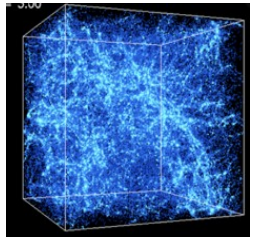


Halo field in small boxes



Reconstructed field
in small boxes

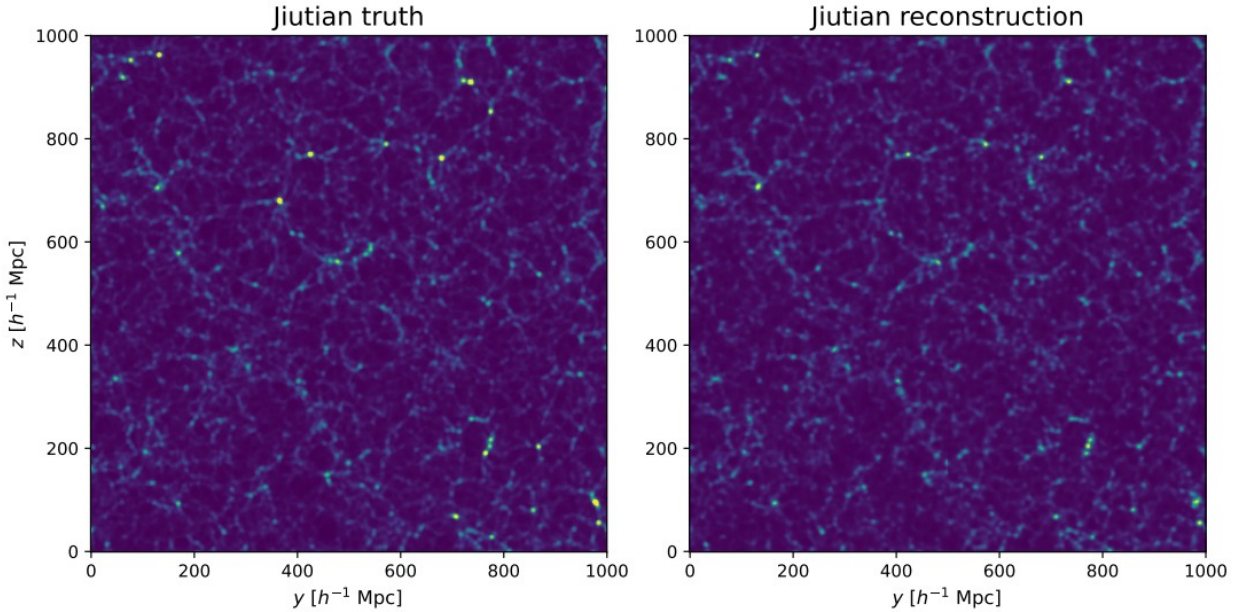
Concatenated back



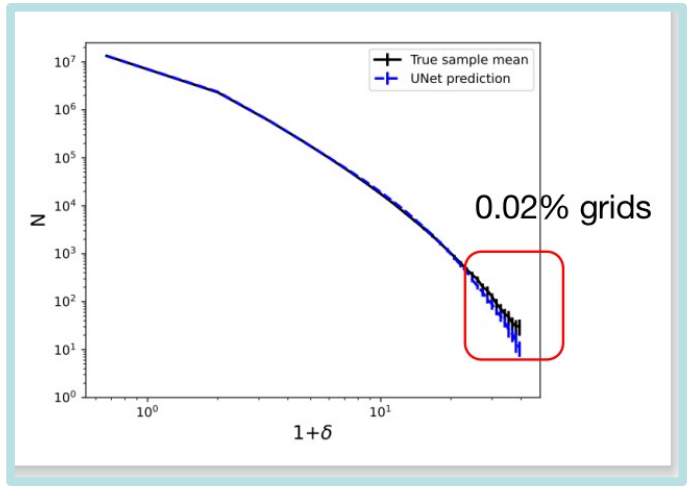
Reconstructed field
in original volume

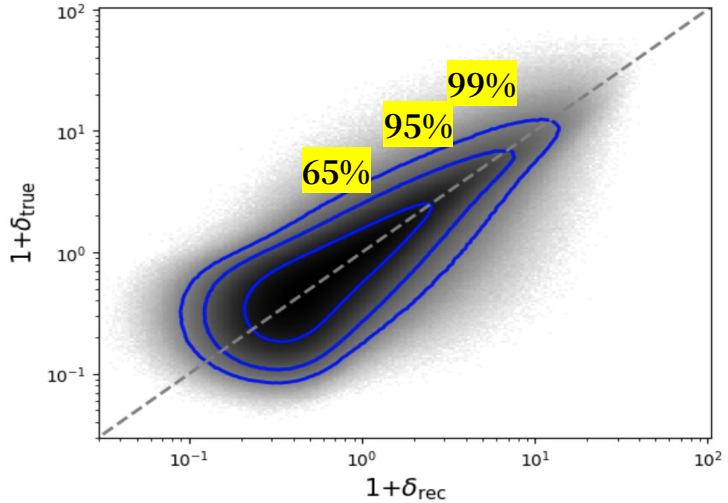
Result: Jiutian simulation

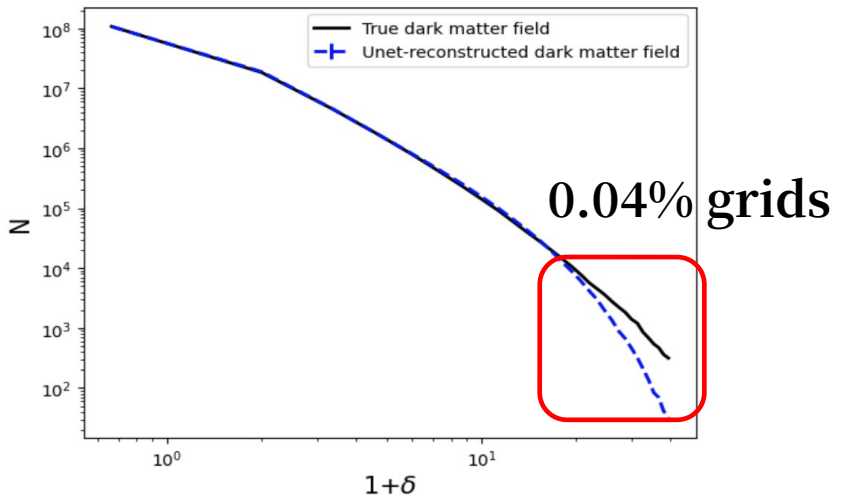
- **Reconstructing dark matter density field based on UNet**



COLA







Application to ELUCID simulation

Check the impact of cosmology

- COLA and Jiutian simulations :

