

Introduction to KSB

Catherine Heymans
University of British Columbia
Department of Physics and Astronomy, Vancouver, BC, Canada.

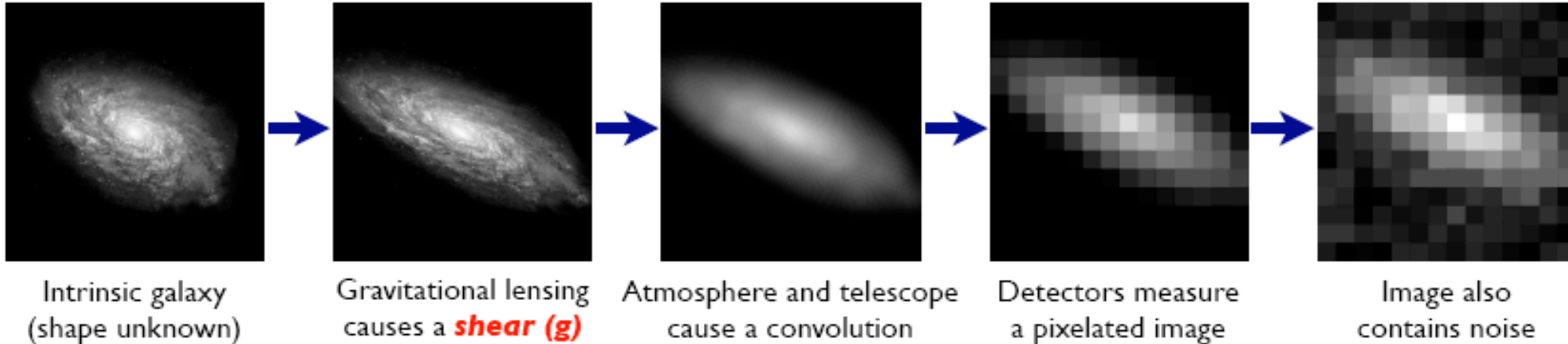
IPM School on Gravitational Lensing Techniques,
March 2008, Tehran, Iran.

- KSB+ (Kaiser Squires and Broadhurst 1995)
 - Shear measurement method
 - From Quadrupole moments to shear
- Introduction to this afternoons practical
 - Running KSB on STEP1 psf0lens4

Weak lensing shear measurement

The Forward Process.

Galaxies: Intrinsic galaxy shapes to measured image:



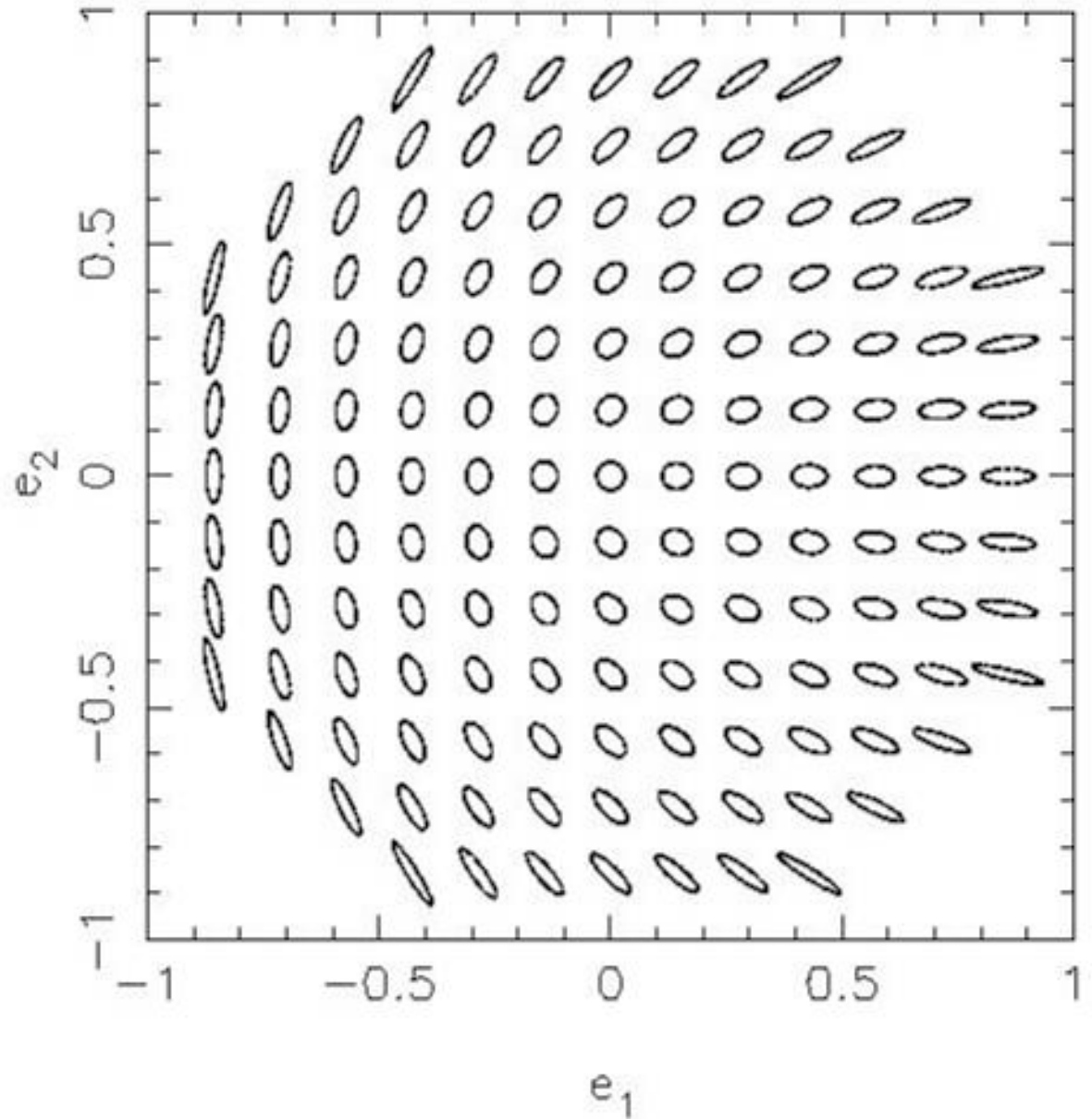
- The Kaiser Squires and Broadhurst method (KSB) is the most widely used method in current weak lensing analyses.
- It uses stars to model the the atmosphere and telescope distortion and essentially subtracts it from the data.
- The end project is a shear estimate for each galaxy.

Observables : Galaxy Ellipticity

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

$$\langle e^{\text{source}} \rangle = 0$$

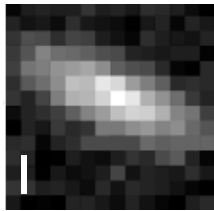
$$\gamma = \langle e^{\text{obs}} \rangle$$



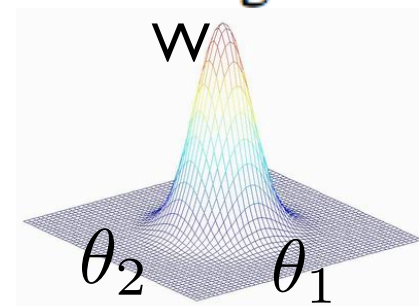
Ellipticity and Quadrupole Moments

Kaiser et al. (1995), Luppino & Kaiser (1997) and Hoekstra et al. (1998) (KSB+) prescribe a method to invert the effects of the PSF smearing and shearing, recovering a shear estimator uncontaminated by the systematic distortion of the PSF.

