What I’m going to talk about:

1. Lensing measurement:
   • why it's hard
   • how to solve it
2. Lensing from galaxy kinematics
   • how it works
   • how I’m hoping to measure it
Lensing is sensitive to both growth and geometry:

- Lens mass
- Distances

modify deflection angle
Weak lensing is a key probe of the growth of structure.
Galaxy shape and matter fluctuations are correlated by lensing.

- Well understood dependence on cosmological parameters
- ‘Sharp’ features (e.g., BAO)

- Smooth in scale and redshift
- Weak, hard to measure
- …but observable
Understanding the physics of cosmic acceleration requires measuring the growth of structure.

Key signature: disagreement between early-time forecasts and late-time structure measurements.
For this reason, lensing is a key driver of the Stage IV dark energy experiments.
The success of these programs depends on the accuracy of lensing shear measurement.

\[ \Psi(\theta) = \frac{4G}{c^2} \frac{D_l D_s}{D_{ls}} \int d^2 \theta' \Sigma(\theta') \ln |\theta - \theta'|, \]

Bridle et al. 2008
The success of these programs depends on the accuracy of lensing shear measurement. The shape of an extended source can be described by angular mo-

\[ \Psi(\theta) = \frac{4G}{c^2} \frac{D_l D_s}{D_{ls}} \int d^2\theta' \Sigma(\theta') \ln |\theta - \theta'|, \]

\[ \left( \delta_{ij} - \frac{\partial^2 \Psi(\theta)}{\partial \theta_i \partial \theta_j} \right) = \begin{pmatrix} 1 - \kappa - \gamma_1 & -\gamma_2 \\ -\gamma_2 & 1 - \kappa + \gamma_1 \end{pmatrix} \]
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\[ g = \frac{\gamma}{1 - \kappa} \]

we usually re-parameterize with \( g \)
How do we get $g$ from a galaxy image?

$$Q_{ij...k} = \int I(\theta)\theta_i\theta_j...\theta_k d^2\theta.$$  

$$\chi = \frac{(Q_{11} - Q_{22}) + 2iQ_{12}}{Q_{11} + Q_{22}}$$
How do we get $g$ from a galaxy image?

$$Q_{ij...k} = \int I(\theta)\theta_i\theta_j...\theta_k d^2\theta.$$ 

$$\chi = \frac{(Q_{11} - Q_{22}) + 2iQ_{12}}{Q_{11} + Q_{22}}.$$ 

$$g \approx \frac{\langle \chi \rangle}{2(1 - \sigma_\chi^2)}$$

g and $\chi$ are related...
How do we get $g$ from a galaxy image?

$Q_{ij...k} = \int I(\theta) \theta_i \theta_j ... \theta_k d^2 \theta$.

$\chi = \frac{(Q_{11} - Q_{22}) + 2iQ_{12}}{Q_{11} + Q_{22}}$

$g \approx \frac{\langle \chi \rangle}{2(1 - \sigma^2 / \chi)}$

$g$ and $\chi$ are related...

...but in a way that depends on the ensemble.
How do we get $g$ from a galaxy image?

$$e = (1 + m) g + c$$

preferred direction
How do we get $g$ from a galaxy image?

$$e = (1 + m) g + c$$

calibration
bias
(what all the fuss is about)
1. Compute second moments.
2. Calculate the responses to shear ($P_g$) and PSF ellipticity ($P^{sm}$).
3. Correct for PSF ellipticity ($e^*$).

$$g = P_g^{-1} \left( e^{\text{obs}} - \frac{P^{sm}}{P^{sm*}} e^* \right)$$

This doesn’t seem that bad.
Alas, still broad dissensus in lensing results.
Figure 17. Multiplicative and additive biases for constant-shear branches in the control (left) and realistic galaxy (right) experiments, for ground (top) and space (bottom) branches. For each branch, we show the averaged (over components) multiplicative bias $\langle m \rangle$ vs. $c_{+}$, the additive bias defined in the coordinates system defined by the PSF anisotropy. The axes are linear within the target region ($|m| < 2 \times 10^{-3}$ and $|c_{+}| < 2 \times 10^{-4}$, shaded grey) and logarithmic outside that region.
Shear measurement biases have complex dependencies on galaxy properties.
At low signal-to-noise, most estimators are biased.

The size and direction of these biases depends greatly on the details, including sub-threshold galaxy population.
What’s going on?

- Images seem easy; you have an intuition that getting an ‘ellipticity’ from a ‘galaxy’ should be simple.

