Shape Measurement: An introduction to KSB

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DUEL Weak Lensing School
September 2009

at the end of the week you'll be able to....

- Use SExtractor to detect astronomical sources in multi-colour data
- Make simulated astronomical images
- Separate stars from the galaxies and model the PSF
- Measure weak lensing shear using KSB
- Measure photometric redshifts
- Make a dark matter map

Practicalities

- 28 students, 14 computers: find a partner
  - Recommendation - choose someone you don't know well
- Presentations
  - On Friday, 7 groups of 4 will give 10 minute summary presentations on different parts of the course (assigned randomly on Thurs afternoon)

Outline

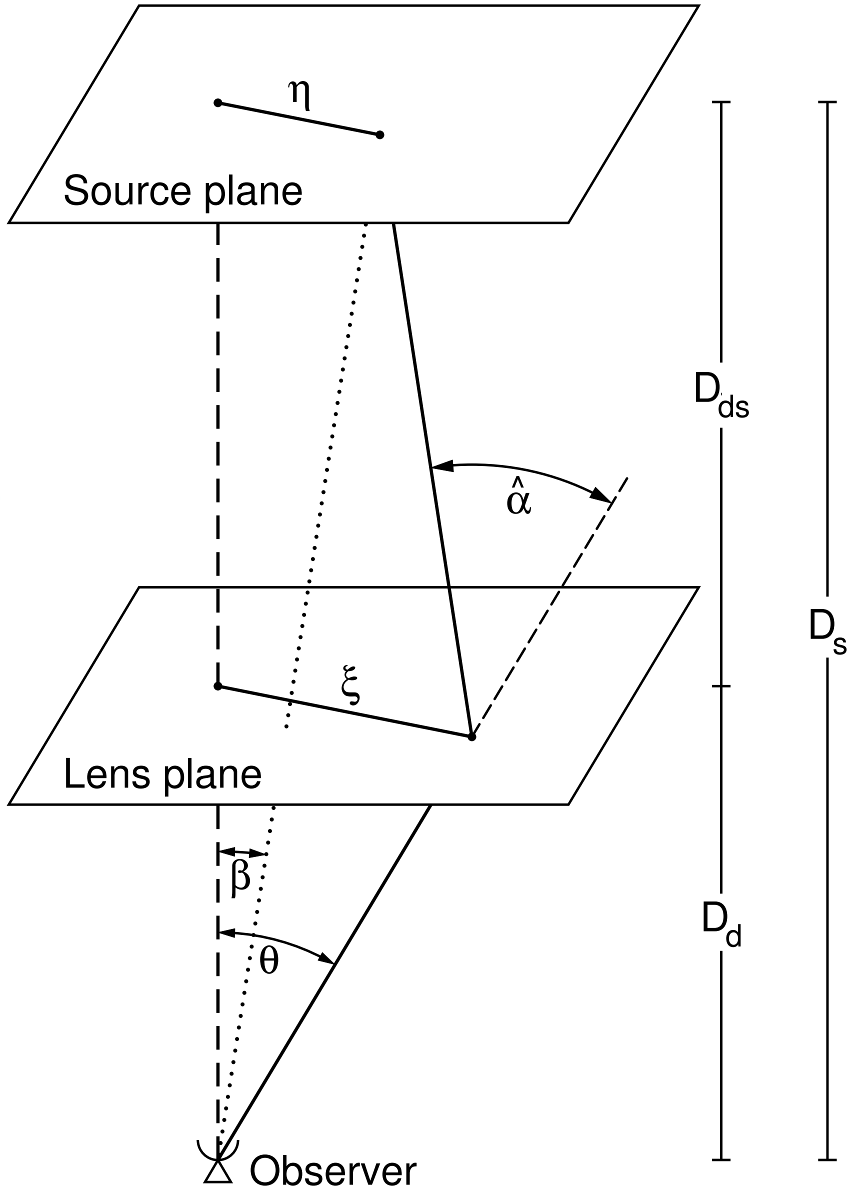
- Recap: Weak lensing in practice, from galaxy to CCD pixel
- Shape measurement methods - and why we'll be teaching you KSB
- Recap: KSB
- Introduction to Tuesdays practical - running KSB on simulated images

Recap on week 1

$$A_{ij} = \frac{\delta\beta_i}{\delta\theta_j}$$ ← true position ($\delta\beta_i$) ← lensed position ($\delta\theta_j$)

$$A = \begin{pmatrix} 1-\kappa-\gamma_1 & -\gamma_2 \\ -\gamma_2 & 1-\kappa+\gamma_1 \end{pmatrix},$$

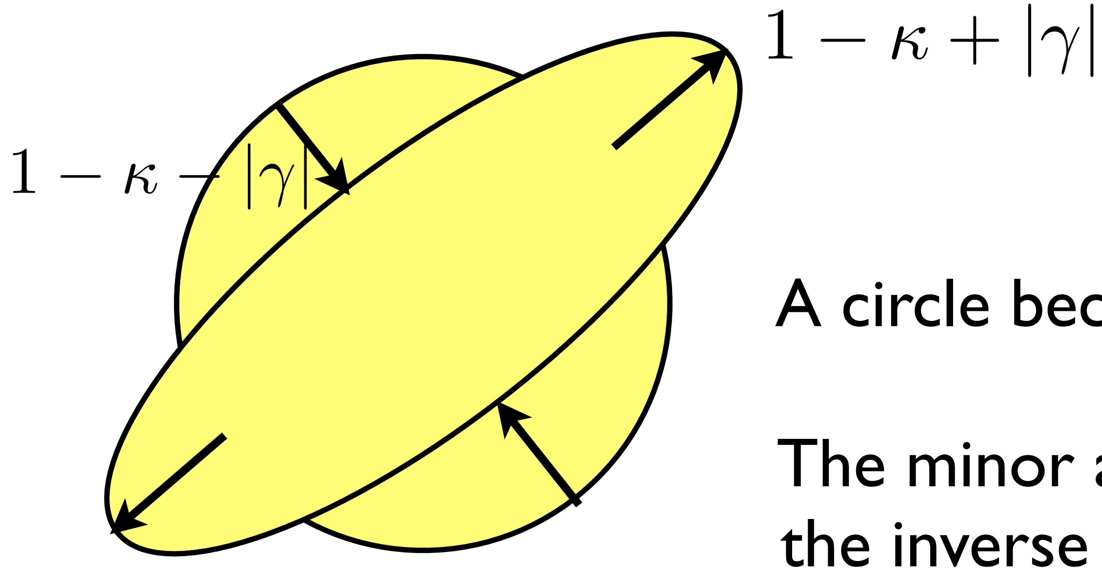
- The lensing Jacobian maps the source to the image plane.
- The effect depends on the lensing potential, through the shear and convergence terms
- We want to measure the convergence (mass), but we can only observe the shear.



What happens to a circular source?

$$I(\vec{\theta}) = I^{(s)}\left[\vec{\beta}_0 + \mathcal{A}(\vec{\theta}_0)\cdot(\vec{\theta}-\vec{\theta}_0)\right]$$

The observed image = The true image distorted by A



A circle becomes an ellipse.

The minor and major axes given by the inverse of the eigenvalues of A.

The orientation is given by the eigenvectors of A

Centroids and Quadrupole Moments

- Lensing changes the shapes of galaxies, so we need a statistic with which to quantify their shape.
- The first moment determines an objects centroid

$$\begin{aligned}\bar{x} &= \int I(x,y)\, x \,\mathrm{d}x\, \mathrm{d}y \\ \bar{y} &= \int I(x,y)\, y \,\mathrm{d}x\, \mathrm{d}y \ ,\end{aligned}$$

- The second moment (or quadrupole moments determines shape)

$$\begin{aligned}Q_{xx} &= \int I(x,y)\,(x-\bar{x})^2 \,\mathrm{d}x\, \mathrm{d}y \\ Q_{xy} &= \int I(x,y)\,(x-\bar{x})(y-\bar{y}) \,\mathrm{d}x\, \mathrm{d}y \\ Q_{yy} &= \int I(x,y)\,(y-\bar{y})^2 \,\mathrm{d}x\, \mathrm{d}y.\end{aligned}$$

Quadrupoles, ellipticity and shear

$$\epsilon \equiv \epsilon_1 + i\epsilon_2 = \frac{Q_{xx} - Q_{yy} + 2iQ_{xy}}{Q_{xx} + Q_{yy} + 2(Q_{xx}Q_{yy} - Q_{xy}^2)^{1/2}} \,,$$

$$\begin{aligned} \epsilon_1 &= \frac{a-b}{a+b}\cos(2\theta) \\ \epsilon_2 &= \frac{a-b}{a+b}\sin(2\theta). \end{aligned}$$

$$Q^{(s)} = \mathcal{A}\, Q\, \mathcal{A}^T$$

$$\boxed{\epsilon_{obs} = \frac{\epsilon^s + g}{1 + g^* \epsilon^s}}$$

Lensing of an elliptical source

Observables : Galaxy Ellipticity

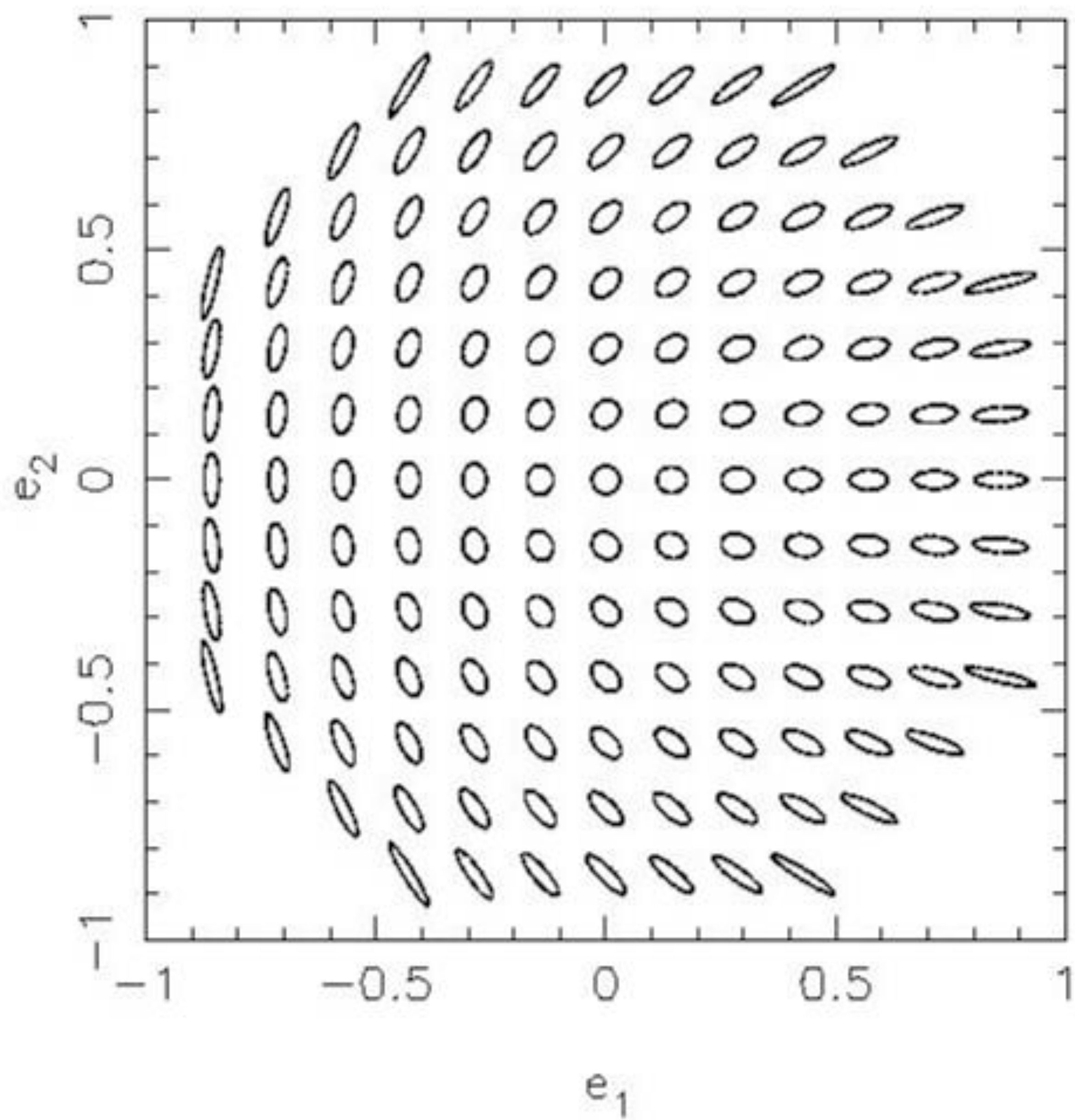
$$e^{\rm obs} = e^{\rm source} + \gamma$$

