A Flexible Halo Model for the Intrinsic Alignments of Galaxies

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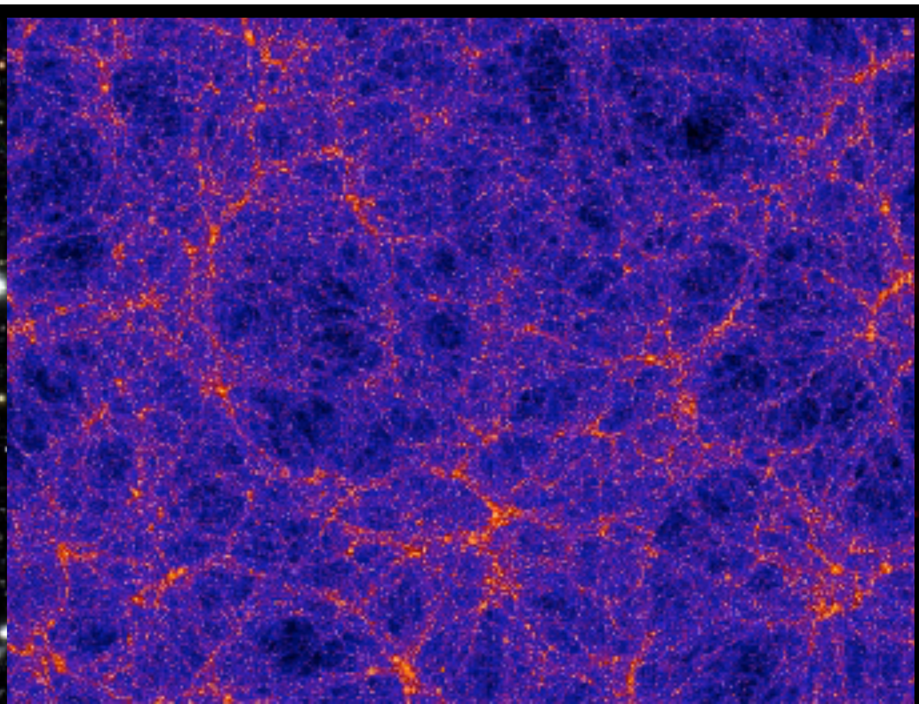
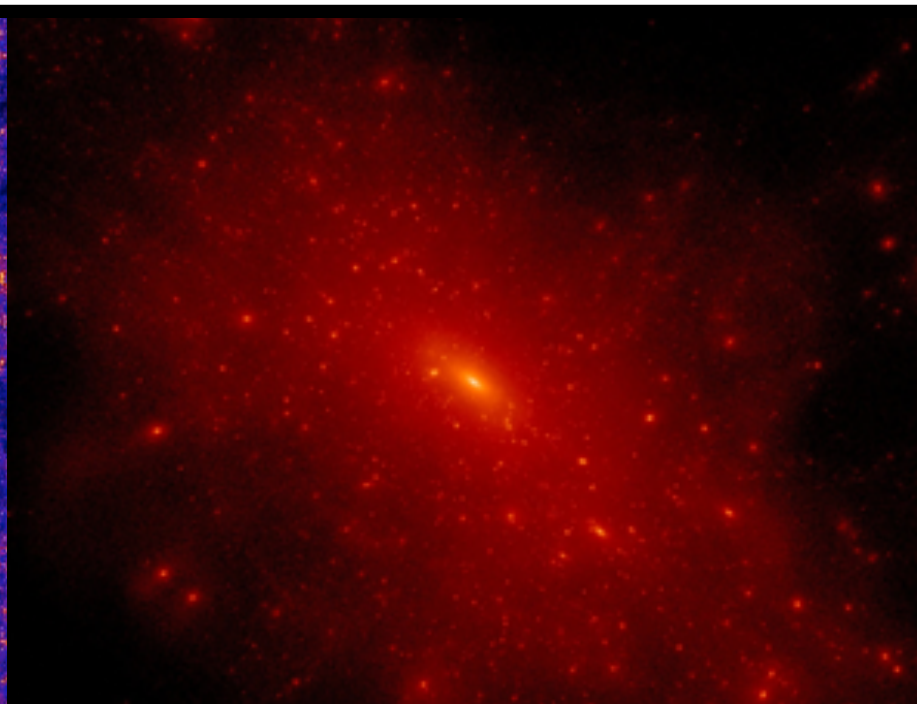
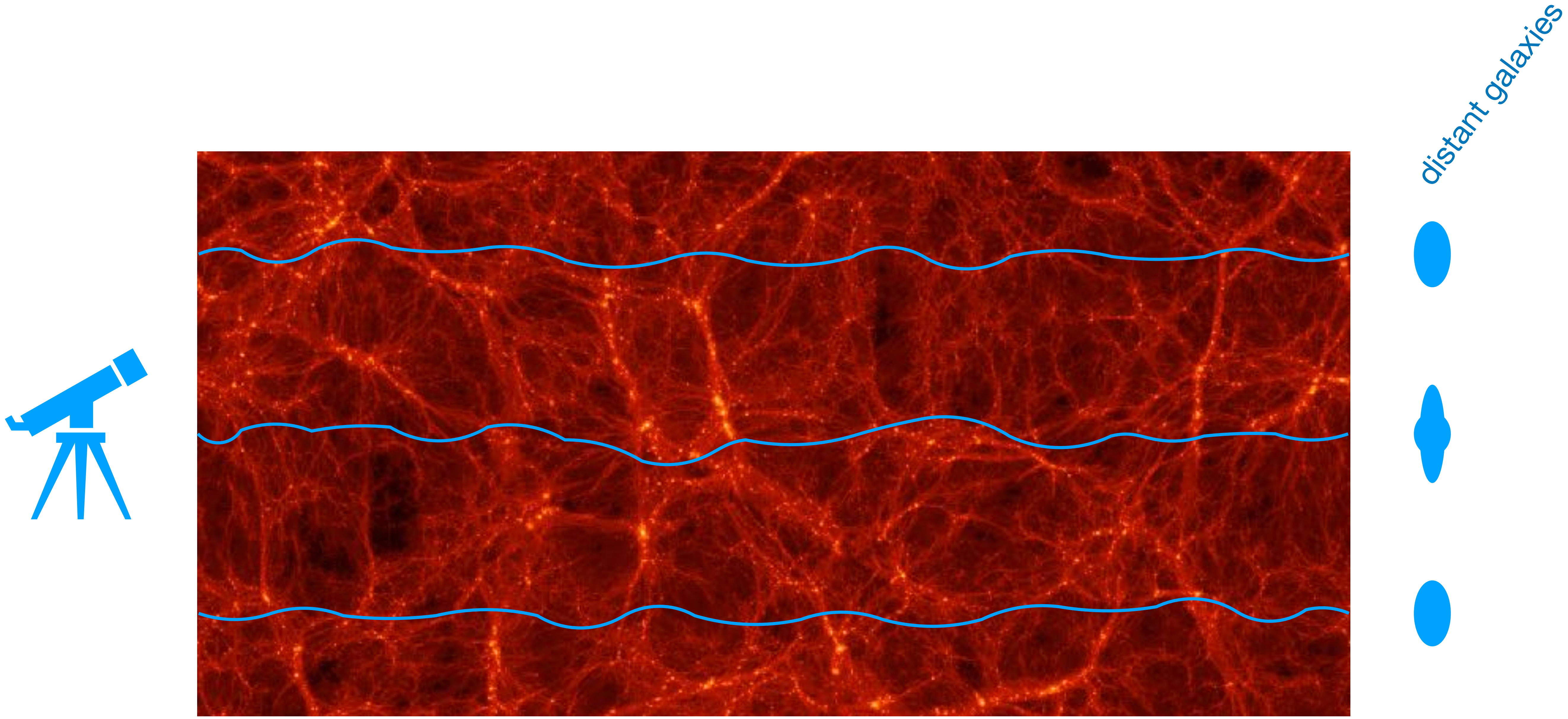



Outline

- Overview of gravitational lensing
- Introduction to intrinsic alignments (IA)
- Review of galaxy alignment 2-point functions
- Review of previous models of IA
- Introduction to a flexible halo-based model of IA
- Phenomenology of alignment correlations in the halo model context
- Discussion of future work and applications

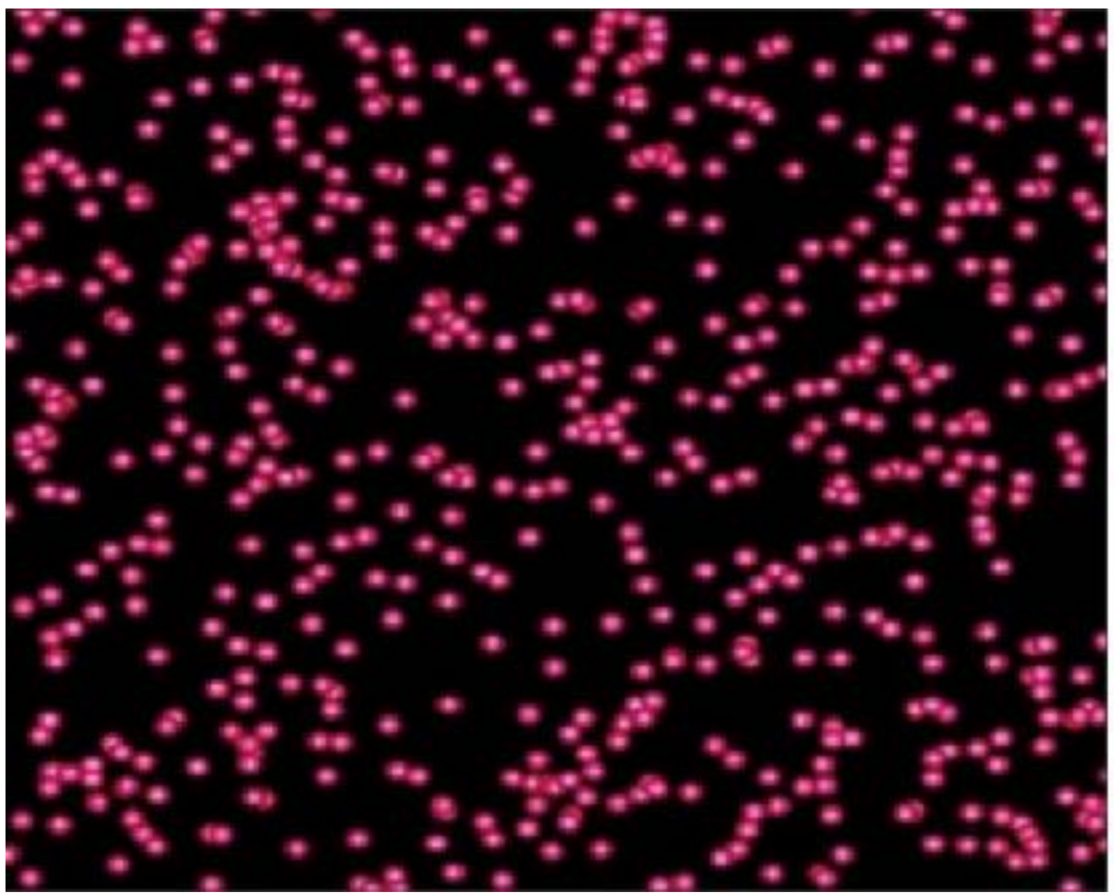
Gravitational Lensing



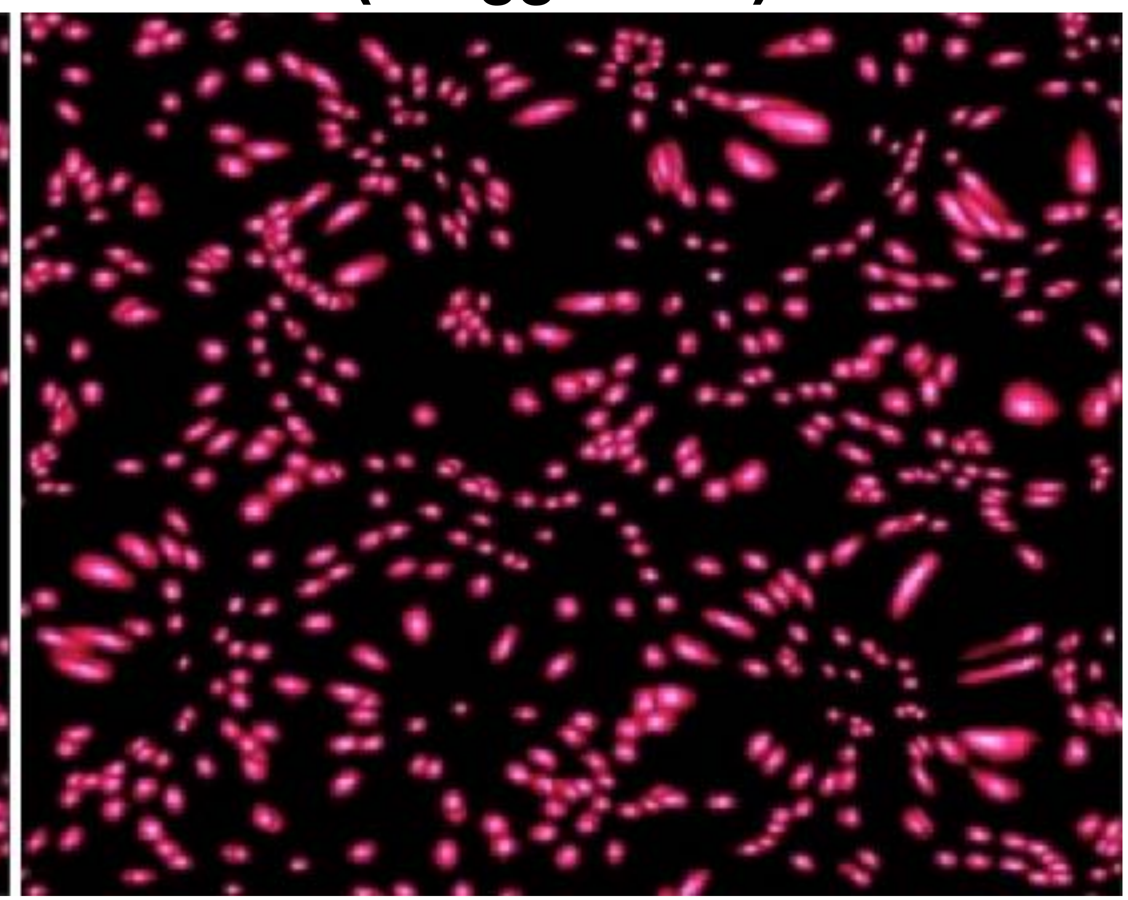
- Light from distant galaxies is deflected by the intervening matter distribution.
- Deflections result in galaxy shape distortions and magnification.

Weak Gravitational Lensing

Un-lensed "galaxies"

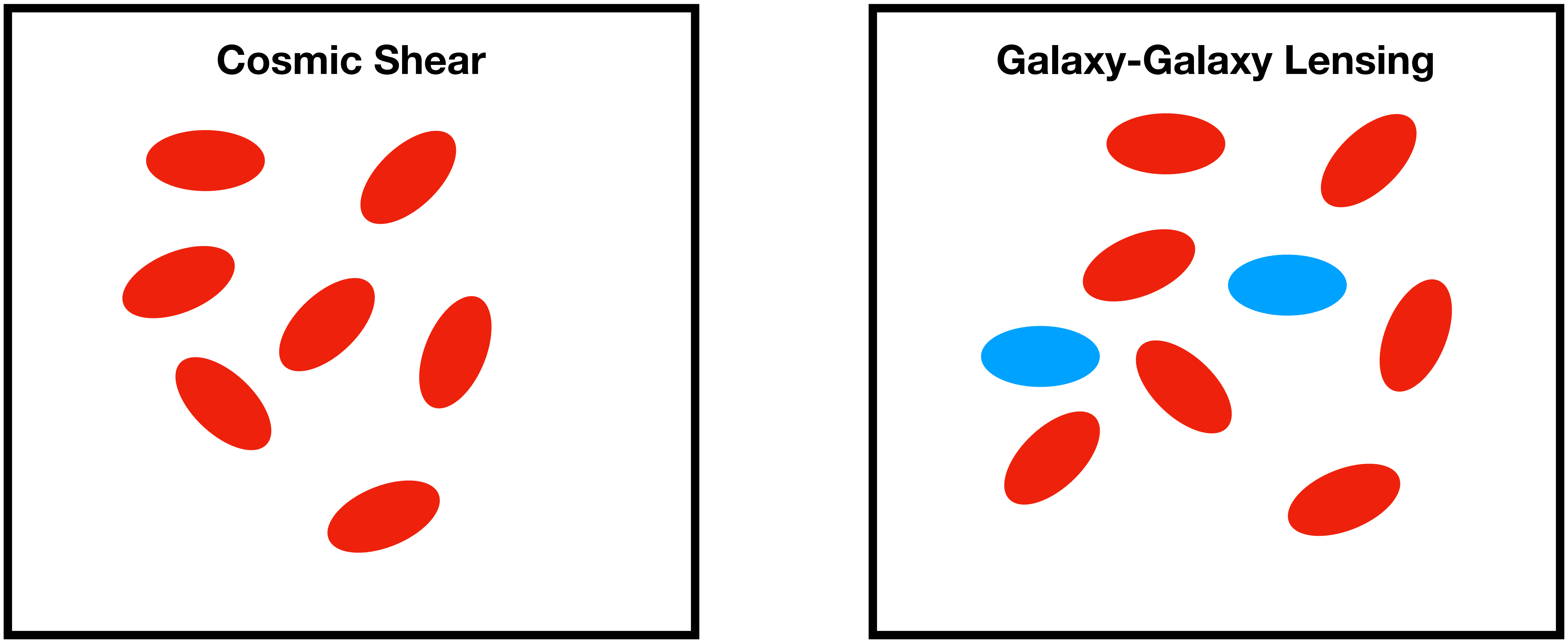


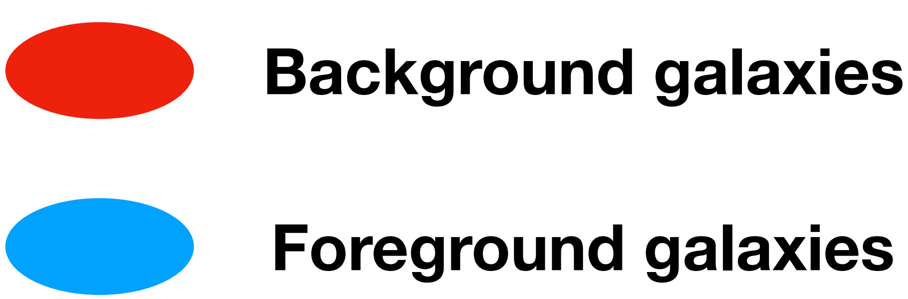
lensed "galaxies" (exaggerated)



- Deflections result in galaxy shape distortions and magnification.
- Weak lensing results in tangential shear in the direction of mass over densities.

