Day 2. Reminder: Overview

Day 1: Principles of gravitational lensing

- Brief history of gravitational lensing
- Light deflection in an inhomogeneous Universe
- Convergence, shear, and ellipticity
- Projected power spectrum
- Real-space shear correlations

Day 2: Measurement of weak lensing

- Galaxy shape measurement
- PSF correction
- Photometric redshifts
- Estimating shear statistics

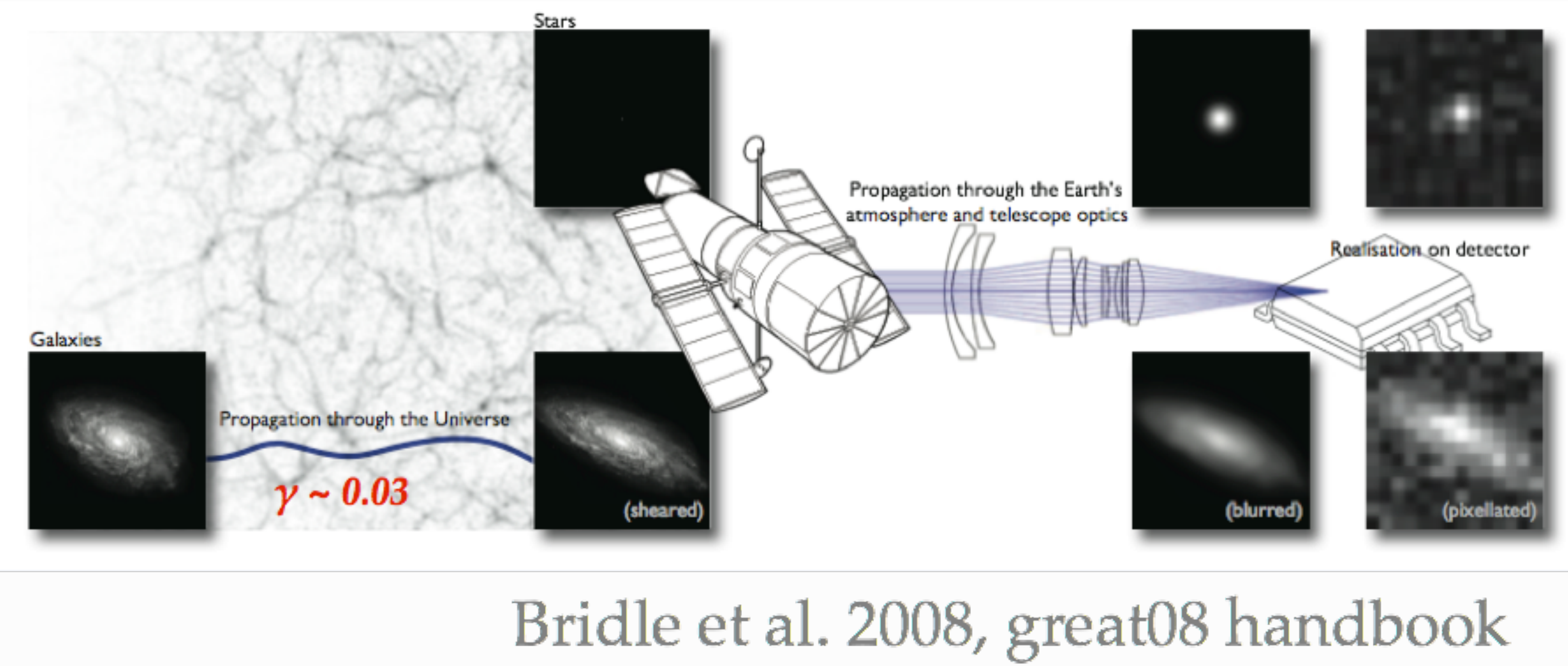
Day 3: Surveys and cosmology

- Cosmological modelling
- Results from past and ongoing surveys (CFHTlenS, KiDS, DES)
- Euclid

