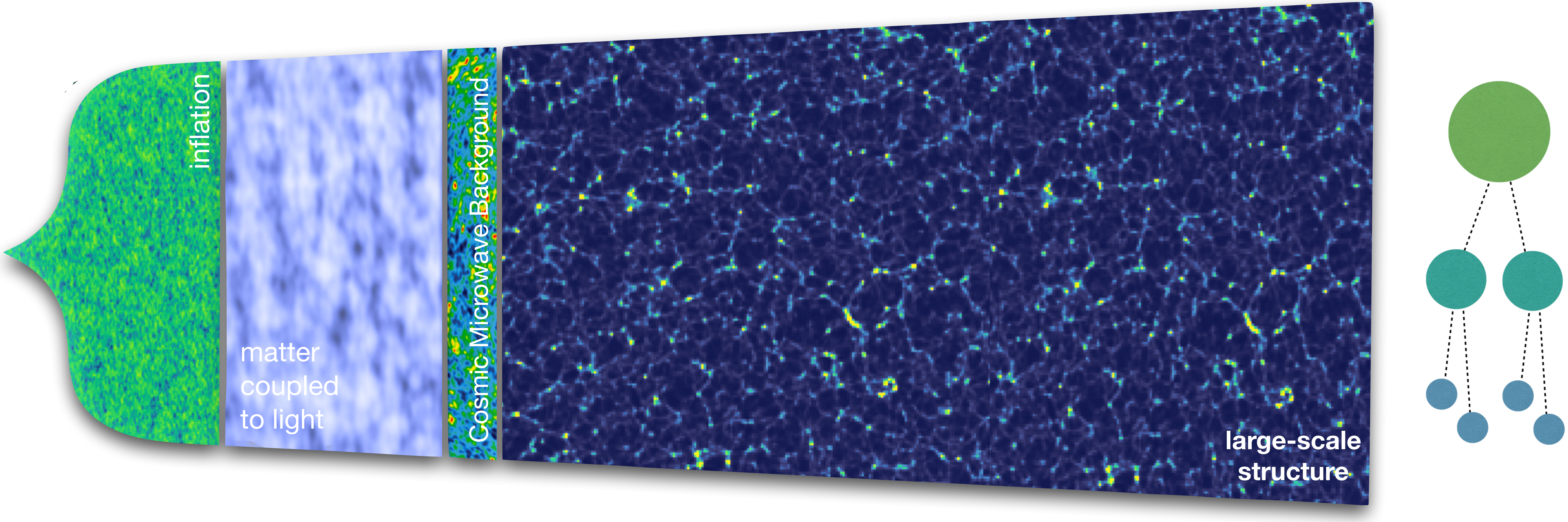
Physics-informed inferences of galaxy clustering

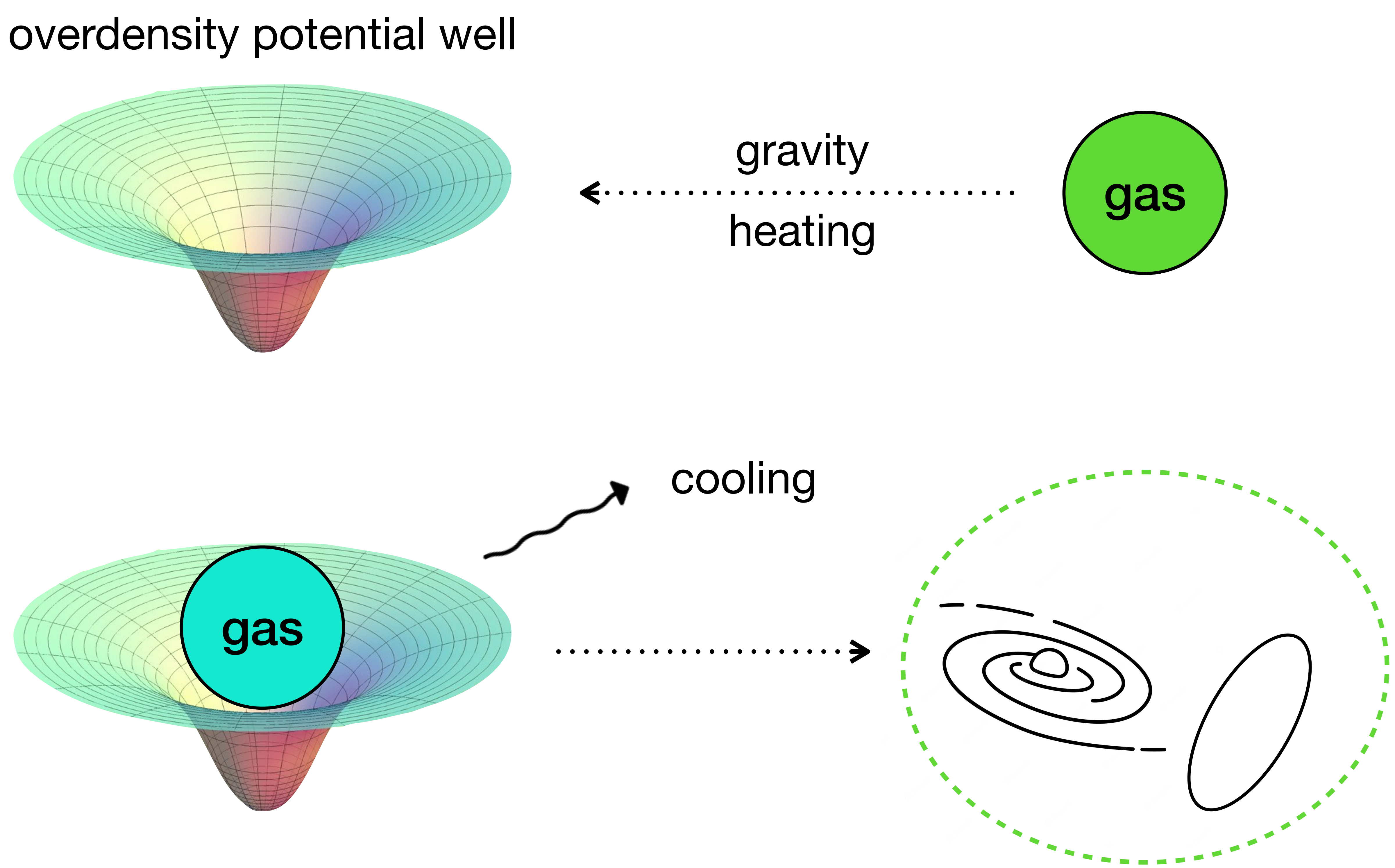
Eleni Tsaprazi, Stockholm University, September 2023

A brief chronology of the Universe

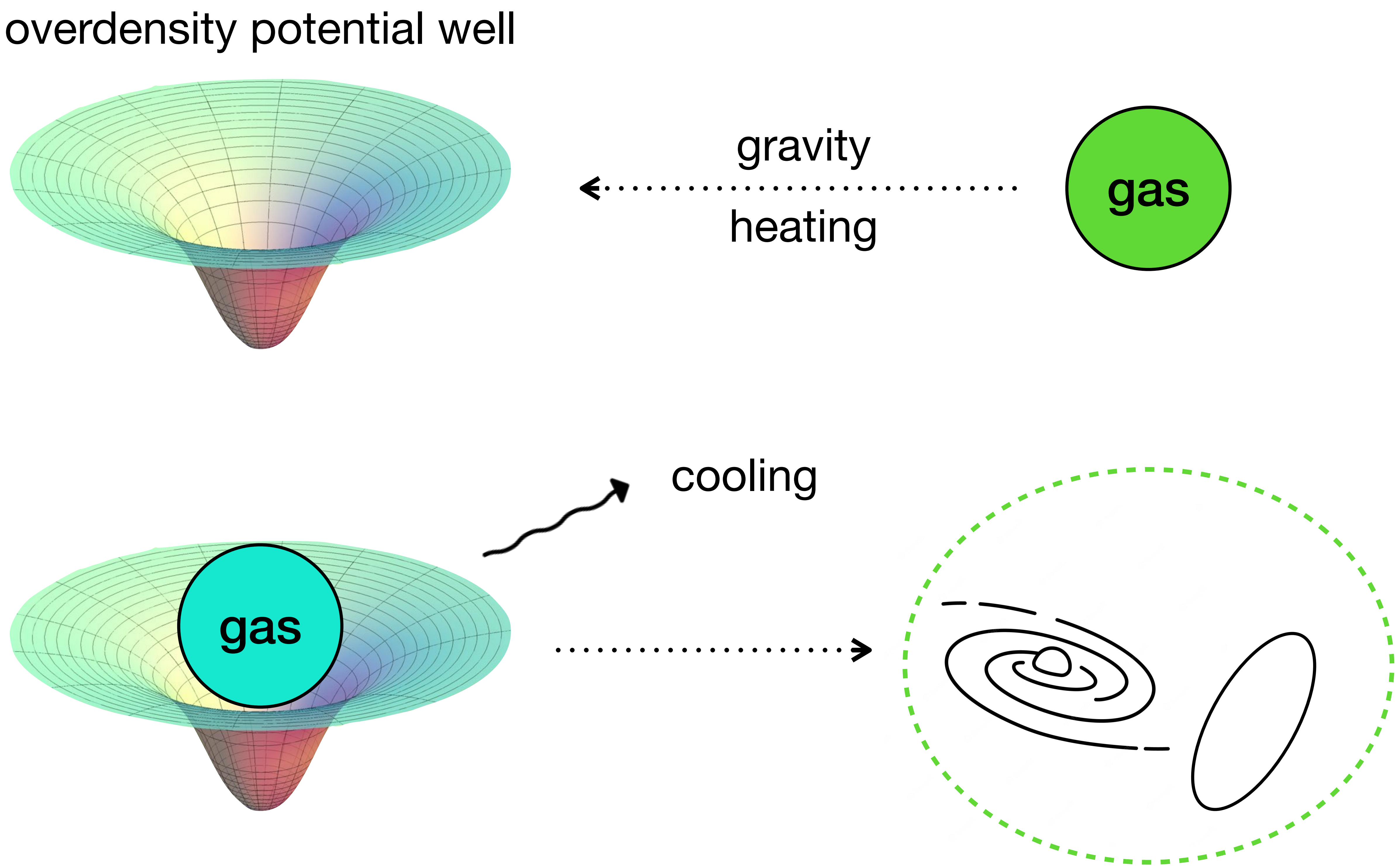


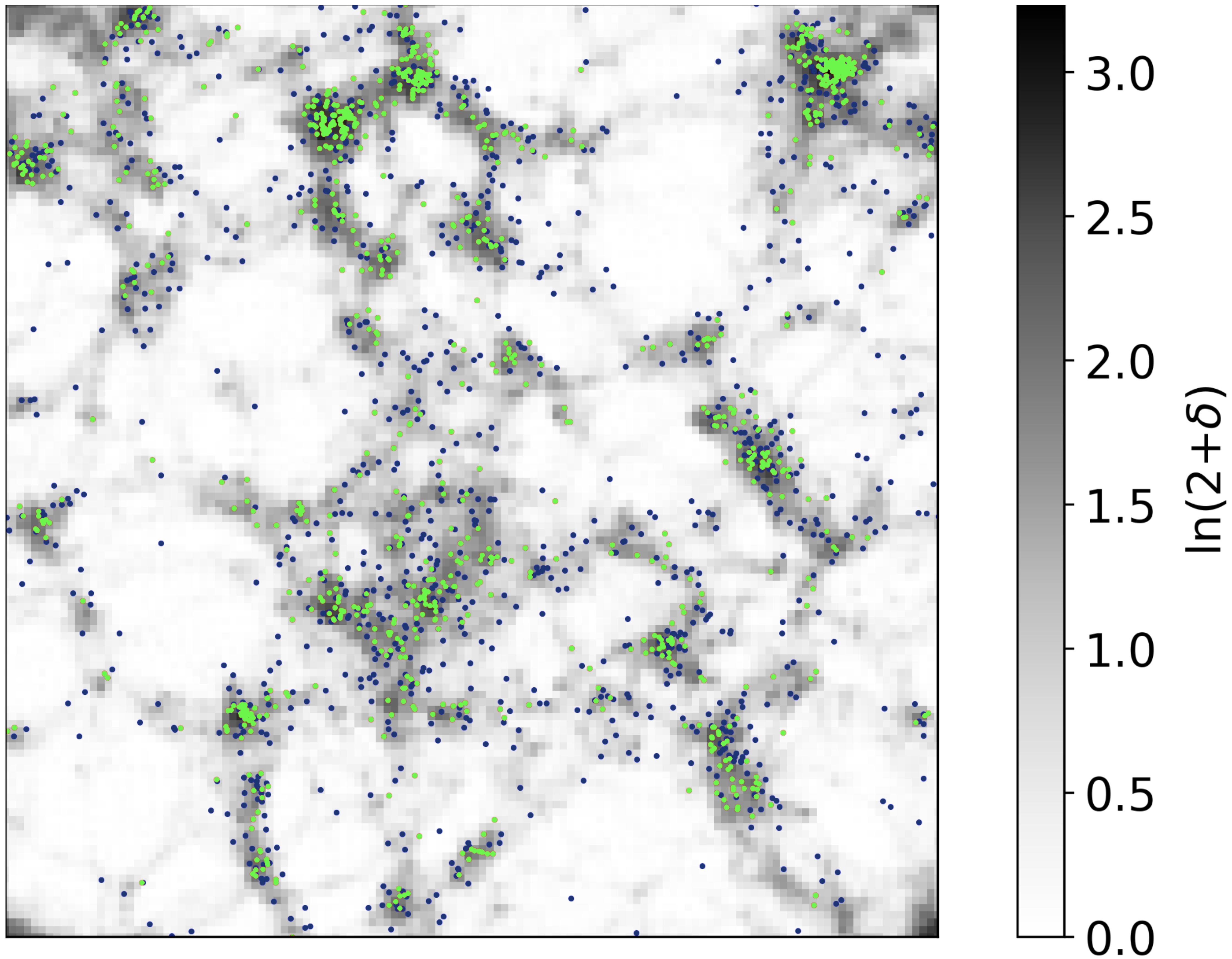
While structure formation has been understood on large scales, further work on small ones is required…

