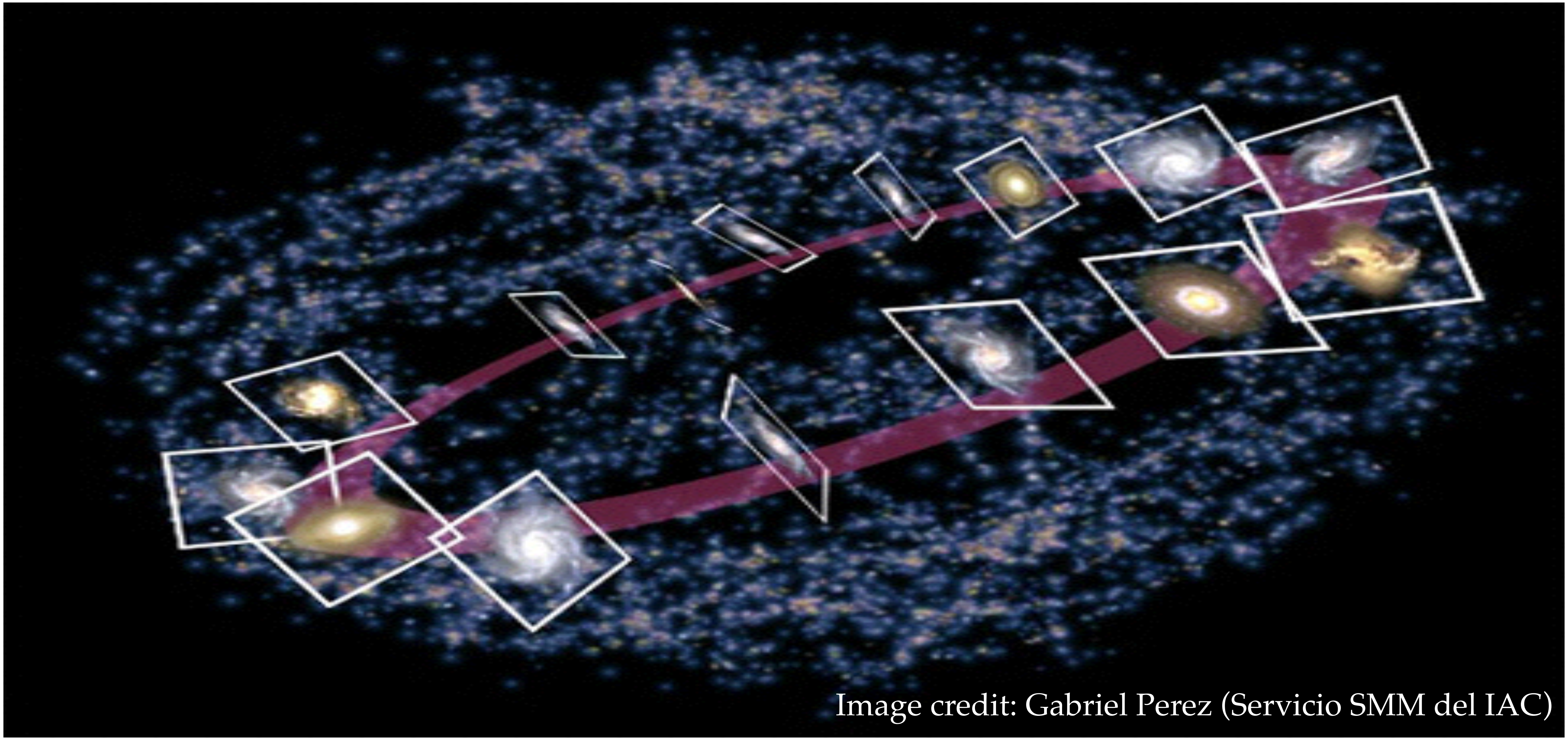

IAU 308 Symposium: The Zel'dovich Universe: Genesis and Growth of the Cosmic Web

Cosmic Shear from Galaxy Spins: a Review

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II. Modelling

III. Observed signals

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I. Introduction

Linear Tidal Torque Theory

1. The framework
2. The key predictions
3. Numerical evidences

Origin of the Galaxy Angular Momentum

- Tidal interaction of a proto-galaxy with the surrounding matter (Hoyle 1949; Peebles 1969; Doroskevich 1970)
  - continuing tidal influence till the turn-around moment
  - non-linear evolution after the turn-around

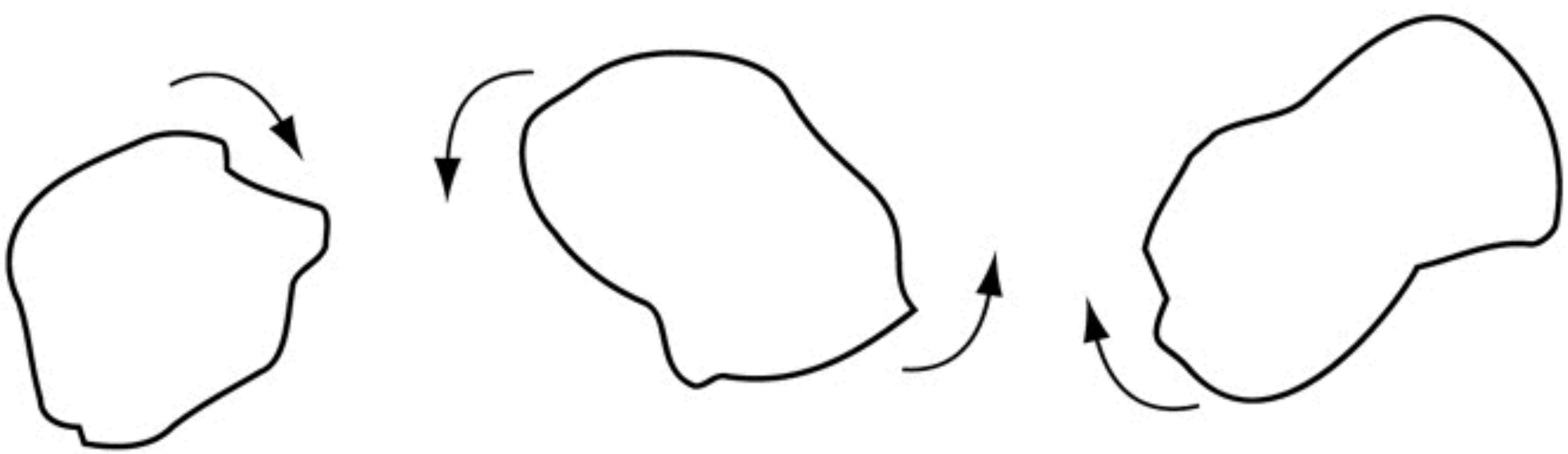


Fig 4.13 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Intrinsic Alignments of Galaxy Spins

- The evolution of the galaxy spin vector at first order (Doroshkevich 1970; White 1984; Catelan & Theuns 1996) based on the ZEL Approx.

$$L_i(t) = -a^2(t)\frac{dD(t)}{dt}\epsilon_{ijk}I_{jl}T_{lk} \, ,$$

  - where ***I*** and ***T*** are the inertia and the tidal shear tensor, respectively

- In the principal frame of the tidal shear tensor

$$L_1 \propto (\lambda_2 - \lambda_3)I_{23}, \ L_2 \propto (\lambda_3 - \lambda_1)I_{31}, \ L_3 \propto (\lambda_1 - \lambda_2)I_{12},$$

  - where λ_1, λ_2, λ_3 are the three eigenvalues of ***T*** in a decreasing order.

- Alignment tendency between ***L*** and the intermediate principal axis of ***T*** provided that ***I*** and ***T*** are not identical.

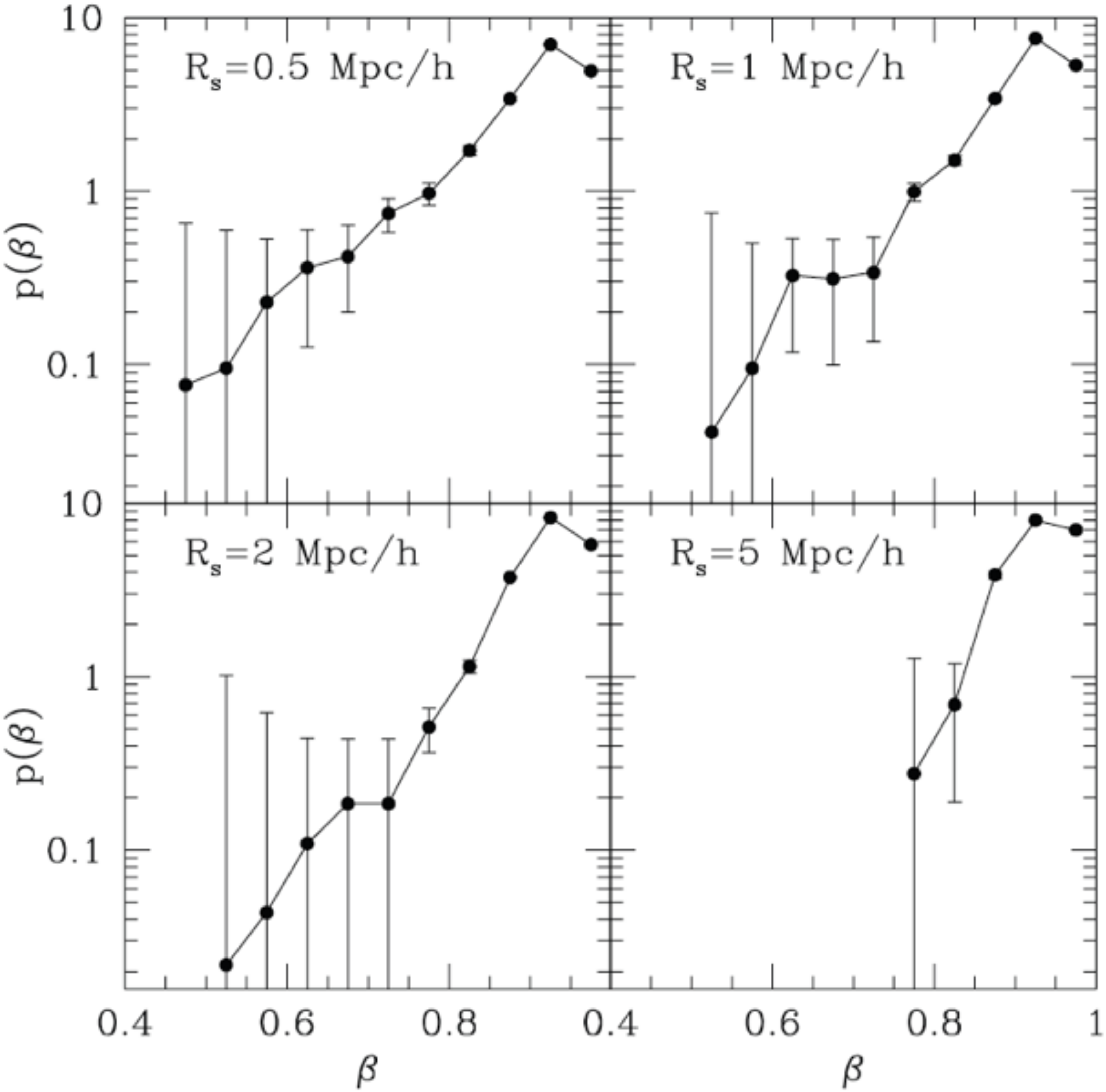
Correlations between Tidal and Inertia Tensors

- *N*-body simulations showed that ***I*** and ***T*** are strongly correlated (Lee & Pen 2000; Porciani, Dekel, & Hoffman 2002)