Day 3+: Extra stuff

- Cluster lensing; nature of DM; tests of GR

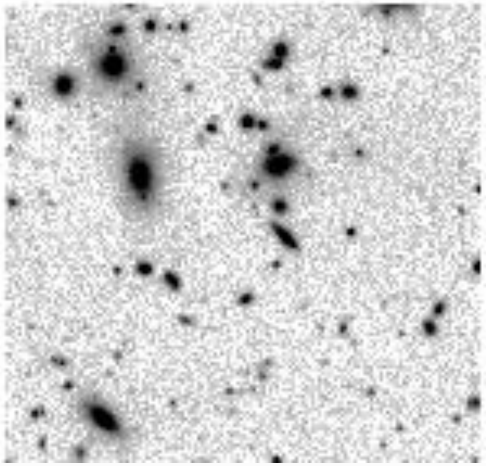
The shape measurement challenge

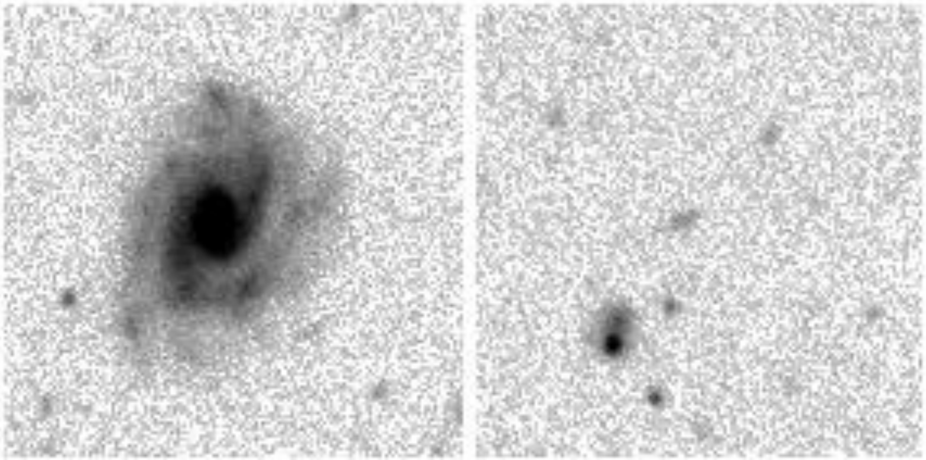


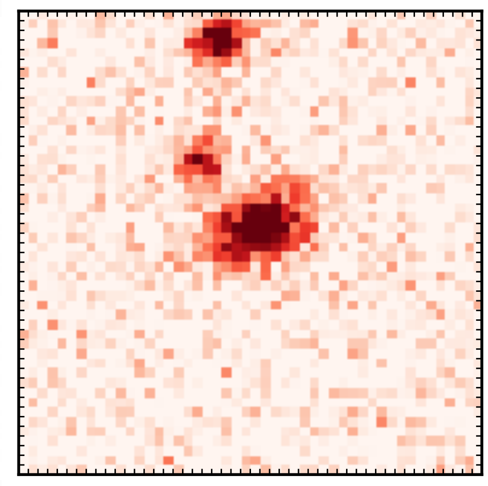
- Cosmological shear $\gamma \ll \varepsilon$ intrinsic ellipticity
- Galaxy images corrupted by PSF
- Measured shapes are biased

The shape measurement challenge

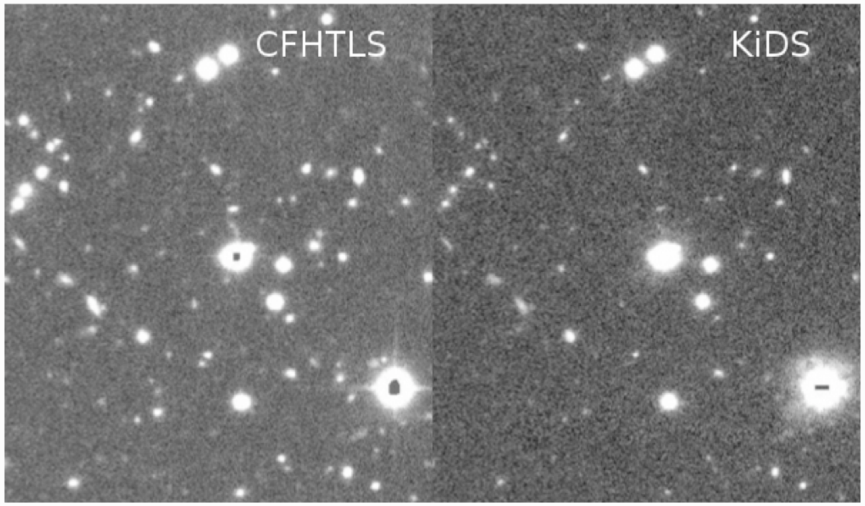
How do we measure ”ellipticity” for irregular, faint, noisy, blended objects?