  Planck2018 cosmology

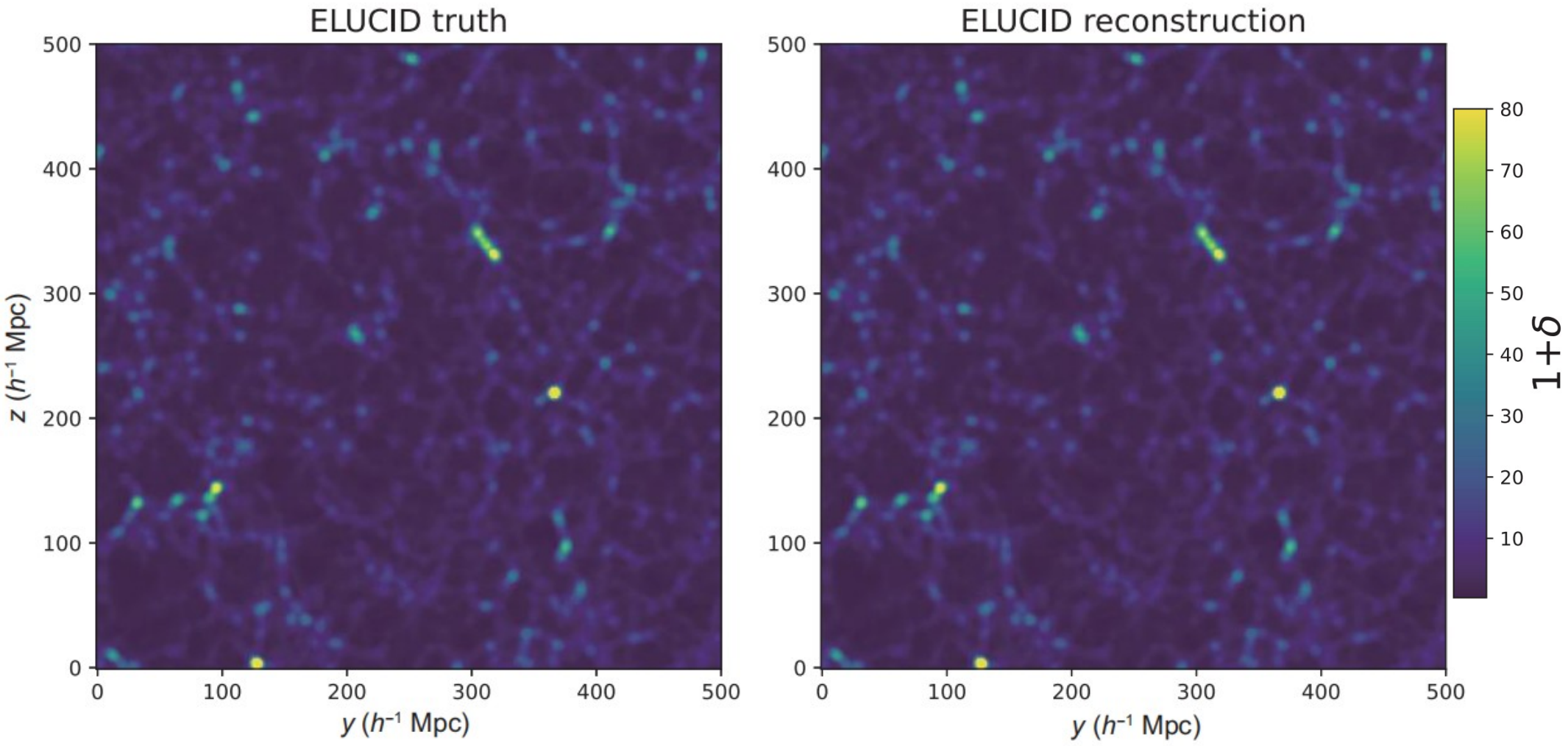
  $\Omega_m = 0.3111, \Omega_\Lambda = 0.6889, \boldsymbol{h} = 0.6766 , \Omega_b = 0.049, \sigma_8 = 0.817.$

- ELUCID simulation (500Mpc/h, 3072^3 particles):

  WMAP5 cosmology

  $\Omega_m = 0.258, \Omega_\Lambda = 0.742, \Omega_b = 0.044, h = 0.72, \sigma_8 = 0.80$