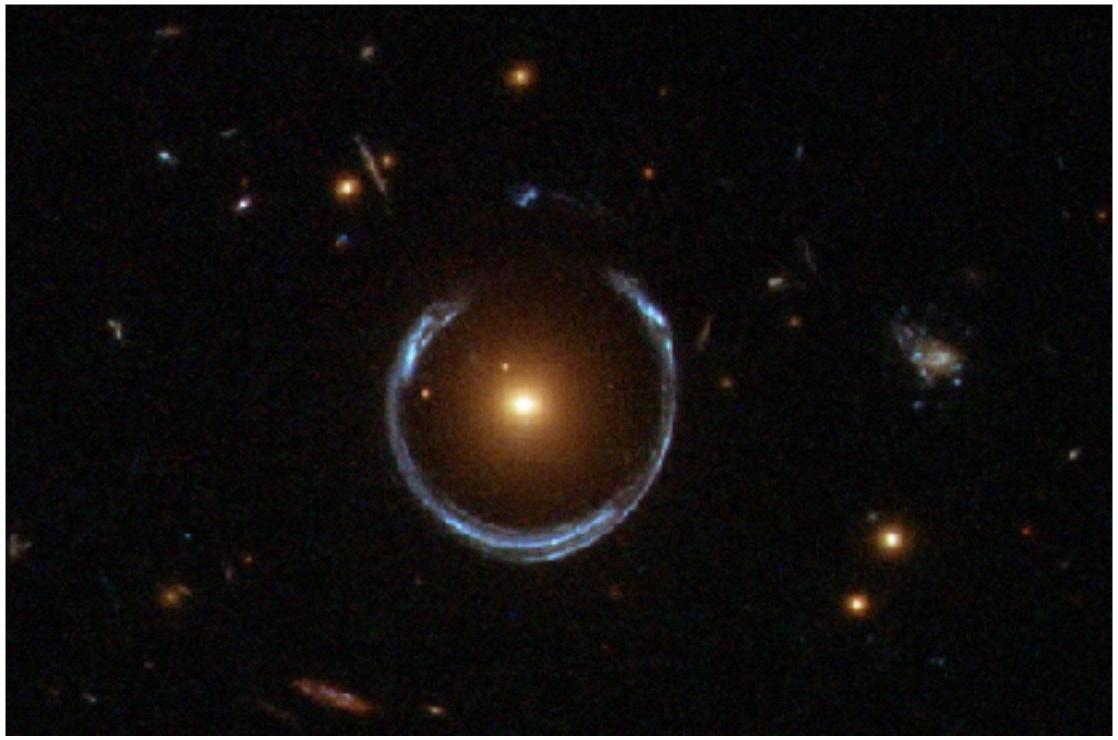
Weak Gravitational Lensing

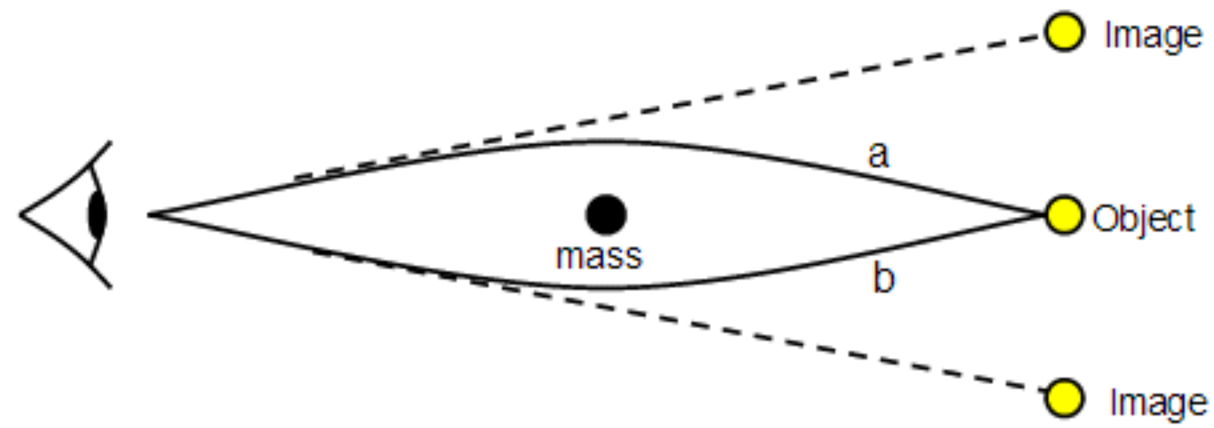




- Cosmic shear: correlated shapes of background galaxies
- Galaxy-galaxy lensing: correlated shapes of background and foreground galaxies

Strong Gravitational Lensing

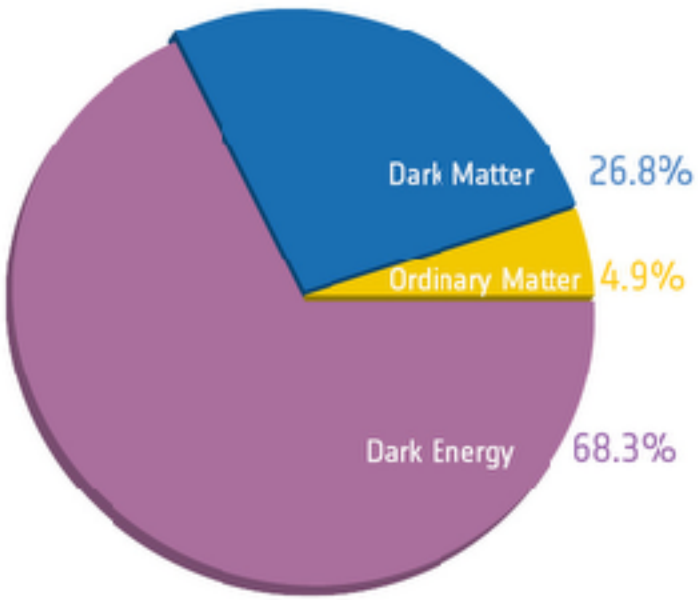




- Strong lensing results in multiple images or rings of background galaxies.
- Strong lensing probes significantly smaller scales and larger over densities.
- Strong lenses are very rare in comparison to weakly lensed galaxies.

Weak Gravitational Lensing

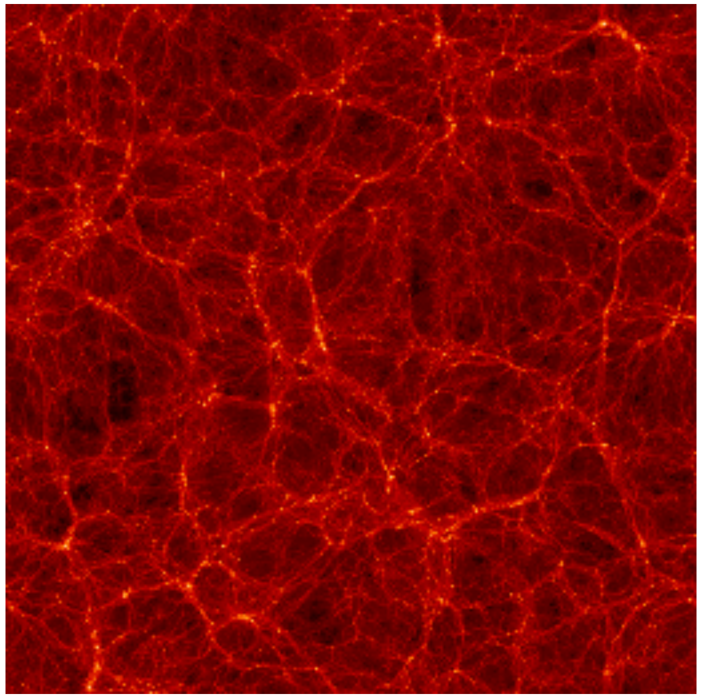
Dark Energy



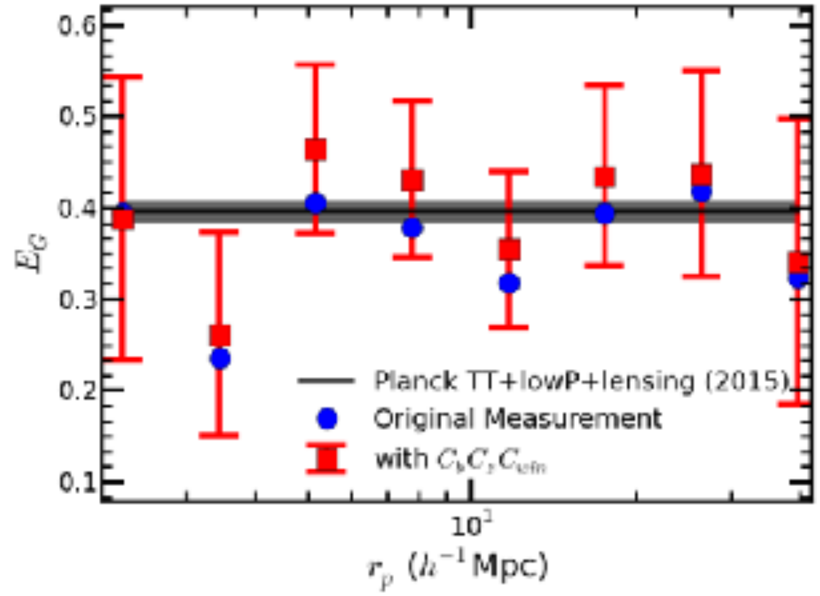
Why should you be interested in weak lensing (systematics)?