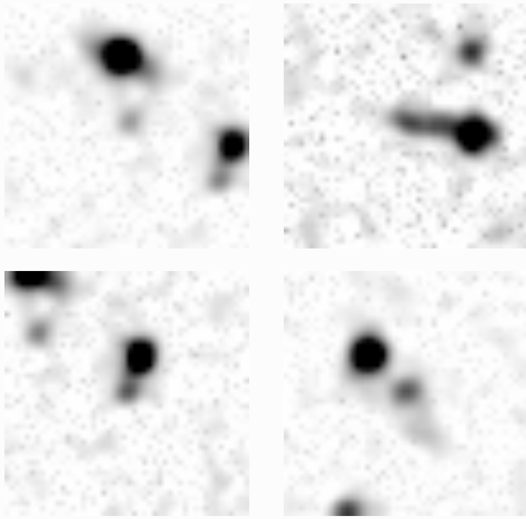


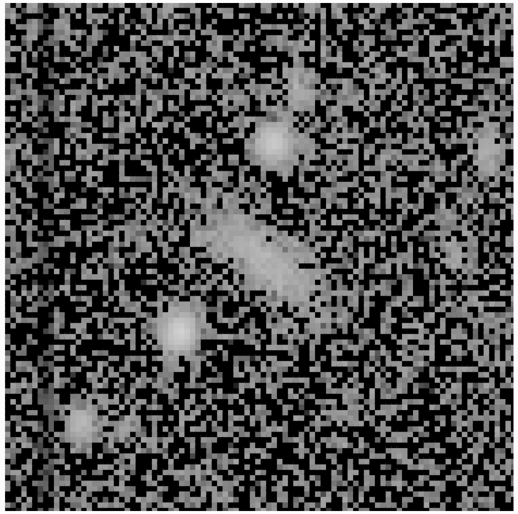




CFHT [(from Y. Mellier)] — DES-SV (Jarvis et al. 2016)





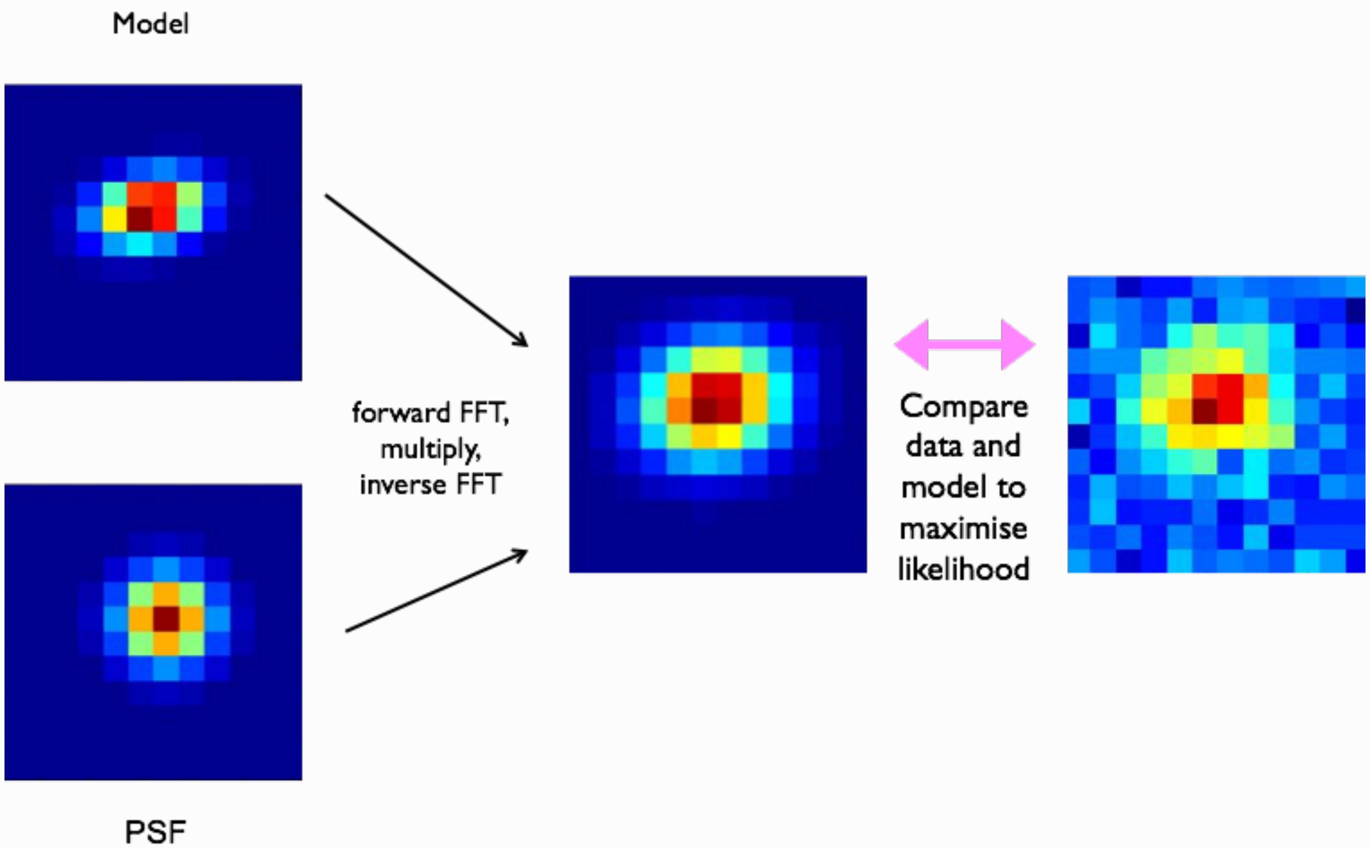


CFHTLenS/KiDS — CFHTlenS (Miller et al. 2013) — DES-Y1 (Drlica-Wagner et al. 2017)

