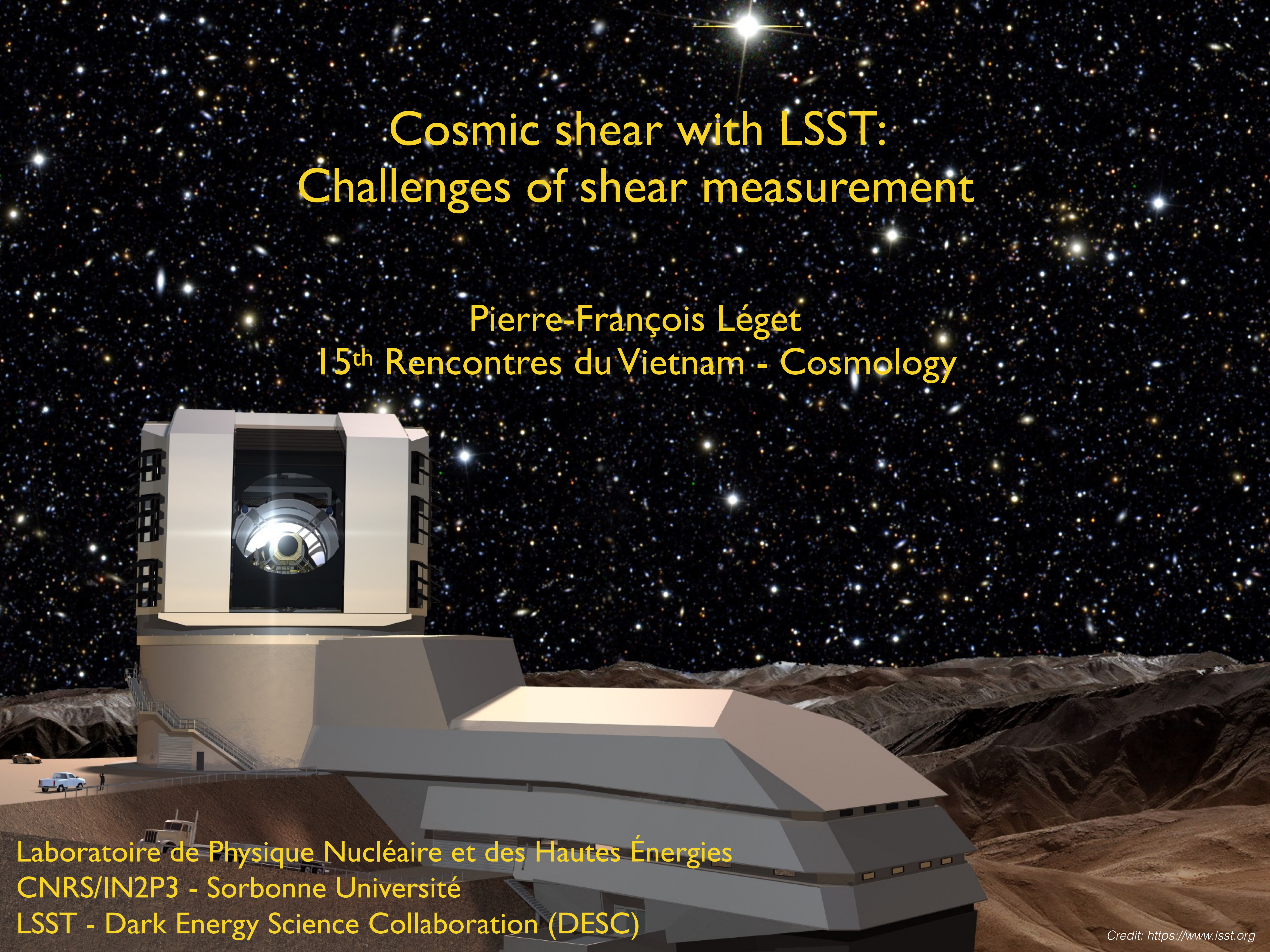
Cosmic shear with LSST: Challenges of shear measurement

