DARK ENERGY SURVEY

Weak Lensing Pipeline accuracy and validation tests for the Dark Energy Survey

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Outline of talk

- What is Dark Energy?
- The Dark Energy Survey (DES)
- Weak Lensing: a powerful tool
- Weak Lensing is hard to measure: systematics
  - Testing the DES Weak Lensing pipeline: custom tests.
  - Multiplicative and additive erros
  - Calibrating low-S/N biases with high S/N data.
  - PSF recovery measurements
  - Validation tests (Astrometry, Shear)
- Conclusions

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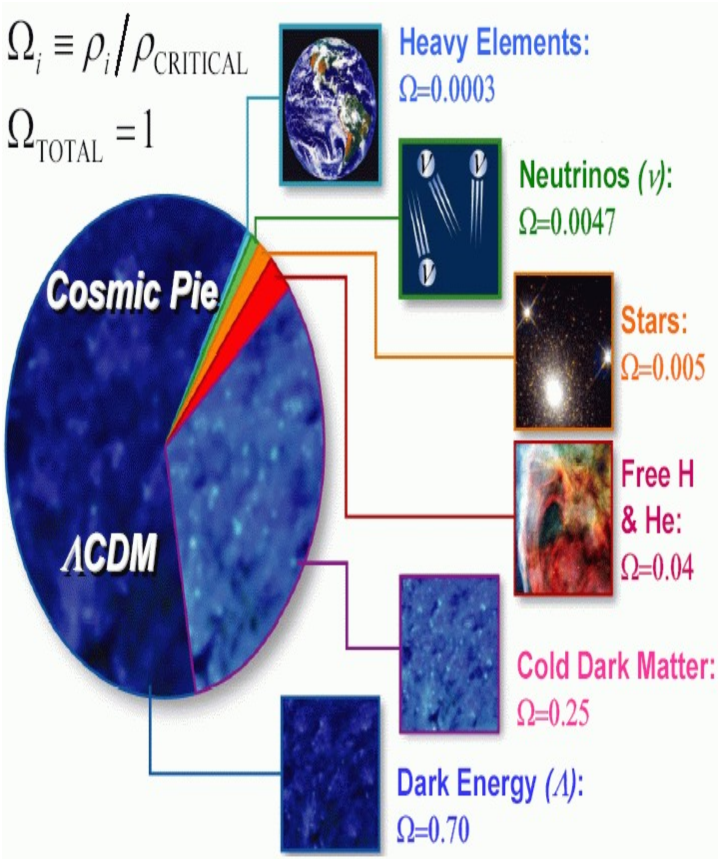
Dark Energy



Observations show strong evidence for an accelerated expansion.

* The causative agent of this phenomenon is named **Dark Energy.**

It has three defining properties:

i) Emits no light

ii) Has large, negative pressure.

iii) It's approximately homogeneous.

* It makes up almost 70% of all the energy-mass in the Universe. It can be characterized by an equation of state relation of the form
w(a) = p(a) / rho(a)

* Is it a new particle? The vacuum energy? A modification of gravity at large scales ?
* Deciphering its nature is just possibly *"the most important problem in all Physics"* [M. Turner]

The Dark Energy Survey

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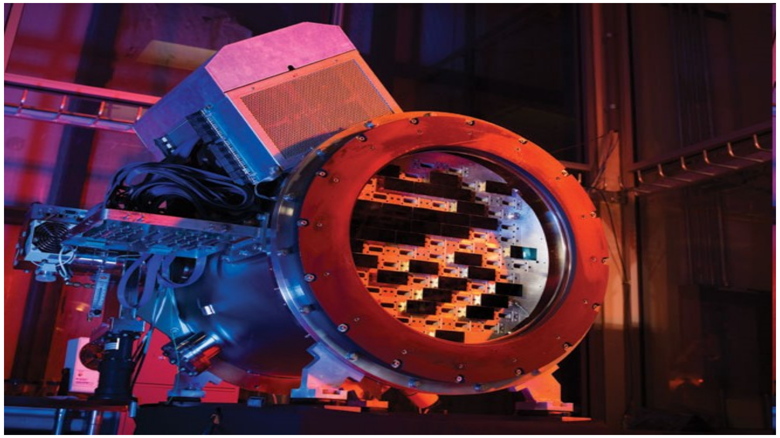
- DES will survey over 300 million of galaxies in different color bands (g, r, i, z, Y).
- 5000-sq degrees in the southern cap.
- 525 nights over 5 years, starting in 2012.
- An all-new designed 500 Megapixel CCD camera (Dark Energy Camera) was built and recently arrived in Cerro Tololo, Chile, to be mounted at the 4-m Blanco telescope.
- DES will be complemented by the South Pole Telescope experiment, a 4000-sq survey which started to take data in 2007.



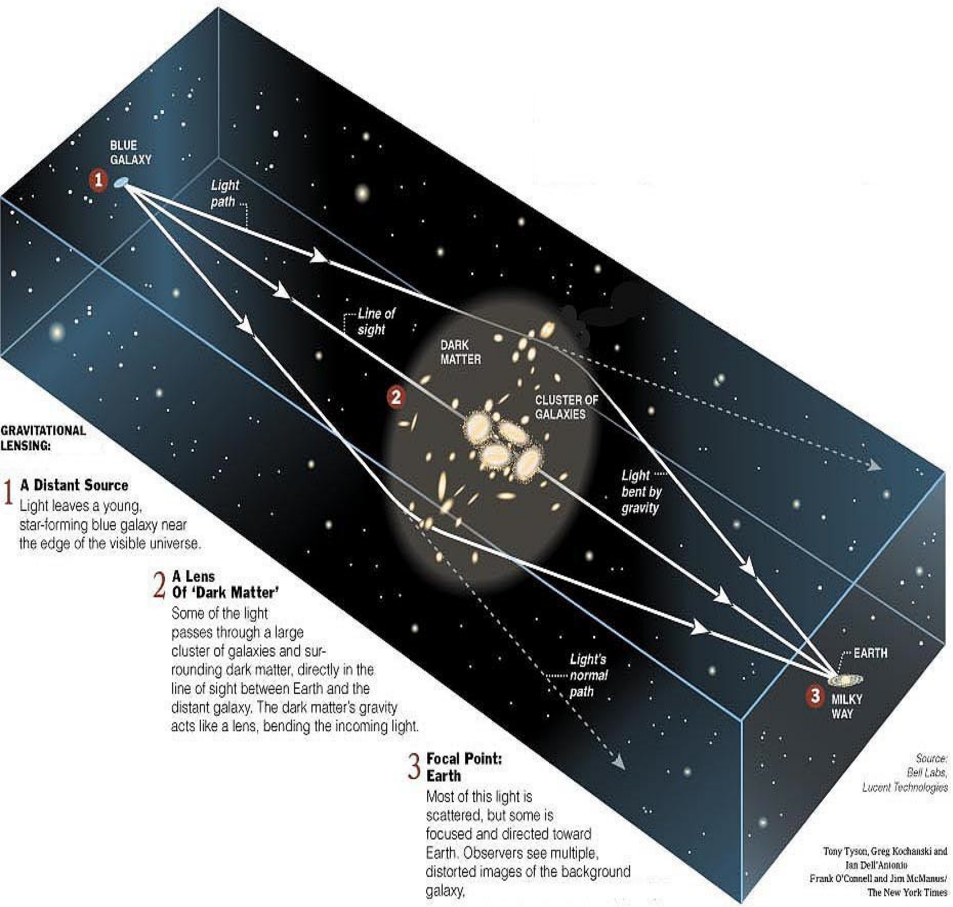
Will use four complementary techniques:
SNe , BAO, Clusters, Weak Lensing

What does DES plan to answer?

- Is the Dark Energy a cosmological constant (i.e., a component with w=-1) ?.
- Is Dark energy a modification to Einstein's Theory of Gravity?.

Gravitational Lensing

Bending of light by any matter distribution



Strong Lensing:

Belokurov et al, 2007/ Image NASA-ESA

Weak Lensing

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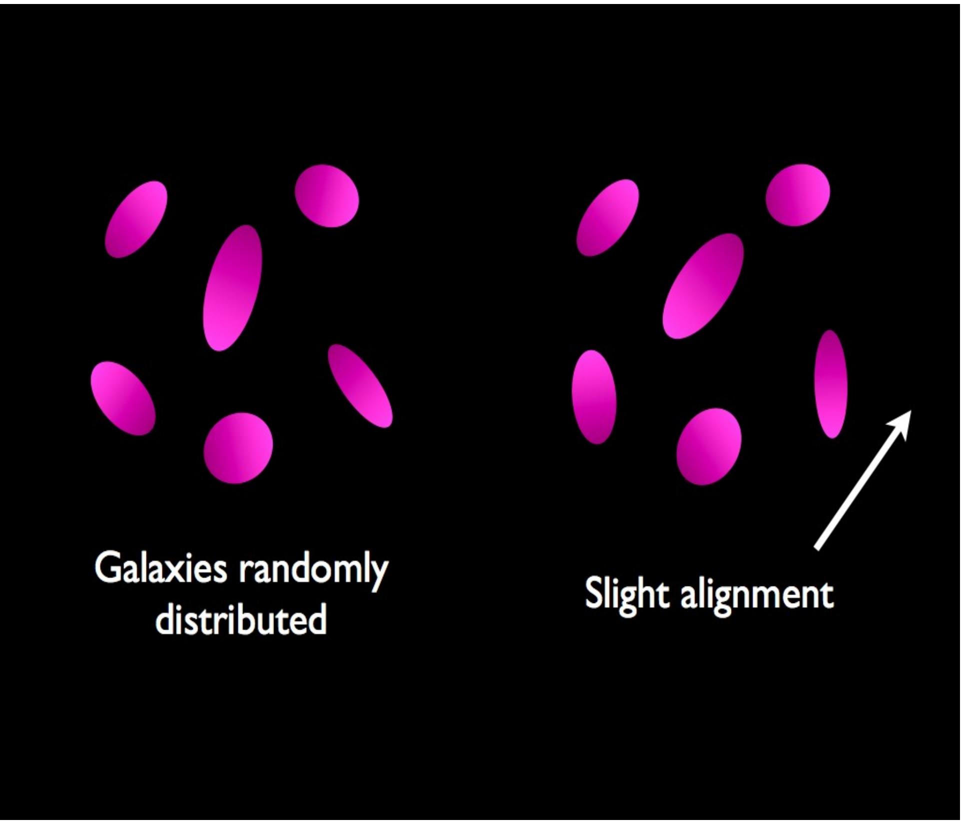
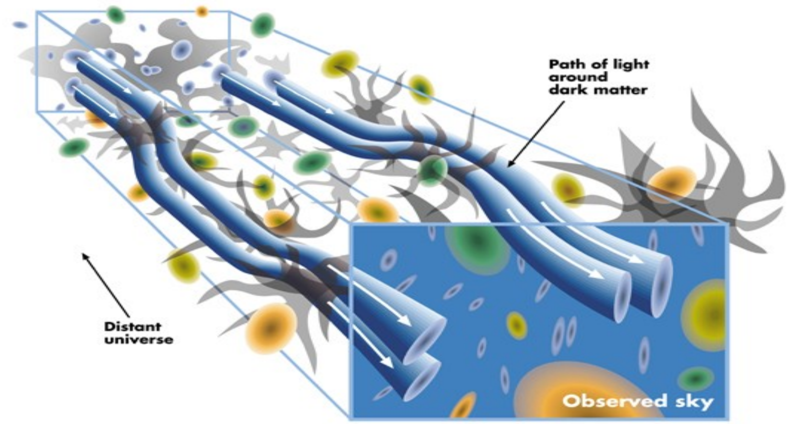
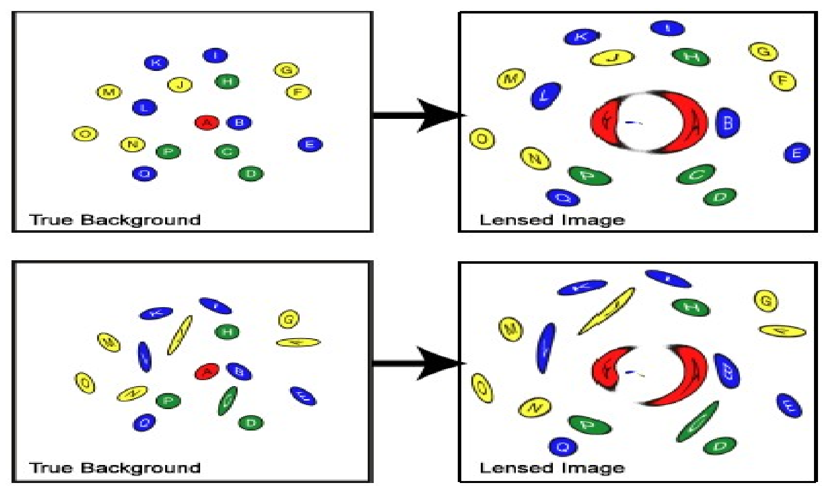


E Grocutt, IfA, Edinburgh





This effect is only of about 1%

Lensing stretches the galaxies in the same direction on a given patch of the sky: they tend to align.

Weak Lensing

- Sensitive to both growth of structure and geometry of the Universe

$$D(z) = \int_0^r \frac{dr'}{\sqrt{1-kr'^2}} = \int_t^{t_0} \frac{dt'}{a(t')} = \int_0^z \frac{dz'}{H(z')} \qquad \ddot{g} + 2H\dot{g} = 4\pi G \rho_m g = \frac{3\Omega_m H_0^2}{2a^3} g$$

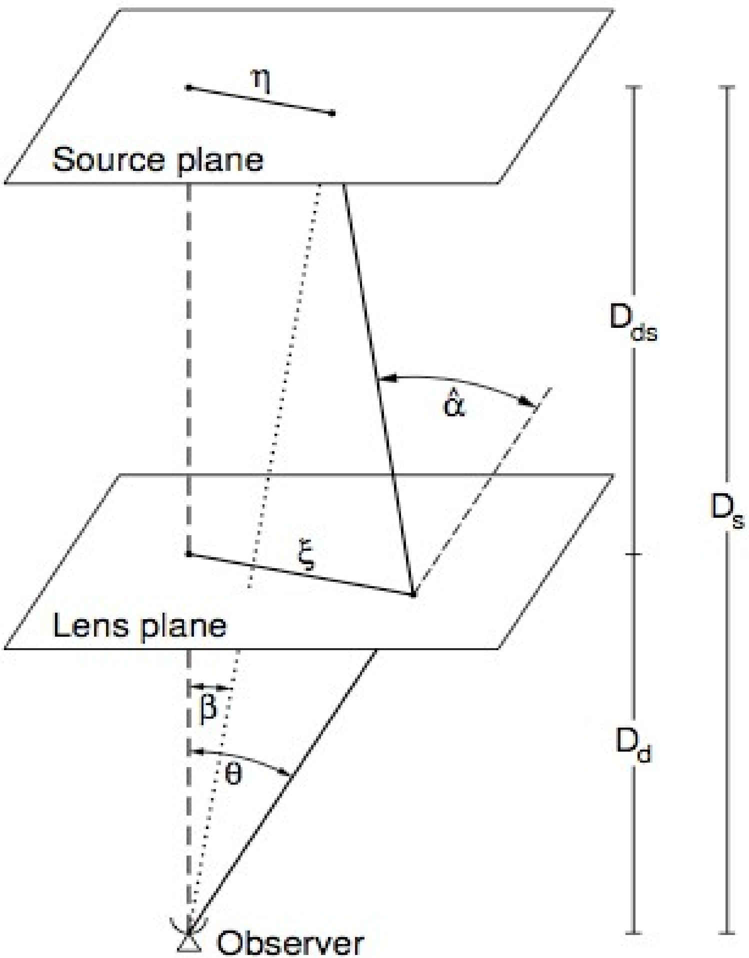
- Power spectra
- Cosmological parameters
- Tests of GR (the growth equation assumes GR is the right theory of gravity)

Systematics

Weak Lensing *"...is likely to be the most powerful individual technique, and also the most powerful component in a multi-technique program..."* to learn about Dark Energy if systematics can be controlled (DETF 06, *Albrecht et al*)

- Multiplicative (calibration) errors in the signal (shear)
- Shear Additive errors
- PSF measurement and interpolation
- Photo-z biases, catastrophic errors
- Intrinsic Alignments: physically close galaxies
- Errors in theory (non-linear power spectrum predictions)

Weak Lensing Basics



→ Lens Equation (small angles)

$$\boldsymbol{\theta} \mathrm{D_s} = \boldsymbol{\beta} \mathrm{D_s} + \hat{\boldsymbol{\alpha}} \mathrm{D_{ds}} \qquad \boldsymbol{\alpha} = \hat{\boldsymbol{\alpha}}\, \mathrm{D_{ds}}/\mathrm{D_s}$$

We can define the Lensing Potential as the projected and scaled 3D Newtonian Potential

$$\psi(\vec{\theta}) = \frac{D_{\rm ls}}{D_{\rm l} D_{\rm s}} \frac{2}{c^2} \int \Phi(D_{\rm l}\vec{\theta}, z)\, dz$$

Important relation: the deflection angle is the gradient of the lensing potential.

$$\vec{\nabla}_\theta \psi = D_{\rm d} \vec{\nabla}_\xi \psi = \frac{2}{c^2} \frac{D_{\rm ds}}{D_{\rm s}} \int \vec{\nabla}_\perp \Phi\, dz = \vec{\alpha}$$

And the laplacian of the lensing potential is related to the normalized surface-mass density

$$\begin{aligned} \nabla_\theta^2 \psi &= \frac{2}{c^2} \frac{D_{\rm d} D_{\rm ds}}{D_{\rm s}} \int \nabla_\xi^2 \Phi\, dz = \frac{2}{c^2} \frac{D_{\rm d} D_{\rm ds}}{D_{\rm s}} \cdot 4\pi G \Sigma \\ &= 2 \frac{\Sigma(\vec{\theta})}{\Sigma_{\rm cr}} \equiv 2\kappa(\vec{\theta}) \, , \end{aligned}$$

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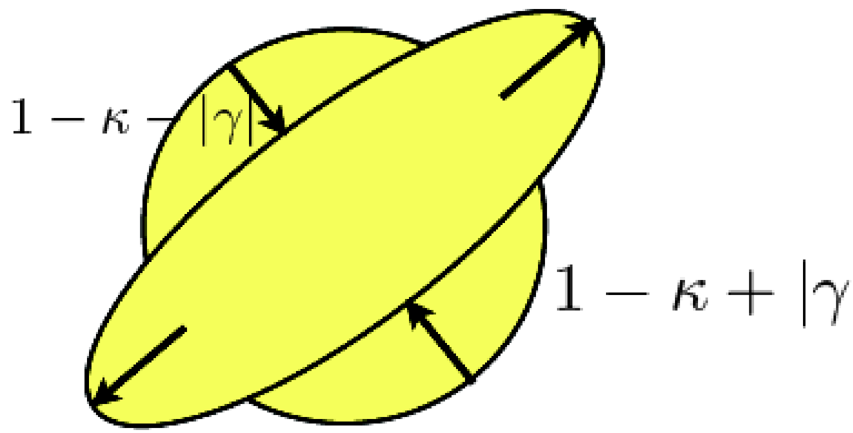
Observable: gravitational shear

It's useful to consider the Jacobian of the transformation between the observed and unlensed image. It can be related to the gradients of the gravitational potential.

