# Weak Lensing and Alignments of Galaxies

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## Spin-Lensing

- Spin: angular momentum correlations of disks (initial shape correlations mostly erased)
- Lensing: apparent alignments introduced by (weak) gravitational lensing
- Which effect is bigger?
- How can we tell them apart?

# Intrinsic Alignments

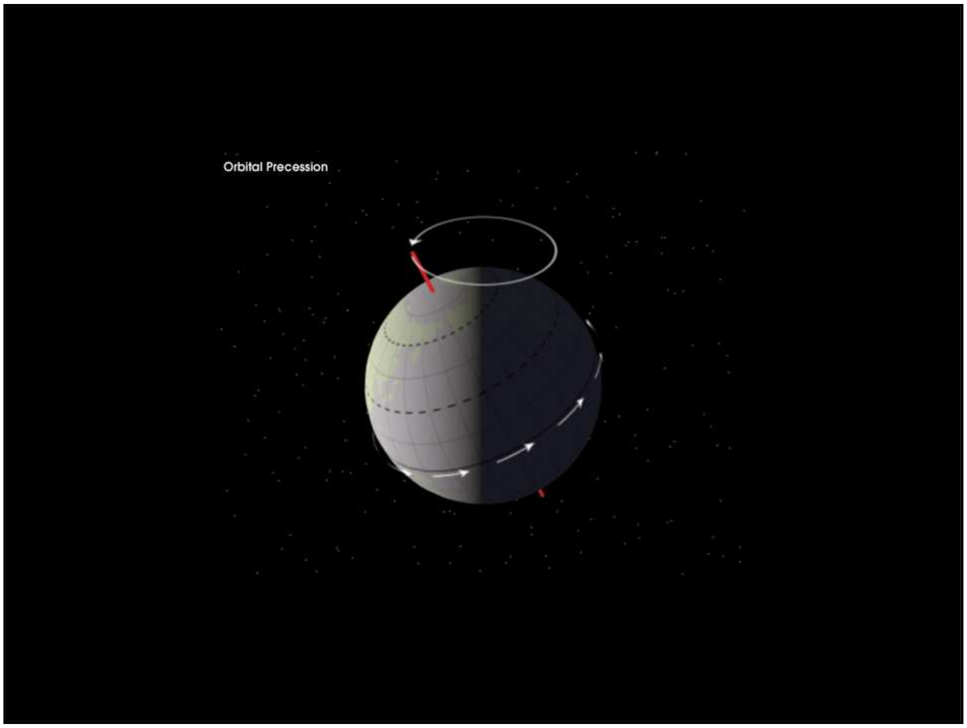
- What determines the orientation of galaxies?
- Are they random? Pointing towards something?
- Do neighboring galaxies have correlated alignments?
- If they are aligned, can one use them for something?
- Does intrinsic alignment affect weak lensing statistics?

## Evolution of Galaxy Alignment

- Disk galaxies have rotation axis and angular momentum vector
- What was the origin of angular momentum?
- Goedel suggested that the universe has net rotation
- Doreshkevich (1972) proposed gravitational torquing
- White (1983) first quantified tidal torques

## Tidal Torquing

- Earth tidally torqued by moon: leads to 26000 year precession.
- Torquing conditions: 1. Asphericity (quadrupole). 2. Misaligned tidal shear.



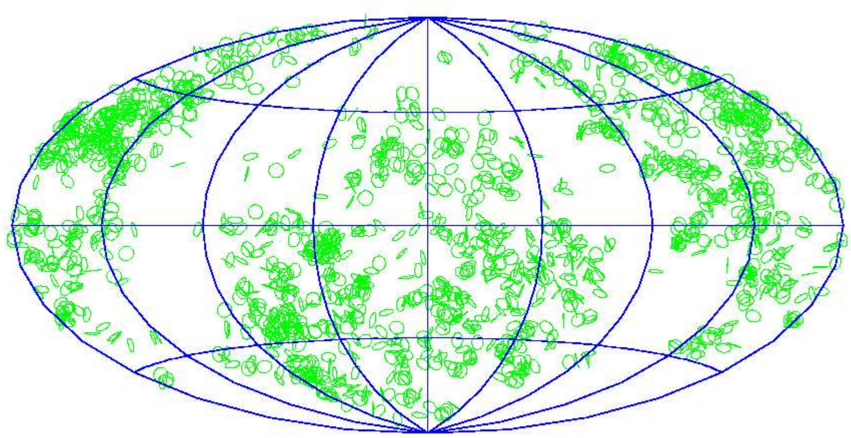

## More technically…

$$
\begin{aligned}
\vec{L} &= \int \rho r \times v d^3x \\
&\propto \epsilon_{ijk} \int \rho x_j \partial_k \phi(x) d^3x \\
&\sim \epsilon_{ijk} \partial_k \partial_l \phi(0) \int \rho x_j x_l d^3x \\
&= \epsilon_{ijk} T_{kl} I_{lj}
\end{aligned}
$$

