WEAK LENSING
THE NEXT GENERATION

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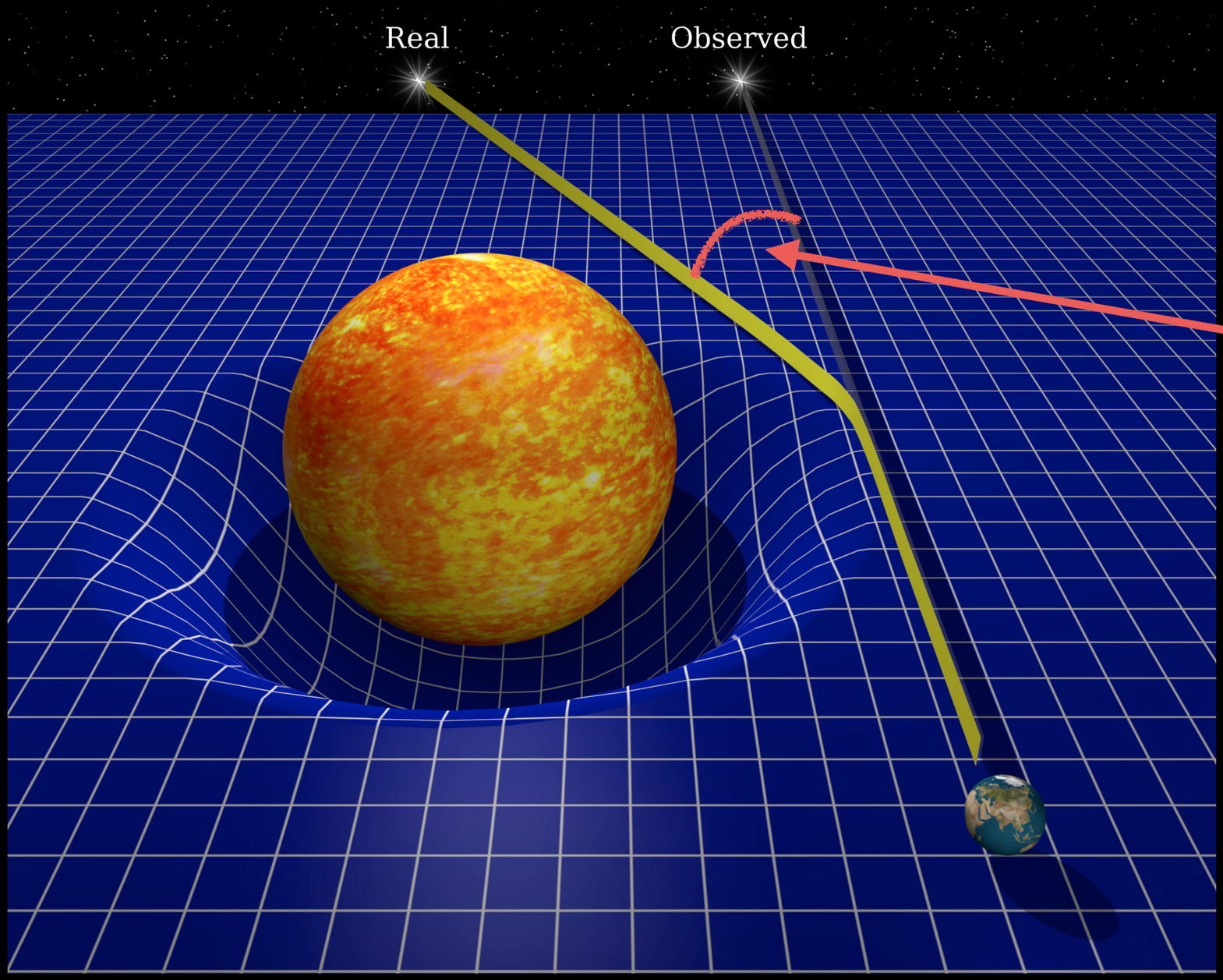
What I’m going to talk about:

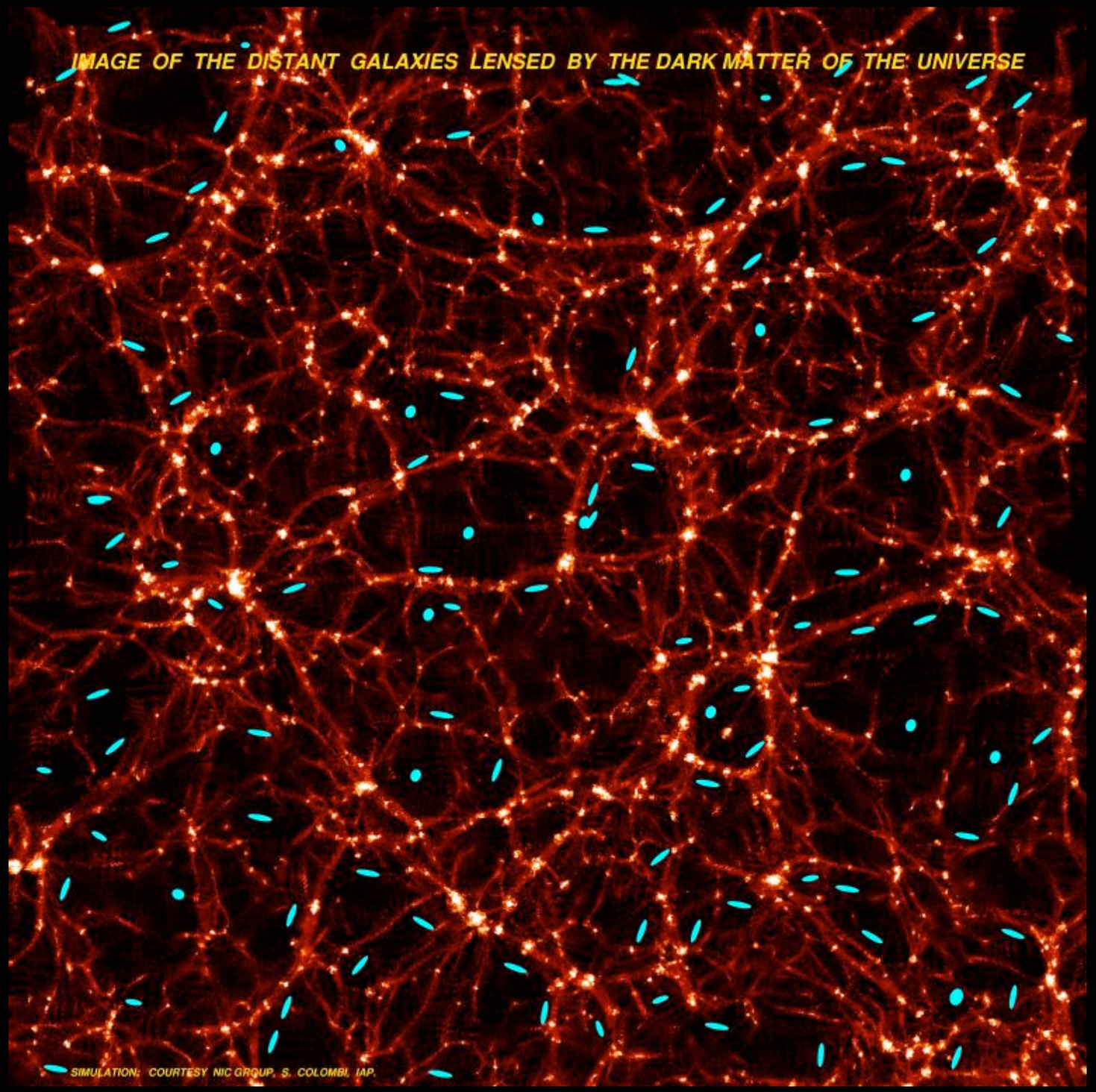
1. Lensing measurement:
    - why it’s hard
    - how to solve it
2. Lensing from galaxy kinematics
    - how it works
    - how I’m hoping to measure it

Lensing is sensitive to both growth and geometry:



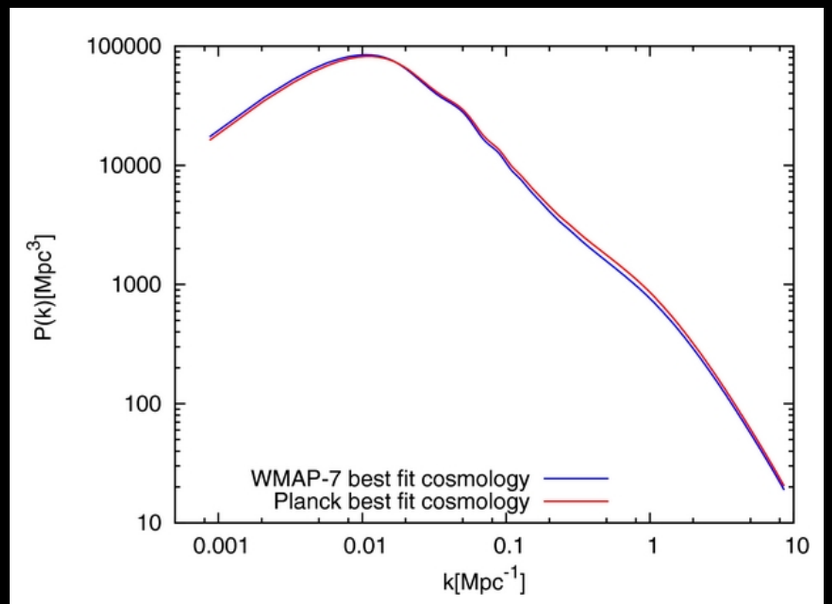
lens **mass** and **distances** modify deflection angle

Weak lensing is a key probe of the growth of structure.



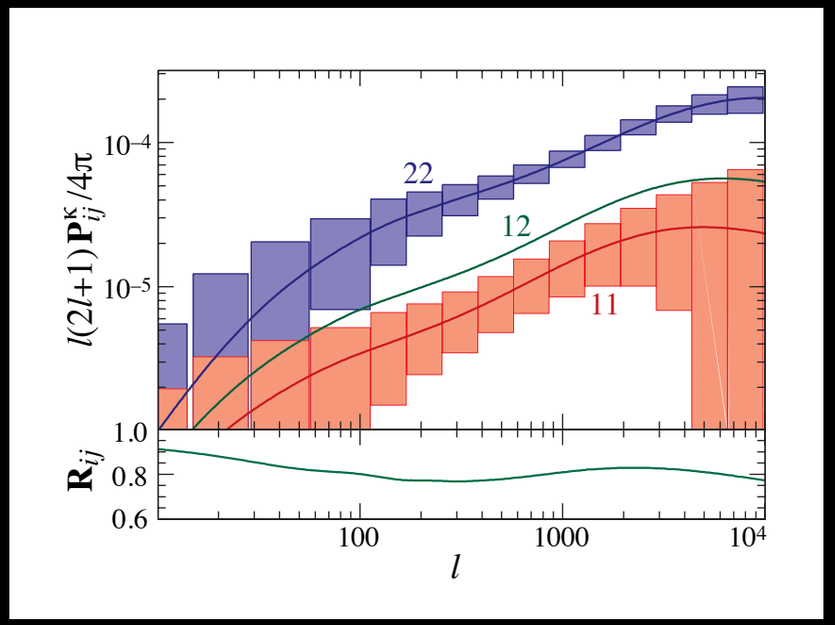
Galaxy shape and matter fluctuations are correlated by lensing.

Matter Power Spectrum



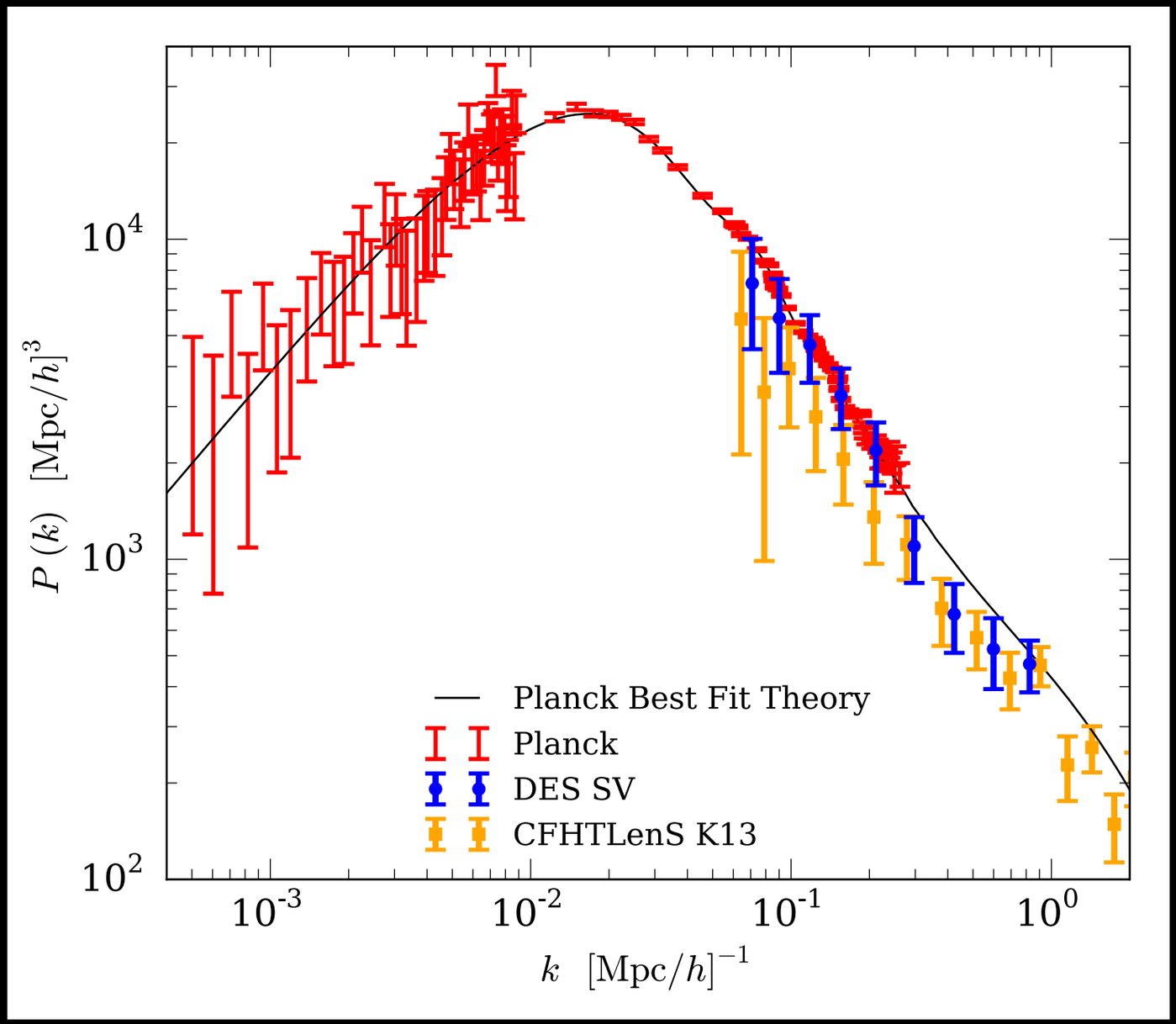
- Well understood dependence on cosmological parameters
- ‘Sharp’ features (e.g., BAO)

Galaxy Shear Power Spectrum



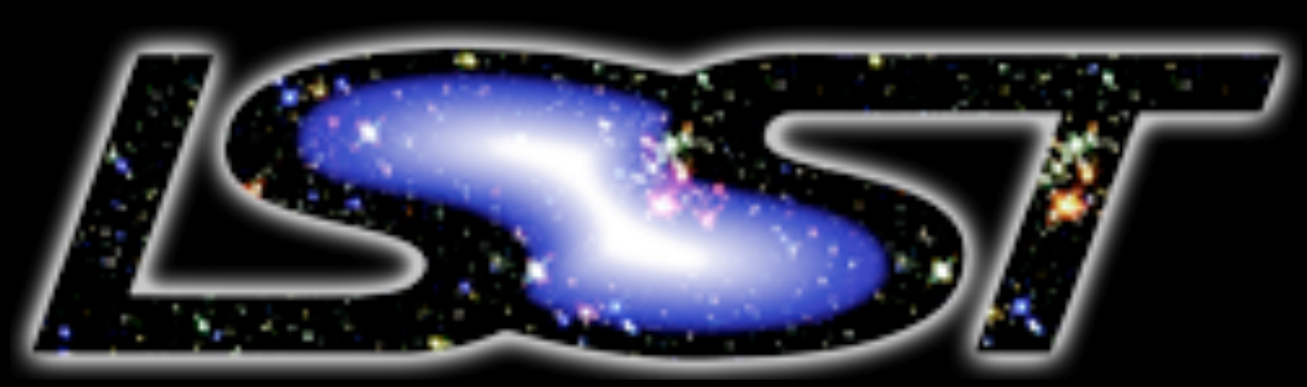
- Smooth in scale and redshift
- Weak, hard to measure
- …but observable

Understanding the physics of cosmic acceleration requires measuring the growth of structure.

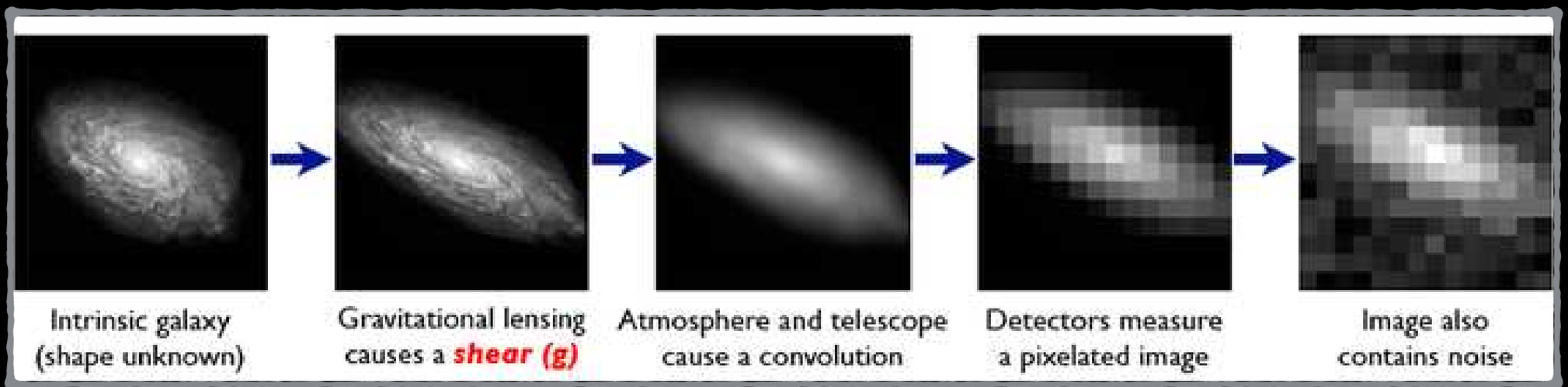


Key signature: disagreement between early-time forecasts and late-time structure measurements

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.



Bridle et al. 2008

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

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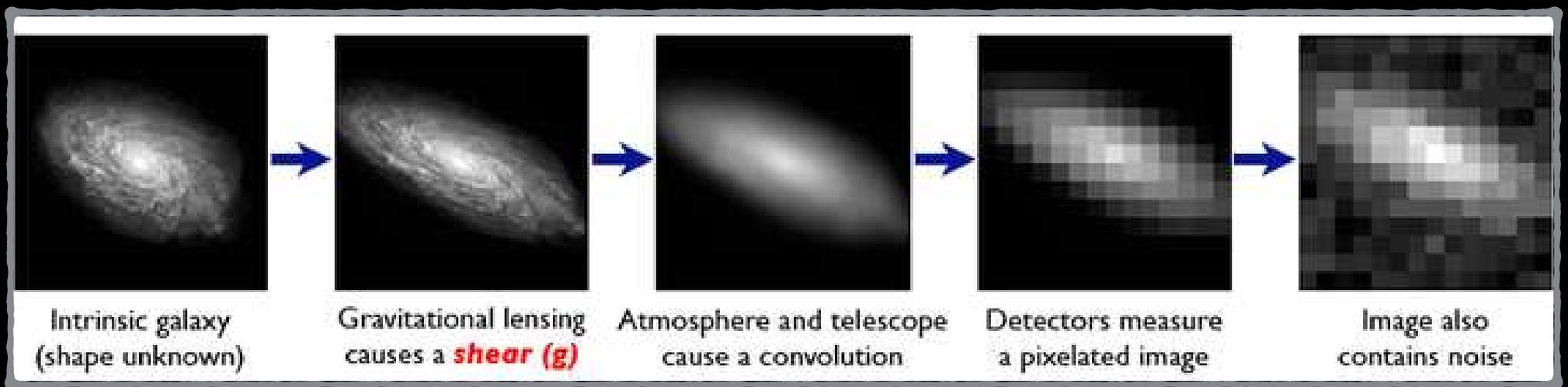

Bridle et al. 2008

linear(ized) remapping of the image

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

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

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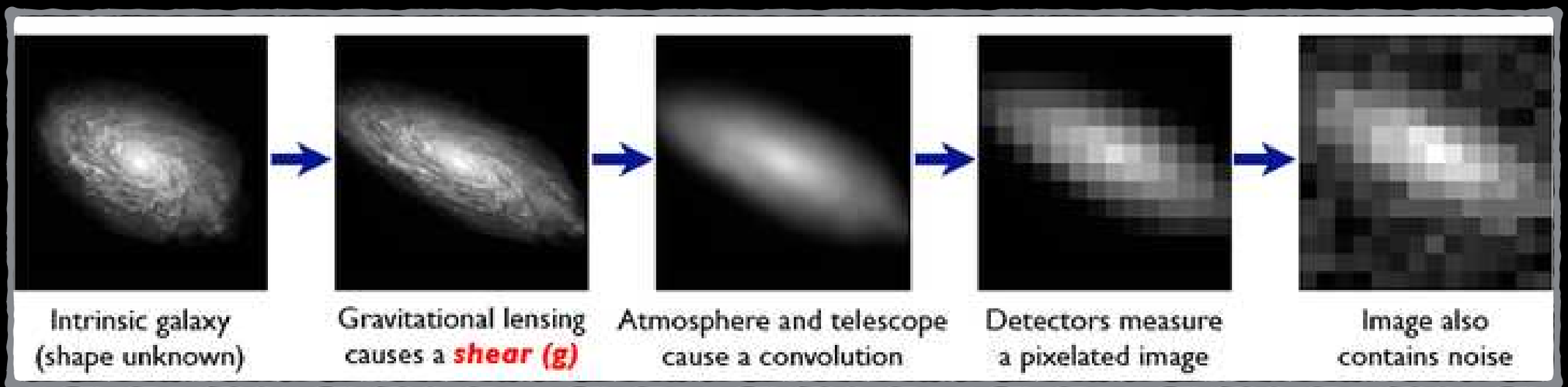

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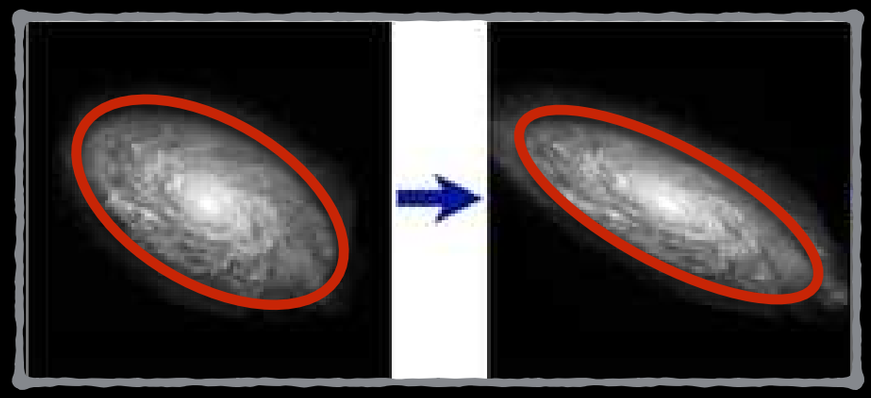
we usually re-parameterize with *g*

$$g = \frac{\gamma}{1-\kappa}$$

How do we get g from a galaxy image?



ellipticity suggests 2nd moments

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

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

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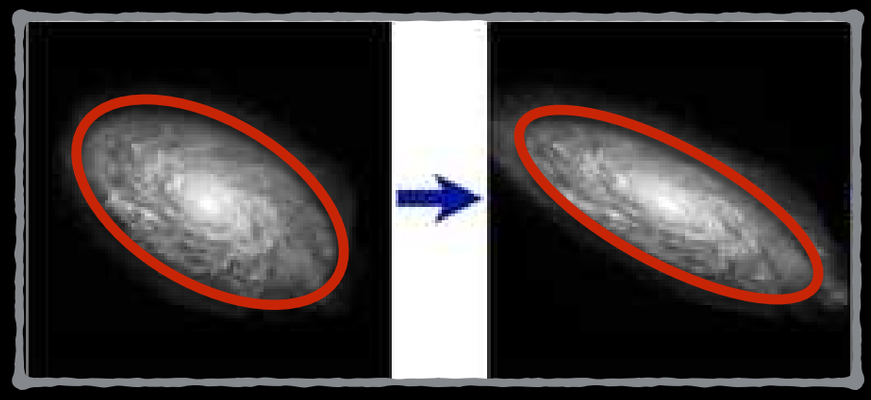

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g and χ are related...

