Intrinsic Alignments Between Galaxies and the Cosmic Web at z ~ 1−2 in the IllustrisTNG Simulations

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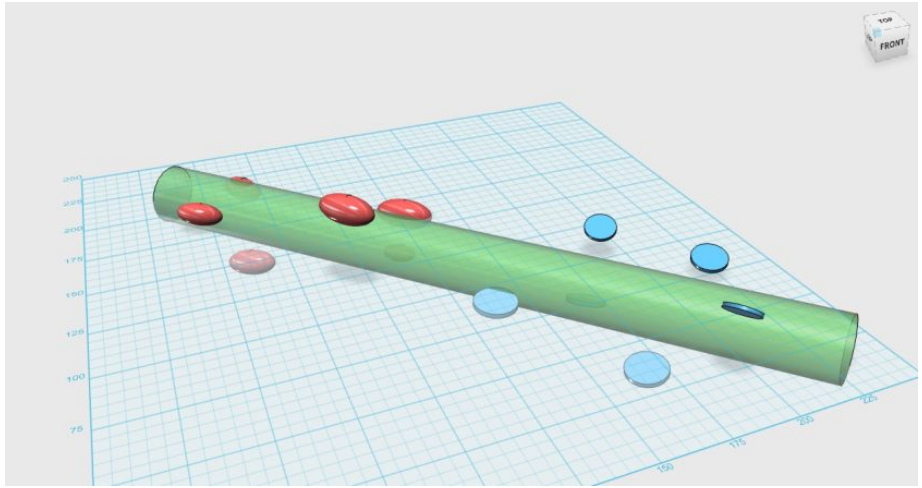
Overview

- Intrinsic alignment background, overview
- Idealized intrinsic alignments from IllustrisTNG hydrodynamic simulation suite
- Observational prospects for intrinsic alignments with PFS-GE

Intrinsic Alignment

- Non-random alignment of elliptical galaxy orientations, disc galaxy angular momenta with matter overdensities
- Creates galaxy-galaxy alignment on sky, degenerate with weak lensing effects
- For remainder of talk, referring to **density-galaxy** alignment only



Joachimi+2015

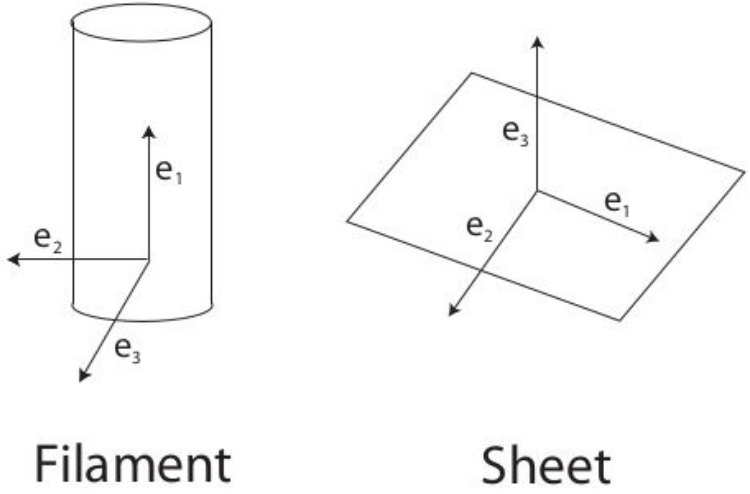
Intrinsic Alignment

- Elliptical galaxy longest-axis vector (**“shape”**) aligned parallel to cosmic web filaments, walls
  - From sims, strength of alignment increases with galaxy mass (see eg. Forero-Romero+14, Pandya+19)
- Disc galaxy angular momenta (**“spin”**) aligned parallel to cosmic web filaments/walls at low mass, perpendicular at high mass
  - “Spin-flip transition mass” $10^{9.5}$~$10^{10.5}$ $M_{\odot}$ from hydrosims (Codis+2015, Codis+2018, Wang+2018, etc.)
- Few observations beyond z~0, due to difficulty of density reconstruction
- For z=1-2, PFS-GE well-placed to do that!

IllustrisTNG Idealized Intrinsic Alignments

Cosmic Web Characterization

- **Deformation tensor**
  - Calculated from density field: Hessian of gravitational potential at each point
  - Ordered eigenvalues of tensor $e_1 \geq e_2 \geq e_3$, corresponding eigenvectors $\mathbf{e_1}$, $\mathbf{e_2}$, $\mathbf{e_3}$
  - Physical meaning under Zeldovich approximation: $\mathbf{e_3}$ filament direction + wall plane-parallel direction.
  - Generalized “cosmic web direction” for every point