Result: ELUCID simulation



Testing: velocity field reconstruction

UNet-reconstructed $\delta(\mathrm{k})$

$$\boldsymbol{v}(\boldsymbol{k}) = H\ a\ f(\Omega)\ \frac{i\boldsymbol{k}}{k^2}\ \delta(\boldsymbol{k})$$

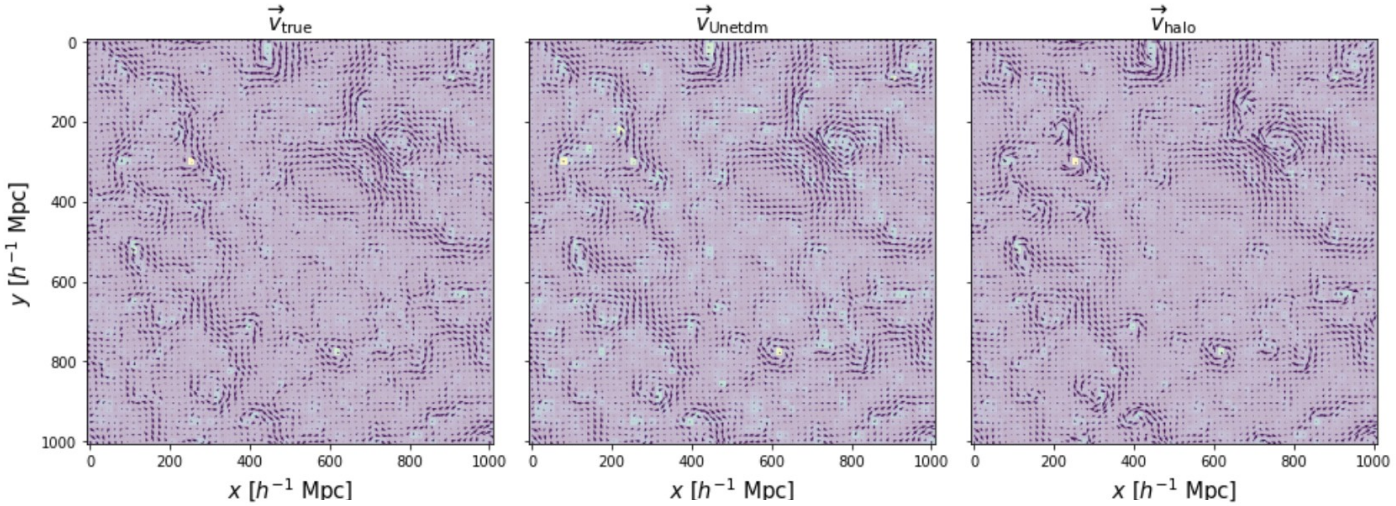
VS.

