# Forecasting z~2 direct galaxy-cosmic web alignment for Subaru-PFS

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# Overview

- Review recent results by Codis et al. 2018 (arXiv:1809.06212v1) on direct galaxy shape/spin-cosmic web alignment in the Horizon-AGN hydrosim
- Corresponding study of direct alignments in IllustrisTNG hydrosim @ z=2
- Forecast of expected spin, shape alignment signal detected by upcoming Subaru Prime Focus Spectrograph (PFS) survey

# Codis et al. 2018: “Galaxy orientation with the cosmic web across cosmic time”

Codis et al. 2018 Review

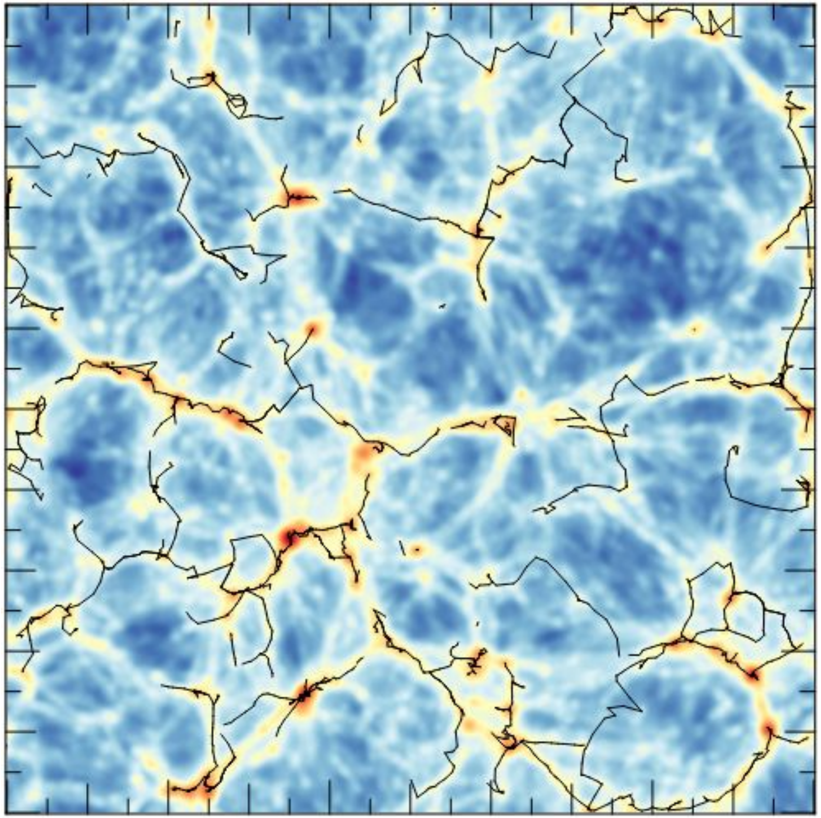
# Data

- Horizon-AGN cosmological hydrodynamic simulation
  - Box length: 100 Mpc/h
  - Baryons, stars, stellar feedback
  - Cosmological redshifts: $z = 2, 1.5, 1.0, 0.5, 0$
- Galaxy sample
  - >50 star particles
  - Angular momentum vector (**spin**), minor axis of inertia tensor ellipsoid (**minor-axis shape**) calculated from star particles only
  - Stellar mass range: $\sim 10^{8}$-$10^{11\text{-}12}$ $M_{\odot}$

Codis et al. 2018 Review

# Cosmic web characterization

- DisPerSE density ridge-extractor code (arXiv:1009.4015v1)
  - “Skeleton” line segments along ridges in density, but using galaxy distribution directly instead of continuous density fields



Codis et al. 2018, Figure 2

Codis et al. 2018 Review

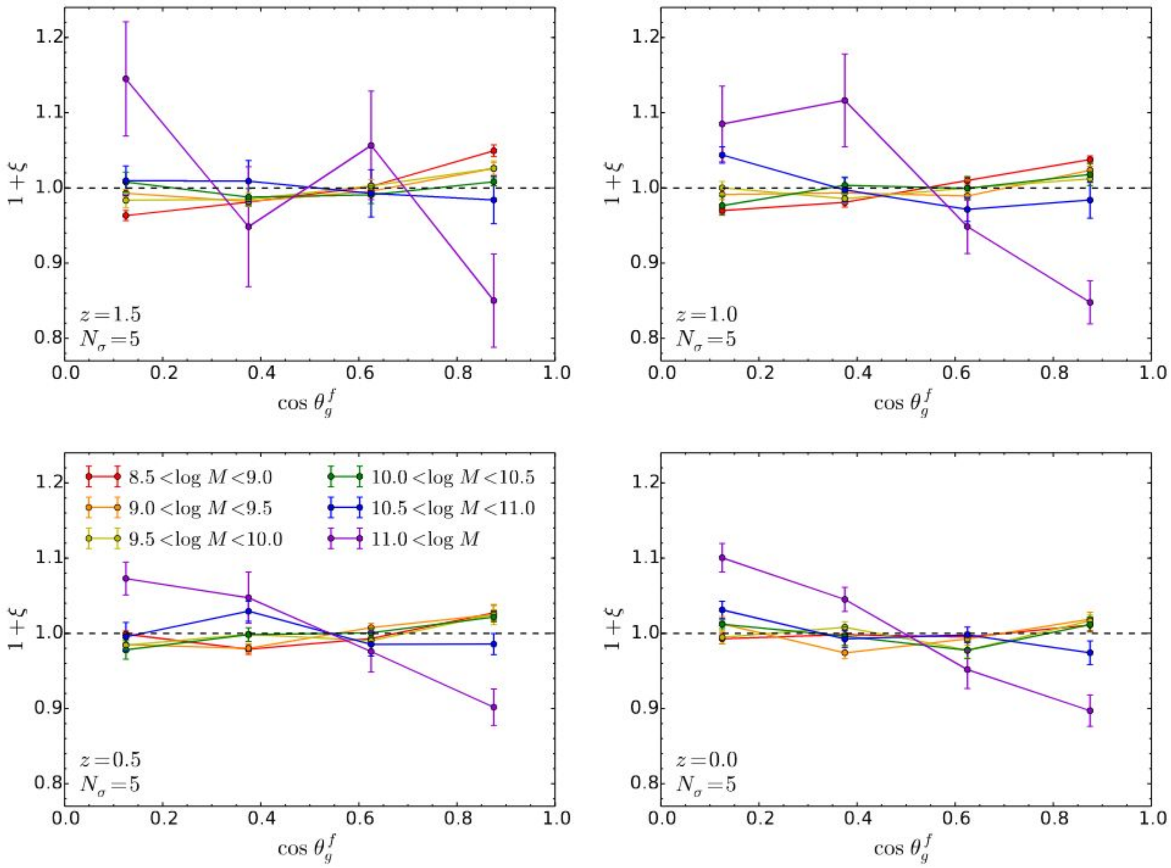
# Methods

- Alignment metric for each galaxy
  - Absolute-valued dot product of galaxy's spin/minor-axis shape vector and average direction of 2 closest DisPerSE line segments
  - $|\cos\theta|$ (**alignment**)
  - [0, 1] with 0 = perpendicular, 1 = parallel
- **Mean alignment** of collection of galaxies: $\langle|\cos\theta|\rangle$
  - Null case: $\langle|\cos\theta|\rangle = 0.5$ (2 vectors with independent uniformly random direction)
- Alignment error estimation
  - Error on mean alignment computed separately on 8 sub-cubes of simulation