- Analysis procedure seems ‘hard’, lots of details, thresholds, and nonlinear transformations.

- “How would this image be different with more shear” is easier than “How would this measurement be different with more shear.”
We will construct counterfactual images.

\[ I'(x | g) = P \ast (\hat{s}_g G) \]
We will construct counterfactual images.

\[
I'(x|g) = P \ast (\hat{s}_g G)
\]

\[
I'(x|g) = \Gamma \ast [\hat{s}_g (P^{-1} \ast I)]
\]

remove the PSF, shear, and add a new PSF
We will construct counterfactual images.

\[ I'(x|g) = P \ast (\hat{s}_g G) \]

\[ I'(x|g) = \Gamma \ast [\hat{s}_g (P^{-1} \ast I)] \]

we get to choose our final PSF
We will construct counterfactual images.

\[ I'(x|g) = P \ast (\hat{s}_g G) \]

\[ I'(x|g) = \Gamma \ast [\hat{s}_g (P^{-1} \ast I)] \]

\[ e^+ = \hat{E} \{ I'(x|g^+) \} \]

any ~linear measurement algorithm
We will construct counterfactual images.

\[ I'(x|g) = P \ast (\hat{s}_g G) \]

\[ I'(x|g) = \Gamma \ast [\hat{s}_g (P^{-1} \ast I)] \]

\[ e^+ = \hat{E} \{ I'(x|g^+) \} \]

\[ 1 + m = \frac{e^+ - e^-}{2\Delta g} \]
This is what it looks like in practice.

original data
This is what it looks like in practice.

sheared, reconvolved
(1% shear)
Make measurement on unsheared counterfactual with reconvolved PSF
To validate, we test on image simulations. Starting with GREAT3 analogues.
We wrapped Metacalibration around several measurement algorithms.

KSB:

regauss:
We wrapped Metacalibration around several measurement algorithms.

...including uncorrected second moments, which should not work at all.
We ran many simulations, varying the complexity

- real galaxy morphology
- heterogeneous PSF
- increased noise
- large optical aberrations
- flawed measurement algorithms

Huff & Mandelbaum 2017
Where the algorithms are correctable, MetaCal calibrates them.
Parallel collaboration with Erin Sheldon: pushing Metacalibration’s limits

BDK+ Simulations:
Much larger simulation volume ($5 \times 10^9$)
Bulge+Disk+knots
realistic size/flux distribution (COSMOS)
stellar contamination
full Dark Energy Survey PSF
Large sub-threshold population (low S/N)

Simplified Measurement:
fit elliptical gaussian
no PSF correction (!!!)
reconvolve to symmetric PSF
add noise to symmetrize
These simulations include large sub-threshold populations, so selection effects matter.

**PSF (r_{50})**

**S/N threshold**

![Image of PSF and S/N thresholds](image)
Selection effects are large, but now effectively mitigated.

There is no evidence for any remaining calibration bias.
Future problems
We will soon run out of universe for dark energy measurements.

It is unlikely that we will have solved everything by then.
If we cannot find more galaxies, we need more information per galaxy.
Shear changes the orientation of an ellipse

But shear has no solid-body rotation component.
Lensing *mis-aligns* the kinematic and photometric axes.

With spectroscopic maps, this should be detectable.
Kinematics break degeneracy between shape and shear

- **Face-on**
- **Face-on, but sheared**
- **Inclined, but not sheared**
Consider the Tully-Fisher relation.

Reyes et al. 2011

Schlegel (private comm.)

Reyes et al. 2011

SDSSJ124259+42

Reyes et al. 2011
With spectroscopy, the Tully-Fisher relation tells us the inclination angle.

For a disk, \( \sin(i) \) tells us what ellipticity we should measure in the absence of lensing.
Shear messes up the inclination correction.

Tully-Fisher: \[ v_{\text{obs}} = v_{\text{TF}} \sin(i) + \sigma_{\text{TF}} \]

For a disk: \[ \sin(i) = \left( \frac{2e}{1 + e} \right)^{\frac{1}{2}} \]

The effect of a shear: \[ e \mapsto e + \gamma \]

\[ \sin(i)|_{\gamma} = \sin(i)|_{\gamma=0} + \frac{\gamma}{2 \sqrt{e(1 + e)^3}} \]
The reduction in shape noise can be very large…

…For face-on disks, factors of $\sim 10$. 
For this level of per-galaxy shape noise:

\[ \text{Shape noise: } \propto \frac{\sigma_e}{\sqrt{n_{\text{gal}}}} \]

