Perturbative models for imaging surveys
(Intrinsic alignments in the Dark Energy Survey)

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Outline

• “3x2” cosmology and intrinsic alignments
• Analytic modeling of IA
• Observational results and future directions
• Galaxy-galaxy lensing at smaller scales

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Summary

• “3x2” cosmology and intrinsic alignments
  • Intrinsic shape correlations are important
    arXiv: 1506.08730
  • Analytic modeling of IA
    • PT model analogous to bias expansion
      arXiv: 1504.02510, 1708.09247, 1805.02649
  • Observational results and future directions
    • Hints of quadratic alignments in DES Y1
      arXiv: 1708.01538, 1811.06989
  • Galaxy-galaxy lensing at smaller scales
    • Simple “point-mass” parameter
      arXiv: 1903.07101
Combining probes

DES Year 1: Elvin-Poole+ 2017; Chang+ 2018

\[ \delta_g = b \delta_m \]

\[ \langle \delta_g | \delta_g \rangle = \xi_{gg} \sim b^2 \sigma_8^2 \]

\[ \langle \delta_g | \gamma \rangle = \xi_{mg} \sim b \sigma_8^2 \]

\[ \langle \gamma | \gamma \rangle = \xi_{mm} \sim \sigma_8^2 \]

“3x2” analysis

- More statistical power, different systematics, “self-calibration”
- Also: CMB, clusters, SNe, strong lensing, RSD, 21cm…

  e.g. Mandelbaum+ 2013; Krause & Eifler 2017; DES Y1; Joudaki+ KiDS 2017
Galaxy observables: positions and shapes

$z = 0.06$

(MassiveBlack II: Khandai+ 2014; Tenneti+ 2014a,b)
Galaxy positions ("bias")

\[ \delta_g = \mathcal{F} \Phi \]
Galaxy positions ("bias")

\[ \delta_g = b_1 \delta + b_2 \delta^2 + b_s s^2 + \cdots \]
Galaxy shapes ("intrinsic alignments")

\( \gamma^{\text{obs}} = \gamma^{G} + \epsilon_{n} \)

\[ \langle \gamma_{i}^{\text{obs}} \gamma_{j}^{\text{obs}} \rangle = \langle \gamma_{i}^{G} \gamma_{j}^{G} \rangle \]

\( z = 0.06 \)

\( 20 \text{ Mpc/h} \)
Galaxy shapes ("intrinsic alignments")

\[ \gamma^{\text{obs}} = \gamma^G + \gamma^I + \epsilon_n \]

\[ \langle \gamma_i^{\text{obs}} \gamma_j^{\text{obs}} \rangle = \langle \gamma_i^G \gamma_j^G \rangle + \langle \gamma_i^G \gamma_j^I \rangle + \langle \gamma_i^I \gamma_j^I \rangle \]
Galaxy shapes ("intrinsic alignments")

\[ I_{ij} = \sum_{m} \sum_{n} \rho_{n} \mathbf{x}_{ni} \mathbf{x}_{nj}, \]

where \( \rho_{n} \) represents the mass of the \( n \)th particle and \( \mathbf{x}_{ni}, \mathbf{x}_{nj} \) represent the position coordinates of the \( n \)th particle with \( 0 \leq i, j \leq 2 \) for 3D and \( 0 \leq i, j \leq 1 \) for 2D. It is to be noted that in this simulation, all particles of the given type (either dark matter or star particle) have the same mass. Hence the mass of a particle has no effect on the inertia tensor. The inertia tensor can also be defined by weighting the positions of particles by their luminosity instead of mass.

Schneider et al. (2012) used the definition of reduced inertia tensor and investigated the radial dependance of halo shapes in the \( N \)-body simulation by considering only particles within a given fraction of the virial radius. In this paper, we are only concerned with the standard unweighted inertia tensor definition for determining shapes and defer investigation of other definitions for a future study.

Consider the 3D case. Let the eigenvectors of the inertia tensor be \( \mathbf{e}_a, \mathbf{e}_b, \mathbf{e}_c \) and the corresponding eigenvalues be \( a, b, c \), where \( a > b > c \). The eigenvectors represent the shape of the system.
Galaxy shapes ("intrinsic alignments")

\[ \gamma_{ij}^I = \mathcal{F}_{ij}[\Phi] \]

\( z = 0.06 \)

20 Mpc/h
Tidal alignment: collapse in a tidal field
Tidal alignment
Tidal alignment: collapse in a tidal field

\[ \gamma_{ij}^I = \frac{C_1}{4\pi G} \nabla_i \nabla_j \Phi \sim C_1 \nabla_i \nabla_j \nabla^{-2} \delta = C_1 s_{ij} \]

"NLA" model (see T. Okumura talk, T. Kurita poster)
Analytic IA models

Tidal field: $s$

- Tidal alignment: linear in $s$

- Tidal torquing: quadratic in $s$
  - (e.g. Lee & Pen 2000; Hirata & Seljak 2004)

Hybrid/halo model
- (e.g. Schneider & Bridle 2009)
Analytic vs simulation modeling