Galaxy-Halo connection

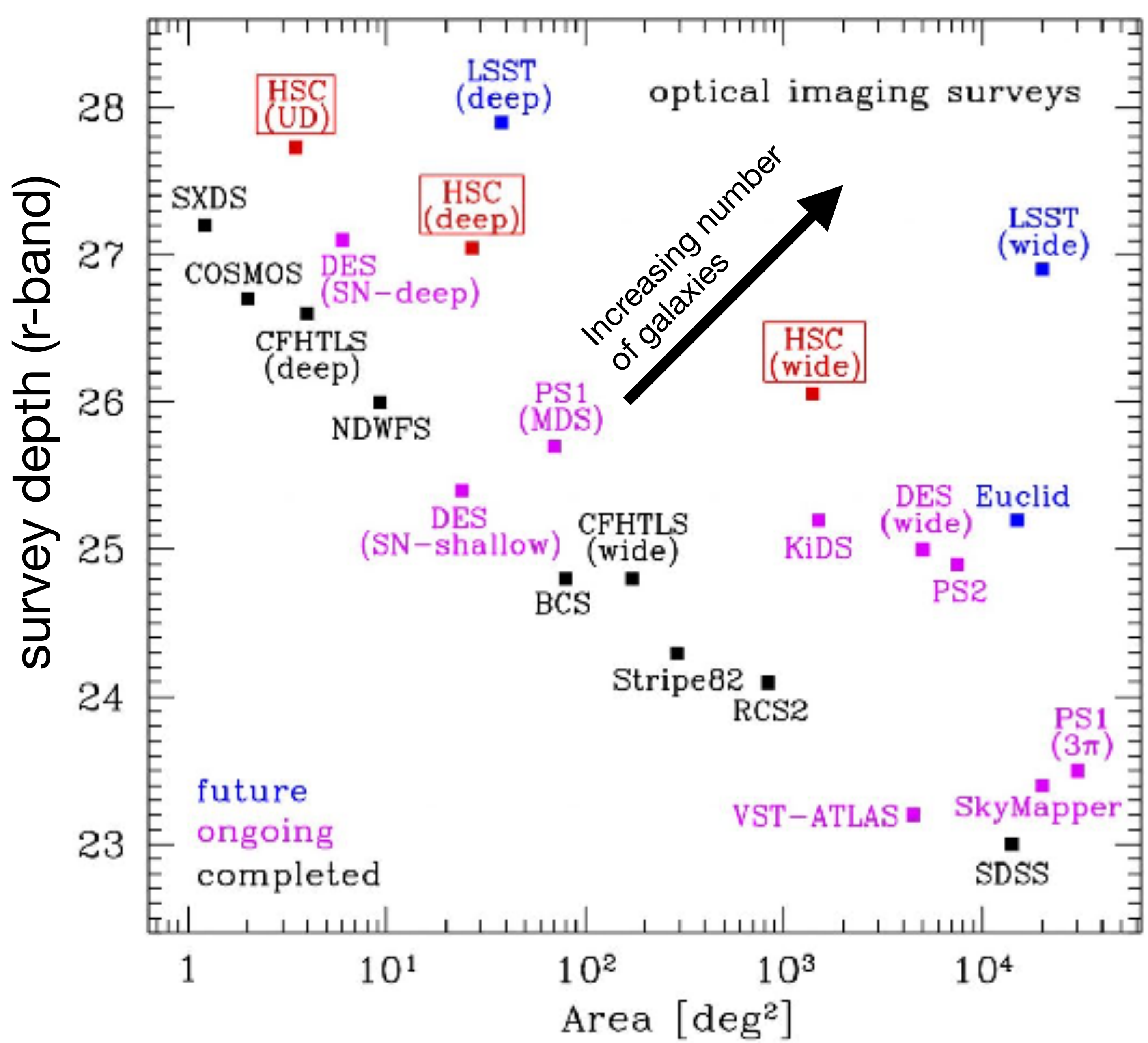
Growth of Structure



Testing of Gravity



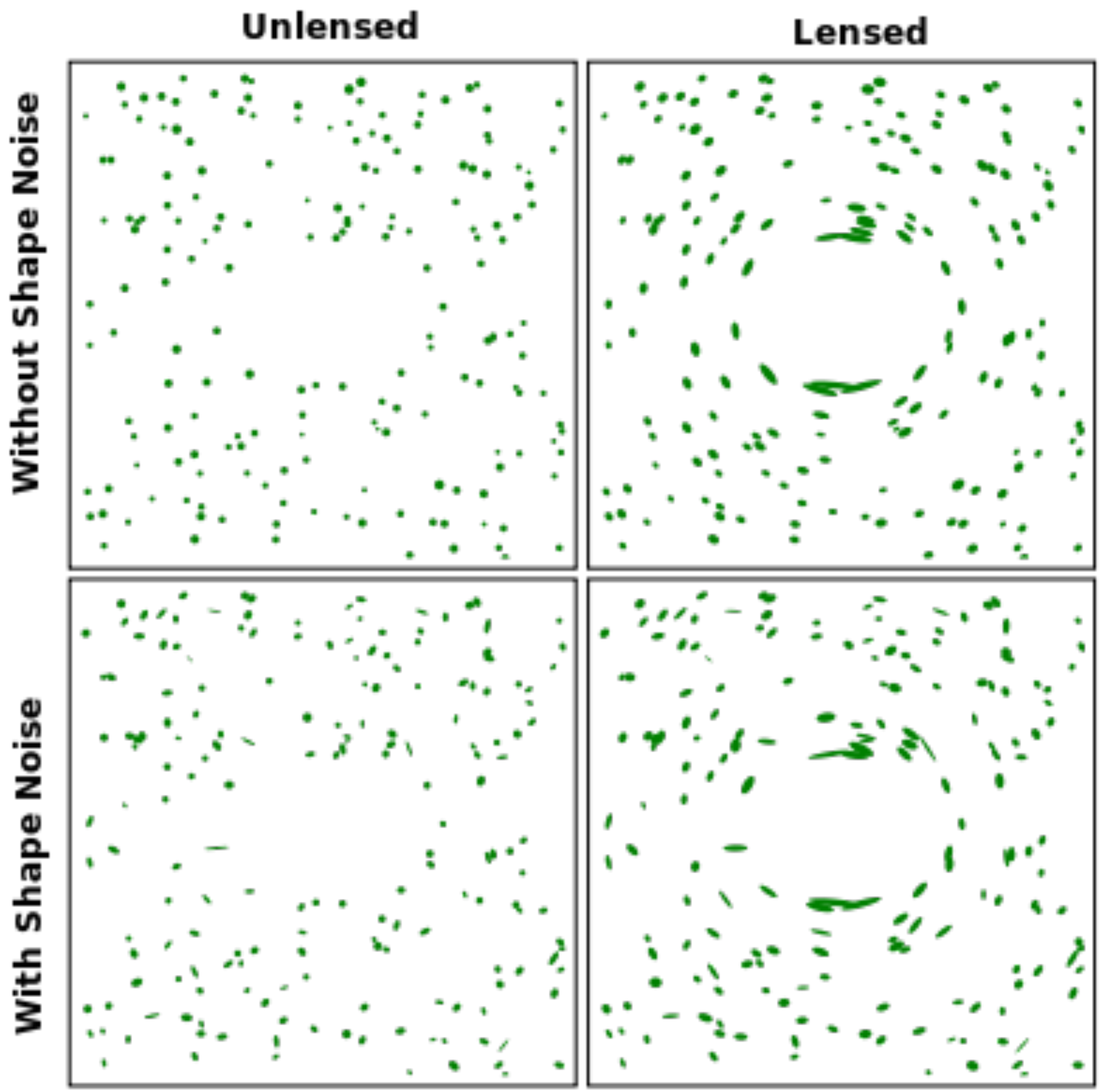
Weak Lensing Surveys



Credit: HSC

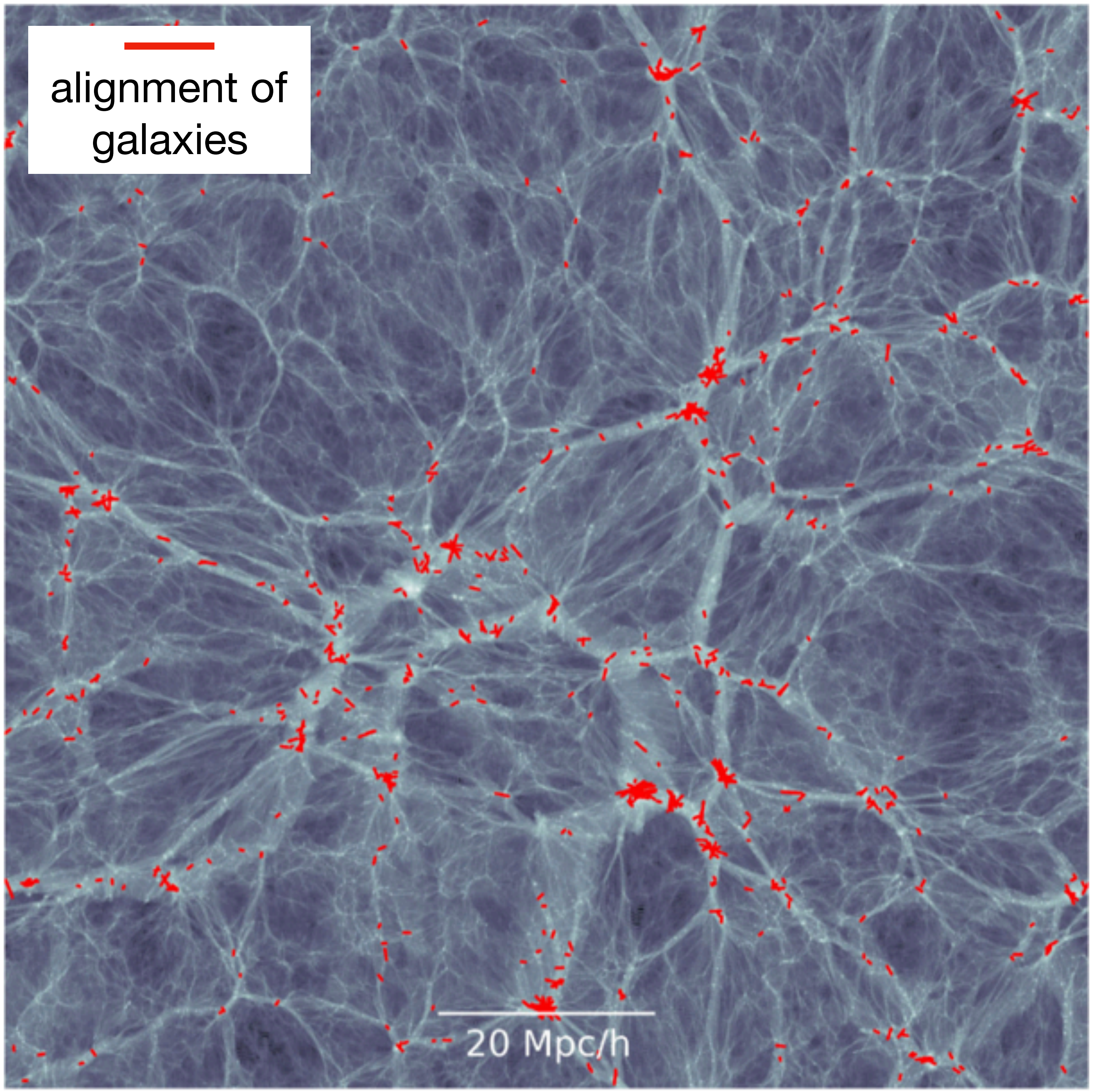
Statical power of surveys must be matched by increasing control of astrophysical and observational systematics.

Galaxy Shapes



- Weak lensing induces ellipticities of ~0.001
- Intrinsic shapes of galaxies have ellipticities of ~0.1
- Shape noise is overcome by measuring shapes of many (~1000) galaxies

Intrinsic Alignments

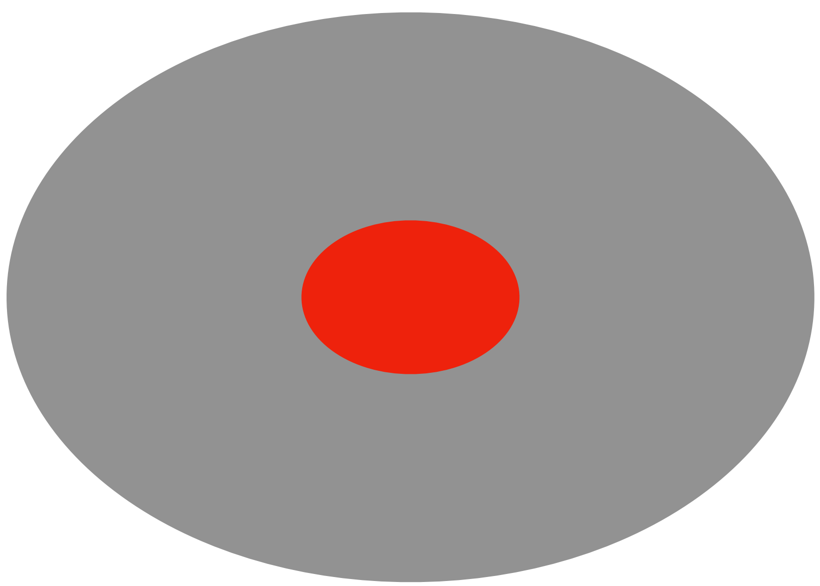


Tenneti + 2015

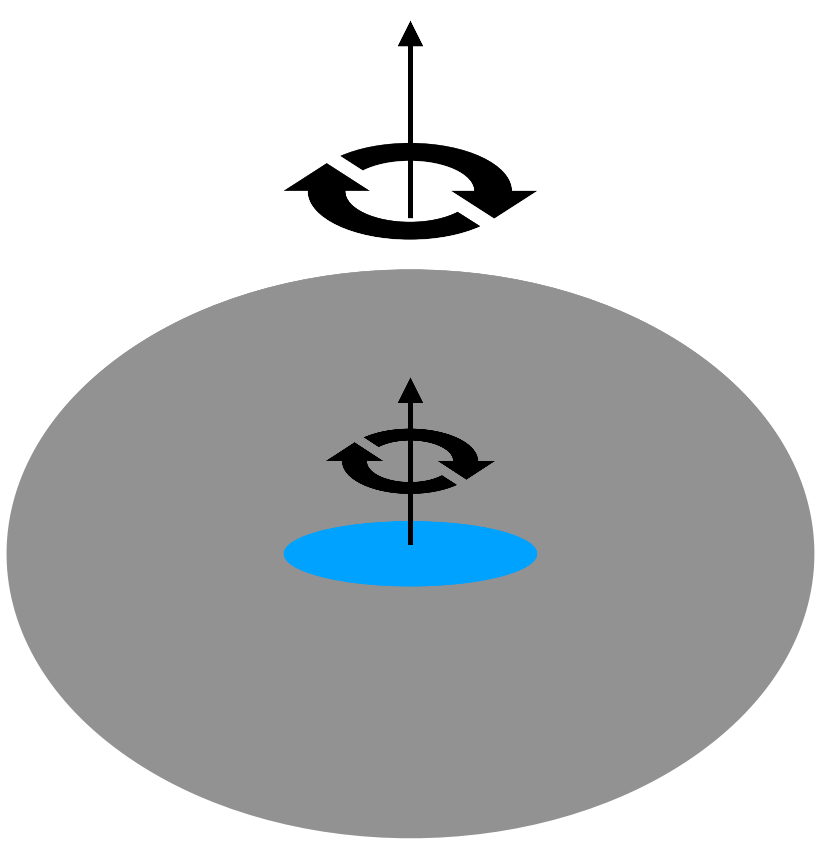
Hydrodynamic simulations of galaxy formation show intrinsic alignments between galaxies and large scale structure.

- Any correlated ellipticities not caused by lensing can contaminate lensing signals
- Galaxy alignments with large scale structure and other galaxies are seen in both simulations and observations!

Physics of Intrinsic Alignments

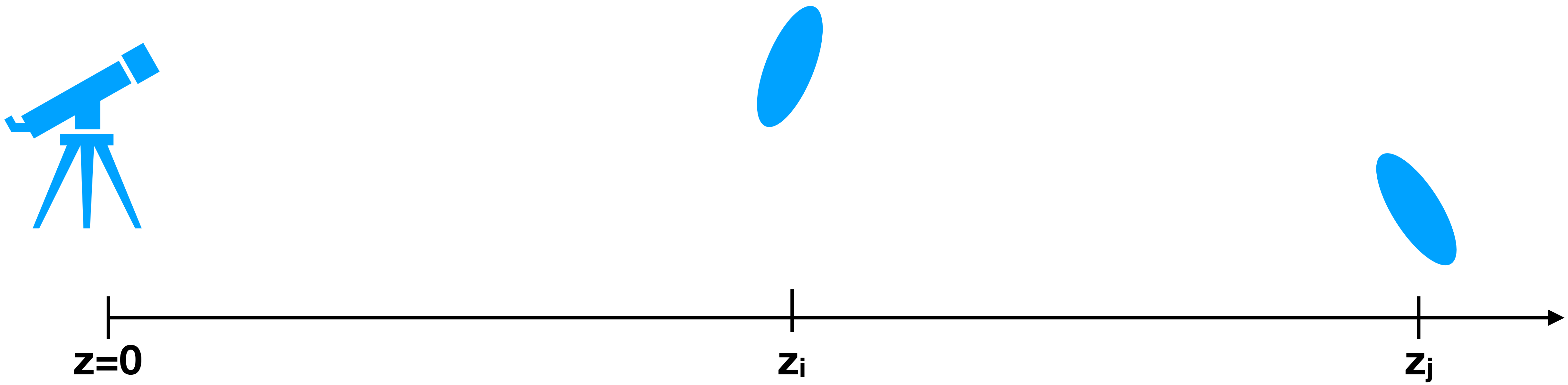


- Elliptical Galaxies (Early Type)
  - pressure supported systems
  - triaxial collapse of host halo in tidal field
  - galaxy follows halo shape



- Disk Galaxies (Late Type)
  - angular momentum supported systems
  - coupling of halo to quadruple moment of tidal field at time of collapse
  - galaxy preserves angular momentum during formation
  - galaxy and halo spin axis align

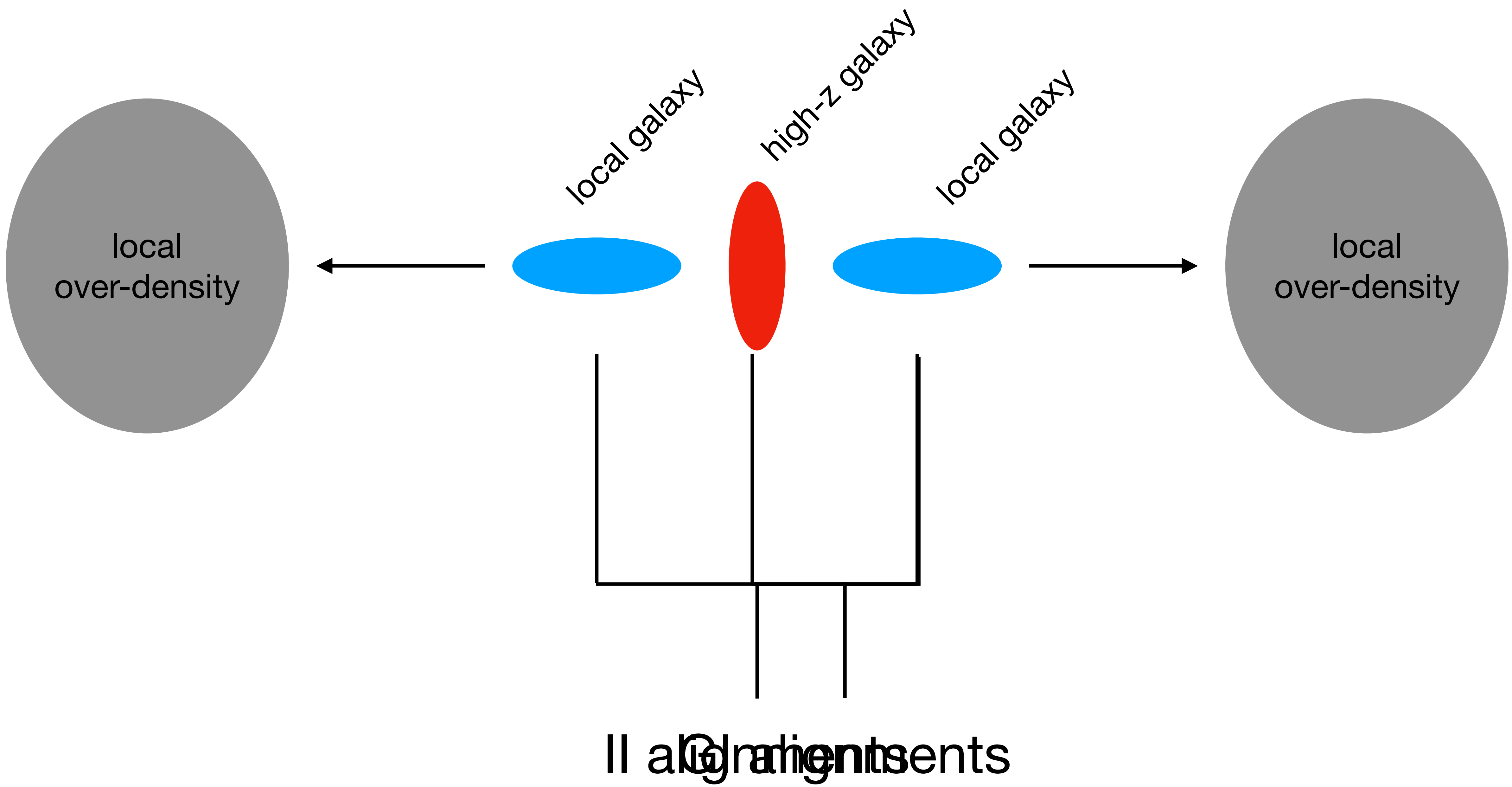
Intrinsic Alignments



- ϵ^I **intrinsic ellipticity**
- ϵ **observed ellipticity**
- γ **gravitational shear**

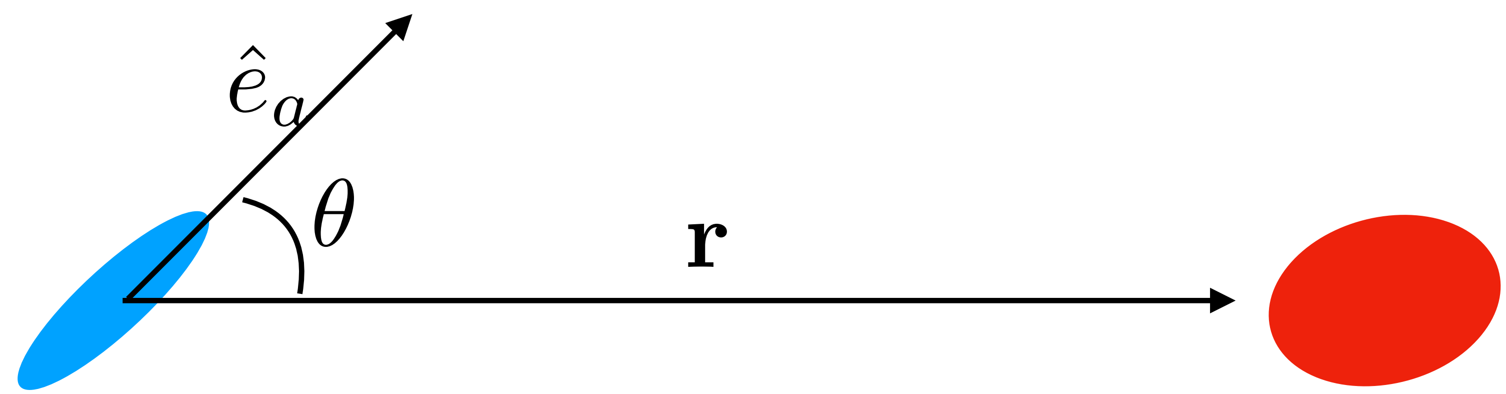
$$\underbrace{\langle \epsilon_i \epsilon_j \rangle}_{\text{observed shape correlation}} = \underbrace{\langle \gamma_i \gamma_j \rangle}_{\text{cosmic shear}} + \underbrace{\langle \epsilon_i^I \epsilon_j^I \rangle}_{\text{II}} + \underbrace{\langle \gamma_i \epsilon_j^I \rangle}_{\text{zero if } z_j >> z_i} + \underbrace{\langle \epsilon_i^I \gamma_j \rangle}_{\text{GI}}$$