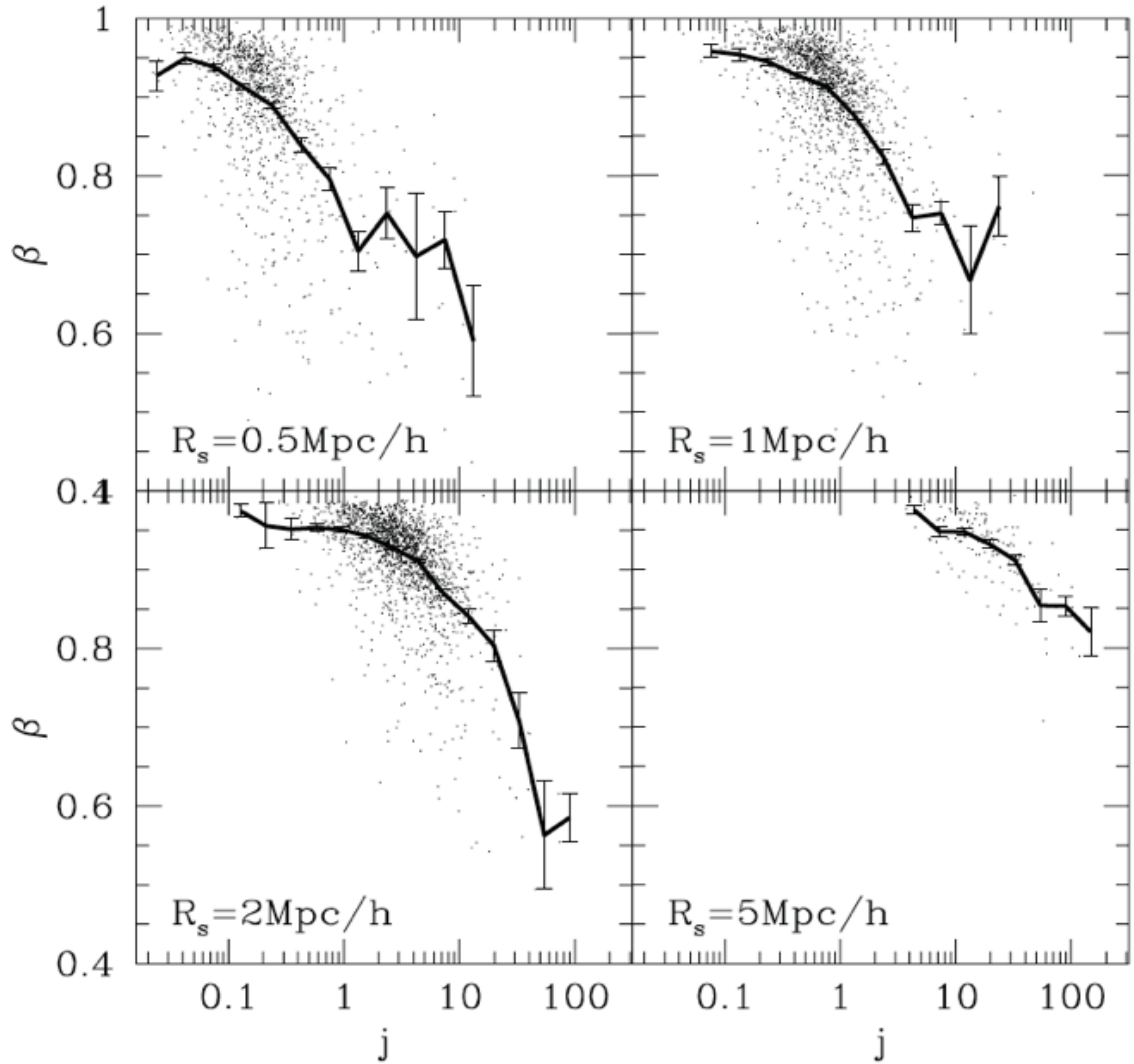
- The correlation between ***I*** and ***T*** can be quantified by (Lee, Hahn & Porciani 2009)

$$\beta = 1 - \left[\frac{I_{12}^2 + I_{23}^2 + I_{31}^2}{I_{11}^2 + I_{22}^2 + I_{33}^2}\right]^{1/2},$$

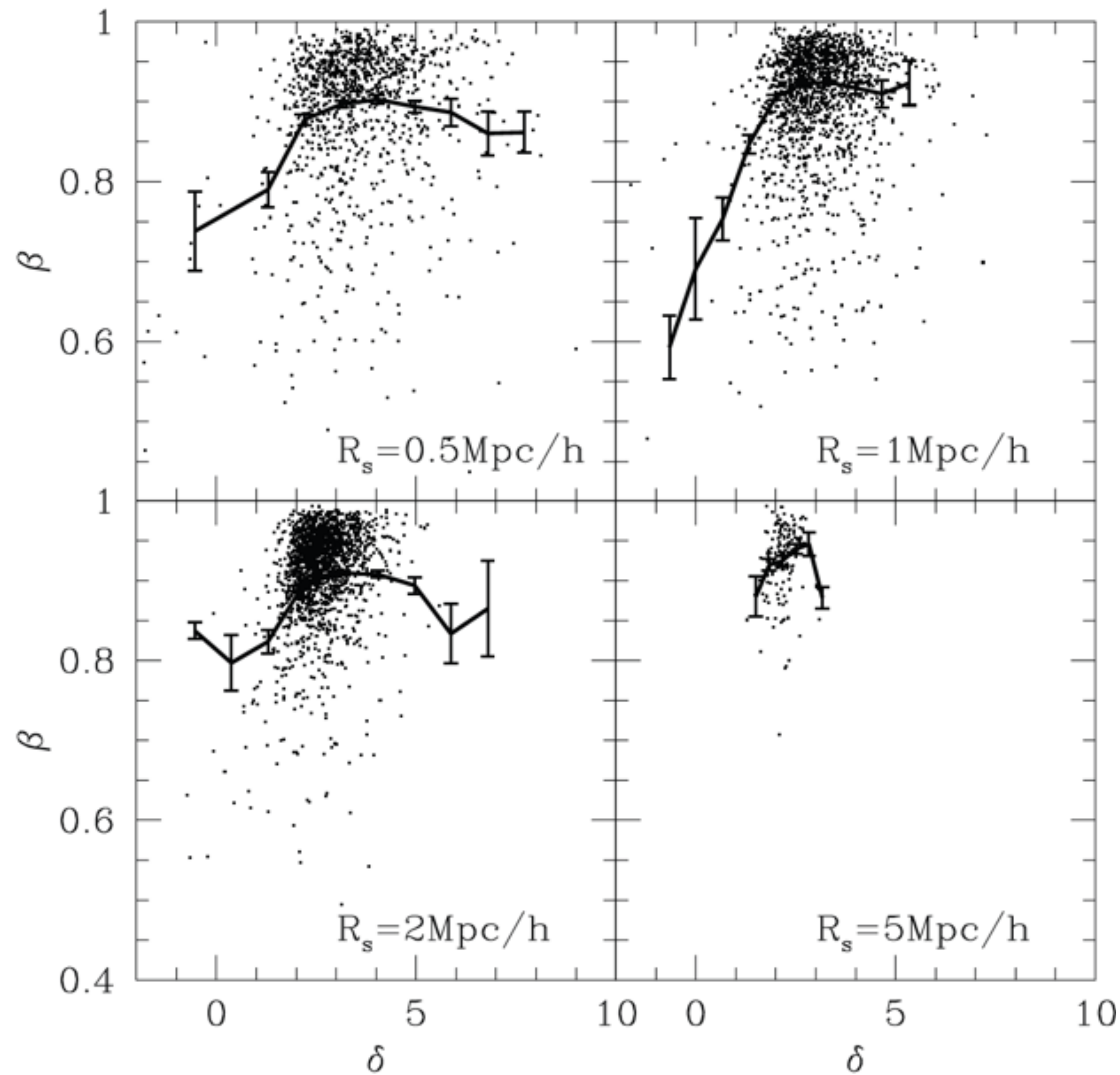
  - where $\{I_{11}, I_{22}, I_{33}\}$, and $\{I_{12}, I_{23}, I_{31}\}$ are the diagonal and off diagonal elements of the inertia tensor in the principal frame of the tidal shear tensor.



Lee, Hahn & Porciani 2009, ApJ, 707, 761

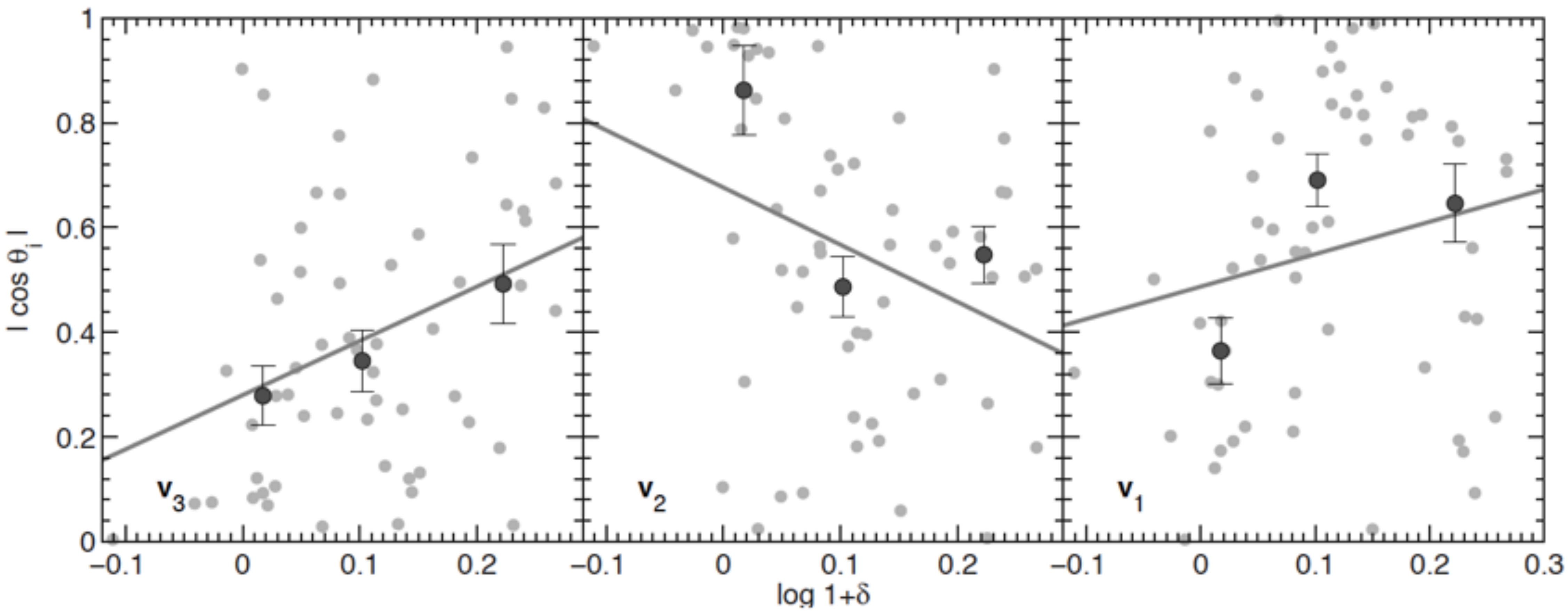


Lee, Hahn & Porciani 2009, ApJ, 707, 761



Lee, Hahn & Porciani 2009, ApJ, 707, 761

- The correlation between ***I*** and ***T*** increases as the environmental density increases.
  - consistent with the hydro-simulation result that the strength of spin-shear alignment diminishes as the environmental density increases (Hahn, Teyssier & Carollo 2010)



Hahn, Teyssier, & Carollo 2010,MNRAS,405,274

II. Physical Analysis

A Model for the Galaxy Intrinsic Alignments

1. The spin-shear alignments
2. The spin-spin alignments

Linear Theory Prediction

- Under the assumption that I and T are not correlated:

$$\langle L_i L_j | \mathbf{T} \rangle = \epsilon_{iab} \epsilon_{jcd} T_{ak} T_{cl} \langle I_{kb} I_{ld} \rangle \ ,$$

- The ensemble average of the inertia tensors:

$$\langle I_{kb} I_{ld} \rangle = (\delta_{kb} \delta_{ld} + \delta_{kl} \delta_{bd} + \delta_{kd} \delta_{bl})/3,$$

- The expectation value of galaxy spins given the shear

$$\langle L_i L_j | \mathbf{T} \rangle = \frac{\epsilon_{iab} \epsilon_{jcd} (T_{ab} T_{cd} + T_{ad} T_{bd}) + \delta_{ij} | T |^2 - T_{ik} T_{kj}}{3} \ .$$

$$\langle L_i L_j | \tilde{\mathbf{T}} \rangle = \tfrac{2}{3} \delta_{ij} | \tilde{T} |^2 - \tilde{T}_{ik} \tilde{T}_{kj} \ .$$

A Model of the Spin-Shear Correlations

- A correlation parameter, *c*, is introduced for a practical model for the intrinsic alignments between ***L*** and ***T*** (Lee & Pen 2000; Lee & Pen 2001):

$$\langle L_i L_j | \hat{\mathbf{T}} \rangle = \frac{1}{3}\delta_{ij} + c\left(\frac{1}{3}\delta_{ij} - \hat{T}_{ik}\hat{T}_{kj}\right) .$$