Krolewski+2017

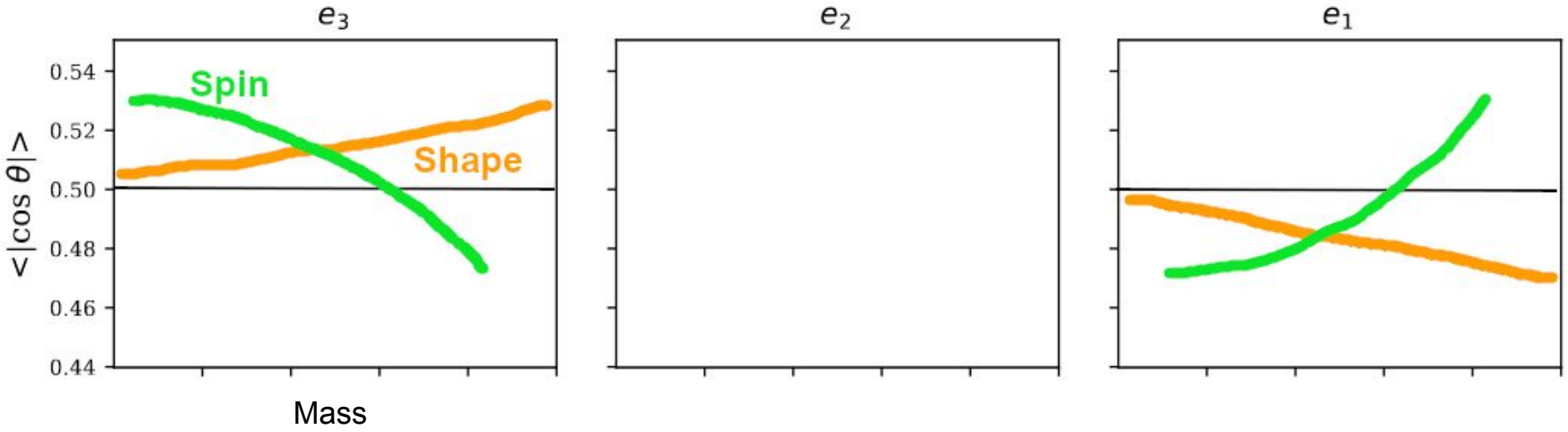
Simulations

- IllustrisTNG hydrodynamical simulation suite
  - TNG300-1 (205 Mpc/h box length) & TNG100-1 (75 Mpc/h) used; TNG100-1 better mass resolution
  - z=1, z=2 snapshots
- Galaxy longest-axis (shape) sample: Shi+2021
  - Galaxies modelled as ellipsoids: reduced-mass inertia tensor formalism
  - Stellar mass ≥ 10^9 $M_\odot$
- Galaxy angular momentum (spin) sample
  - ≥ 50 total particle cut
- Galaxy shape/spin & density deformation tensor calculated for {z=1, z=2} ⊗ {TNG300-1, TNG100-1} DM density

Quantifying Intrinsic Alignments

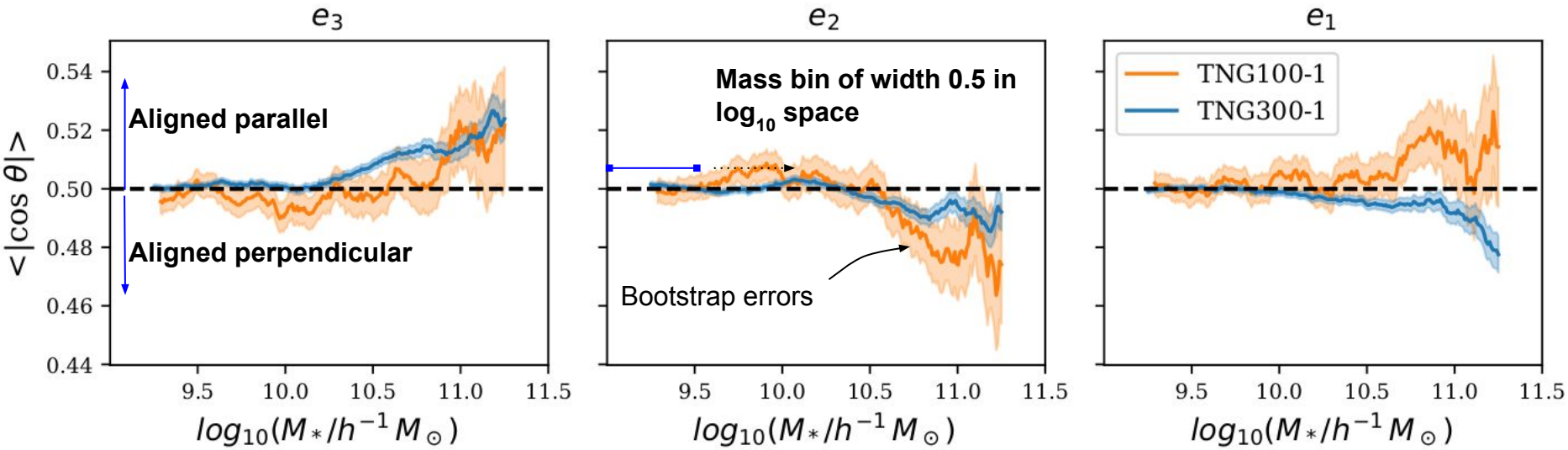
- Alignment metric for each galaxy
  - Absolute-valued dot product of galaxy's shape/spin with 3 deformation tensor eigenvectors at nearest point
  - $|\cos \theta|$ (**alignment**)
  - [0, 1] with 0 = perpendicular, 1 = parallel
- **Mean alignment** of galaxy ensemble: $\langle|\cos \theta|\rangle$
  - Null case: $\langle|\cos \theta|\rangle = 0.5$ (2 vectors with independent uniformly random directions)

Expected Intrinsic Alignments (from past simulations)