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

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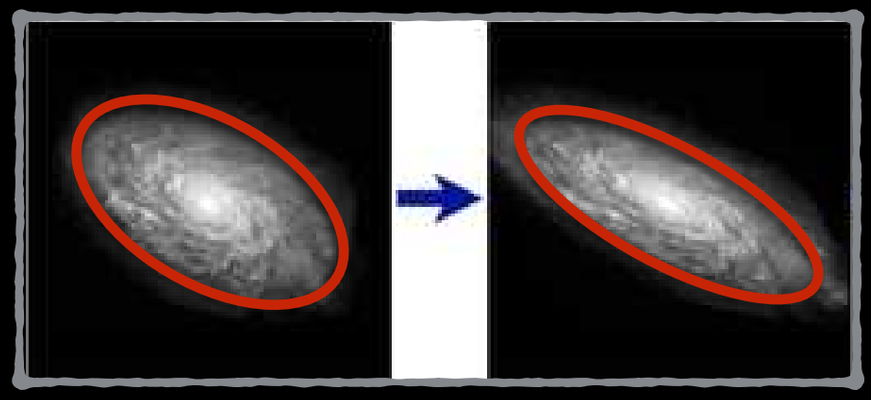

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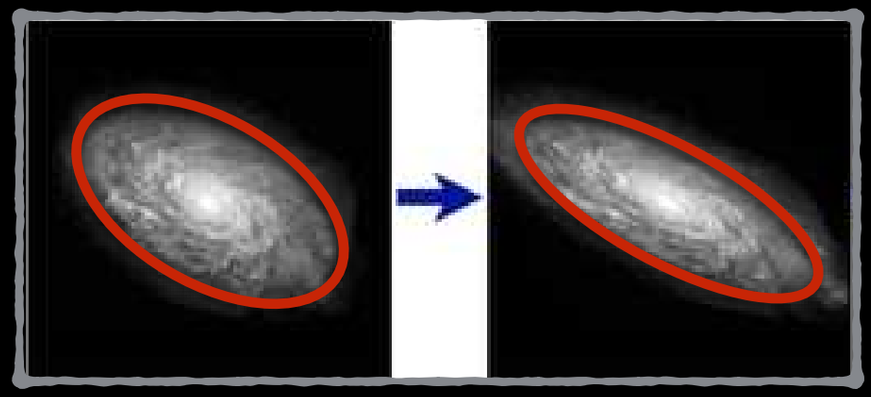
g and χ are related...

...but in a way that depends on the ensemble.

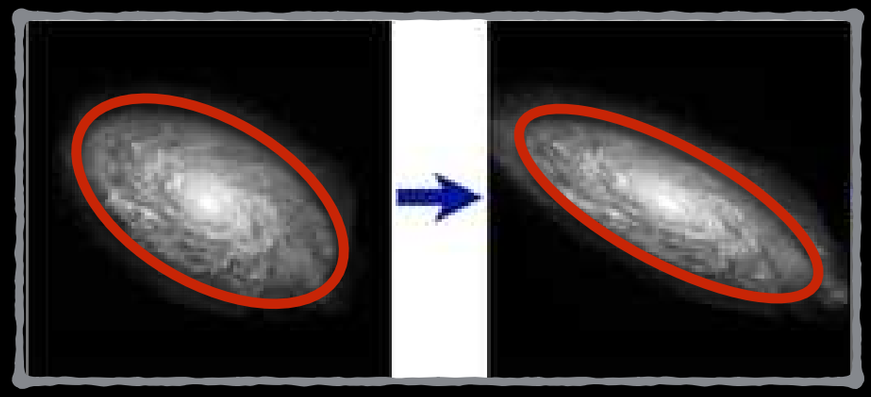
How do we get g from a galaxy image?



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

preferred direction

How do we get g from a galaxy image?



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

calibration

bias

(what all the fuss is about)

Kaiser, Squires, Broadhurst (1995)

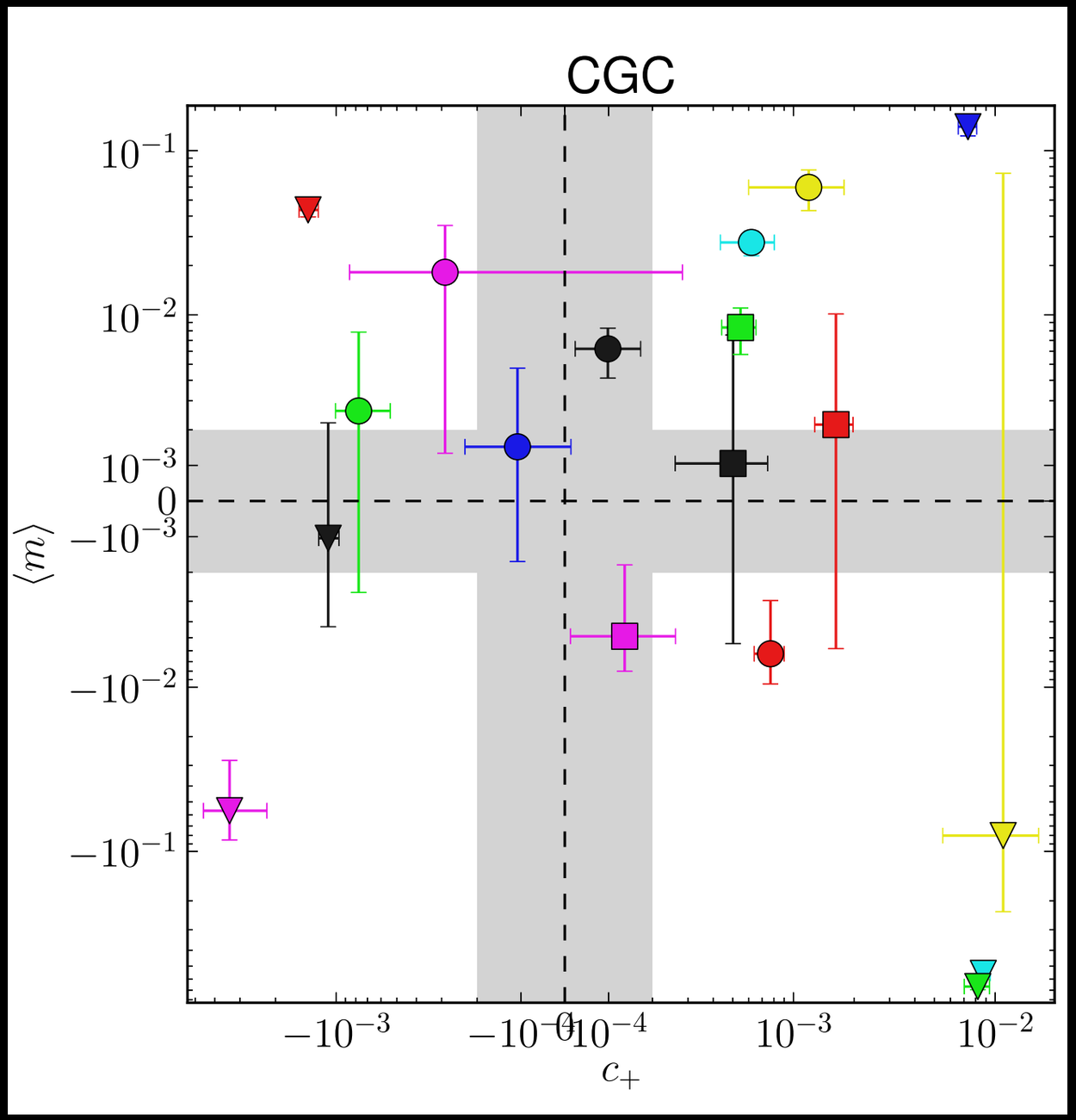
1. Compute second moments.
2. Calculate the responses to shear (P_g) and PSF ellipticity (P^{sm}).
3. Correct for PSF ellipticity (e^*).

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

This doesn’t seem that bad.

Mandelbaum et al. 2014

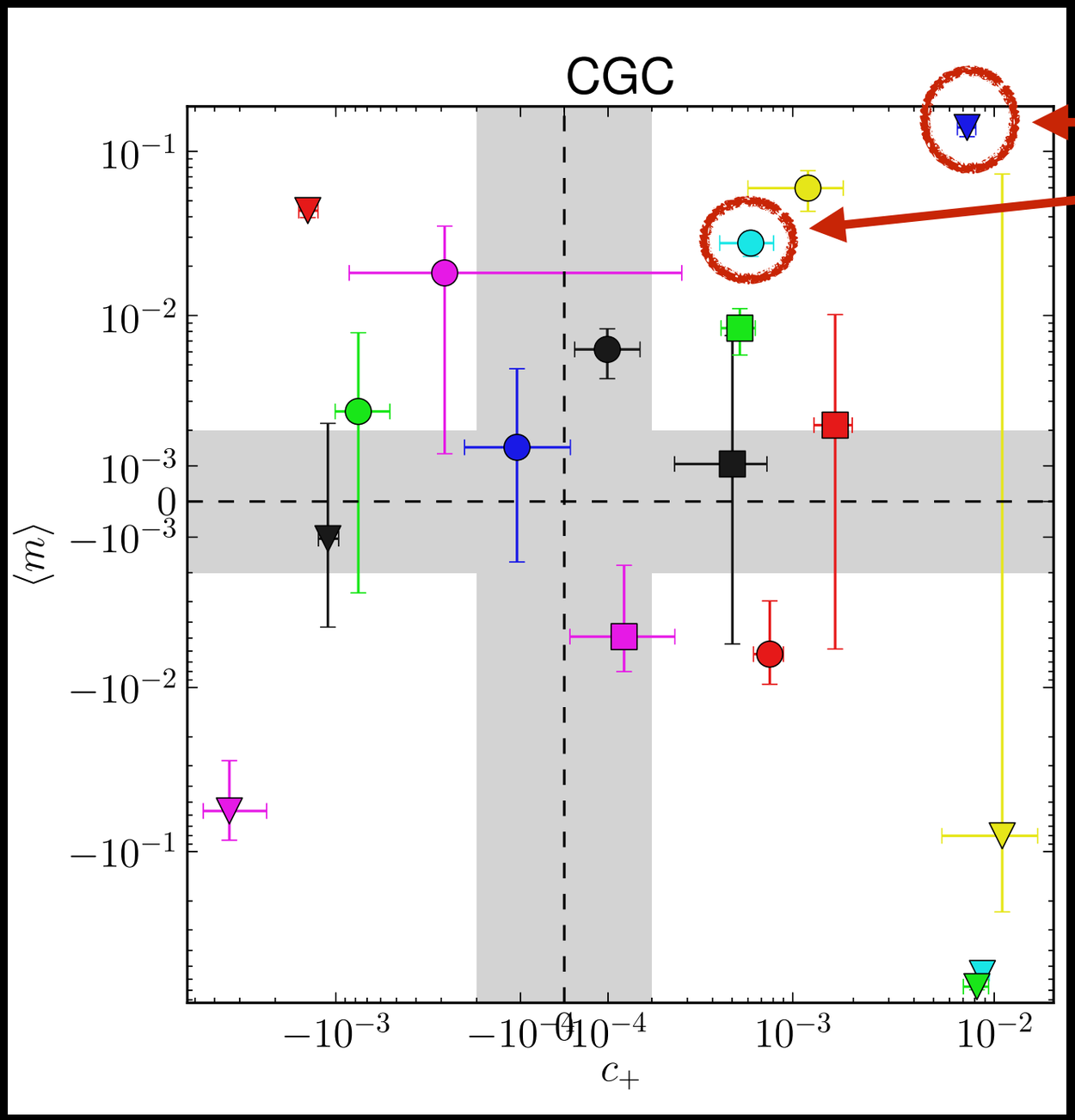
GREAT3 Shear Calibration Community Challenge



Alas, still broad dissensus in lensing results.

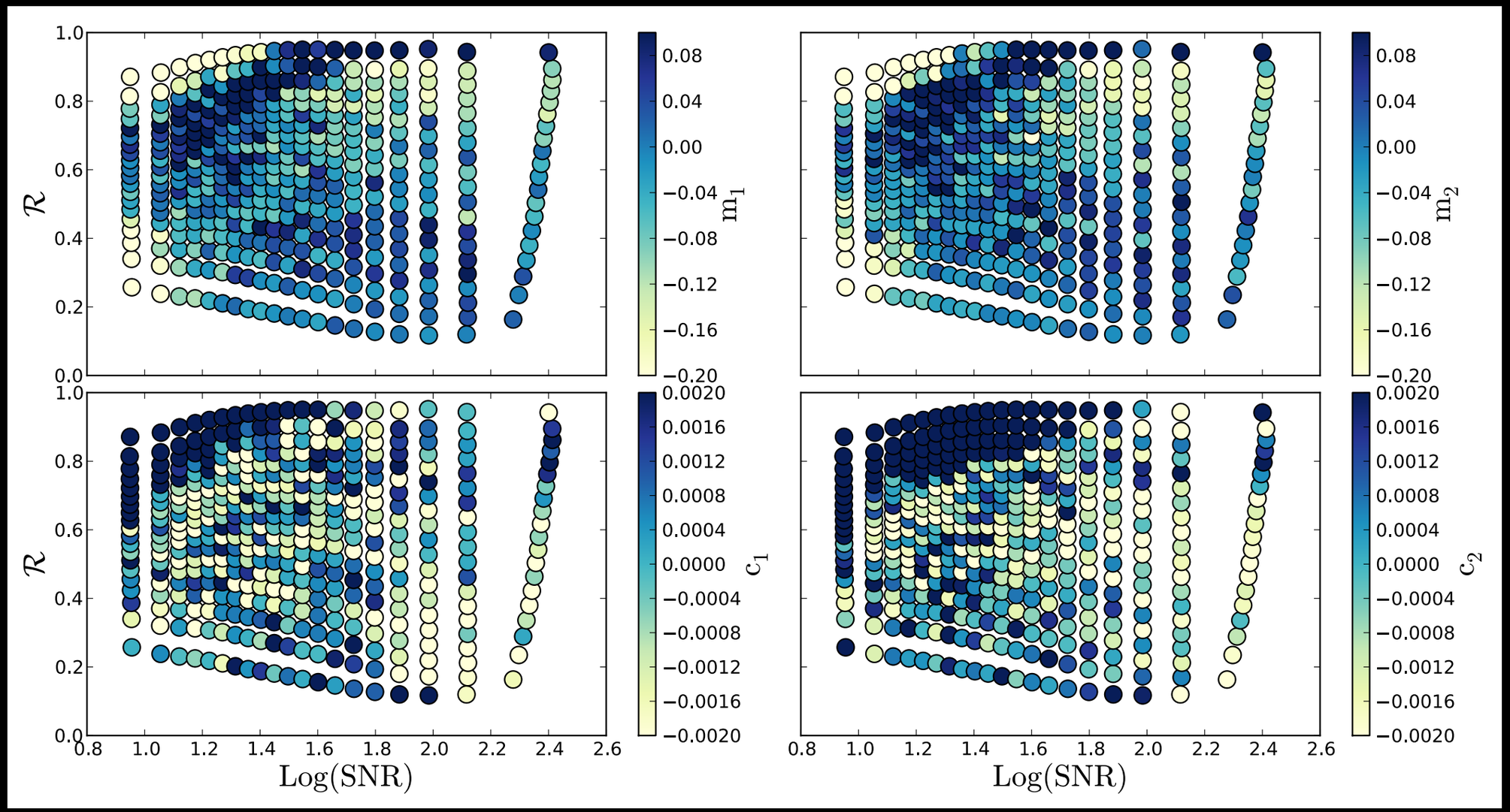
Mandelbaum et al. 2014

GREAT3 Shear Calibration Community Challenge



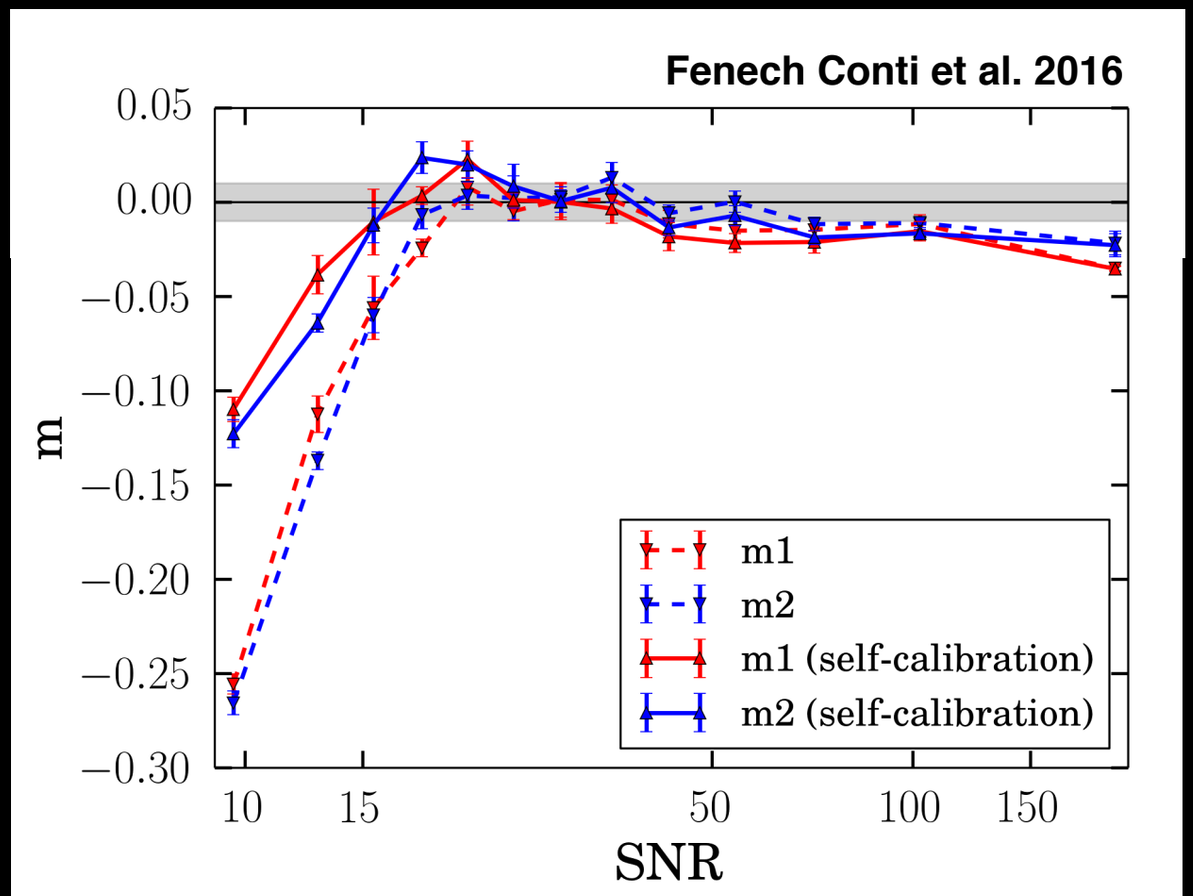
Alas, still broad dissensus in lensing results.

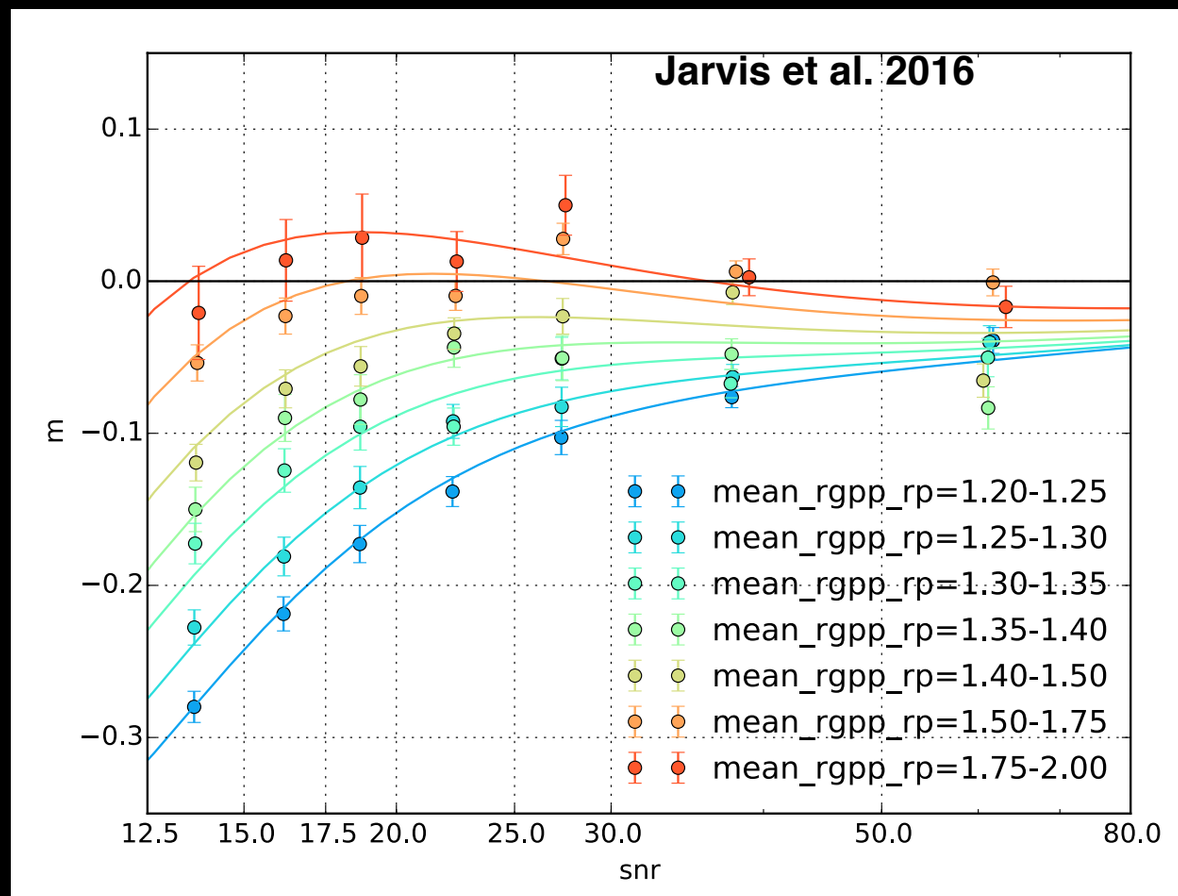
Shear measurement biases have complex dependencies on galaxy properties.