Codis et al. 2018 Review

# Spin-Filament Results

- Clear spin-flip at transition mass
- Alignment strength decreases slightly with cosmic time

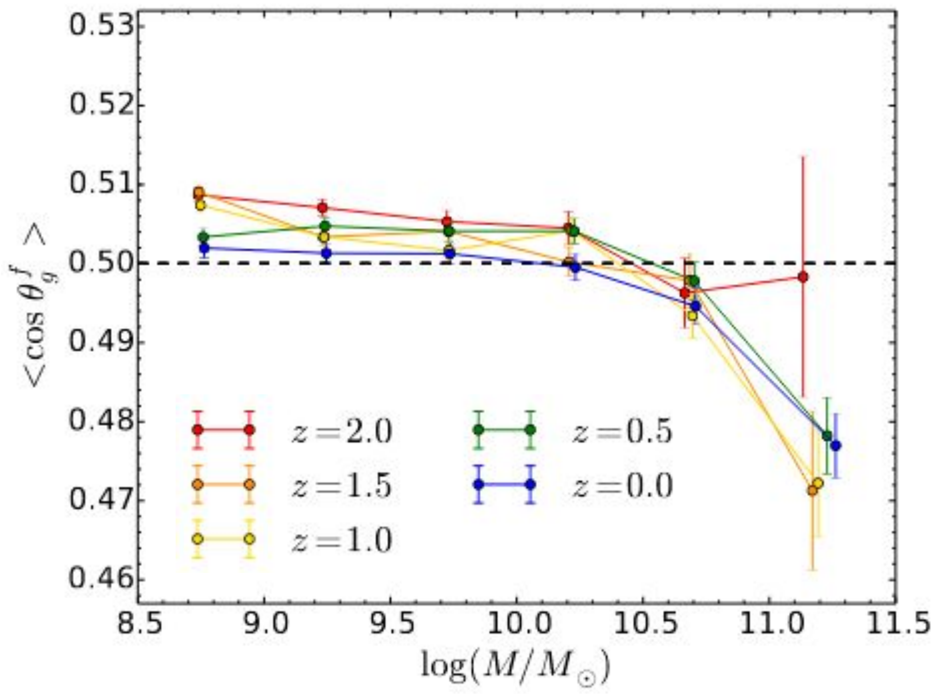



PDF of |cos θ|

Codis et al. 2018 Review

# Spin-Filament Results contd.

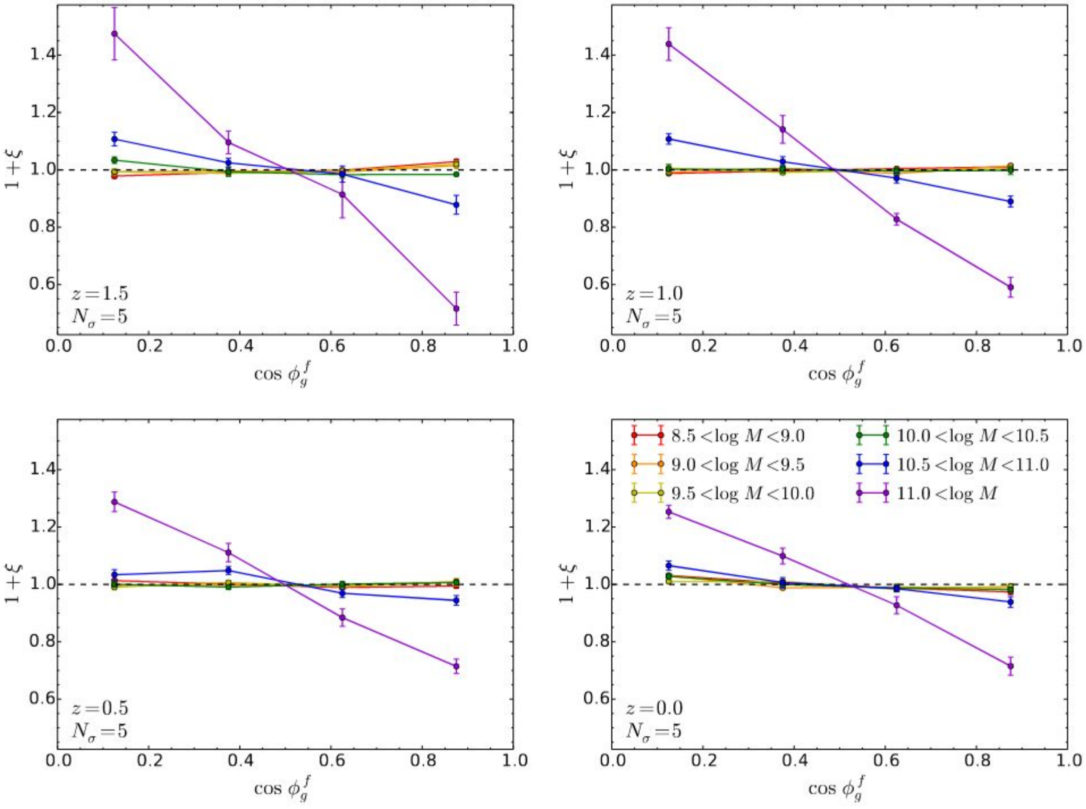
- Transition mass at $\log_{10}(M_*/M_\odot)$ = 10.1 ± 0.3
- No clear redshift dependence for transition mass (likely due to galaxy sample size)



Codis et al. 2018 Review

# Minor-axis Shape-Filament Results

- Monotonic mass dependence
- Minor positive alignment for low-mass bins @ z=1.5
  - But unclear results for lower redshifts
- Suggestive of positive major axis-filament alignment trends