$$\boldsymbol{\theta} \mathrm{D_s} = \boldsymbol{\beta} \mathrm{D_s} + \hat{\boldsymbol{\alpha}} \mathrm{D_{ds}}.$$

$$\begin{aligned} A_{ij} &= \frac{\delta \beta_i}{\delta \theta_j} = \frac{\delta}{\delta \theta_j}[\theta_i - \alpha_i(\boldsymbol{\theta})] \\ &= \delta_{ij} - \frac{\delta \alpha_i(\boldsymbol{\theta})}{\delta \theta_j} \\ &= \delta_{ij} - \frac{\delta^2 \psi(\boldsymbol{\theta})}{\delta \theta_i \, \delta \theta_j} \end{aligned}$$



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

$$\gamma = \gamma_1 + i\gamma_2 \longrightarrow$$

$$\begin{aligned} \gamma_1 = \frac{1}{2}(\psi_{,11} - \psi_{,22}) &= \gamma \cos(2\phi) \\ \gamma_2 = \psi_{,12} = \psi_{,21} &= \gamma \sin(2\phi). \end{aligned}$$

$$A = (1 - \kappa) \begin{pmatrix} 1 - g_1 & -g_2 \\ -g_2 & 1 + g_1 \end{pmatrix}$$

$$g = \gamma / (1 - \kappa) \longrightarrow$$ Reduced shear

Estimating the shear: an inverse problem

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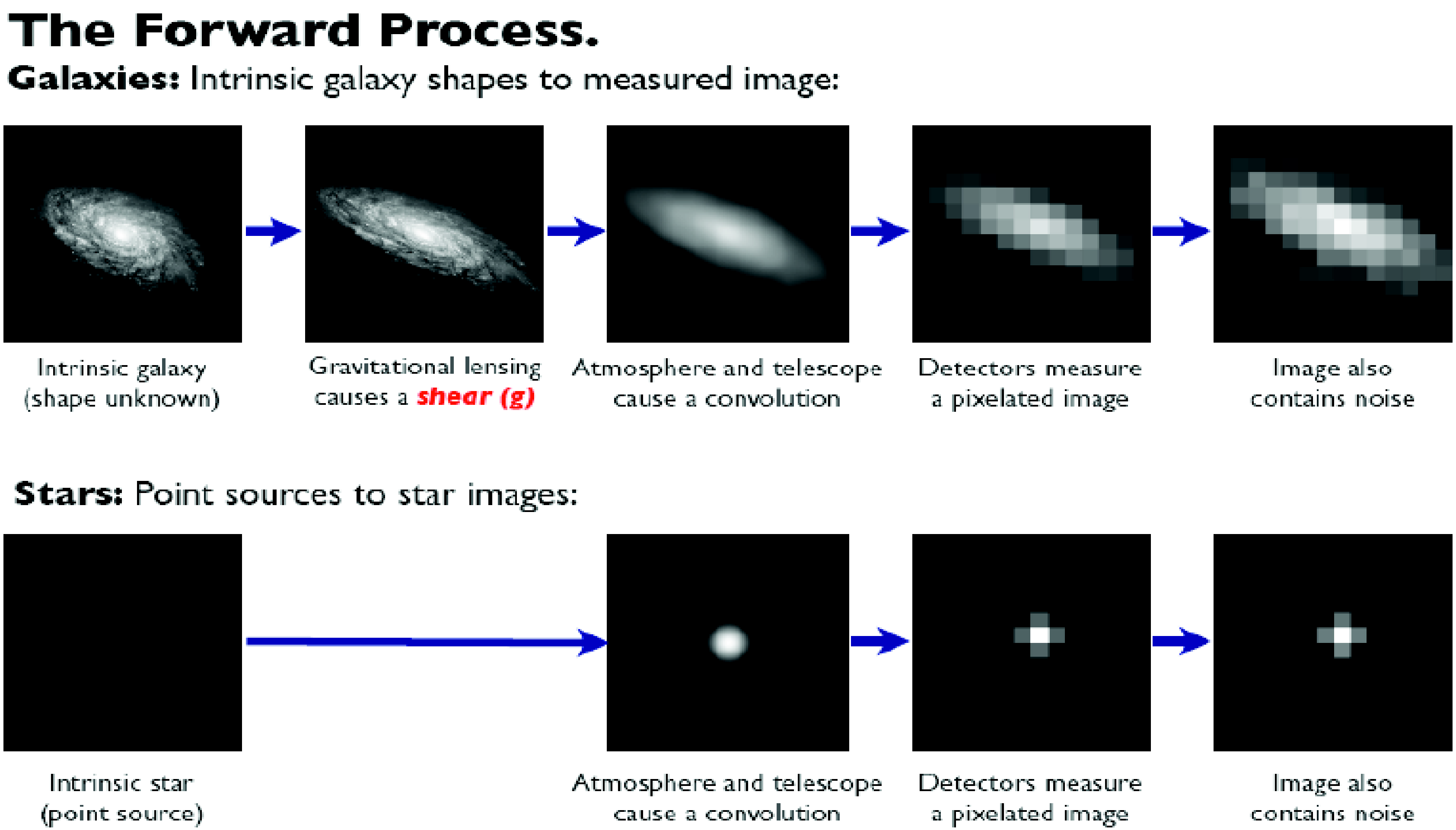

Bridle *et al.*, 2008

Measuring Shear: the pipeline

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.

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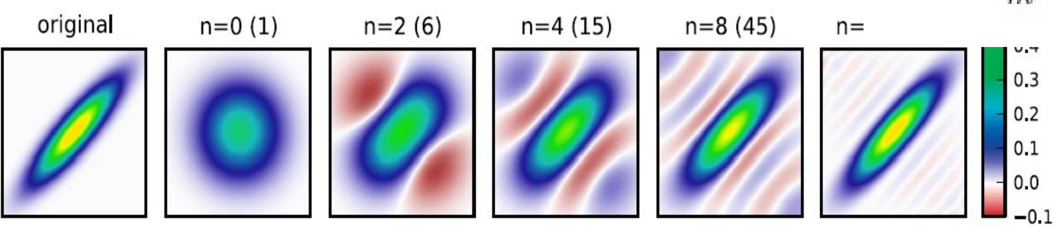
Weak lensing pipeline

The code we use (method described in Bernstein & Jarvis 2002 and implemented by Mike Jarvis) is based on the Elliptical Gauss Laguerre method (shapelets) .

- Decompose the surface brightness of the galaxy and PSF into the Elliptical Gauss-Laguerre orthonormal basis of the plane.
- Shapelets can be summed together to model galaxy morphologies:

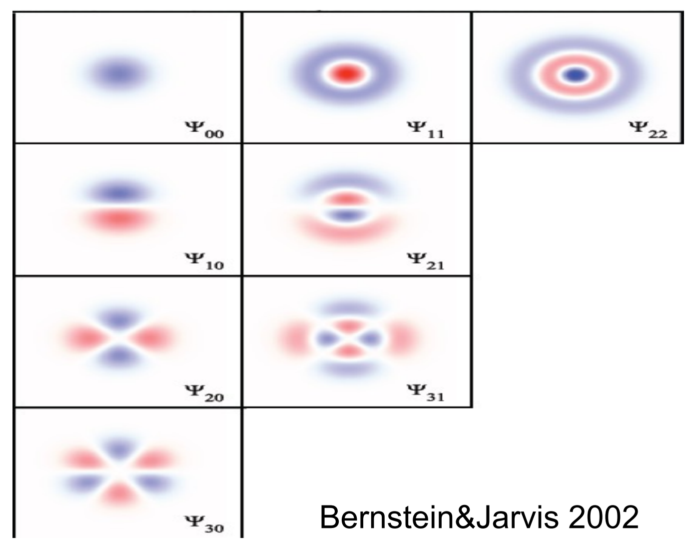
$$
\begin{aligned}
I(r,\theta) &= \sum_{p,q\geq 0} b_{pq}\psi^{\sigma}_{pq}(r,\theta) \\
\psi^{\sigma}_{pq}(r,\theta) &= \frac{(-1)^q}{\sqrt{\pi}\sigma^2}\sqrt{\frac{q!}{p!}}\left(\frac{r}{\sigma}\right)^m e^{im\theta}e^{-r^2/2\sigma^2}L_q^{(m)}(r^2/\sigma^2) \qquad (p\geq q) \\
\psi^{\sigma}_{qp} &= \bar{\psi}^{\sigma}_{pq} \\
m &\equiv p-q.
\end{aligned}
$$



Bosh 2010

We use elliptical basis instead, so we don't have to go to a very high order.

- Convolve galaxy and PSF models to create an image model.
- Then compare this model to data through a Chi-square fit.