Fenech Conti et al. 2016

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.

$$I'(\mathbf{x}|\mathbf{g}) = P * (\hat{\mathbf{s}}_{\mathbf{g}} G)$$

We will construct counterfactual images.

$$I'(\mathbf{x}|\mathbf{g}) = P * (\hat{\mathbf{s}}_{\mathbf{g}} G)$$

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

remove the PSF, shear, and add a new PSF

We will construct counterfactual images.

$$I'(\mathbf{x}|\mathbf{g}) = P * (\hat{\mathbf{s}}_{\mathbf{g}} G)$$

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

we get to choose our final PSF

We will construct counterfactual images.

$$I'(\mathbf{x}|\mathbf{g}) = P * (\hat{\mathbf{s}}_{\mathbf{g}} G)$$

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

$$e^+ = \hat{E}\{\, I'(\boldsymbol{x}|\boldsymbol{g}^+)\}$$

any ~linear measurement algorithm

We will construct counterfactual images.

$$I'(\mathbf{x}|\mathbf{g}) = P * (\hat{\mathbf{s}}_{\mathbf{g}} G)$$

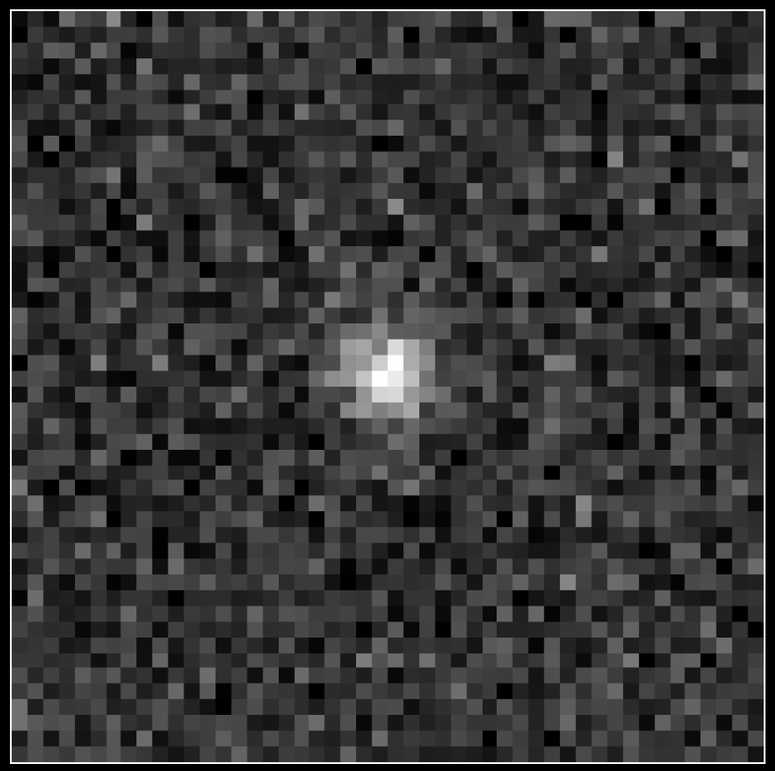
$$I'(x|g) = \Gamma * \left[\hat{s}_g (P^{-1} * I)\right]$$

$$e^+ = \hat{E}\left\{ I'(\boldsymbol{x}|\boldsymbol{g}^+)\right\}$$

$$1 + m = \frac{e^+ - e^-}{2\Delta g}$$

repeated measurement on counterfactuals

This is what it looks like in practice.



original data

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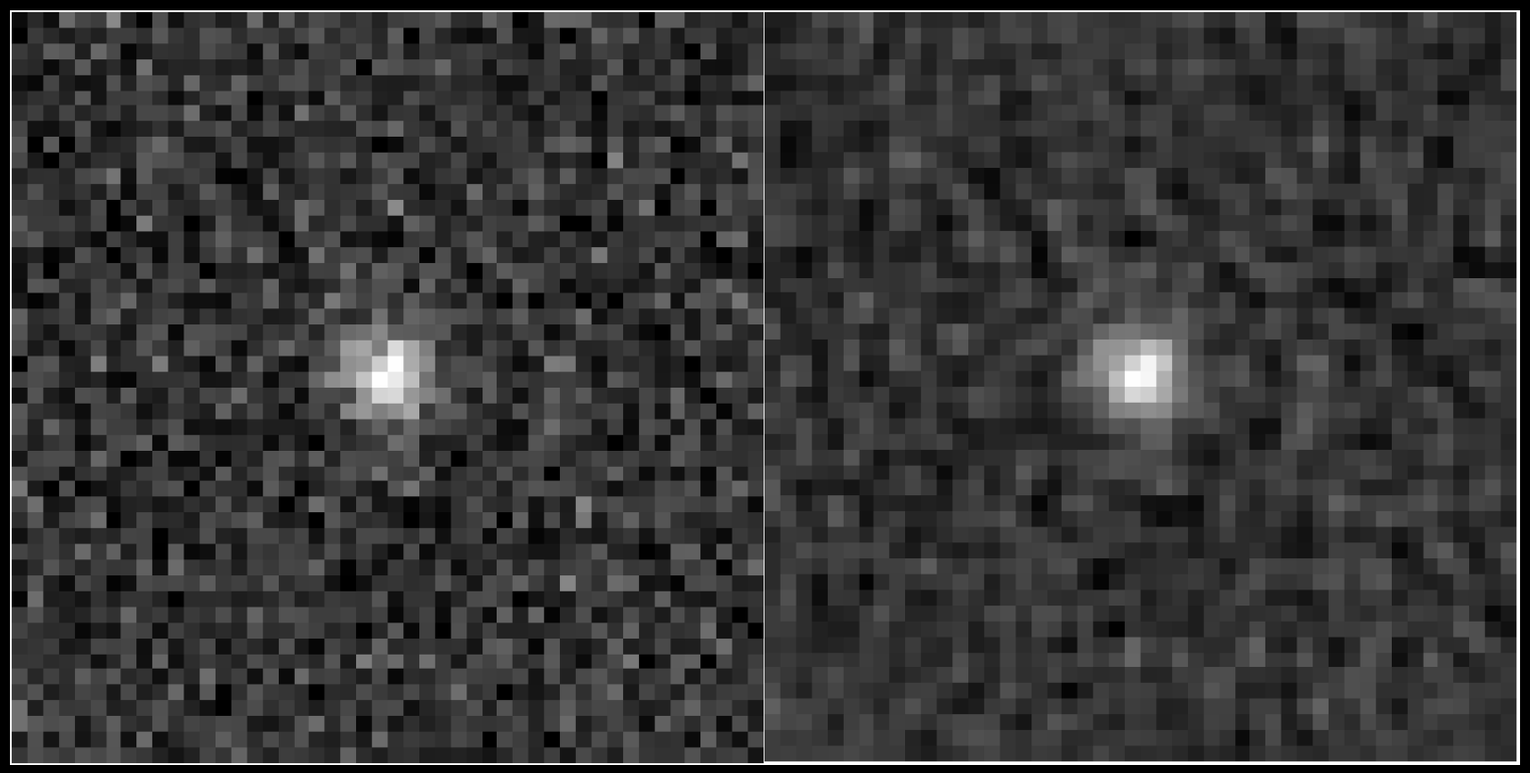
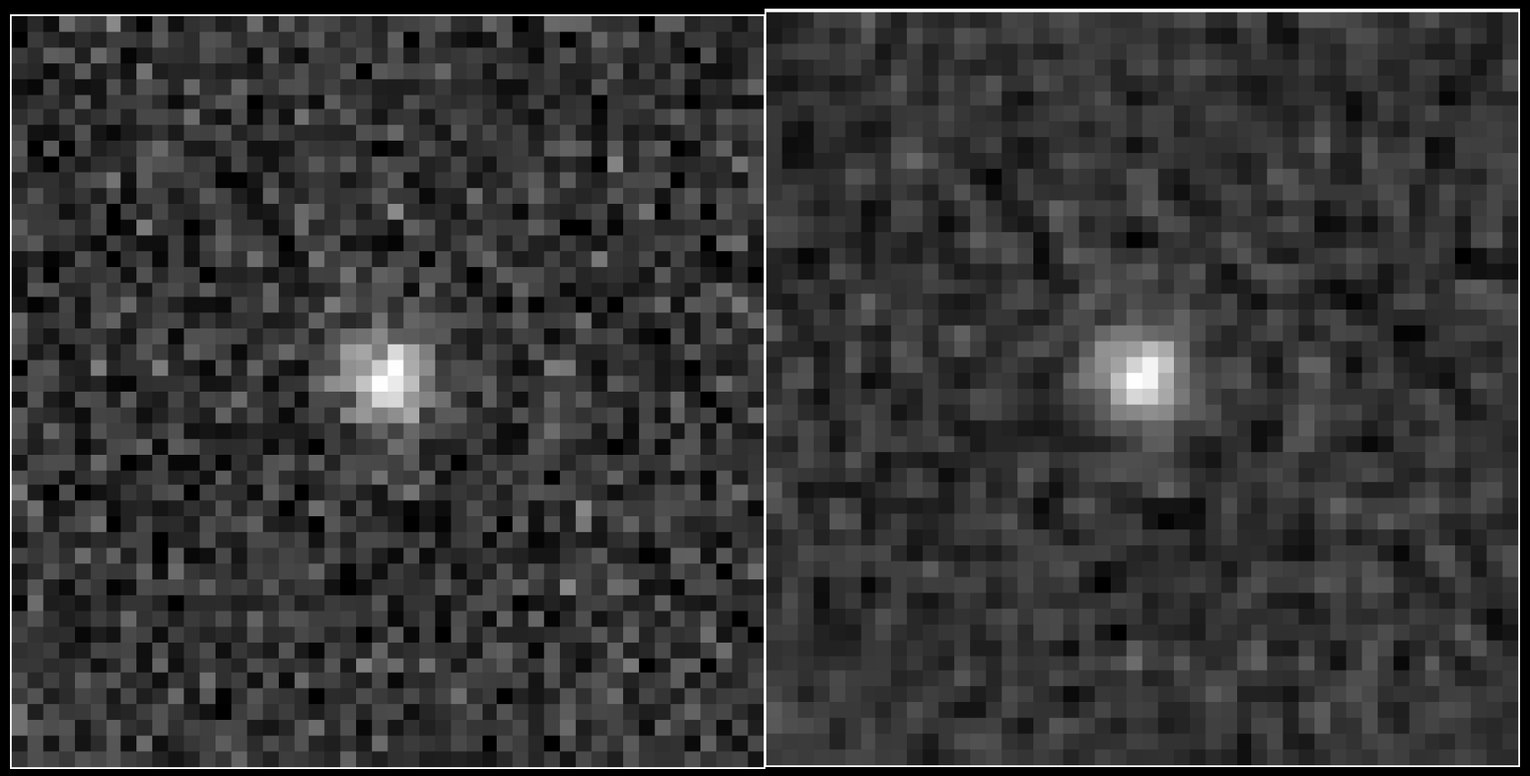


sheared, reconvolved
(1% shear)

Make measurement on unsheared counterfactual with reconvolved PSF



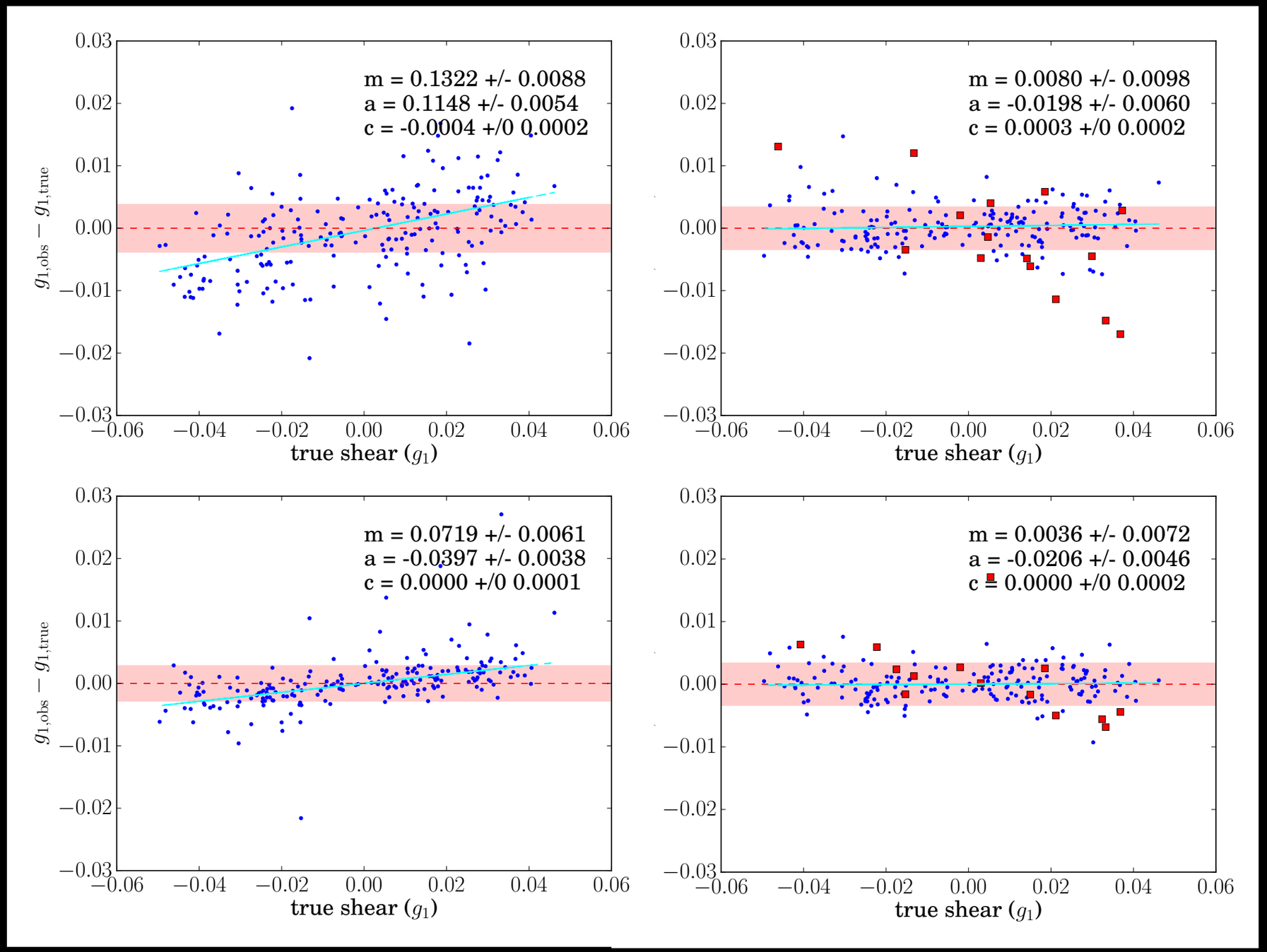
unsheared, reconvolved

To validate, we test on image simulations.

Starting with GREAT3 analogues.

We wrapped Metacalibration around several measurement algorithms.

KSB:



regauss:

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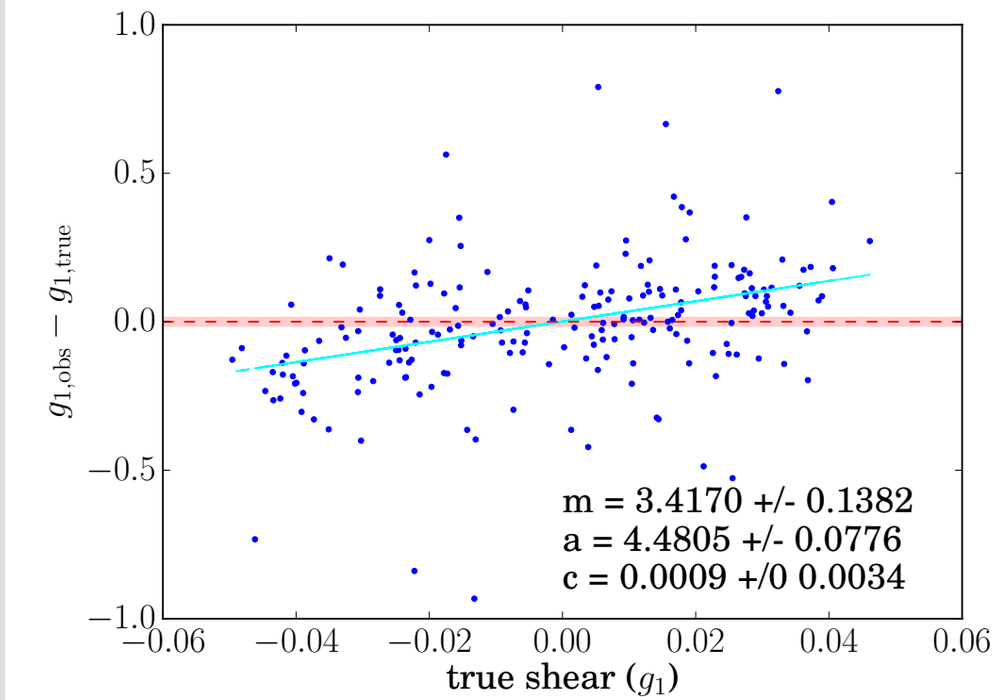
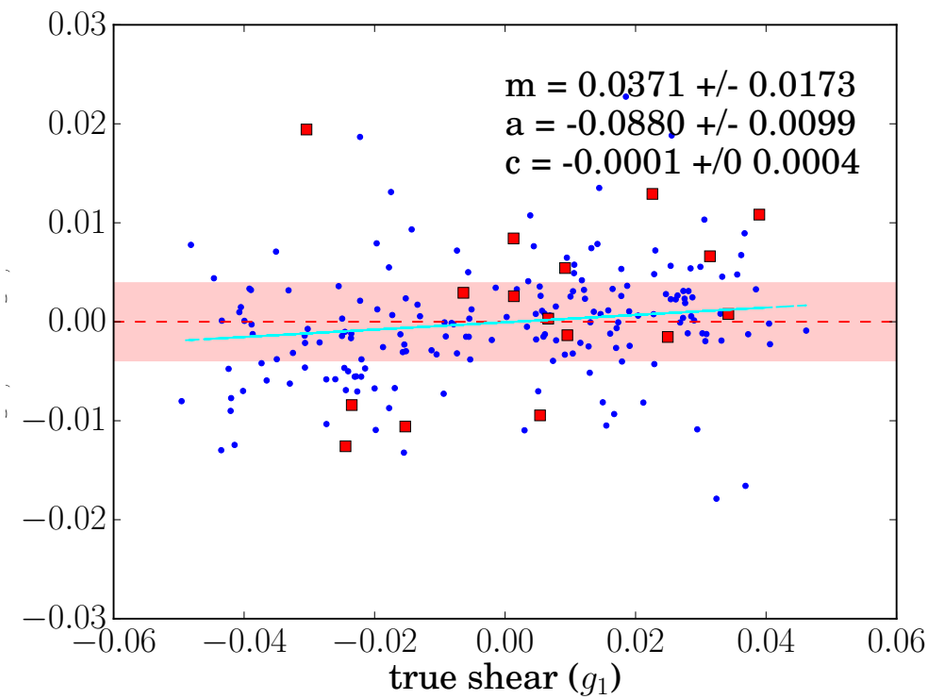




$$M_{ij} = \frac{\int (x_i - \langle x_i \rangle)(x_j - \langle x_j \rangle) w(\mathbf{x}) I(\mathbf{x}) \mathrm{d}^2\mathbf{x}}{\int w(\mathbf{x}) I(\mathbf{x}) \mathrm{d}^2\mathbf{x}}$$

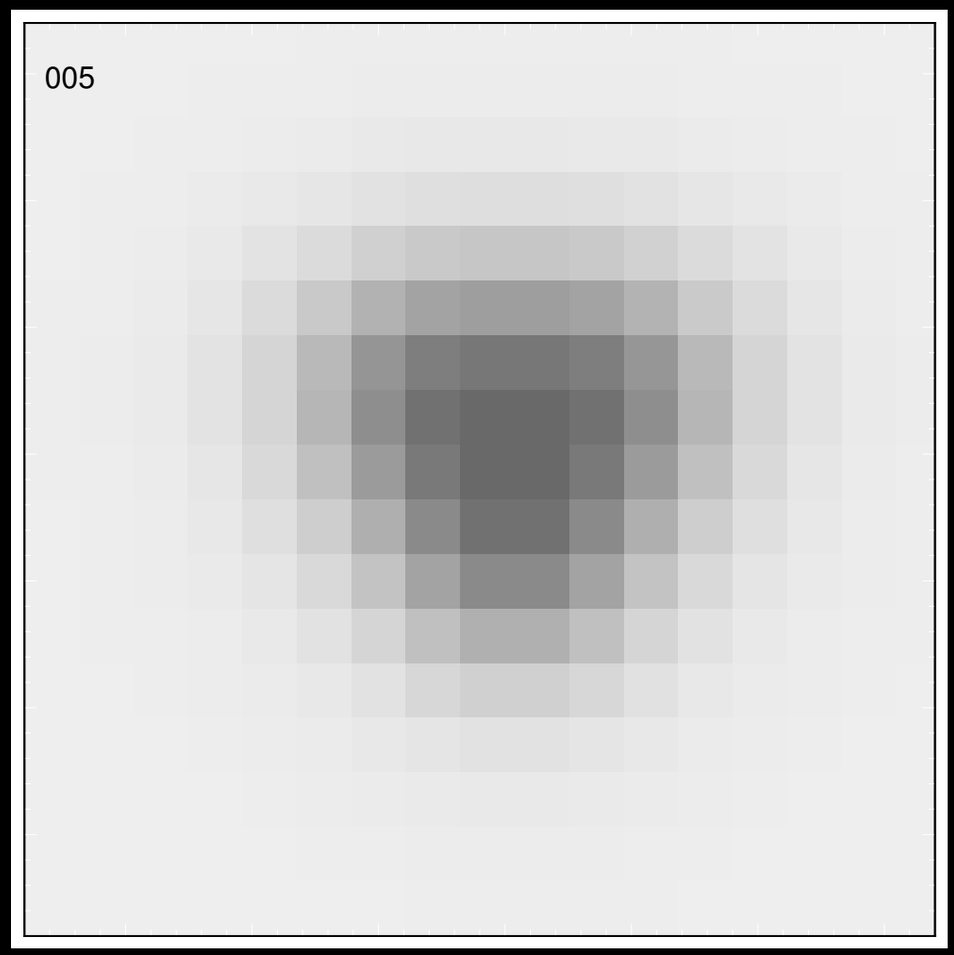
$$e_1 = \frac{M_{11} - M_{22}}{M_{11} + M_{22}}, \qquad e_2 = \frac{2M_{12}}{M_{11} + M_{22}}.$$

$$\hat{M}_i = (M_{11} - M_{22}, 2M_{12}).$$

...including uncorrected second moments, which should not work at all.