Objects are parameterised according to their weighted quadrupole moments



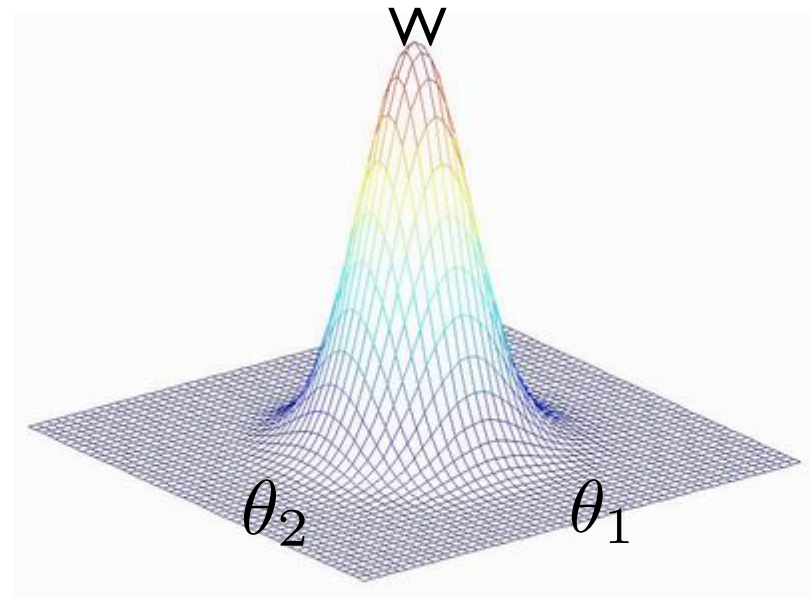
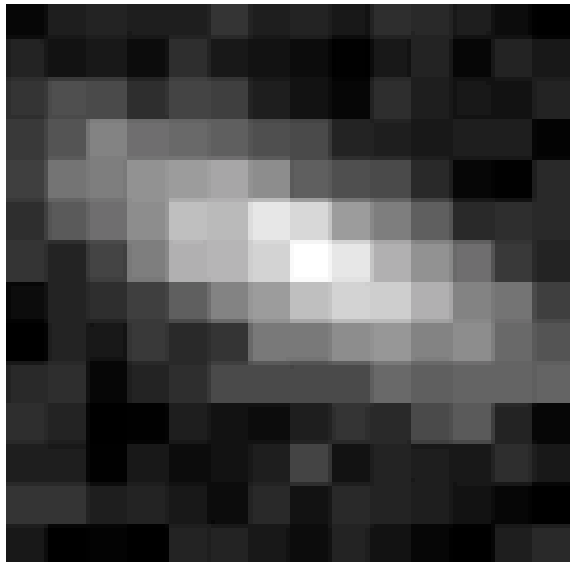
$$Q_{ij} = \frac{\int d^2\theta W(\theta) I(\theta) \theta_i \theta_j}{\int d^2\theta W(\theta) I(\theta)},$$



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. For a perfect ellipse, the weighted quadrupole moments are related to the weighted ellipticity parameters⁴ ε_α by

$$\begin{pmatrix} \varepsilon_1 \\ \varepsilon_2 \end{pmatrix} = \frac{1}{Q_{11} + Q_{22}} \begin{pmatrix} Q_{11} - Q_{22} \\ 2Q_{12} \end{pmatrix}. \quad (3)$$

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

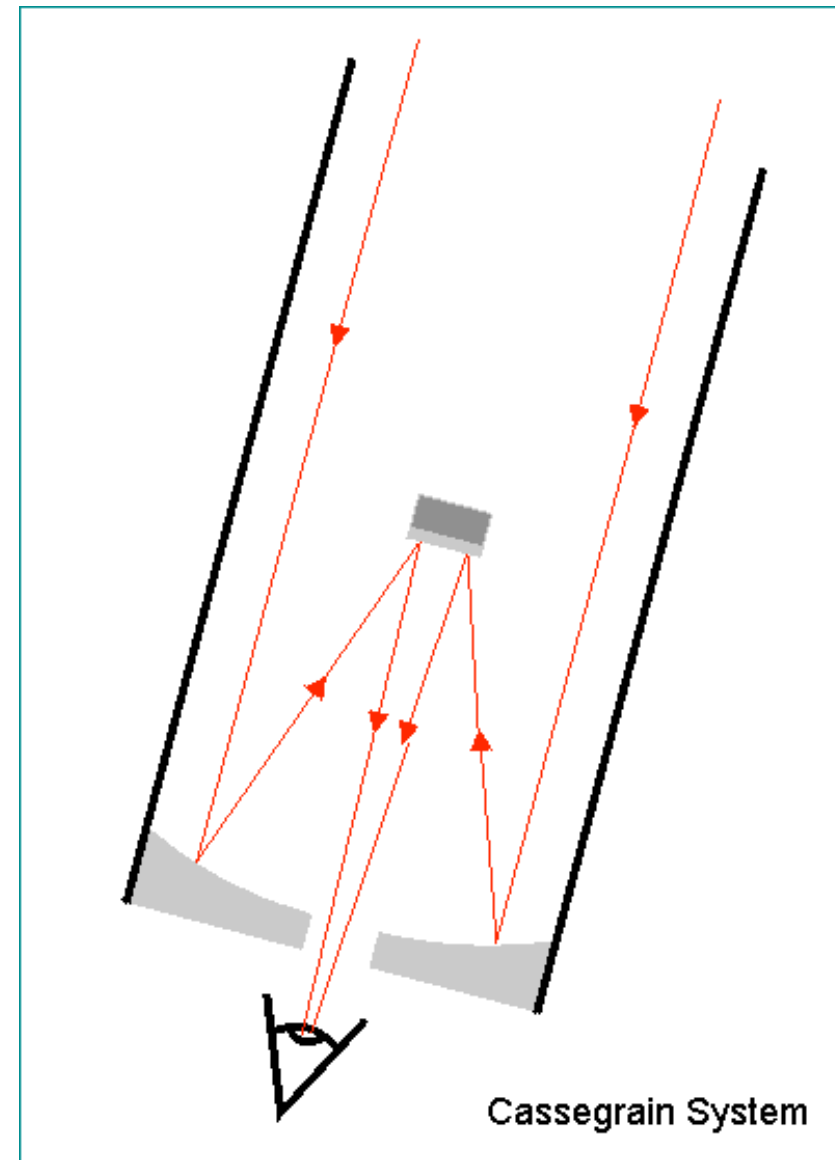
$$\varepsilon_{\alpha}^{\text{cor}} = \varepsilon_{\alpha}^{\text{obs}} - P_{\alpha\beta}^{\text{sm}} p_{\beta}, \quad (4)$$

where p is a vector that measures the PSF anisotropy, and P^{sm} is the smear polarisability tensor given in Hoekstra et al. (1998). $p(\theta)$ can be estimated from images of stellar objects at position θ by noting that a star, denoted throughout this paper with $*$, imaged in the absence of PSF distortions has zero ellipticity: $\varepsilon_{\alpha}^{*\text{cor}} = 0$. Hence,

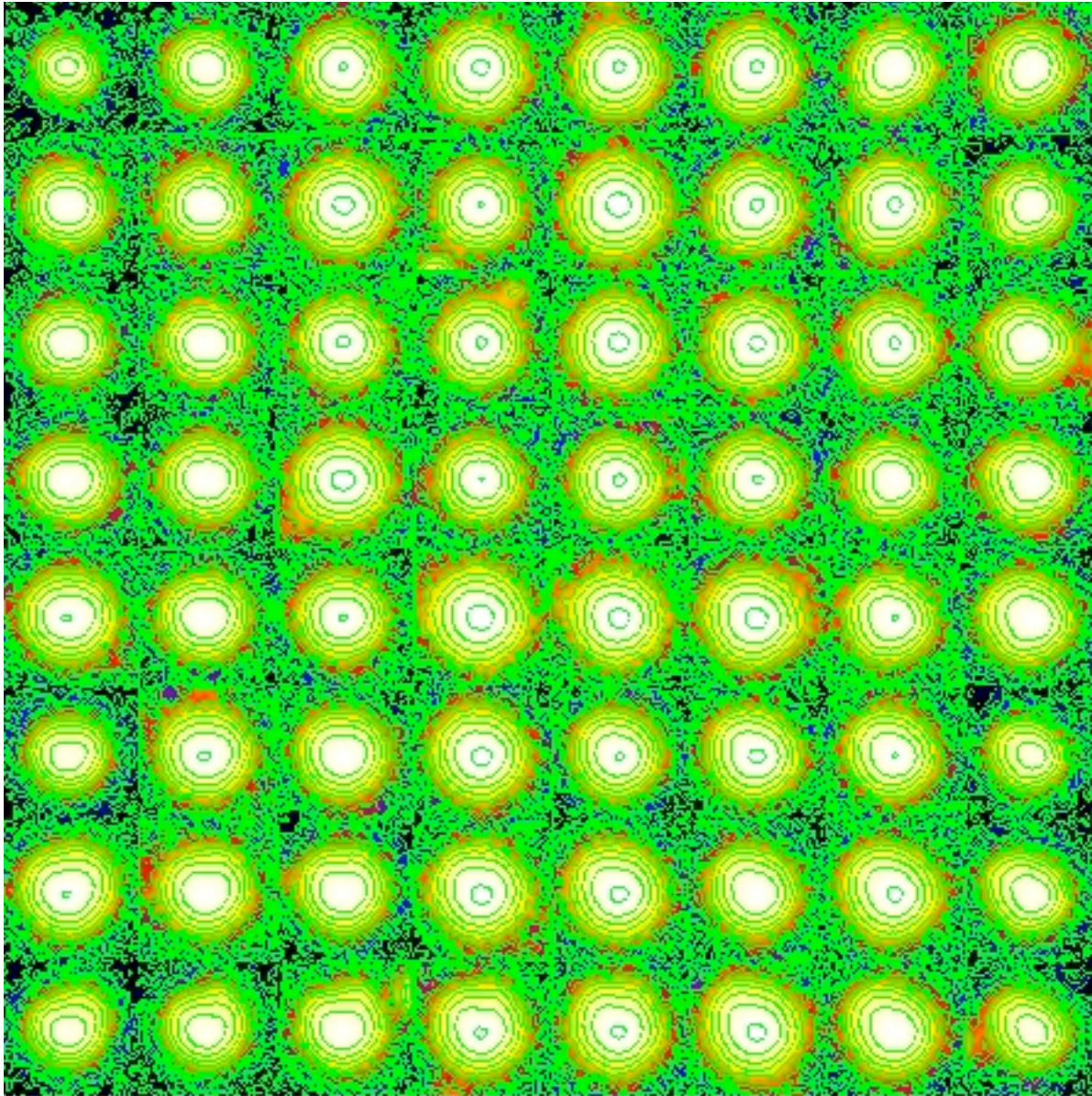
$$p_{\mu} = (P^{\text{sm}*})_{\mu\alpha}^{-1} \varepsilon_{\alpha}^{*\text{obs}}. \quad (5)$$

