Untangling the Cosmic Web

Correlations between small-scale clustering and large-scale structure

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RPM
11.12.2024

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science
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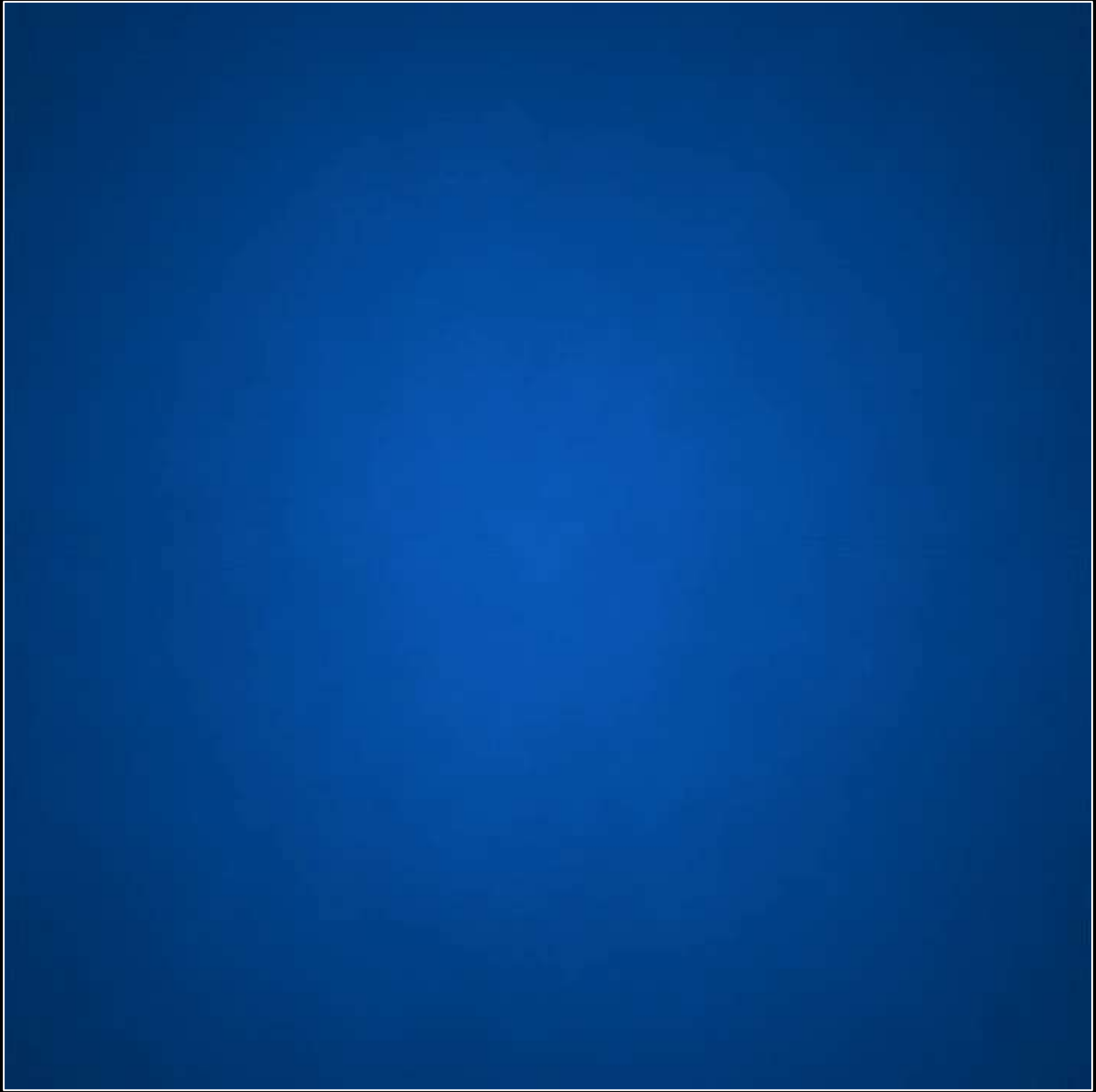
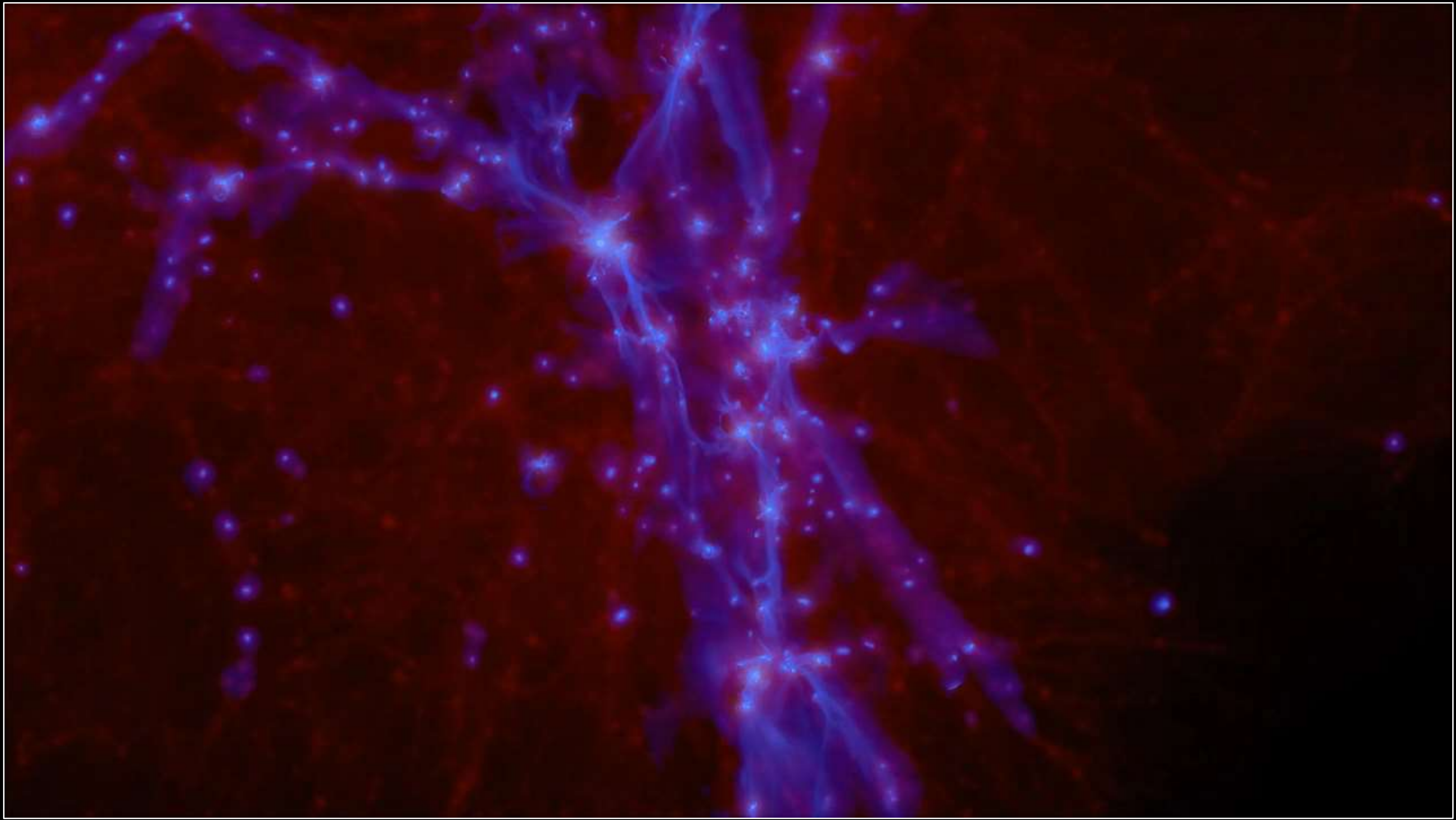


Dark Matter Simulation | CLUES *Gottloeber et al. 2010*



Cosmological simulation of a Milky Way-like galaxy | VINTERGATAN *Renaud et al. 2020*

Intrinsic Alignments (IA)

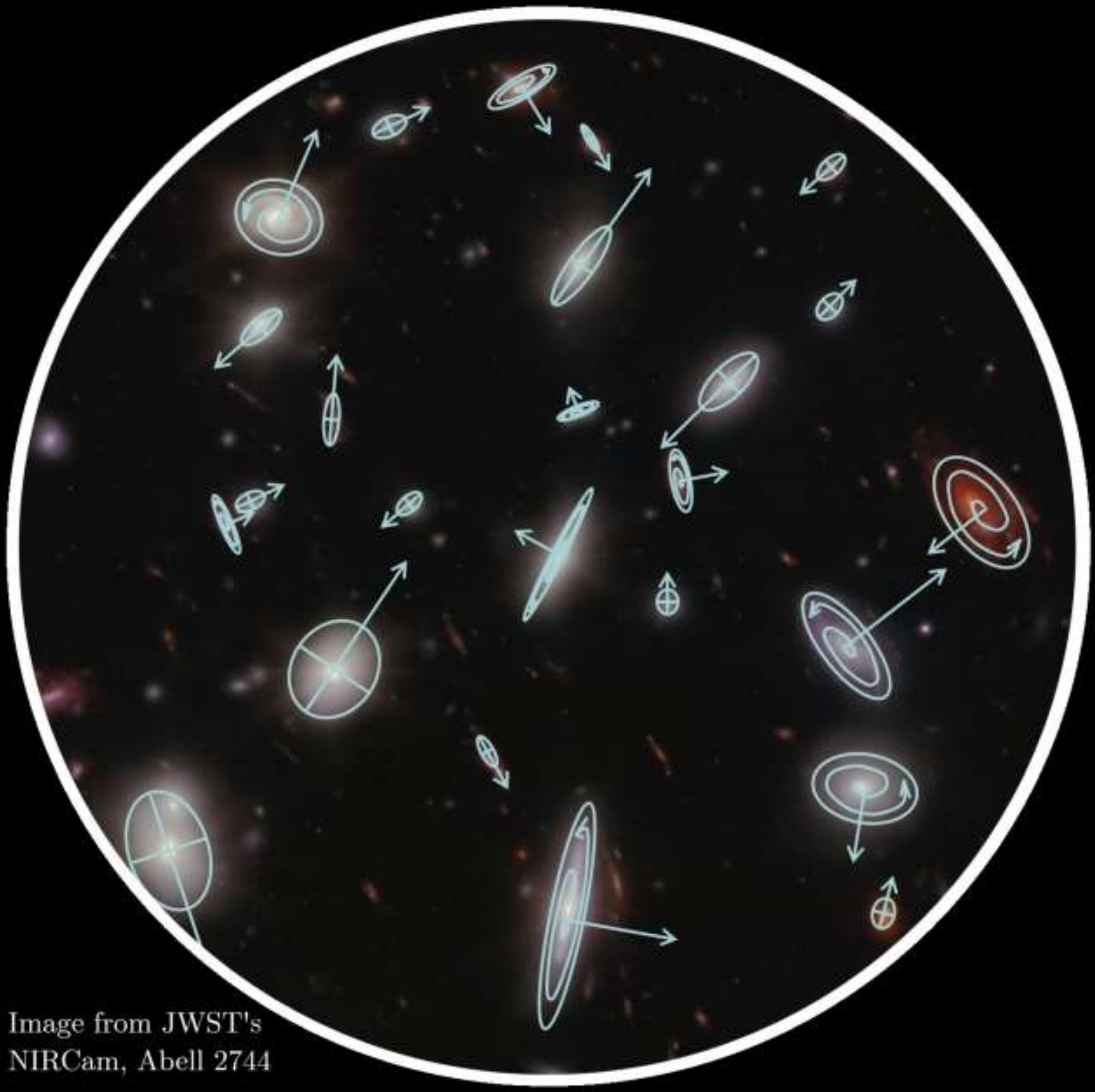


Image from JWST's
NIRCam, Abell 2744

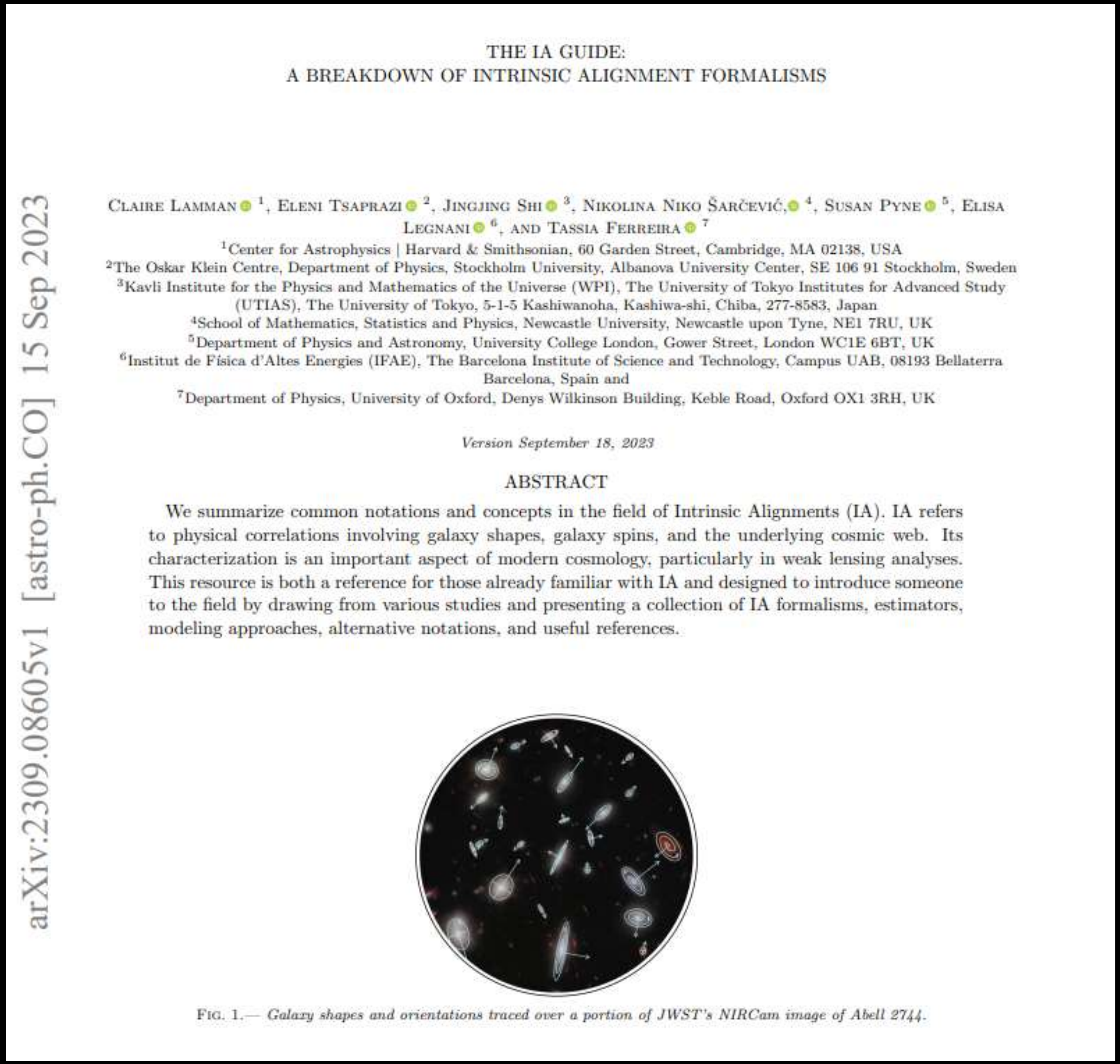
Intrinsic Alignments

Galaxy (and halo) shapes are correlated with each other and with the underlying density

Generally:

- The longest axis of 'red' galaxies are aligned in direction of tidal field

- The spin vector of 'blue' galaxies are aligned in direction of tidal field



arXiv:2309.08605v1 [astro-ph.CO] 15 Sep 2023

THE IA GUIDE:
A BREAKDOWN OF INTRINSIC ALIGNMENT FORMALISMS

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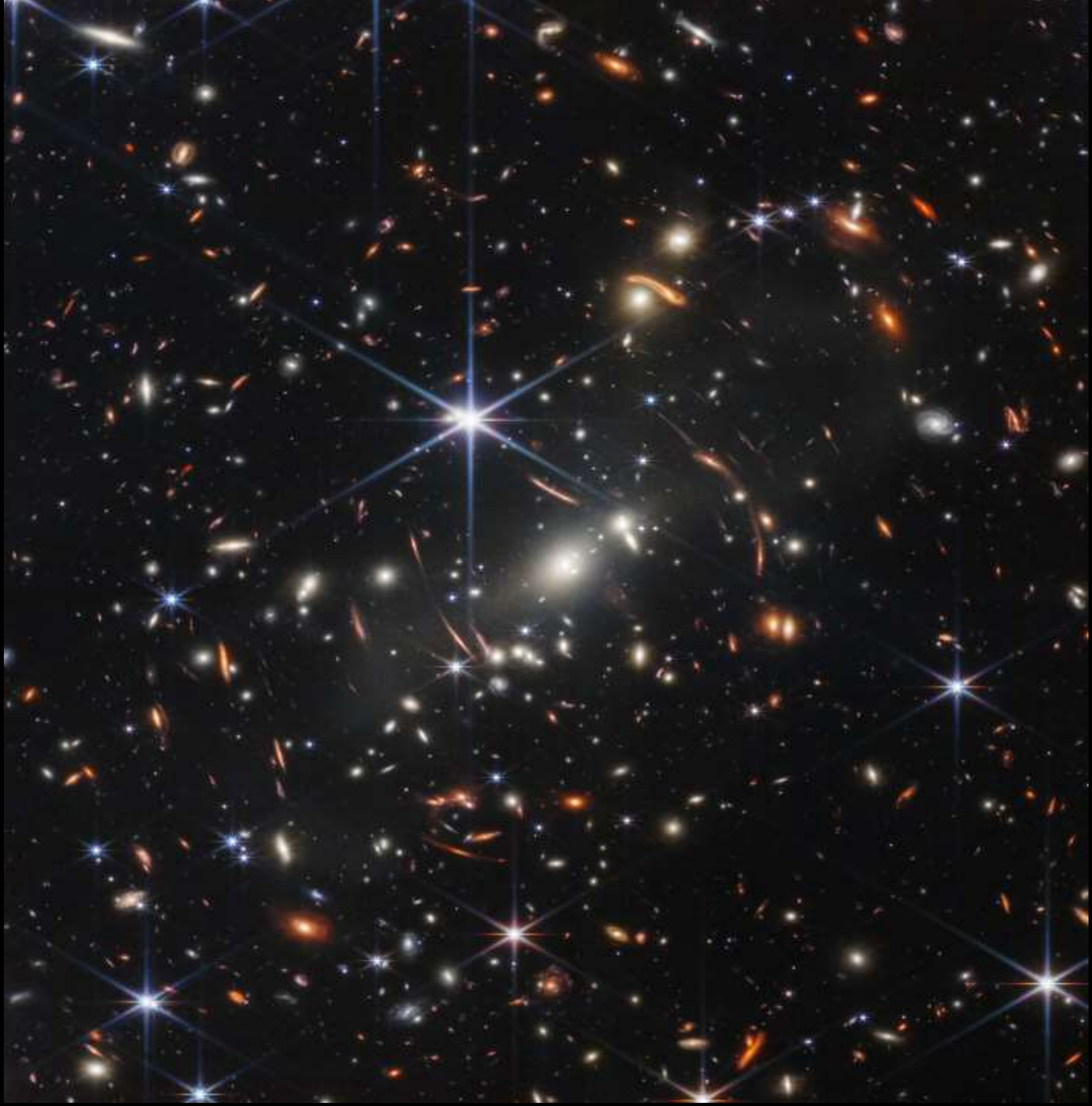
Version September 18, 2023

ABSTRACT

We summarize common notations and concepts in the field of Intrinsic Alignments (IA). IA refers to physical correlations involving galaxy shapes, galaxy spins, and the underlying cosmic web. Its characterization is an important aspect of modern cosmology, particularly in weak lensing analyses. This resource is both a reference for those already familiar with IA and designed to introduce someone to the field by drawing from various studies and presenting a collection of IA formalisms, estimators, modeling approaches, alternative notations, and useful references.

FIG. 1.— *Galaxy shapes and orientations traced over a portion of JWST's NIRCam image of Abell 2744.*