- The value of *c* has to be determined empirically:

$$c \in [0,1]$$

$$c = 0 \Rightarrow \text{no alignment}$$

$$c = 1 \Rightarrow \text{strongest alignment}$$

$$P(\boldsymbol{L} \mid \tilde{\mathbf{T}}) = \frac{|\mathbf{Q}|^{-1/2}}{\sqrt{(2\pi)^3}} \exp\left(-\frac{\boldsymbol{L}^T \cdot \mathbf{Q}^{-1} \cdot \boldsymbol{L}}{2}\right),$$

$$\langle \hat{L}_i \hat{L}_j \mid \hat{\mathbf{T}} \rangle = \int \hat{L}_i \hat{L}_j P(\hat{\boldsymbol{L}} \mid \hat{\mathbf{T}}) d\hat{\boldsymbol{L}}$$
$$= \left(\frac{1}{3} + \frac{c}{5}\right)\delta_{ij} - \frac{3}{5} c \hat{T}_{ik} \hat{T}_{kj} .$$

$$\langle \hat{L}_i \hat{L}_j \mid \hat{\mathbf{T}} \rangle = \frac{1+a}{3} \delta_{ij} - a \hat{T}_{ik} \hat{T}_{kj} .$$

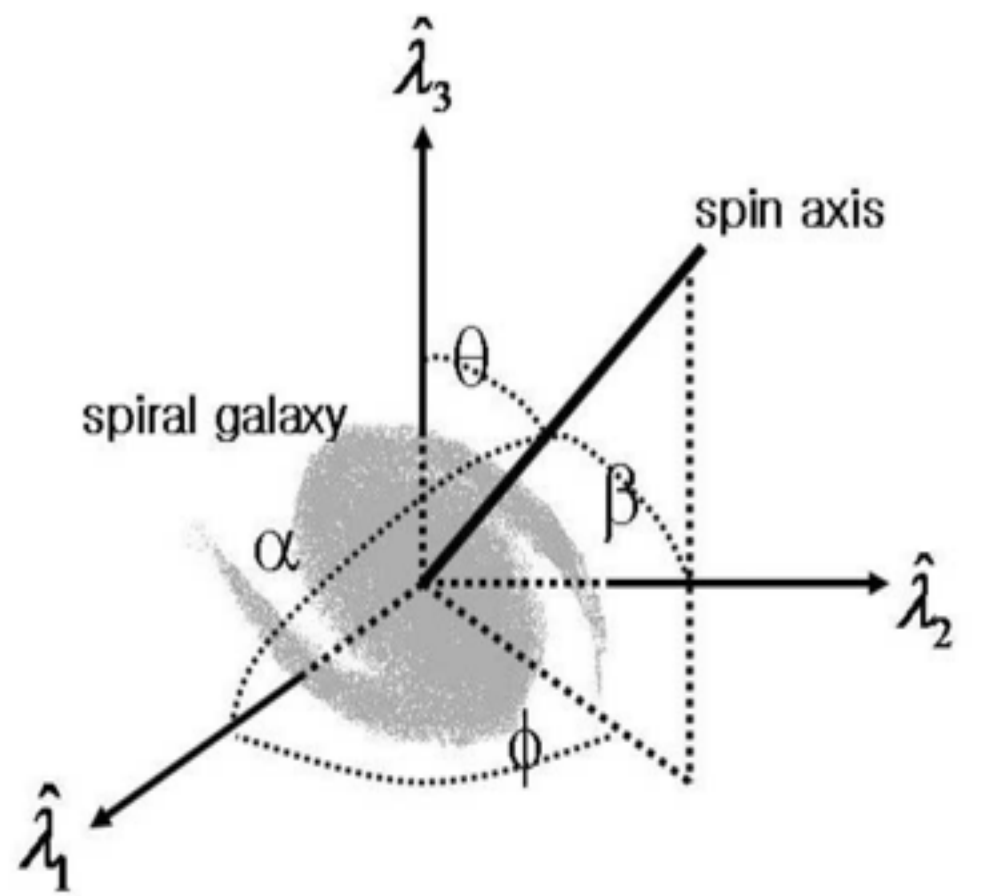
$$a = 2 - 6\hat{\lambda}_i^2 \hat{L}_i^2$$

Galaxy Spins in the Shear Principal Frame

$$p(\cos\alpha, \cos\beta, \cos\theta) = \frac{1}{2\pi}\prod_{i=1}^{3}\left(1 + c - 3c\hat{\lambda}_i^2\right)^{-1/2}$$
$$\times\left(\frac{\cos^2\alpha}{1+c-3c\hat{\lambda}_1^2} + \frac{\cos^2\beta}{1+c-3c\hat{\lambda}_2^2} + \frac{\cos^2\theta}{1+c-3c\hat{\lambda}_3^2}\right)^{-3/2},$$

$$p(\cos\beta) = (1+c)\sqrt{1-\frac{c}{2}}\left[1+c\left(1-\frac{3}{2}\cos^2\beta\right)\right]^{-3/2},$$

$$p(\phi) = \frac{2}{\pi}(1+c)\sqrt{1-\frac{c}{2}}$$
$$\times\int_0^1\left[1+c\left(1-\frac{3}{2}\sin^2\theta\sin^2\phi\right)\right]^{-3/2} d\cos\theta,$$



in the principal axis of the local tidal shear

Lee & Erdogdu 2007, ApJ, 671, 1248

A Model for the Spin-Spin Correlations

- The spatial correlations of the tidal shear field induces the galaxy spin-spin correlations (Lee & Pen 2001):

$$\langle|\hat{\mathbf{L}}(\mathbf{x})\cdot\hat{\mathbf{L}}(\mathbf{x}+\mathbf{r})|^2\rangle = \left\langle\left(\frac{1+a}{3}\,\delta_{ij} - a\hat{T}_{ik}\,\hat{T}_{kj}\right)\left(\frac{1+a}{3}\,\delta_{ij} - a\hat{T}'_{il}\,\hat{T}'_{lj}\right)\right\rangle$$

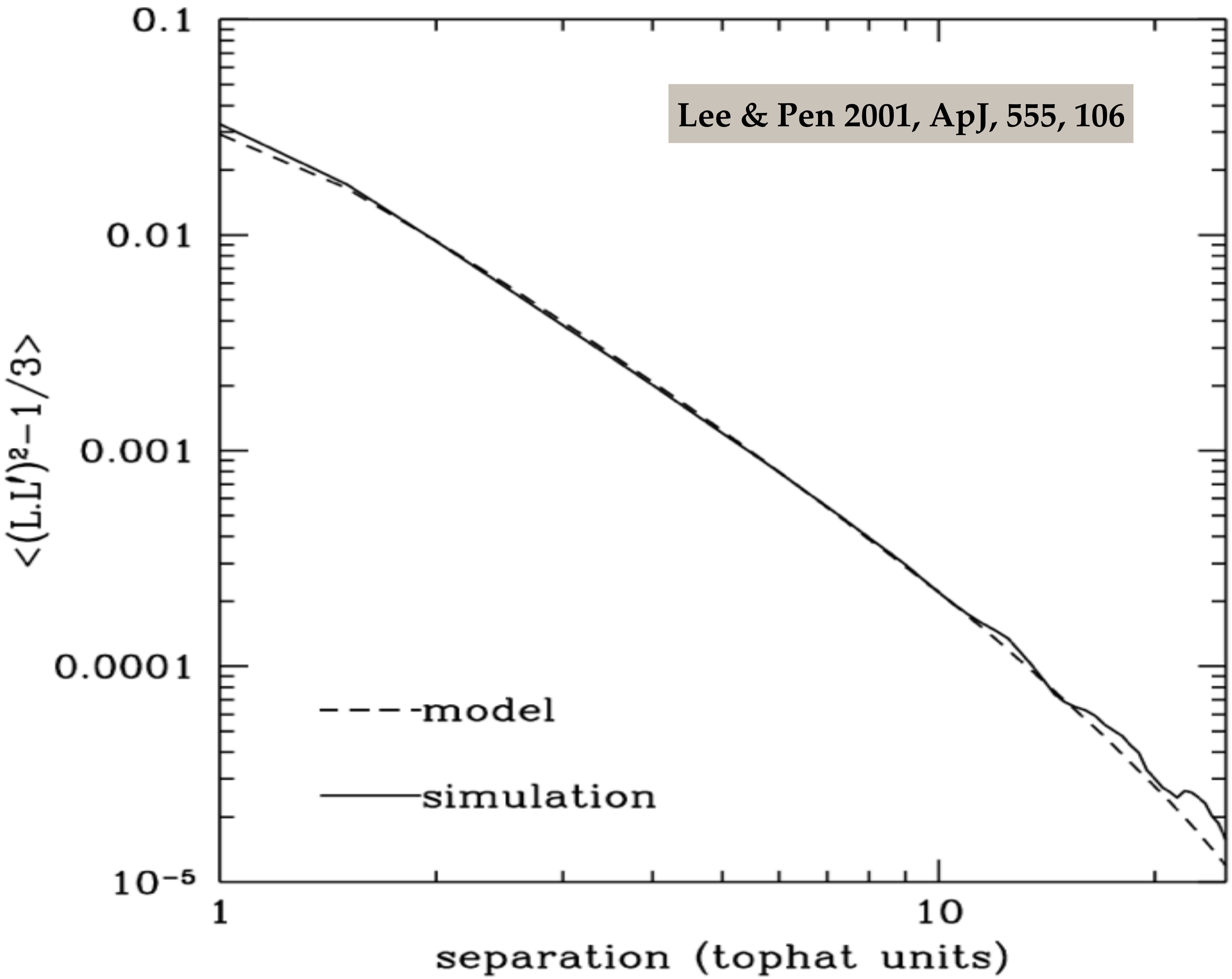
$$= \frac{1}{3} - \frac{a^2}{3} + a^2\langle\hat{T}_{ik}\,\hat{T}_{kj}\,\hat{T}'_{il}\,\hat{T}'_{lj}\rangle\ .$$

where

$$\langle\hat{T}_{ik}\,\hat{T}_{kj}\,\hat{T}'_{il}\,\hat{T}'_{lj}\rangle = \left\langle\frac{\tilde{T}_{ik}\,\tilde{T}_{kj}\,\tilde{T}'_{il}\,\tilde{T}'_{lj}}{|\tilde{\mathbf{T}}|^2|\tilde{\mathbf{T}}'|^2}\right\rangle \approx \frac{\langle\tilde{T}_{ik}\,\tilde{T}_{kj}\,\tilde{T}'_{il}\,\tilde{T}'_{lj}\rangle}{\langle|\tilde{\mathbf{T}}|^2|\tilde{\mathbf{T}}'|^2\rangle}$$

$$= \frac{9}{4\xi^2(0)}\left(\langle\tilde{T}_{ik}\,\tilde{T}_{kj}\rangle\langle\tilde{T}'_{il}\,\tilde{T}'_{lj}\rangle + \langle\tilde{T}_{ik}\,\tilde{T}'_{il}\rangle\langle\tilde{T}_{kj}\,\tilde{T}'_{lj}\rangle + \langle\tilde{T}_{ik}\,\tilde{T}'_{lj}\rangle\langle\tilde{T}_{kj}\,\tilde{T}'_{il}\rangle\right)$$

testing the approximation of $\left\langle \frac{\tilde{T}_{ik}\tilde{T}_{kj}\tilde{T}'_{il}\tilde{T}'_{lj}}{|\tilde{\mathbf{T}}|^2|\tilde{\mathbf{T}}'|^2} \right\rangle \approx \frac{\langle \tilde{T}_{ik}\tilde{T}_{kj}\tilde{T}'_{il}\tilde{T}'_{lj} \rangle}{\langle |\tilde{\mathbf{T}}|^2|\tilde{\mathbf{T}}'|^2 \rangle}$



$$
\begin{aligned}
\langle \hat{L}_i \hat{L}'_i \hat{L}_j \hat{L}'_j \rangle &= \frac{1}{3} - \frac{a^2}{3} + a^2 \langle \hat{T}_{ik} \hat{T}_{kj} \hat{T}'_{il} \hat{T}'_{lj} \rangle \\
&\approx \frac{1}{3} - \frac{a^2}{3} + a^2 \left[\frac{1}{3} + \frac{1}{6} \xi_R^2(r) \right] \\
&\approx \frac{1}{3} + \frac{a^2}{6} \xi_R^2(r) ,
\end{aligned}
$$

where ξ_R is the linear density correlation function

$$
\begin{aligned}
\eta(r) &\equiv \langle |\hat{\mathbf{L}}(\mathbf{x}) \cdot \hat{\mathbf{L}}(\mathbf{x}+\mathbf{r})|^2 \rangle - \frac{1}{3} \\
&\approx \frac{a^2}{6} \frac{\xi^2(r;R)}{\xi^2(0;R)},
\end{aligned}
$$