Shape measurement methods

- Parametric: model fitting.
  (Kuijken 1999), *lens*fit (Miller et al. 2007)), *gfit* (Gentile et al. 2012), *im3shape* (Zuntz et al. 2013), *ngmix* (Jarvis et al. 2016) and many more.
- Non-parametric: direct estimation.
  - Perturbative: weighted moments.
    KSB — (Kaiser et al. 1995) + many improvements
    DEIMOS — (Melchior et al. 2011) PSF correction in moment space
    HOLICs — (Okura & Futamase 2009) — Higher-order moments
  - Non-perturbative: decomposition into basis functions.
    shapelets — (Refregier 2003) + many improvements

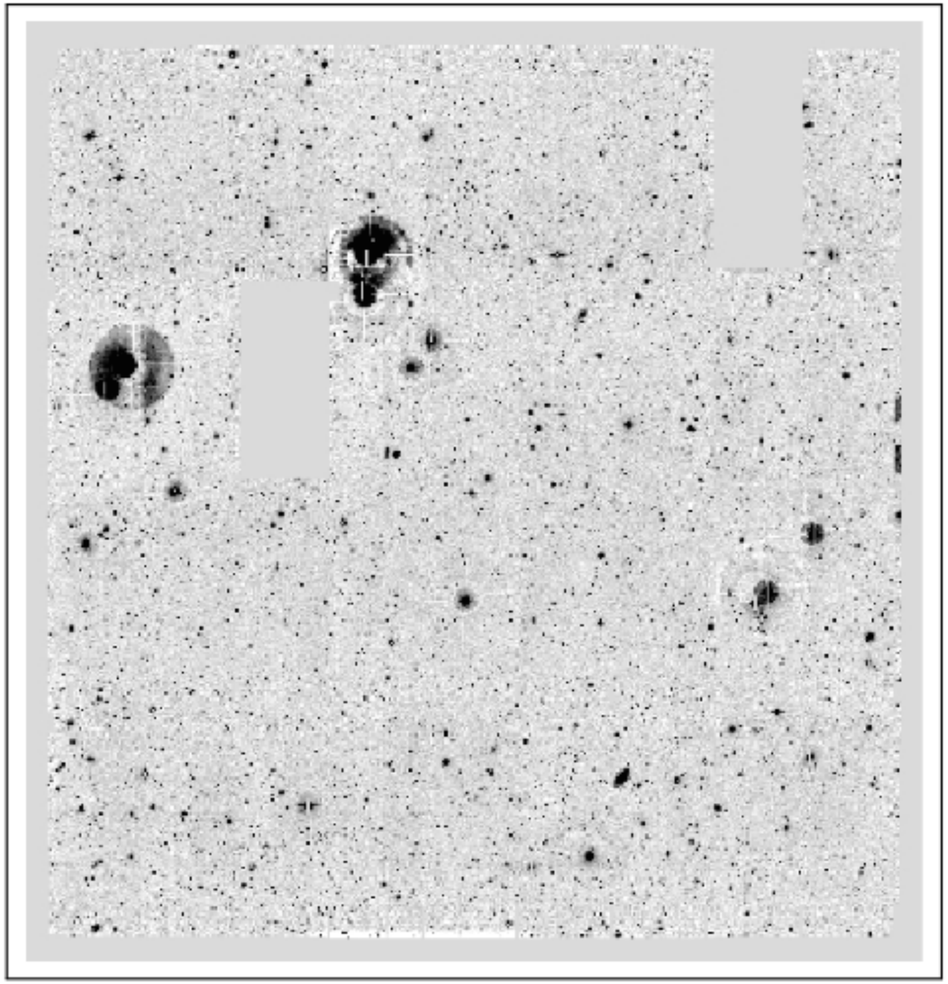
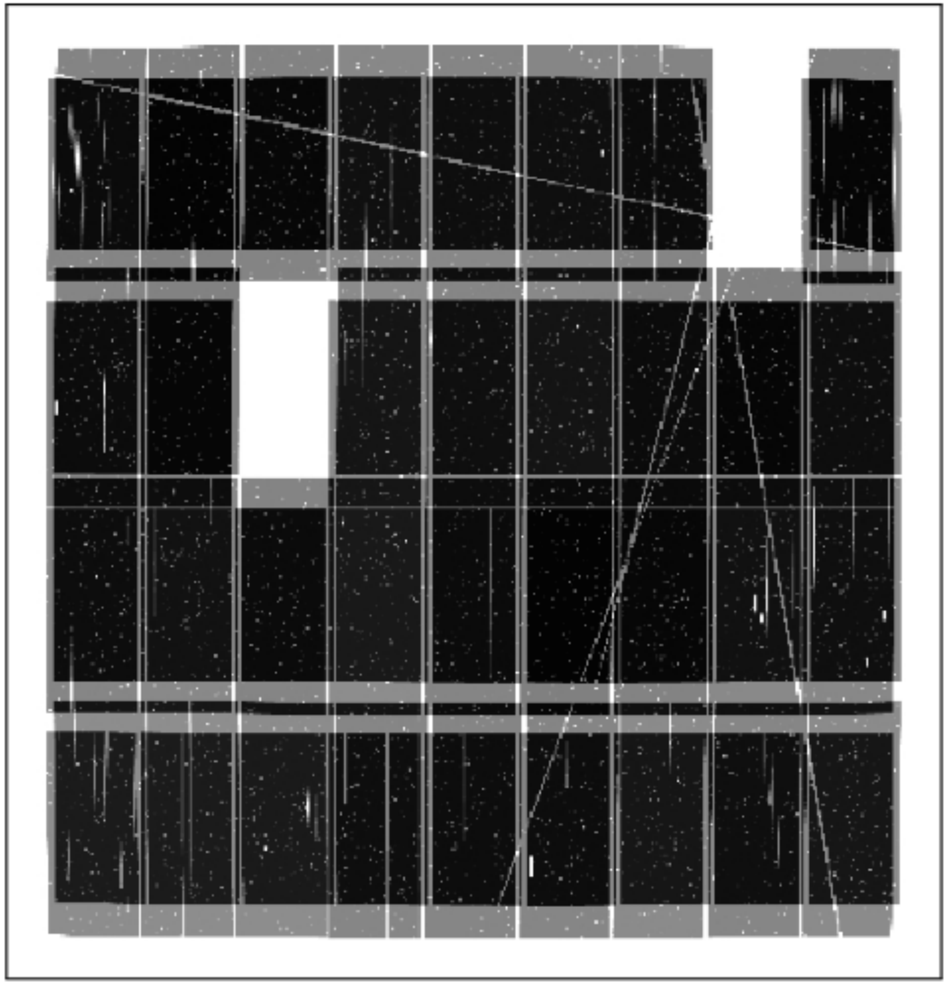
Model fitting methods