Galaxies trace the large-scale structure



Galaxies trace the large-scale structure up to a bias

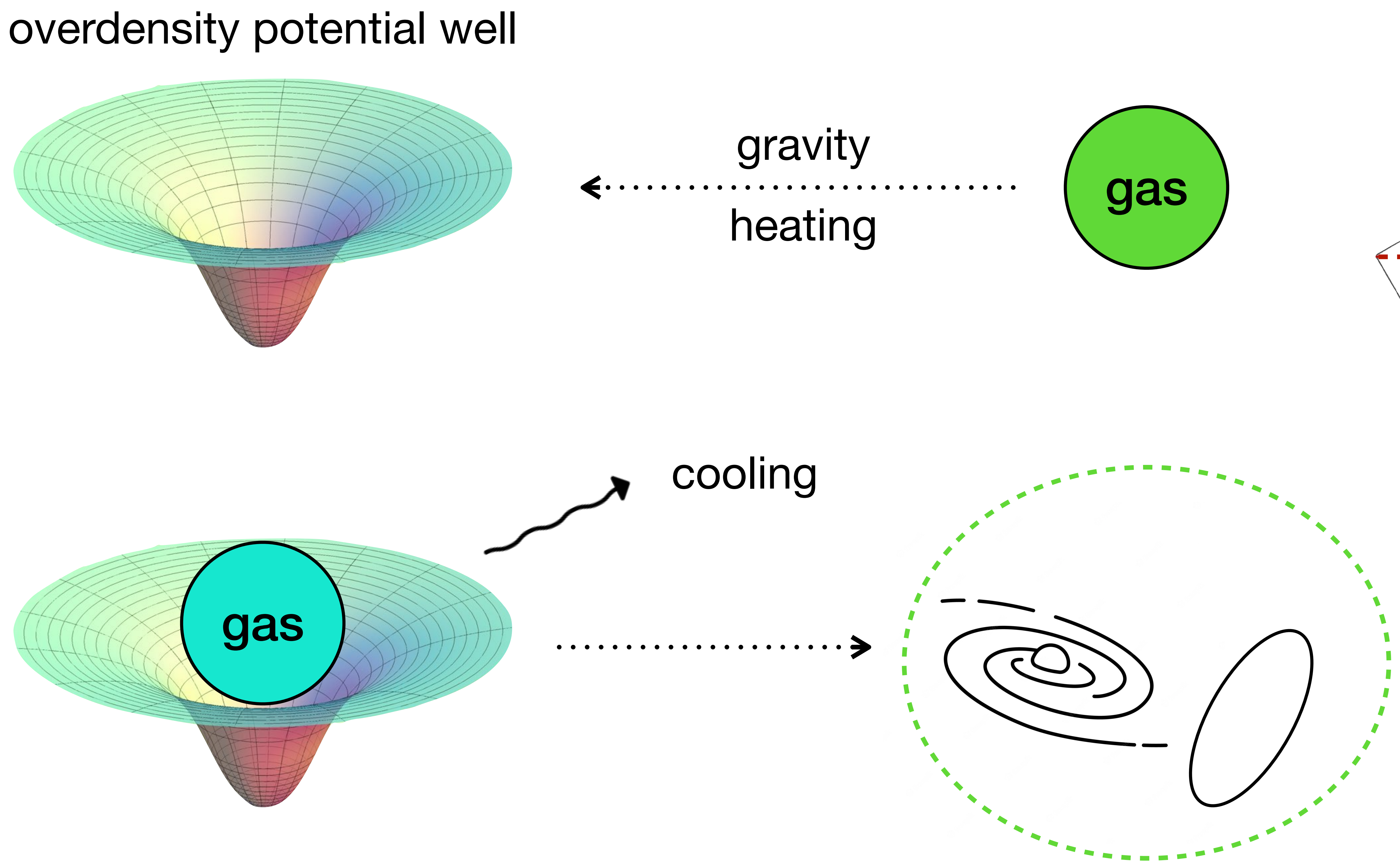




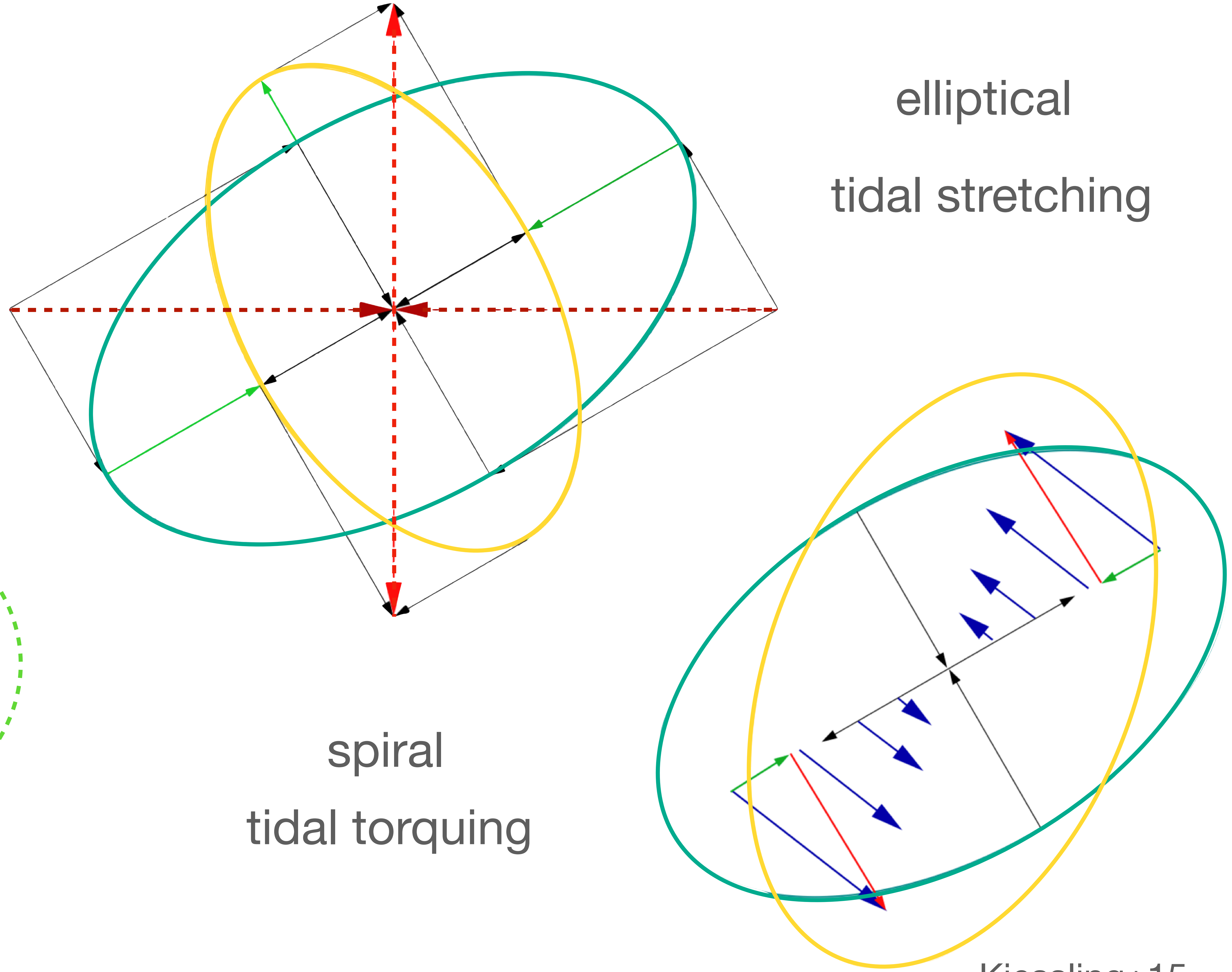
Baryonic processes depend on halo properties

Galaxy observations allow us to map the large-scale structure

Tidal shear lead to intrinsic alignments



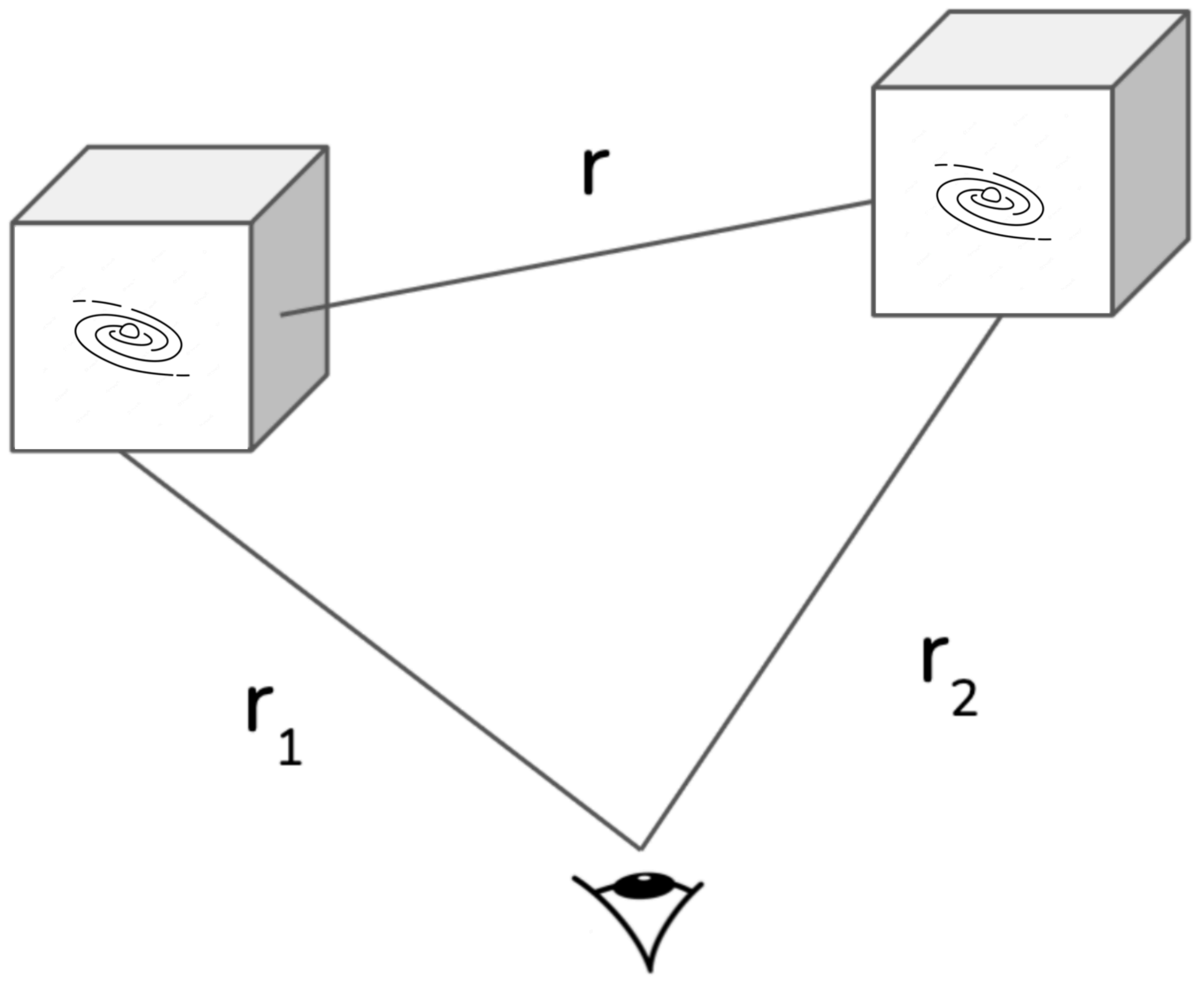
Galaxy ellipticities trace the tidal shear



Kiessling+15

Mapping through clustering — ellipticities: how to estimate?

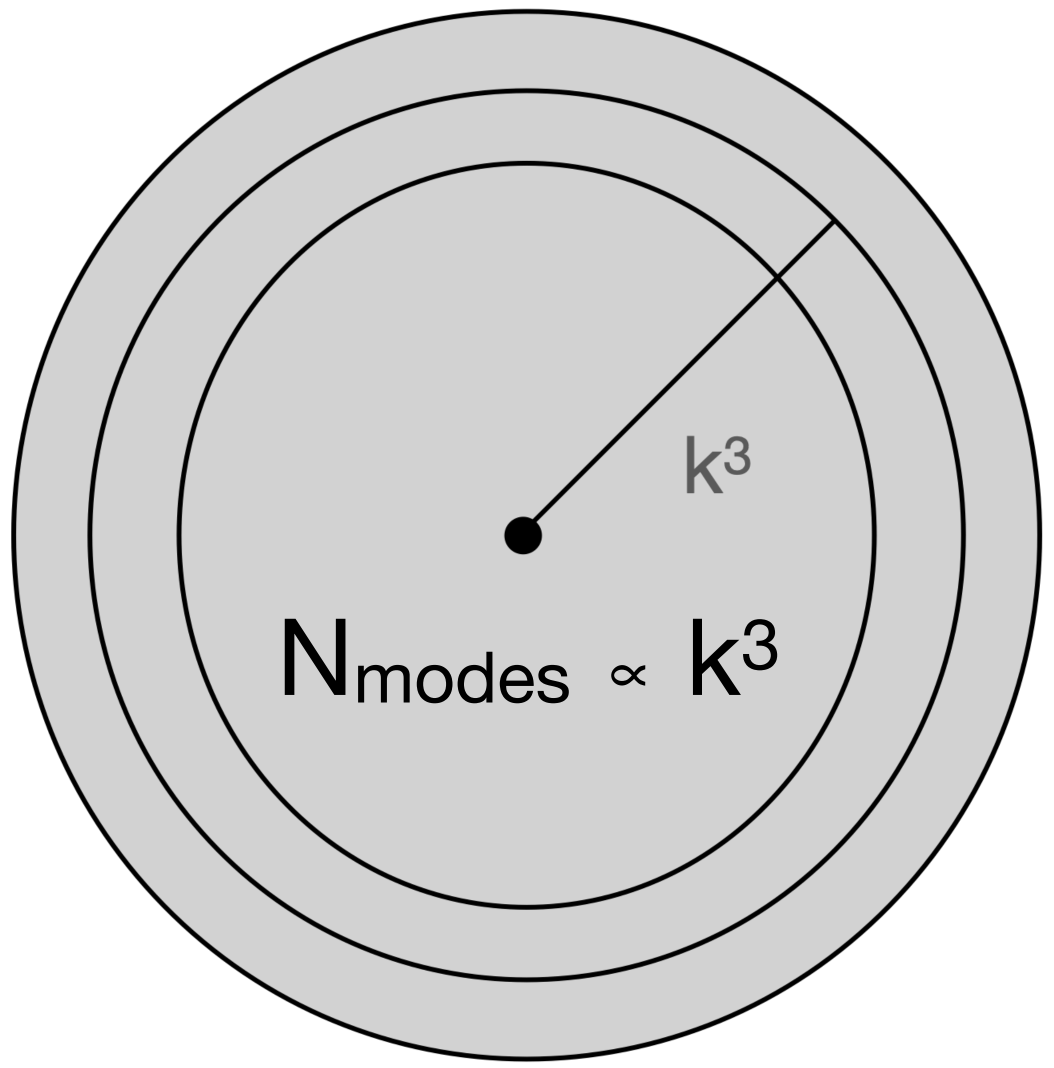
Traditional estimation through 2-point statistics



$$\xi(r) = \langle \delta(\mathbf{r_1})\delta(\mathbf{r_2}) \rangle$$

probability above uniform

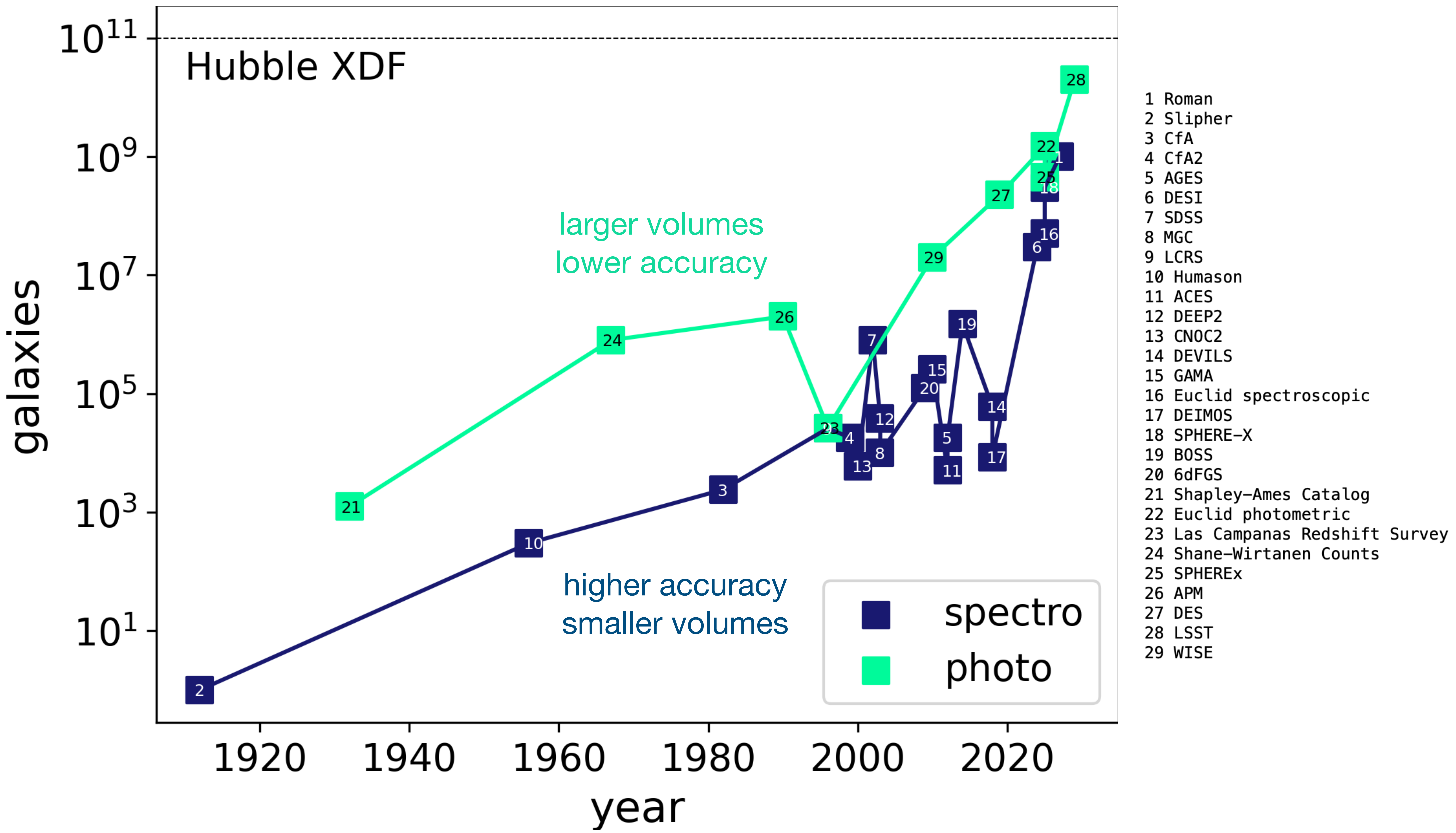
Fourier space



$$P(k) = \frac{1}{(2\pi)^{3/2}} \int \xi(r) e^{i\mathbf{kr}} d^3\mathbf{r}$$

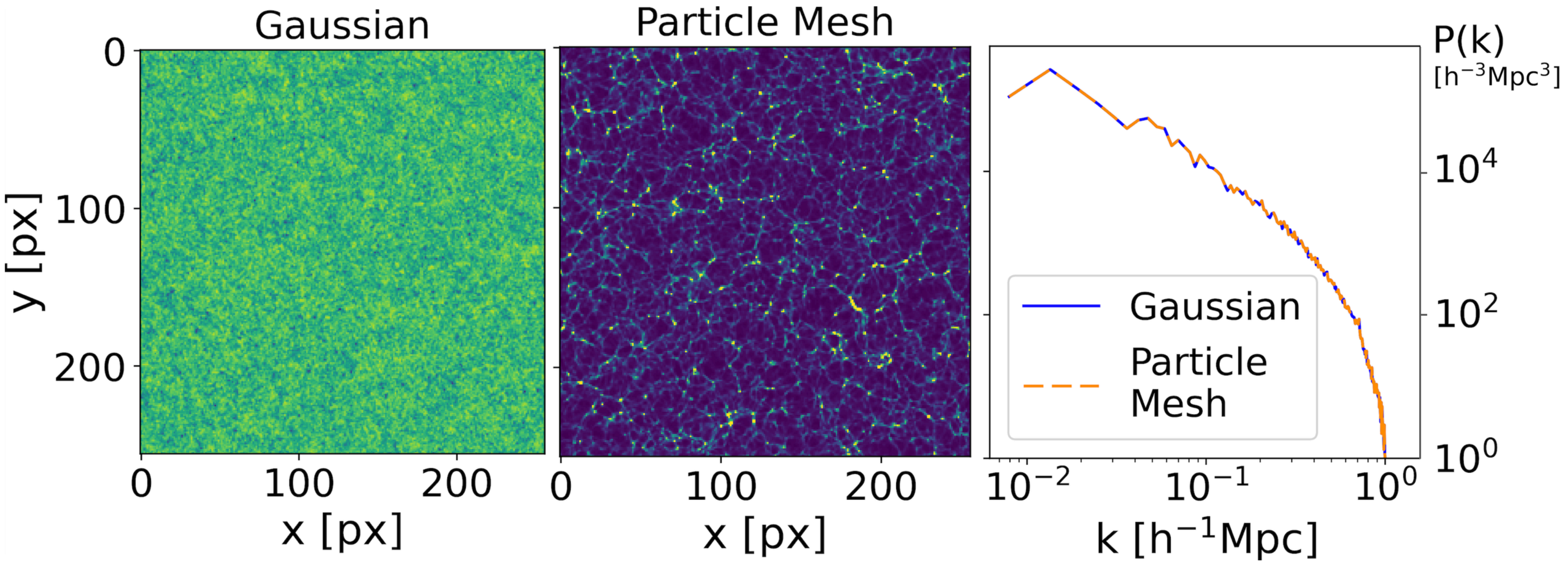
Averages compress information, we need to go beyond