[The IA Guide: arxiv 2309.08605]()
Lamman et al. 2023b



IA interferes with cosmological measurements

- Weak lensing

Can bias matter power spectrum by 30%

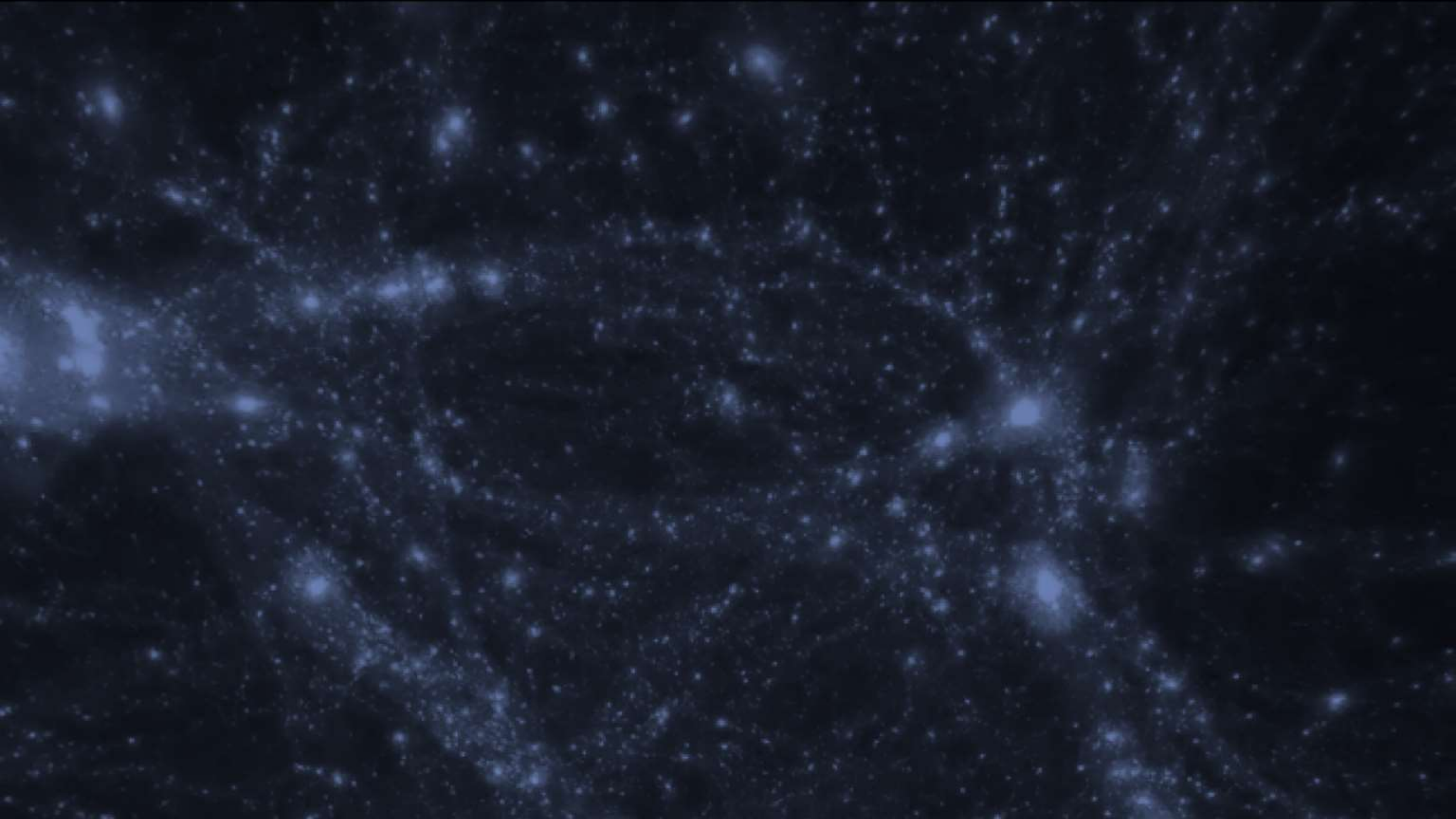
Hirata et al. 2007

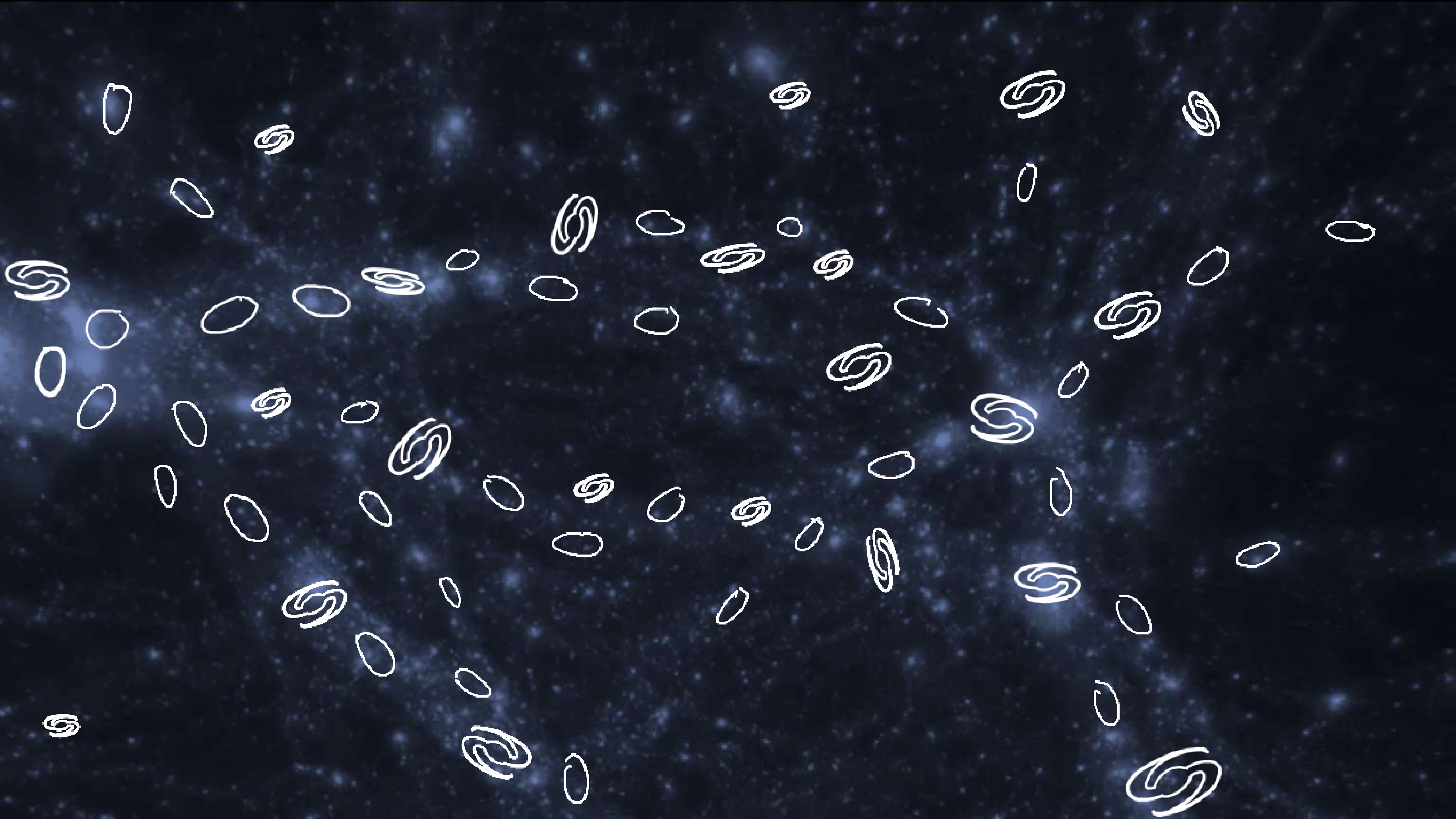
- Redshift-Space Distortions

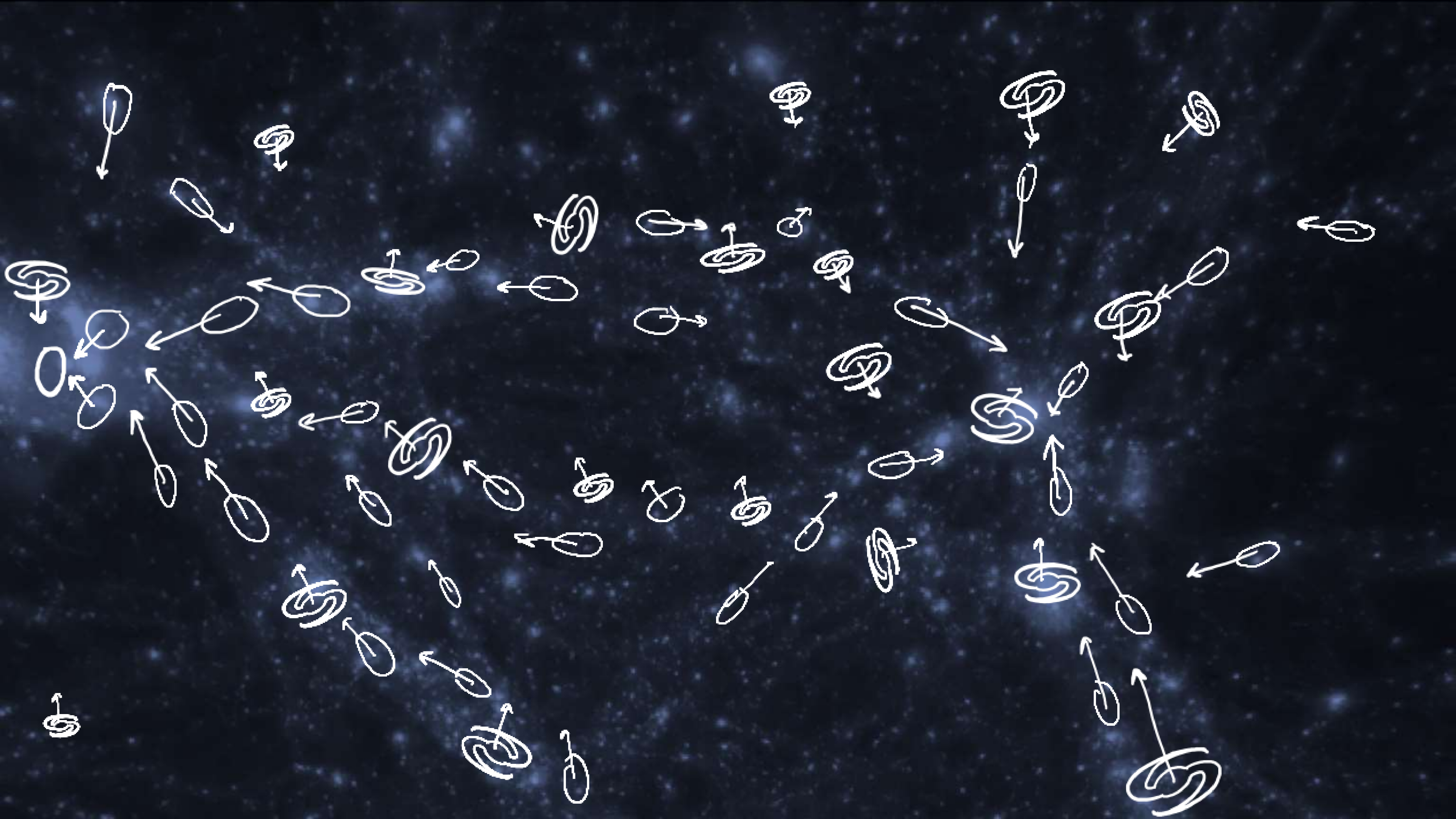
Can bias RSD by 1% (for DESI)

Lamman et al. 2023a & 2024a

JWST NIRCam
(strong lensing)







IA as a cosmological probe

PNG

Chisari & Dvorkin 2013

Schmidt et al. 2015

Akitsu et al. 2021

Kurita & Takada 2023

BAO

Chisari & Dvorkin 2013

Okumura et al. 2019

Van Dompseler et al. 2023

RSD

Okumura & Taruya 2022

B-modes

Georgiou et al. 2023

Akitsu et al 2023

Saga et al. 2024

IA as a cosmological probe: difficulties

1. IA is a systematic effect - typically need $>^{\sim}10^4$ gal to even see a signal

2. Many galaxy populations display no IA in observations. These populations make up most available data beyond z=1.
   (currently no direct IA detections of spiral galaxies)

3. Requires high-quality imaging
   (not a lot of overlap with spec targets)

4. Imaging systematics

Legacy Imaging Survey

Dark Energy Spectroscopic Instrument (DESI)

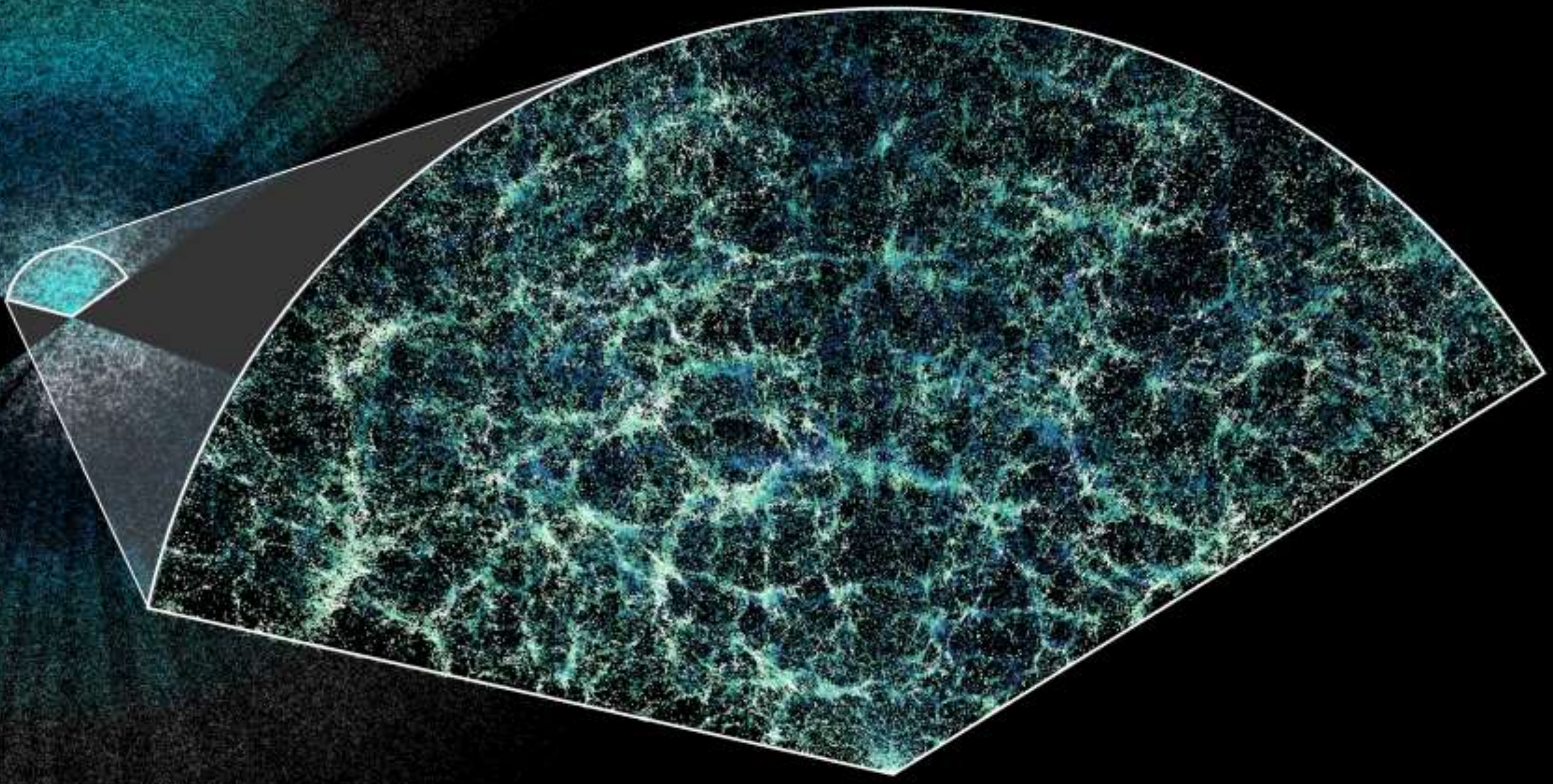
DESI

Dark Energy Spectroscopic Instrument

- Year one:
  14 million extragalactic redshifts

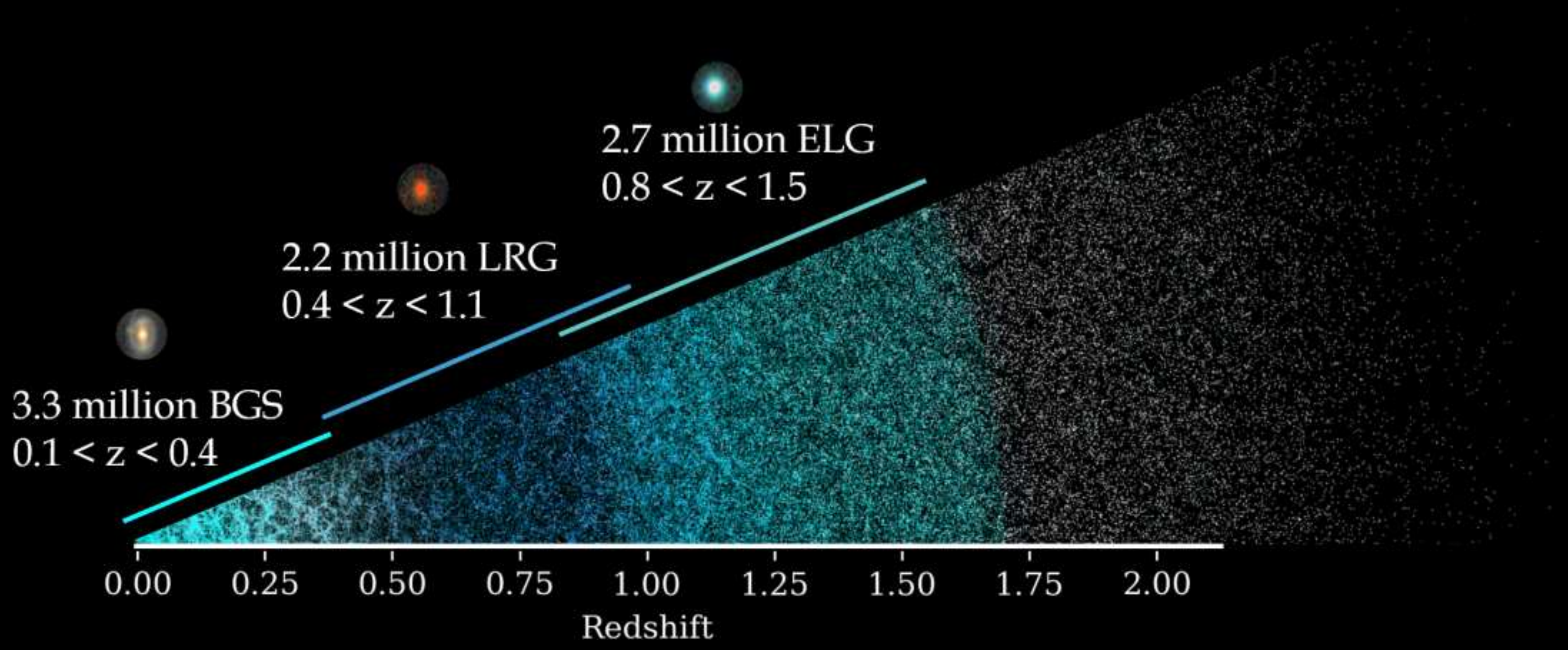
- ~ 50 million redshifts over 5 years

- Goals: map out LSS and its evolution, test dark energy through BAO and RSD

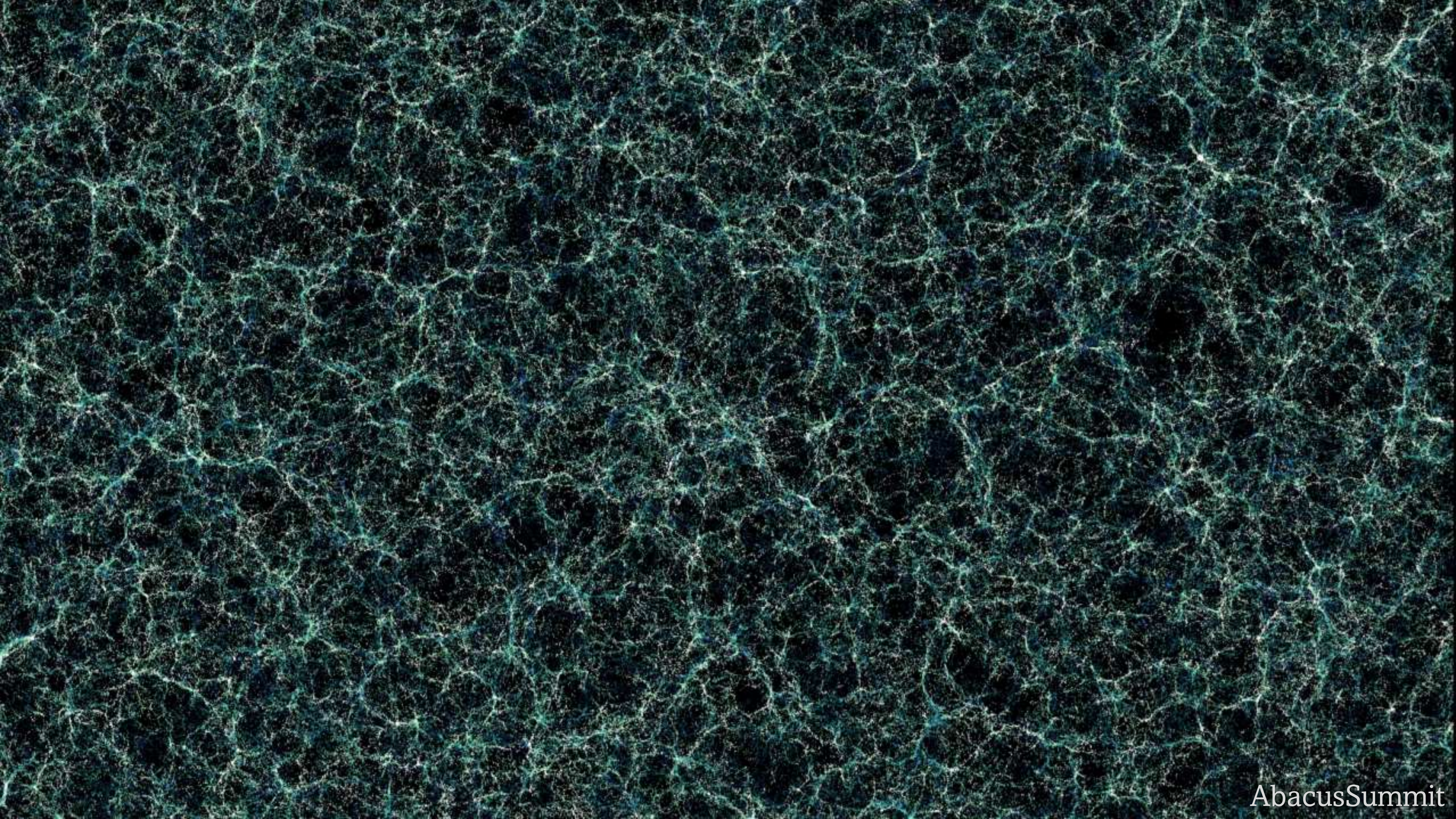


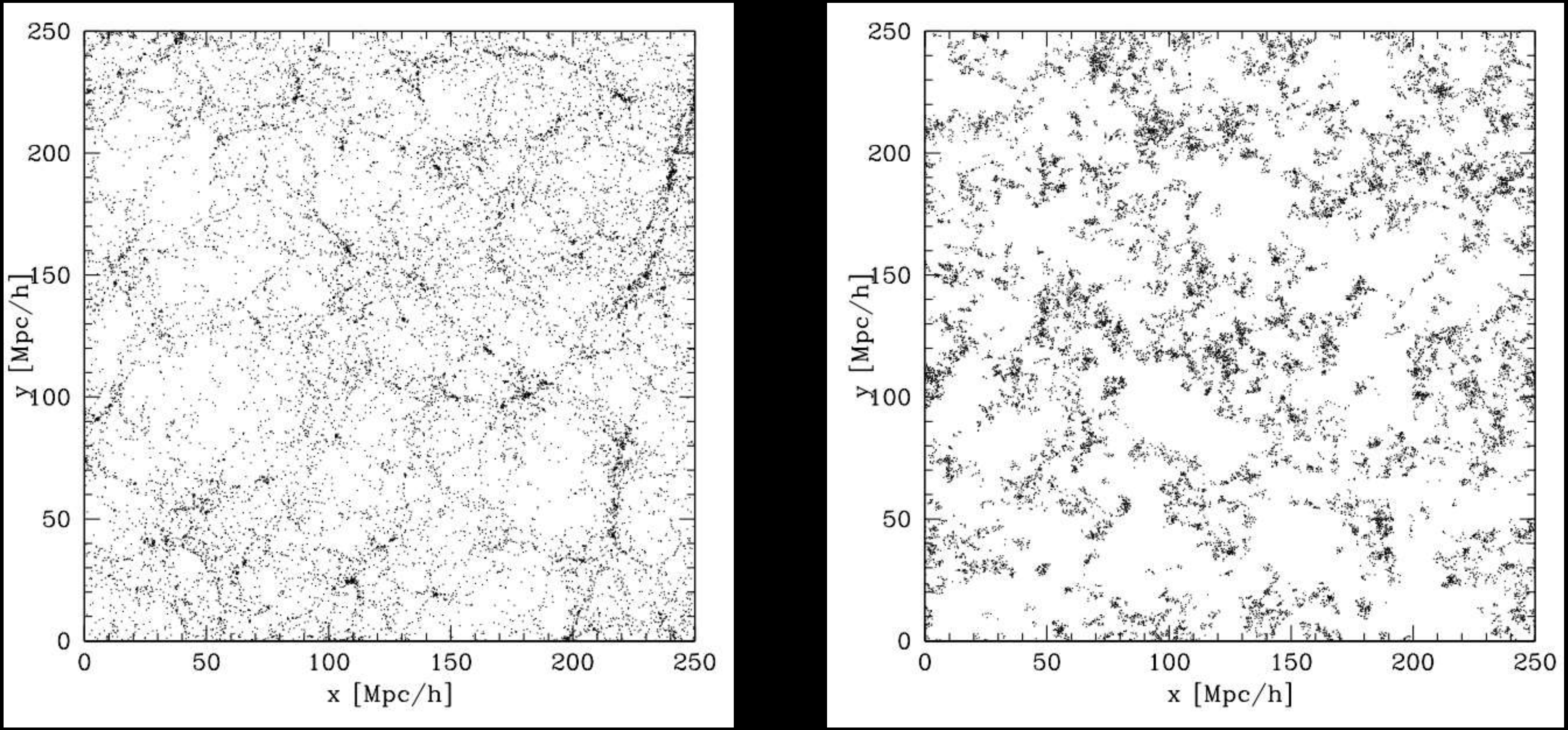
Claire Lamman | The DESI Collabortation

DESI Year One Samples



Measurements of Large-Scale Structure


AbacusSummit

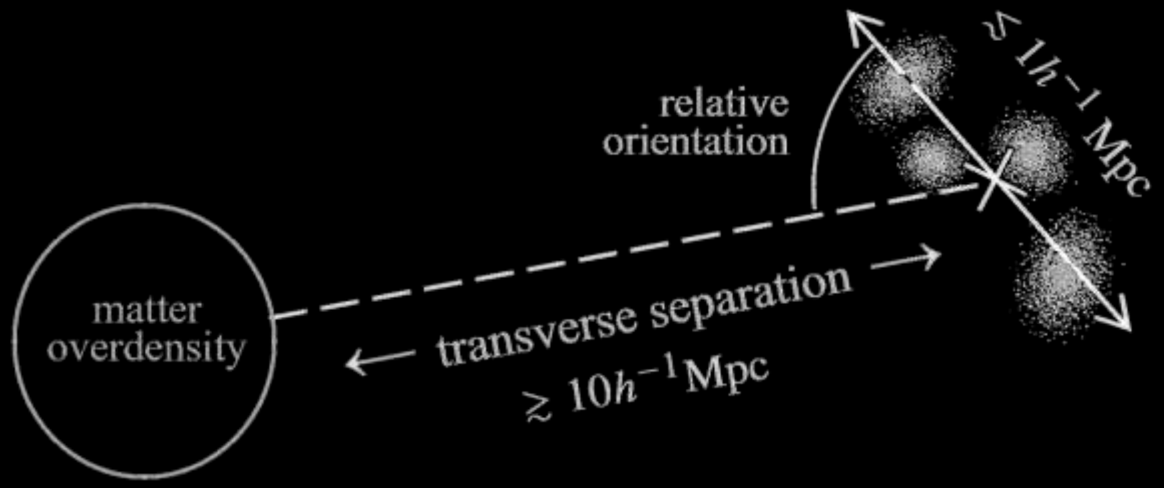


Sefusatti & Scoccimarro, 2004

IA of groups! (or "multiplets")

- Ensembles of galaxies less affected by imaging and typically display stronger alignment
  Clusters: Smargon et al. 2012, Halos: Fortuna et al. 2021

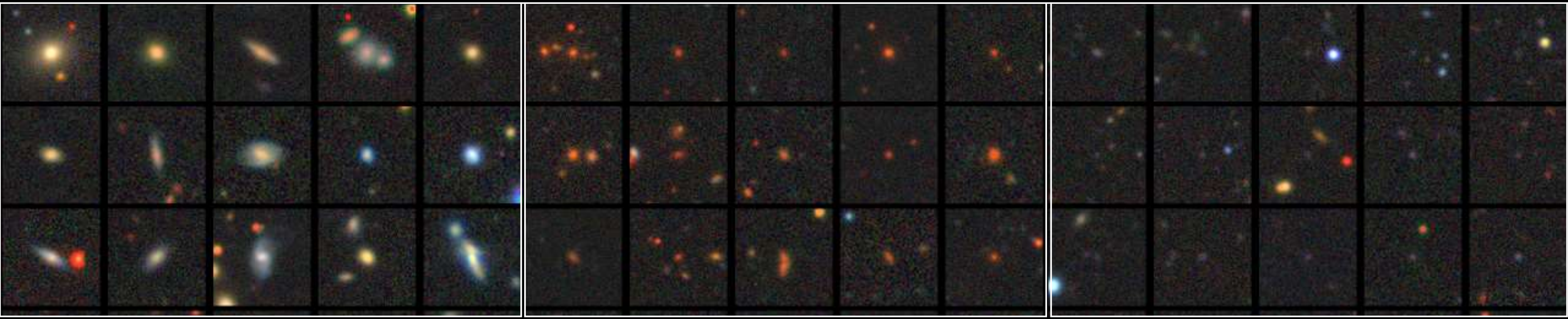
- Smallest ensemble where still possible to get orientation: Multiplets.