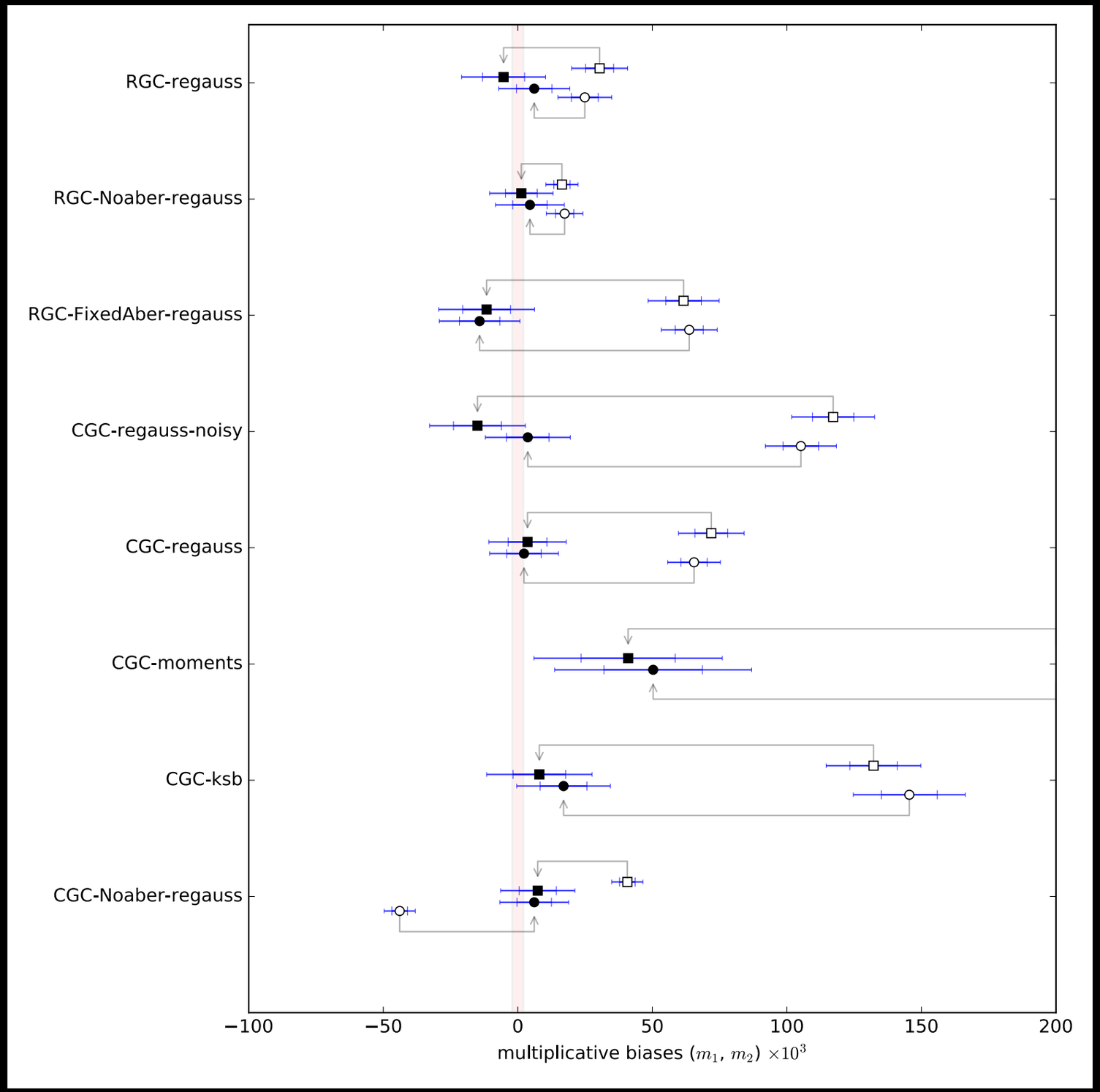
We ran many simulations, varying the complexity

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

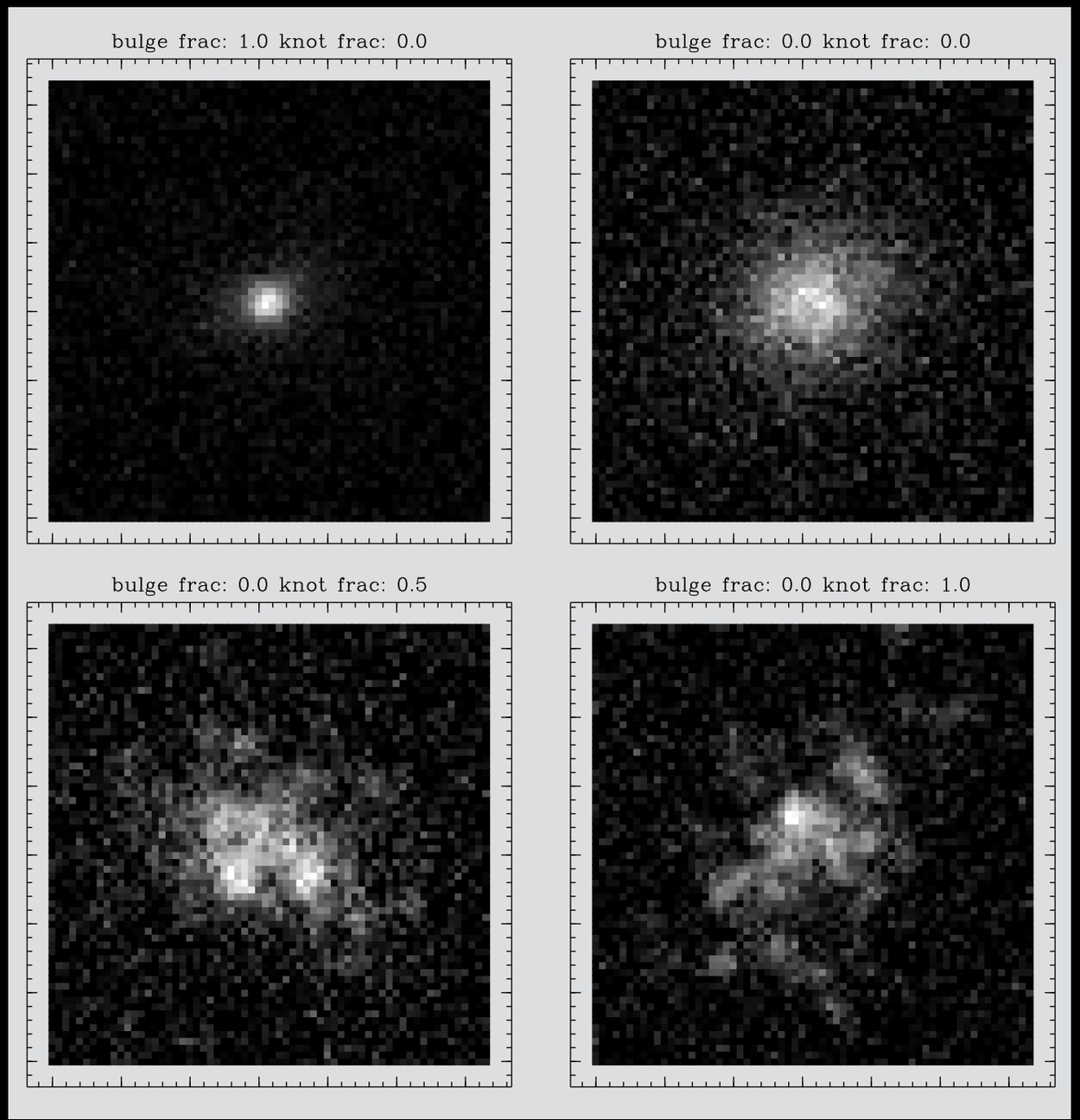


Huff & Mandelbaum 2017

Where the algorithms are correctable, MetaCal calibrates them.



Parallel collaboration with Erin Sheldon: pushing Metacalibration's limits



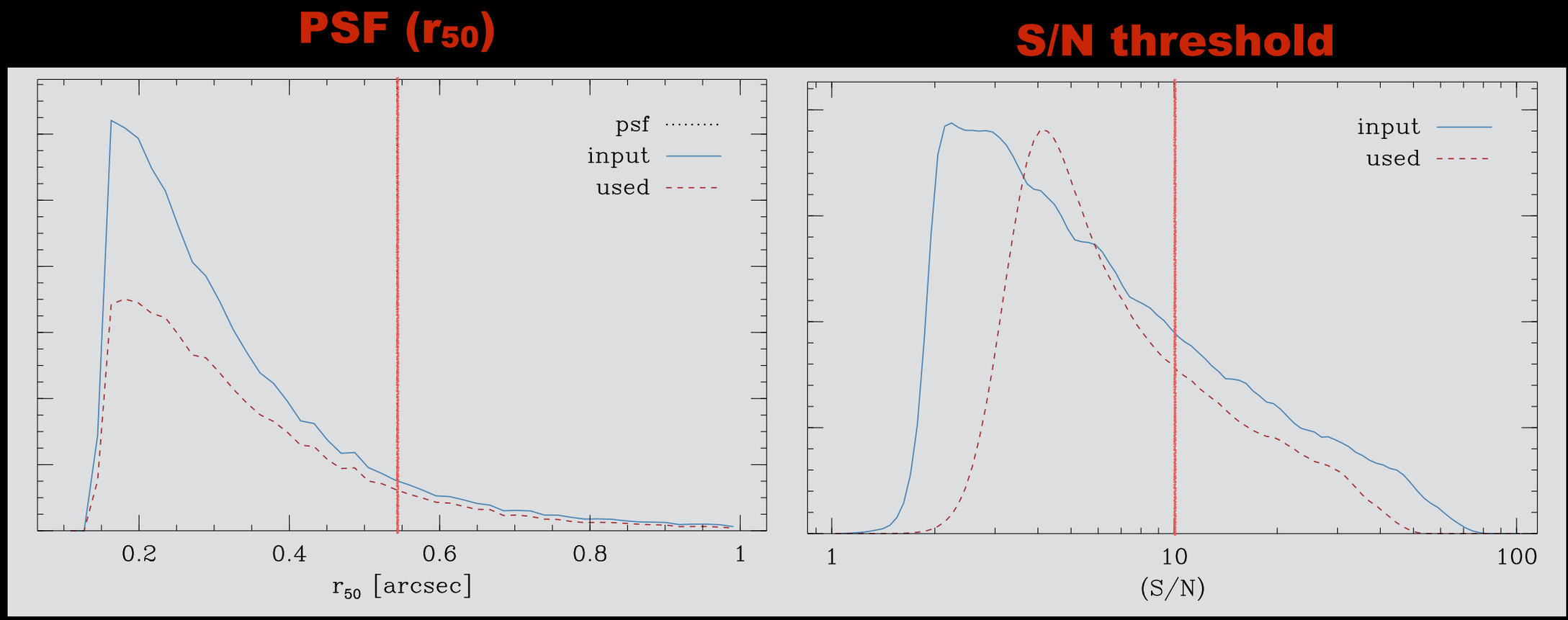
BDK+ Simulations:

Much larger simulation volume ($5x10^9$)
Bulge+Disk+knots
realistic size/flux distribution (COSMOS)
stellar contamination
full Dark Energy Survey PSF
Large sub-threshold population (low S/N)

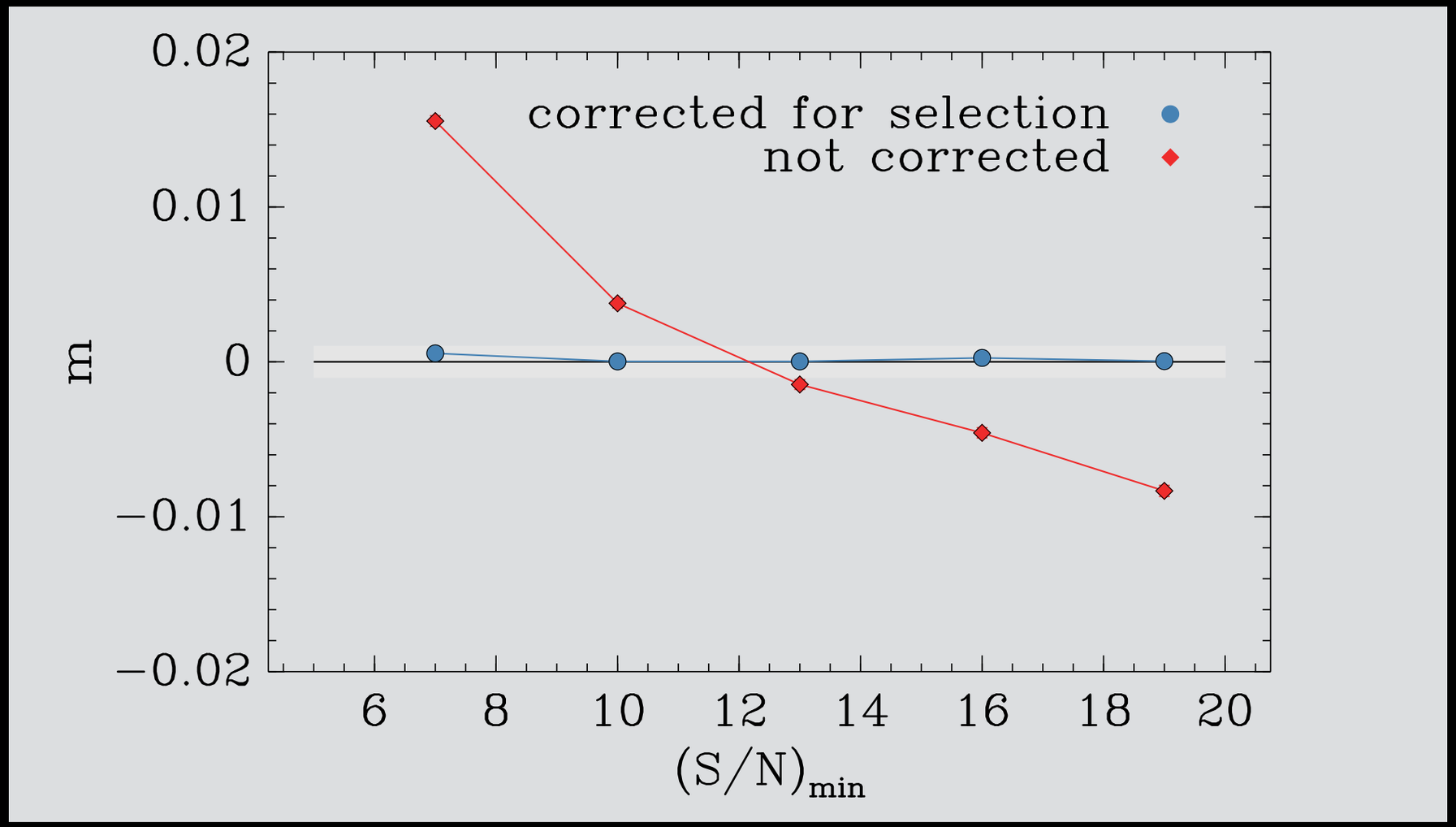
Simplified Measurement:

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.



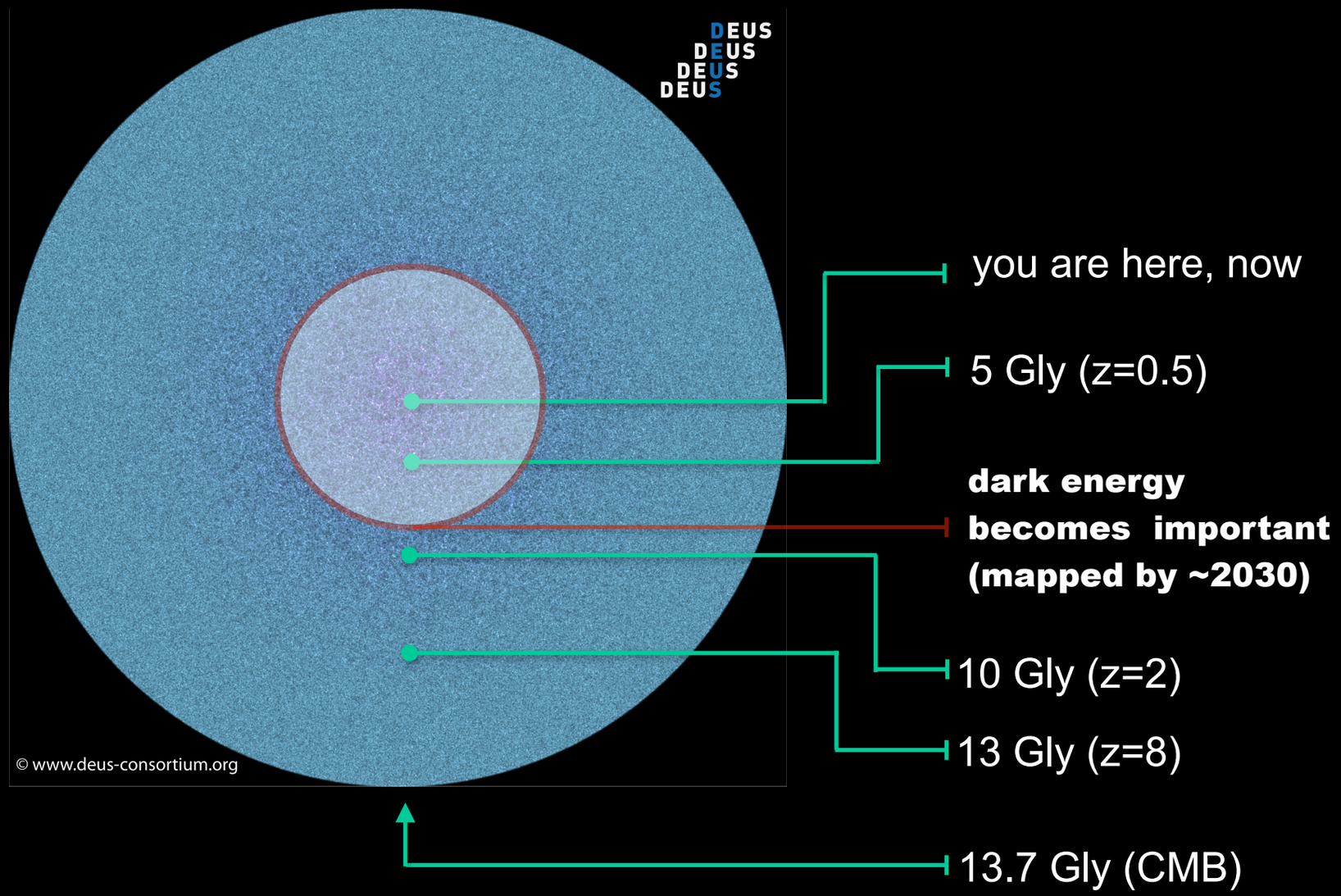
Selection effects are large, but now effectively mitigated.



There is no evidence for any remaining calibration bias.

Future problems

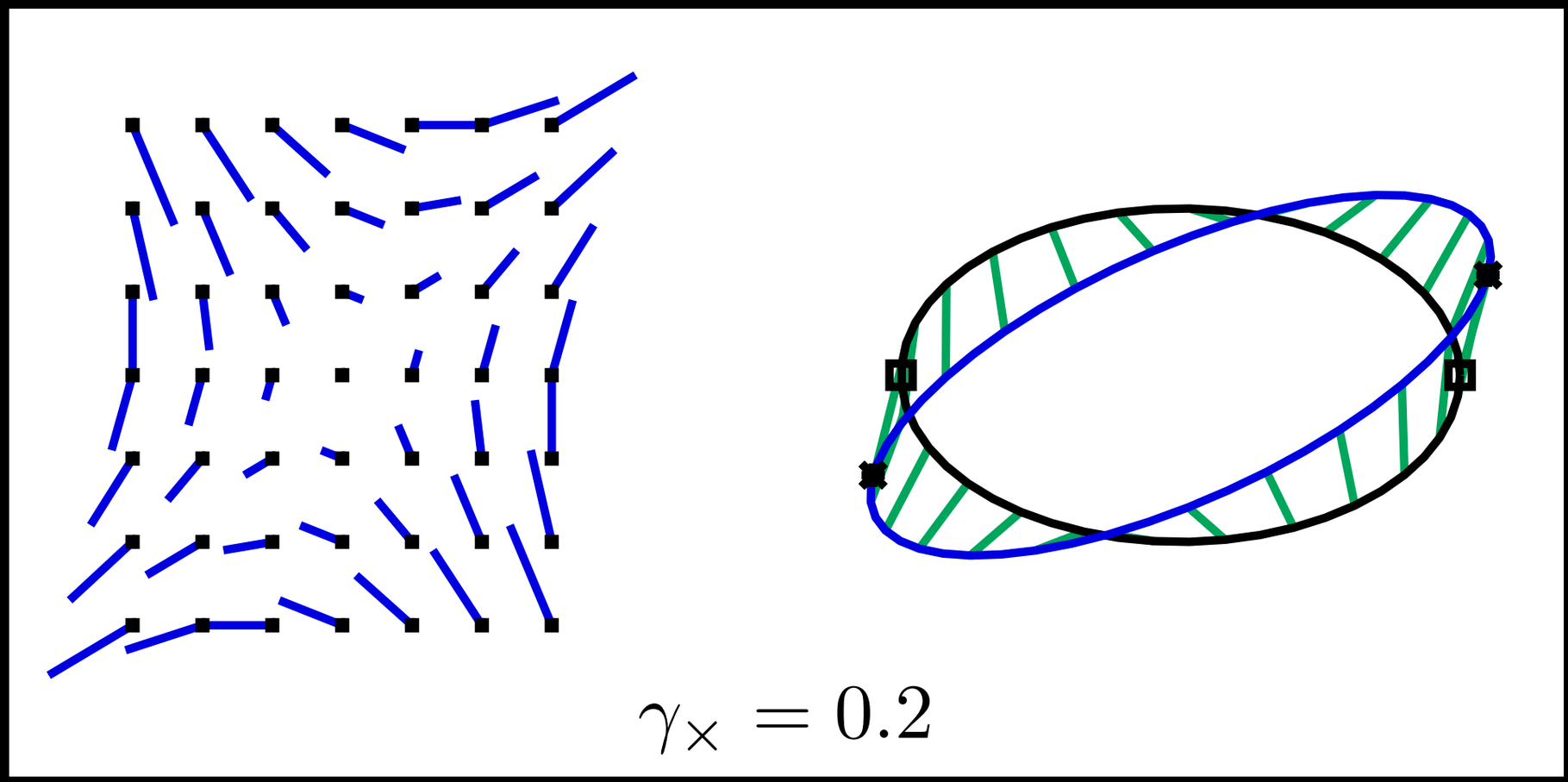
We will soon run out of universe for dark energy measurements.