**IA in hydro sims:** MassiveBlack, Illustris, Horizon-AGN, EAGLE/Cosmo-OWLS
(e.g. Chisari+2016, Tenneti+ 2016, Codis+ 2018)

This is a hard problem!
Perturbative expansions for galaxy observables

galaxy bias (e.g. McDonald & Roy 2009; Desjacques, Jeong, Schmidt 2018)

\[
\delta_g(x) = b_1 \delta_m(x) + b_2 \delta^2_m(x) + b_3 s^2(x) + \cdots
\]

\[
\gamma^I_{ij} = C_1 s_{ij} + C_2 (s_{ik} s_{kj}) + C_3 (\delta s_{ij}) + C_4 t_{ij} + \cdots
\]

galaxy intrinsic alignments
(JB+ 2015; Schmidt+ 2015; JB+ 2017; Schmitz, Hirata, JB, Krause 2018; Z. Vlah talk)
FIG. 3. Constraints on cosmological and intrinsic alignment parameters for an idealized LSST-like cosmic shear survey. Dashed lines indicate the input parameter values used to create the data vectors. Green outlined contours use a data vector and model without intrinsic alignment contributions, case (i). The orange outlined contour uses a data vector with contamination by the full intrinsic alignment model, with fiducial amplitudes (see Sec. IV B), but uses a model which assumes the NLA model for the intrinsic alignment contribution, case (ii). The black contour is the same as the orange, except the model also includes a free power law in redshift, case (iii). The purple contour uses the same data vector as orange and black, but uses the full intrinsic alignment modeling, thereby recovering unbiased parameter constraints, case (iv).

The recent weak lensing analysis of DES Year 1 data [18] applied this model and found indications for non-zero values of both $C_1$ and $C_2$, respectively at the 82% and 84% confidence levels. Using this more flexible IA model caused a non-trivial shift in the recovered cosmological parameters, although they caution that further study is required to understand this result. This model will also provide a valuable tool in "combined probe" analyses that use both weak lensing and galaxy clustering.

$\gamma_{ij}^I = \boxed{C_1} s_{ij} + \boxed{C_2} (s_{ik} s_{kj}) + \boxed{C_\delta} (\delta s_{ij}) + \boxed{C_t} t_{ij} + \cdots$

JB, Vlah, Seljak 2015
Schmidt, Chisari, Dvorkin 2015
Schmitz, Hirata, JB, Krause 2008

\[ \langle \delta g | \delta g \rangle \sim w_{gg} \]
\[ \langle \delta g | \gamma \rangle \sim w_{g\gamma} (\text{GI}) \]
\[ \langle \gamma | \gamma \rangle \sim w_{++} (\text{II}) \]

LSST-like cosmic shear
Green: no IA
Orange: NLA
Black: NLA + power-law z
Purple: Full model
FFT evaluation of PT integrals

McEwen, Fang, Hirata, JB 2016; Fang, JB, McEwen, Hirata 2017
see also: Schmittfull, Vlah, McDonald 2016; Schmittfull & Vlah 2016; Simonovic+ 2017

**FAST-PT on github:** JoeMcEwen/FAST-PT

\[
I(k) = \int \frac{d^3 q_1}{(2\pi)^3} K(\hat{q}_1 \cdot \hat{q}_2, \hat{q}_1 \cdot \hat{k}, \hat{q}_2 \cdot \hat{k}, q_1, q_2) P(q_1)P(q_2)
\]

\[
f(k) = \int \frac{d^3 q_1}{(2\pi)^3} P_\ell(\hat{q}_1 \cdot \hat{q}_2) P_{\ell_1}(\hat{k} \cdot \hat{q}_2) P_{\ell_2}(\hat{k} \cdot \hat{q}_1) q_1^\alpha q_2^\beta P(q_1)P(q_2)
\]

\[
J_{J_1, J_2}^{\alpha \beta}(r) \equiv \left[ \int_0^\infty dq_1 \ q_1^{2+\alpha} P(q_1) j_{J_1} (q_1 r) \right] \left[ \int_0^\infty dq_2 \ q_2^{2+\beta} P(q_2) j_{J_2} (q_2 r) \right]
\]

(e.g. **FFTLog:** Talman 1978, Hamilton 2000)

- Python; easy to use and integrate into other code
- Contact us! Always adding new features
Probing IA in DES Y1

Cosmic Shear
Troxel+ 2018, DES Y1
Probing IA in DES Y1
3x2 and morphology/color split
Samuroff, JB+ 2018, DES Y1
Are these results robust?

• Degeneracy with photo-z or other systematic?

• Under-constrained parameters and degeneracies with cosmology causing shifts? (cf. E. Krause talk on nonlinear bias tests)
Are these results robust?

