Shape Measurements in Weak Gravitational Lensing

Andean Cosmology School, Universidad de Los Andes, Bogotá Week 4, lecture 2 24-6-2015

Andrés Alejandro Plazas Malagón
andres.a.plazas.malagon@jpl.nasa.gov

Caltech Postdoctoral Scholar
Astrophysics and Space Sciences Section
NASA JPL-Caltech

Jet Propulsion Laboratory
California Institute of Technology

Overview of this week

- First lecture: Weak Gravitational Lensing (WL): history, basics, applications, systematics
- **Second Lecture:** The challenge of measuring shapes for WL, current and planned WL experiments
- Third Lecture: Charge-Coupled Devices: basics, characterization.
- Fourth Lecture: Instrumental signatures on astrophysical observables: photometry, astrometry, shapes.

Lecture 2: outline

- Observational challenges
  -The Problem of Shape Measurement in WL

- Shape Measurement Methods
  -Simulations: WL Challenges (STEP, GREAT)
  -Software: GalSim

- Current and Future Surveys: DES, LSST, WFIRST-AFTA

The challenge of measuring shapes to get shear

- It would seem that we "just" have to obtain a shear catalog, do cosmology, and then win the Nobel prize for figuring out what dark energy is!
- It actually requires a bit more effort than that…

The challenge of measuring shapes to get shear

From raw images:

* Object Detection : distinguish stars from galaxies

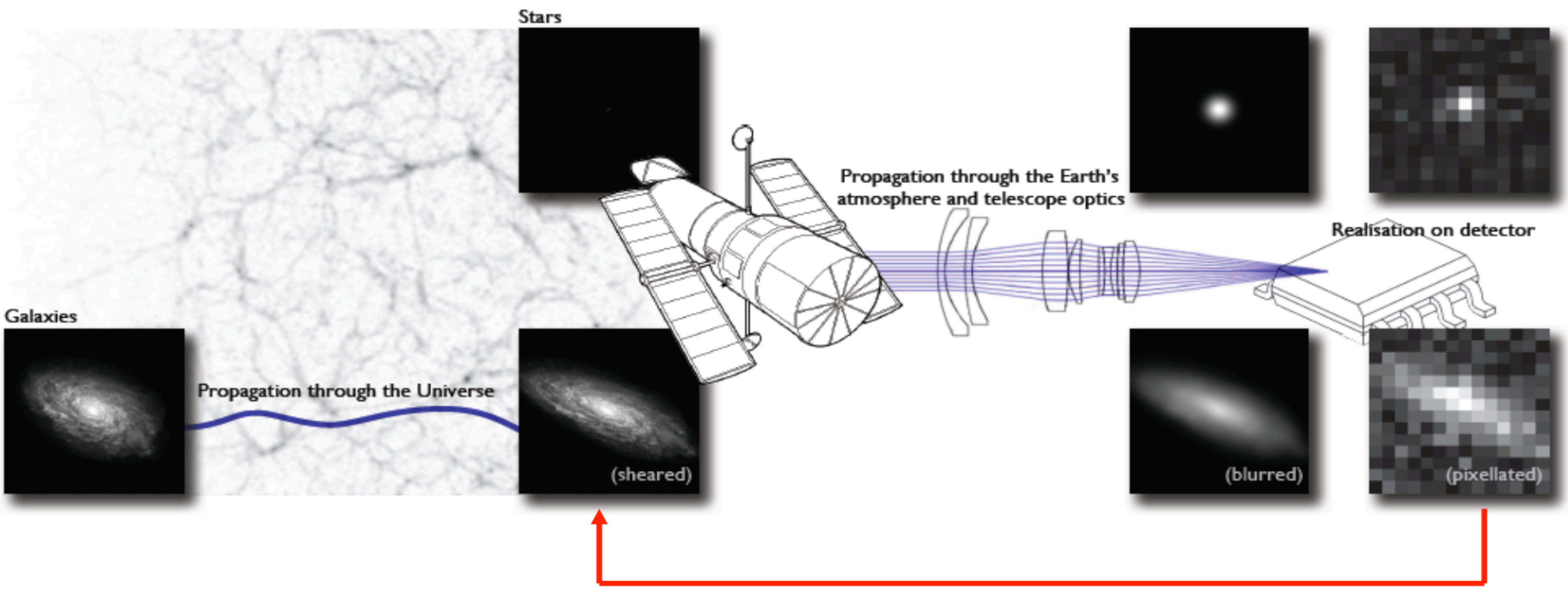
* PSF estimation: use bright stars . Interpolate across the FOV

* PSF correction: deconvolve PSF from galaxy shapes.

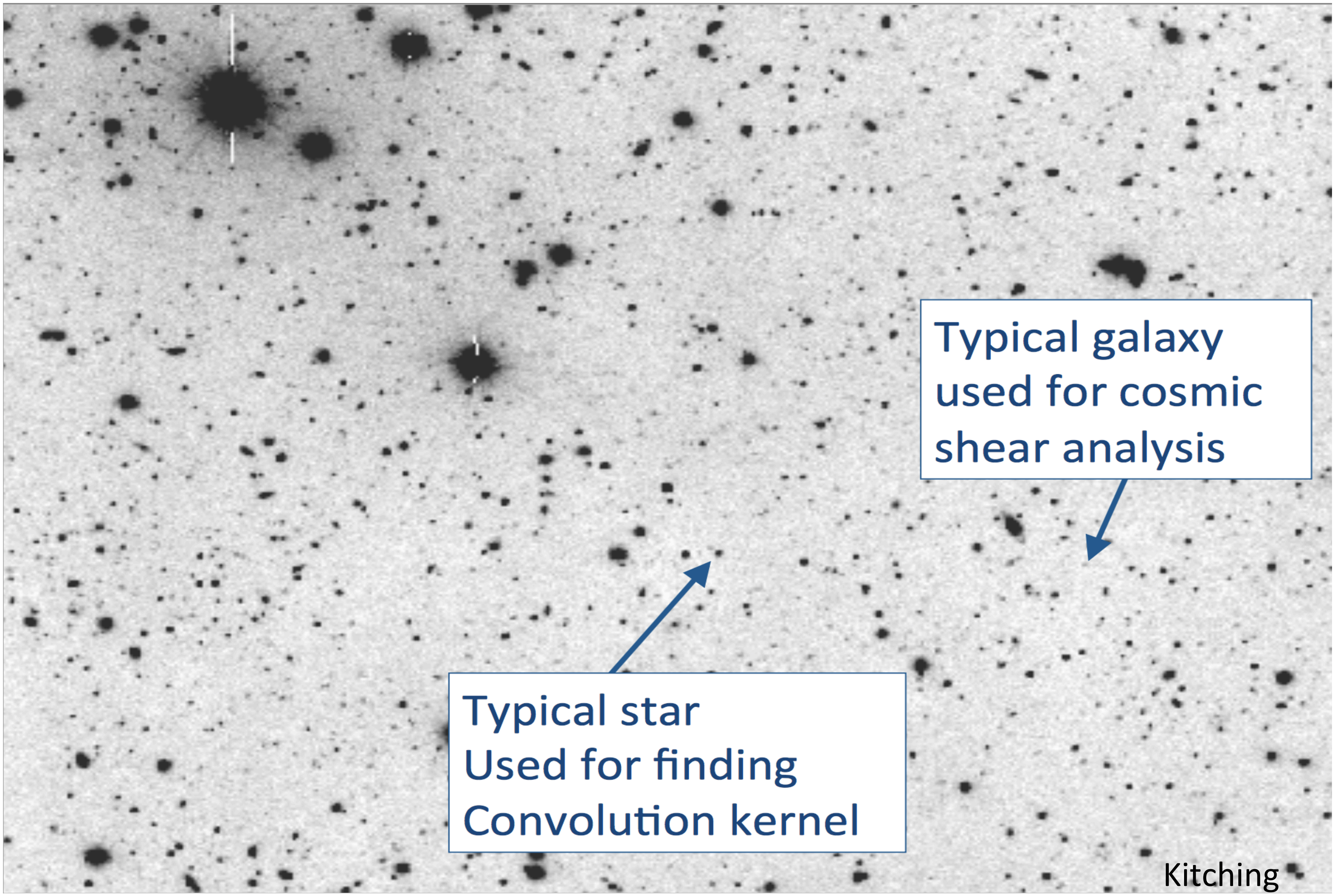
* Do Cosmology: once we have a catalog of galaxy shapes, we can estimate the shear and then calculate masses , statistics (2,3-point correlations, etc), obtain cosmological parameters, etc.

The Problem

-We want to recover the coherent distortion due to weak lensing (shear) from the images in our detectors



- To beat shape noise, we need tons of galaxies!
- But the galaxies we usually use for WL are small and faint!



Observational Challenges

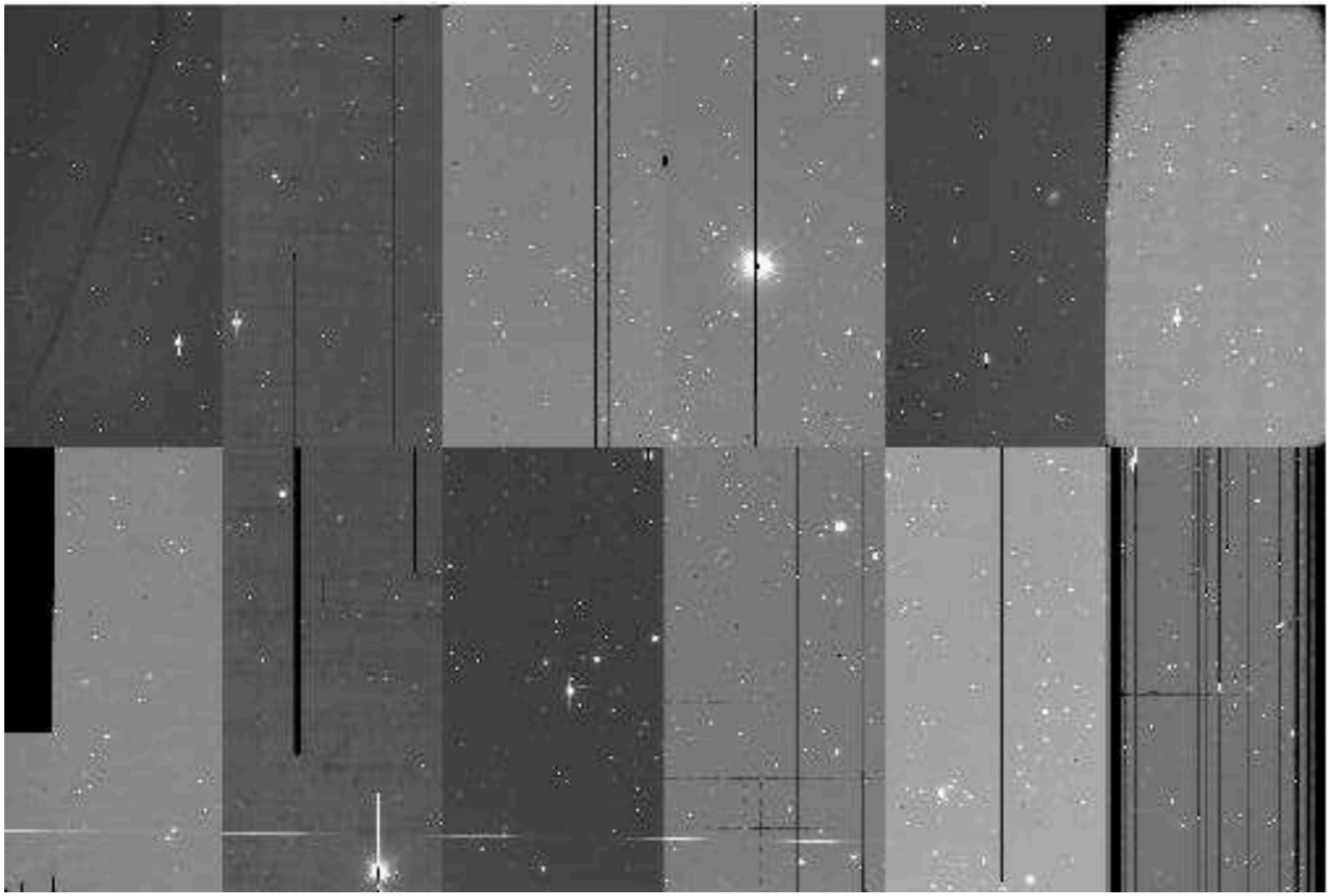
- We find more sources in the optical and NIR: need adequate detectors
- Need wide field cameras: expensive!
- Long exposures are needed to have high number density of sources
- Deep observations of a field require multiple exposures: high data rate
- Seeing (and/or PSF): blurs the images and make them rounder

Observational Challenges: data reduction of individual images

- Flat fielding: corrects for the difference in sensitivity amongst pixels. Need a uniform source of illumination: dome screen, twilight
- Bad pixels: some pixels are dead or show a signal unrelated to their illumination.
- Bright stars, satellites, trails, fringing, gaps: more on this in tomorrow's lecture on CCDs!

Observational Challenges: data reduction of individual images

Raw image example:



Observational Challenges: coaddition

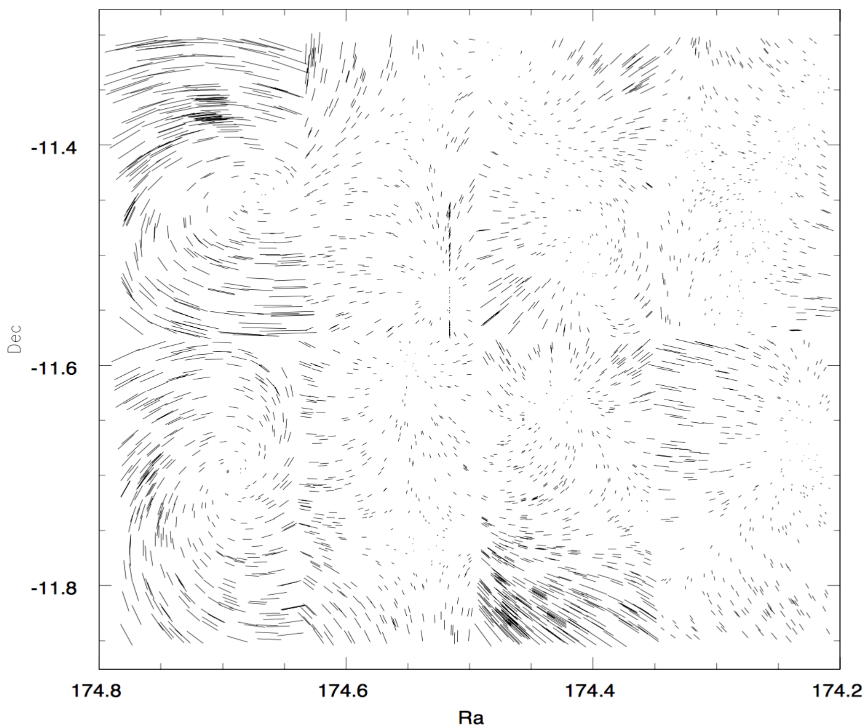
- Take multiple exposures at slightly different pointings to correct for gaps
- Exposures are also taken with different exposure times
- We need to stack them together and produce a coadded image, where we will detect sources.

Observational Challenges: coaddition

- Astrometric solution: map from pixel to sky coordinates.

We need to coadd data from the same true (or sky) position, not the same pixel position. Field distortions and sensor effects makes this map complicated.

- Photometric solution: different exposures are tied together by matching the brightness of joint objects. Need external dataset of standard stars.

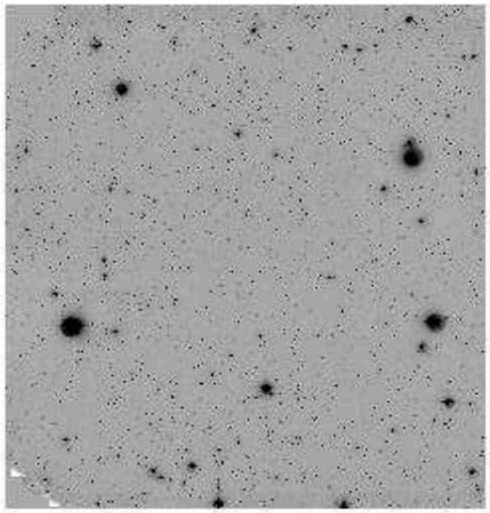
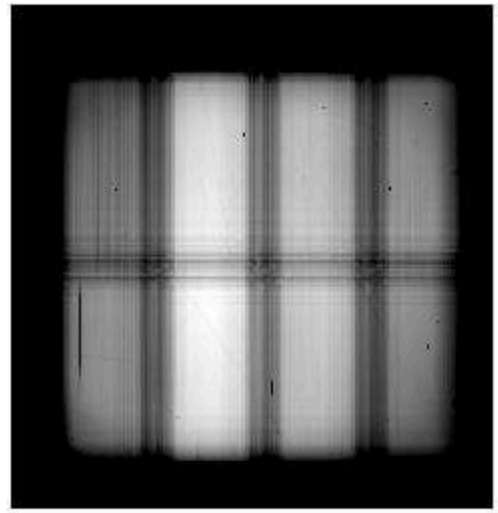
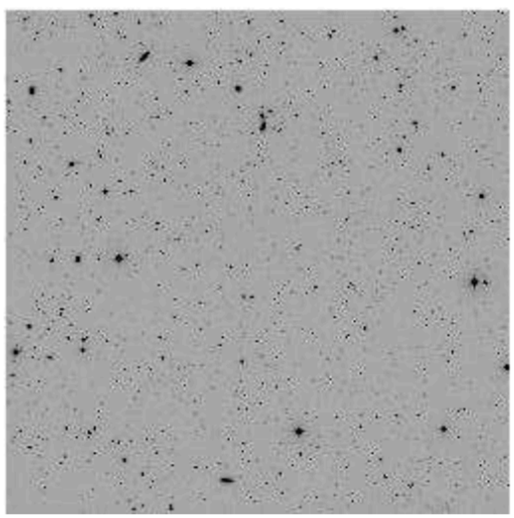
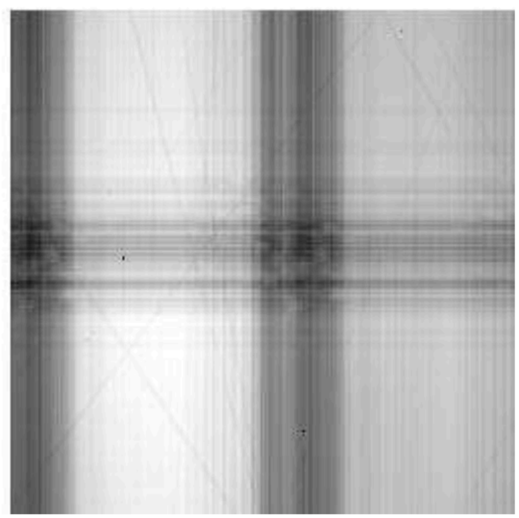


Code: **SCAMP** by Emmanuel Bertin

Observational Challenges: coaddition

- Coaddition process: needs to have sub-pixel accuracy, so has to be done carefully
- Individual frames with the astrometric and photometric solution applied are now remapped onto a new pixel grid
- Weights are assigned, accounting for the noise properties of the individual exposures
- Algorithms and code: “drizzle”, SWARP (Emmanuel Bertin)

Observational Challenges: coaddition

Observational Challenges: Image analysis

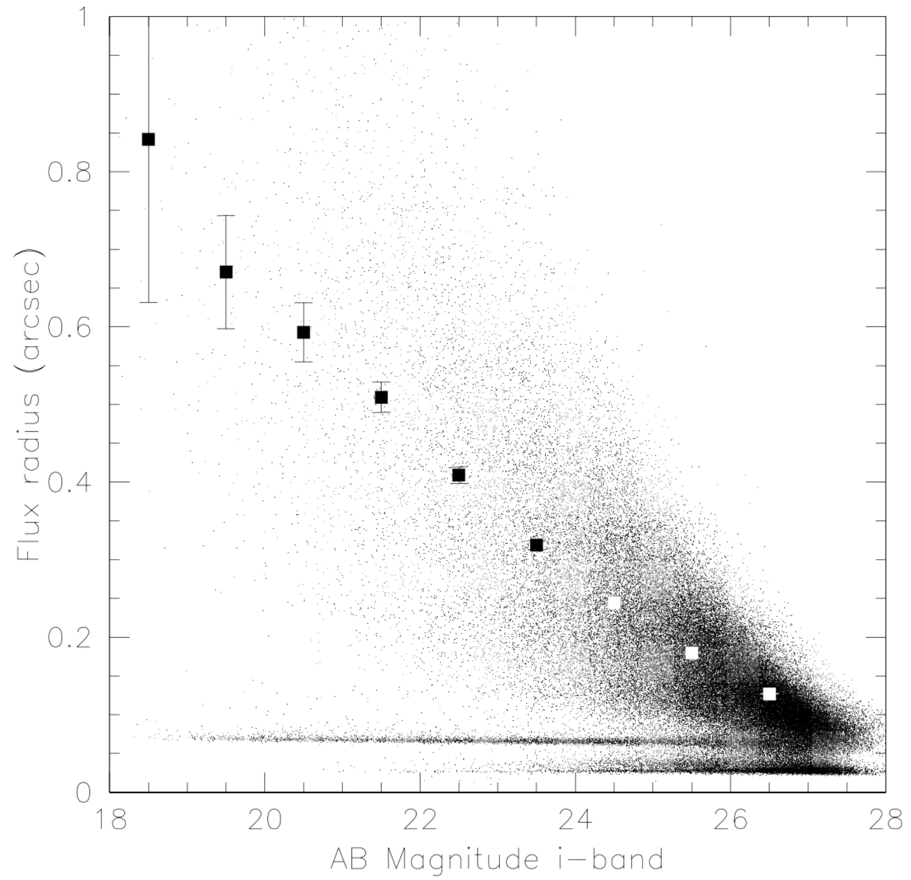
- Outcome of coaddition: image + weight map
- Next:

  -Identification of sources

  -measure their magnitude, size and shape

Observational Challenges: Image analysis

- Star-galaxy separation:
- Challenging!
- Images of sources can be overlapping
- Substructure in brightness distribution of galaxies
- Galaxies are faint
- The PSF!



Observational Challenges: object identification

- Widely used code: **Source Extractor (SExtractor)** by Emmanuel Bertin

-Performs star-galaxy separation, photometry, astrometry, and shape measurements

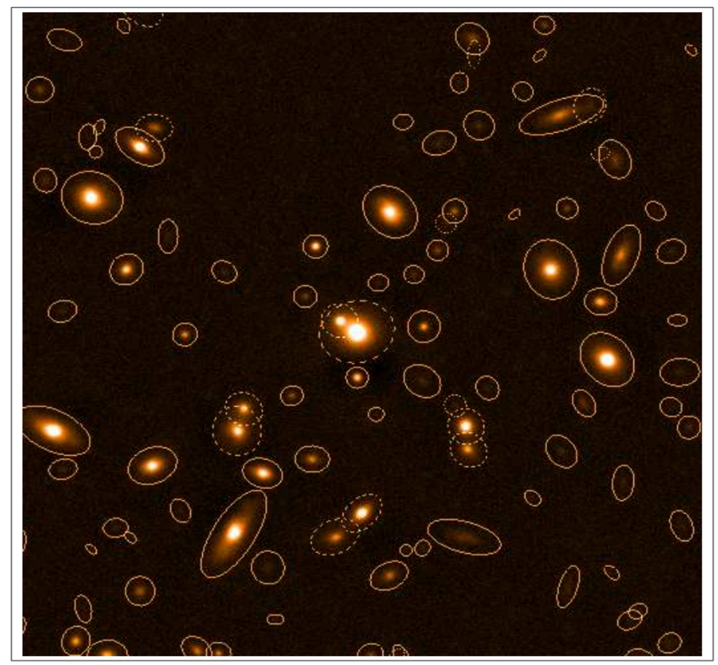
-Unfortunately, for WL, the accuracy given by SExtractor alone is **not enough**. We still use it as a first guess in each of the quantities of interest, though.