$$< e^{\rm source} >= 0$$

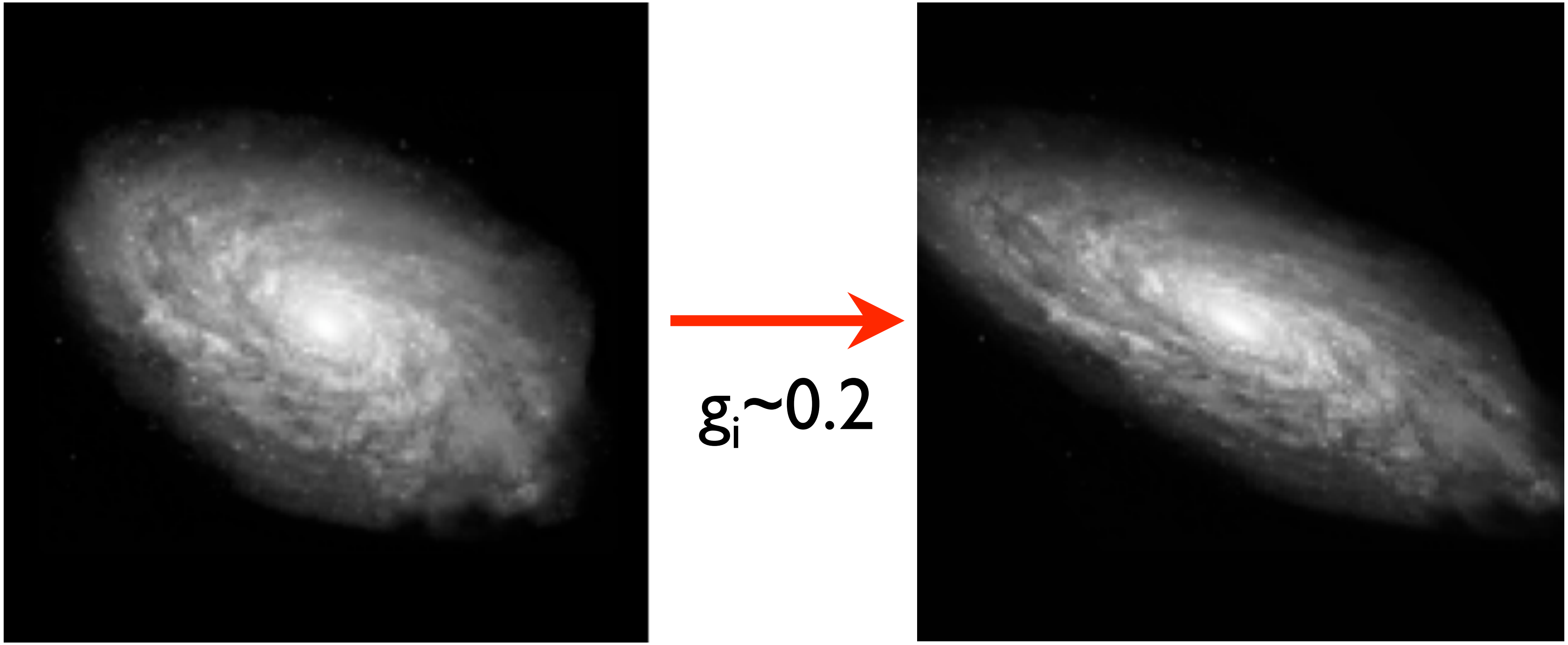
$$\gamma =< e^{\rm obs} >$$

So it's easy! Measure the ellipticity, you have the shear and all knowledge of cosmology?

Sadly not - instrumental, atmospheric and physical distortions are an order of magnitude larger than the weak lensing signal you want to detect.



Cosmic Lensing



$$\begin{pmatrix} x_u \\ y_u \end{pmatrix} = \begin{pmatrix} 1-g_1 & -g_2 \\ -g_2 & 1+g_1 \end{pmatrix} \begin{pmatrix} x_l \\ y_l \end{pmatrix}$$

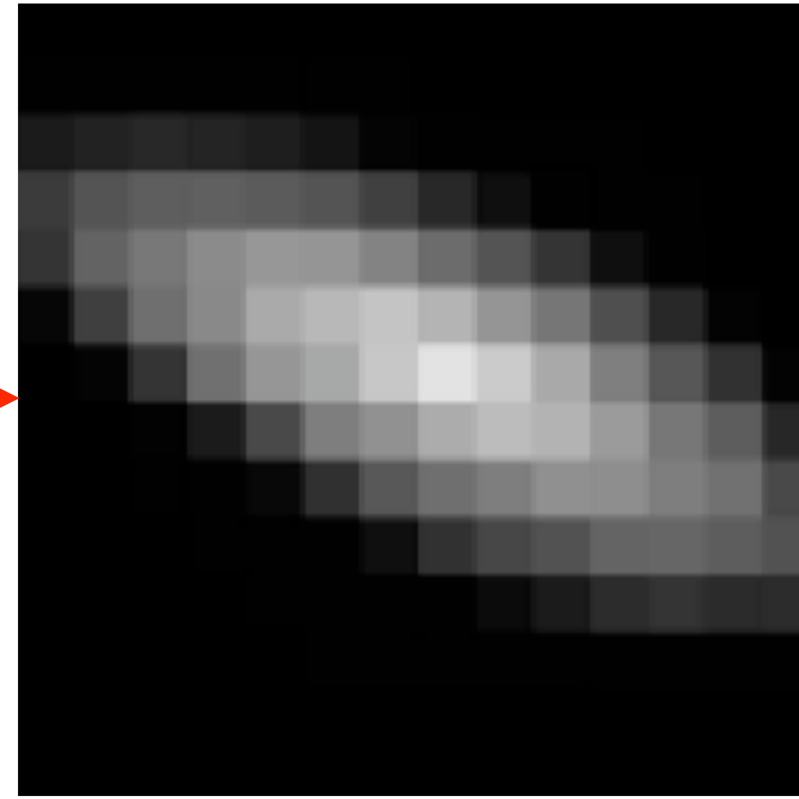
Real data:
g_i~0.03

Atmosphere and Telescope

Atmospheric Seeing and telescope PSF

Real data: seeing disk ~ Galaxy size

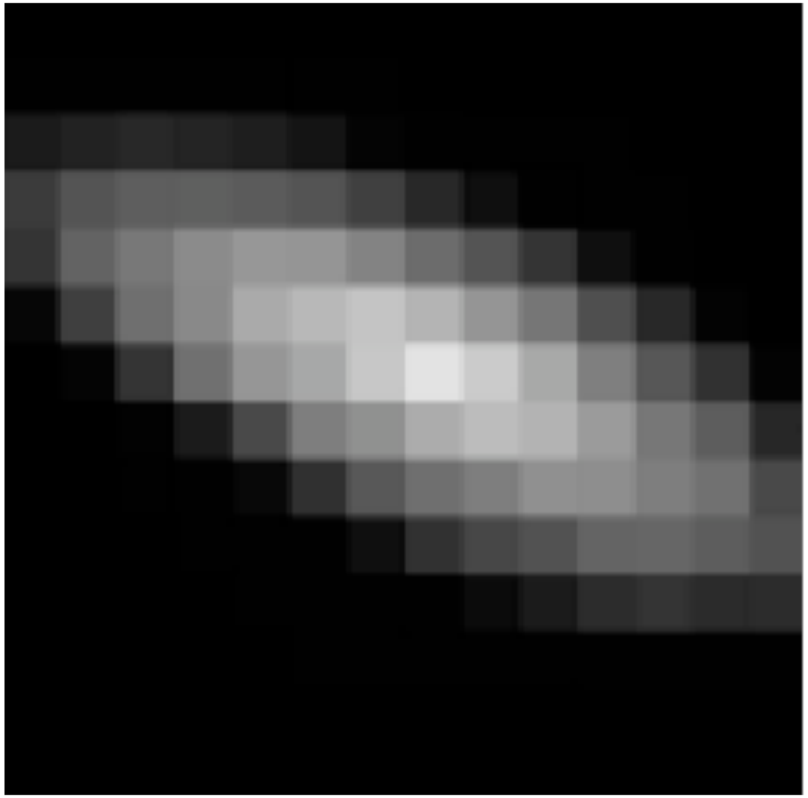
Pixelisation

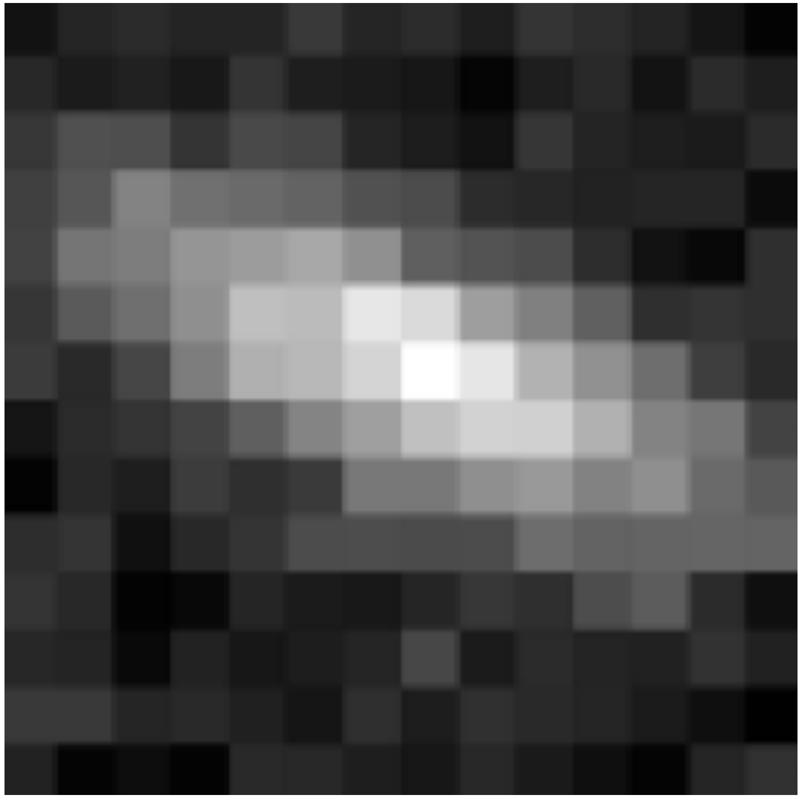


Sum light in each square

Real data: Pixel size ~ seeing size /3

Noise



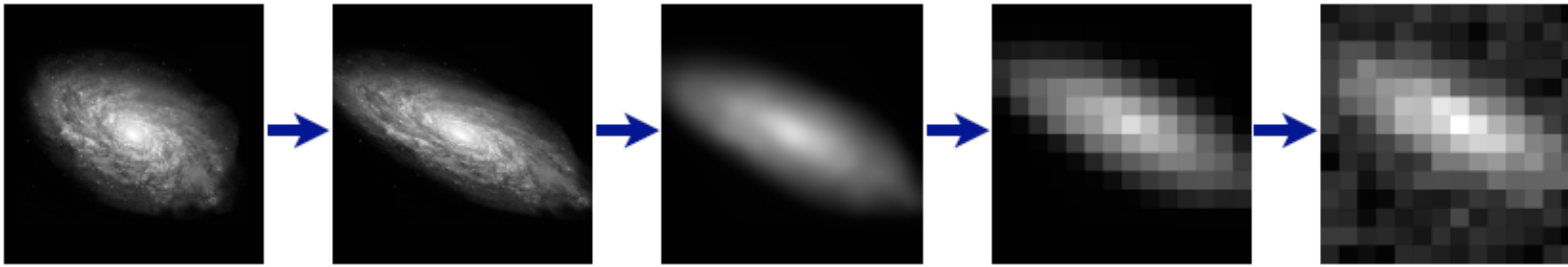


Mostly Poisson. Some Gaussian and bad pixels.
Uncertainty on total light ~ 5 per cent

From Galaxy and Star to CCD

The Forward Process.

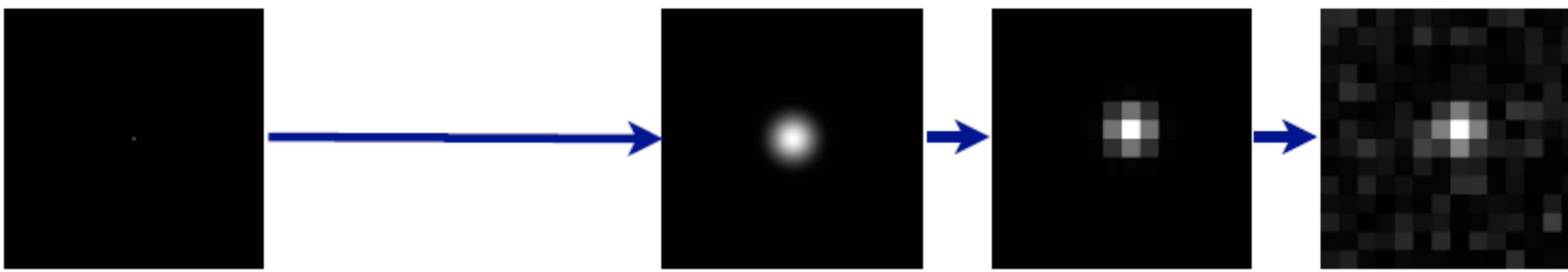
Galaxies: Intrinsic galaxy shapes to measured image:



Intrinsic galaxy (shape unknown) | Gravitational lensing causes a ***shear (g)*** | Atmosphere and telescope cause a convolution | Detectors measure a pixelated image | Image also contains noise

