Title: Untangling the Cosmic Web: Correlations between small-scale clustering and large-scale structure

Speakers: Claire Lamman

Collection/Series: Cosmology and Gravitation

Subject: Cosmology

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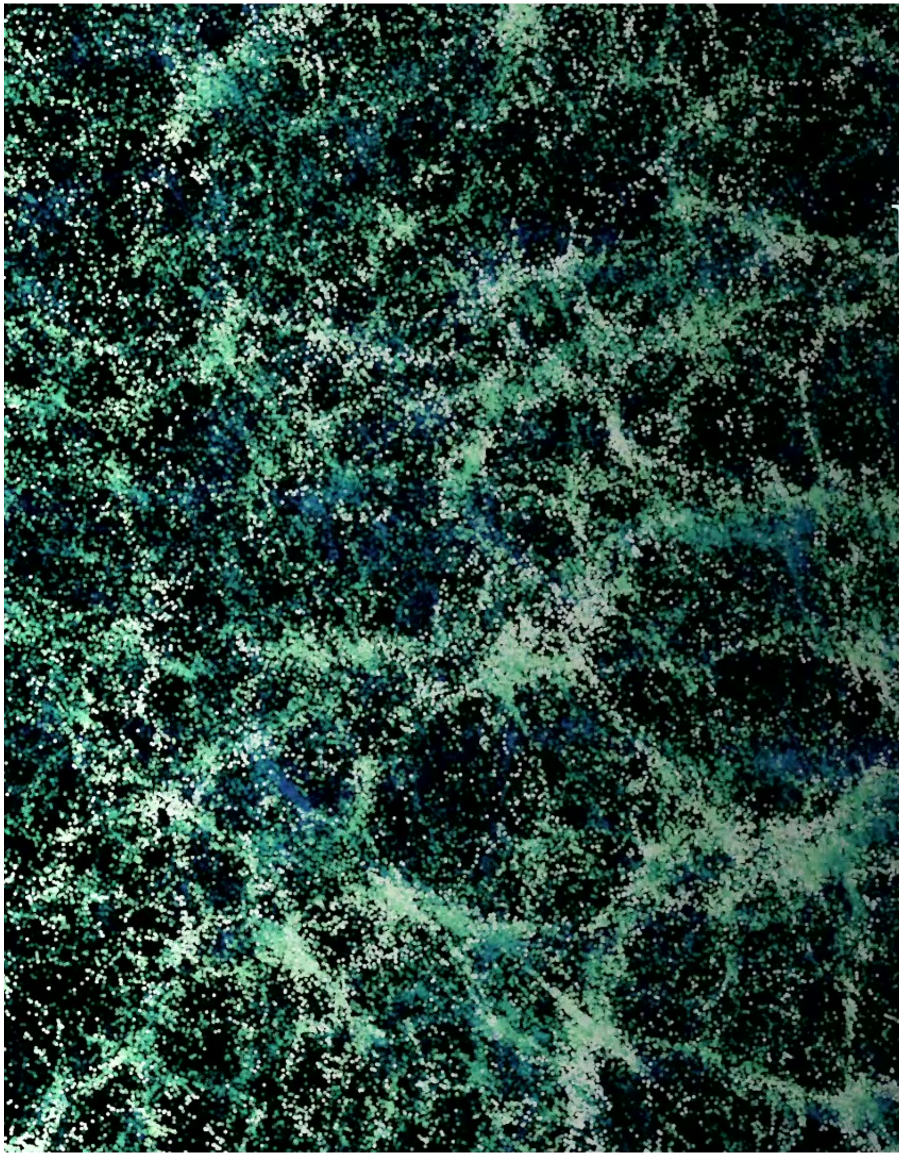
Abstract:

Gravitational forces from the largest structures in the Universe leave a detectable imprint on galaxies and their local environment. I will present a new approach to tracing the tidal field using these correlations: the intrinsic alignment of small groups of galaxies, or "multipelts". Multiplets mostly consist of 2-4 galaxies within 1 Mpc/h of each other, and we measure their orientations relative to the galaxy-traced tidal field. Using spectroscopic redshfits from the DESI Y1 survey, we detect intrinsic alignment out to projected separations of 100 Mpc/h and beyond redshift 1. We find a simillar signal regardless of galaxy luminosity or color, which could make multiplet alignment a useful tool for mapping the direction of the tidal field and any cosmological effects which impact it. Our detection demonstrates that galaxy clustering in the non-linear regime of structure formation preserves an interpretable memory of the large-scale tidal field.



Untangling the Cosmic Web

Correlations between small-scale clustering and large-scale structure

Claire Lamman
Claire.Lamman@cfa.harvard.edu

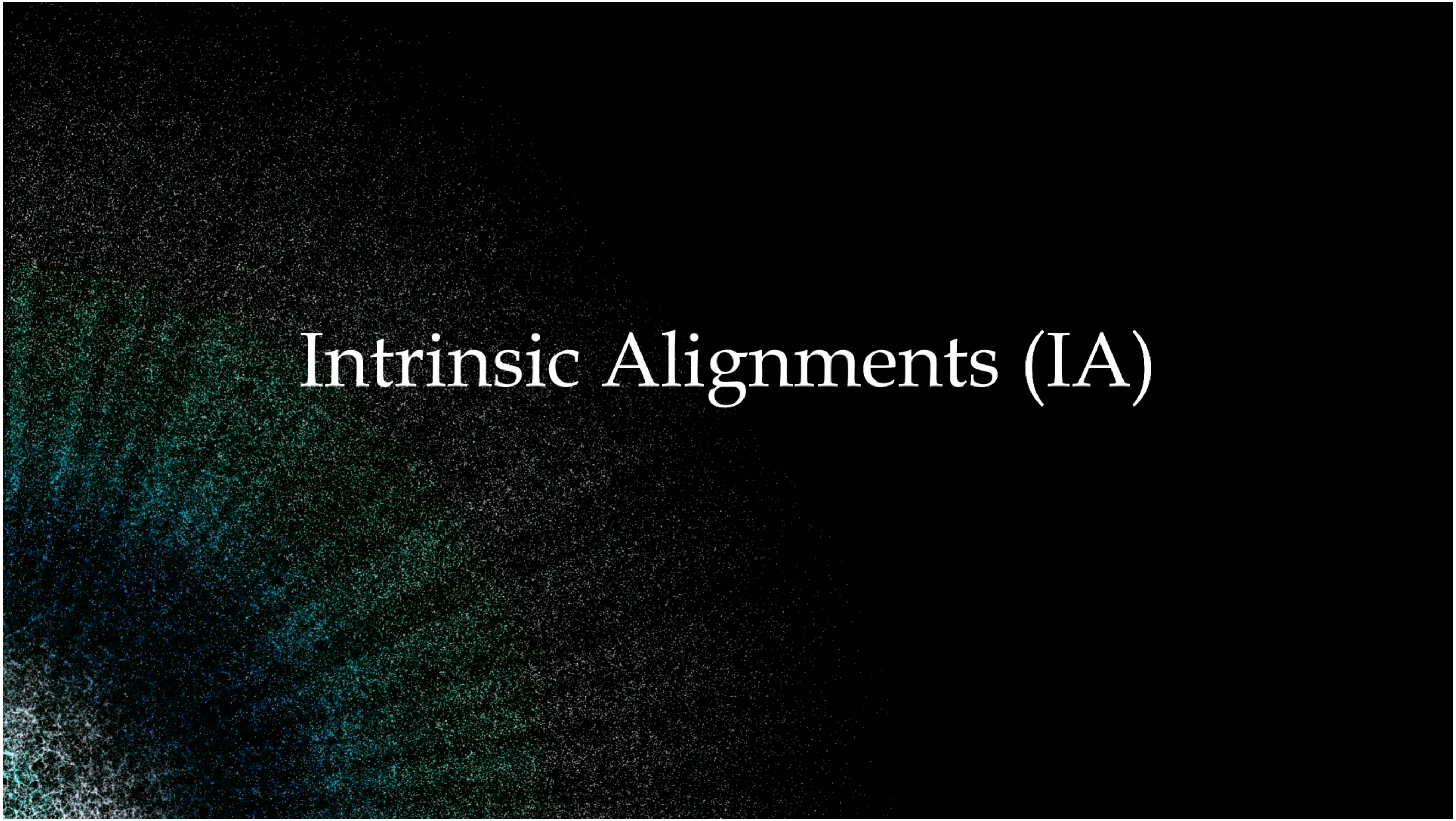
Perimeter Institute Cosmology Seminar
01.07.2025

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

CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN

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

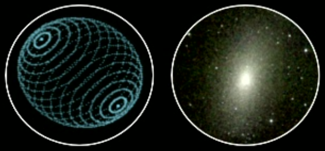
Intrinsic Alignments (IA)



Intrinsic Alignments

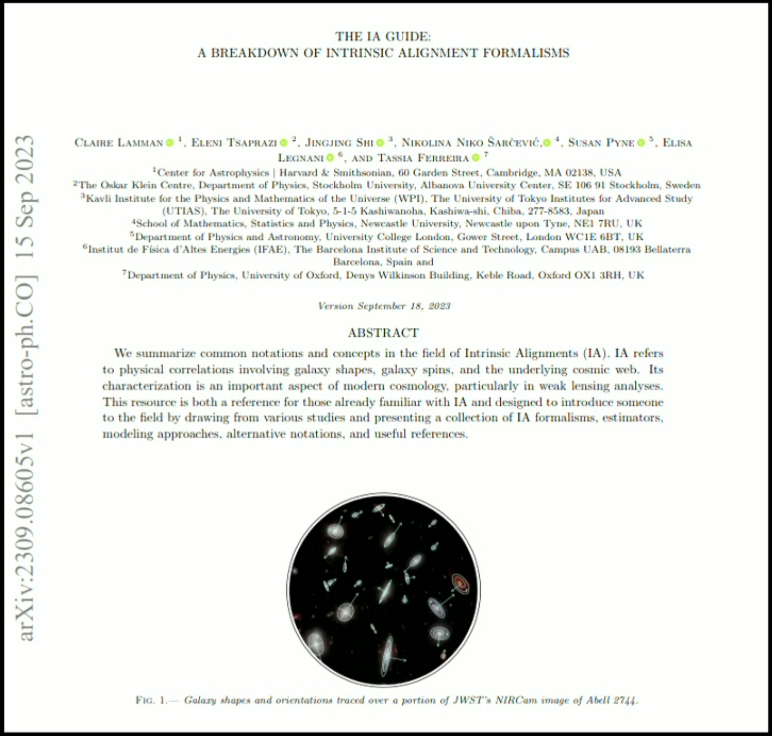
Galaxy orientations are aligned with the underlying density

Generally:



The longest axis of ‘red’ galaxies and halos 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

Claire Lamman [1], Eleni Tsaprazi [2], Jingjing Shi [3], Nikolina Niko Šarčević, [4], Susan Pyne [5], Elisa Legnani [6], and Tassia Ferreira [7]

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[3] Kavli Institute for the Physics and Mathematics of the Universe (WPI), The University of Tokyo Institutes for Advanced Study (UTIAS), The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa-shi, Chiba, 277-8583, Japan
[4] School of Mathematics, Statistics and Physics, Newcastle University, Newcastle upon Tyne, NE1 7RU, UK
[5] Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, UK
[6] Institut de Física d’Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Campus UAB, 08193 Bellaterra Barcelona, Spain and
[7] Department of Physics, University of Oxford, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH, UK