Nonlinear Evolution of the Spin-Spin Correlations

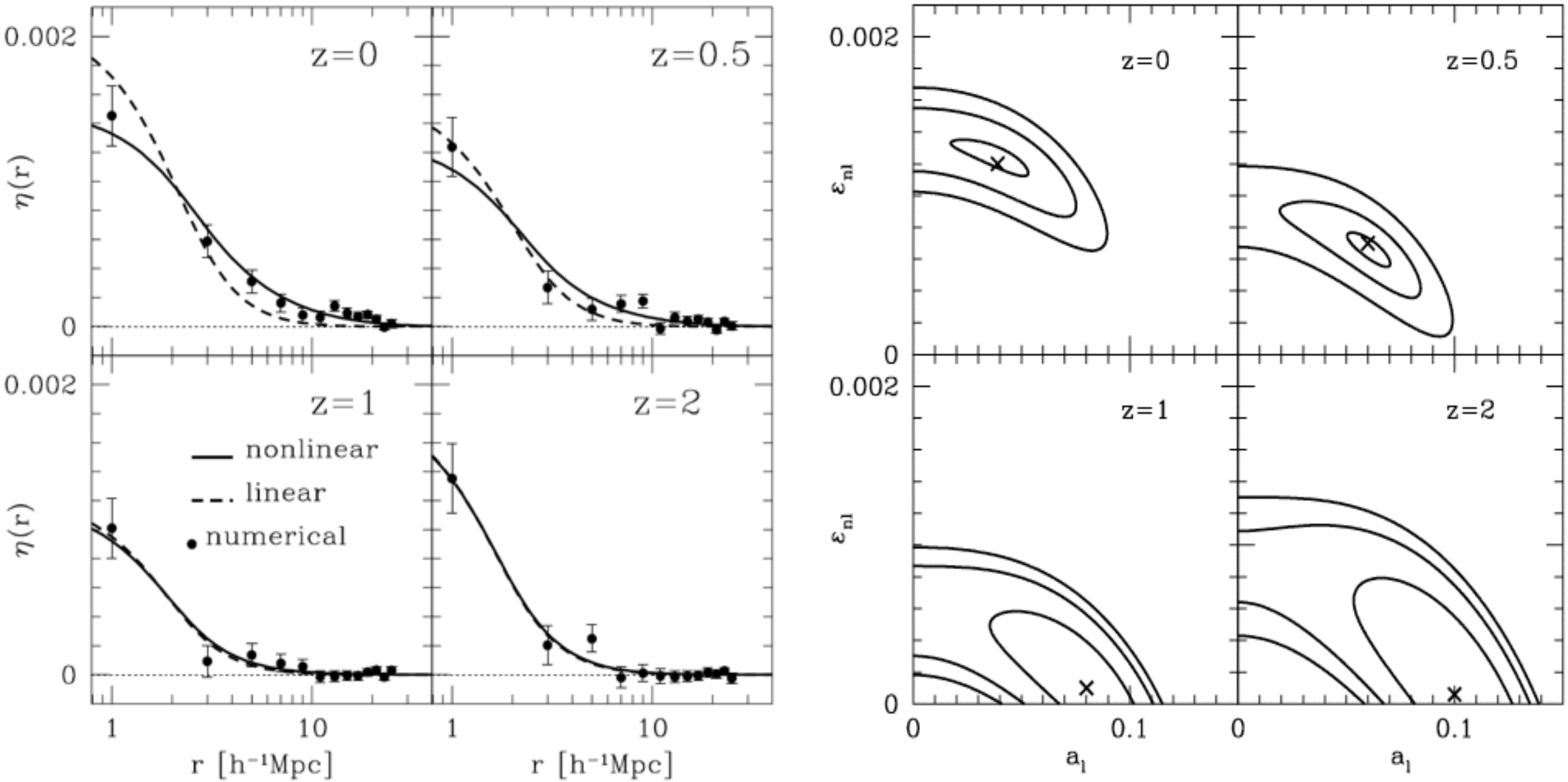
- In the subsequent evolution, the spin-spin correlation develops a linear scaling of the density correlation (Hu & Zhang 2002; Lee & Pen 2008):

$$\eta(r) \approx \frac{a_l^2}{6} \frac{\xi^2(r;R)}{\xi^2(0;R)} + \varepsilon_{\rm nl} \frac{\xi(r;R)}{\xi(0;R)},$$

  where ε_{nl} is the nonlinear correlation parameter.

- At high redshifts, the value of ε_{nl} is expected to be small. But, as the universe evolves, it would become larger.

Results from the Millennium Simulations



Lee & Pen 2008, ApJ, 681, 798

III. Observation (part one)

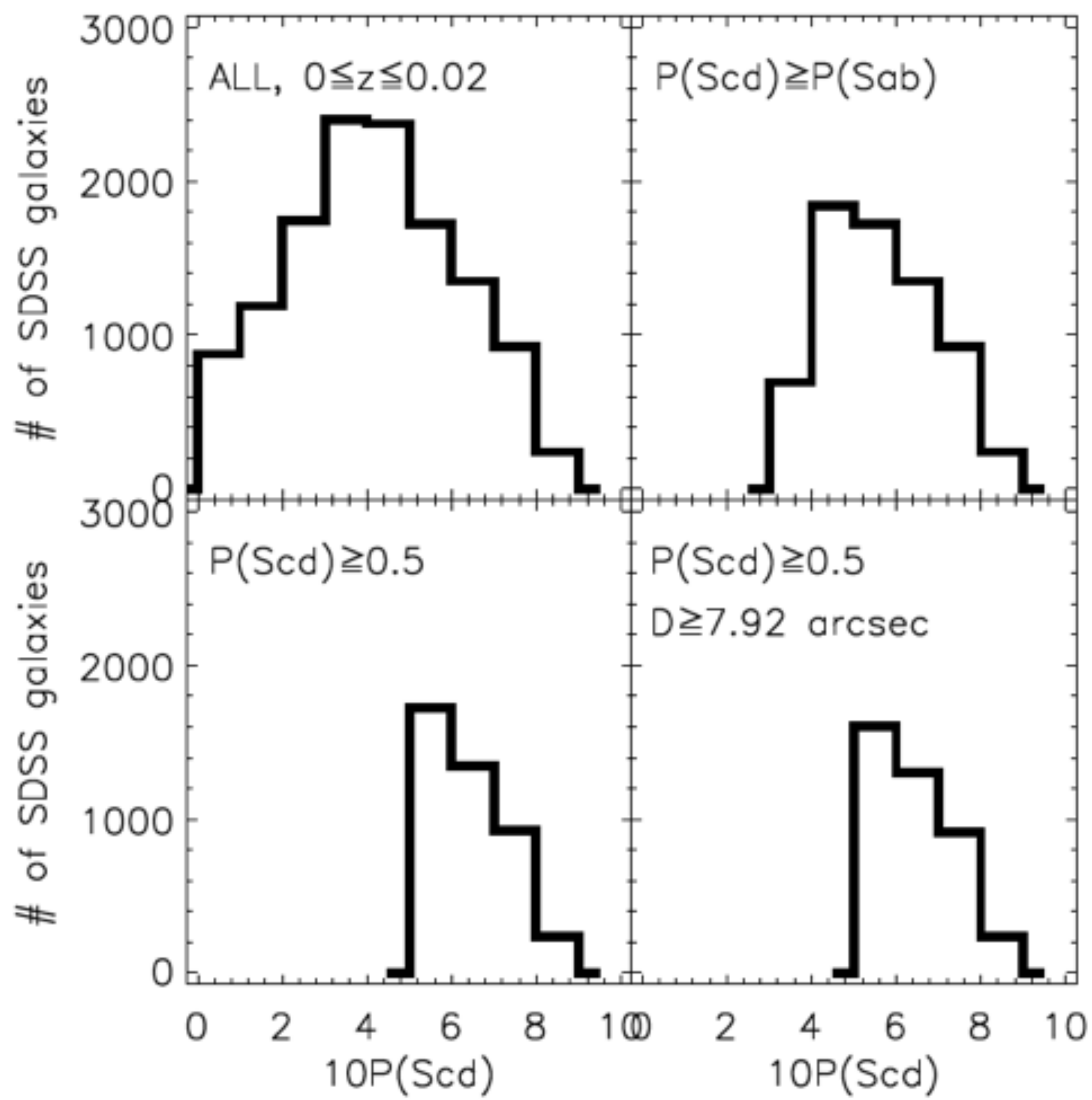
Detection of the Spin-Spin Correlations

1. Observational data
2. Signal vs. Theory

Observational Data

- From a spectroscopic sample of the SDSS galaxies (Huertas-Company et al. 2009)
- Selecting only the Scd galaxies at $0 \leq z \leq 0.02$ with angular size $\theta \geq 7.92$ arc sec
  - a total of 4065 large low-z Scd galaxies
  - determining the 3D positions assuming the WMAP7 cosmology

Lee 2011, ApJ, 732, 99

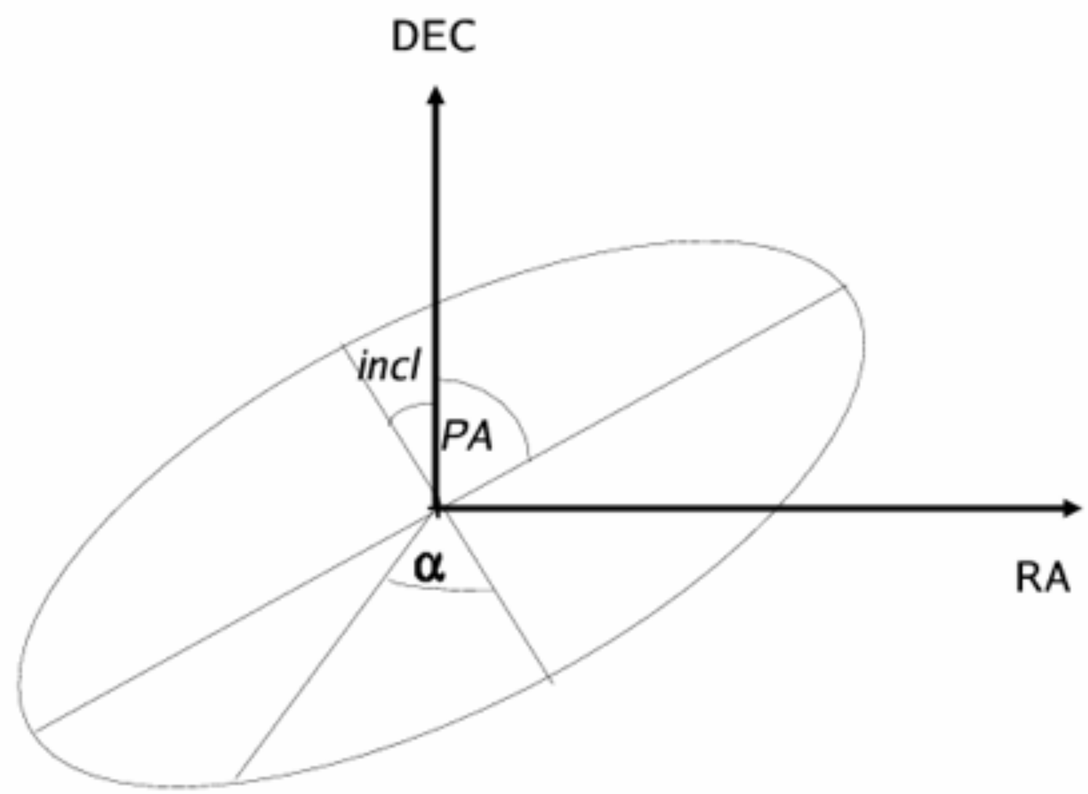


Determining Spin Axes of Disk Galaxies

- The unit spin vector of a spiral galaxy in the circular thin disk approximation:

$$\hat{L}_r = \cos i,$$
$$\hat{L}_\vartheta = (1 - \cos^2 i)^{1/2} \sin \mathrm{P.A.},$$
$$\hat{L}_\varphi = (1 - \cos^2 i)^{1/2} \cos \mathrm{P.A.},$$