PSF

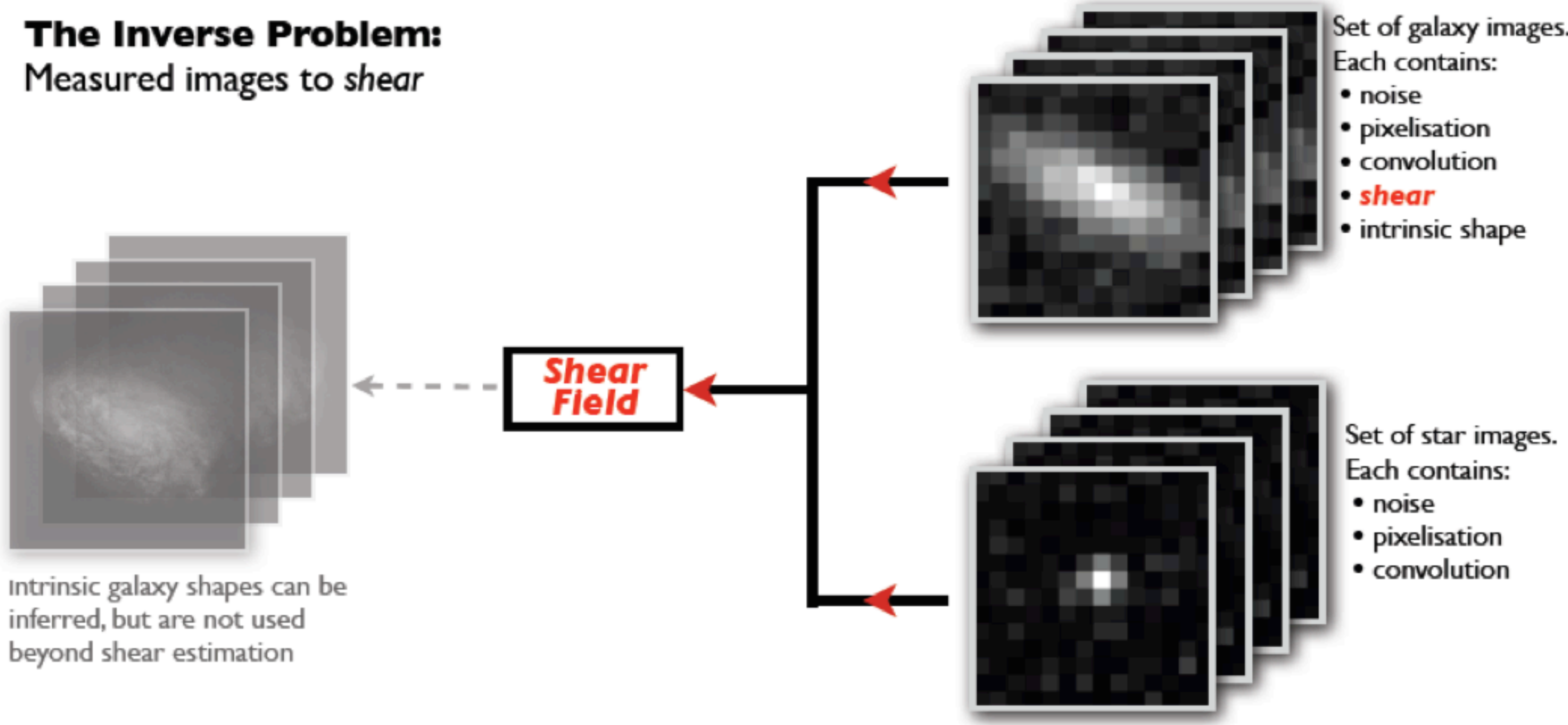
Stars: Point sources to star images:



Intrinsic star (point source) | Atmosphere and telescope cause a convolution | Detectors measure a pixelated image | Image also contains noise

Weak lensing analyses reverse this process

The Inverse Problem:
Measured images to *shear*



Steps to creating a shear catalogue

1. Reduce your data well
2. Detect objects
3. Separate stars from galaxies
4. Model the PSF with the stars
5. Remove the effect of the PSF
6. Measure the galaxy shape

Shape Measurement Methods only differ in parts 5 and 6

Classification of different methods

PSF correction scheme	Shear measurement method: **Passive** Measure a number	Shear measurement method: **Active** Fit a number
Subtraction	KSB+ (various) Reglens (RM) RRG* K2K* Ellipto*	BJ02 (MJ, MJ2)
Deconvolution	Shapelets (JB)	Shapelets (KK) BJ02 (RN) im2shape*

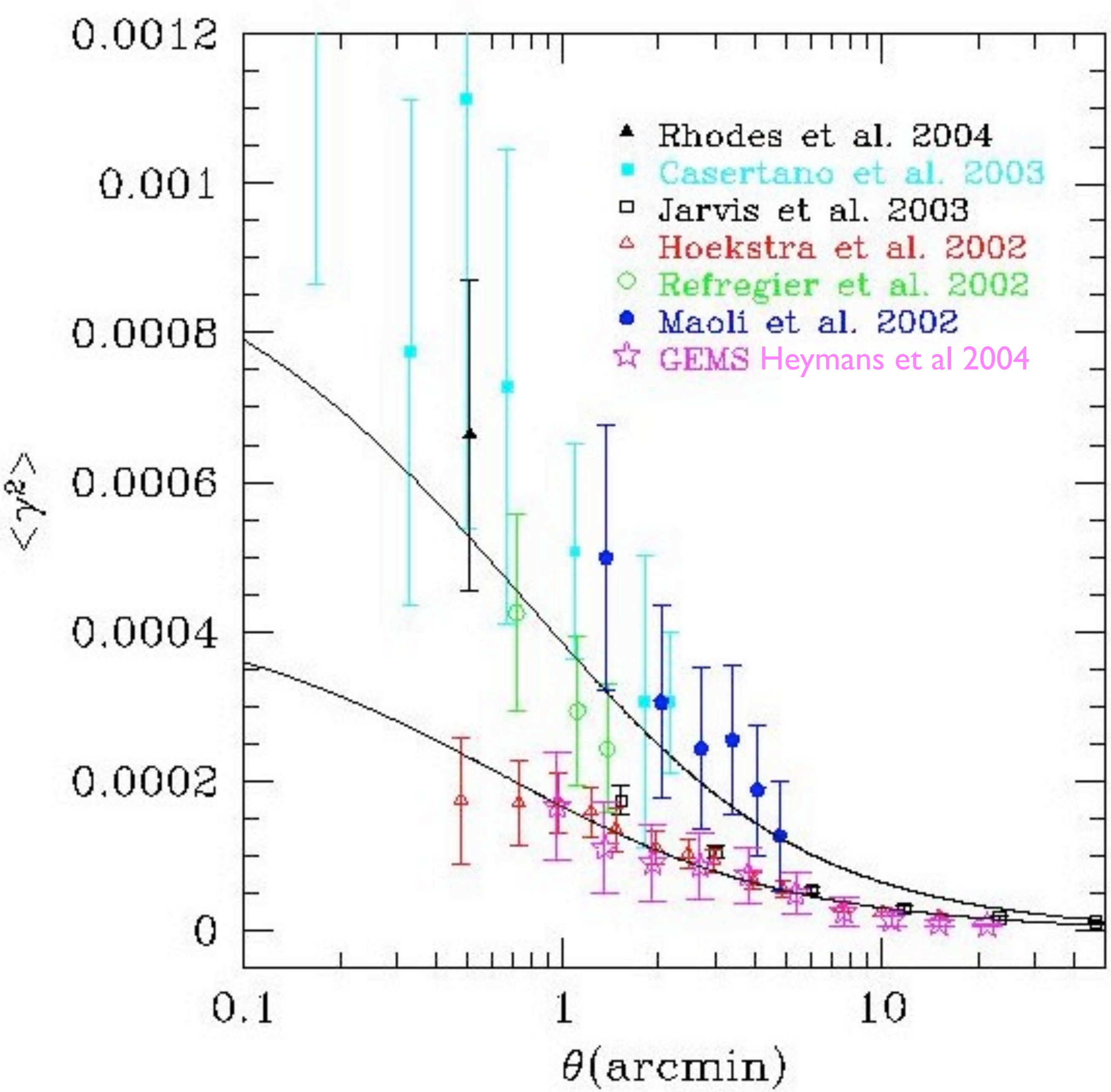
The Shear TEsting Programme: STEP

- STEP started in 2005 to address the question of whether variations in the accuracy of different shear measurement pipelines could be responsible for the discrepancies found between different cosmic shear results.