Modelling the PSF in practise

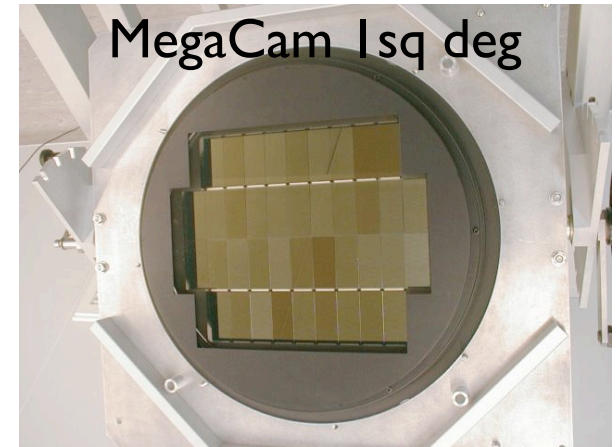
- The atmosphere causes circular smearing.
- Differences in the optical light path cause shearing.
- In principle the distortions introduced by the telescope and detector can be predicted.
- In practise many other factors effect the PSF including the the angle observed on the sky, the temperature, the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



Example PSFs: CFHT Megacam

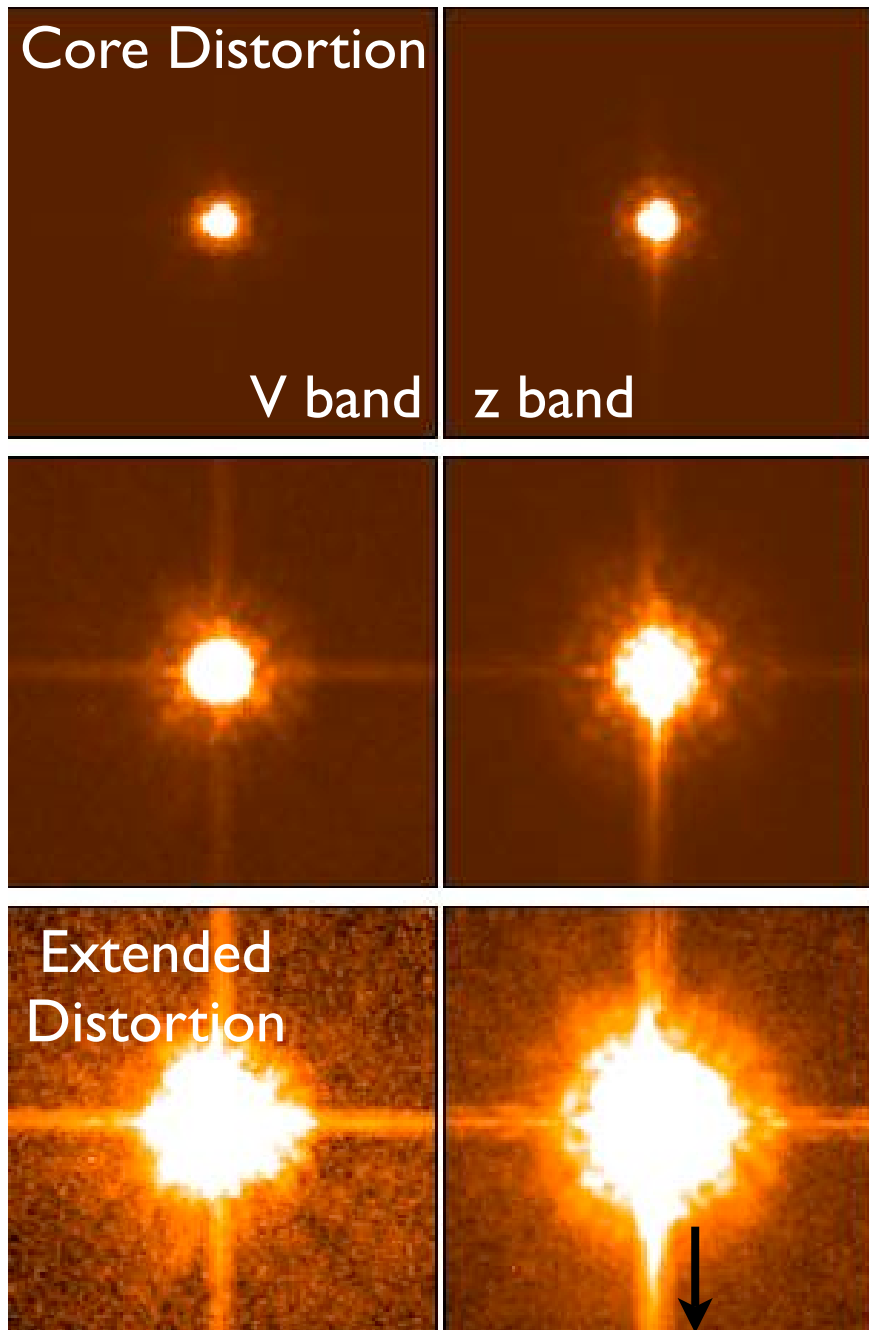


A CFHT MegaCam image



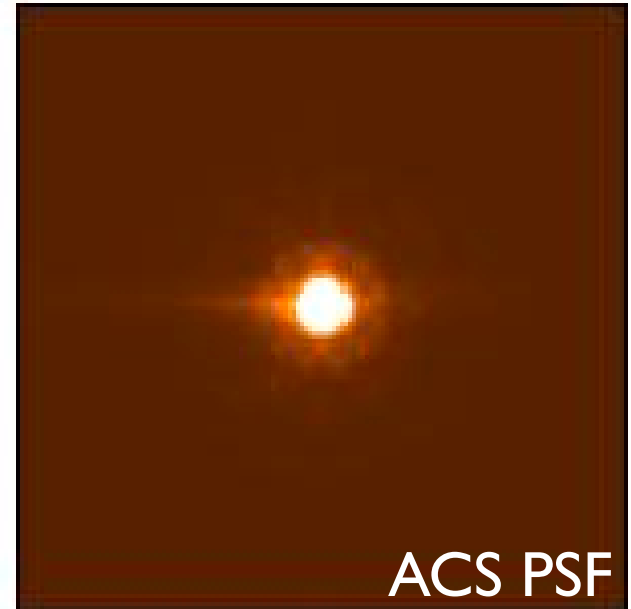
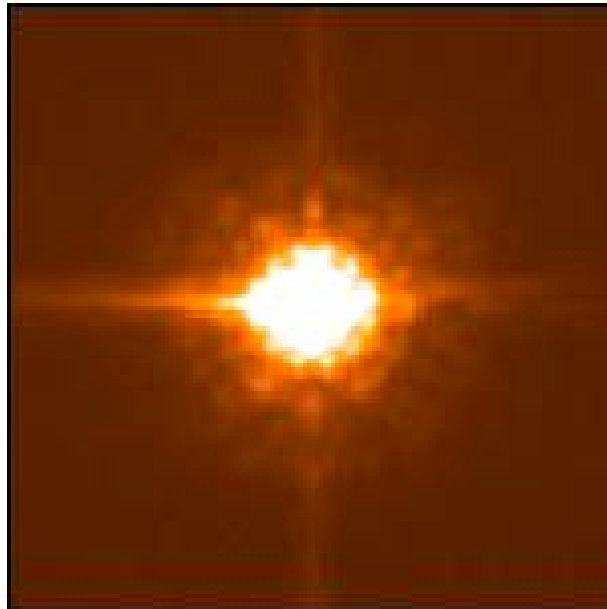
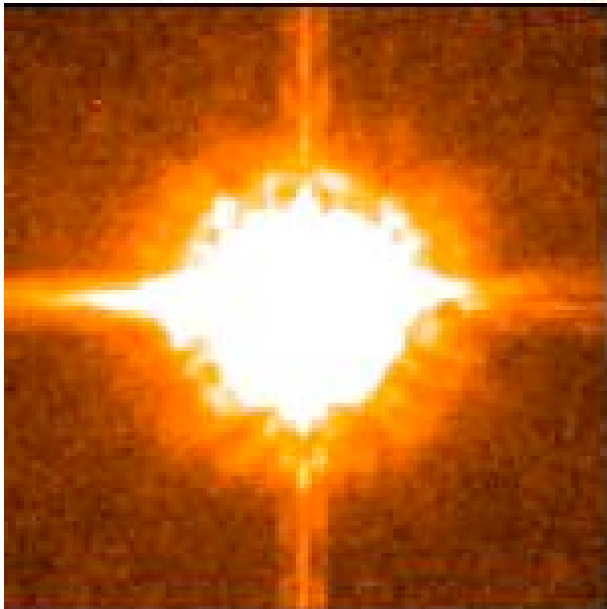
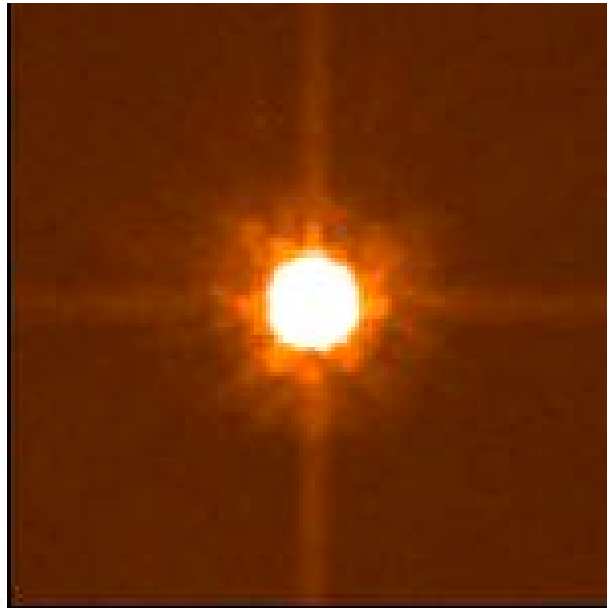
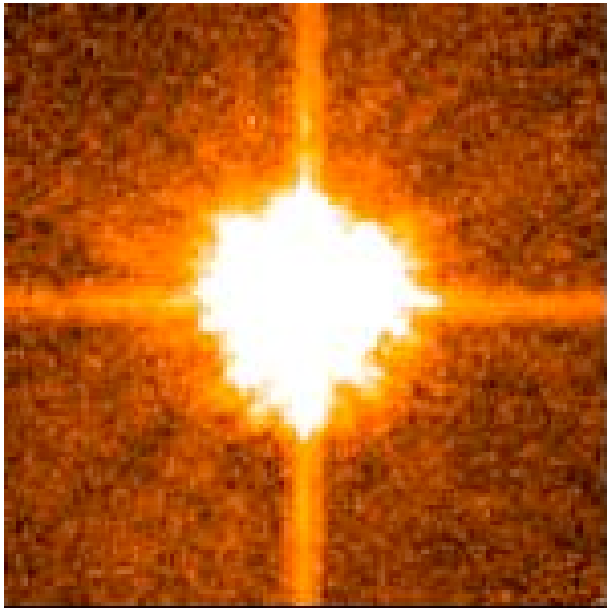
- The PSF varies across the image
- The PSF is not Gaussian
- The ellipticity of the PSF varies at different isophotes
- The centroid of the PSF shifts for different isophotes
- The worst PSFs are at the edges of the chip

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

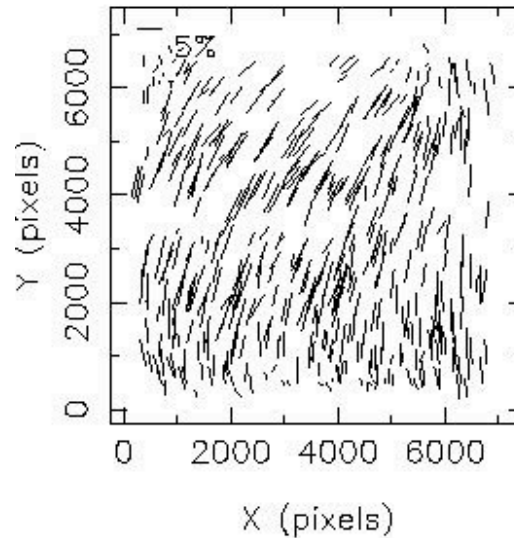
How good is the KSB PSF assumption?



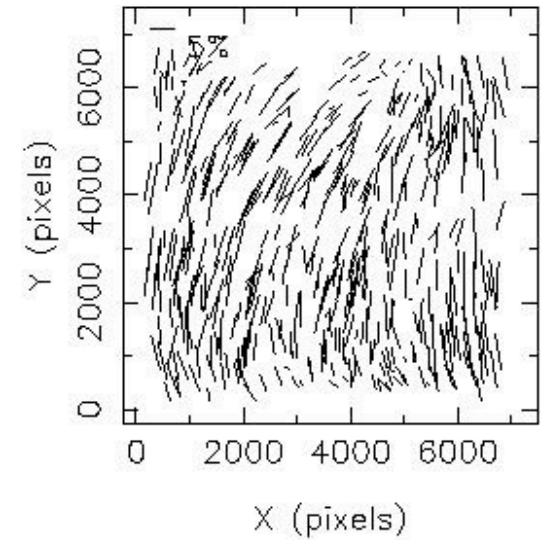
Example measurements of ρ

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