We're reaching a limit observationally

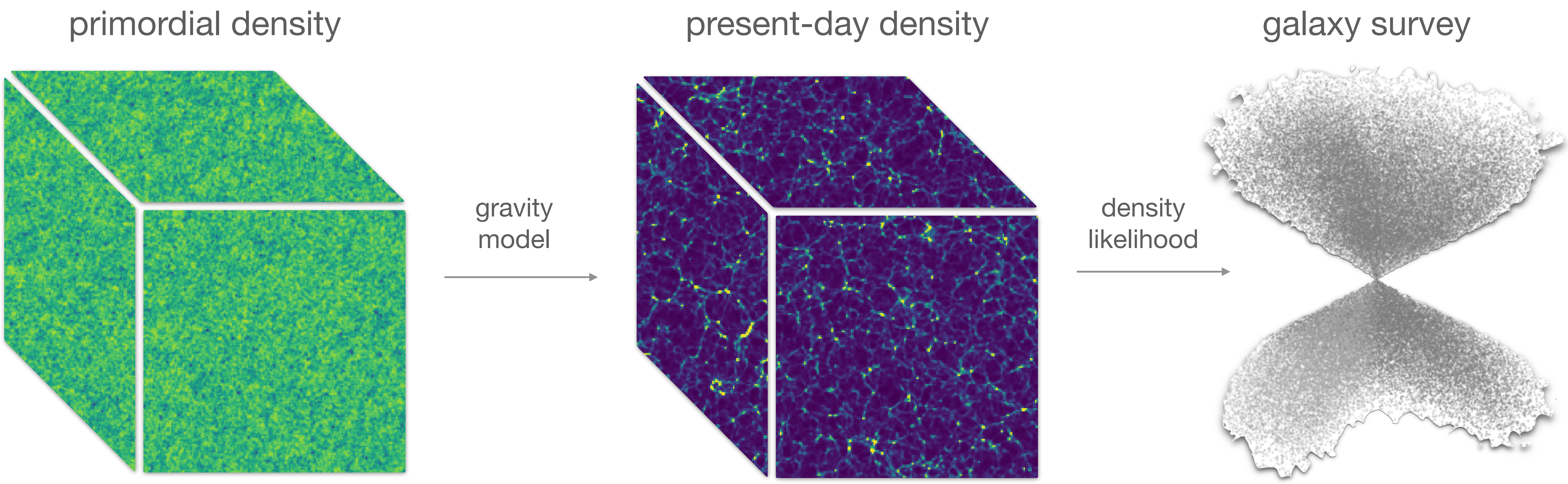


What is there beyond 2-point statistics?

Information beyond 2-point statistics



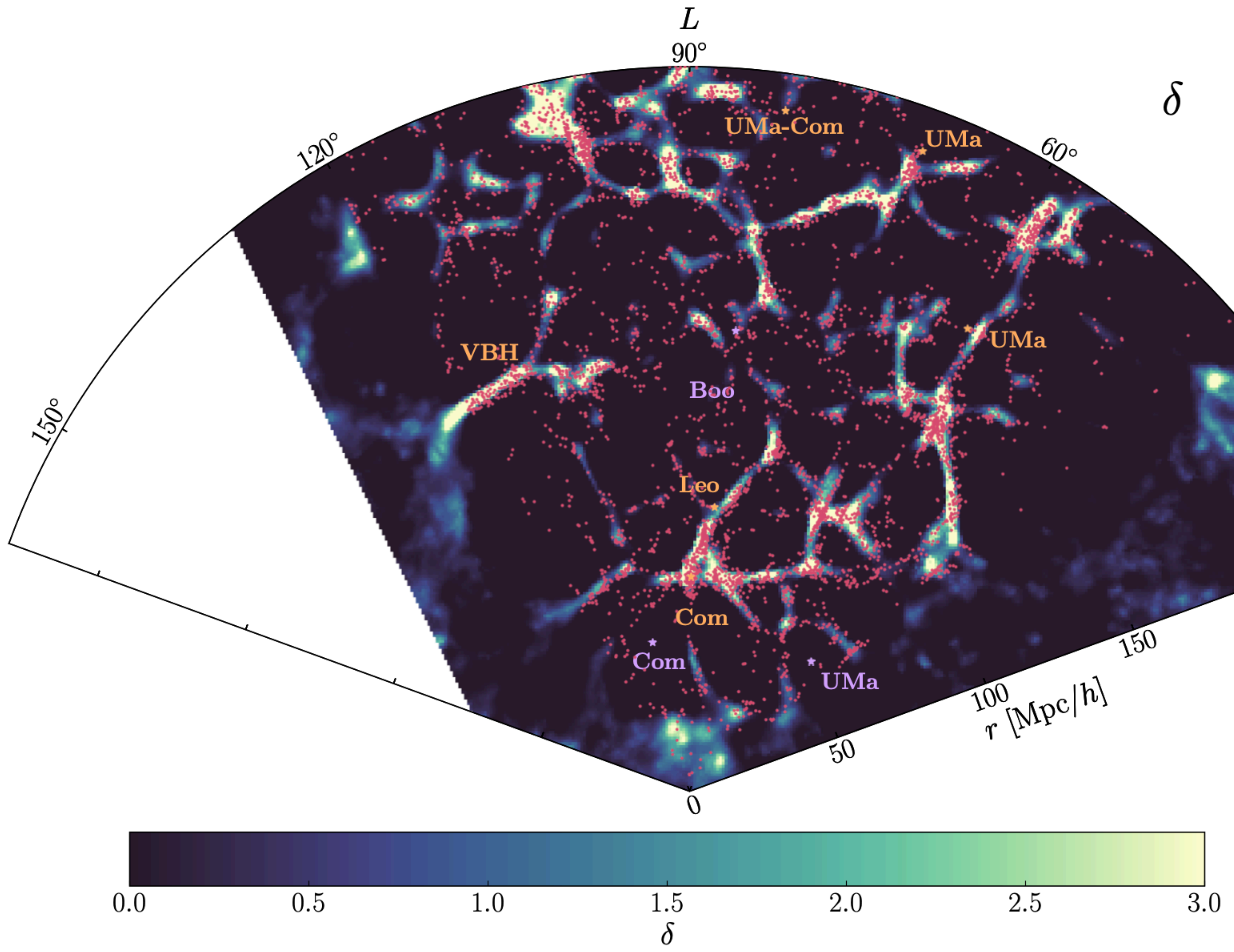
Extracting full-field statistics with BORG



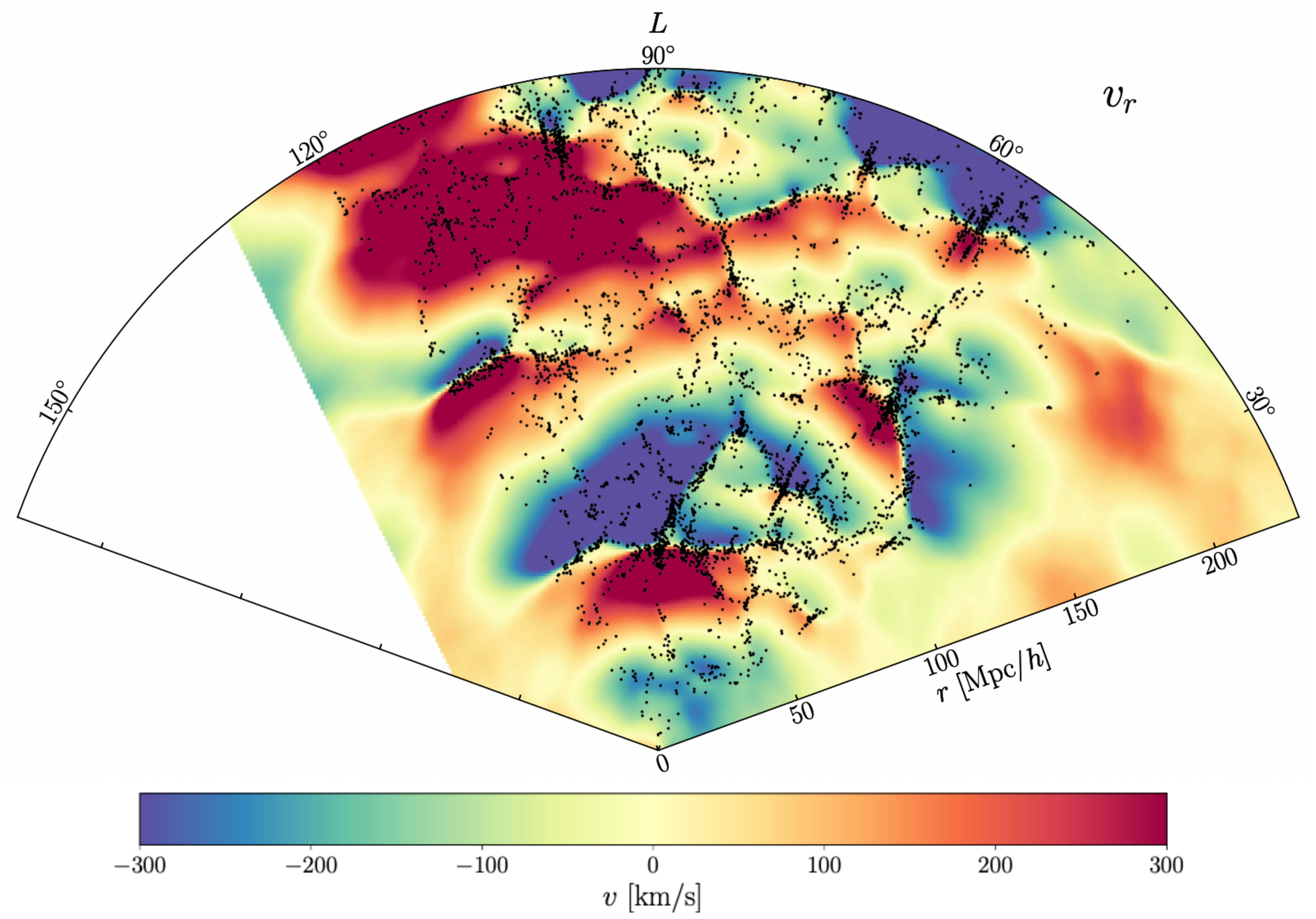
- 3D structure formation history: ensemble of Markov Chain Monte Carlo realizations
- Beyond 2- and N- point statistics

BORG has been successfully applied to real data

dark matter density



radial peculiar velocity

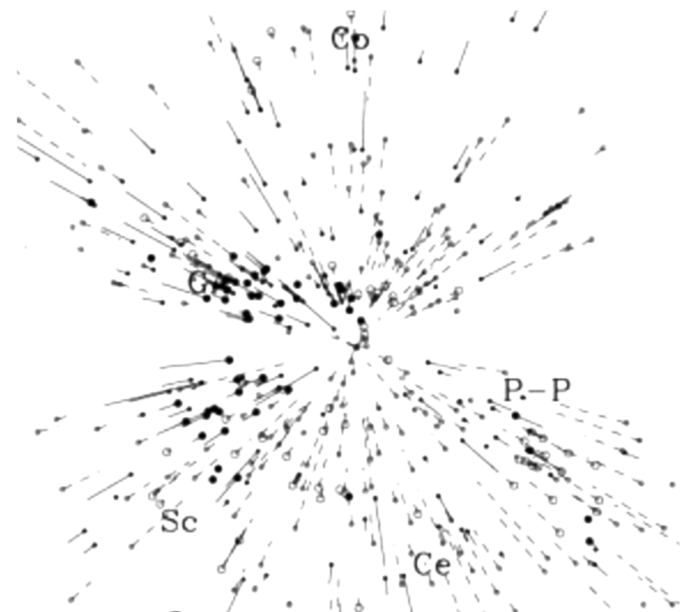


Leclercq+17

We can start asking questions with the prospect of using next-generation data

Can we use supernovae as complementary probes of the dark matter density?