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.*

For more info, see The IA Guide!
arxiv 2309.08605
Lamman et al. 2023b

IA interferes with cosmological measurements

- Weak lensing

Can bias matter power spectrum by 30%

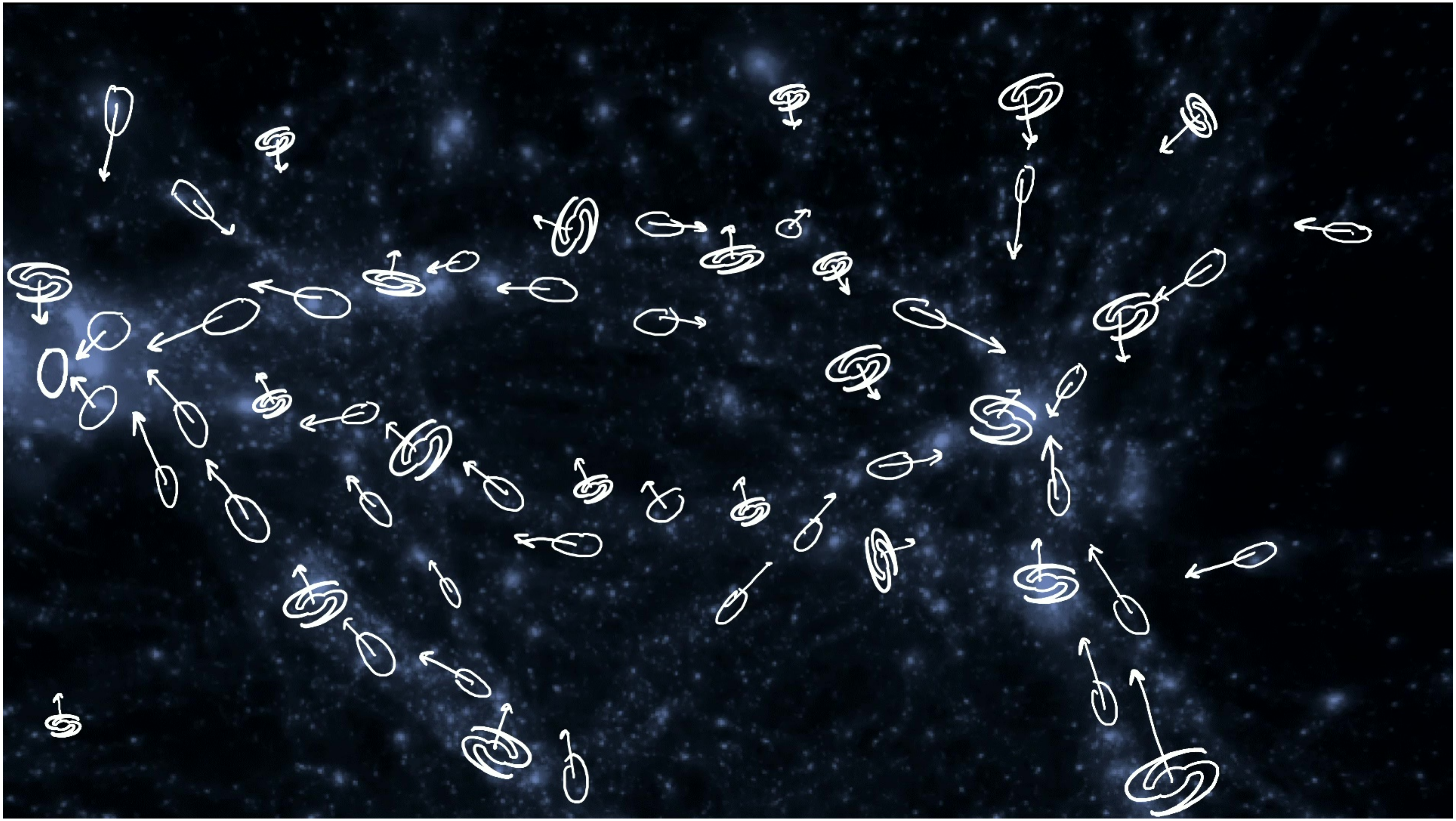
Hirata et al. 2007

- 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

RSD

Okumura & Taruya 2022

BAO

Chisari & Dvorkin 2013

Okumura et al. 2019

Van Dompseler et al. 2023

B-modes

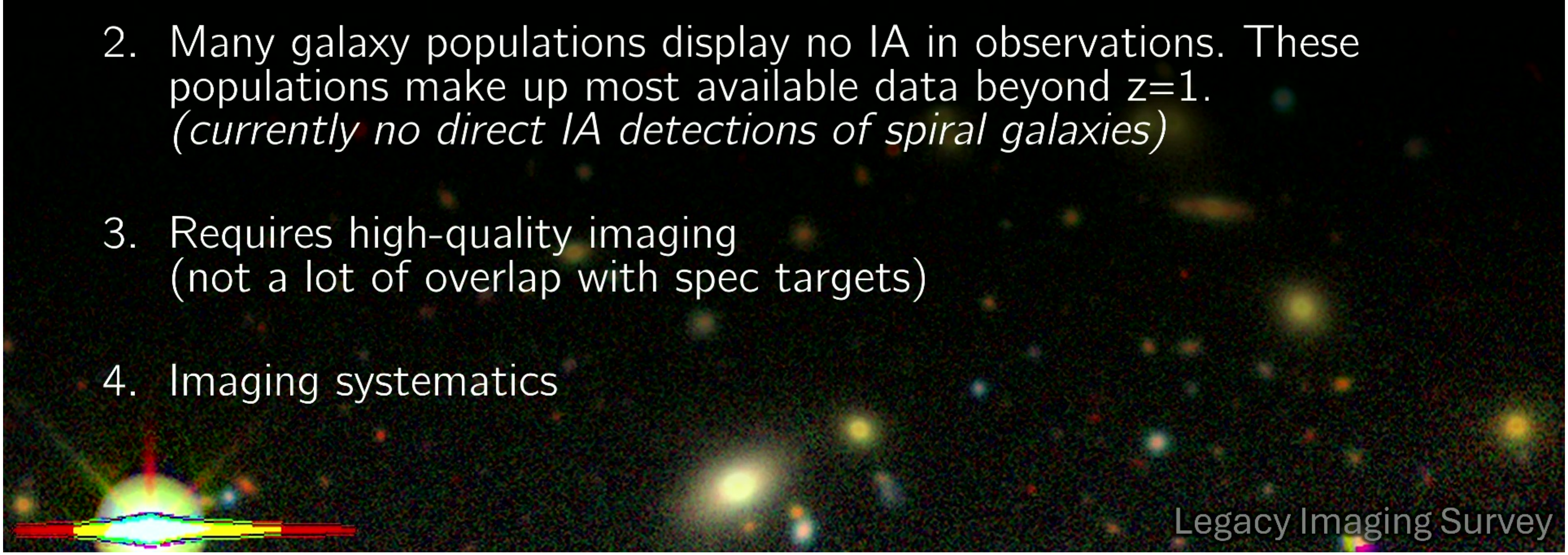
Georgiou et al. 2023

Akitsu et al 2023

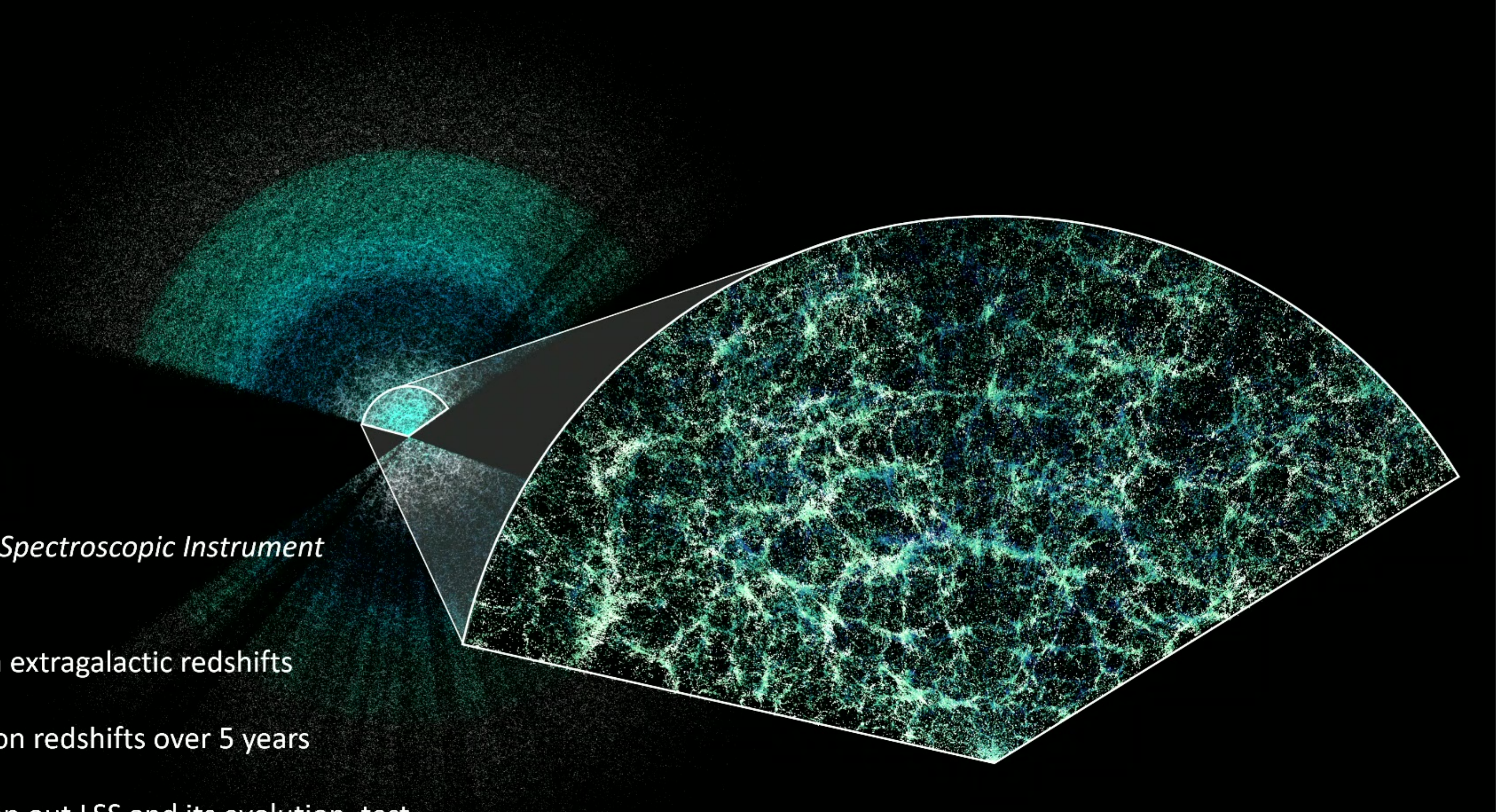
Saga et al. 2024

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



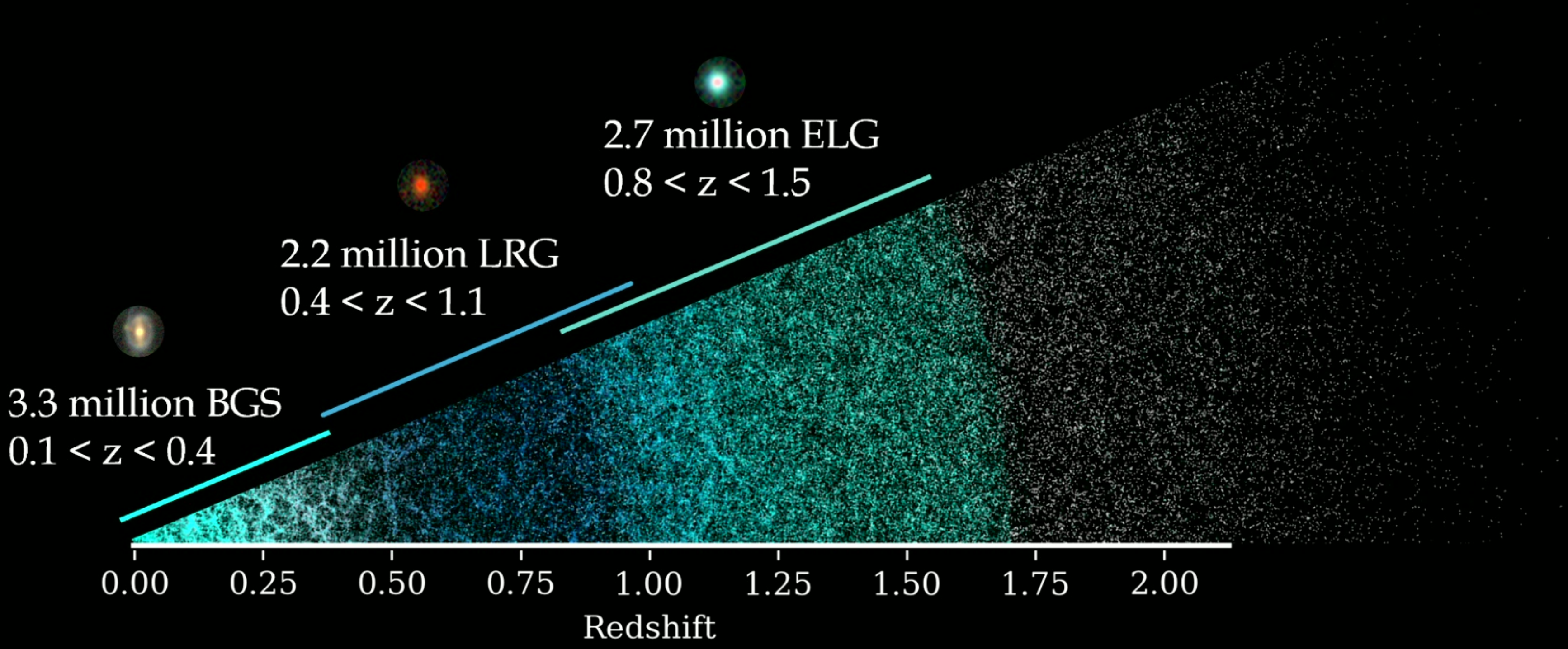
DESI

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



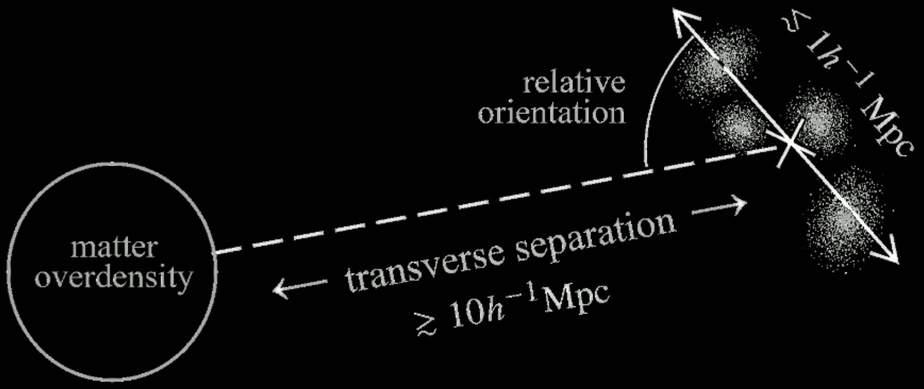
3.3 million BGS
$0.1 < z < 0.4$

2.2 million LRG
$0.4 < z < 1.1$

2.7 million ELG
$0.8 < z < 1.5$

IA of groups! (or "multiplets")