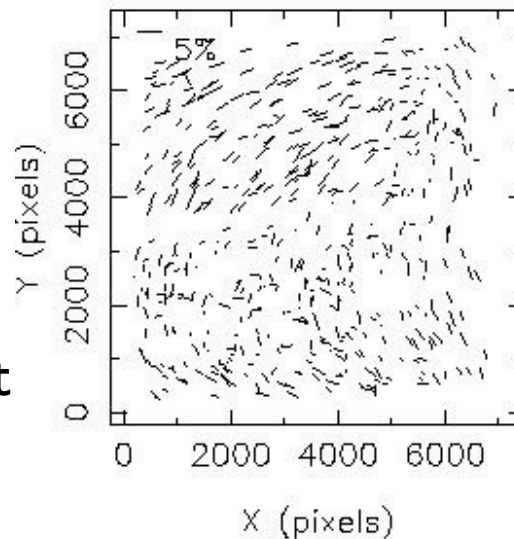
V_{AB} : PSF Core



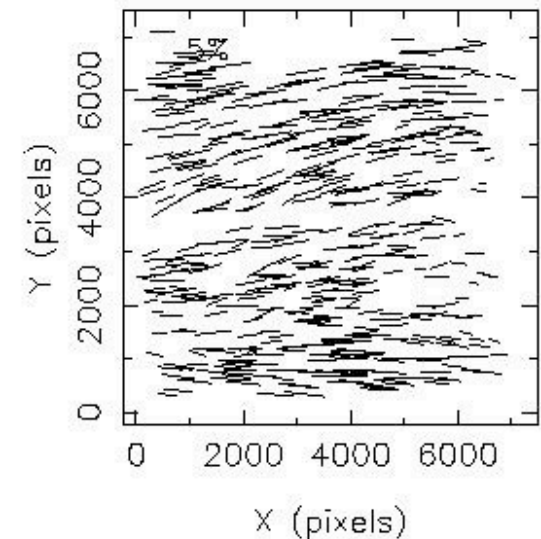
V_{AB} : PSF Wings



z_{AB} : PSF Core



z_{AB} : PSF Wings



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

$$\varepsilon_\alpha^{\text{cor}} = \varepsilon_\alpha^s + P_{\alpha\beta}^\gamma \gamma_\beta, \quad (6)$$

where ε^s is the intrinsic source ellipticity and γ is the pre-seeing gravitational shear. Luppino & Kaiser (1997) show that

$$P_{\alpha\beta}^\gamma = P_{\alpha\beta}^{\text{sh}} - P_{\alpha\mu}^{\text{sm}} (P^{\text{sm}*})_{\mu\delta}^{-1} P_{\delta\beta}^{\text{sh}*}, \quad (7)$$

where P^{sh} is the shear polarisability tensor given in Hoekstra et al. (1998) and $P^{\text{sm}*}$ and $P^{\text{sh}*}$ are the stellar smear and shear polarisability tensors respectively. Combining the PSF correction, equation (4), and the P^γ seeing correction, the final KSB+ shear estimator $\hat{\gamma}$ is given by

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

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

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

- 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%.