Shape Alignment Results

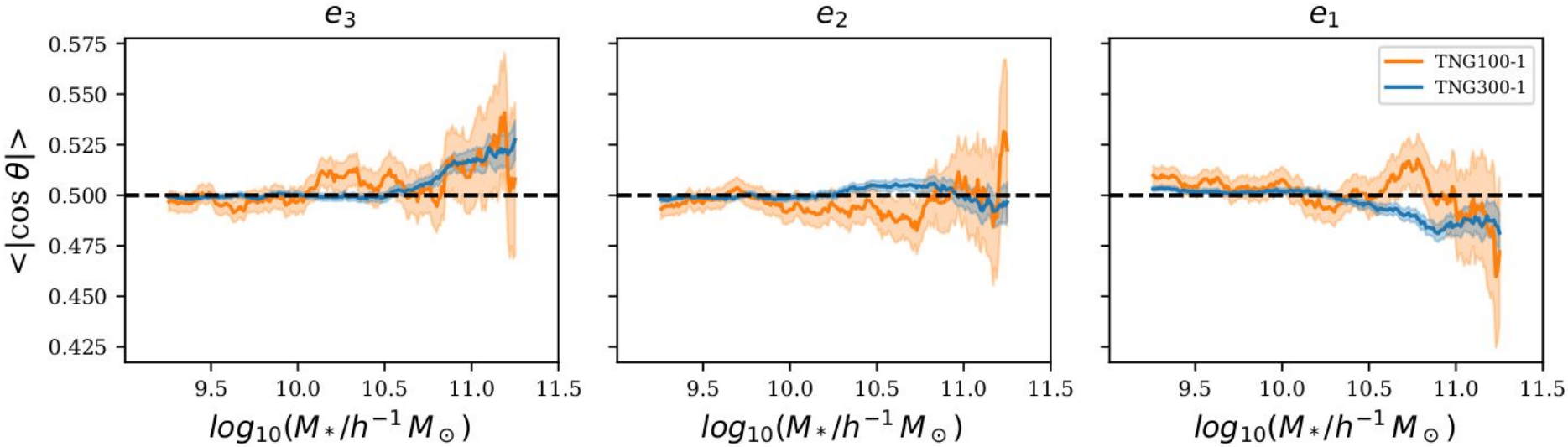
z = 1



- Shape alignment strength increasing with mass, consistent with previous simulation-based studies
- Good observational prospects for high-mass (i.e. bright) galaxies

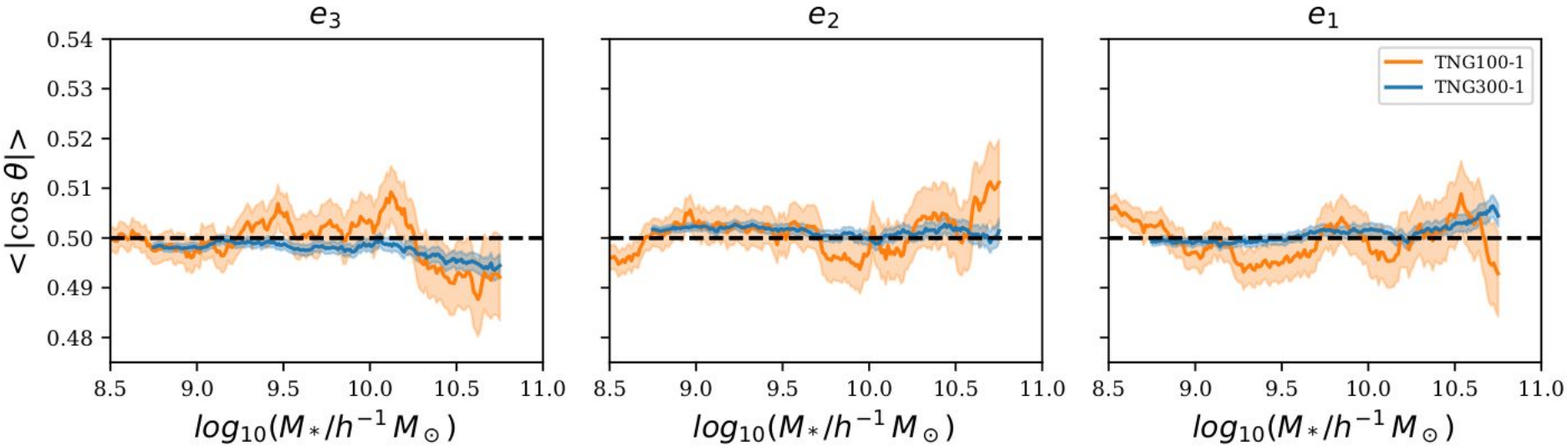
Shape Alignment Results contd.

z = 2



Spin Alignment Results

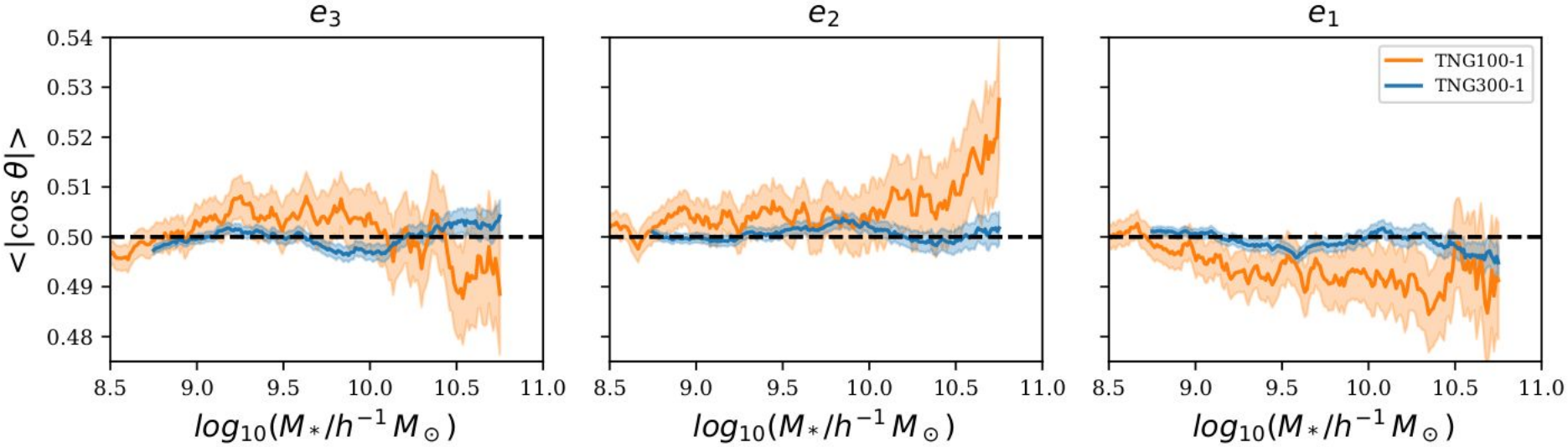
z = 1



- **No significant "spin-flip"** along filament direction (**e_3**) from parallel to perpendicular/positive to negative <|cos θ|> (!)
- Magnitude of <|cos θ|> less than seen in prev. works for Horizon-AGN hydrosim (Codis+2015)
- Possibly because our sample is stellar-mass selected, like PFS. Probably fewer SF galaxies

