Constrained simulations of distant galaxy surveys

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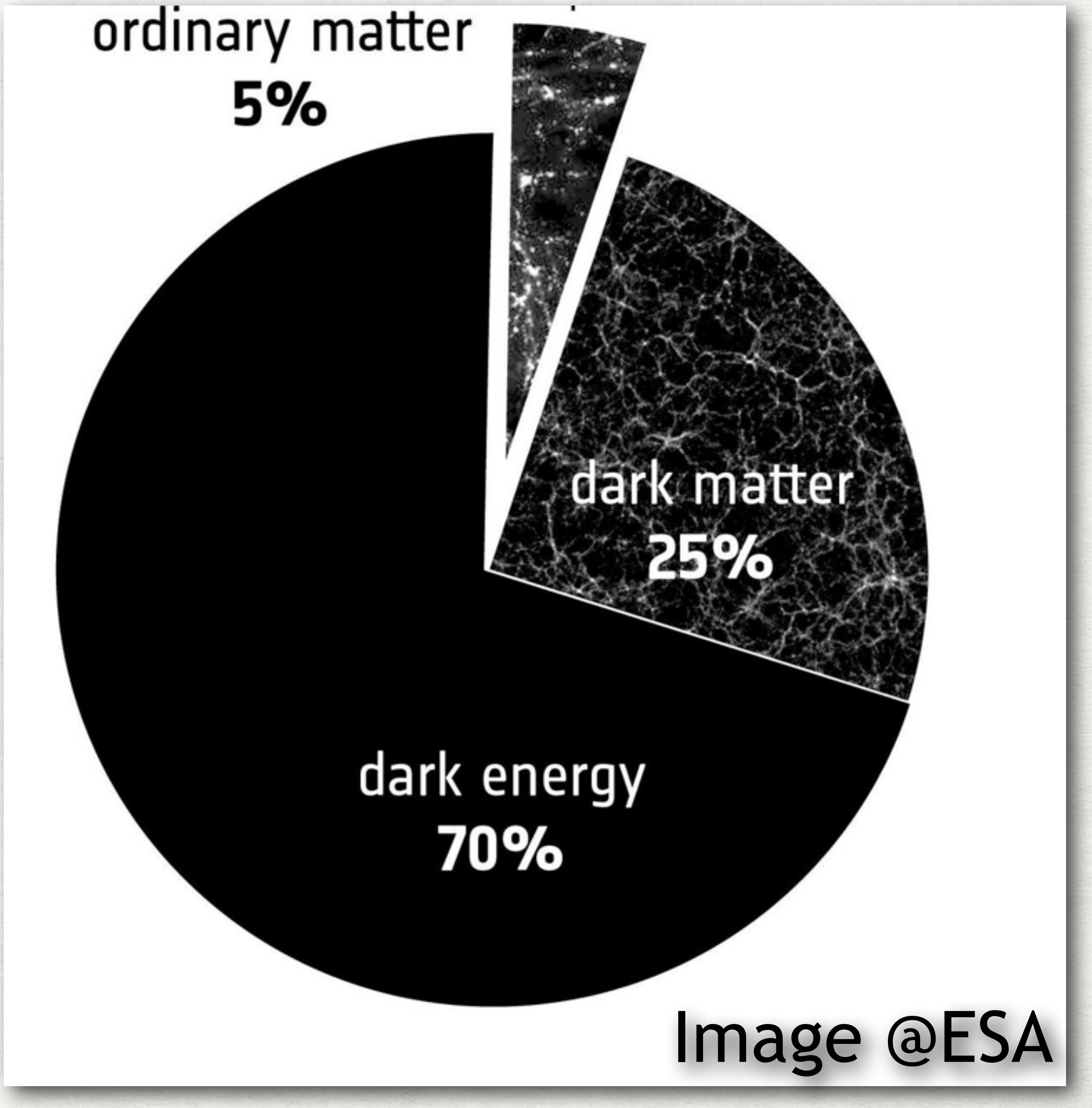
科研費 KAKENHI

TODAY'S MENU

- Introduction
- Gaussian Random Fields
- Initial Conditions
- Application to galaxy surveys

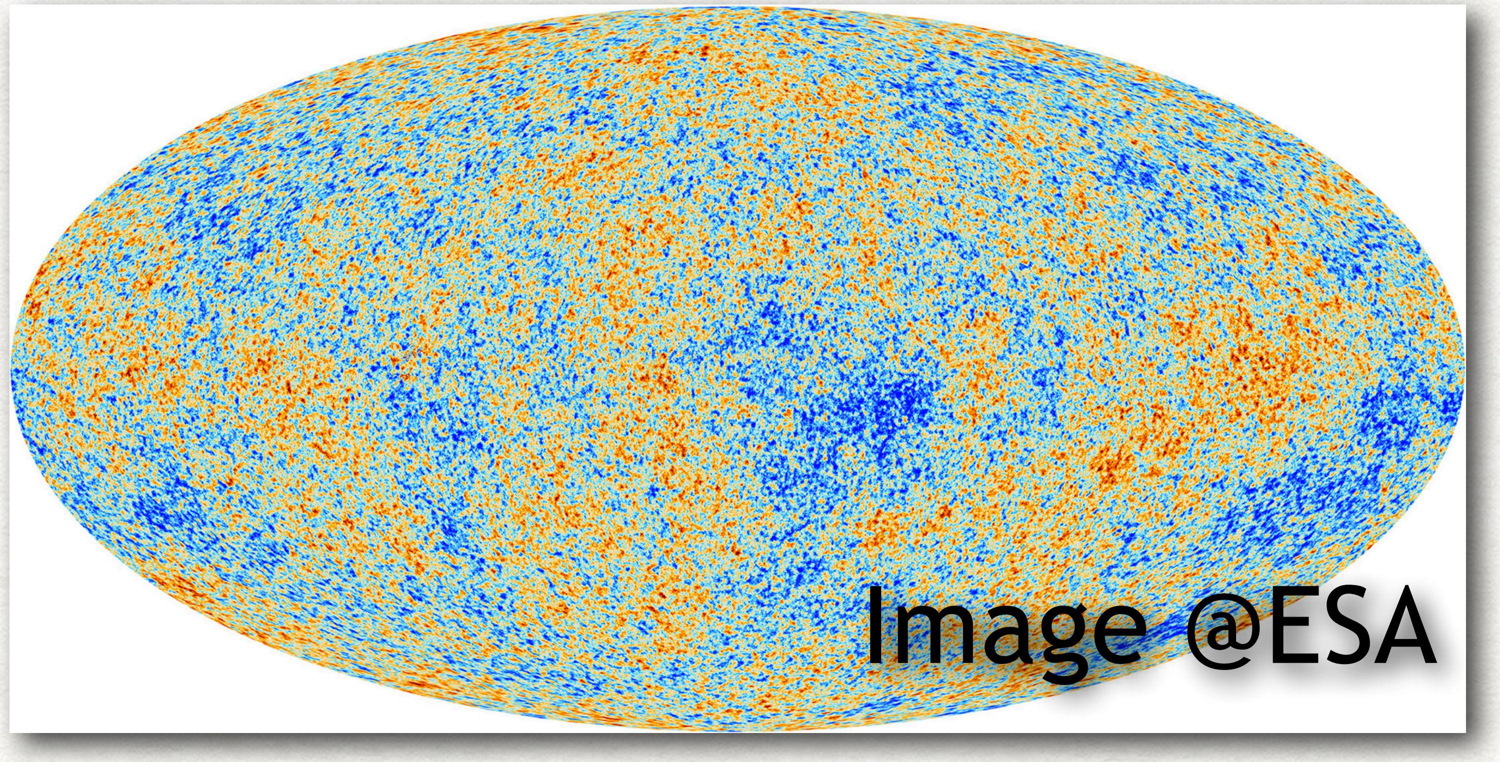
INTRODUCTION

- ΛCDM theory with 6 independent parameters
- Different observables (digest):
  - Cosmic microwave background radiation
  - Galaxy redshift surveys
  - Lensing surveys
  - Supernova distance ladders
  - Absorption/Emission lines of luminous sources



GAUSSIAN RANDOM FIELDS

- Cosmological principle: Universe is homogenous and isotropic on large scales



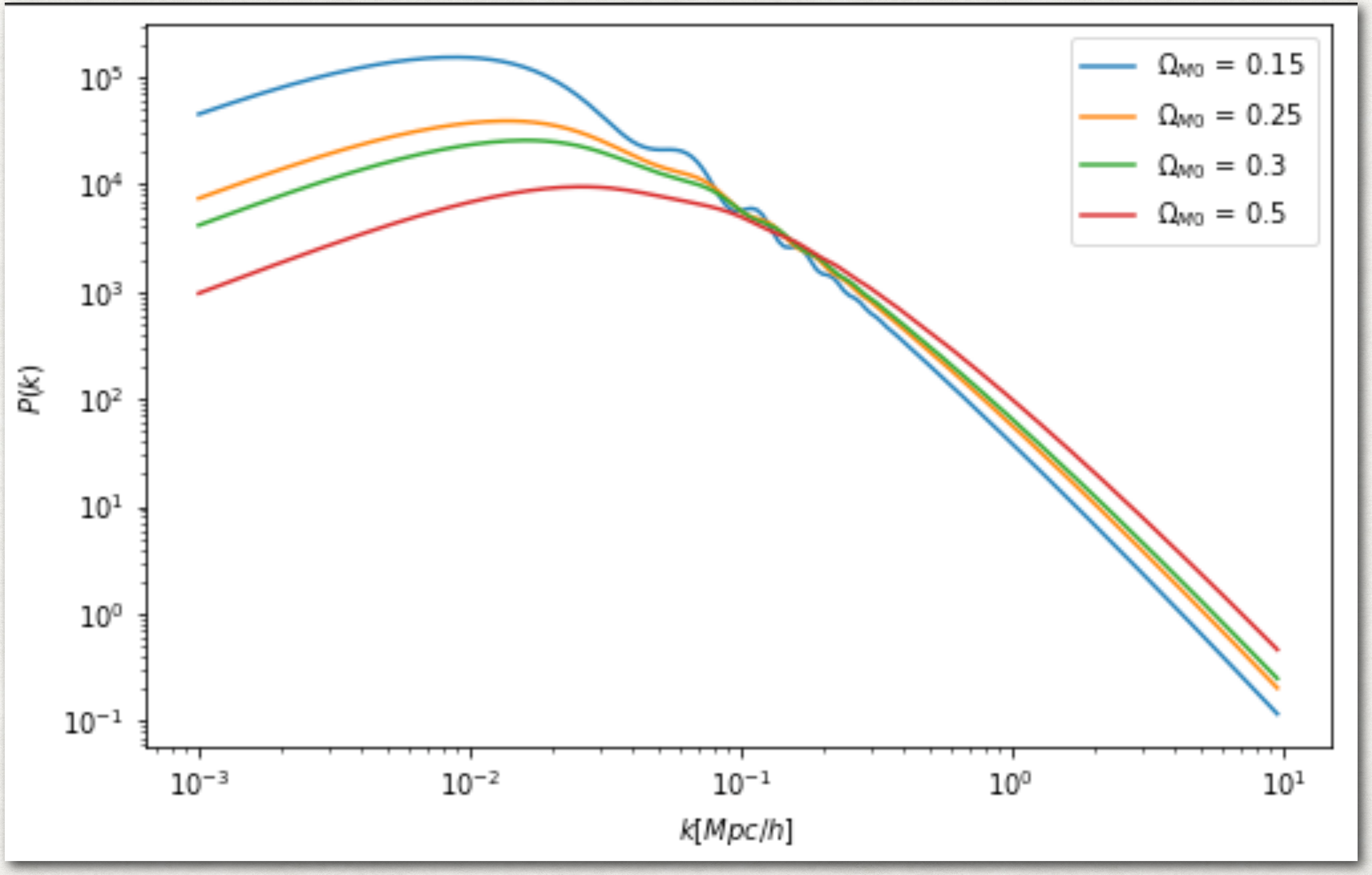
- Perturbation/Anisotropies: $\delta(\vec{r}) = \dfrac{\varrho(\vec{r}) - \bar{\varrho}}{\bar{\varrho}}$
- CMB anisotropies show a very Gaussian spectrum
- If $\delta(\vec{r})$ is 3dim Gaussian PDF $\mathscr{P}(\delta(\vec{r})) = \dfrac{1}{\sqrt{(2\pi)^3 \det(C)}} \exp\left[-\dfrac{1}{2}\delta(\vec{r}_i) C_{ij} \delta(\vec{r}_j)\right], C_{ij} = \langle \delta(\vec{r}_i)\delta(\vec{r}_j) \rangle$
- Every point in the density perturbation field is also Gaussian $\mathscr{P}(\delta) = \dfrac{1}{\sqrt{2\pi\sigma^2}} \exp\left[-\dfrac{1}{2}\dfrac{\delta^2}{\sigma^2}\right]$