Lesson: KSB can be in/accurate from 1-20%

KSB Author	Heymans	Hoekstra	Schrabback	Van Waerbeke
Key	CH	HH	TS	LV
Source Detection	<i>SExtractor</i>	<i>hfindpeaks</i>	<i>SExtractor</i>	<i>SExtractor</i>
PSF: 2D polynomial model	2 nd order to $p^\mu(r_g)$ and $(P^{sm*})_{\alpha\beta}^{-1} P^{sh*}_{\beta\gamma}(r_g)$	2 nd order to $\varepsilon^*(r_g)$, $P^{sm*}(r_g)$ and $P^{sh*}(r_g)$	3 rd order to $p^\mu(r_g)$	2 nd order to $\varepsilon^*(r_g)$ $P^{sm*}(r_g)$ and $P^{sh*}(r_g)$
Galaxy size r_g	flux_radius	from <i>hfindpeaks</i>	flux_radius	flux_radius
Quadrupole estimate θ_{max} and $\Delta\theta$ P^{sh} and P^{sm} estimate	Approx Int[$4r_g$], 1 pix Integer	Interpolation Interpolation	Interpolation $3r_g$, 0.25 pix Interpolation	Approx Int[$4r_g$], 1 pix Approx
P^γ correction	$\frac{1}{2} \text{Tr}[P^\gamma]$ (no fit)	$P^{sh} \rightarrow (1 - \varepsilon^2/2)P^{sh}$ Fit to $\frac{1}{2} \text{Tr}[P^\gamma](r_g)$	$\frac{1}{2} \text{Tr}[P^\gamma]$ (no fit)	Fit in (r_g, mag) to $\frac{1}{2} \text{Tr}[P^\gamma]$
Weights	none	Hoekstra et al. eqn A8,9	$\langle \gamma^2 \rangle^{-1} (r_g, \text{mag})$	Hoekstra et al. eqn A8,9
γ correction	3% error	1% error	17% error	7% error
Ellipticity cut	$ \varepsilon_{obs} \leq 0.5$		$ \varepsilon_{cor} \leq 0.8$	
Size cut	$1.2r_g^* < r_g < 7\text{pix}$	r_h selection	$r_h > 1.2r_h^*$	
Significance cut	$\nu > 10$	$\nu > 5$		$\nu > 15$
P^γ cut			$\frac{1}{2} \text{Tr}[P^\gamma] > 0$	
γ cut	$ \gamma < 2$			
Other	Close pairs < 10pix removed		$ d < 3 \text{pix}$	

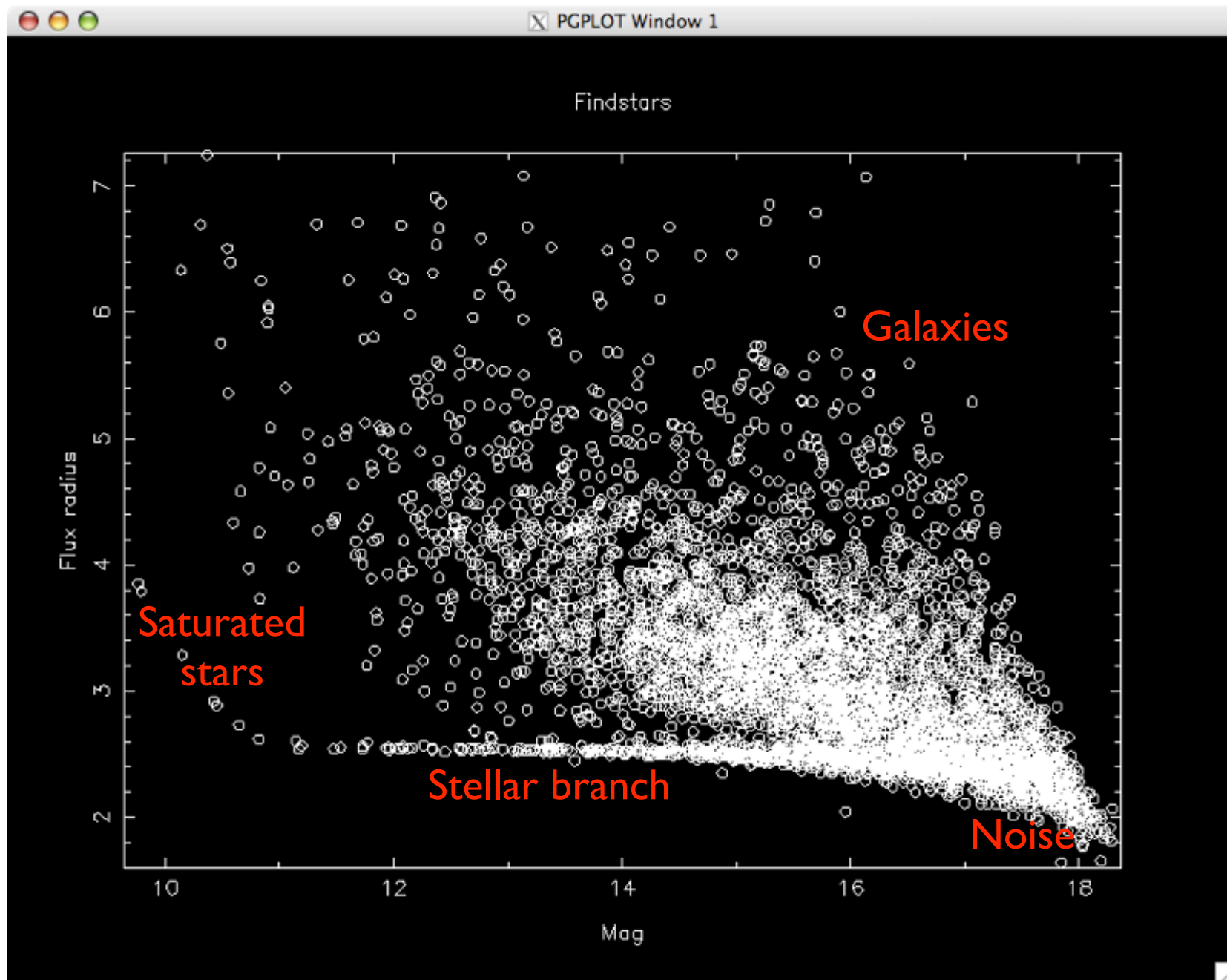
If you modify any of the code YOU NEED TO TEST THE IMPACT OF THOSE CHANGES WITH STEP!!