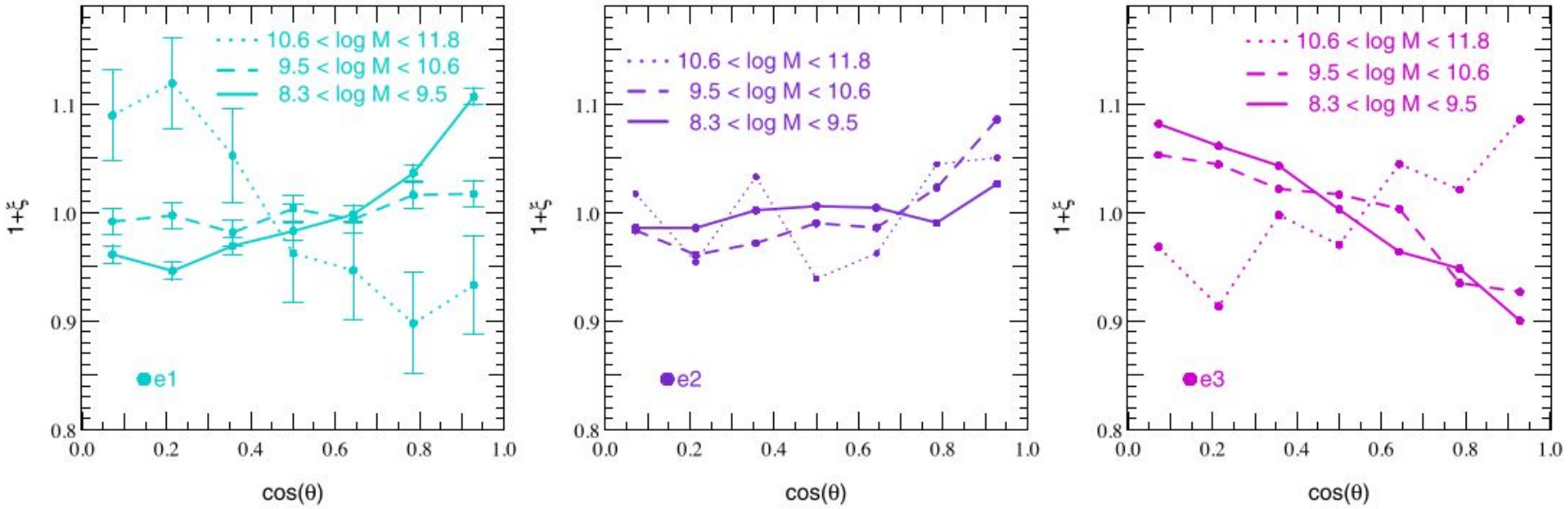
Spin Alignment Results contd.

z = 2

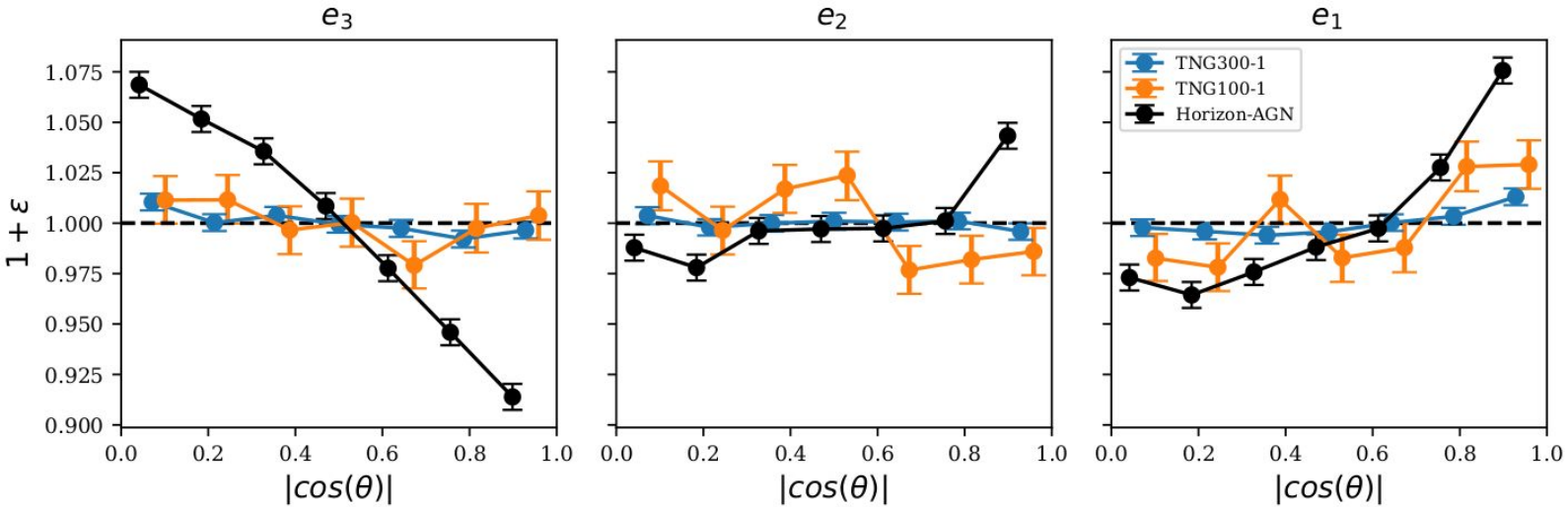


- No significant spin-flip for z=2 as well

Horizon-AGN Alignment Spin-flip (Codis+2015)