Cosmological model: ΛCDM

upper curve $\sigma_8 = 0.7$

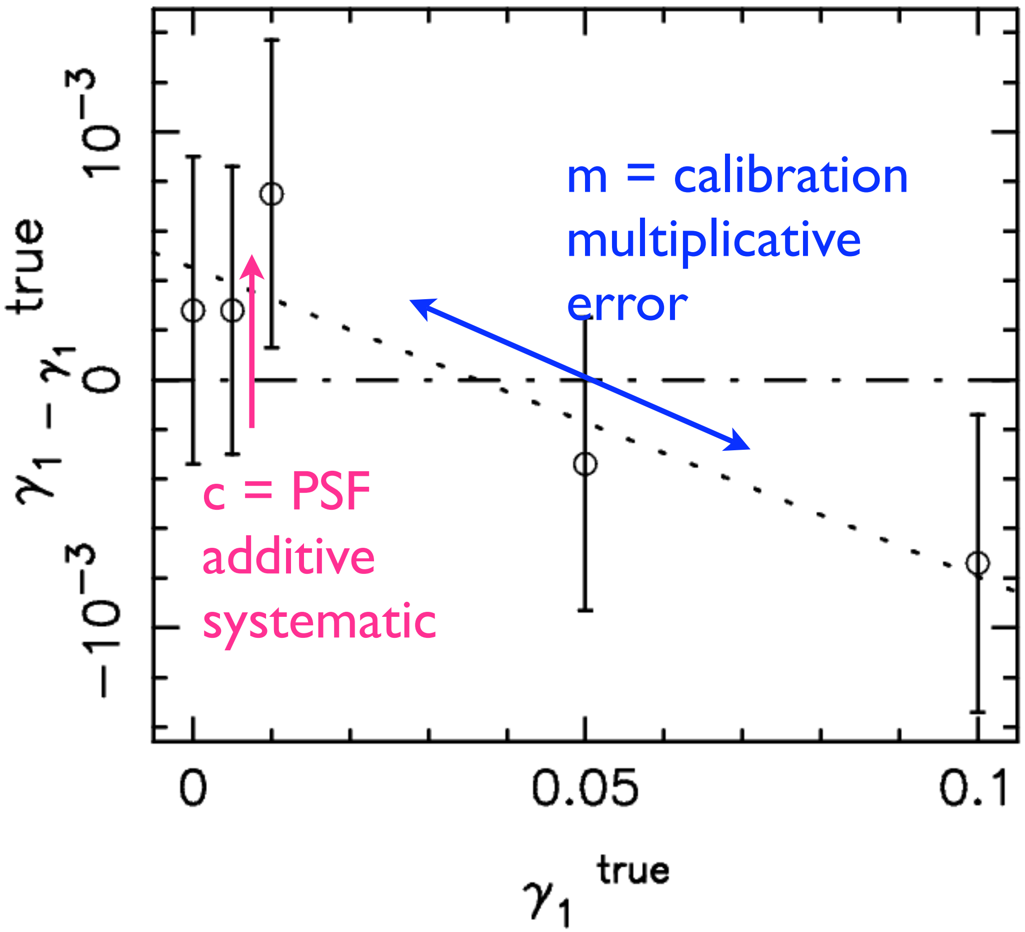
lower curve $\sigma_8 = 1.0$



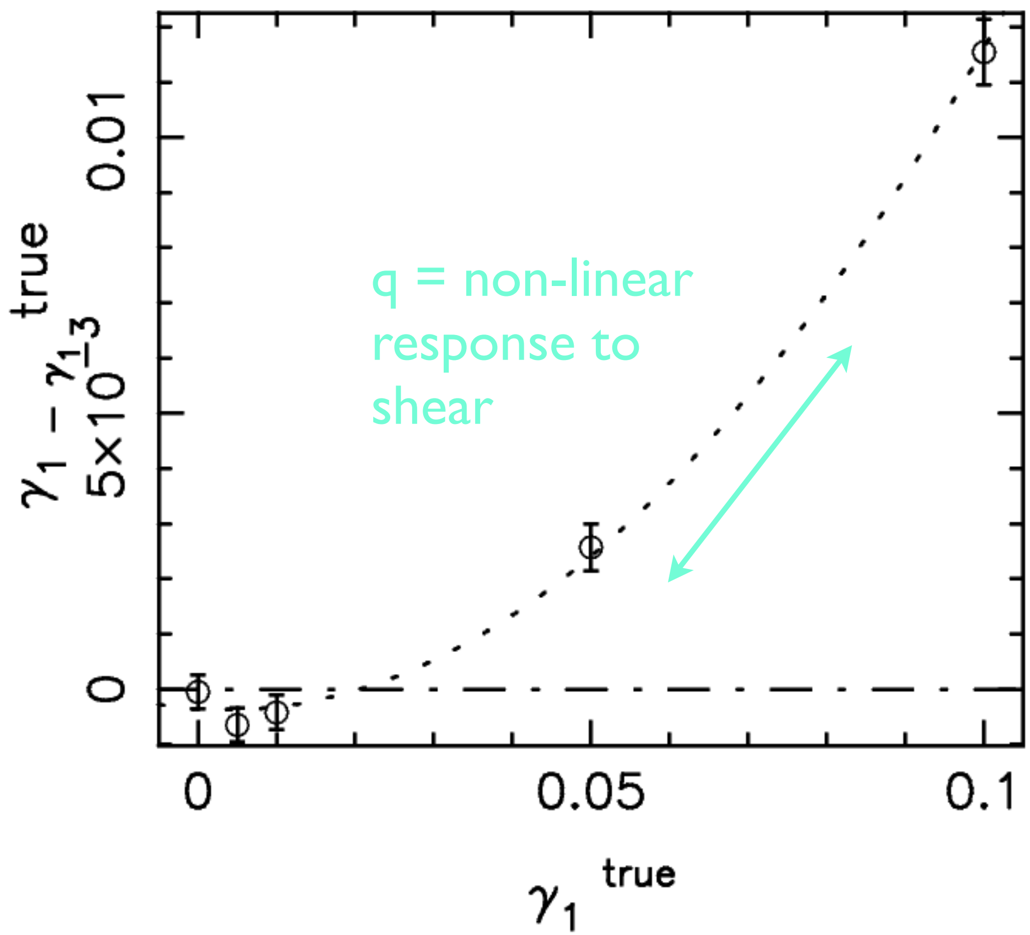
STEP parameters: m and c

$$(\gamma_{measured} - \gamma_{true}) = c + m\gamma_{true} + q\gamma_{true}^2$$

The best method has m=0 and c=0



KSB example



BJ02 example

Weak lensing shear measurement

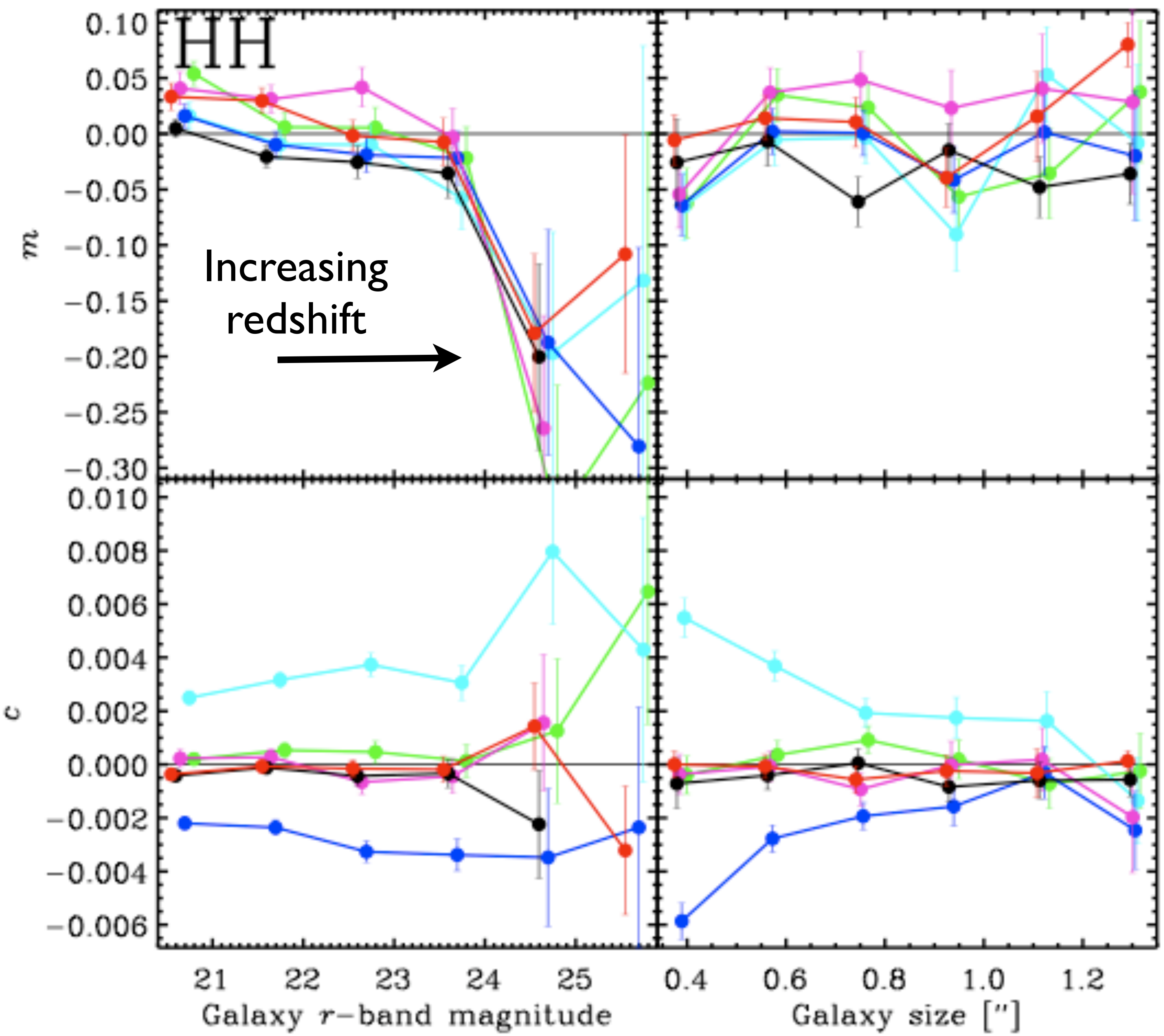
The Forward Process.

Galaxies: Intrinsic galaxy shapes to measured image:

Intrinsic galaxy (shape unknown) → Gravitational lensing causes a ***shear (g)*** → Atmosphere and telescope cause a convolution → Detectors measure a pixelated image → Image also contains noise

- The Kaiser Squires and Broadhurst method (KSB) is the most widely used method in current weak lensing analyses.
- It uses stars to model the the atmosphere and telescope distortion and essentially subtracts it from the data.
- The end product is a shear estimate for each galaxy.

Shear bias as a function of galaxy magnitude and size



- These biases average out when the full sample is combined
- This result found in all but one of the tested methods is a disaster for 3D weak lensing and any hope of measuring dark energy.

KSB (Kaiser, Squires and Broadhurst 1995)

Reasons to use KSB

1. It's several orders of magnitude faster than all other methods
2. It's accurate to the percent level on average
3. For large high signal-to-noise galaxies it's very accurate

Reasons to not use KSB

1. It is unstable to small changes in the method
2. It has size and magnitude dependent biases
3. For small low signal-to-noise galaxies it's very inaccurate

Why are we teaching it to you?

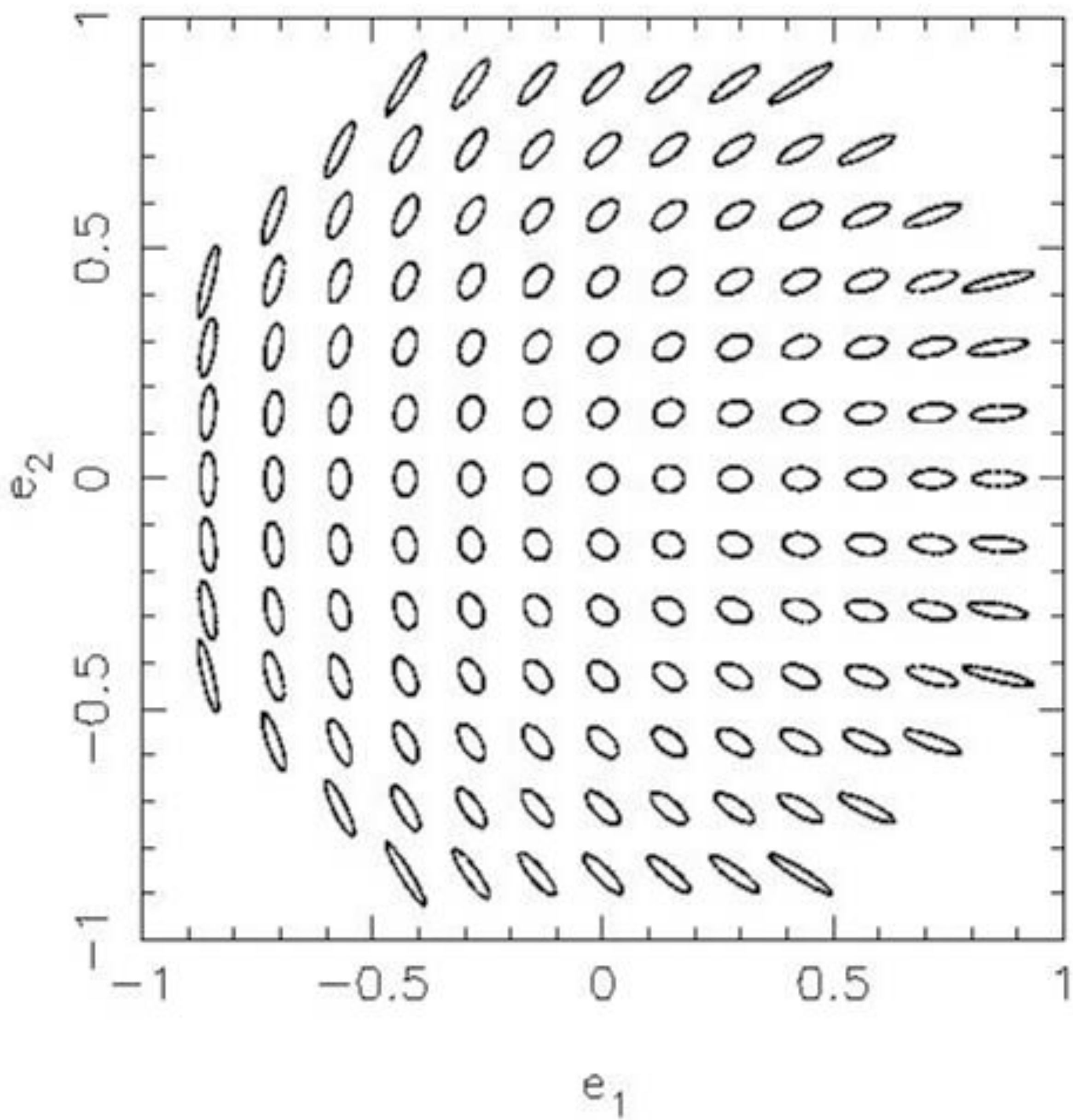
For a first pass analysis of the data KSB is excellent. Lensfit (see last lecture) is the only method suited to data that surpasses KSB, but it's still evolving. The steps you'll take in the KSB analysis are broadly common to all weak lensing methods.

Observables : Galaxy Ellipticity

$$e^{\mathrm{obs}} = e^{\mathrm{source}} + \gamma$$

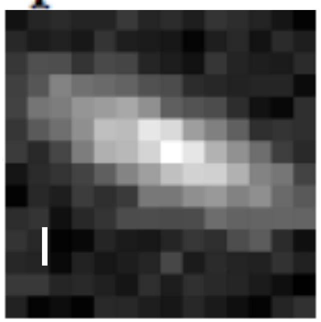
$$< e^{\mathrm{source}} > = 0$$

$$\gamma = < e^{\mathrm{obs}} >$$

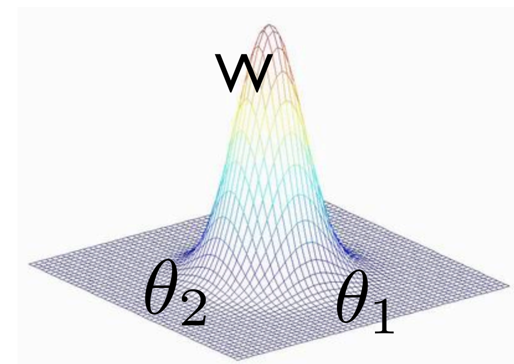


Ellipticity and Quadrupole Moments

Objects are parameterised according to their weighted quadrupole moments



$$Q_{ij} = \frac{\int d^2\theta \, W(\boldsymbol{\theta}) \, I(\boldsymbol{\theta}) \, \theta_i \theta_j}{\int d^2\theta \, W(\boldsymbol{\theta}) \, I(\boldsymbol{\theta})},$$



where I is the surface brightness of the object, θ is the angular distance from the object centre and W is a Gaussian weight function of scale length r_g, where r_g is some measurement of galaxy size.

Quadrupoles, ellipticity and shear

$$\epsilon \equiv \epsilon_1 + i\epsilon_2 = \frac{Q_{xx} - Q_{yy} + 2iQ_{xy}}{Q_{xx} + Q_{yy} + 2(Q_{xx}Q_{yy} - Q_{xy}^2)^{1/2}},$$

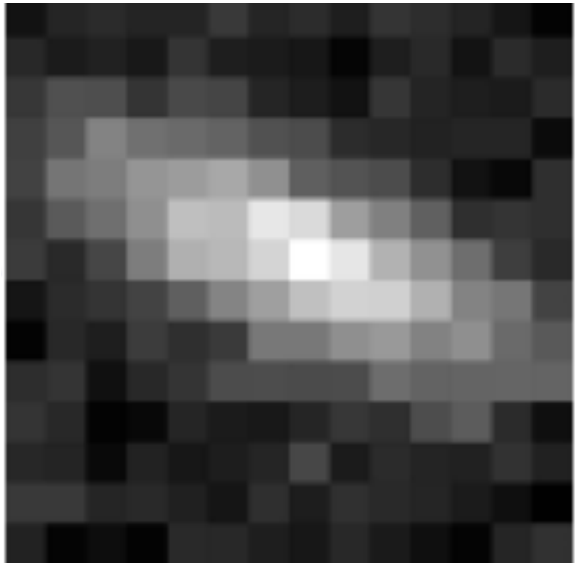
$$\begin{aligned} \epsilon_1 &= \frac{a-b}{a+b}\cos(2\theta) \\ \epsilon_2 &= \frac{a-b}{a+b}\sin(2\theta). \end{aligned}$$

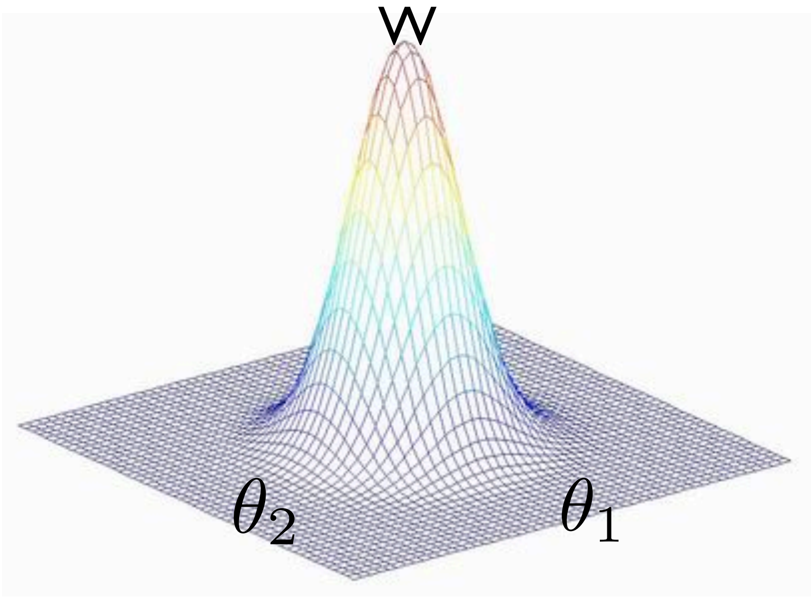
$$Q^{(s)} = \mathcal{A}\, Q\, \mathcal{A}^T$$

$$\boxed{\epsilon_{obs} = \frac{\epsilon^s + g}{1 + g^*\epsilon^s}}$$

Lensing of an elliptical source

Weighted and unweighted quadrupole moments





- If you do not include a weight, or make the size of the weight function too big, noise will bias your quadrupole moment
- However including this weight means the simple relationship between shear and ellipticity no longer applies.
- KSB calculate how a weighted ellipticity measure is related to the shear and use the same formalism to remove the effects of the PSF