Intrinsic Alignments



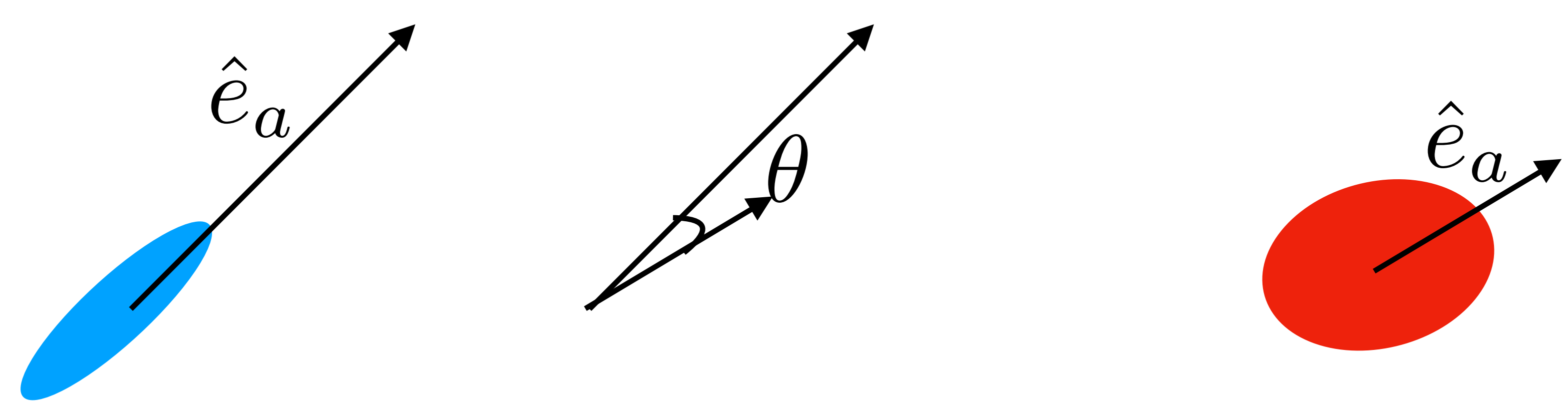
Alignment Correlations

Ellipticity-Direction correlation (ED)



$$\omega(r) = \langle |\hat{e}_a(\mathbf{x}) \cdot \hat{\mathbf{r}}(\mathbf{x})|^2 \rangle - \frac{1}{3}$$

Ellipticity-Ellipticity correlation (EE)



$$\eta(r) = \langle |\hat{e}_a(\mathbf{x}) \cdot \hat{e}_a(\mathbf{x}+\mathbf{r})|^2 \rangle - \frac{1}{3}$$

Alignment Correlations

Gravitational shear-Intrinsic ellipticity correlation (GI)

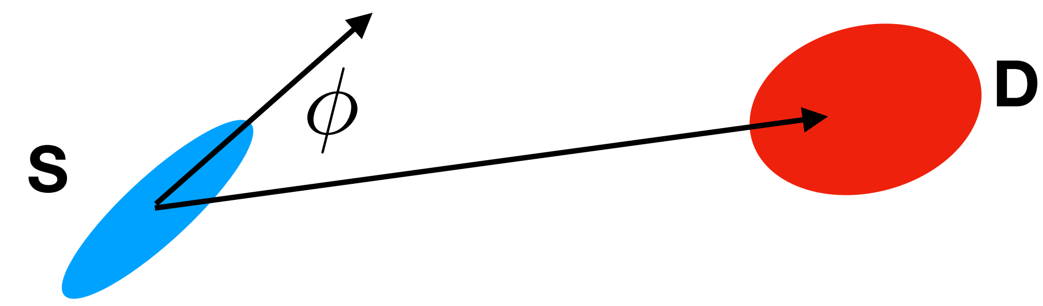
$$\xi_{g+} = \frac{S_+D - S_+R_D}{R_S R_D}$$

$$S_+X = \sum_{i\in S, j\in X} \gamma_+^{(i)} \langle j|i\rangle$$

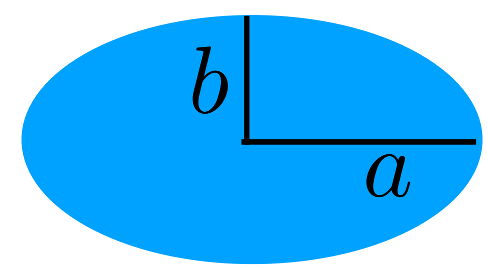
Intrinsic-Intrinsic ellipticity correlation (II)

$$\xi_{++} = \frac{S_+S_+}{R_S R_S}$$

$$S_+S_+ = \sum_{i\in S, j\in S} \gamma_+^{(i)} \gamma_+^{(j)} \langle j|i\rangle$$



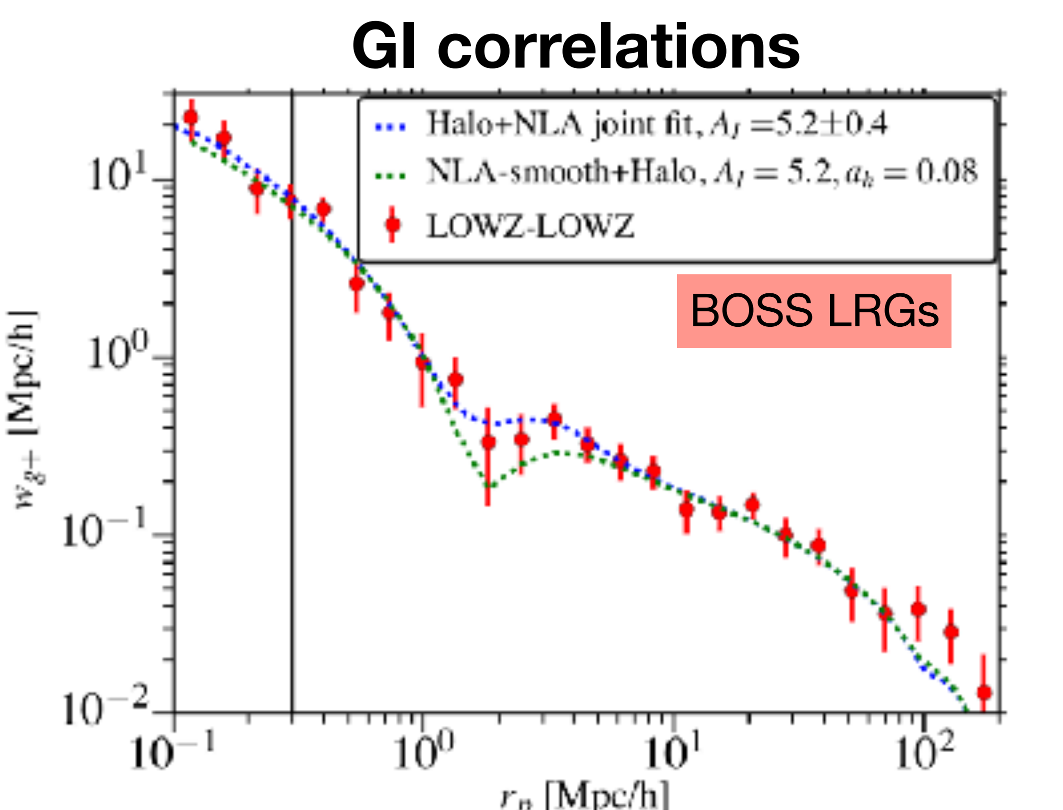
$$\gamma_+ = \frac{1-q^2}{1+q^2}\cos(2\phi)$$



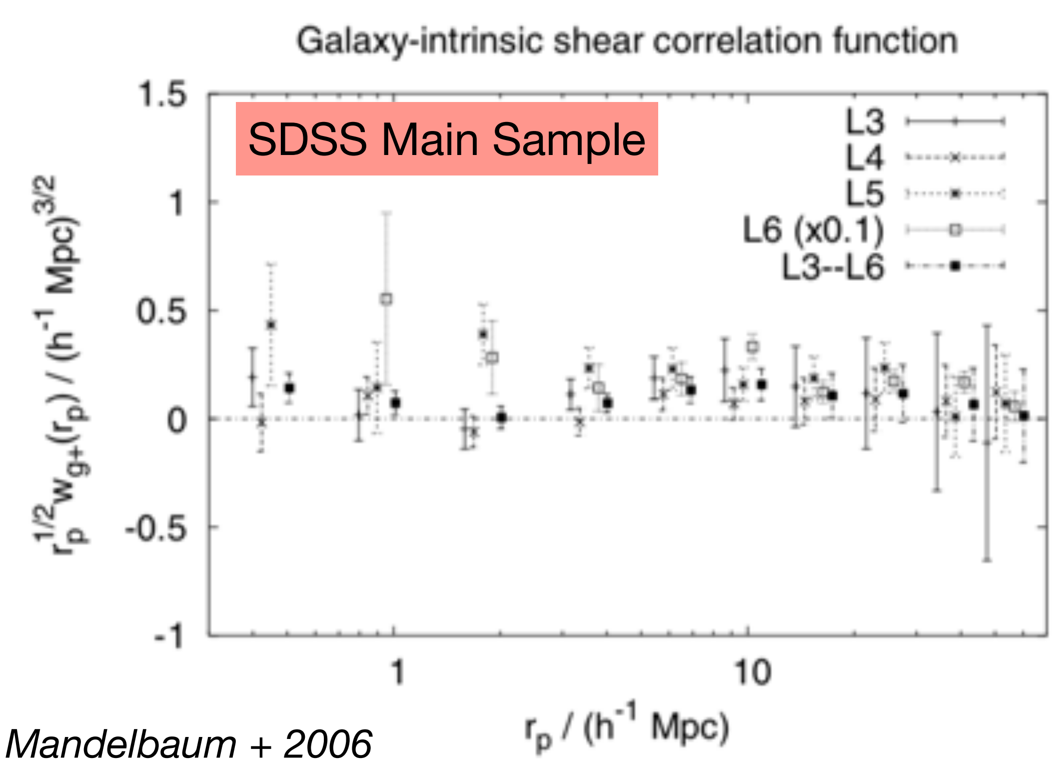
$$q = \frac{a}{b}$$

Correlations weighted by density and ellipticity

Observations of Intrinsic Alignments



Singh + 2015



Mandelbaum + 2006

- Elliptical Galaxies (Early Type)
  - Consensus is that there are significant alignments
  - GI alignments are strong
  - II alignments are weak
- Disk Galaxies (Late Type)
  - most measurements are consistent with no alignments
  - How much alignment does the noisy data allow?
- Satellite Galaxies (Both)
  - Inconsistent results
  - Mounting indications for radial alignment within host halo

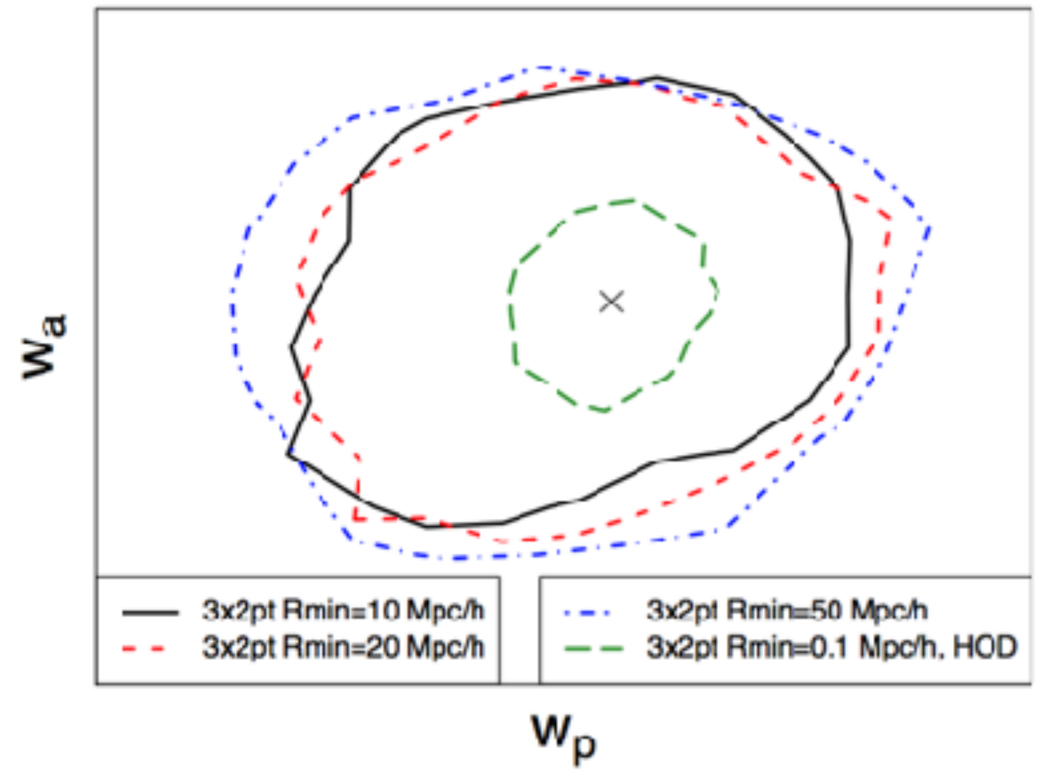
Impact on Cosmological Surveys

- Ignoring intrinsic alignments can bias parameters by ~10%
- The goal is to subtract and marginalize over uncertainty in IA

We would like:

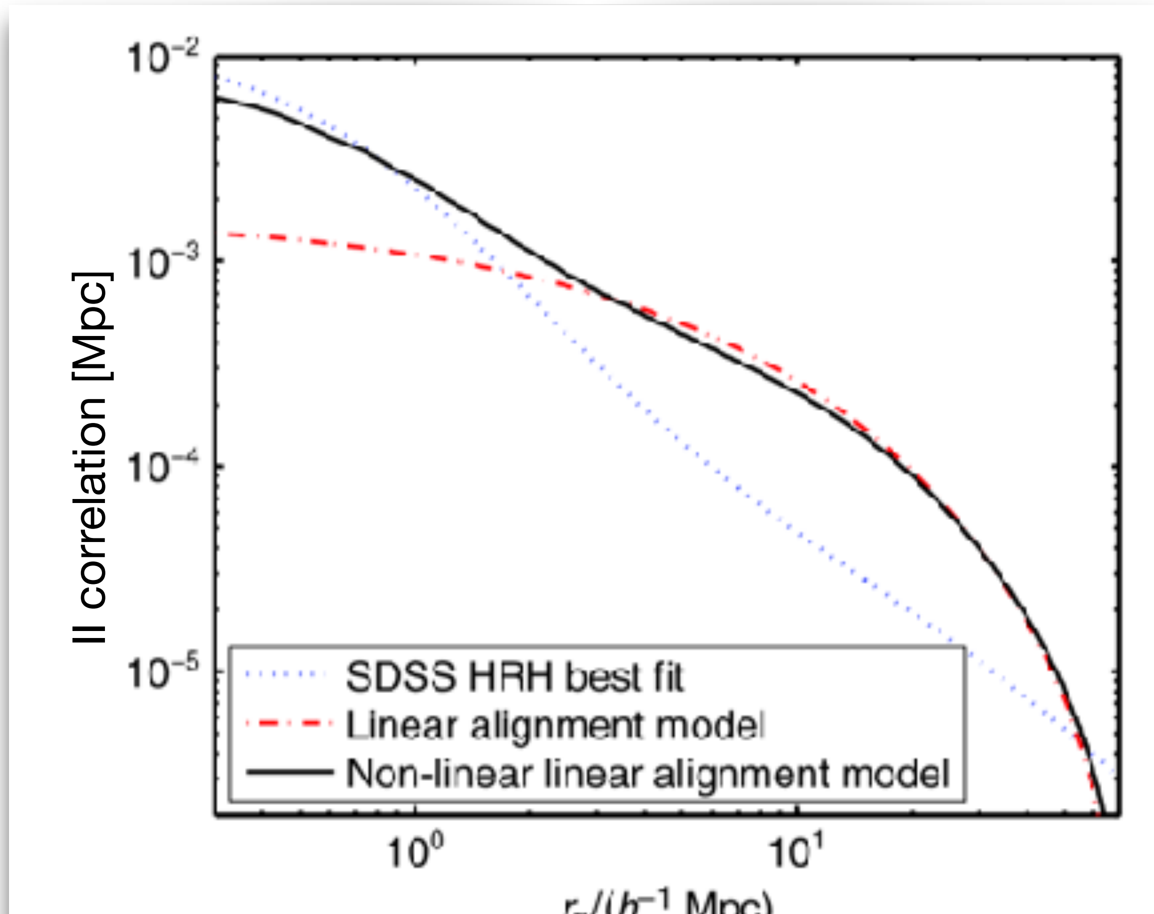
- physically motivated models for IA
- priors to go along with those models!
- the ability to create mock data sets in order to test cosmological parameter extraction from surveys
- model and therefore use small scale data
- learn about galaxy formation mechanisms

constraining dark energy

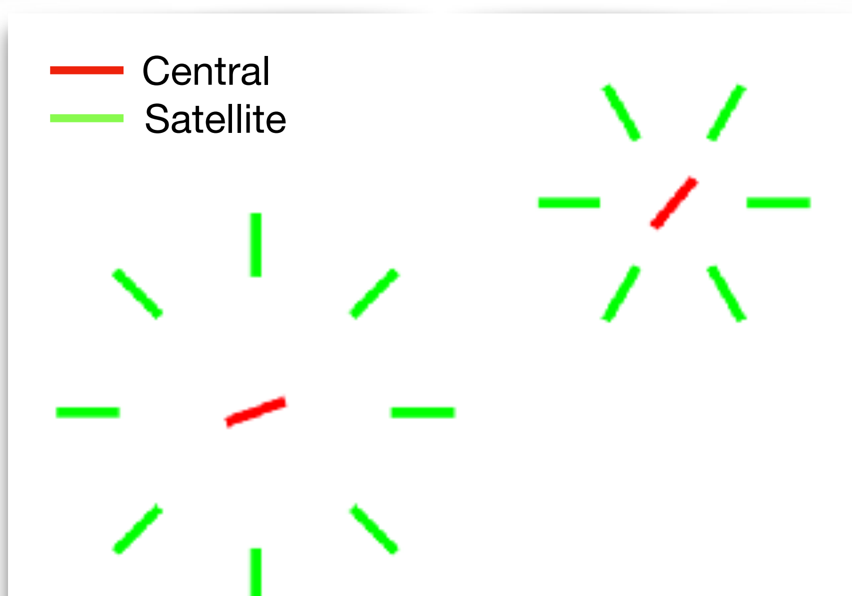


Krause & Eifler (2016)