Bernstein&Jarvis 2002

Requirements and types of tests

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

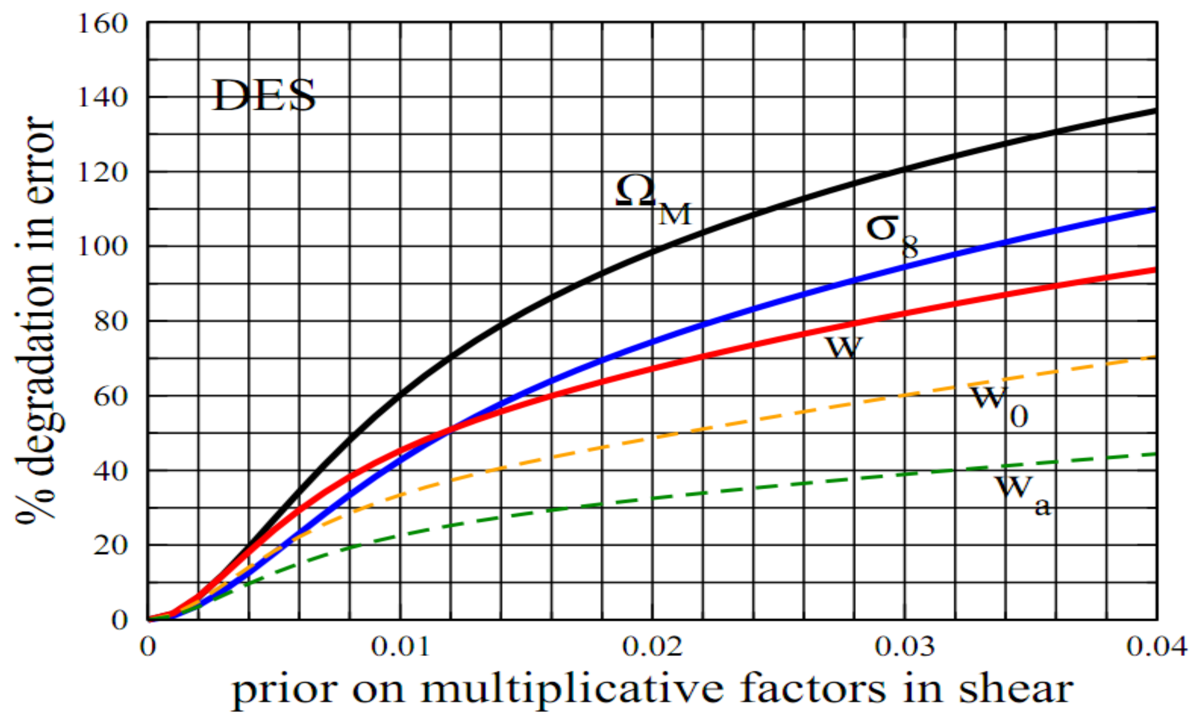
g_measured – *g_true* = *m***g_true* + *c* →

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

Types of tests: End-to-end simulations

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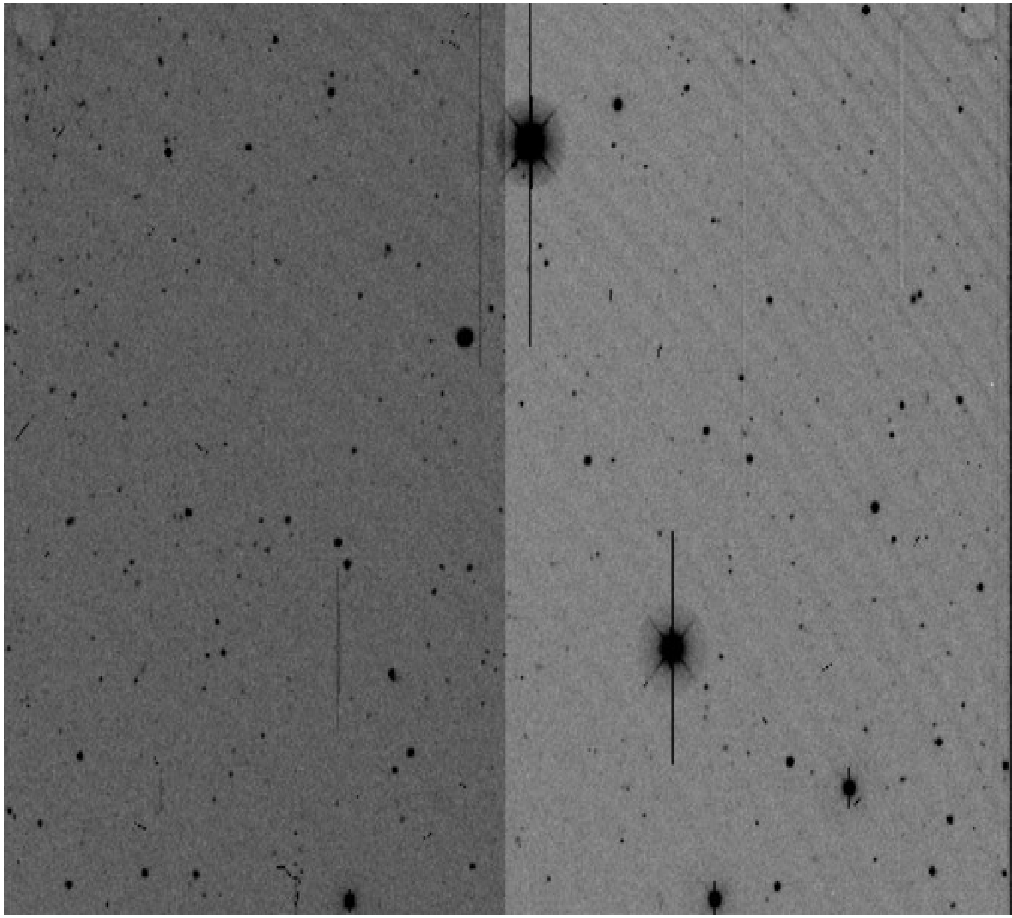
End-to-end tests: simulated images of the sky with a full population of galaxies and stars are produced . These images are then analyzed with the pipeline that's going to be used with real data.

Try to be as close as possible to real life conditions. (e.g., STEP1, STEP2, GREAT08, GREAT10, DES Data Challenges)

DES Data Challenge simulation (H. Lin)



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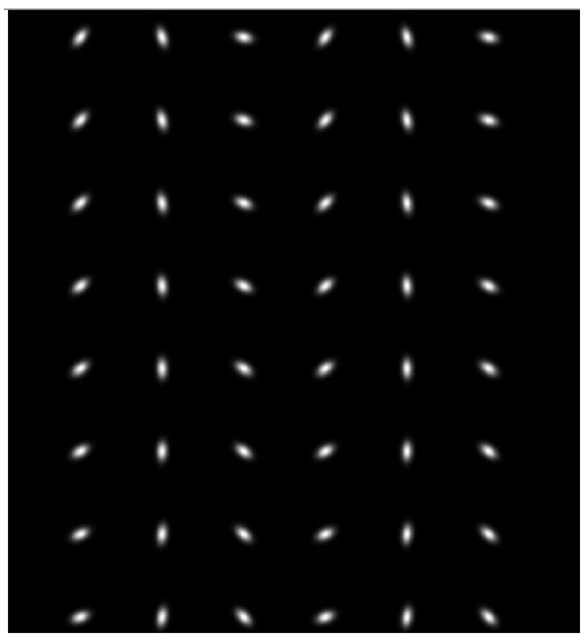
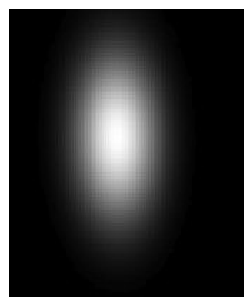
Types of tests : custom images

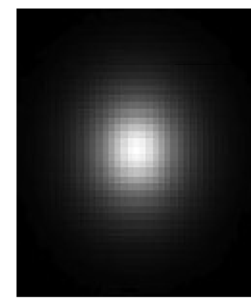
"Dissection tests": custom tests in which the performance of the pipeline is analyzed one parameter at a time. The PSF is controlled and well known.

Different code is used to create the galaxies and stars profiles (Elliptical Gauss-Laguerre decomposition or shapelets).





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
- PSF Size
- Galaxy Size
- Pixel Size
- PSF type
- Expansion order

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Testing our pipeline: custom tests

(taken from document 5440 of DES document data base by Mike Jarvis)

-With the help of these tests we have found and fixed several bugs that have allowed us to improve our shear measurement pipeline.

-At high signal to noise, we get excellent results:

* Biases <~ 1.e-3

-But at low signal noise (S/N < 20) we still get a significant bias

* We are still working on this , creating more customized simulations to pinpoint the problem.

* At the same time we are developing a method to calibrate this low-S/N bias with high S/N data (more on this below).

Testing our pipeline: custom tests

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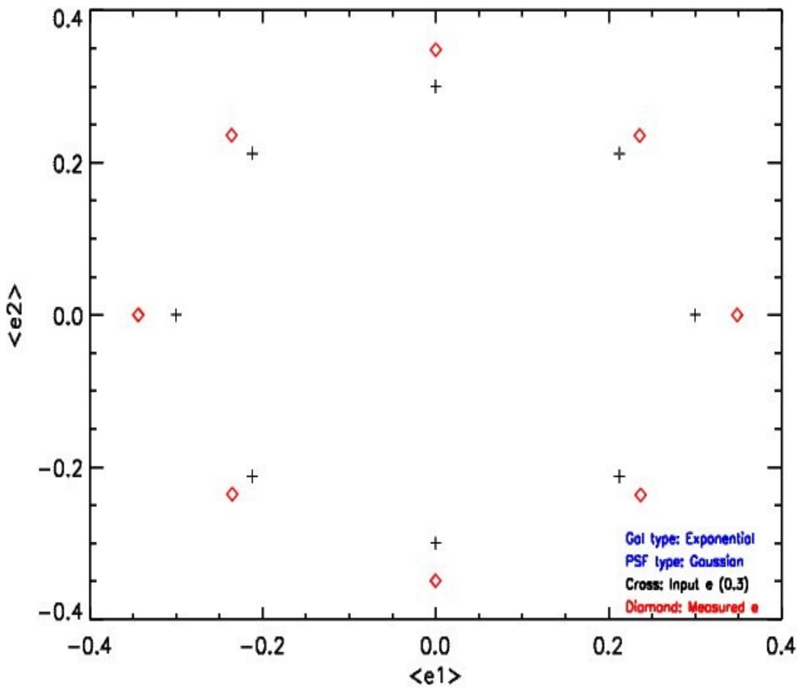
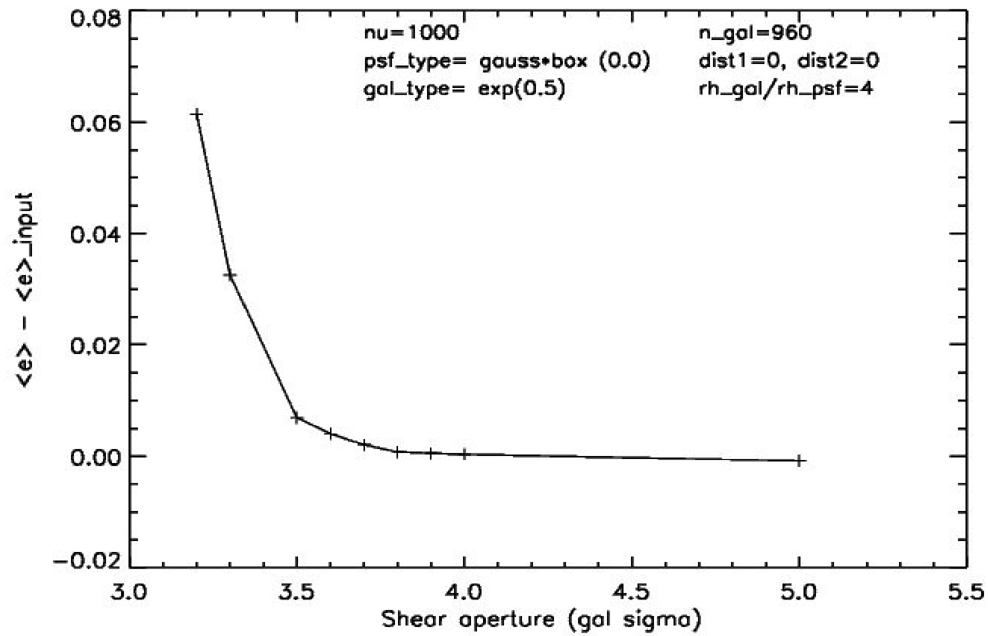
Shear bias as a function of aperture size.