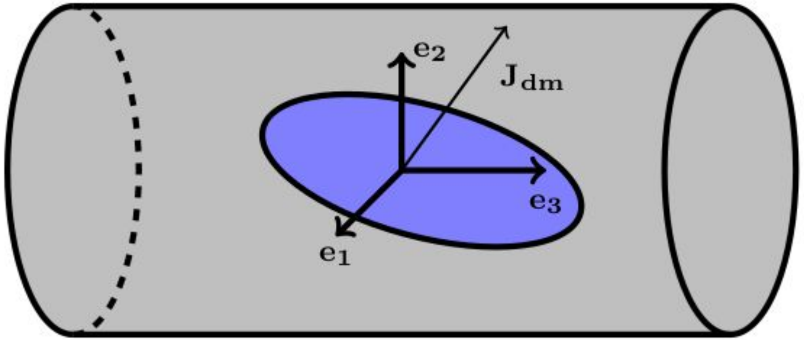
# IllustrisTNG shape/spin alignments

# Data

- IllustrisTNG 300-1 cosmological hydrodynamical simulation
  - Box length: 205 Mpc/h
  - “Full-physics”: DM, baryons, stars, supermassive black holes
  - z=2 simulation snapshot
- Galaxy major-axis shape sample: Shi et al. 2021
  - Contrast with Codis et al.: reduced inertia-tensor’s **major** axis
  - Stellar mass ≥ $10^9$ $M_\odot$
- Galaxy spin sample
  - ≥ 50 *total* particles
- Simulation resolution comparison: TNG100-1
  - 75 Mpc/h: greater mass/physics resolution
  - Galaxy spins only; same cuts as 300-1

# Cosmic Web Characterization

- **Deformation tensor**
  - Calculated from binned DM density field: Hessian of gravitational potential at each point
  - Ordered eigenvalues of tensor $e_1 \geq e_2 \geq e_3$: matter collapse order in Zel'dovich approximation, along corresponding eigenvectors $\mathbf{e_1}$, $\mathbf{e_2}$, $\mathbf{e_3}$
  - $\mathbf{e_3}$ filament direction + wall plane-parallel: generalized "cosmic web direction" for every point
  - $\mathbf{e_1}$ also encodes useful information; $\mathbf{e_2}$ less so

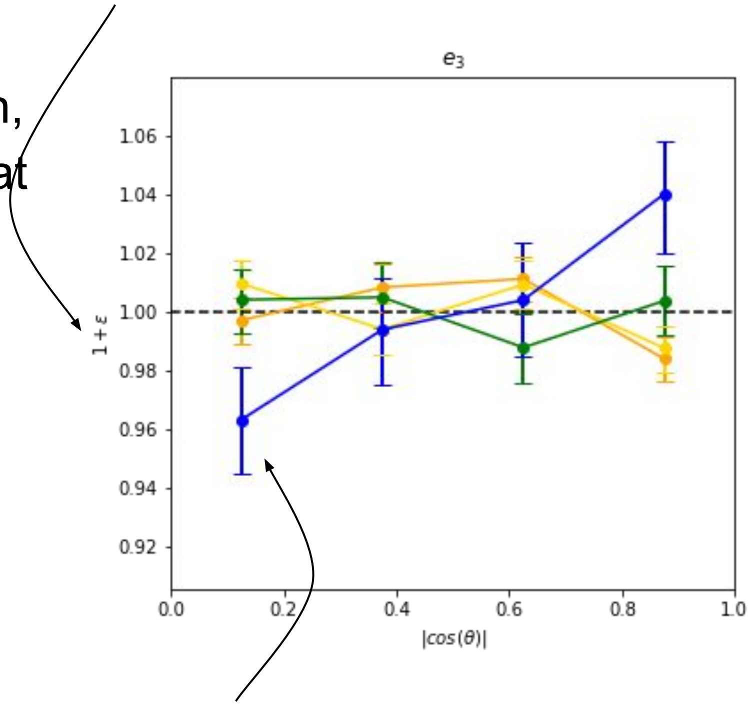



Veena et al. 2020, Figure 4

# Methods

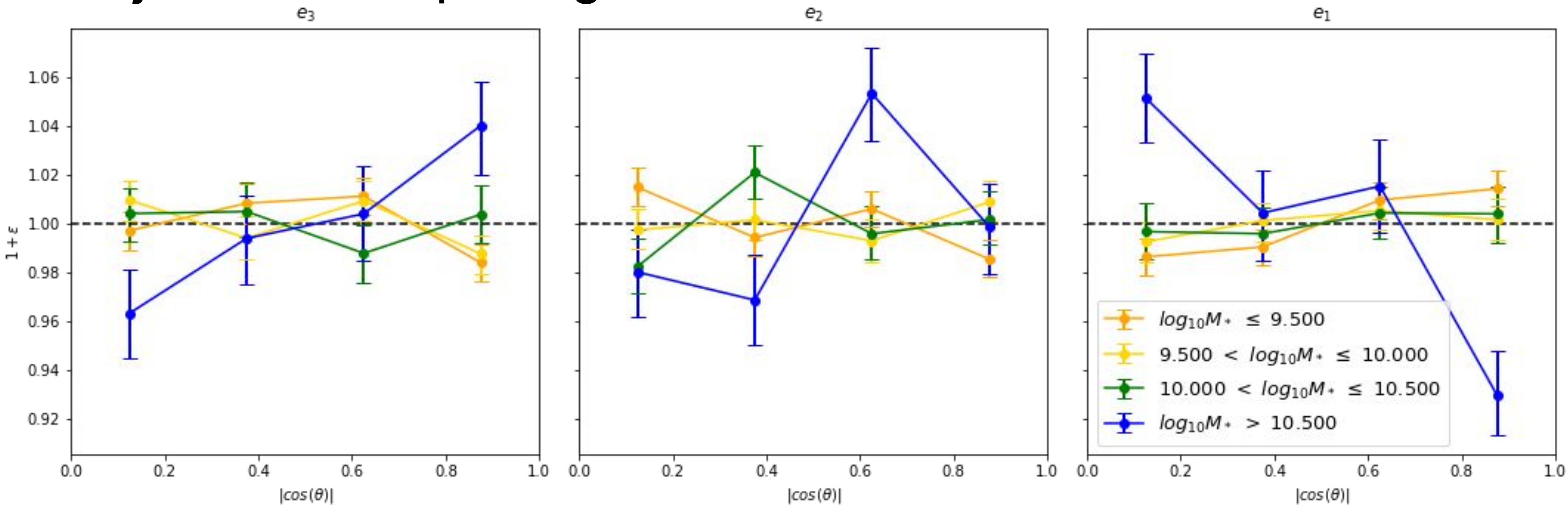
- Dark matter density binned to $512^3$ grid, smoothed to 2 Mpc/h, deformation tensor calculated at each point
- Closest tensor to each galaxy found, |cos θ| calculated between each eigenvector and major-axis shape/spin