# Tully Catalog of Nearby Galaxies

- 12000 spiral galaxies with distance, position angle, inclination, Hubble type
- used for least action principle orbit and velocity reconstruction

Tully Catalog 80<r<100/h Mpc



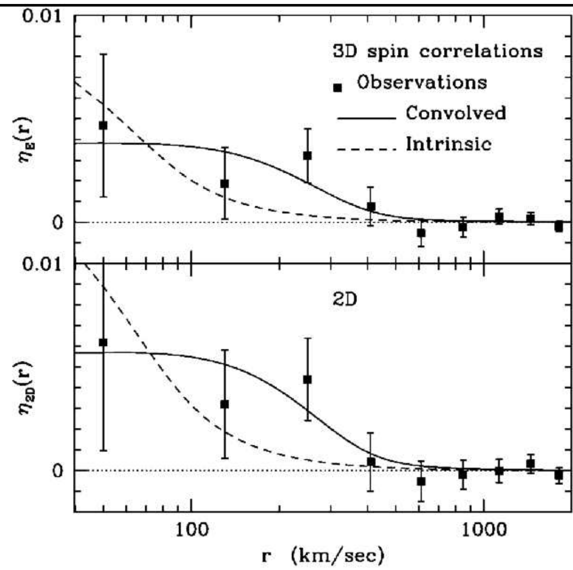



FIG. 1.—Spin-spin correlation as a function of galaxy separations, $r = cz$ (km $s^{-1}$). The power-law spectrum, $P(k) = k^{-2}$, and the correlation parameter, $a = 0.24$, are used for the theoretical curves. The solid theoretical curve is a Gaussian convolved version of the dashed curve with a peculiar velocity dispersion of $\sigma_v = 150$ km $s^{-1}$.

Lee, Pen

& Seljak

2000

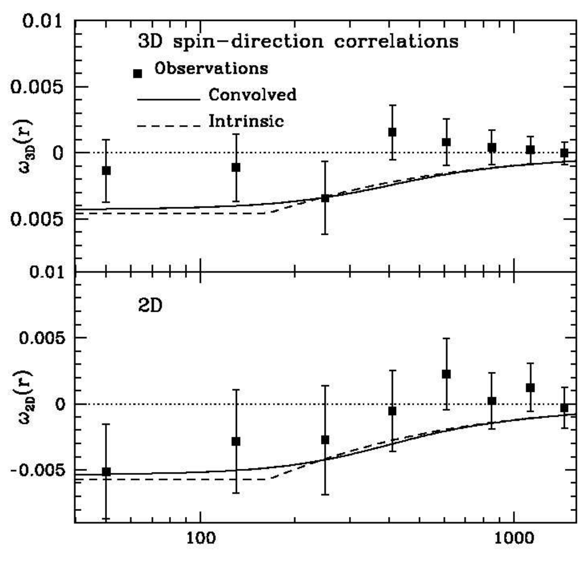



Fig. 2.— The spin-direction correlation signal for the case of a power-law spectrum of $P(k) = k^{-2}$ with the correlation parameters having the value of $a = 0.24$ and $b = 0.3$.

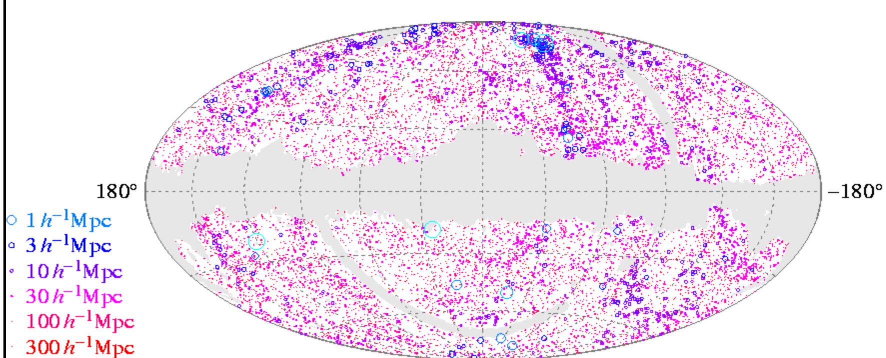
Lee &

Pen 2000

# Quantitative Test of Torquing

- Measure the position of all matter (galaxies) and the tidal effects on each other. All-sky survey: *IRAS*-PSCz
- Compare predicted spin with observed spin for each Tully catalog galaxy