It is unlikely that we will have solved everything by then.

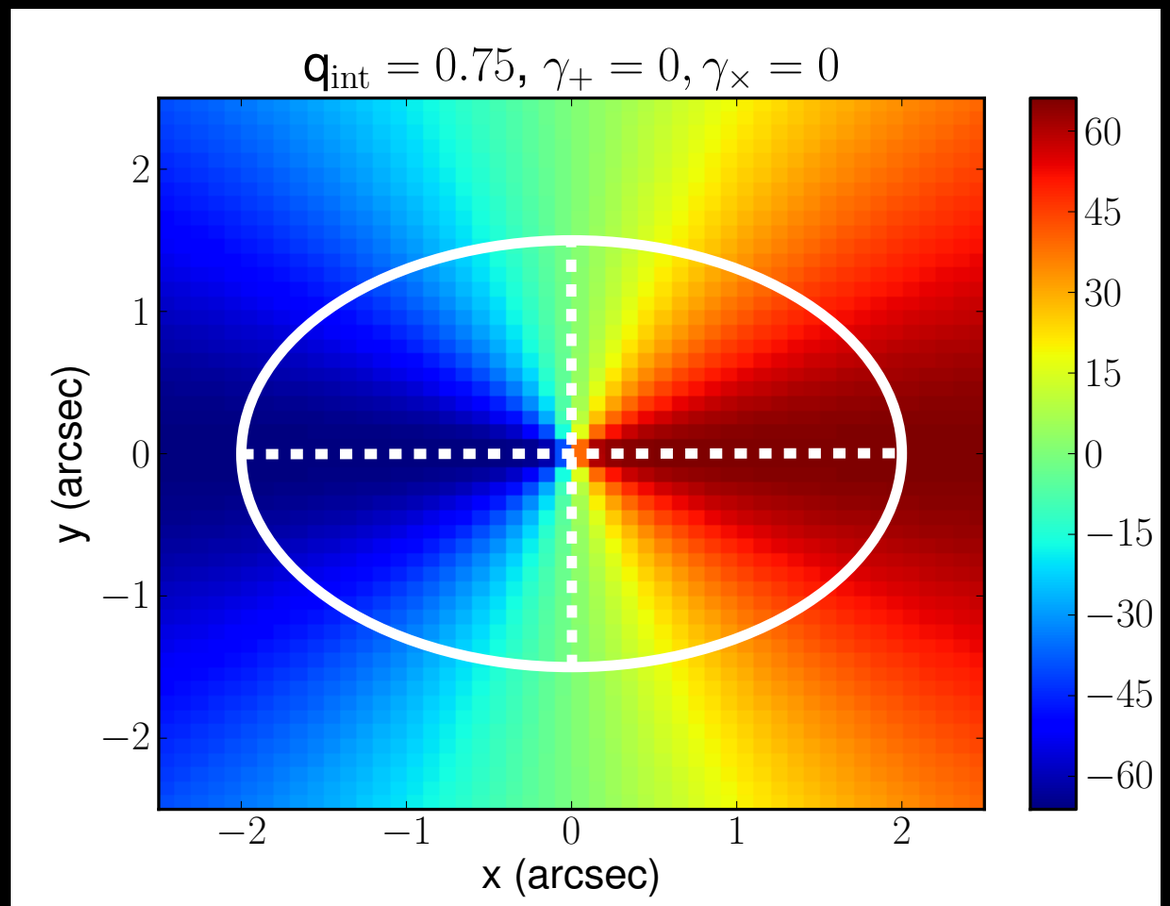
If we cannot find more galaxies,
we need more information per galaxy.

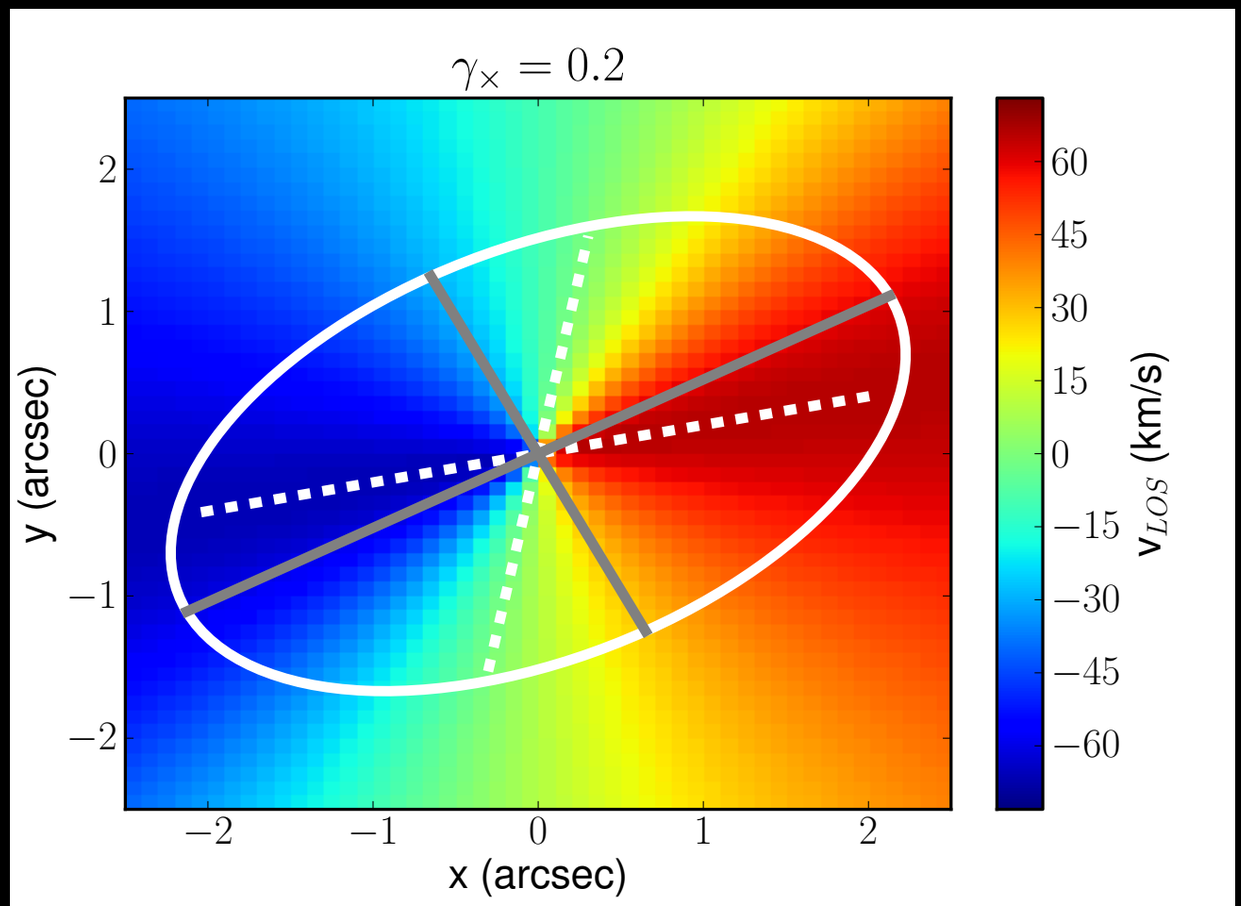
Shear changes the orientation of an ellipse



But shear has no solid-body rotation component.

Lensing *mis-aligns* the kinematic and photometric axes





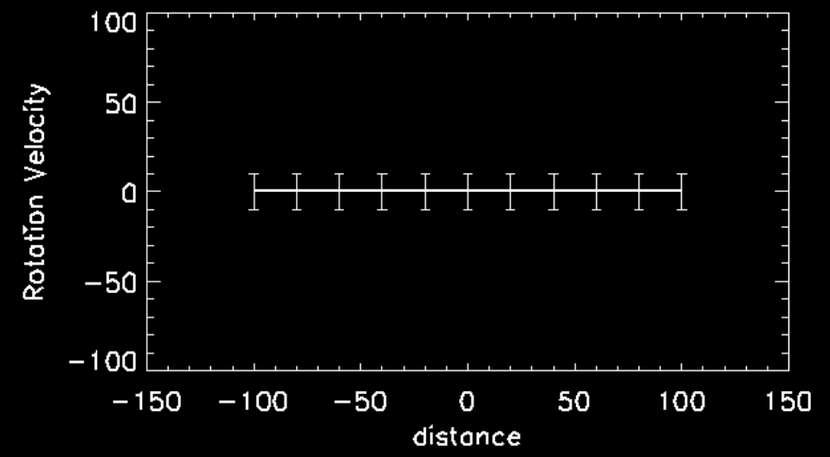
With spectroscopic maps, this should be detectable.

Kinematics break degeneracy between shape and shear

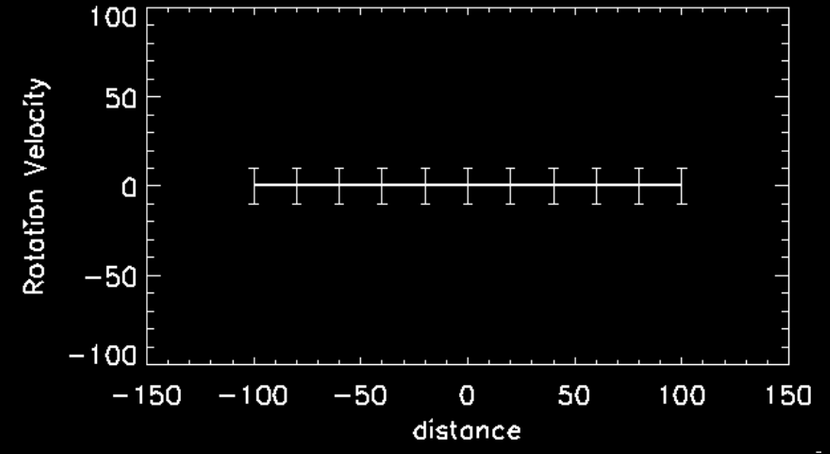
<u>image</u>

<u>rotation curve</u>

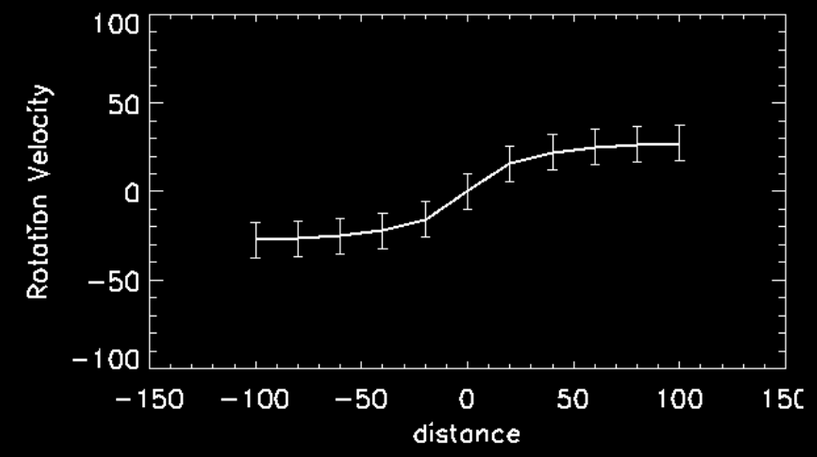
face-on



face-on, but sheared



inclined, but not sheared



Consider the Tully-Fisher relation.

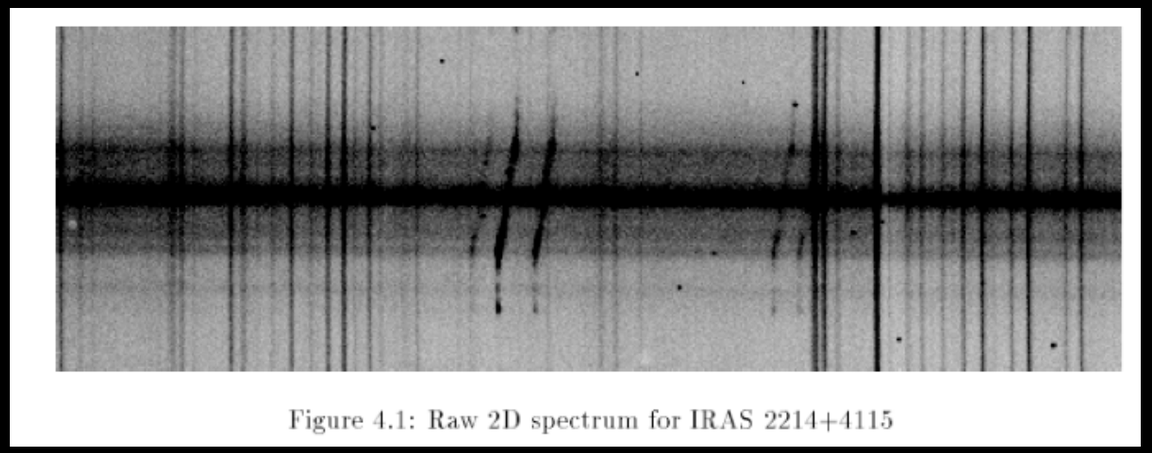
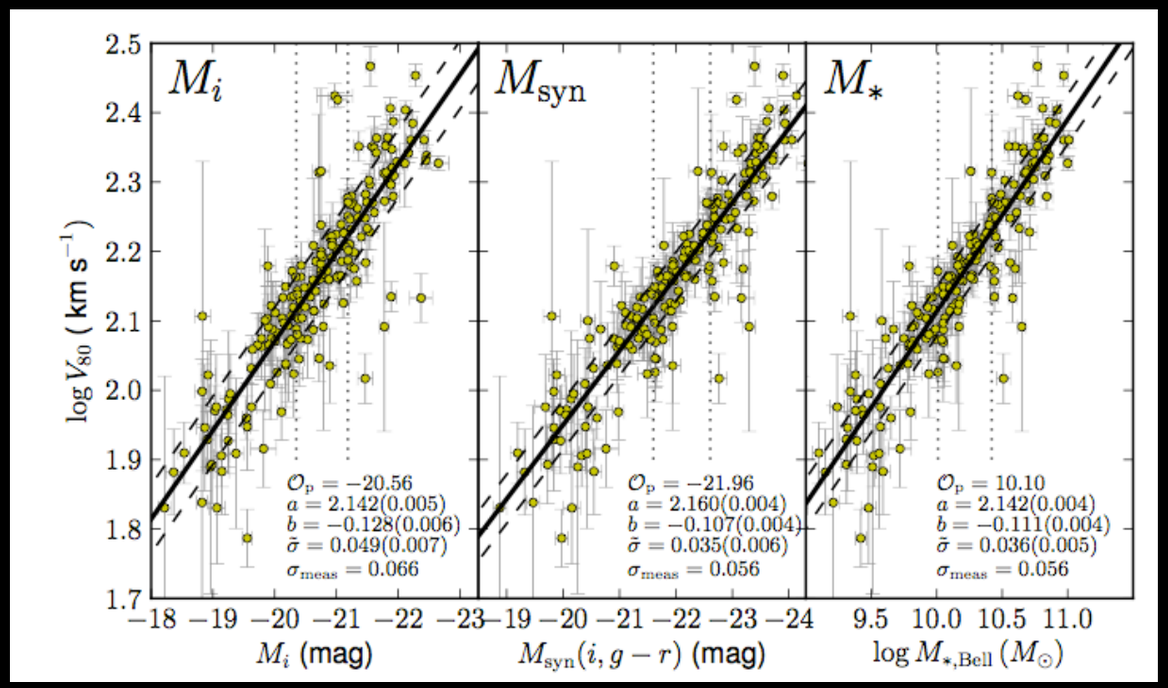
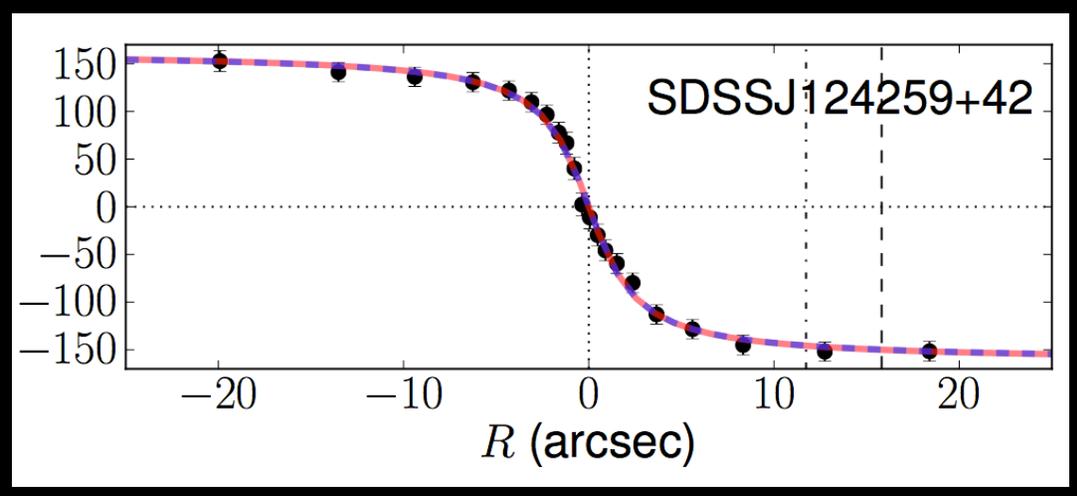


Figure 4.1: Raw 2D spectrum for IRAS 2214+4115

Schlegel (private comm.)

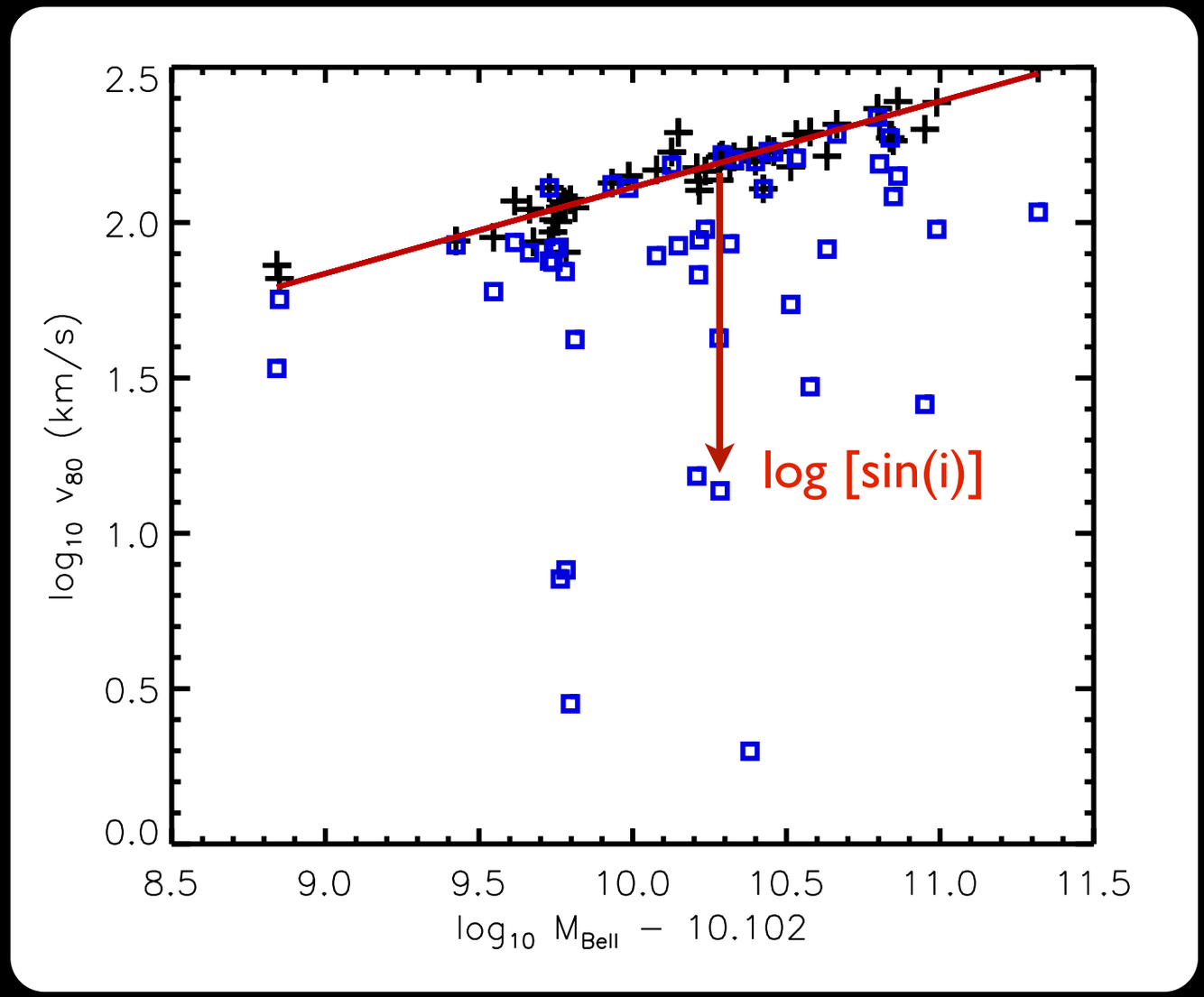


Reyes et al 2011



Reyes et al 2011

With spectroscopy, the Tully-Fisher relation tells us the inclination angle.



Red trendline:
TF relation, which we treat as given

Blue points:
not corrected for inclination

For a disk, sin(i) tells us what ellipticity we should measure in the absence of lensing.

Shear messes up the inclination correction.