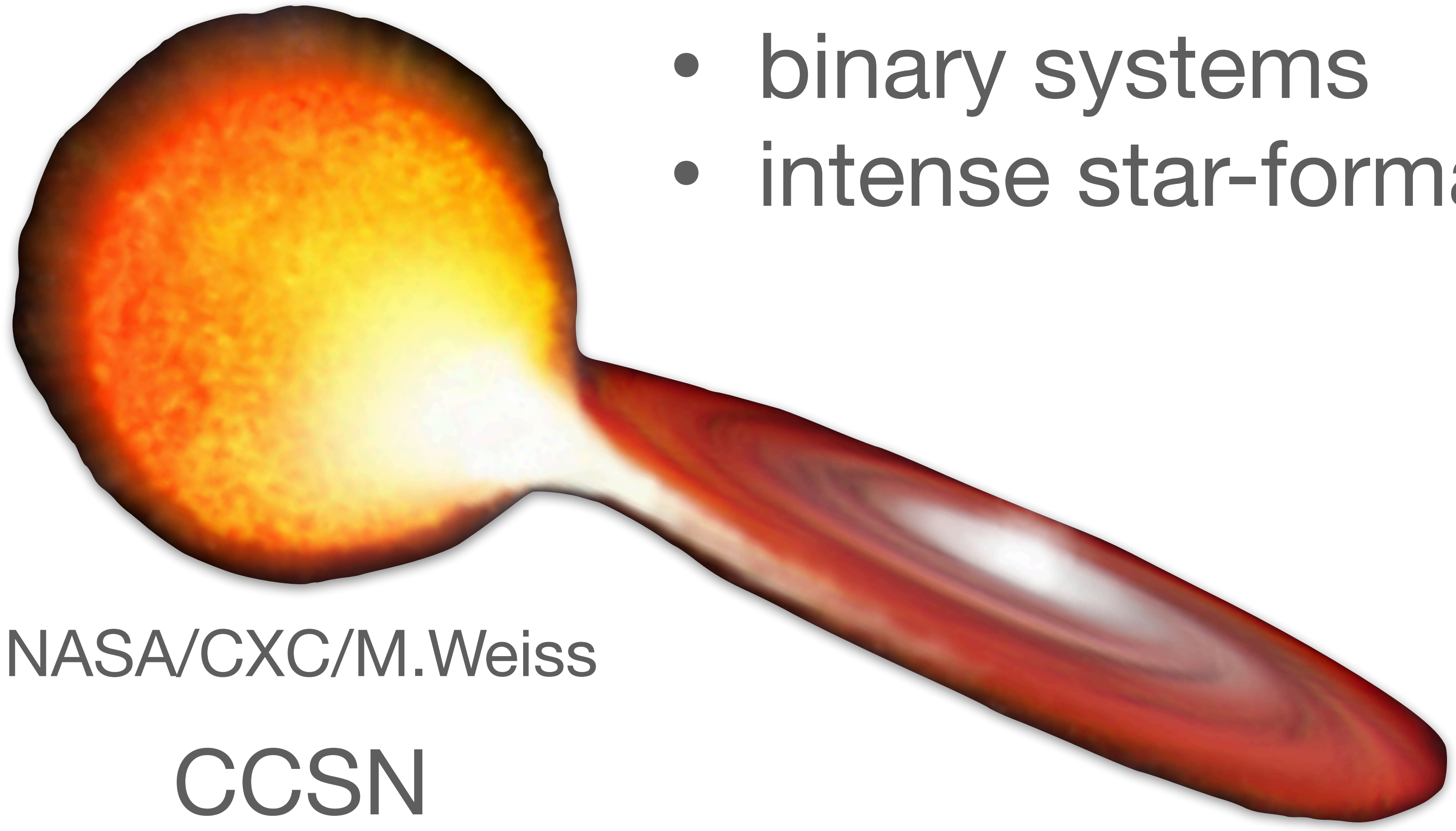
Paper I



Strauss & Willick

Supernovae occur mostly in young galaxies

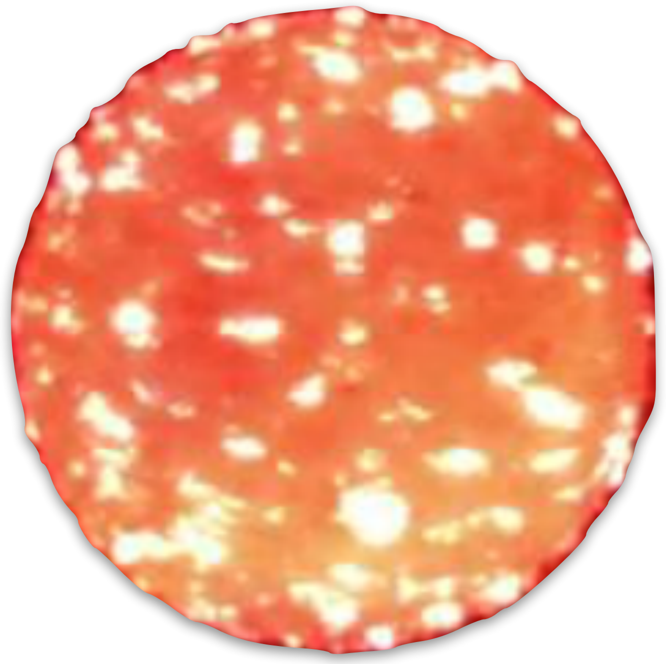
SNIa



- binary systems
- intense star-formation

NASA/CXC/M.Weiss

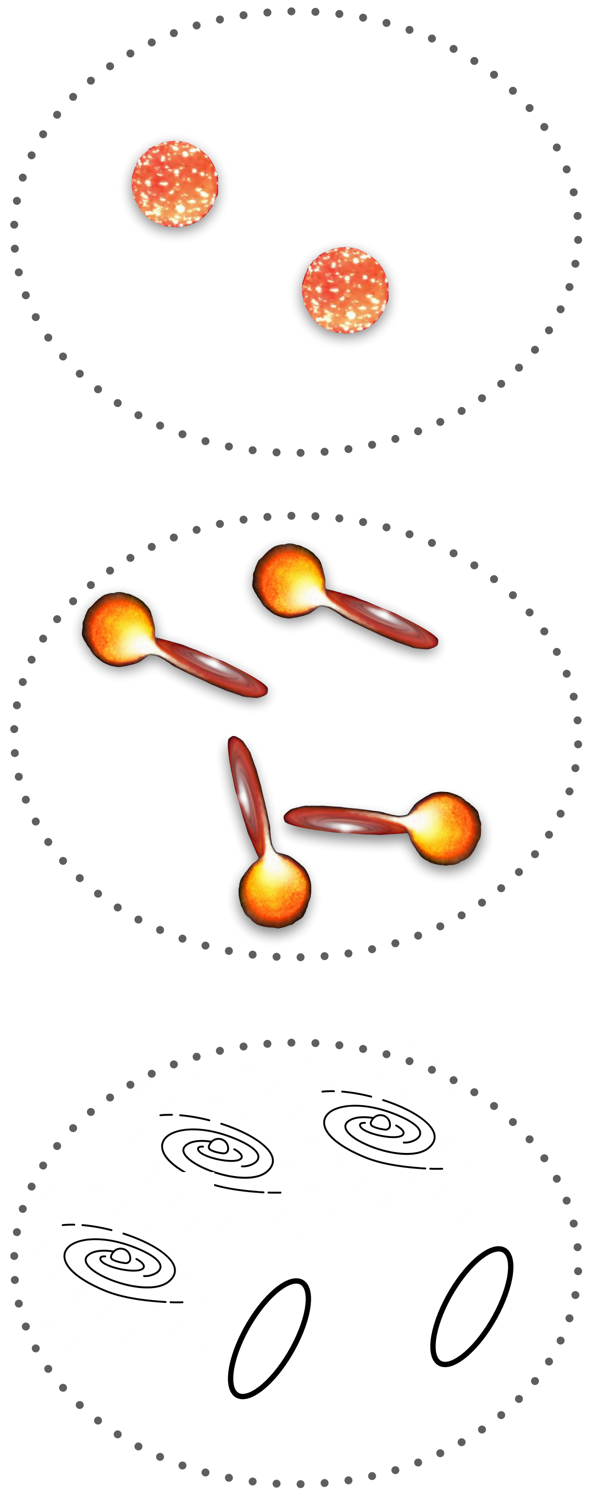
CCSN



- short-lived massive stars
- very intense star-formation

Exoplanet Exploration - NASA

MPA



Cross-correlate observed SN locations with the large-scale structure

The observations

- 1.200 SNIa & CCSN out to z = 0.036
- 60.000 spectroscopic galaxies
- 3D dark matter density constrained by BORG with spectroscopic data, 2.7 Mpc/h

Systematic uncertainties in the SN observations:

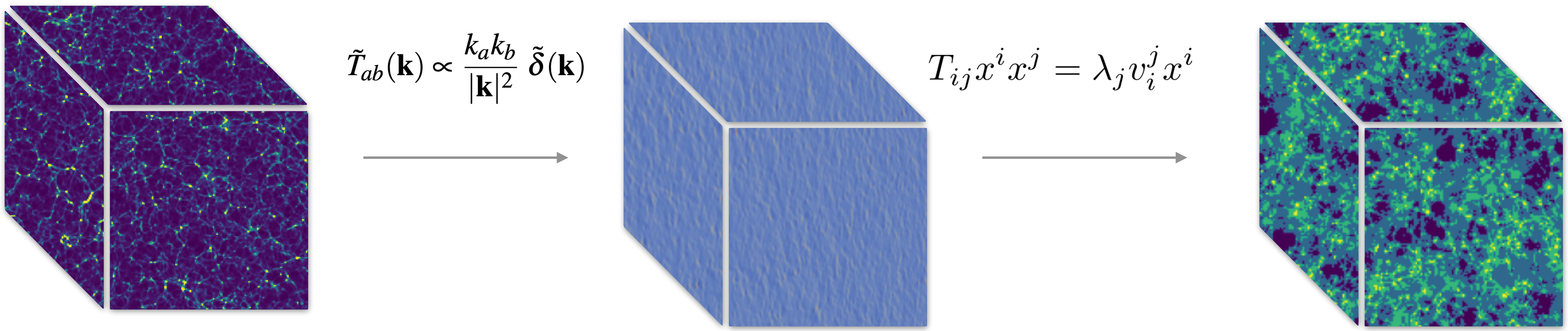
- Kaiser effect
- Fingers-of-God
- Redshift uncertainty

$$\mu_n = z_n + \frac{\mathbf{v}_{h,n}\hat{\mathbf{n}}}{c}$$

$$\sigma_n^2 = \sigma_{v,n}^2 + \sigma_{z,n}^2$$

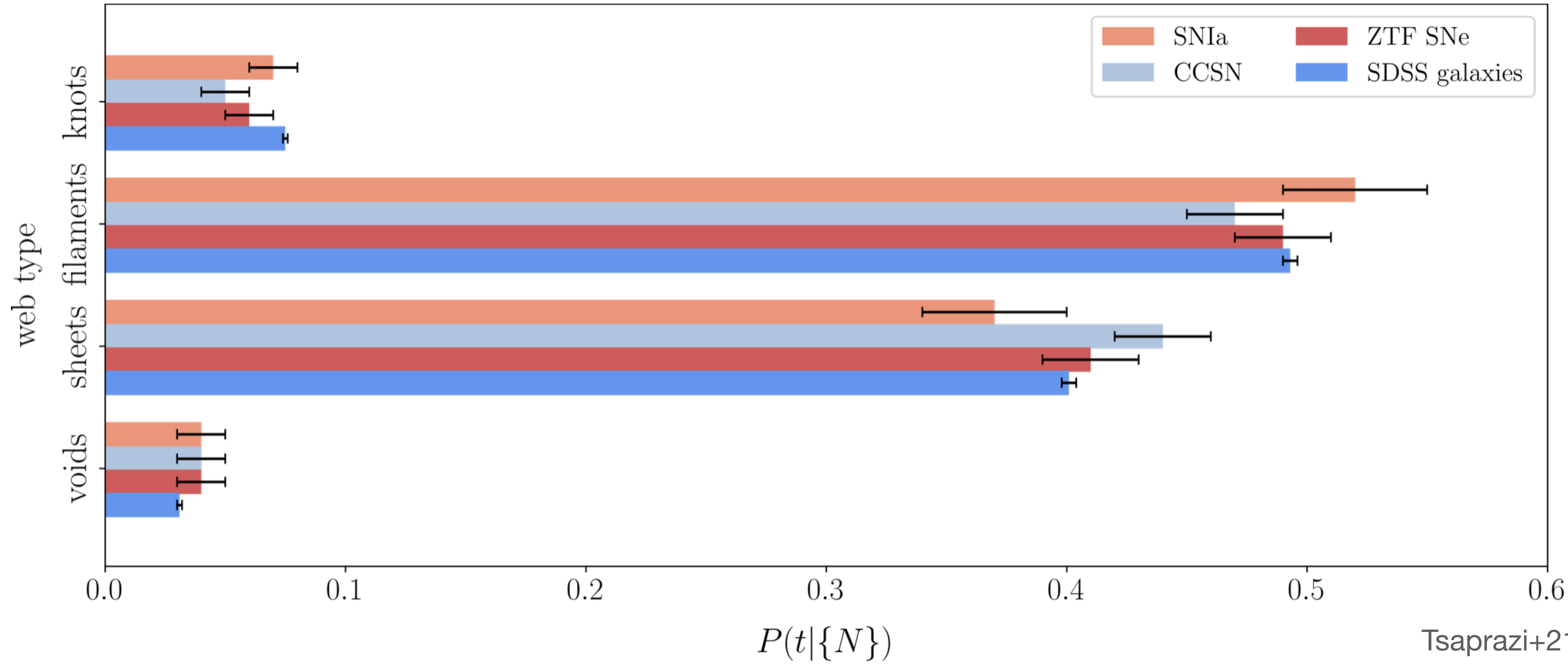
Cross-correlate observed SN locations with the large-scale structure

The large-scale structure



Web structure	Eigenvalues
voids	$\lambda_1, \lambda_2, \lambda_3 < 0$
sheets	$\lambda_1, \lambda_2 < 0, \lambda_3 > 0$
filaments	$\lambda_1 < 0, \lambda_2, \lambda_3 > 0$
knots	$\lambda_1, \lambda_2, \lambda_3 > 0$

Supernovae cluster like typical galaxies



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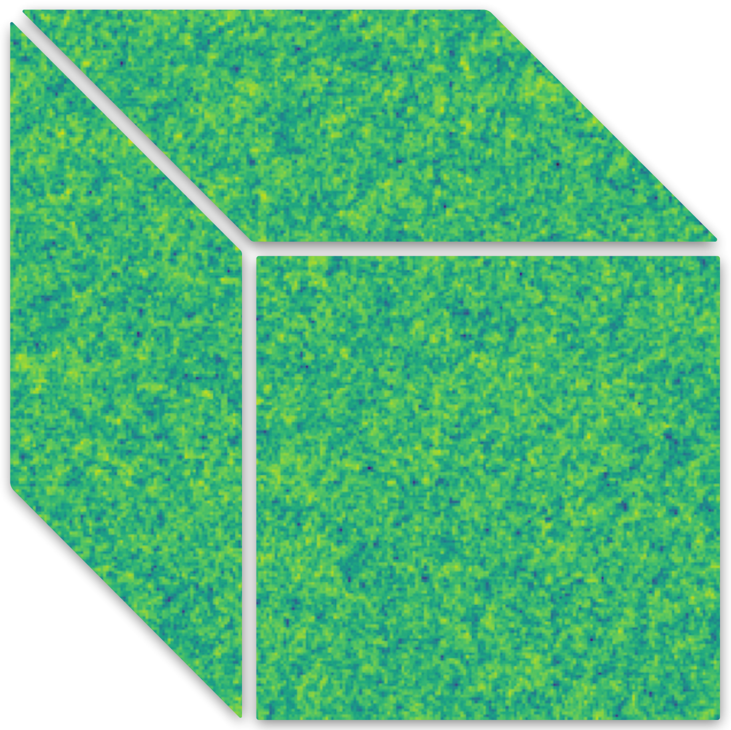
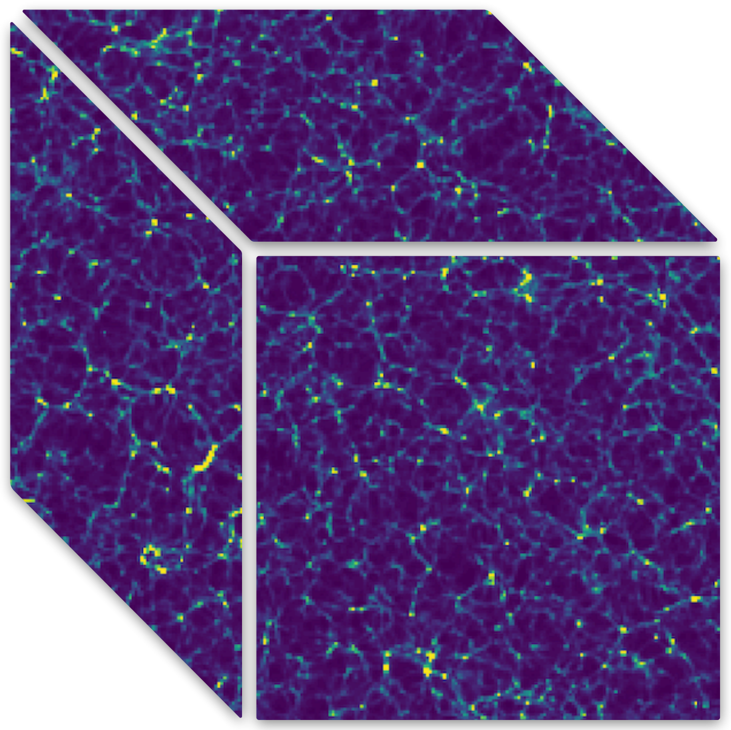
Shot noise dominates, need more supernovae