The anisotropy correction

Kaiser et al. (1995) show that if the PSF distortion can be described as a small but highly anisotropic distortion convolved with a large circularly symmetric seeing disk, then the ellipticity of a PSF corrected galaxy is given by

$$\varepsilon_\alpha^{\rm cor} = \varepsilon_\alpha^{\rm obs} - P_{\alpha\beta}^{\rm sm} p_\beta , \tag{4}$$

corrected ellipticity

observed ellipticity

how easily the galaxy responds to the PSF

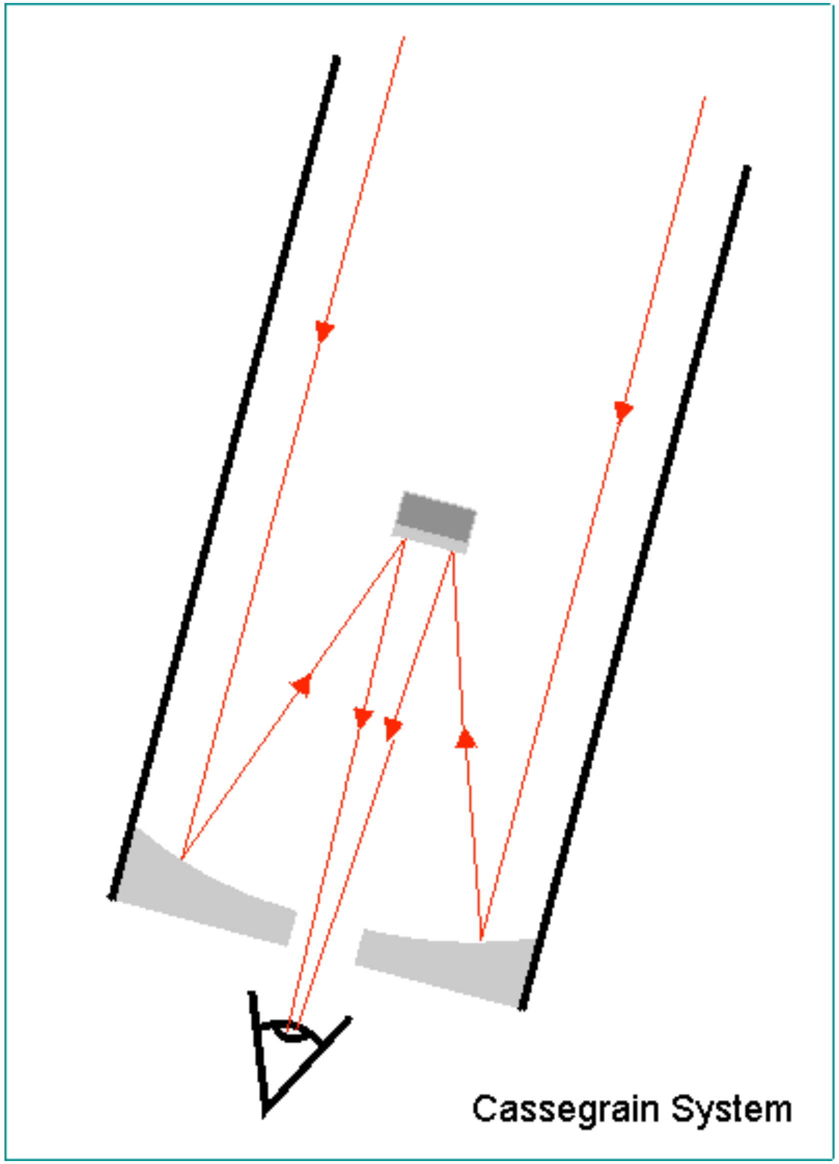
psf ellipticity

As the corrected stellar ellipticity must be zero

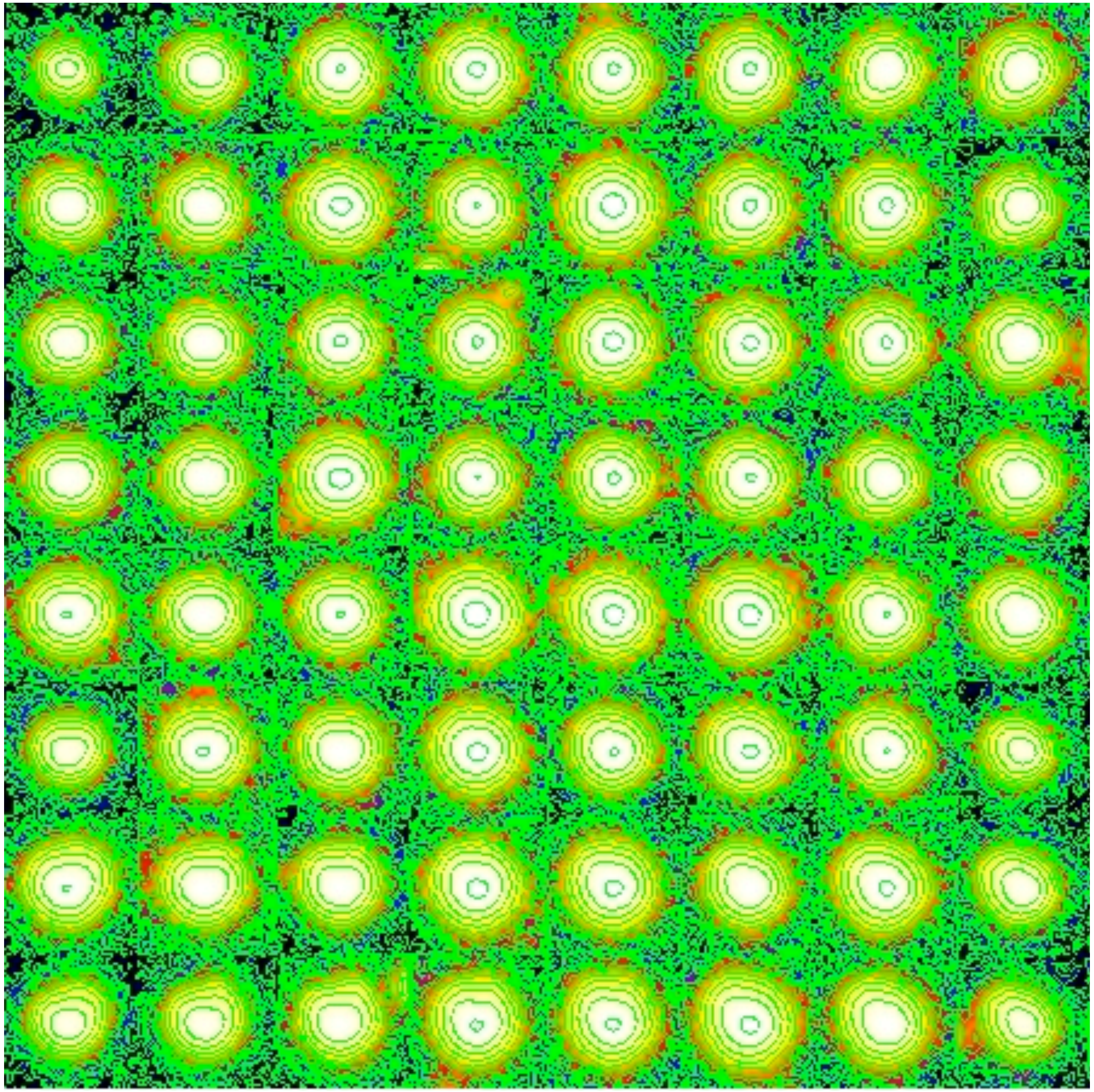
$$p_\mu = (P^{\rm sm*})^{-1}_{\mu\alpha}\, \varepsilon_\alpha^{\rm *obs} .$$

Modelling the PSF in practise

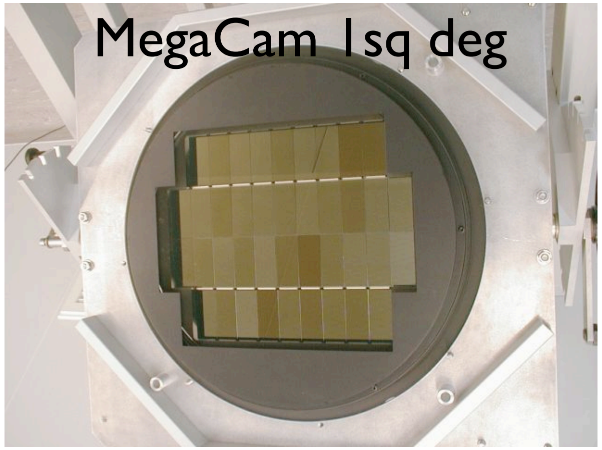
- The atmosphere causes circular smearing.
- Differences in the optical light path cause shearing.
- In principle the distortions introduces by the telescope and detector can be predicted.
- In practise many other factors effect the PSF including the the angle observed on the sky, the temperature, the filter etc.
- We therefore have to be able to model the PSF directly from the data using stars.