Comparison with Horizon-AGN hydrosim



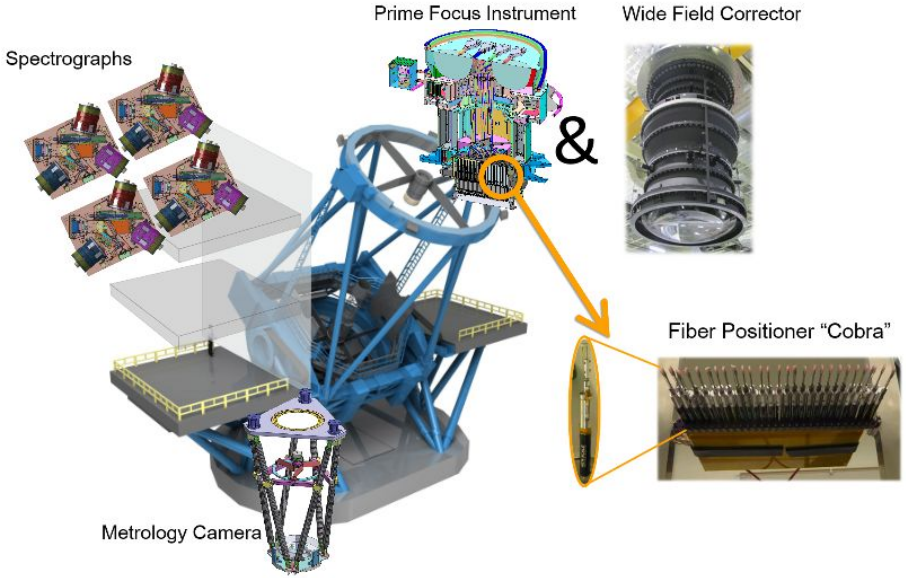
- Compare with z=1.2 spin alignments from Codis+2015; same cosmic web formalism
- z=1 IllustrisTNG spin alignment signal **~2.4x weaker** than contemporary Horizon-AGN sim's!
- Suggests intrinsic alignment has significant subgrid physics dependence?

PFS Alignment Signal Forecast

How well can we measure the alignment we see in sims?

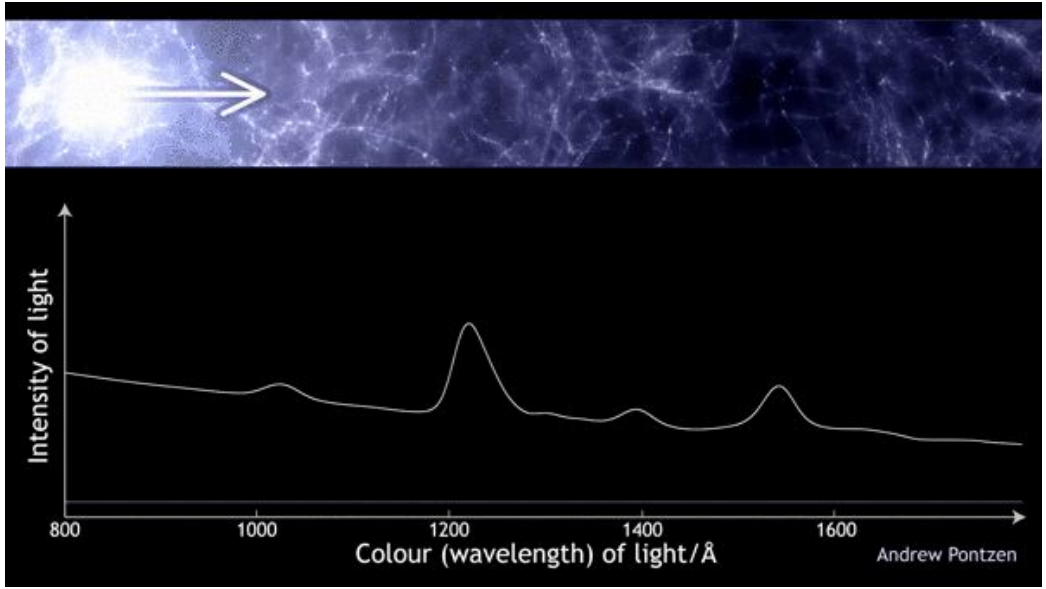
Subaru Prime Focus Spectrograph Survey

- Spectrographic redshifts (spec-z) from $0.7 < z < 7$
- Focus is on Galaxy Evolution program @ z~0.7–2.5
  - For z~1.2, spec-z for 250,000 galaxies in $3.25 * 10^7\ h^{-3}\ Mpc^3$
  - For z~2.3, spec-z for 15,000/30,000 galaxies in $2.7 * 10^7\ h^{-3}\ Mpc^3$ + **independent density reconstruction from IGM tomography**
- Matched shapes from near-IR Hubble, Roman imaging
- Need deep IFU spectra to estimate spins, so not considering spin alignment