Draft

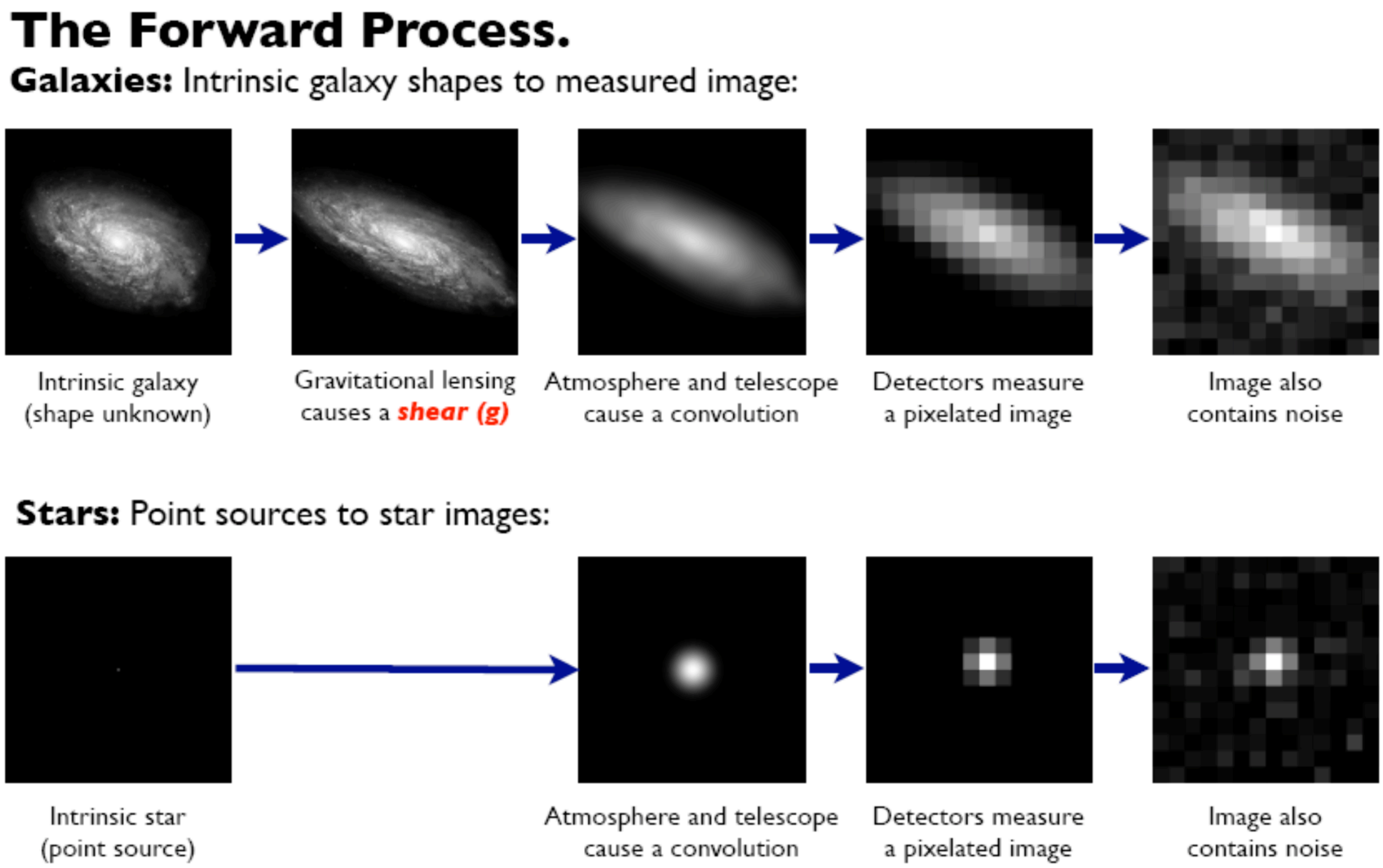
SExtractor
$v2.5$
User's manual

E. BERTIN

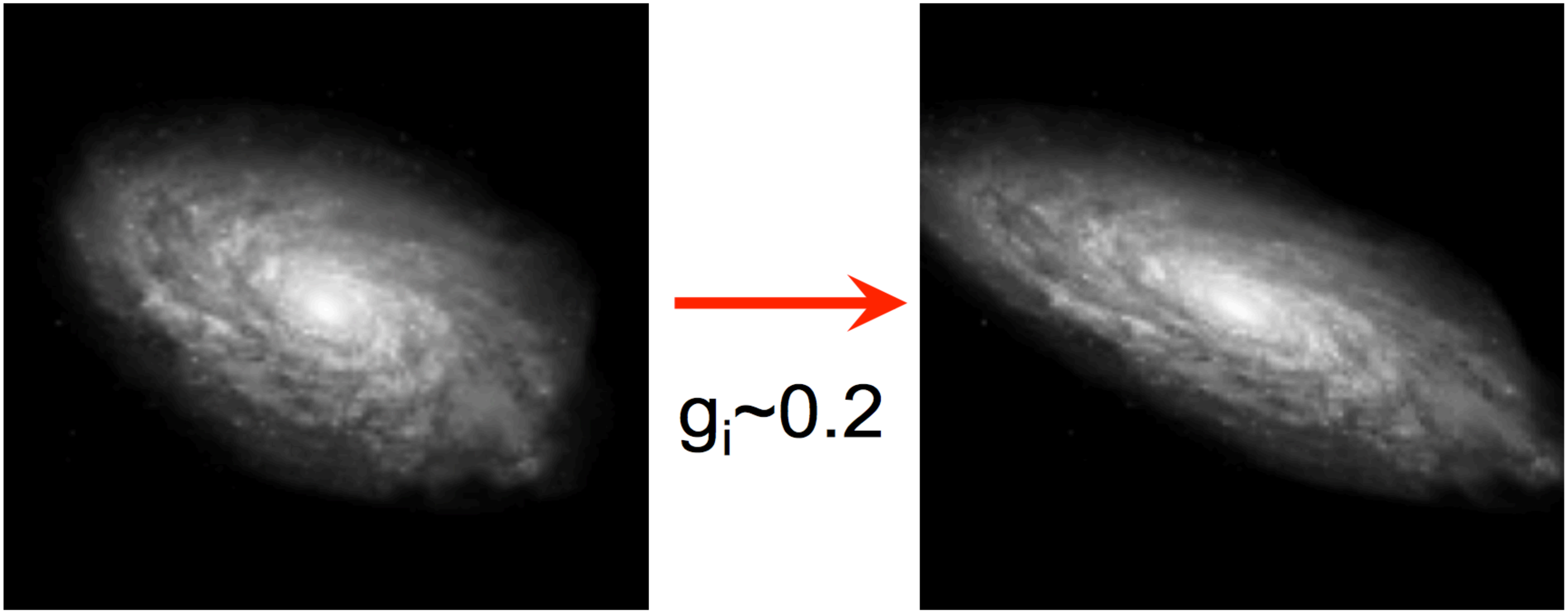
Institut d'Astrophysique
& Observatoire de Paris



The shear measurement problem



The shear measurement problem: the cosmic WL signal

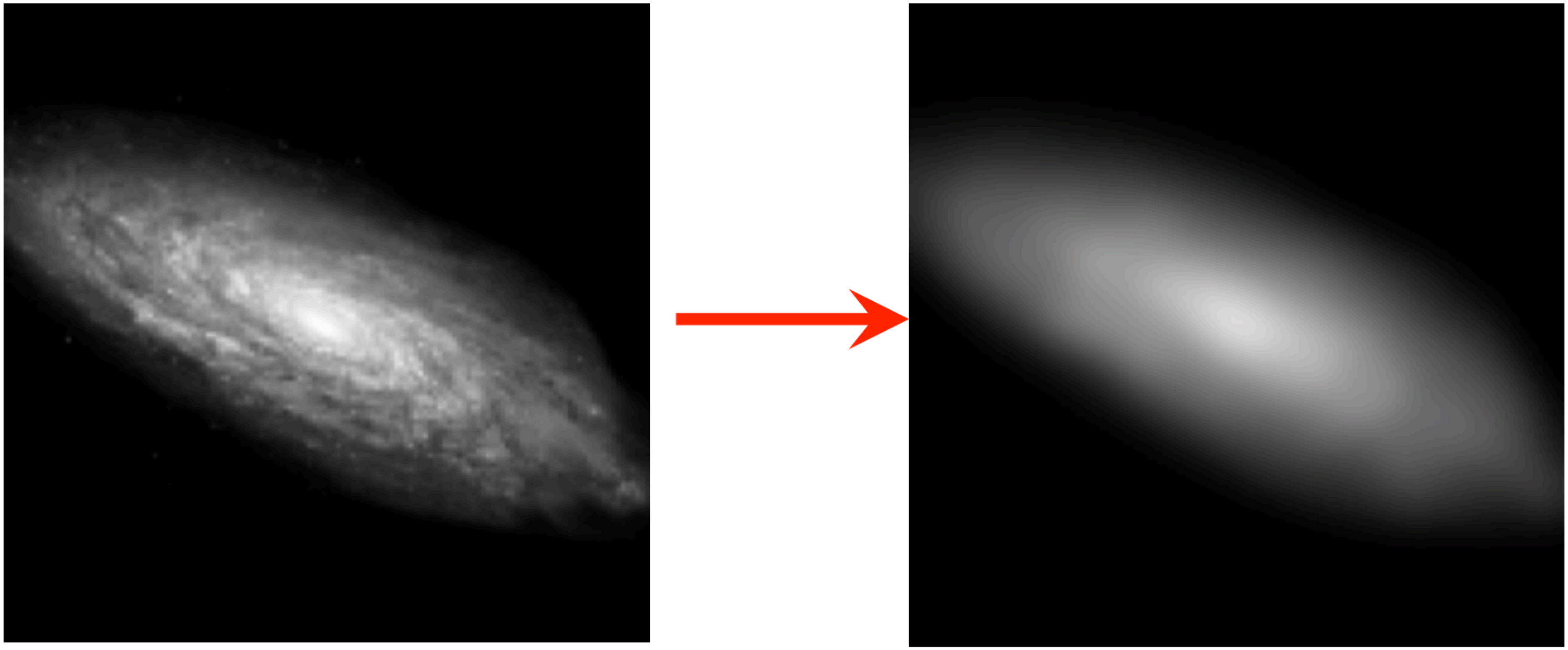


$$\begin{pmatrix} x_u \\ y_u \end{pmatrix} = \begin{pmatrix} 1-g_1 & -g_2 \\ -g_2 & 1+g_1 \end{pmatrix} \begin{pmatrix} x_l \\ y_l \end{pmatrix}$$

(ignoring magnification for now)

Shear in real data:
~0.01-0.03

The shear measurement problem: atmosphere and telescope



The image is convolved by a kernel: the **Point Spread Function (PSF)**

In real data, the size of the kernel is about the same as the size of the galaxy. PSF usually creates coherent patterns

The Point Spread Function

- Describes how point sources would appear on the image

- Shape and size of the images are affected by the point-spread function

- PSF has many contributions: optics, atmosphere (ground), detector diffusion, etc.

- Ground: to first order, can be a Gaussian (space: Airy)

-Its FWHM is called "seeing": 0.7-0.8 arcsec for a great site.

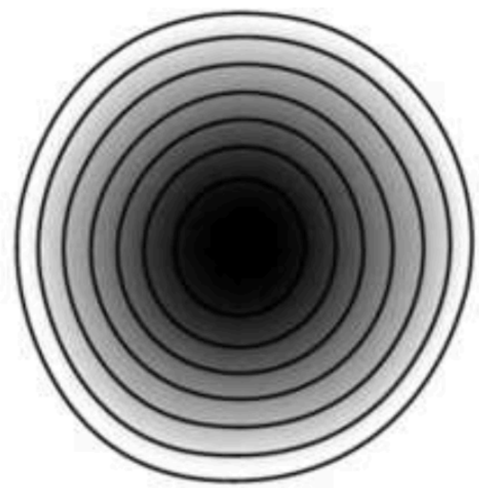
- Galaxies are usually smaller than PSF

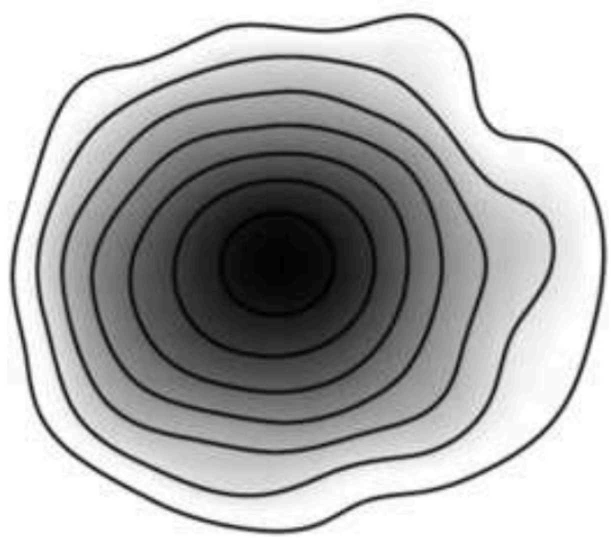
- Seeing makes an elliptical source rounder

-An anisotropic PSF makes round sources elliptical, and therefore mimics a shear

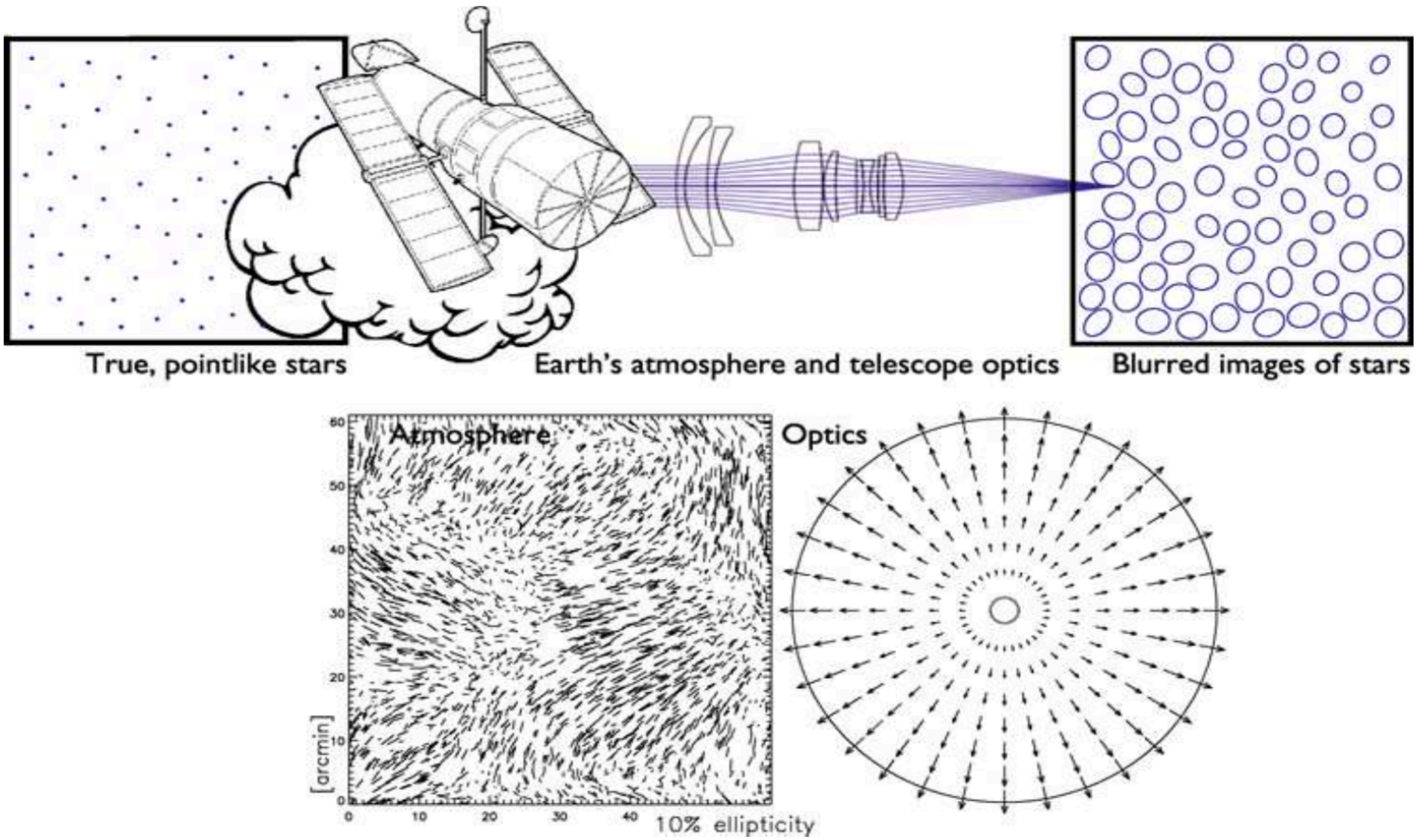
$$I^{\mathrm{obs}}(\boldsymbol{\theta}) = \int \mathrm{d}^2\vartheta \; I(\boldsymbol{\vartheta}) \, P(\boldsymbol{\theta} - \boldsymbol{\vartheta})$$

Examples of PSFs (convolution kernels)

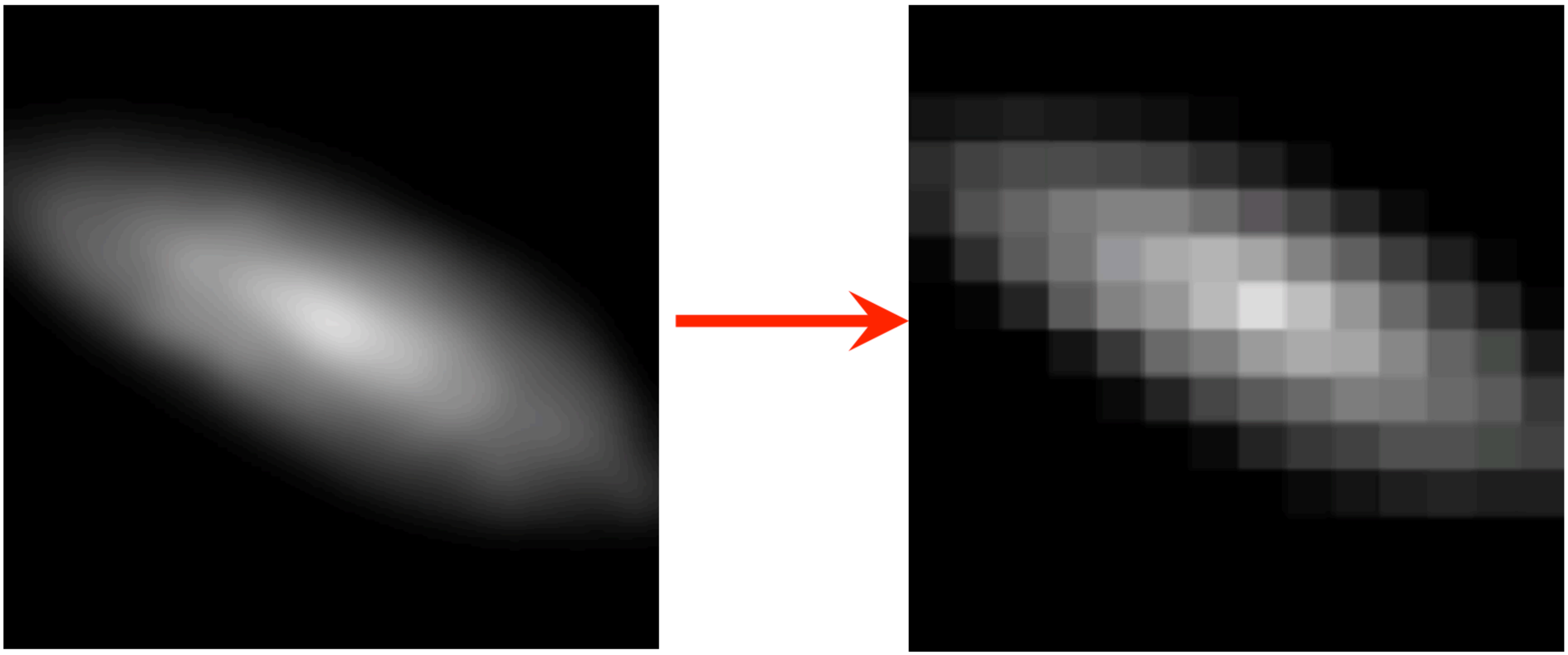




The Point Spread Function



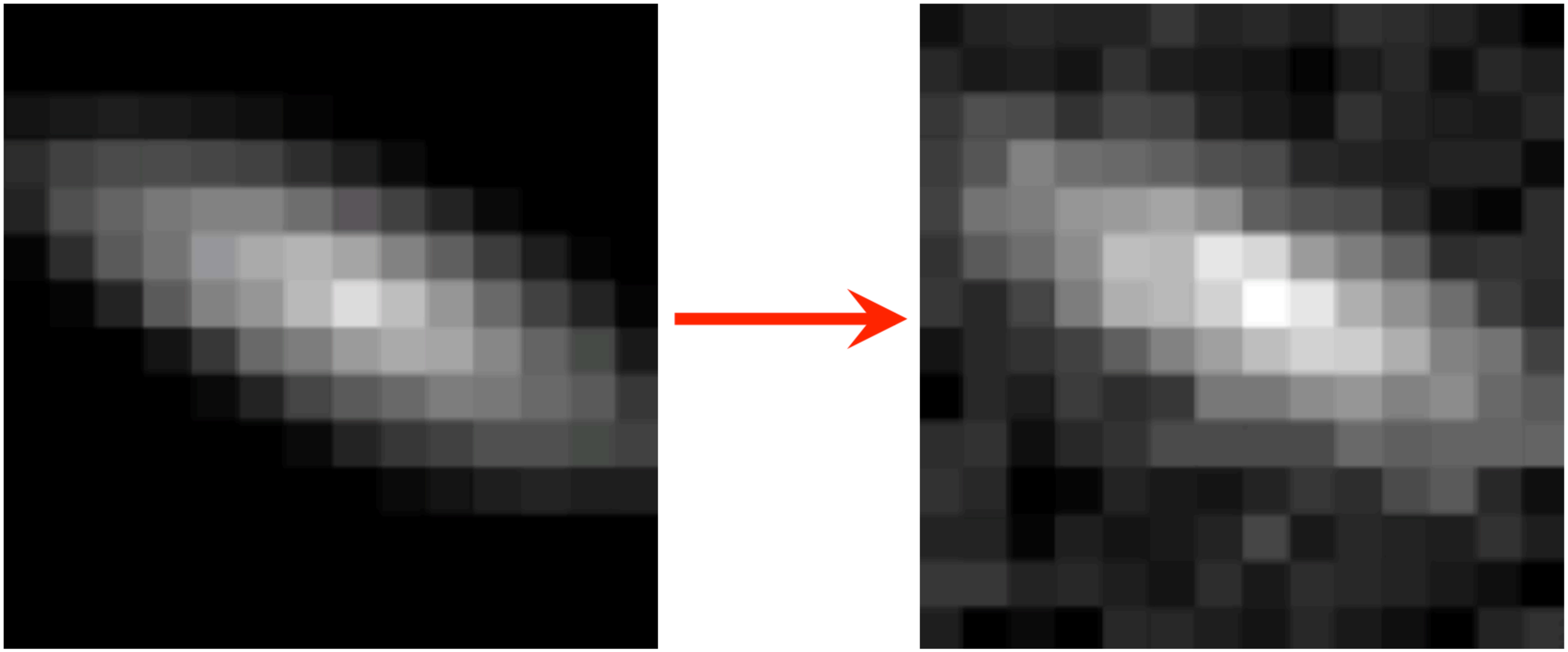
The shear measurement problem: pixelization



In real data, the pixel size is about one half of the kernel size

Many detectors effects: biases in observables (photometry, astrometry shapes): see tomorrow’s and Friday’s lecture!