Identifying Multiplets

Within comoving space…

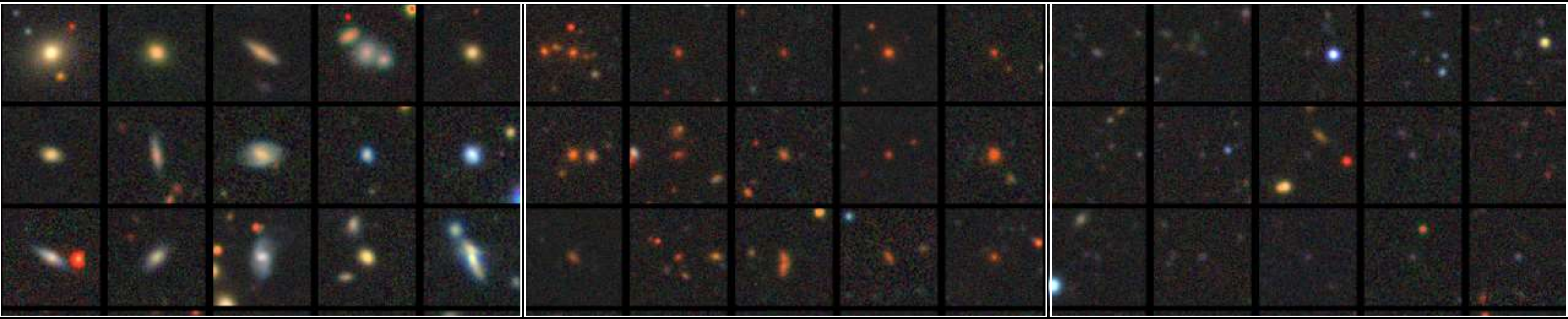
1. For each galaxy, find the nearest neighbor.
2. Limit these pairs to a $r\perp < 0.5$ Mpc/h and $r \parallel < 12$ Mpc/h
3. Identify groups within the graph created by these pairs



Legacy Imaging of multiplets in DESI’s BGS, LRG, and ELG samples. Each image is 25.6″ across

What are Multiplets?

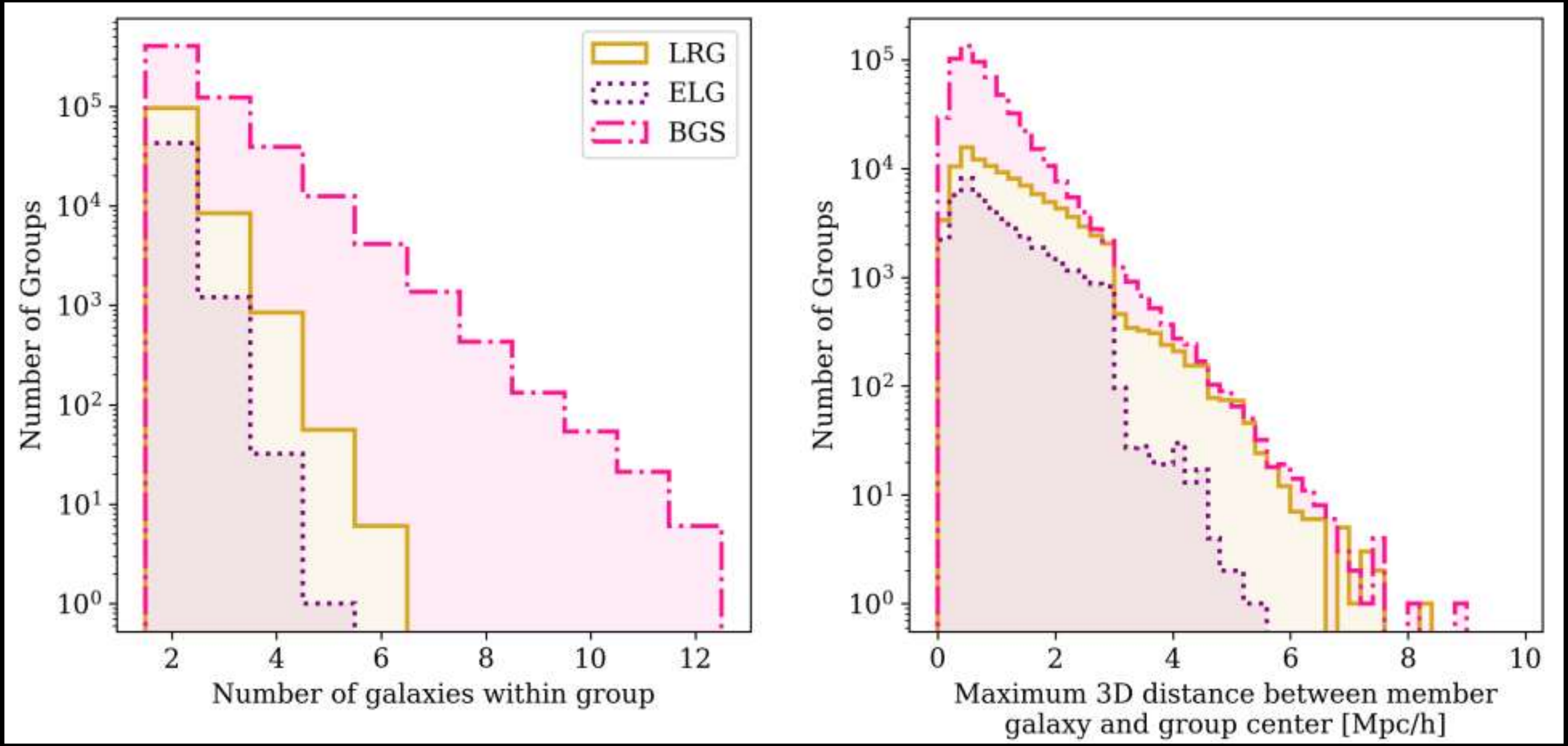
- A small number of galaxies (~2-5), mostly within a Mpc of each other.
- Different than groups and clusters: *not necessarily virialized*
- (A way to reframe the "short side" of a triangle in a very squeezed 3-point CF)

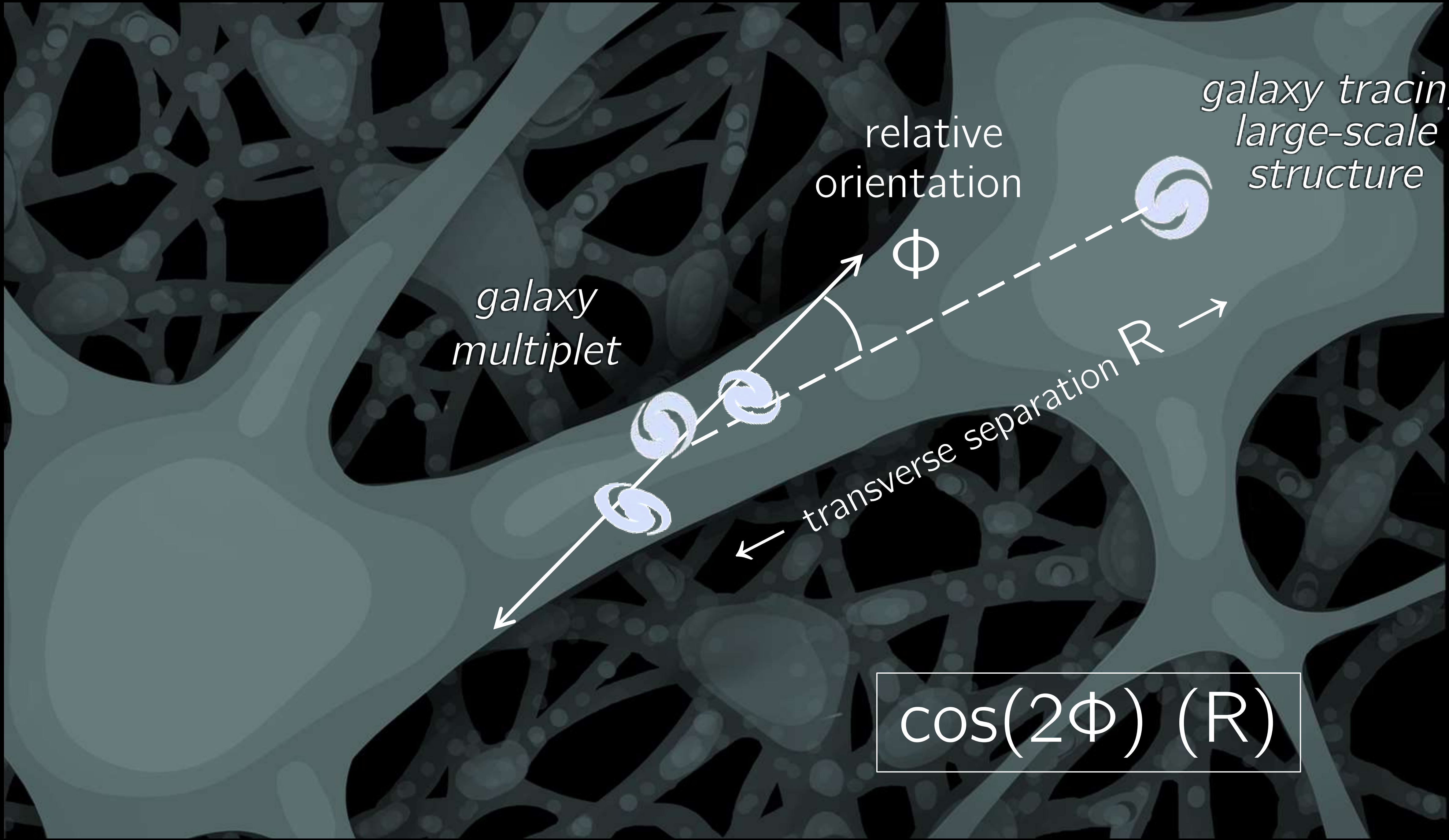


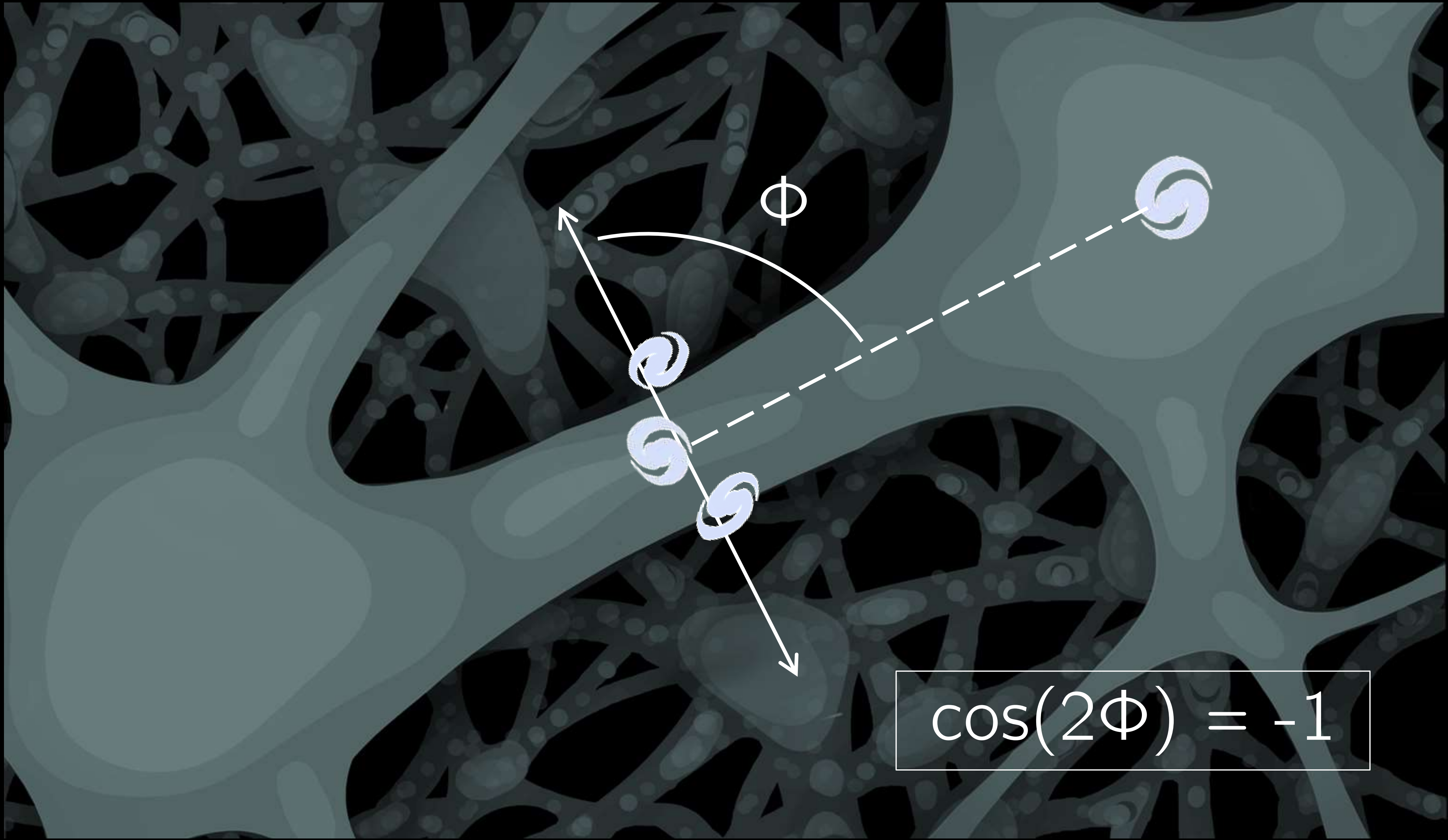
Legacy Imaging of multiplets in DESI's BGS, LRG, and ELG samples. Each image is 25.6" across

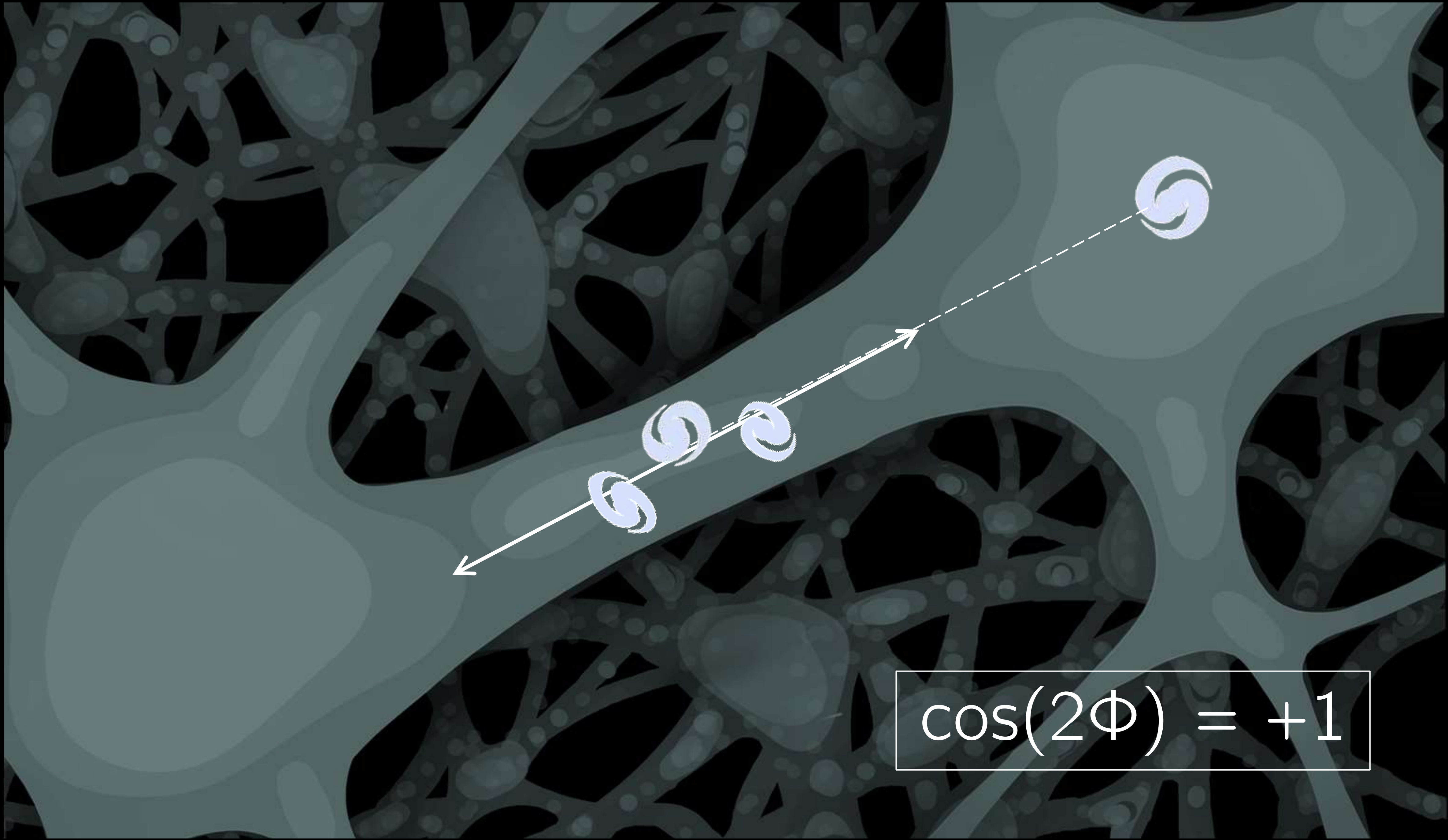
Identifying Multiplets

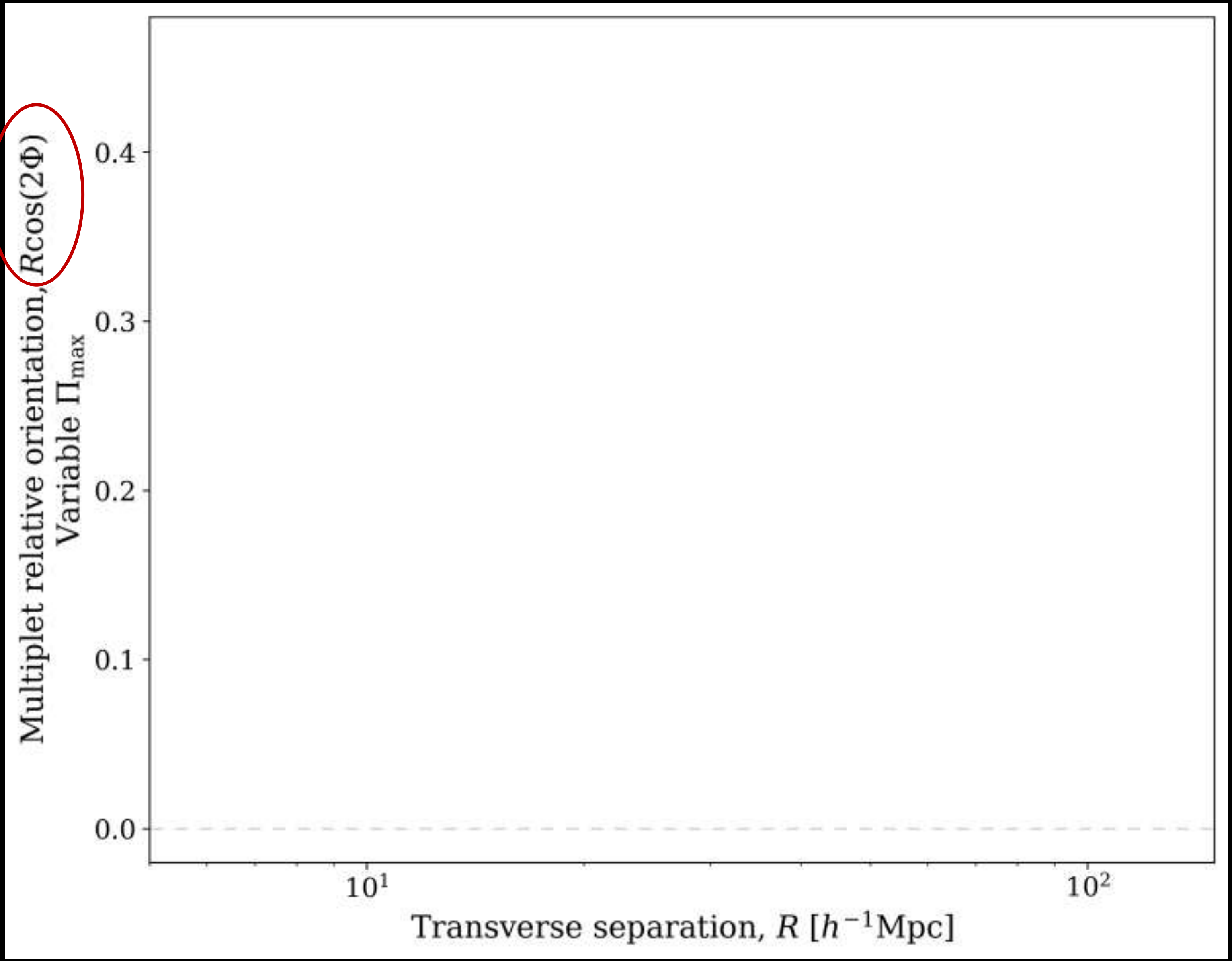
The majority of multiplets are pairs, separated by 1-2 Mpc/h




galaxy tracing large-scale structure
relative orientation
Φ
galaxy multiplet
← transverse separation R →
cos(2Φ) (R)