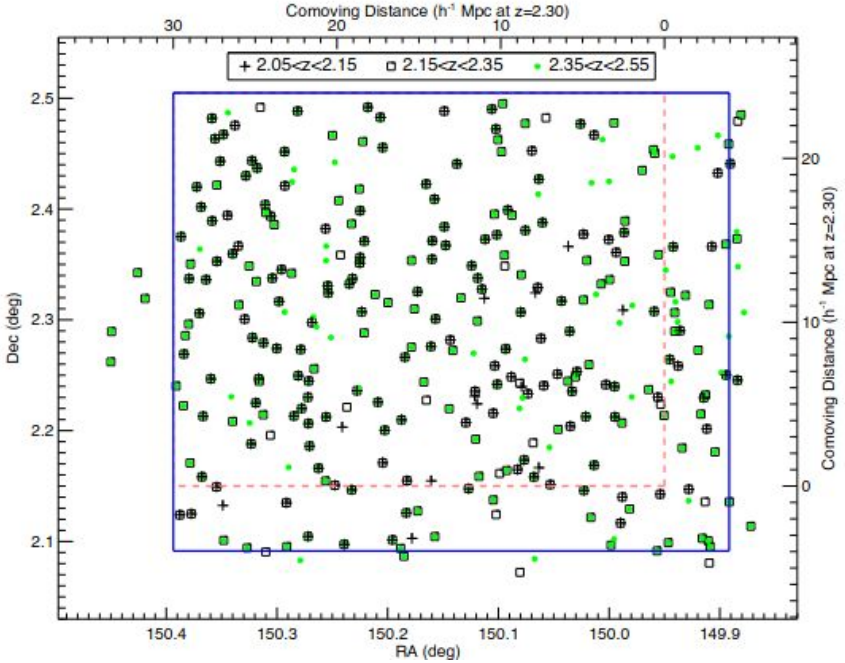
IGM Tomography

- Density reconstruction at high-z hard: few galaxies!
  - COSMOS-level of coverage needed to attempt (Ata+2020)
- IGM tomography offers direct probe of cosmic web
  - Neutral H produces redshifted absorption lines (Lyman-alpha forest) in spectrum of background objects
- CLAMATO survey: 4.1 * 10^5 h^{-3} Mpc^3 (Lee+2018, Horowitz+2021)
  - PFS to probe 2 orders of magnitude higher volume!



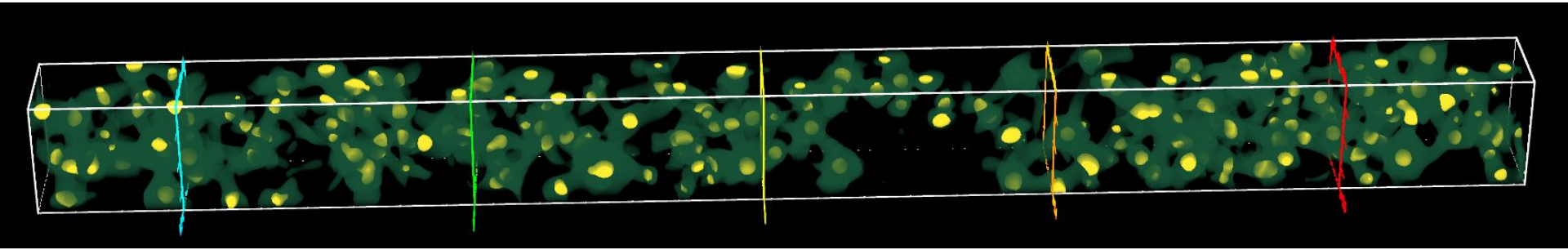
Source: UCL Mathematical & Physical Sciences

IGM Tomography contd.

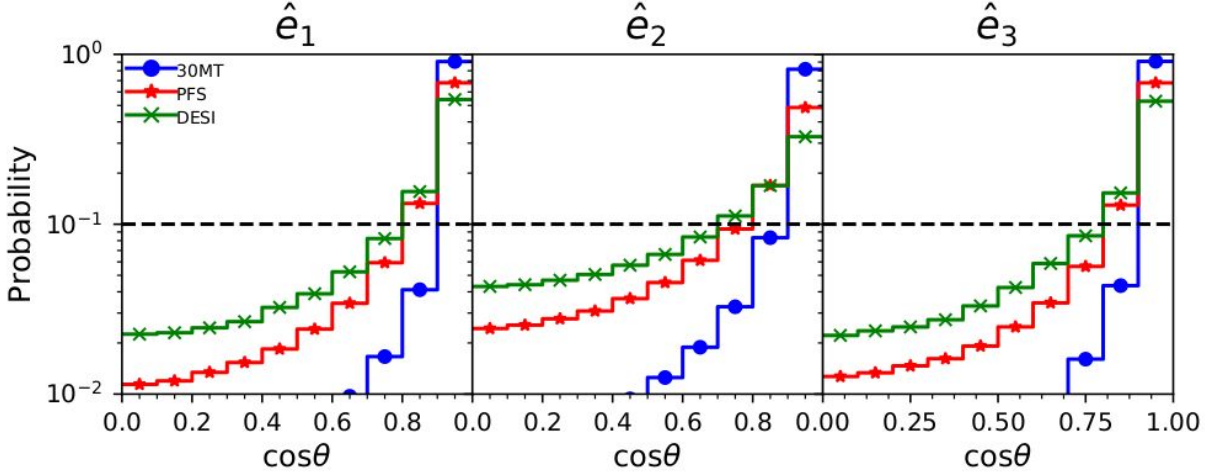


↑ Source: CLAMATO DR2 (Horowitz+2021)

IGM Tomography contd.



↑ Source: CLAMATO DR2 (Horowitz+2021)



↑ Alignment between reconstructed and true deformation tensor eigenvectors (Horowitz+2019)

Detailed Procedure

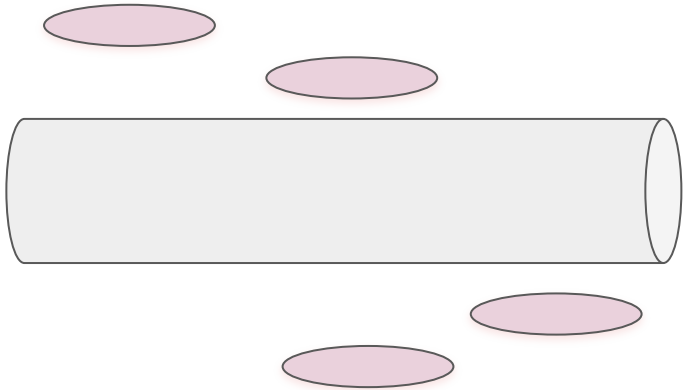
- Density, galaxies from TNG300-1 (L = 205 Mpc/h); z=1, z=2 snapshots
- Galaxy sample from abundance-matching via simulated magnitudes (note: no dust)
- Density reconstruction at z=1: galaxies as tracers via TARDIS-II code (Horowitz+2021)
- Density reconstruction at z=2: galaxies + mock IGM tomography survey via TARDIS-II
- For 64 “viewing angles onto volume” on half-sphere:
  - Reconstruct z=2 density from IGM tomographic “skewers” along viewing angle
  - Project galaxy shape ellipsoid onto viewing angle plane to get projected (“2D”) shape
  - Project reconstructed deformation tensor eigenvectors onto viewing plane plane
- Marginalize observed alignment over viewing angles: **significant uncertainties!**

