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

arXiv:2211.09331

Benjamin Zhang[1], Khee-Gan Lee[2], Alex Krolewski[3], Jingjing Shi[2], Benjamin Horowitz[4], Robin Kooistra[2]

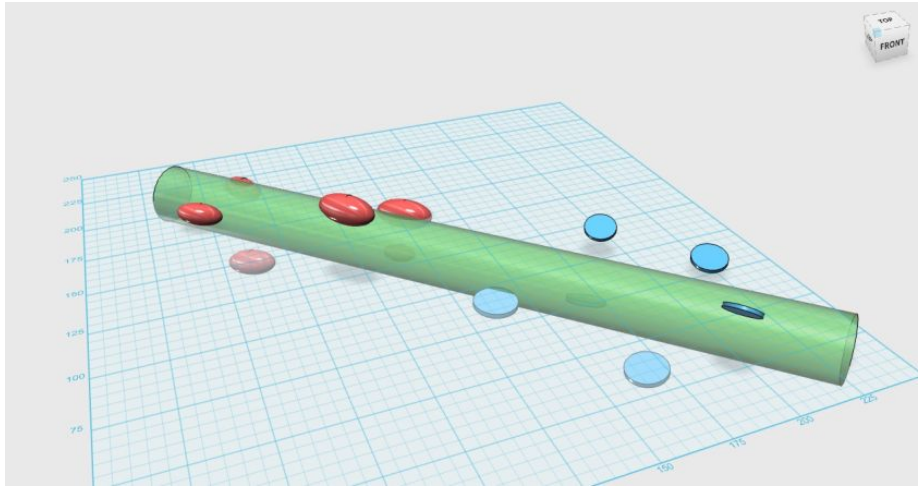
[1]**University of Southern California** [2]Kavli IPMU [3]Perimeter Institute [4]LBNL

Overview

- Galaxy-cosmic web alignment background, overview
- Idealized alignments from IllustrisTNG simulations
- Observational prospects for alignment detection with Subaru Prime Focus Spectrograph survey (Subaru-PFS)

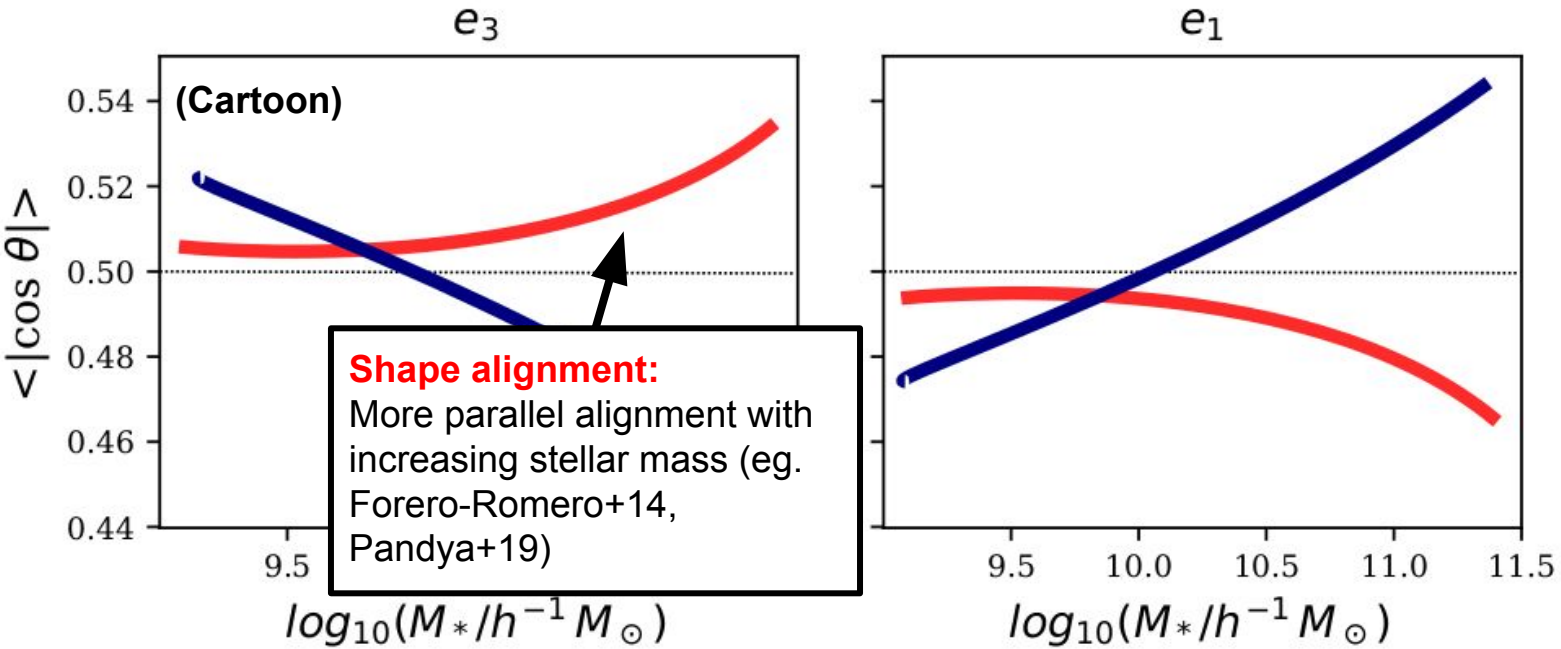
Galaxy-Cosmic Web Alignment

- Non-random alignment of galaxy orientations, angular momenta with cosmic web
- Creates galaxy-galaxy **intrinsic alignment** on sky, degenerate with weak lensing effects
- For remainder of talk, referring to **density-galaxy** alignment only