RANDOM FIELDS FOURIER SPACE

- Decompose density perturbations in Fourier modes: $\delta(\vec{k}) = \int d^3r\, \delta(\vec{r})\, \exp\left[i\,\vec{k}\,\vec{r}\right]$
- If $\delta(\vec{r})$ is real, then $\delta^*(\vec{k}) = \delta(-\vec{k})$ Hermiticity
- Power spectrum $(2\pi)^3 \delta_D(\vec{k} - \vec{k'}) P(k) = \langle \delta(\vec{k}) \delta^*(\vec{k'}) \rangle$
- Variance given by: $\sigma_R^2 = \int \frac{dk}{2\pi^2} k^2 P(k) W_R^2(k)$: Window function for *practical* reasons
- Power spectrum is equivalently describing variance of perturbations as covariance

RANDOM FIELDS & POWER SPECTRUM

- Power spectrum $P(k) \propto \langle \delta(\vec{k})\delta^*(\vec{k}) \rangle$ encoding information about cosmological parameters



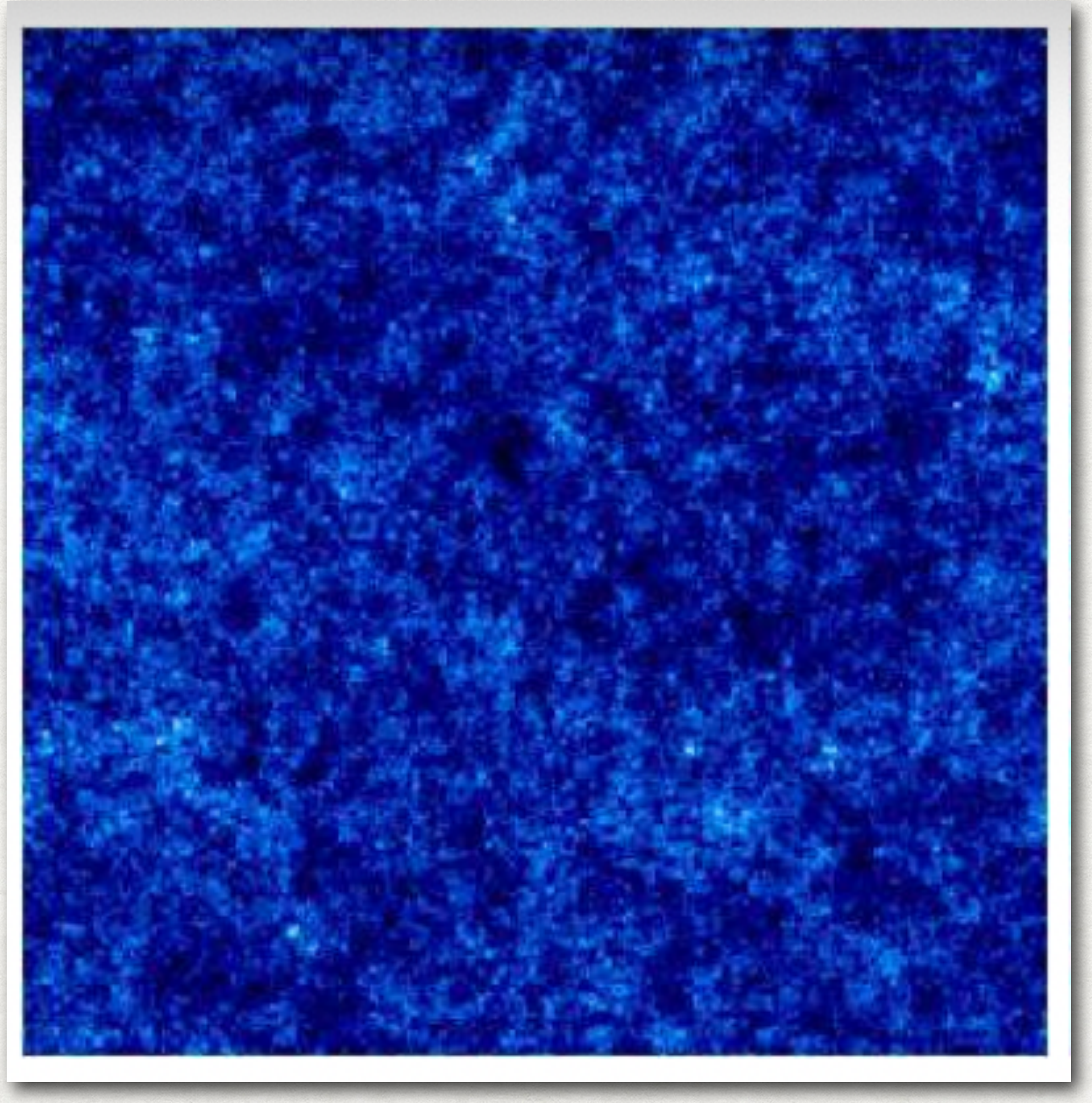
PROPERTIES OF GAUSSIAN RANDOM FIELDS

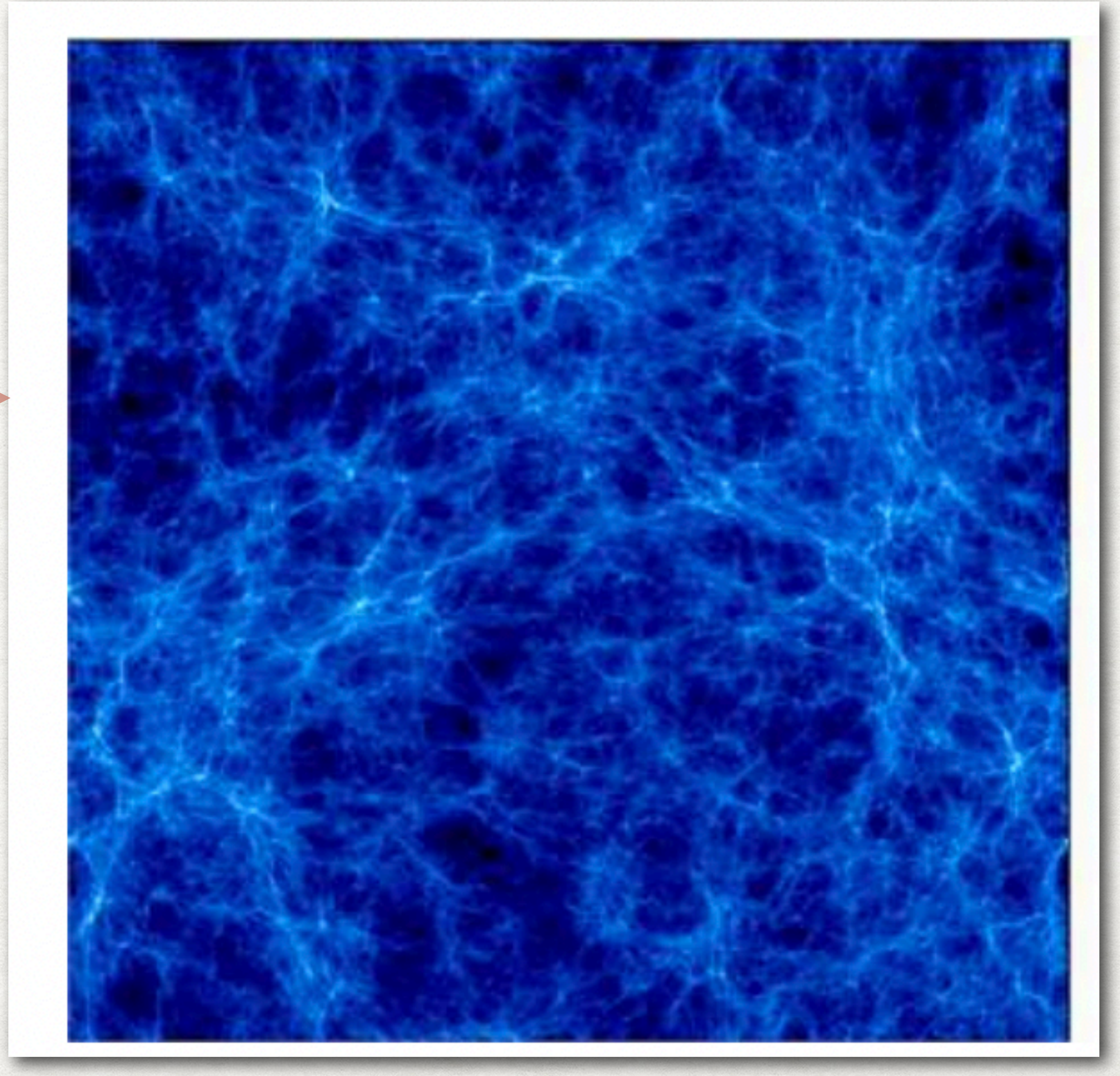
- Gaussian random fields come with many interesting properties
- $\delta(\overrightarrow{k}) = \delta_r(\overrightarrow{k}) + i\delta_i(\overrightarrow{k}) = \left|\delta(\overrightarrow{k})\right| \mathrm{e}^{\mathrm{i}\theta(\mathrm{k})}$
- Real and imaginary part independent Gaussians with variance $P/2$
- Rayleigh distribution for $\mathscr{P}(|\delta(k)|) = \frac{2|\delta(k)|}{P} \exp\left(-\frac{|\delta(k)|^2}{P}\right)$
- Uniform for phases $\mathscr{P}(\theta(k)) = U(-\pi, \pi)$

INITIAL CONDITIONS

- Why this obsession with Gaussian random fields?

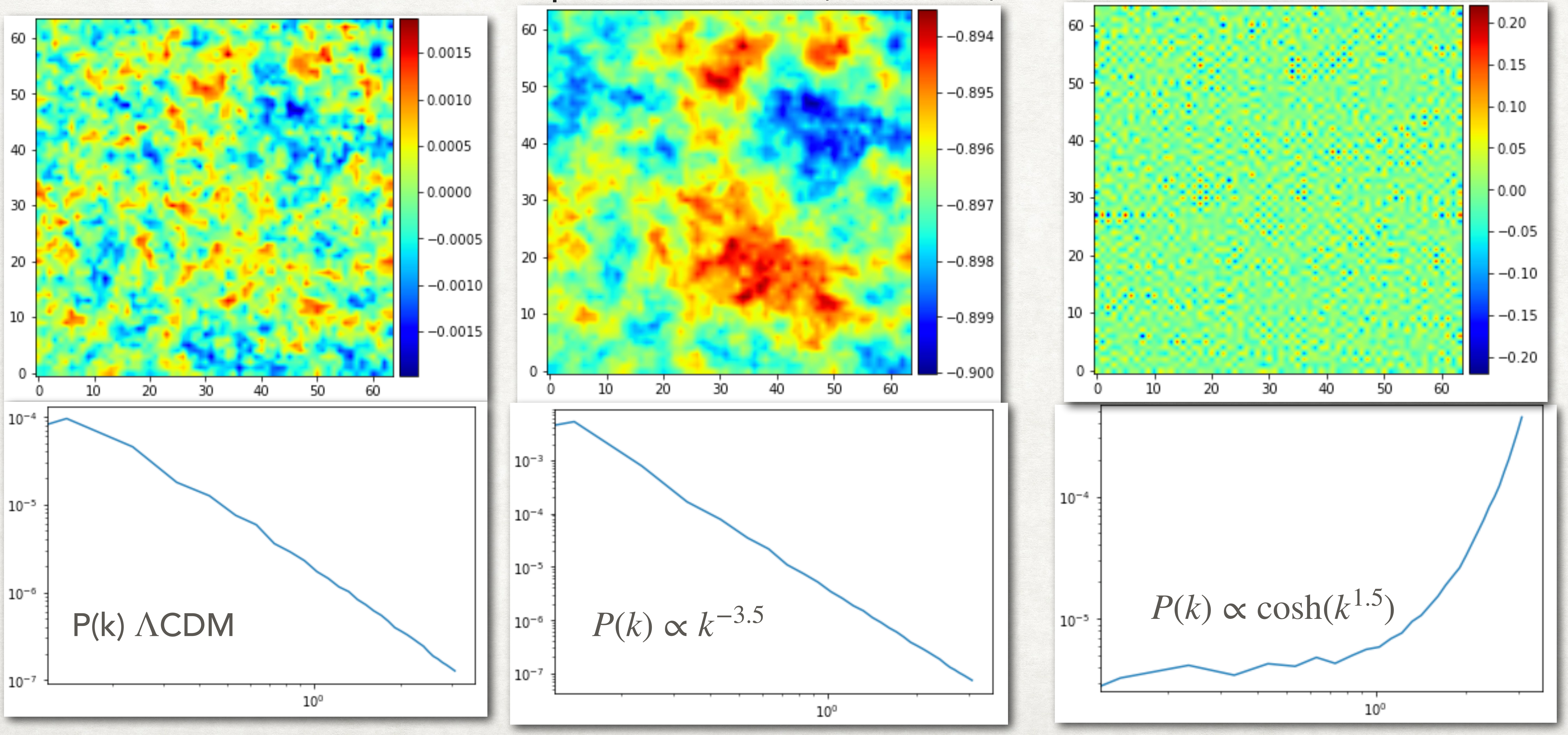
- Initial conditions of Cosmological simulations usually (nearly) Gaussian Fields