The shear measurement problem: noise



Poisson noise from photons
Gaussian noise: readout

Surface Brightness

- Galaxies morphologies are characterized through their surface brightness profiles

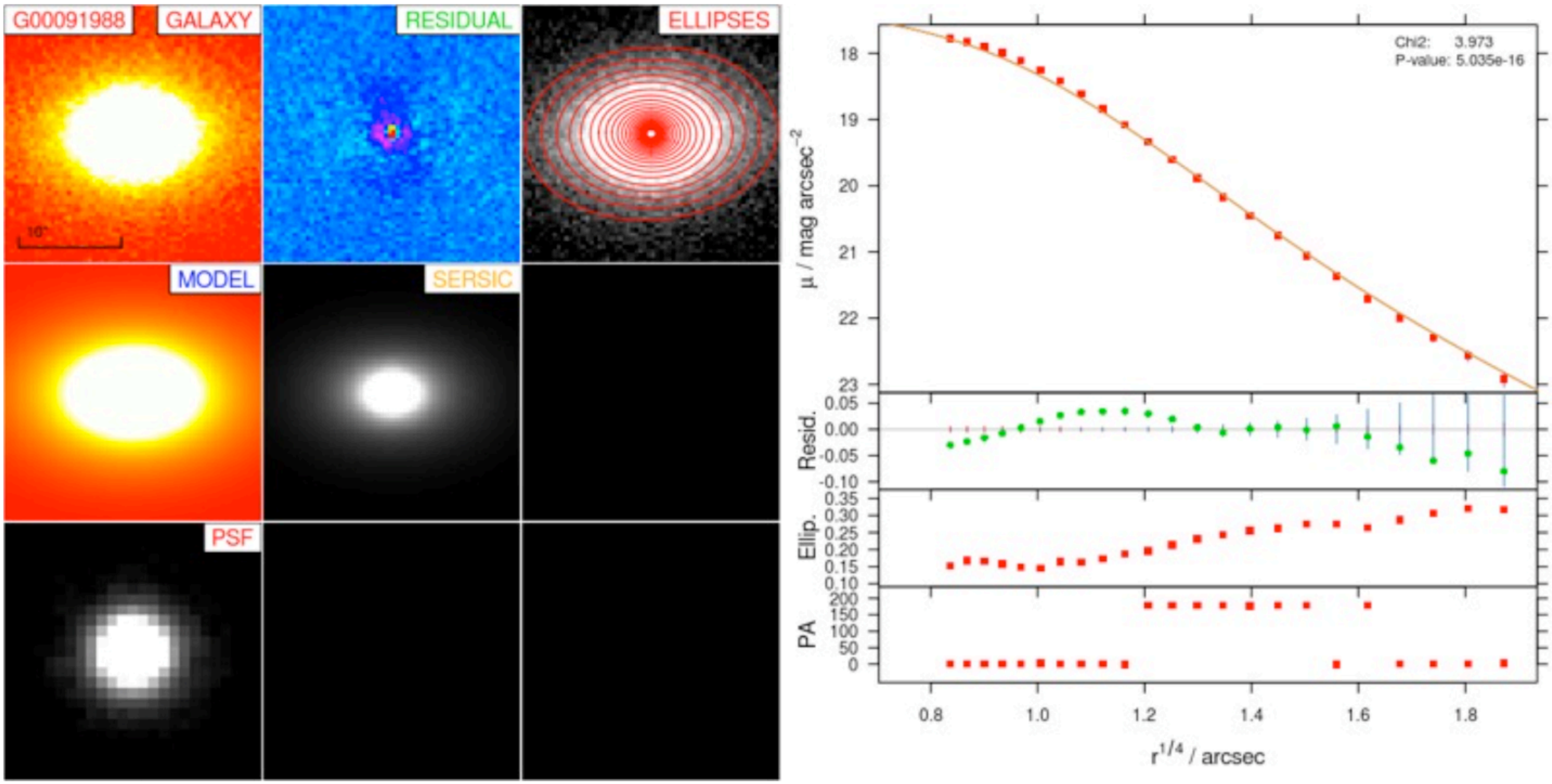
-Light from galaxies follows a distribution of brightness I(x,y)

- **I(x,y):**   intensity or surface brightness distribution.
It is measured in units of brillo per unit area at position (x,y): physical units (e.g., pc^2) or angular area (e.g, square arcseconds)

- Surface brightness is often represented by a radially-averaged function   I(R)

Surface Brightness Profiles: examples

Examples:



Surface Brightness Profiles

Sérsic Profile:

$$I(r) = \frac{F}{2n\pi\Gamma(2n)r_0^2} e^{-(r/r_0)^{1/n}}$$
$$= \frac{F}{a(n)r_e^2} e^{-b(n)(r/r_e)^{1/n}},$$

Exponential profile:

-Sérsic n =1

-Good description of the outer, star-forming regions of spiral galaxies

$$I(r) = \frac{F}{2\pi r_0^2} e^{-r/r_0}$$

Surface Brightness Profiles

De Vaucouleurs:

-Good fit to the light profiles of both elliptical galaxies and the central bulge regions of spiral galaxies

- Sérsic n=1/4
- Have very cuspy cores and also very broad wings

$$I(r) = \frac{F}{7! \cdot 8\pi r_0^2} \mathrm{e}^{-(r/r_0)^{1/4}}$$

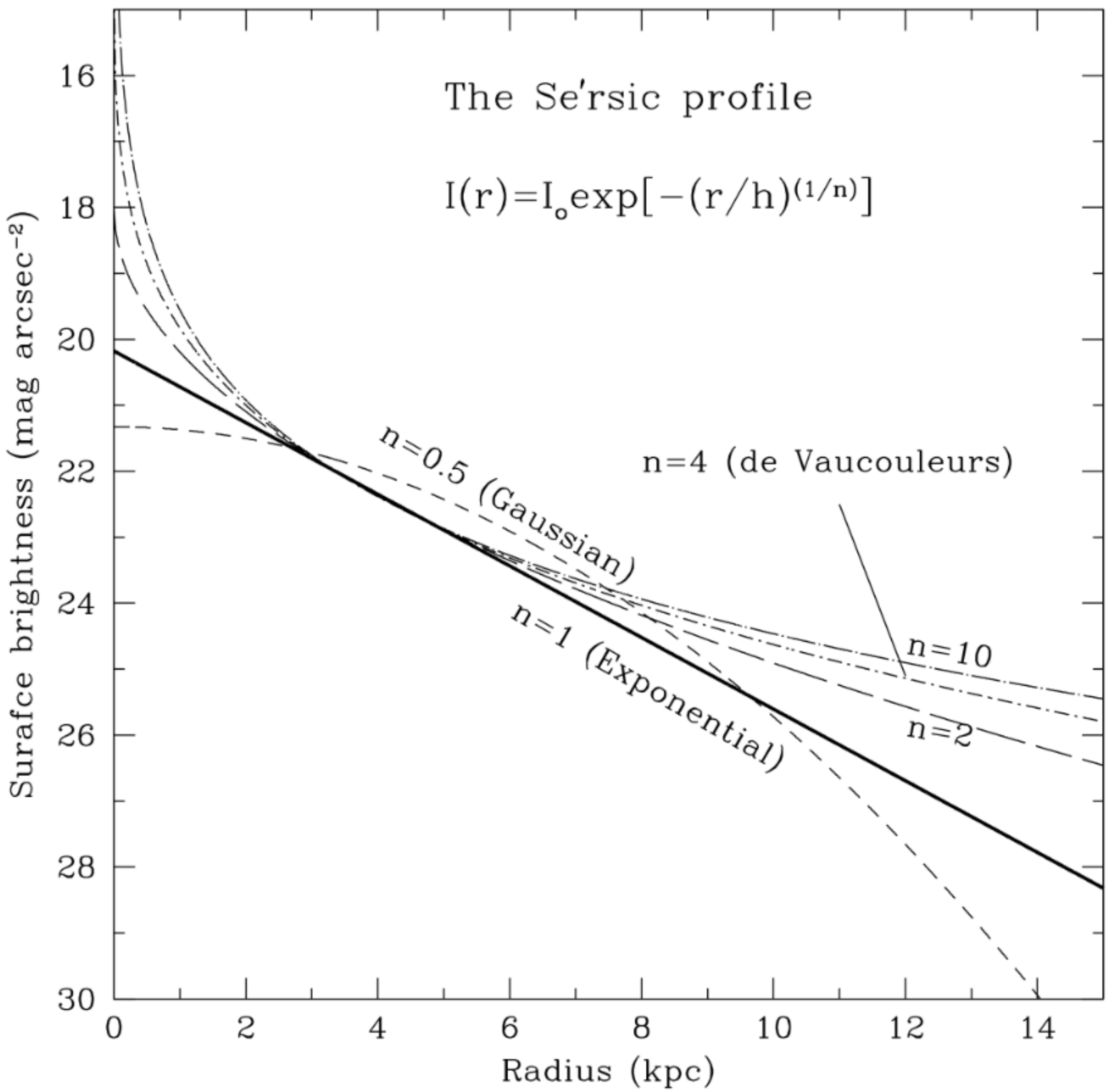
Gaussian:

-Sérsic n=1

-Convenient analytical properties

$$I(r) = \frac{F}{2\pi\sigma^2} \mathrm{e}^{-r^2/2\sigma^2}$$

Surface Brightness Profiles



Surface Brightness Profiles : PSF models

Airy profile: Diffraction pattern of a circular aperture

$$I(r) = \left[\frac{J_1(\nu)}{\nu}\right]^2$$

$$\nu \equiv \pi r D/\lambda\,,$$

$$I(r) = \left[\frac{J_1(\nu) - \epsilon J_1(\epsilon\nu)}{\nu}\right]^2$$

Moffat: analytic model for stellar PSFs with broader wings than Gaussian that provides a better fit to observations

$$I(r) = \frac{F(\beta - 1)}{\pi r_0^2}\left[1 + (r/r_0)^2\right]^{-\beta}$$

Kolmogorov: atmospheric, long exposure PSFs

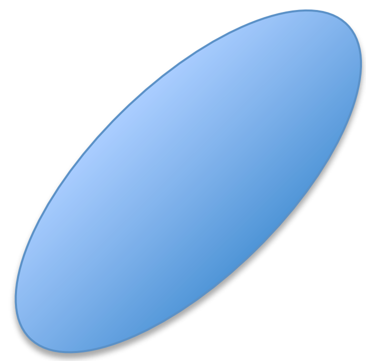
$$\widetilde{I}(k) = F\mathrm{e}^{-(k/k_0)^{5/3}}$$

Galaxy Shapes

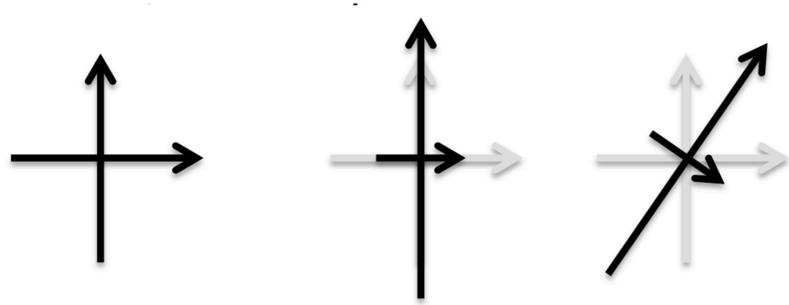
To estimate shear, start by measuring shapes of galaxy images

Assign an ellipticity (3 numbers):

- semi-major axis
- semi-minor axis
- orientation angle



You can think of it as an stretching or compression of the coordinate axes, followed by a rotation



How to measure galaxy ellipticities?

First, consider an idealized case: no pixelization, convolution, or noise

Centroid: first central moment of the surface brightness

$$\bar{x} = \frac{\int I(x,y)x\,dx\,dy}{\int I(x,y)\,dx\,dy}$$

$$\bar{y} = \frac{\int I(x,y)y\,dx\,dy}{\int I(x,y)\,dx\,dy}$$

Three second order moments will help us define the ellipticity

Recall that we need 3 numbers to define an ellipticity

$$Q_{xx} = \frac{\int I(x,y)(x-\bar{x})^2\,dx\,dy}{\int I(x,y)\,dx\,dy},$$

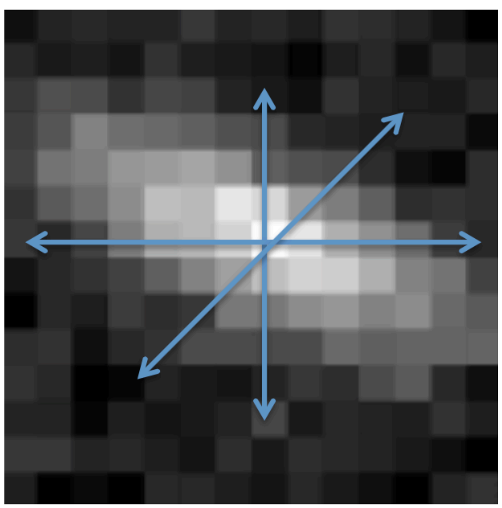
$$Q_{xy} = \frac{\int I(x,y)(x-\bar{x})(y-\bar{y})\,dx\,dy}{\int I(x,y)\,dx\,dy},$$

$$Q_{yy} = \frac{\int I(x,y)(y-\bar{y})^2\,dx\,dy}{\int I(x,y)\,dx\,dy}.$$

Galaxy ellipticity

From the second order moments, it is possible to come up with one or more definitions of ellipticity:

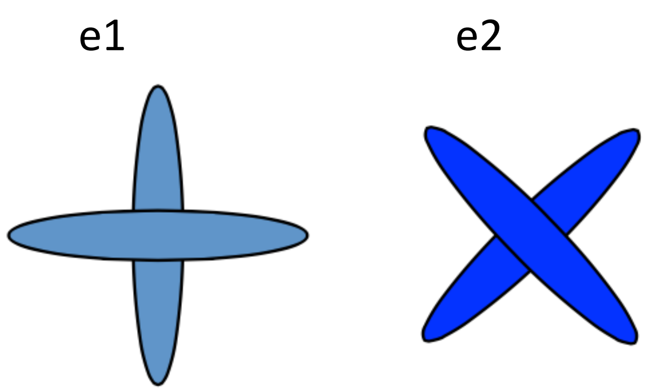
$$\chi \equiv \frac{Q_{11} - Q_{22} + 2\mathrm{i}Q_{12}}{Q_{11} + Q_{22}} \quad \text{and} \quad \epsilon \equiv \frac{Q_{11} - Q_{22} + 2\mathrm{i}Q_{12}}{Q_{11} + Q_{22} + 2(Q_{11}Q_{22} - Q_{12}^2)^{1/2}}$$

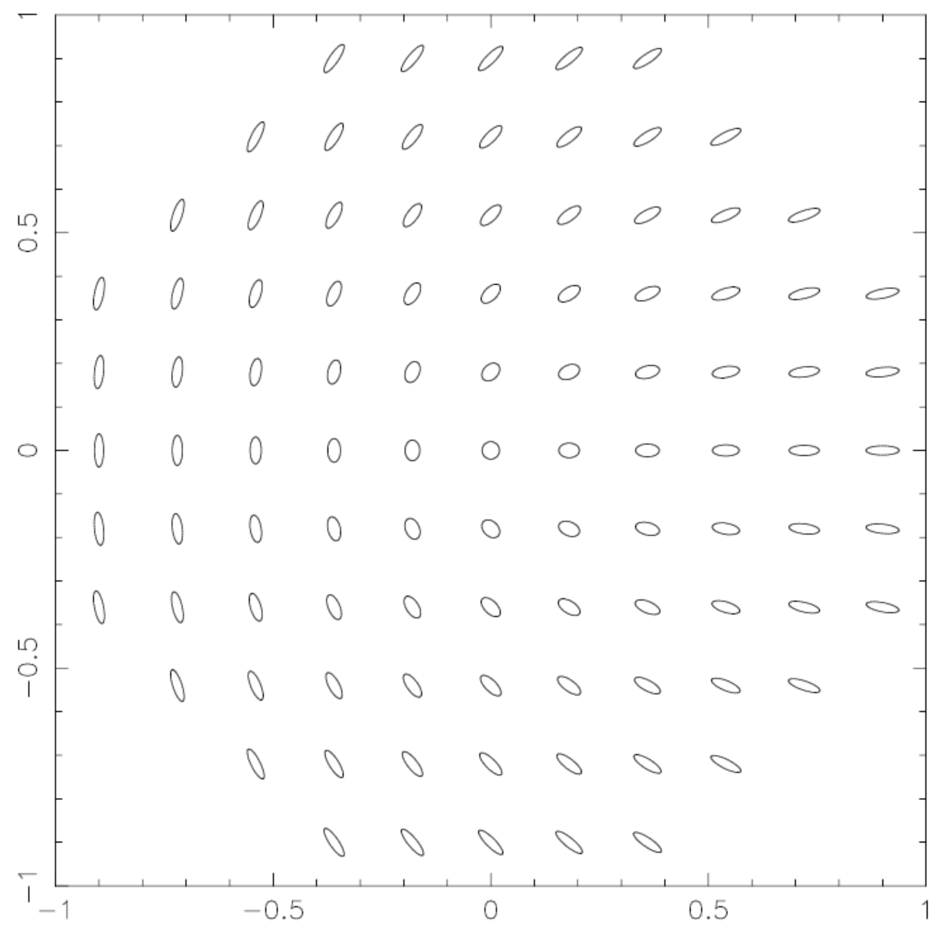


They are both complex numbers with different amplitude but same phase.

Galaxy ellipticity

If we rotate an ellipse by 180 degrees we are back to where we started





Galaxy ellipticity

For an image with elliptical isophotes
with **r=b/a** (axis ratio)

$$|\chi| = \frac{1-r^2}{1+r^2} \quad ; \quad |\epsilon| = \frac{1-r}{1+r}$$

$$\chi_1 = \frac{a^2-b^2}{a^2+b^2}\cos(2\theta),$$

$$\chi_2 = \frac{a^2-b^2}{a^2+b^2}\sin(2\theta).$$

$$\epsilon_1 = \frac{a-b}{a+b}\cos(2\theta),$$

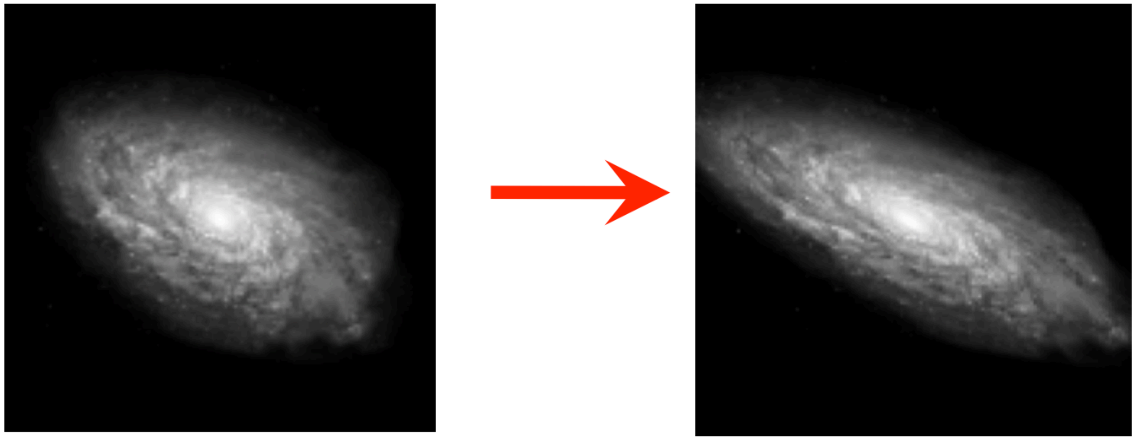
$$\epsilon_2 = \frac{a-b}{a+b}\sin(2\theta).$$

Depending on the context, one can use one or the other.
They are related by:

$$\epsilon = \frac{\chi}{1+(1-|\chi|^2)^{1/2}}\,, \quad \chi = \frac{2\epsilon}{1+|\epsilon|^2}$$

Relation of shear to shape

- The sources themselves are already elliptical: shape noise
-*"Shear"* is an **additional ellipticity** imprinted by lensing



Relation of shear to shape

We write the ellipticities of the source and the observed image in terms of their second order moments, and use the lens equation to relate the two of them.

$$\chi = \frac{\int d\beta I(\beta)\beta^2}{\int d\beta I(\beta)\beta\beta^*}$$

$$\chi^S = \frac{\int d\theta I(\theta)\theta^2}{\int d\theta I(\theta)\theta\theta^*}$$

$$\boldsymbol{\beta} = \boldsymbol{\theta} - \hat{\boldsymbol{\alpha}}\frac{D_{ds}}{D_s}$$

$$\boldsymbol{\beta} = \boldsymbol{\theta} - \boldsymbol{\alpha}.$$

Relation of shear to shape

$$\chi^{(s)} = \frac{2g + \chi + g^2\chi^*}{1 + |g|^2 + 2\mathcal{R}\mathrm{e}\,(g\chi^*)}$$

$$\chi = \frac{\chi^S - 2g + g^2\chi^{S*}}{1 + |g|^2 - 2\mathrm{Re}(g\chi^{S*})}$$

Schneider & Seitz (1995)

Allows the *observed ellipicity* (moments) to be related to the intrinsic (unlensed) ellipicity and shear

Relation of shear to shape

An analogous relation is valid for the other definition of ellipticity:

$$\chi^{(\mathrm{s})} = \frac{\chi - 2g + g^2\chi^*}{1 + |g|^2 - 2\mathcal{R}\mathrm{e}(g\chi^*)} \; ; \quad \epsilon^{(\mathrm{s})} = \begin{cases} \dfrac{\epsilon - g}{1 - g^*\epsilon} & \text{if } |g| \le 1 \, ; \\ \dfrac{1 - g\epsilon^*}{\epsilon^* - g^*} & \text{if } |g| > 1 \, . \end{cases}$$

Relation of shear to shape: the weak lensing limit

When we average over (enough) galaxies in the universe the intrinsic ellipticity is randomly oriented such that :

$$\epsilon = \epsilon^{\mathrm{S}} - g$$

$$\begin{aligned} \langle \epsilon \rangle &= \langle \epsilon^S \rangle - \langle g \rangle \\ \langle \epsilon \rangle &\approx \langle g \rangle . \end{aligned}$$

Fundamental assumption: intrinsic orientation of galaxies is random (valid if Universe is istropic)*

* Intrinsic alignments due to galaxies physically close to each other violates this assumption

Relation of shear to shape: the weak lensing limit

Key weak lensing result
Relates observable (moments) to physics (lens equation) and shear

$$\begin{aligned} \langle \epsilon \rangle &= \langle \epsilon^S \rangle - \langle g \rangle \\ \langle \epsilon \rangle &\approx \langle g \rangle . \end{aligned}$$

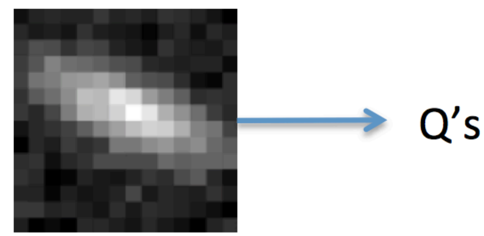
Important result: each image ellipticity provides an unbiased estimate of the local shear, though a very noisy one

when averaging over N galaxy images all subject to the same reduced shear, the 1-σ deviation of their mean ellipticity from the true shear is

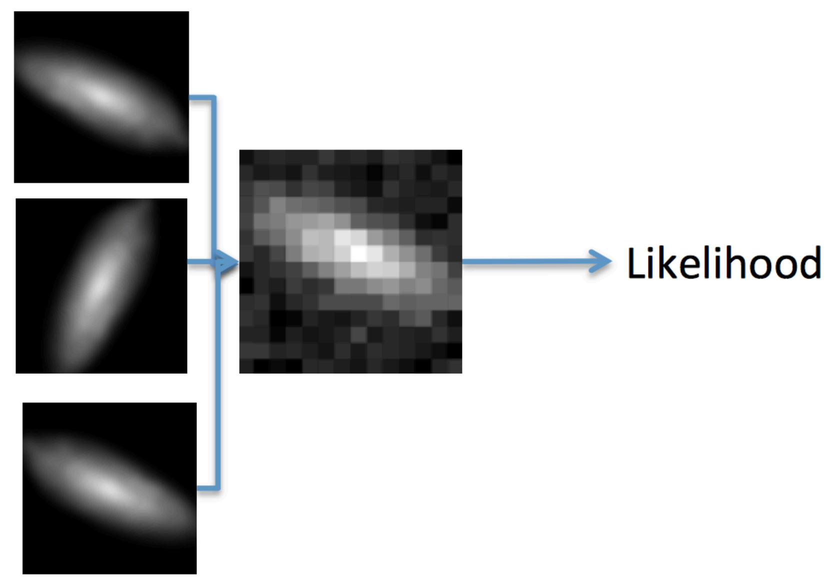
$$\sigma_\epsilon / \sqrt{N}.$$

Shape measurement methods

There are two main approaches to measure shapes:



1) Moments based



2) Forward modeling: fitting to a model

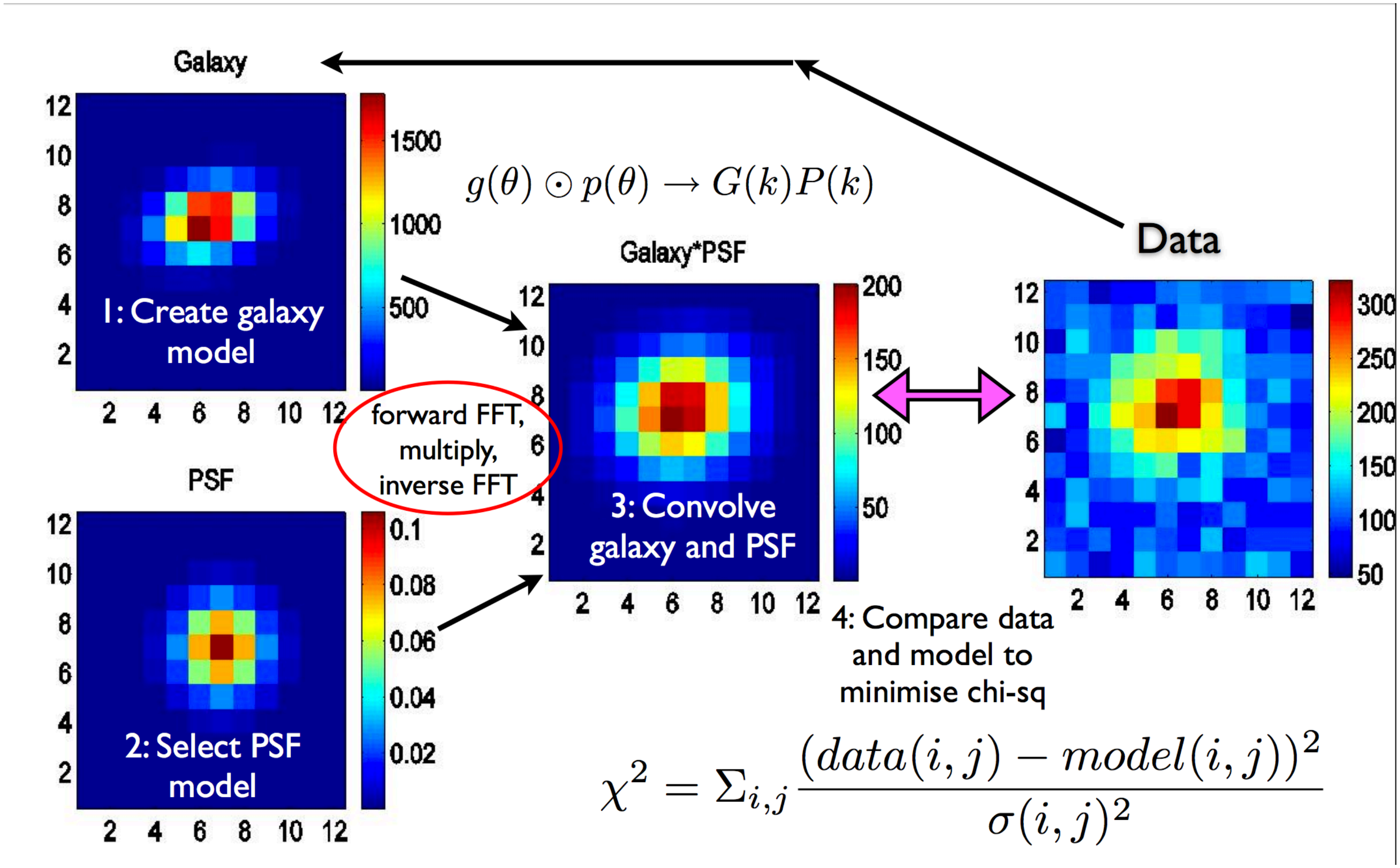
Shape measurement methods: moments based

- **KSB:** The very first and still used (by some) weak lensing method by **Kaiser, Squires, and Broadhust (1995**)
- It uses stars to model the the atmosphere and telescope distortion and essentially subtracts it from the data to get a shear estimate for each galaxy
- Assumes PSF can be modeled as a Gaussian kernel plus a small anisotropy.