Cosmic Variance from Projected Alignments

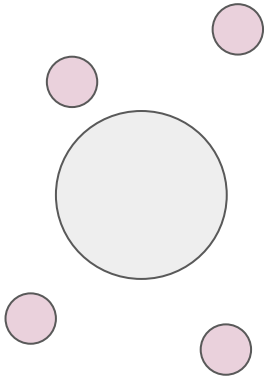
Large-scale anisotropies lead to variance in the projected alignment signal (even if have full 3D scalar information)

Even 300Mpc box significantly affected by this… possibility of ‘false negative’

Viewed from ‘side-on’

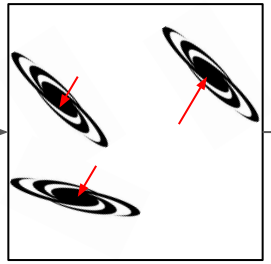


Viewed from ‘head-on’

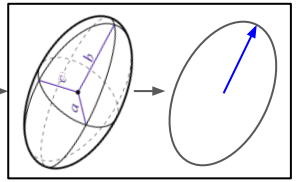


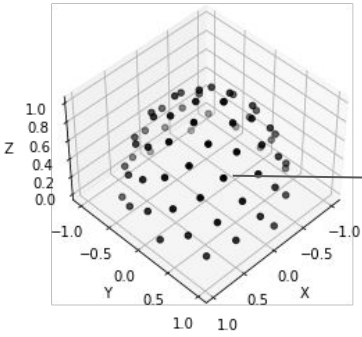
Observational galaxy sample

RSD



Ellipsoid projection onto viewing angle





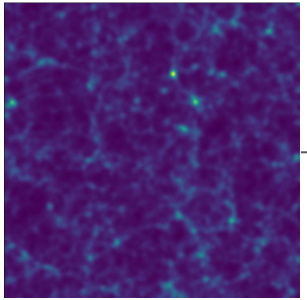
Viewing angle ℓ

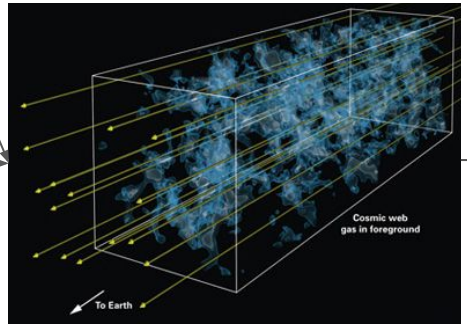
Eigenvector projection onto viewing angle

Galaxy positions + mock IGM tomo. survey (z=2 only)

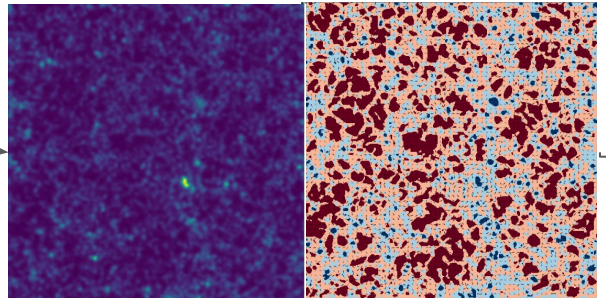
Reconstructed DM density + deformation tensor