INITIAL CONDITIONS

- Closer look as GRFs, same phases $P(k) \propto \langle \delta(k)\delta^*(k) \rangle$



INITIAL CONDITIONS

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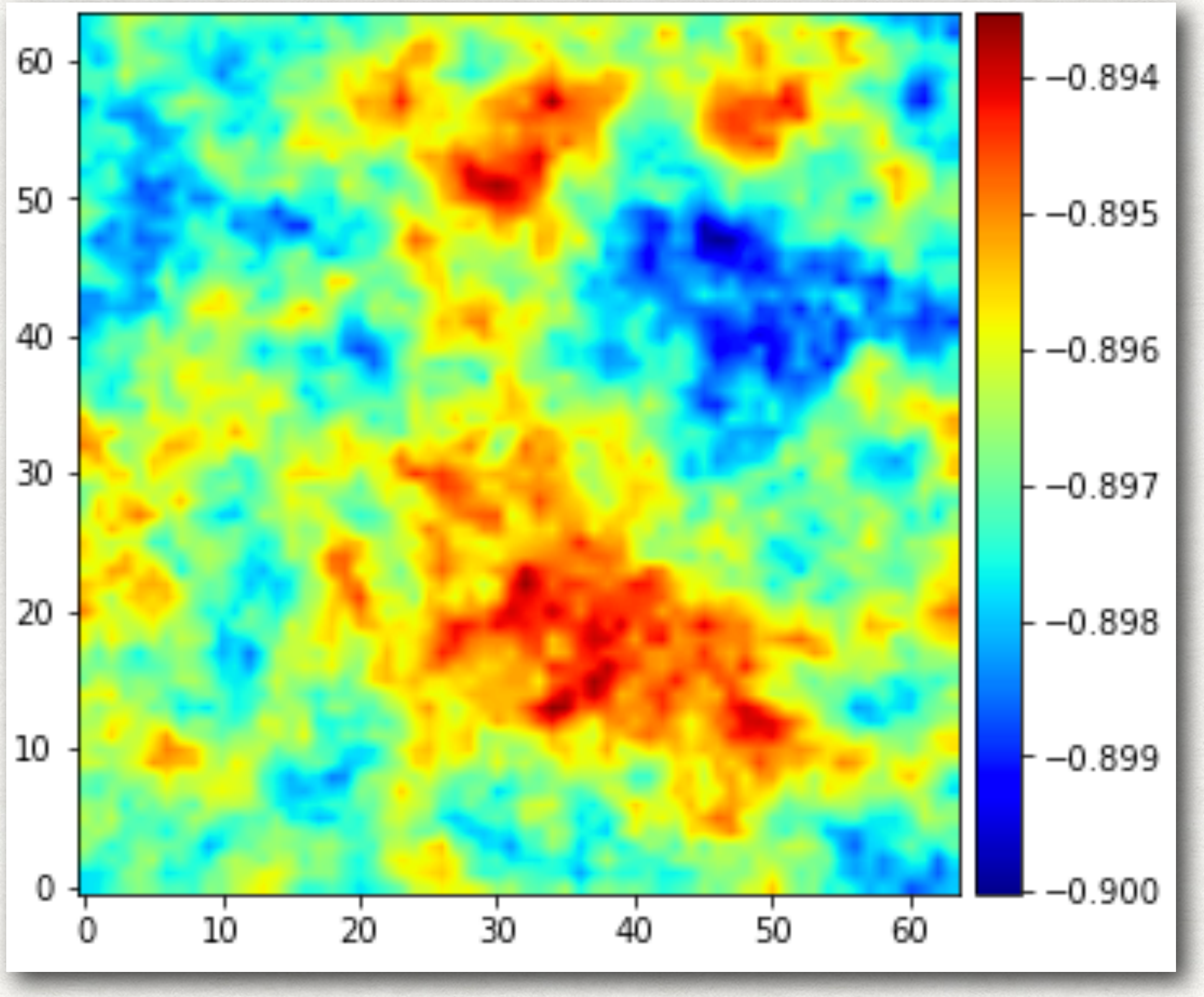
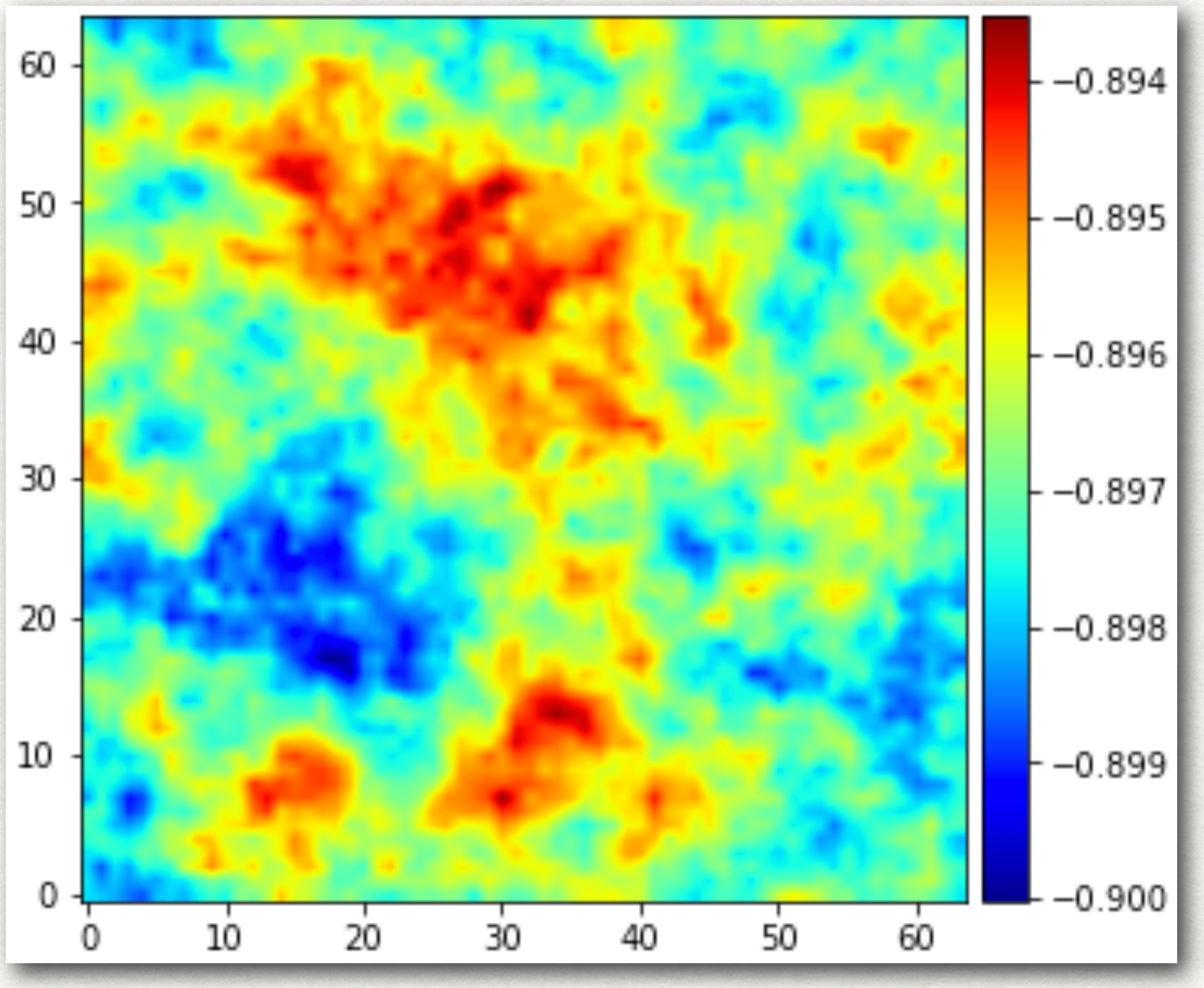
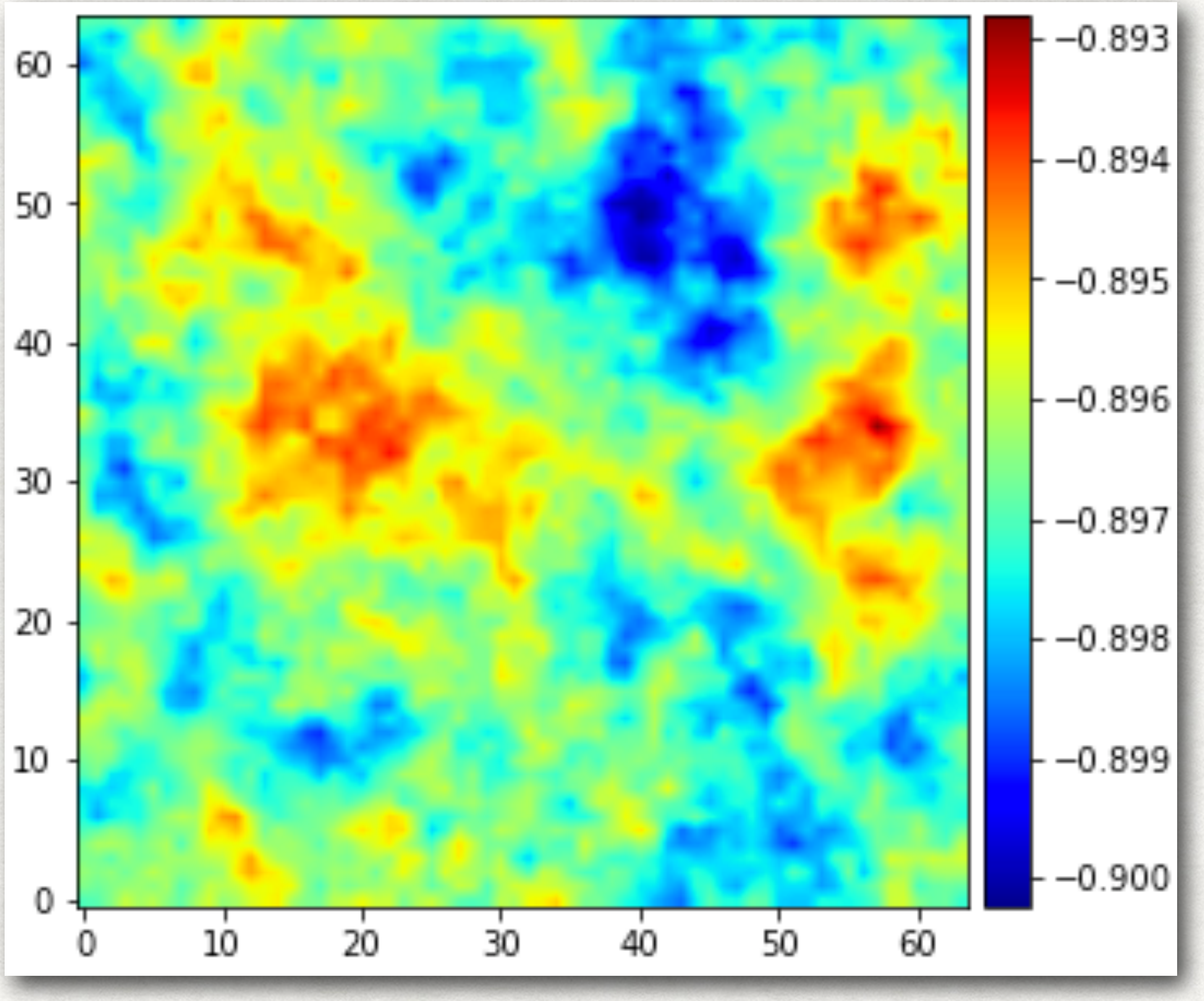