- Another moment-based is DEIMOS (Deconvolution in Moment Space) ,by Peter Melchior

Shape measurement methods: fit a model

- You can **also create a model of the PSF** and **the galaxy**, convolve them, and **compare with real data** through optimization of the parameters of the model.



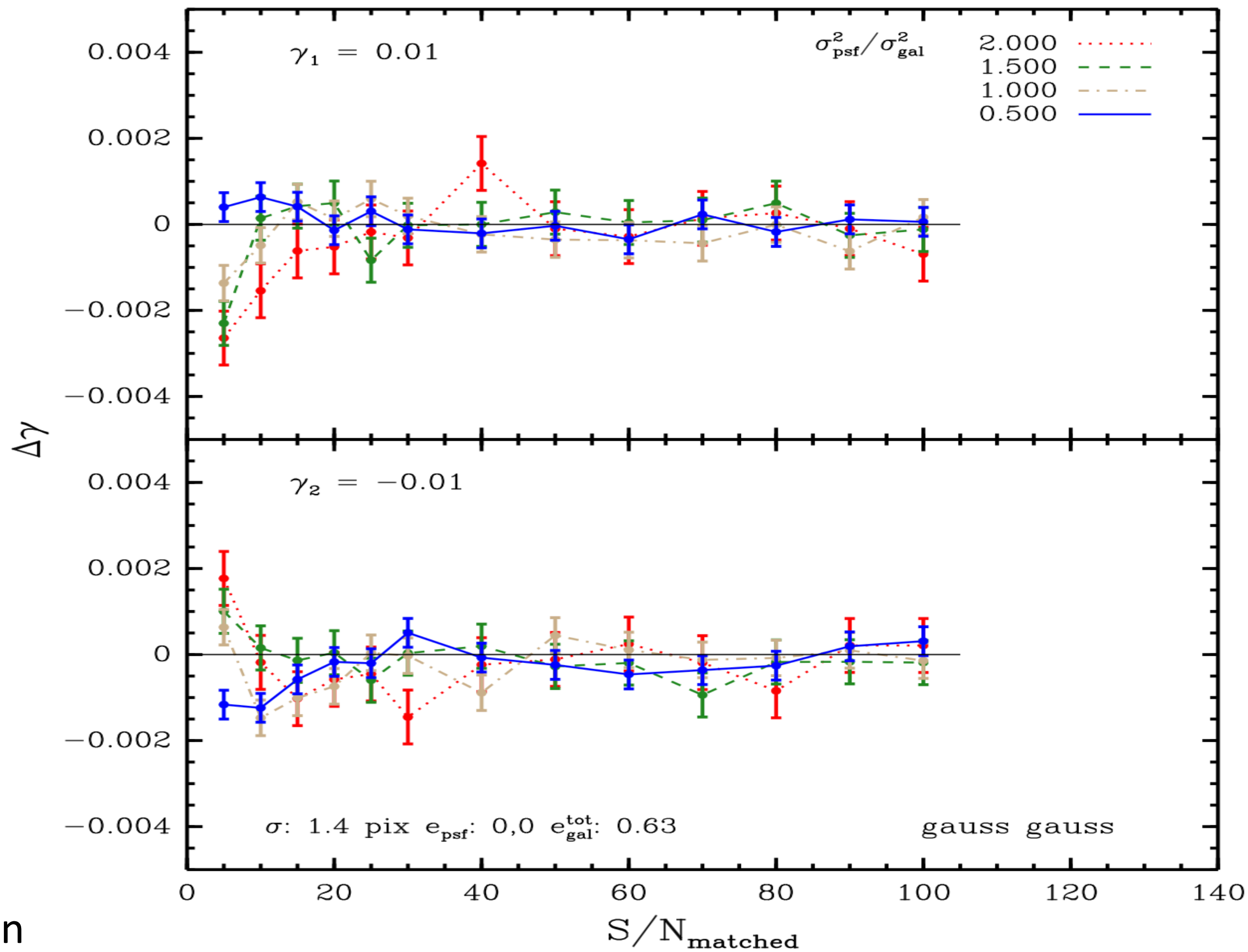
Shape measurement methods: fit a model

- Limited by how well one can model the galaxy and PSF (e.g. Miller et al., Bernstein & Armstrong 2012)
- These methods can be made to work well, as long as the S/N is still pretty high, say 50 or higher

Shape measurement methods: fit a model

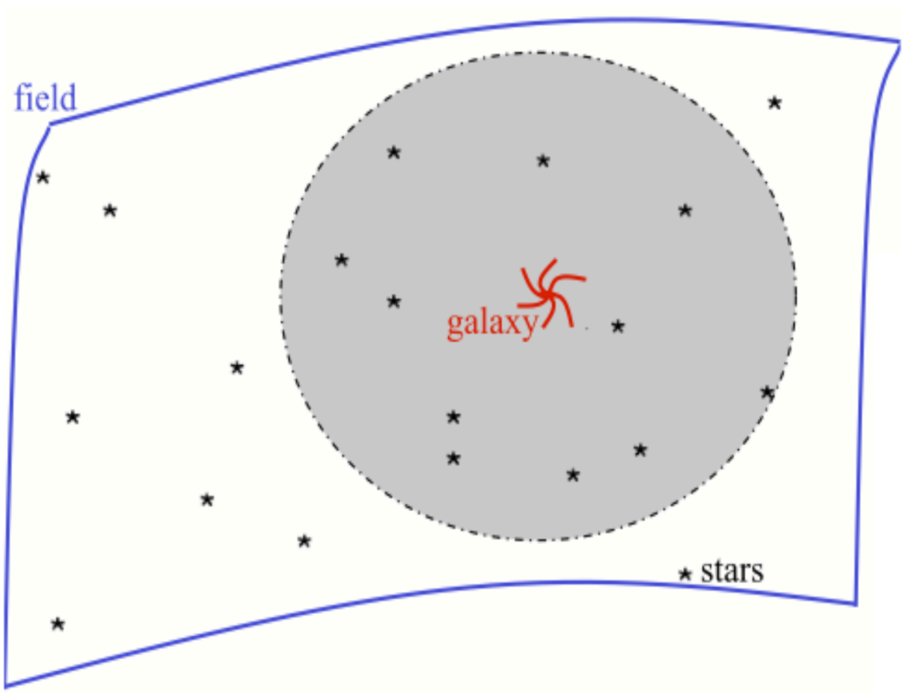
- When the S/N is low, these techniques break down
- Non-linear fitting in the presence of noise is biased, both the maximum likelihood and expectation value: using the mean shape won't work (Hirata, Refregier, etc). Results in a calibration error.
- The noise also causes problems for moment based methods

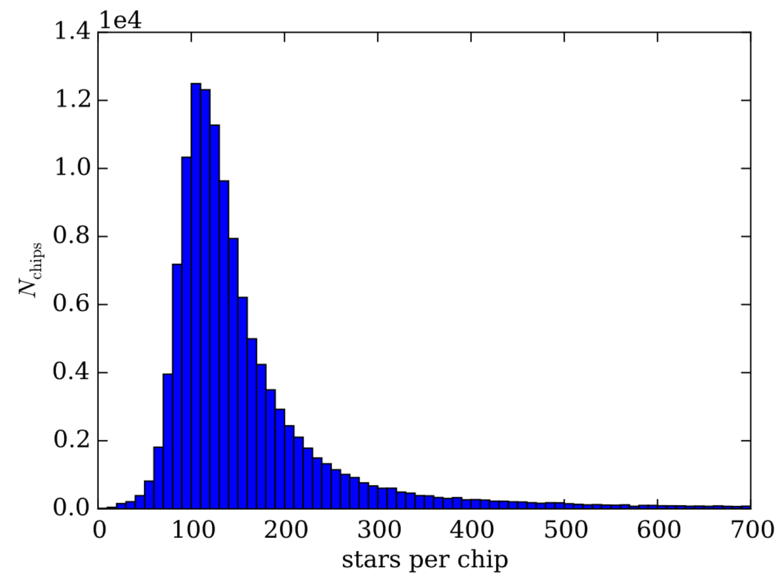
Noise Biases in Maximum Likelihood Method



E. Sheldon

Need to model the PSF as well

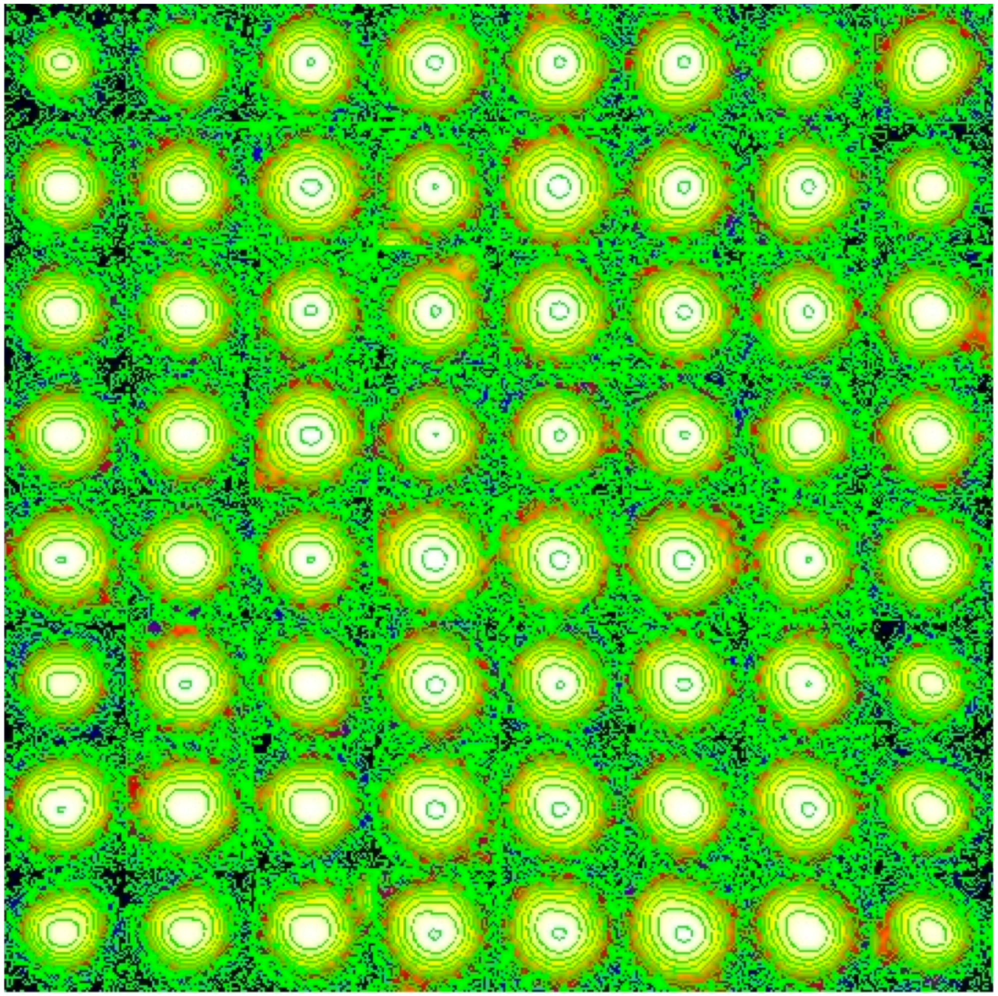




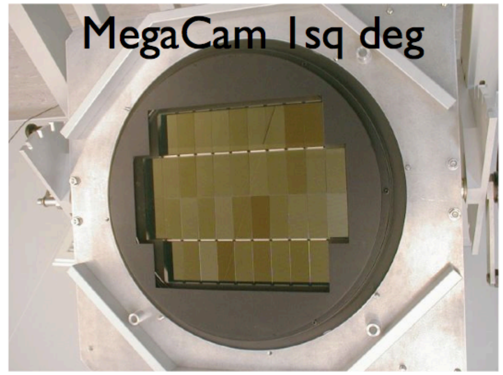
Want : PSF at the Galaxy Position

Have : PSF sampled at Star Position

Fitting a model: the PSF

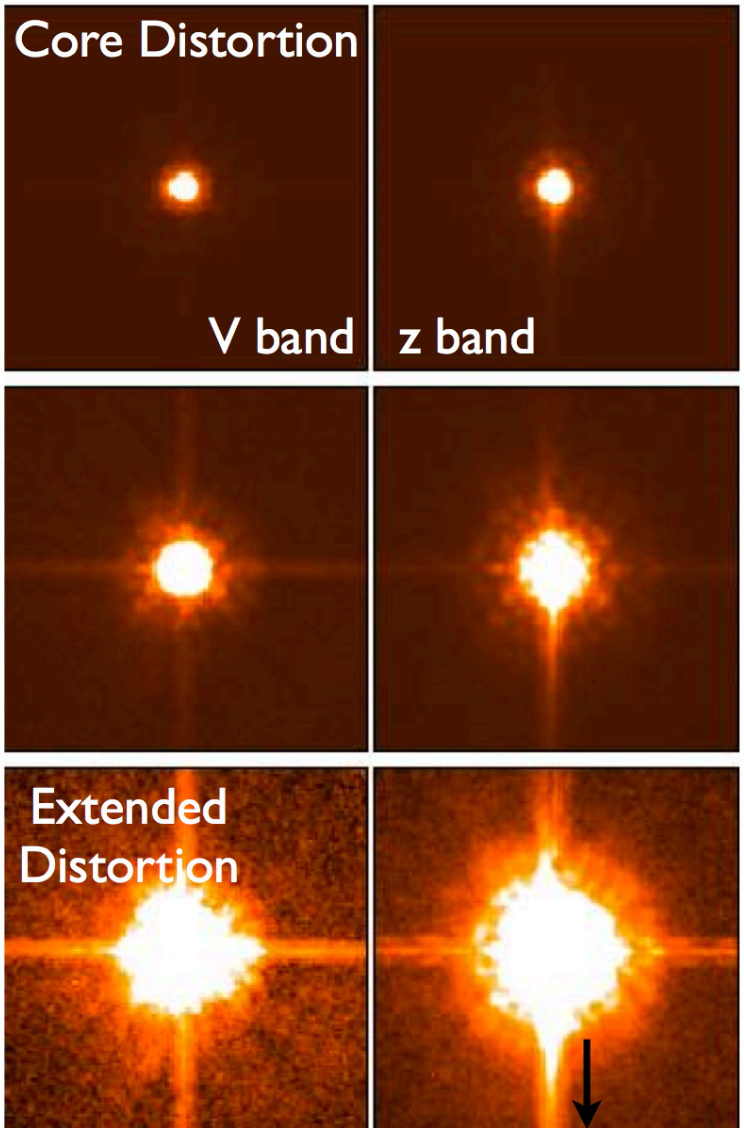


A CFHT MegaCam image



- 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

Fitting a model: the PSF



- 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

Quantifying biases in shear estimation

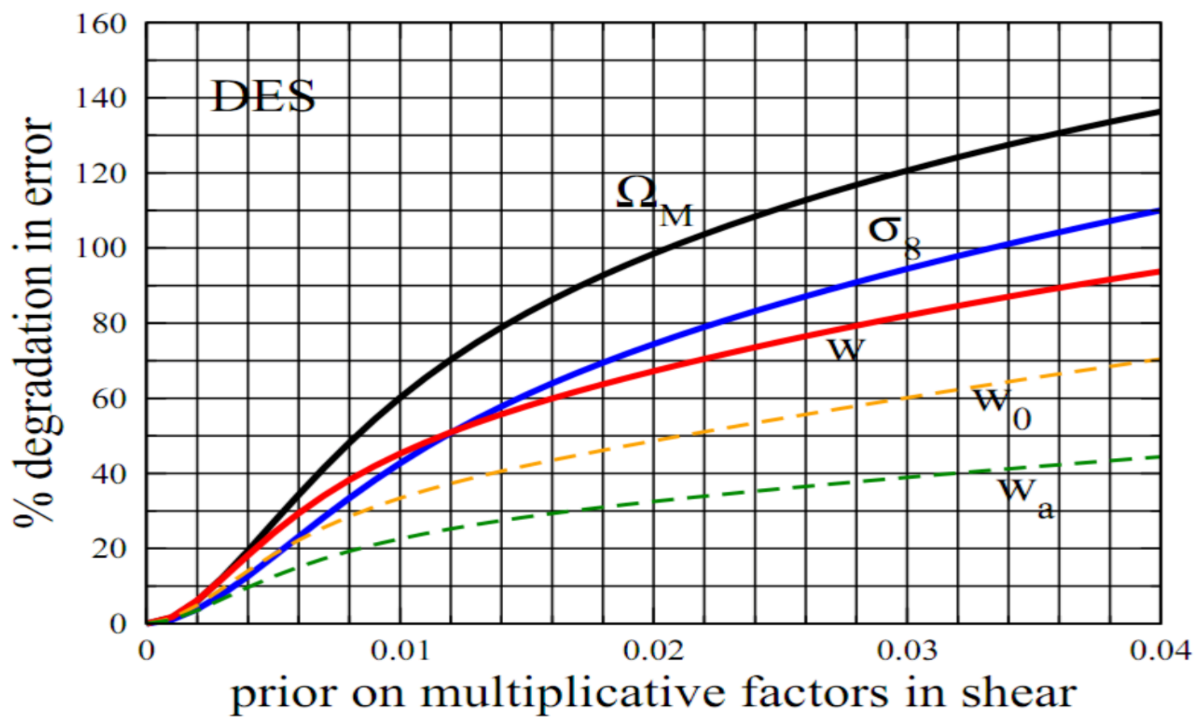
Since we don't know the answers for the real Universe, we test our shear measurement methods by creating simulations with known input shear:

g_measured – g_true = m*g_true + c → m: multiplicative error
c: additive error
They both should be zero

DES requirements:

m < 0.003
c < 0.0004

Cosmological parameter estimation can be biased!