PDF of |cos θ|




1σ errors bootstrapped over (sub)sample

# Major-Axis Shape Alignment Results

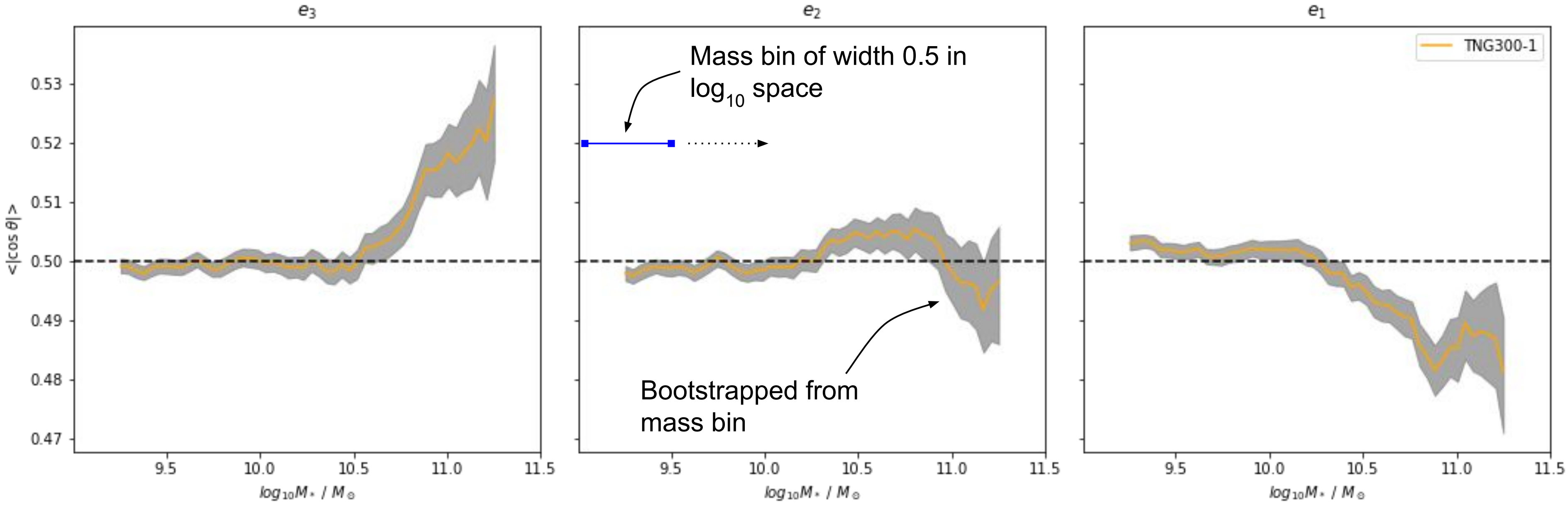



- Slightly negative trend until highest stellar mass bin
- Qualitatively agrees with Codis et al. minor-axis vs. filament

- No clear trends; less information about cosmic web encoded

- Monotonically more negative trend with mass

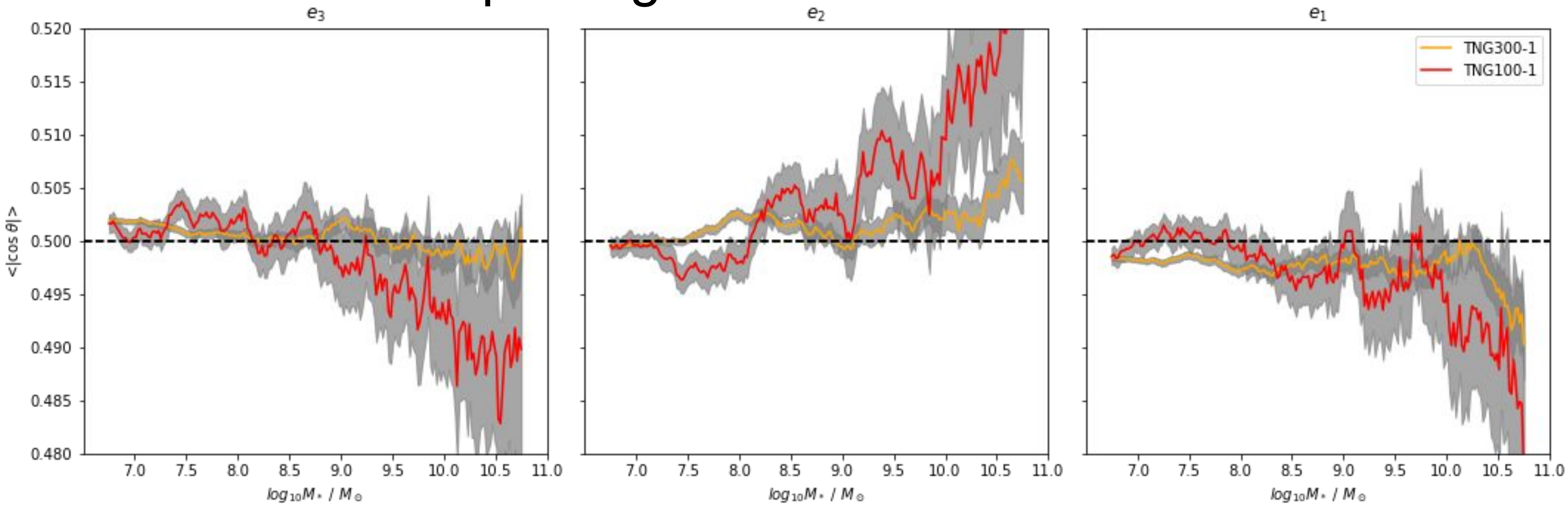
# Major-Axis Shape Alignment Results contd.




- Clear transition mass at $M_*$ ~ $10^{10.5}$ $M_\odot$!
- After transition mass, major-axis shape alignment strength monotonically increases

- Transition mass at $M_*$ ~ $10^{10.25}$ $M_\odot$
- Negative signal after transition; similar amplitude to $\mathbf{e_3}$