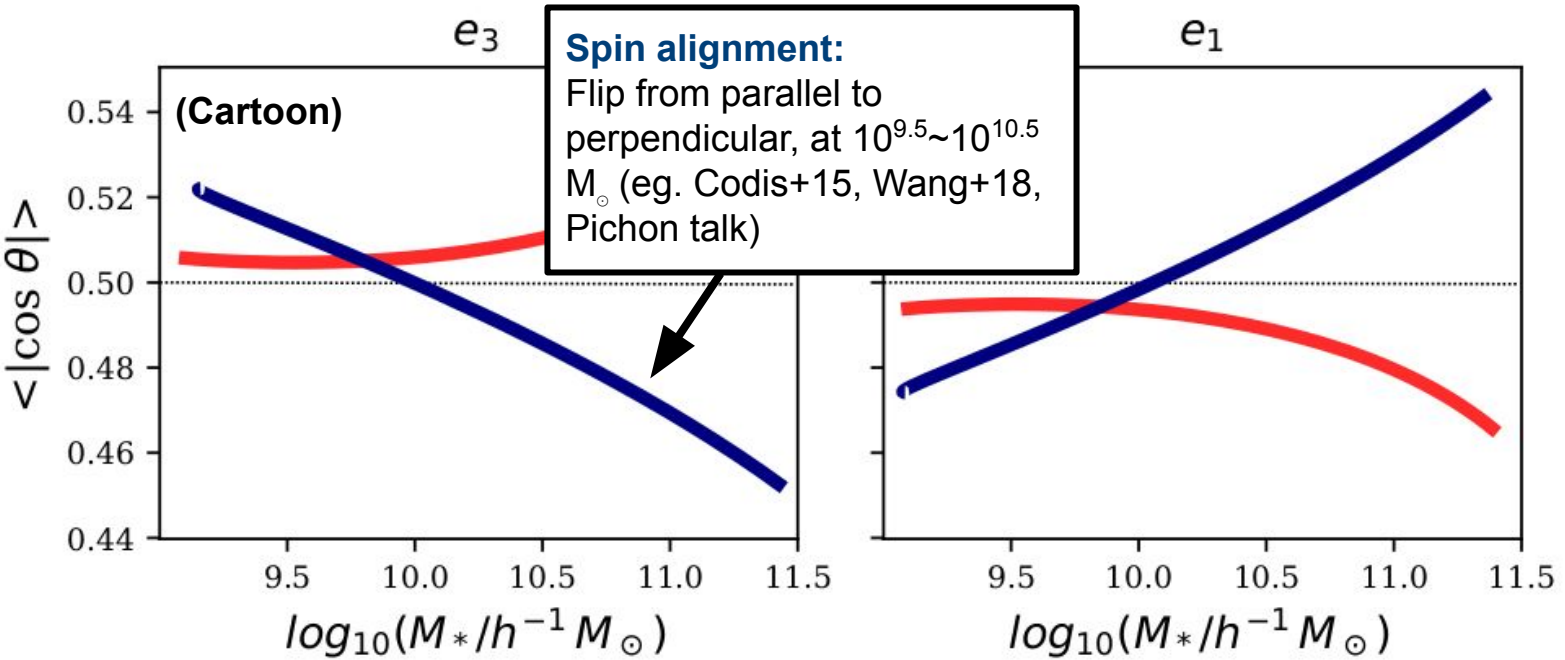


Joachimi+2015

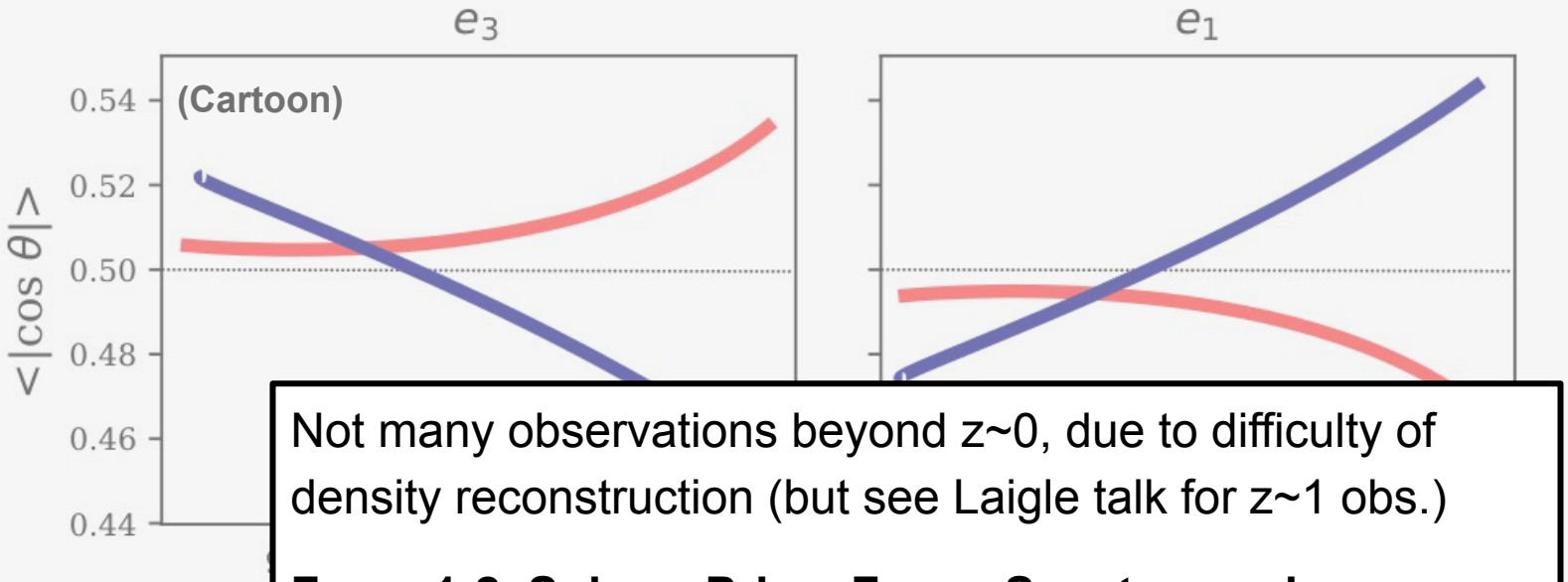
Expected Galaxy-cosmic web Alignments (prev. works)



Expected Galaxy-cosmic web Alignments (prev. works)



Expected Galaxy-cosmic web Alignments (prev. works)



Not many observations beyond z~0, due to difficulty of density reconstruction (but see Laigle talk for z~1 obs.)

For z=1-2, Subaru Prime Focus Spectrograph well-placed to constrain alignment!