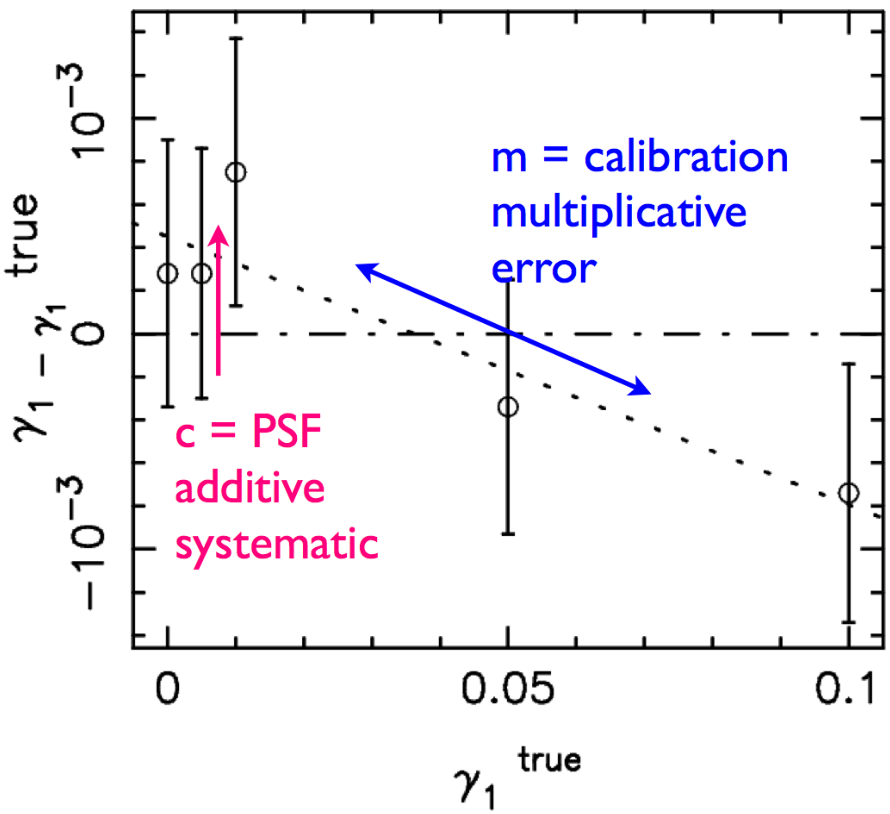


Huterer, Takada, Bernstein, Jain 06

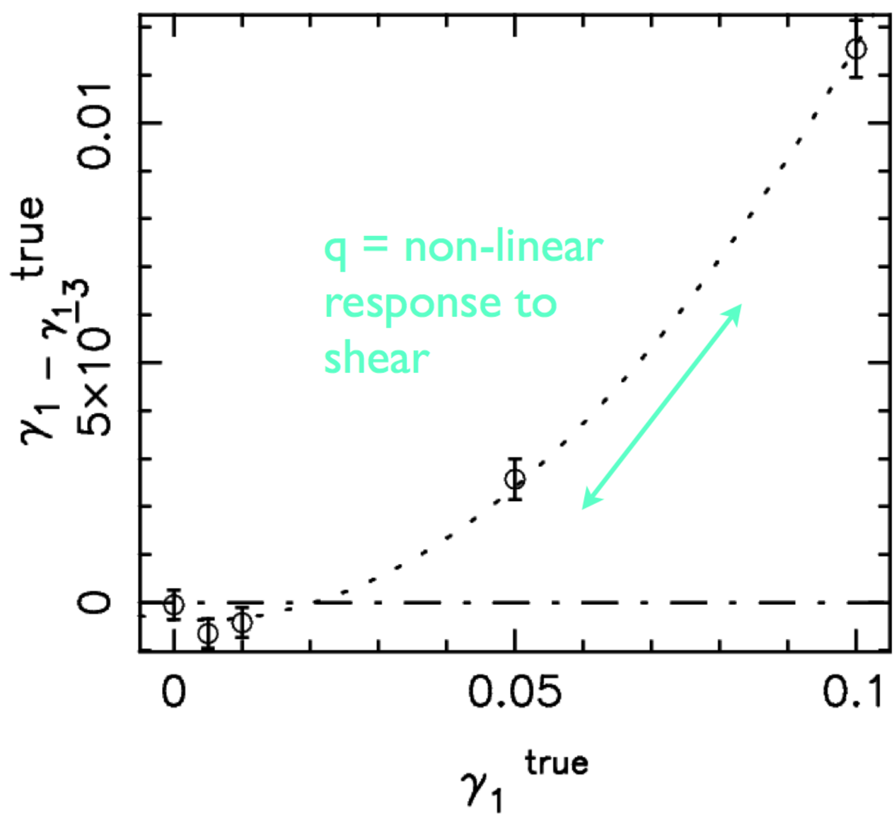
Quantifying biases in shear estimation

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

The best method has m=0 and c=0

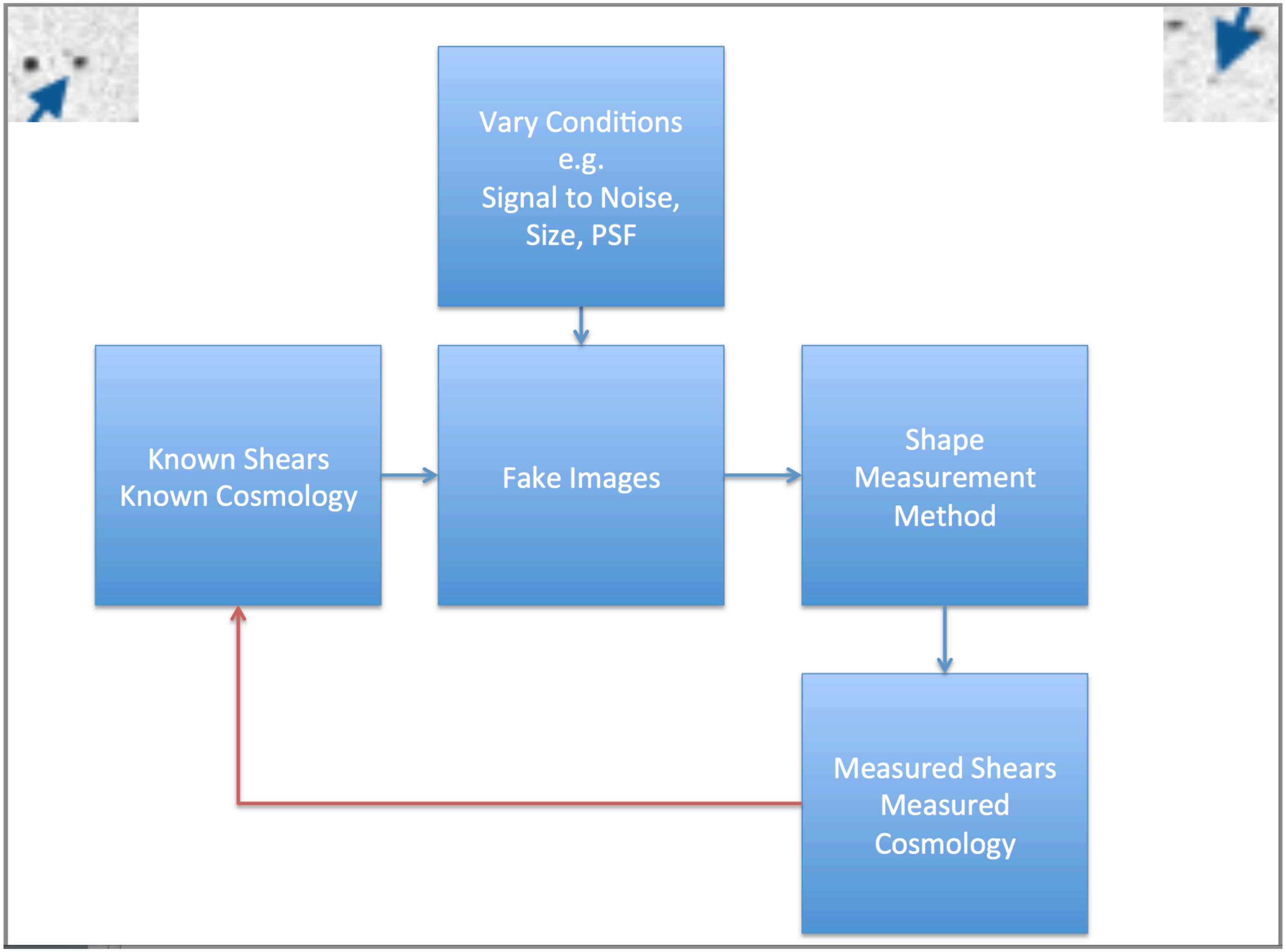


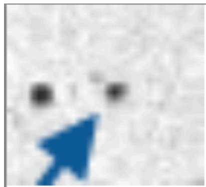
KSB example



BJ02 example

Simulations to calibrate biases





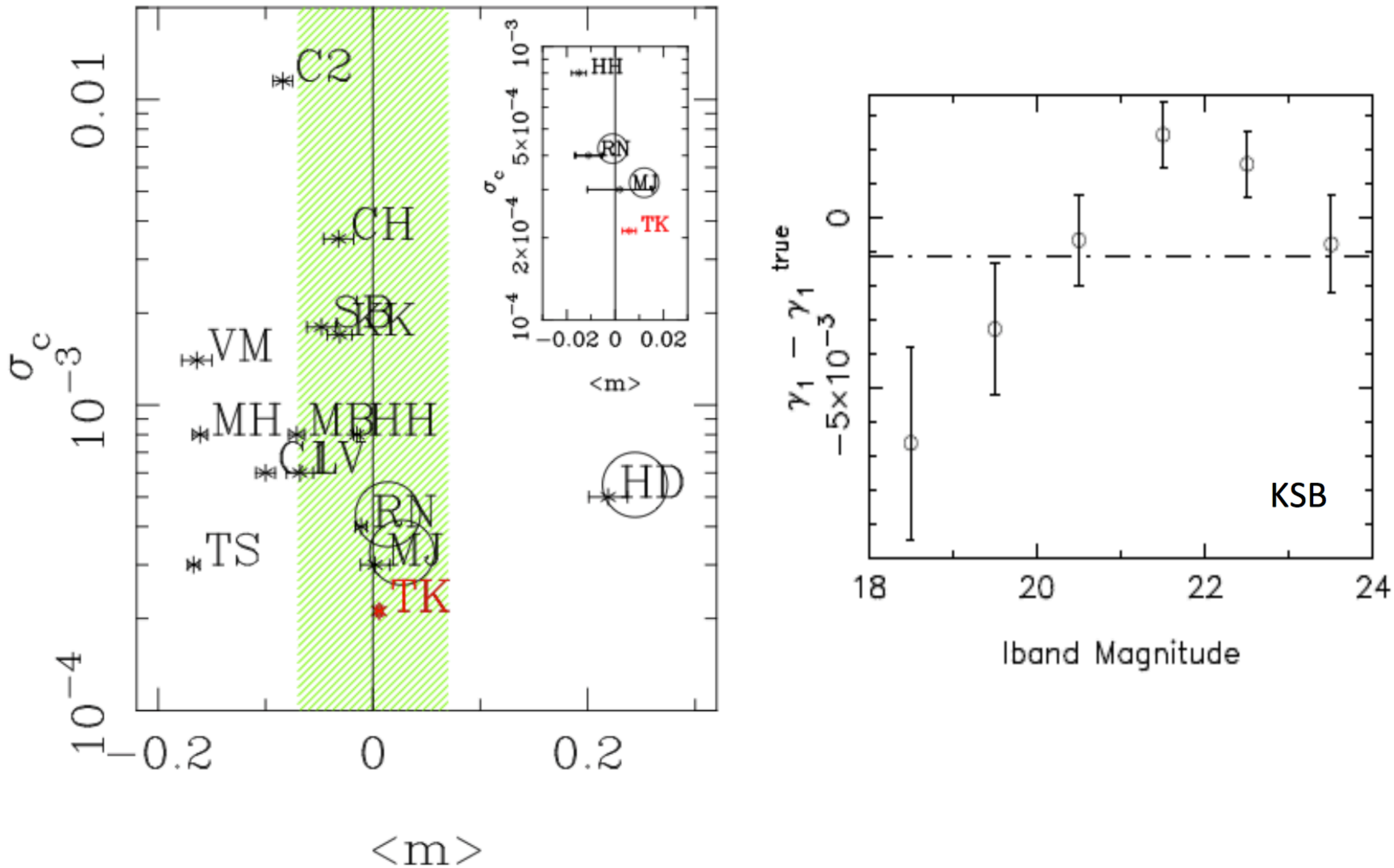
STEP

- Shear TEsting Programme

- Created in 2006 to compare existing methods
  - which disagreed on results of cosmological parameter measurements

- Blind simulations set to weak lensing community

- STEP 1:
  - Simple galaxy models
  - Complex unknown ground-based PSF
  - Constant unknown shear in each image
- STEP 2:
  - Complicated galaxy models (made using Shapelets)
  - Complex unknown ground-based PSF
  - Constant unknown shear in each image



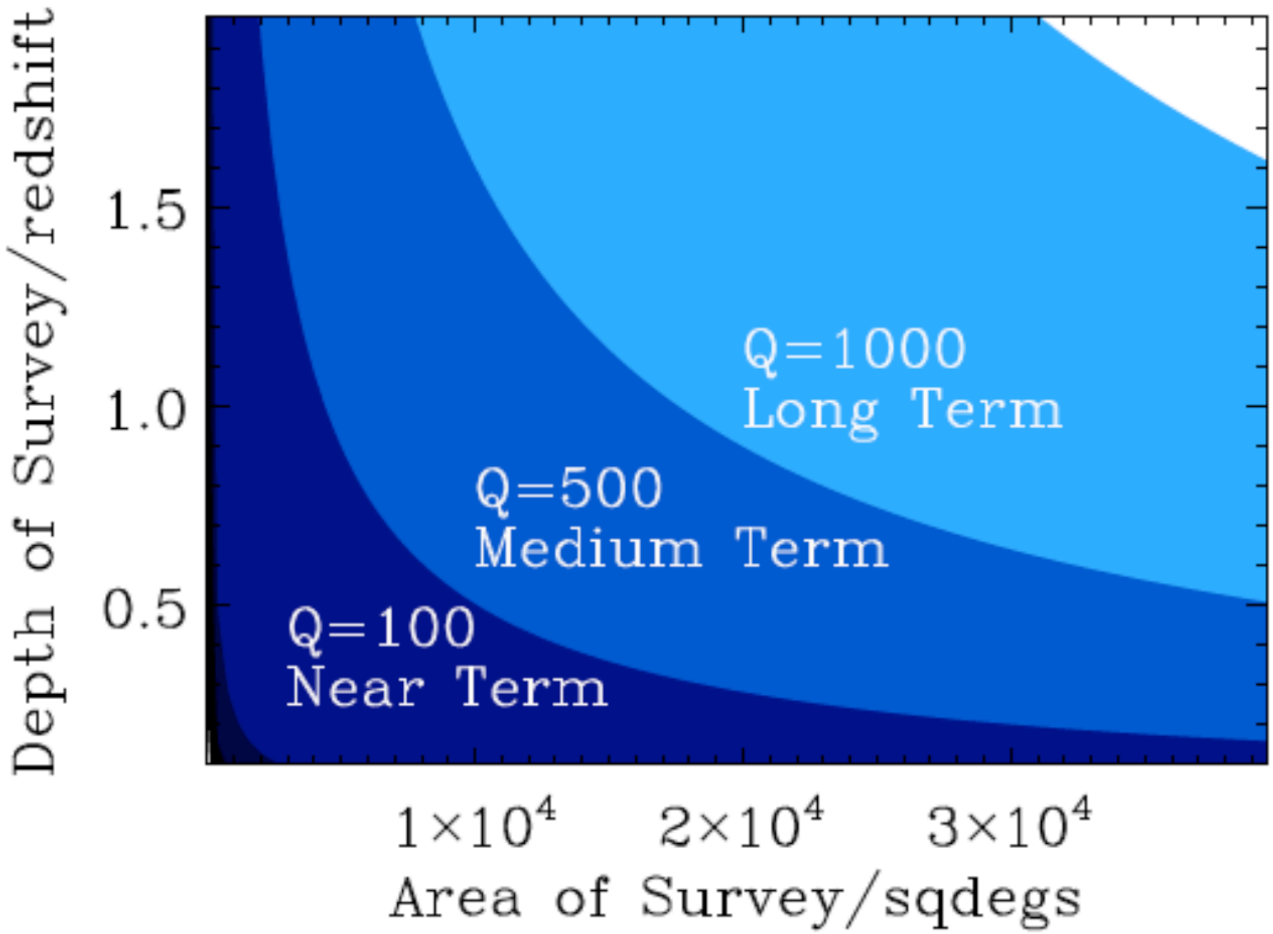
C2
CH
SB
KK
VM
MH
MB
HH
CL
LV
HD
RN
MJ
TS
TK
0.01
10^{-3}
10^{-4}
σ_c
−0.2
0
0.2
<m>
10^{-3}
5×10^{-4}
2×10^{-4}
10^{-4}
−0.02
0.02
$\gamma_1 - \gamma_1^{true}$
0
-5×10^{-3}
18
20
22
24
Iband Magnitude
KSB

- STEP results were complicated

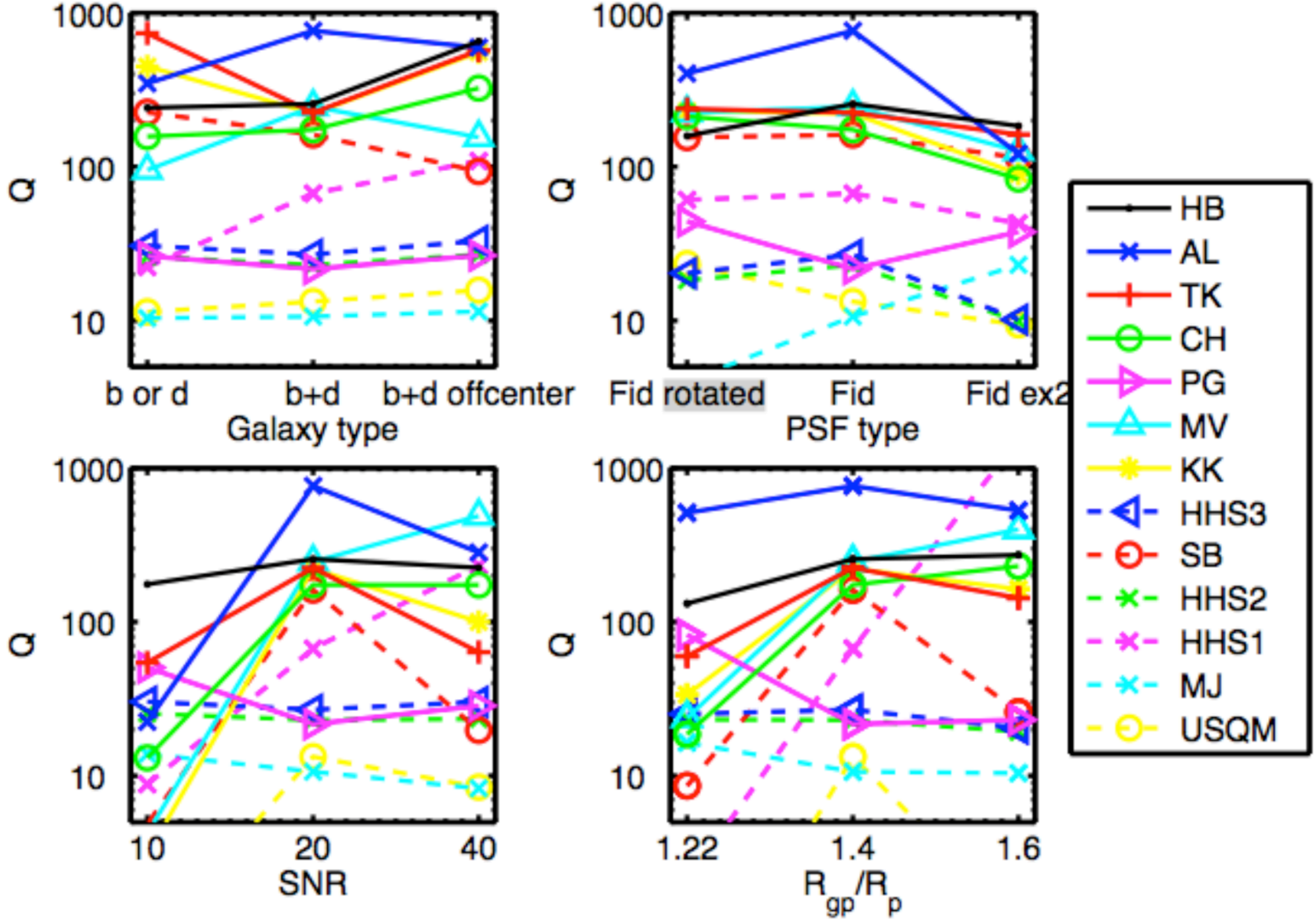
- Community decided to simplify the problem
  - Known PSFs
  - Simple galaxy models (exponentials)
  - Known galaxy positions on a grid
  - “Re-branded” as GREAT
    - GRavitational lEnsing Accuracy Testing
  - Made fully public
  - Constant unknown shear in each image

Quality Factor

$$Q = \frac{10^{-4}}{\langle(\langle g^{m}_{ij} - g^{t}_{ij}\rangle_{j\in k})^2\rangle_{ik}}$$



Kitching et al., 2008 (form filling functions); Amara & Refregier (2007)

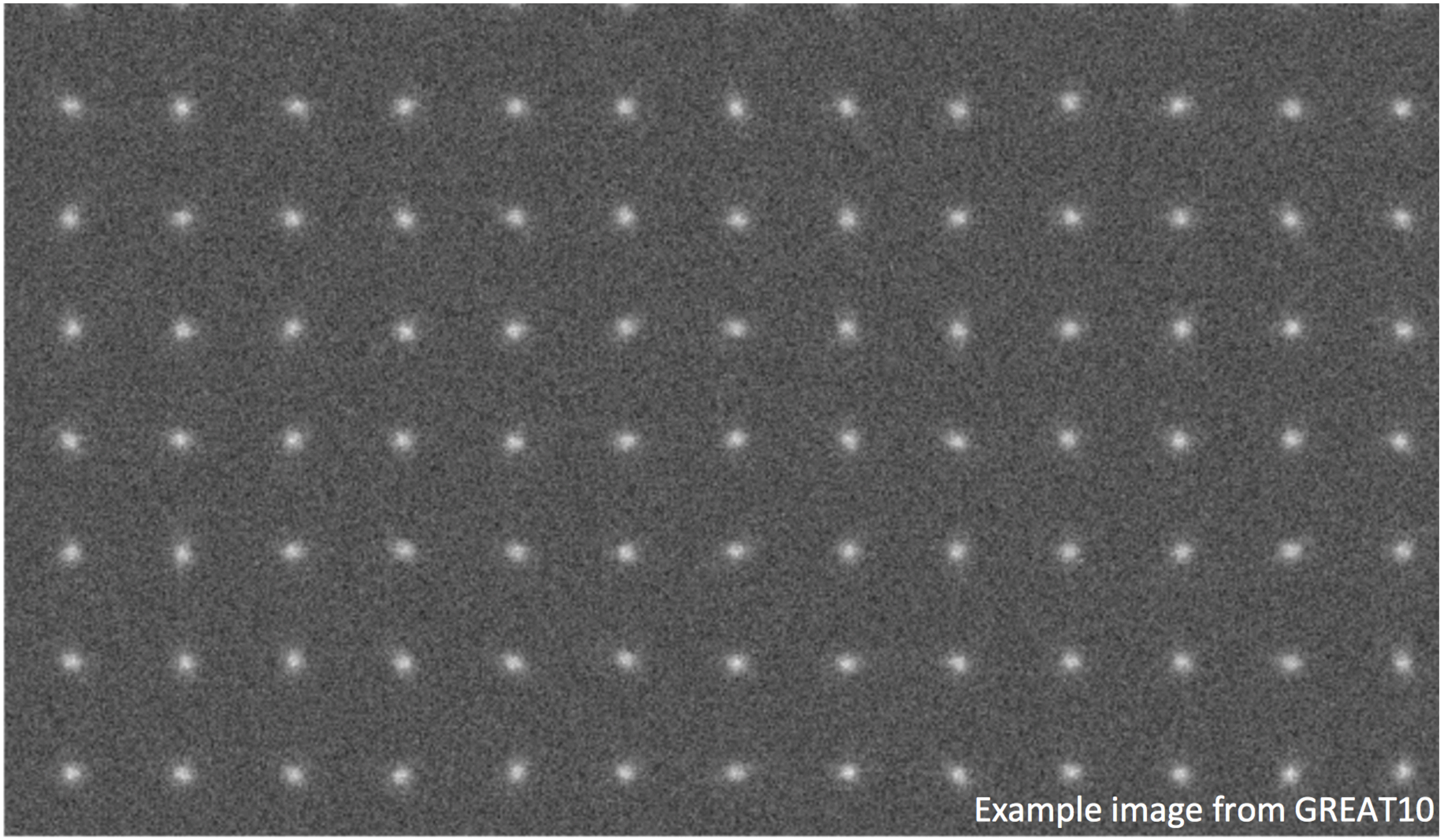


7 non-lensing participants
Q~1000 in some regimes

Bridle et al. 2011

Simulations

After GREAT08, there was GREAT10, and GREAT3



GalSim

GalSim: open source software to make lensing simulations (Rowe et al 2014).

It was used to create the images in GREAT3.
You can use it to:

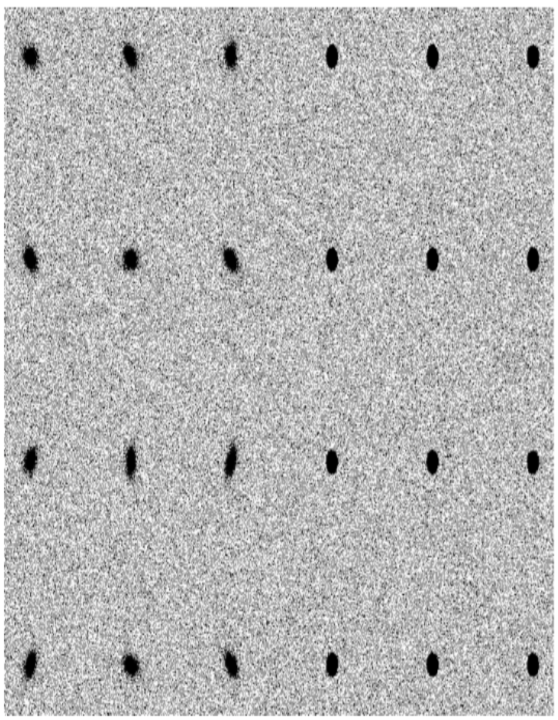
- Representing astronomical objects, including any transformations, distortions, and convolutions
- Generating gravitational lensing distortions to be applied to astronomical objects
- Characterizing the connection between image coordinates and world coordinates.
- Rendering the profiles into images.
- Generating random numbers, and using these to apply noise to images according to physically-motivated models.
- Estimating the shapes of objects once these have been rendered into images (useful for testing)

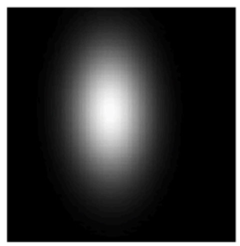
GalSim: custom tests

"Dissection" tests: custom tests in which the performance of the pipeline is analyzed one parameter at a time. The PSF is controlled and well known.

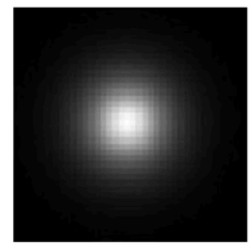
Sérsic profiles: $$I(r) = I_h \exp\left\{ -b_n \left[\left(\frac{r}{r_h} \right)^{1/n} - 1 \right] \right\}$$

n=0.5: Gaussian
n=1: Exponential (disk gals.)
n=4: de Vaucouleurs (elliptical gals.)





Exponential profile

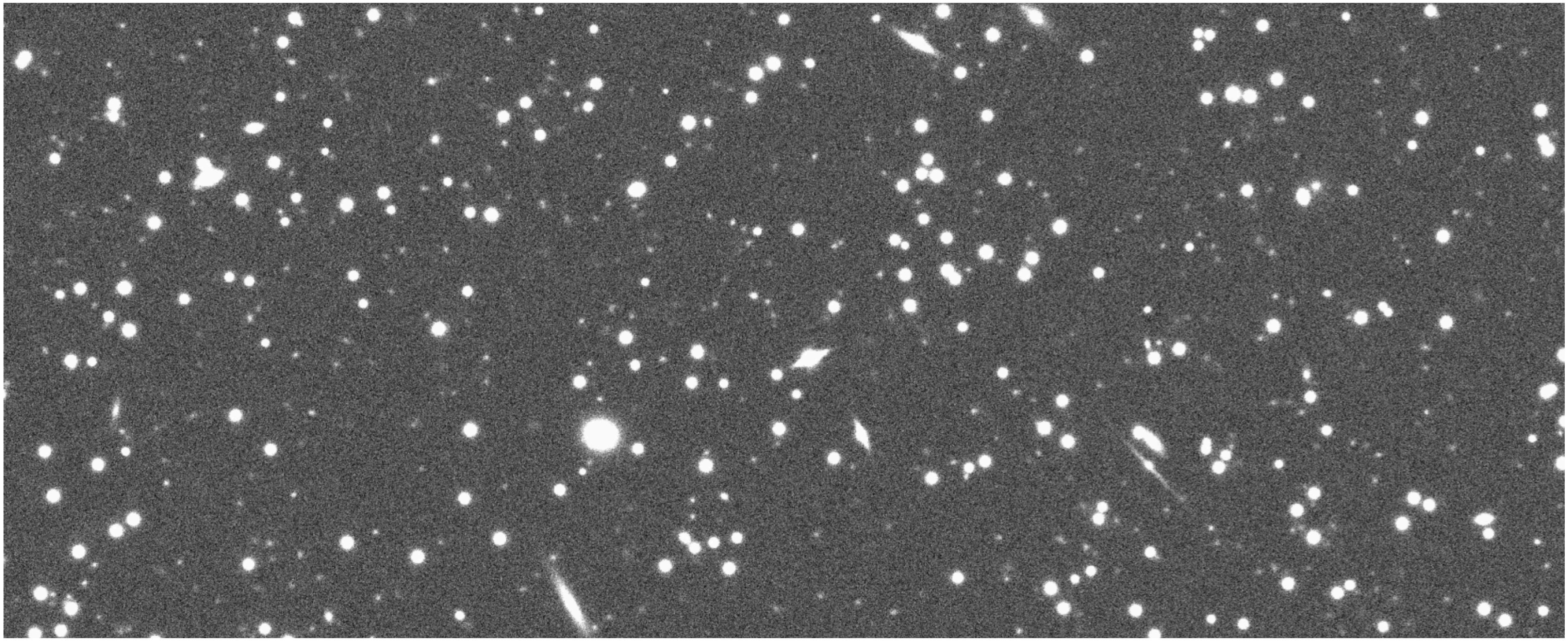


Gaussian PSF

Parameter Space:
Some of the parameters we control and want to explore are:

- Galaxy Type
- PSF Ellipticity
- Shear (input distortion)
- Significance: S/N
- Galaxy Ellipticity$_5$
- PSF Size
- Galaxy Size
- Pixel Size
- PSF type
- Expansion order

GalSim: more realistic images



GalSim paper

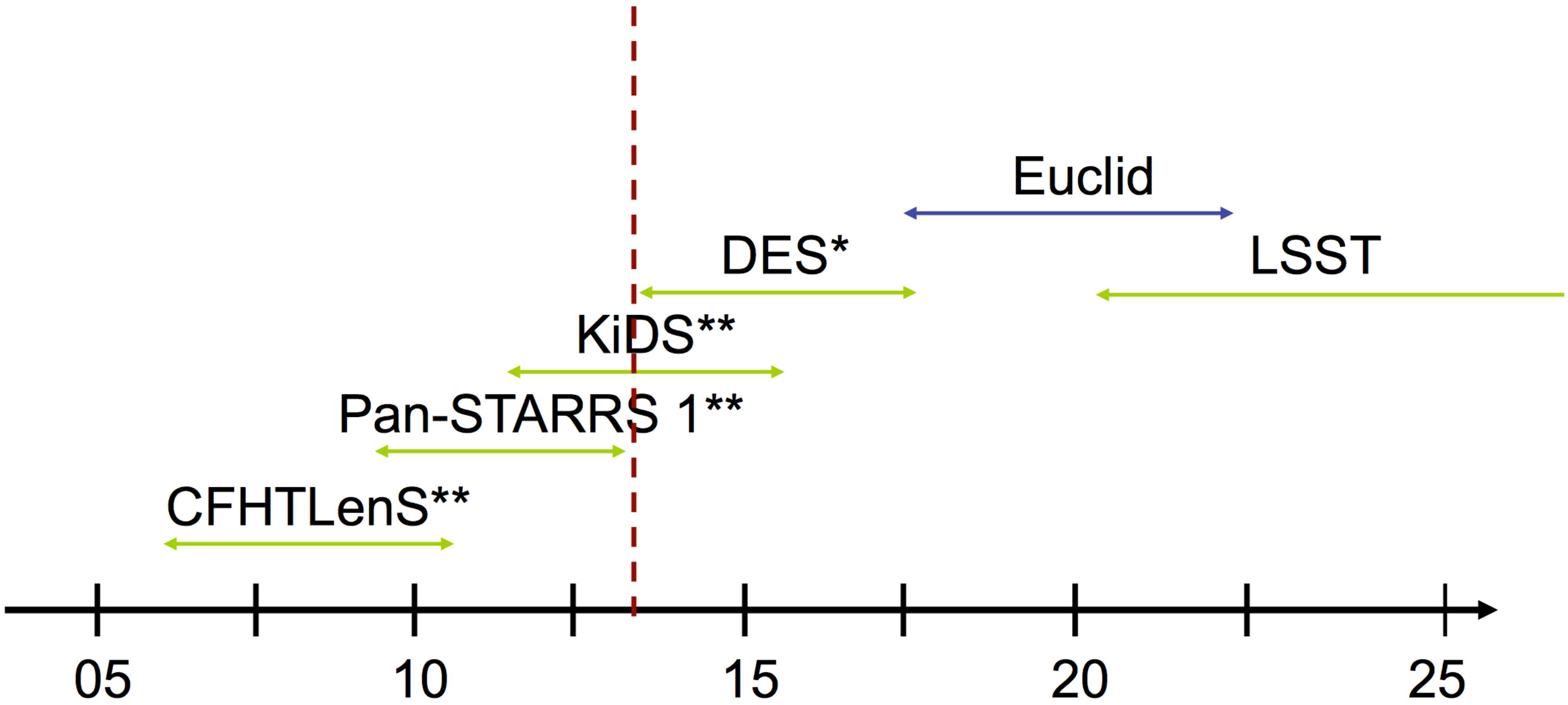
Simulations: The Future

What's missing from GREAT3?