# TNG300 & 100 Spin Alignment Results



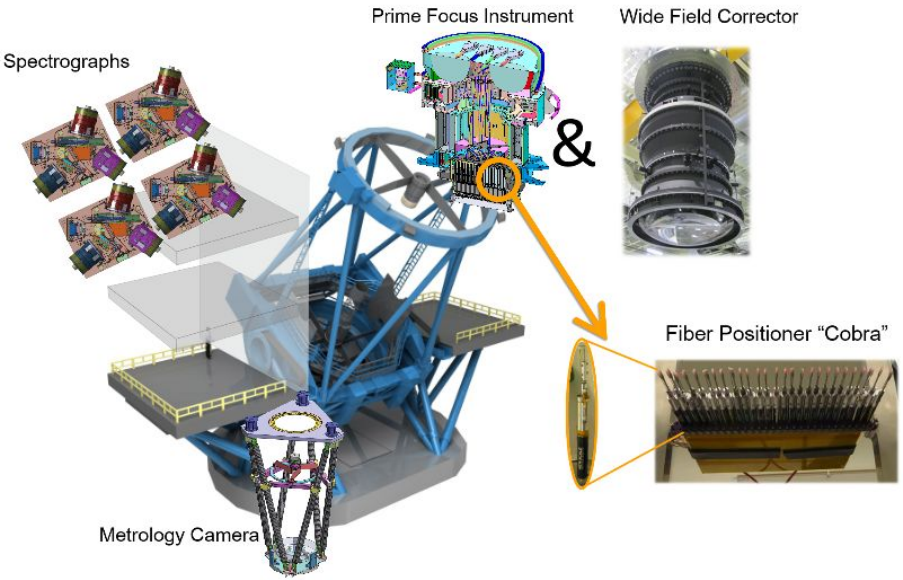

- Relatively small galaxy sample for TNG100 from ~$10^{8.5}$ $M_\odot$ on
- For $\mathbf{e_1}$ & $\mathbf{e_3}$, 1σ bootstrap errors of TNG100 agree with TNG300 above ~$10^8$ $M_\odot$
- $\mathbf{e_3}$ spin-flip transition mass ~$10^{8.75}$ for TNG100, ~$10^{9.4}$ for TNG300
  - Disagrees with Codis et al. (~$10^{10.4}$). Different cosmic web formalism / sim physics
  - Wang et al. 2018 (arXiv:1810.04581v1) reports $M_{tr}$~$10^8$ for same cosmic web formalism on Illustris (75 Mpc/h)

# Subaru-PFS Alignment Signal Forecast

## How well can we measure this signal in PFS?

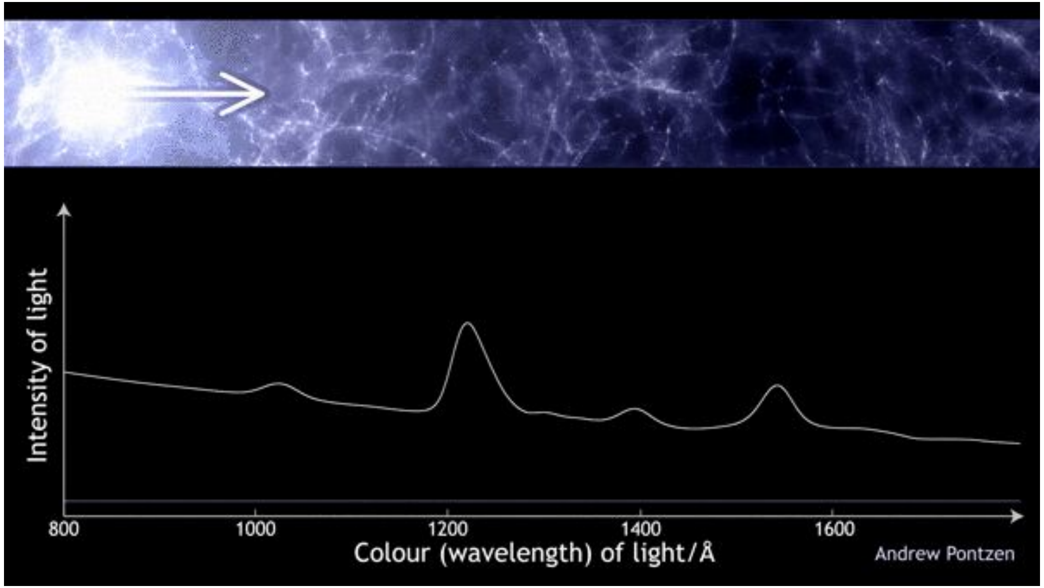
# Subaru Prime Focus Spectrograph Survey

- Starting mid-2023
- Spectrographic redshifts / spectra from 0.6 < z < 7
- Our focus is on “cosmic noon” subprogram @ z~2.3
  - Spectrographic redshifts for galaxies within volume 2.7 * $10^7$ $h^{-3}$ $Mpc^3$
  - 15,000/30,800 galaxies for program, depending on exact distribution of observing time



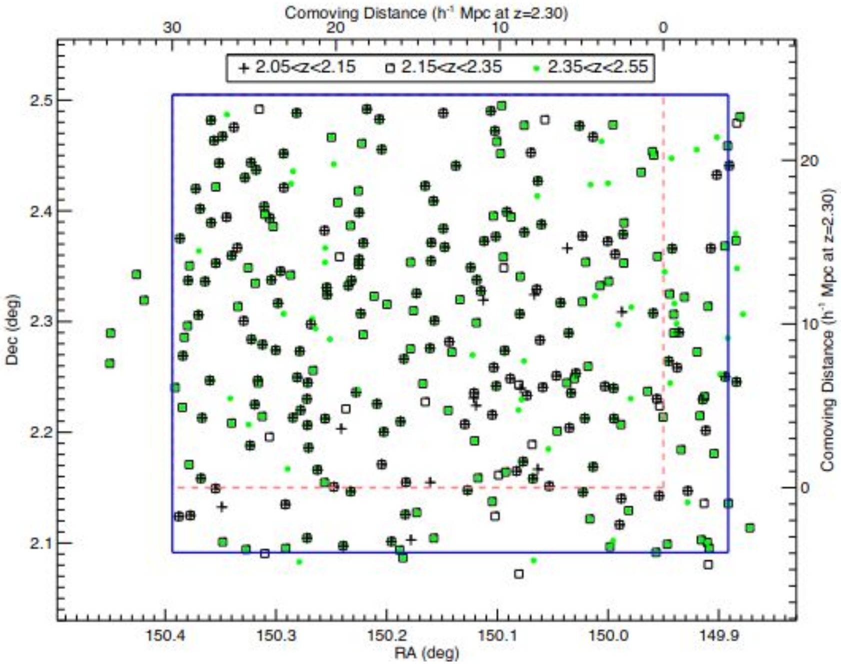
# IGM Tomography

- Cosmic web reconstruction at high-z hard: few galaxies!
  - COSMOS-level of study needed to attempt: see Ata et al. 2020 (arXiv:2004.11027v2)
- 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 * $10^5$ $h^{-3}$ $Mpc^3$
  - PFS to probe 2 orders of magnitude higher volume!