Forward model-fitting (example *lens*fit)

- Convolution of model with PSF instead of devonvolution of image
- Combine multiple exposures (in Bayesian way, multiply posterior density), avoiding co-adding of (dithered) images

Dithering

Left: Co-add of two r-band exposures of CFHTLenS.
Right: Weight map.

Moment-based methods I

Moments and ellipticity

How are moments connected to ellipticity?

Q: Simple case: qualitatively, what are the $0^{\rm th}, 1^{\rm st}, 2^{\rm nd}$ moments of a 1D distribution? Of a 2D distribution?

Quadrupole moment of weighted light distribution $I(\boldsymbol{\theta})$:

$$Q_{ij} = \frac{\int \mathrm{d}^2\theta \, q[I(\boldsymbol{\theta})] \, (\theta_i - \bar\theta_i)(\theta_j - \bar\theta_j)}{\int \mathrm{d}^2 \, \theta \, q[I(\boldsymbol{\theta})]}, \quad i, j = 1, 2$$

q : weight function

$$\bar{\boldsymbol{\theta}} = \frac{\int \mathrm{d}^2\theta \, q_I[I(\boldsymbol{\theta})] \, \boldsymbol{\theta}}{\int \mathrm{d}^2\theta \, q_I[I(\boldsymbol{\theta})]} : \quad \text{barycenter (first moment!)}$$

Ellipticity

$$\varepsilon = \frac{Q_{11} - Q_{22} + 2\mathrm{i}Q_{12}}{Q_{11} + Q_{22} + 2(Q_{11}Q_{22} - Q_{12}^2)^{1/2}}$$

Circular object $Q_{11} = Q_{22}, Q_{12} = Q_{21} = 0$

Moment-based methods II

KSB PSF correction

Perturbative ansatz for PSF effects

$$\varepsilon^{\rm obs} = \varepsilon^{\rm s} + P^{\rm sm}\varepsilon^* + P^{\rm sh}\gamma$$

[c.f. $\varepsilon^{\rm obs} = \varepsilon^{\rm s} + \gamma$ from before]

$P^{\rm sm}$	smear polarisability, (linear) response of to ellipticity to PSF anisotropy
e^*	PSF anisotropy
$P^{\rm sh}$	shear polarisability, isotropic seeing correction
γ	shear

$P^{\rm sm}, P^{\rm sh}$ are functions (2×2 tensors) of galaxy brightness distribution.