For LSST: \[ n_{\text{gal}} \approx 25 \text{ gal arcmin}^{-2} \]
\[ \sigma_e \approx 0.2 \]

For kinematic lensing, equivalent shape noise with:

\[ \sigma_e \approx 0.025 \]
\[ n_{\text{gal}} \approx 0.25 \text{ gal arcmin}^{-2} \]
\[ n_{\text{gal}} \approx 0.25 \text{ gal arcmin}^{-2} \]

\[ \sim 10^3 \text{ deg}^2 \]

\[ \implies 10^7 \text{ spectra} \]

This is comparable to PFS or DESI.
A spectroscopic weak lensing measurement with slit spectroscopy
A spectroscopic weak lensing measurement with slit spectroscopy

Less rotation along the major axis than TFR would predict
A spectroscopic weak lensing measurement with slit spectroscopy

More rotation along the minor axis than TFR would predict
Simulating the measurement: Slit Spectroscopy

simple galsim-based simulation

consistent with DES/DESI exposure time calculations

Keck-DEIMOS
But *spatially resolved* slit spectroscopy does not scale to wide-field surveys.

We need hyperspectral imaging.
One possible solution: Imaging Fabry-Perot Interferometer
Example: GHASP survey data

Epinat et al. 2010
Massively Multiplexed Galaxy Kinematics from space

SPECTRE: A Fabry-Perot Imager concept

**Concept**
- square-degree FP imager
- meter-class telescope with 0.1” resolution
- H-alpha kinematics to z<0.5
- ~all-sky survey

**Science**
- Kinematic Lensing
- Peculiar Velocities
- Resolved kinematics of star forming regions

<table>
<thead>
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<th>Survey</th>
<th>Number of galaxies (millions)</th>
<th>Spectral resolution elements per galaxy</th>
<th>Spatial resolution elements per galaxy</th>
<th>Total independent resolution elements (billions)</th>
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<td>100</td>
<td><strong>80,000</strong></td>
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*Table 1: Relative measure of information content of selected wide-field surveys, counting the number of usable galaxy targets and the spatial and spectral resolution of each.*
Shear response depends on unresolved modes.
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Shear response depends on unresolved modes
Convolve to larger PSF to ‘hide’ noisy modes
Reconvolution+shearing modifies the noise field.

We can mitigate by adding more noise, restoring symmetry.
Are there other useful ways to perturb the image?

\[ I'(x|e^+_{\text{PSF}}) = \Gamma^+ \left[ P^{-1} \ast I \right] \]

We tried modifying the PSF. This could allow detrending of PSF correction errors.
PSF perturbation and detrending:

KSB:

regauss:
PSF perturbation and detrending:

**moments:**
PSF perturbation and detrending:
How to calibrate blends:
How to calibrate blends:

1. Don’t deblend.

(it’s really a photo-z problem)
Correcting for selection effects:

\[
\langle R \rangle = \int \left. \frac{\partial S(e)P(e)e}{\partial \gamma} \right|_{\gamma=0} de
\]

\[
= \int \left[ S(e) \left. \frac{\partial P(e)e}{\partial \gamma} \right|_{\gamma=0} + P(e) \left. \frac{\partial S(e)}{\partial \gamma} \right|_{\gamma=0} \right] de
\]

\[
= \frac{\langle e^+_i \rangle^S - \langle e^-_i \rangle^S}{\Delta \gamma_j} + \frac{\langle e^+_i \rangle^S - \langle e^-_i \rangle^S}{\Delta \gamma_j}
\]

Apply a shear.
See how your measured shapes change.
Correcting for selection effects:

\[
\langle R \rangle = \int \left| \frac{\partial S(e) P(e) e}{\partial \gamma} \right|_{\gamma=0} \, de
\]

\[
= \int \left[ S(e) \frac{\partial P(e) e}{\partial \gamma} \bigg|_{\gamma=0} + P(e) e \frac{\partial S(e)}{\partial \gamma} \bigg|_{\gamma=0} \right] \, de
\]

\[
= \frac{\langle e_i^+ \rangle_S - \langle e_i^- \rangle_S}{\Delta \gamma_j} + \frac{\langle e_i \rangle_{S^+} - \langle e_i \rangle_{S^-}}{\Delta \gamma_j}
\]

Apply a shear.
See which galaxies enter and leave your sample.
Imperfect star-galaxy separation does not appear to bias the inference.
Peculiar Velocity Cross-Correlations

![Graph showing cross-correlations between peculiar velocities and galaxy density](image)