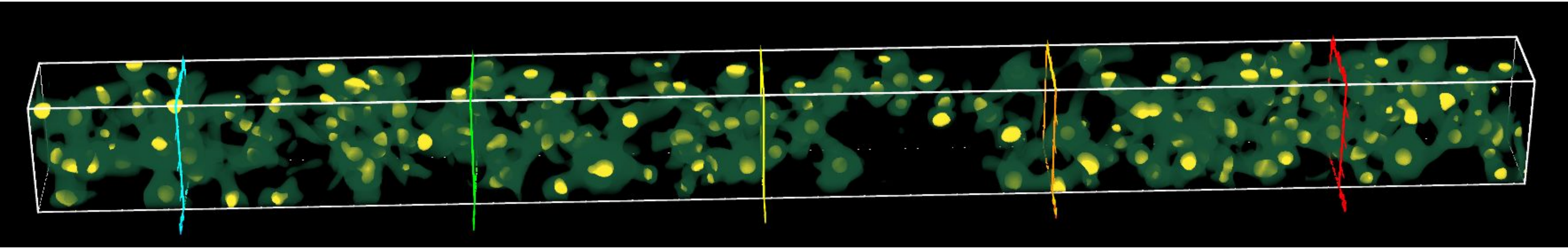

Source: UCL Mathematical & Physical Sciences

# IGM Tomography contd.

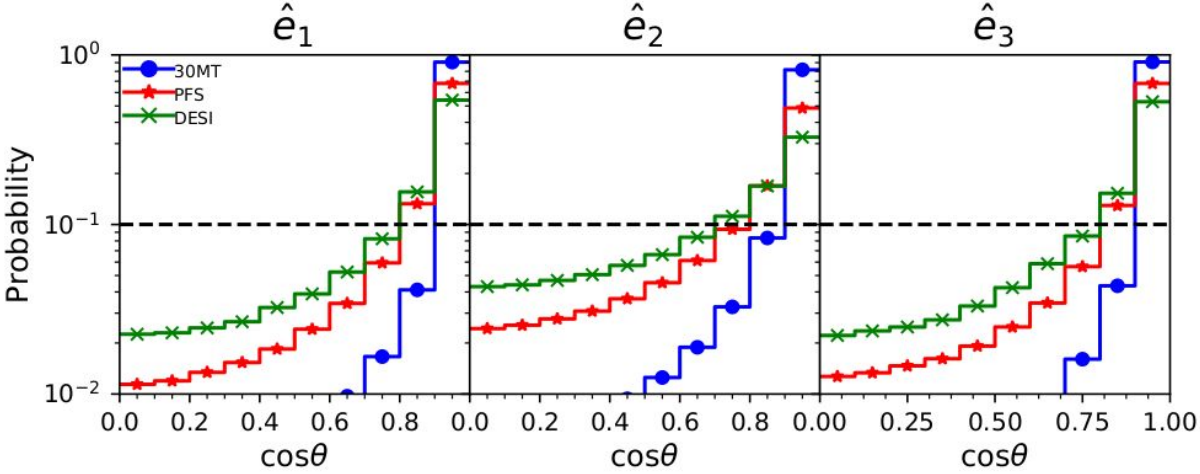



↑ Source: CLAMATO DR2 (Horowitz et al. 2021, arXiv:2109.09660v1)

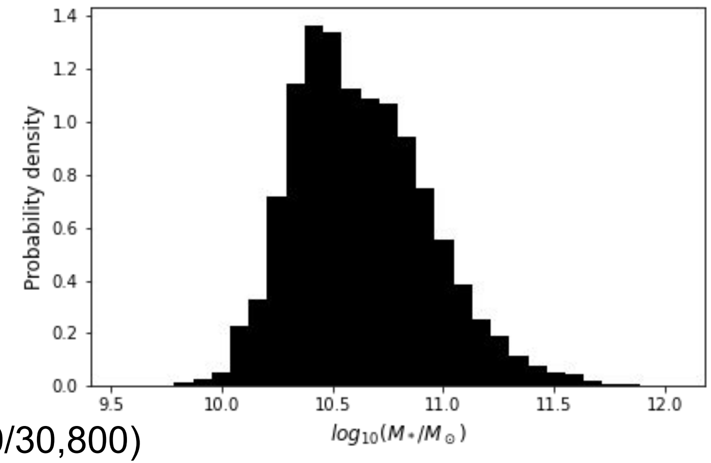
# IGM Tomography contd.



↑ Source: CLAMATO DR2 (Horowitz et al. 2021, arXiv:2109.09660v1)