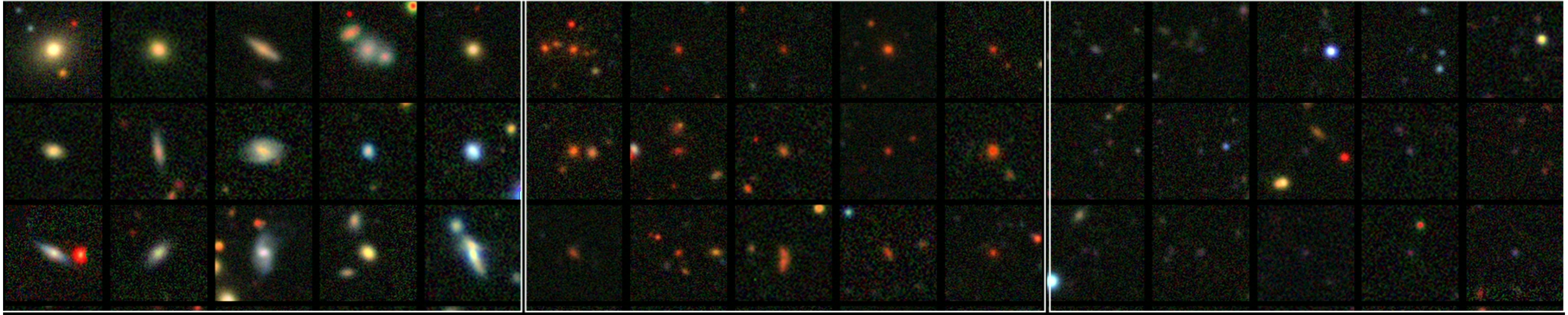
- Ensembles of galaxies less affected by imaging and typically display stronger alignment
  Clusters: Smargon et al. 2012, Halos: Fortuna et al. 2021



Identifying Multiplets

Within comoving space...

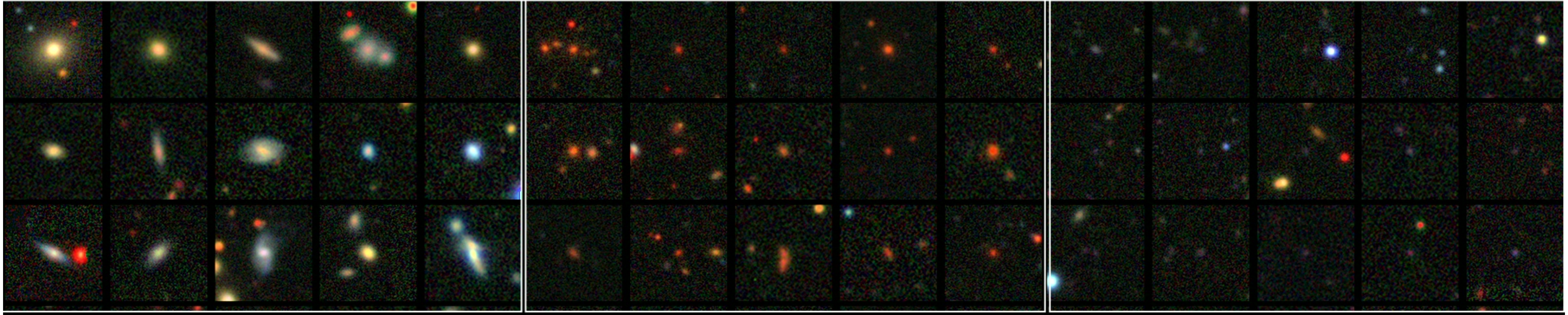
1. For each galaxy, find the nearest neighbor.
2. Limit these pairs to a $r\perp$< 0.5 Mpc/h and r ∥ <12 Mpc/h
3. Identify groups within the graph created by these pairs



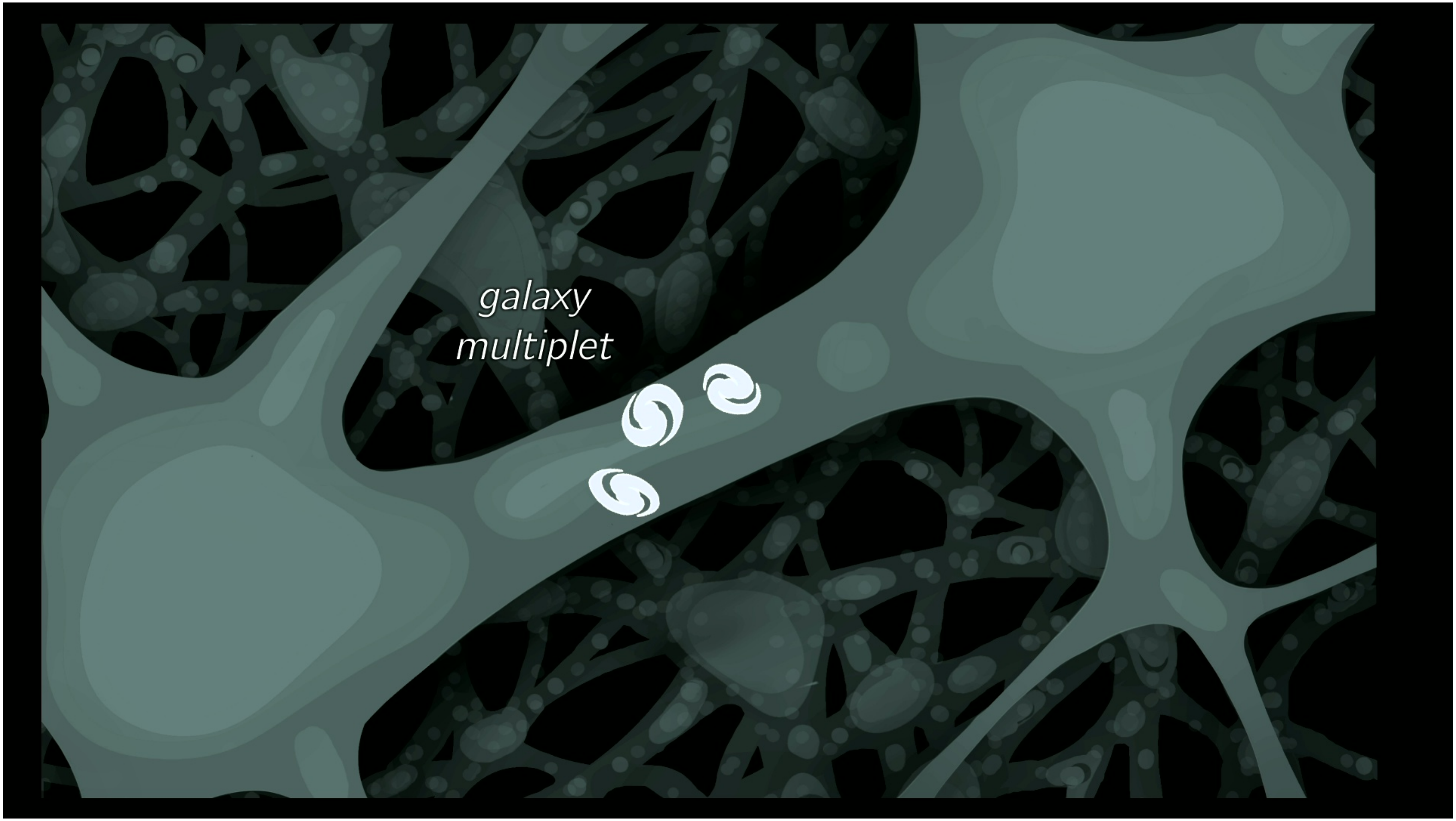
Legacy Imaging of multiplets in DESI's BGS, LRG, and ELG samples. Each image is 25.6″ across

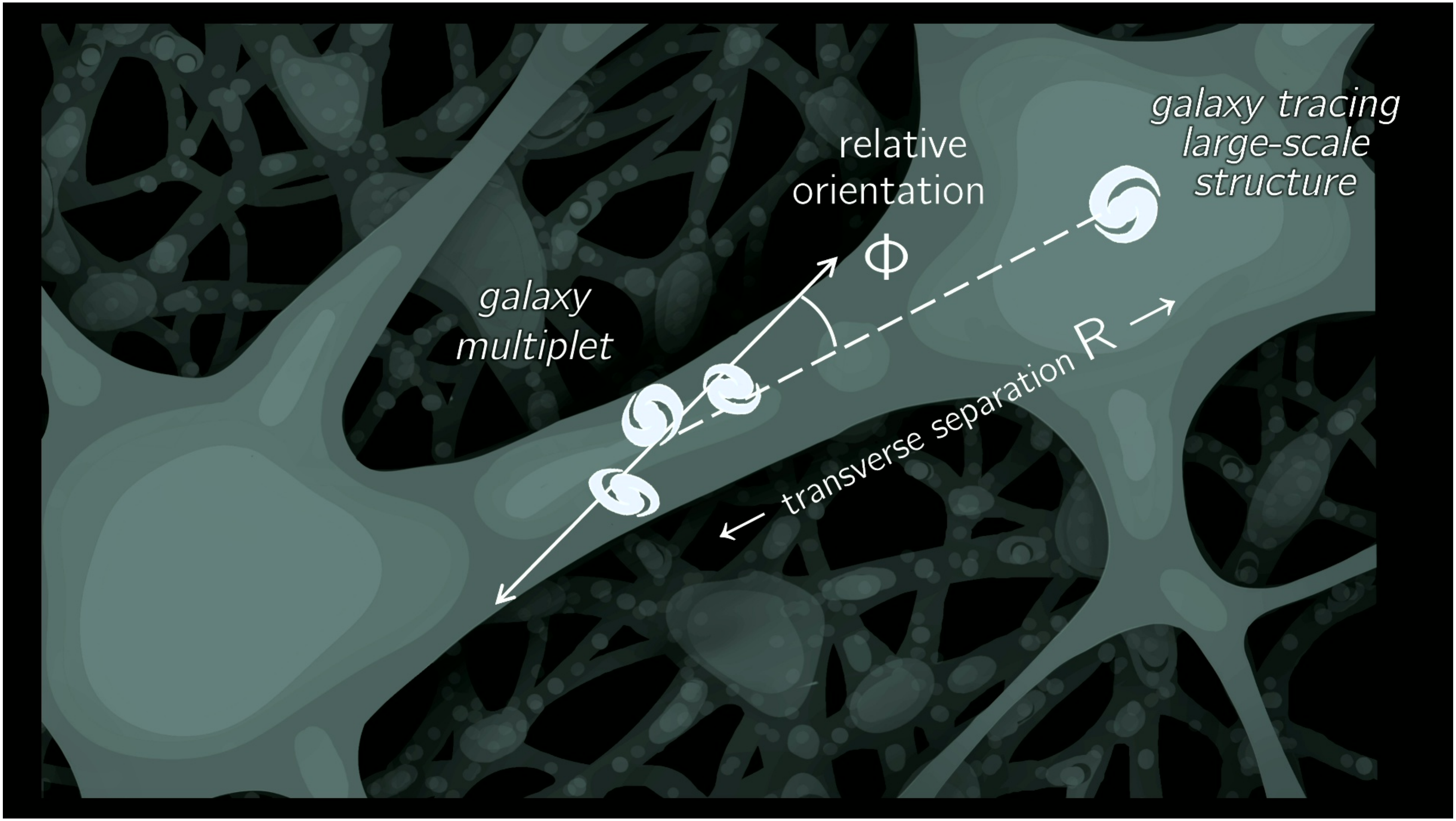
What are Multiplets?