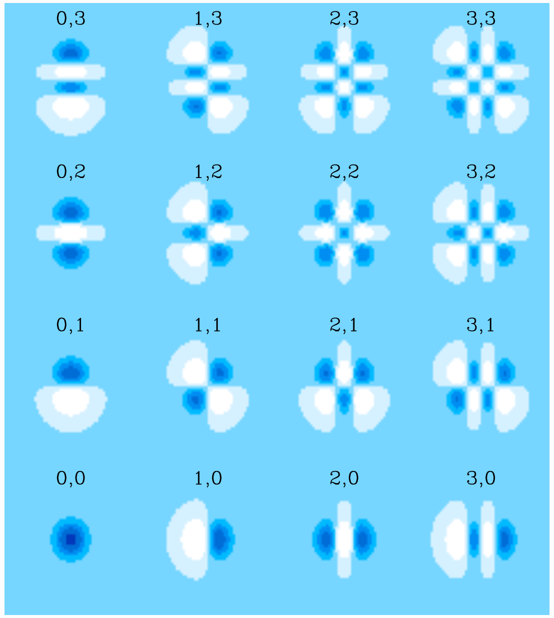
Problematic: Strongly anisotropic PSF, error estimation, combining multiple exposures.

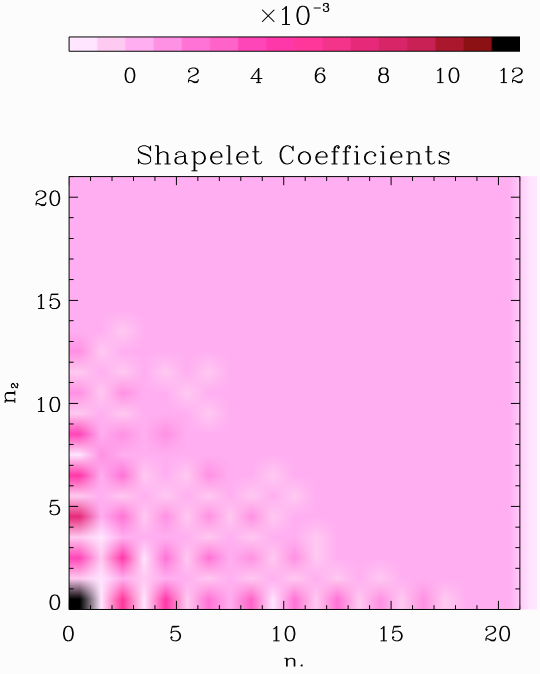
Non-perturbative methods

Shapelets

(Refregier 2003, Massey & Refregier 2005, Kuijken 2006)

- Decompose galaxies and stars into basis functions.





- PSF correction, convergence and shear acts on shapelet coefficients, deconvolution feasible
- Problems: series truncation, basis functions not representative, need to set size parameter

Further methods and techniques

- Generic approaches of shape estimation and/or calibration (can be used together with many shape-measurement methods)
  - Machine-Learning, e.g. LUT by supervised learning, (Tewes et al. 2012)
  - Self-calibration (Fenech Conti et al. 2017)
  - MetaCalibration (Sheldon & Huff 2017, Huff & Mandelbaum 2017)
- Further Bayesian methods
  - Hierarchical Multi-level Bayesian Inference (MBI), (Schneider et al. 2014). Joint posterior of shear, galaxy properties, PSF, nuisance parameters given pixel data.
  - (Bernstein & Armstrong 2014). Does not measure ellipticity of individual galaxies, direct posterior estimation of shear for population. Needs prior from deep images.

Shear measurement biases: Origin

- **Noise bias**
  In general, ellipticity is non-linear in pixel data (e.g. normalization by flux). Pixel noise $\to$ biased estimators.
- **Model bias**
  Assumption about galaxy light distribution is in general wrong.
  - Model-fitting method: wrong model
  - Perturbative methods (*KSB*, *DEIMOS*, *HOLICS*): weight function not appropriate
  - Non-perturbative methods (*shapelets*): truncated expansion, bad eigenfunction representation
  - Color gradients
  - Non-elliptical isophotes
- **Other**
  - Imperfect PSF correction
  - Detector effects (CTI — charge transfer inefficiency)
  - Selection effects (probab. of detection/sucessful ε measurement depends on ε and PSF)

Shear measurement biases: Characterisation

Bias can be multiplicative ($\boldsymbol{m}$) and additive ($\boldsymbol{c}$):

$$\gamma_i^{\rm obs} = (1 + m_i)\gamma_i^{\rm true} + c_i; \quad i = 1, 2.$$

Biases $\boldsymbol{m}$, $\boldsymbol{c}$ are typically complicated functions of galaxy properties (e.g. size, magnitude, ellipticity), redshift, PSF, ... They can be scale-dependent.

Current methods: $|m| = 1\% - 10\%, |c| = 10^{-3} - 10^{-2}$.

Challenges such as STEP1, STEP2, great08, great10, great3 quantified these biases with blind simulationes.