Φ
cos(2Φ) = -1

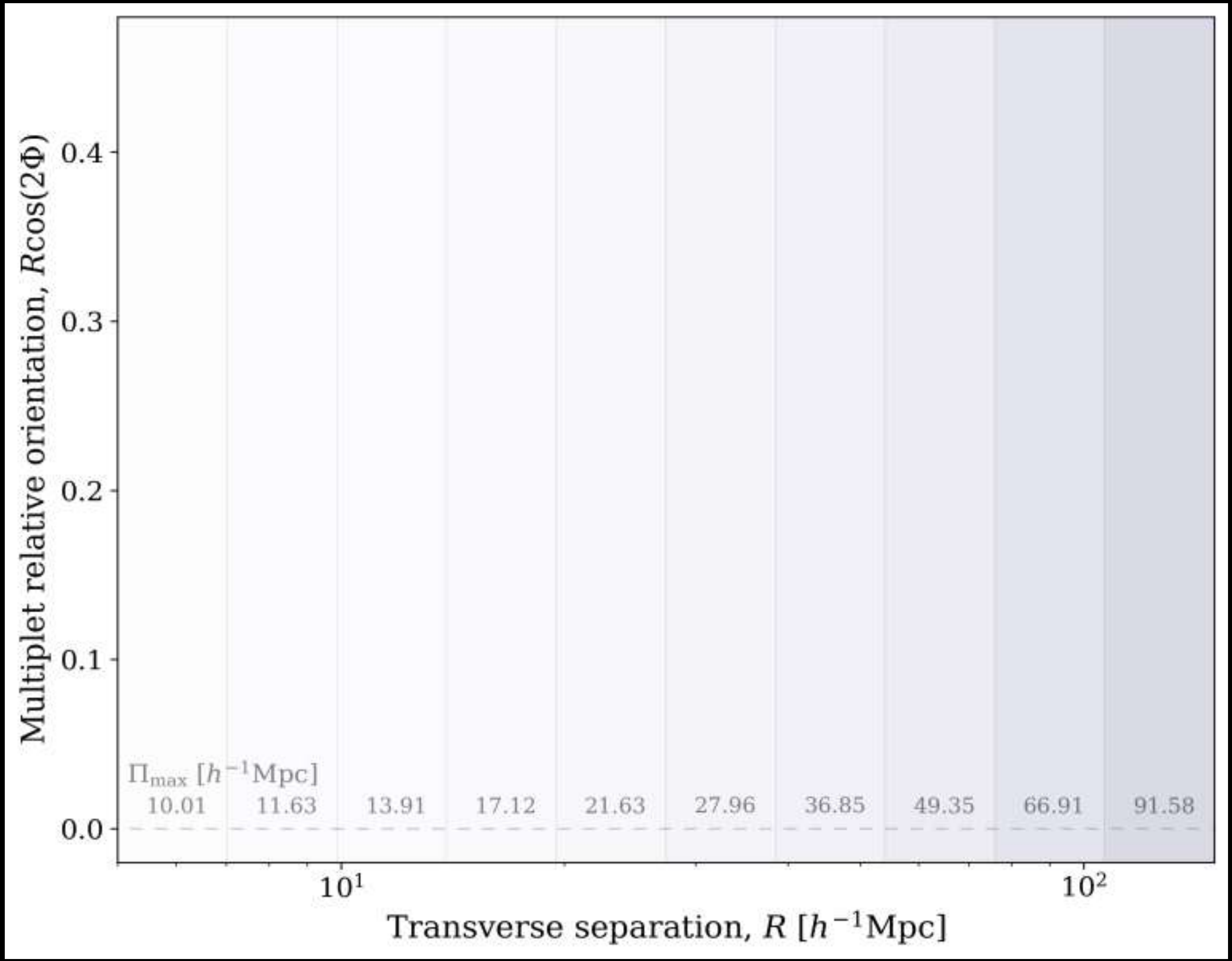

$\cos(2\Phi) = +1$



↑ Stronger tidal alignment

↓ Weaker tidal alignment

Lamman, Eisenstein et al. 2024
arXiv: 2408.11056

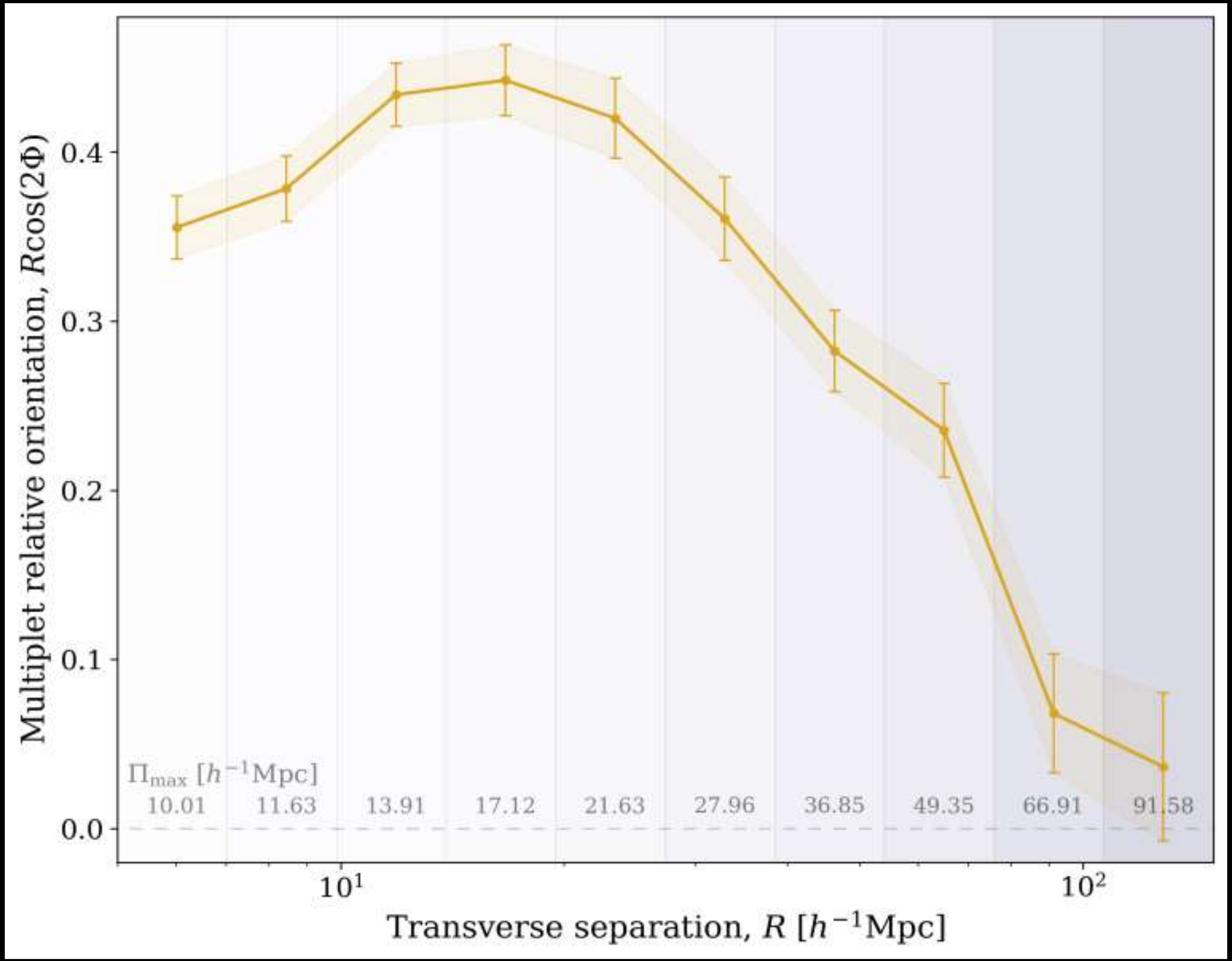


To optimize the measurement:

We vary the maximum distance along the line-of-sight for each multiplet-tracer pair

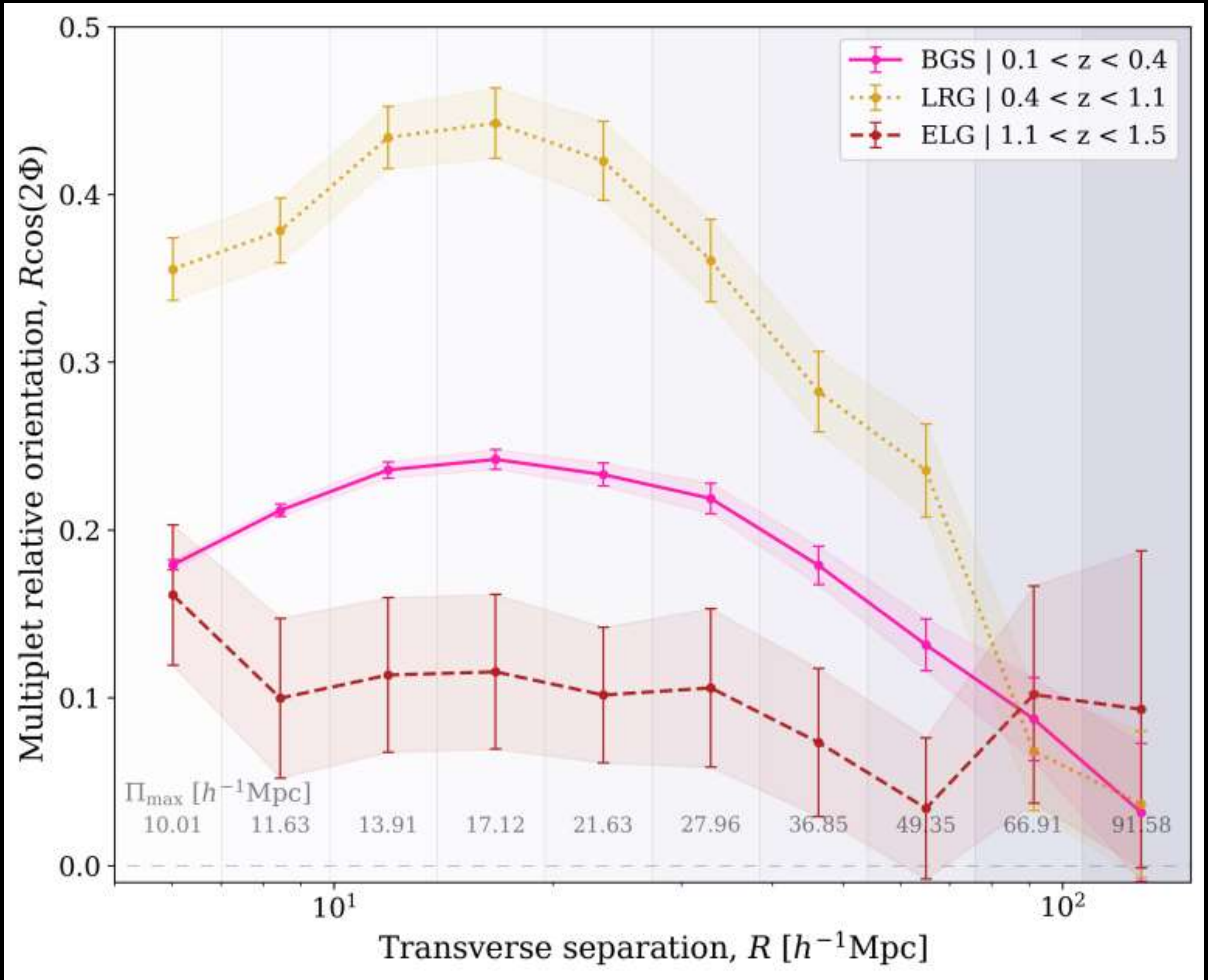
Lamman, Eisenstein et al. 2024
arXiv: 2408.11056

LRG Multiplet Alignment



Measurement of tidal field out to ~100 Mpc/h

Lamman, Eisenstein et al. 2024
arXiv: 2408.11056



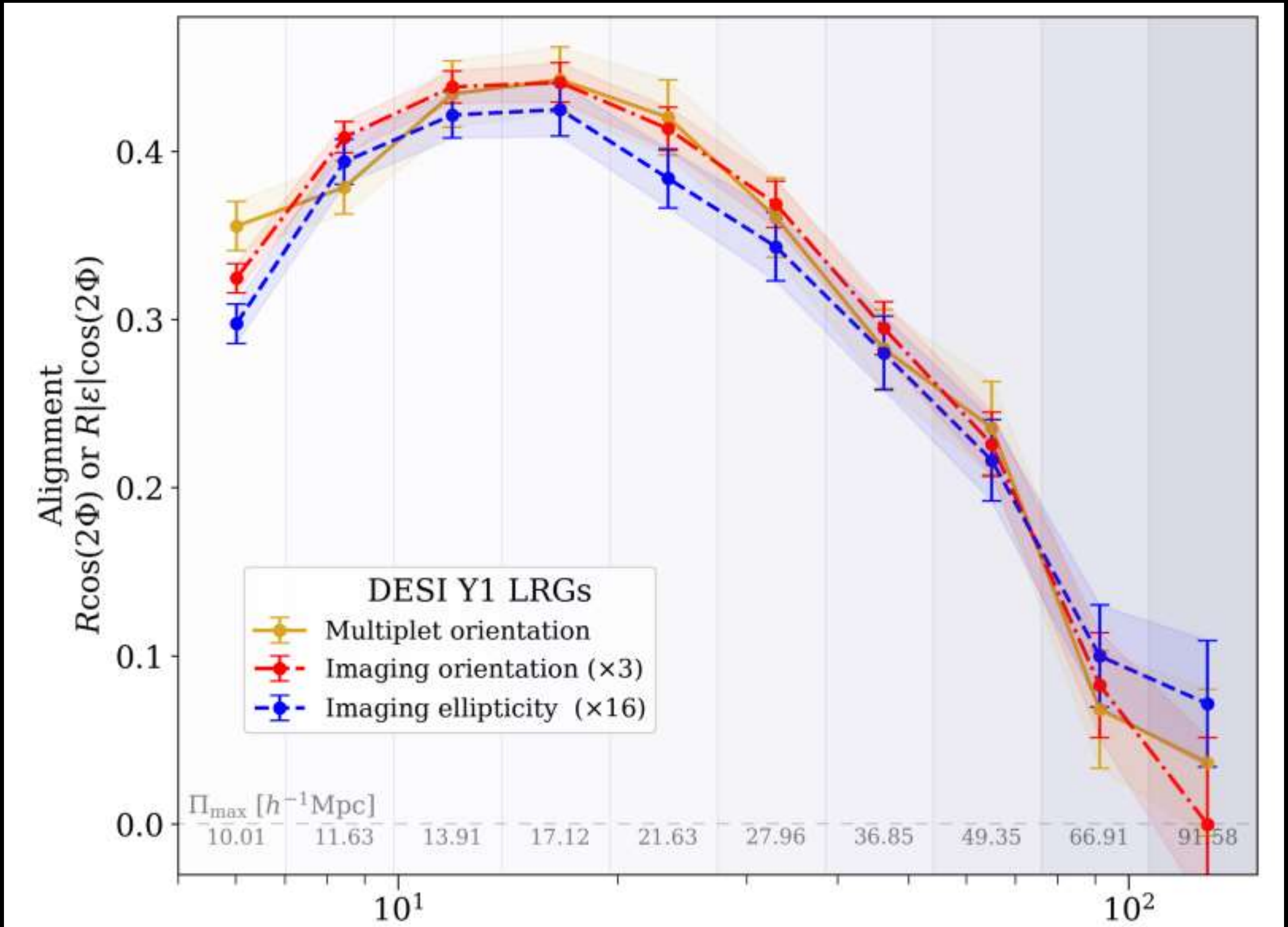
BGS is especially dense
many multiplets, high SNR.

ELG subsample:
IA detection beyond z = 1 !

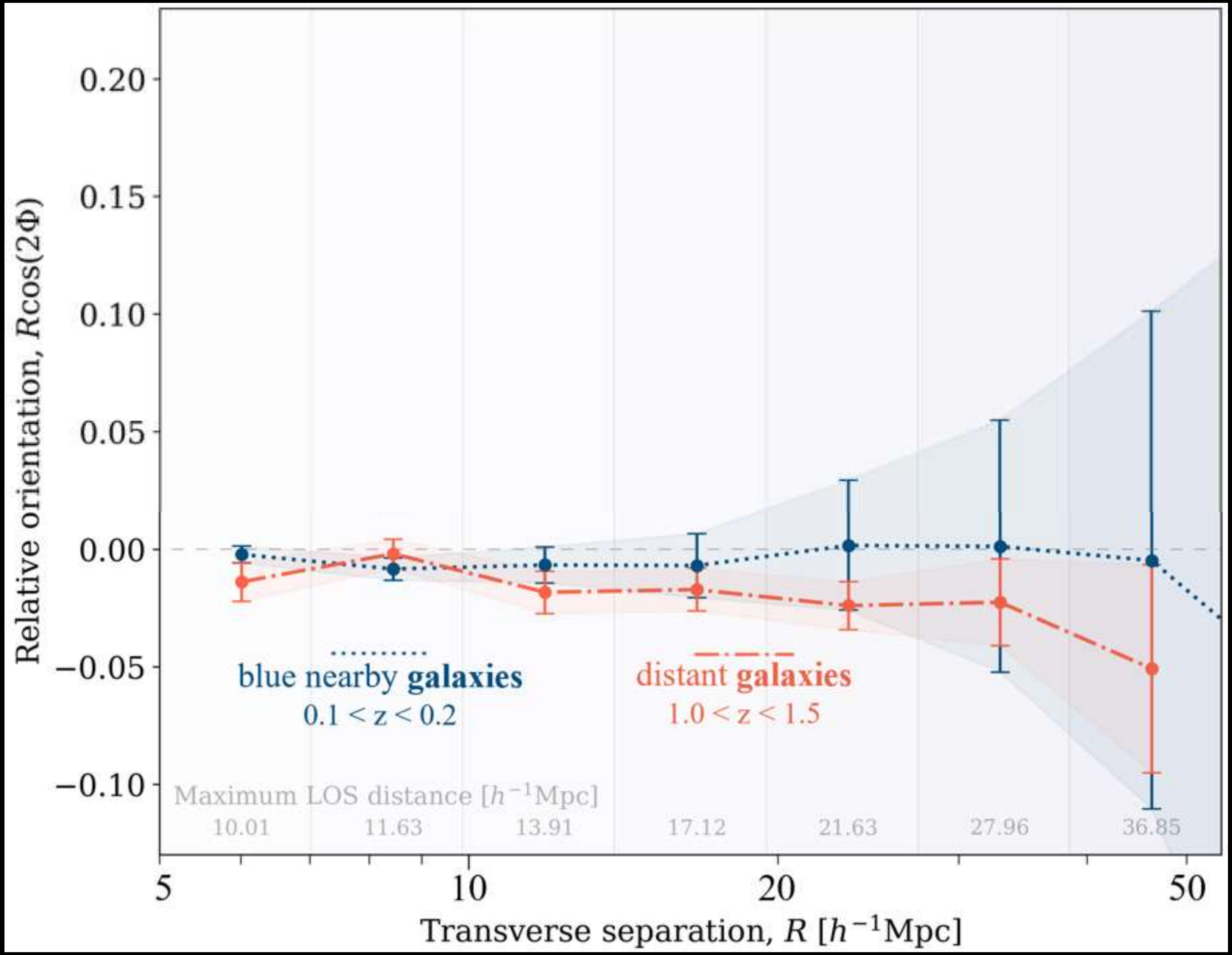
Lamman, Eisenstein et al. 2024
arXiv: 2408.11056

Multiplet alignment has same scale dependence as the alignment of individual galaxies.

(made with 2.2M LRGs and 105k LRG multiplets)



Comparison to traditional estimators



Unlike the alignment of individual galaxies, multiplets can trace LSS with galaxies that are blue, faint, or beyond z=1!

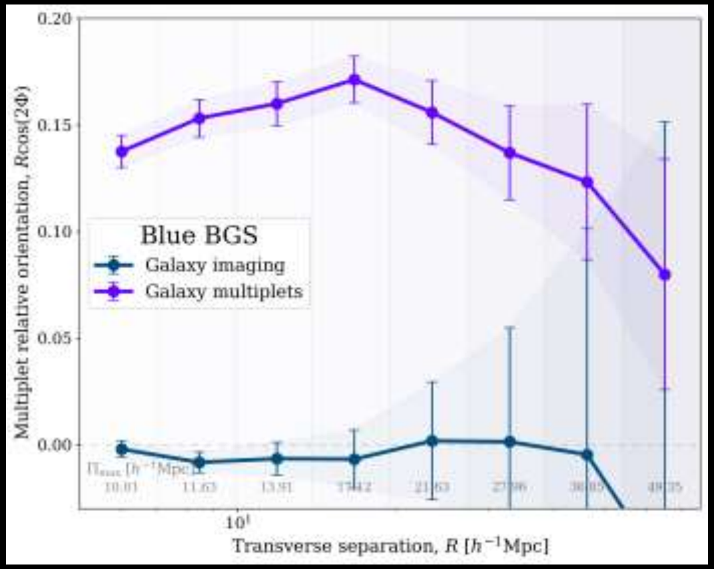
Lamman et al. 2024c
arXiv: 2408.11056

Multiplet Alignment: Measurement Takeaways

We see similar signals regardless of galaxy intrinsic properties.

Promising for measuring IA in samples that are:

Dense, faint, blue, beyond redshift 1



IA of faint, blue multiplets (≠ 0)

IA of faint, blue galaxies (= 0)

Previously, measurements and use of IA were limited to samples of bright red galaxies with high-quality imaging.

*Multiplet alignment opens the possibility of using **all galaxies** in spectroscopic surveys to trace the gravitational shear of LSS.*

Interpreting Multiplet Alignment

Modeling

Linear relationship between the 3D shapes of objects and the underlying tidal field.

Alignment of multiplets = **(Some scalar)** x **(Tidal shear)**

$$\underbrace{\cos(2\Phi)(R)}_{\text{Alignment of multiplets}} = \tau \underbrace{\frac{-1}{(2\Pi_{max}+\bar{w}_p)}}_{\text{2pt clustering, LOS distance}} \underbrace{\int K dK \mathcal{J}_2(K,R)\mathcal{P}_\Pi(K)}_{\text{Relevant Matter}}$$

Alignment of multiplets

??

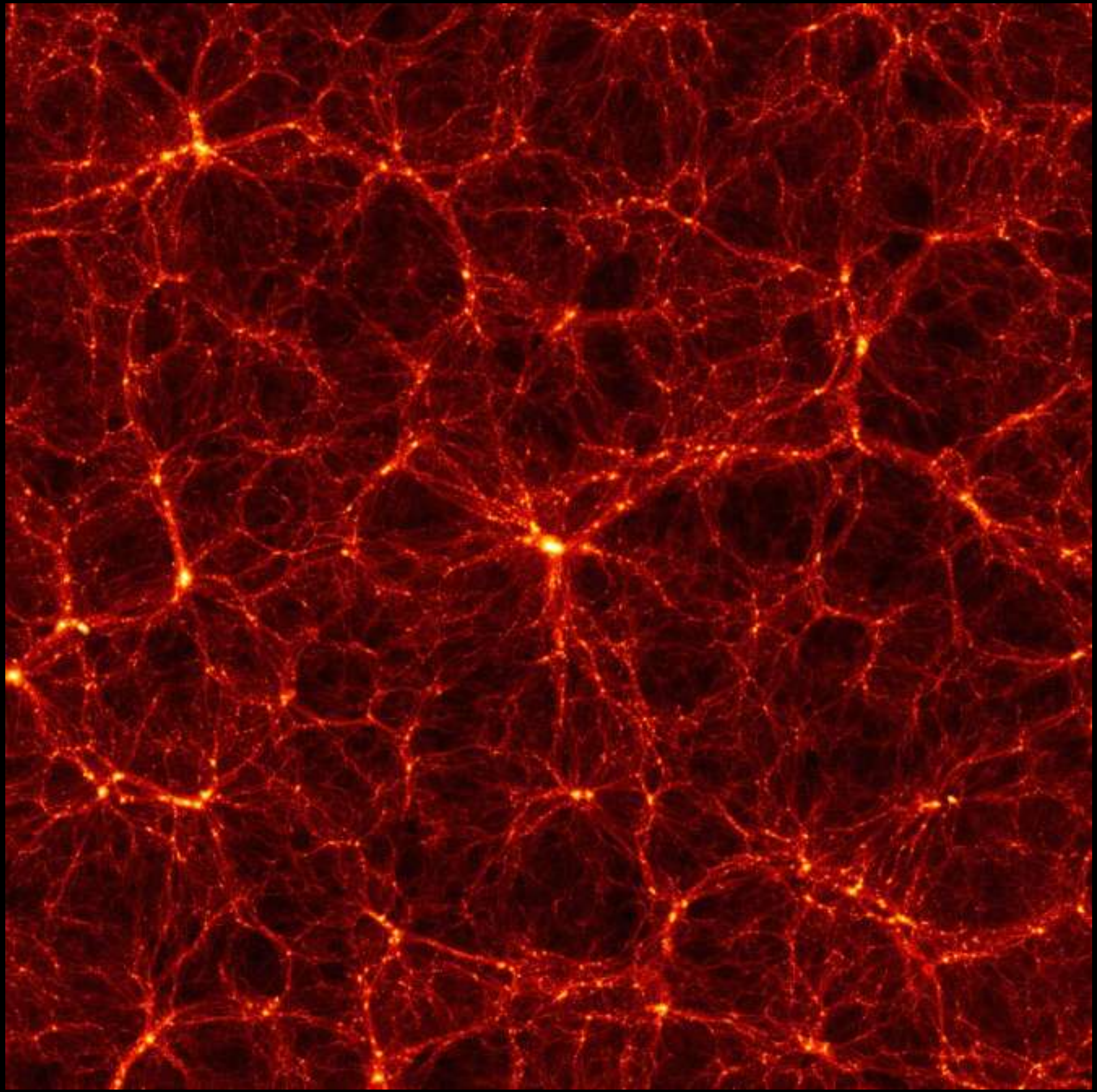
2pt clustering,
LOS distance

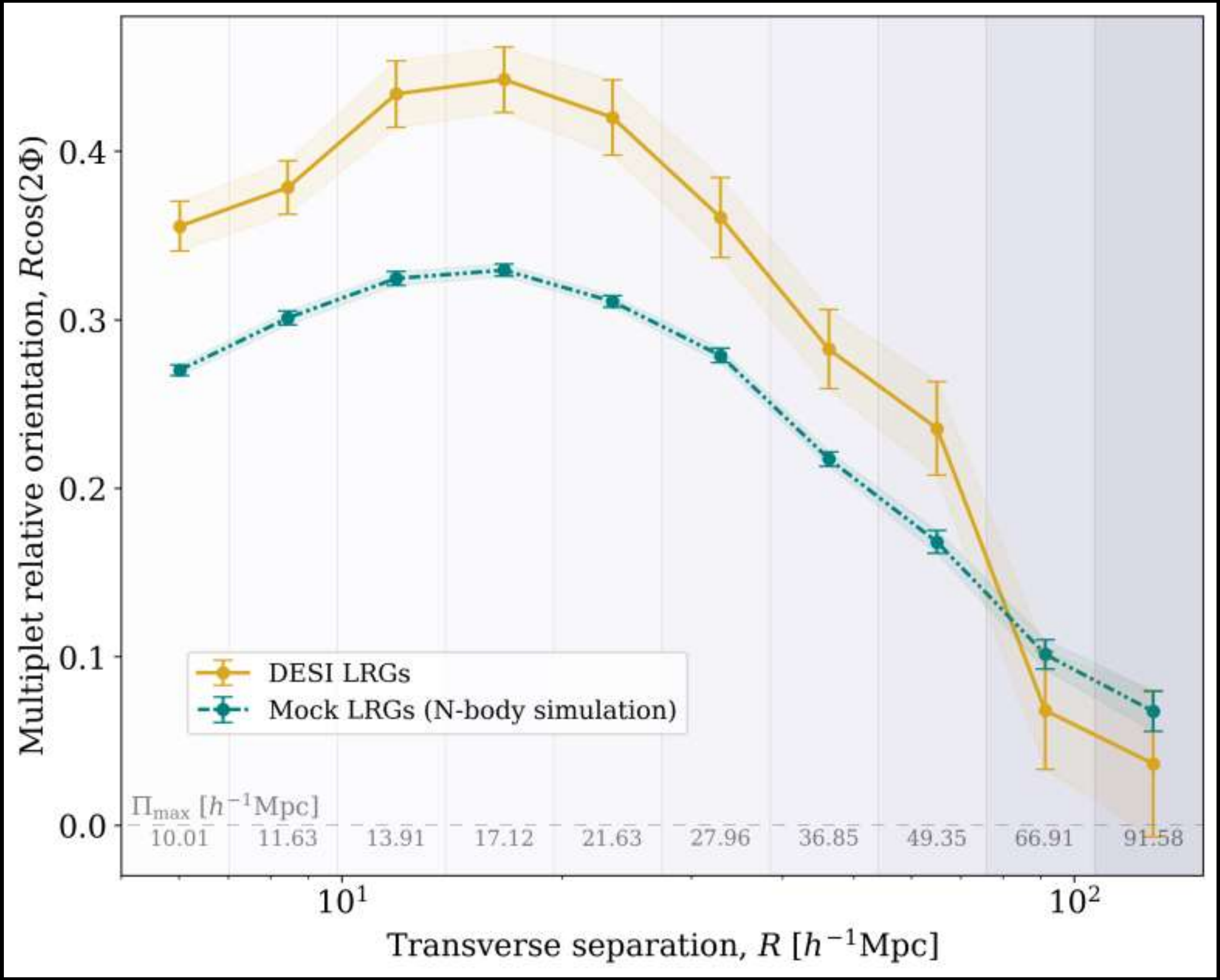
Relevant Matter
(matter power spectrum,
selection in LOS and projection)