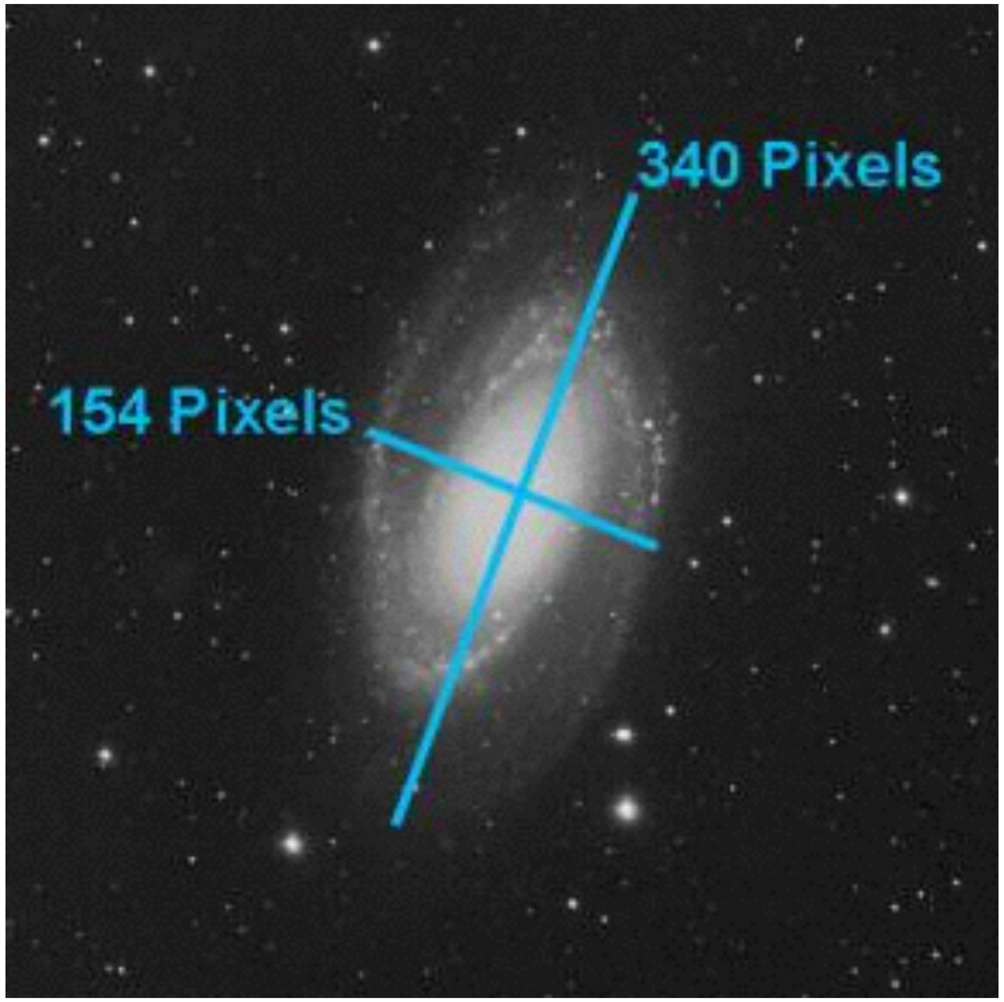
  - *i* : the inclination angle
  - *cos i* : the axial ratio
  - P.A. : the position angle.



- An intrinsic flatness parameter introduced to account for the finite thickness of the bulges (Haynes & Giovanelli 1984).

$$\cos^2 i = \frac{(b/a)^2 - p^2}{1 - p^2}.$$

$$p = \begin{cases} 0.23, & \text{S0–Sa}, \\ 0.20, & \text{Sab}, \\ 0.175, & \text{Sb}, \\ 0.14, & \text{Sbc}, \\ 0.103, & \text{Sc}, \\ 0.10, & \text{Scd–Sdm}. \end{cases}$$



- The two-fold ambiguity in the sign of L_r

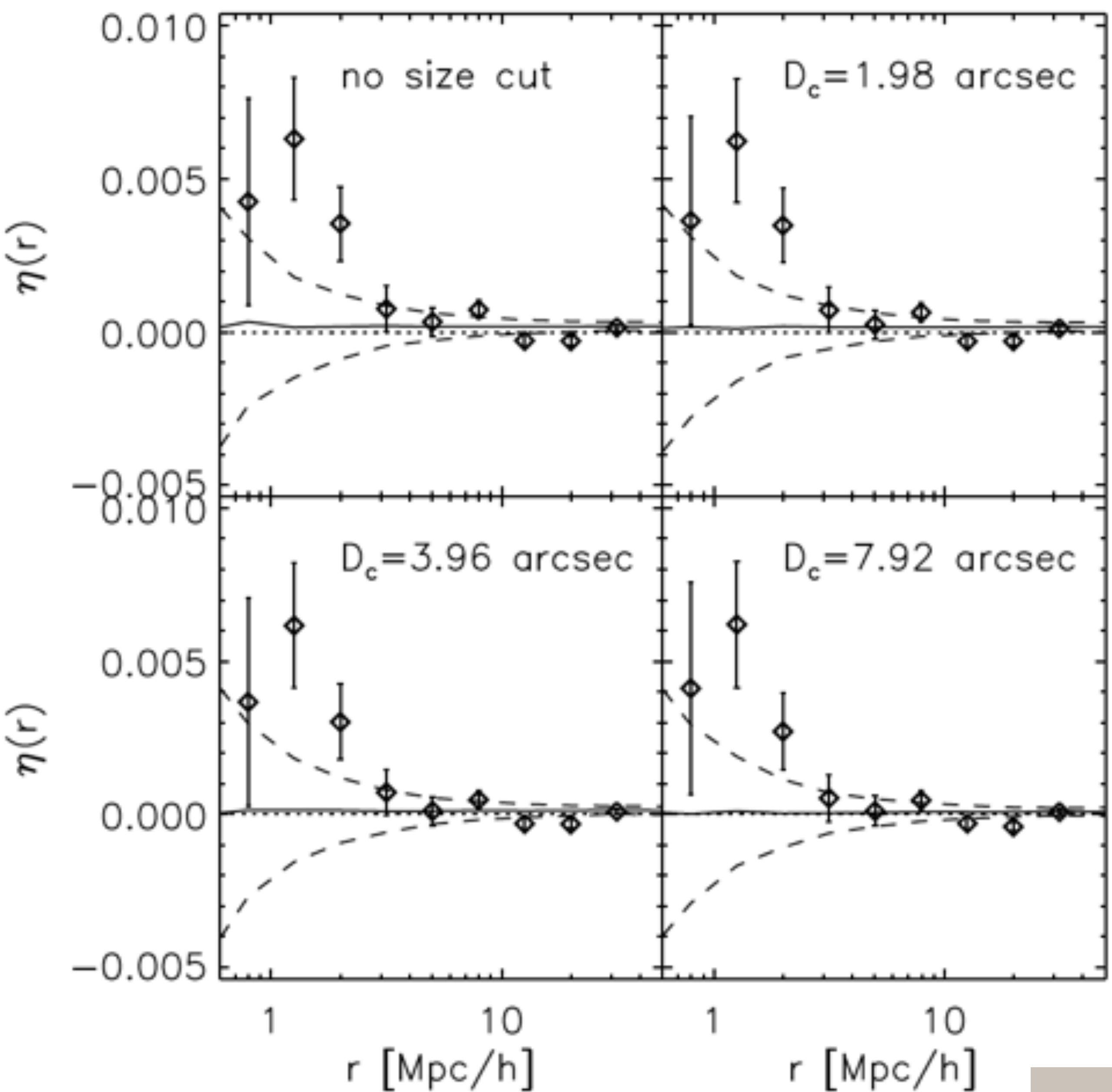
$$\begin{aligned}
\hat{L}_{a1} &= \hat{L}_r \sin\theta\cos\phi + \hat{L}_\theta \cos\theta\cos\phi - \hat{L}_\phi \sin\phi, \\
\hat{L}_{a2} &= \hat{L}_r \sin\theta\sin\phi + \hat{L}_\theta \cos\theta\sin\phi + \hat{L}_\phi \cos\phi, \\
\hat{L}_{a3} &= \hat{L}_r \cos\theta - \hat{L}_\theta \sin\theta,
\end{aligned}$$

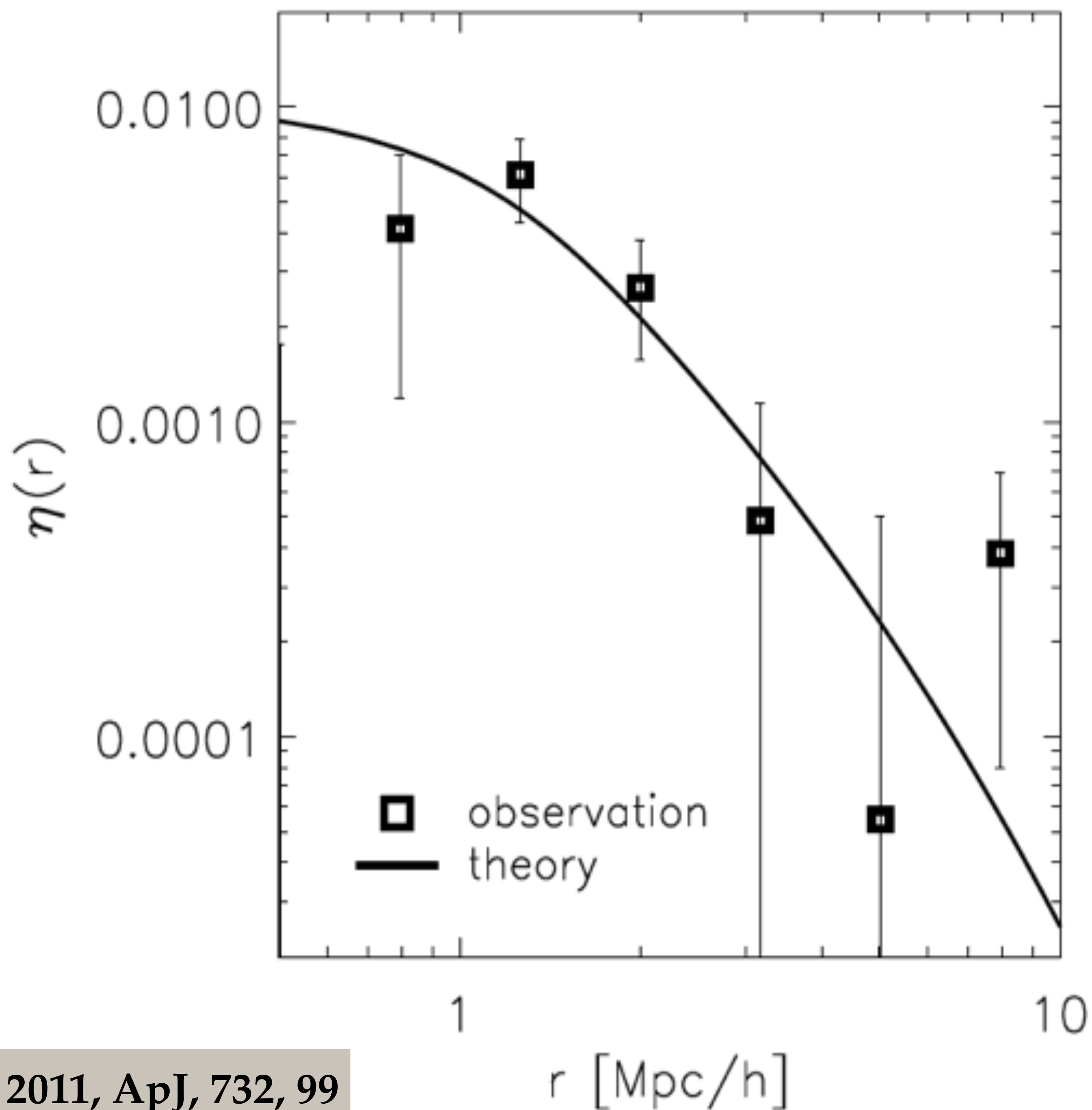
$$\begin{aligned}
\hat{L}_{b1} &= -\hat{L}_r \sin\theta\cos\phi + \hat{L}_\theta \cos\theta\cos\phi - \hat{L}_\phi \sin\phi, \\
\hat{L}_{b2} &= -\hat{L}_r \sin\theta\sin\phi + \hat{L}_\theta \cos\theta\sin\phi + \hat{L}_\phi \cos\phi, \\
\hat{L}_{b3} &= -\hat{L}_r \cos\theta - \hat{L}_\theta \sin\theta,
\end{aligned}$$