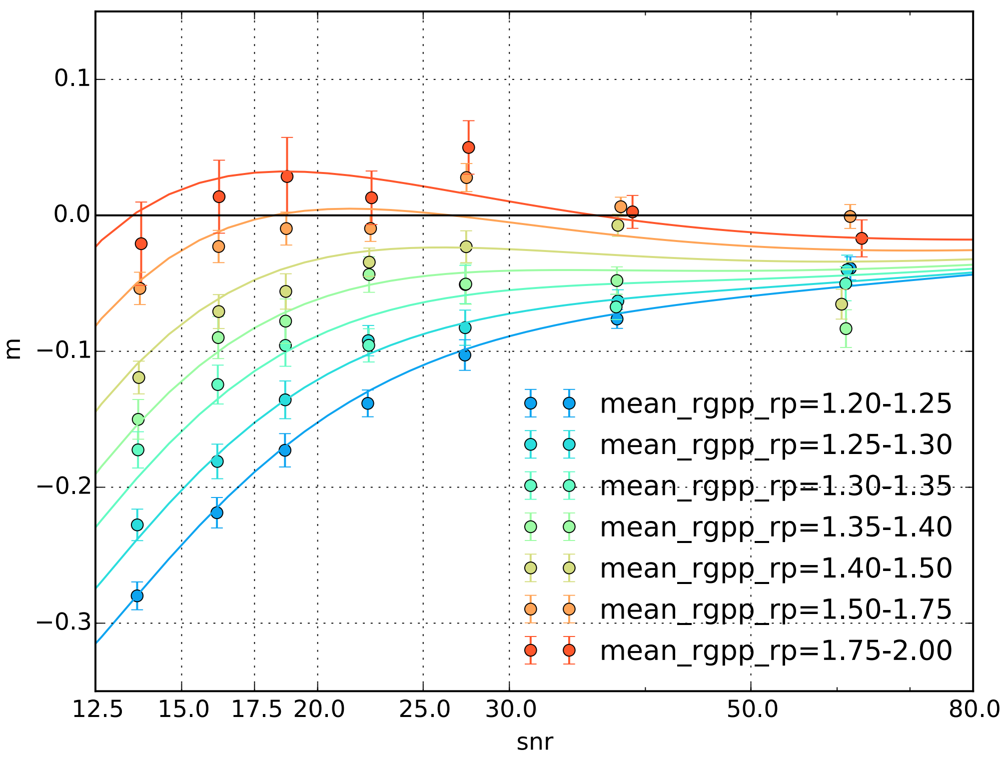
Requirements

Normalisation $\sigma_8 \propto m$!
Necessary knowledge of residual biases $|\Delta m|, |\Delta c|$ (after calibration):
Current surveys 1%.
Future large missions (Euclid, LSST, ...) $10^{-4} = 0.1\%$!

Shear measurement biases: Calibration

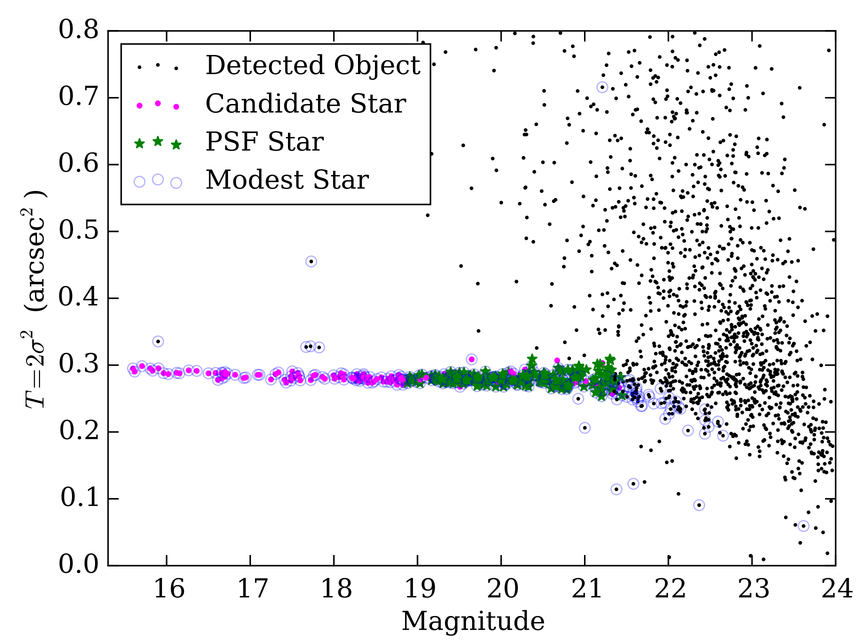
Usually biases are calibrated using simulated or emulated data, or the data (self-calibration, metacalibration) themselves.
Current surveys typicall produce corresponding image simulations with matching properties of galaxy sample, selection, and PSF matching to data.

Functional dependence of m on observables must not be too complicated (e.g. not smooth, many variables, large parameter space), or else measurement is *not calibratable*!