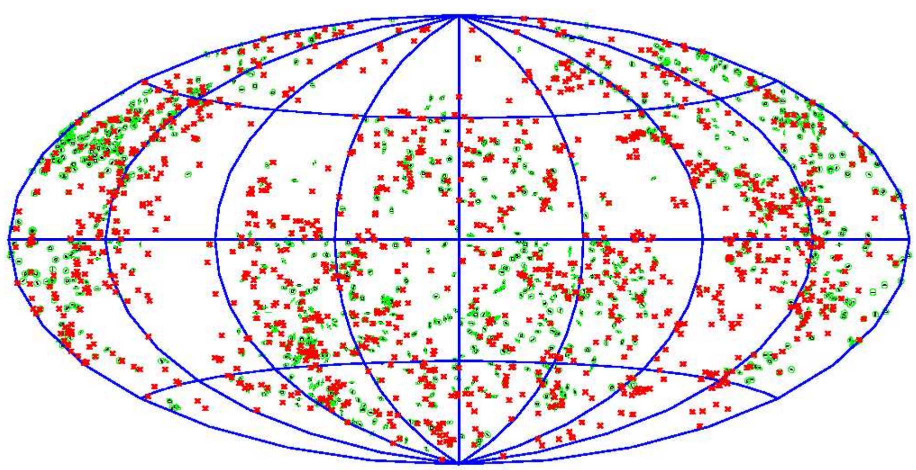
PSCz redshift survey




15000 galaxy redshifts in 83% of sky

# Tully-PSCz cross-correlation

- Predict alignment for each Tully position due to torques from all PSCz galaxies
- result is confirmed at greater than 99.98% confidence (Lee and Pen 2002)
- Consistent with computer simulations of tidal torquing



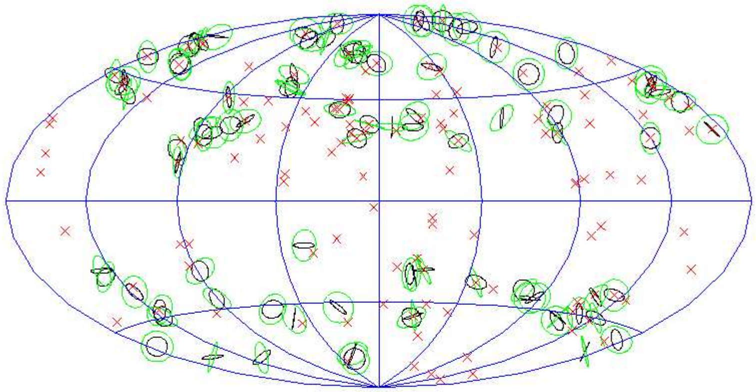


Fig. 1.— The two-dimensional illustration for different realizations of intrinsic shear effect. It is an Aitoff projected sky map in galactic coordinates within distance range [98-100] $h^{-1}$ Mpc. The smaller black ellipses correspond to the actual alignment of disk galaxies while the green larger ellipses represent the expectation value of predicted disk alignments where spins are perfectly aligned with the intermediate principal axes of tidal shears. The black ellipses are determined using the observed position angles and axis ratios rescaled to the thin disk model. The red crosses show the positions of PSCz galaxies in the same distance range.

# Parametrized Estimation

$$\langle L_i L_j \rangle = \frac{1+a}{3}\delta_{ij} - a\hat{T}_{ik}\hat{T}_{kj}$$