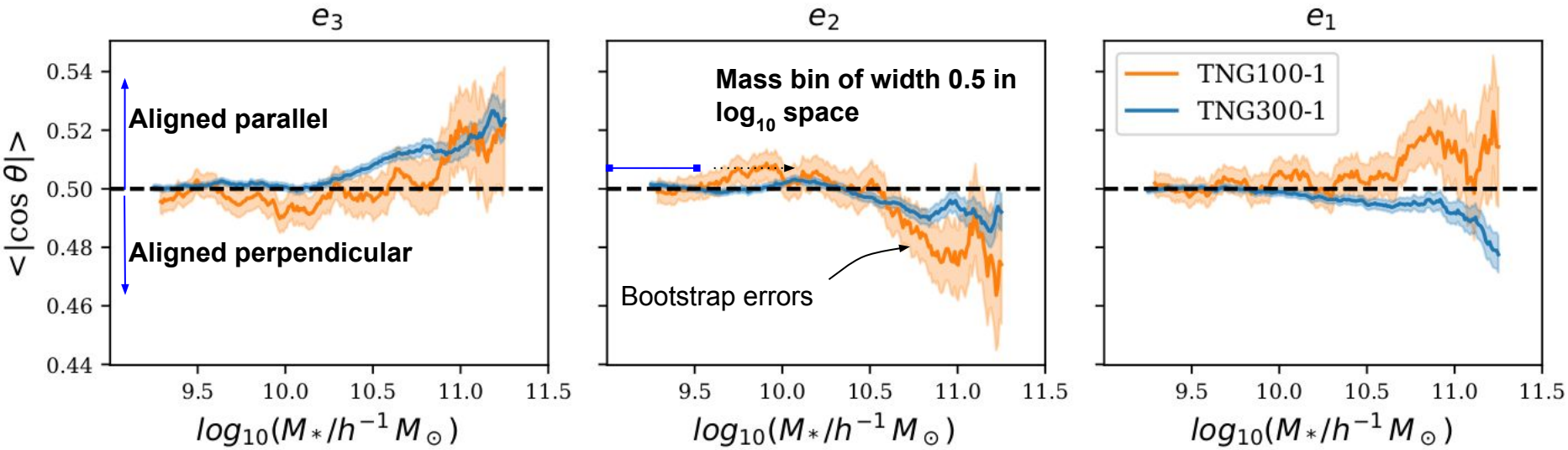
IllustrisTNG Idealized Alignments

Data

- 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
- Cosmic web characterized with deformation tensor
  - Convention: $\mathbf{e}_3$ eigenvector filament/wall direction (most negative eigenvalue)
- Galaxy longest-axis (shape) sample: reduced inertia tensors from Shi+2021
  - Stellar mass ≥ 10^9 $M_\odot$
- Galaxy angular momentum (spin) sample
  - ≥ 50 total particle cut
- Calculated for {z=1, z=2} ⊗ {TNG300-1, TNG100-1}

Shape Alignment Results

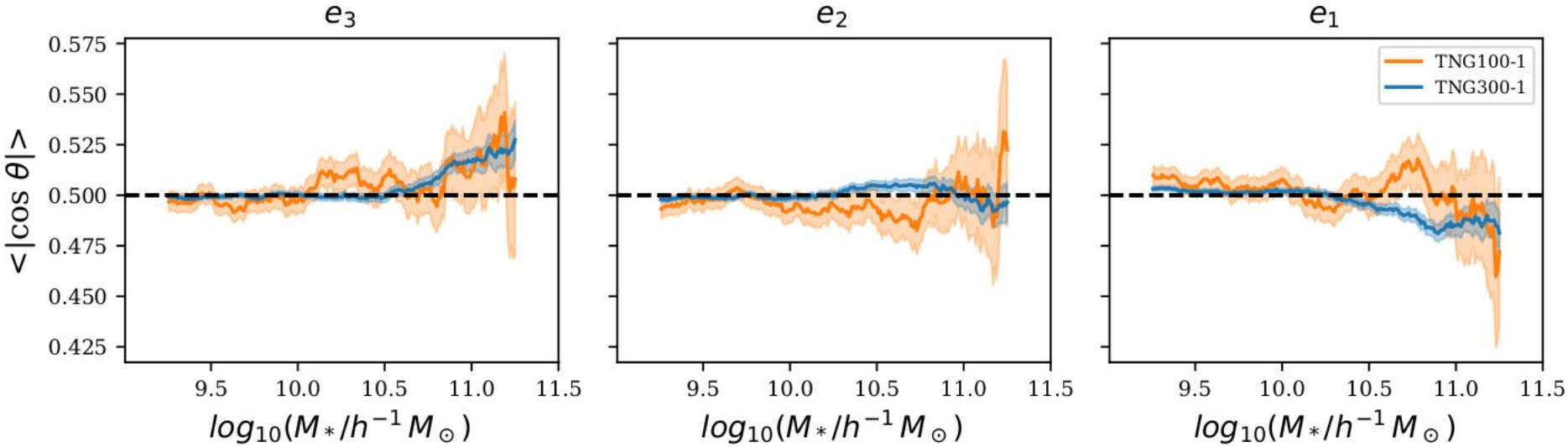
z = 1



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

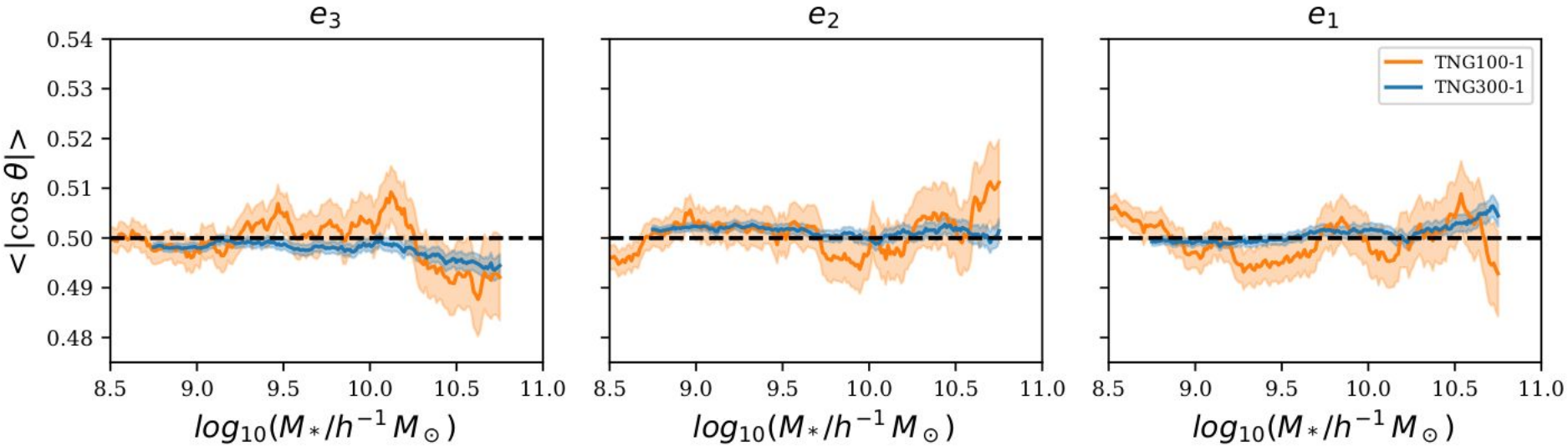
Shape Alignment Results contd.