AbacusSummit

Suite of large, high-accuracy n-body simulations designed to meet DESI's science requirements

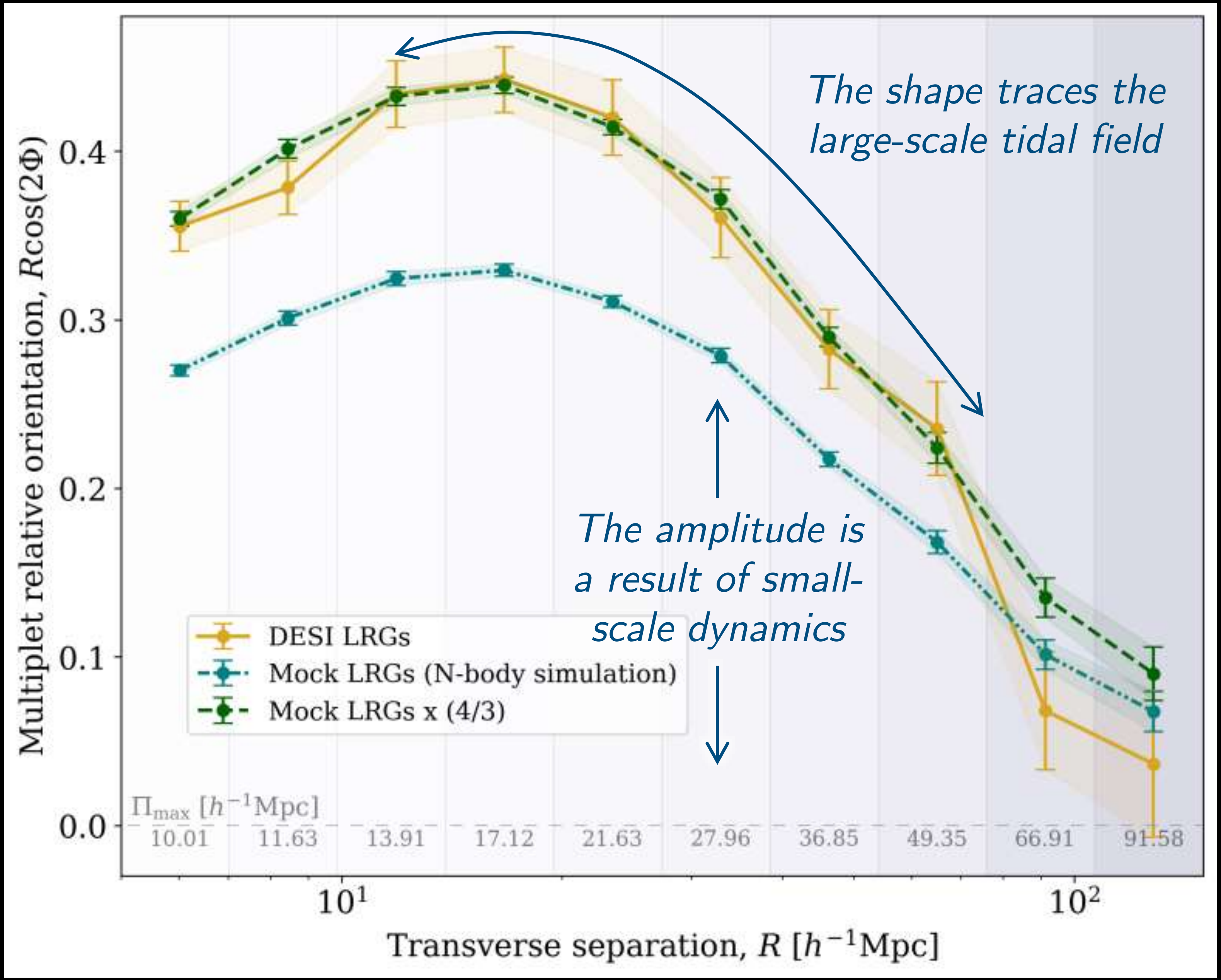
AbacusHOD





N-body simulation reproduces shape but not amplitude

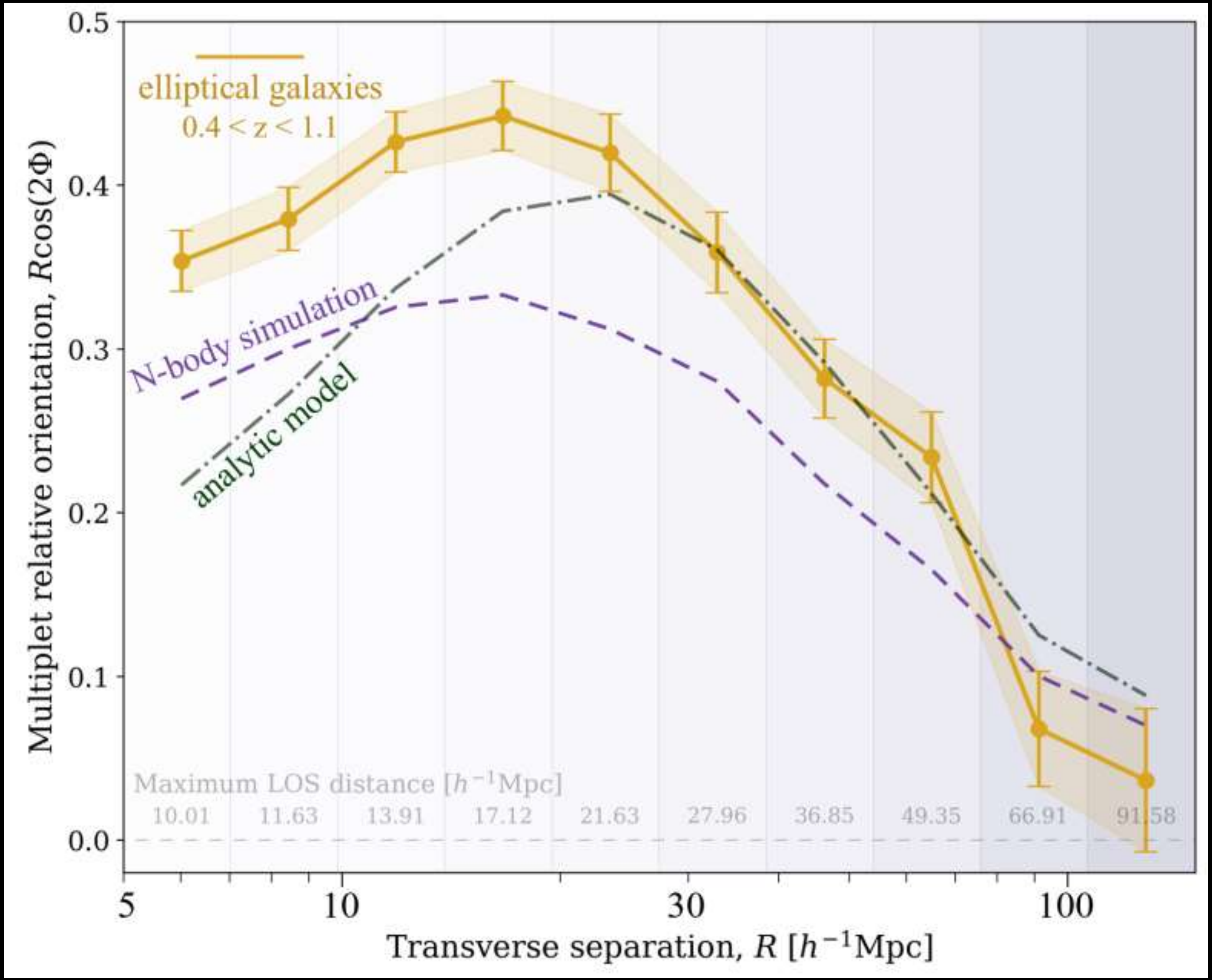
Lamman et al. 2024c
arXiv: 2408.11056



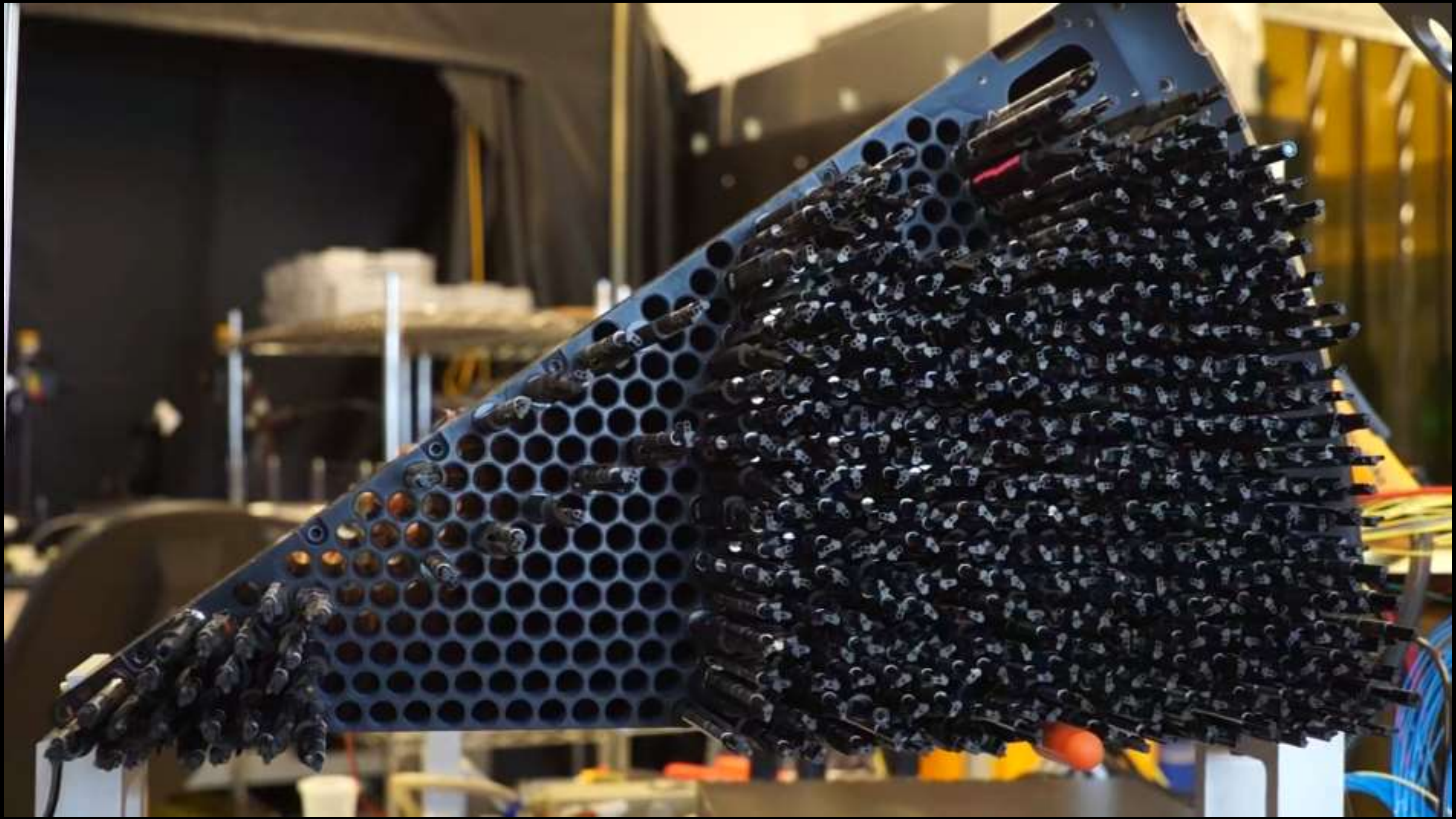
N-body simulation reproduces shape but not amplitude.

~ 1/3 lower on all scales

Lamman et al. 2024c
arXiv: 2408.11056

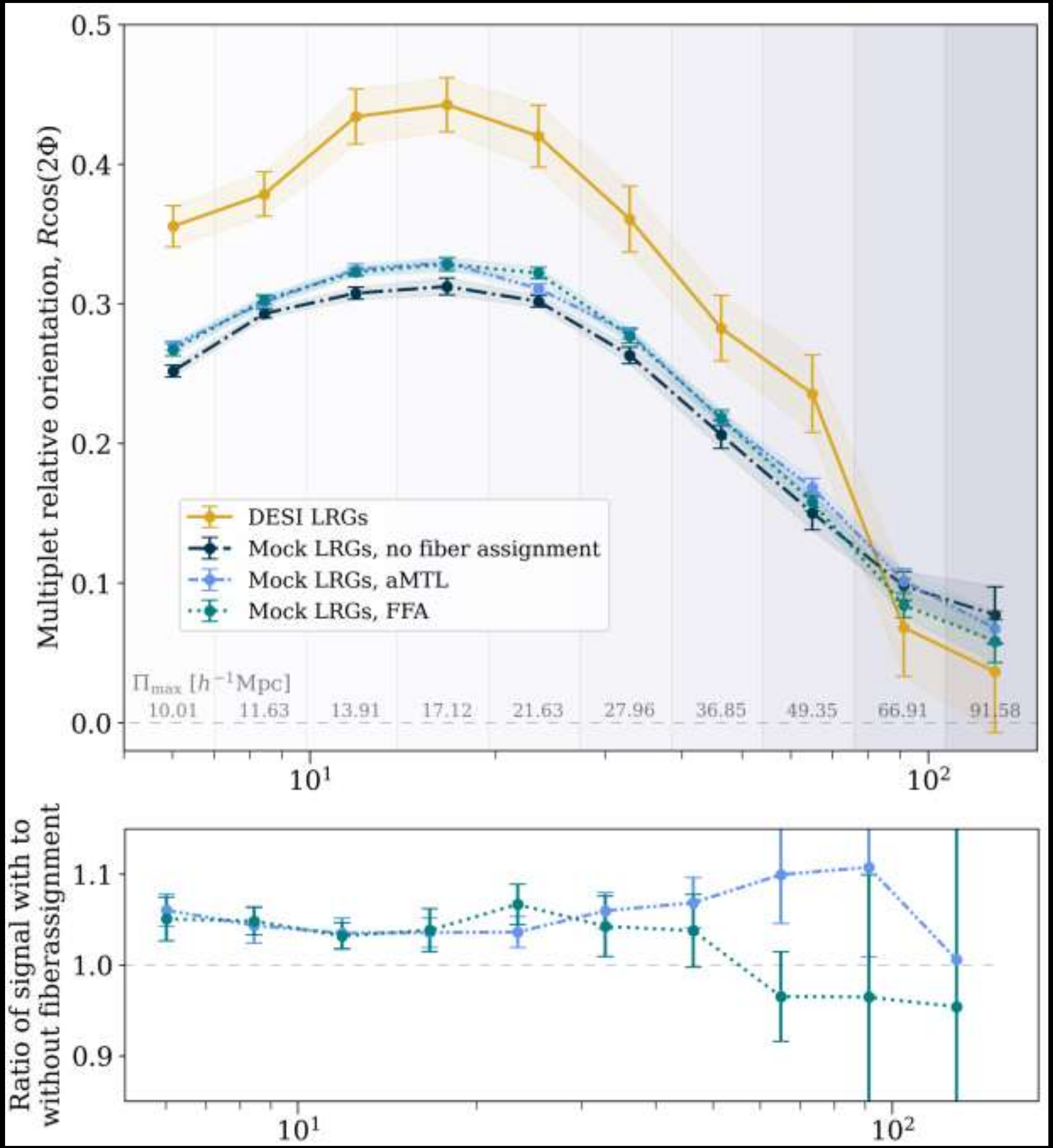


elliptical galaxies
0.4 < z < 1.1
N-body simulation
analytic model
Maximum LOS distance [h^{-1}Mpc]
10.01
11.63
13.91
17.12
21.63
27.96
36.85
49.35
66.91
91.58
Multiplet relative orientation, $R\cos(2\Phi)$
Transverse separation, R [h^{-1}Mpc]
0.0
0.1
0.2
0.3
0.4
0.5
5
10
30
100



Fiber assignment enhances the signal!

(tidal torquing?)

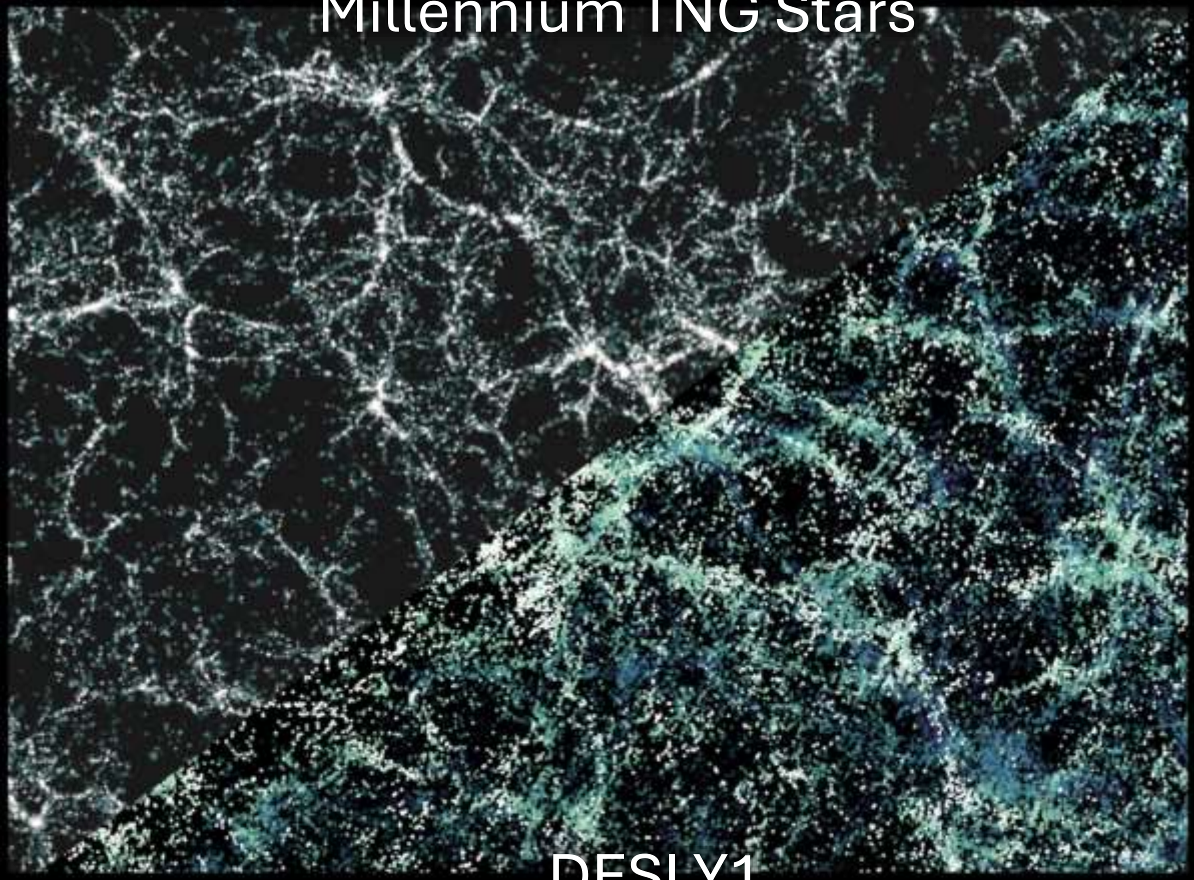


Current Work

- Multiplet Alignment can be supplemented with imaging
  Student: Annika Kumwembe

- Sub-trends in DESI's densest sample (BGS)
  Student: Miguel Perdomo
  – with Jaime Forero-Romero

- Multiplet alignment in MilleniumTNG
  (500 Mpc/h box with hydro effects)



Applications of Multiplet Alignment

Future Data

- DESI, DESI-ext, DESI-II:
  will especially increase observations of spiral galaxies beyond z=1 (ELGs), the ideal application of multiplet alignment.

- Other spectroscopic surveys
  - PFS (2025): *deep, dense – morphology and z dependence*
  - SPHEREx (2025): *all-sky – large-scale modes*

- Imaging:
  - Rubin Observatory / LSST-DES
  - Euclid
  - Roman






1. Connecting Galaxies to Cosmology

- **Creating full-scale simulations**
  Multiplet Alignment directly correlates large and small-scale clustering and could be used as a unique test of semi-analytic models

- **The nature of Intrinsic Alignments**
  Multiplet alignment can constrain nonlinear behavior and redshift evolution of IA: providing novel insights into intrinsic alignments for cosmic shear

2. Mapping the large-scale distribution of matter

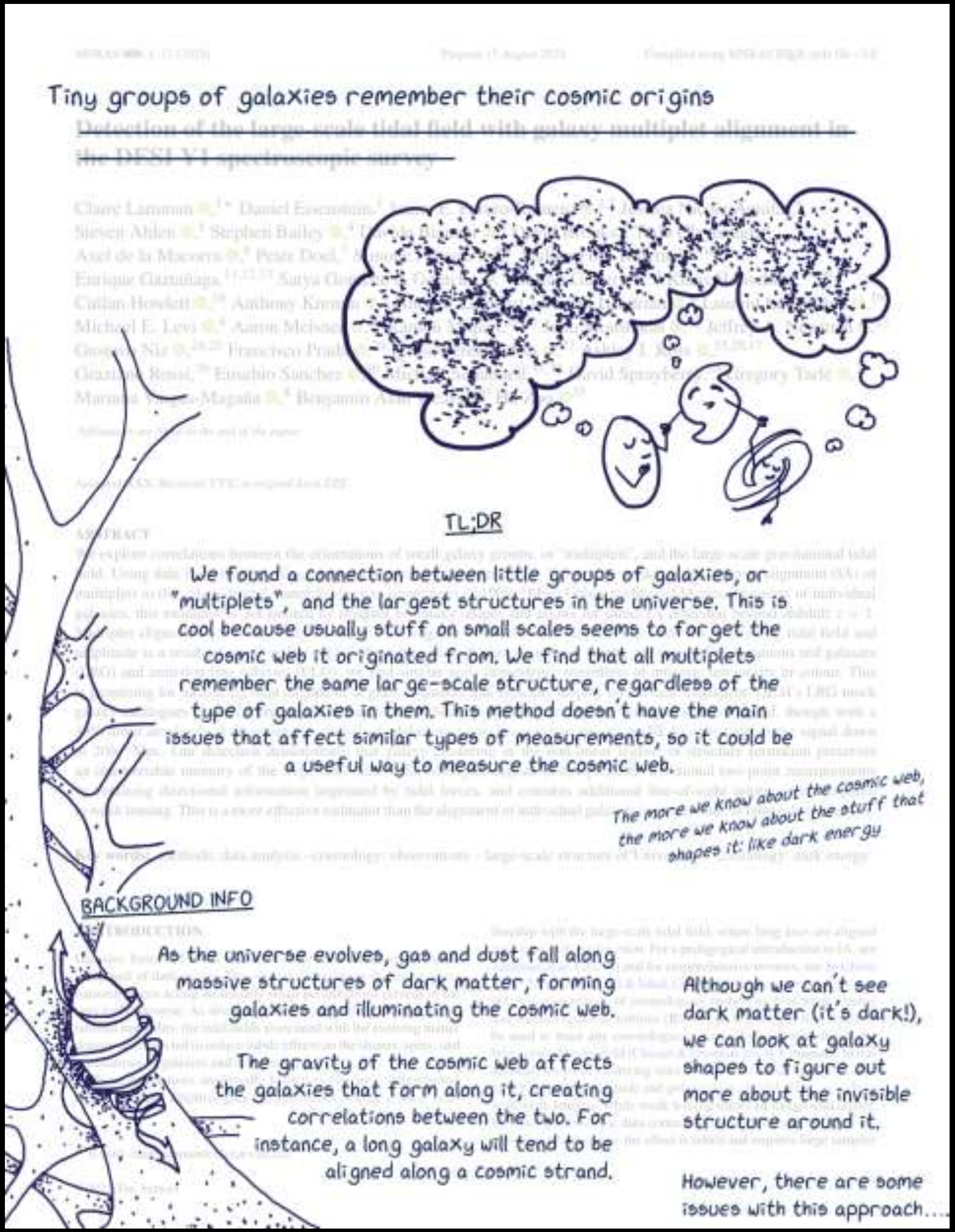
- **Detecting large-scale density modes**
  Direct measurements of the very large distribution of matter is limited by survey boundaries. Could measure indirectly through large-scale impact on small-scale clustering (Chiang et al. 2014).