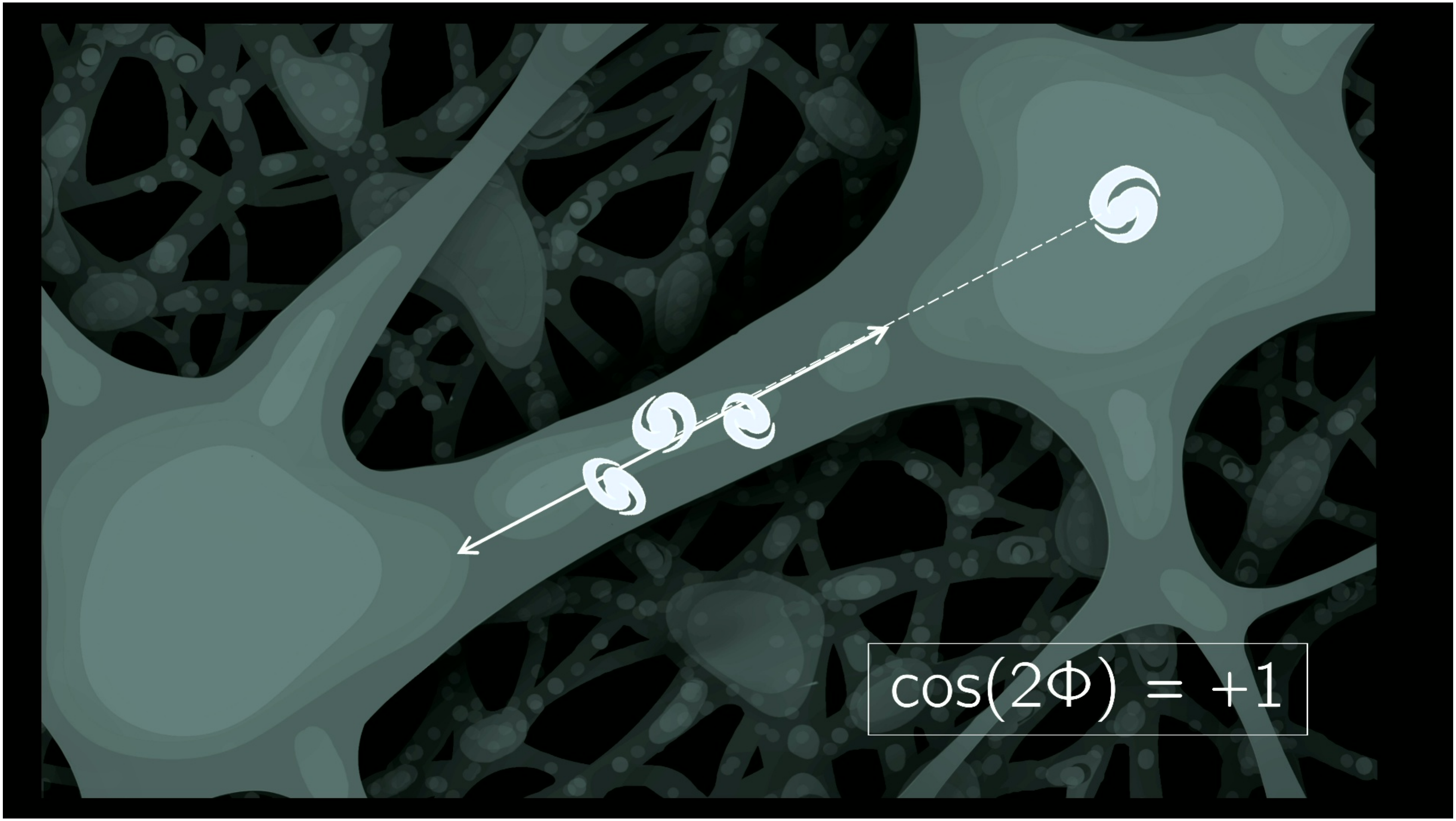
- A small number of galaxies (~2-5), mostly within a Mpc of each other.
- Different than groups and clusters: *not necessarily virialized*



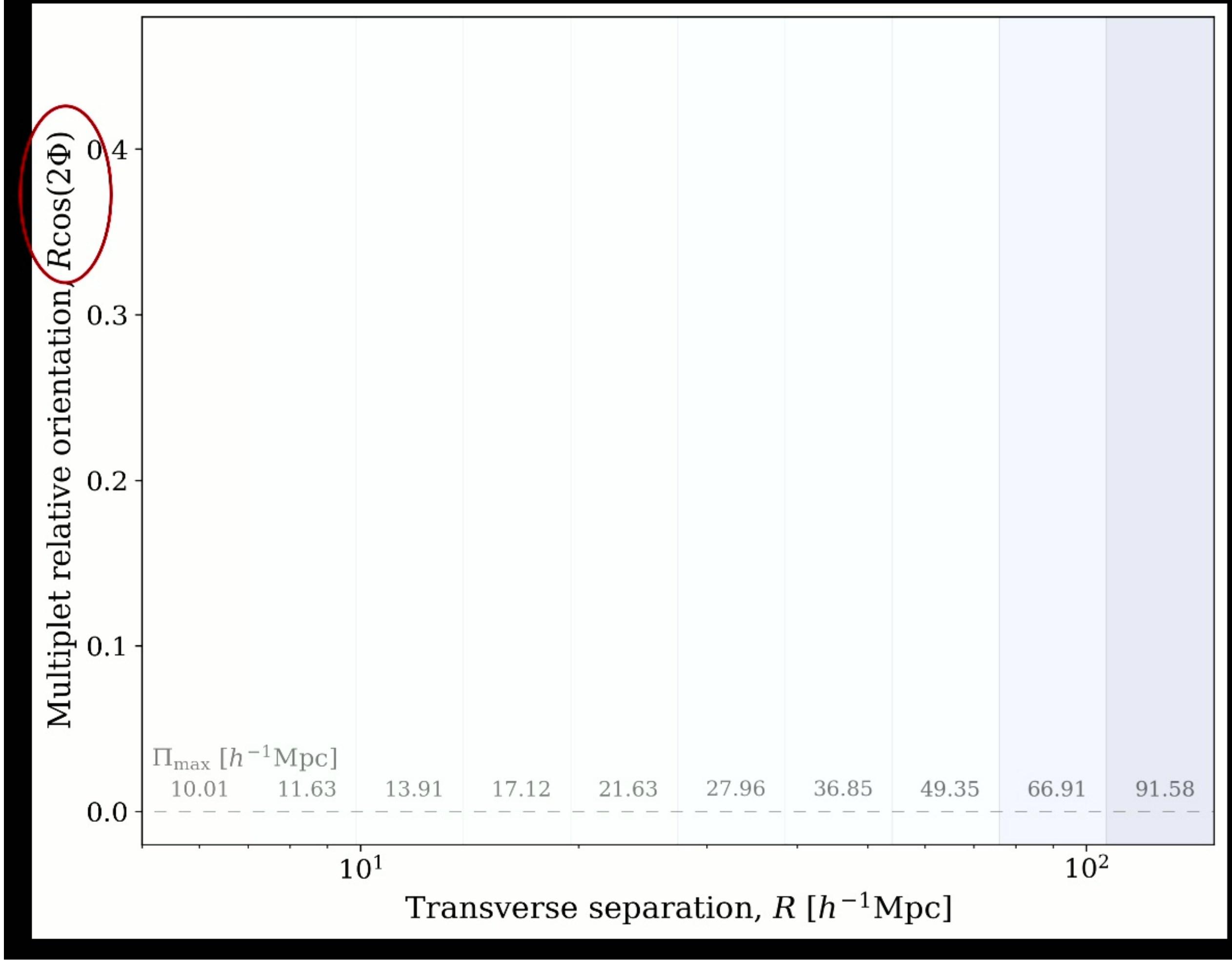
Legacy Imaging of multiplets in DESI's BGS, LRG, and ELG samples. Each image is 25.6" across


galaxy
multiplet


galaxy tracing large-scale structure
relative orientation
Φ
galaxy multiplet
← transverse separation R →

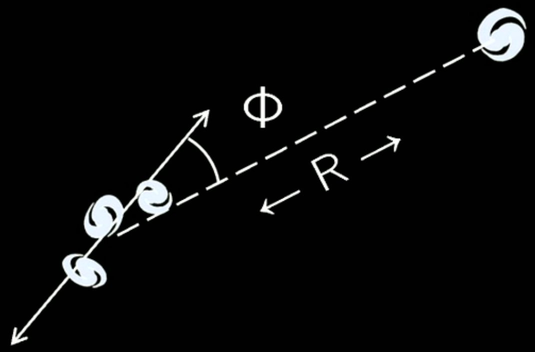


$\cos(2\Phi) = +1$



↑ Stronger tidal alignment

↓ Weaker tidal alignment

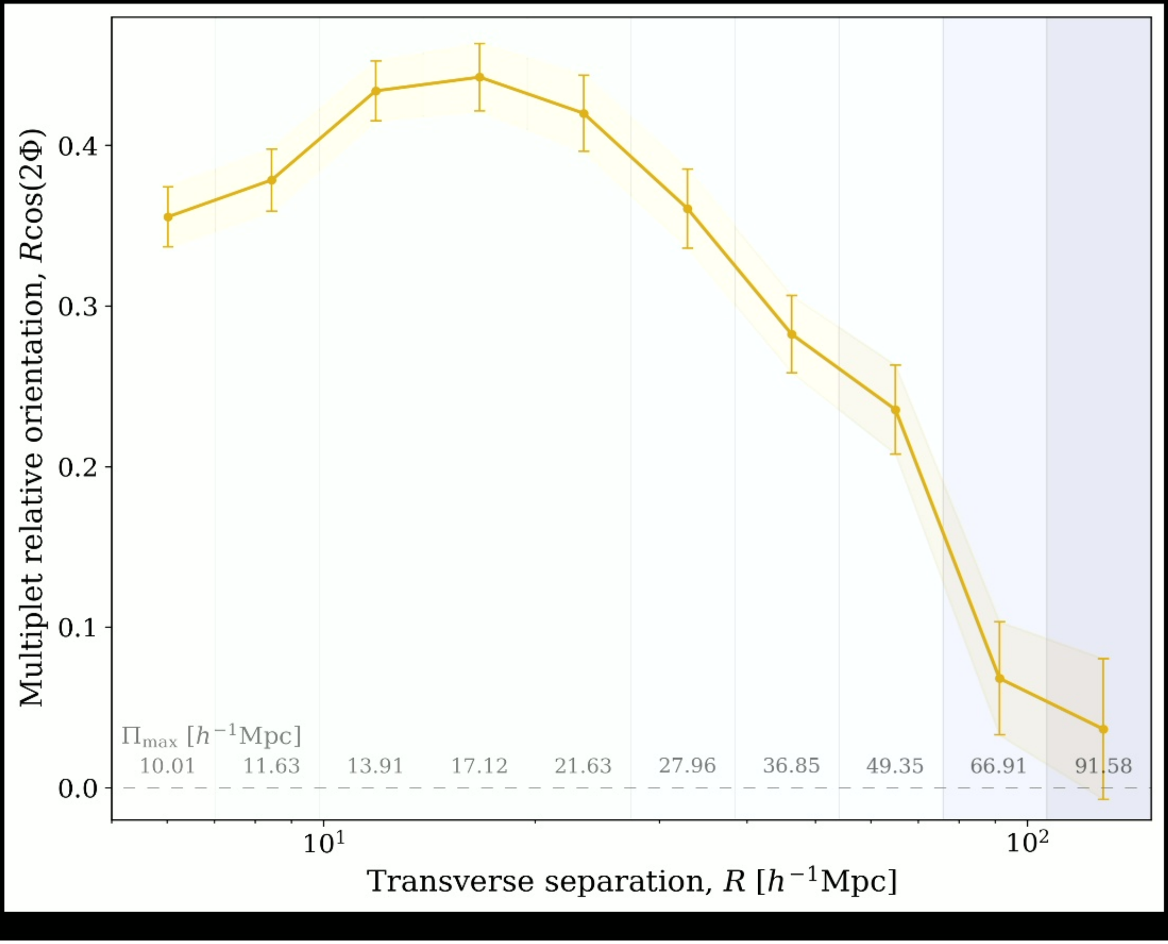


Lamman et al. 2024c

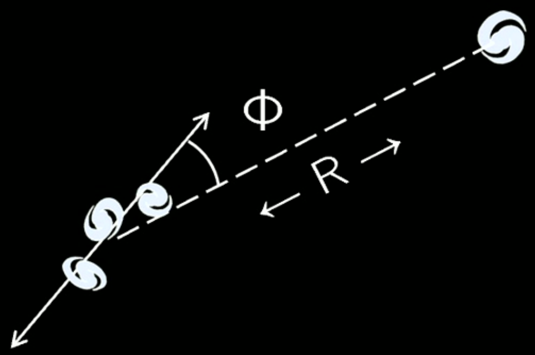
arXiv: 2408.11056

Strong Multiplet Alignment signal in elliptical galaxies

(DESI Y1 LRGs, 0.4 < z < 1.1)



Measurement of tidal field out to ~100 Mpc/h



Lamman et al. 2024c

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Modeling Multiplet Alignment