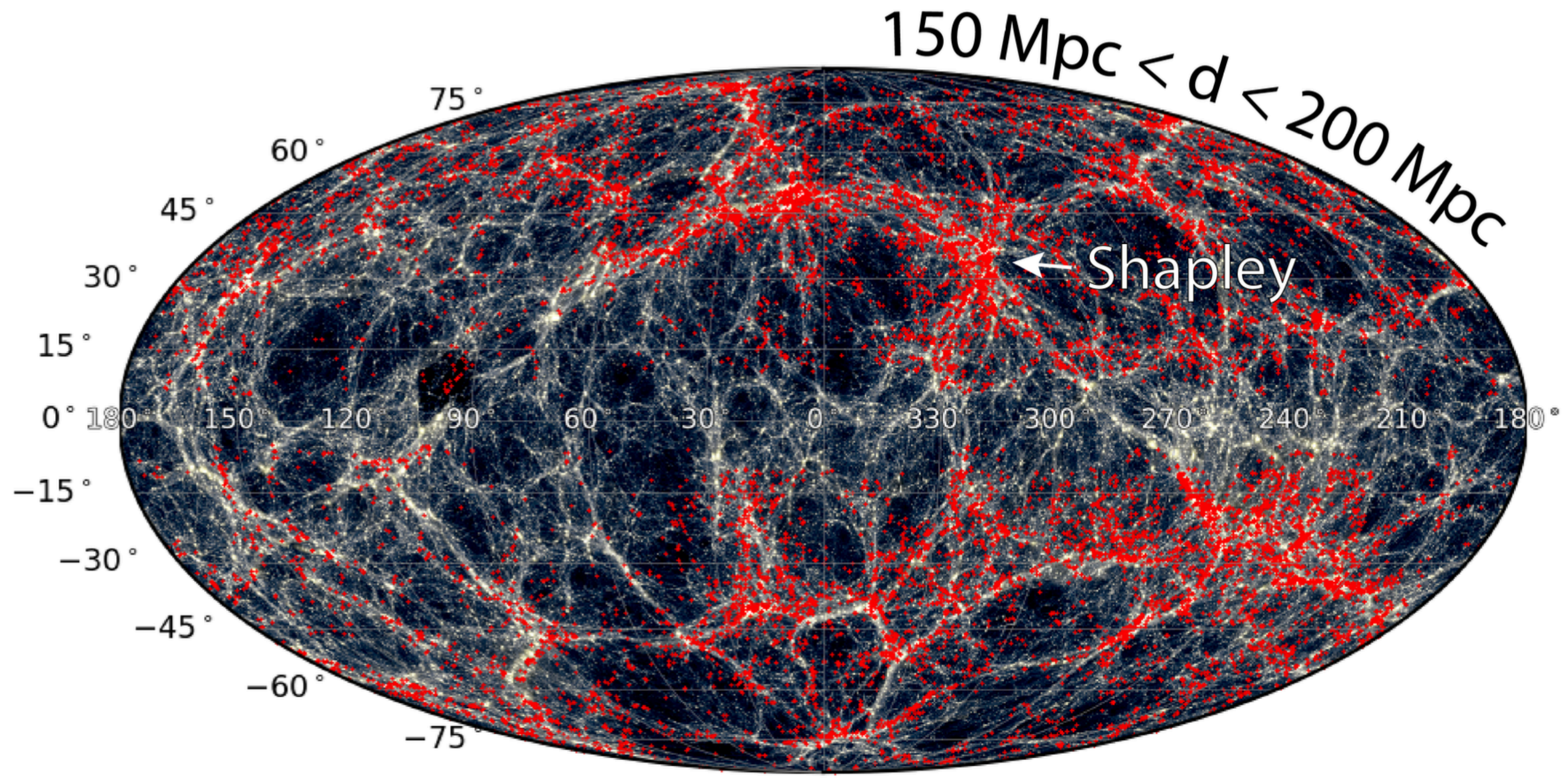
The SIBELIUS simulation

BORG initial conditions





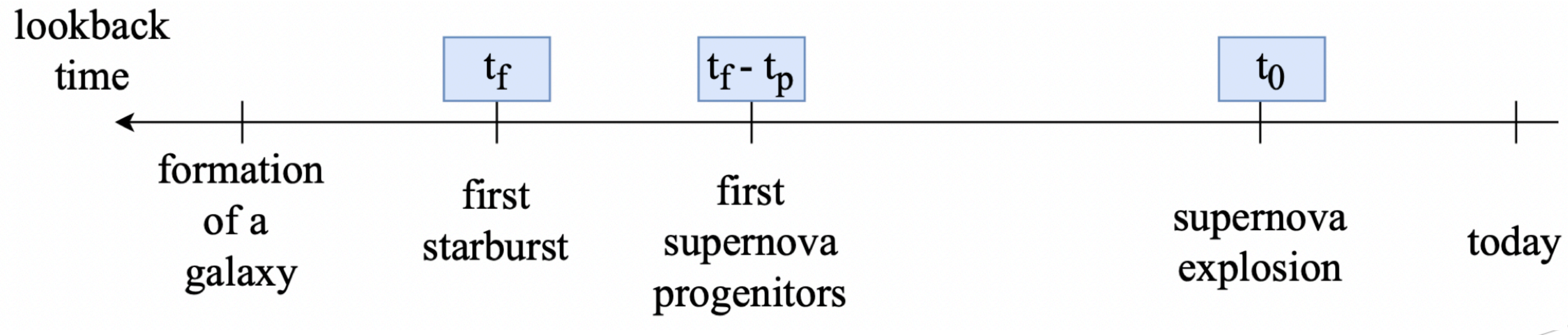
GALFORM



McAlpine+22

- 90.000 simulated galaxies and their properties (stellar mass, star-formation history)
- Generate SN simulation informed by galaxy clustering

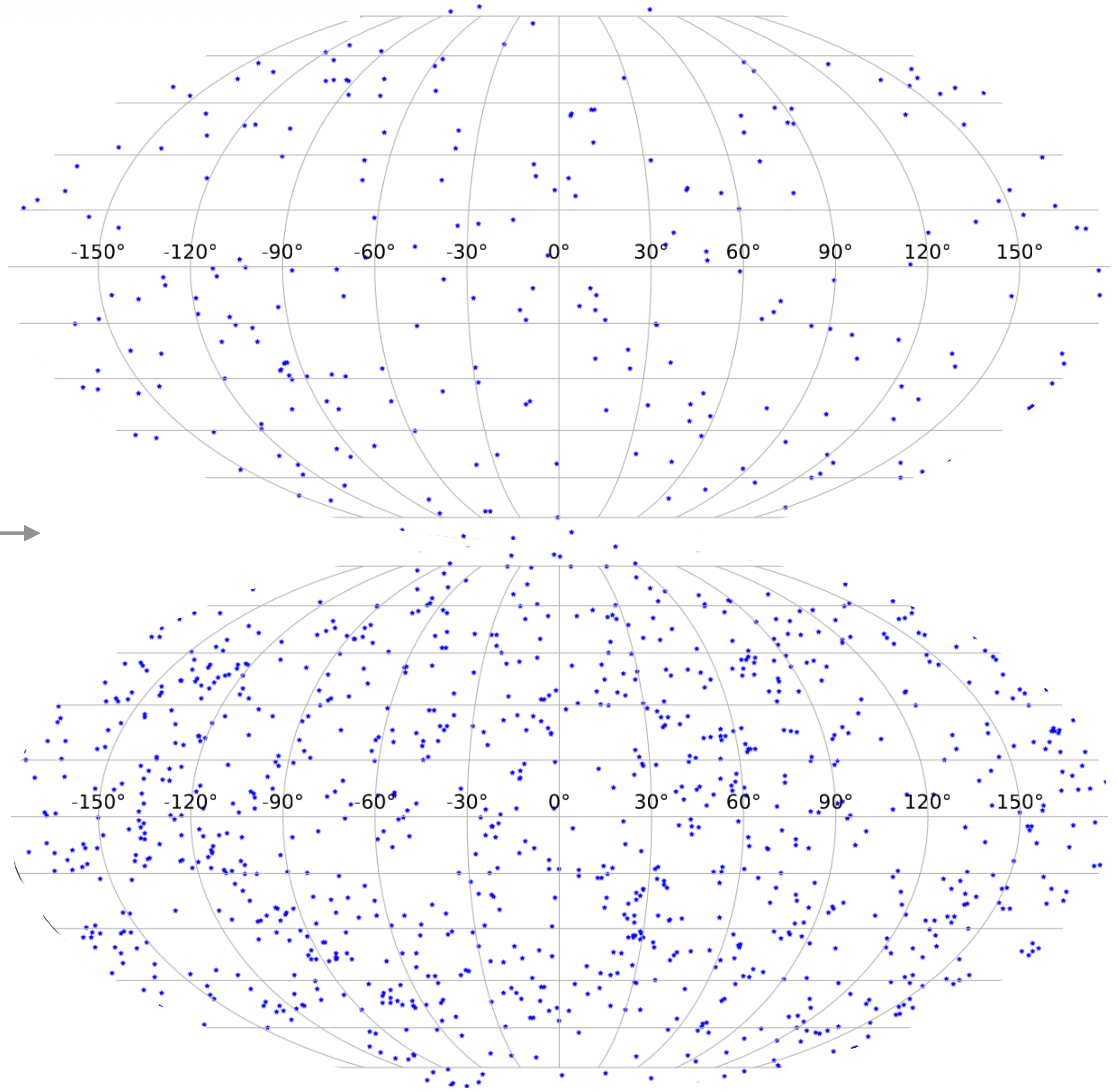
Supernova production within a galaxy



$$R_{IA}(t_0) = \int_{t_0}^{t_f} \Psi(t_0 - \tau) \Phi_{IA}(\tau) d\tau$$

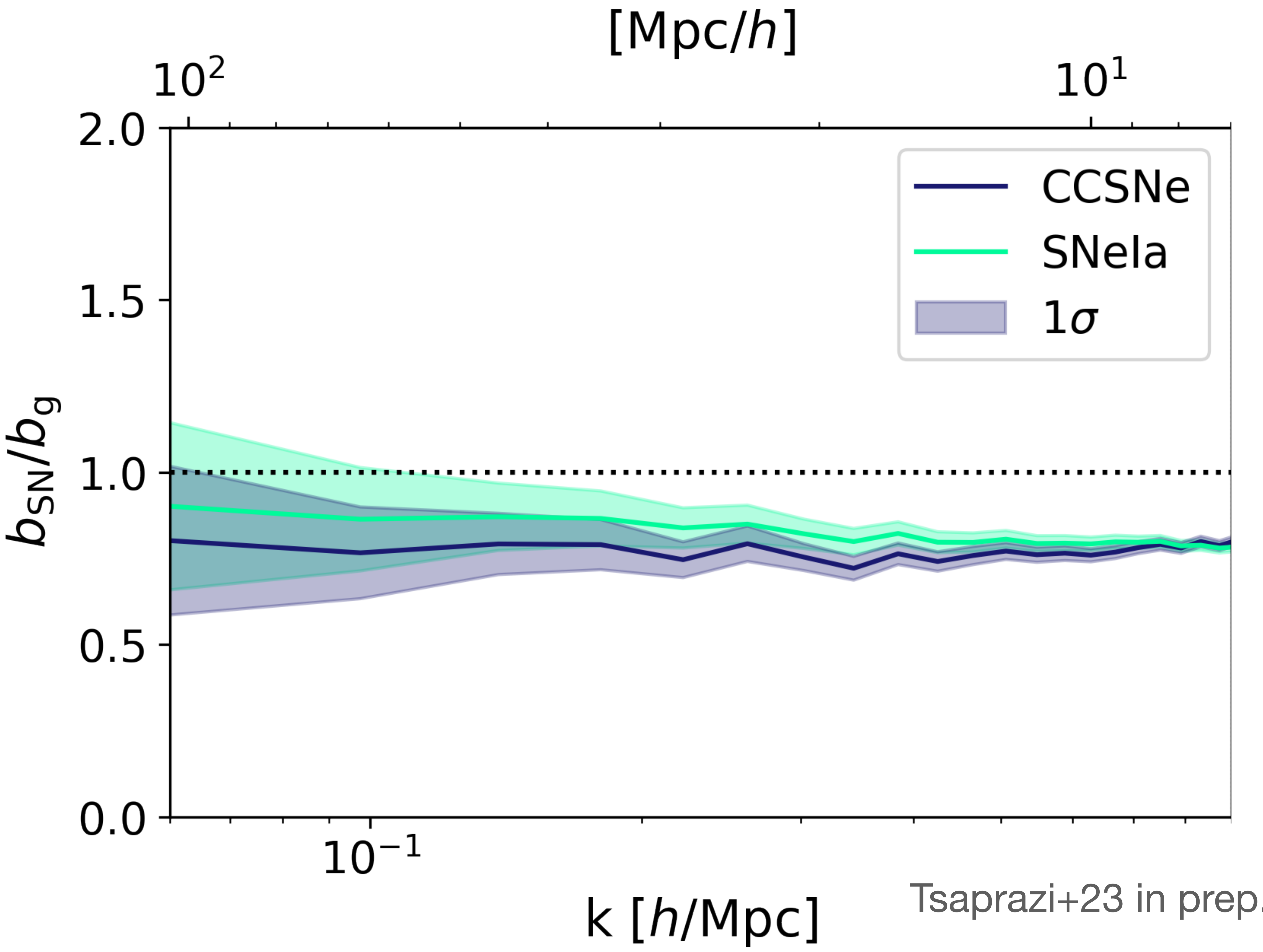
$$R_{CC}(t_0) = \Psi(t_0) k_{CC}$$

$$P(N|R_{IA}) = \frac{\lambda^N e^{-R_{IA}\Delta t}}{N!}$$



Tsaprazi+23 in prep.

Supernova simulation as a physics laboratory



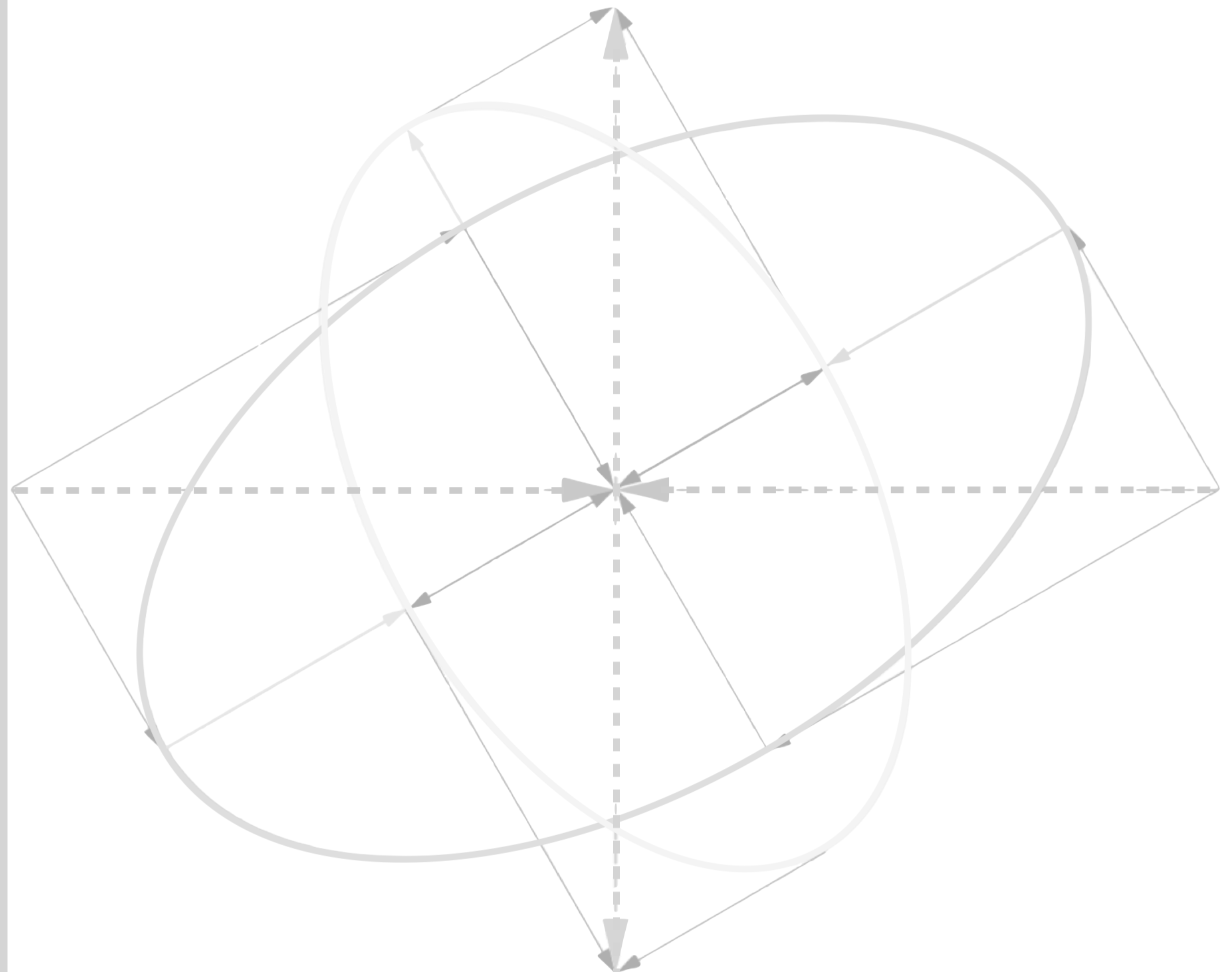
Tsaprazi+23 in prep.