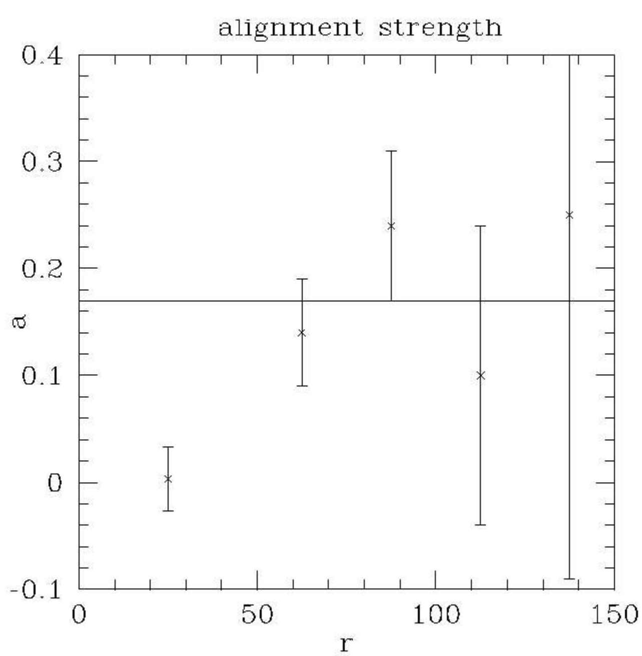
$$0 < a < \frac{3}{5}$$

$$a = 2 - 6\sum_{i=1}^{3}\tilde{\lambda}_i^2|\hat{L}_i|^2$$

Table 1: Observed and rescaled signal of intrinsic shear

| # of galaxies | $r$ ($h^{-1}$Mpc) | $a^{obs}$ | $a$ |
|---|---|---|---|
| 5727 | 0-50 | $(0.1 \pm 0.8) \times 10^{-2}$ | $0.003 \pm 0.03$ |
| 3336 | 50-75 | $(3.2 \pm 1.1) \times 10^{-2}$ | $0.14 \pm 0.05$ |
| 1940 | 75-100 | $(4.6 \pm 1.4) \times 10^{-2}$ | $0.24 \pm 0.07$ |
| 898 | 100-125 | $(1.4 \pm 2.1) \times 10^{-2}$ | $0.10 \pm 0.14$ |
| 221 | 125-150 | $(3.0 \pm 4.3) \times 10^{-2}$ | $0.25 \pm 0.34$ |

*Note:* $\bar{a}$ has been found to be $0.17 \pm 0.04$. The signal of the first sample was not used in the calculation of $\bar{a}$, since its statistical weight should be dominated by cosmic variance.



## Discussion

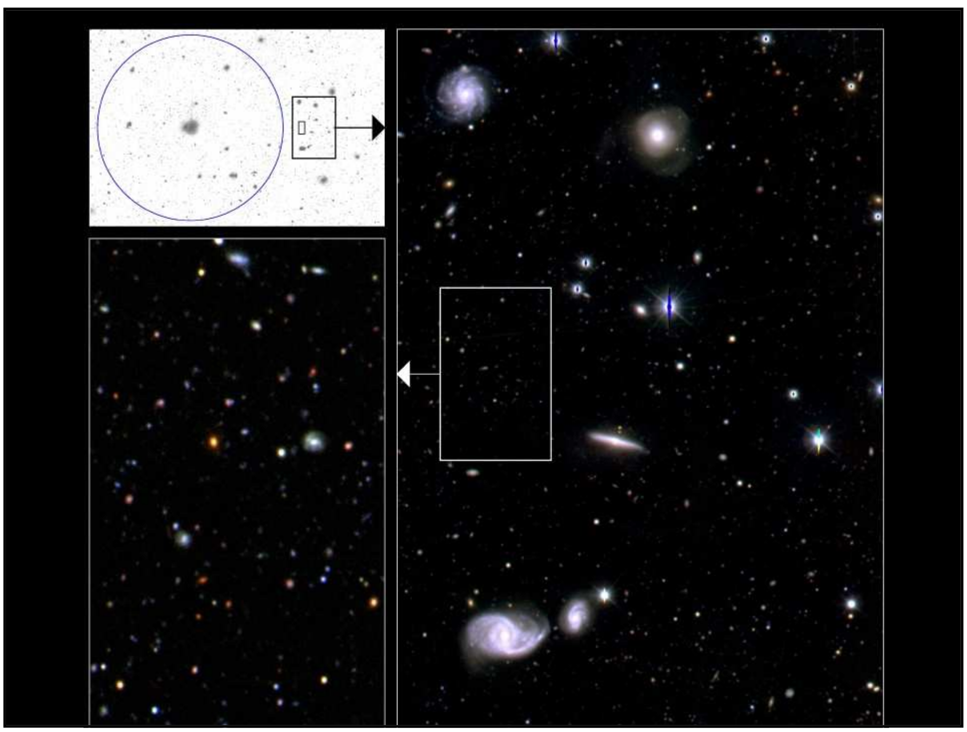
- Formally, a=0 (random alignment) null hypothesis rejected at 99.98% confidence
- Difficulty in weighting sample variance for first bin (smallest volume)
- Interpretation for weak lensing surveys