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

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

Modeling Multiplet Alignment

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

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

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

Modeling Multiplet Alignment

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

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

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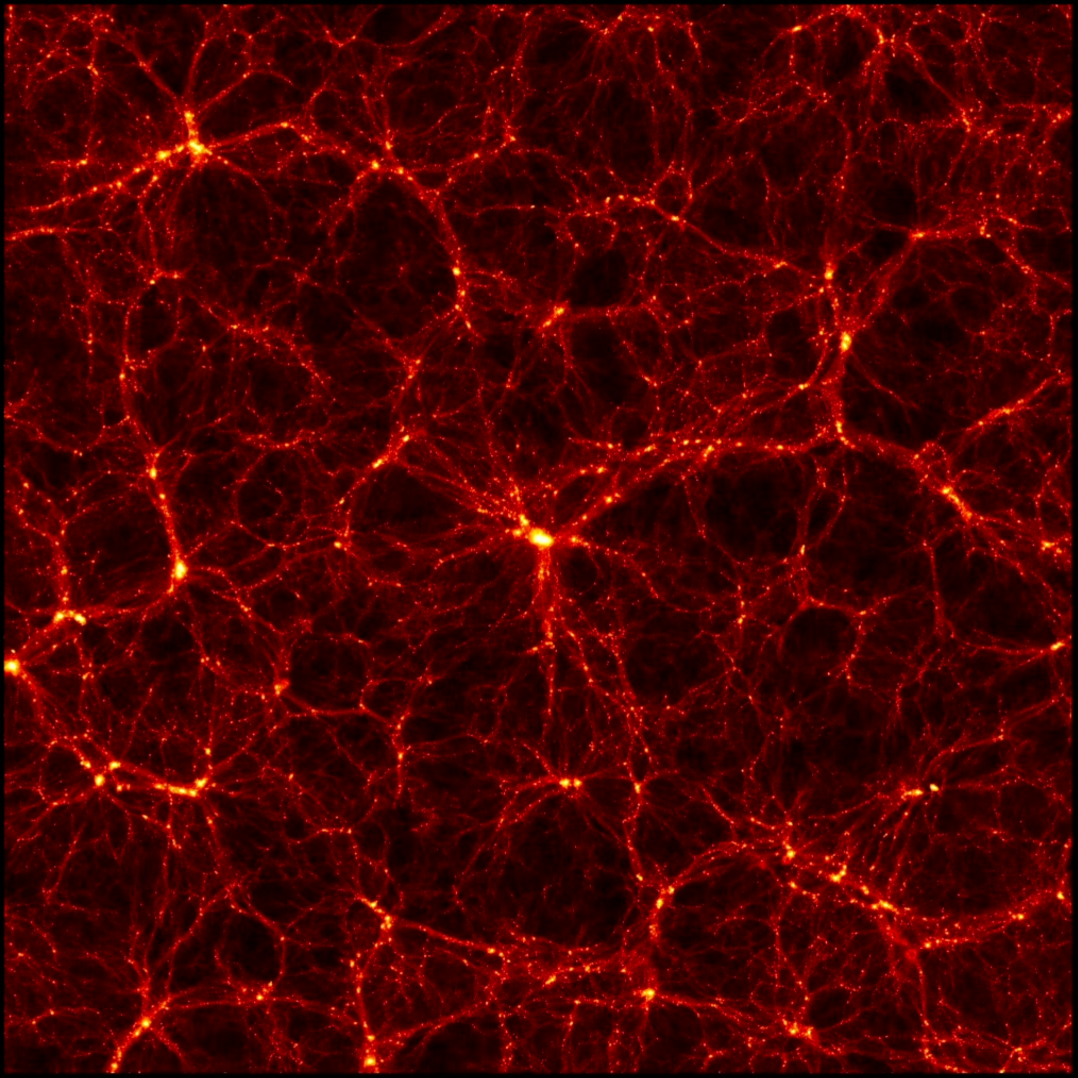
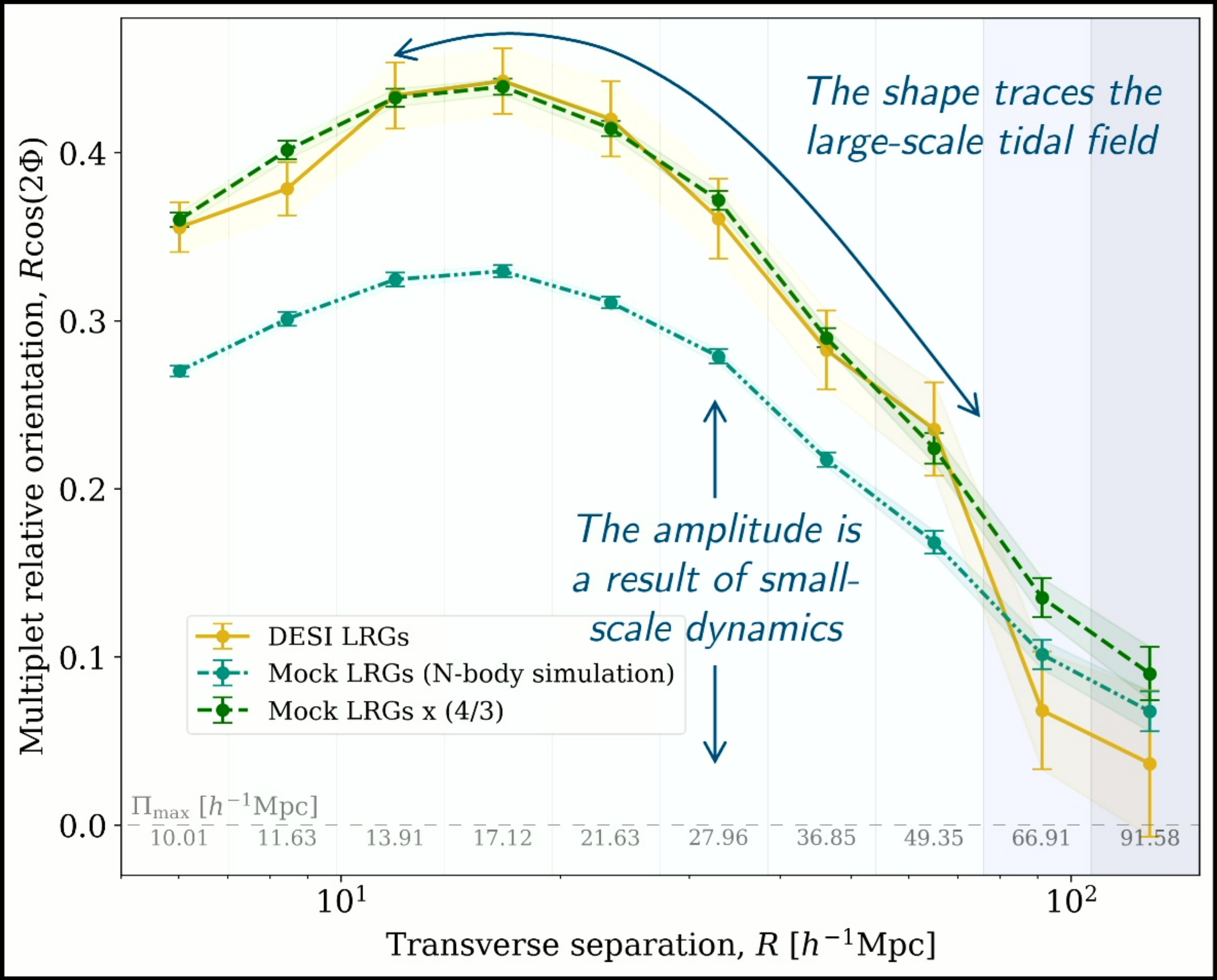
AbacusSummit

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

AbacusHOD



Garrison et al. 2018

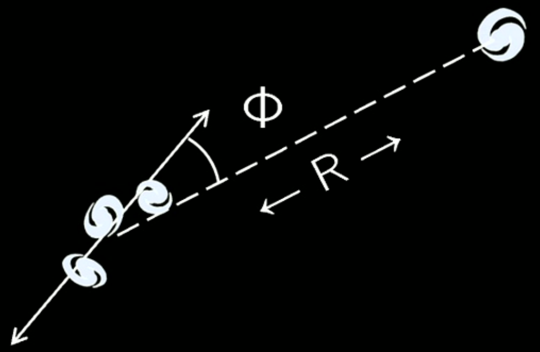


The shape traces the large-scale tidal field

The amplitude is a result of small-scale dynamics

N-body simulation reproduces shape but not amplitude.

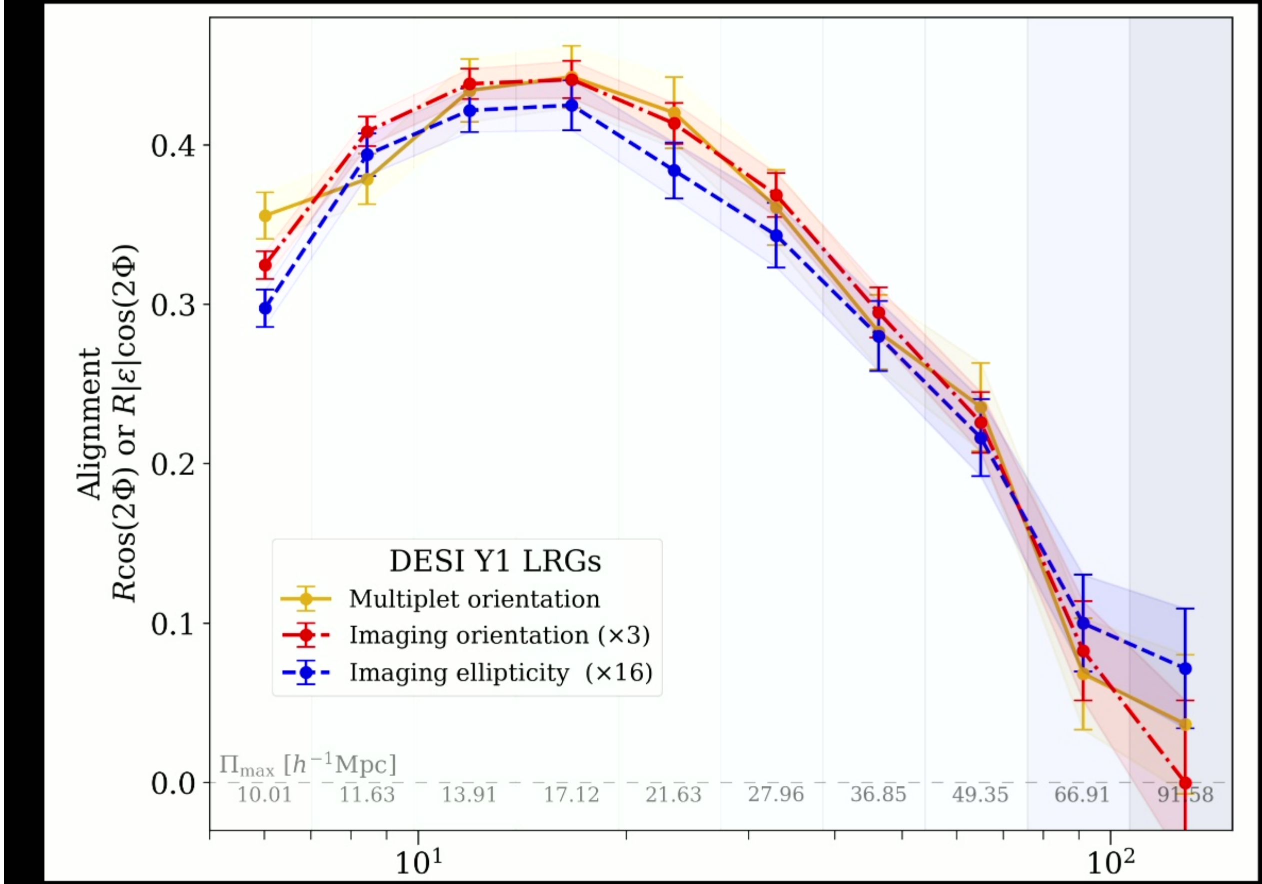
~ 1/3 lower on all scales



Lamman et al. 2024c
arXiv: 2408.11056

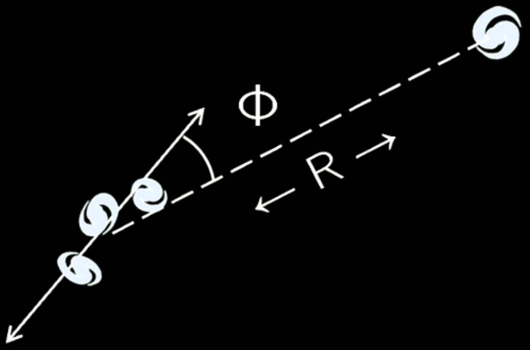
Comparison to traditional estimators

(DESI Y1 LRGs, 0.4 < z < 1.1)