Mitigating Intrinsic Alignments



Bridle & King + 2007



Schneider & Bridle+ 2010

- Linear Alignment Model
  - Alignments set at formation time
  - Scaling of the linear power spectrum

$$P^{\rm lin}_{\tilde{\gamma}^I}(k) = \frac{C_1^2 \bar{\rho}^2}{\bar{D}^2} P^{\rm lin}_{\delta}(k) \qquad \textbf{II}$$

$$P^{\rm lin}_{\delta,\tilde{\gamma}^I}(k) = -\frac{C_1 \bar{\rho}}{\bar{D}} P^{\rm lin}_{\delta}(k) \qquad \textbf{GI}$$

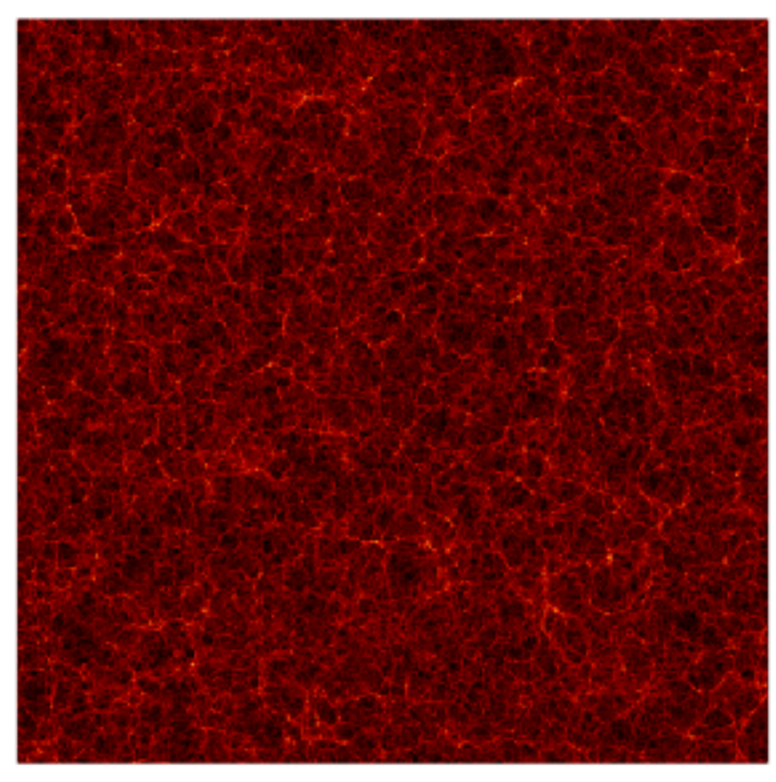
- Nonlinear Alignment Model
  - Uses nonlinear power spectrum
  - No physical motivation beyond linear model
- Schneider & Bridle Halo Model
  - Radial satellite alignments
  - Fitting function for 1-halo term

$$P^{1h}_{\delta,\gamma_I} = a_h \frac{(k/p_1)^2}{1+(k/p_2)^{p_3}}$$

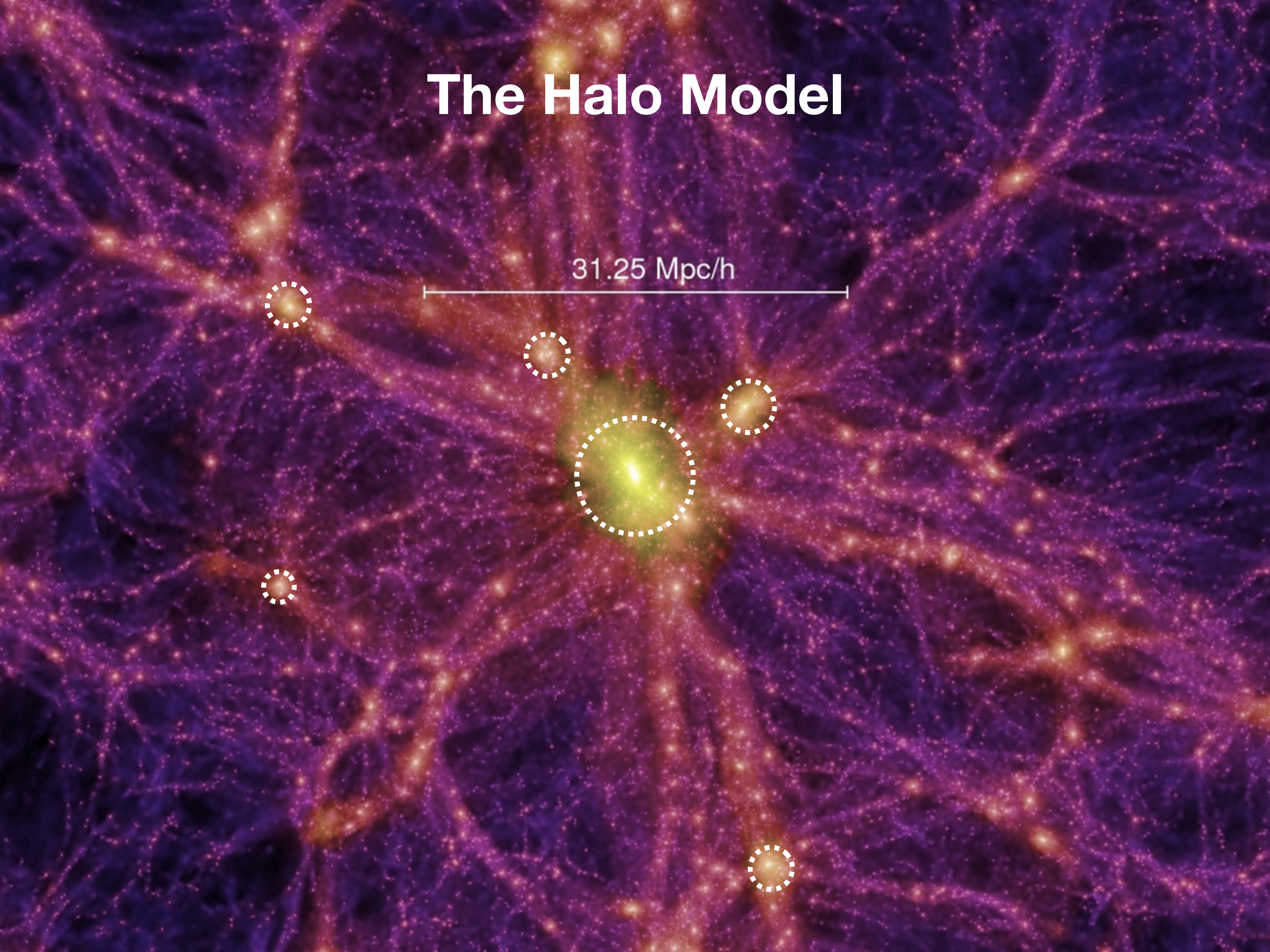
Halo Model for IA

- Hydrodynamic simulations are too expensive for cosmological volumes
- (Non-)linear alignment models are crude, limited to >10 Mpc scales
- Fitting functions provide no physical insight, no obvious way to scale for different galaxy samples
- No current model accounts for all small scale terms.

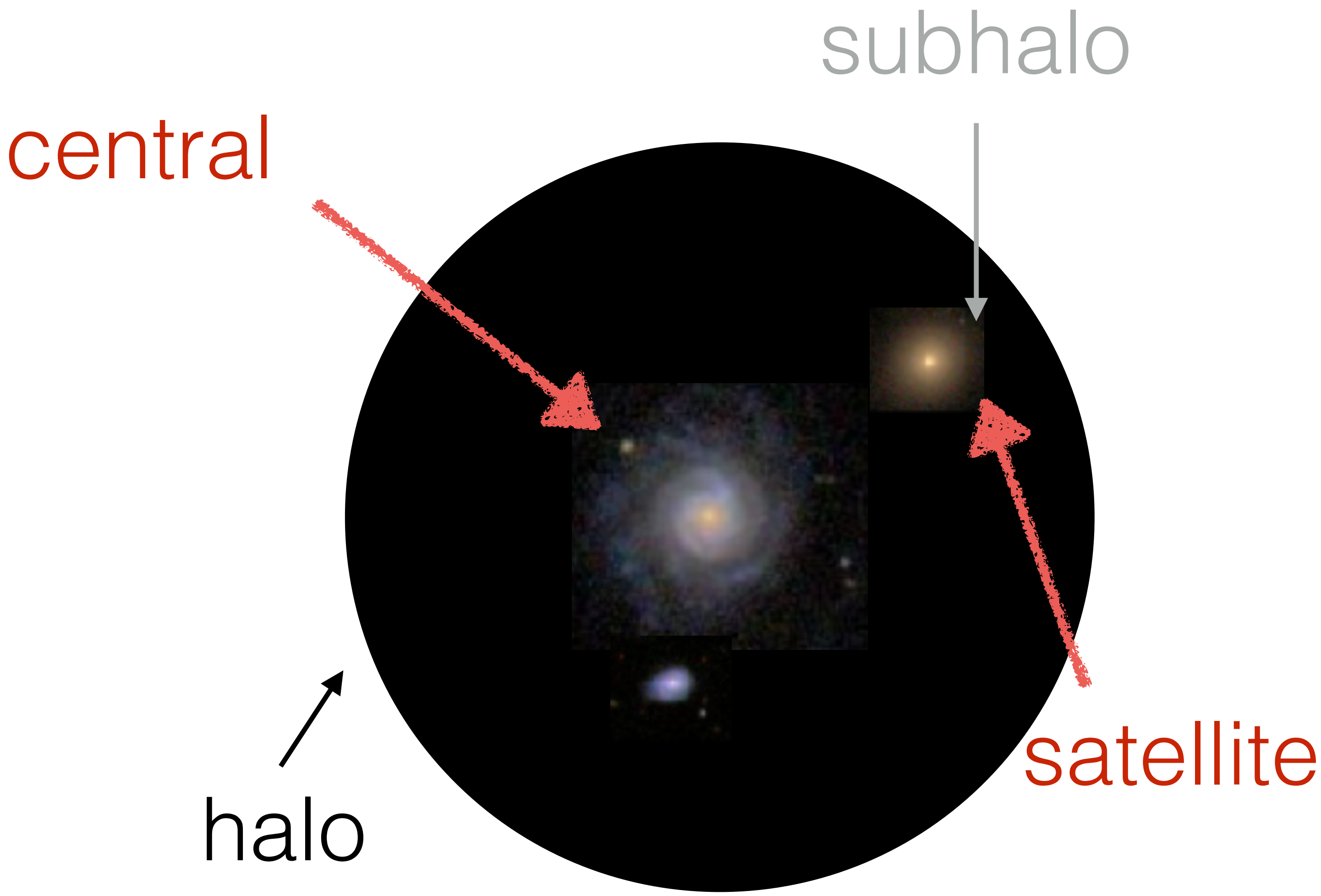
- A halo model can be used to build mocks, e.g. HOD, by populating large dark matter simulations
- A halo model naturally extends from small to large scales
- A halo model provides physical context for understanding IA



The Halo Model

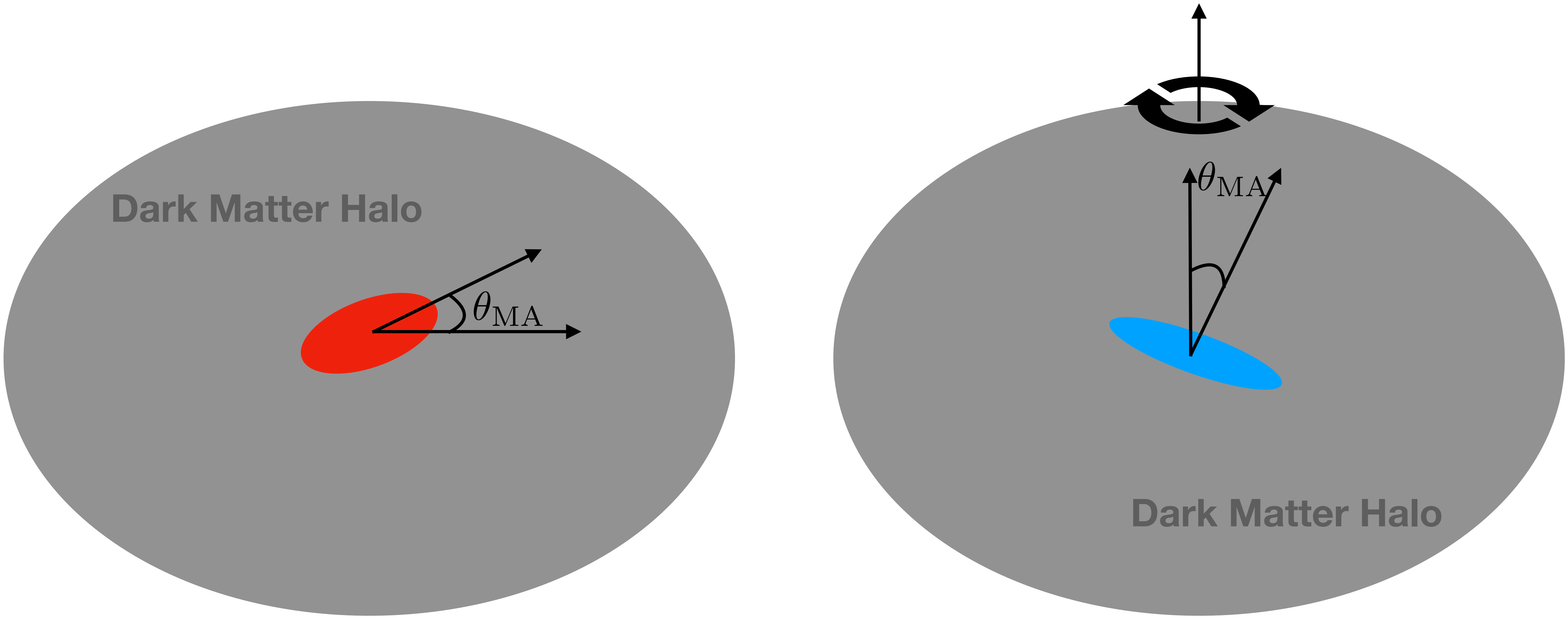


The Halo Model



- Quasi-spherical haloes form in the large scale structure
- Haloes form hierarchically
- Previously distinct haloes become substructure in more massive haloes
- Galaxies form in haloes
- Massive central galaxies occupy the central regions of haloes
- Satellites live in sub-haloes