z = 2



Spin Alignment Results

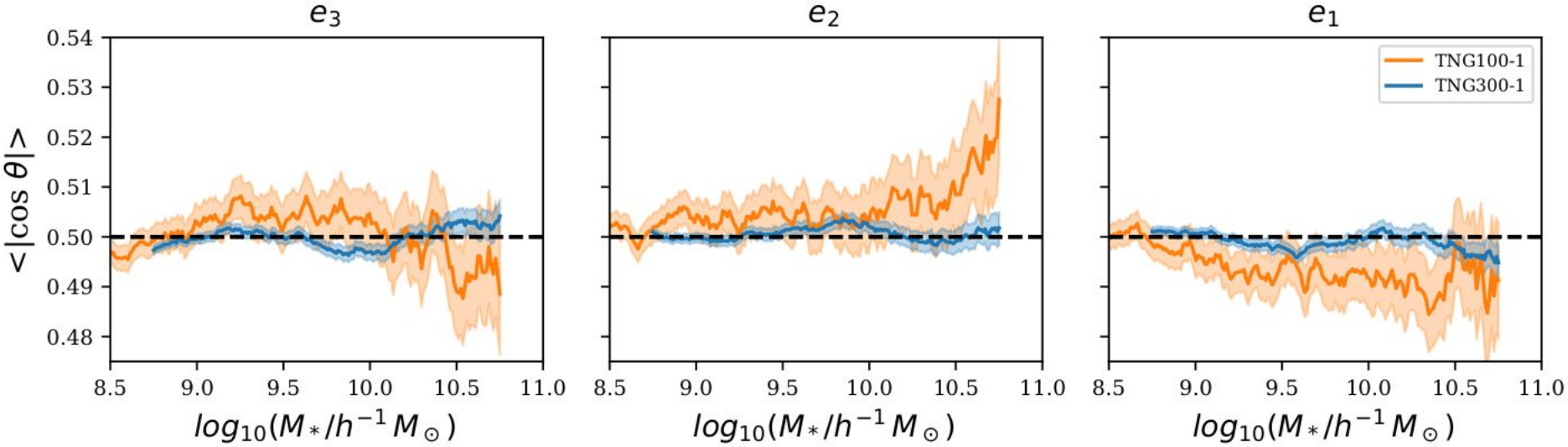
z = 1



- **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)

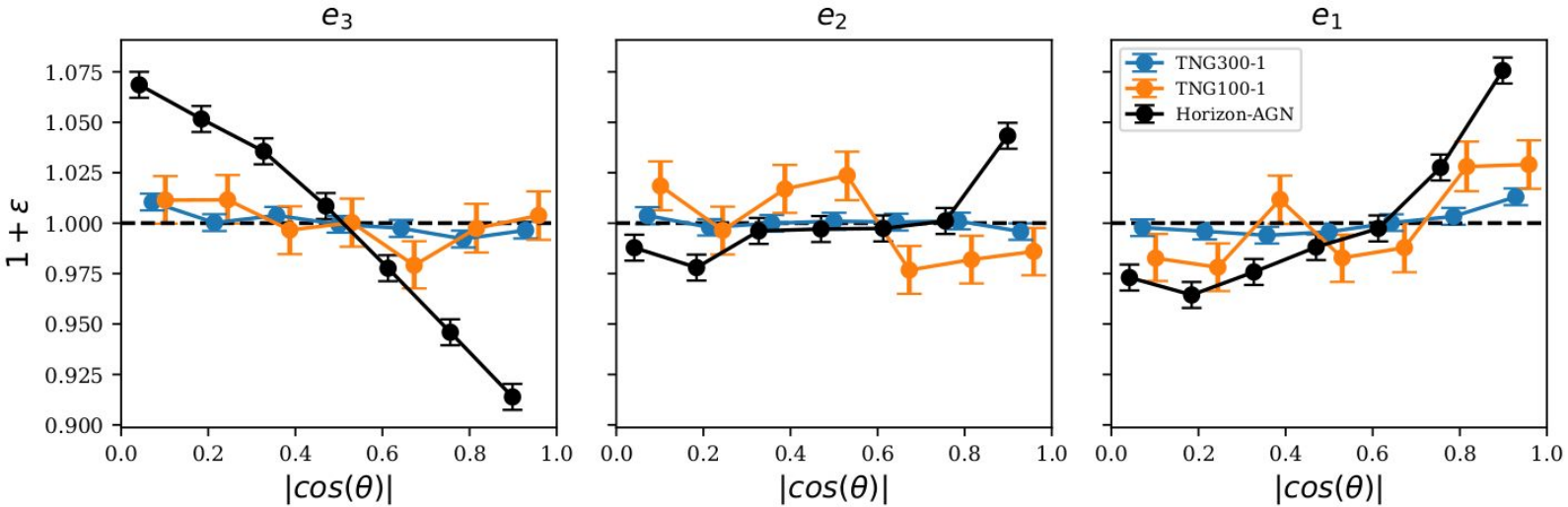
Spin Alignment Results contd.

z = 2



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

Spin comparison with Horizon-AGN hydrosim



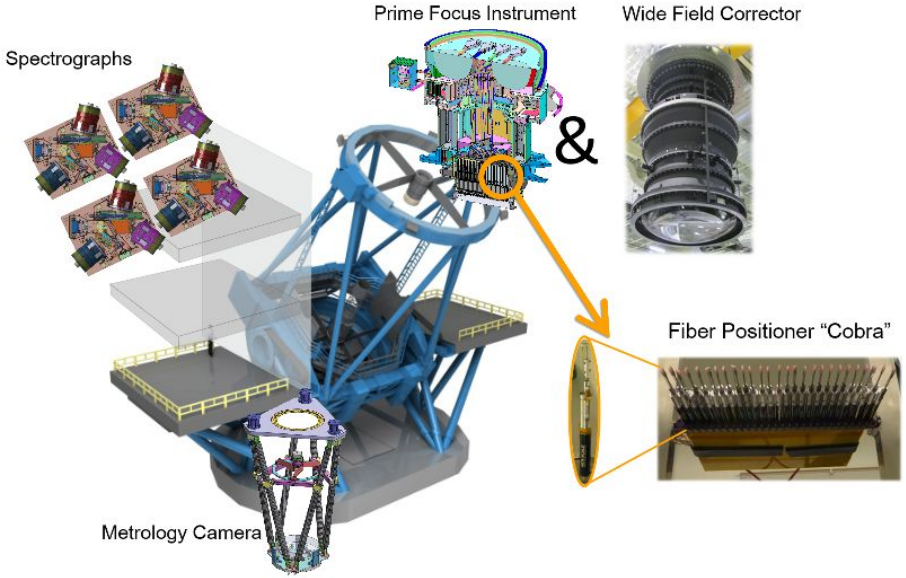
- Compare with z=1.2 spin alignments from Codis+2015; same cosmic web formalism, same mass range ($8.3 < \log M_*/M_\odot < 11.8$)
- z=1 IllustrisTNG spin alignment signal **~2.4x weaker** than Horizon-AGN
- Suggests alignment has significant dependence on detailed physics (see also Laigle talk)