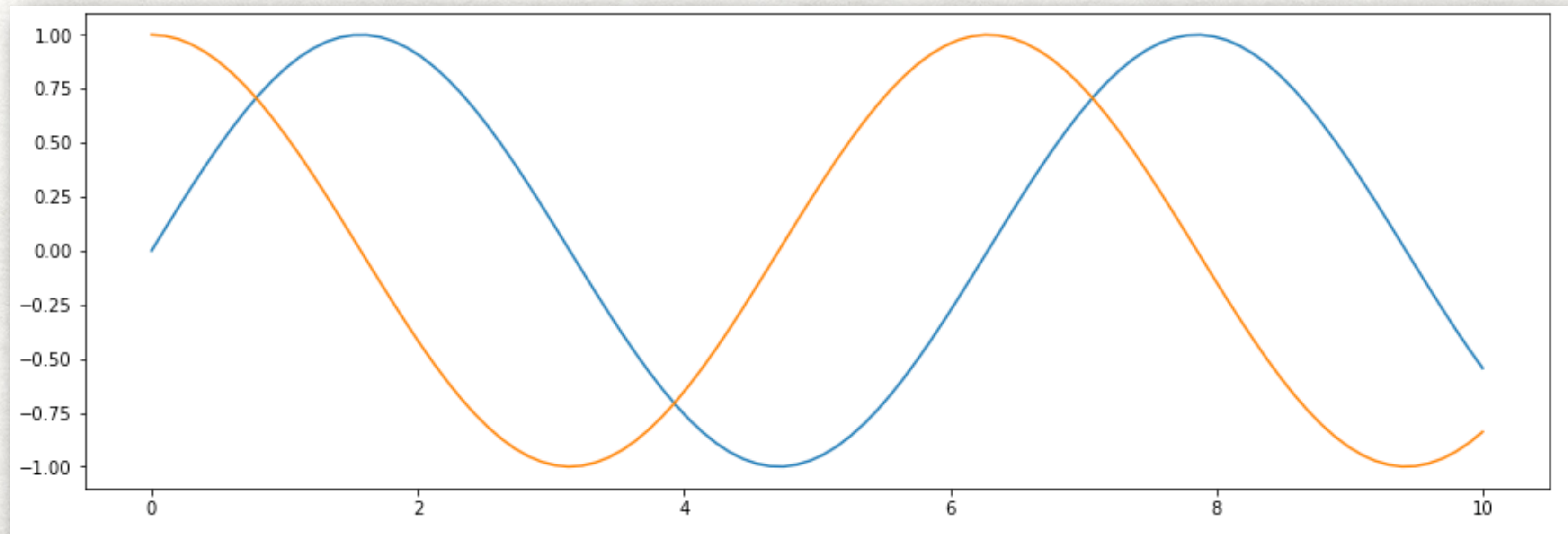
$\theta(k) \in U(-\pi, \pi)$



$\theta(k) \in U(\pi, -\pi)$

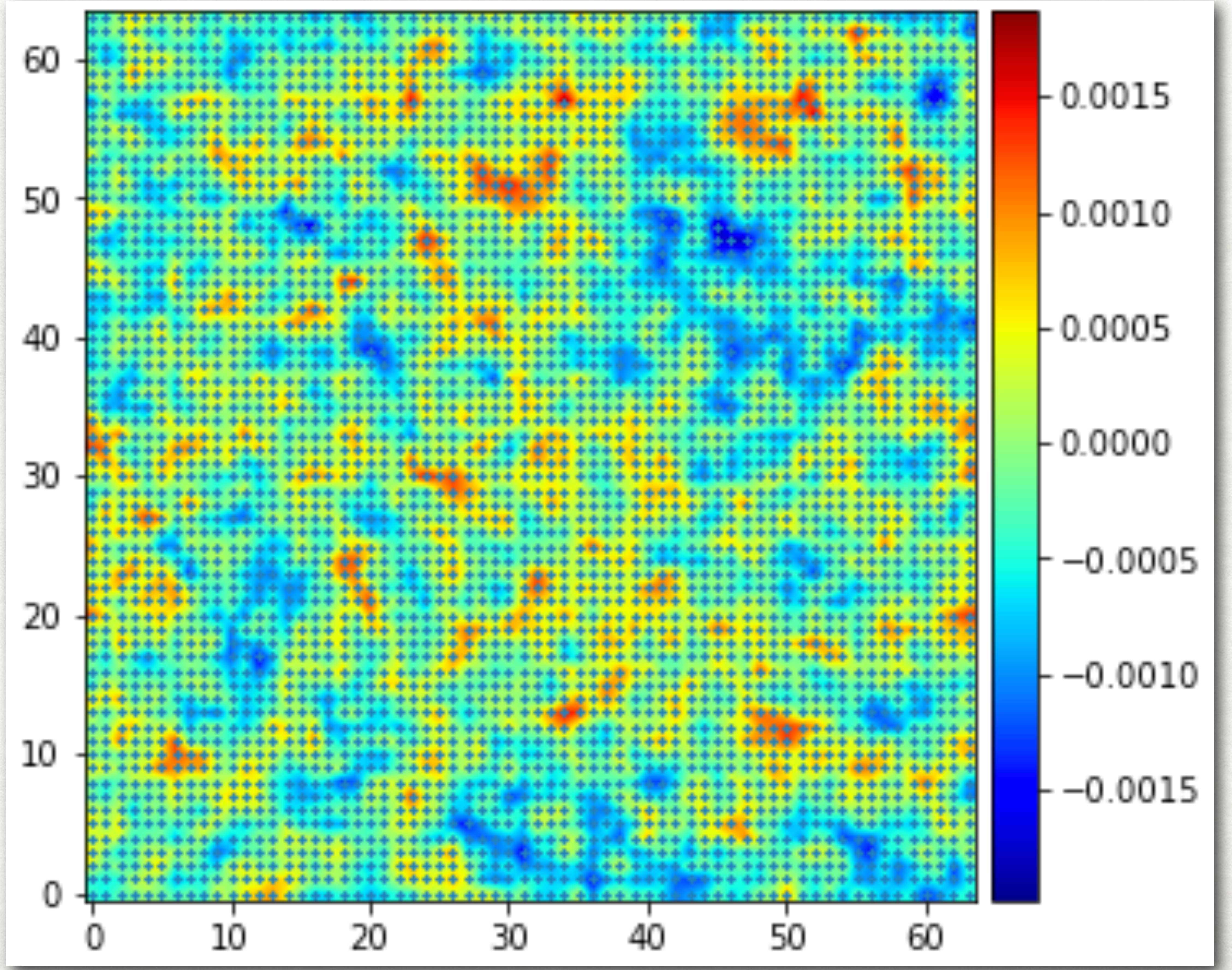


$\theta(k) \in U(-\pi + \phi, \pi + \phi)$



INITIAL CONDITIONS

- How to go from densities to initial conditions?
- We define the initial phase-space for N particles in a volume with *Lagrangian perturbation theory*



INITIAL CONDITIONS

- Take away:
  - Power spectrum/Covariance completely characterizes GRF
  - We can impose ΛCDM power spectrum on GRF
  - Power spectrum blind to phases
  - Phases determine "where" fluctuations are
  - Initial conditions for simulations are a set of N particles with initial $\vec{x}$ & $\vec{v}$

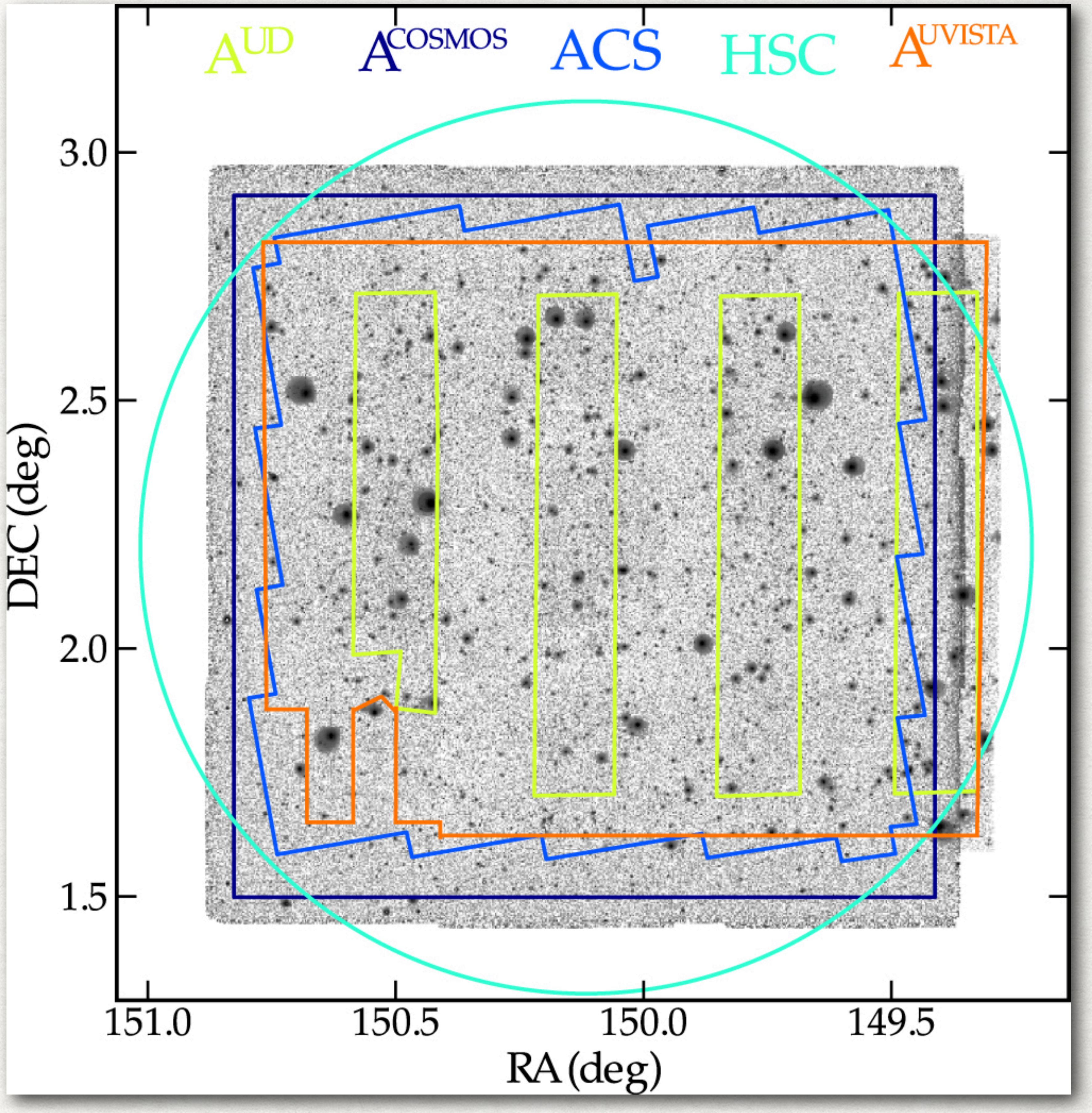
GALAXY SURVEYS

HIGH REDSHIFT GALAXY SURVEYS

- Local Universe and near field galaxy surveys conducted with great success over the last 2 decades (2MRS, 6DFRS, SDSS…)
- We will be able to test ΛCDM predictions on early ($z \gtrsim 1.5$) large-scale structure formation and galaxy evolution with next generation surveys (PFS, DESI…)
- We use the current high redshift surveys to develop tools to compare these observations to theory

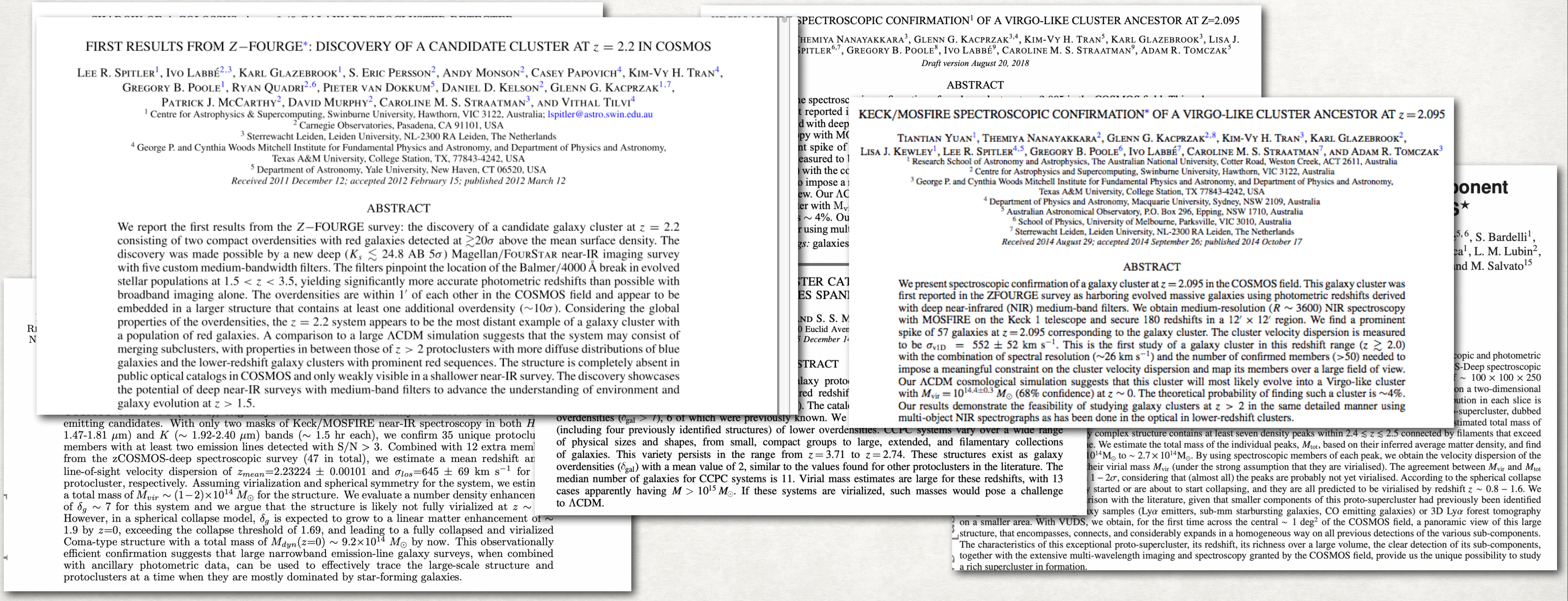
THE COSMOS FIELD

- COSMOS Survey (Capak+2007; Laigle+2016)
- Photometric survey ($1 < z < 6$) with 5×10^5 galaxies
- Covers the peak of star formation (e.g. Madau+2014)
- Lyα tomography in this field:
  CLAMATO (Lee+2014,2016,2018)
  LATIS(Newman+2020)