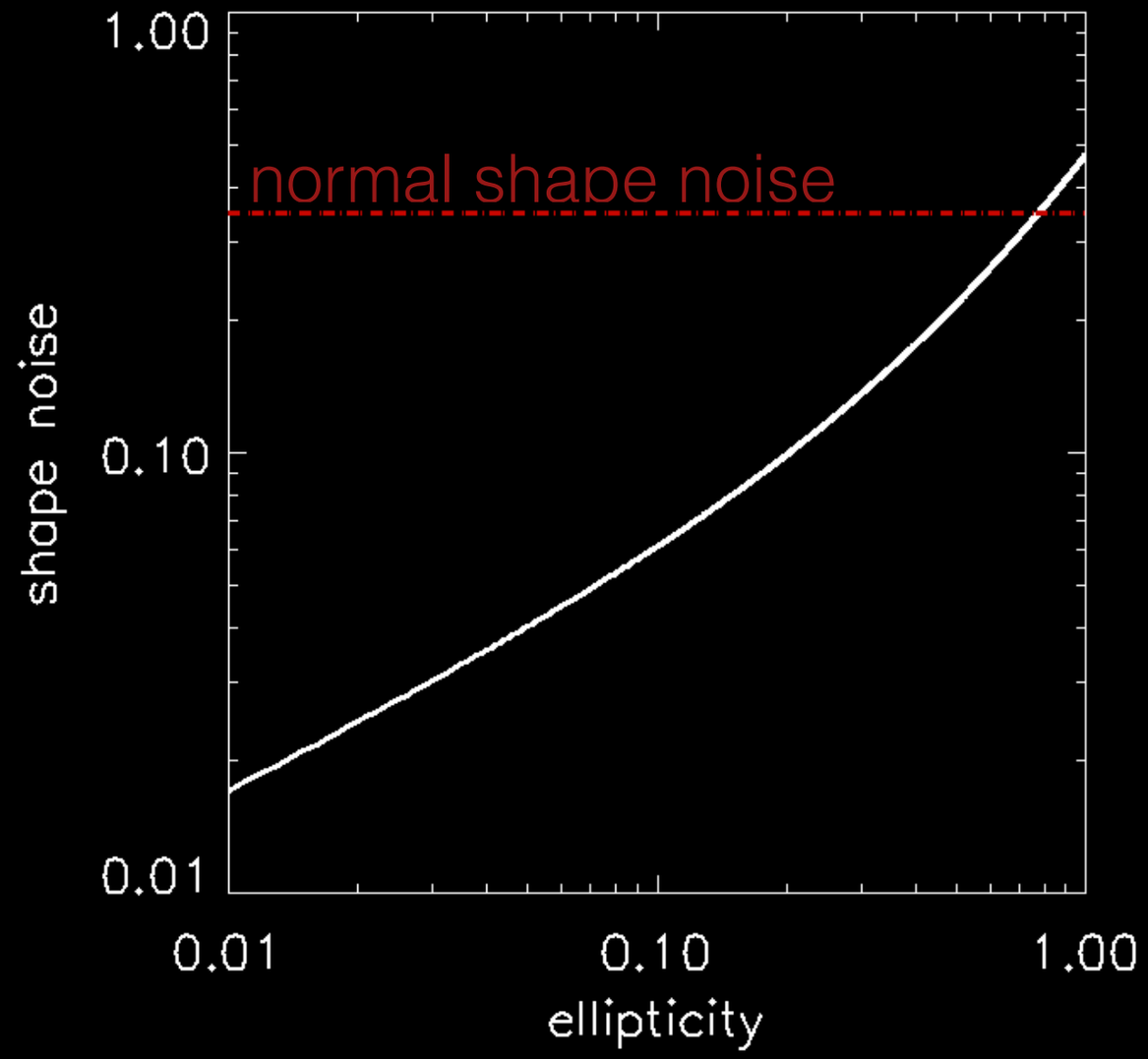
Tully-Fisher: $v_{\rm obs} = v_{\rm TF}\ \sin(i) + \sigma_{\rm TF}$

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 ~10.

For this level of per-galaxy shape noise:

Shape noise: $\propto \dfrac{\sigma_e}{\sqrt{n_{\rm gal}}}$

For LSST: $n_{\rm gal} \approx 25\ {\rm gal\ arcmin}^{-2}$

$\sigma_e \approx 0.2$

For kinematic lensing, equivalent shape noise with:

$\sigma_e \approx 0.025$

$n_{\rm gal} \approx .25\ {\rm gal\ arcmin}^{-2}$

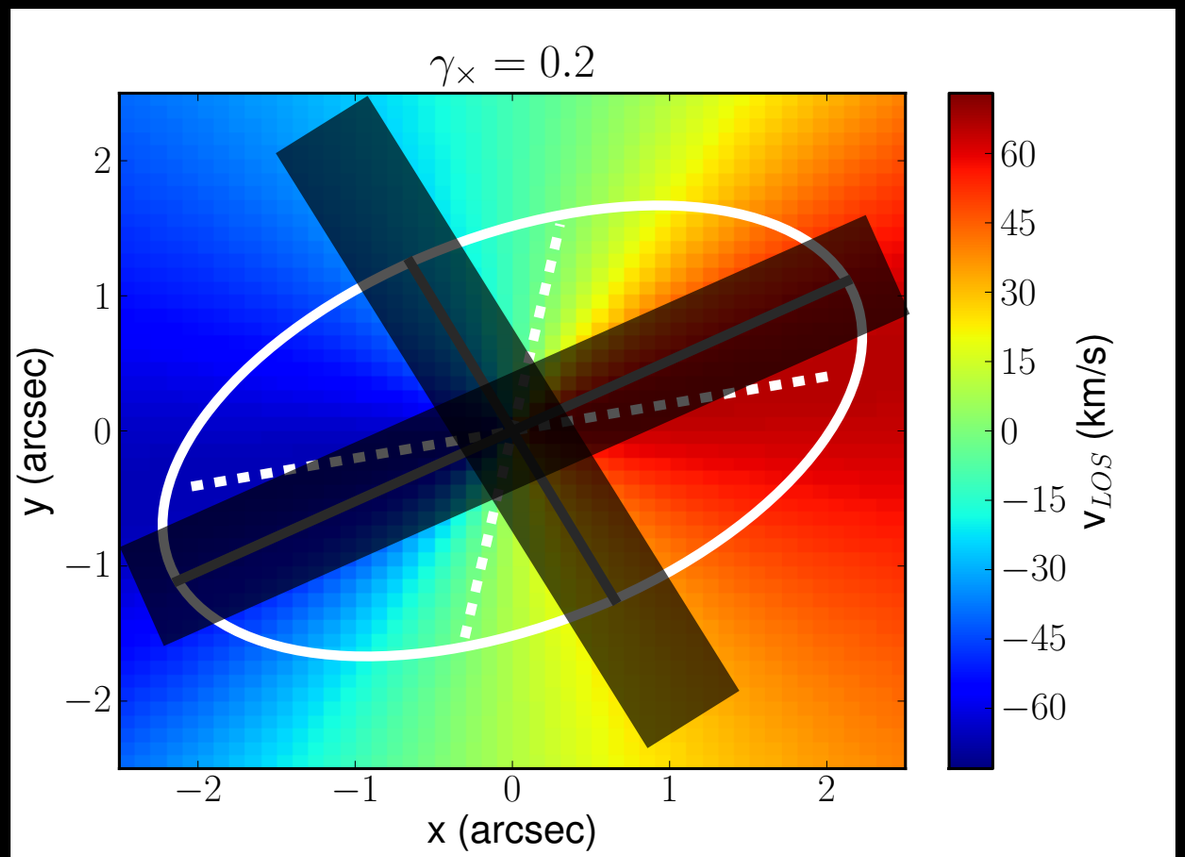
$$n_{\rm gal} \approx .25 \text{ gal arcmin}^{-2}$$

$$\sim 10^3 \text{ deg}^2$$

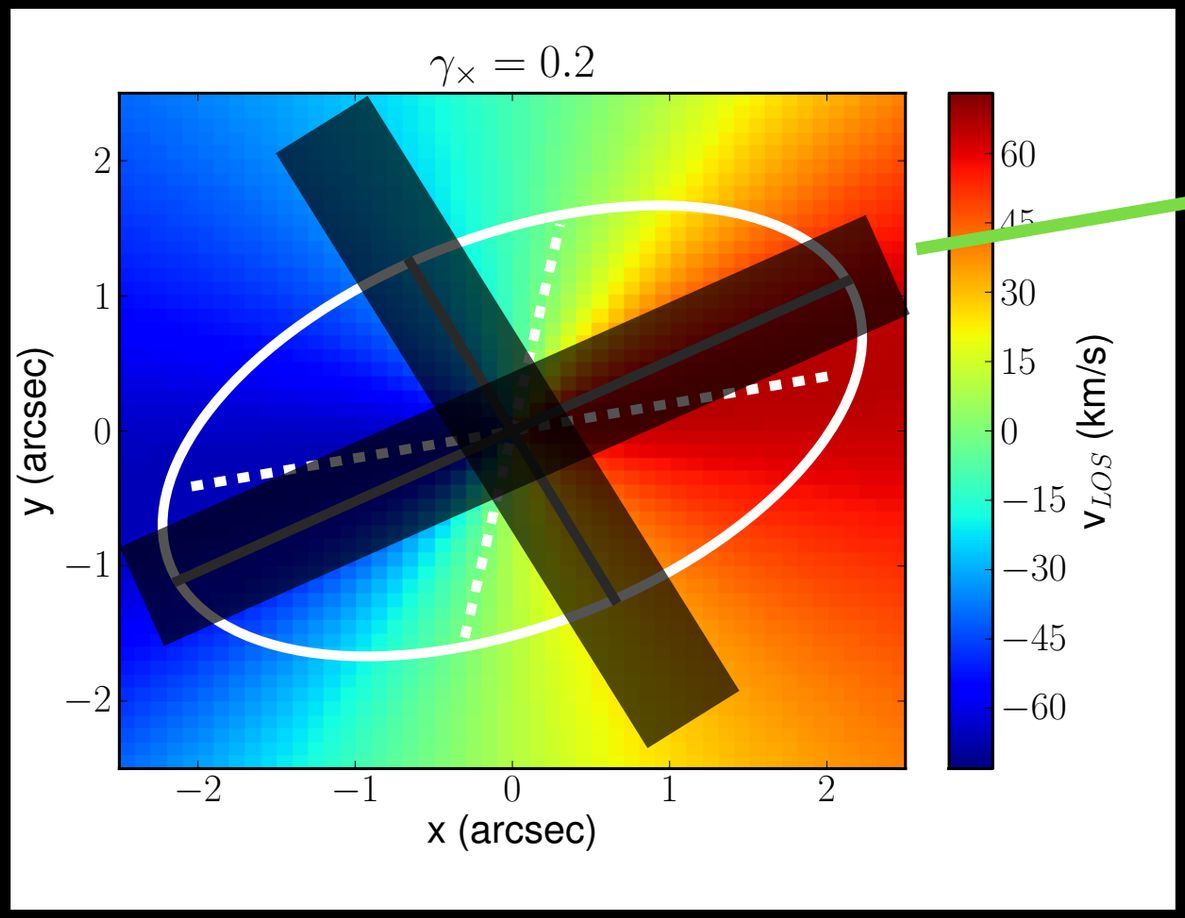
$$\implies 10^7 \text{ spectra}$$

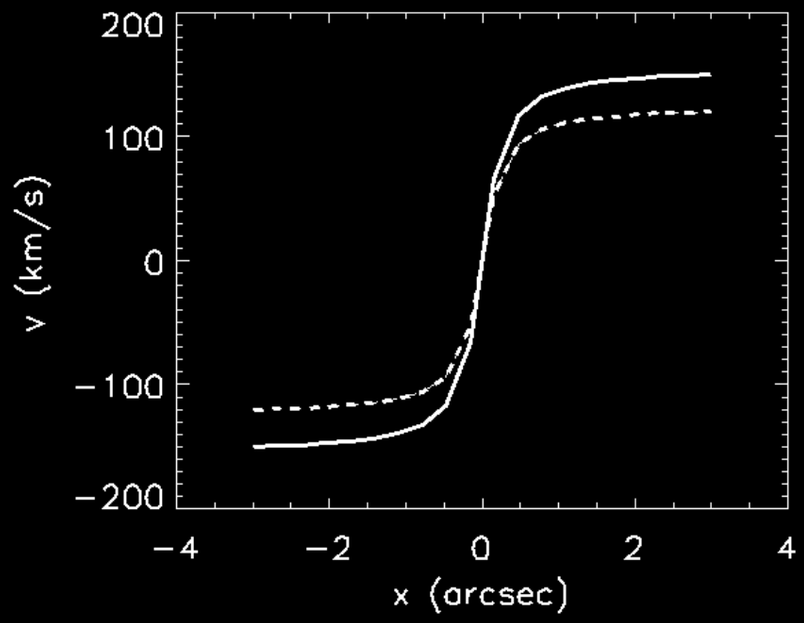
This is comparable to PFS or DESI.

A spectroscopic weak lensing measurement with slit spectroscopy



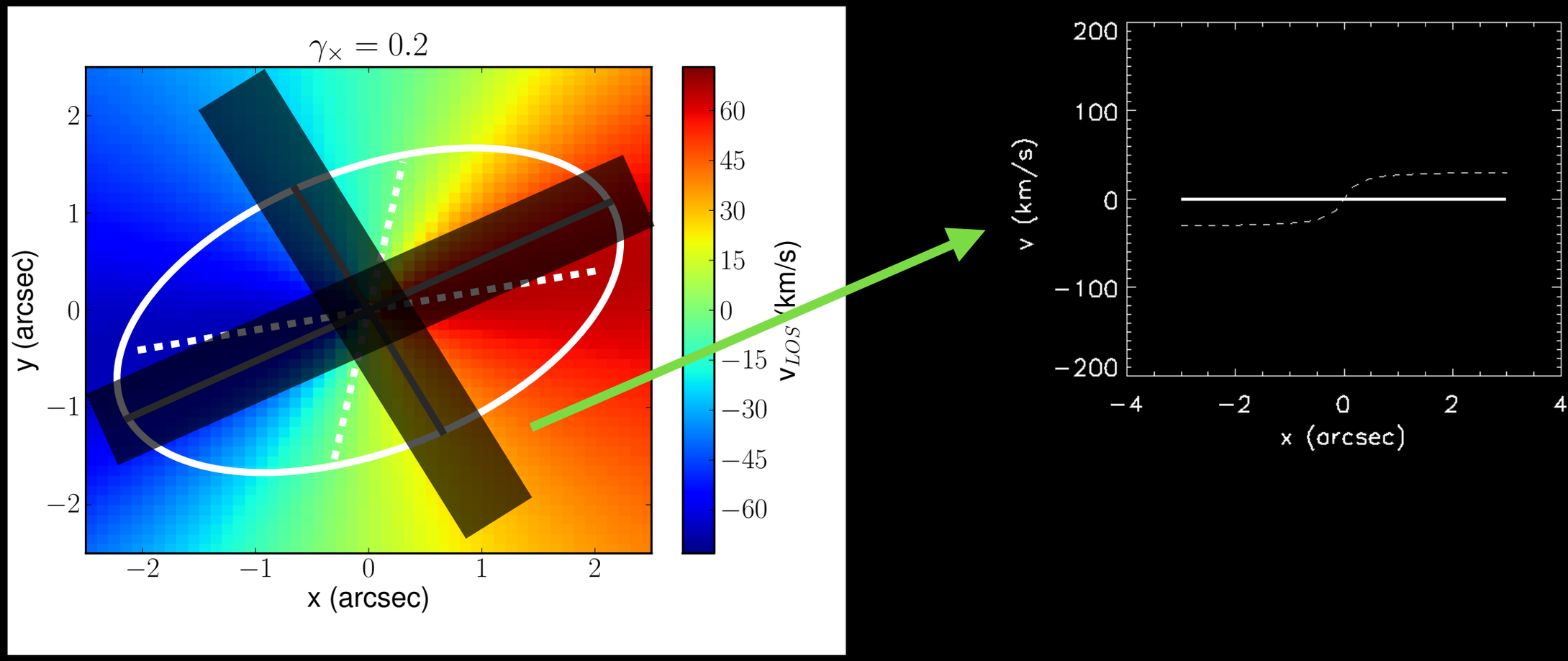
A spectroscopic weak lensing measurement with slit spectroscopy





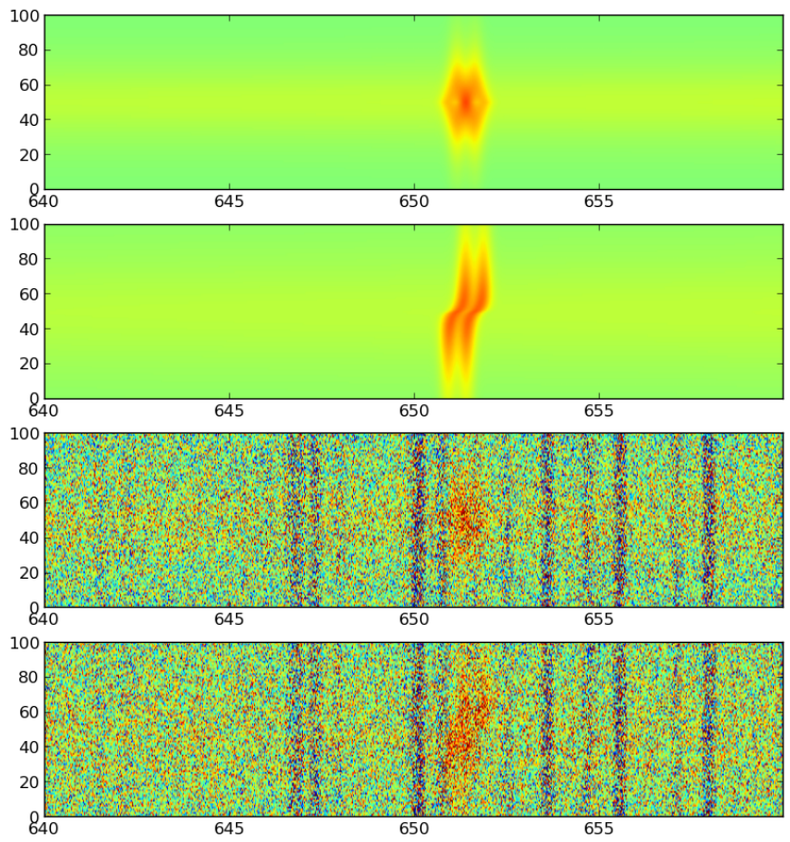
Less rotation along the major axis than TFR would predict

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

---

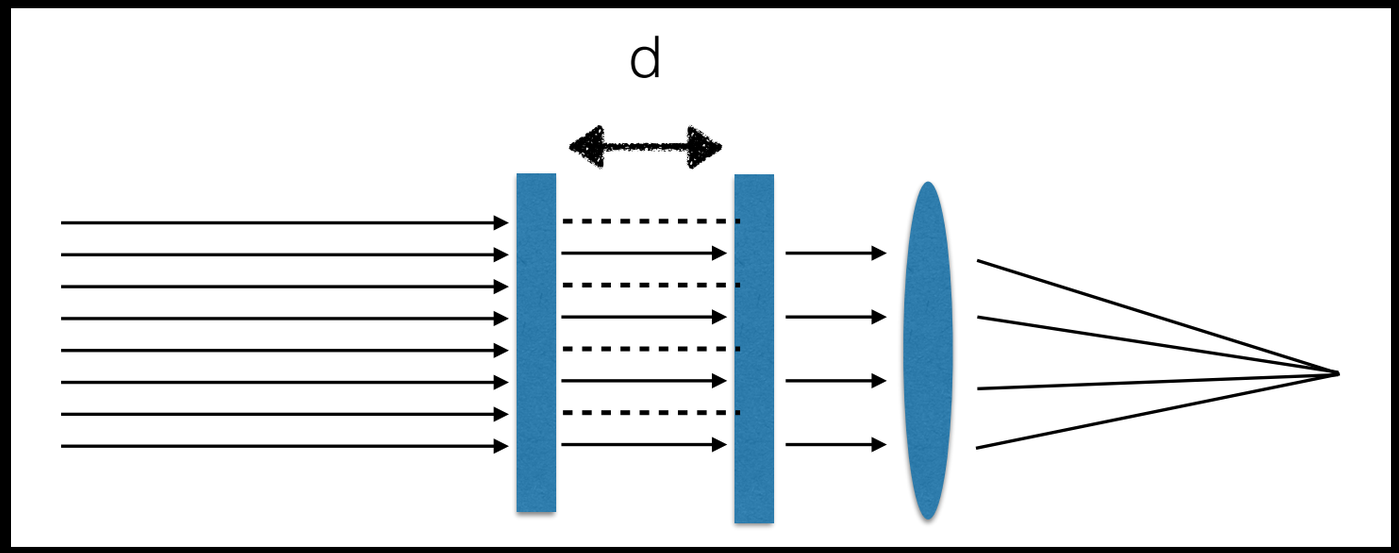
consistent with DES/DESI exposure time calculations

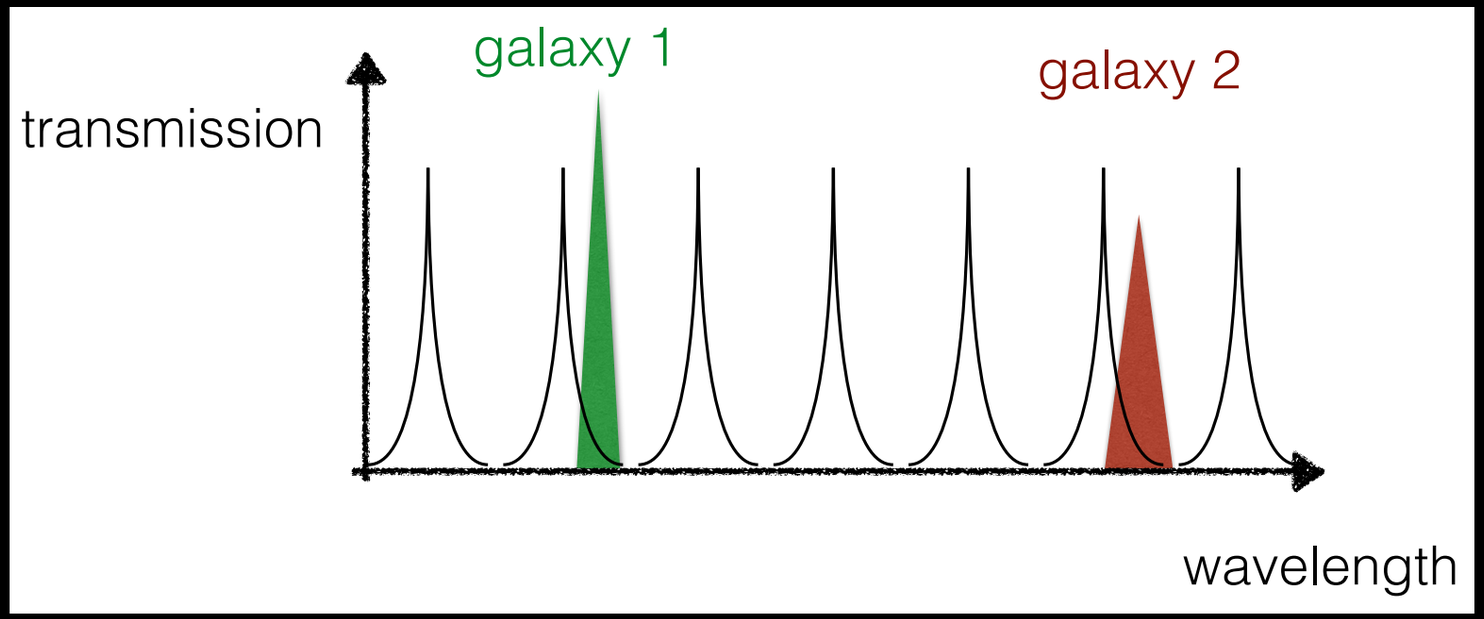
Keck-DEIMOS

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

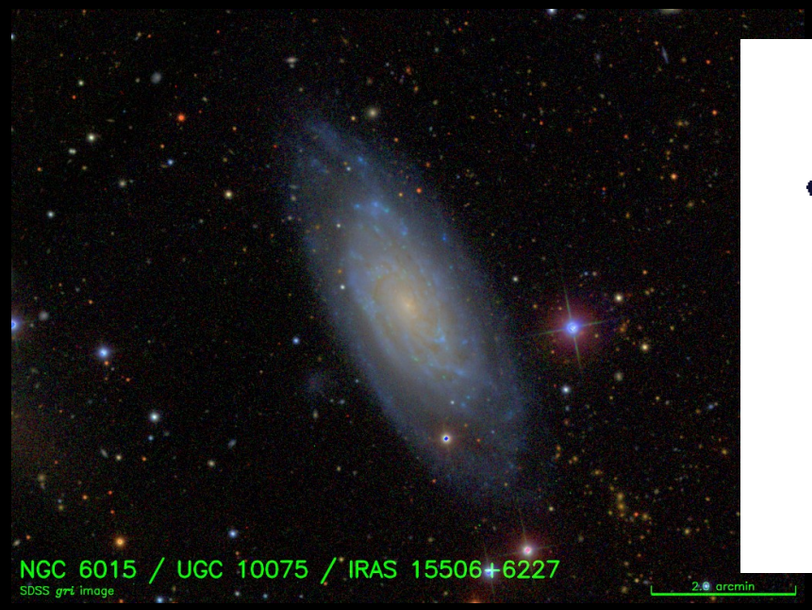
We need hyperspectral imaging.