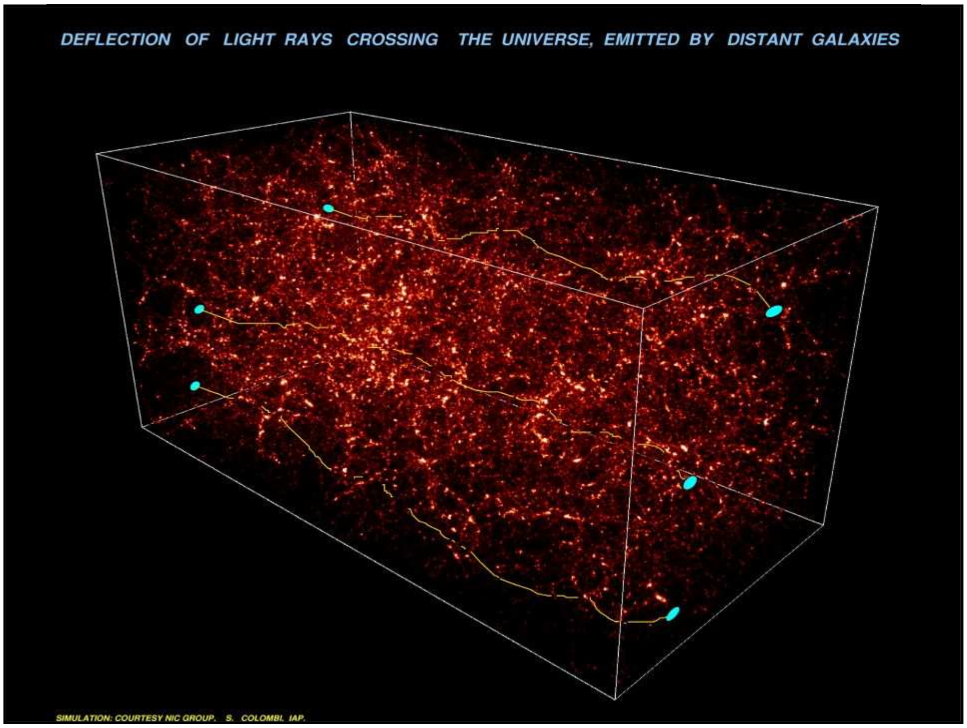
## Applications of Galaxy Spins

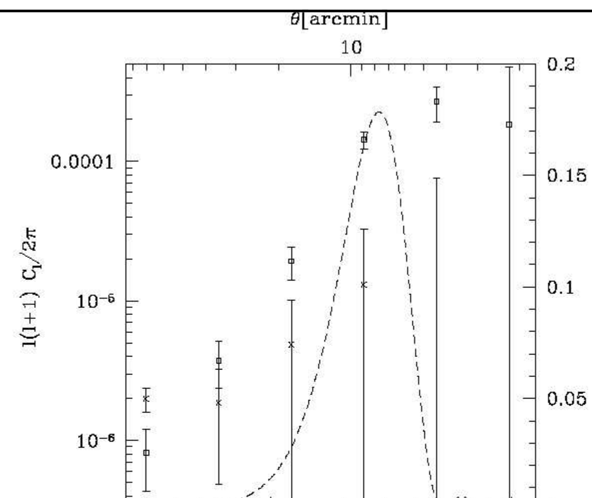
- Primordial gravity probe: measures conditions billions of years ago when galaxies form
- reconstruct 3-D shear and density field
- may be very feasible with Sloan Digital Sky survey (Lee and Pen 2000)

# Extrinsic Shear

- Apparent alignment induced by gravitational lensing between source and observer
- Direct probe of dark matter power spectrum