- Object detection / selection effects / blends
- Detector nonlinearity or other image artifacts
- Chromatic effects
- Background estimation
- More complex noise models
- Redshift-dependent shear
- Marginally resolved galaxies, and those with SNR<~12
- Non-weak shear, higher order effects

Weak Lensing surveys

- Current and on going surveys

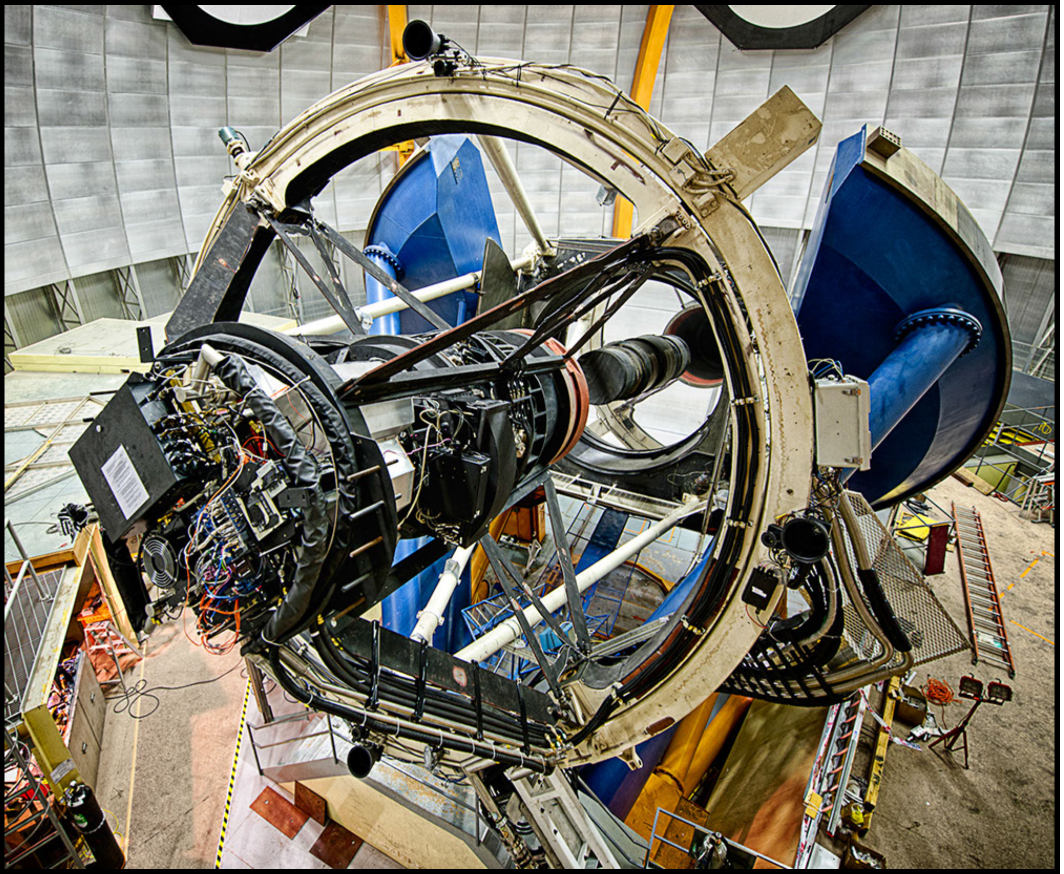


** complete or surveying
* first light

The Dark Energy Survey

- Probe origin of Cosmic Acceleration:
  - Distance vs. redshift
  - Growth of Structure
- Two multicolor surveys:
  300 M galaxies over 5000 s.d.
  grizY to 24th mag
  3500 supernovae (30 sq deg)
- New camera for CTIO Blanco telescope
  Facility instrument
- Five-year Survey started Aug. 31, 2013
  525 nights (Sept.-Feb.)

DECam on the CTIO Blanco 4m



www.darkenergysurvey.org
www.darkenergydetectives.org

DARK ENERGY SURVEY

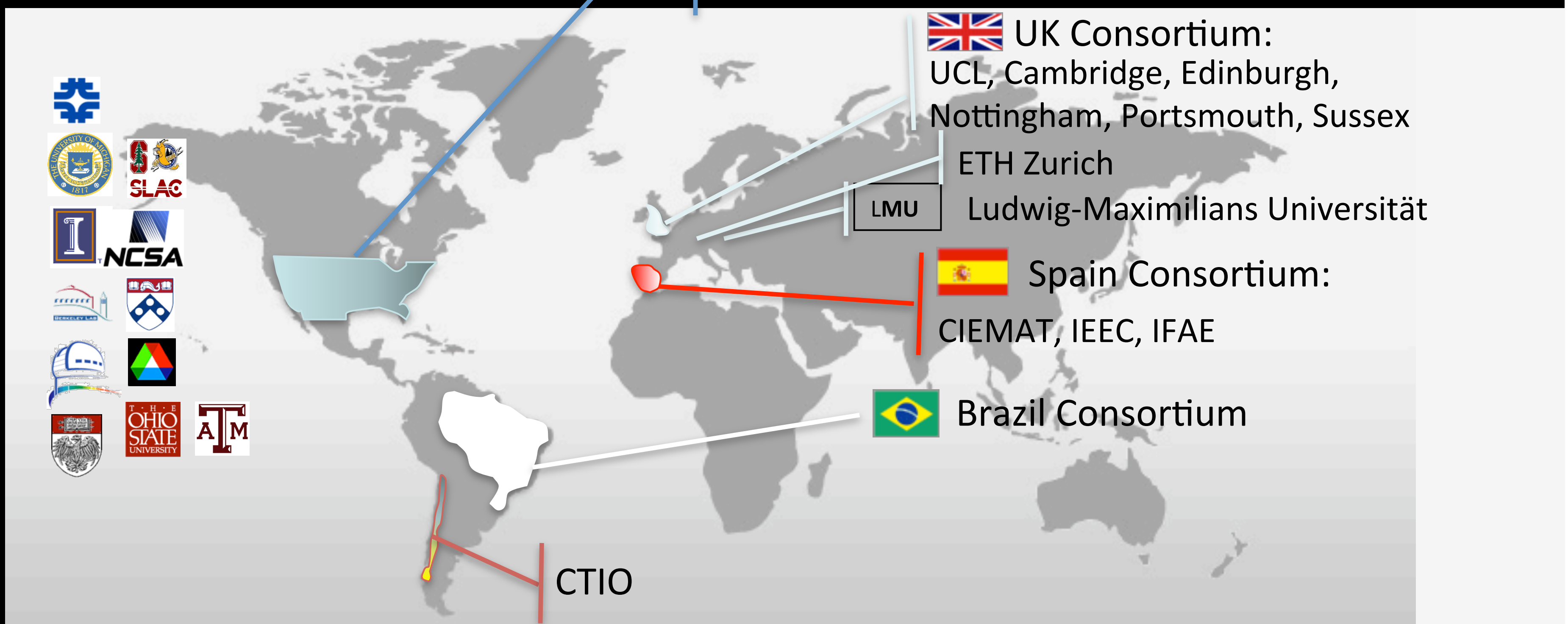
DES Timeline

- Project start 2003
- Research & Development 2004-8
- DECam Construction 2008-11
- Installation 2012
- First Light Sept. 2012
- Commissioning Sept-Oct. 2012
- Science Verification Nov. 2012-Feb. 2013
- First Season (Year 1) Aug. 2013-Feb. 2014
- Second Season (Y2) Aug. 2014-Feb. 2015
- Five 105-night seasons

Dark Energy Survey Collaboration

~300 scientists
US support from DOE+NSF

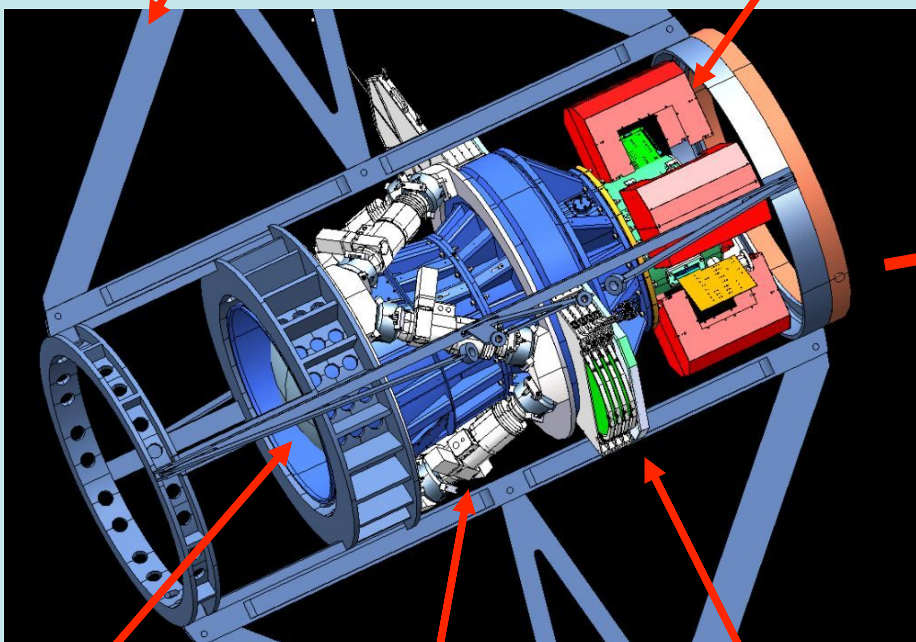
Fermilab, UIUC/NCSA, University of Chicago, LBNL, NOAO, University of Michigan, University of Pennsylvania, Argonne National Lab, Ohio State University, Santa-Cruz/SLAC/Stanford, Texas A&M



Dark Energy Camera

Mechanical Interface of DECam Project to the Blanco

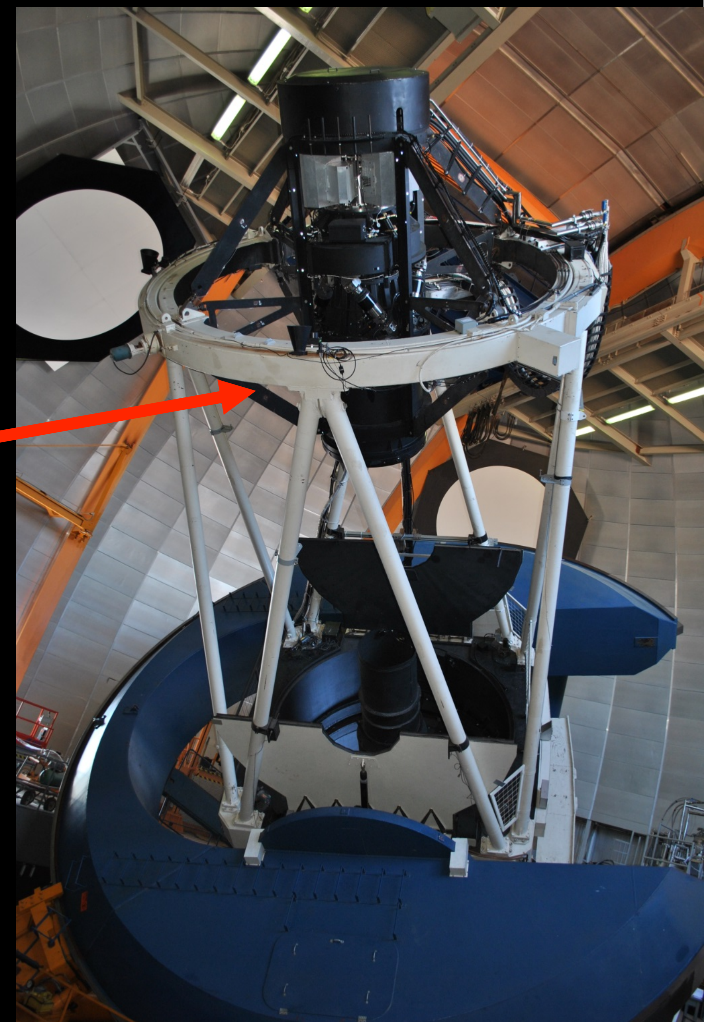
CCD Readout



Optical Corrector Lenses

Hexapod: optical alignment

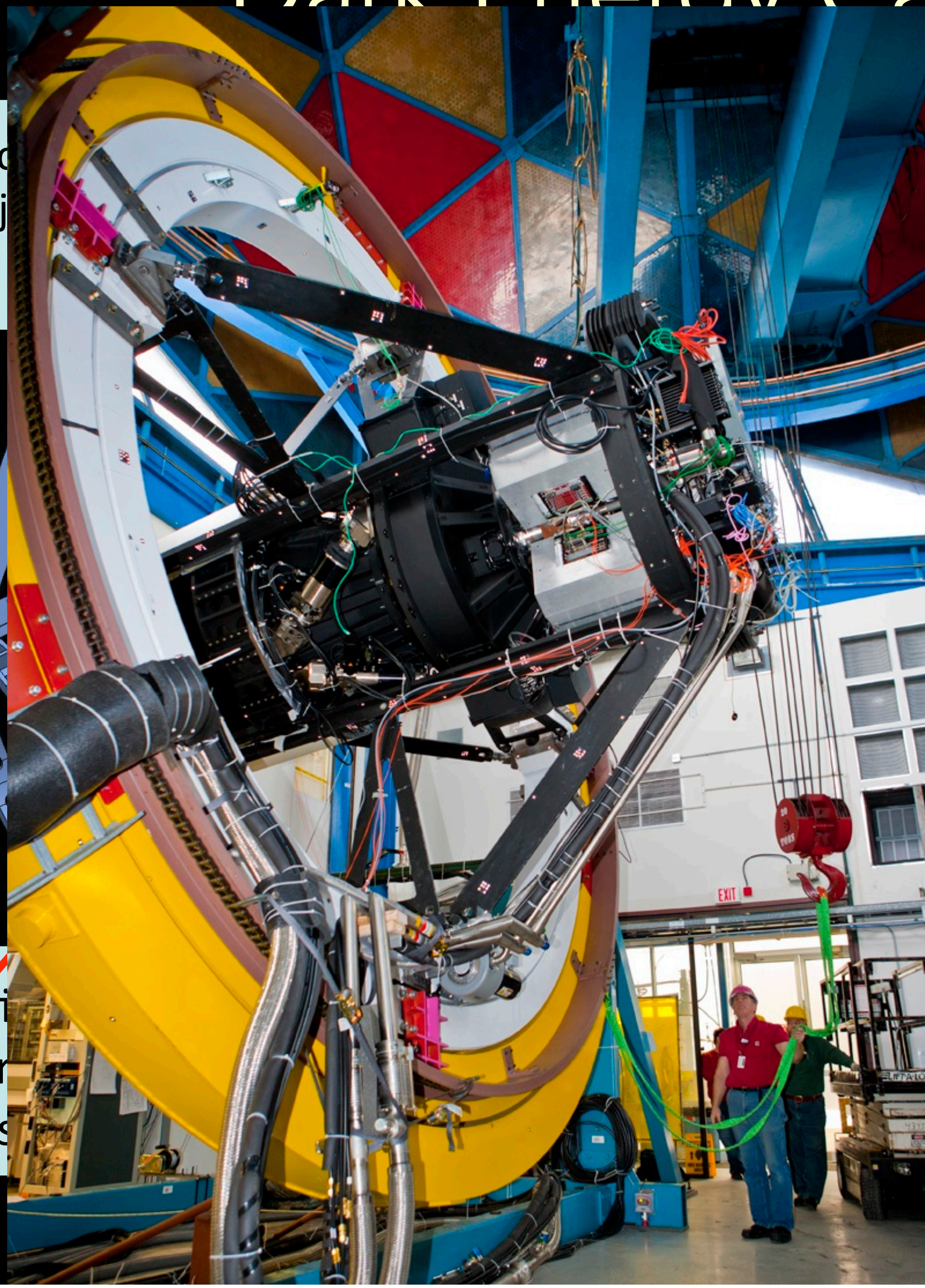
Filters & Shutter



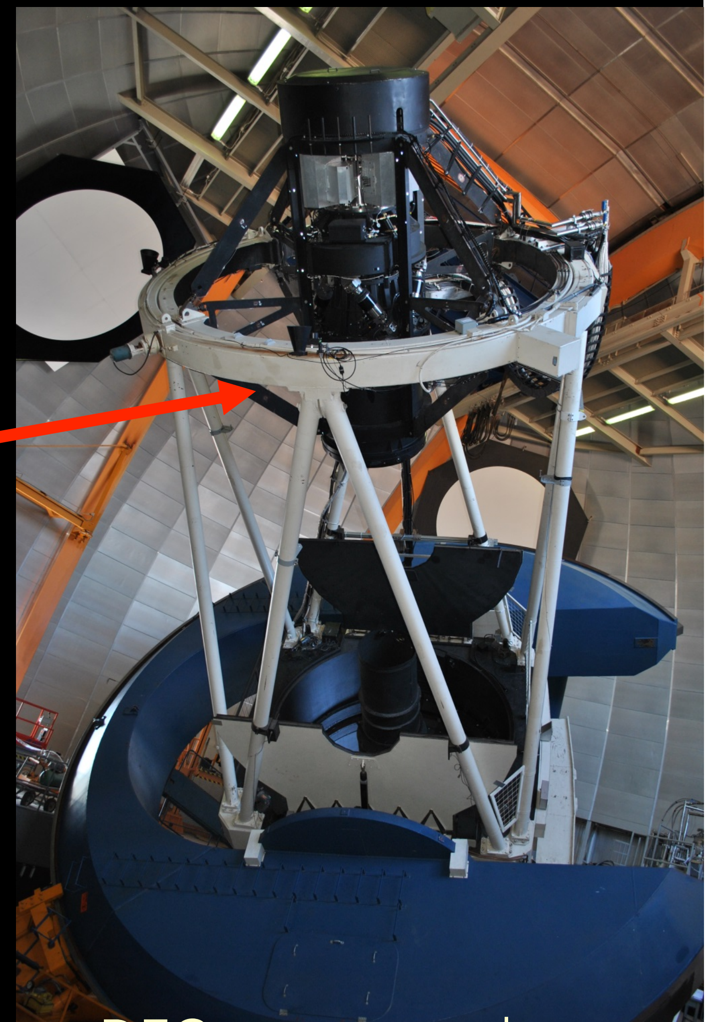
Dark Energy Camera

DAR
SUR

Mec
Proj

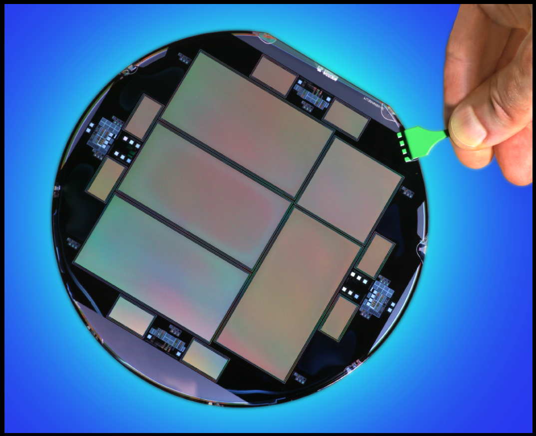


Opti
Corr
Lens

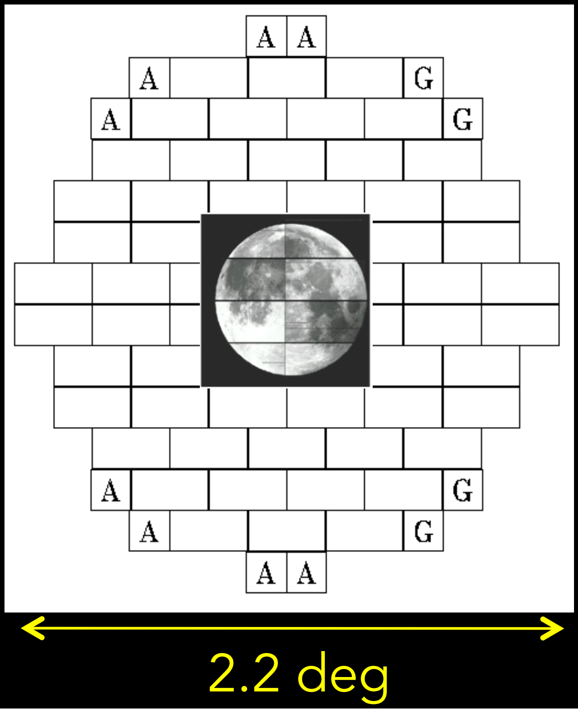


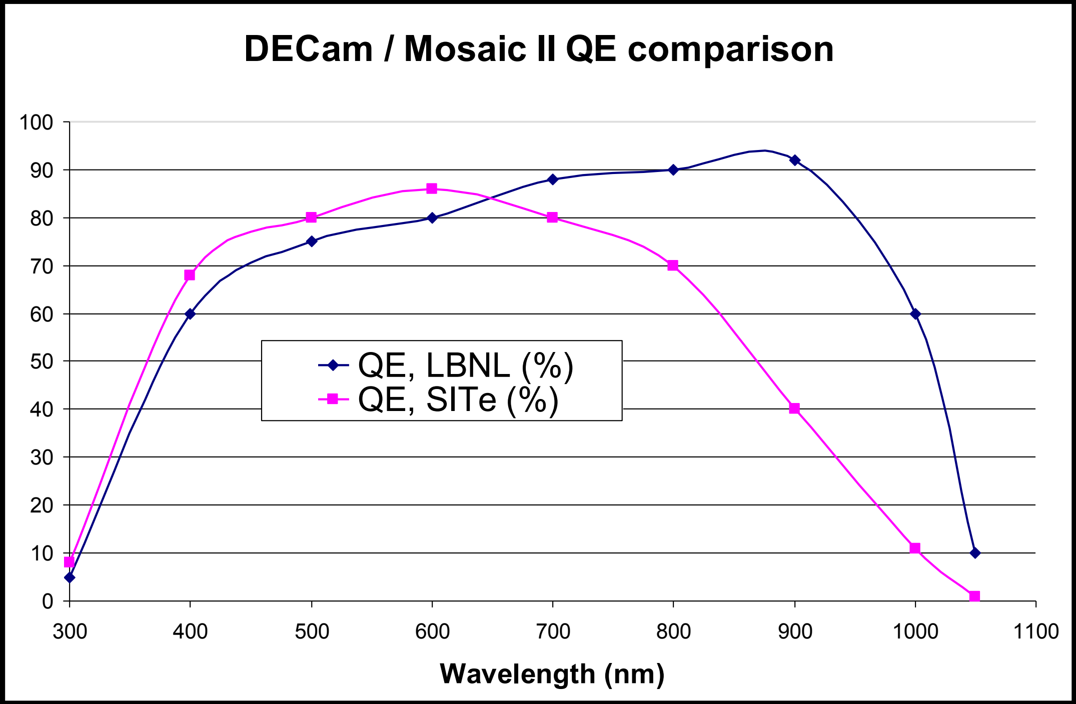
DECam mounted on
Telescope Simulator
at Fermilab in early 2011