- The spin-spin correlations can be obtained as an average of

$$\eta(r) = \frac{1}{4}\left(\langle|\hat{\mathbf{L}}_a \cdot \hat{\mathbf{L}}'_a|^2\rangle + \langle|\hat{\mathbf{L}}_a \cdot \hat{\mathbf{L}}'_b|^2\rangle + \langle|\hat{\mathbf{L}}_b \cdot \hat{\mathbf{L}}'_a|^2\rangle + \langle|\hat{\mathbf{L}}_b \cdot \hat{\mathbf{L}}'_b|^2\rangle\right) - \frac{1}{3}$$

Signal of the Spin-Spin Correlations





Lee 2011, ApJ, 732, 99

III. Observation (part two)

Detection of the Spin-Shear Correlations

1. Observational data
2. Signal vs. Theory

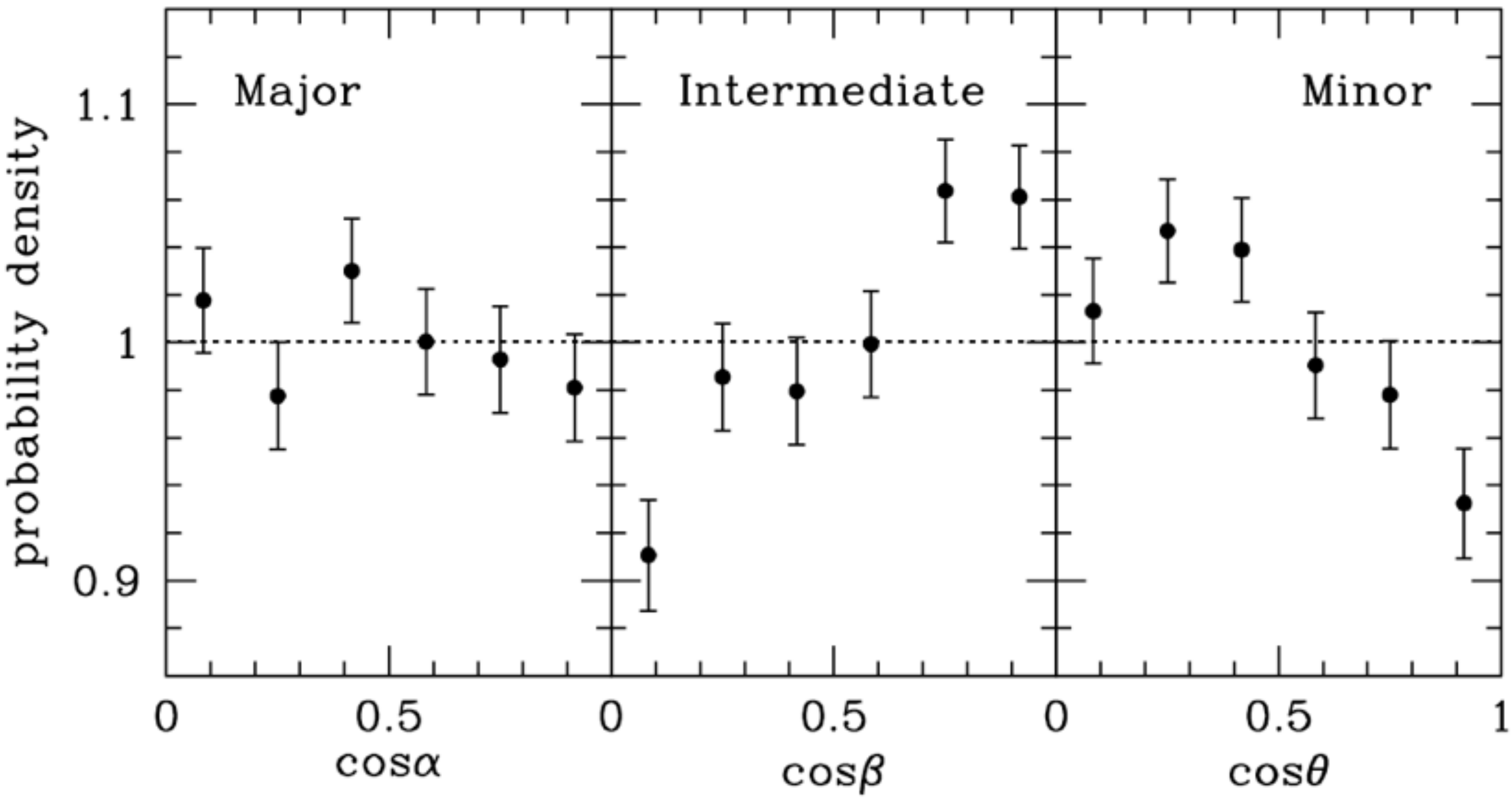
Observational Data

- The linear tidal shear field:
  - from the density field reconstructed from the 2MASS Redshift Survey (Erdogdu et al. 2006) on 64^3 grids in a regular cubic of linear size 400 h^{-1}Mpc
  - calculating the Fourier amplitudes of the tidal shears as

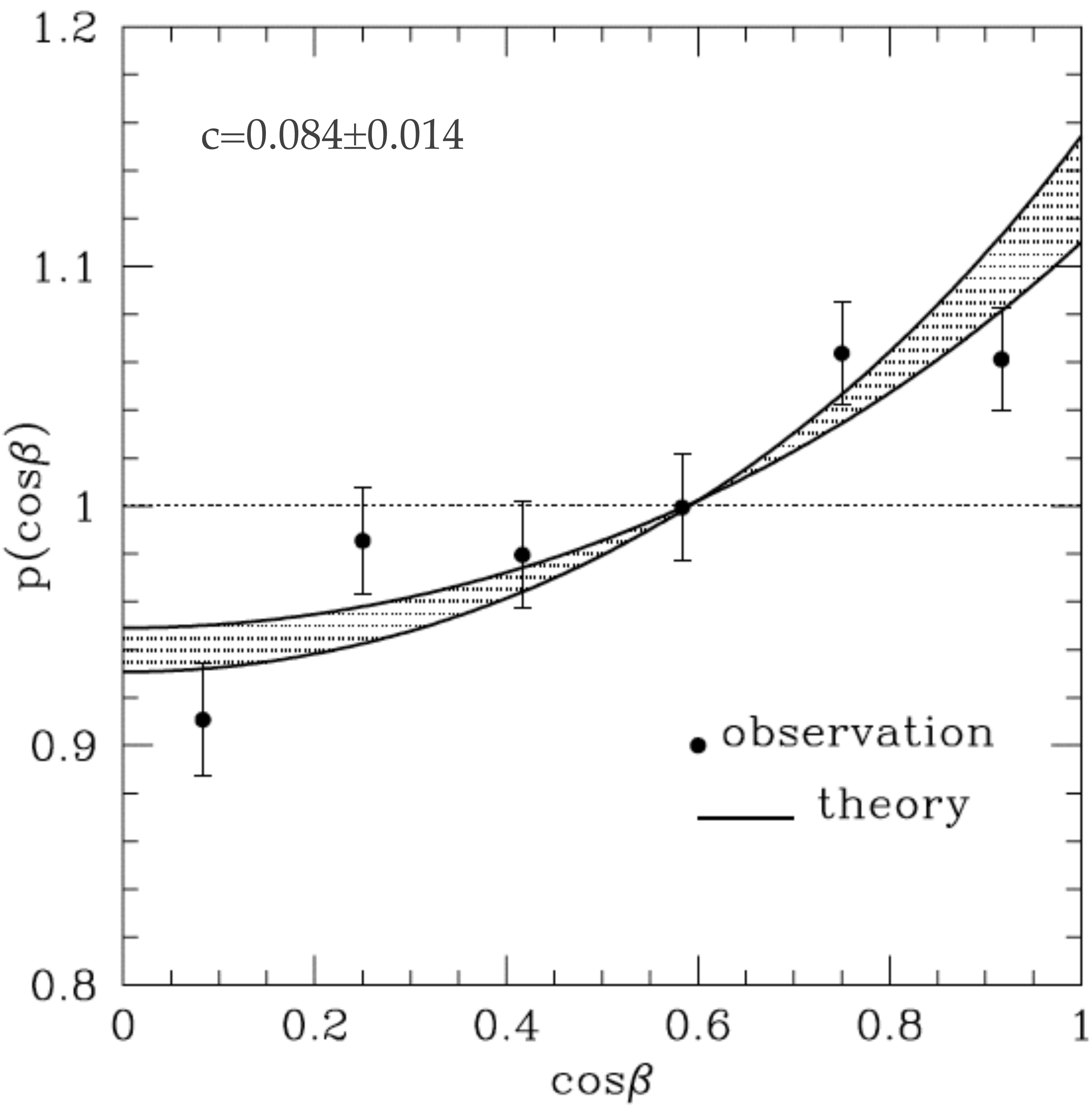
$$T_{ij}(\boldsymbol{k}) = k_i k_j \delta(\boldsymbol{k})/k^2$$

- The galaxy spin field
  - Using the Tully catalog of nearby galaxies (Tully 2000)
  - a total of 12122 spiral galaxies with morphological types (0-9) and median redshifts z~0.02