True DM density



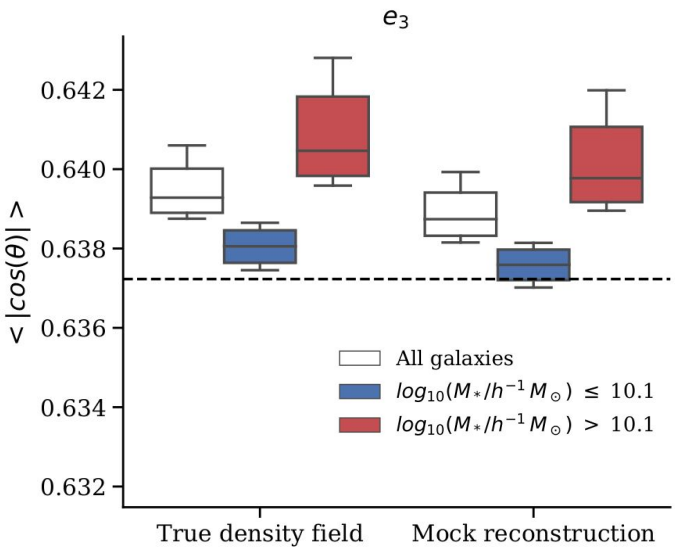


TARDIS-II



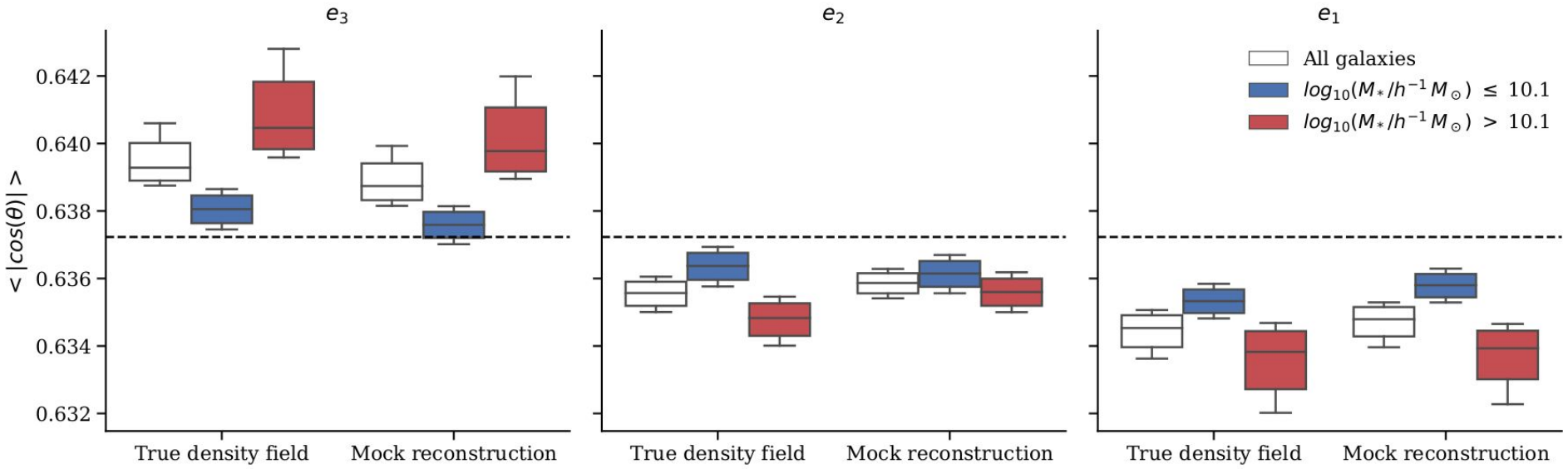
2D Alignment

- Alignment null distribution after projection (2D): upper half of Beta[α = β = 0.5]
  - Random 3D vectors after projection → random 2D vectors
- Uncertainties from bootstrapping over galaxies in sample **+ over all viewing angles** simultaneously



Observational z=1 Shape Alignment

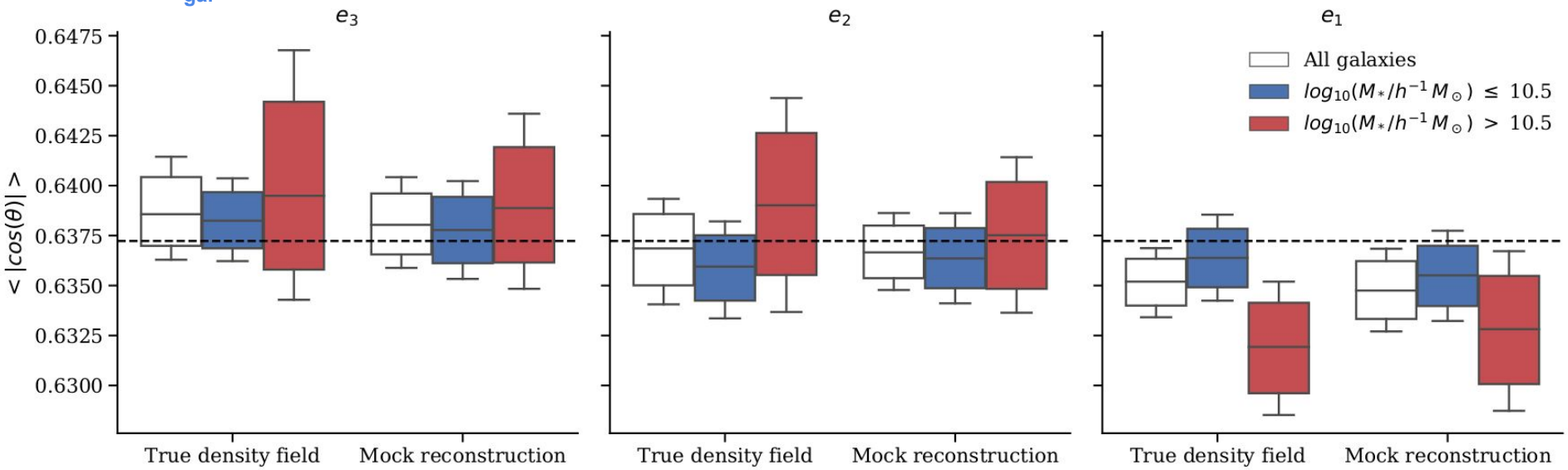
z = 1



- Large galaxy sample (N_{gal} = 250,000) + accurate density reconstruction => significant detection! 🎉
- Overall significance $\Delta\chi^2 = 5.3\sigma$

Observational z=2 Shape Alignment

z = 2, N_{gal} = 15,000



- Smaller galaxy sample + more uncertain density reconstruction => $\Delta\chi^2 = 1.3\sigma < 3\sigma$
  - If N_{gal} = 30,000, $\Delta\chi^2 = 1.5\sigma$
- But if ideal alignment signal actually ~2.4x stronger, as in Horizon-AGN, then z=2 $\Delta\chi^2 = 1.3 * 2.4 = 3.1\sigma$ ***EXTREMELY ROUGH ESTIMATE***

Observational Bottleneck: Galaxy Shapes

- Estimation of galaxy shapes needs high-resolution ($\Delta\theta \sim 0.2$ arcsec) near-IR images – i.e. space-based telescopes
- Currently, images from HST only cover ~2.4 deg^2 of PFS-GE footprint, well short of total 12.3 deg^2 footprint
- Roman Space Telescope should cover full footprint, but only post-2029

Summary

- Cosmic web-galaxy intrinsic alignments important nuisance parameter for weak lensing. Subaru-PFS well placed to constrain alignment at high redshift (z~1-2)
- IllustrisTNG intrinsic alignments **surprisingly much weaker** than contemporary Horizon-AGN sim; significant subgrid physics dependence?
- Observational prospects for detecting z = 1 shape intrinsic alignment good, more uncertain for z = 2
- But depends on ideal intrinsic alignment signal; significant detection possible at z = 2, if ideal alignment magnitude larger than IllustrisTNG prediction
- Need more galaxy imaging to get matched shapes!

Appendix

Viewing Angle Variance