Indications that supernovae cluster less than typical galaxies

- Cosmic web
- Study systematic effects
- Simulate more tracers

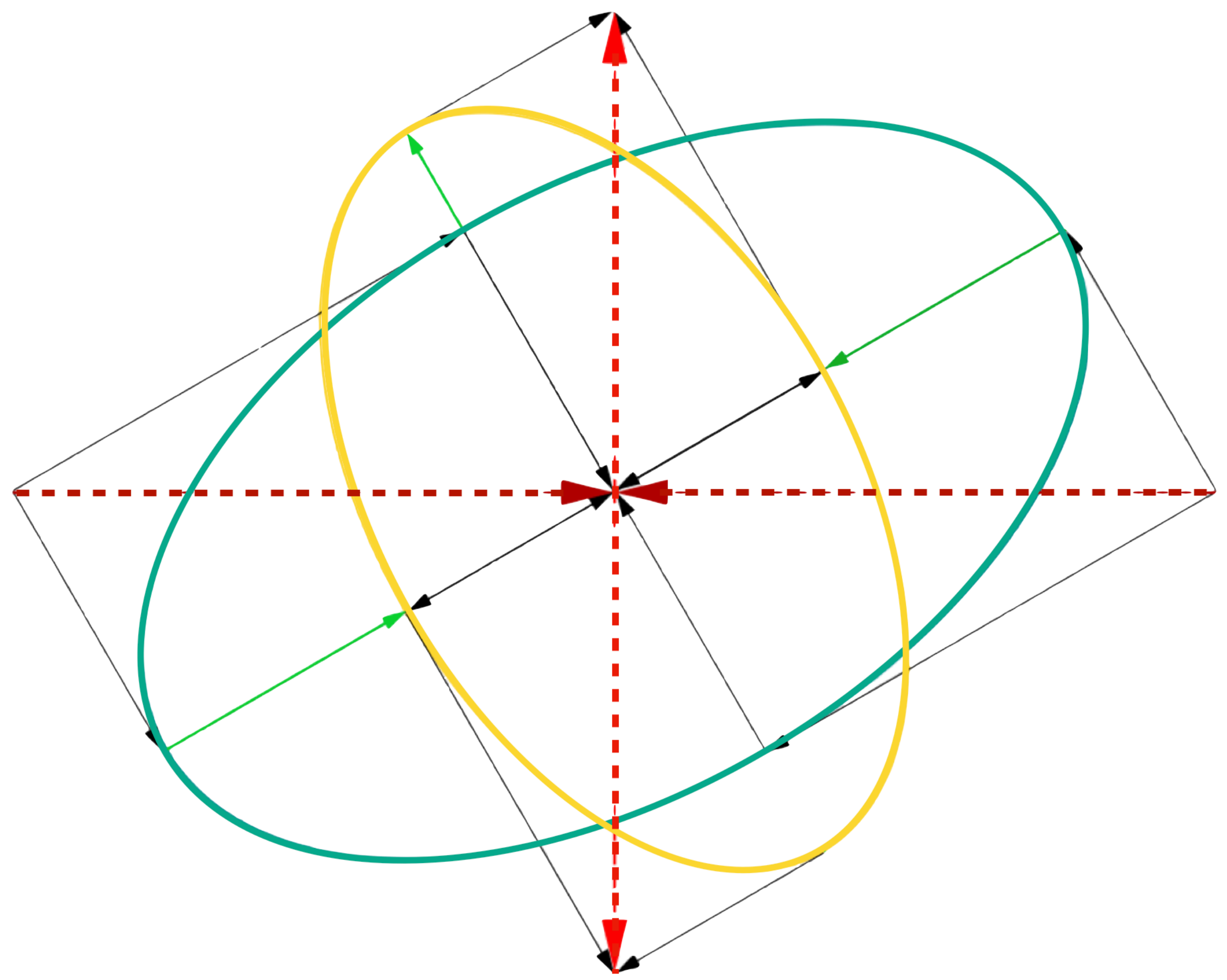
Constraining galaxy intrinsic alignment with the full large-scale structure

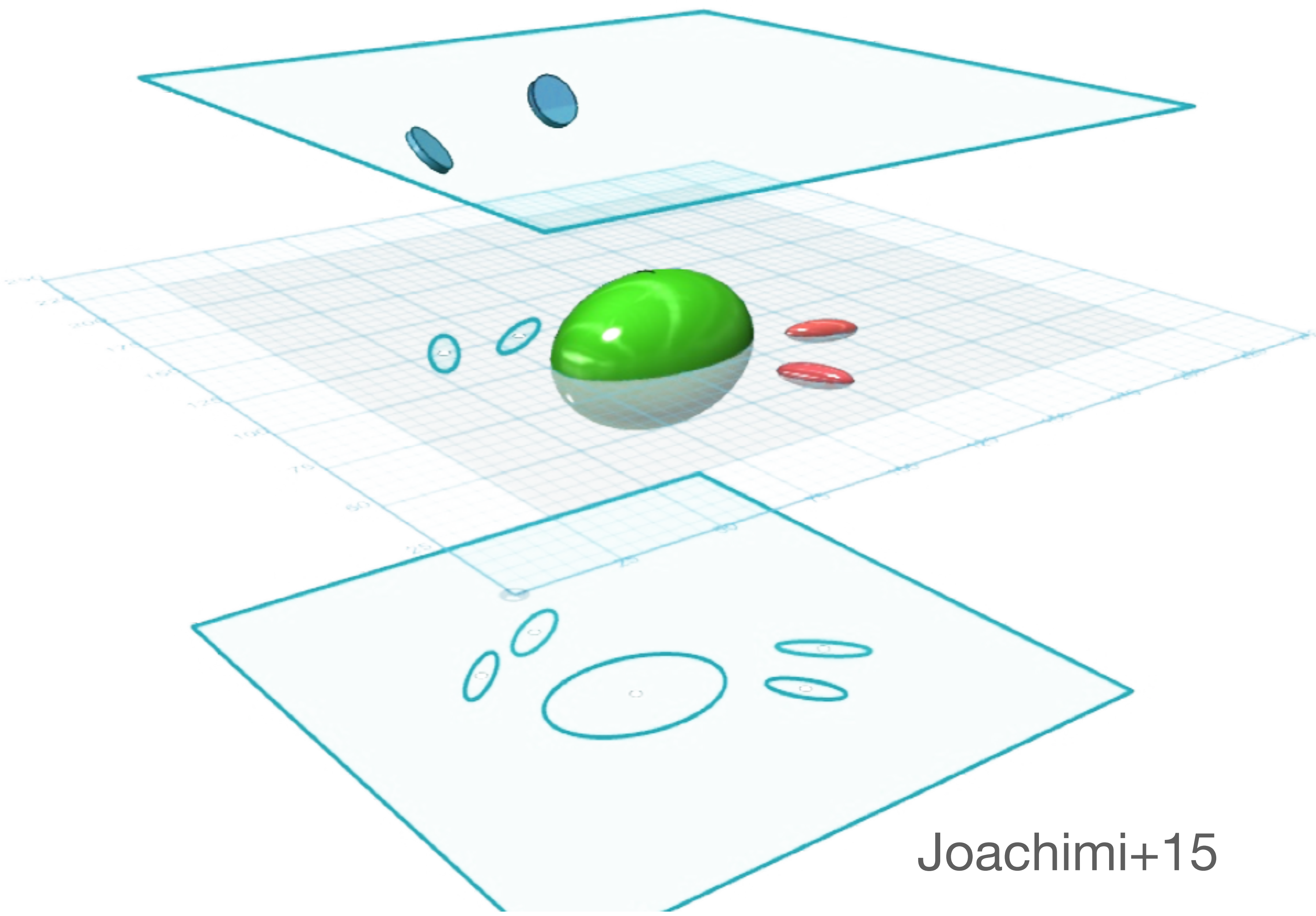
Paper II



Galaxy intrinsic alignment

A systematic effect and a probe of galaxy formation and cosmology





Joachimi+15

- Galaxy formation and evolution
- Systematic effect for weak lensing
- 2-point statistics

The tidal shear is non-Gaussian on small scales

- 70.000 elliptical galaxy shapes from SDSS
- 3D tidal shear constrained by BORG with spectroscopic data, 15.6 Mpc/h

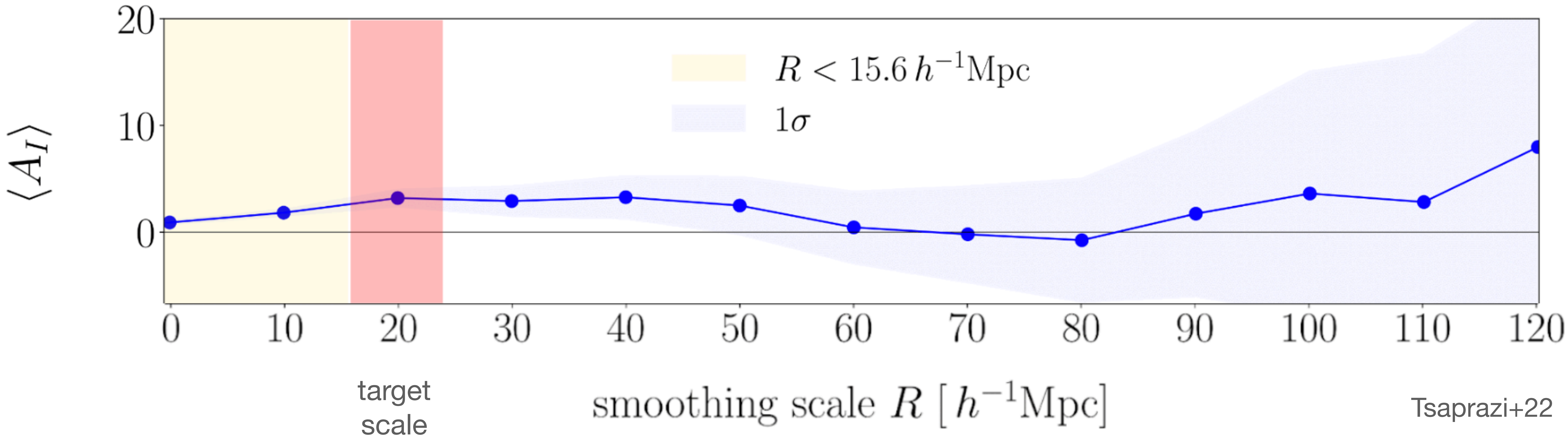
$$e_1^{\mathrm{I}} \pm \iota\, e_2^{\mathrm{I}} = -\frac{C}{4\pi G} T_{\pm}$$

$$e_a^{\mathrm{obs}} = e_a^{\mathrm{I}} + \epsilon_a^{\mathrm{msm}} + \epsilon_a^{\mathrm{WL}} + \epsilon_a^{\mathrm{rnd}}$$

$$\mathcal{P}\left(e \middle| C, T_s, \sigma^2\right) = \prod_{g=1}^{2N_g} \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left[-\frac{(e_g - CT_{g,s})^2}{2\sigma^2}\right]$$

Alignment amplitude as a function of scale

4σ detection of intrinsic alignment at 20 Mpc/h



target scale

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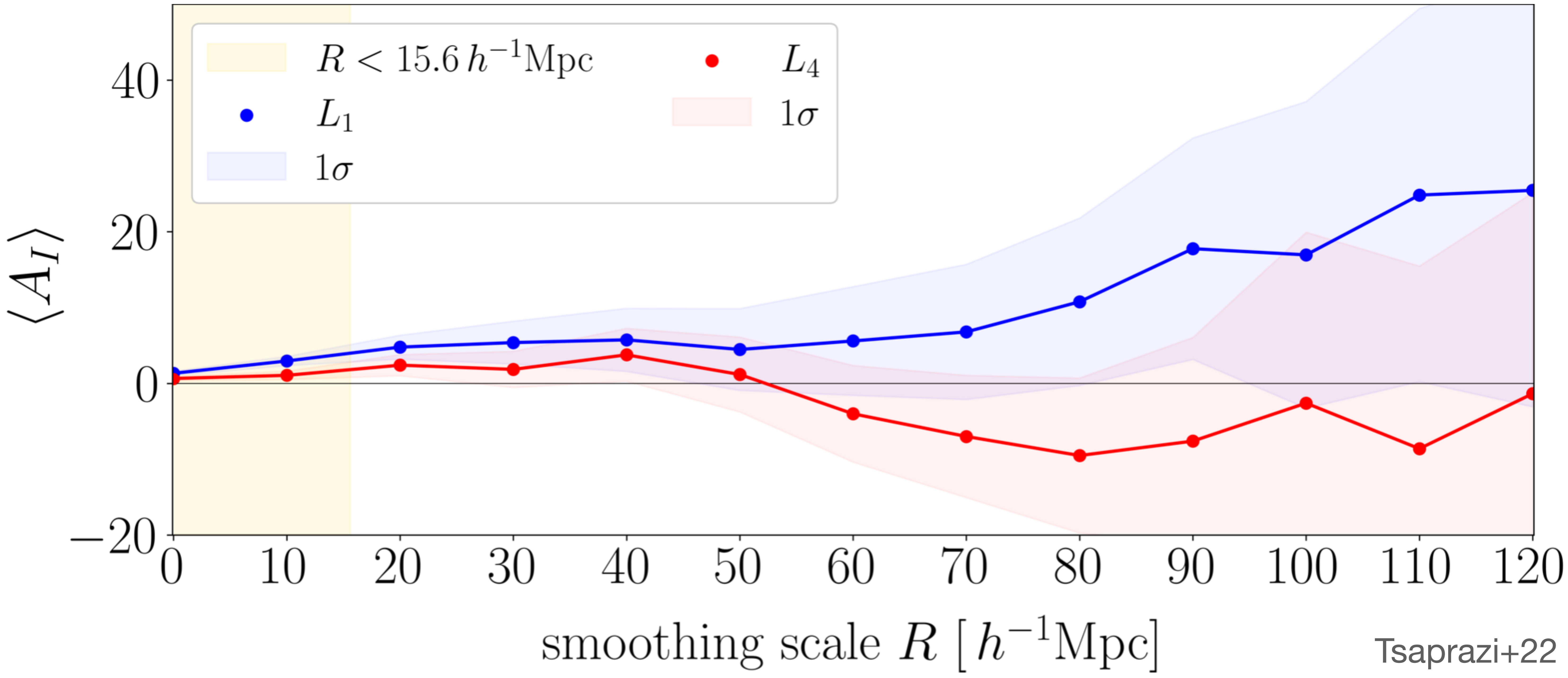
Alignment amplitude as a function of luminosity

Luminous galaxies tend to align more strongly because they live in more massive halos



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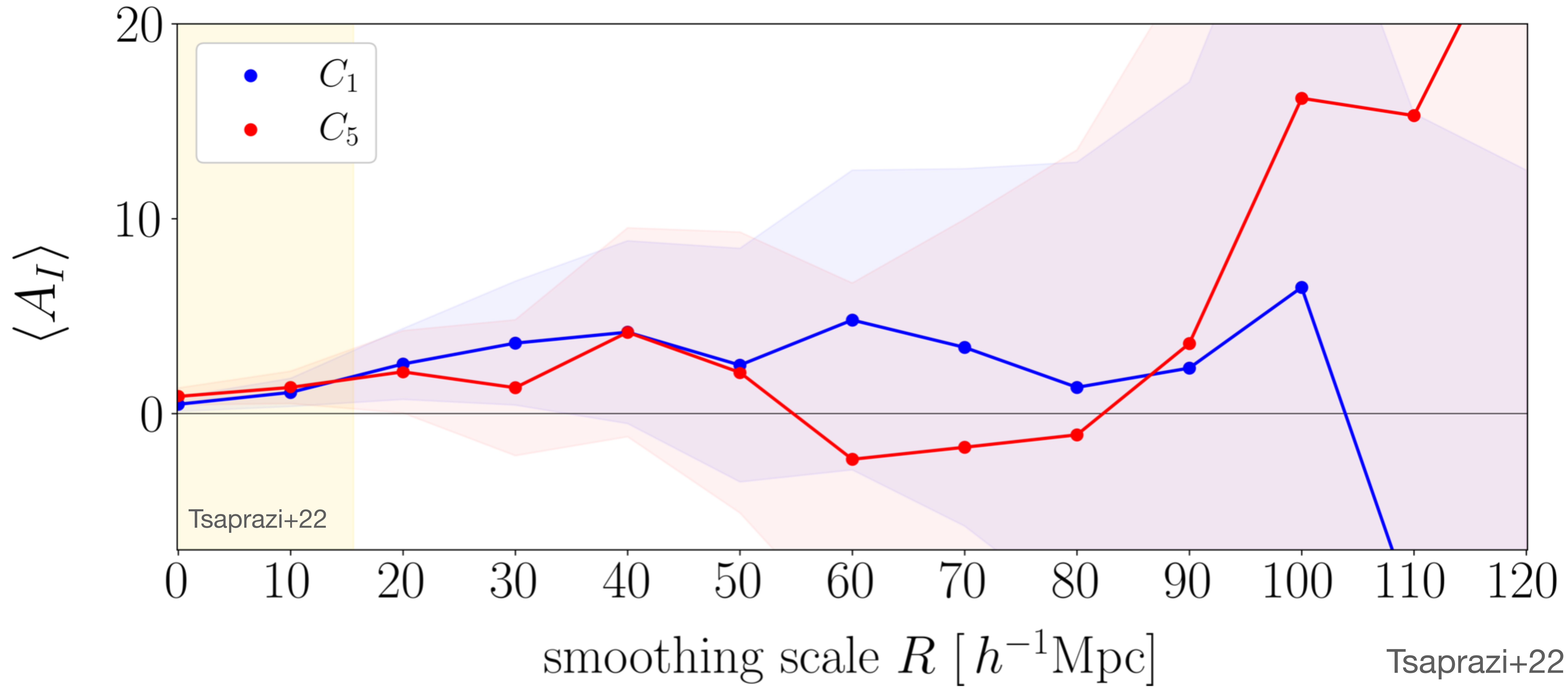
Alignment amplitude as a function of color