PFS Alignment Signal Forecast

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

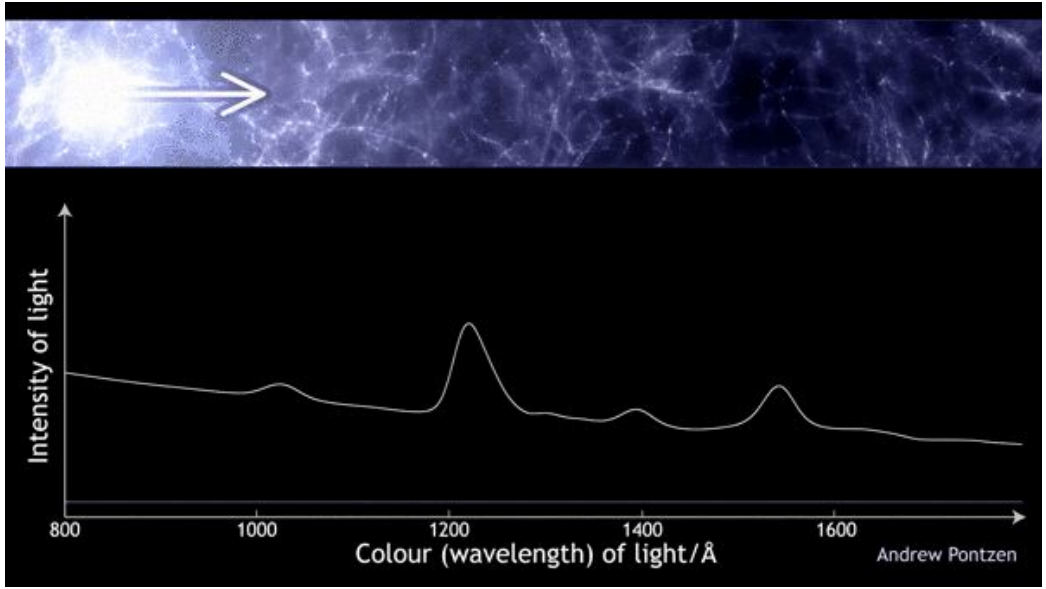
Subaru Prime Focus Spectrograph Survey

- 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



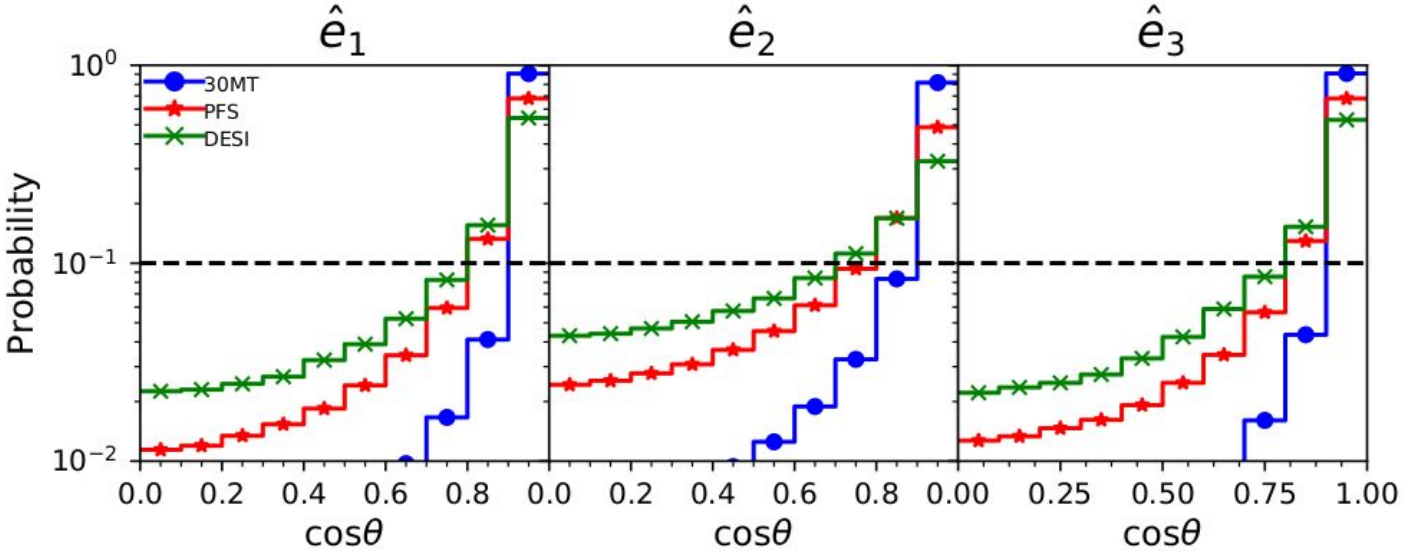
IGM Tomography

- 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
- CLAMATO survey: 4.1 * 10^5 h^{-3} Mpc^3 (Lee+2018, Horowitz+2021)
  - Subaru-PFS to probe 2 orders of magnitude higher volume!



Source: [UCL Mathematical & Physical Sciences]

IGM Tomography contd.



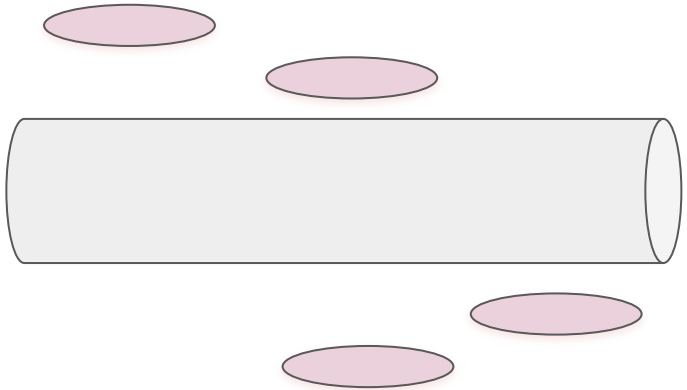
↑ Alignment between reconstructed and true deformation tensor eigenvectors (Horowitz+2019)

Cosmic Variance of Projected Alignments

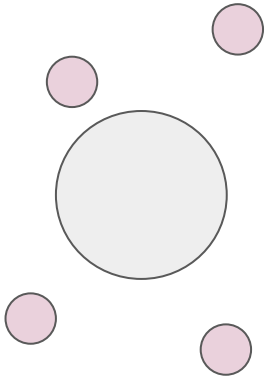
Large-scale anisotropies lead to variance in the projected alignment signal (even if have full 3D scalar information)