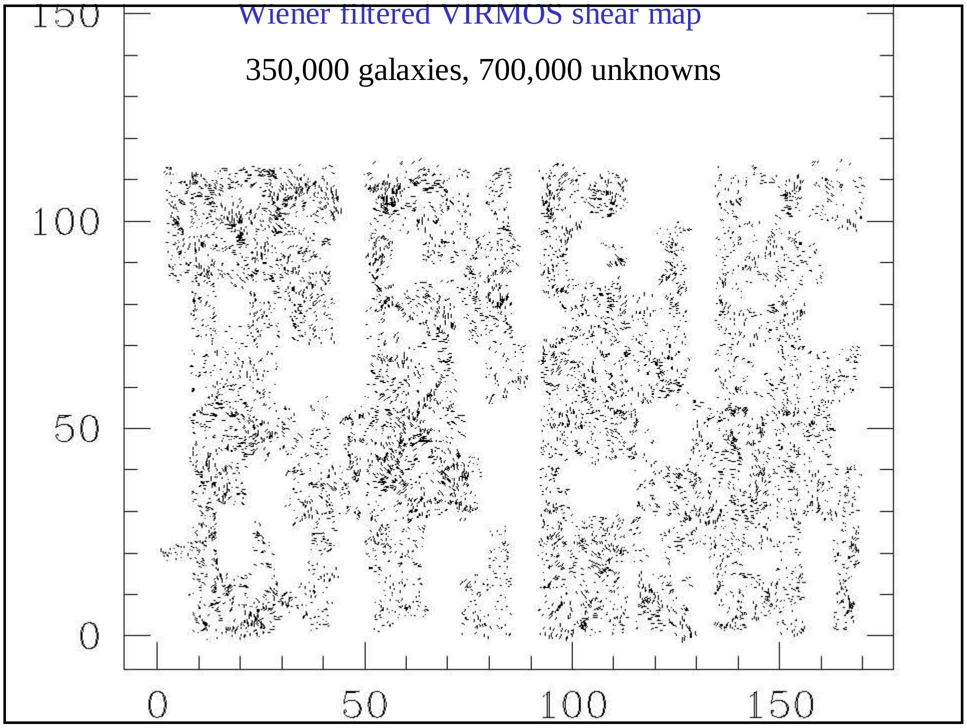


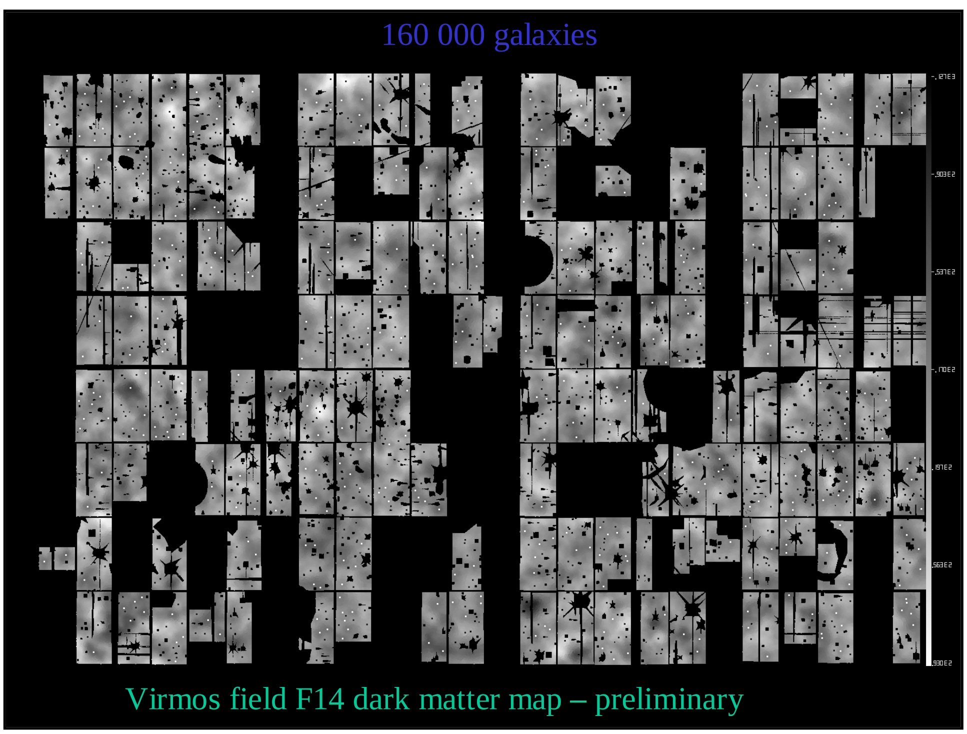


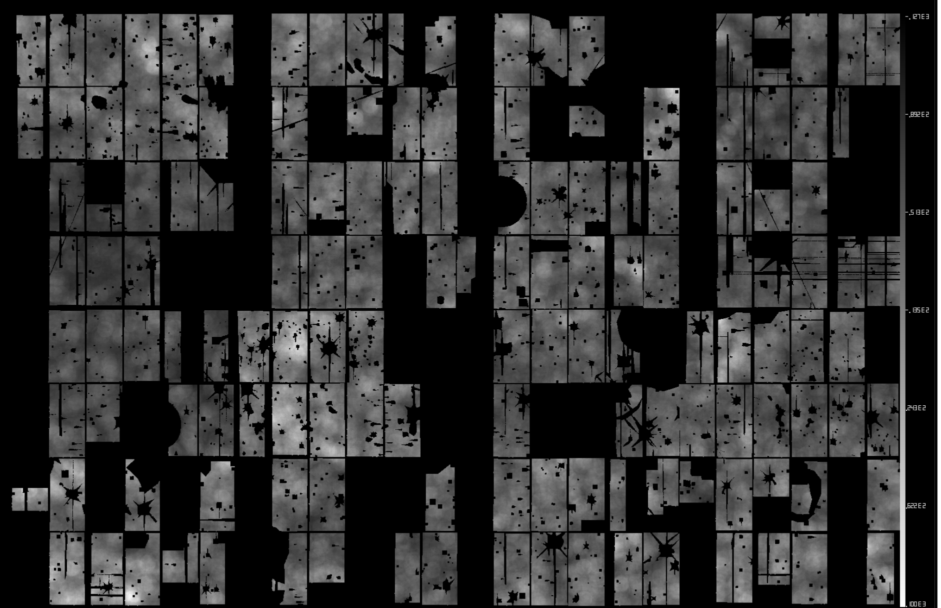




Pen, van Waerbeke & Mellier, 2002

Fig. 5.— Spherical harmonic power spectrum. Again, the boxes indicate the $E$ type power spectrum, while the crosses denote the $B$ type power. The angular scale is the spacing of peaks of the wave functions at the equator for m=l. The dashed line is the window function for the aperture mass statistic at 5', with amplitude labeled on the right bounding box edge. The aperture mass is analogous to the integral of the window with the power spectrum using equal weight per natural logarithmic interval.