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

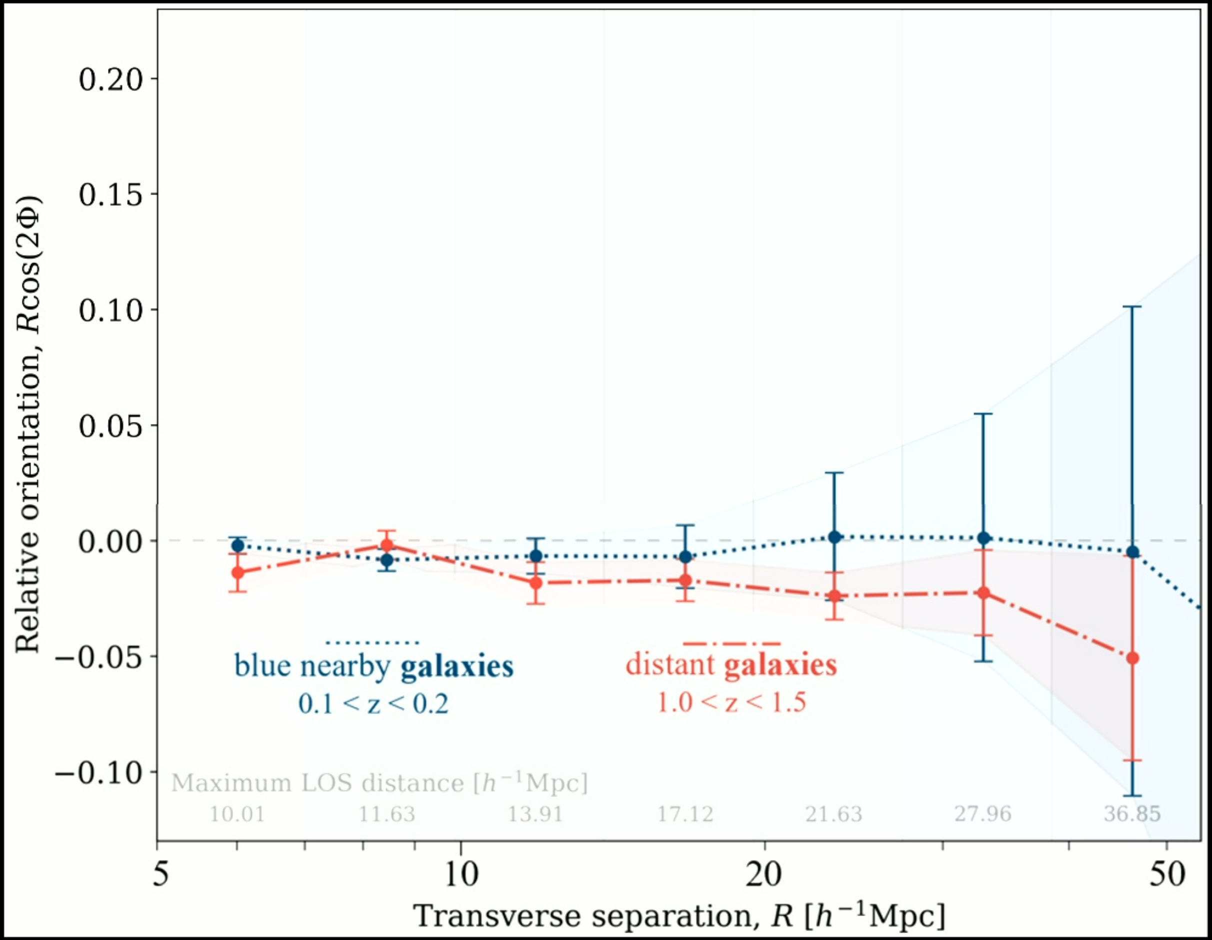
(made with 2.2M LRGs and 105k LRG multiplets)



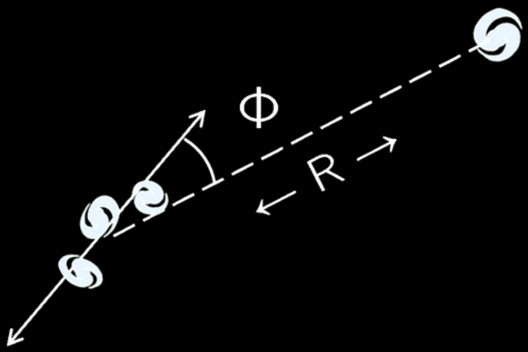
Lamman et al. 2024c
arXiv: 2408.11056

Beyond LRGs

Comparison to traditional estimators

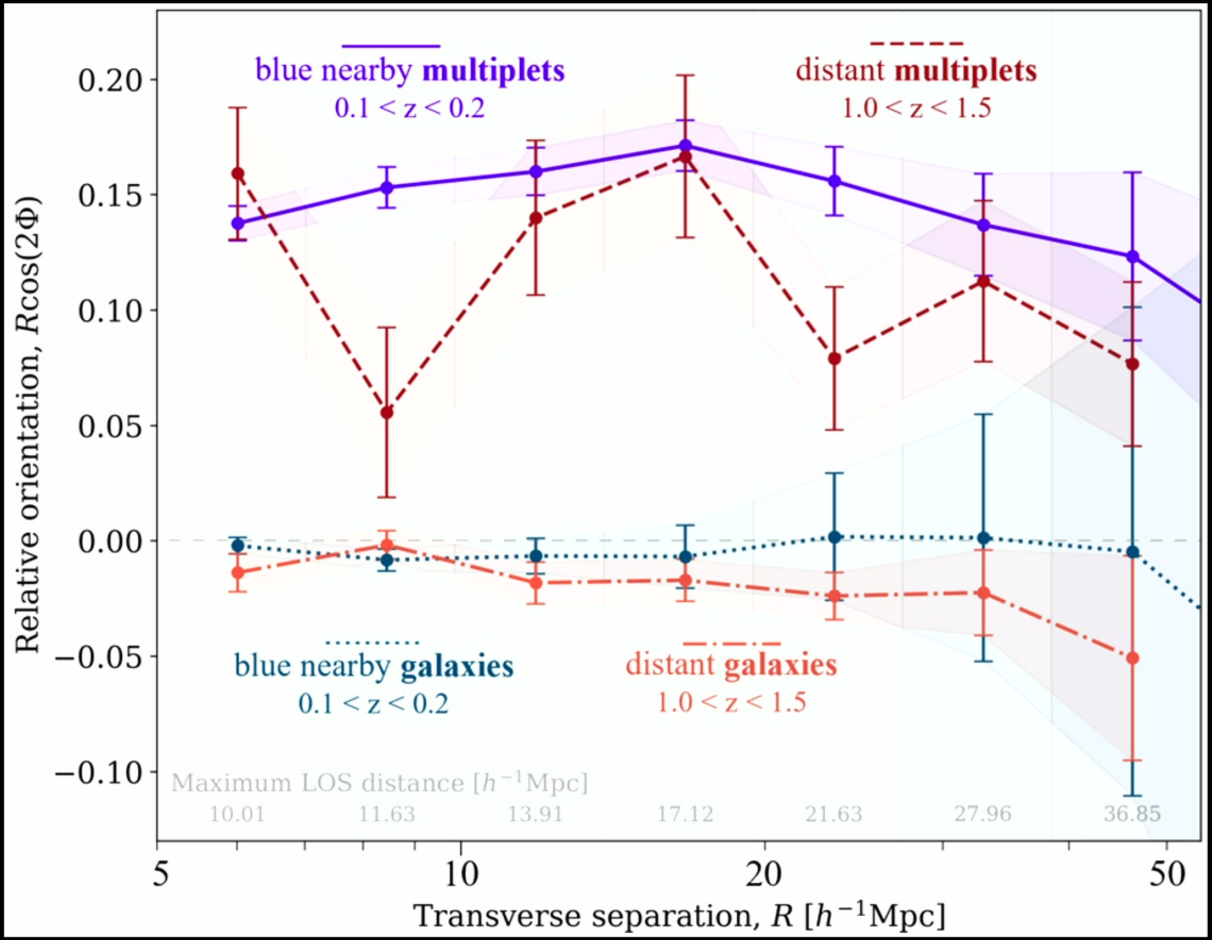


As expected, blue / spiral galaxies display no intrinsic alignment in DESI

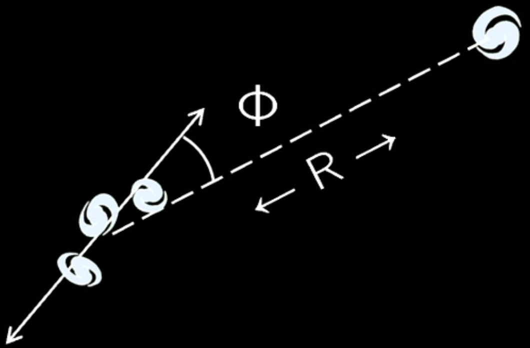


Lamman et al. 2024c
arXiv: 2408.11056

Comparison to traditional estimators



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



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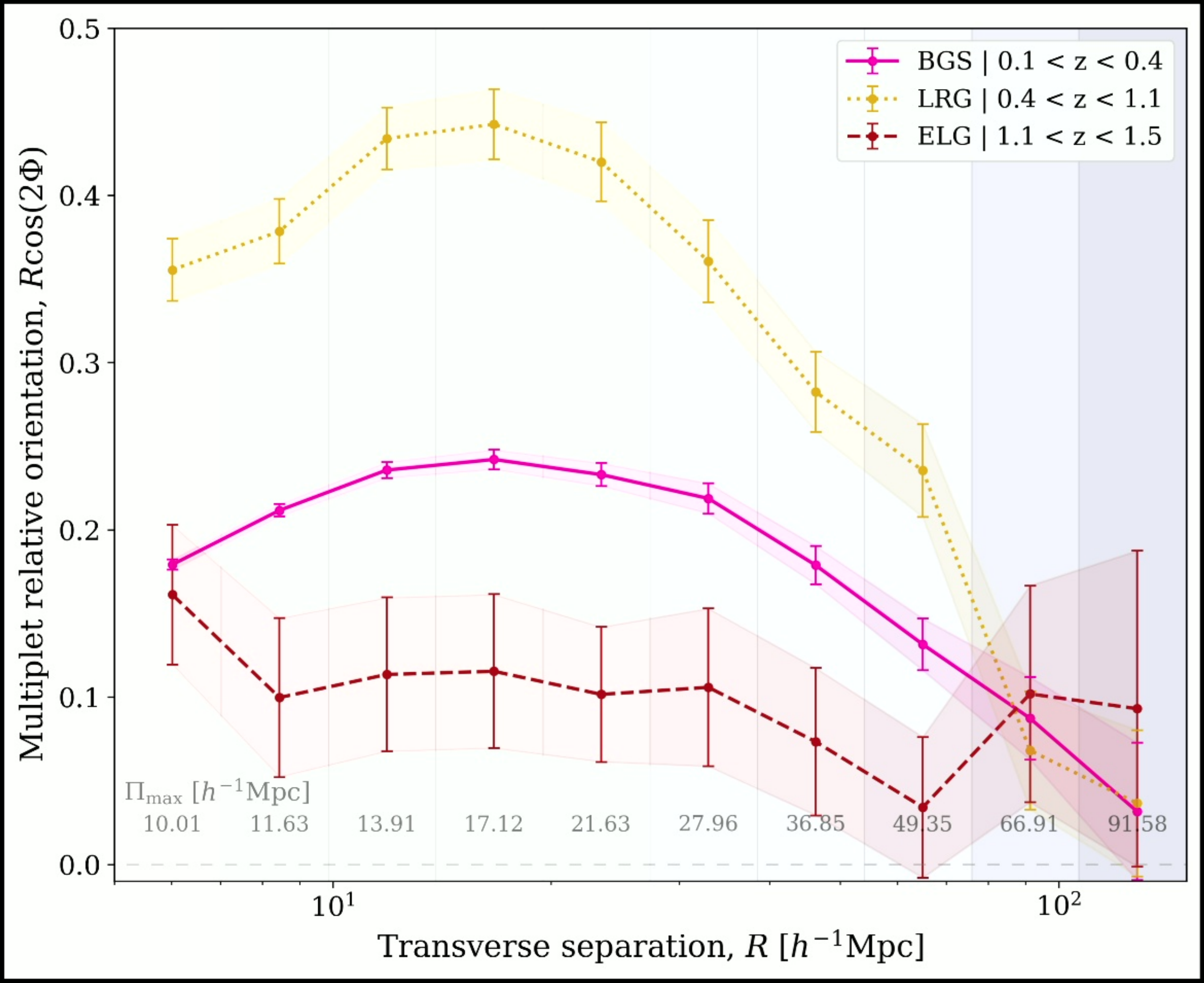
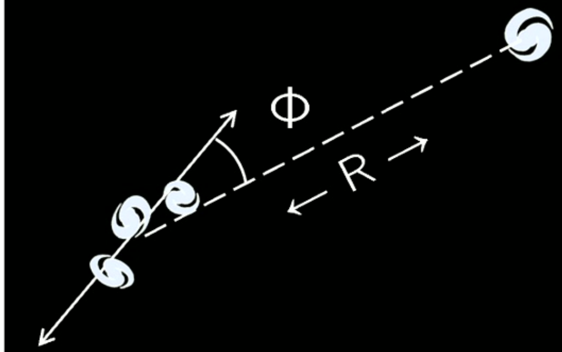


BGS is especially dense many multiplets, high SNR.

ELG subsample:
IA detection beyond z = 1 !