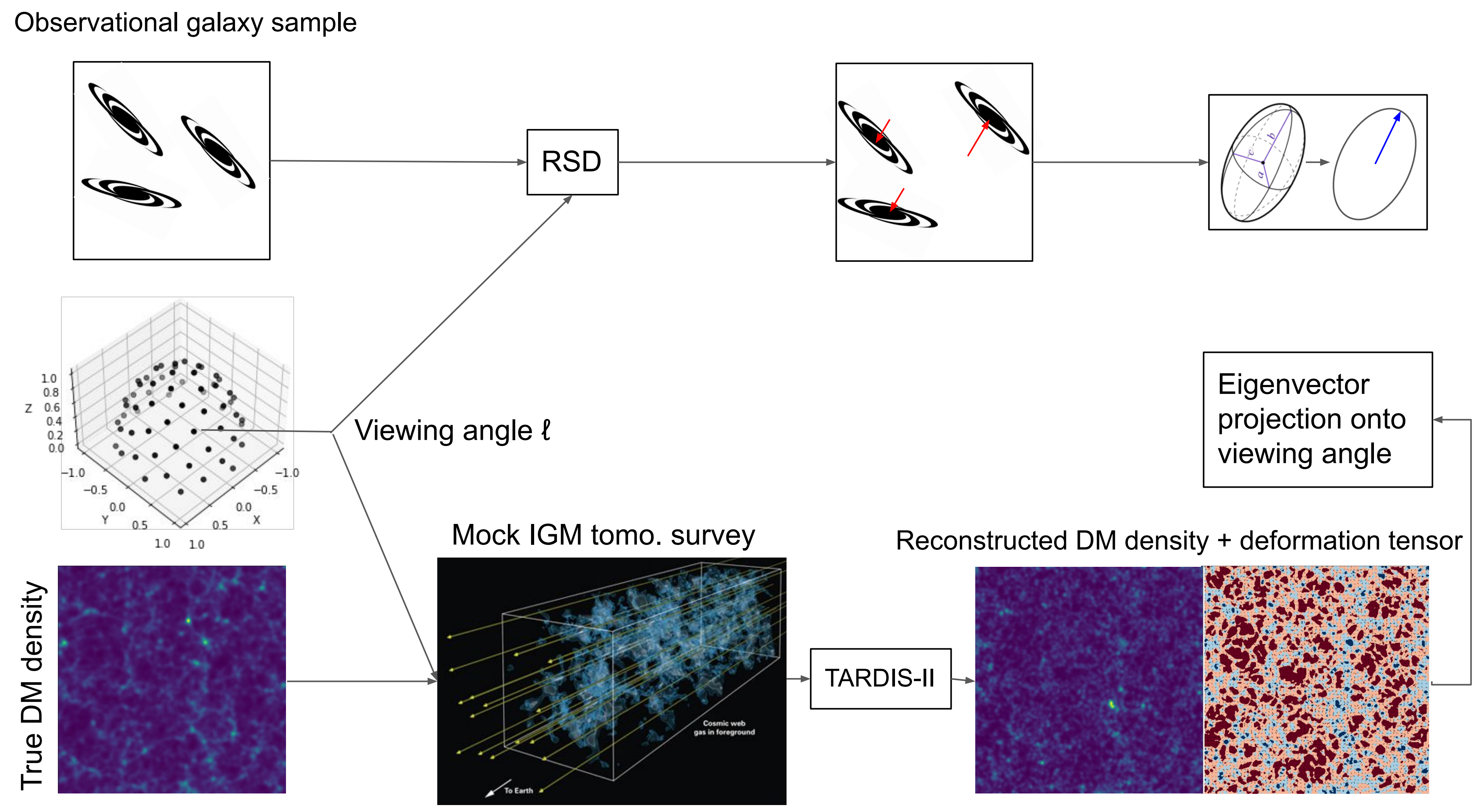



↑ Alignment between reconstructed eigenvec and true eigenvec. Source: Horowitz et al. 2019 (arXiv:1903.09049v3)




# Observational Data

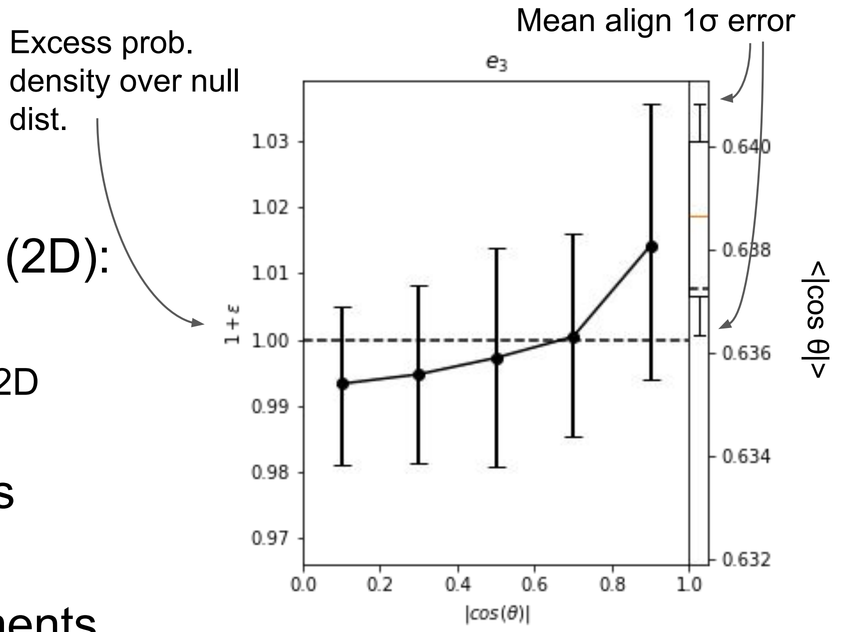
- Illustris TNG300 simulation @ z=2
- Galaxy sample magnitude-limited
  - Observed J-band magnitude (no dust)
  - Match expected number of PFS galaxy spec-z's (15,000/30,800)
  - Select dispersion-dominated (spheroid) galaxies via $\kappa_{rot} < 0.5$ ($\kappa_{rot} = K_{rot} / K$)
  - $M_* = [10^{10}, 10^{11.5}]\ M_\odot$
- For 64 viewing angles on half-sphere:
  - Displace galaxies by peculiar velocities along viewing angle LoS: redshift-space distortion (RSD)
  - Construct mock PFS-like IGM tomography survey along viewing angle LoS
  - Reconstruct cosmic web deformation tensor using TARDIS-II code (Horowitz et al. 2021, arXiv:2007.15994v1)
  - Project shape ellipsoid onto viewing angle plane, take longest axis of ellipse as major-axis shape
  - Project deformation tensor eigenvectors onto viewing angle plane



Observational galaxy sample
RSD
Viewing angle ℓ
Eigenvector
projection onto
viewing angle
Mock IGM tomo. survey
Reconstructed DM density + deformation tensor
True DM density
TARDIS-II
Cosmic web
gas in foreground
To Earth

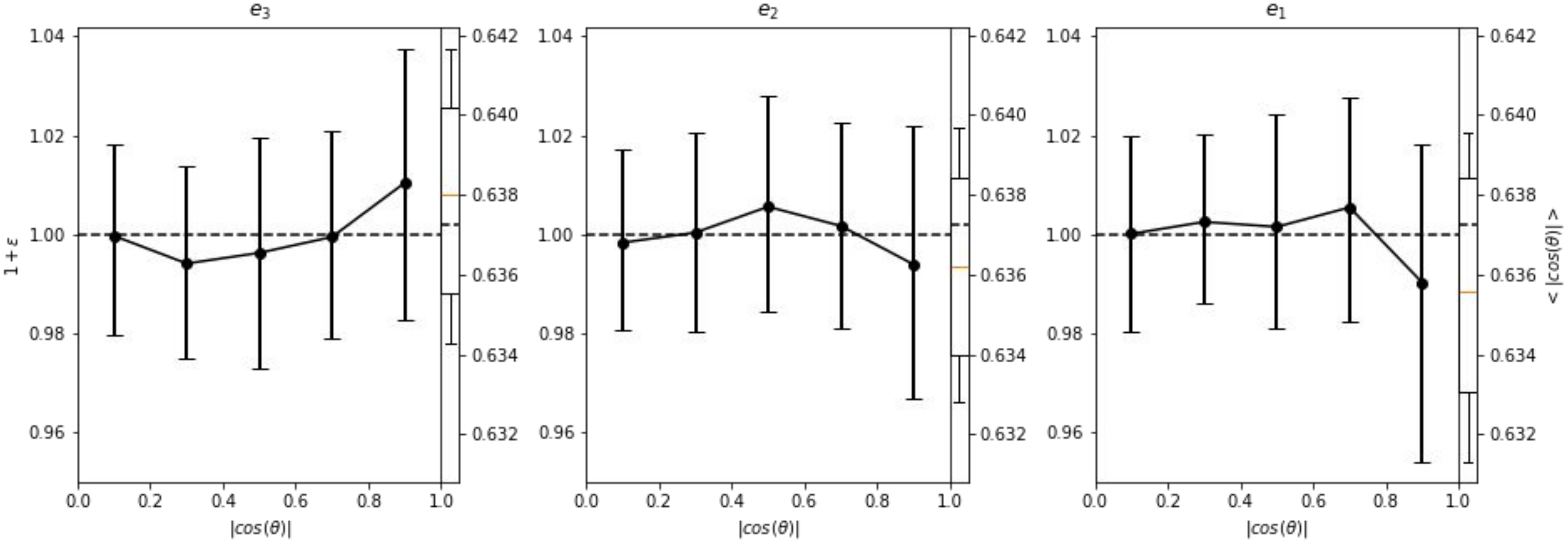
# 2D Alignment

- Alignment null distribution after projection (2D): upper half of Beta[α = β = 0.5]
  - Random 3D vectors after projection → random 2D vectors
- Histogram bins calculated over alignments from all viewing angles
- For each bootstrap iteration, select alignments from random viewing angle first