DECam CCDs

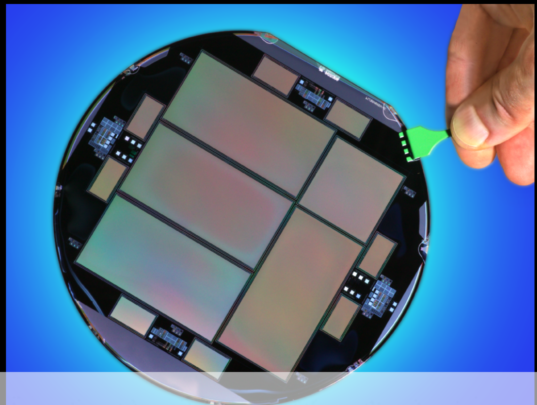


- 62 2kx4k fully depleted CCDs: 520 Megapixels, 250 micron thick, 15 micron (0.264") pixel size
- 12 2kx2k guide and focus chips
- Excellent red sensitivity
- Developed by LBNL, packaged and tested at FNAL
- Total 570 Megapixels





DECam CCDs



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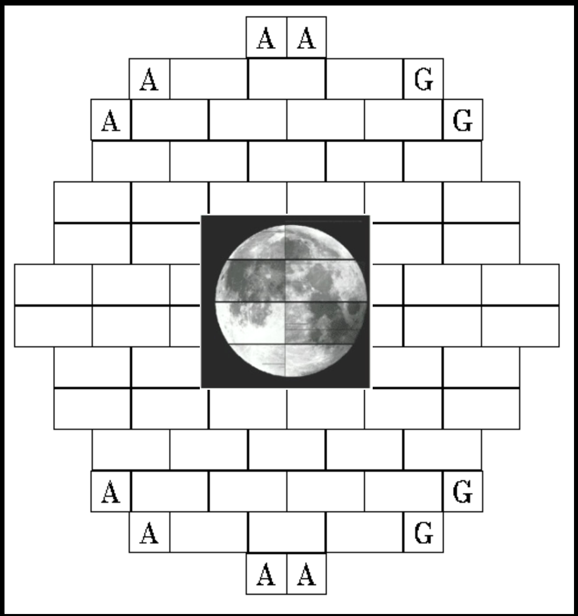
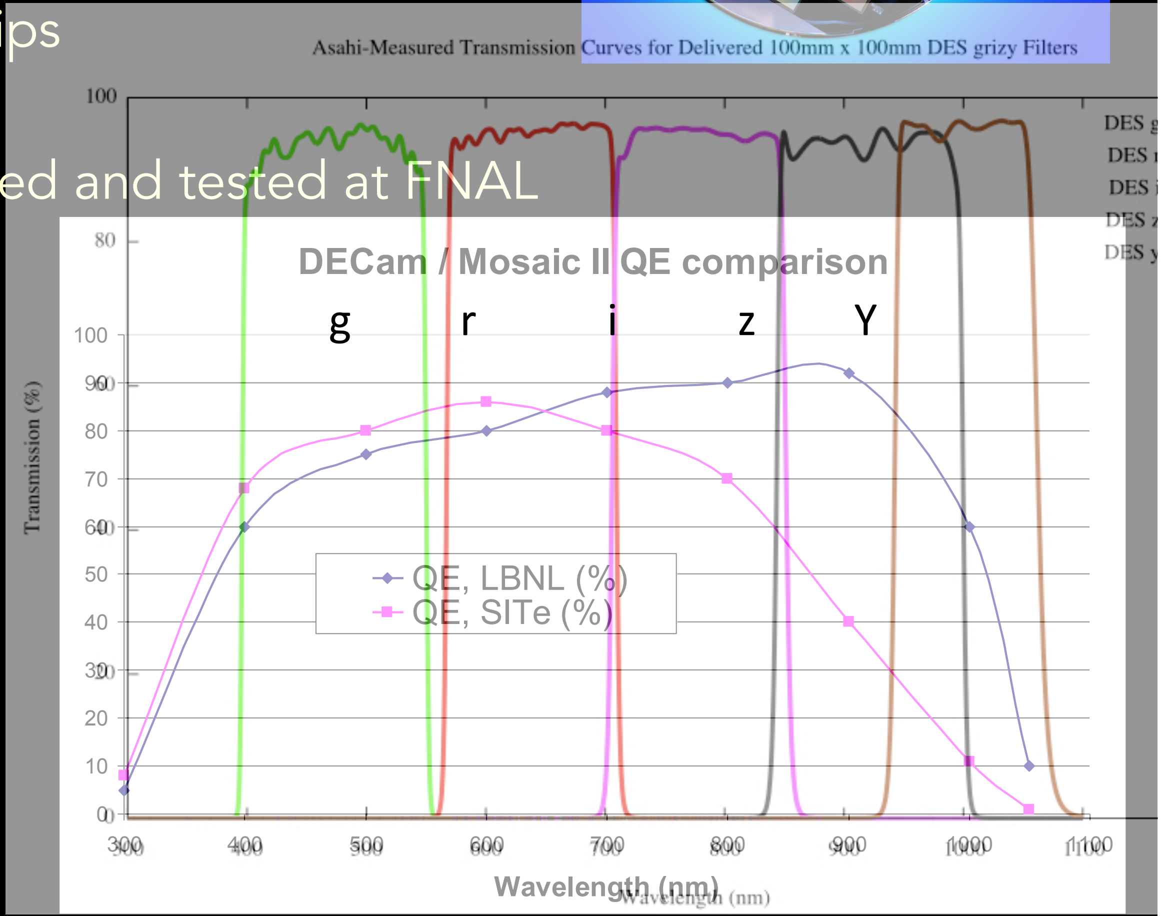


2.2 deg

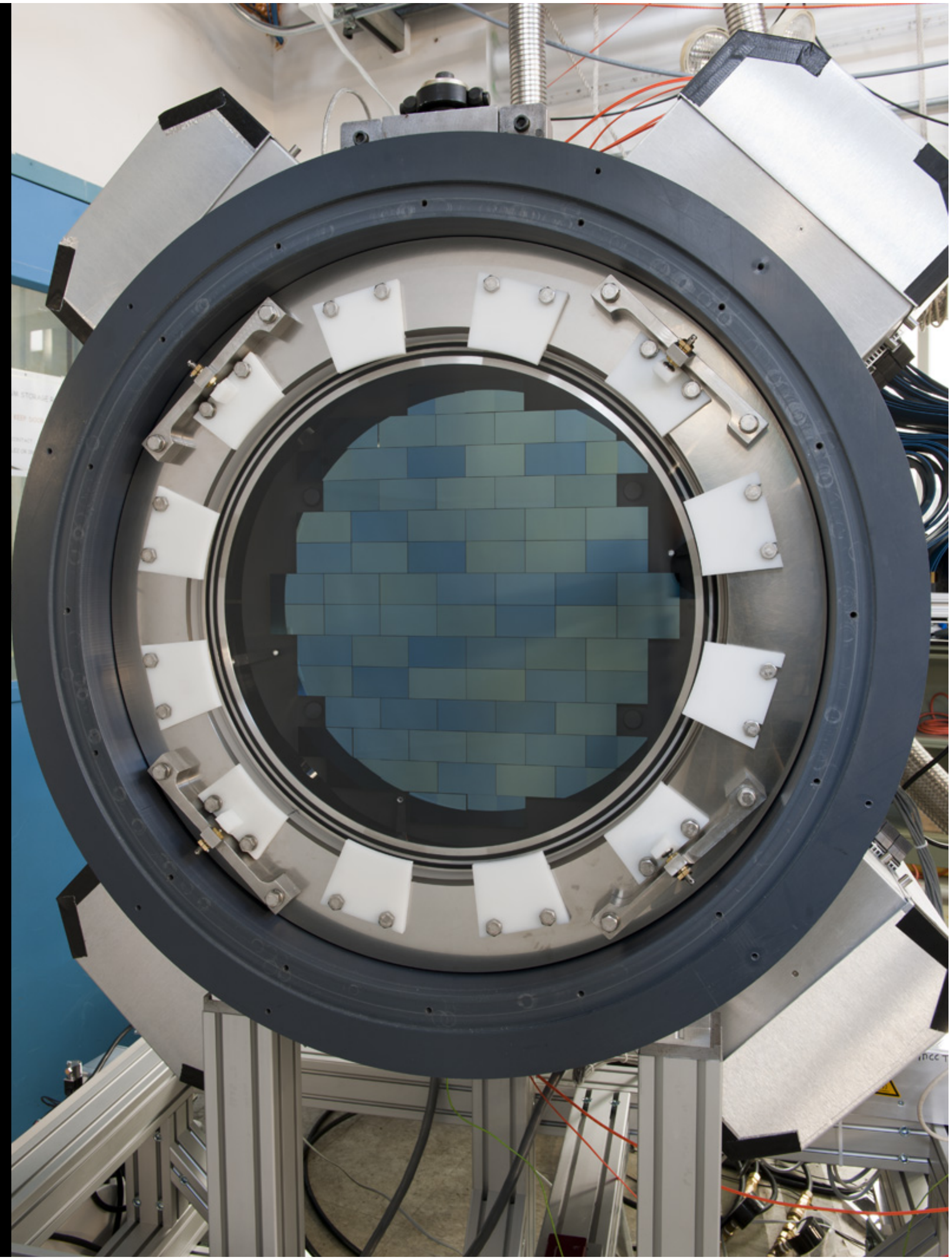


DES filters

DARK ENERGY SURVEY

570-Million pixel
Dark Energy
Camera

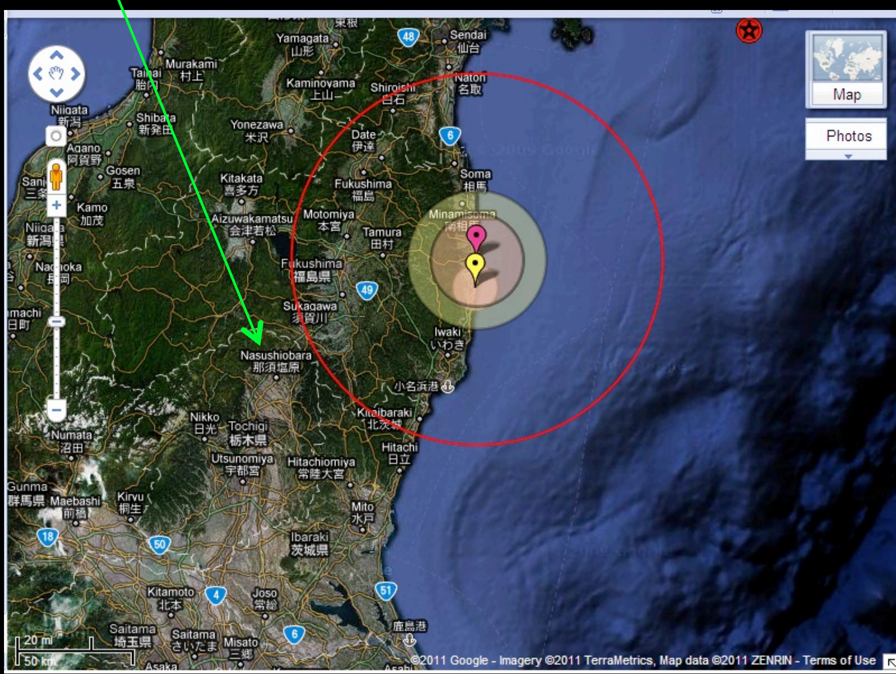
3 sq. deg. FOV

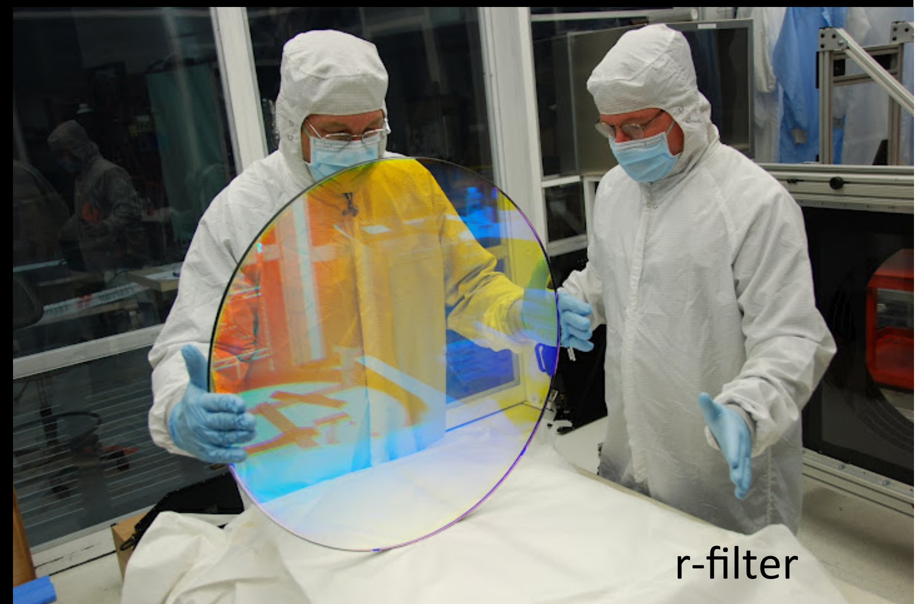


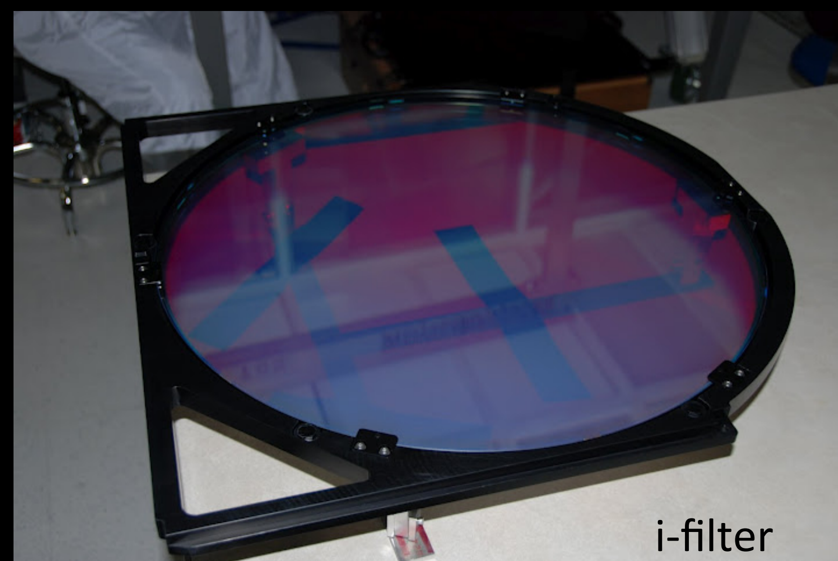
DARK ENERGY SURVEY

Filters

- 600 mm clear aperture, tight uniformity constraints, excellent throughput.
- Fabrication completed by Asahi within months of the tsunami in Japan.



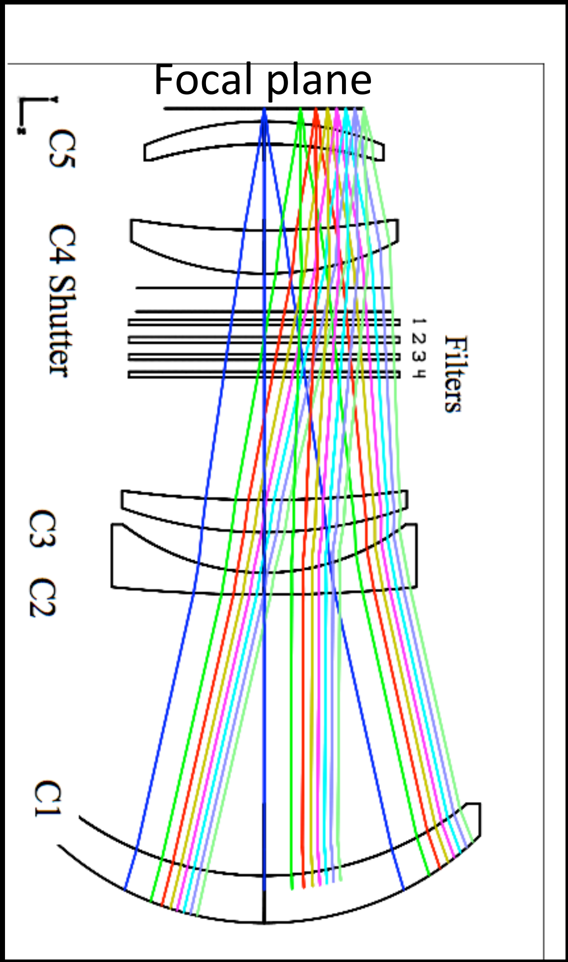

r-filter

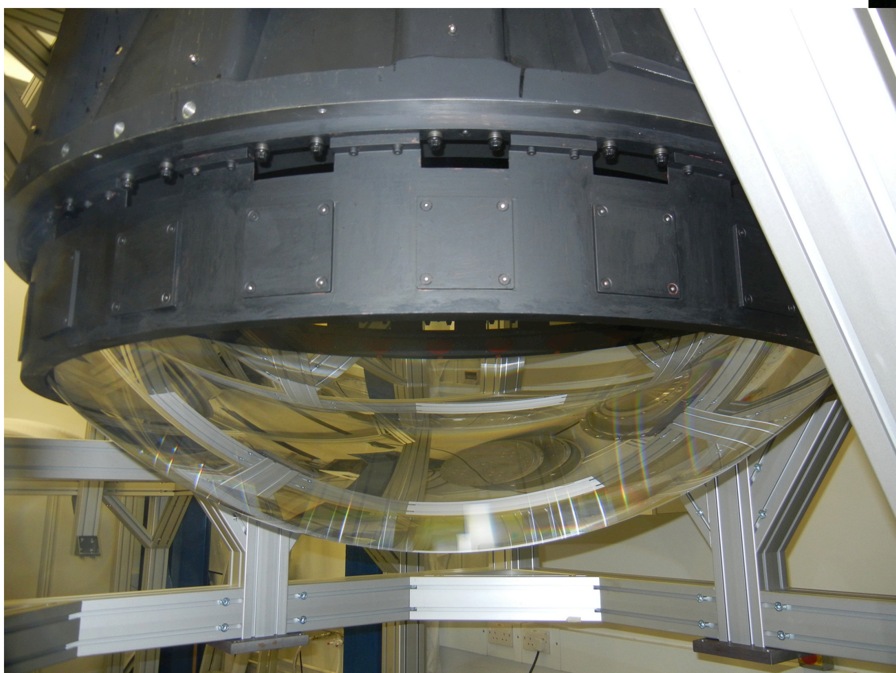

i-filter

Optical Corrector Lenses

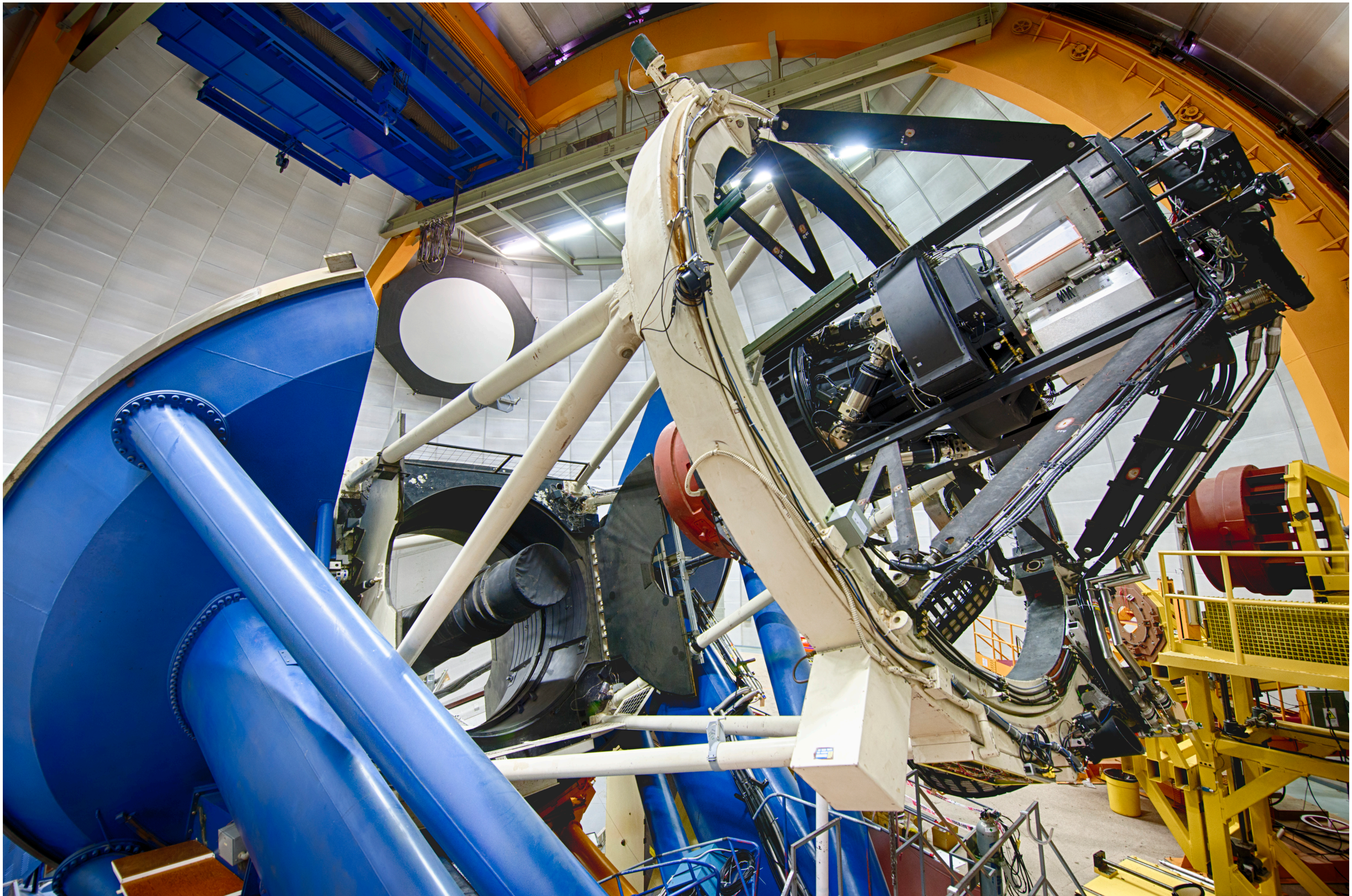
- Field of view: 2.2° diameter
- Good image quality across FOV
- Optical elements aligned at UCL

S. Kent (Fermilab)





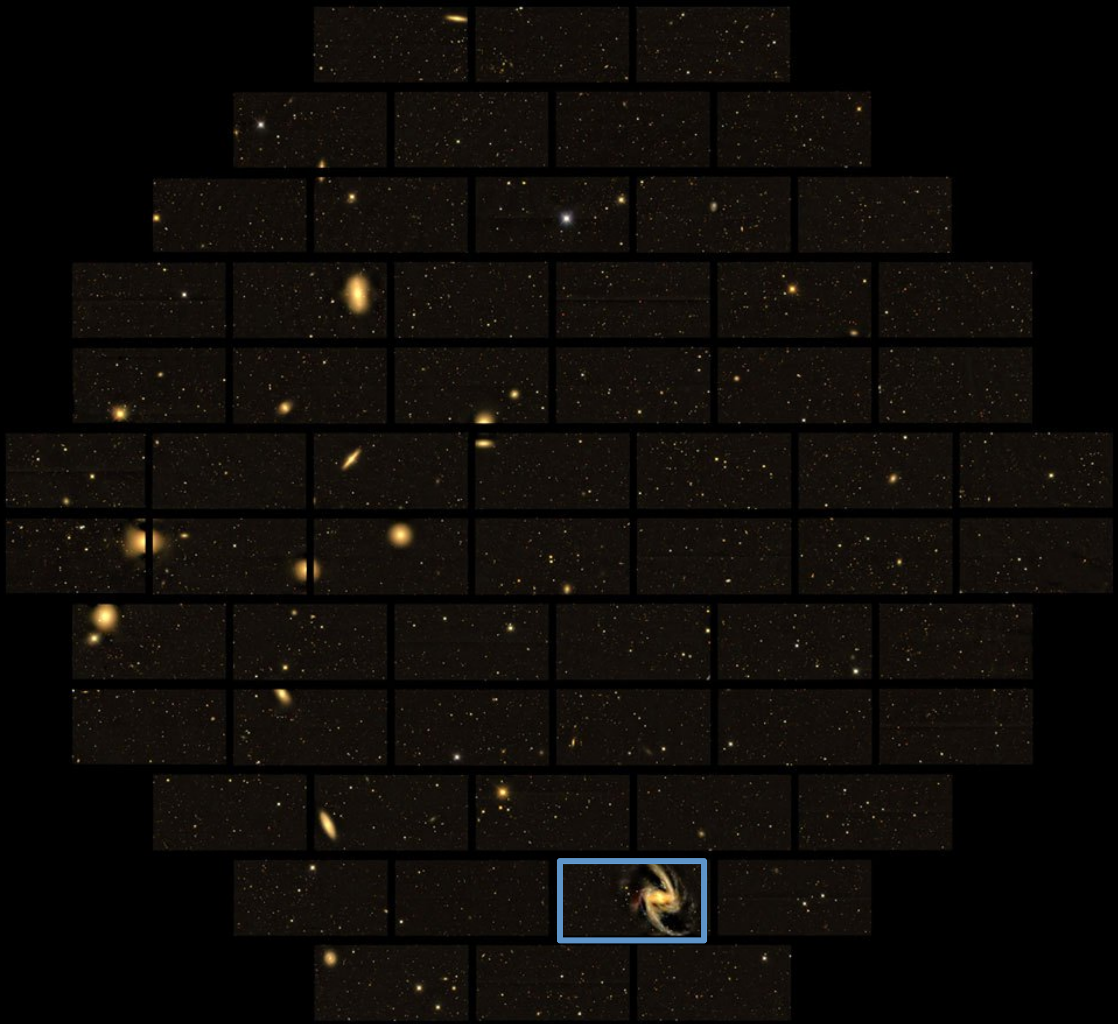
Biggest Lens
(out of 5 lenses)