The Practical: Testing KSB on STEP

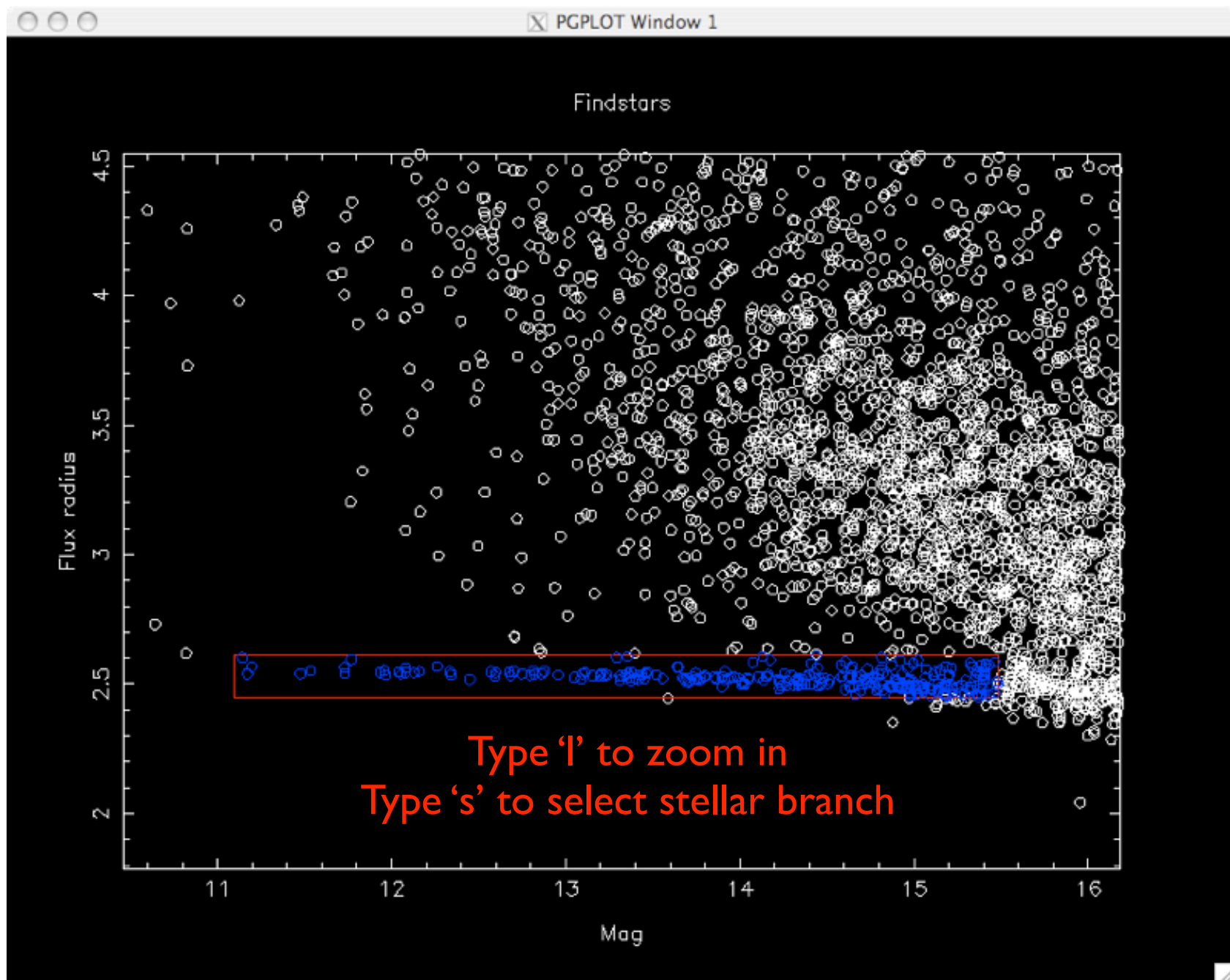
1. Reduce your data well (Joerg Dietrichs course and Thomas Erbens course in the summer)
2. Detect objects in the data (using SExtractor)
3. Separate stars and galaxies
4. Model the PSF using the stars
5. Remove the effects of the PSF on the galaxy image (using KSB)
6. Measure the shear from the PSF corrected image

I. Separating galaxies and stars

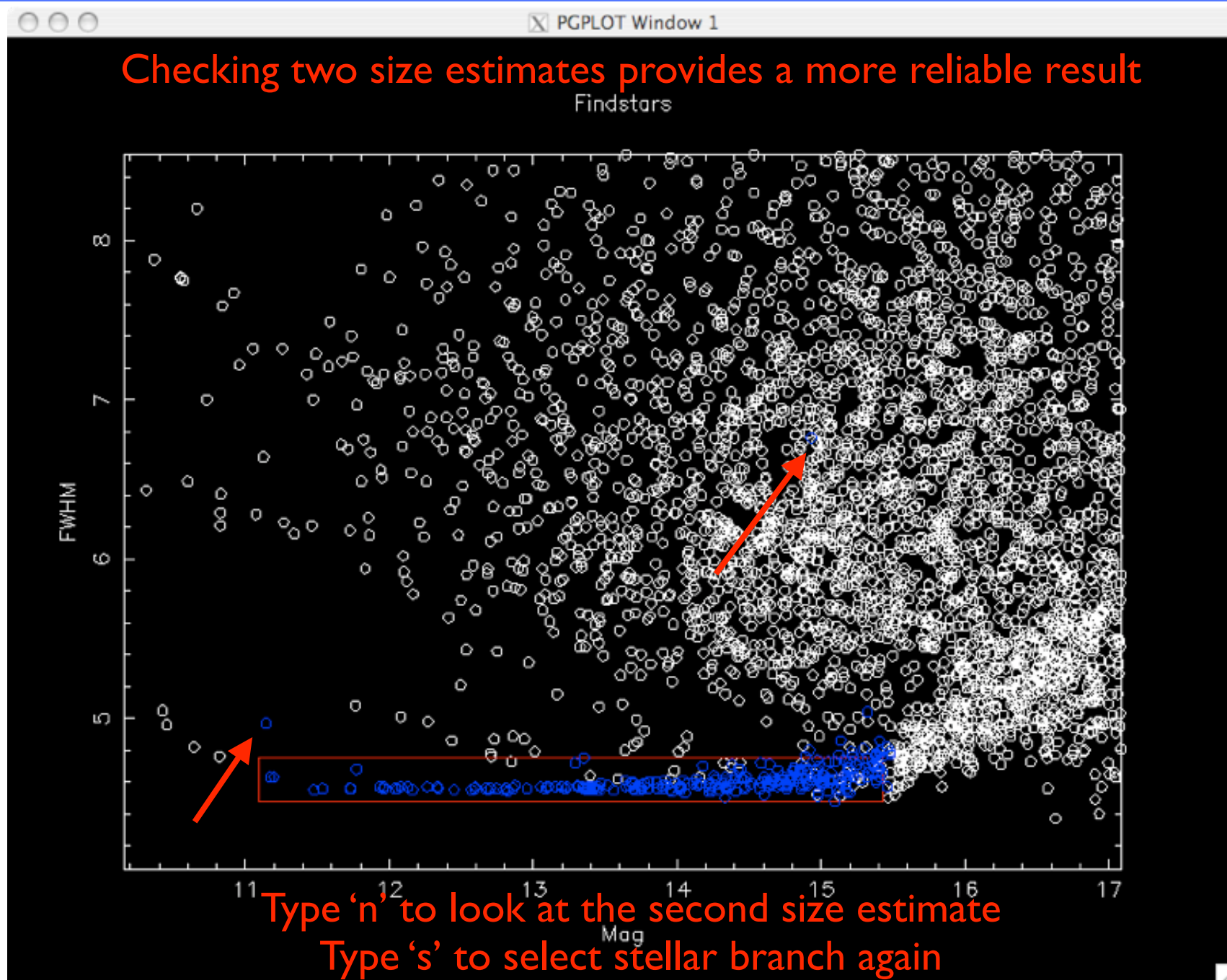
- Stars have a range of magnitudes, but have a constant size given by the width of the PSF.
- You can select stars from their position in a size/magnitude plot.
- We will use 'Findstars.a' in the practical to select stars