# Fiducial Observation Time (N = 15,000)

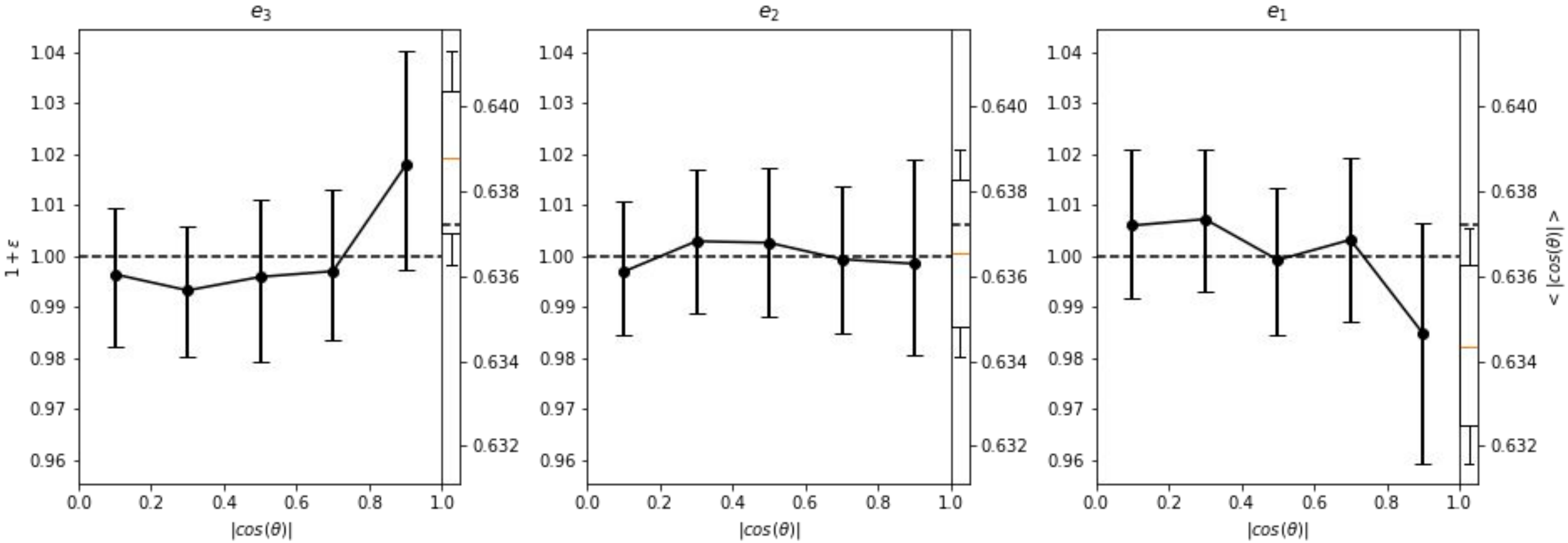
**Cosmic web reconstructed with IGM tomography**
**Major-axis shape projected on 64 viewing angles**




| $e_3$ | $e_2$ | $e_1$ |
|---|---|---|
| +0.21σ | -0.30σ | -0.41σ |

# Extra Observations (N = 30,800)

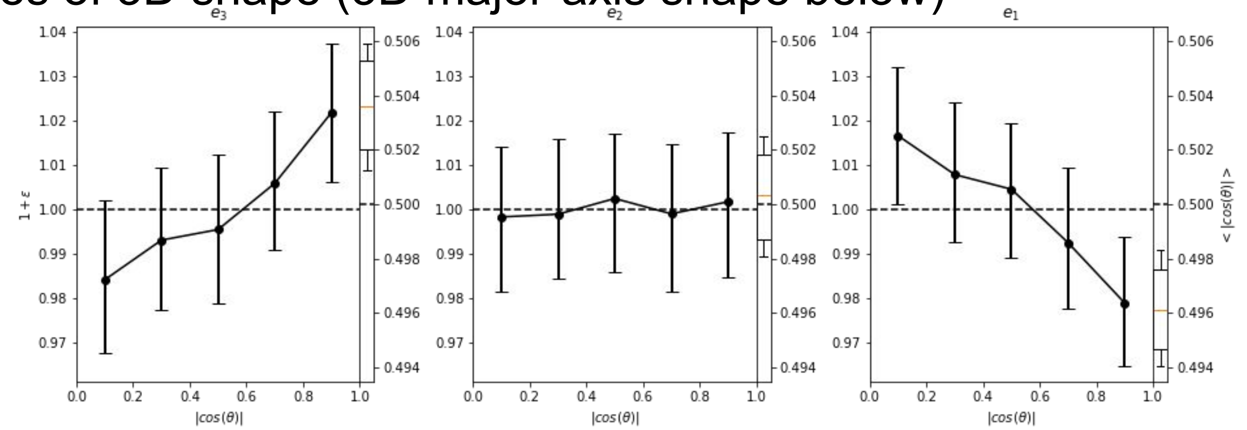
**Cosmic web reconstructed with IGM tomography**
**Major-axis shape projected on 64 viewing angles**




| $e_3$ | $e_2$ | $e_1$ |
|---|---|---|
| +0.58σ | -0.27σ | -1.02σ |

# Avenues for Improvement

- Increased volume for next-gen survey
  - Approximate overall significance $\sigma_T$ as $\sqrt{(\sigma_3^2 + \sigma_1^2)}$.
  - $\sigma_T$ = 0.46 | 1.17, for N=15,000 | N=30,800
  - Assuming same magnitude distribution and errors $\propto N^{0.5}$, need 3x volume (N=90,000) for $\sigma_T$=2
- Improved IGM tomography reconstruction
- Estimates of 3D shape (3D major-axis shape below)



# Appendices

# Appendix A: Viewing Angle Projection Error

3D

2D