Example PSFs: CFHT Megacam

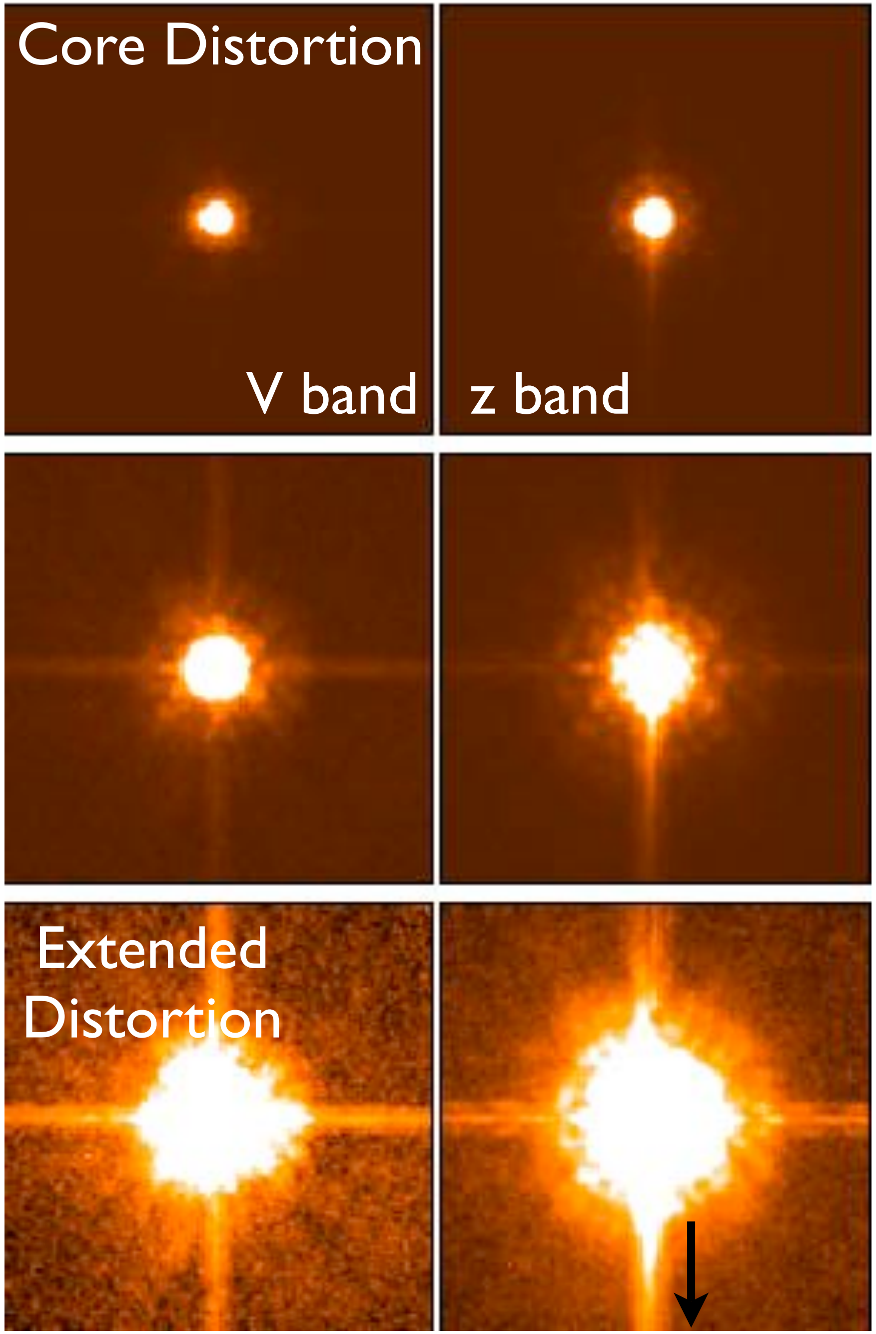


A CFHT MegaCam image



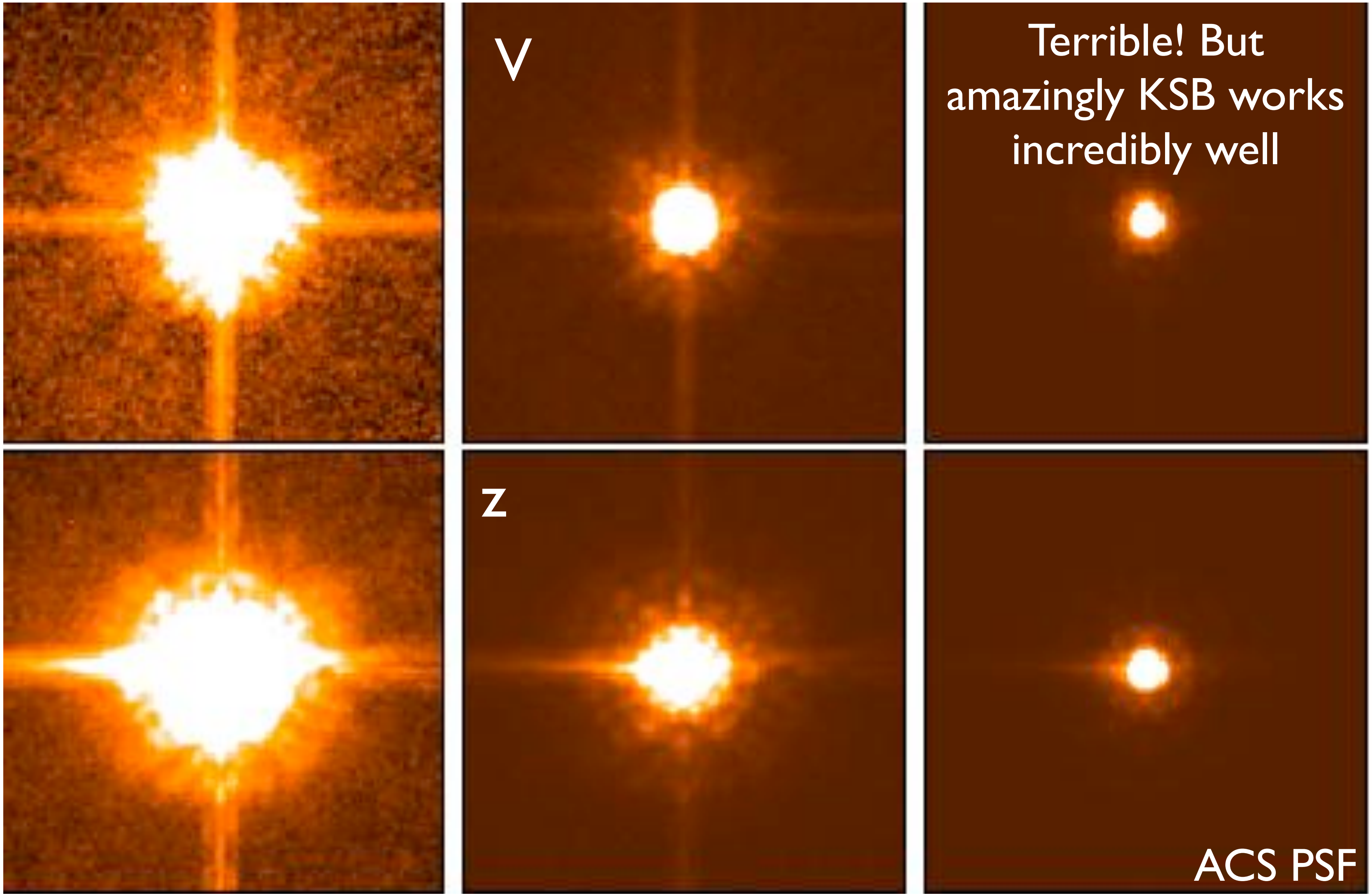
- The PSF varies across the image
- The PSF is not Gaussian
- The ellipticity of the PSF varies at different isophotes
- The centroid of the PSF shifts for different isophotes
- The worst PSFs are at the edges of the chip

Example PSFs: ACS on the Hubble Space Telescope



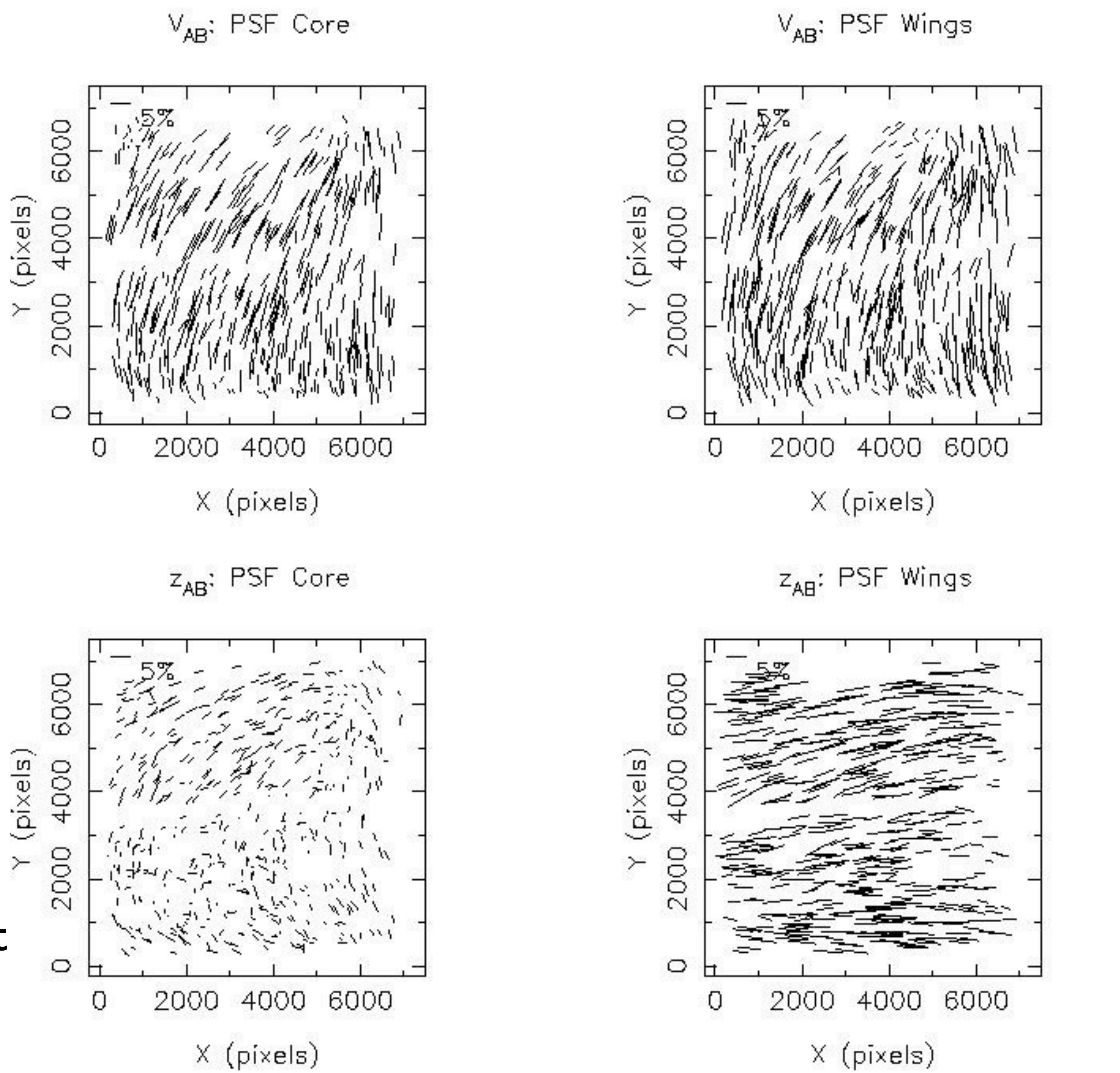
- In space the diffraction spikes become stronger
- You can see the airy pattern
- The ellipticity of the PSF again changes at different isophotal levels
- Here you can also see the effect of different filters

How good is the KSB PSF assumption?



Example measurements of p

- This example is taken from the ACS on Hubble.
- p changes as a function of
  - Position on the chip
  - Filter
  - Time
  - The weight size W(rg)
- Fit a polynomial to measurements of p to model variations across the field of view
- These models are time and weight size dependent



Removing the smearing effect of the atmosphere

The isotropic effect of the atmosphere and weight function can be accounted for by applying the pre-seeing shear polarisability tensor correction P^γ, as proposed by Luppino & Kaiser (1997), such that

$$\varepsilon_\alpha^{\rm cor} = \varepsilon_\alpha^s + P^\gamma_{\alpha\beta}\gamma_\beta \, , \tag{6}$$

sheared ellipticity

source ellipticity

how easily the galaxy responds to the shear

lensing distortion

Note these mysterious tensors are weighted higher order moments of the galaxies light distribution. See Kaiser et al 1995 for details.

Putting it all together:

$$\hat{\gamma}_\alpha = (P^\gamma)^{-1}_{\alpha\beta} \left[\varepsilon_\beta^{\rm obs} - P^{\rm sm}_{\beta\mu} p_\mu \right] . \tag{8}$$

Problems with KSB

- P^{γ} should be calculated on the PSF corrected image we don't have
- The underlying PSF assumption is poor
- P^{sm}, P^{sh} are noisy quantities measured from data so people sometimes approximate

$$(P^{sm})^{-1} = 1/(2\,Tr(P^{sm})$$

- Which weight function to use where? P^{sm*}, P^{sh*} should really be evaluated with the same weight function as the galaxy.
- KSB assumes the centroids are known
- All of these choices lead to huge variations in the performance of KSB as demonstrated by STEP! If you get it right KSB can be accurate to 1%.

Tues Practical: Testing KSB on simulated data

1. Use Stuff and SkyMaker to create a simulated image
2. Detect objects in the data (using SExtractor)
3. Separate stars and galaxies
4. Model the PSF using the stars
5. Remove the effects of the PSF on the galaxy image (using KSB)
6. Measure the shear from the PSF corrected image

www.roe.ac.uk/~heymans/KSBf90_for_DUEL

DUEL Home   KSBf90.param   findstars.f90   psffit.f90   gal_correct.f90   gal_select.f90
mass recon

Analysing real astronomical data with KSBf90:

The IAP DUEL weak lensing summer school 2009 will be hosting a KSBf90 practical session. What follows are the instructions for the students who will be analysing a section of the CFHTLS D1 field.

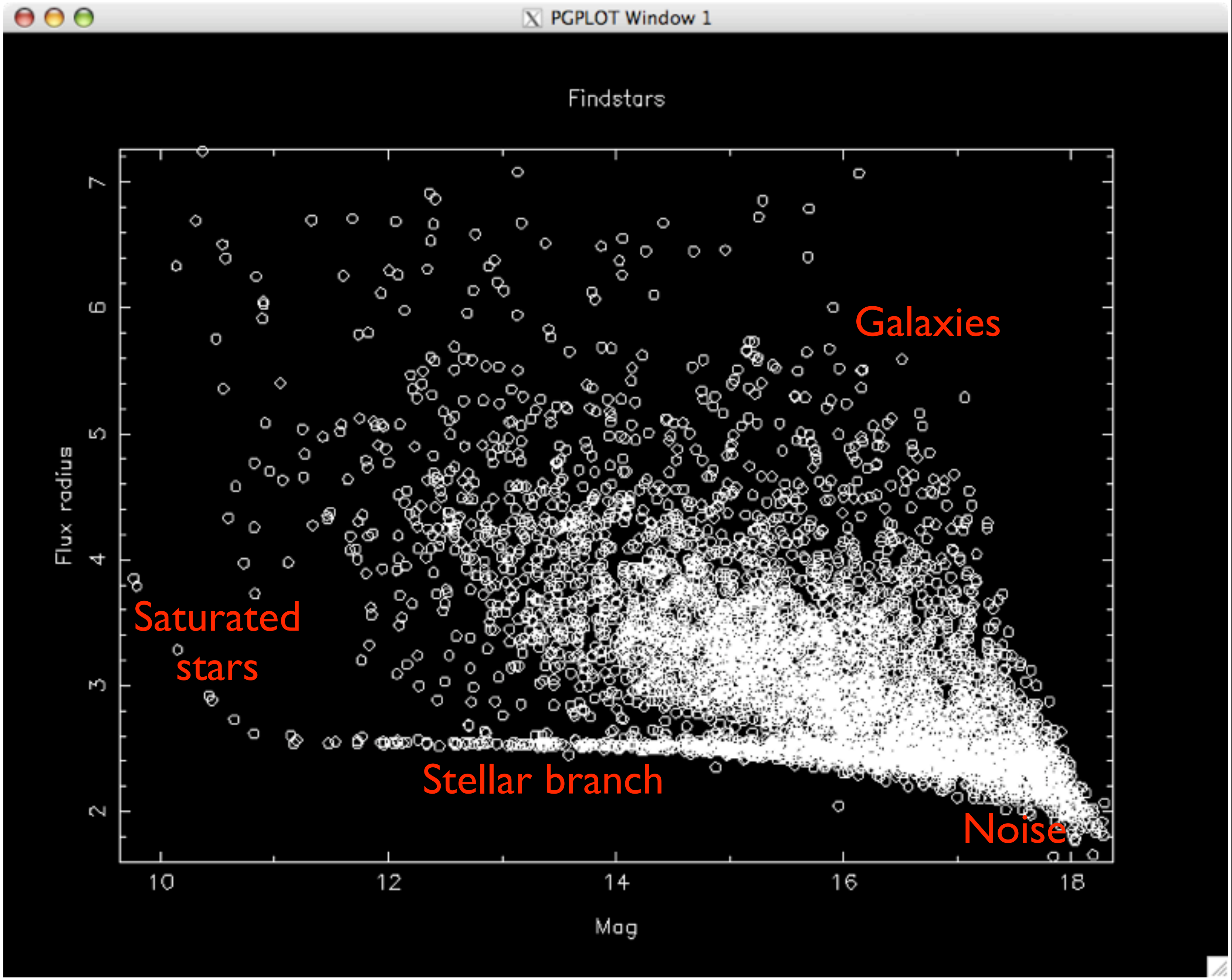
The weak lensing analysis consists of six steps