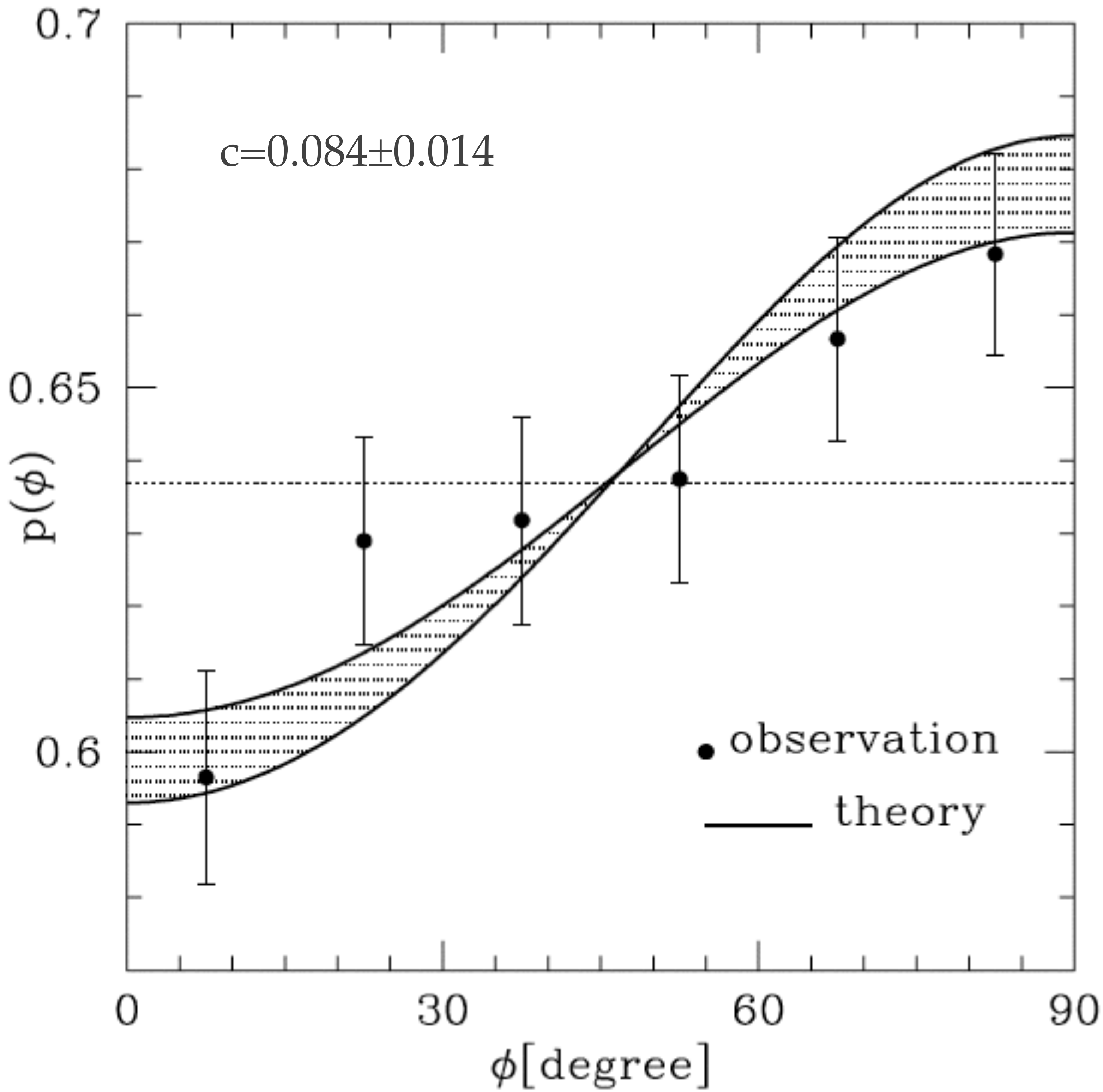
Observed Spin-Shear Correlations



Lee & Erdogdu 2007, ApJ, 671, 1248



Lee & Erdogdu 2007, ApJ, 671, 1248



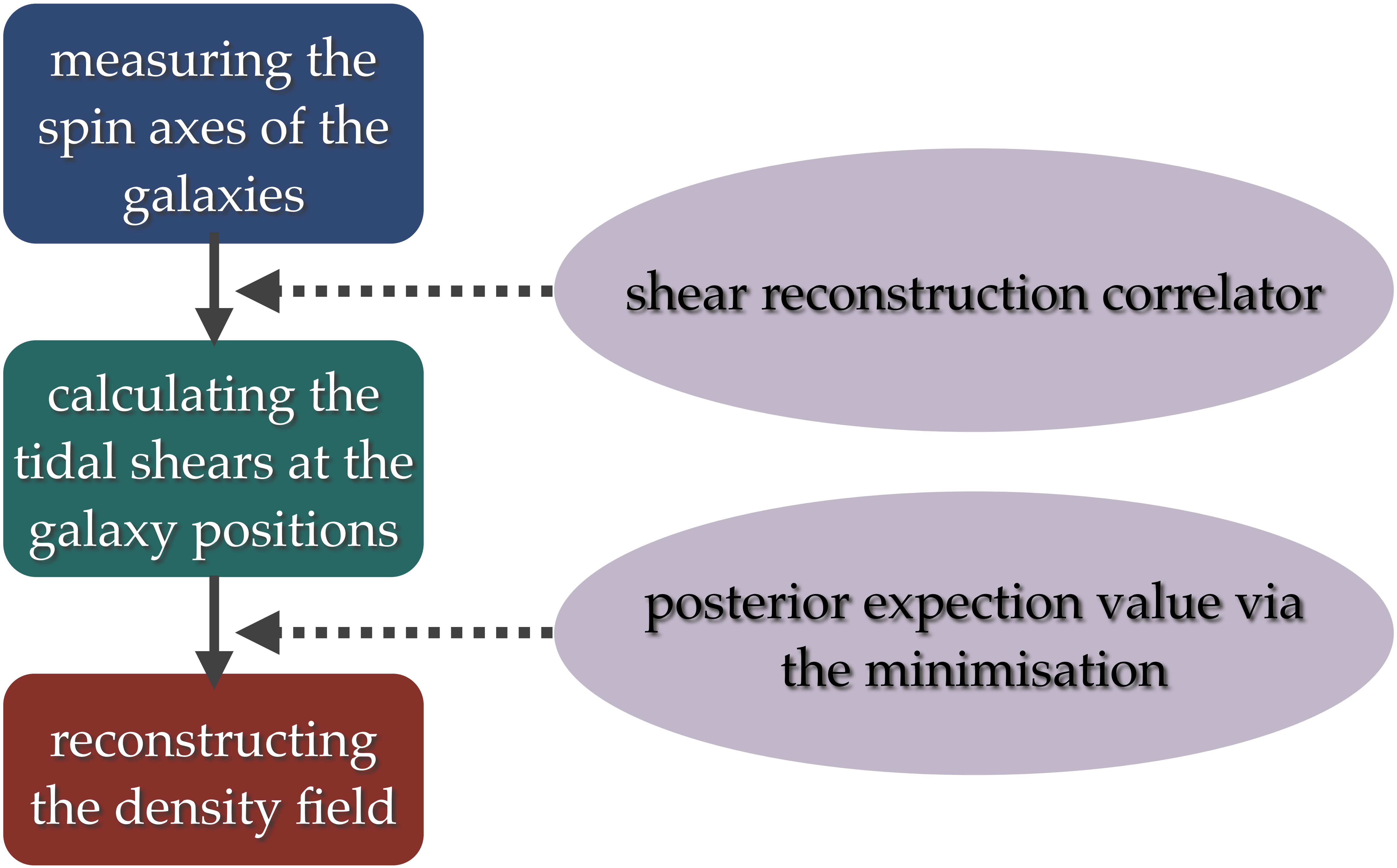
Lee & Erdogdu 2007, ApJ, 671, 1248

IV. Application

Density Field from the Galaxy Spins

1. Reconstruction algorithm
2. Numerical tests

Density Reconstruction from Galaxy Spins



Shear Reconstruction Correlator

$$\langle \tilde{T}^{\alpha}_{ij} \tilde{T}^{\beta}_{lm} | \hat{L}^{\gamma} \rangle = \int d\tilde{\mathbf{T}}^{\alpha} \int d\tilde{\mathbf{T}}^{\beta}\, \tilde{T}^{\alpha}_{ij} \tilde{T}^{\beta}_{lm} P(\tilde{\mathbf{T}}^{\alpha}, \tilde{\mathbf{T}}^{\beta} | \hat{L}^{\gamma})$$

$$= \int \mathscr{D}\tilde{\mathbf{T}}^{\gamma} \int d\tilde{\mathbf{T}}^{\alpha} \int d\tilde{\mathbf{T}}^{\beta}\, \tilde{T}^{\alpha}_{ij} \tilde{T}^{\beta}_{lm} P(\tilde{\mathbf{T}}^{\alpha}, \tilde{\mathbf{T}}^{\beta}, \tilde{\mathbf{T}}^{\gamma} | \hat{L}^{\gamma})$$

$$= \int \mathscr{D}\tilde{\mathbf{T}}^{\gamma} \int d\tilde{\mathbf{T}}^{\alpha} \int d\tilde{\mathbf{T}}^{\beta}\, \tilde{T}^{\alpha}_{ij} \tilde{T}^{\beta}_{lm} P(\tilde{\mathbf{T}}^{\alpha}, \tilde{\mathbf{T}}^{\beta}, \tilde{\mathbf{T}}^{\gamma}) \frac{P(\hat{L}^{\gamma} | \tilde{\mathbf{T}}^{\alpha}, \tilde{\mathbf{T}}^{\beta}, \tilde{\mathbf{T}}^{\gamma})}{P(\hat{L}^{\gamma})}$$

$$= \int \mathscr{D}\tilde{\mathbf{T}}^{\gamma} \int d\tilde{\mathbf{T}}^{\alpha} \int d\tilde{\mathbf{T}}^{\beta}\, \tilde{T}^{\alpha}_{ij} \tilde{T}^{\beta}_{lm} P(\tilde{\mathbf{T}}^{\alpha}, \tilde{\mathbf{T}}^{\beta}, \tilde{\mathbf{T}}^{\gamma}) P(\hat{L}^{\gamma} | \tilde{\mathbf{T}}^{\gamma}) \,,$$

where

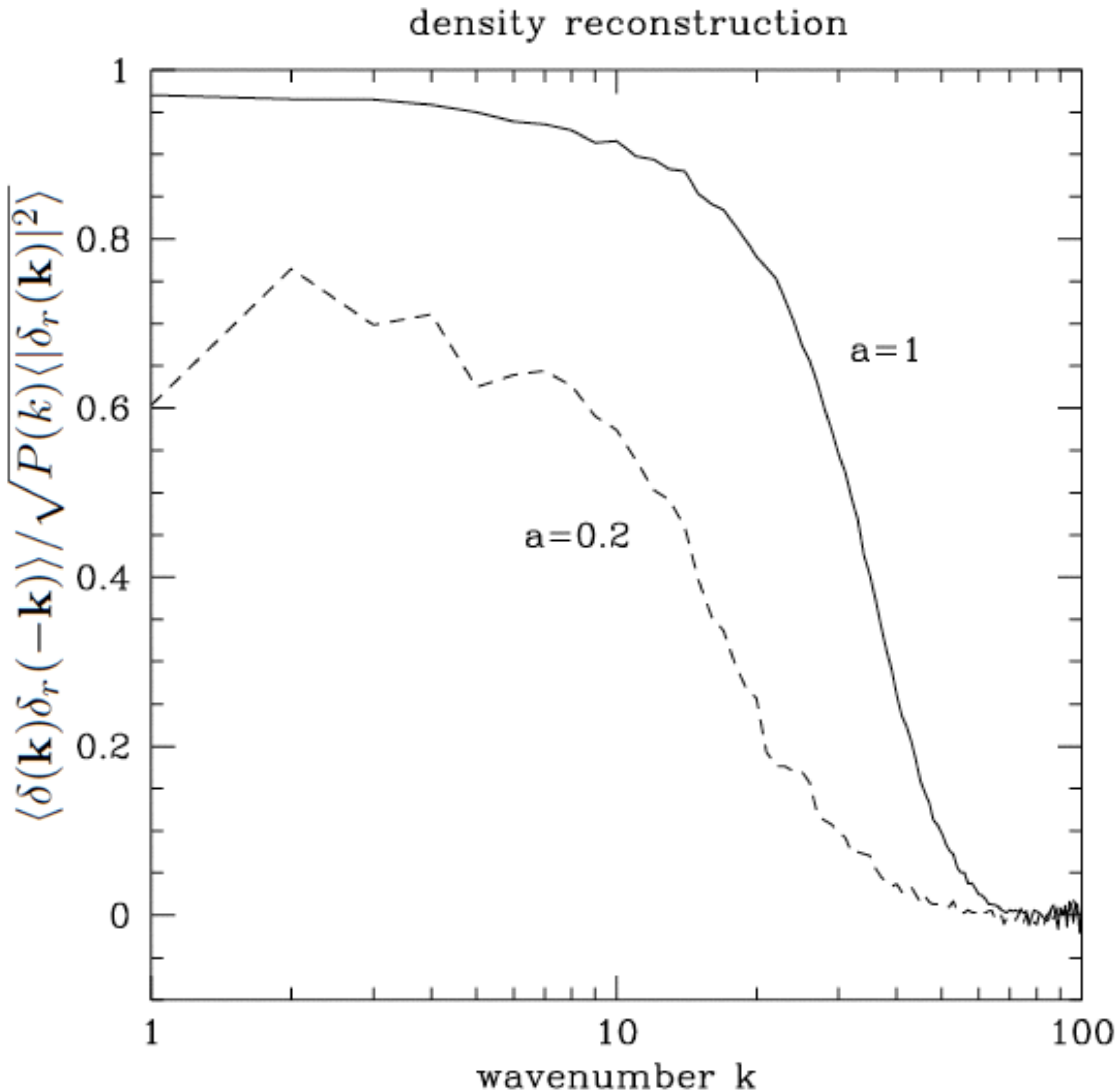
$$P(\hat{L}^{\gamma} | \tilde{\mathbf{T}}^{\gamma}) = -a \tilde{T}^{\gamma}_{nk} \tilde{T}^{\gamma}_{ko} \hat{L}^{\gamma}_{n} \hat{L}^{\gamma}_{o} \,,$$

$$
\begin{aligned}
\tilde{\xi}_{ijlm}(\boldsymbol{x}_\alpha, \boldsymbol{x}_\beta) &= -a \int \mathscr{D}\tilde{\mathbf{T}}^\gamma \int d\tilde{\mathbf{T}}^\alpha \int d\tilde{\mathbf{T}}^\beta \, \tilde{T}^\alpha_{ij} \, \tilde{T}^\beta_{lm} \, \tilde{T}^\gamma_{nk} \, \tilde{T}^\gamma_{ko} \, P(\tilde{\mathbf{T}}^\alpha, \tilde{\mathbf{T}}^\beta, \tilde{\mathbf{T}}^\gamma) \hat{L}^\gamma_n \hat{L}^\gamma_o \\
&= -a \int d\boldsymbol{x}_\gamma \langle \tilde{T}^\alpha_{ij} \, \tilde{T}^\beta_{lm} \, \tilde{T}^\gamma_{nk} \, \tilde{T}^\gamma_{ko} \rangle \hat{L}^\gamma_n \hat{L}^\gamma_o \\
&= -a \int d\boldsymbol{x}_\gamma \, \tilde{C}_{ijnk}(\boldsymbol{x}_\alpha - \boldsymbol{x}_\gamma) \tilde{C}_{lmok}(\boldsymbol{x}_\beta - \boldsymbol{x}_\gamma) \hat{L}_n(\boldsymbol{x}_\gamma) \hat{L}_o(\boldsymbol{x}_\gamma) \; .
\end{aligned}
$$

$$
\int \frac{\tilde{\xi}_{ijlm}(\boldsymbol{k}_\alpha, \boldsymbol{k}_\beta)}{P(k_\alpha) P(k_\beta)} \, \tilde{T}_{ij}(\boldsymbol{k}_\alpha) d^3\boldsymbol{k}_\alpha = \Lambda \tilde{T}_{lm}(\boldsymbol{k}_\beta) \; .
$$

Concerns and Consolations

- Galaxy biasing
  - It would not affect the reconstruction since only the spin directions matter.
- Merging of galaxies
  - The spin-shear correlations persists since the orbital angular momentum of the constituents become the spin angular momentum of the merged system
- Weak lensing effect
  - At low redshifts ($z<0.05$), the intrinsic alignment signals would dominate the weak lensing effect.