Redder galaxies would align more strongly due to morphology



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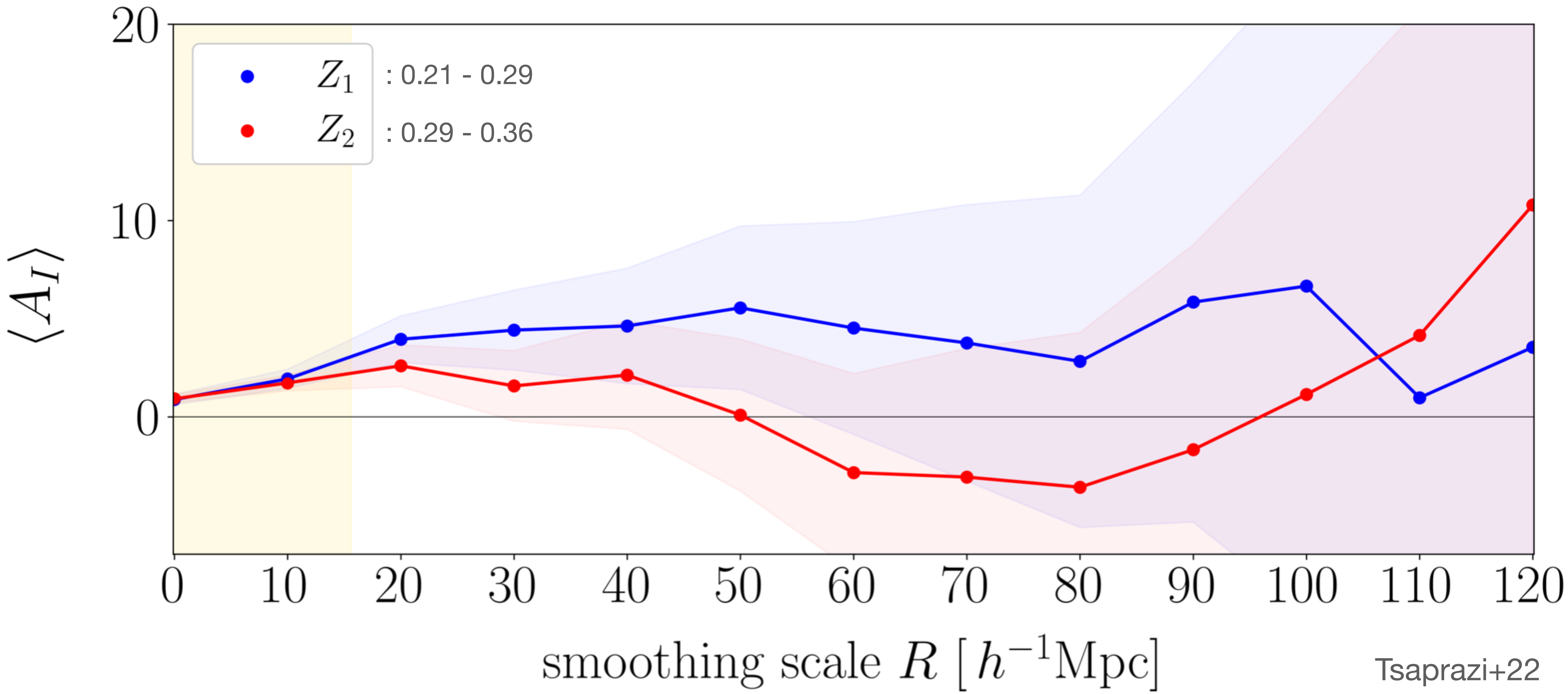
Alignment amplitude as a function of redshift



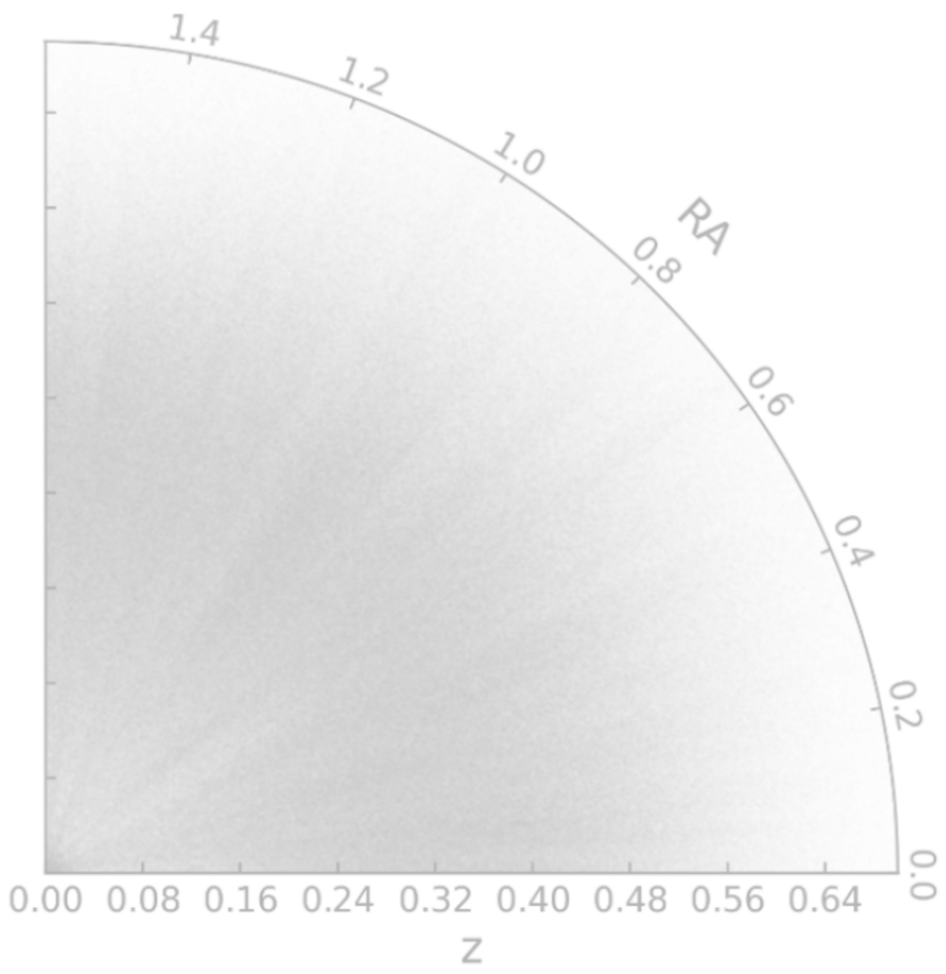
consistent with previous studies

Tsaprazi+22

- 4σ detection of intrinsic alignment constant with luminosity, color and redshift
- **2pt: 9σ at 6 Mpc/h, smaller scales — higher redshifts: need photometry**

Joint inference of the large-scale structure from photometric galaxy clustering

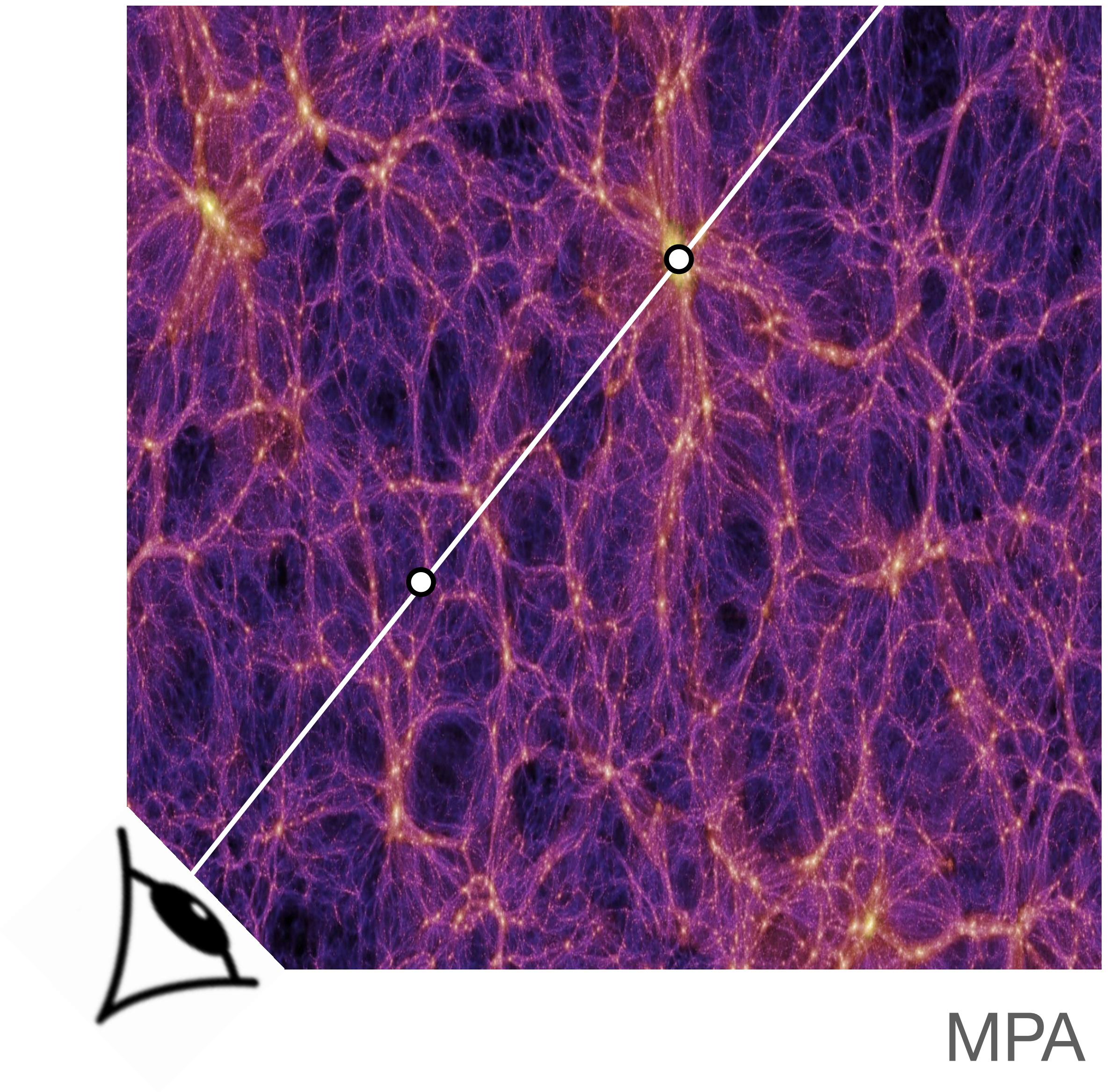
Paper III



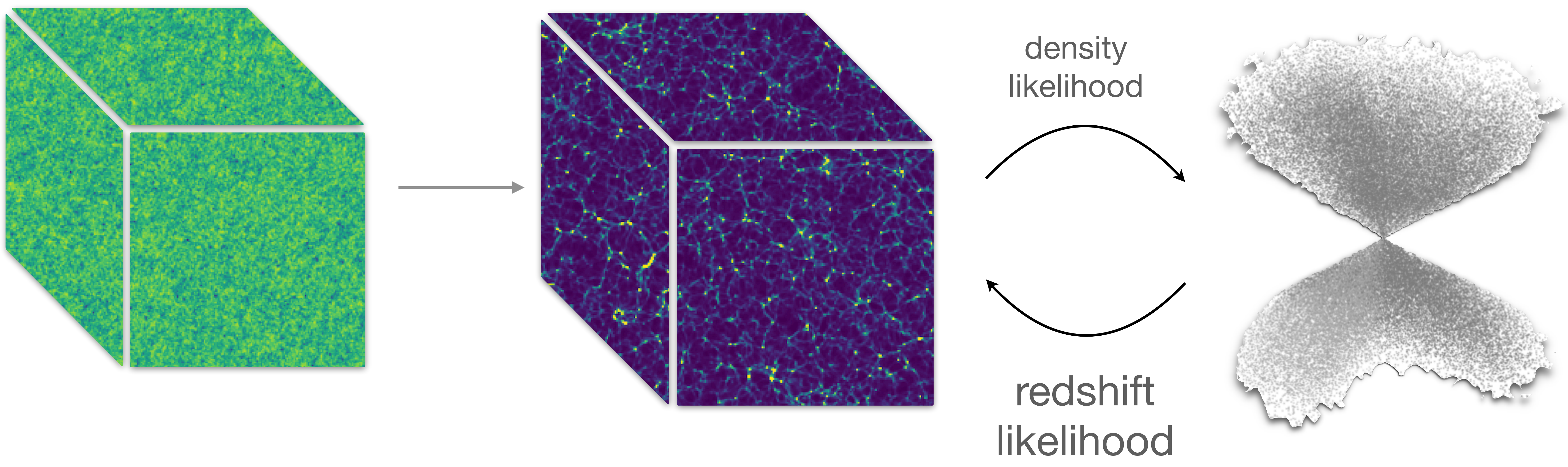
Photometric surveys reach fainter and more distant galaxies

- Photometric surveys provide uncertain redshift measurements
- Dark matter density provides information on most likely galaxy locations

Joint sampling of galaxy redshifts and density

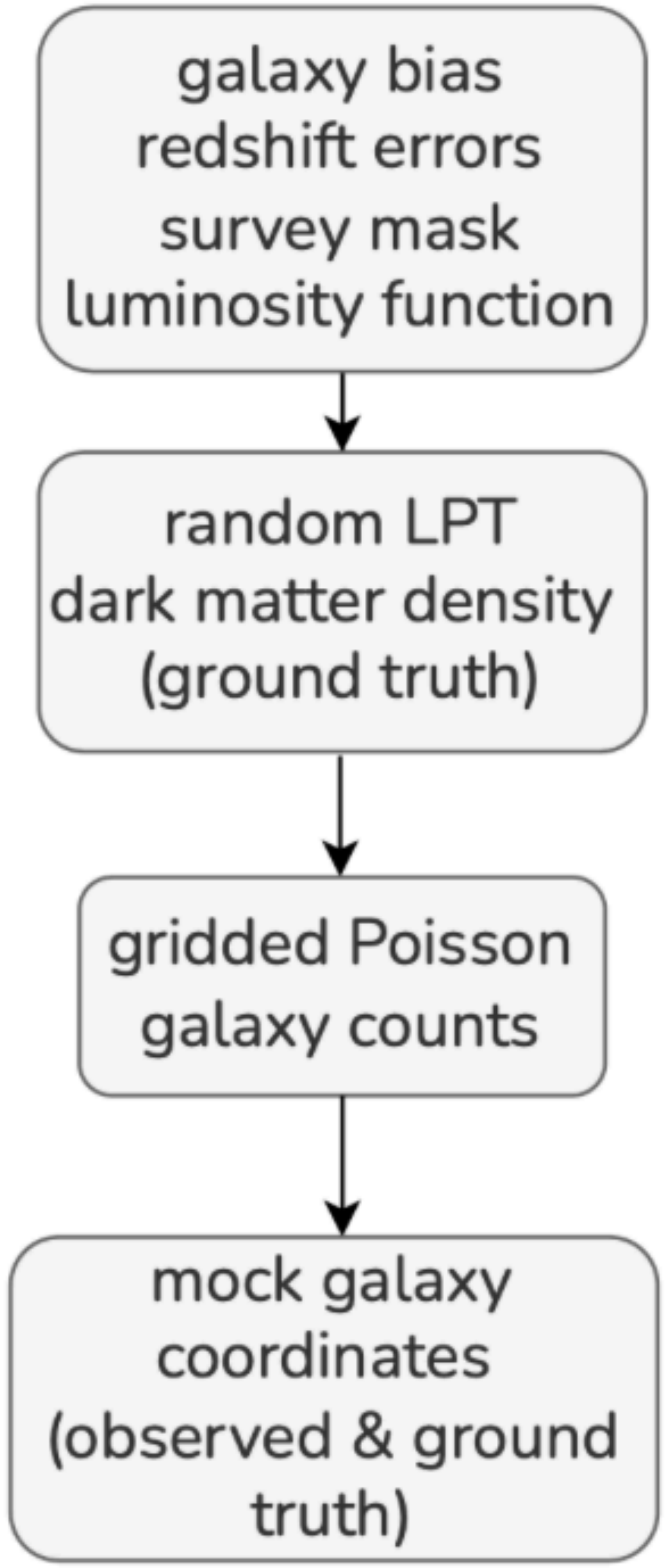


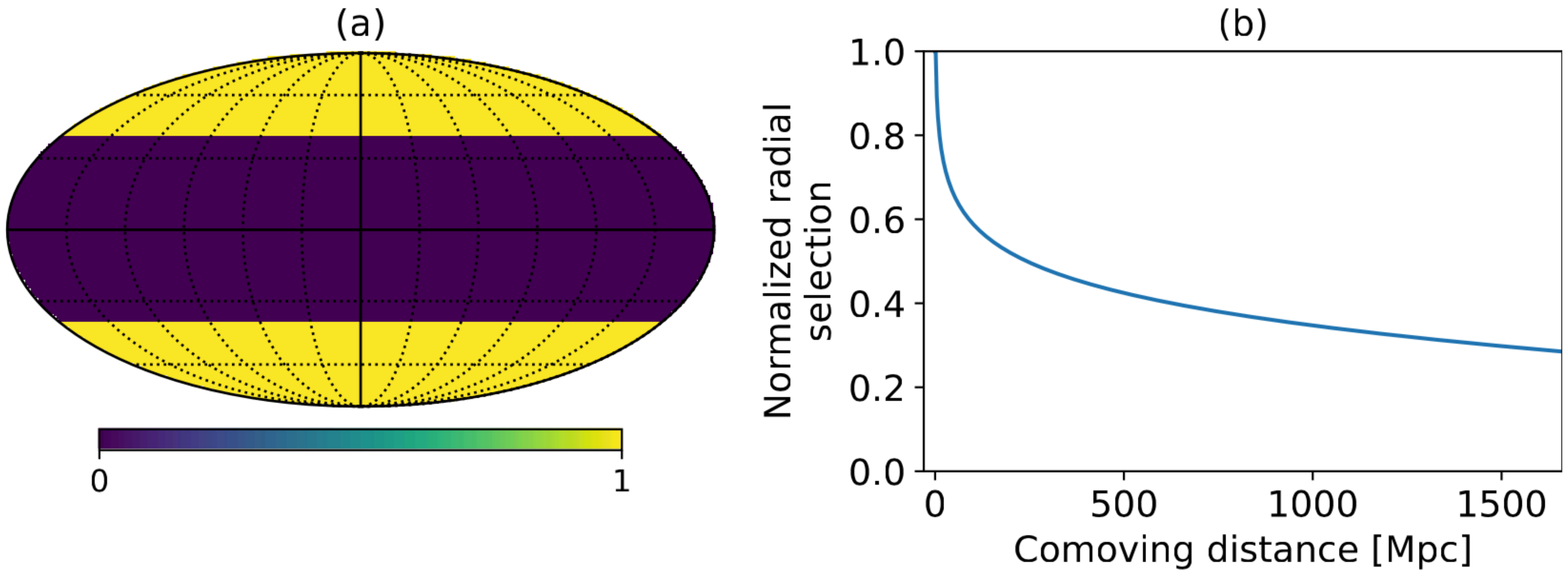
MPA



- Self-consistent propagation of photometric uncertainties to large-scale structure inferences