Pierre-François Léget

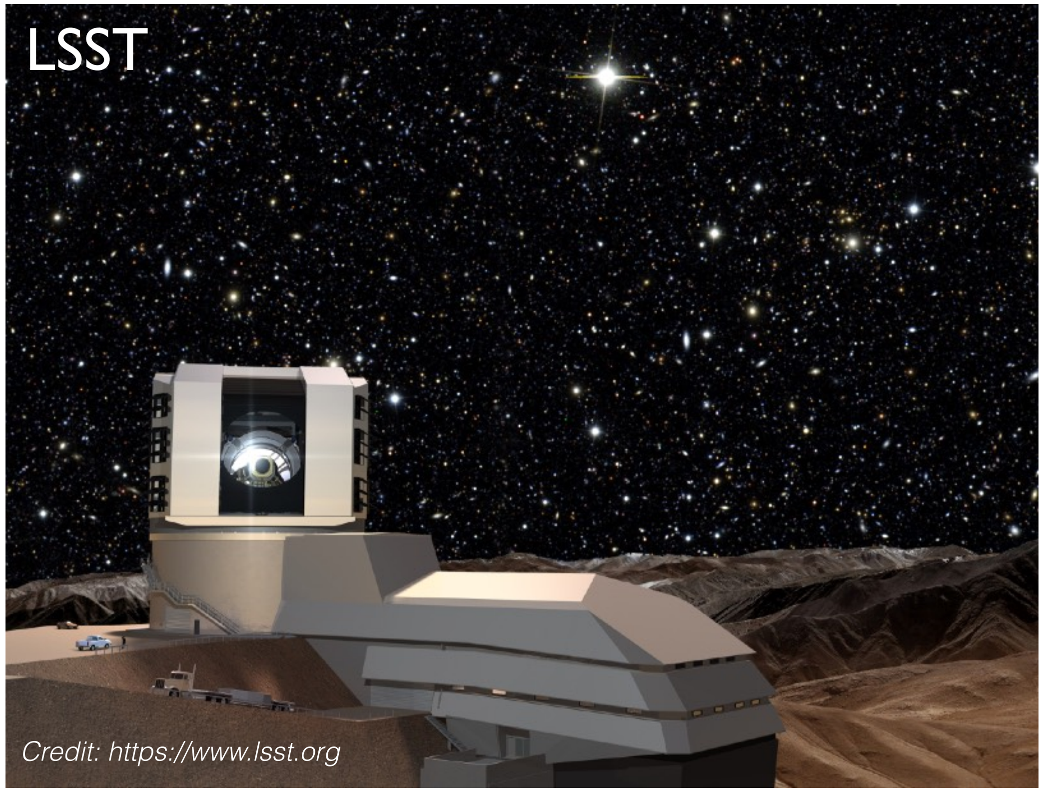
15th Rencontres du Vietnam - Cosmology

Laboratoire de Physique Nucléaire et des Hautes Énergies
CNRS/IN2P3 - Sorbonne Université
LSST - Dark Energy Science Collaboration (DESC)