- **Creating a tidal shear map**
  Similar to weak lensing, except a measurement of local shear and independent of common systematic errors.

Lamman et al. 2024

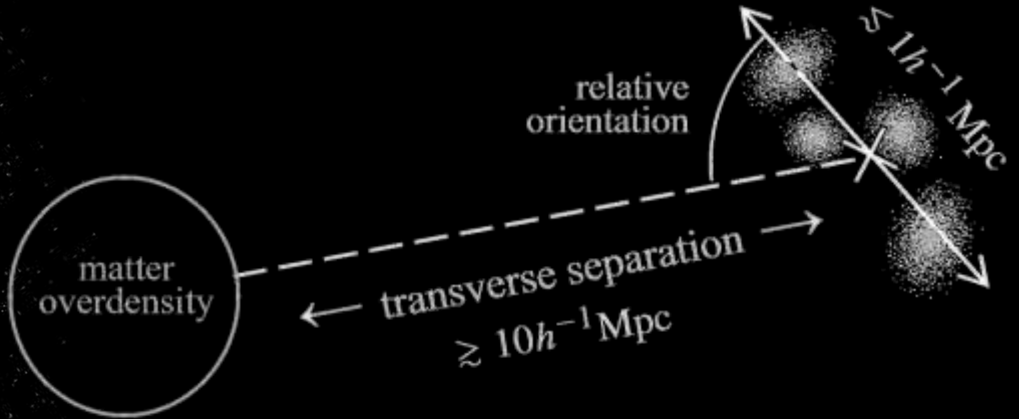
arXiv: 2408.11056

Accessible version in arXiv comments ->



Summary

- Galaxy multiplets can **uniquely trace the large-scale tidal field**
- We detect tidal alignment out to separations of h^{-1}Mpc. Including samples beyond z=1 and blue galaxies. Neither has been achieved with traditional estimators.
- This **unlocks the potential of IA** as a practical cosmological probe and has promising applications for upcoming surveys



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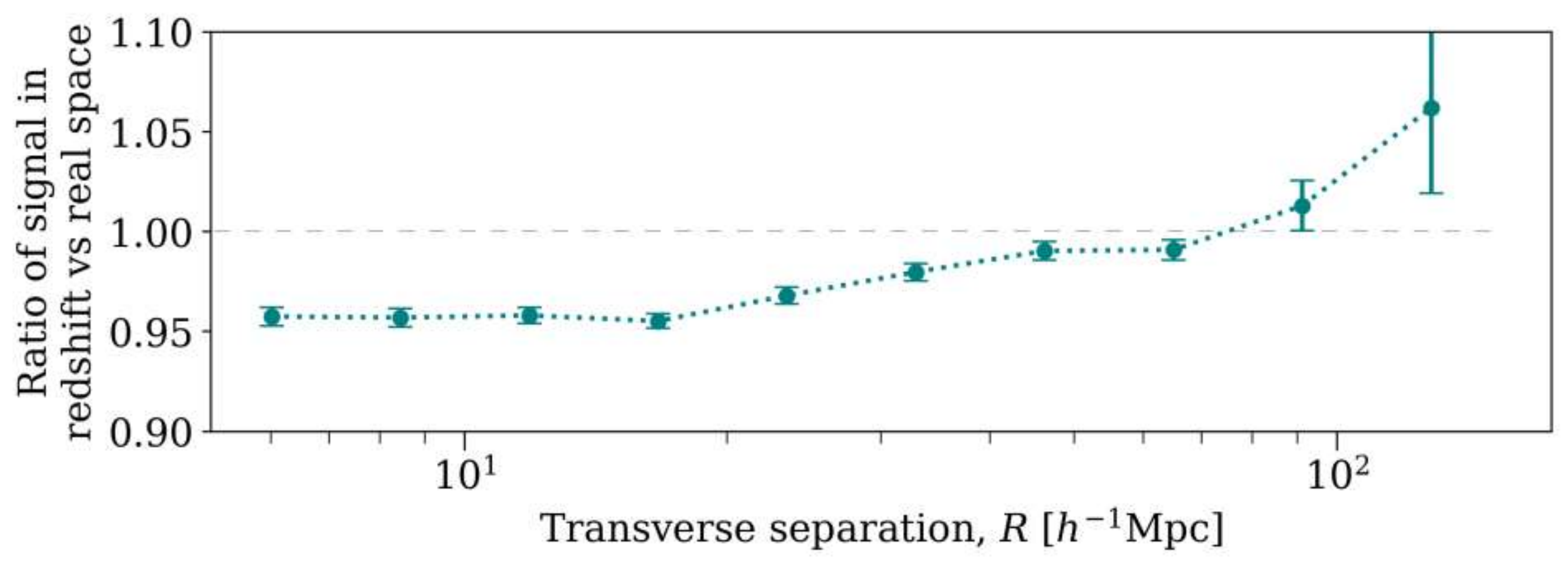
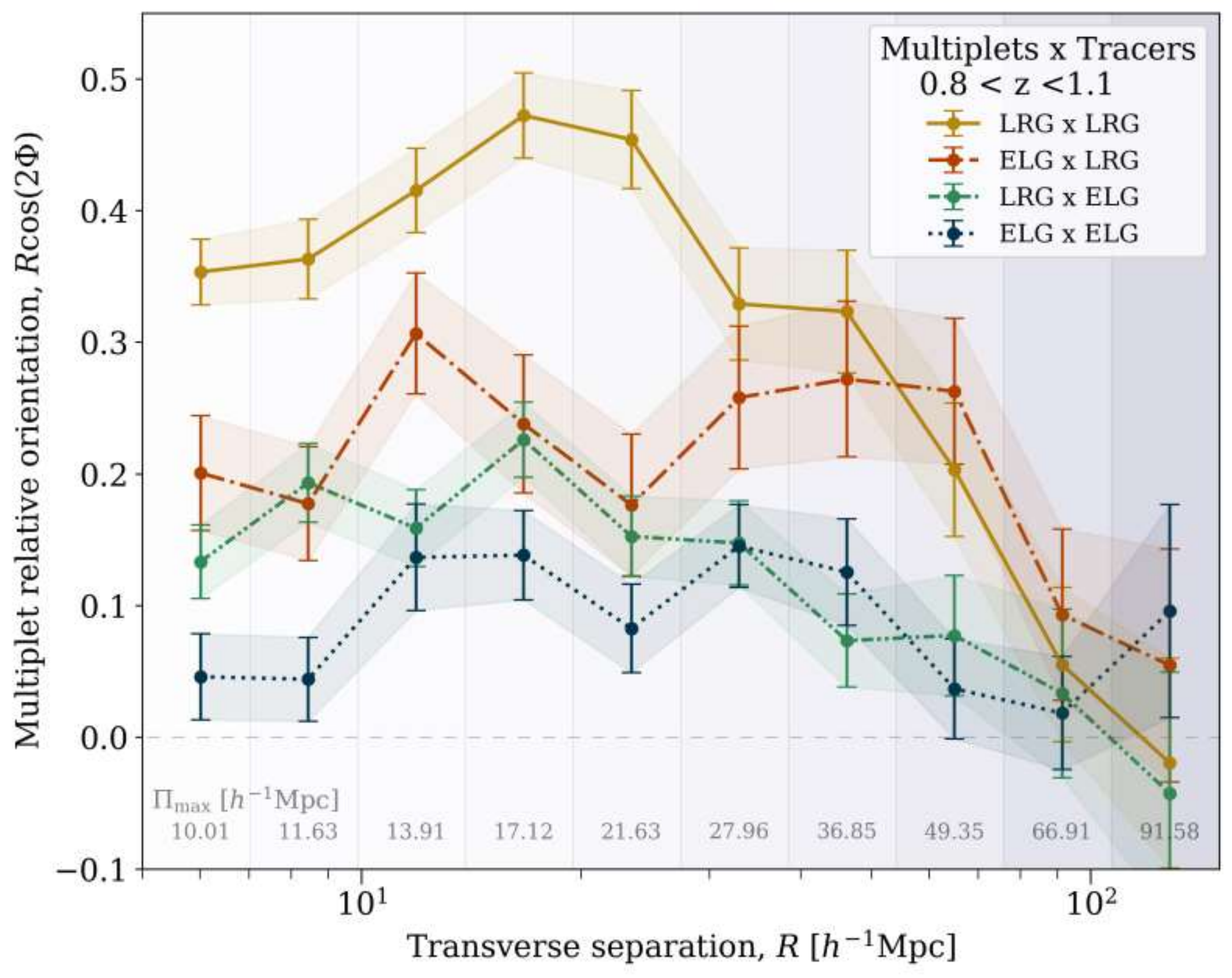
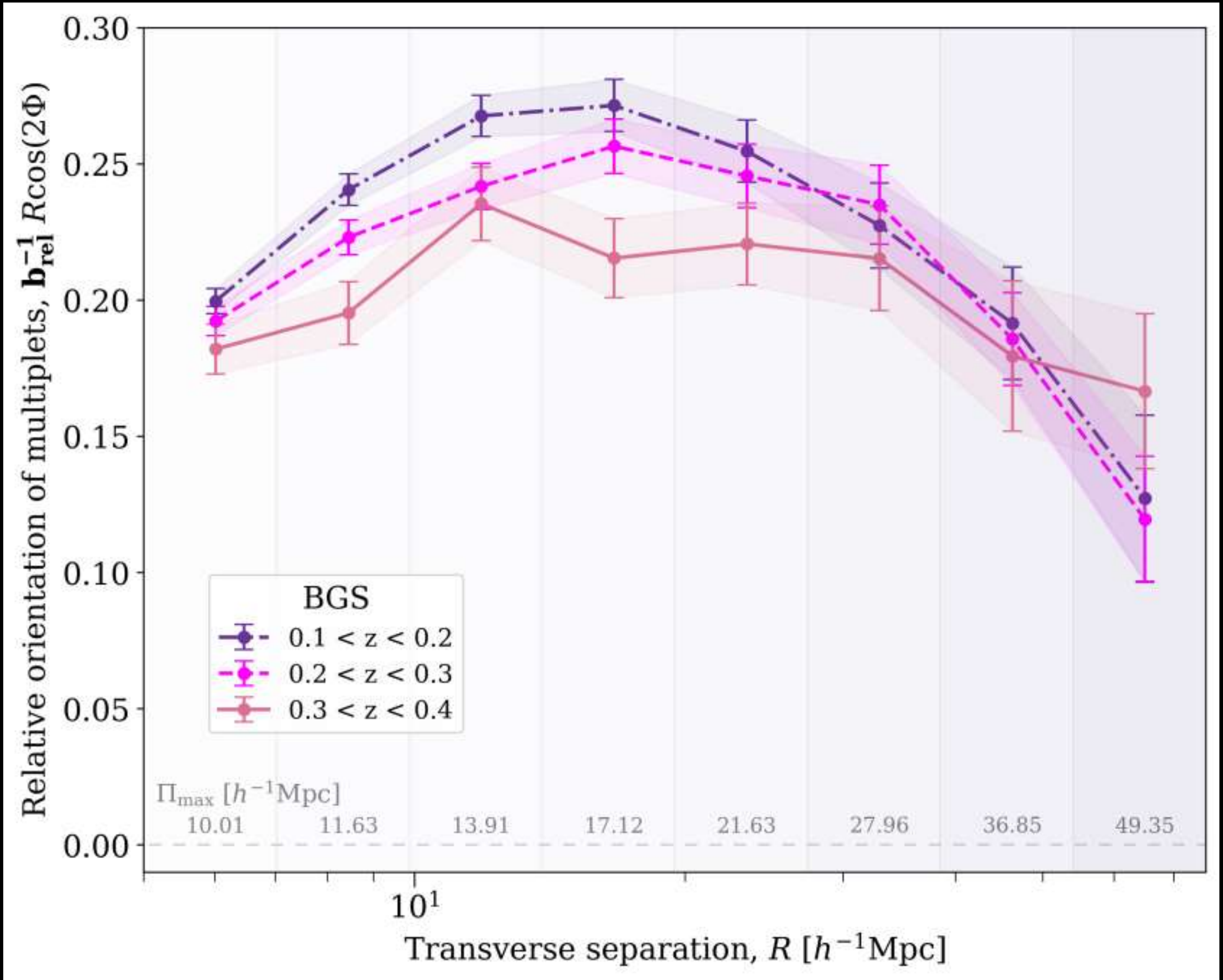
Extra Plots

RSD impacts at ~5%

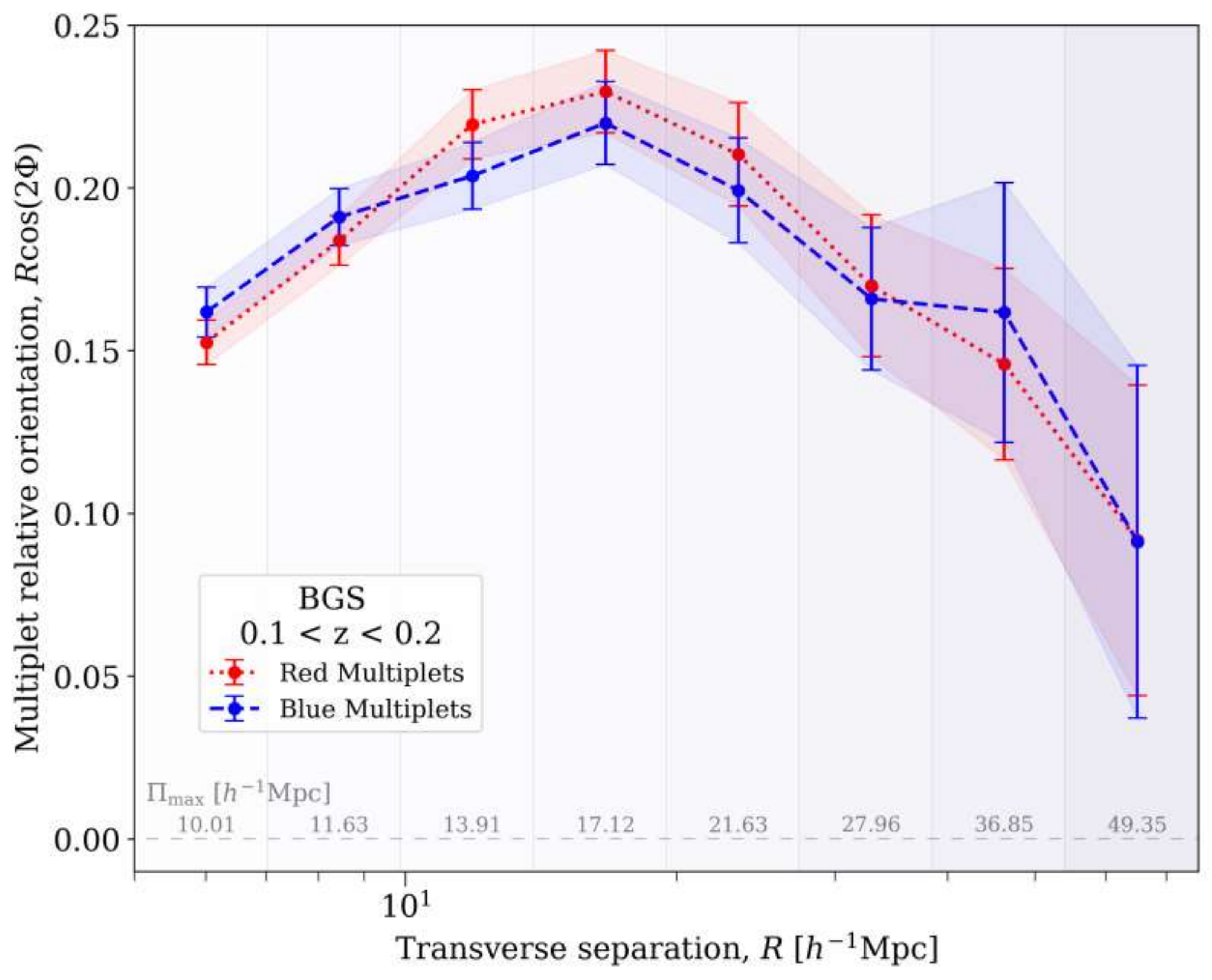




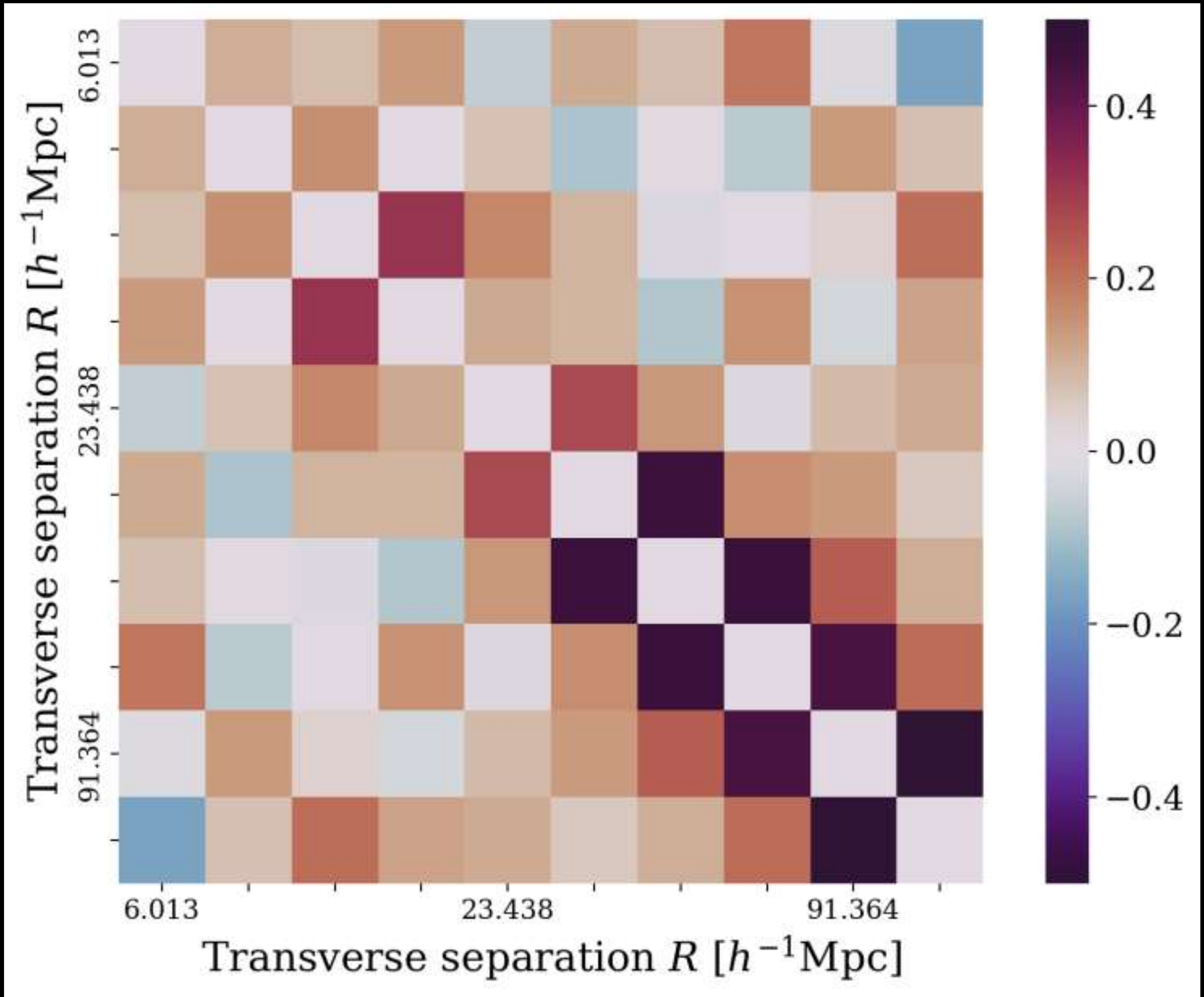
Multiplets x Tracers
0.8 < z <1.1
LRG x LRG
ELG x LRG
LRG x ELG
ELG x ELG
Multiplet relative orientation, $R\cos(2\Phi)$
Transverse separation, R [h^{-1}Mpc]
$\Pi_{\rm max}$ [h^{-1}Mpc]
10.01
11.63
13.91
17.12
21.63
27.96
36.85
49.35
66.91
91.58
0.5
0.4
0.3
0.2
0.1
0.0
−0.1
10^1
10^2



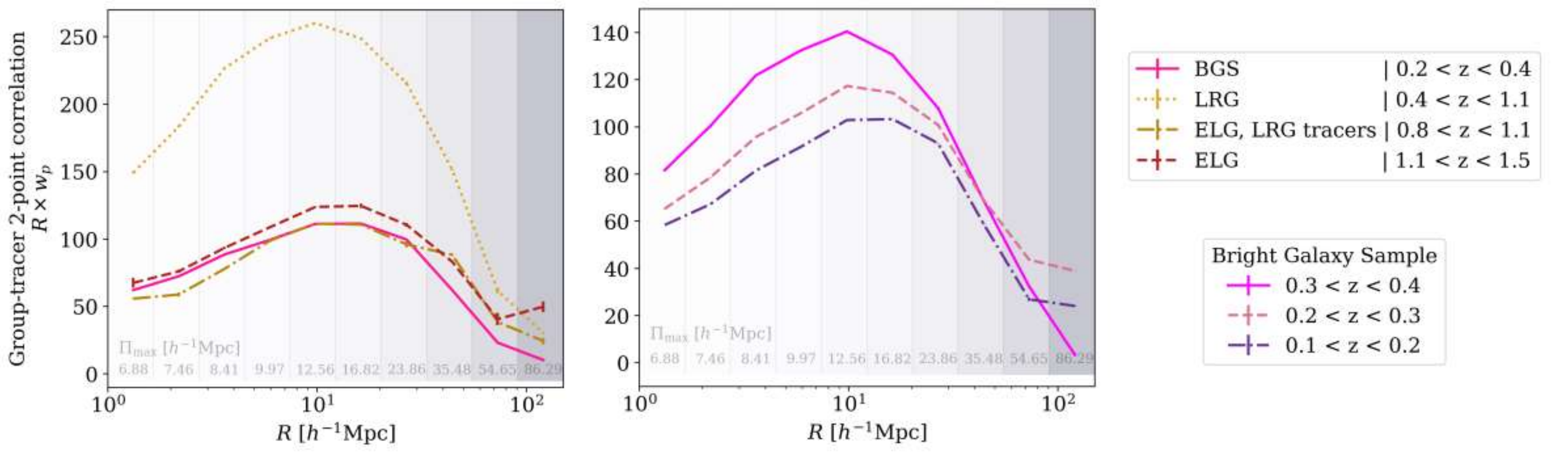
Relative orientation of multiplets, $\mathbf{b}_{\mathbf{rel}}^{-1}\, R\cos(2\Phi)$
Transverse separation, R [h^{-1}Mpc]
BGS
0.1 < z < 0.2
0.2 < z < 0.3
0.3 < z < 0.4
$\Pi_{\max}$ [h^{-1}Mpc]
10.01
11.63
13.91
17.12
21.63
27.96
36.85
49.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
10^1