COSMOS FIELD

- (Too) Many significant overdensities in a relatively small volume at redshifts~2.5



FIRST RESULTS FROM Z−FOURGE*: DISCOVERY OF A CANDIDATE CLUSTER AT $z = 2.2$ IN COSMOS

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ABSTRACT

We report the first results from the Z−FOURGE survey: the discovery of a candidate galaxy cluster at $z = 2.2$ consisting of two compact overdensities with red galaxies detected at $\gtrsim 20\sigma$ above the mean surface density. The discovery was made possible by a new deep ($K_s \lesssim 24.8$ AB 5σ) Magellan/FourStar near-IR imaging survey with five custom medium-bandwidth filters. The filters pinpoint the location of the Balmer/4000 Å break in evolved stellar populations at $1.5 < z < 3.5$, yielding significantly more accurate photometric redshifts than possible with broadband imaging alone. The overdensities are within $1'$ of each other in the COSMOS field and appear to be embedded in a larger structure that contains at least one additional overdensity ($\sim 10\sigma$). Considering the global properties of the overdensities, the $z = 2.2$ system appears to be the most distant example of a galaxy cluster with a population of red galaxies. A comparison to a large ΛCDM simulation suggests that the system may consist of merging subclusters, with properties in between those of $z > 2$ protoclusters with more diffuse distributions of blue galaxies and the lower-redshift galaxy clusters with prominent red sequences. The structure is completely absent in public optical catalogs in COSMOS and only weakly visible in a shallower near-IR survey. The discovery showcases the potential of deep near-IR surveys with medium-band filters to advance the understanding of environment and galaxy evolution at $z > 1.5$.

KECK/MOSFIRE SPECTROSCOPIC CONFIRMATION* OF A VIRGO-LIKE CLUSTER ANCESTOR AT $z = 2.095$

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ABSTRACT

We present spectroscopic confirmation of a galaxy cluster at $z = 2.095$ in the COSMOS field. This galaxy cluster was first reported in the ZFOURGE survey as harboring evolved massive galaxies using photometric redshifts derived with deep near-infrared (NIR) medium-band filters. We obtain medium-resolution ($R \sim 3600$) NIR spectroscopy with MOSFIRE on the Keck 1 telescope and secure 180 redshifts in a $12' \times 12'$ region. We find a prominent spike of 57 galaxies at $z = 2.095$ corresponding to the galaxy cluster. The cluster velocity dispersion is measured to be $\sigma_{v1D} = 552 \pm 52$ km s^{-1}. This is the first study of a galaxy cluster in this redshift range ($z \gtrsim 2.0$) with the combination of spectral resolution (~ 26 km s^{-1}) and the number of confirmed members (>50) needed to impose a meaningful constraint on the cluster velocity dispersion and map its members over a large field of view. Our ΛCDM cosmological simulation suggests that this cluster will most likely evolve into a Virgo-like cluster with $M_{vir} = 10^{14.4\pm0.3}\,M_\odot$ (68% probability) at $z \sim 0$. The theoretical probability of finding such a cluster is ~4%. Our results demonstrate the feasibility of studying galaxy clusters at $z > 2$ in the same detailed manner using multi-object NIR spectrographs as has been done in the optical in lower-redshift clusters.

emitting candidates. With only two masks of Keck/MOSFIRE near-IR spectroscopy in both H 1.47-1.81 μm) and K ($\sim$ 1.92-2.40 μm) bands ($\sim$ 1.5 hr each), we confirm 35 unique protoclu members with at least two emission lines detected with S/N > 3. Combined with 12 extra memb from the zCOSMOS-deep spectroscopic survey (47 in total), we estimate a mean redshift an line-of-sight velocity dispersion of z_{mean}=2.23224 ± 0.00101 and σ_{los}=645 ± 69 km s^{-1} for protocluster, respectively. Assuming virialization and spherical symmetry for the system, we estin a total mass of $M_{vir} \sim (1-2)\times10^{14}\,M_\odot$ for the structure. We evaluate a number density enhance of $\delta_g \sim 7$ for this system and we argue that the structure is likely not fully virialized at $z \sim$ However, in a spherical collapse model, δ_g is expected to grow to a linear matter enhancement of $\sim$ 1.9 by z=0, exceeding the collapse threshold of 1.69, and leading to a fully collapsed and virialized Coma-type structure with a total mass of $M_{dyn}(z{=}0) \sim 9.2\times10^{14}\,M_\odot$ by now. This observationally efficient confirmation suggests that large narrowband emission-line galaxy surveys, when combined with ancillary photometric data, can be used to effectively trace the large-scale structure and protoclusters at a time when they are mostly dominated by star-forming galaxies.

overdensities ($\delta_{gal} > 7$), 6 of which were previously known. We (including four previously identified structures) of lower overdensities. CCPC systems vary over a wide range of physical sizes and shapes, from small, compact groups to large, extended, and filamentary collections of galaxies. This variety persists in the range from $z = 3.71$ to $z = 2.74$. These structures exist as galaxy overdensities (δ_{gal}) with a mean value of 2, similar to the values found for other protoclusters in the literature. The median number of galaxies for CCPC systems is 11. Virial mass estimates are large for these redshifts, with 13 cases apparently having $M > 10^{15}\,M_\odot$. If these systems are virialized, such masses would pose a challenge to ΛCDM.

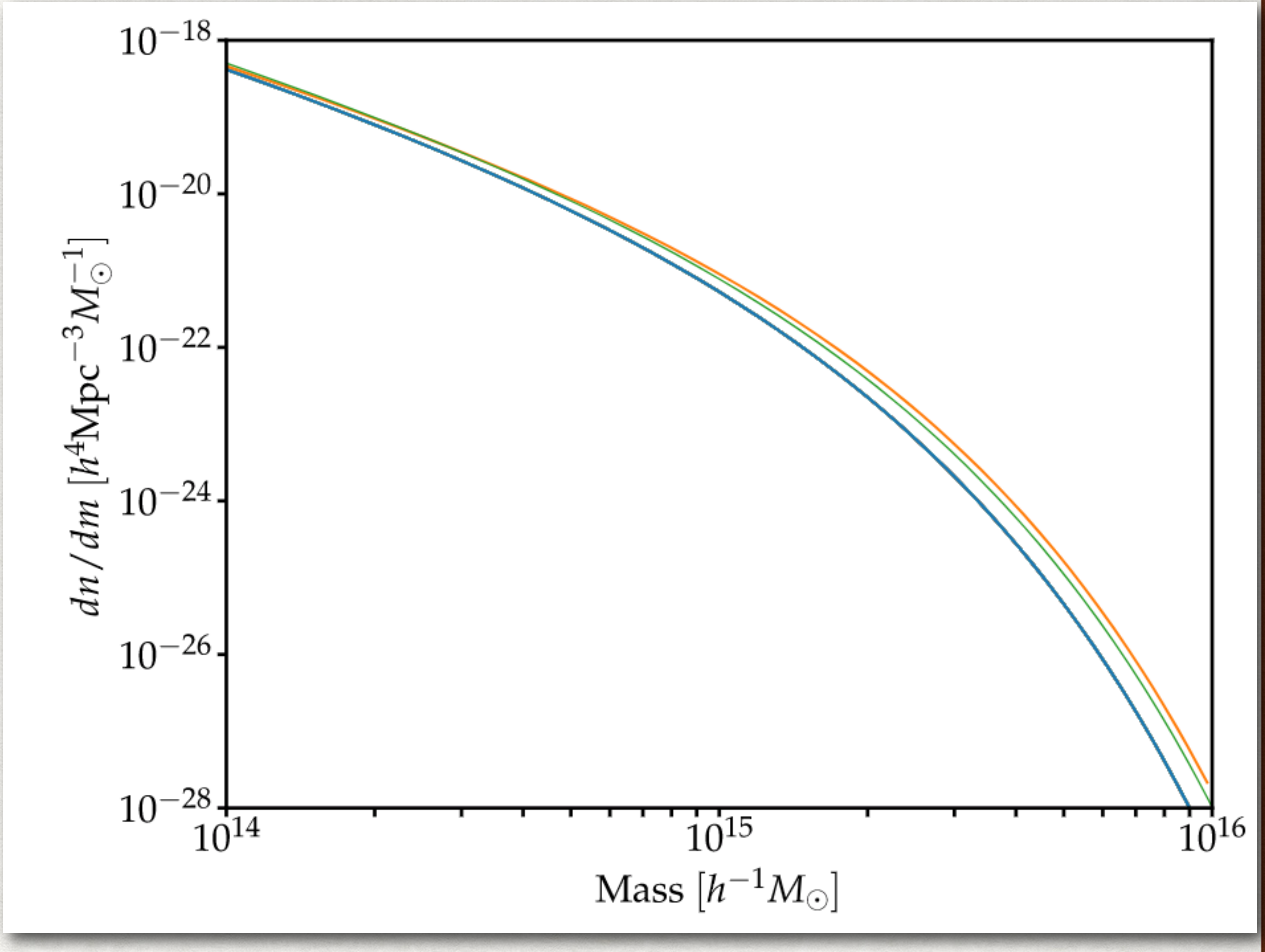
y complex structure contains at least seven density peaks within $2.4 \lesssim z \lesssim 2.5$ connected by filaments that exceed e. We estimate the total mass of the individual peaks, M_{tot}, based on their inferred average matter density, and find $10^{14} M_\odot$ to $\sim 2.7\times10^{14} M_\odot$. By using spectroscopic members of each peak, we obtain the velocity dispersion of the heir virial mass M_{vir} (under the strong assumption that they are virialised). The agreement between M_{vir} and M_{tot} $1-2\sigma$, considering that (almost all) the peaks are probably not yet virialised. According to the spherical collapse started or are about to start collapsing, and they are all predicted to be virialised by redshift $z \sim 0.8 - 1.6$. We rison with the literature, given that smaller components of this proto-supercluster had previously been identified xy samples (Lyα emitters, sub-mm starbursting galaxies, CO emitting galaxies) or 3D Lyα forest tomography on a smaller area. With VUDS, we obtain, for the first time across the central $\sim$ 1 deg^2 of the COSMOS field, a panoramic view of this large structure, that encompasses, connects, and considerably expands in a homogeneous way on all previous detections of the various sub-components. The characteristics of this exceptional proto-supercluster, its redshift, its richness over a large volume, the clear detection of its sub-components, together with the extensive multi-wavelength imaging and spectroscopy granted by the COSMOS field, provide us the unique possibility to study a rich supercluster in formation.

MOTIVATION

- Observations show numerous promising overdensities in the COSMOS field
  We call them observed protocluster candidates

- Protoclusters: progenitors (halos/dark matter)
  that will collapse to a cluster

- Observers find (too) many "COMA progenitors"
  of $M \sim 10^{15} M_{\odot}$ mass in a relatively small field