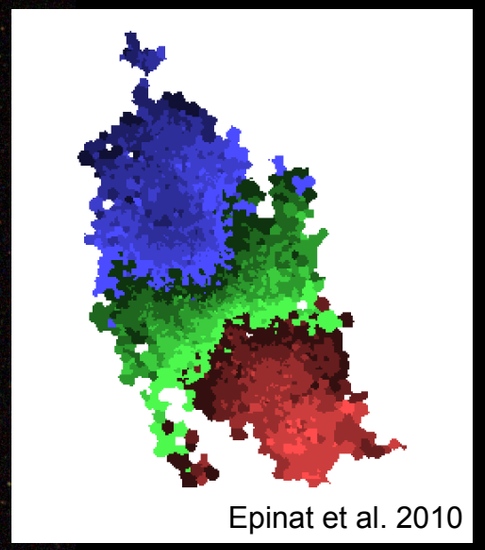
One possible solution:
Imaging Fabry-Perot Interferometer

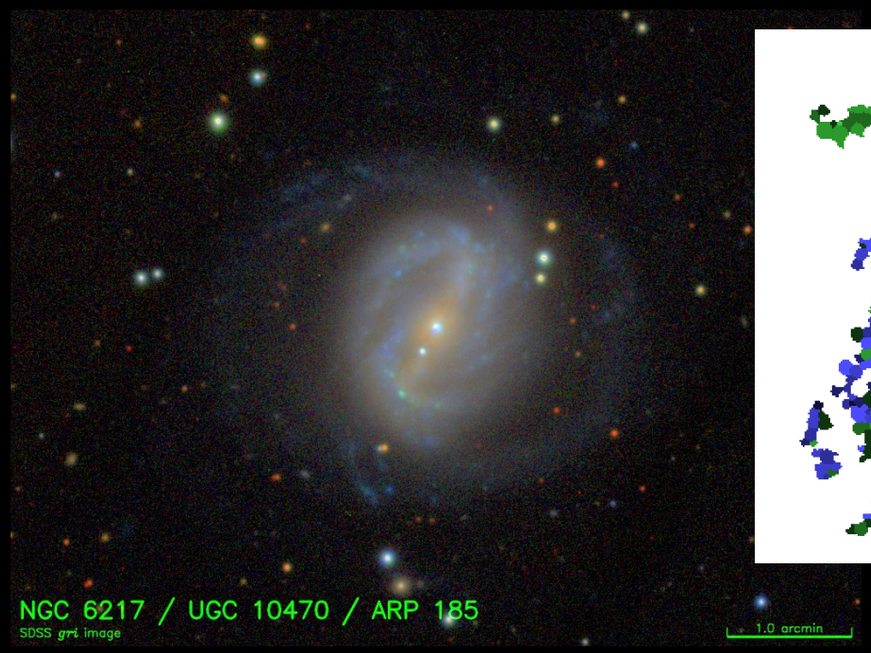


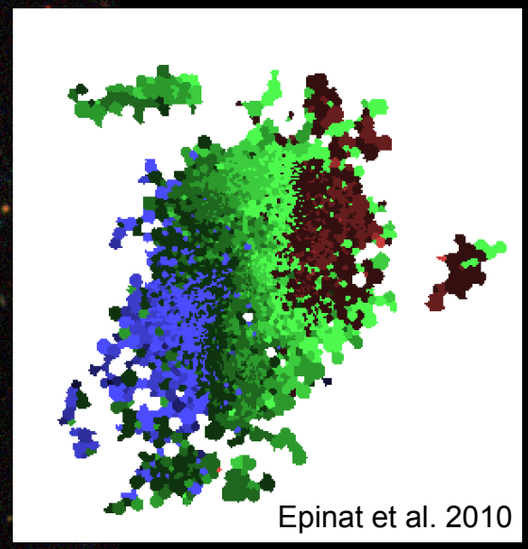


Example: GHASP survey data









Jet Propulsion Laboratory
California Institute of Technology

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

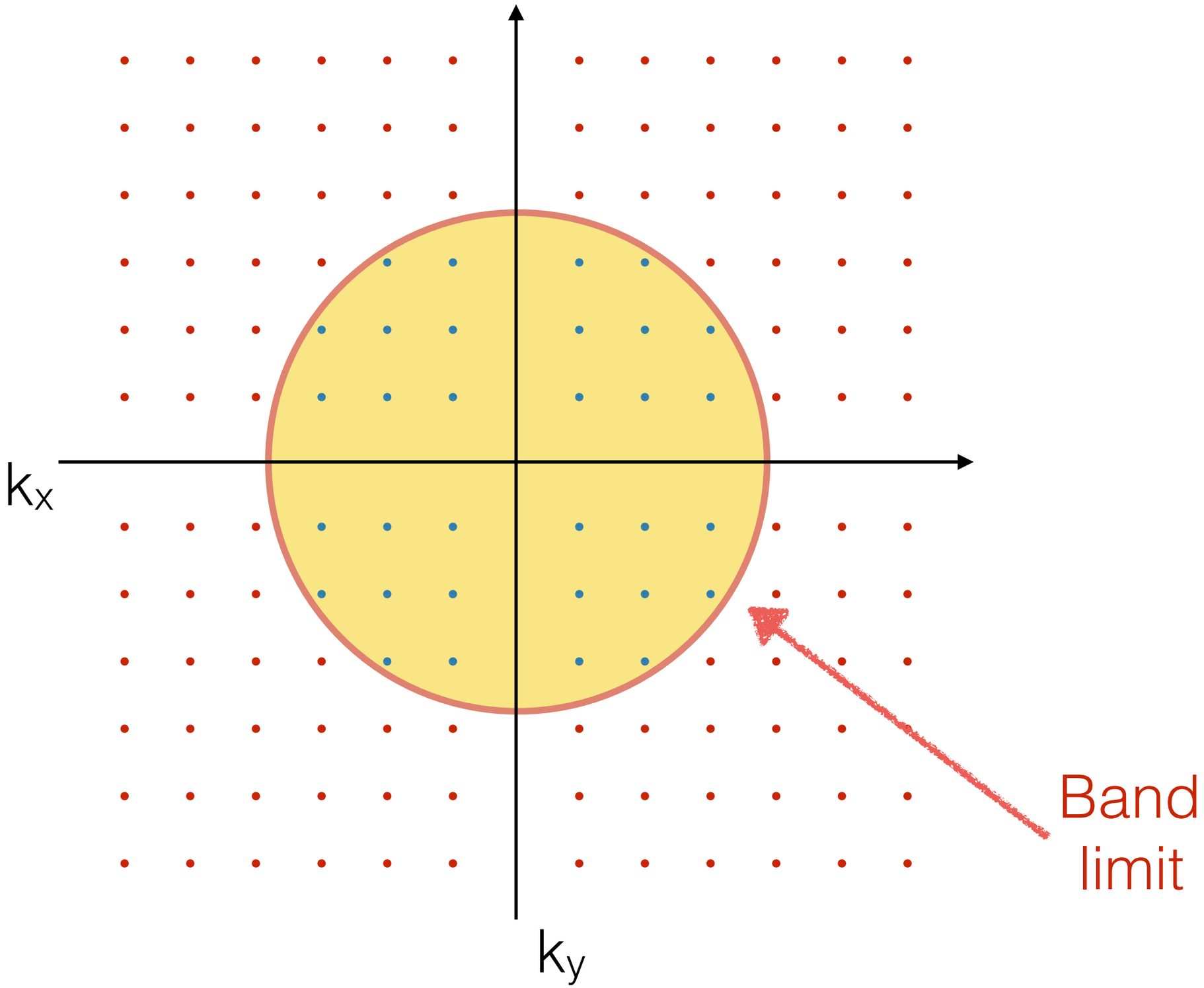
Survey	Number of galaxies (millions)	Spectral resolution elements per galaxy	Spatial resolution elements per galaxy	Total independent resolution elements (billions)
LSST	1,700	6	9	90
WFIRST (imaging)	320	3	400	380
WFIRST (grism)	20	600	1	12
SDSS	2	2,000	1	4
DESI	20	4,000	1	80
SPHEREx	450	130	1	60
Euclid (imaging)	1,620	1	100	160
Total:				**800**
SPECTRE	80	10,000	100	**80,000**

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.

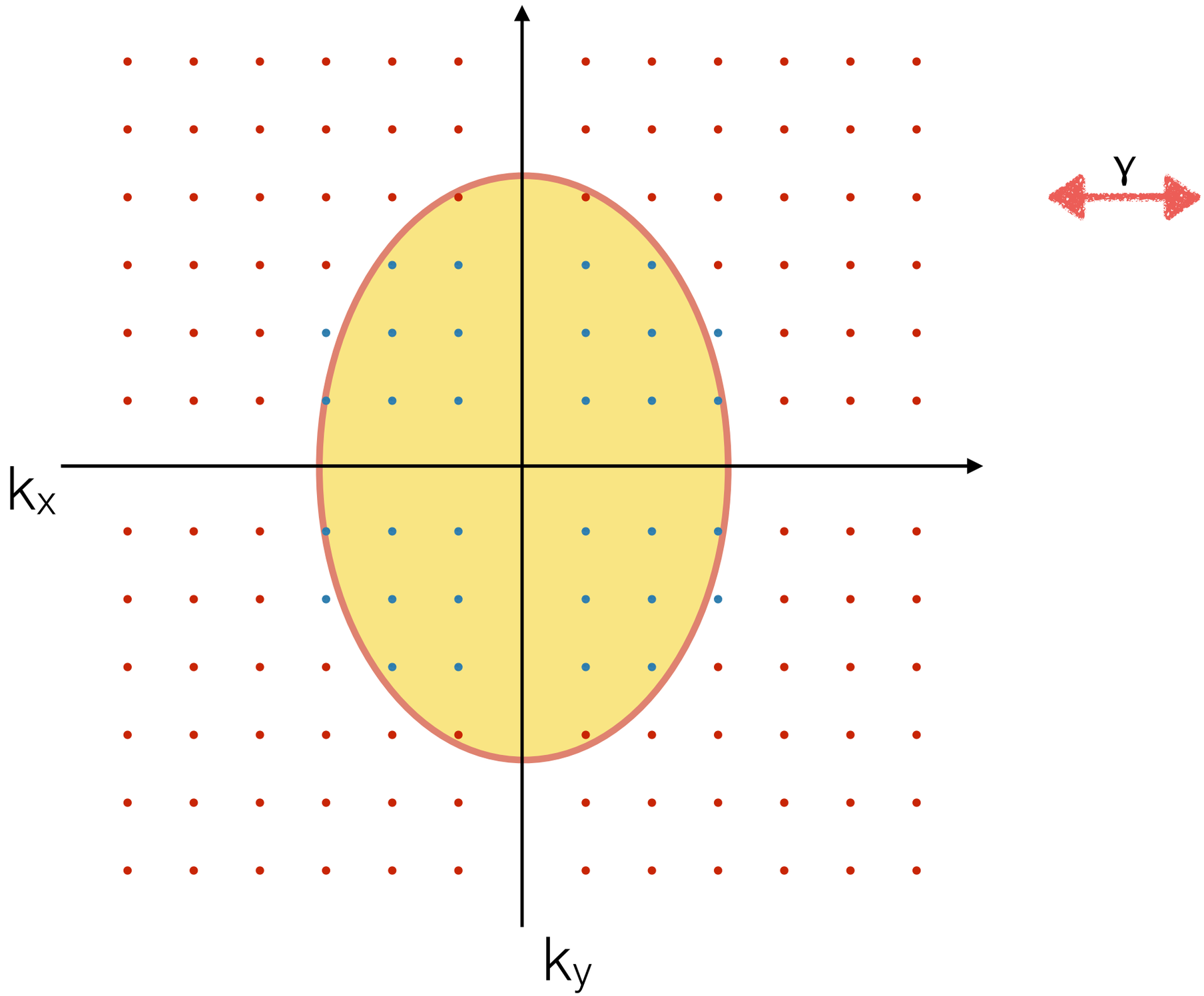
Jet Propulsion Laboratory
California Institute of Technology

jpl.nasa.gov

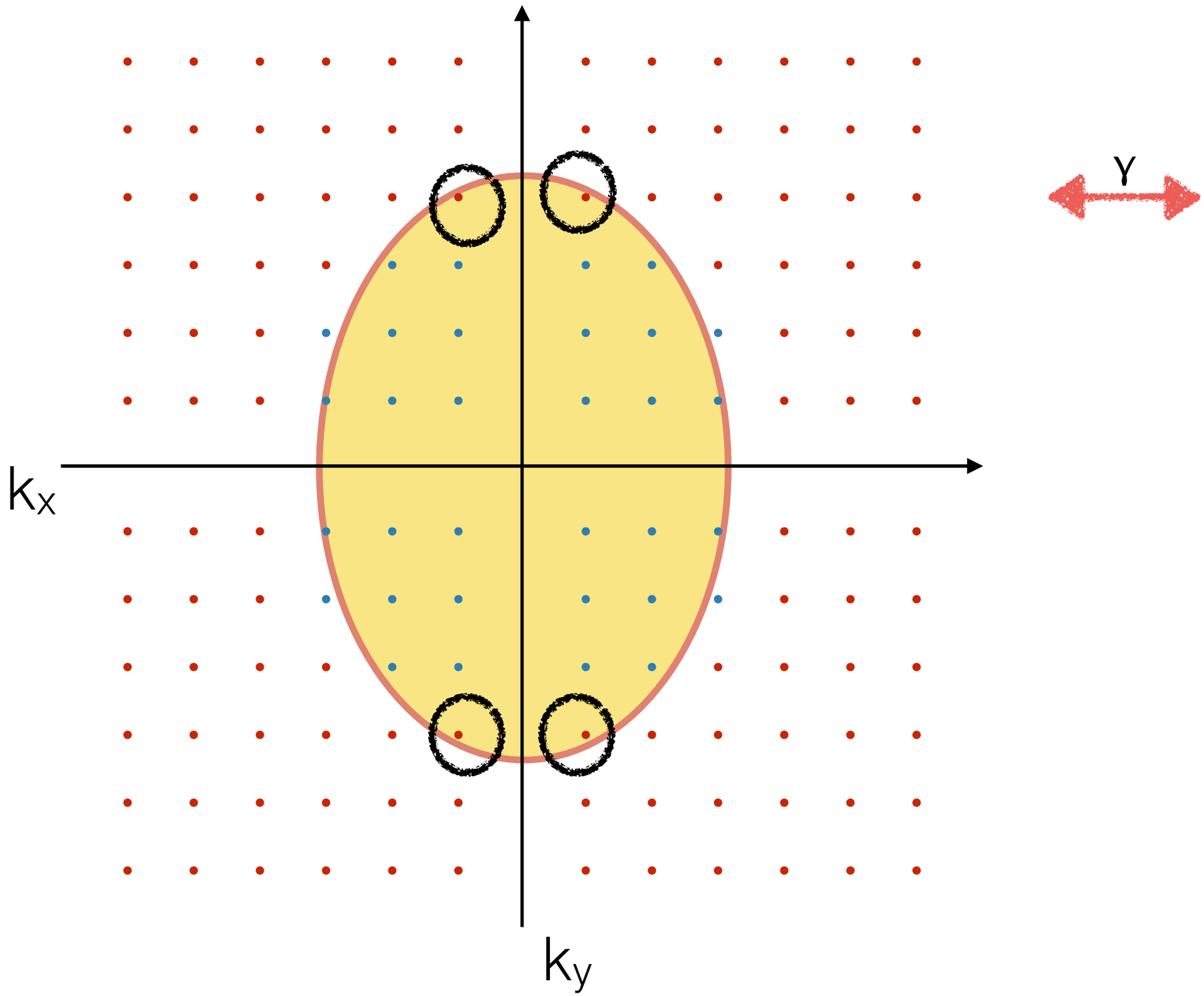
Shear response depends on unresolved modes



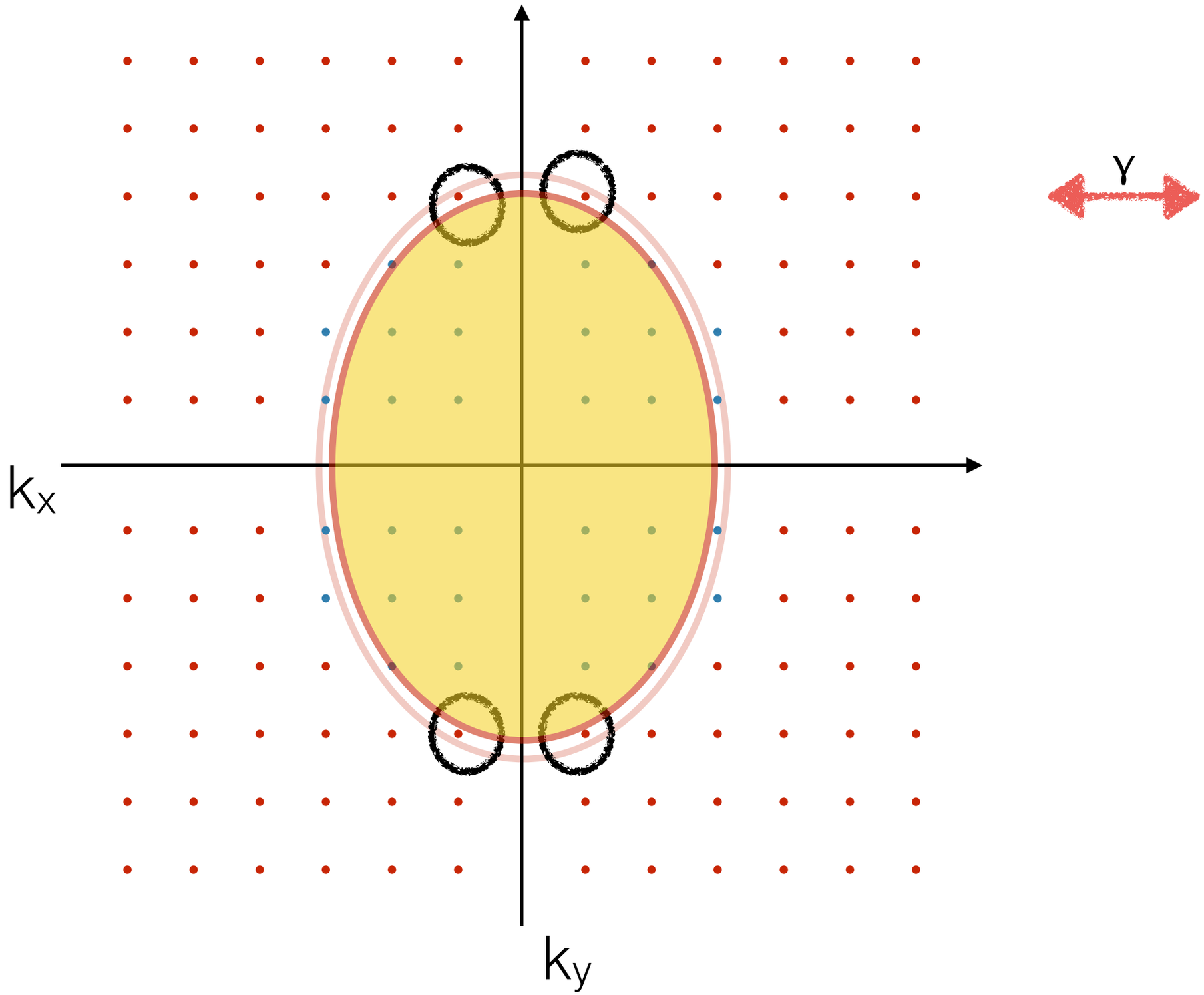
Shear response depends on unresolved modes



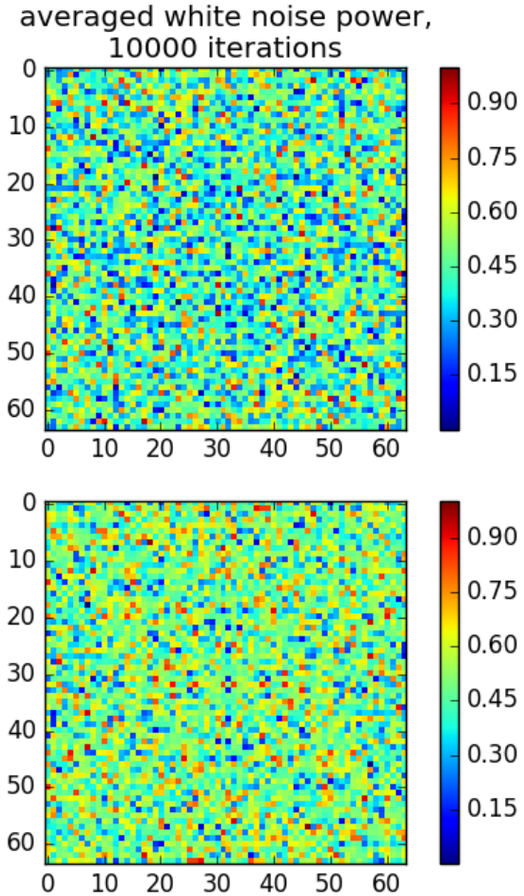
Shear response depends on unresolved modes

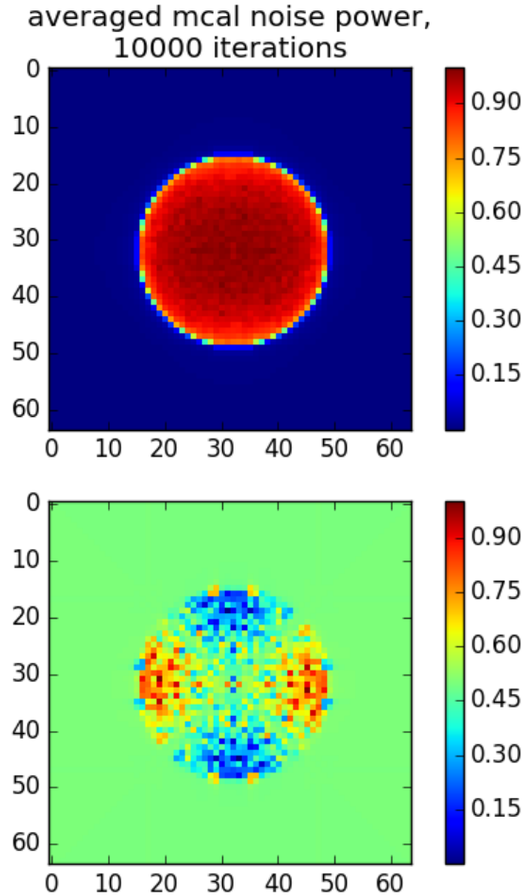


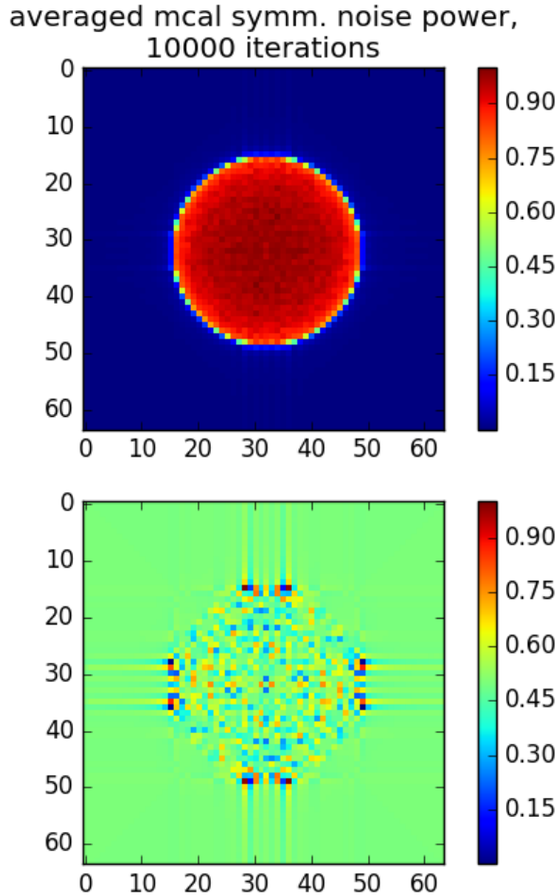
Convolve to larger PSF to ‘hide’ noisy modes



Reconvolution+shearing modifies the noise field.