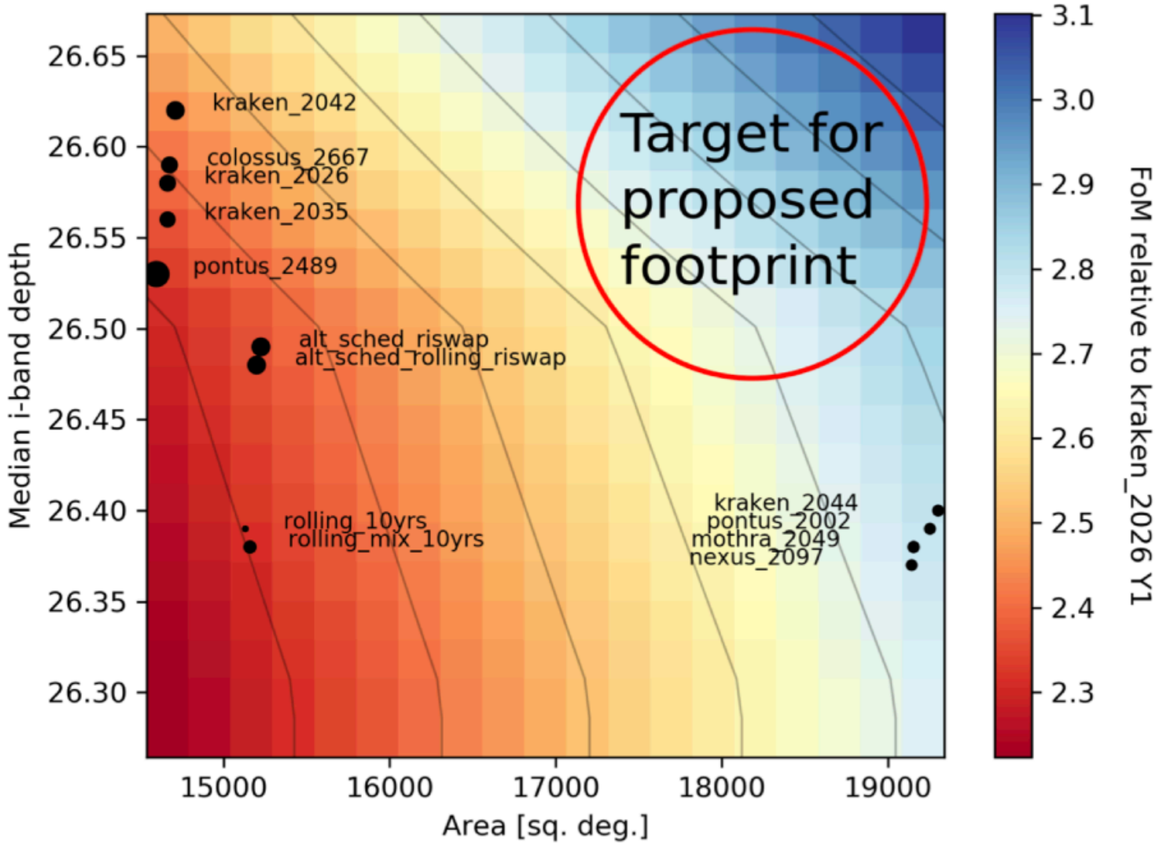
Credit: https://www.lsst.org

Introduction: Cosmic shear and the Large Synoptic Survey Telescope (LSST)