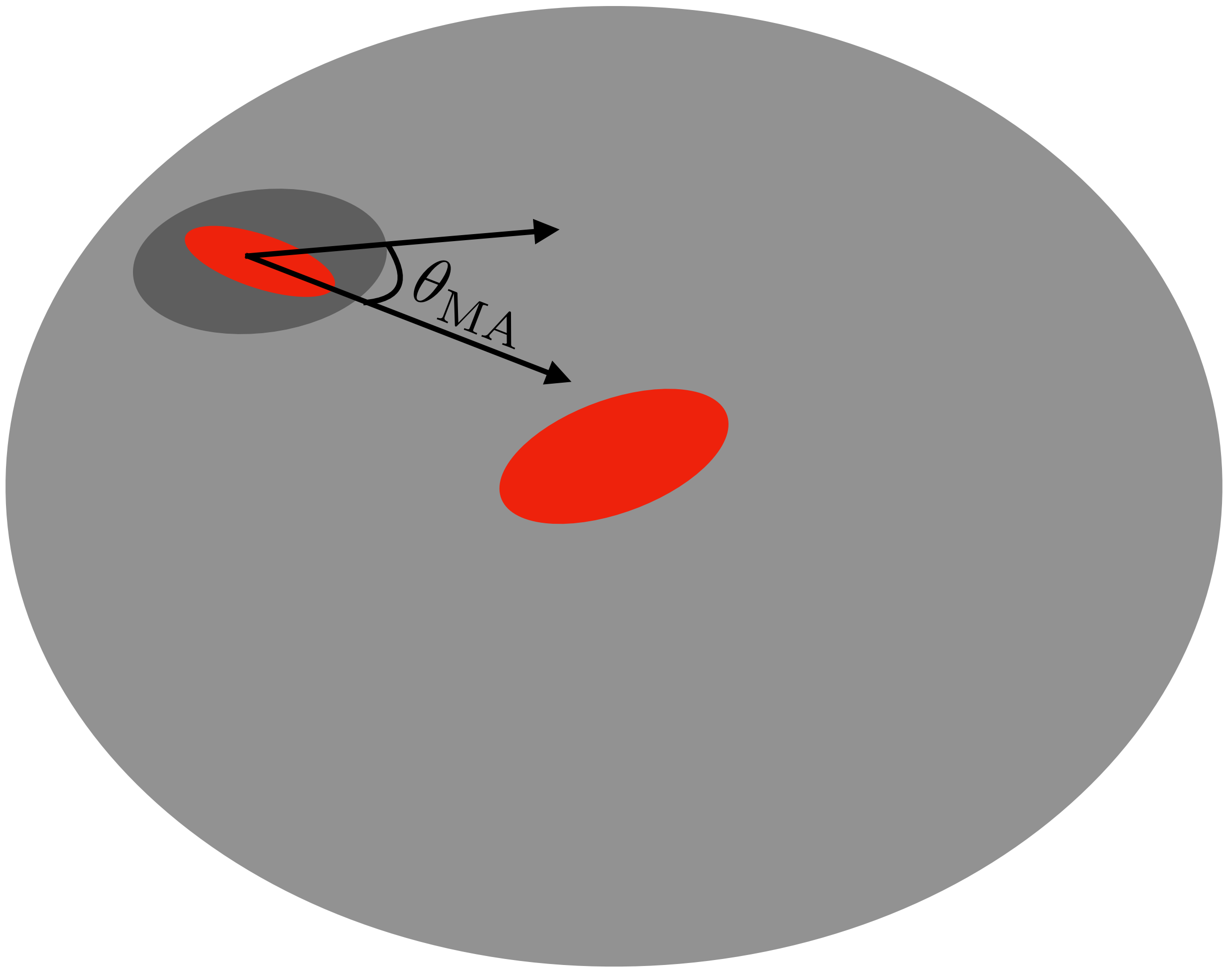
Alignment Halo Model: Centrals



- define halo alignment vector
  - Halo major axis for elliptical galaxies
  - Halo spin axis for disk galaxies
- define galaxy alignment vector
  - major/minor axis
  - spin axis
- specify distribution of misalignments

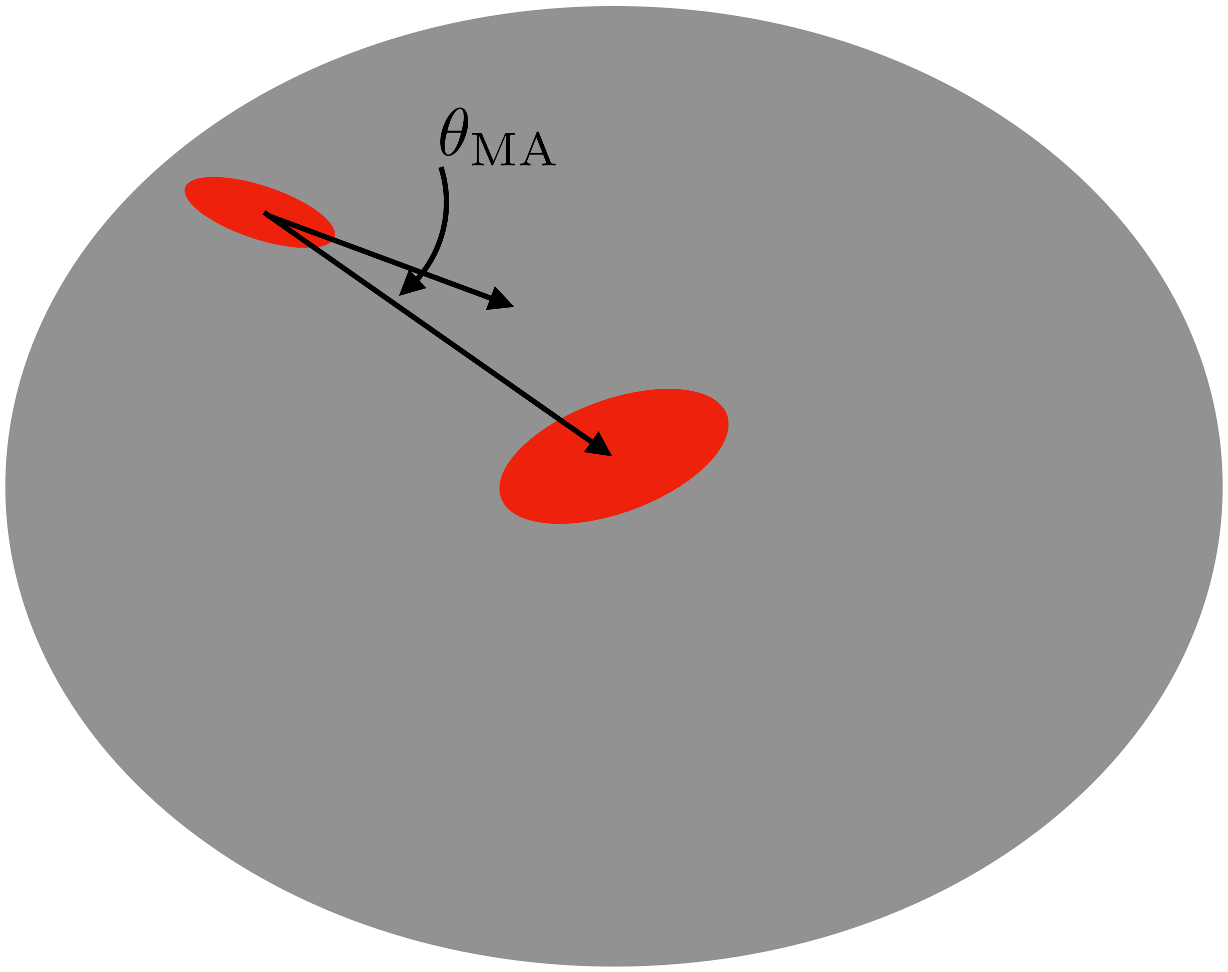
Alignment Halo Model: Satellites

With sub-haloes



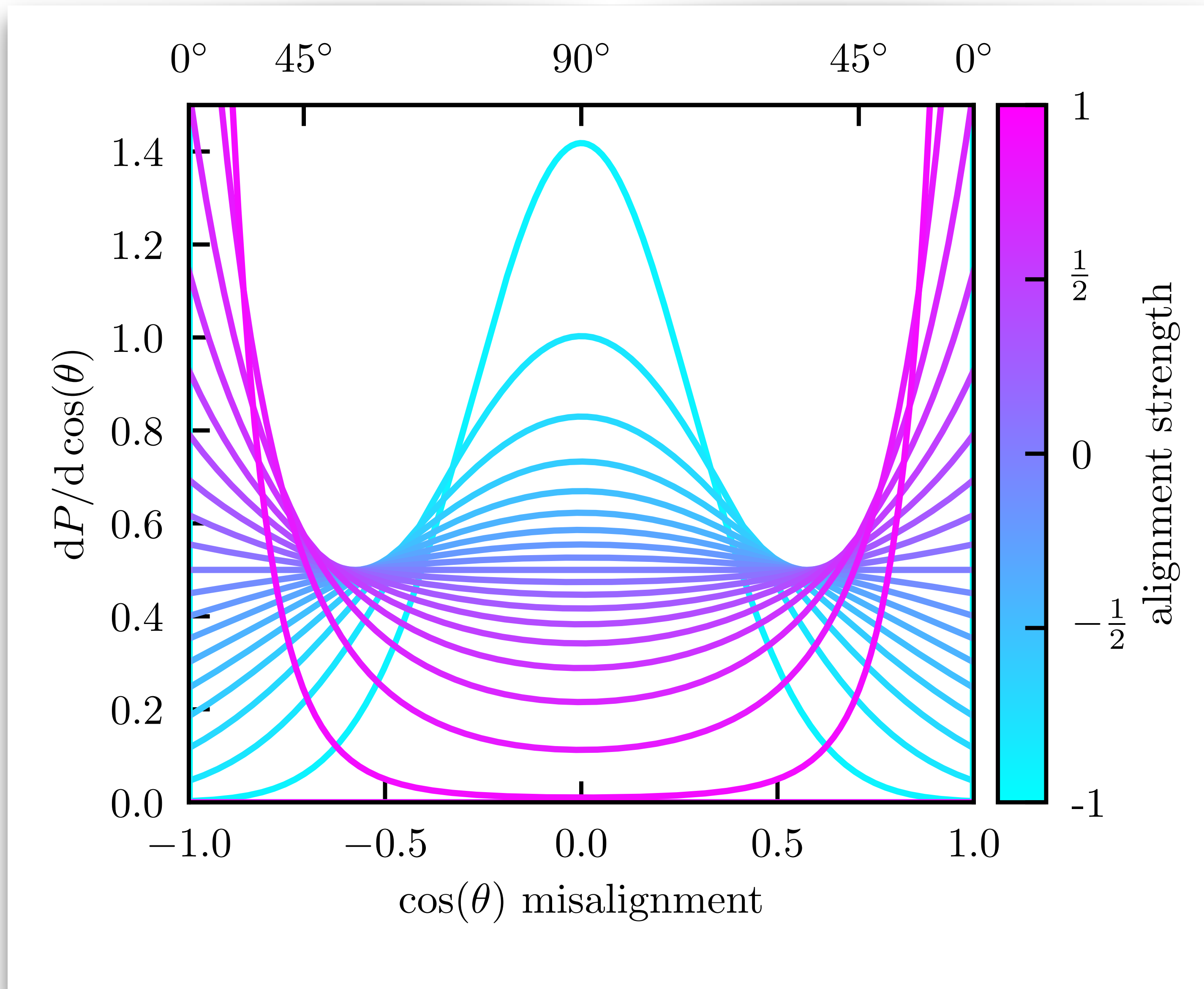
- use sub-halo orientations
- limited to use in ‘high resolution’ simulations

Without sub-haloes



- use host-satellite radial vector
- can be scaled up to large simulations

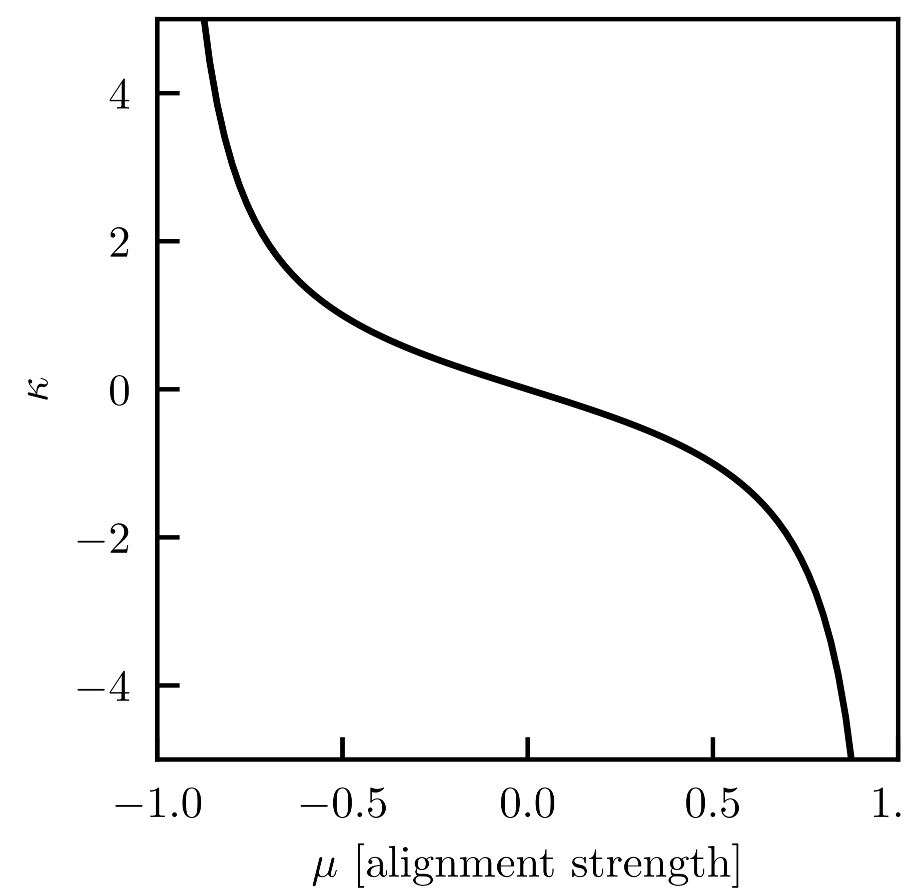
Misalignment Model



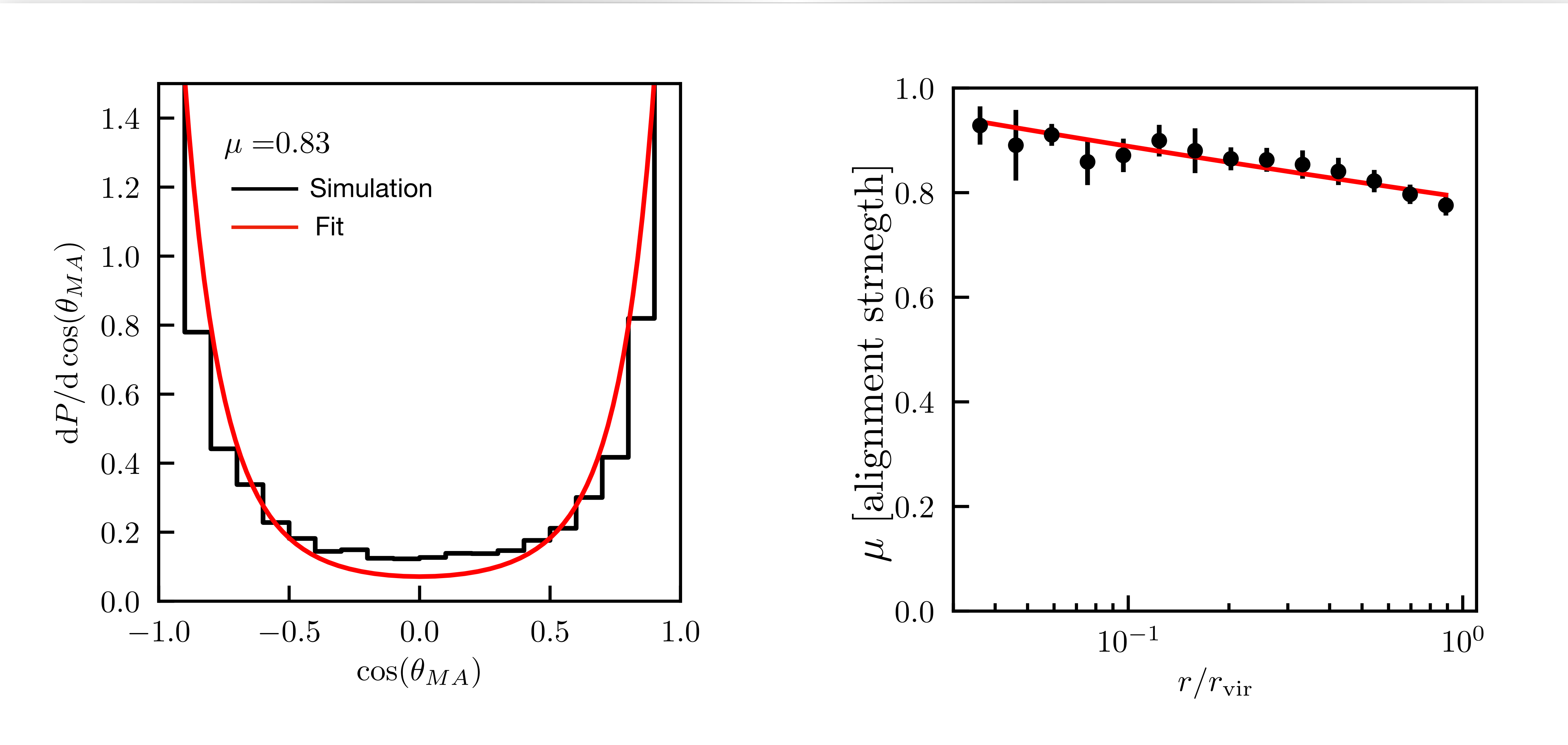
Watson Distribution

$$P(\theta, \phi) = \frac{B(\kappa)}{2\pi} e^{-\kappa \cos^2 \theta} \sin \theta \mathrm{d}\theta \mathrm{d}\phi$$