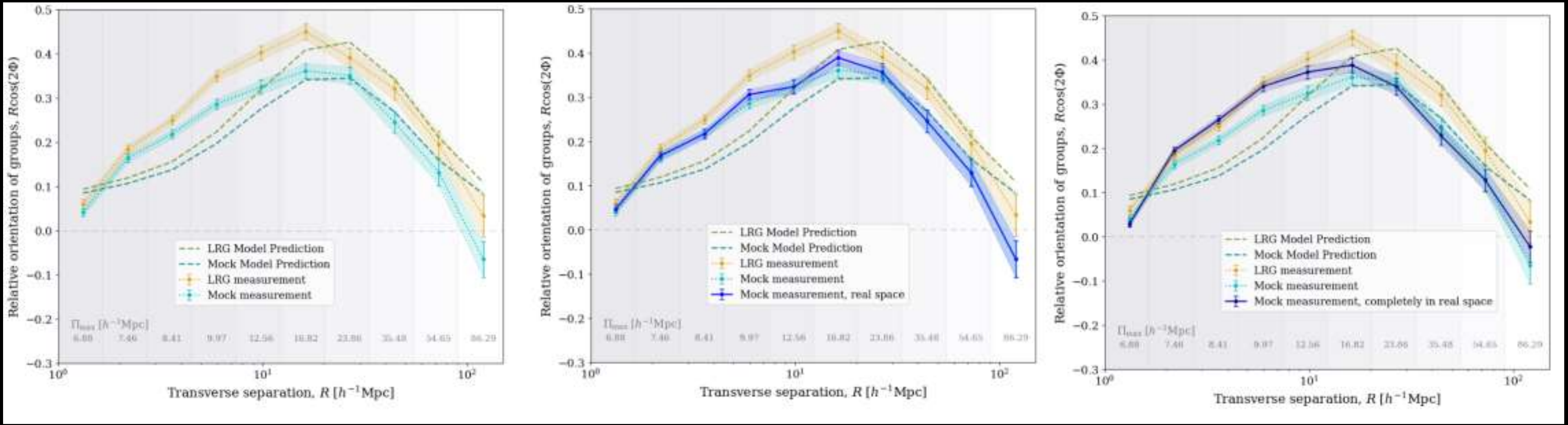
0.25
0.20
0.15
0.10
0.05
0.00
Multiplet relative orientation, $R\cos(2\Phi)$
Transverse separation, R [h^{-1}Mpc]
10^1
BGS
0.1 < z < 0.2
Red Multiplets
Blue Multiplets
$\Pi_{\rm max}$ [h^{-1}Mpc]
10.01
11.63
13.91
17.12
21.63
27.96
36.85
49.35



6.013
23.438
91.364
Transverse separation R [h^{-1}Mpc]
6.013
23.438
91.364
Transverse separation R [h^{-1}Mpc]
0.4
0.2
0.0
−0.2
−0.4



Group-tracer 2-point correlation
$R \times w_p$
$\Pi_{\max}$ [h^{-1}Mpc]
6.88 7.46 8.41 9.97 12.56 16.82 23.86 35.48 54.65 86.29
R [h^{-1}Mpc]
BGS | 0.2 < z < 0.4
LRG | 0.4 < z < 1.1
ELG, LRG tracers | 0.8 < z < 1.1
ELG | 1.1 < z < 1.5
Bright Galaxy Sample
0.3 < z < 0.4
0.2 < z < 0.3
0.1 < z < 0.2



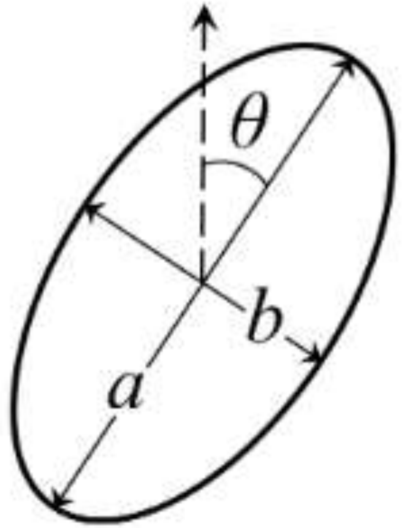
Relative orientation of groups, $R\cos(2\Phi)$
Transverse separation, R [h^{-1}Mpc]
LRG Model Prediction
Mock Model Prediction
LRG measurement
Mock measurement
Mock measurement, real space
Mock measurement, completely in real space
$\Pi_{\rm max}$ [h^{-1}Mpc]
6.88
7.46
8.41
9.97
12.56
16.82
23.86
35.48
54.65
86.29

Background: Quantifying IA

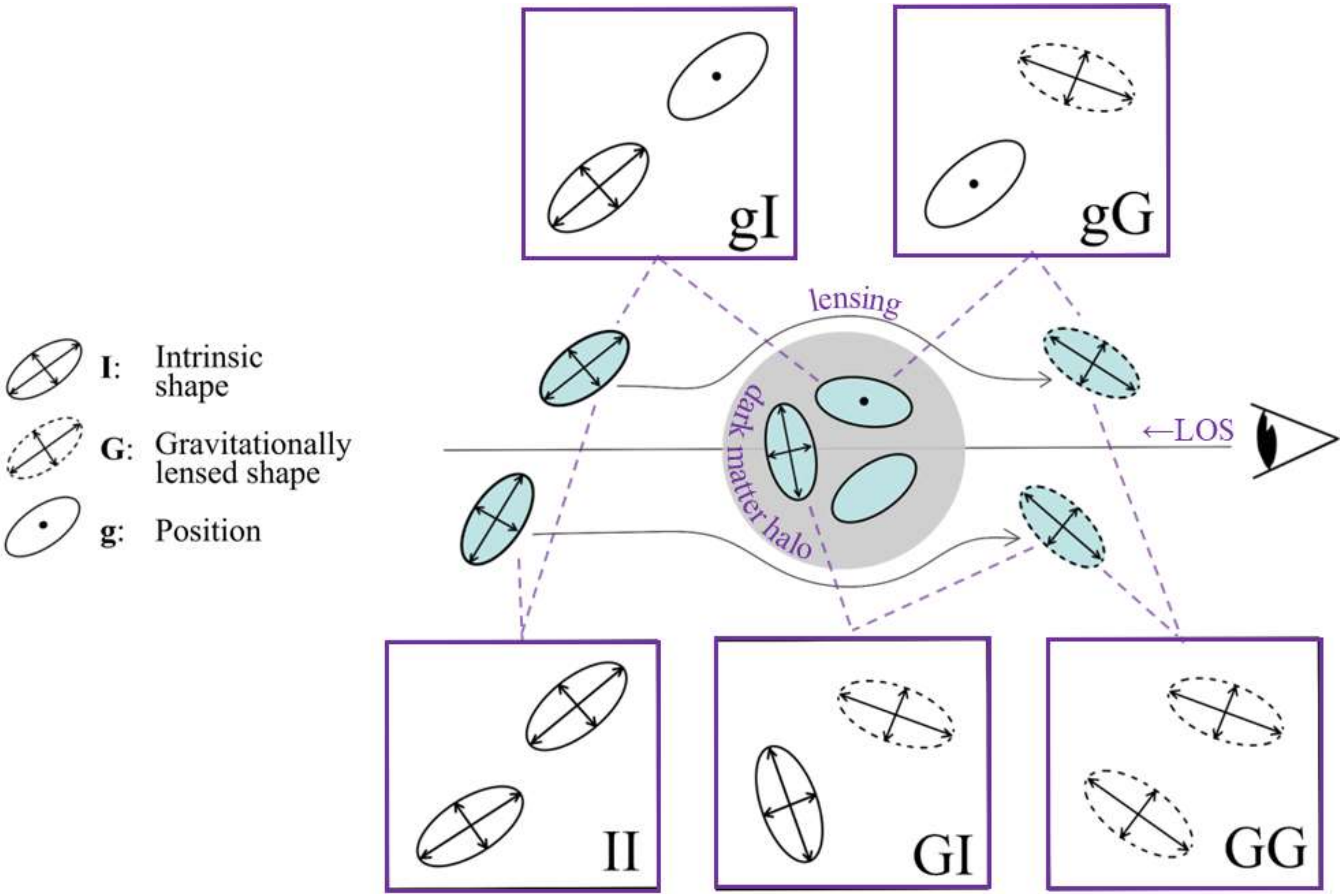
1. Get gal shape
   Obs: projected image, fundamental plane
   Theory: inertia tensor (ellipticals), angular momentum (spirals), tidal field (ellipticals)

2. Measure shape relative to direction of tidal field
   (or tracer)

$$\epsilon = \frac{a-b}{a+b}\exp(2i\theta) = \epsilon_1 + i\epsilon_2$$

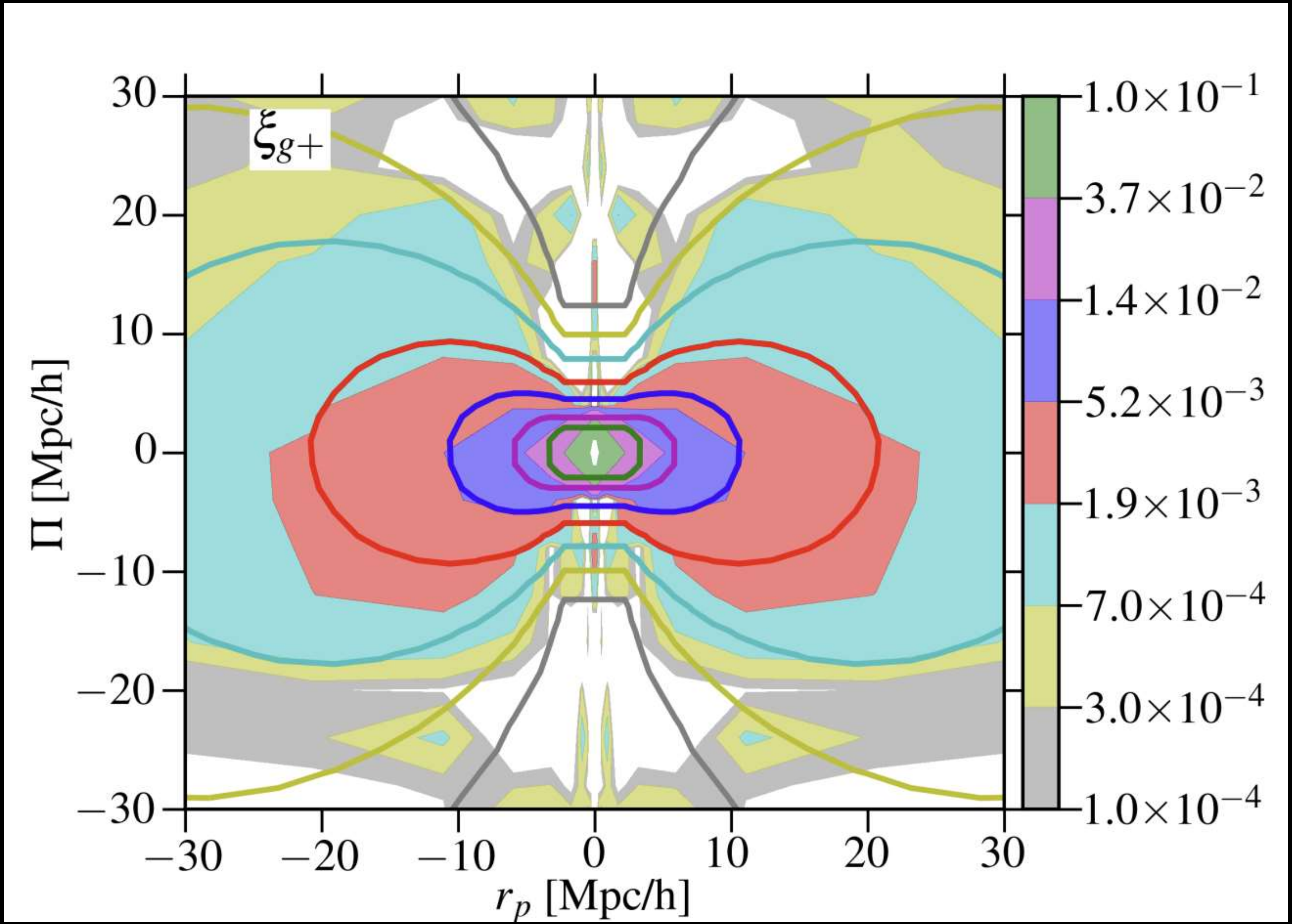


$$\langle \epsilon_i g_i \rangle = \langle G_i g_j \rangle + \langle I_i g_j \rangle$$



$$\langle \epsilon_i \epsilon_j \rangle = \langle G_i G_j \rangle + \langle G_i I_j \rangle + \langle I_i G_j \rangle + \langle I_i I_j \rangle$$

Lamman et al. in prep



ξ_{g+}
Π [Mpc/h]
r_p [Mpc/h]
30
20
10
0
−10
−20
−30
1.0×10^{-1}
3.7×10^{-2}
1.4×10^{-2}
5.2×10^{-3}
1.9×10^{-3}
7.0×10^{-4}
3.0×10^{-4}
1.0×10^{-4}

Background: Modeling IA

Model	Scales	Galaxy type
LA	> 10 Mpc$/h$	clusters
NLA	> 6 Mpc$/h$	LRG
TATT	> 2 Mpc$/h$	LRG, ELG
EFT	> 0.3 Mpc$/h$	LRG, ELG
Halo	0.3-1.5 Mpc$/h$	LRG

Alignment Amplitude, A_{IA}

Linear Alignment (LA)

$A_{IA} \propto$ grav potential

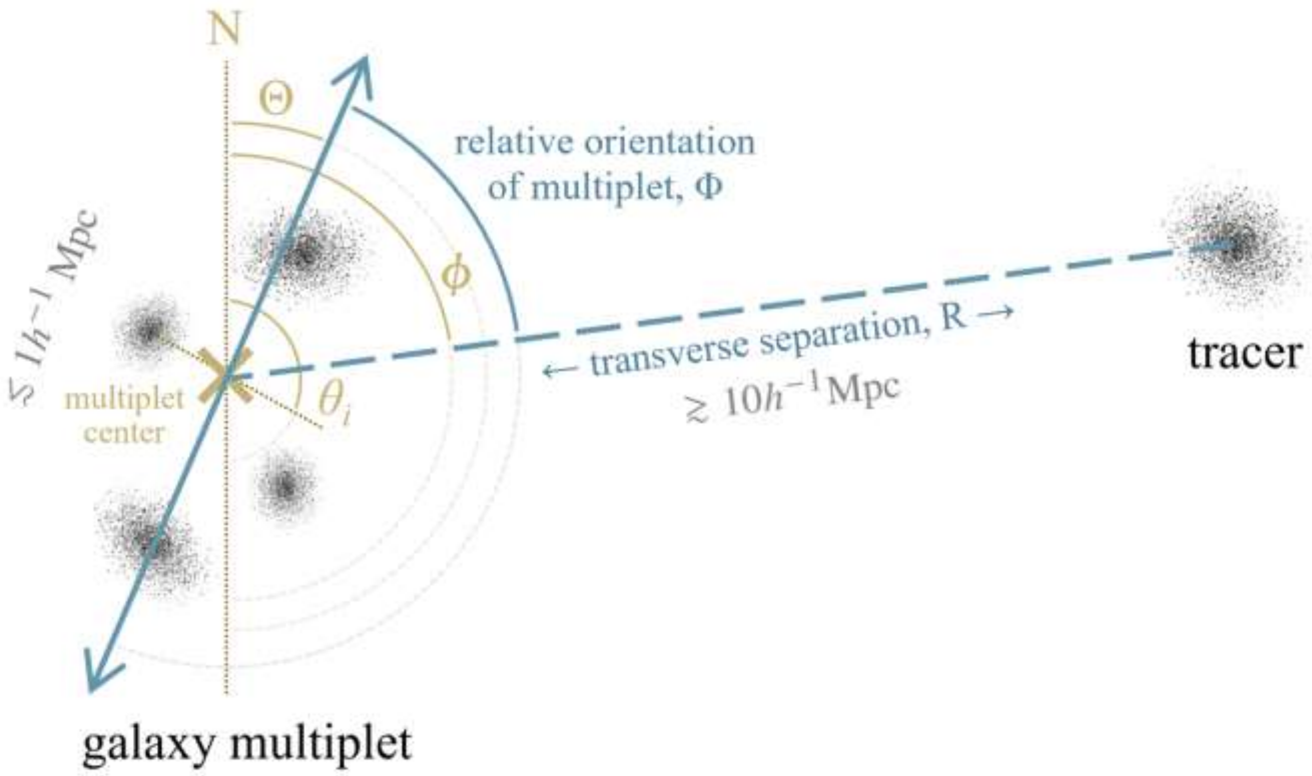
Non-linear Alignment (NLA)

LA but uses full non-linear power spectrum


Tidal Alignment and Tidal Torquing (TATT)

A_{IA} broken into IA from tidal alignemt (A_1) and IA from tidal torquing (A_2)

Lamman et al. in prep



$$\epsilon_{\text{multiplet}} = \frac{1}{N}\sum_{i=1}^{N} r_i \exp 2i\theta_i = a + bi$$

$$\Theta = \frac{1}{2}\arctan\frac{b}{a}$$

$$\Phi = \Theta - \phi$$

$$\cos(2\Phi)$$

$$T_{ij}(\vec{r}) = \int \frac{d^3k}{(2\pi)^3}\left(\frac{k_ik_j - \frac{1}{3}\delta^{\mathrm{K}}_{ij}k^2}{k^2}\right)\tilde{\delta}_m(\vec{k})e^{i\vec{k}\cdot\vec{r}}$$

$$\mathcal{E}_{\mathrm{model}} = \frac{1}{2}\langle\epsilon^* Q + \epsilon Q^*\rangle$$

$$\epsilon_{\alpha,\beta} = \tau(T_{\alpha\beta} + \frac{1}{2}T_{zz})$$

$$Q(R_{\mathrm{bin}}, \pm\Pi_{\mathrm{max}}) = \frac{\int d^3rW(\bar{r})\delta_g e^{2i\theta_r}}{\int d^3rW(\bar{r})(1+\xi_{\epsilon g})}$$

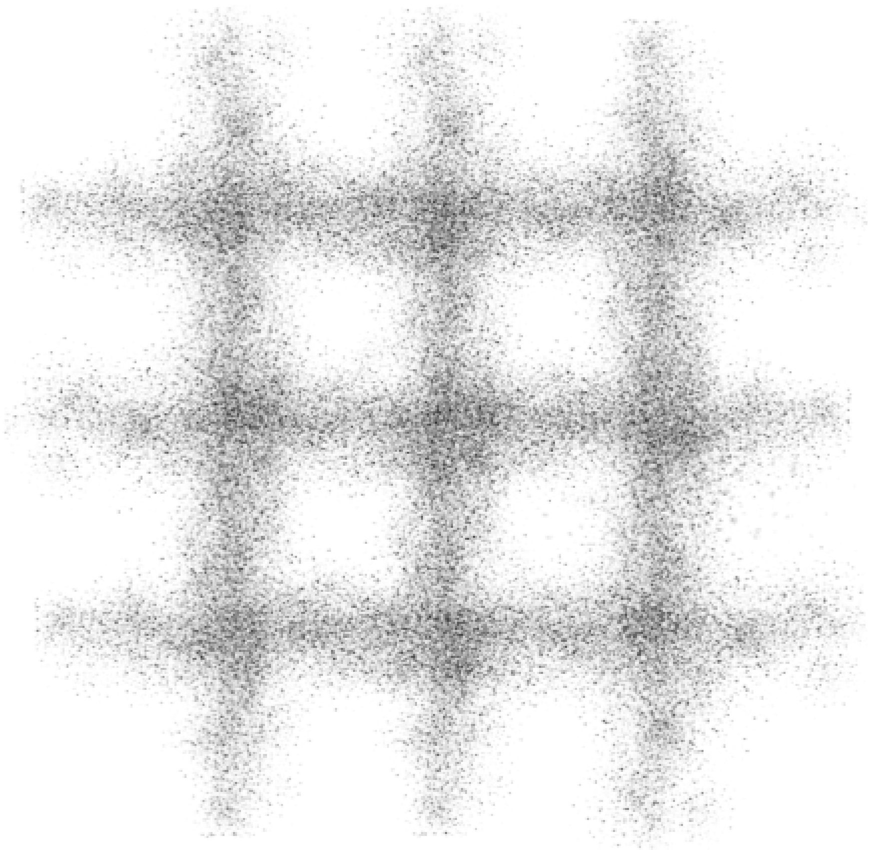
$$\epsilon = \tau[T_{xx} - T_{yy} + 2iT_{xy}]$$

$$\boxed{\begin{aligned}\mathcal{E}_{\mathrm{model}} = \frac{-\tau}{\int d^3rW(\bar{r})(1+\xi_{\epsilon g})}\int d^3rW(\bar{r})\\ \int \frac{dk_z}{2\pi}\int KdKJ_2(KR)\frac{K^2}{k^2}P_{gm}(k)e^{ik_zz},\end{aligned}}$$

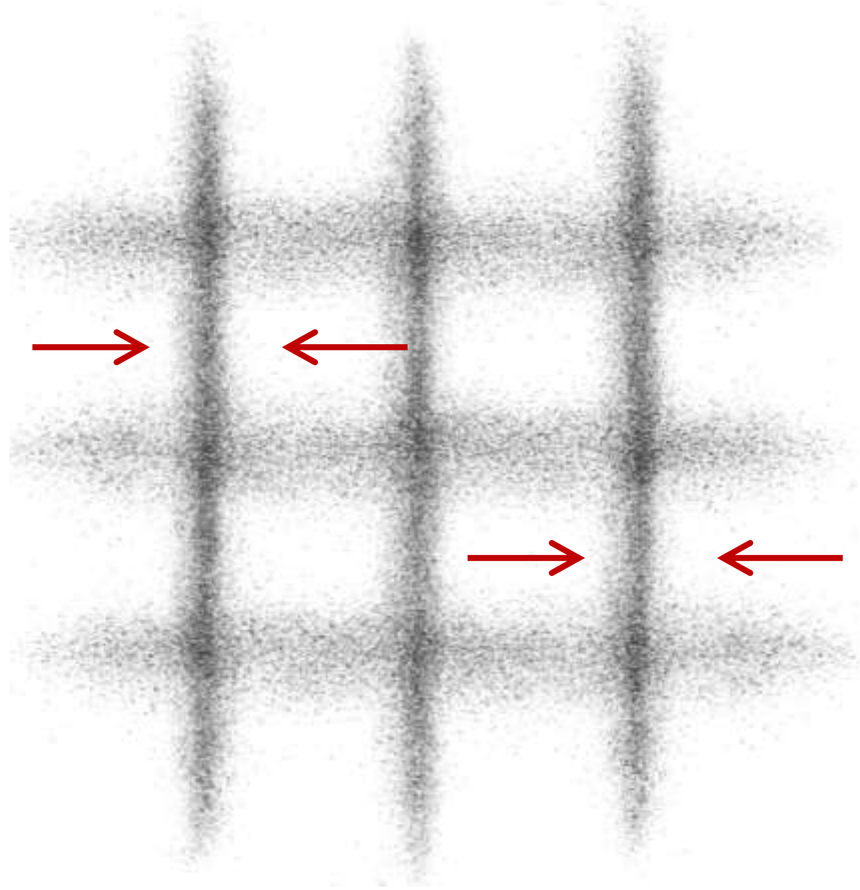
Galaxy type	Redshift Range	N galaxies	N galaxy multiplets	Volume [$Gpc^3 h^{-3}$]
ELG	1.1 < z < 1.5	1.5 M	21 K	67.8
ELG	0.8 < z < 1.1	1.2 M	22 K	35.8
LRG	0.8 < z < 1.1	0.9 M	34 K	34.6
LRG	0.4 < z < 1.1	2.2 M	105 K	34.6
BGS	0.3 < z < 0.4	0.6 M	64 K	3.2
BGS	0.2 < z < 0.3	1.3 M	212 K	1.5
BGS	0.1 < z < 0.2	1.4 M	307 K	0.5
BGS Blue	0.1 < z < 0.2	0.56 M	81 K	0.5
BGS Red	0.1 < z < 0.2	0.54 M	100 K	0.5

RSD: Kaiser Effect

LOS →



Real Space

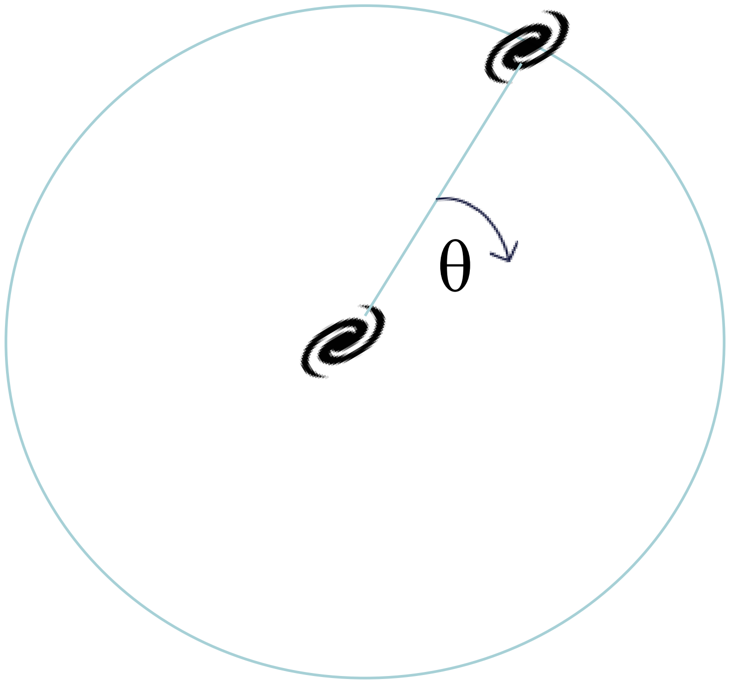


Redshift Space

Quantifying anisotropic clustering

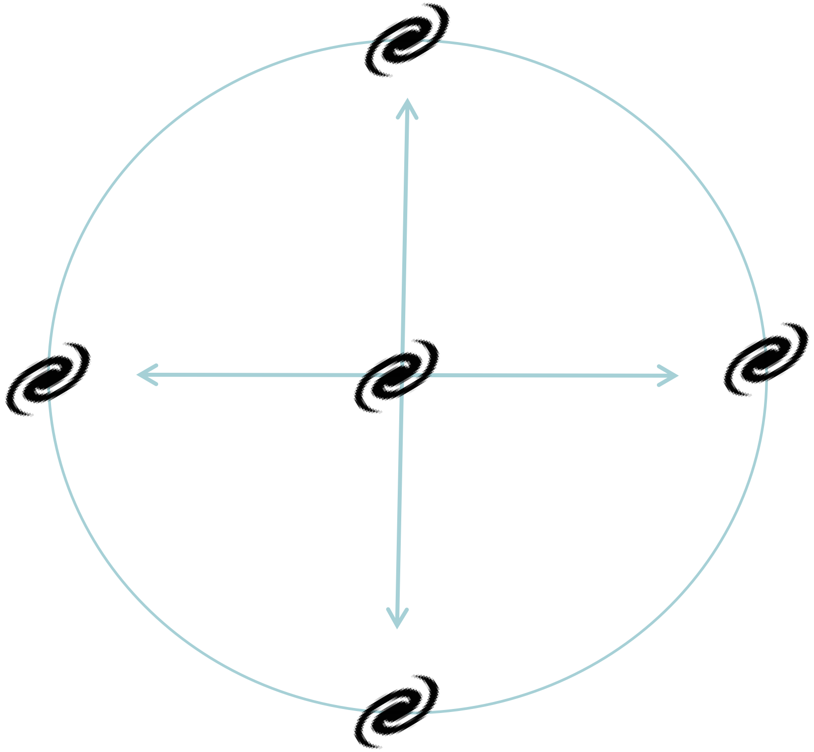
Monopole

ξ_0



Quadrupole

ξ_2



Fake RSD!