Lee & Pen 2000, ApJ, 532, L5

V. Discussion

Remaining Issues

1. Halo spins vs. galaxy spins
2. Observational errors

Galaxy Spins vs. Halo Spins

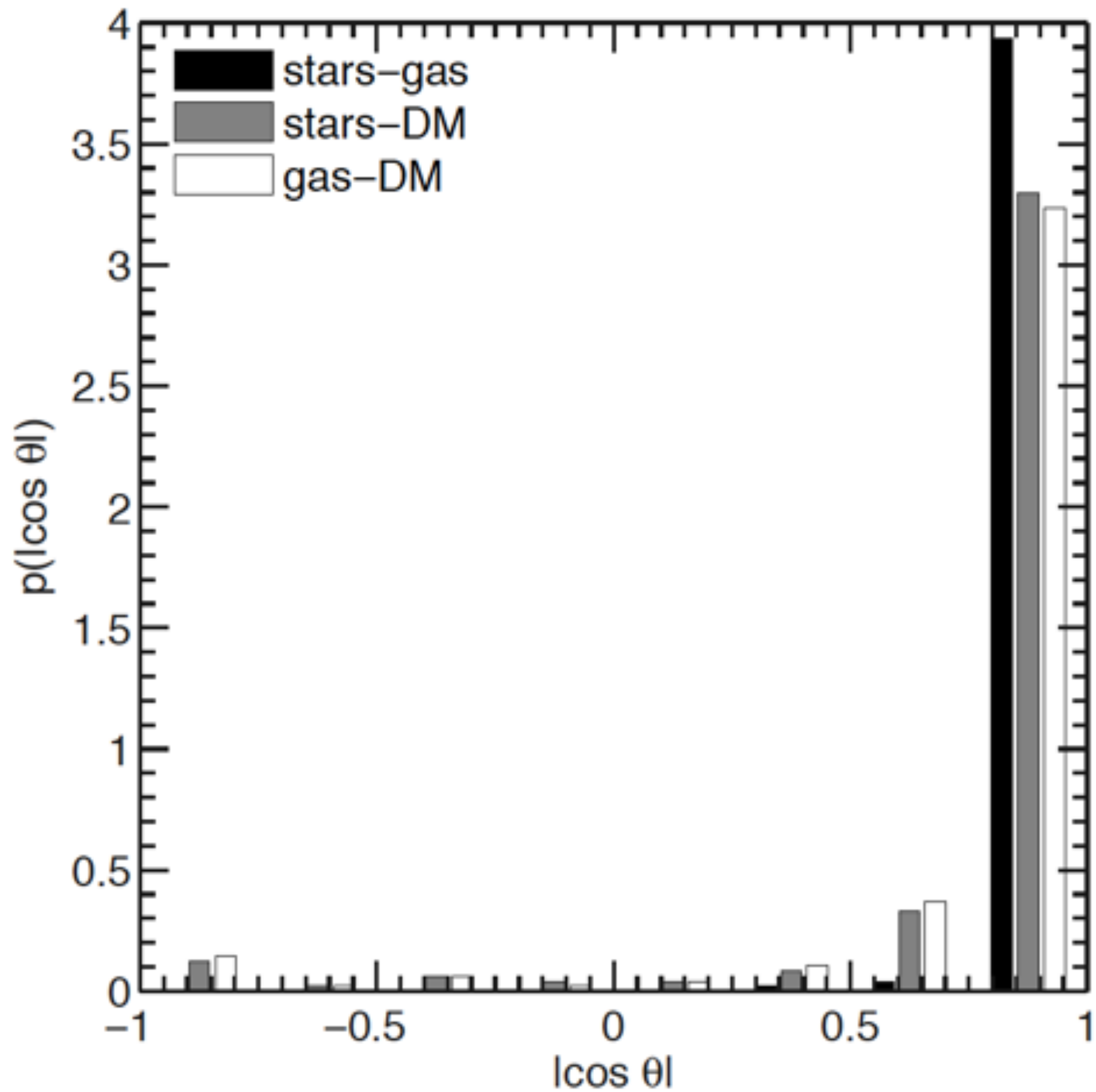
- The spin axes of DM halos are not perfectly aligned with those of stellar parts in hydrodynamic simulations (e.g., Hahn et al. 2010)
  - in the inner region at z=0

    $\theta_{med} = 18^{\circ}$

  - at virial radii at z=0.

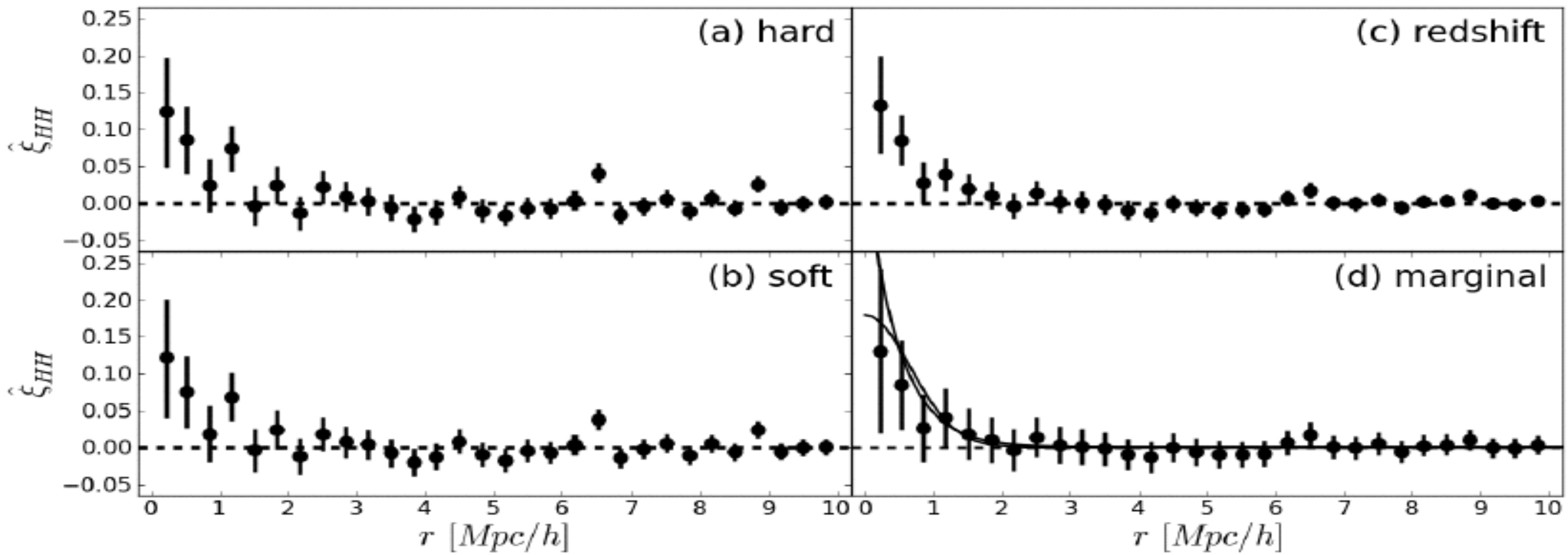
    $\theta_{med} = 50^{\circ}$

Hahn, Teyssier, & Carollo 2010,MNRAS,405,274



Propagation of Observational Errors

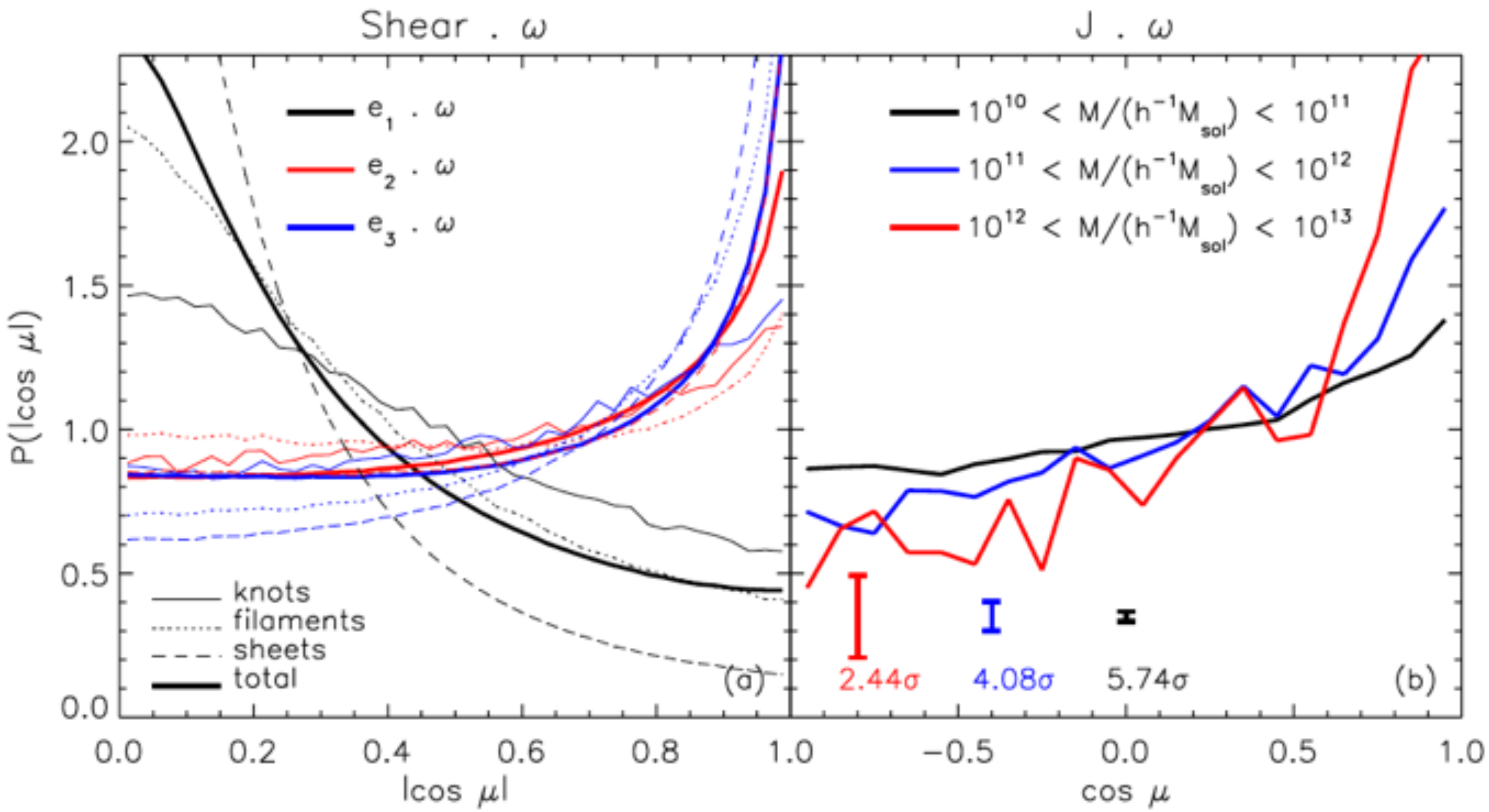
- Errors in redshifts, ellipticities, and morphological classifications would generate spurious signals of the galaxy spin-spin alignment (Andrae & Jahnke 2011).



Andrae & Jahnke 2011, MNRAS, 418, 2014

Effect of Cosmic Vorticity

- The effect of the vorticity on the galaxy angular momentum becomes dominant in the nonlinear regime (Libeskind et al. 2013,2014)



Libeskind et al. 2013, ApJ, 766, L15

Conclusion

- We have constructed a practical model for the intrinsic spin-shear and spin-spin correlations in the framework of the tidal torque theory.
- We have detected several observational evidences to constrain the model parameters.
- We have shown that it is in principle possible to reconstruct the linear density field from the galaxy spin field.
- There are several issues regarding the observational errors that have yet to be fully addressed.