1) Install KSB90 for astronomers
2) Create SExtractor catalogue (see Thomas Erbens catalogue practical)
3) Separate the stars from the galaxies
4) Measure and model the PSF
5) Measure and correct the galaxy shapes
6) Select galaxies for shear measurement
7) Create a mass map

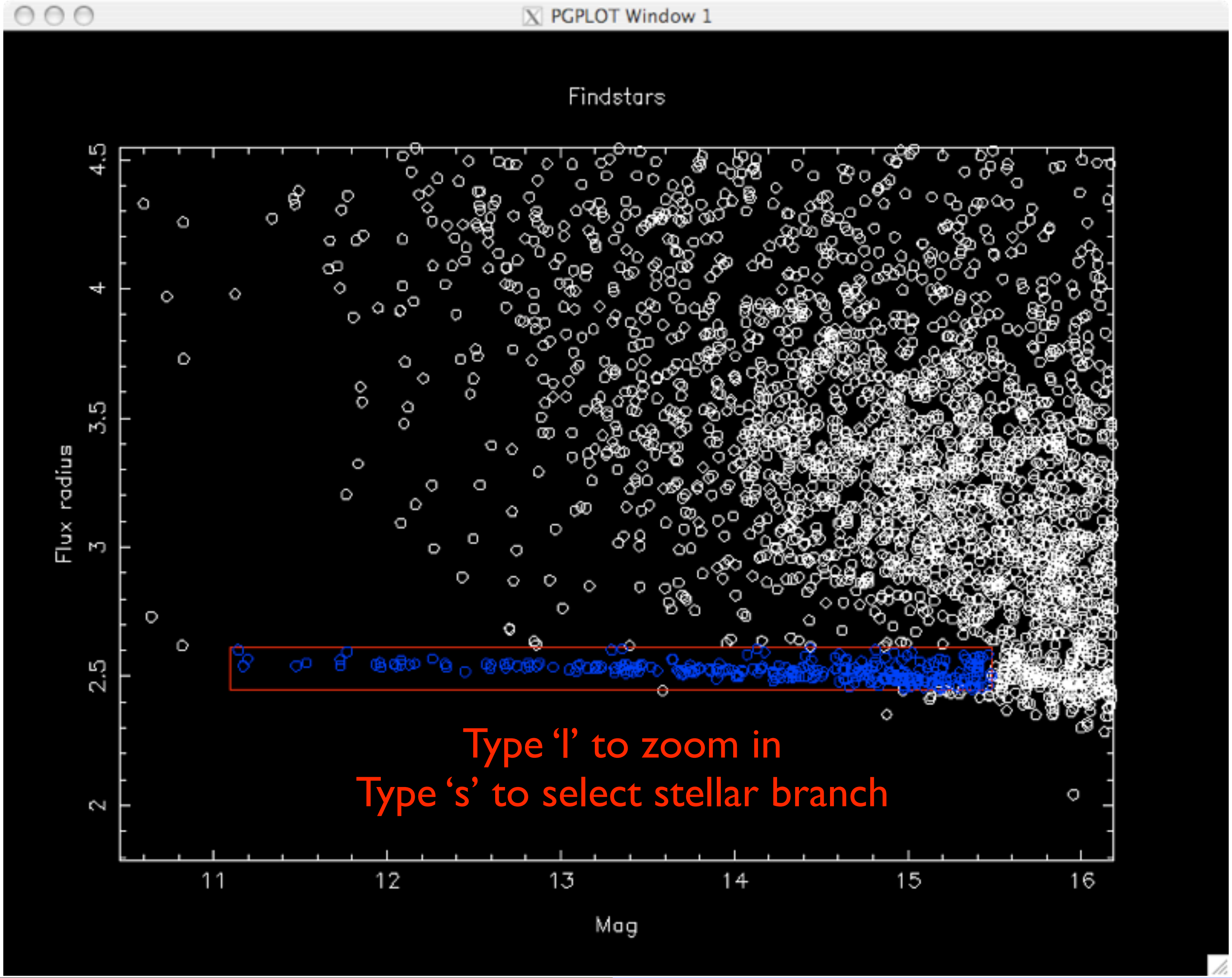
Note for any of the code, you can always use the option '-h' to see what command line input is expected.

1. Separating galaxies and stars

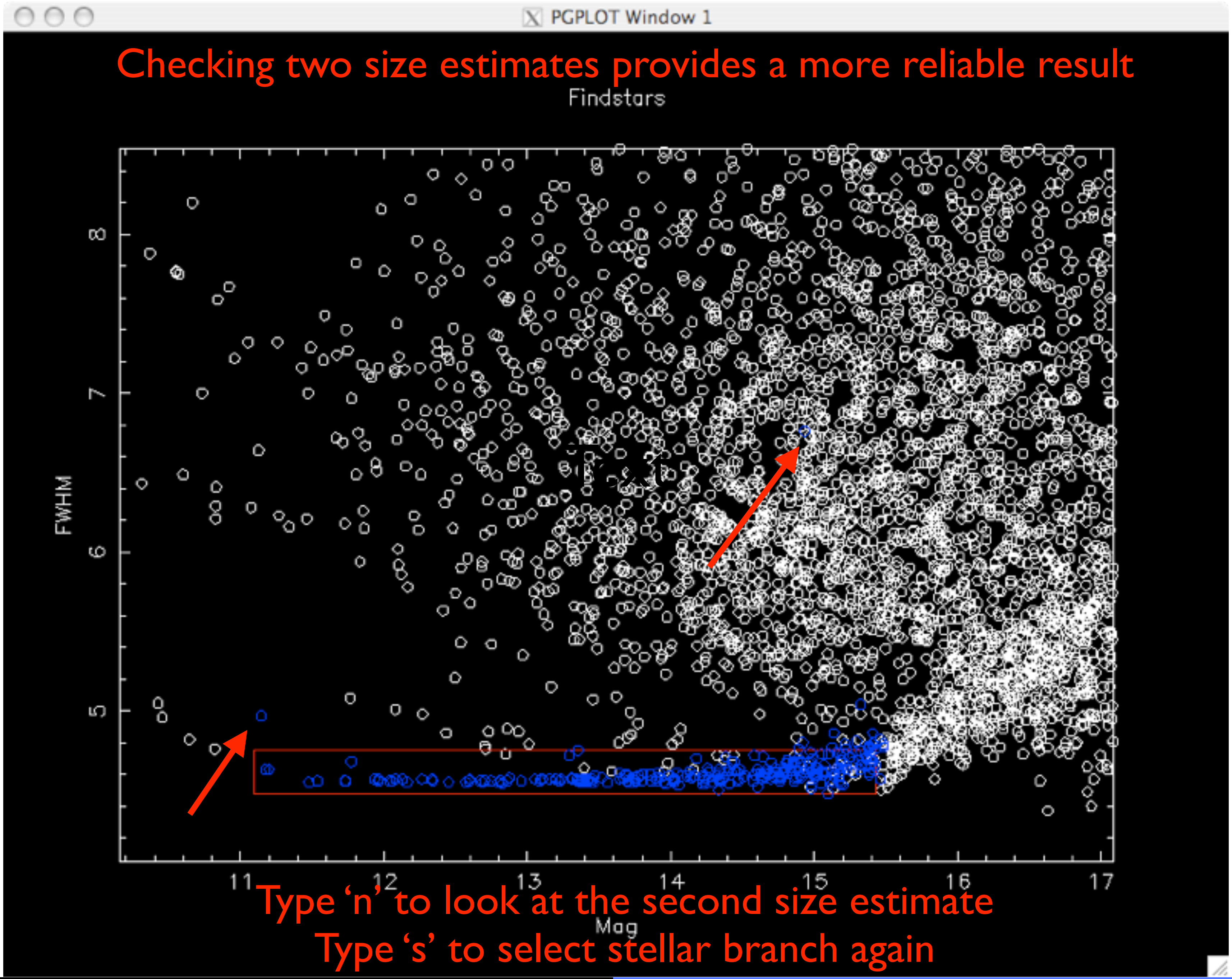
- Stars have a range of magnitudes, but have a constant size given by the width of the PSF.
- You can select stars from their position in a size/magnitude plot.
- We will use 'Findstars.a' in the practical to select stars



Selecting objects based on their half light radius



Double check with the full width half maximum



Findstars.a options

```
Terminal — ssh — 78x33
---------------------------------------------
                Menu Options
---------------------------------------------
d -- delete everything and start again
l -- zoom in to user defined box
q -- exit without saving changes
r -- redraw field and delete current size/mag selection
s -- select region
n -- next selection
x -- write current stellar selection and exit
z -- zoom in about cursor position
---------------------------------------------
Hit l again to define zoom region

---------------------------------------------
                Menu Options
---------------------------------------------
d -- delete everything and start again
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z -- zoom in about cursor position
---------------------------------------------
Hit s again to define selection region

---------------------------------------------
                Menu Options
---------------------------------------------
d -- delete everything and start again
l -- zoom in to user defined box
```
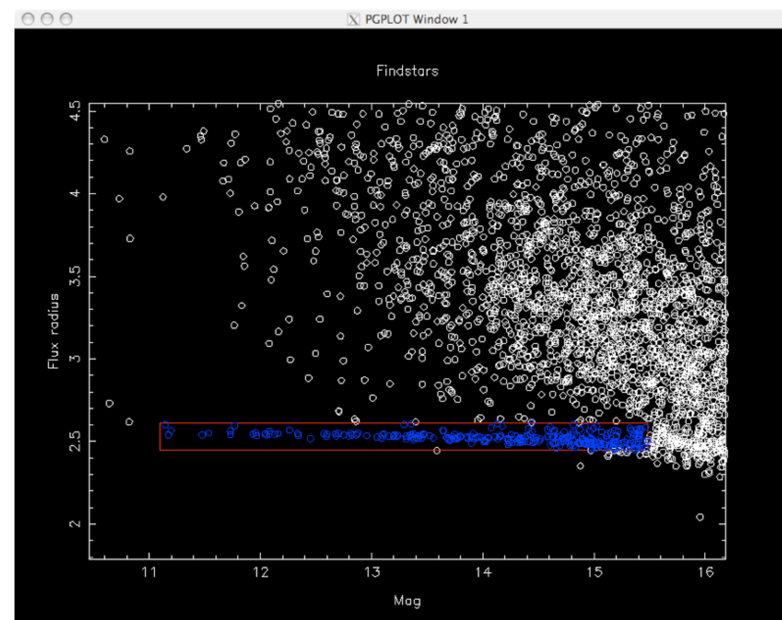
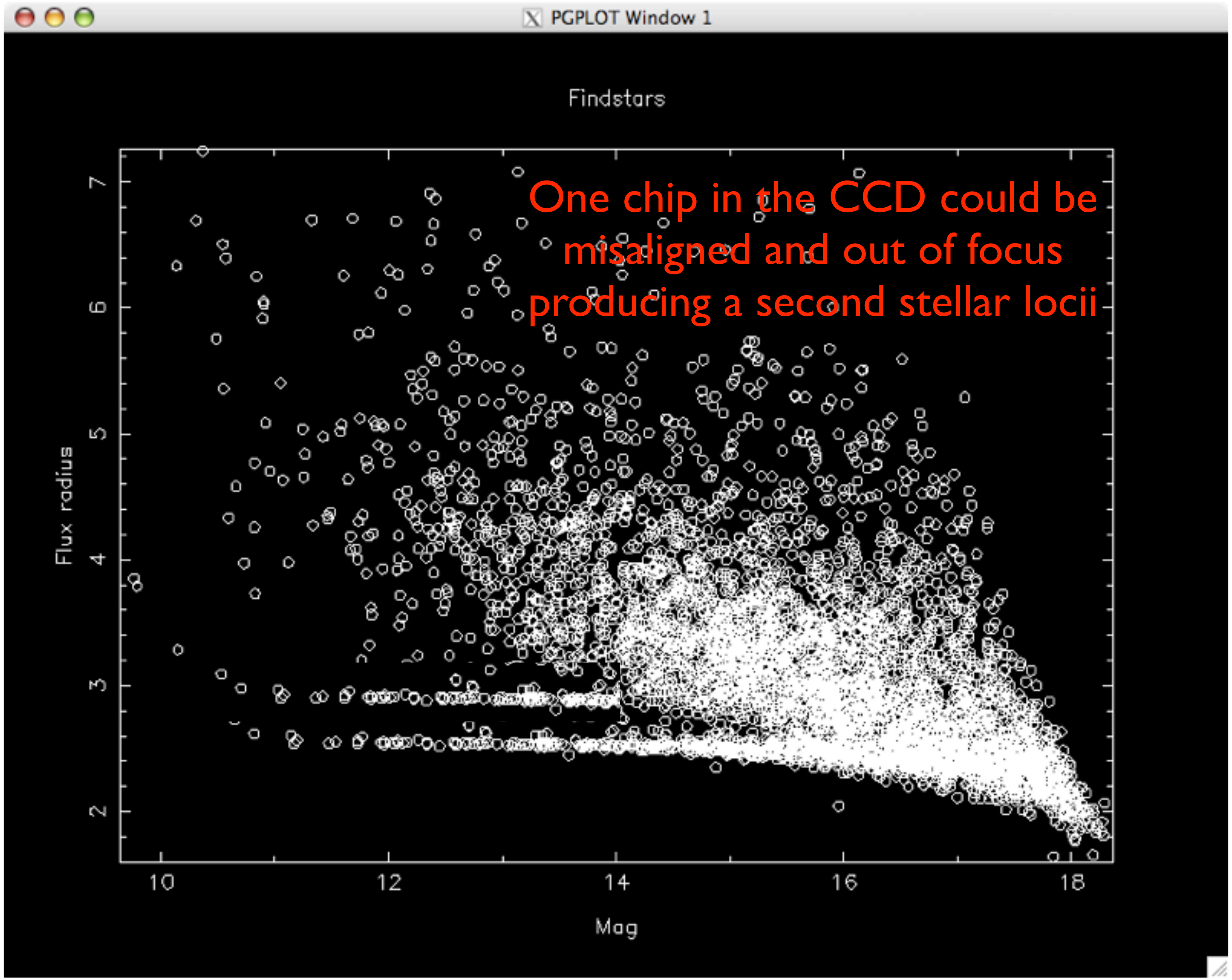