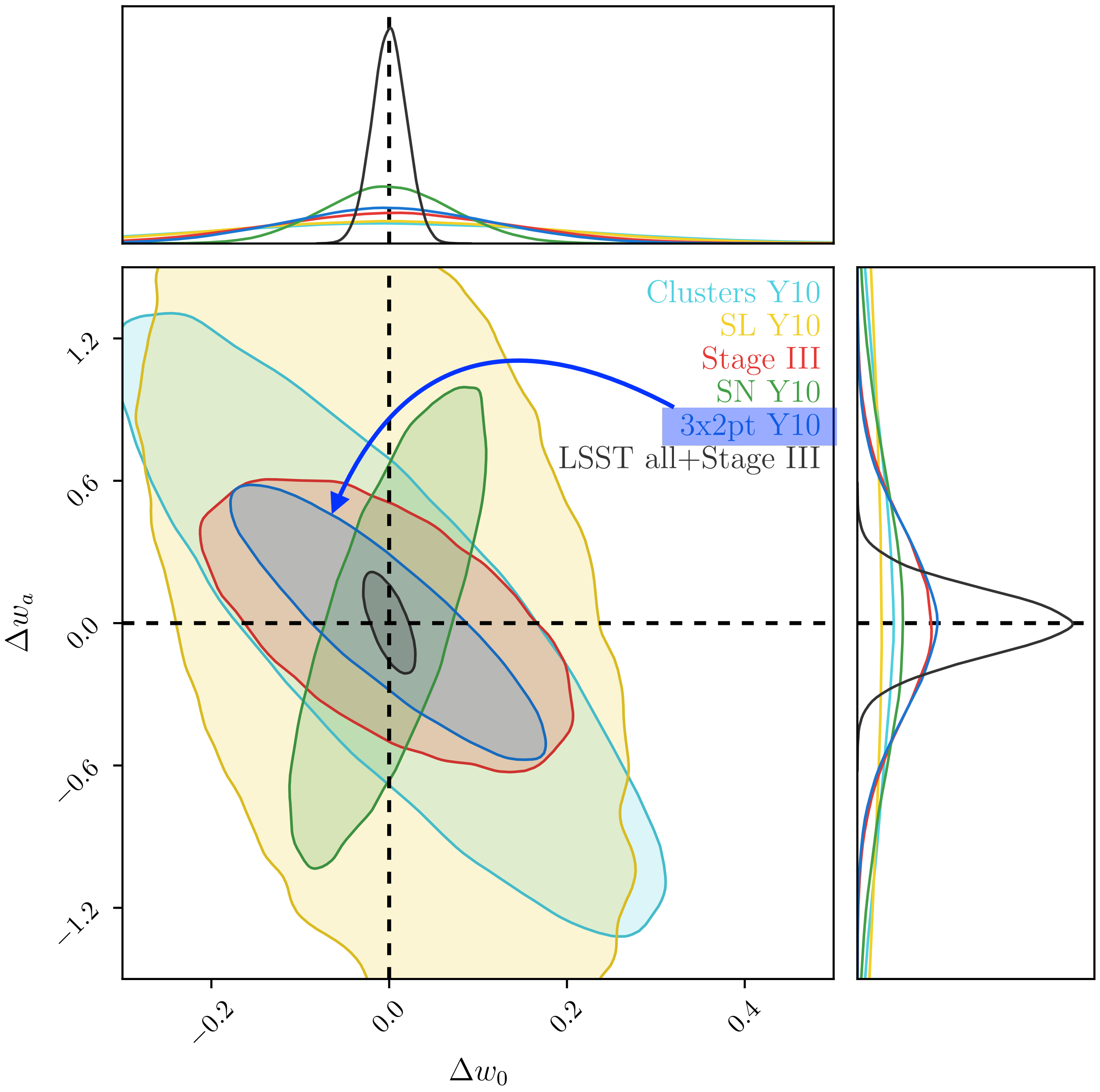
- 8.4 meters telescope
- Camera of 3.2 GigaPixels
- 6 filters: u, g, r, i, z, y (only 5 mounted on the telescope)
- ~17000 square degree survey to ~26 mag depth in the i filter after 10 years.
- Can observe the full sky in ~3 days
- First light in 2021

Lochner et al. 2018



Introduction: Cosmic shear and the Large Synoptic Survey Telescope (LSST)

LSST-DESC Science Requirements Document, Mandelbaum et al. 2018



- LSST will provide multi-probe constraints on Dark Energy properties:
  - SNIa
  - Galaxy Clusters
  - Cosmic Shear
  - …
- The 3x2pt should be the most powerful cosmological probe within LSST.
- 3x2pt:
  - <shear ; shear> (cosmic shear)
  - <shear ; galaxy> (galaxy-galaxy lensing)
  - <galaxy ; galaxy> (galaxy clustering)

Introduction: Cosmic shear and the Large Synoptic Survey Telescope (LSST)

Cosmic shear, what is it?