Halo density field $\delta_{\mathrm{h}}(\mathrm{k})$ with a bias b_{hm}

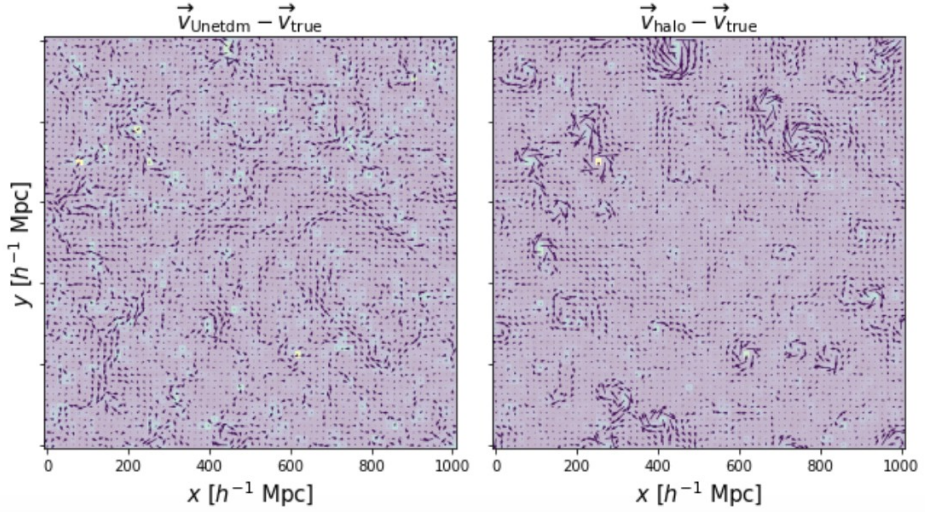
$$\boldsymbol{v}(\boldsymbol{k}) = H\ a\ f(\Omega)\ \frac{i\boldsymbol{k}}{k^2}\ \frac{\delta_{\mathrm{h}}(\boldsymbol{k})}{b_{\mathrm{hm}}}$$

(Wang et al 2012, Shi et al 2016)