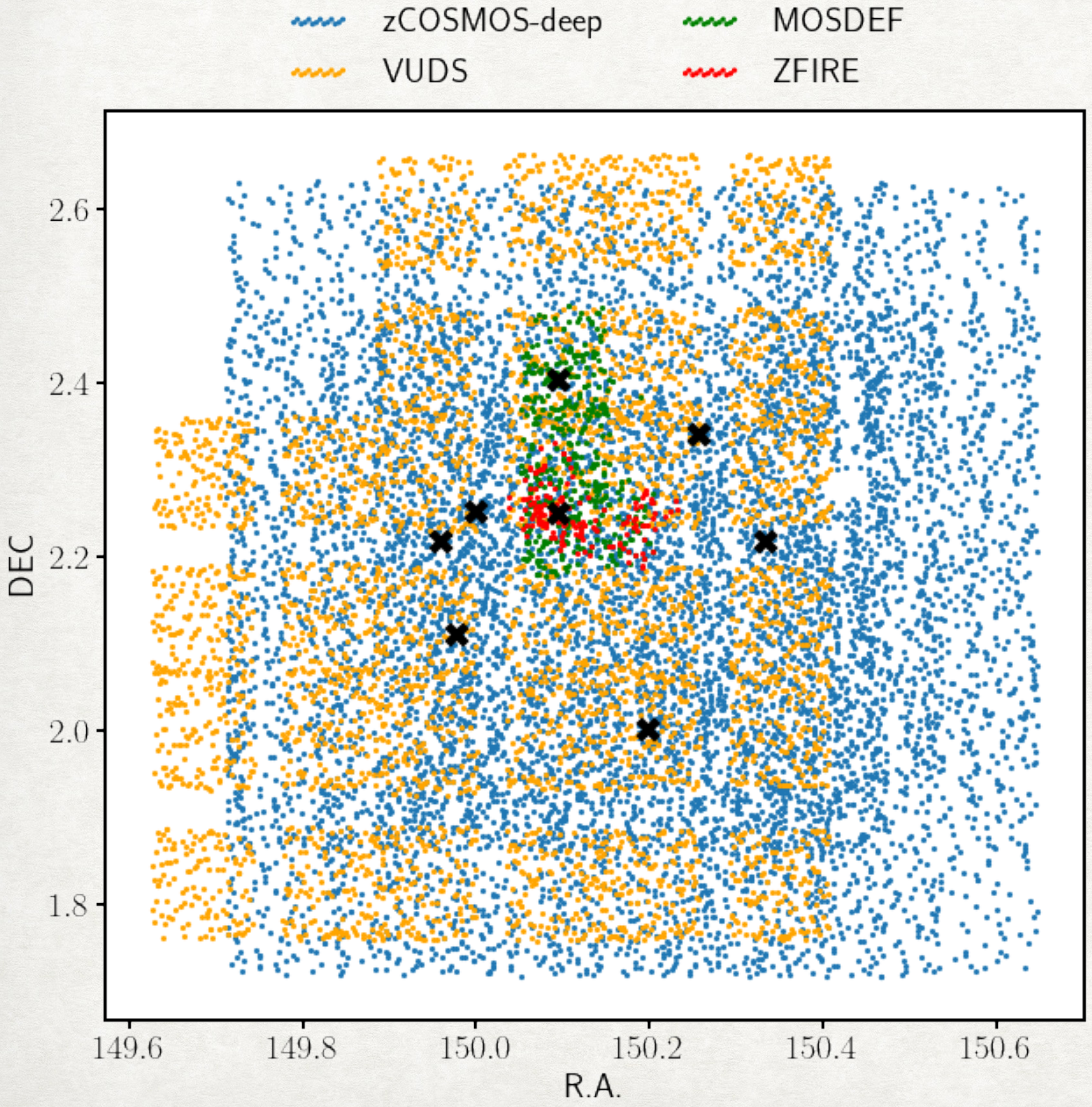
- **Question: Are these findings likely?**

OUTLINE OF THE ANALYSIS

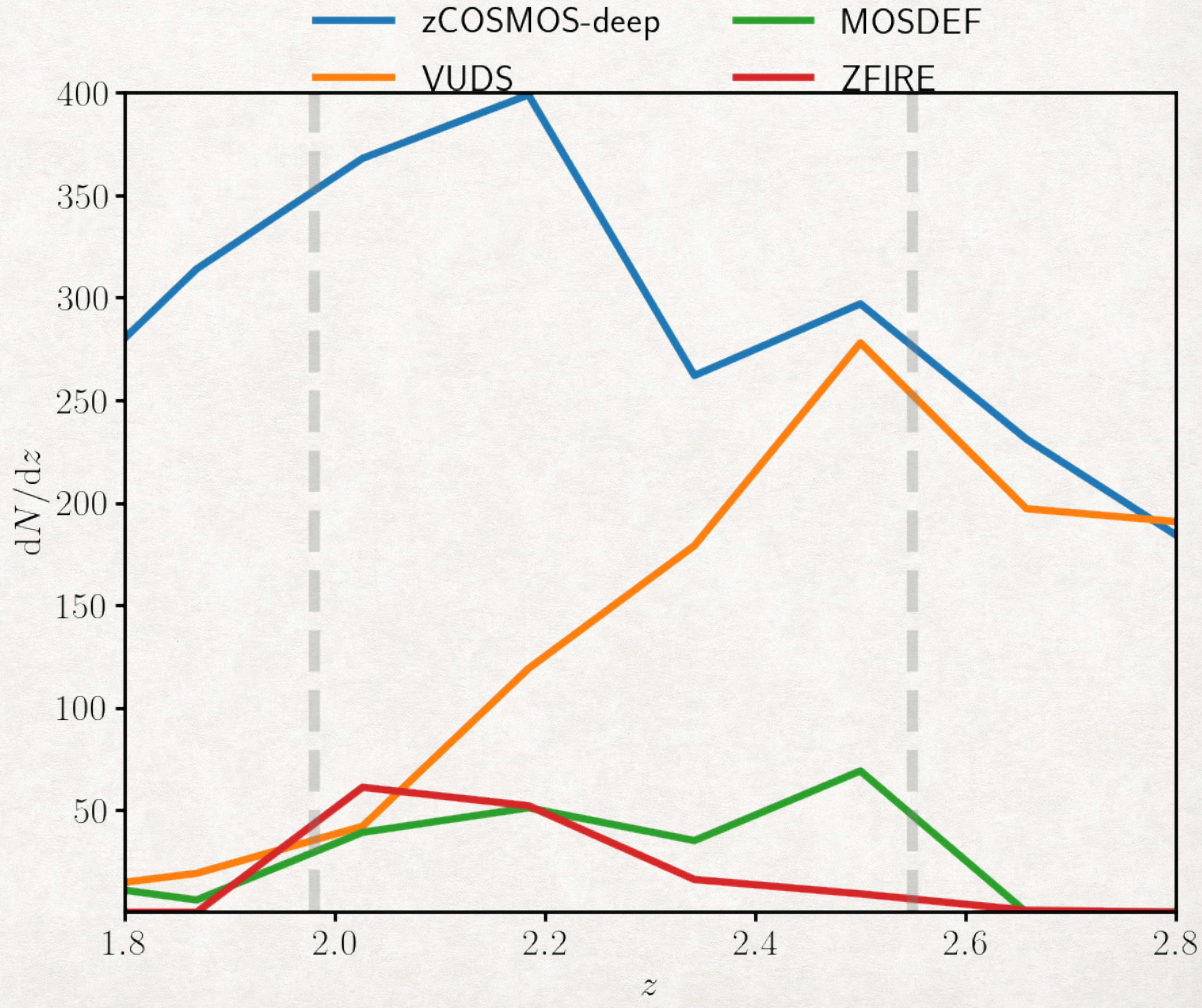
- Goal: Predict the $z = 0$ masses, positions and merging history of galaxy protoclusters, that have been observed at $z \sim 2.3$
- Large-scale structure environment is decisive for the density evolution
- We need to find initial conditions, that reproduces the galaxy survey data and:
  - At the right time,
  - At the right position,
  - Forms the right densities

Constrained Simulations

THE DATA



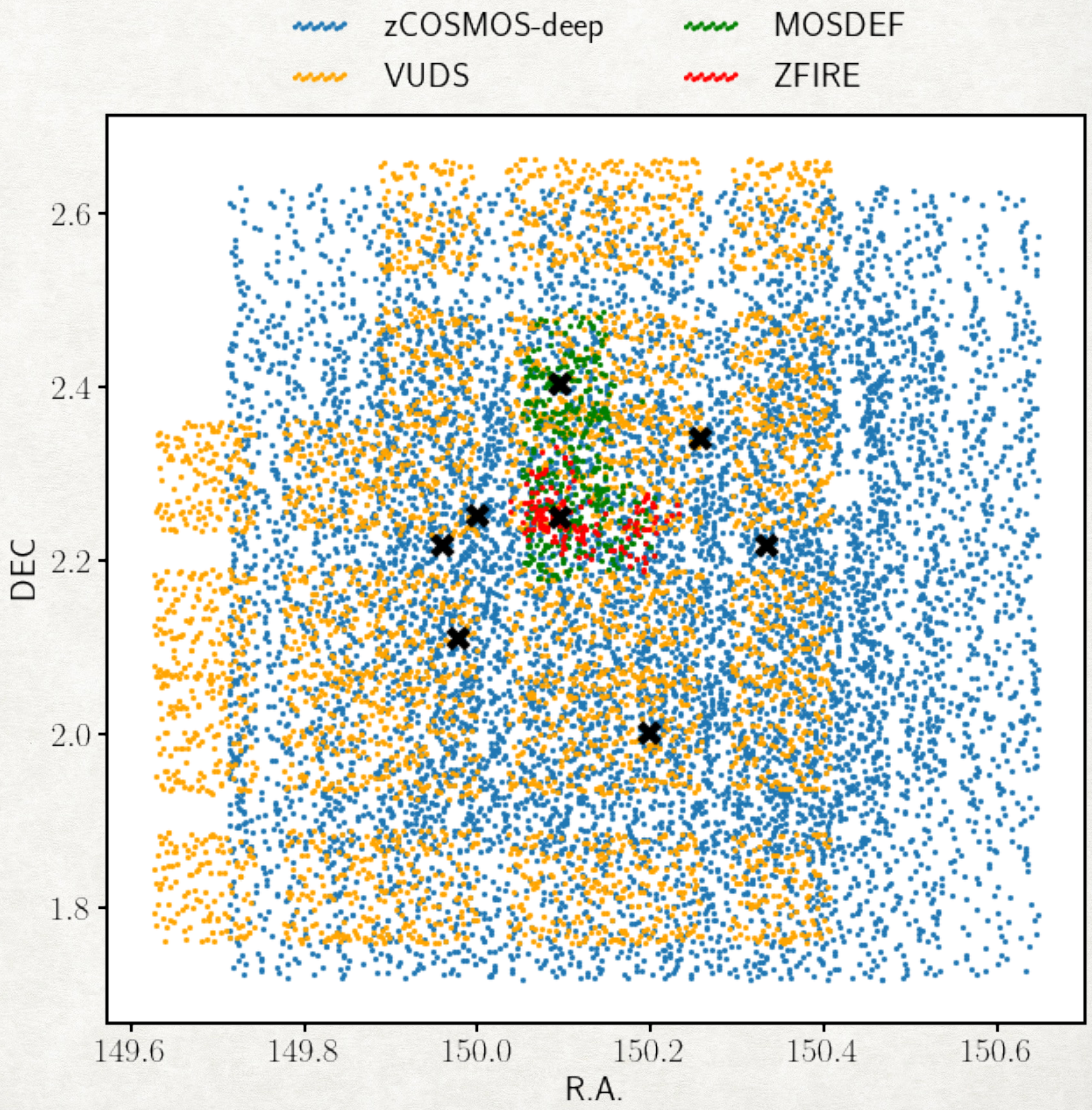
zCOSMOS-deep
MOSDEF
VUDS
ZFIRE
DEC
R.A.
2.6
2.4
2.2
2.0
1.8
149.6
149.8
150.0
150.2
150.4
150.6



zCOSMOS-deep
MOSDEF
VUDS
ZFIRE
$\mathrm{d}N/\mathrm{d}z$
z
400
350
300
250
200
150
100
50
1.8
2.0
2.2
2.4
2.6
2.8

THE DATA

- Systematic uncertainties of the data:
  - Data quality (redshift estimates)
  - Galaxy bias
  - Survey geometry, no selection function
  - Redshift space distortions/
    no velocity information
- This means: Initial conditions are not unique
  <u>We need a set of starting points</u>
  <u>that lead to the same structures</u>