- Use 'l' to zoom in to get a clearer view of the stellar branch
- Use 's' to select branch (tip start with the top right corner)
- Use 'n' to move on to the next size test and repeat
- Use 'x' to save selection and exit



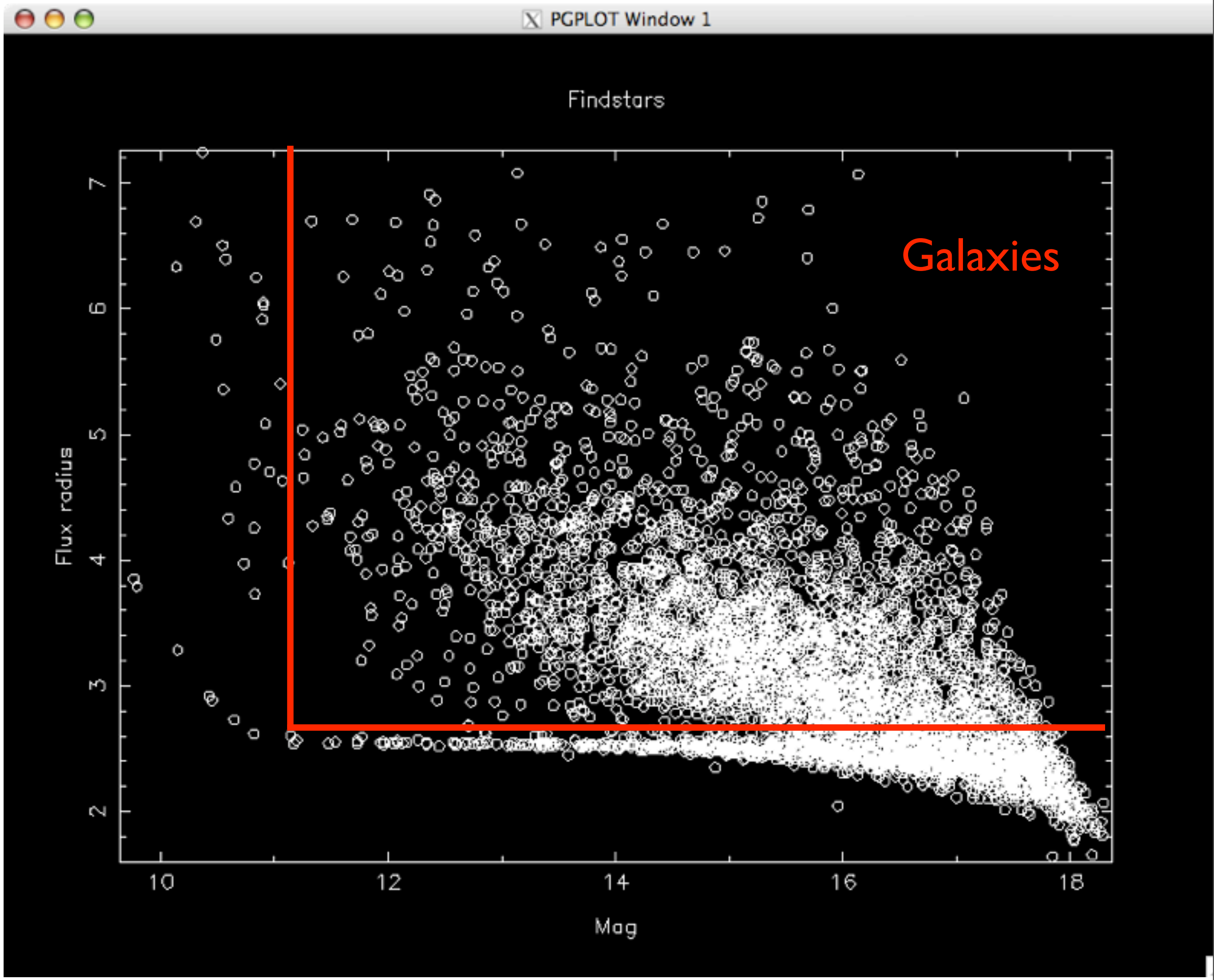
Selecting stars

- The stellar sample does not need to be 100% complete!
- But it needs to be uncontaminated by galaxies or saturated stars
- It needs to be a representative sample of the PSF - it might be necessary to select your stars chip by chip in the CCD



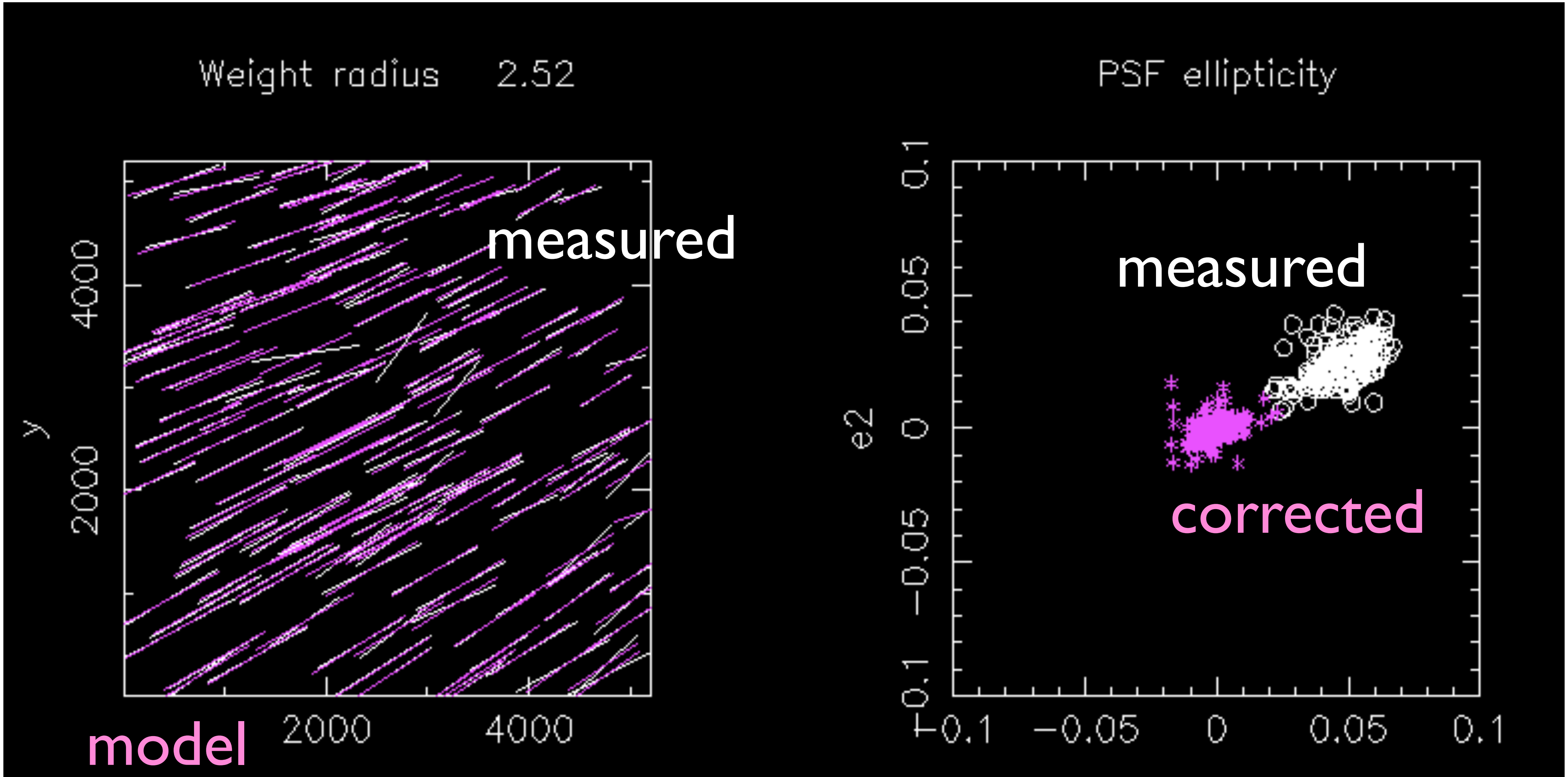
Galaxy Selection

- Once you've selected the stars, the galaxy selection is easy
- Pick only those objects that are larger than the PSF and fainter than the saturation limit
- Anything else will have had all its weak lensing shear information erased



Scripts

- There are c-shell scripts to run all of the code

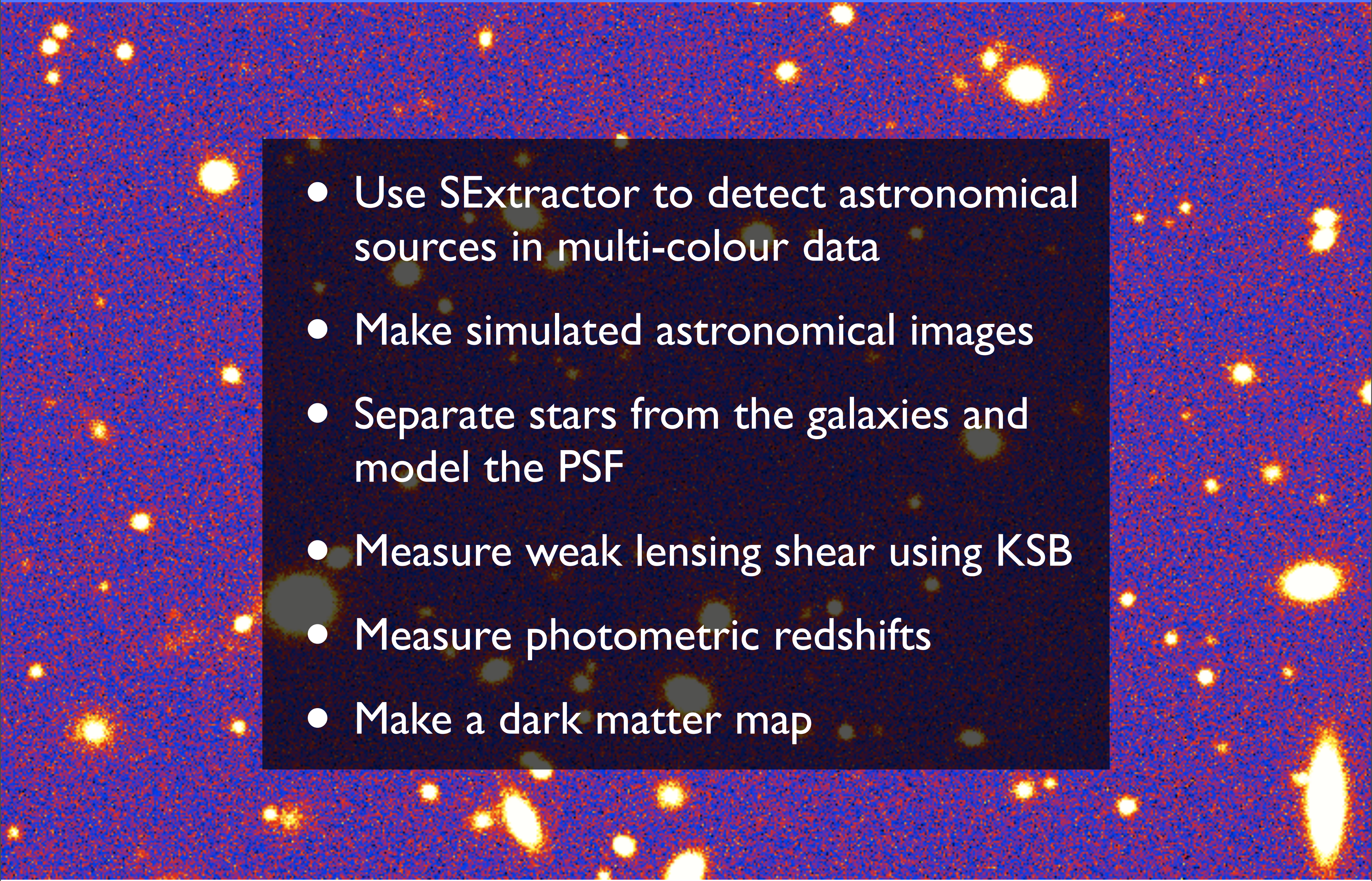


Plot from KSBf90/psffit.a

Summary

- KSB uses weighted quadrupole moments to calculate shear estimators for each galaxy.
- As an input it needs a stellar catalogue and a galaxy catalogue.
- Findstars.a lets you select stars
- Choose your parameters in KSBf90.param to select how to model the resulting PSF
- Once happy with the PSF model measure the galaxy shapes with rungals.scr
- Finally see how your choices impact on the final shear measurement with gal_select
- The challenge can you measure the shears that you put in?

at the end of the week you'll be able to....



- Use SExtractor to detect astronomical sources in multi-colour data
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