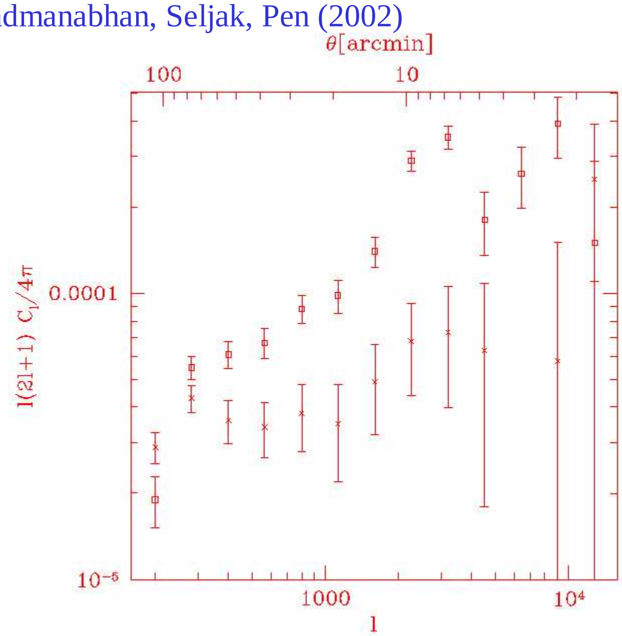

Wiener filtered VIRMOS shear map
350,000 galaxies, 700,000 unknowns
150
100
50
0
0
50
100
150


160 000 galaxies
Virmos field F14 dark matter map – preliminary



Virmos F14 galaxy surface density -- preliminary

Max Likelihood Angular Power Spectrum – all fields. See Padmanabhan, Seljak, Pen (2002)



14 Spin Induced Galaxy Alignments

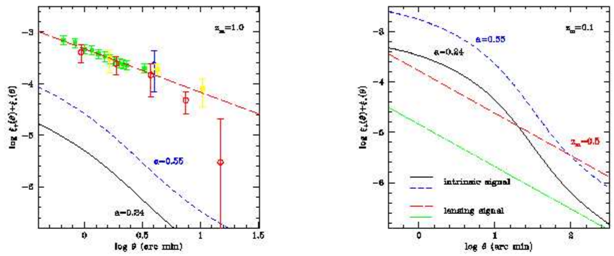



FIG. 5.— The intrinsic correlation signal versus the predictions from weak lensing and current observations. Left panel: $\xi_+(\theta) + \xi_\times(\theta)$ for a median redshift of 1, compared to the measured shear correlation function. At small separations, the intrinsic signal is approximately one percent of the measured value. The amplitude depends on the value of the assumed average galaxy thickness ($\alpha$) and the parameter $a$ that describes how well the angular momentum of the galaxy is correlated with the shear field. We plot $a = 0.24$ (full line) and $a = 0.55$ (short-dashed line) which correspond to the values inferred from numerical simulations by LP00 and Heavens et al. (2000) respectively. $\alpha = 0.73$ corresponds to the value determined from the observed distribution of ellipticities (Ebbels et al. 2000). The data are: van Waerbeke et al. (2000) – solid squares ; Wittman et al. (2000) – filled circles ; Kaiser et al. (2000) – open circles; and Bacon et al. (2000) – filled triangle. The long-dashed line is the theoretical prediction from Jain & Seljak (1997) computed for a $\Omega_\Lambda = 0.7$ galaxy cluster normalized flat universe, $\sim 4.75 \times 10^{-4}(\theta/\mathrm{arcmin})^{-0.84}$. Right panel: as in the left panel but for the predictions for a shallower survey such as SDSS and 2dF with median redshift $z_m = 0.1$. The intrinsic signal is again shown for two values of $a$, and the theoretical prediction for weak lensing is the long-dashed line (for $z_m = 0.1$) and dotted-long-dashed (for $z_m = 0.5$). The lensing prediction for $z_m = 0.1$ is extrapolated from the Jain & Seljak fit beyond the stated range of validity. For such low redshifts, the intrinsic signal is significant and may dominate over the lensing contribution for most scales.