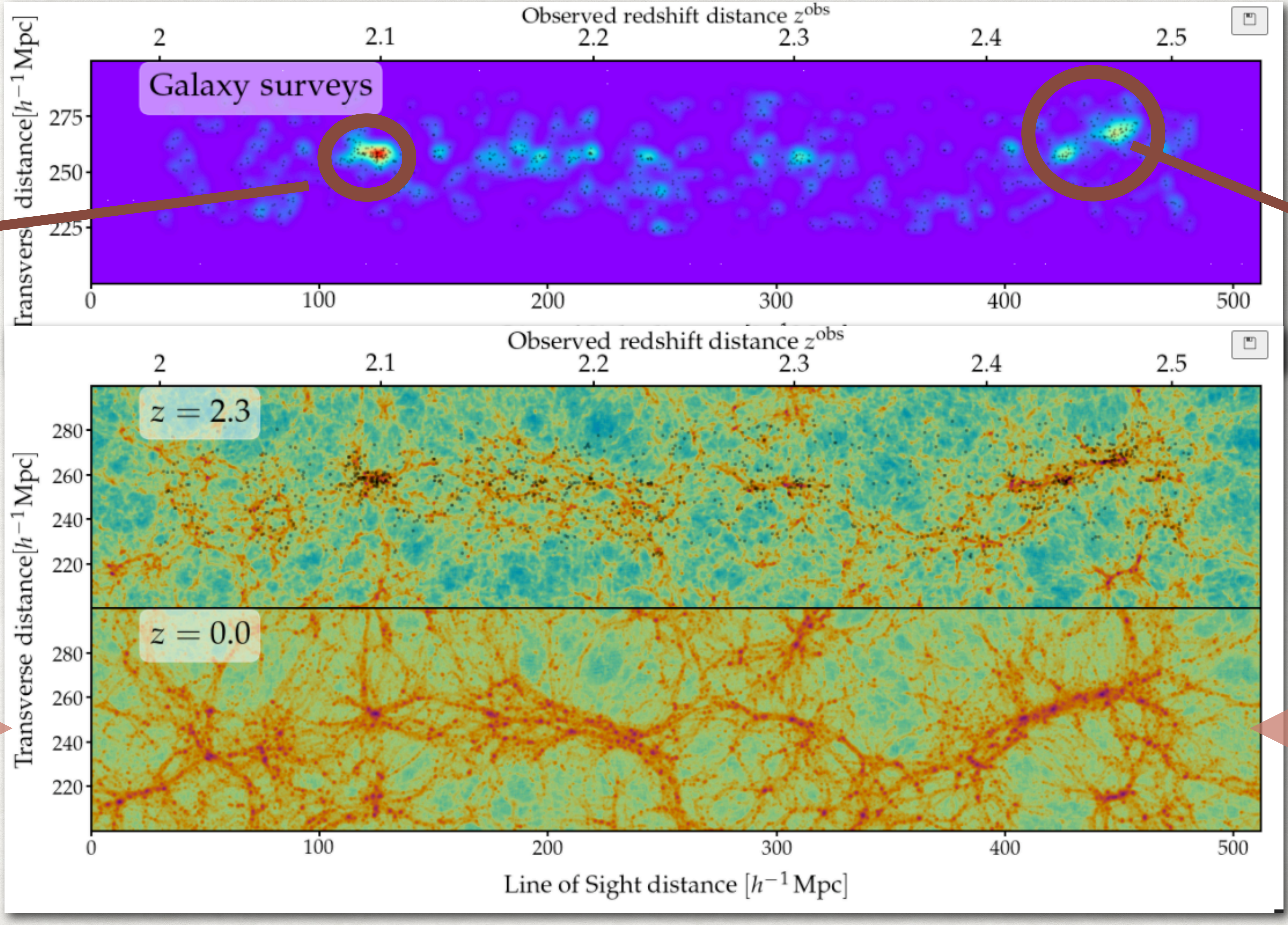
CODE POTPOURRI

- Reconstructed initial density fields in a 256^3 box (Ata+ 2021)
- Initial Densities -> Initial Conditions (MUSIC, (O.Hahn&T.Abel 2011))
- Initial Conditions -> Nbody Sim (PKDGRAV3 (D.Potter+2016))
- Nbody Sim -> Halo Catalogs (Rockstar, (P.Behroozi+2013a))
- Halo Catalogs -> Trees (Consistent trees, (P.Behroozi+2013b))
- Final analysis in pynbody and ytree (A. Pontzen+2013, B. Smith+2019)

CONSTRAINED SIMULATIONS

- ~12000 MCMC samples produced with COSMIC BIRTH (Kitaura, Ata et al 2021)
- 50 random selected (thinning, autocorrelation length…) samples for simulations
- 256^3 particles in a box with 512 Mpc/h side length (~7E11 Msun/h resolution)
- Simulations run from z=100 to z=0
- We write the first snapshot at z~10
- Consistently used Planck 2018 cosmology from Initial Conditions to final analysis

CONSTRAINED SIMULATIONS

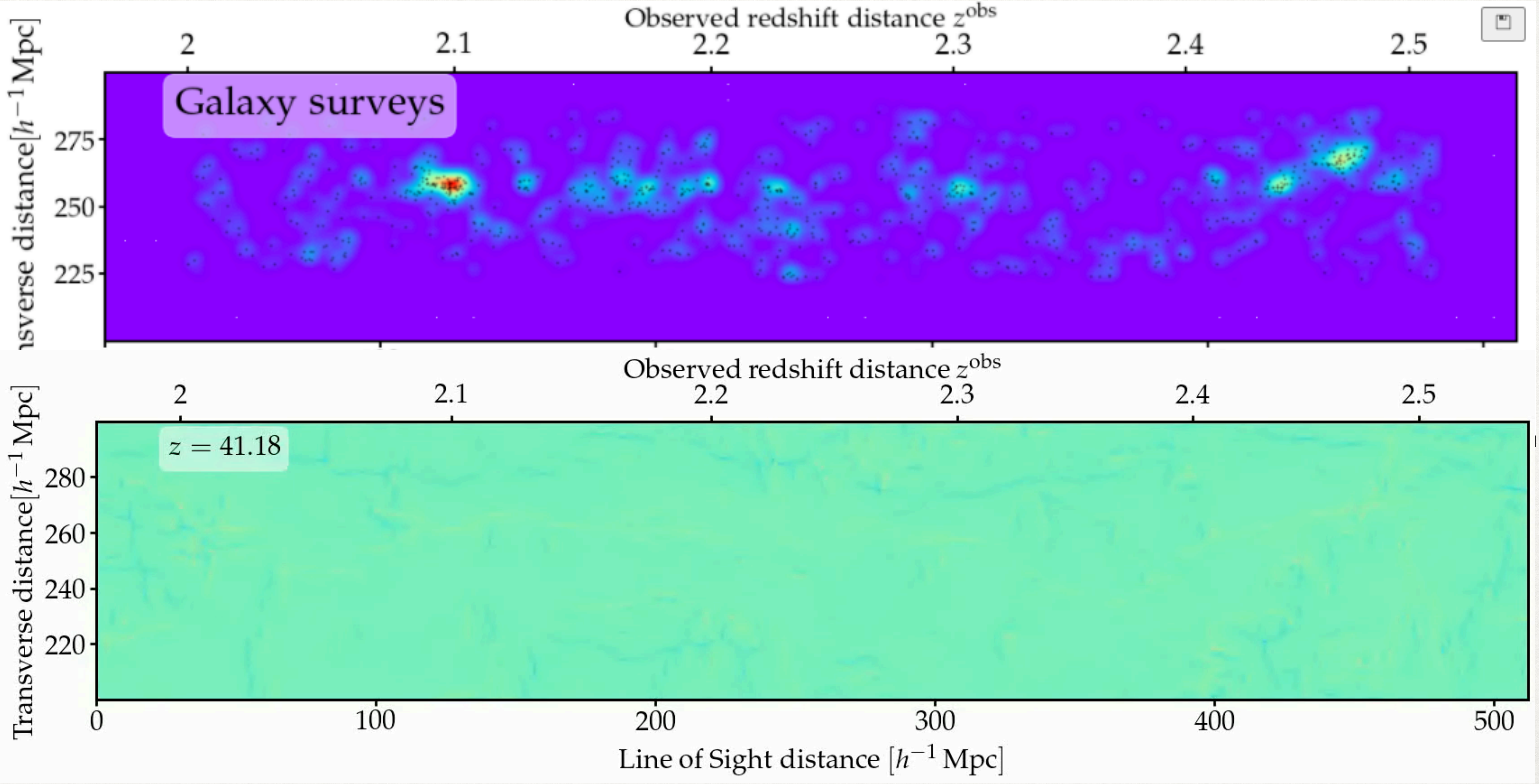


"zFIRE cluster"

"Hyperion"

The Future

CONSTRAINED SIMULATIONS



Observed redshift distance z^{obs}
2
2.1
2.2
2.3
2.4
2.5
$z = 2.3$
$z = 0.0$
0
100
200
300
400
500
Line of Sight distance $[h^{-1}\,\mathrm{Mpc}]$
Observed redshift distance z^{obs}
2
2.1
2.2
2.3
2.4
2.5
$z = 2.3$
$z = 0.0$
0
100
200
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Line of Sight distance $[h^{-1}\,\mathrm{Mpc}]$
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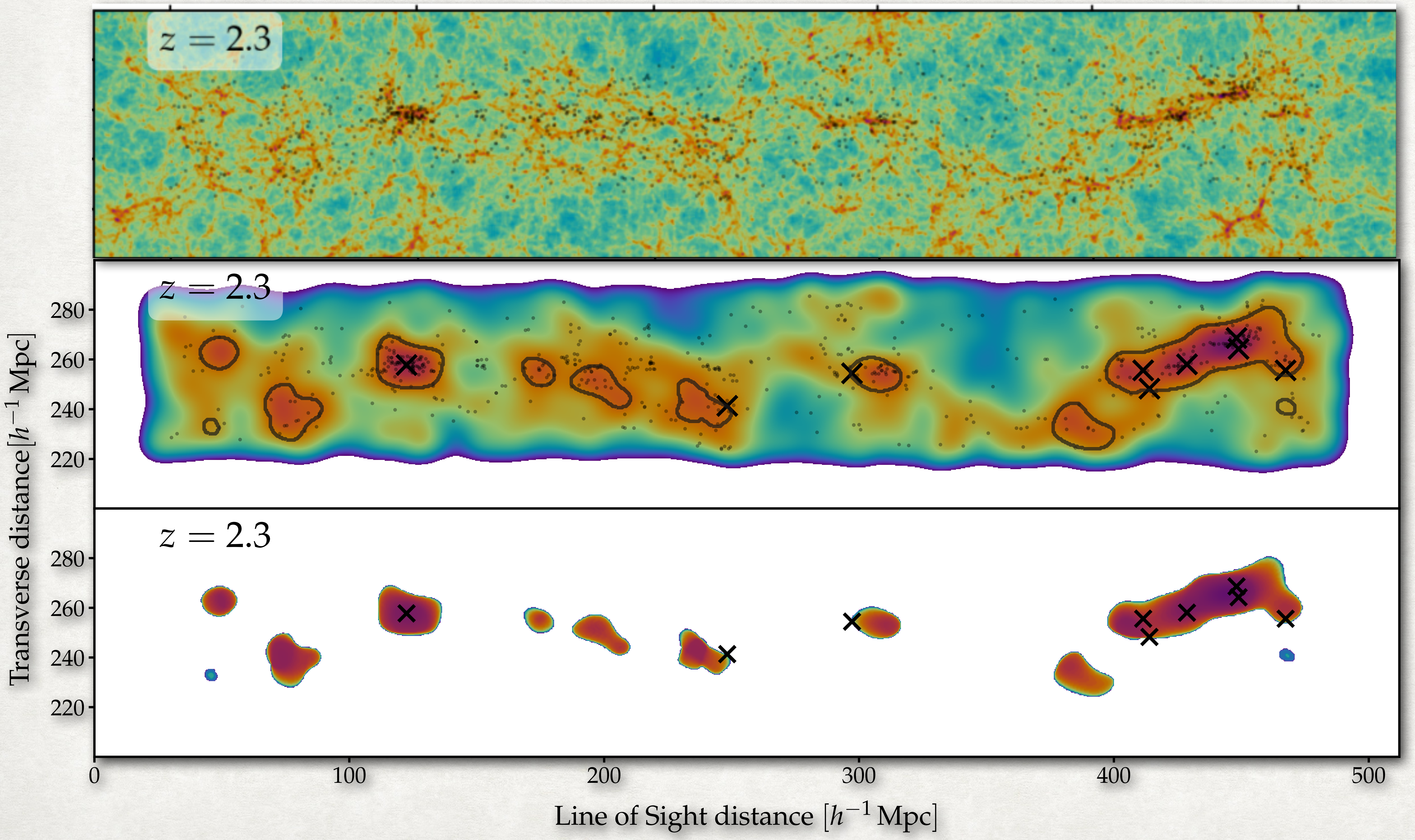
$z = 2.3$
$z = 0.0$
0
100
200
300
400
500
Line of Sight distance $[h^{-1}\,\mathrm{Mpc}]$