Velocity field



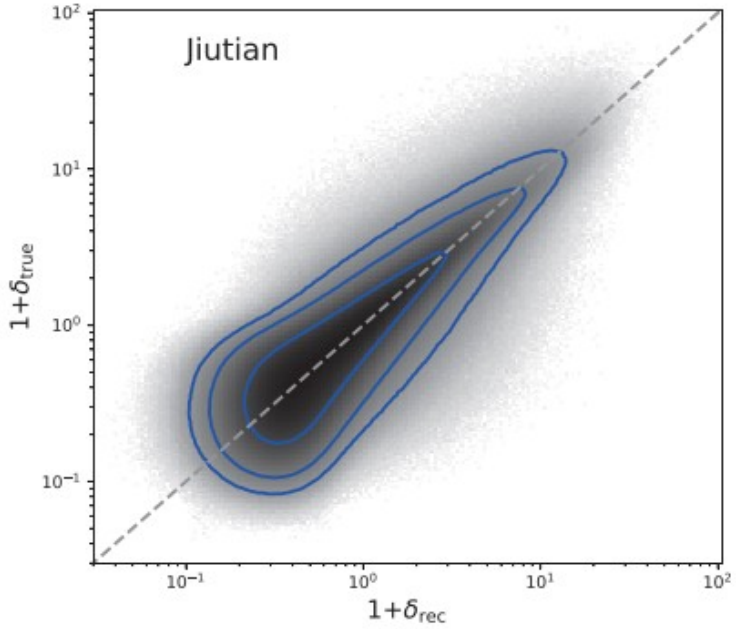
Velocity difference field

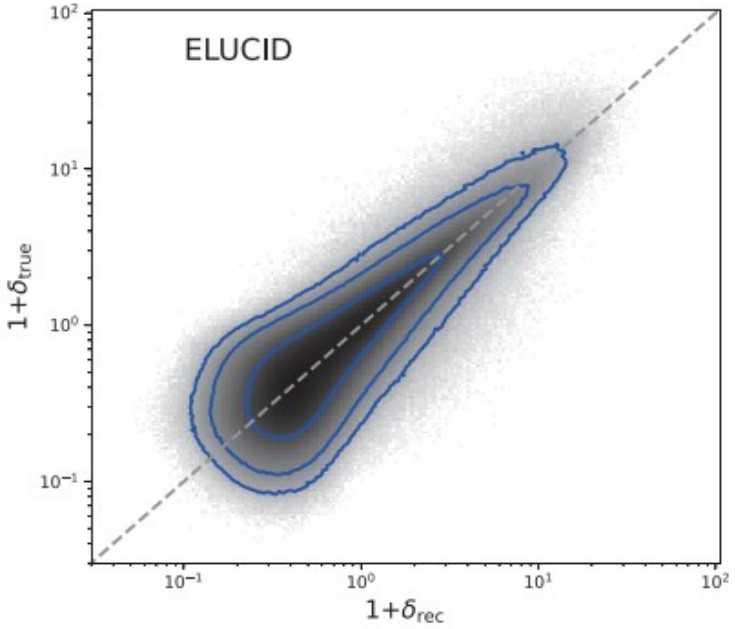


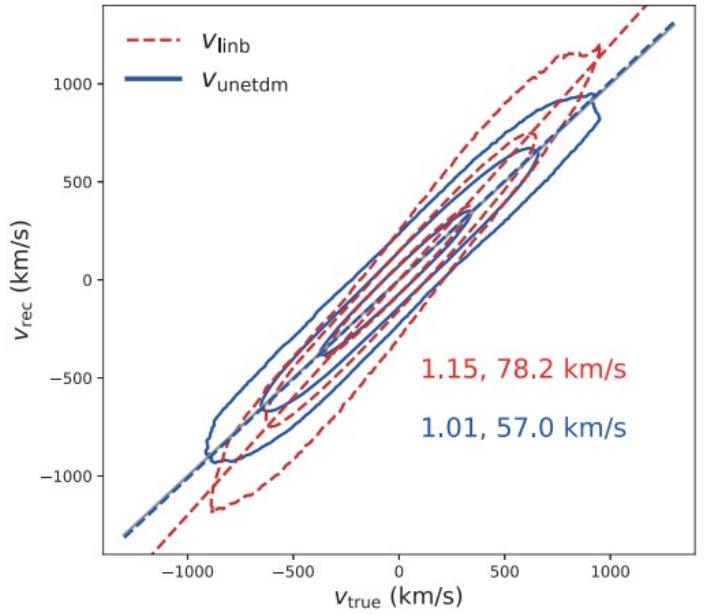
UNet dark matter

Halo-based with linear bias

Accuracy of the density and velocity field reconstruction





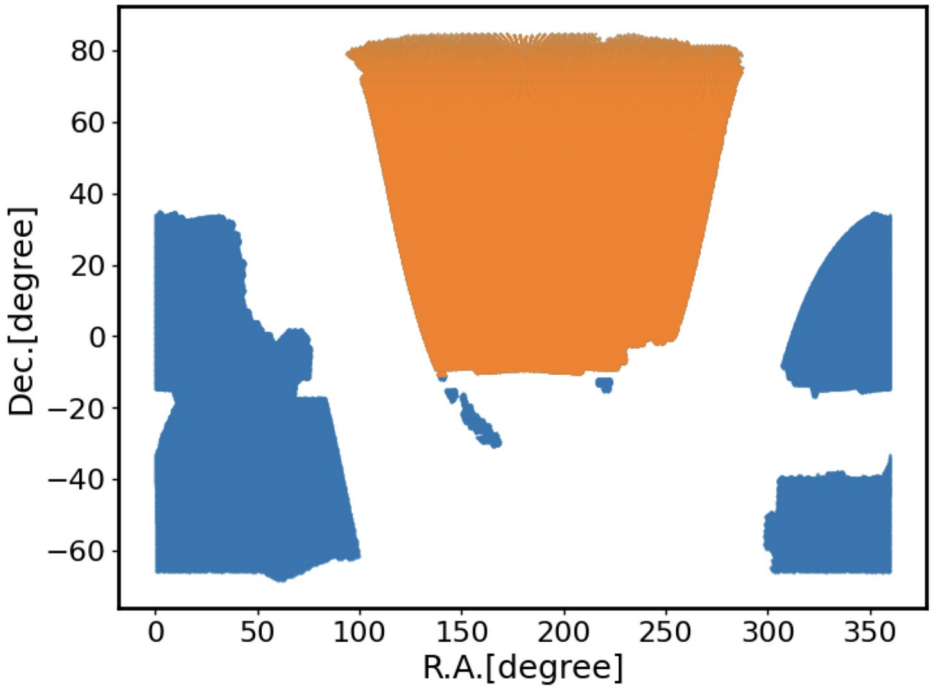


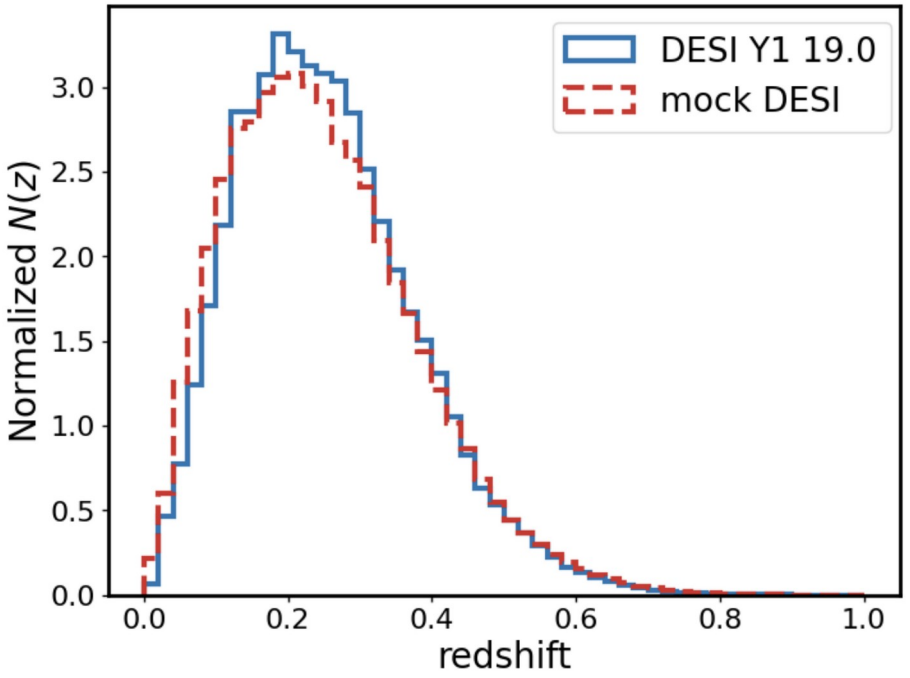
DarkAI: Reconstructing the large-scale density field of dark matter using AI
(Wang Zitong, Shi Feng, et al 2024, SCPMA

Test with mock DESI BGS

Construct the mock DESI survey:

- Use the SHAM method, following DESY Y1 luminocity function.
- Conduct a total of 10 mock samples by randomly rotating and shifting the boxes in the stack.
- DESI BGS selection: 0.1<z<0.4, z-band apparent magnitude < 19.0, 5-year survey mask NGC region.