Lamman et al. 2024c
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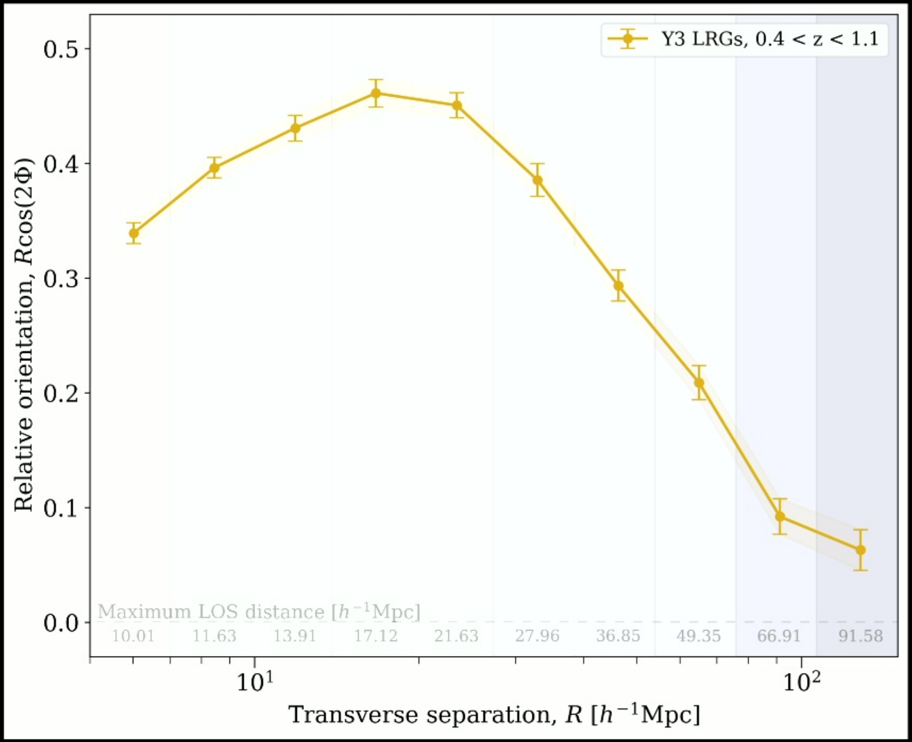
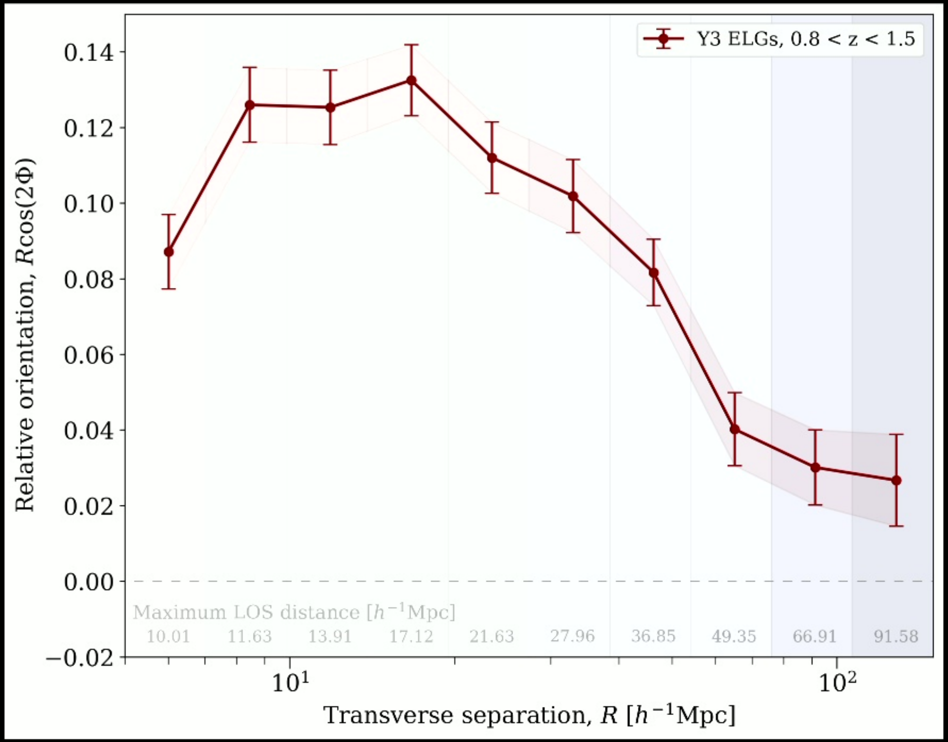
preliminary Y3 Update!

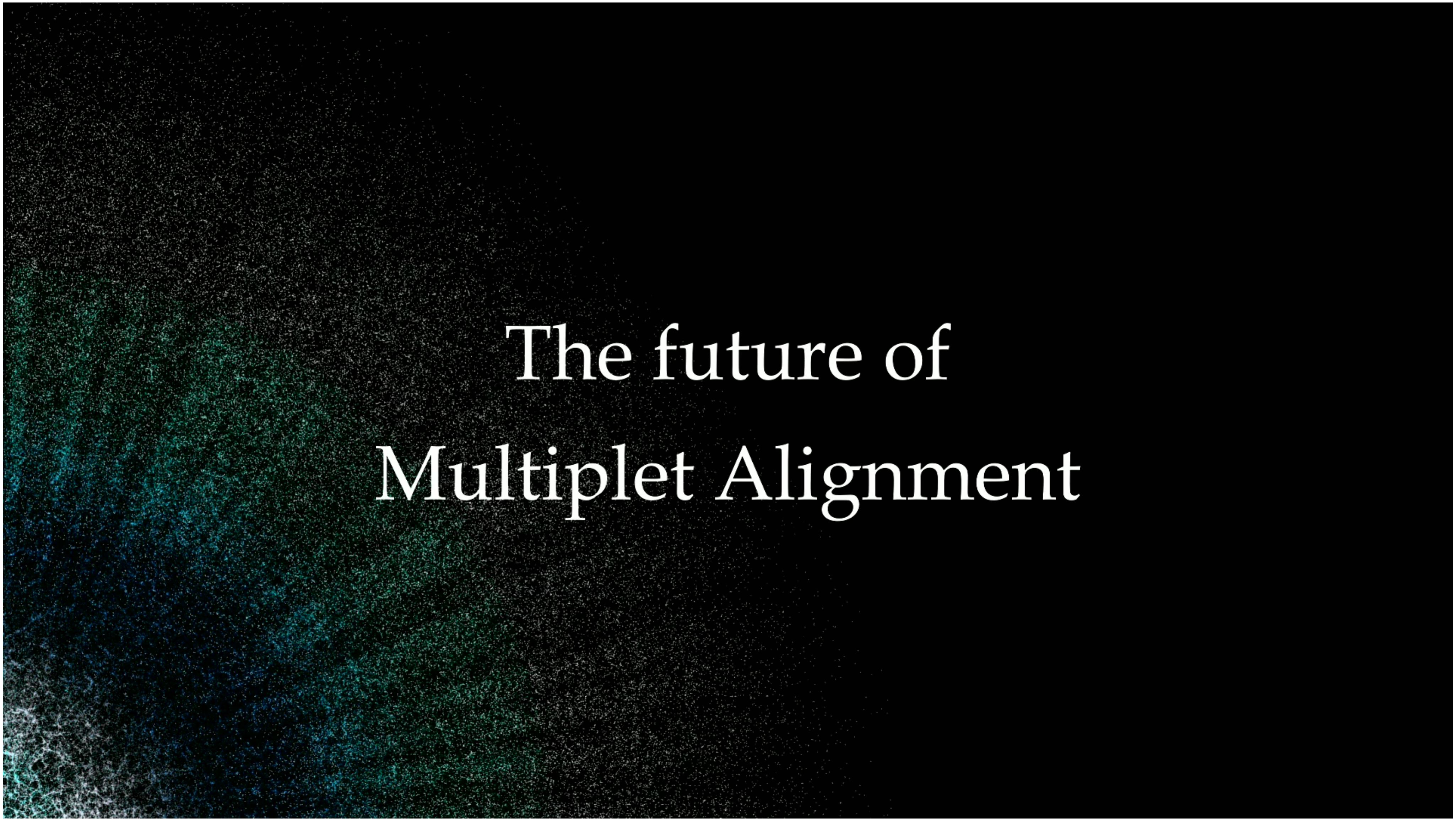
Largest improvement is in ELGs, which is now a much denser sample



Y3 LRGs, 0.4 < z < 1.1



Y3 ELGs, 0.8 < z < 1.5

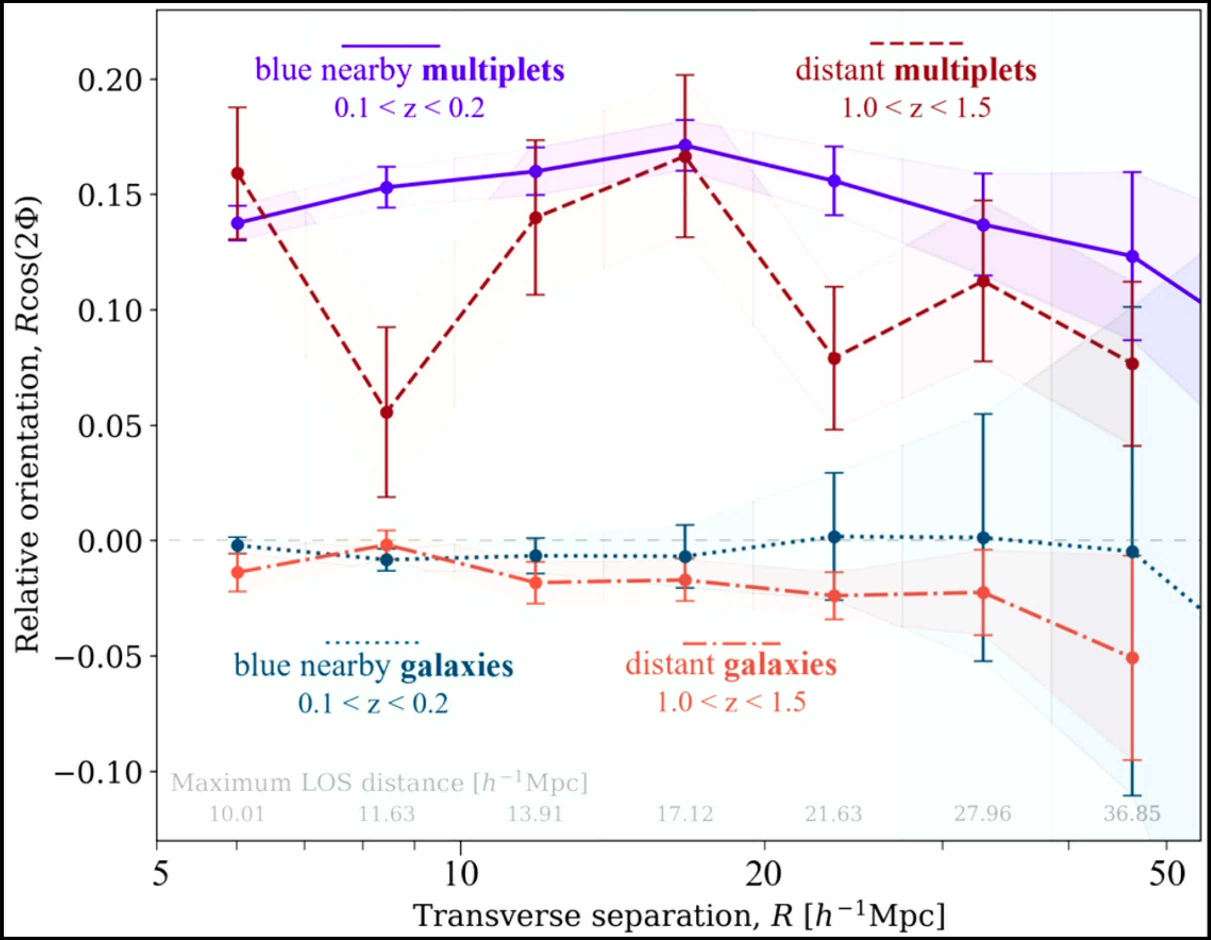


The future of Multiplet Alignment

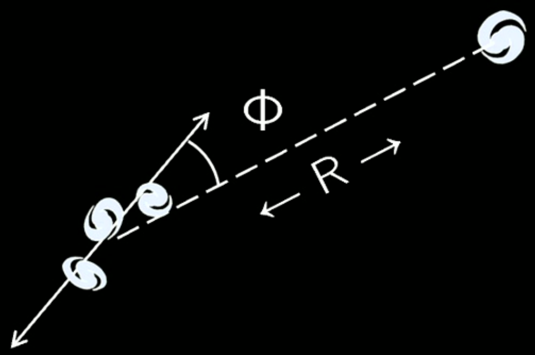
Previously, measurements and use of IA were limited to samples of bright red galaxies with high-quality imaging.