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

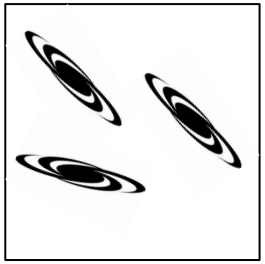
Viewed from ‘side-on’

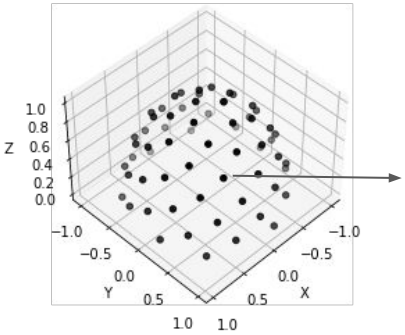


Viewed from ‘head-on’

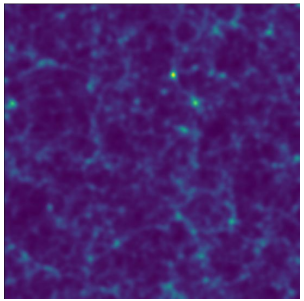


Observational galaxy sample





Viewing angle ℓ



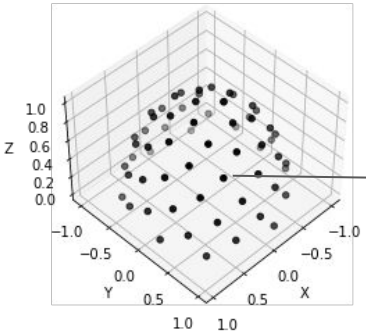
True DM density

- Galaxy sample: TNG300-1 at z=1,2
- Abundance-matched from simulated magnitudes (no dust extinction):

- **“Viewing-angle” (onto simulation volume) agnostic approach:**
- For each of 64 evenly-spaced viewing angles:

Observational galaxy sample

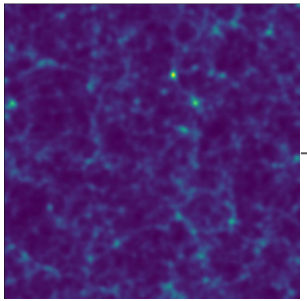
RSD

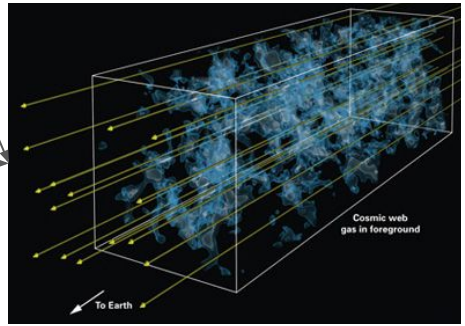


Viewing angle ℓ

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

True DM density

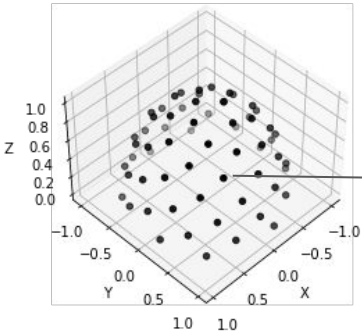




RSD, IGM tomo. skewers **along viewing angle line of sight**

Observational galaxy sample

RSD



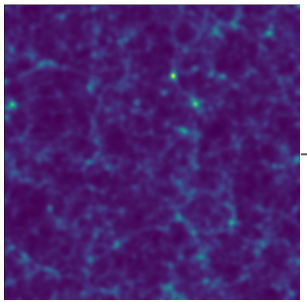
Viewing angle ℓ

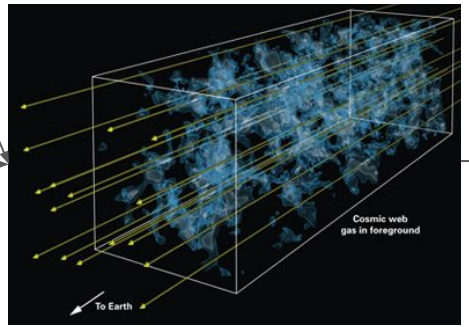
Galaxy positions + mock
IGM tomo. survey (z=2 only)

Eigenvector
projection onto
viewing angle

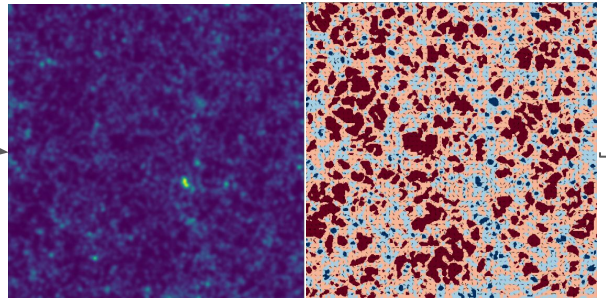
Reconstructed DM density + deformation tensor

True DM density



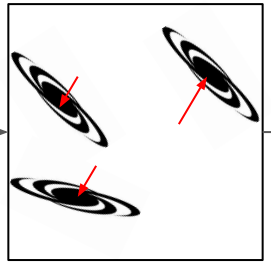


TARDIS-II

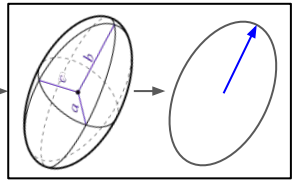


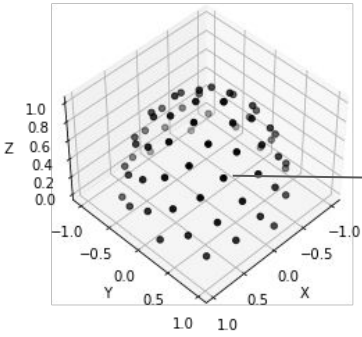
Observational galaxy sample

RSD



Ellipsoid projection onto viewing angle





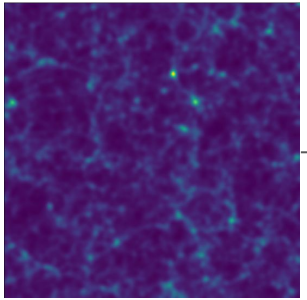
Viewing angle ℓ

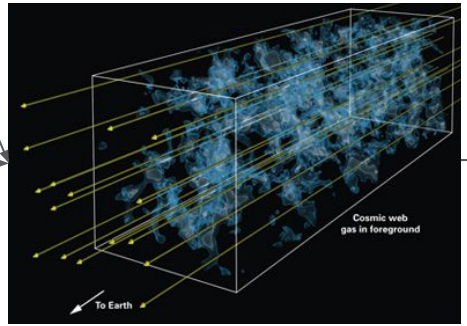
Eigenvector projection onto viewing angle