Parameterize the alignment strength

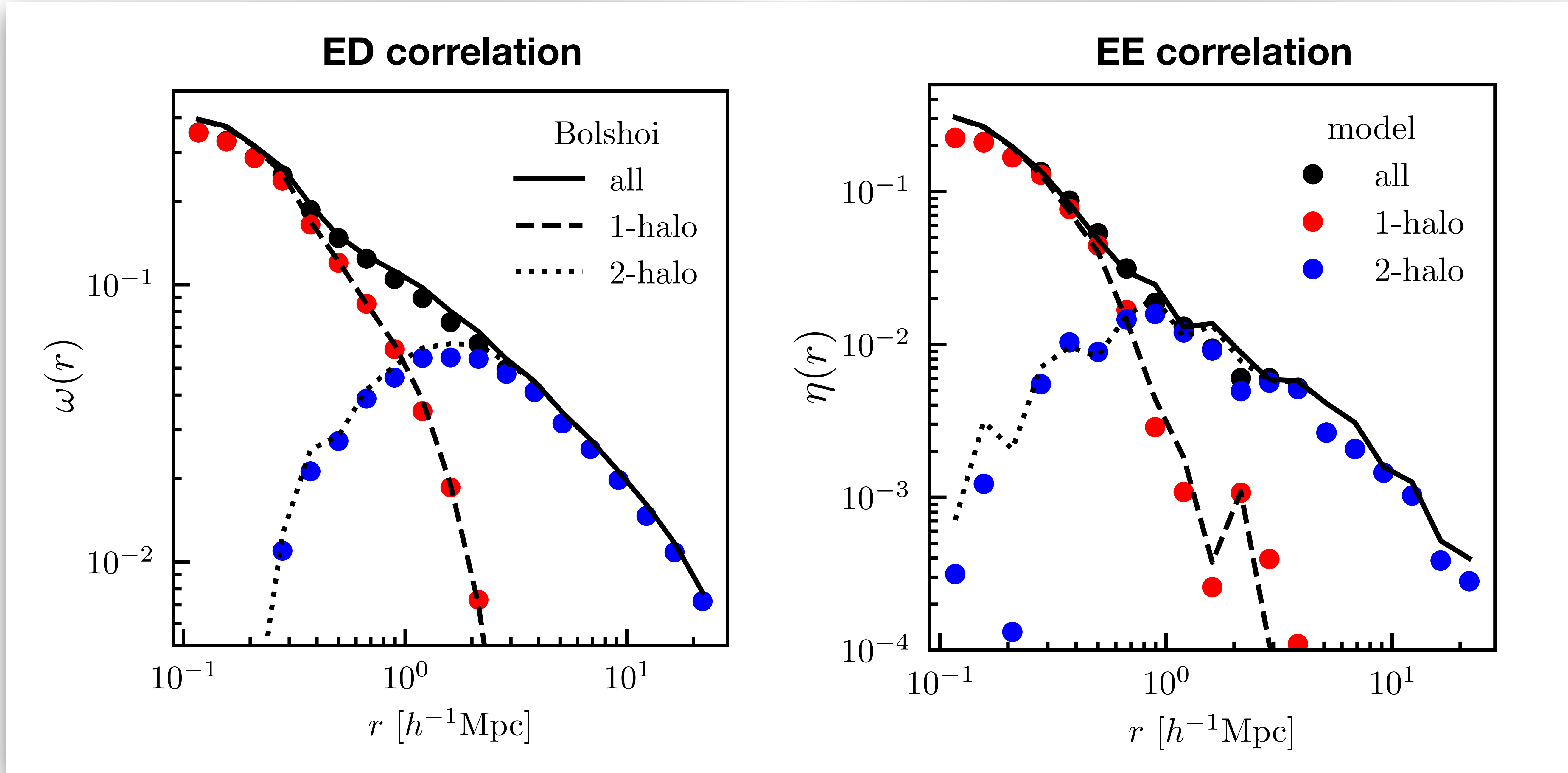


Subhalo Alignments



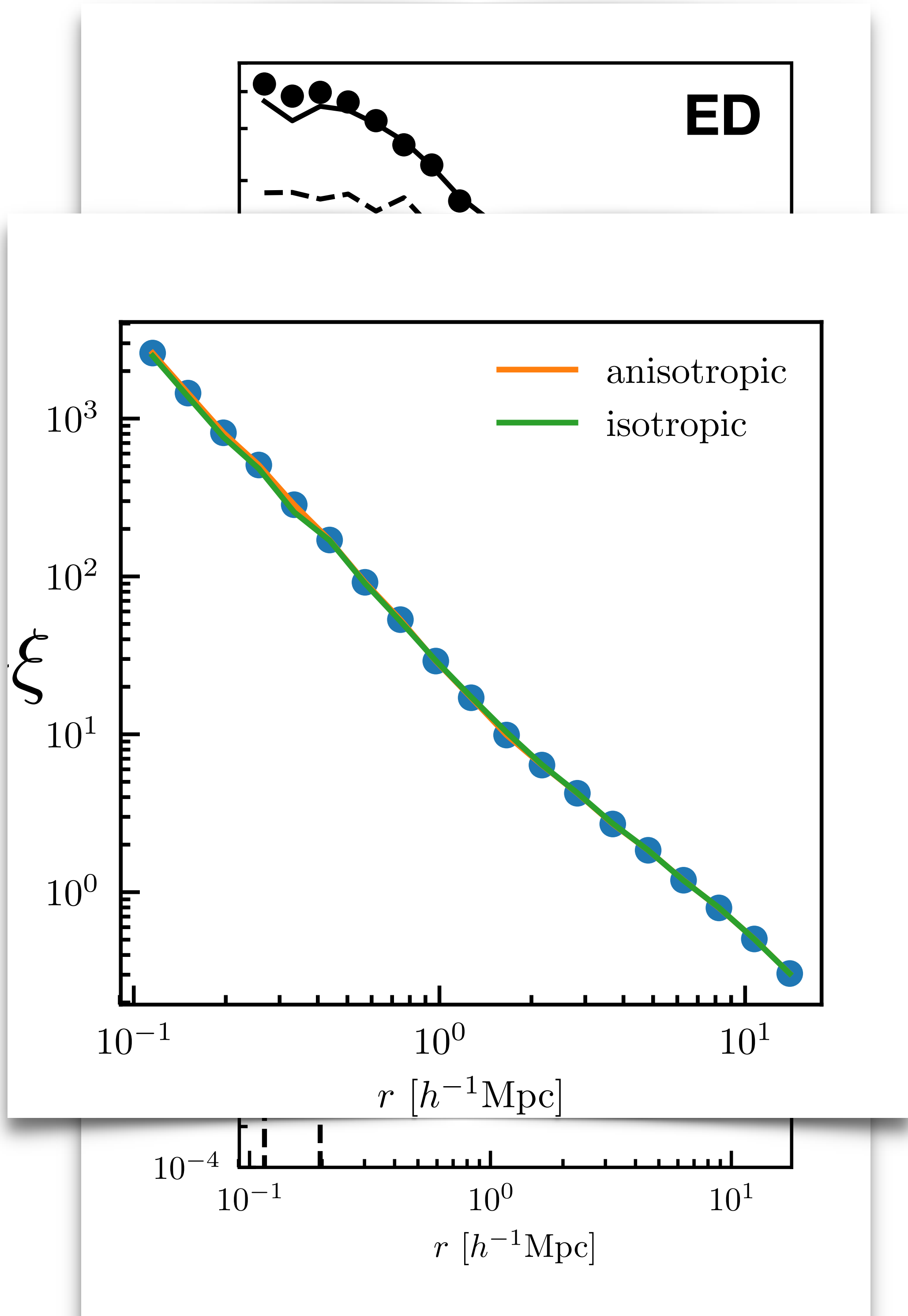
- Sub-haloes display strong radial alignment.
- Distribution of misalignment angles is fit well by a Watson distribution.
- Some radial dependence is seen in alignment strength within haloes.

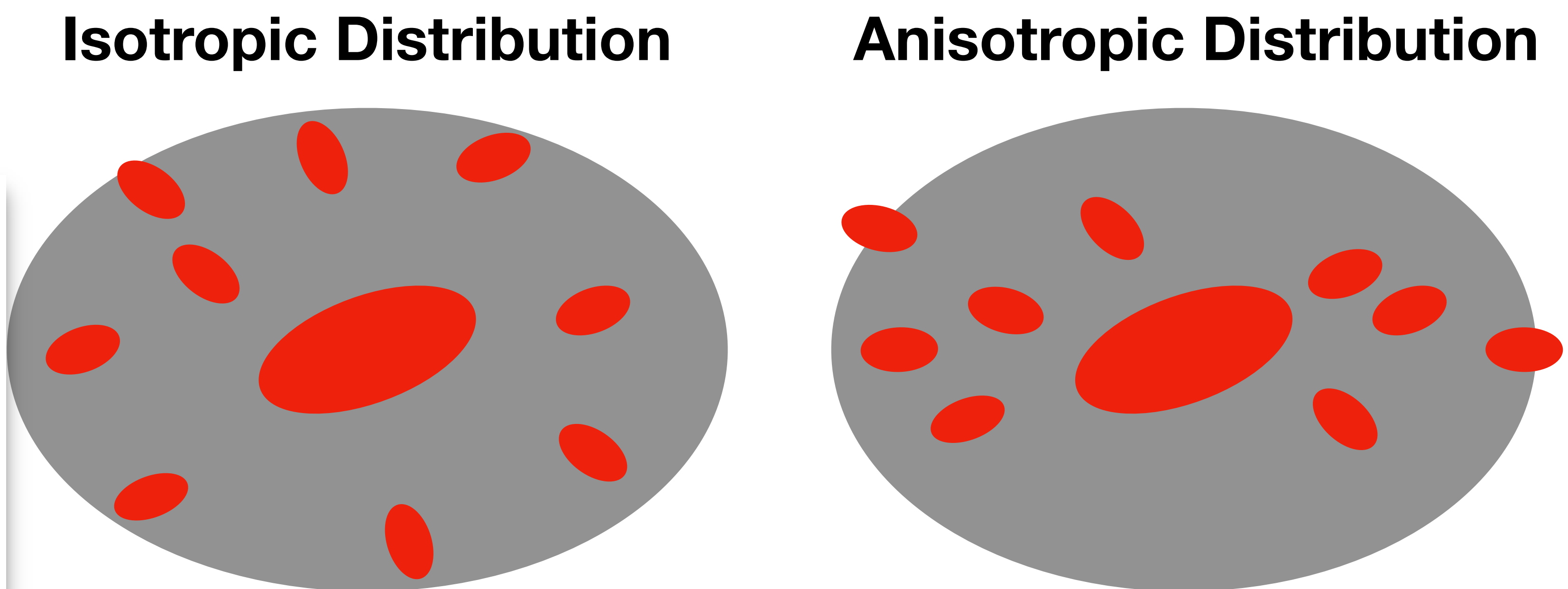
Subhalo Alignments



A radial alignment model can reproduce
1-halo alignment correlations down to ~100 kpc!

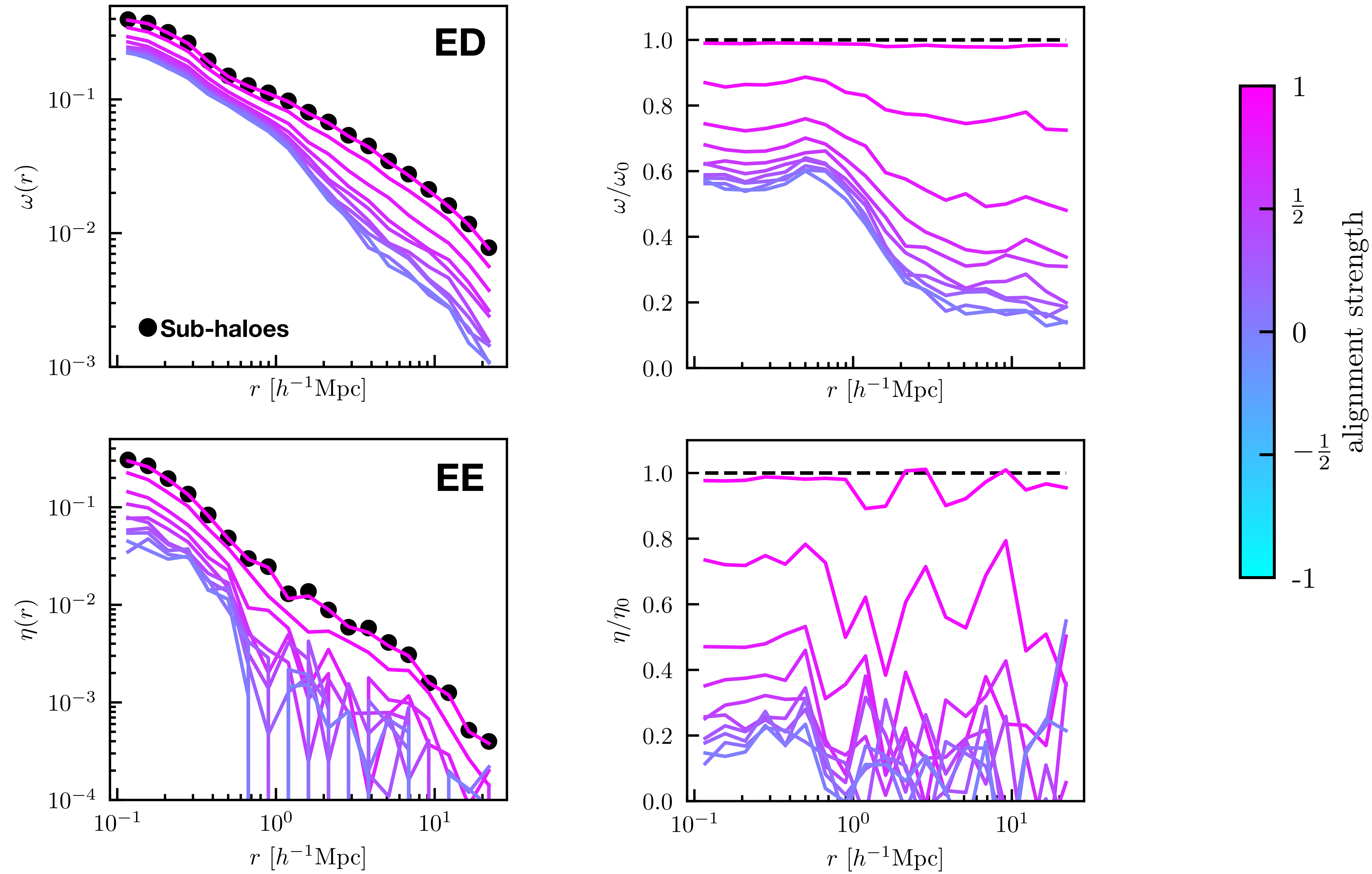
Sub-halo Anisotropy



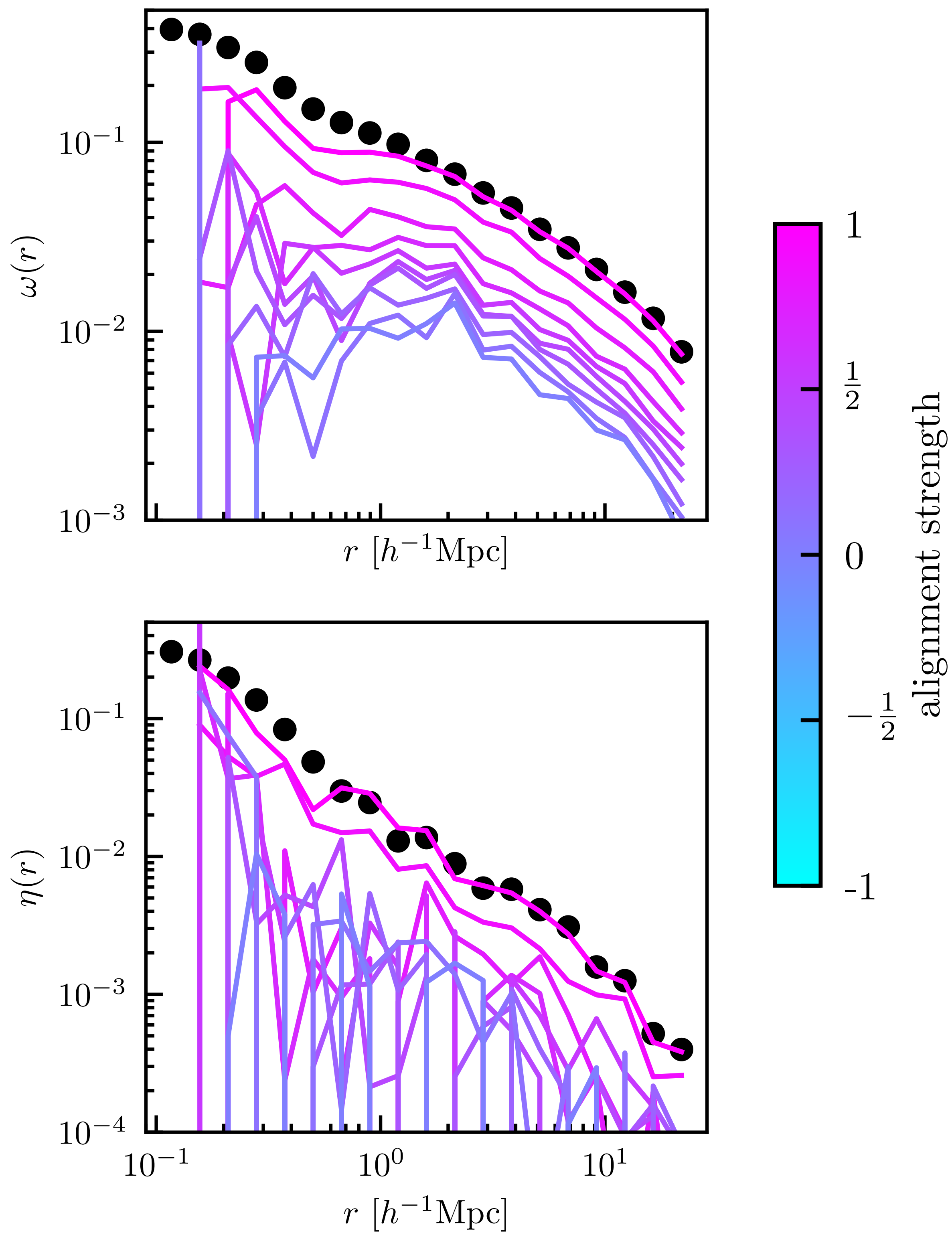


- Spatial distribution of satellites has a significant effect on IA correlations
- EE correlation function is especially sensitive to anisotropy
- EE will go to zero for an isotropic radial model
- Large scale correlations show effect of ~10% due to satellite anisotropy