CNPT 2001

# Separation of Modes

- Distances: intrinsic alignment local, strongest for equidistant galaxies, extrinsic alignment across source plane slices
- Kinematic: galaxy alignment is spin-2 field (polarization), analogous to vector field: magnitude and direction. Div and Curl modes (E, B)
- Lensing induces curl-free mode (gravity derives from scalar potential)

Crittenden, Natarajan, Pen & Theuns

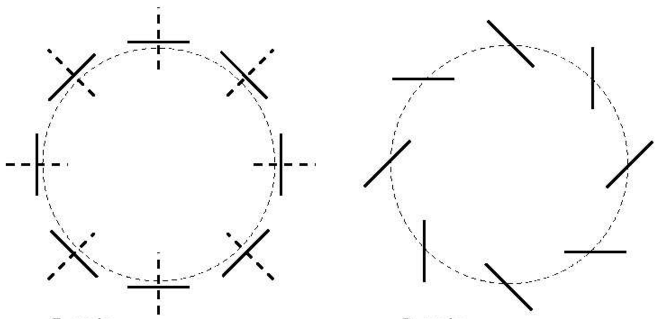



FIG. 2.— Local representations of $E$ (gradient) and $B$ (curl) modes. $E$-modes are either tangential or radial, depending on their sign. $B$-modes can be oriented in either a clockwise or counter-clockwise (shown) direction. Lensing generally brings about only E-modes, while noise and angular momentum correlations can generate both. Local estimators of the $E$ and $B$-modes can be found by doing a radial weighting of these circular integrals (Kaiser et al. 1994).

6 Discriminating weak lensing from intrinsic spin correlations

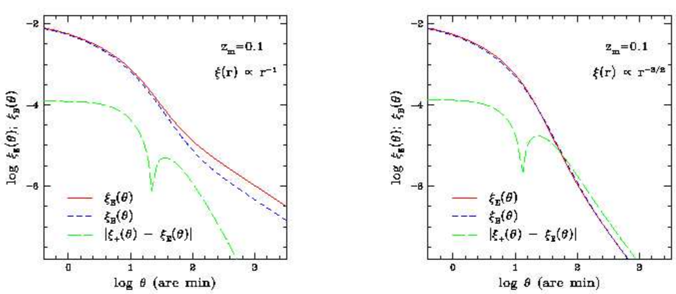



FIG. 1.— The $E$ and $B$-mode correlation functions for intrinsic spin correlations in the model of CNPT (2000). The amplitude of the correlations are determined by the parameters $a$ and $\alpha$, which have been taken to be unity for simplicity. The mean redshift of the sources was taken to be $z_m = 0.1$ and the density correlations were taken to fall off as $r^{-1}$ in the left figure and as $r^{-3/2}$ in the right figure. Also plotted are the differences between $\xi_E$ and $\xi_+$, which is the same as the differences between $\xi_B$ and $\xi_\times$. In the left panel, the projected ellipticity correlations fall off as $\theta^{-1}$ and $\xi_E$ and $\xi_+$ are very nearly the same. This is not the case in general, as can be seen in the right panel where the projected correlations fall as $\theta^{-2}$. However, the $\theta^{-2}$ is also special in that $\xi_E$ and $\xi_B$ are nearly identical.

CNPT 2002

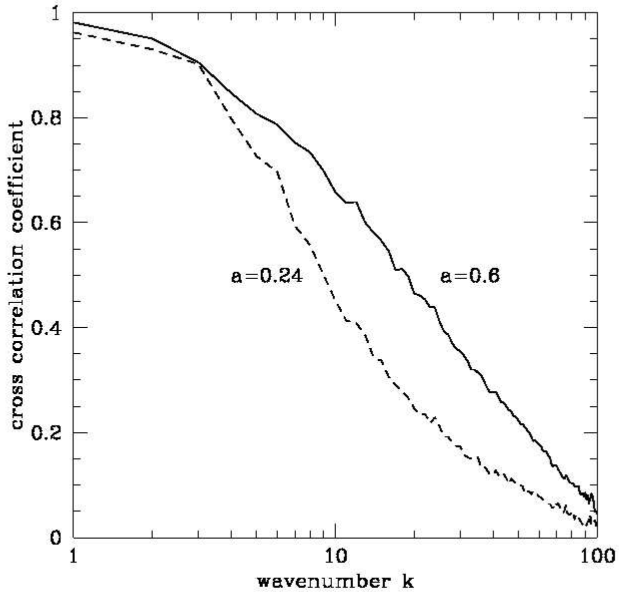



Fig. 1.— Accuracy of the reconstructed density field. The solid line is the ideal linear case, while the dotted line corresponds to the strength of correlations measured in simulations and the Tully data. On large scales, reconstruction is always accurate.

## The Alternative

- Kamionkowski *et al*: alignment with primordial shear major axis. Erased by angular momentum?
- Mackay *et al*: E-B power spectrum. Observable?
- Porciani *et al*: ambiguity in parameter *a*?

# Conclusions

- Galaxies are spun up by tides from surrounding matter
- First quantitative theoretical and observational treatment yield consistent and robust results
- Many potential future directions to use spin axes as probes of universe
- Contamination for statistical weak lensing searches severe for shallow surveys (SDSS), not a problem for deep searches (CFHLS).
- Spin alignments new and quickly expanding field