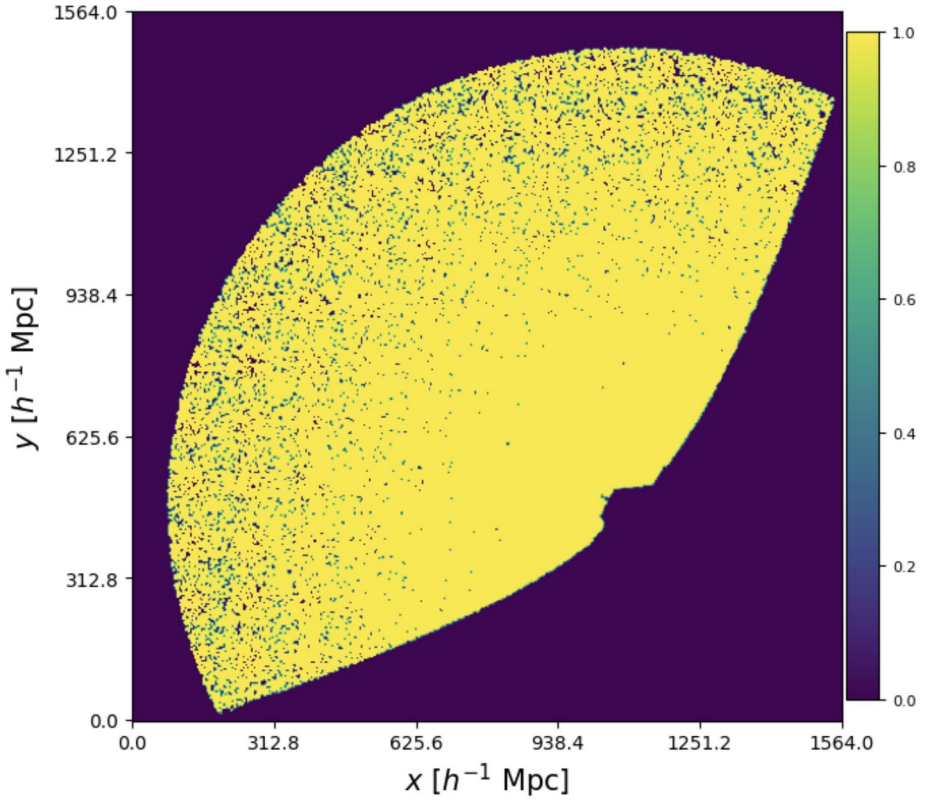
Sky coverage: 9625 deg^2 with 6200000 galaxies.

Gu et al 2024, MNRAS

Test with mock DESI BGS

Construct the density fields:

- **Embed the survey volume in a periodic, cubic box of 1564Mpc/h on a side**
- **CIC scheme, 512^3 voxels**
- **Apply the luminocity weighting for each galaxy**
- **Apply the mask weigting on each grid.**

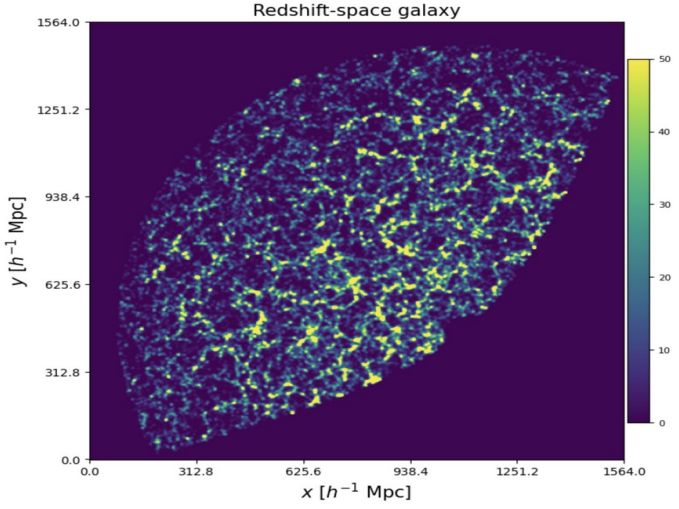


Preliminary

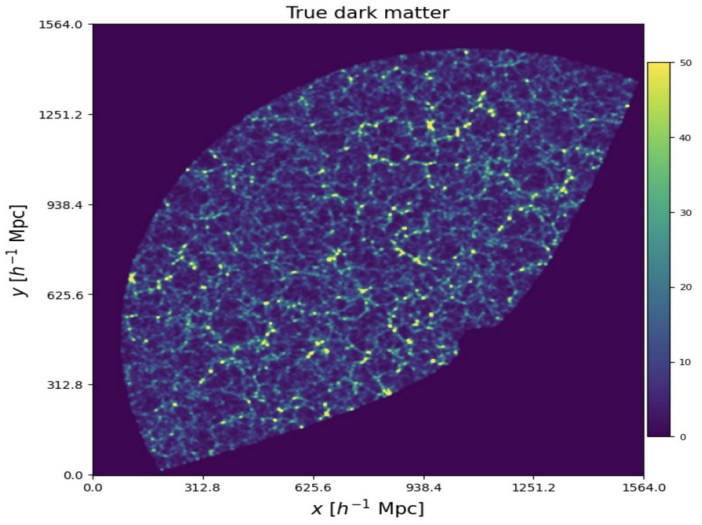
Test with mock DESI BGS

Comparison of the projected density-field distributions in a slice of 1564×1564 ×9.16 Mpc/h