Shear aperture: 3

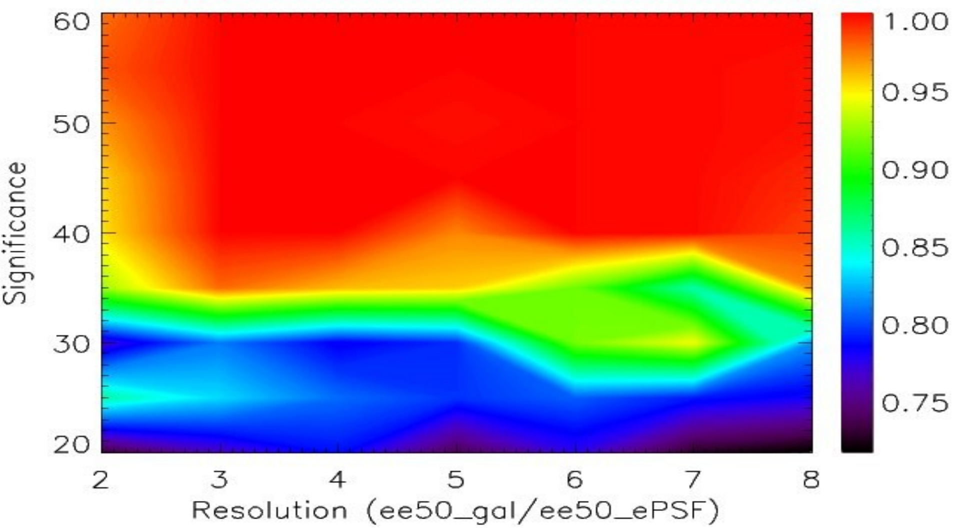




We were using a shear aperture (= number of characteristic size of galaxy to use as aperture on observed galaxy) of 3 - 3.5 . Now we pushed it to 4 to get rid of this bias.

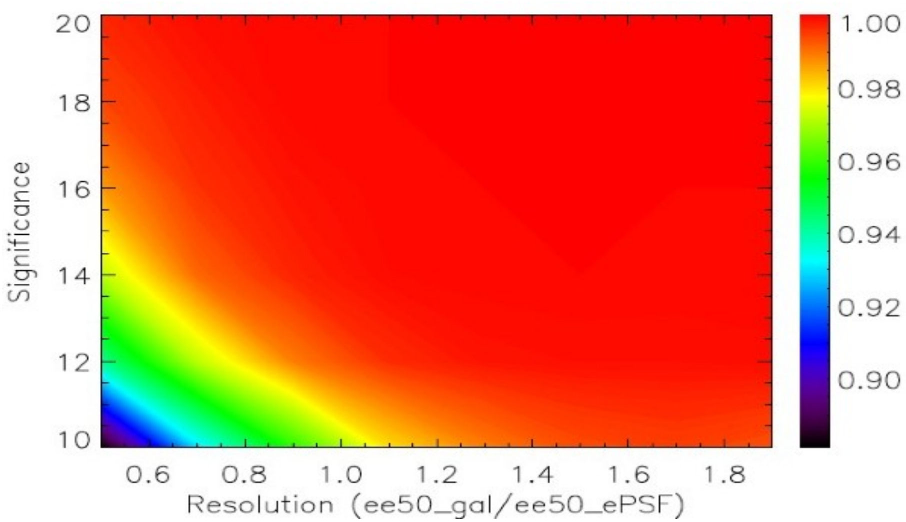
Testing our pipeline: custom tests

Rates of successful shape measurement.



Convergence rate of the code some months ago.

We managed to push the red zone (>99%successful convergence) towards the low S/N zone.



Current Work: Bias in shear measurement from noise

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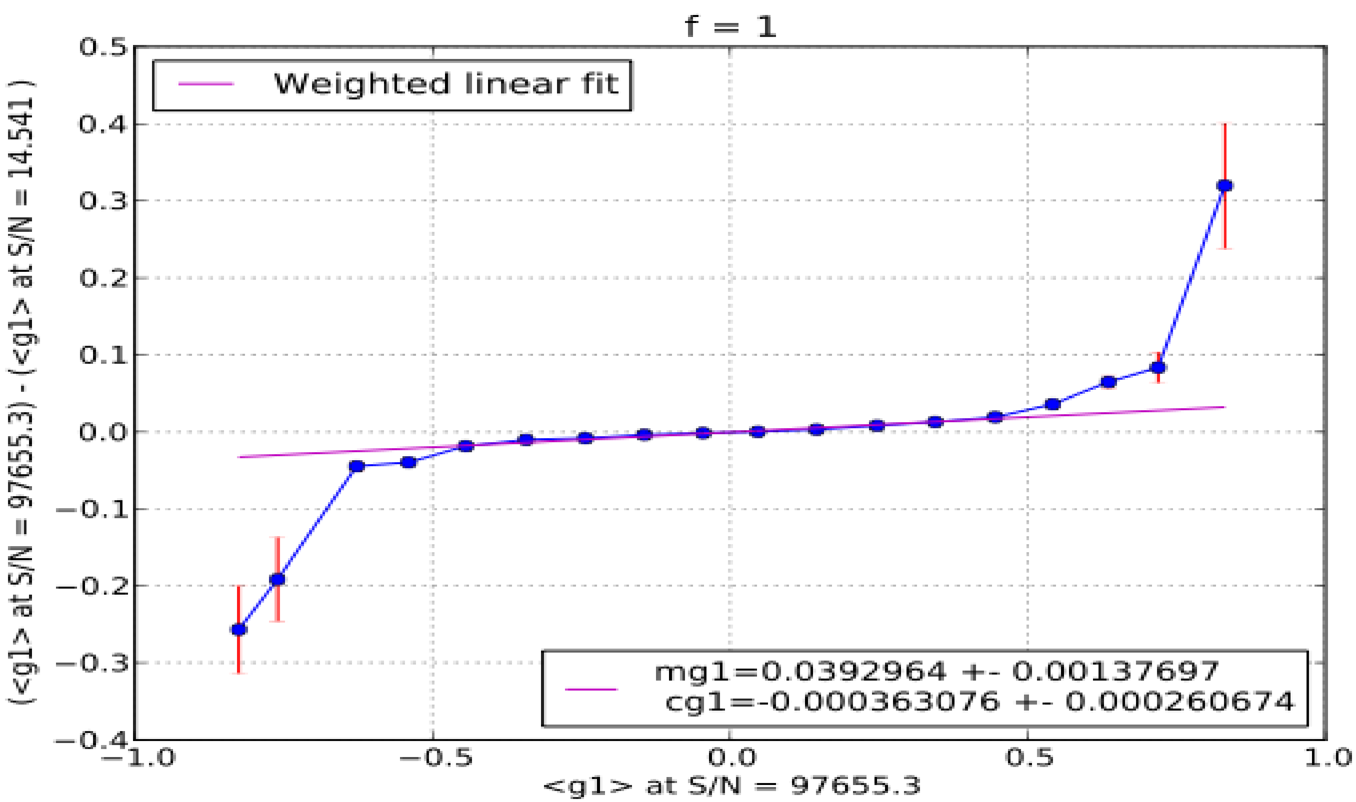
Currently, our code performs quite well at high S/N data.

Use the high-vs-low S/N comparison to derive an m value that can be applied to the low-S/N measurements in order to retrieve a properly calibrated shear.



→ Work still in Progress !!

DES will spend longer time in certain patches of the sky for super-novae observations. These images will have high S/N.