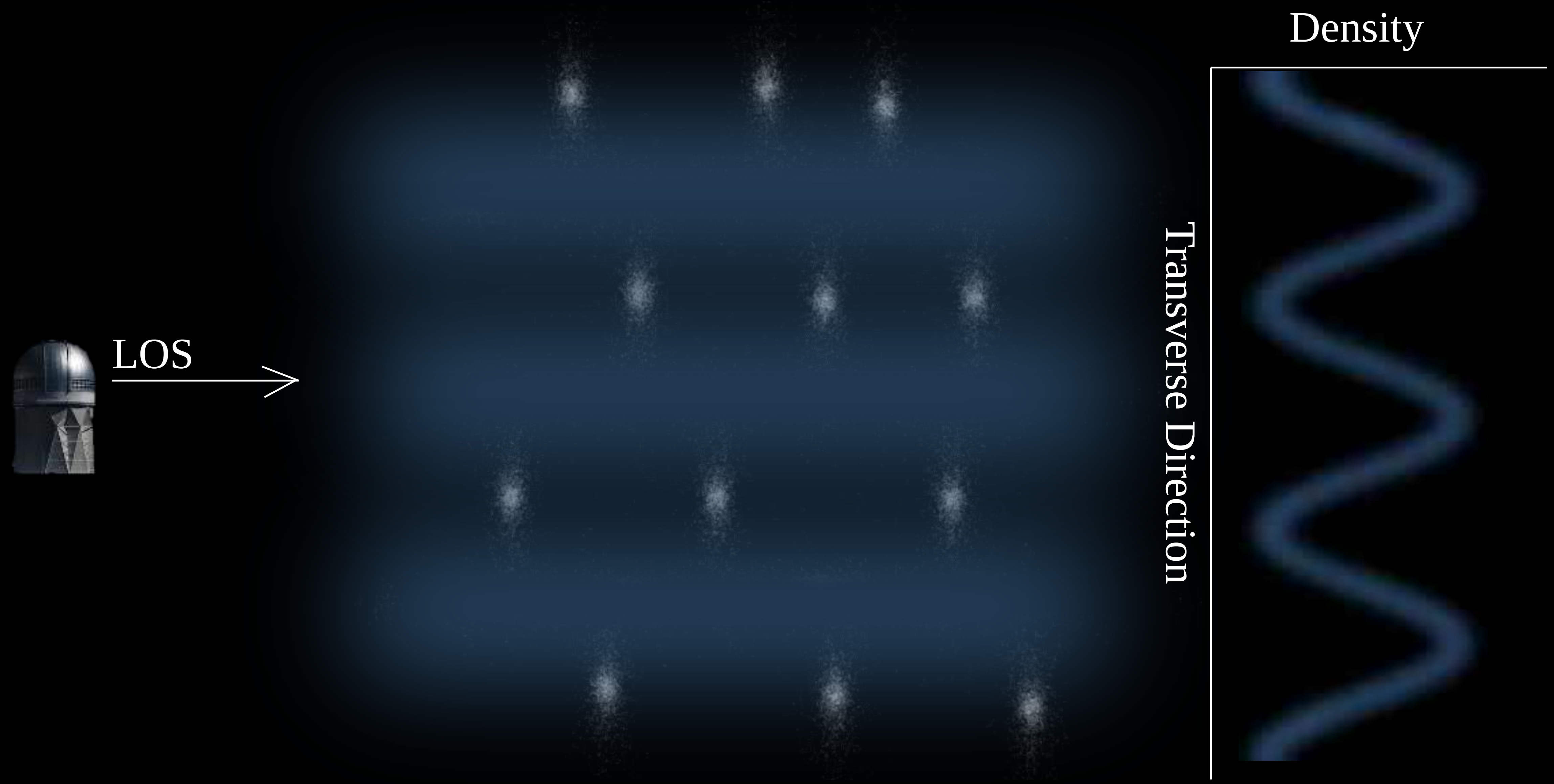
Bias in galaxy orientations
from survey

Bias in LSS
(specifically ξ_2)

How aperture target selection contaminates RSD measurements

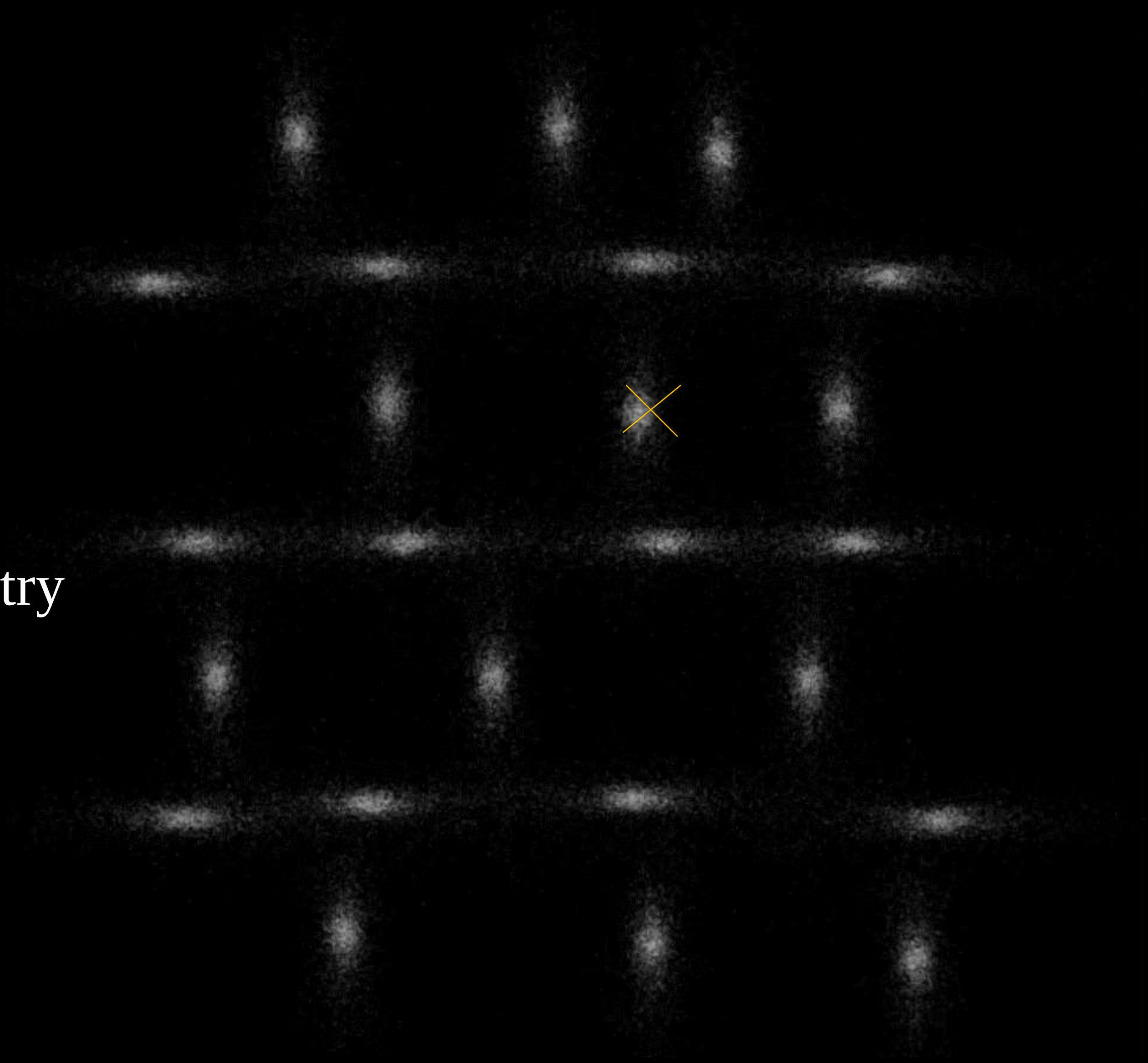
Claire Lamman

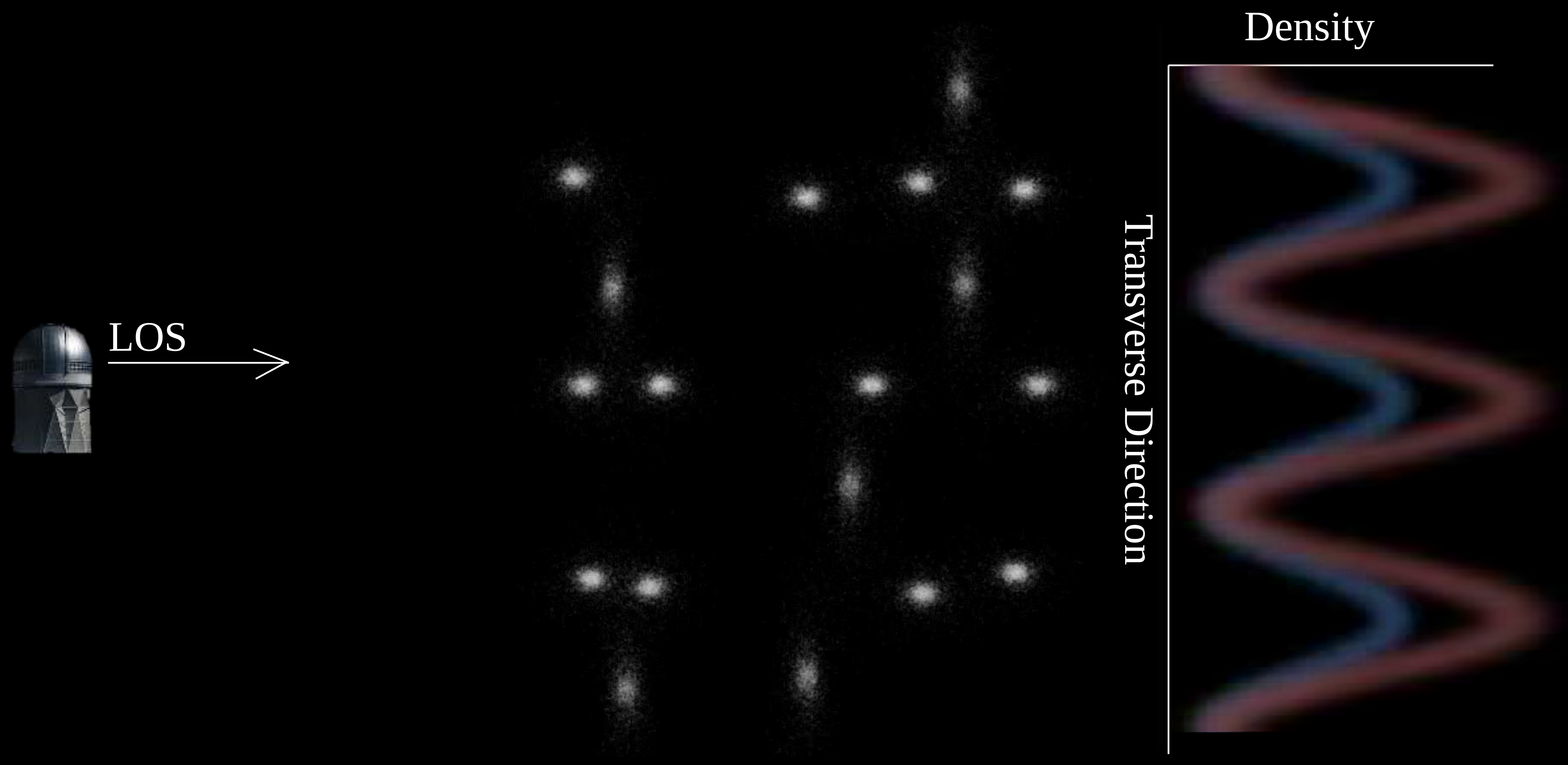
Originally proposed by [Hirata 2009]

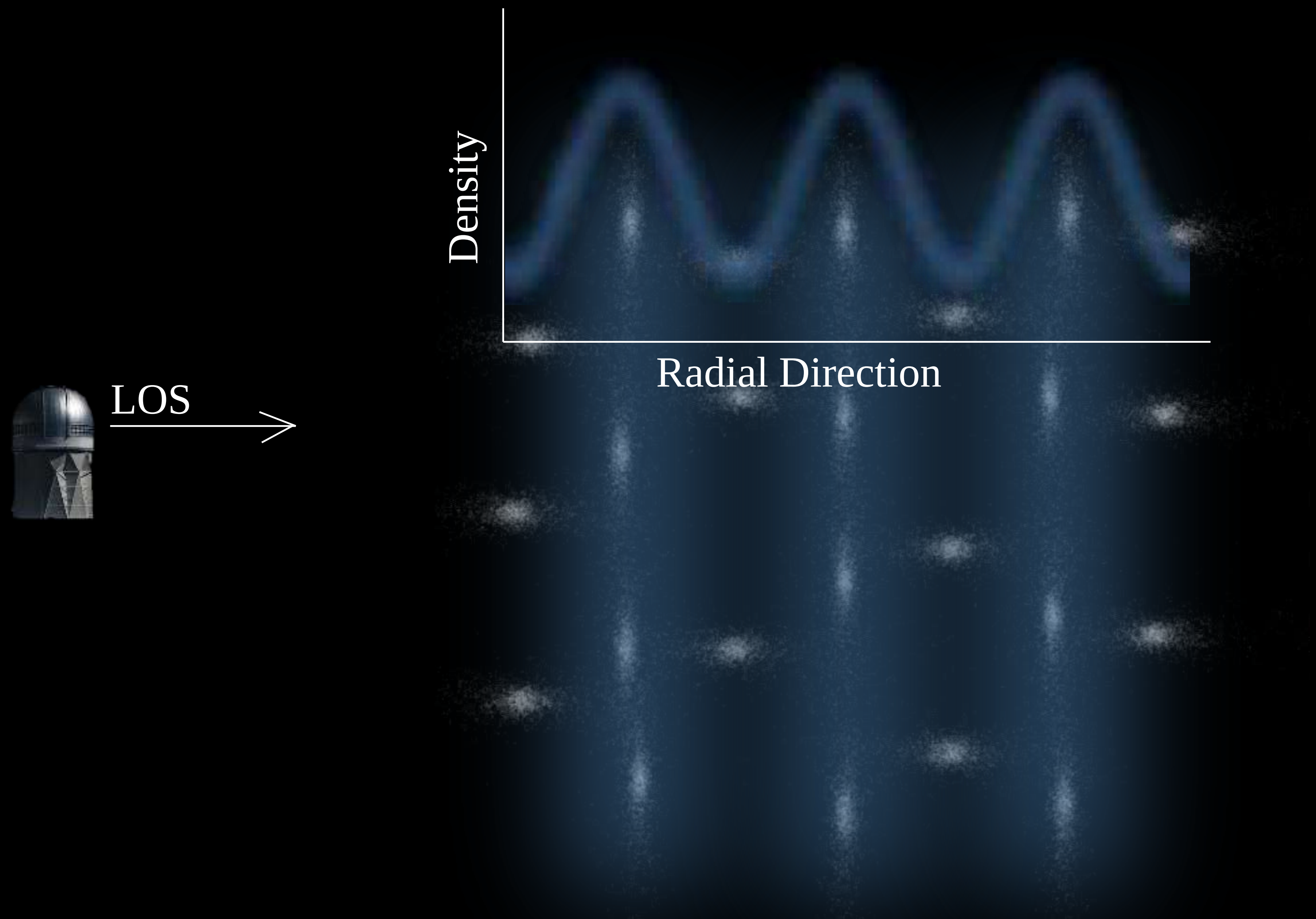


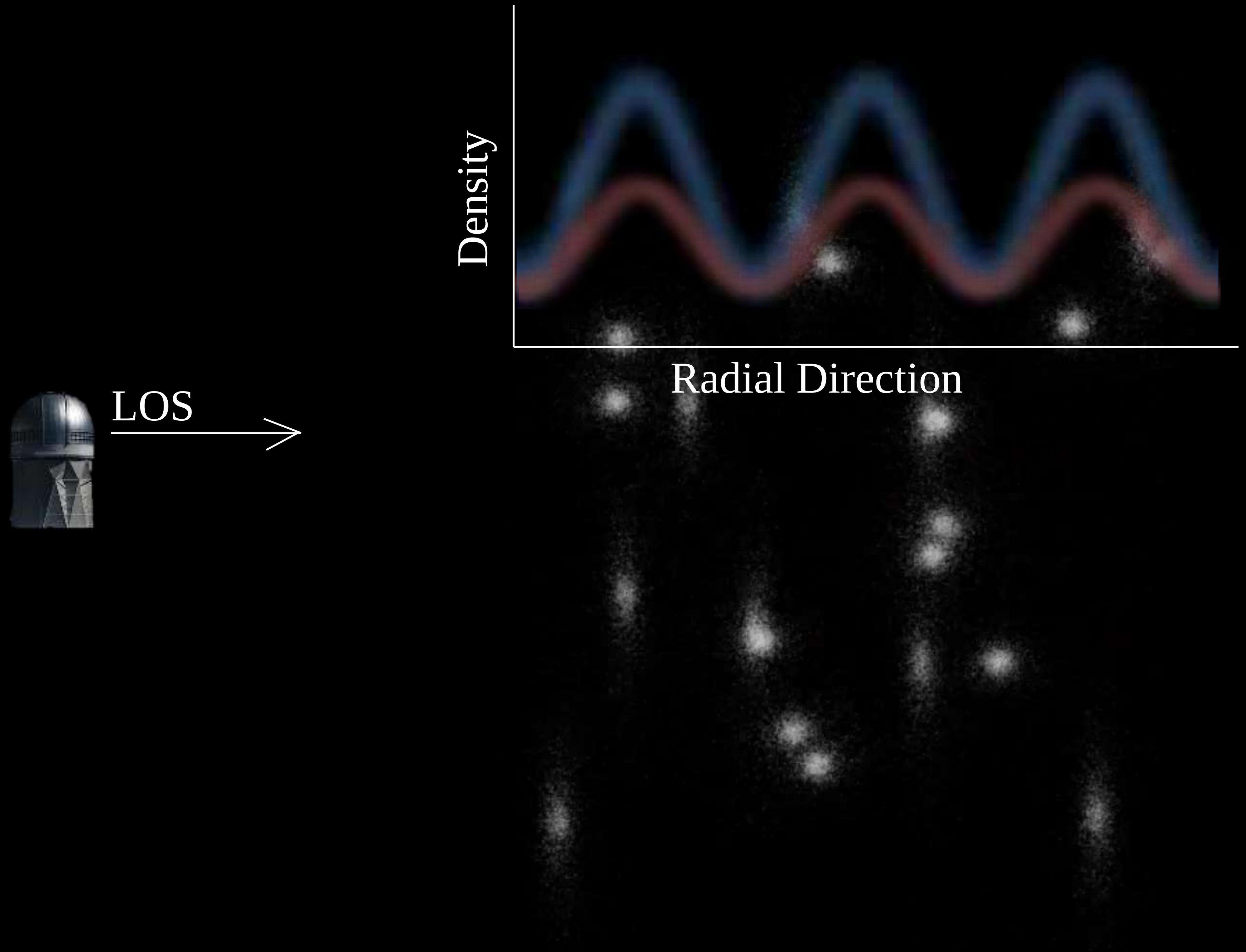
Density
LOS
Transverse Direction

Aperture Photometry

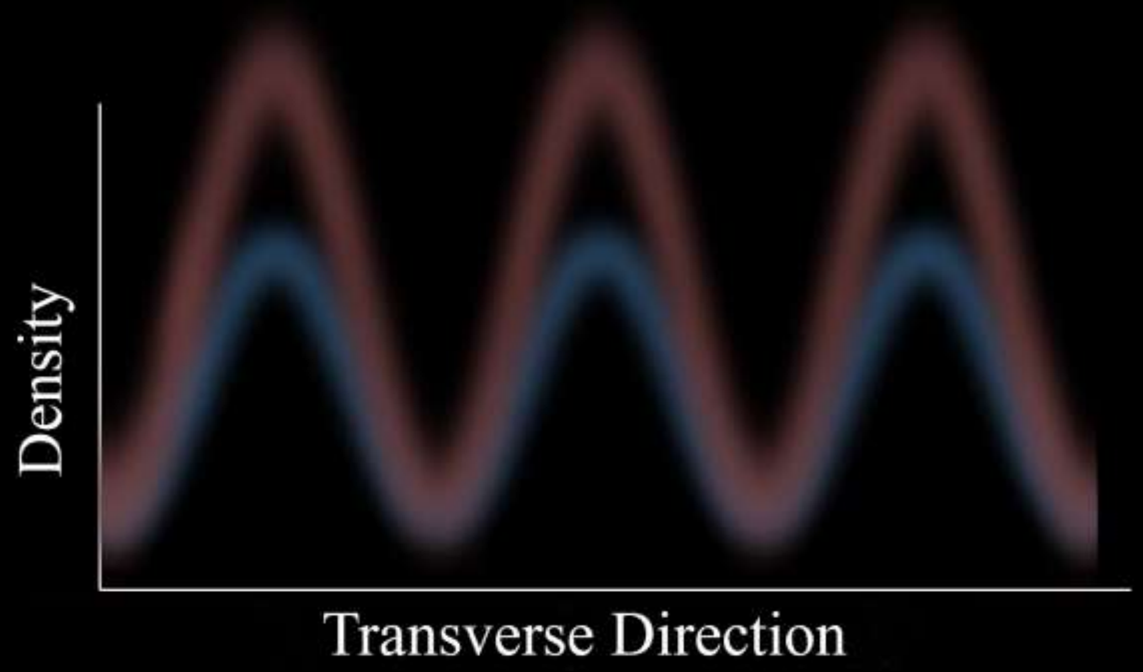


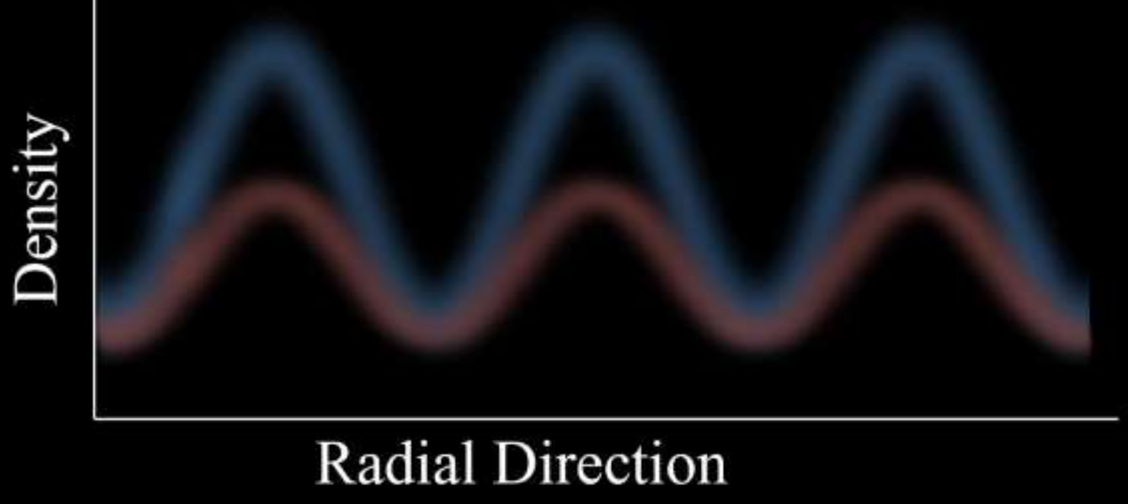

LOS
Density
Transverse Direction


Density
Radial Direction
LOS



Density
Radial Direction
LOS





$$\xi_2$$

Demonstration with AbacusSummit Simulations