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

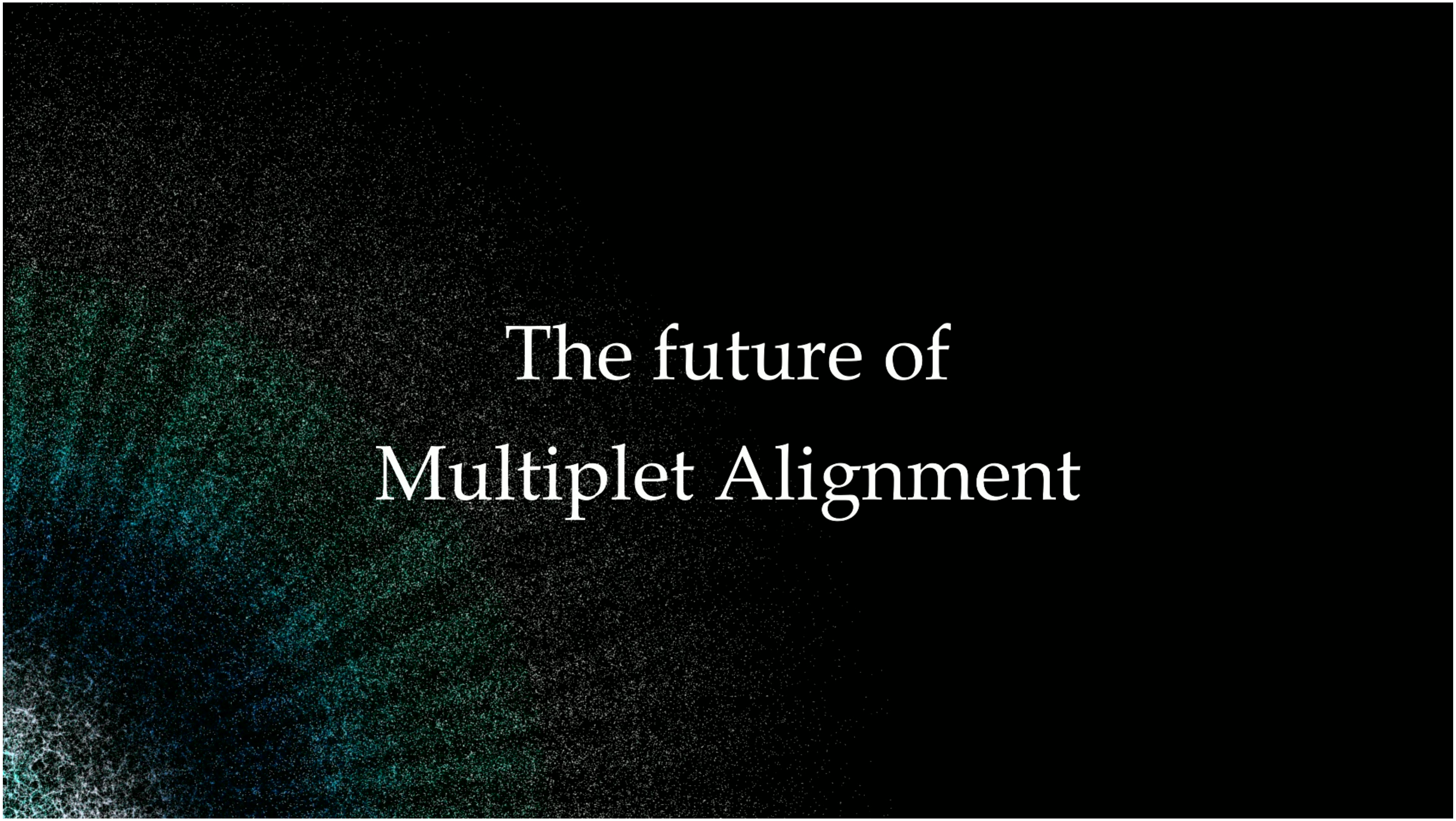
Comparison to traditional estimators



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



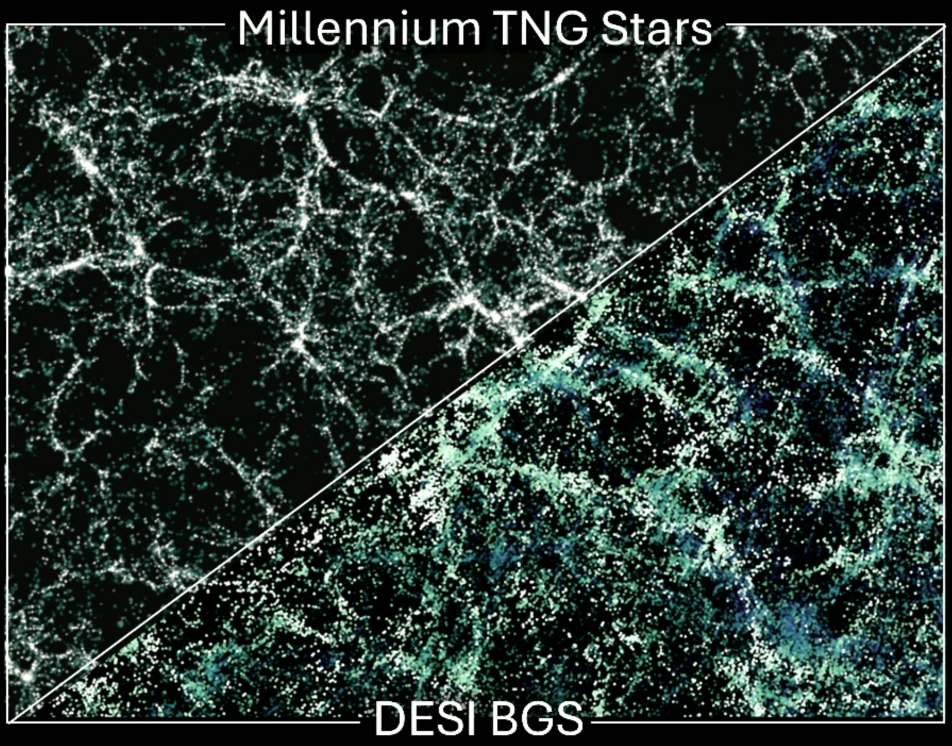
The future of Multiplet Alignment

Initial Explorations

- 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
  Hernández-Aguayo et al., 2023



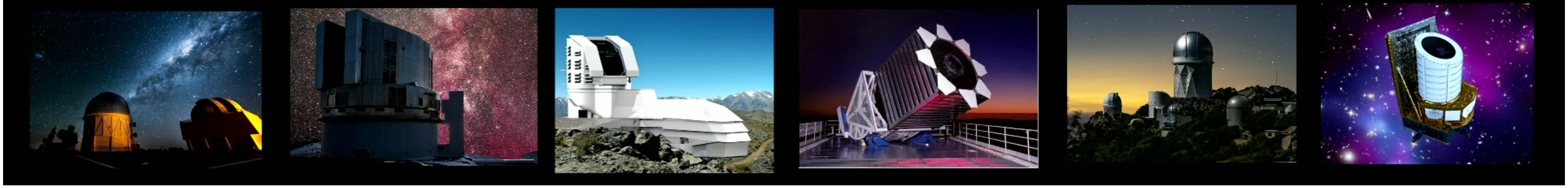
Future Data

DESI, DESI-ext, DESI-II:

will especially increase observations of spiral galaxies beyond z=1 (ELGs), the ***ideal application of multiplet alignment****.*

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

Dense imaging and weak lensing
- Rubin Observatory / LSST-DESC
- **DES**
- HSC
- **Euclid**
- Roman

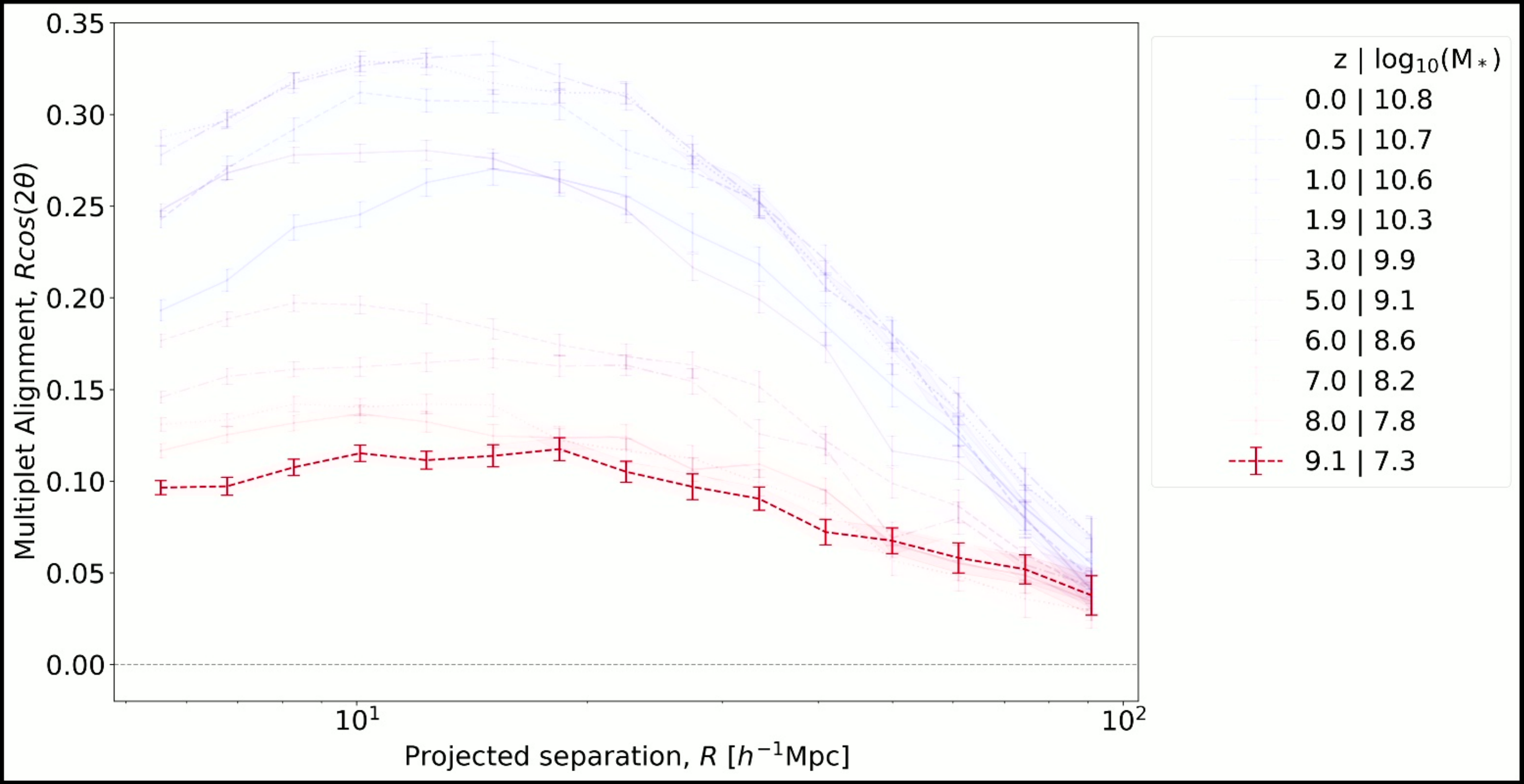


1. Connecting Galaxies to Cosmology

- **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

preliminary Multiplet Alignment in Millenium TNG

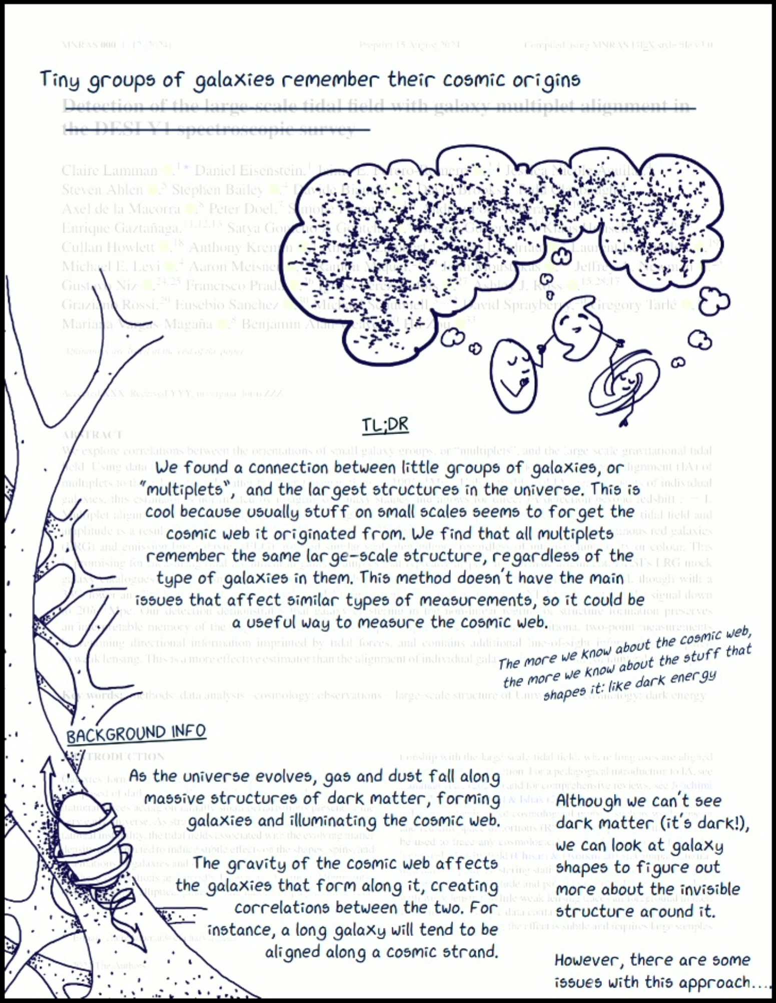


1M galaxies in [500 Mpc/h]^3 periodic box

Lamman et al. 2024

arXiv: 2408.11056

Accessible version in arXiv comments ->



Tiny groups of galaxies remember their cosmic origins

~~Detection of the large-scale tidal field with galaxy multiplet alignment in the DESI Y1 spectroscopic survey~~

TL;DR

We found a connection between little groups of galaxies, or "multiplets", and the largest structures in the universe. This is cool because usually stuff on small scales seems to forget the cosmic web it originated from. We find that all multiplets remember the same large-scale structure, regardless of the type of galaxies in them. This method doesn't have the main issues that affect similar types of measurements, so it could be a useful way to measure the cosmic web.

The more we know about the cosmic web, the more we know about the stuff that shapes it: like dark energy

BACKGROUND INFO

As the universe evolves, gas and dust fall along massive structures of dark matter, forming galaxies and illuminating the cosmic web.

The gravity of the cosmic web affects the galaxies that form along it, creating correlations between the two. For instance, a long galaxy will tend to be aligned along a cosmic strand.

Although we can't see dark matter (it's dark!), we can look at galaxy shapes to figure out more about the invisible structure around it.

However, there are some issues with this approach...

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