PSF recovery

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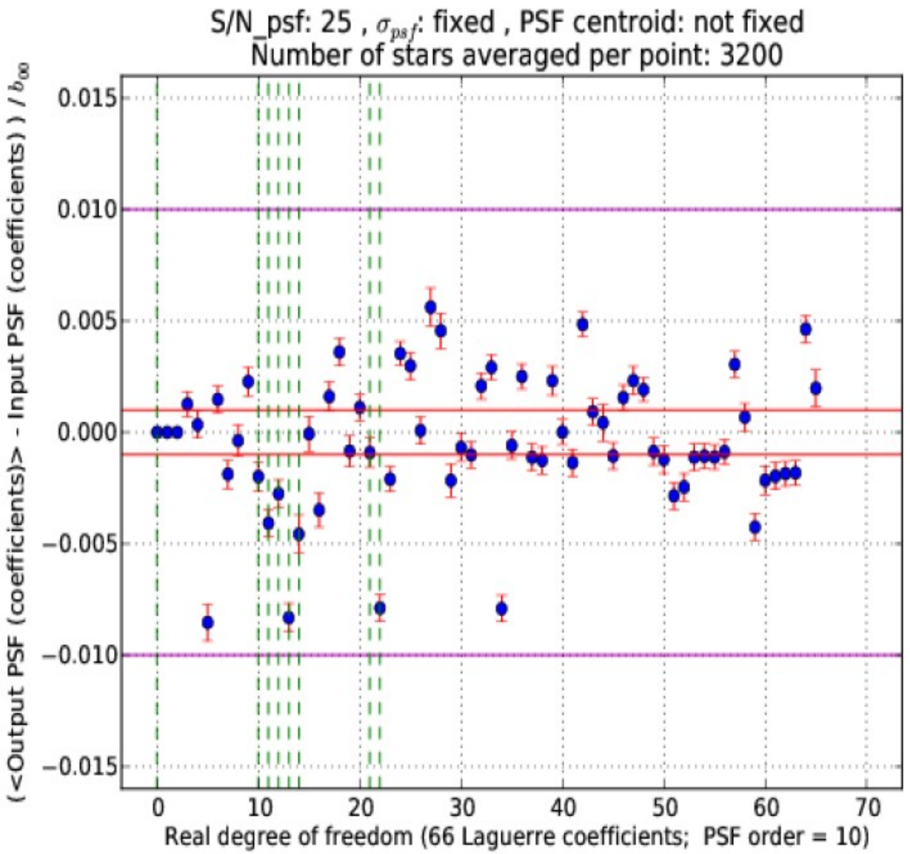
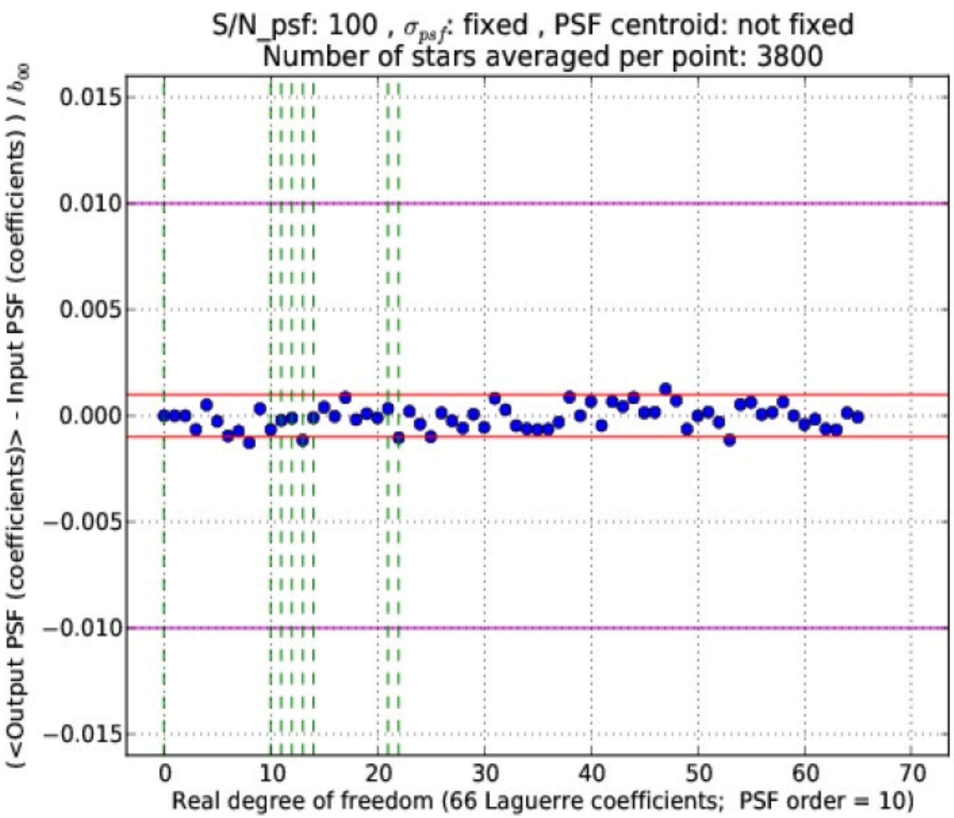
$$I(r,\theta) = \sum_{p,q \geq 0} b_{pq} \psi^{\sigma}_{pq}(r,\theta)$$





PSF recovery

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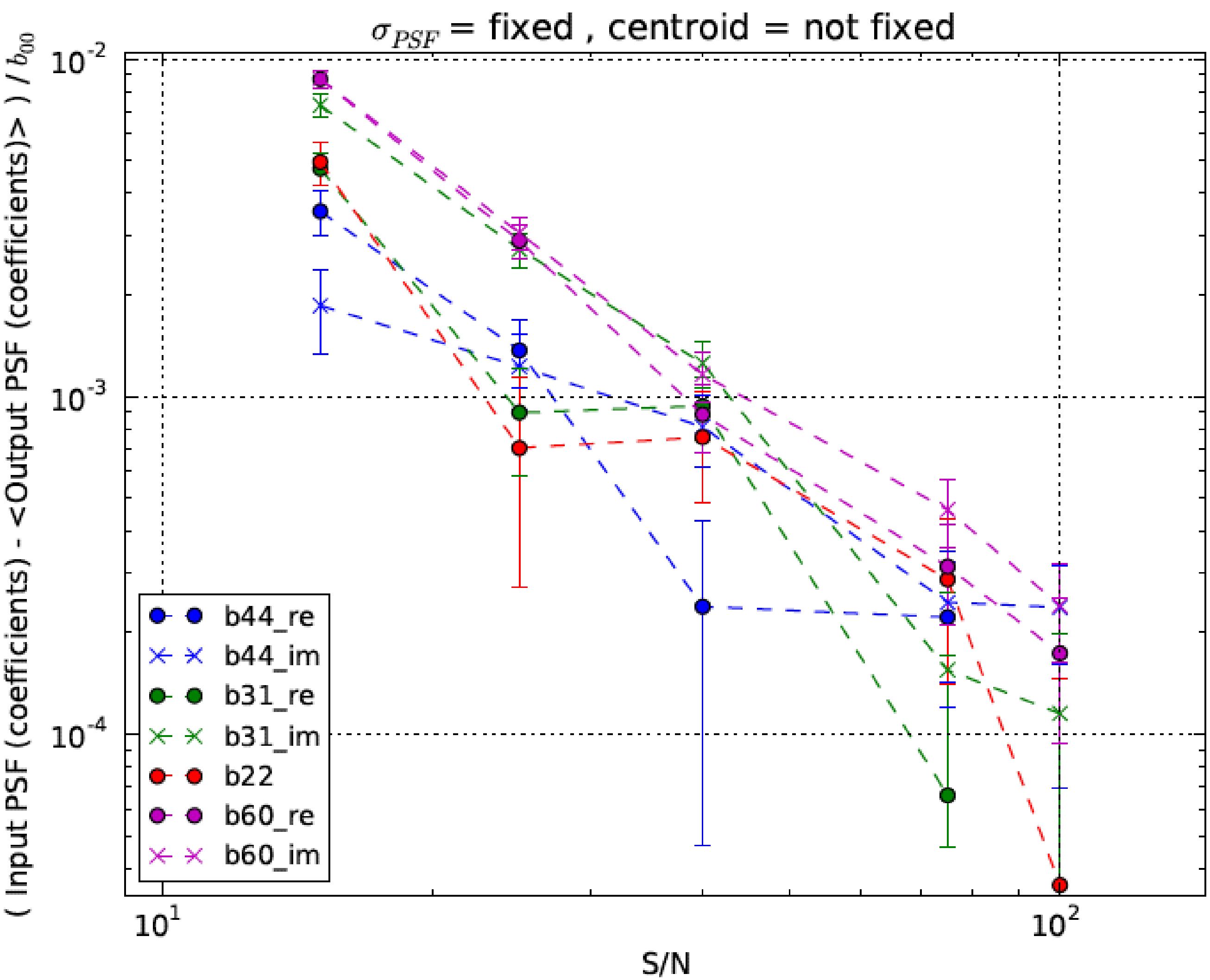

Bias scales roughly as (S/N)^(-2), and gets Below 10^-3 (DES requirement) at about S/N=45.

Stars that will be used in DES for PSF measu-rement are bright, high-S/N stars.

DECam: getting ready for commissioning

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- DECam recently arrived in Cerro Tololo, La Serena, Chile, after about 5 years of development, testing and construction at SiDet.

- Commissioning and science tests are scheduled for this year.
- We want to have our pipeline ready for first light.
- We are also performing validation tests on software to make sure the weak lensing requirements are met.

Current Work: WL Validation Tests

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* Tests designed to validate the performance of DES instrumentation and software and make sure its performance its good enough in order to complete the planned Weak Lensing Science.

* Requirements being validated :

R-14 : absolute positions of stars agree with reference catalog to < 100 m.a.s RMS

R-15 : stellar position measurements in adjacent passbands should agree to < 100 m.a.s.

R-16: positions of bright stars in different exposures of same filter should agree to < 15 m.a.s.

* Based on document written by Gary Bernstein: DES doc db 5145

We want to test:

- Accuracy of astrometric solutions : AST1 - AST7
- The PSF models: PSF1- PSF8
- Accuracy of shape measurements: SHA1 - SHA11
- Accuracy of photo-z: PZ1

* These tests are to be executed on Data Challenges simulations and/or real data ----> commissioning in 2012 , main survey data.

* Success criteria and remedial actions are defined.