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

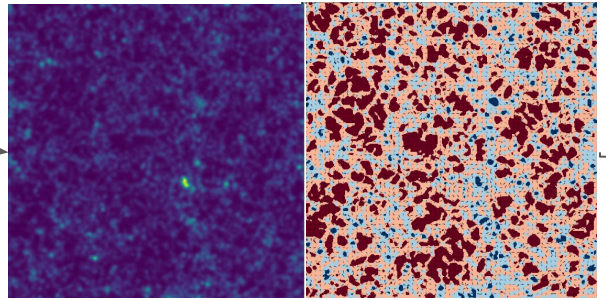
Reconstructed DM density + deformation tensor

True DM density

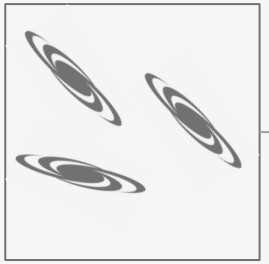




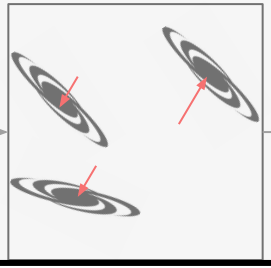
TARDIS-II



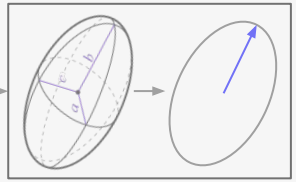
Observational galaxy sample



RSD

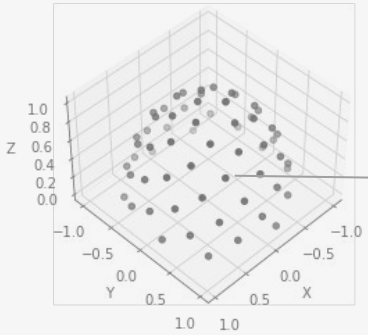


Ellipsoid projection onto viewing angle



Errors marginalized over viewing angles; includes:

RSD + reconstruction + **different projection planes**



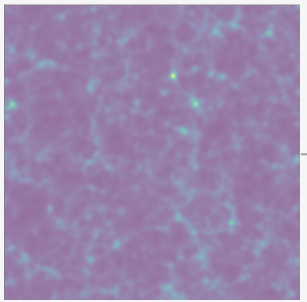
Viewing ang

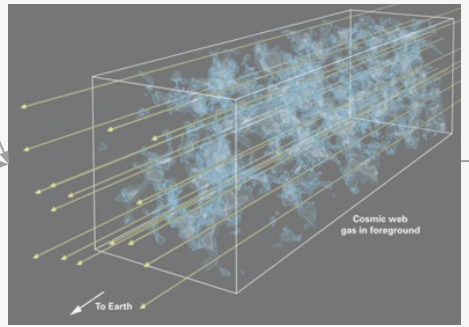
Eigenvector projection onto viewing angle

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

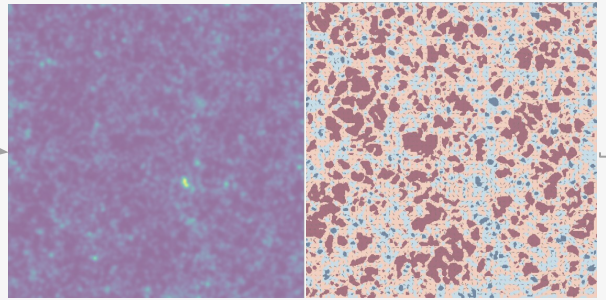
Reconstructed DM density + deformation tensor