Dark Energy Camera on the Blanco Telescope

DARK ENERGY SURVEY

First Images



Fornax Cluster of Galaxies

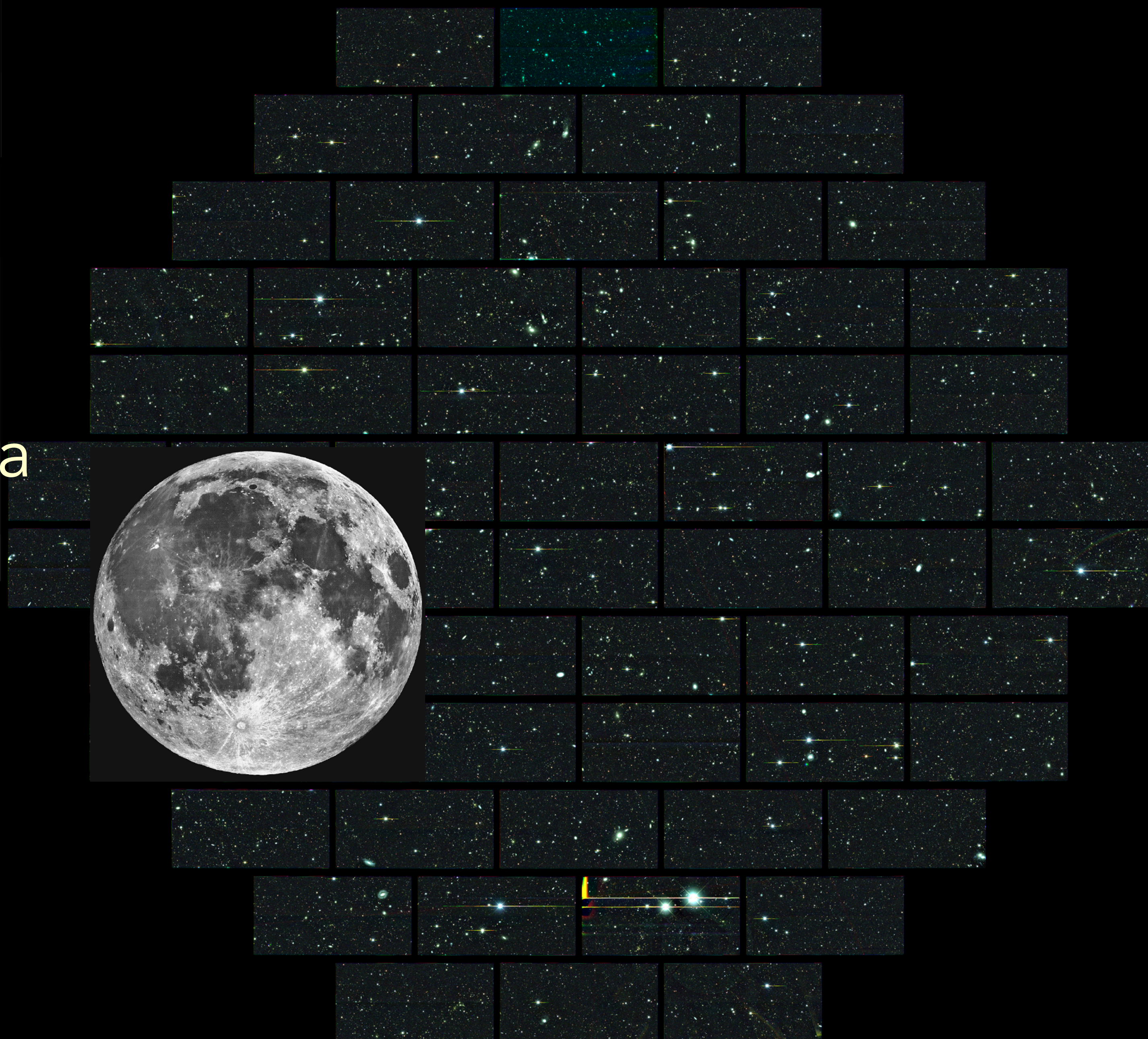
First Light on Sept. 12, 2012

First Images

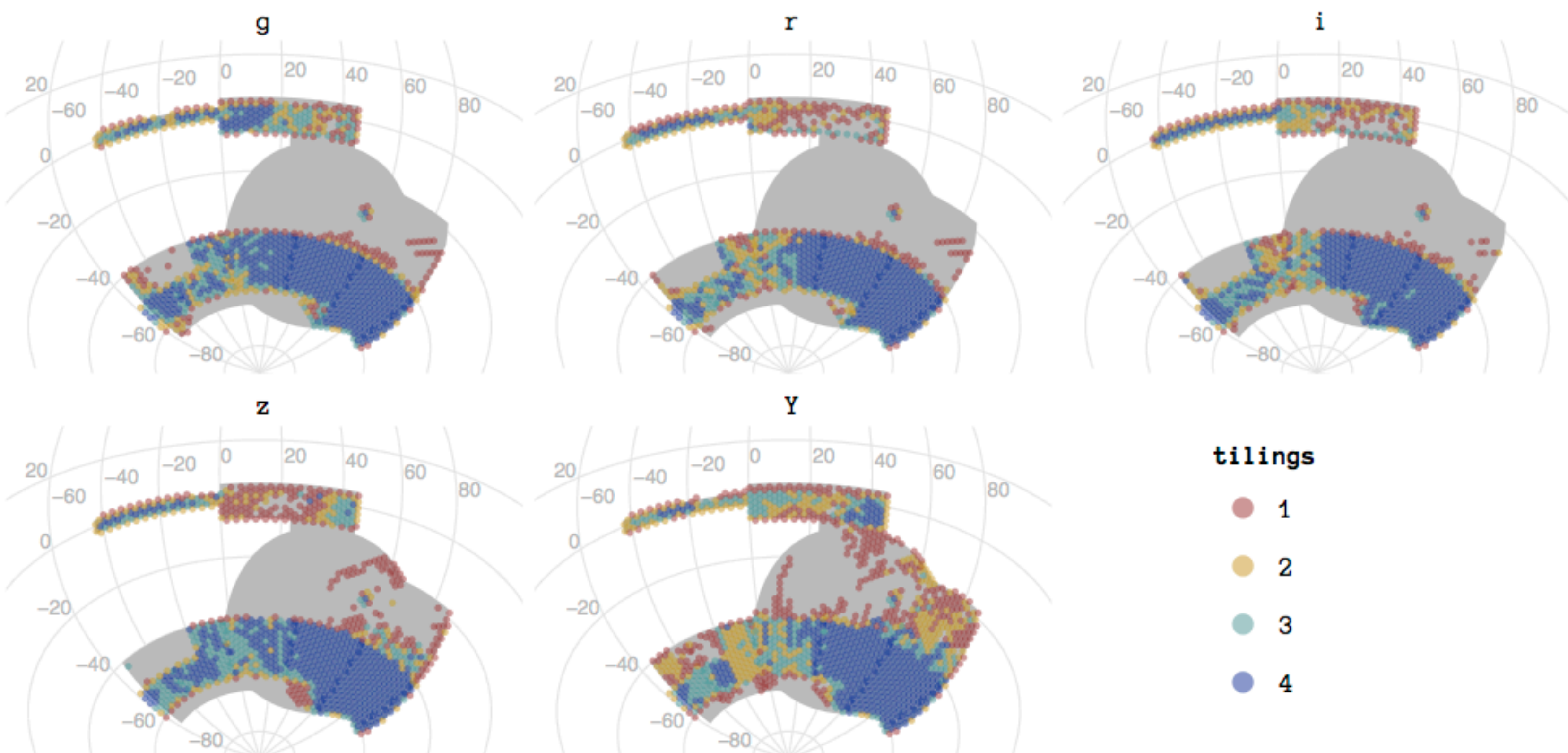
Galaxy NGC 1365 in Fornax   image from a single CCD

Early Image taken with the Dark Energy Camera

DES SV image of a deep SN field

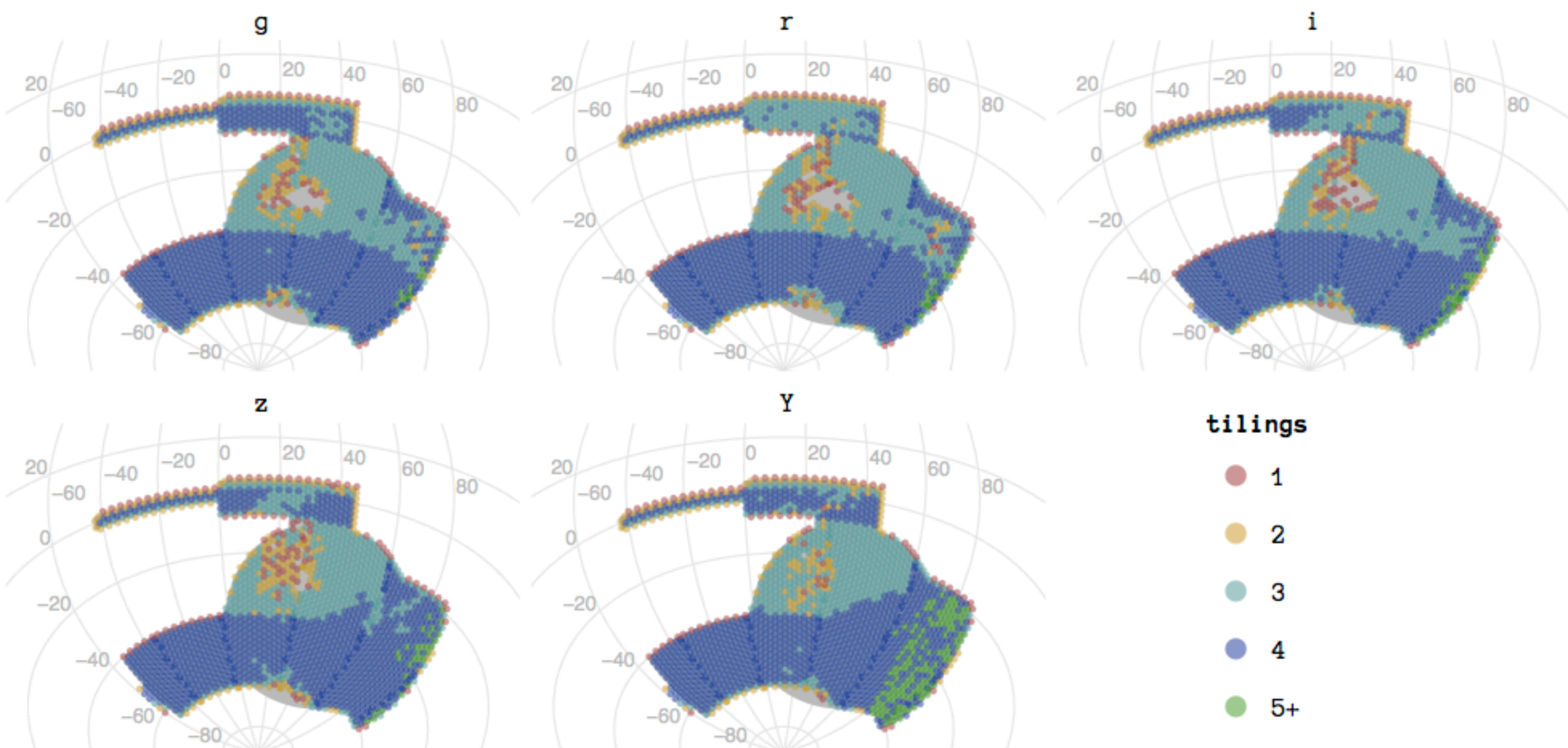


DES Survey Footprint



After Year 1 (Feb. 2014)

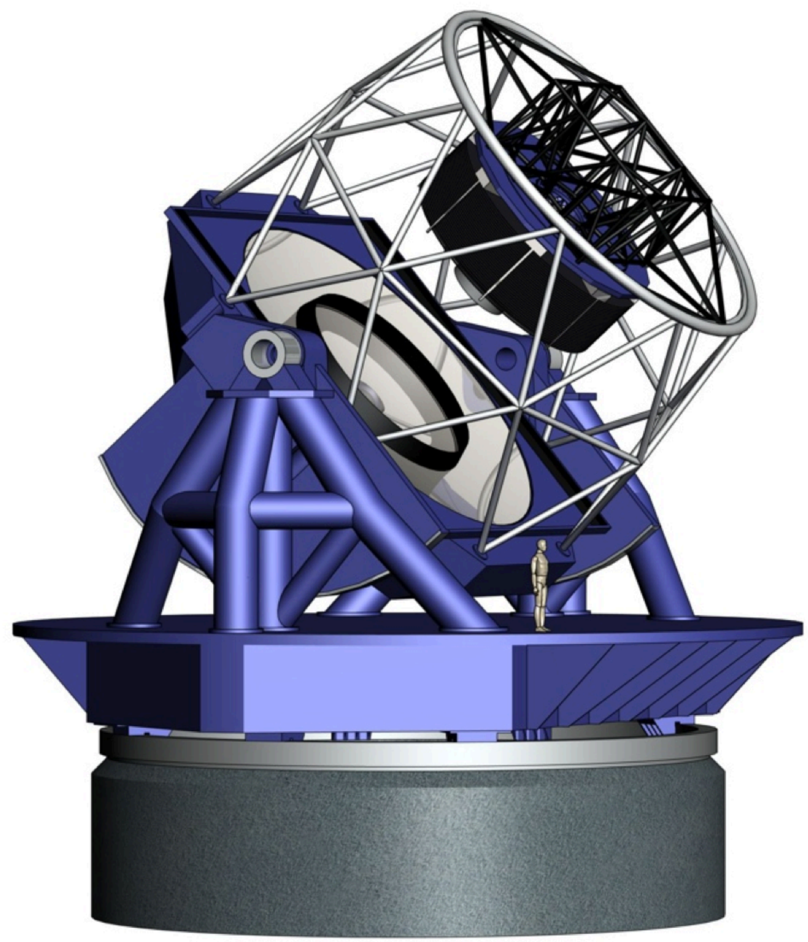
DES Survey Footprint



After Year 2 (Feb. 2014)

Large Synoptic Survey Telescope

- 8.4m ground-based telescope
- 10 square degree field of view
- All sky survey
- 5 optical filters ugriz
- r<27, useable zm~1.0
- Very wide and very deep - the ultimate ground-based survey!



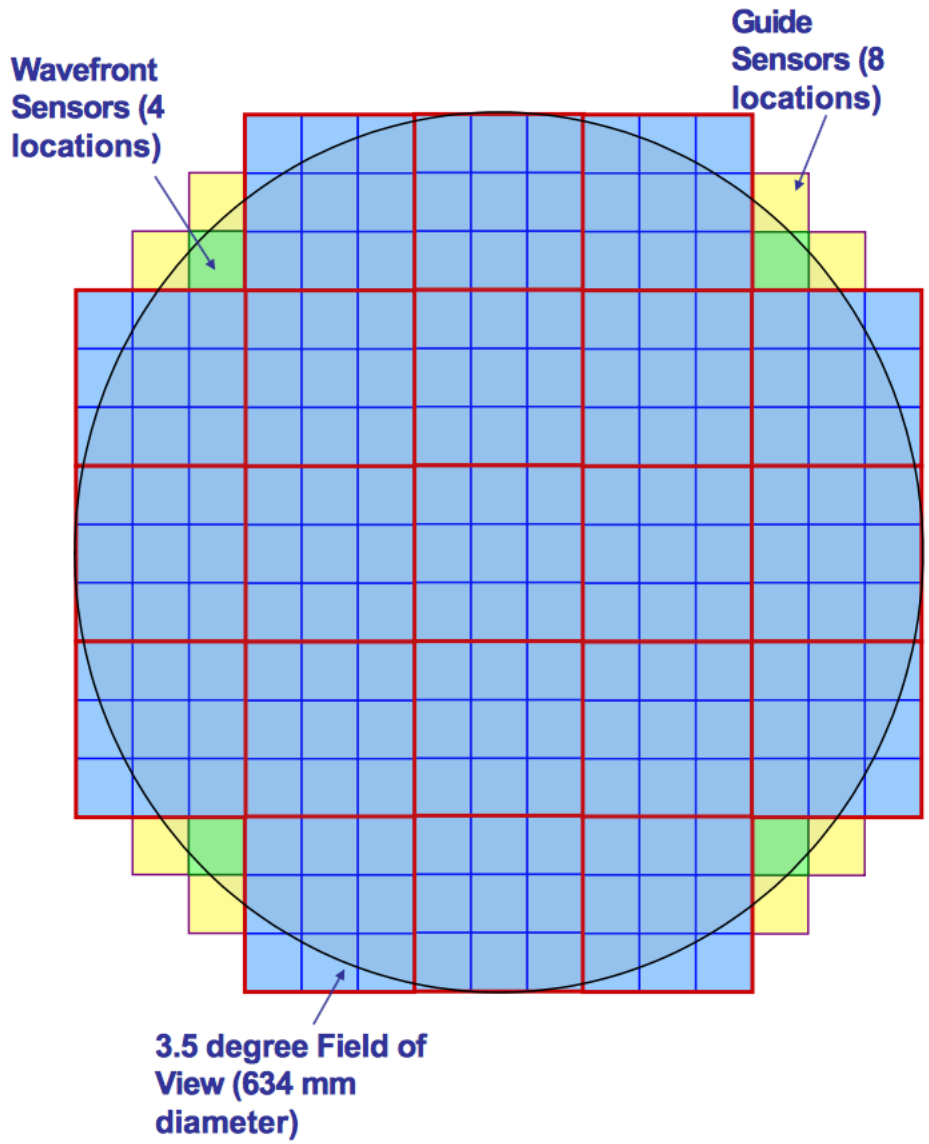
Probing Dark Energy and Dark Matter

Large Synoptic Survey Telescope

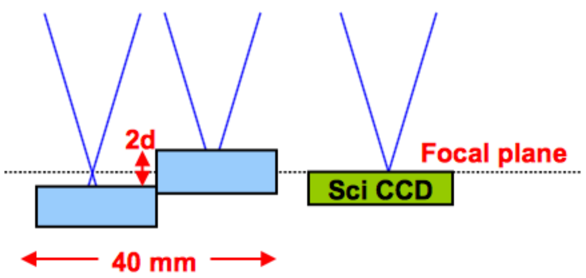
- **Four main observational probes: Weak Lensing, Baryon Acoustic Oscillations, Type 1a SNe, Strong Lensing. Main constraints come from WL and Type 1a's.**
- **Weak Lensing:**
  - **Requires deep, wide-area, multi-color imaging.**
  - **Stringent requirements on image quality in at least two bands.**
  - **Excellent photometry in at least five bands.**
  - **Many short exposures under varying conditions to control shear systematics.**
  - **Covering 20,000 deg^2 with a depth down to r ~ 27.5 gives about 4 million galaxies. Adequate for Stage IV DE constraints.**
- **Type 1a Supernovae**
  - **Requires lightcurves sampled in multiple bands every few days over the course of a few months.**
  - **Samples drawn from all over the sky to enable the study of potential dark energy dependence on direction.**
  - **Single visit depth should be at least down to r ~ 24.**
  - **Good image quality required to separate SNe from their host galaxies.**
  - **Excellent photometric calibration better than 1%.**
  - **Cross-checks with space-based facilities sensitive in the IR.**


Site has been leveled!

The LSST Focal Plane - 64 cm in Diameter

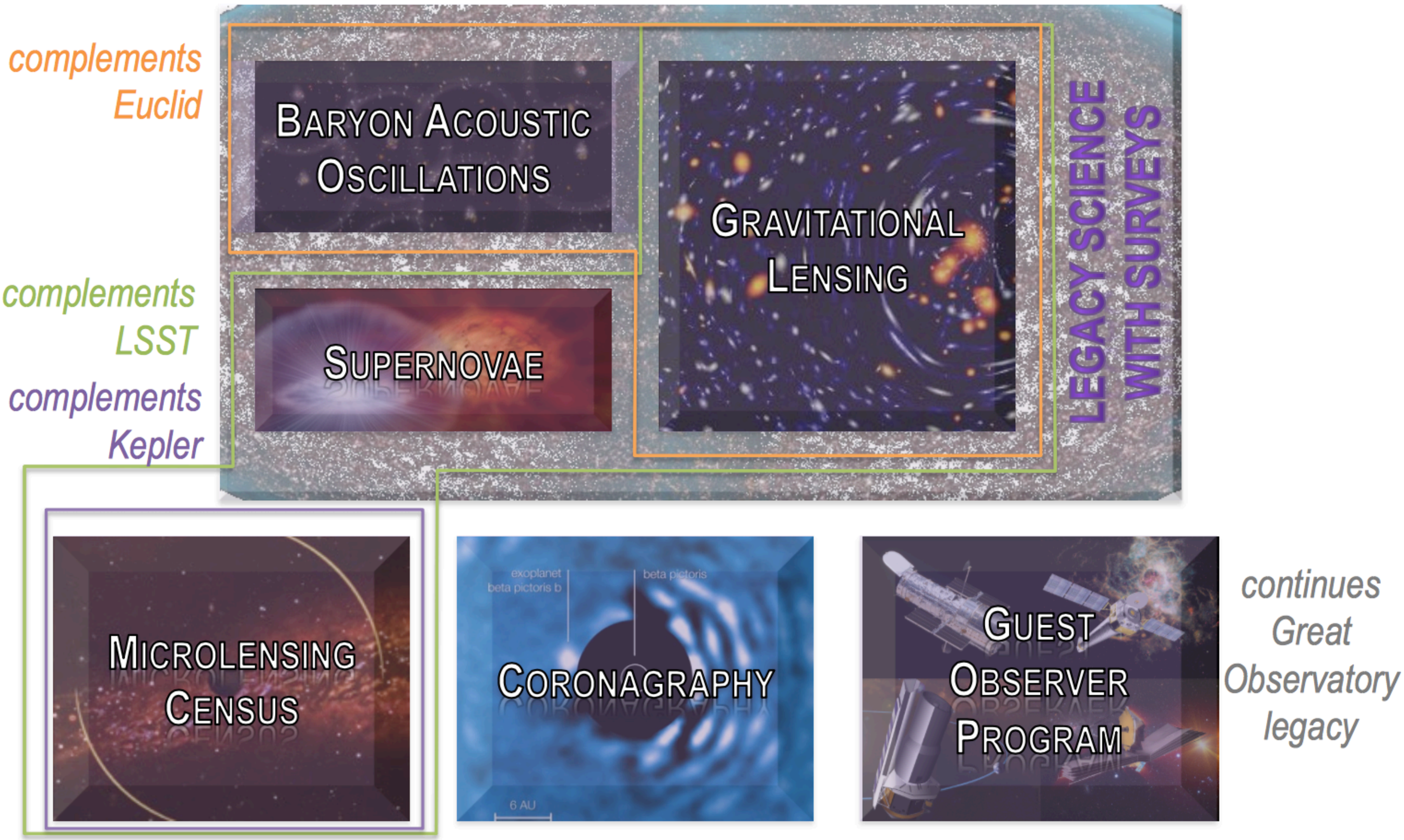


Wavefront Sensor Layout



Curvature Sensor Side View Configuration

WFIRST-AFTA Science



WFIRST AFTA Observatory Concept

Science Areas	NWNH Key Science Questions
Frontiers of Knowledge	• Why is the universe accelerating? • What is dark matter? • What are the properties of neutrinos?
Cosmic Order: Exoplanets	• How diverse are planetary systems? • Do habitable worlds exist around other stars, and can we identify the telltale signs of life on an exoplanet? • How do circumstellar disks evolve and form planetary systems?
Understanding our Origins	• How did the universe begin? • What were the first objects to light up the universe, and when did they do it? • How do cosmic structures form and evolve? • What are the connections between dark and luminous matter? • What is the fossil record of galaxy assembly from the first stars to the present?
Cosmic Order: Stars + Galaxies	• What controls the mass-energy-chemical cycles within galaxies? • How do the lives of massive stars end? • What are the progenitors of Type Ia supernovae and how do they explode?

WFIRST-AFTA addresses many of the key science questions posed in the NWNH Decadal Survey

References

- **GREAT08, GREAT10, GREAT3 Handbooks**
- **STEP1, STEP2 papers**
- Bernstein and Jarvis 2002
- Hirata and Seljak 2003
- Kaiser, Squares, Broadhurst (1995)
- Miller et al (2007)
- Bernstein and Armstrong (2012)