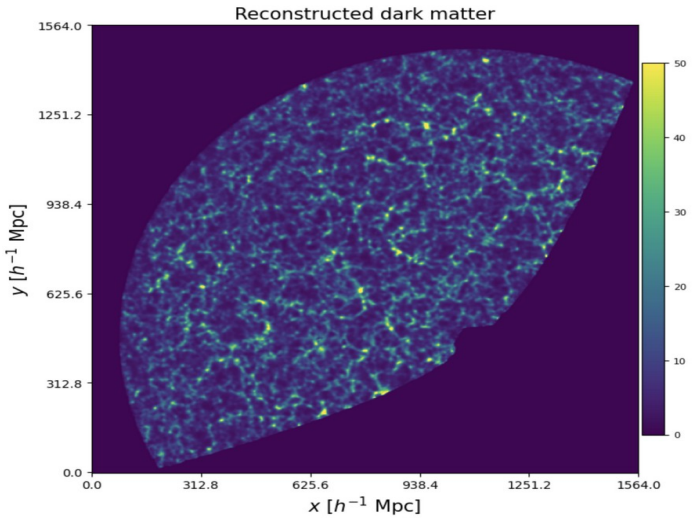
Redshift-space galaxy

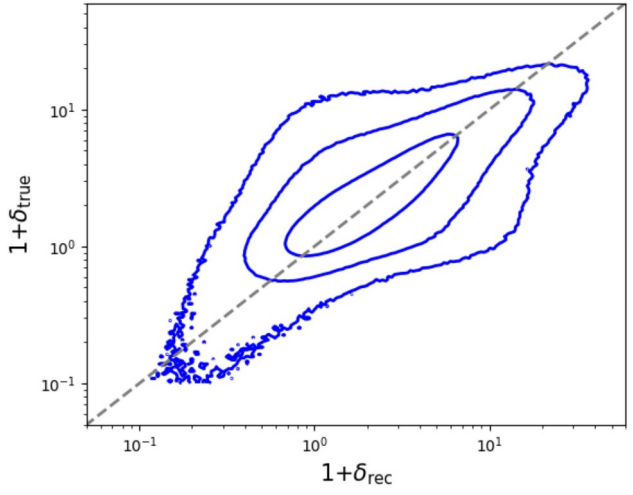


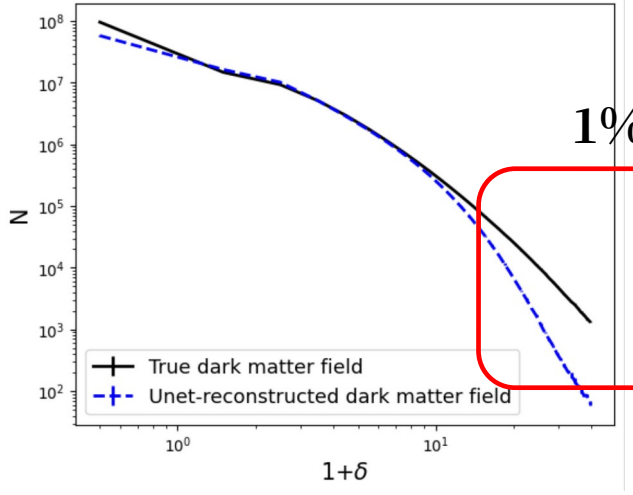
True dark matter



Reconstructed dark matter







1% grids

Preliminary

Summary & Conlusions

1) Toward ELUCID-III, we have already gone through the first four steps

2) We introducced the Unet method to reconstruct the density and velocity field

- Three simulations: COLA, Jiutian and ELUCID
- Statistics: projected density, density-density relation
- Fields: denstiy, velocity and tidal fields

3) More tests based on the mock DESI galaxy/group samples will be carried out

4) Initital condition reconstruction code will be updated to fulfill the new computational needs.

5) The ELUCID-III will be available within about two years...