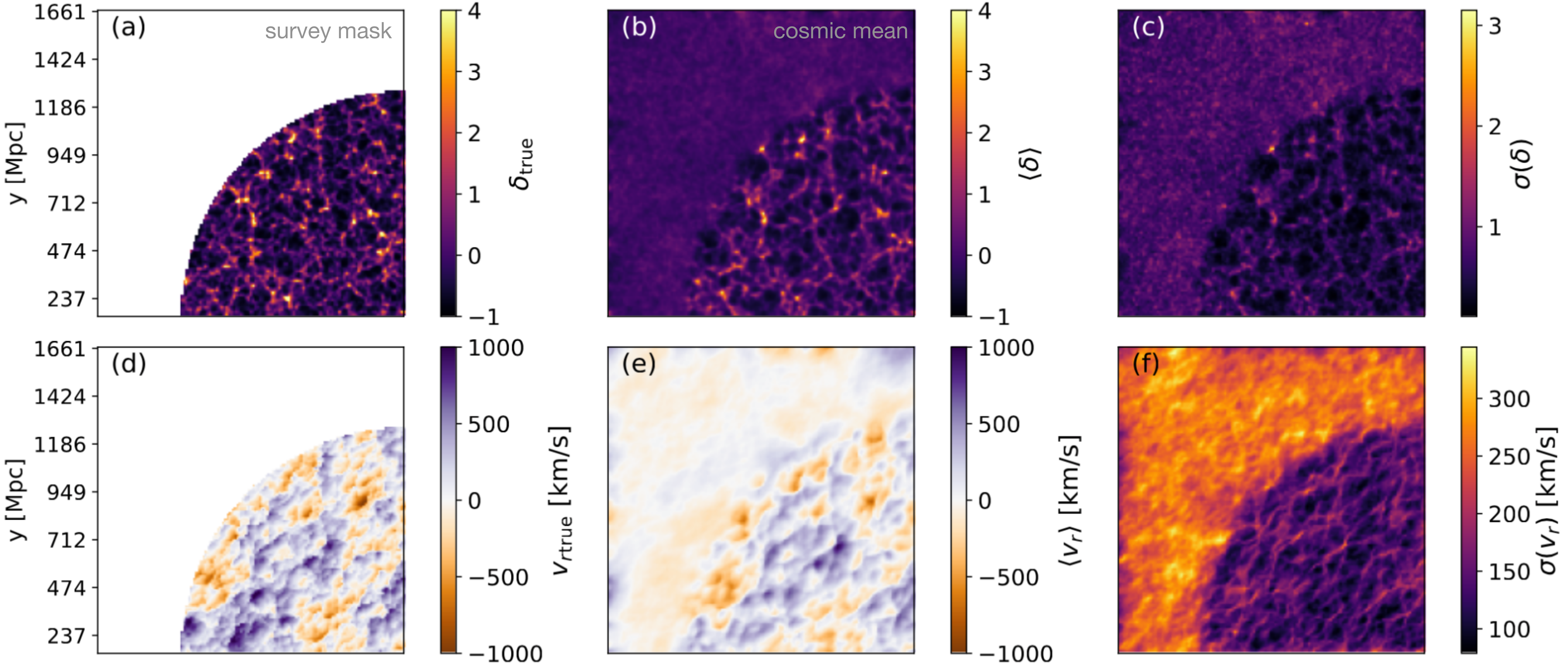
Tests on self-consistent mock data





- Worst-case redshift uncertainties for upcoming surveys (300 Mpc)
- 2e7 photometric and 1% spectroscopic redshifts
- Linear galaxy bias, resolution 13 Mpc

Constrained dark matter density and peculiar velocity



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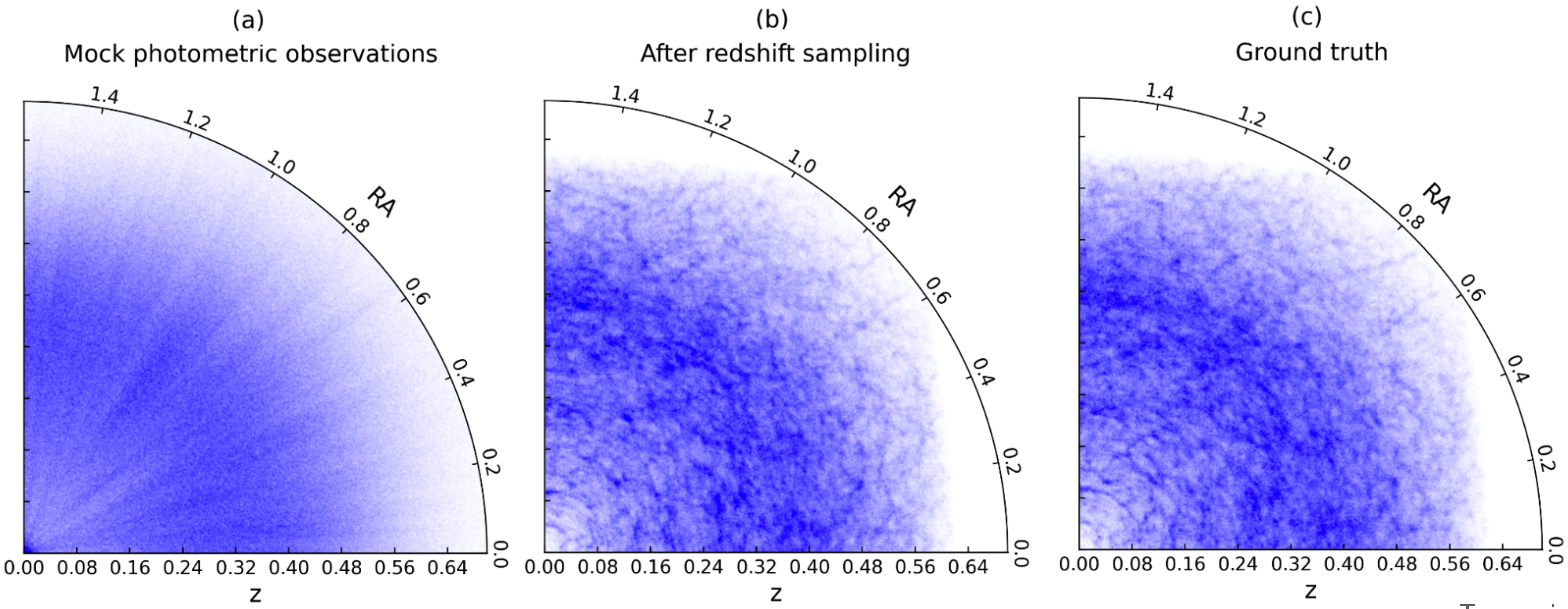
Before and after galaxy positions



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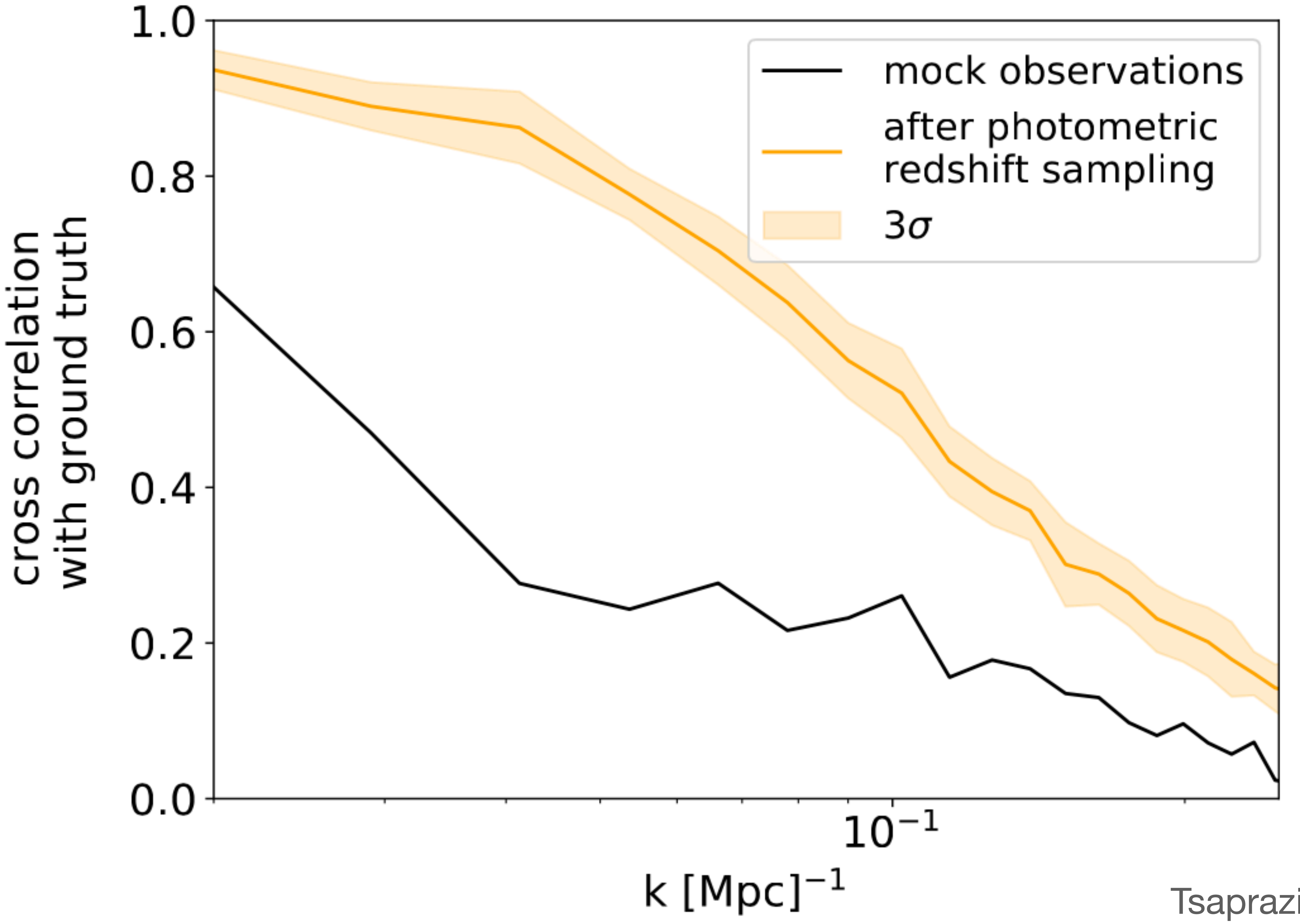
radial distortion mitigation - filamentary structure - similarity to ground truth

Cross-correlation from 28% to 86%



perfect match

random

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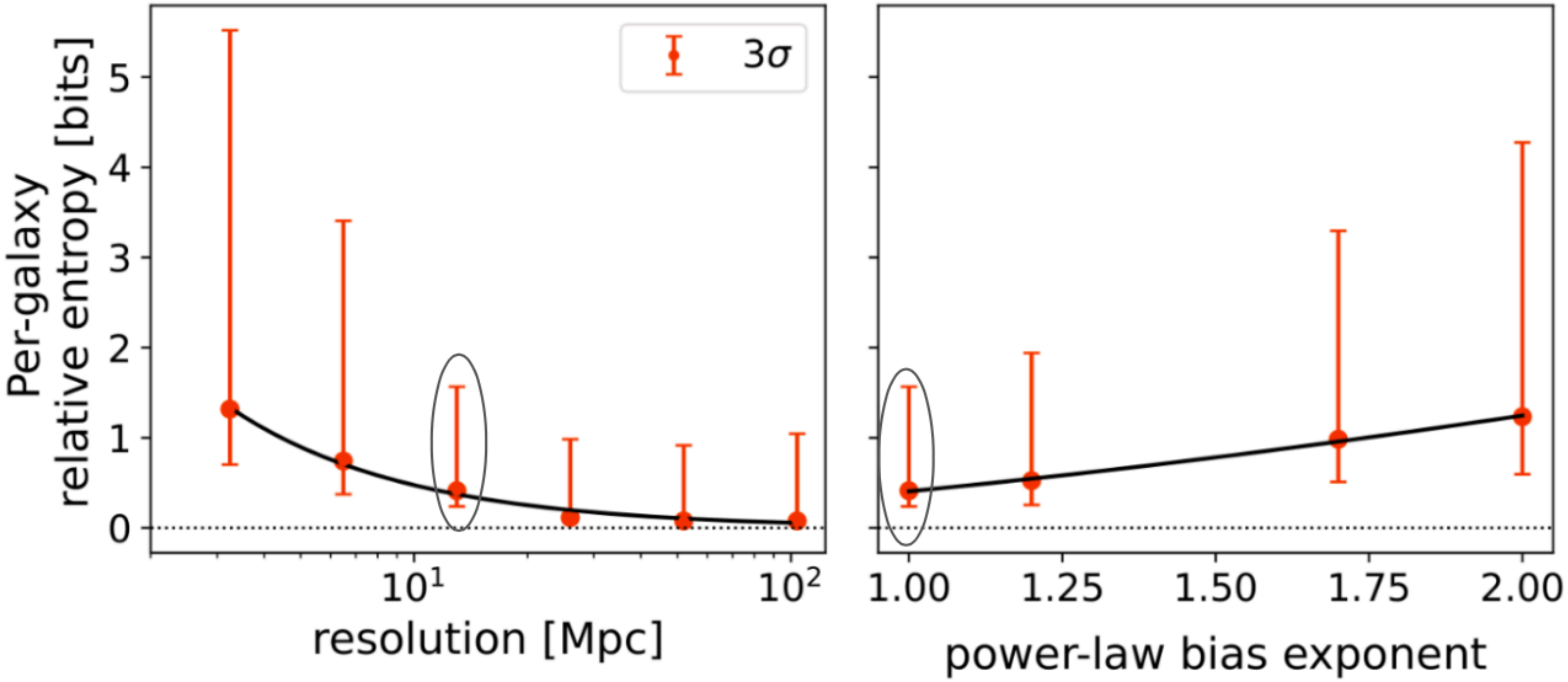
Improvement comes from 1% spectroscopic redshifts



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- Need to advance this study to smaller scales / more strongly biased samples
- Photometric-redshift-only inference

Summary

- Structure formation is nonlinear on the most informative scales
- Existing 2-point estimators miss information
- Need to probe all high-order statistics of the large-scale structure

Summary

- Structure formation is nonlinear on the most informative scales
- Existing 2-point estimators miss information
- Need to probe all high-order statistics of the large-scale structure

- Supernovae in the large-scale structure
- Galaxy intrinsic alignment
- Photometric galaxy clustering

Outlook

- We're reaching the limit of observable galaxies
- Focus on
  - fully exploiting information in the data
  - self-consistently propagating uncertainties
  - demonstrating the power of high-order statistics on small scales