(Jarvis et al. 2016)

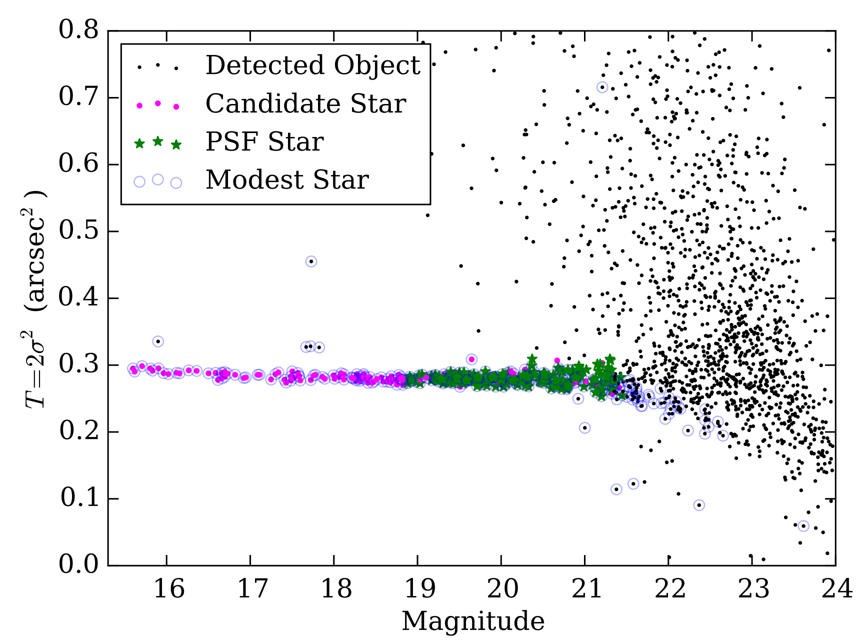
PSF correction



(Jarvis et al. 2016)

- Select clean sample of stars
- Measure star shapes
- Create PSF model and interpolate (pixel values, ellipticity, PCA coefficients, ...) to galaxy positions. Space-based observations: global PSF model from many exposures possible
- Correct for PSF: galaxy image devonvolution or other (e.g. linearized) correction, or convolve model

PSF correction



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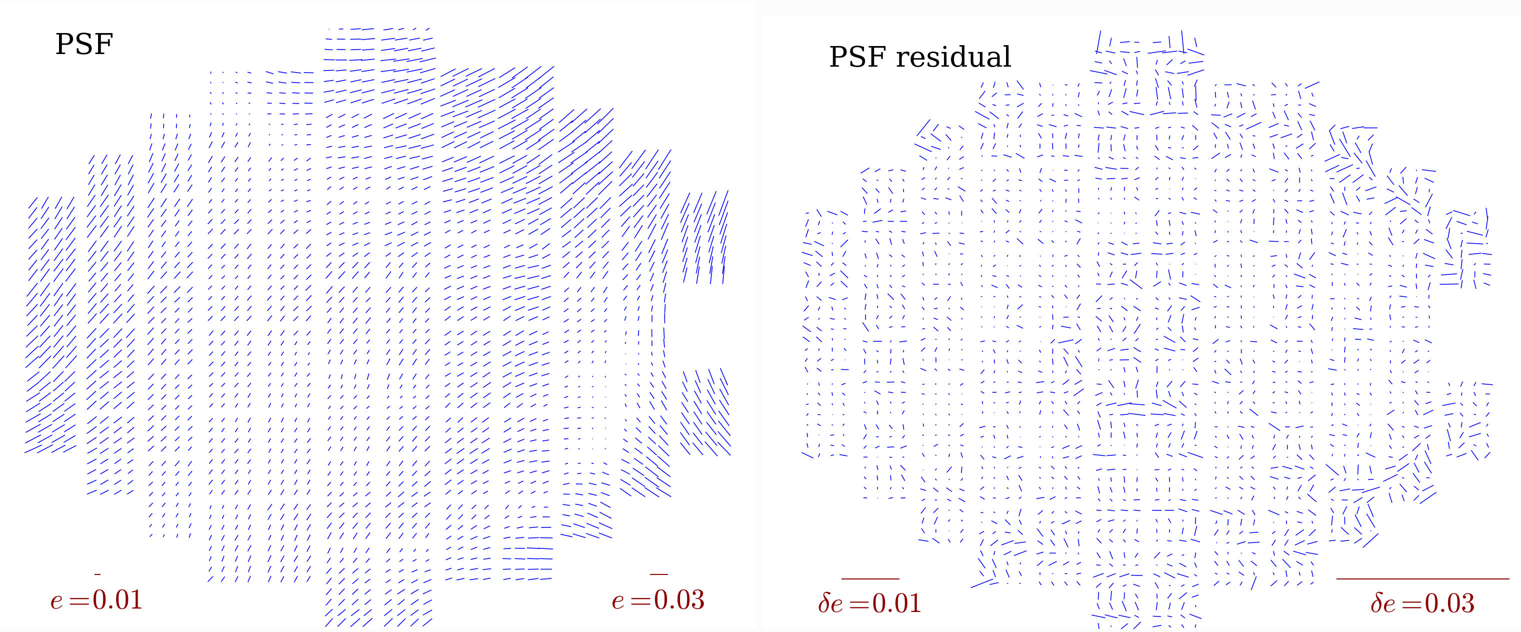

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