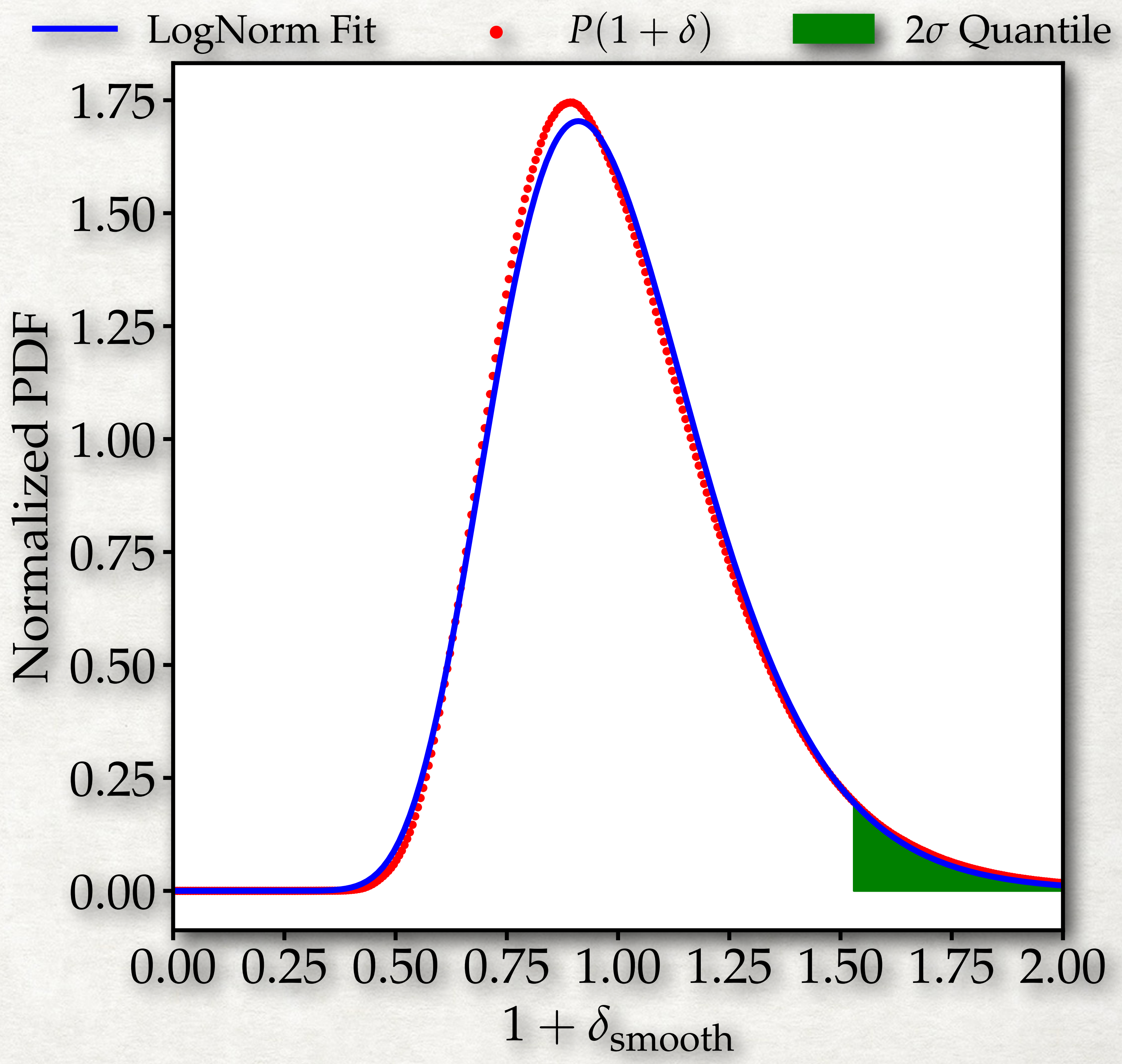
ANALYSIS OF SIMULATIONS

- Outline of NBody simulation analysis:
    - We are interested in massive $z = 0$ halos, that originate from high densities at $z = 2.3$ (observational constraint)
    - We trace back all progenitor dark matter particles of the massive $z = 0$ halos and match the positions to the observed galaxy overdensities
    - We repeat the same analysis for all 50 simulations and make statistical predictions of mass, position and formation probability of clusters

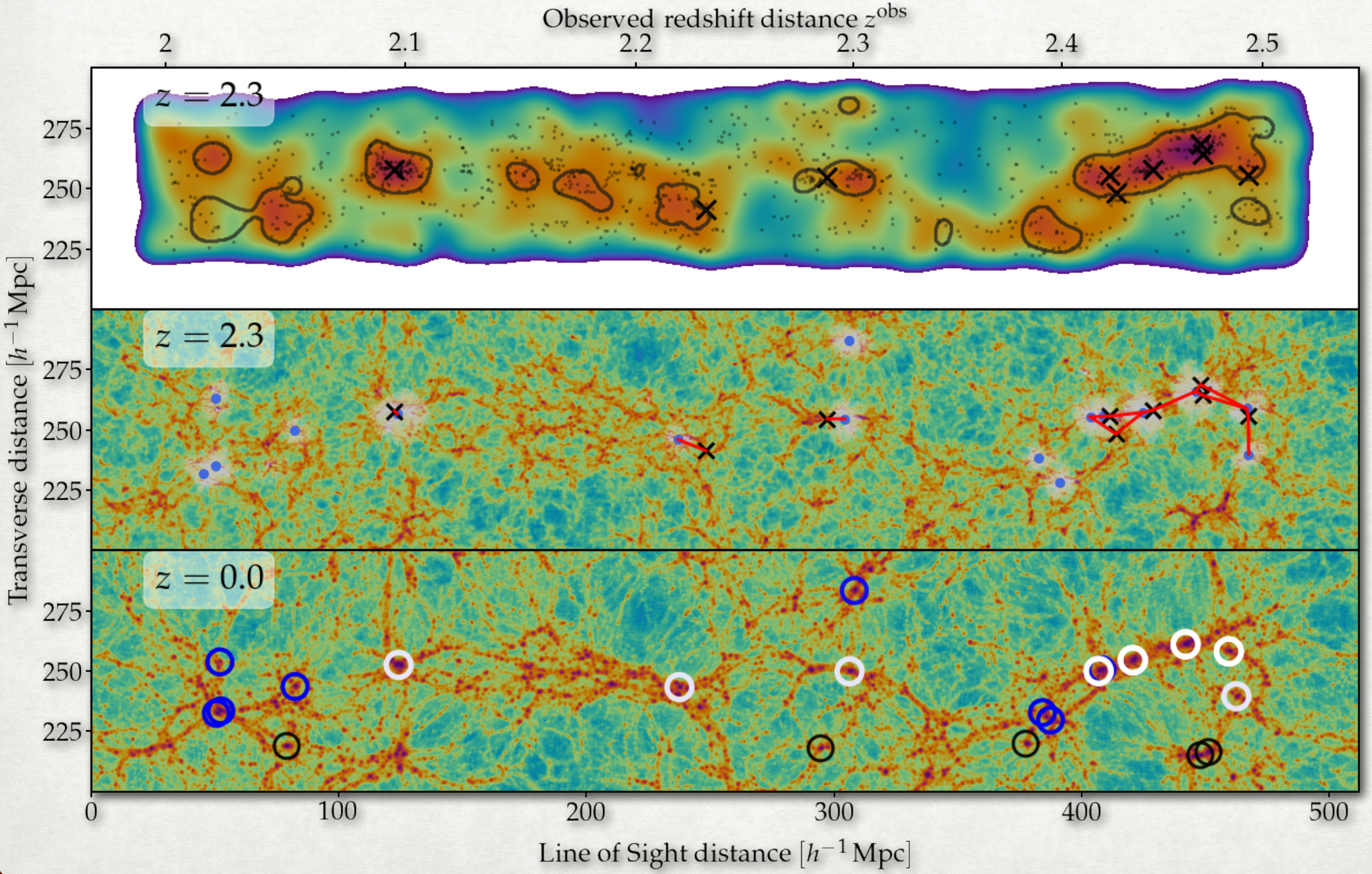
PROTOCLUSTER FRAME

- Identify at $z = 2.3$ over-densities ($r_S = 5\,h^{-1}\,\mathrm{Mpc}$) $> 2\sigma$ -> Protocluster Candidates



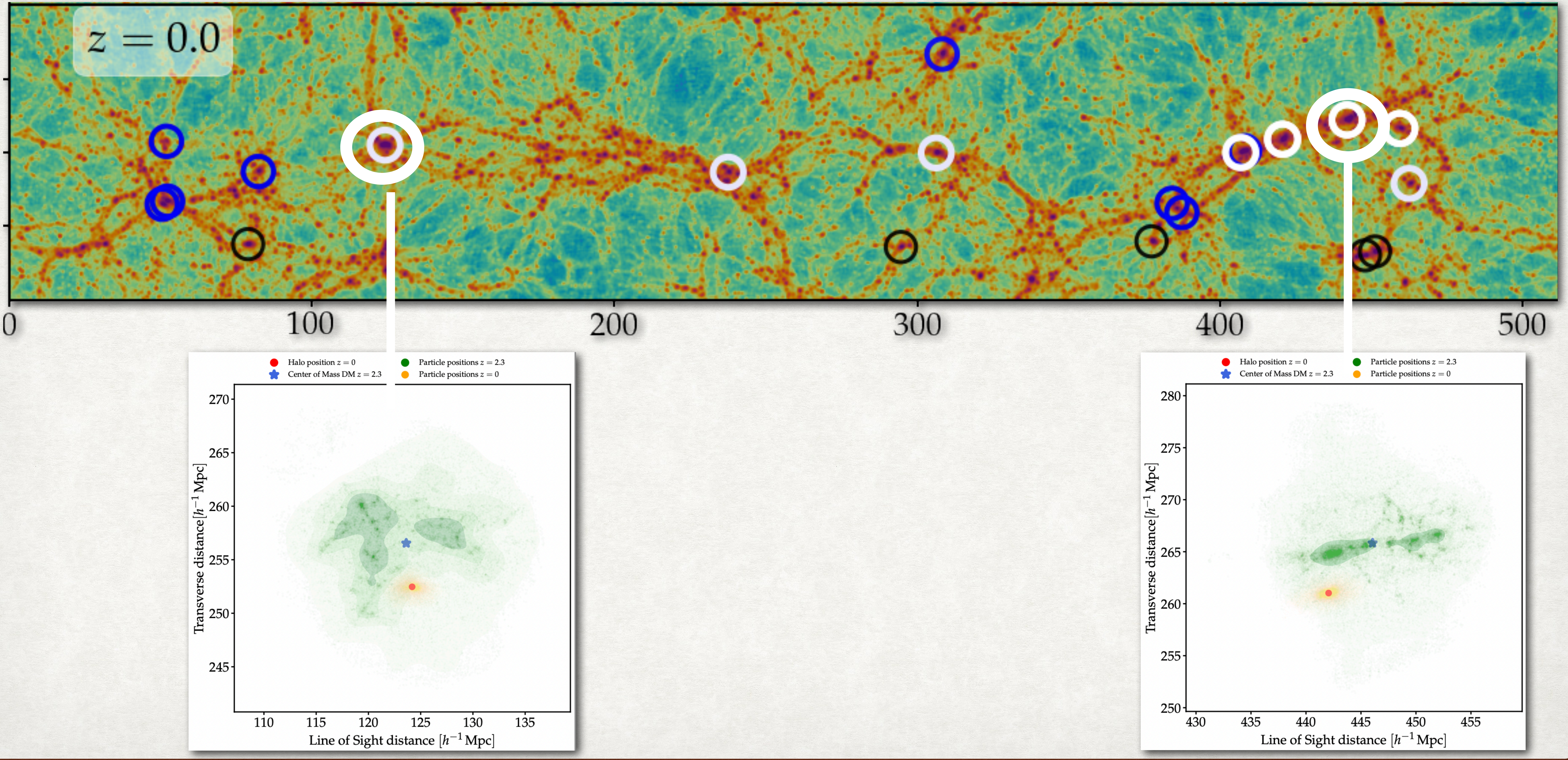


PROTOCLUSTER FRAME

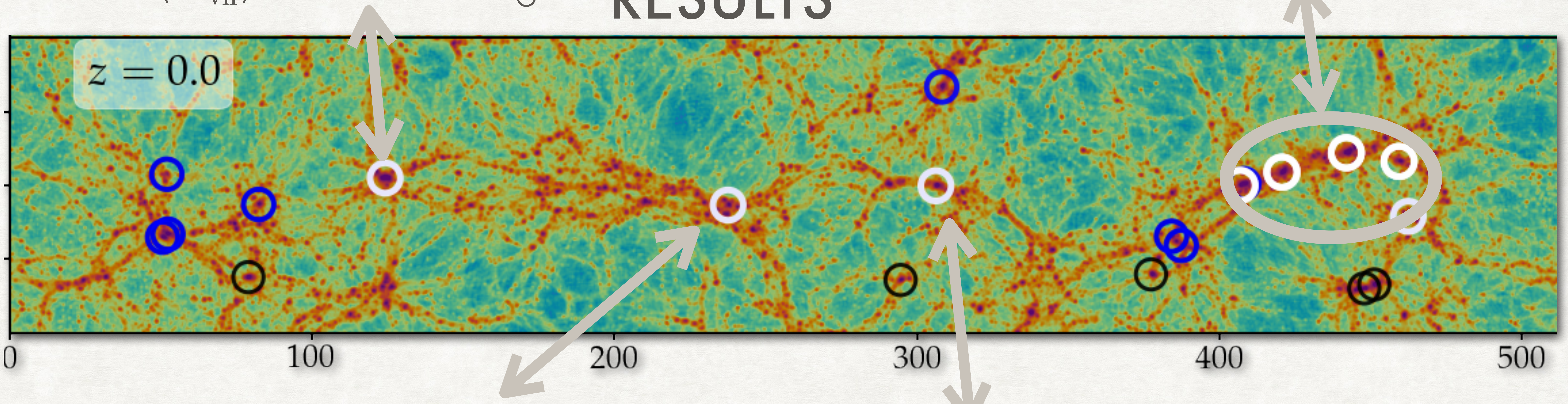


1. Look for $z = 0$ that originate $z = 2.3$ overdose regions
2. Identify progenitors of these halos -> Potoclusters
3. Match centre-of-mass of simulated protoclusters to observed protoclusters

CLUSTER FRAME



RESULTS



- Hyperion seems unlikely to assume $4.8 \times 10^{15}\, M_\odot/h$ mass at $z = 0$, different merging history for different ICs
- We find overdensities that have been reported in literature and can set limits on masses and formation probability.

CONCLUSIONS

- Protoclusters important probes of early structure formation for upcoming deep and dense galaxy surveys
- Build workflow to compute constrained NBody simulations up to $z = 0$
- Matched simulated and observed high densities
- COSMOS field likely contains 1-2 “COMA progenitor”, but not 5!
- We stress the environmental dependency for the fate of protoclusters and discourage extrapolating to $z = 0$ with over-simplified assumptions (e.g. linear theory)