Selecting objects based on their half light radius



Double check with the full width half maximum



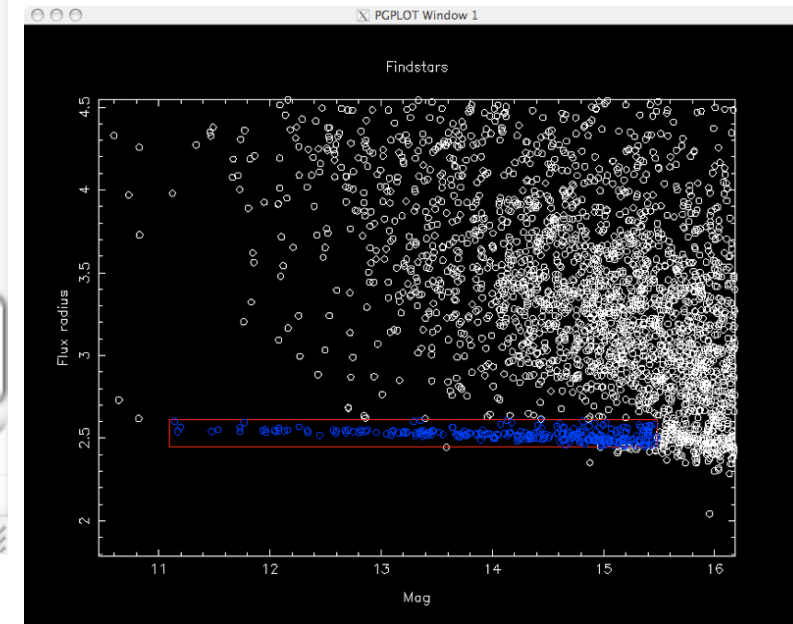
Findstars.a options

```
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
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 s again to define selection region

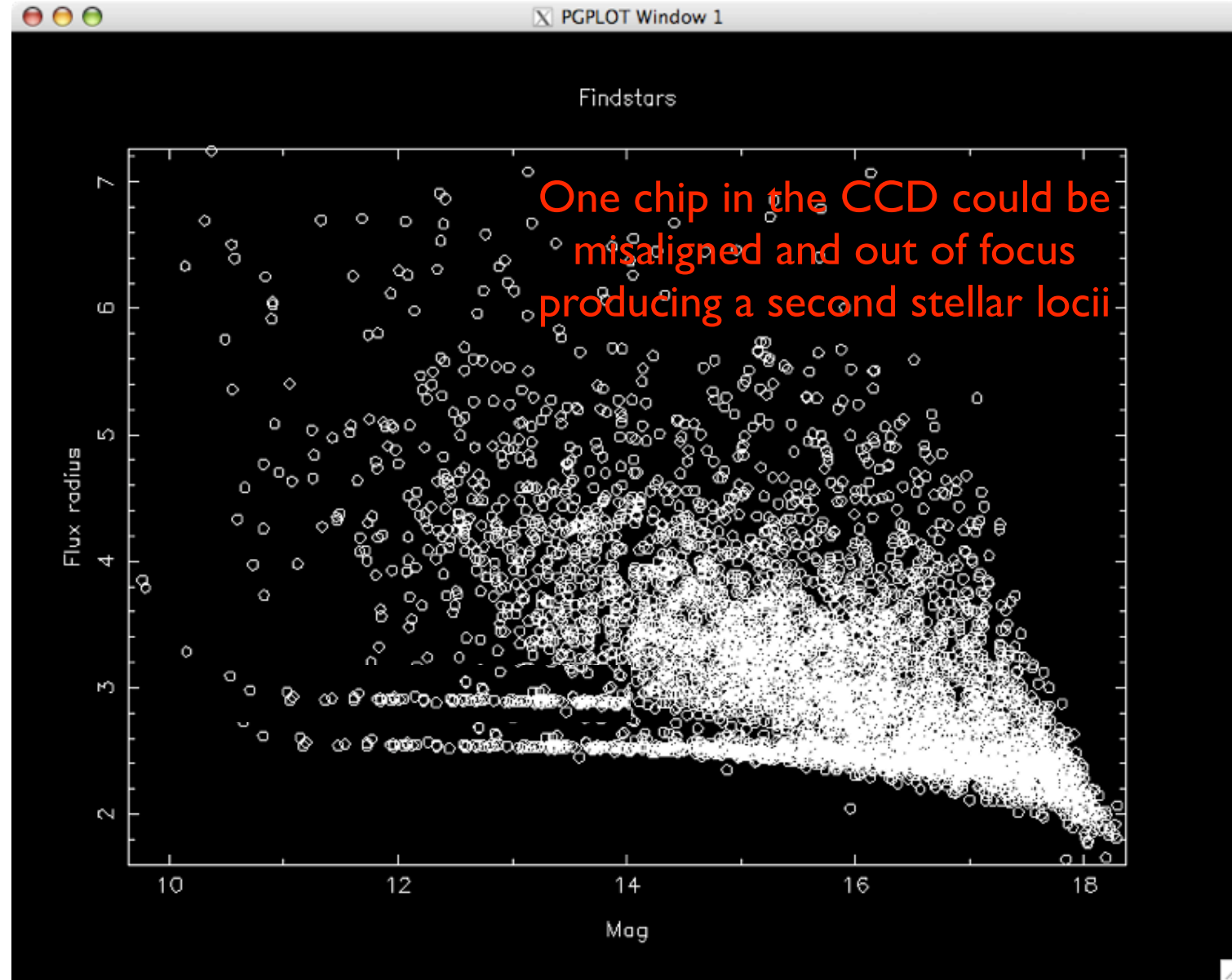
-----
Menu Options
-----
d -- delete everything and start again
l -- zoom in to user defined box
```

- 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



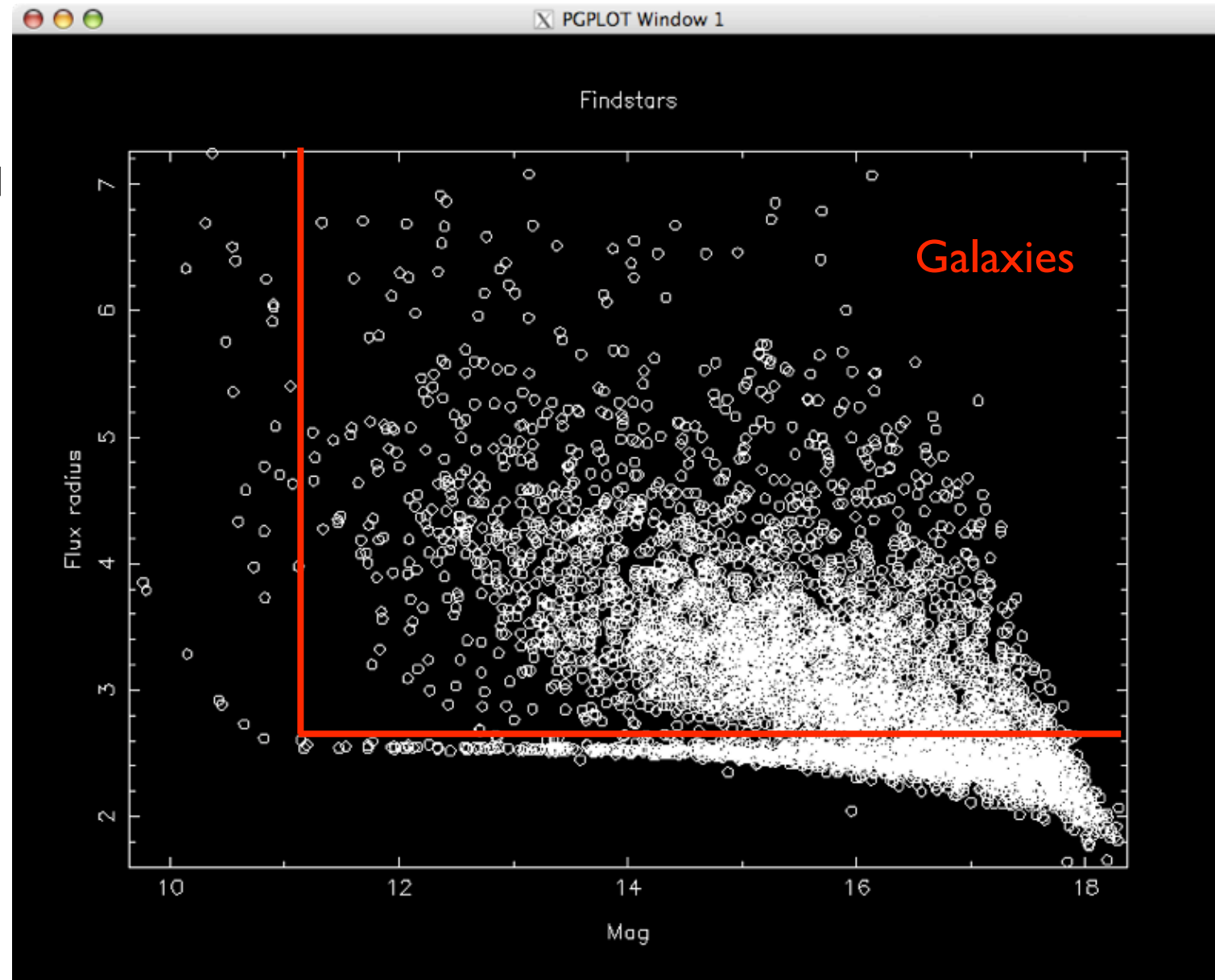
Selecting stars

- 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



KSBf90.param: the parameter file

```
#
# KSBf90 parameter file
# Catherine Heymans IPM Spring School 2008
#
# SExtractor catalogue information
#
-x      7      # x column in SExtractor cat
-y      8      # y column in SExtractor cat
-mag    4      # mag column in SExtractor cat
-fr     11     # fr column in SExtractor cat
-fwhm   12     # fwhm column in SExtractor cat
-flux   2      # flux column in SExtractor cat - must be followed by flux
-ntot   14     # total number of columns in SExtractor cat, max=100
#
# PSF fitting parameters
#
-rgmax  20     # Number of different rg scales PSF measured and fit with
-order  0     # PSF polynomial model order, 0,1,2,3 implemented
-nchipx 1     # Number of CCD chips to fit in the x direction
-nchipy 1     # Number of chips to fit in the y direction
-back   21178.0 # Subtract off flat background sky of amplitude back
```