We can mitigate by adding more noise, restoring symmetry.

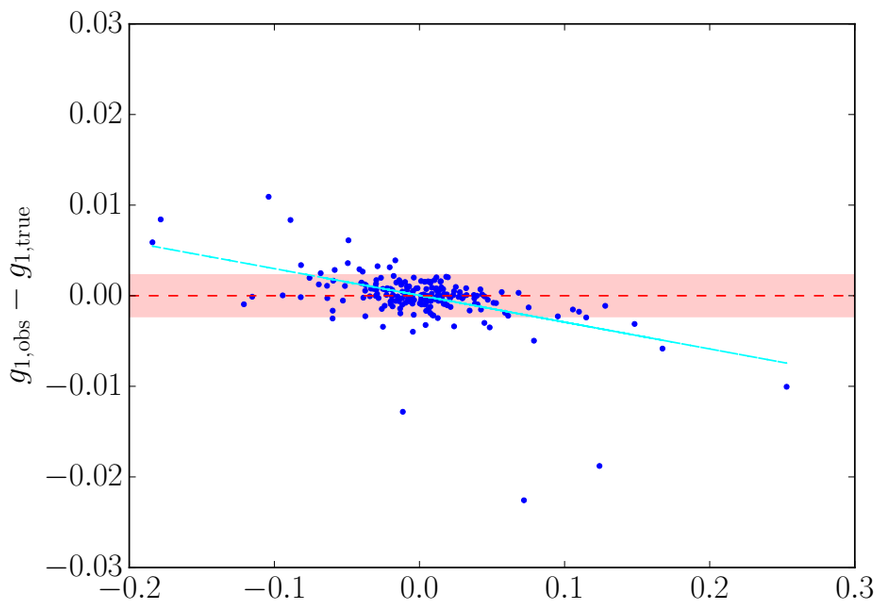
Are there other useful ways to perturb the image?

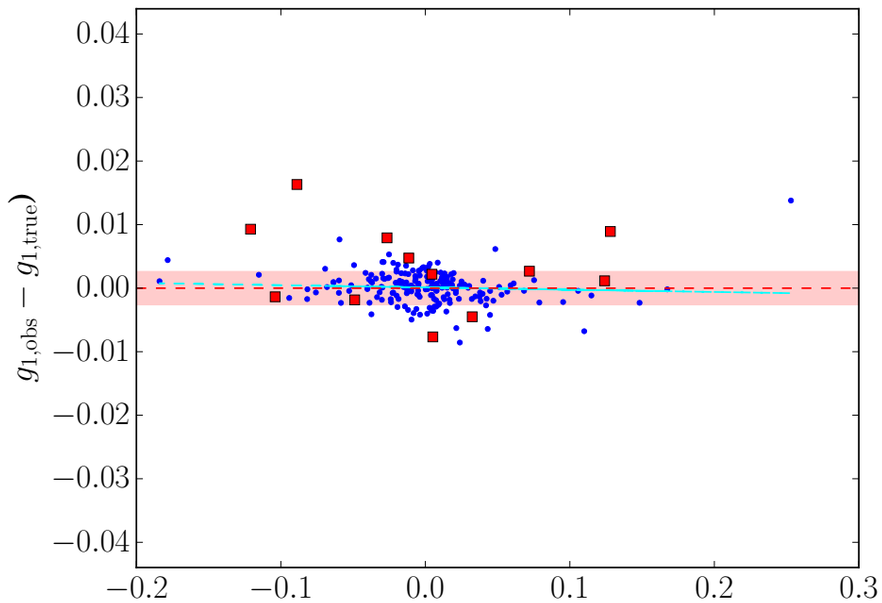
$$I'(x|e^{+}_{\mathrm{PSF}}) = \Gamma^{+}\left[P^{-1} * I\right]$$

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

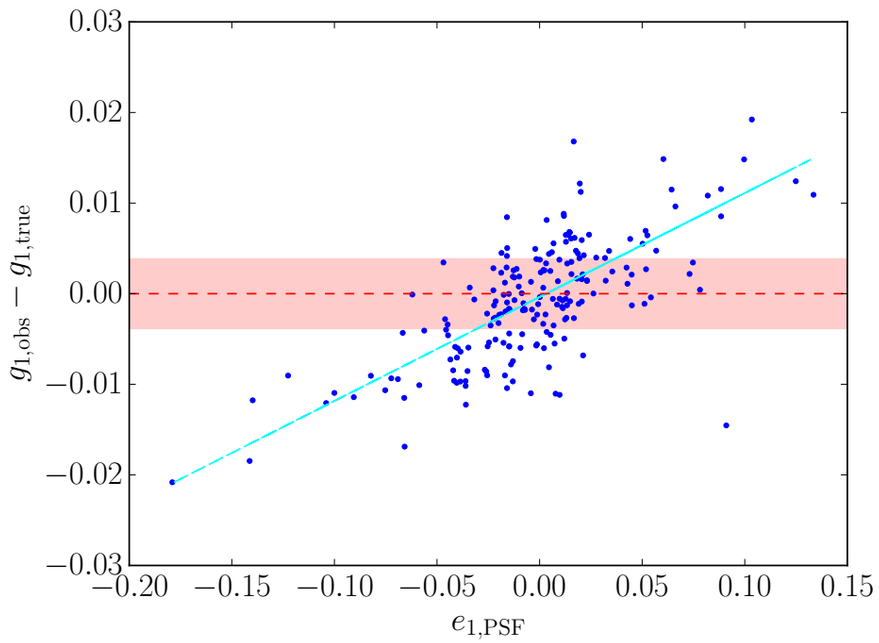
PSF perturbation and detrending:

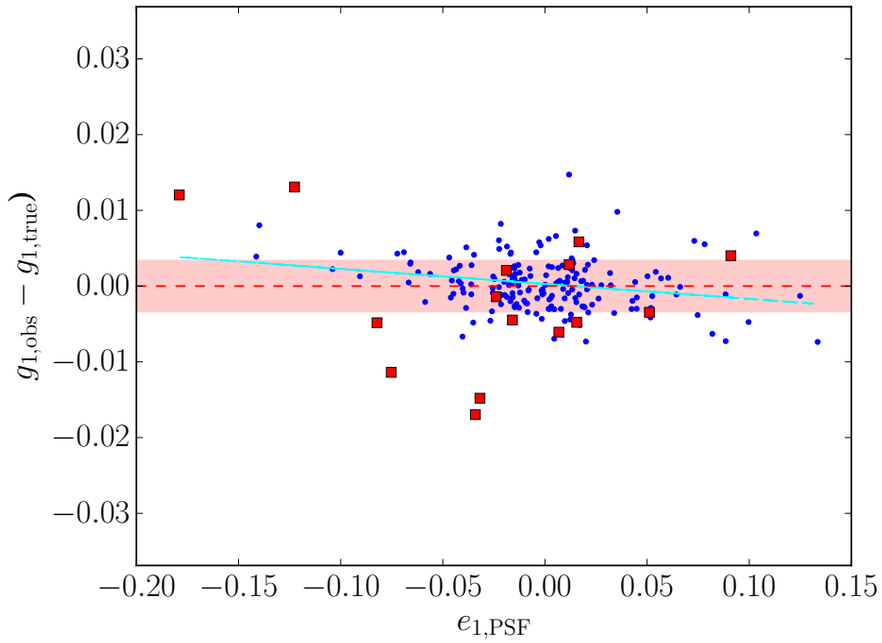
KSB:





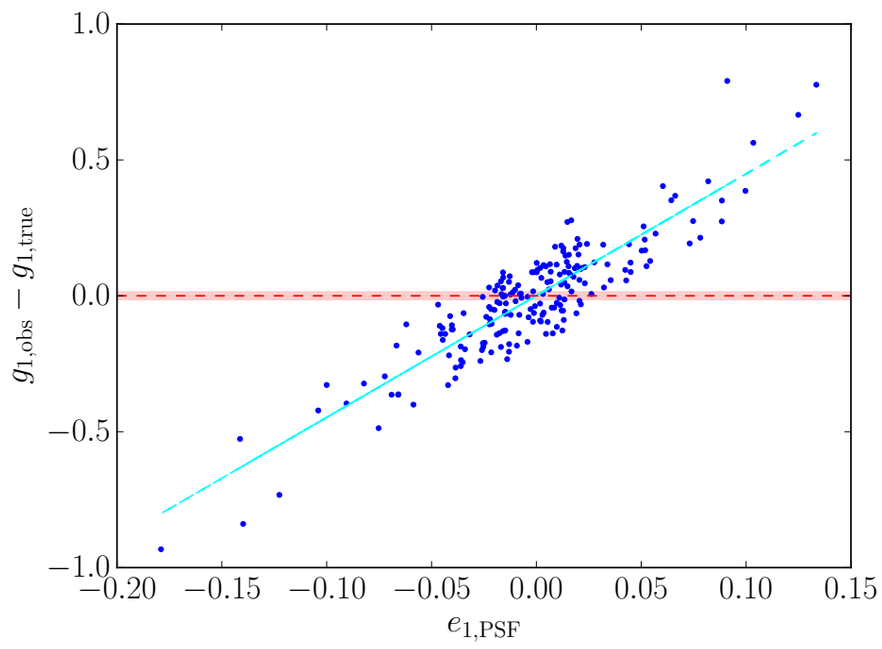
regauss:

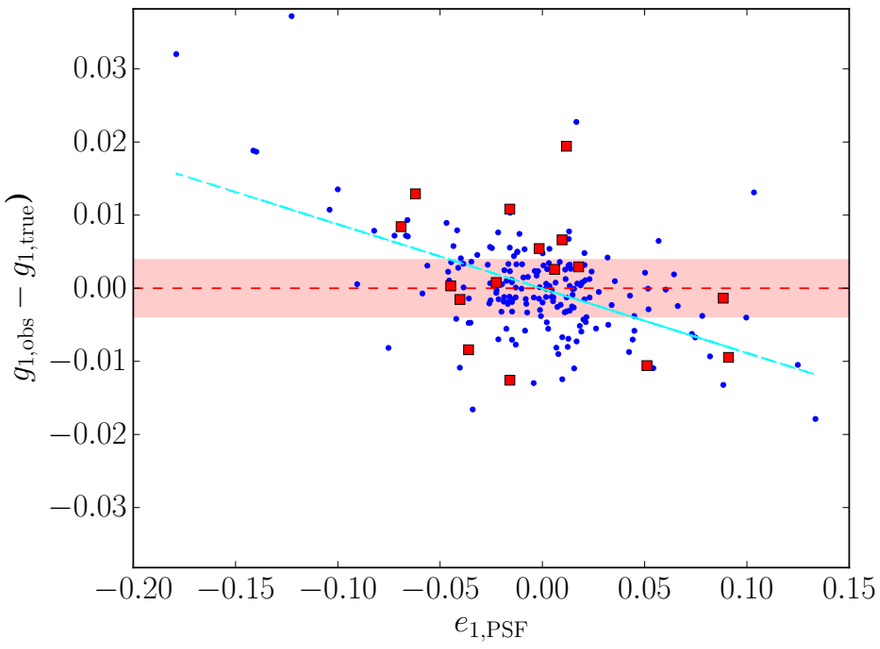




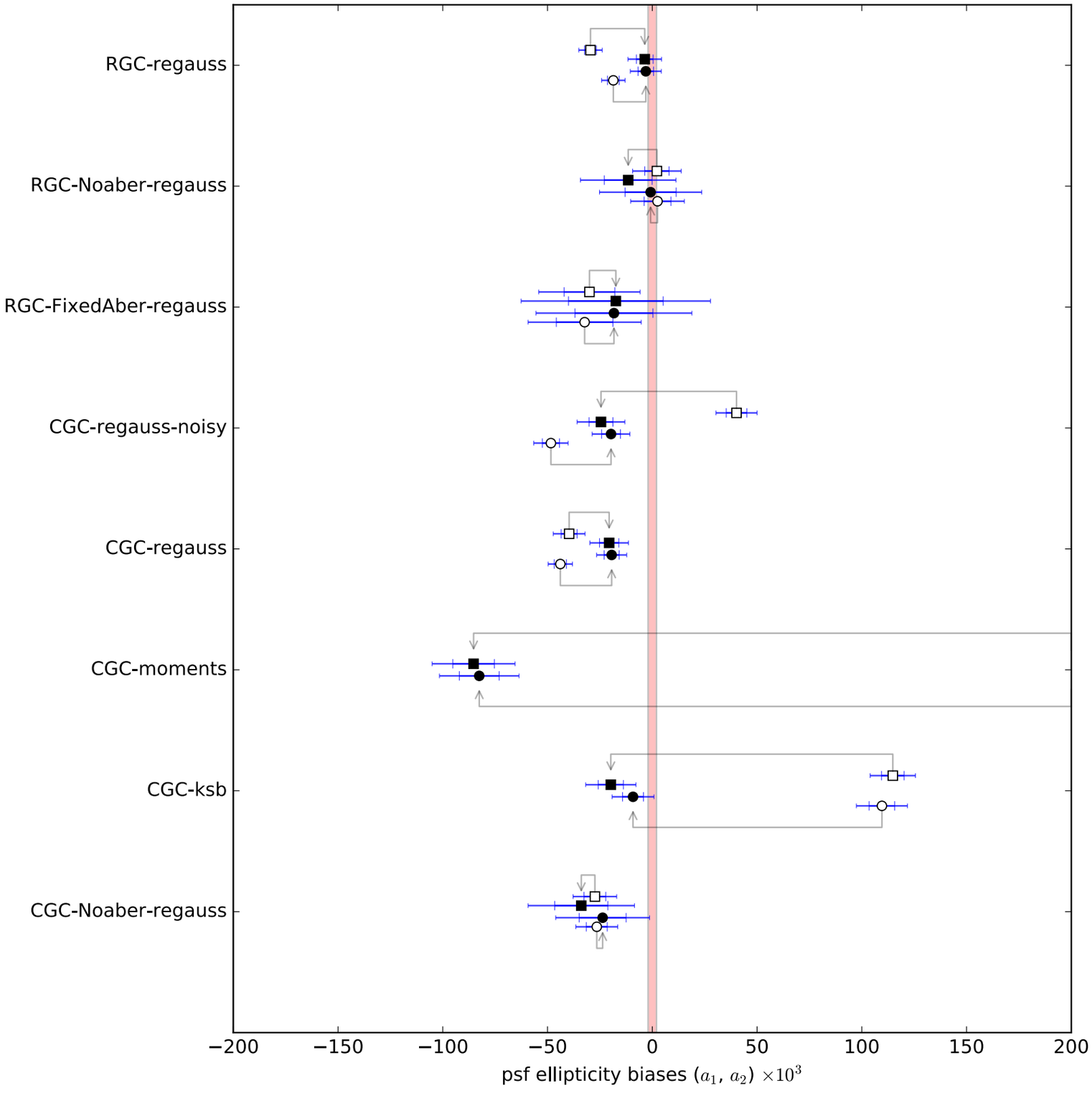
PSF perturbation and detrending:

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:

$$\langle \boldsymbol{R} \rangle = \int \left. \frac{\partial S(\boldsymbol{e}) P(\boldsymbol{e}) \boldsymbol{e}}{\partial \boldsymbol{\gamma}} \right|_{\gamma=0} d\boldsymbol{e}$$

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

$$= \boxed{\frac{\langle e_i^+ \rangle^S - \langle e_i^- \rangle^S}{\Delta \gamma_j}} + \frac{\langle e_i \rangle^{S+} - \langle e_i \rangle^{S-}}{\Delta \gamma_j}$$

Apply a shear.
See how your measured shapes change.

Correcting for selection effects:

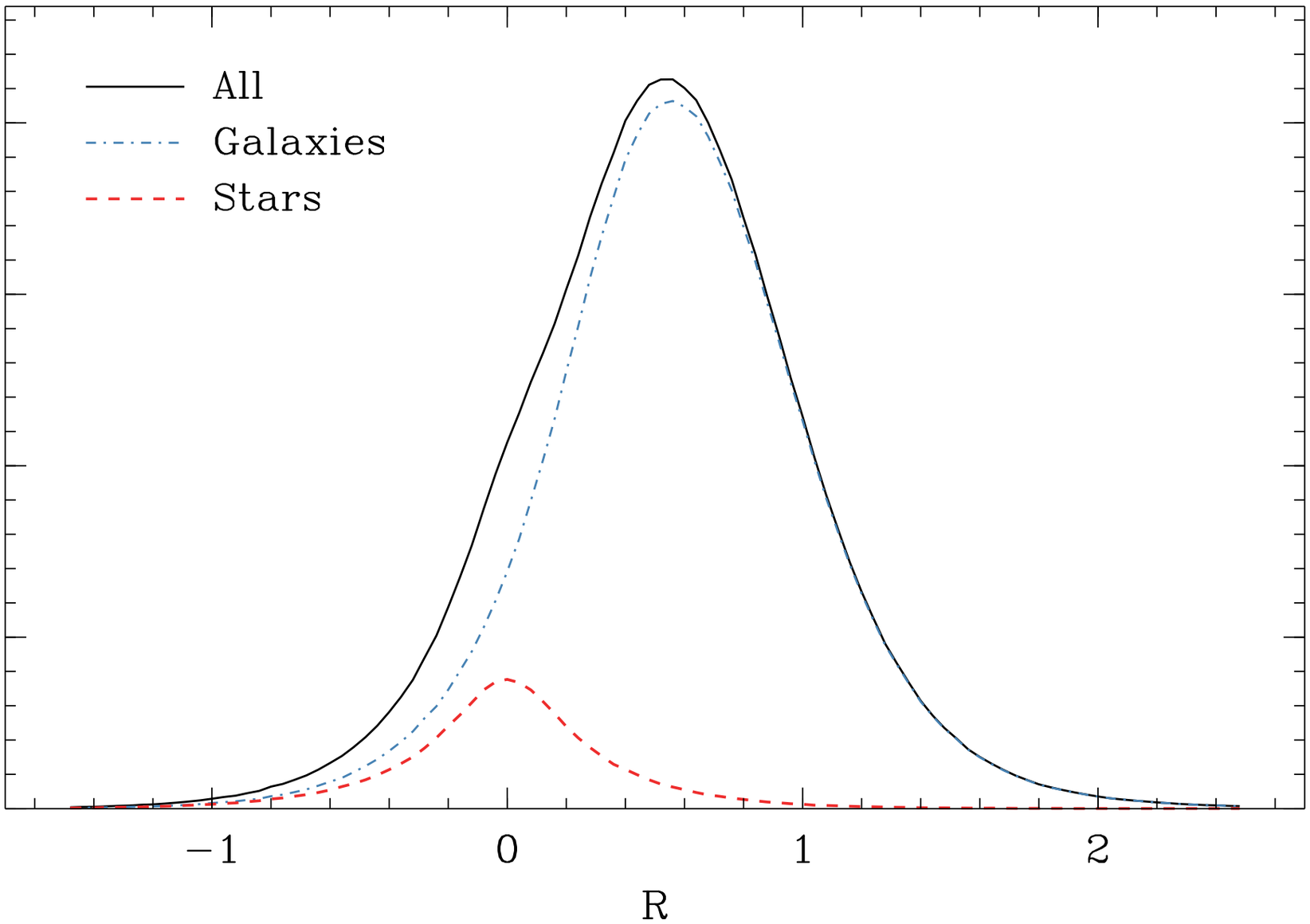
$$\langle \boldsymbol{R} \rangle = \int \left. \frac{\partial S(\boldsymbol{e}) P(\boldsymbol{e}) \boldsymbol{e}}{\partial \boldsymbol{\gamma}} \right|_{\gamma=0} d\boldsymbol{e}$$

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

$$= \frac{\langle e_i^+ \rangle^S - \langle e_i^- \rangle^S}{\Delta \gamma_j} + \boxed{\frac{\langle e_i \rangle^{S+} - \langle e_i \rangle^{S-}}{\Delta \gamma_j}}$$

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