Current work: WL Validation Tests

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(taken from DES document 5015 by Gary Bernstein)

AST1, AST3, AST4 , AST5, AST6, AST7

SHA1, SHA2 for Jarvis pipeline

Bernstein

Proposed tests

AST-1	RMS astrometric residuals on validation set of stars
AST-2	Astrometric error correlation function
AST-3	Astrometric residuals vs CCD number
AST-4	Astrometric residuals vs array position (glowing edges)
AST-5	Astrometric solution stability
AST-6	Astrometric error vs color (differential refraction)
AST-7	Astrometric error vs magnitude (CTI test)

Bernstein

Proposed tests

SHA-1	Recovery of shapes of galaxies with elliptical isophotes
SHA-2	“Ring tests” for galaxies lacking elliptical symmetry
SHA-3	DC-x shear recovery
SHA-4	Star-galaxy shape correlation functions
SHA-5	B-mode tests
SHA-6	Mean shape vs row number (CTI tests)
SHA-7	Mean shape vs airmass & parallactic angle (differential refraction test)
SHA-8	Mean shape vs array position (glowing edges)
SHA-9,10	Color splits, seeing splits
SHA-11	Shear invariance under repeat observations
SHA-12	Crowded-region tests? (for cluster lensing)

Current work: WL Validation Tests

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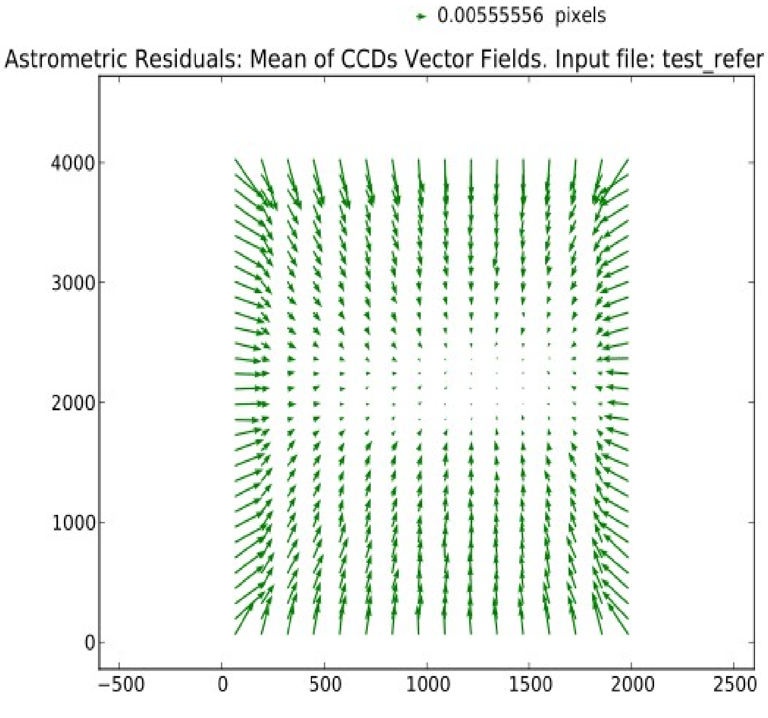
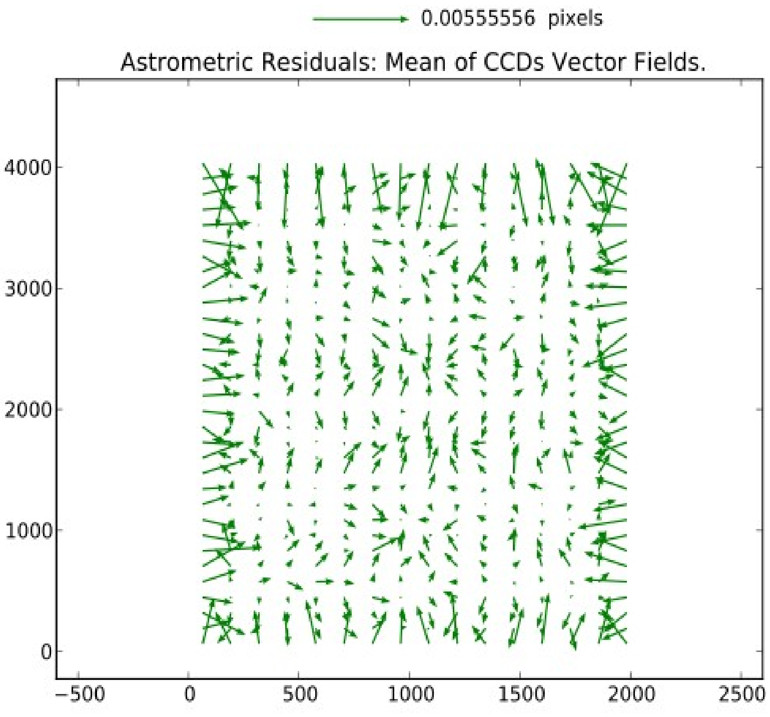
AST4 : astrometric residual vs array positions ----> glowing edges

Output of DES astrometry pipeline :



After refitting with our code:



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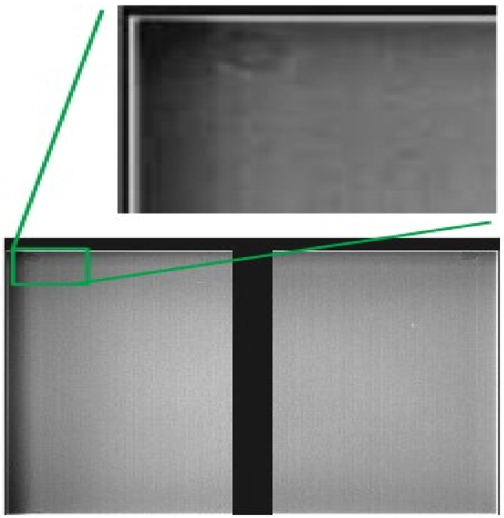
Current work: WL Validation Tests

Astrometry Tests : accuracy of the map between pixel and sky coordinates.

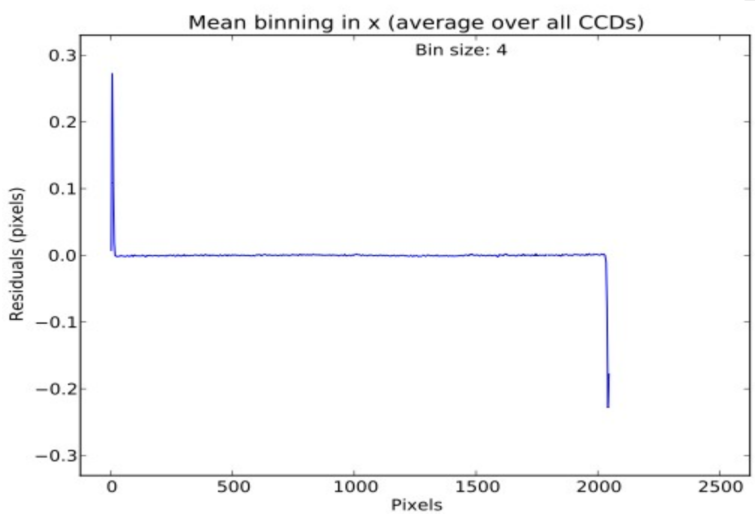
AST4 : astrometric residual vs array positions ----> glowing edges

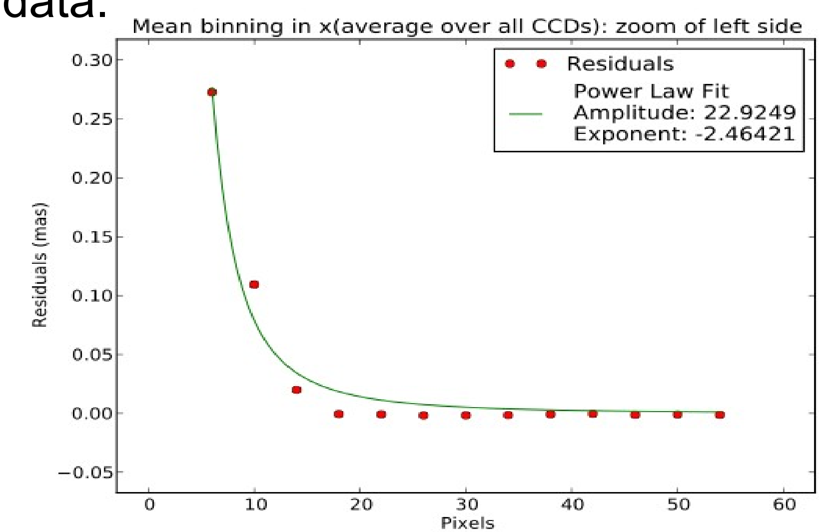


Glowing edges: the electric field created by the substrate voltage bias is wider than the active pixels, causing the effective shape of the edge pixels to stretch

For AST tests , use output of ReMatch (Bernstein) , a code that improves on astrometric solution by SCAMP (E. Bertin).

DC5 data.





Summary and Conclusions

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- The nature of Dark Energy is one of the most important problems in modern Physics.
- Several astronomical surveys -like the Dark Energy Survey- are designed to address this problem.
- Weak Gravitational Lensing is one of the most promising techniques to study Dark Energy, if the systematic errors are well understood and kept under control.
- We have developed software to create customized simulations that have guided us in the refinement of our code.