PSF model: runstars.scr

```
foreach psf (0)#1 2 3 4 5)

  foreach lens (4)# 0 1 2 3)

    echo 'Select stars using findstars for STEP 1 psf '${psf}' lens '${lens}'

    @ i = 1
    while ($i <= 1)

# findstars permits user defined stellar selection.
# It only needs to be run for different seeing conditions.
# For STEP every psf type has the same seeing,
# so only set criteria from one image

      {$KSBDIR}/findstars.a -in {$CATDIR}/psf{$psf}lens{$lens}/STEPimage.{$i}
      .psf{$psf}.lens{$lens}.cat -param KSBf90.param -out {$CATDIR}/psf{$psf}lens{$le
      ns}/star_criteria.dat

      @ i = $i + 1
    end

    echo 'Fit polynomial PSF model to stars using psffit for STEP 1 psf '${psf}'
    lens '${lens}'

    @ i = 1
    while ($i <= 1)

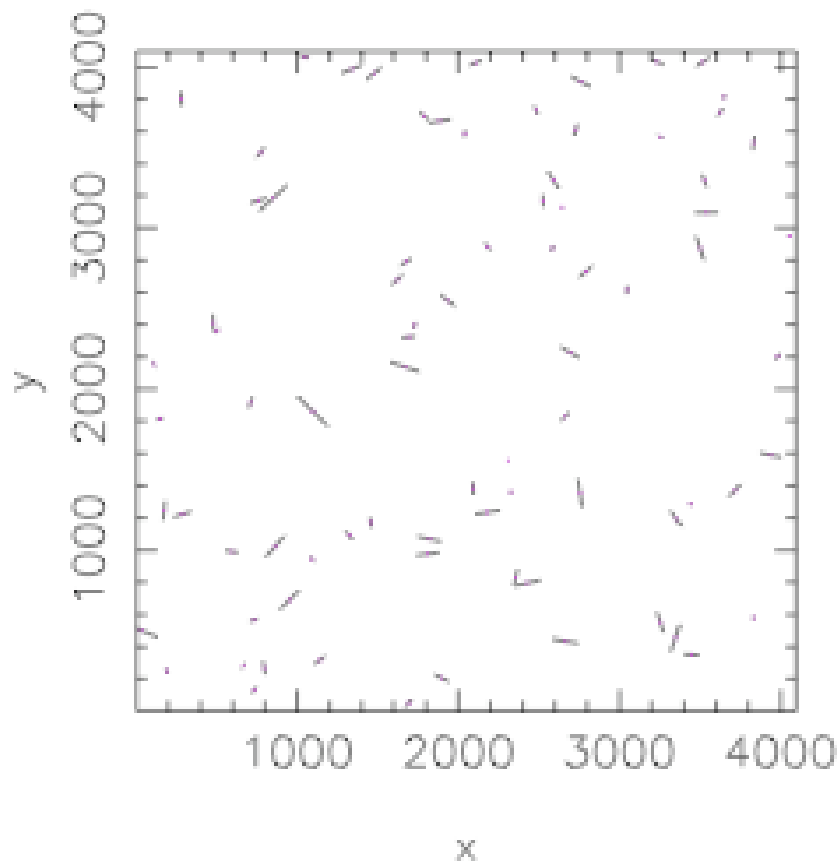
      {$KSBDIR}/psffit.a -in {$CATDIR}/psf{$psf}lens{$lens}/STEPimage.{$i}.psf{$p
      sf}.lens{$lens}.cat -image {$STEPDIR}/psf{$psf}lens{$lens}/STEPimage.{$i}.psf{$
      psf}.lens{$lens}.fits -crit {$CATDIR}/psf{$psf}lens{$lens}/star_criteria.dat -p
      aram KSBf90.param -pgopen {$CATDIR}/psf{$psf}lens{$lens}/psffit_{$i}.ps/cps -ou
      t {$CATDIR}/psf{$psf}lens{$lens}/STEPimage.{$i}.psf{$psf}.lens{$lens}.psffit.ca
      t

      @ i = $i + 1
    end

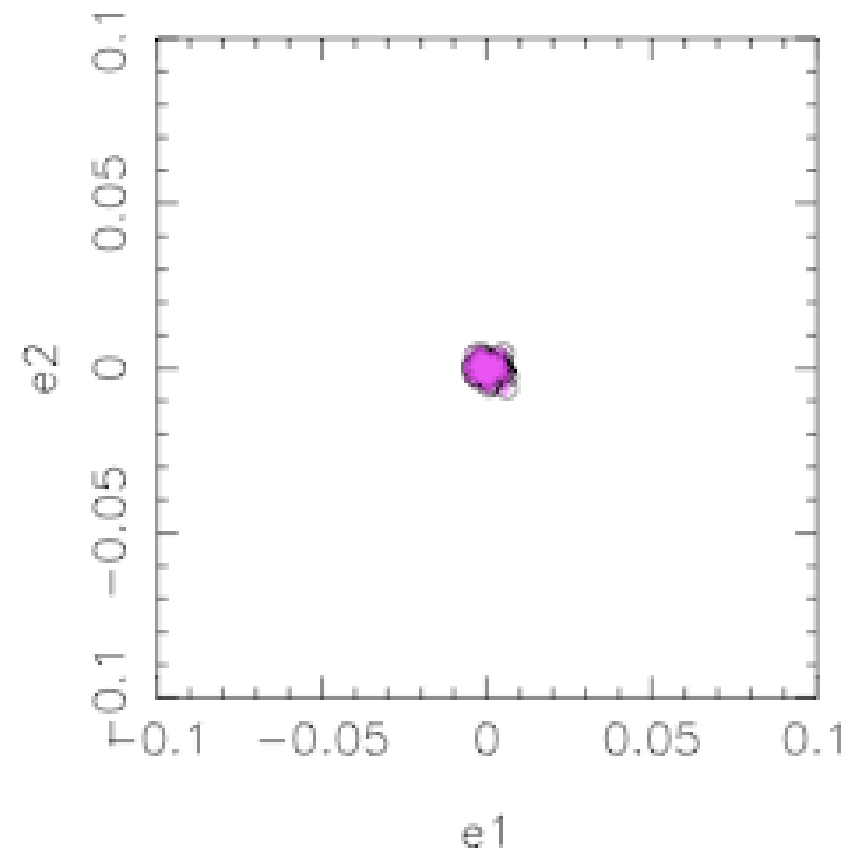
  end

end
end
```

radius = stellar flux radius



PSF ellipticity



Measure galaxy shapes: rungals.scr

```
#!/bin/tcsh
#
# Cshell Script for measuring and correcting galaxy shapes

foreach psf (0)#1 2 3 4 5)

  foreach lens (4)# 0 1 2 3)

    echo 'Measuring galaxy shapes and correcting for the PSF'

    @ i = 1
    while ($i <= 64)

      {$KSBDIR}/gal_correct.a -in {$CATDIR}/psf{$psf}lens{$lens}/STEPimage.{$i}.psf{$psf}.lens{$lens}.cat
      -image {$STEPDIR}/psf{$psf}lens{$lens}/STEPimage.{$i}.psf{$psf}.lens{$lens}.fits -crit {$CATDIR}/psf{$psf}lens{$lens}/star_criteria.dat -psf {$CATDIR}/psf{$psf}lens{$lens}/STEPimage.{$i}.psf{$psf}.lens{$lens}.psffit.cat -param KSBf90.param -out {$CATDIR}/psf{$psf}lens{$lens}/STEPimage.{$i}.psf{$psf}.lens{$lens}.shear.cat

      @ i = $i + 1
    end

  end

end
end
```

Galaxy selection

```
#!/bin/tcsh
#
# Cshell Script for choosing selection criteria for galaxies

foreach psf (0)#1 2 3 4 5)

  foreach lens (4)# 0 1 2 3)

    echo 'Choose selection criteria for galaxies'

    {$KSBDIR}/galaxy_selection.a -in shearcatalog -out selection_criteria.dat -param KSBf90.param -fit 1

  end
end
end
```

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 rungalselect.scr
- The challenge can you get $g_1=0.1$ and $g_2=0$?