True DM density



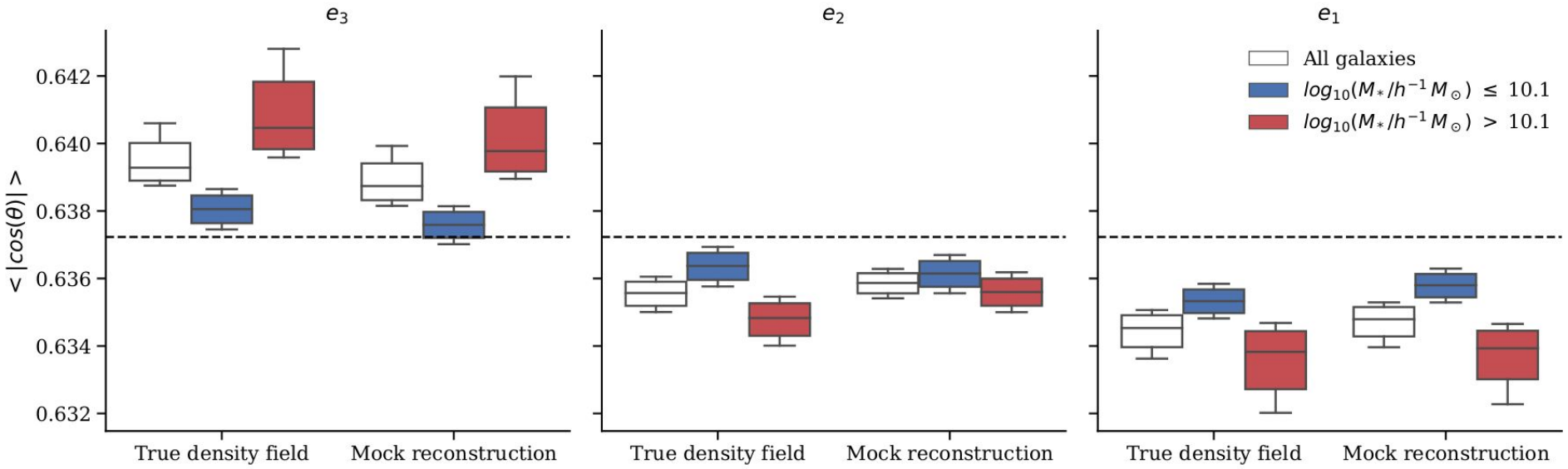


TARDIS-II



Observational z=1 Shape Alignment

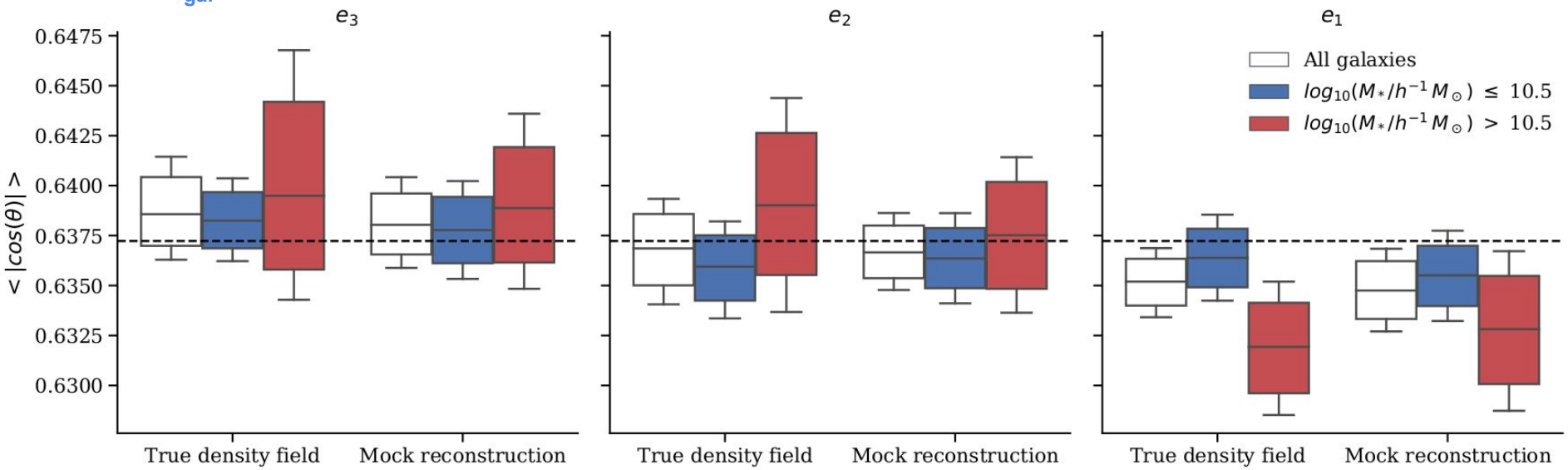
z = 1



- 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***

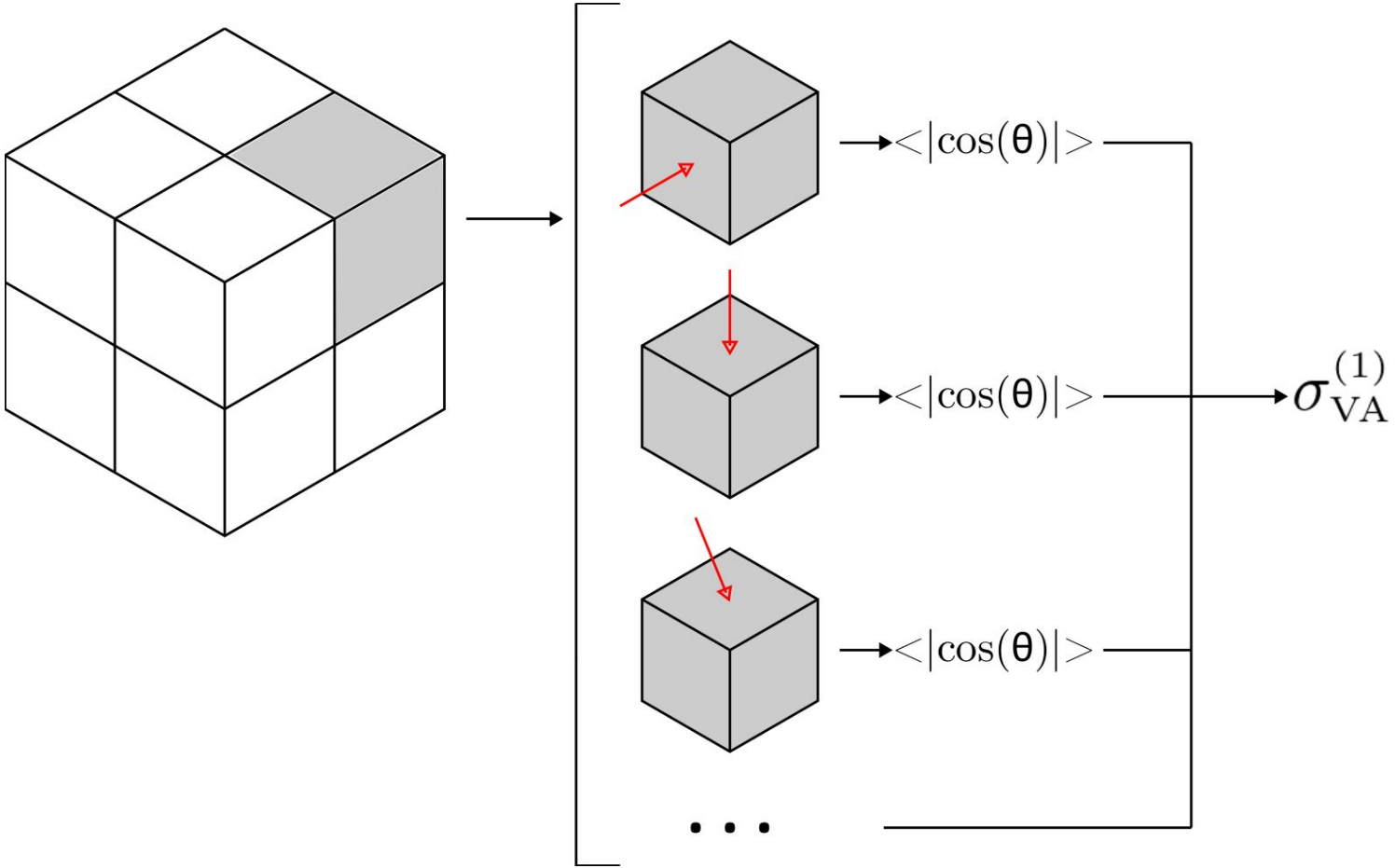
Observational Bottleneck: Galaxy Shapes

- 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 Subaru PFS footprint, well short of total 12.3 deg^2 footprint
- Roman Space Telescope should cover full footprint, but only post-2027

Summary

- Subaru Prime Focus Spectrograph well placed to constrain cosmic web-galaxy alignment at z~1-2
- IllustrisTNG alignments **surprisingly much weaker** than contemporary Horizon-AGN sim; significant subgrid physics dependence?
- Observational prospects for detecting z = 1 shape alignment good, more uncertain for z = 2
- But depends on ideal 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


<|cos(θ)|>
<|cos(θ)|>
<|cos(θ)|>
$\sigma_{\mathrm{VA}}^{(1)}$

Cosmic Variance of Projected Alignments