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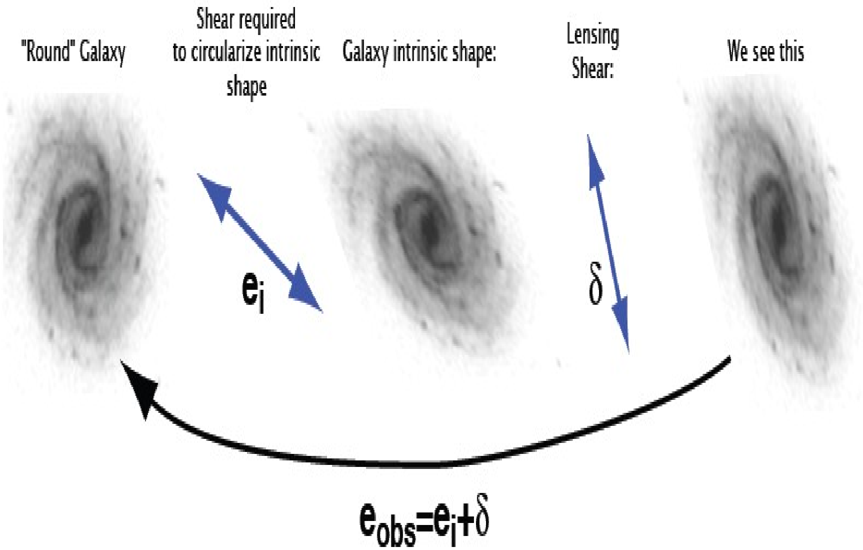
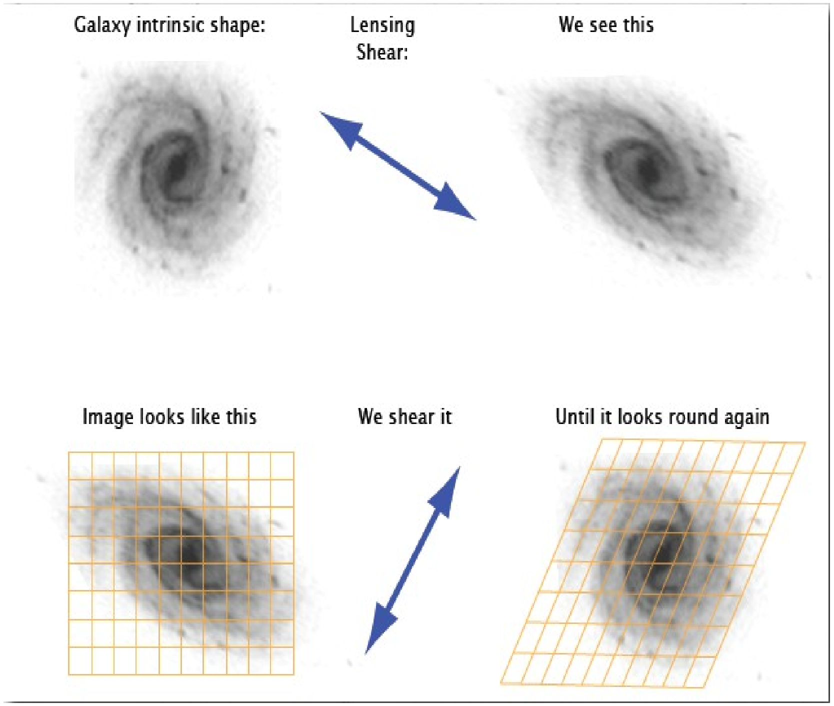
Summary and Conclusions

- At high S/N the performance of the shear measurement module of pipeline is optimal (biases < 10^-3)
- We are developing a method to calibrate biased, low-S/N data with high S/N data.
- The PSF measurement module of our pipeline recovers a given input PSF with an accuracy better than 10<-3 at S/N > 45.
- Validation tests: our astrometry code can improve on existing DES astrometry solution to give the necessary precision for weak lensing, and our tests can detect unexpected features (e.g., glowing edge effect).

Weak lensing pipeline

Geometrical approach to shear: stretch the galaxy until it looks "round".





Testing our pipeline: custom tests

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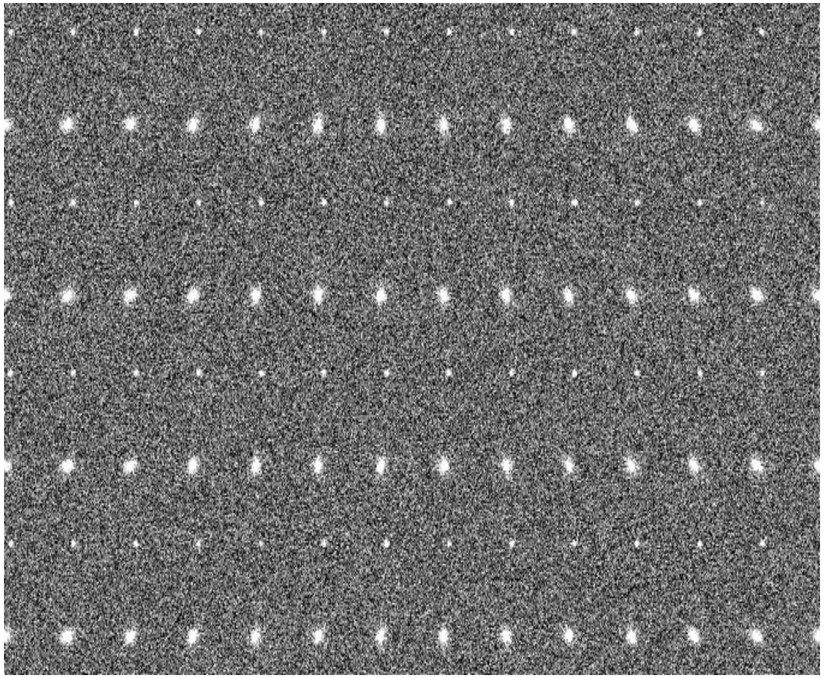
Importance

- Parameters are varied one at a time.
This allows a high level of detailed analysis that is not found in end-to-end tests (eg, STEP1,2; GREAT08; DES DC's)
-Important and fundamental problems that otherwise would go unnoticed in “end-to-end” tests can be diagnosed and corrected.
- Allows us to identify region of parameter space in which the behavior of the code is optimal.
- Part of validation tests proposed in recent DES WL Commissioning Plans document by G. Bernstein.
- Our code (and other candidate shear-measurement pipelines) should be able to pass these types of test successfully before tackling simulations from the DES Data Challenges.



Previous Work in DES: Hardware

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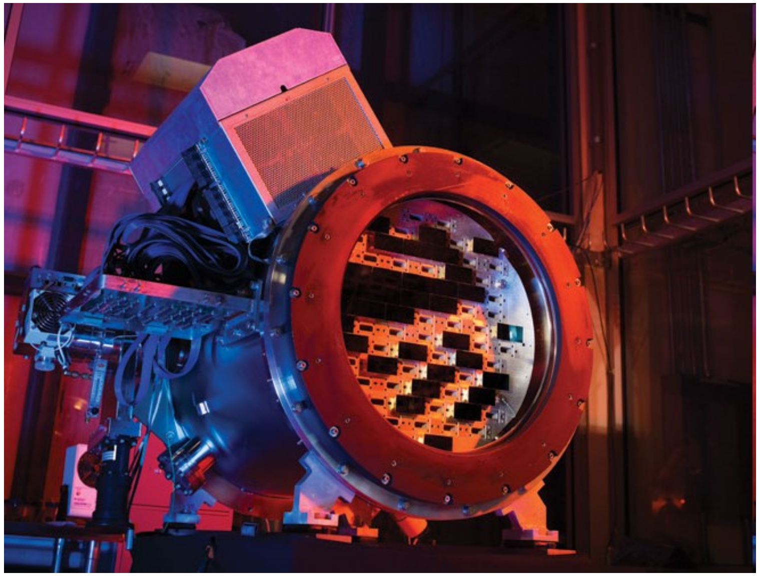
The Science Requirements...	...flow to Technical Requirements
5000 deg^2 of the So. Galactic Cap in 525 nights (5 yrs)	A large camera, on the Blanco 4m 3 deg^2 camera with ≥ 2.2 deg FOV Data Management system 300GB/night, automated processing Publicly available data archive after 1 yr
photometric-redshifts to z=1.3 with dz < 0.02.	Filters, CCDs, Read noise SDSS g,r,i,z filters; 400 - 1100nm QE > 50% in the z band (825-1100nm) Read noise <10 e-
A small and stable point spread function (PSF) < 0.9" FWHM median	Optical Corrector with excellent images Pixel size <0.3" /pixel < 0.4" FWHM in the i and z bands

The Dark Energy Survey: Dark Energy Camera (DECam)



500 megapixel camera

62 2k x 4k CCDs

It will replace the existing
prime focus cage at the Blanco.

Will be 7 times larger in area and
7 times faster in readout time than existing
MOSAIC II camera at Blanco telescope

DECam will be one of the largest CCD cameras.
Each image:
~ 20 Galaxy clusters
~ 200,000 Galaxies
Each night ~ 300 GB
Entire survey ~ 1 PB

Dark Energy

DARK ENERGY SURVEY

We can learn about these issues in four stages (Dark Energy Task Force , Albrecht *et al*. , 2006):

1) What do we know now?
2) What will be known once existing projects are completed?
3) Medium-term projects on a time scale of ~ 5 years
   e.g. , The Dark Energy Survey !
4) Long-term projects (~10 years, more expensive): e.g., LSST, JDEM , SKA

Basic observables that can tell us about the nature of DE: D(z) (comoving distance) , g(z) (growth of structure)

$$D(z)=\int_0^r \frac{dr'}{\sqrt{1-kr'^2}}=\int_t^{t_0} \frac{dt'}{a(t')}=\int_0^z \frac{dz'}{H(z')} \qquad \ddot{g}+2H\dot{g}=4\pi G\rho_m g=\frac{3\Omega_m H_0^2}{2a^3}g$$

Four techniques :

1) SN type Ia : D(z)
2) BAO : D(z)
3) Cluster counts : D(z) , g(z)
4) Weak lensing : D(z) , g(z) very promising method **if** systematics are taken care of

Parameterization of w : w(a) = w_0 + w_a(1-a)