Tests underway, DES Y3 appears to be sufficiently constraining.
Non-locality in IA
Non-locality in IA

\[ x_i = x(z_i) \]
Non-locality in IA

\[ x_i = x(z_i) \]

\[ t_{ij} \sim \nabla_i \nabla_j \nabla^{-2} (\theta - \delta) \]

\[ x_f = x(z_f) \]
Measuring non-locality

Schmitz, Hirata, JB, Krause 2018

\[ B_{ggI} \sim \langle \delta_g(k_1) \delta_g(k_2) \gamma^I(k_3) \rangle \]
Looking ahead in IA

- DES Y3 analysis (~4200 deg 3x area of Y1)
- Implement and analyze complete 1loop model (cf Z. Vlah talk); pipelines for LSST and Euclid
- New hydro simulations and observational constraints (IllustrisTNG, PAU, eBOSS, DES, …)
- IA as a probe of LSS and fundamental physics
Galaxy-galaxy lensing and small scales

- baseline (8,12) Mpc/h
- $b_2, b_5^2$ (8,12) Mpc/h
- $b_2, b_5^2$ (4,4) Mpc/h
- 1 halo term (8,12) Mpc/h
- 1 halo term (8,8) Mpc/h
- 1 halo term (4,4) Mpc/h

Y1 Methods: Krause+ 2017
Galaxy-galaxy lensing and small scales

MacCrann, JB, Jain, Krause 2018
Galaxy-galaxy lensing and small scales

MacCrann, JB, Jain, Krause 2018

\[ \Sigma(R) = \bar{\rho}_m \int_{-\infty}^{\infty} d\Pi \left[ 1 + \xi_{gm} \left( \sqrt{R^2 + \Pi^2} \right) \right] \]

\[ \Delta\Sigma(R) = \bar{\Sigma}(0, R) - \Sigma(R) \]
"Point mass" model
MacCrann, JB, Jain, Krause 2018

\[ \Sigma(R) = \rho_m \int_{-\infty}^{\infty} d\Pi \left[ 1 + \xi_{gm} \left( \sqrt{R^2 + \Pi^2} \right) \right] \]

\[ \Delta \Sigma(R) = \bar{\Sigma}(0, R) - \Sigma(R) \]

\[ \bar{\Sigma}(0, R) = \frac{r_{min}^2 \Sigma(0, r_{min})}{R^2} + \frac{(R^2 - r_{min}^2)\Sigma(r_{min}, R)}{R^2} \]

\[ \Delta \Sigma(R) = \Delta \Sigma^{\text{model}}(R) + B/R^2 \]

cf. Annular statistics, Baldauf+ 2010; Singh+ 2018; S. Sugiyama poster
Figure 4. All panels show constraints on $\Omega_m$ and $S_8 = S_8(\Omega_m \propto 0.3)$.0.5 for a DES-like galaxy-galaxy lensing and galaxy clustering analysis. The simulated data vector has contamination by an un-modeled one-halo term in the galaxy-galaxy lensing signal (described in Section 2.5).

In addition to $\Omega_m$ and $S_8$, the Hubble constant $H_0$, and an arbitrary shift in $r$ (see Section 4 for details). The true values (i.e. those used to generate the data vector) are shown as the grey dashed lines. The three sets of contours represent the three modeling approaches described in Section 4. Blue solid contours result from neither point-mass nor small-scale marginalization. The orange outlined contours use point-mass but not small-scale marginalization. The green outlined contours use both point-mass and small-scale marginalization. The top-left panel is for our fiducial setup described in Section 2.5. In the top-right (bottom-left) panel we use larger (smaller) minimum scale cuts corresponding to $8h^{-1}$Mpc ($2h^{-1}$Mpc) in the lens plane for both galaxy-galaxy lensing and clustering. In the bottom-right panel, a source galaxy number density 4 times higher than the fiducial setup is assumed.

galaxy density) we additionally allow $w_0$, the (constant with redshift) dark energy equation of state parameter, to vary from its $\cdm$ value of 1, in the range $[3, 0.33]$. Figure 5 shows marginalized constraints on $\Omega_m S_8$, $h$ and $w_0$. Again, modeling approach (i) recovers the tightest constraints, but biases with respect to the truth values are present, with the truth lying outside the 68% credible interval in the $S_8 h$ and $S_8$ $\Omega_m$ planes for example. Again, when using small-scale marginalization, modest gains in constraining power are apparent in most of the 2d projections of the posterior, and the constraint on $w_0$ is improved by 16% with respect to the case when only point-mass marginalization is used.

5 DISCUSSION

We have described and demonstrated a methodology which uses an analytic marginalization approach to target two issues with small scale galaxy-galaxy lensing measurements. Firstly, the galaxy-galaxy lensing signal measured at physical separation $R$ in the lens plane receives significant contributions from scales $r < R$ in the galaxy-matter correlation function $\langle g_m(r) \rangle$. We have described how uncertainty in the model prediction for this contribution can be straightforwardly marginalized over by including in the model a $1 \propto R^2$ or $1 \propto \kappa^2$ dependence with free amplitude. We demonstrate that this approach can successfully remove biases in inferred parameters when an un-modeled one-halo contribution is present in the galaxy-galaxy lensing signal, and that this marginalization can be performed analytically, to avoid adding extra sampling parameters to the parameter inference. We note that the approach of Baldauf et al. (2010) also achieves this goal, although our approach may more naturally allow the use of priors and retention of shear-ratio information in a tomographic analysis.

Secondly, we demonstrate that an analytic marginalization
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