Scale Dependence: Central IA

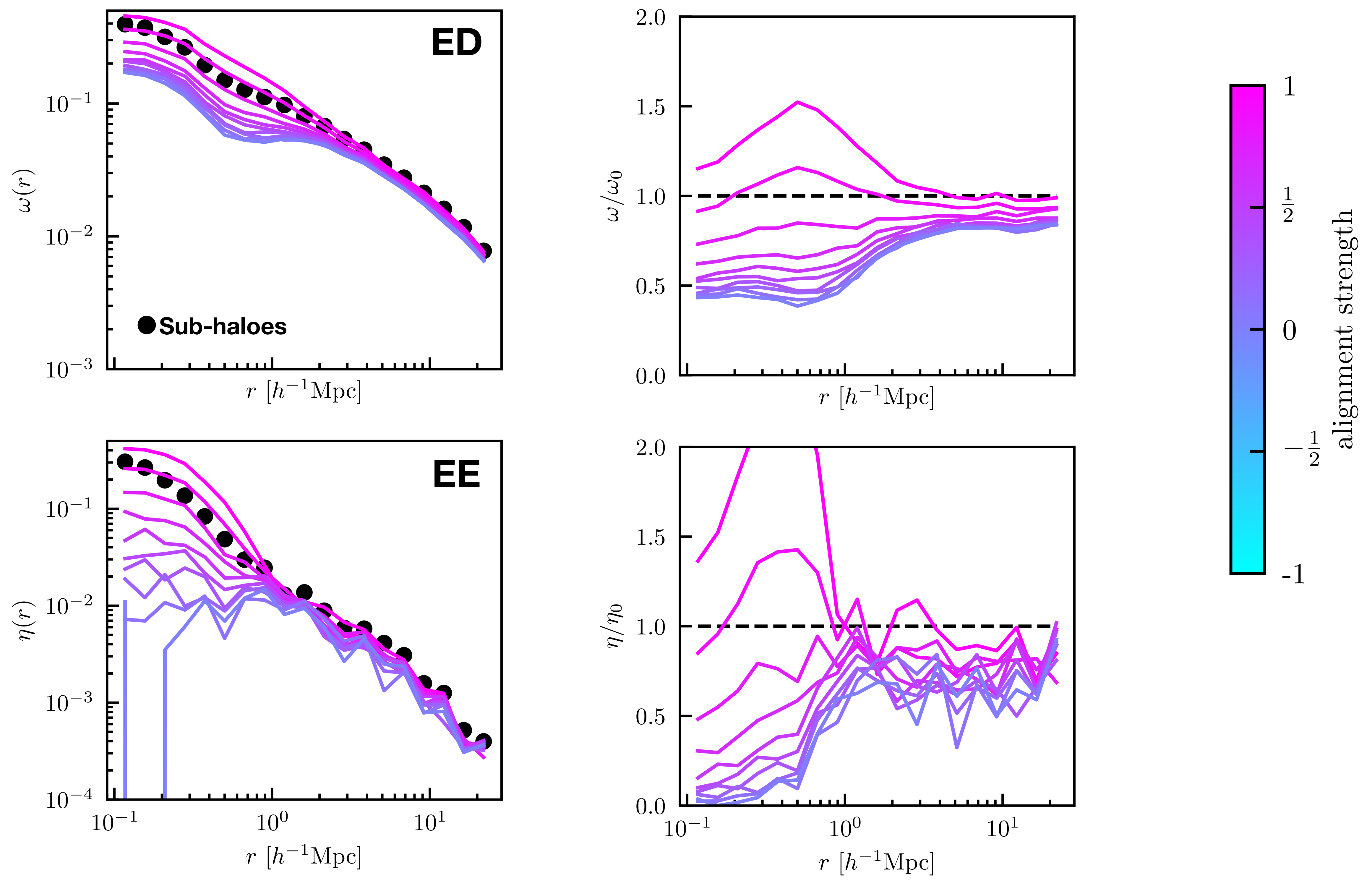


Scale Dependence: Central IA



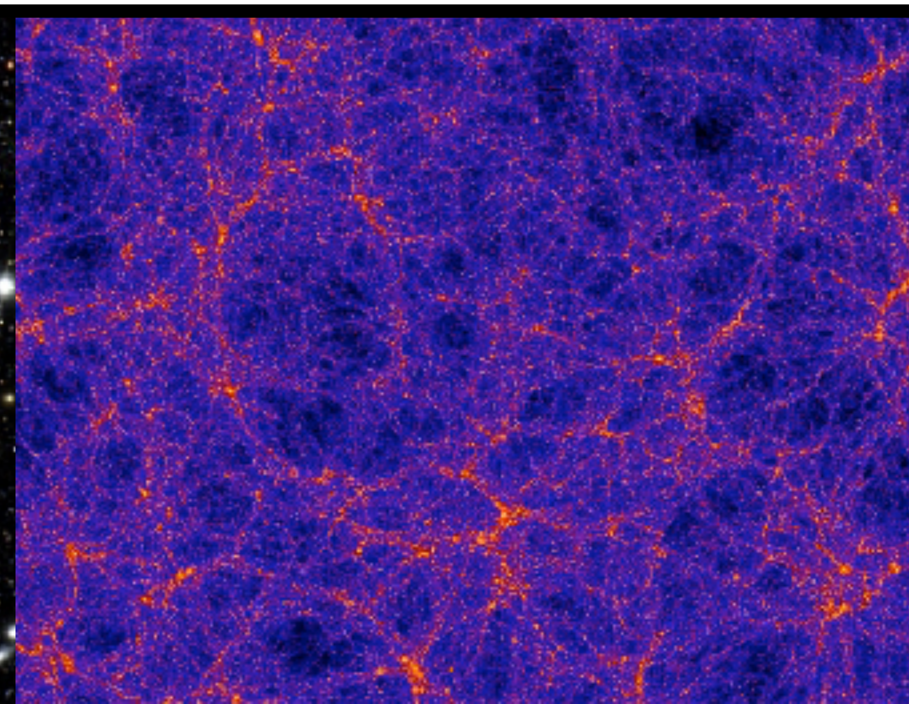
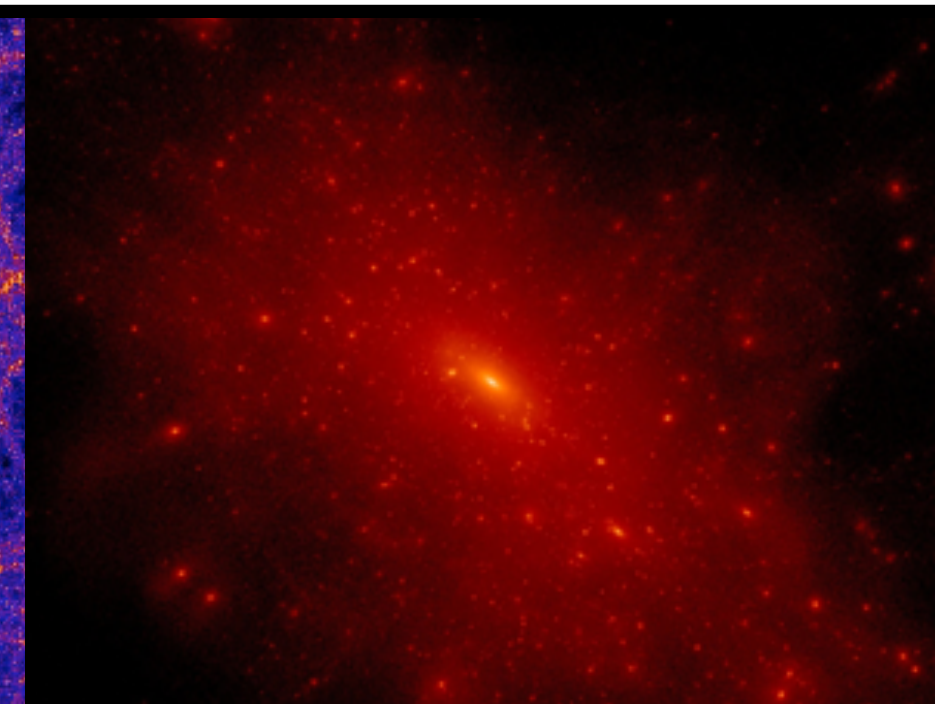
Anisotropic satellite distribution cause central-satellite alignments to decrease more rapidly on small scales as central IA decreases

Scale Dependence: Satellite IA

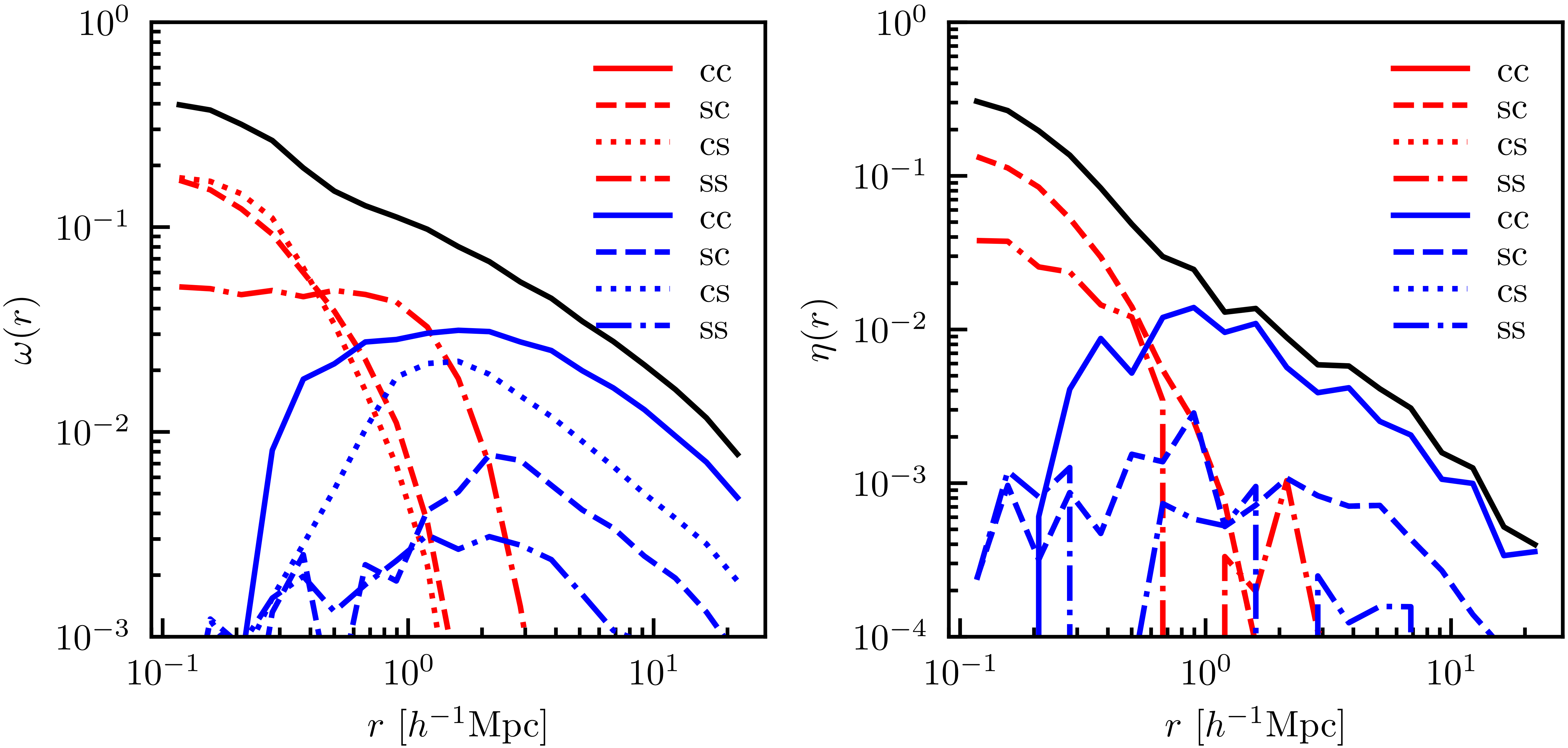


Future Work and Applications

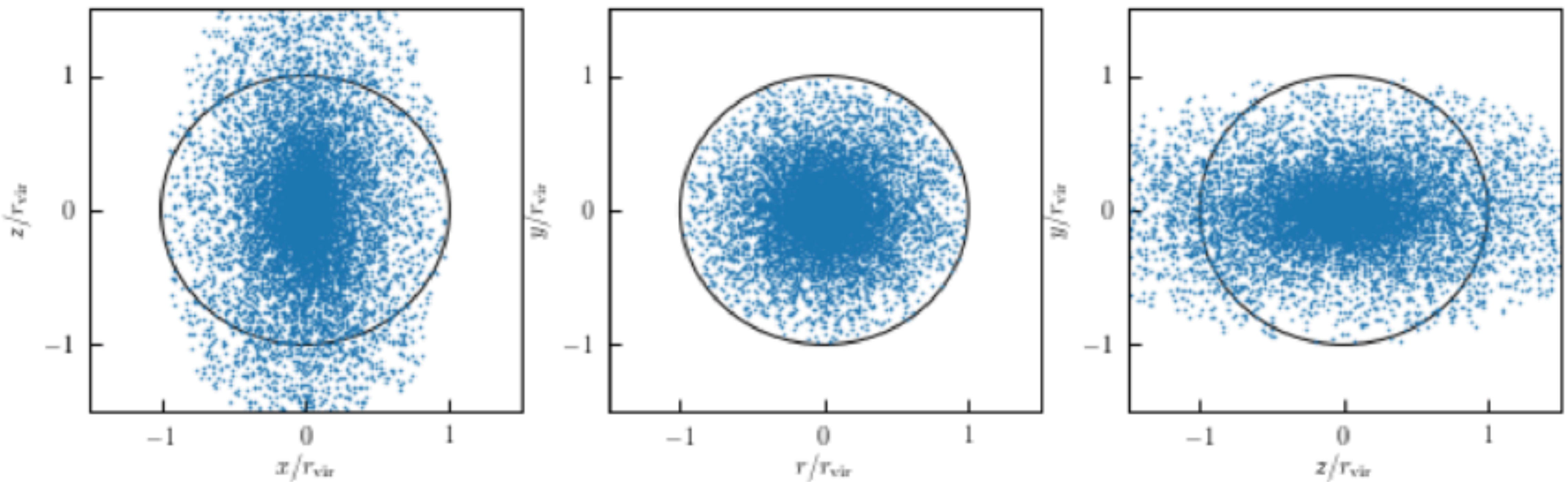
- add model for galaxy shapes
- explore alternate alignment models, e.g. tidal field, spin axis, etc
- compare predictions to (non-)linear alignment models
- constrain alignment parameters in SDSS
- add alignments into cosmology mocks to test mitigation schemes

Extra: alignment decomposition



Extra: Anisotropic NFW



$$x = r\sin\theta\cos\phi = R\frac{a}{c}\sin\Theta\cos\Phi$$

$$\varrho(R) = \frac{\varrho_c}{R/R_s(1+R/R_s)^2}$$

$$y = r\sin\theta\sin\phi = R\frac{b}{c}\sin\Theta\sin\Phi$$

$$z = r\cos\theta = R\cos\Theta,$$

Extra: Satellite Alignment Models