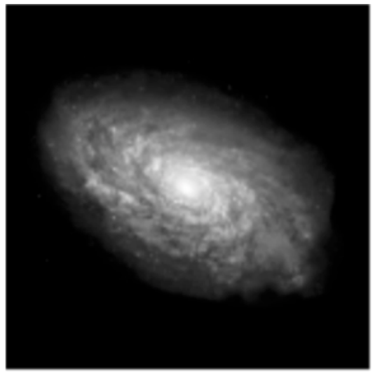
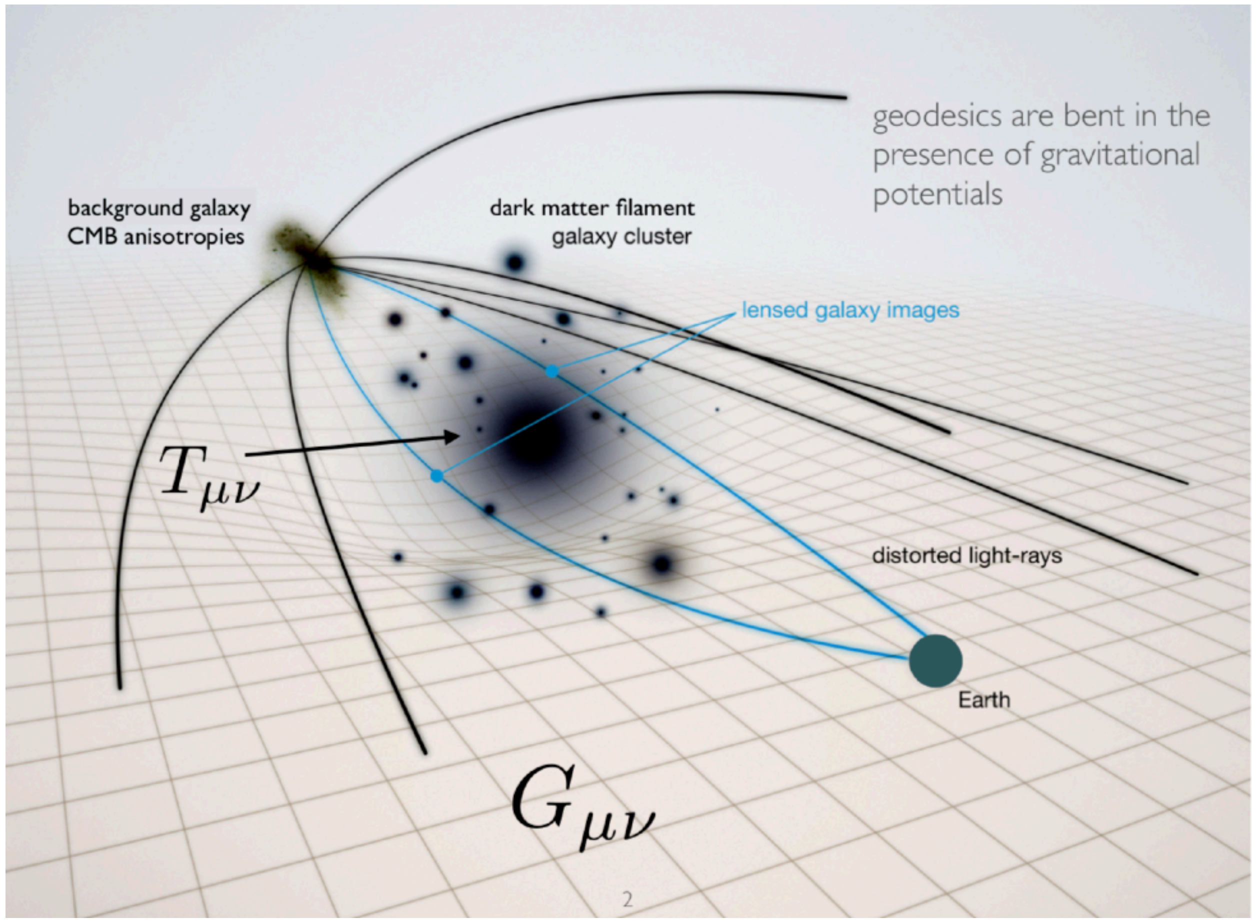


Image of the galaxy before gravitational shear

Introduction: Cosmic shear and the Large Synoptic Survey Telescope (LSST)

Cosmic shear, what is it?



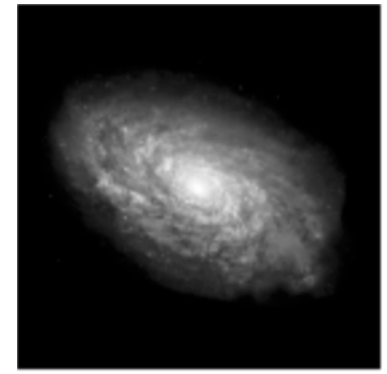


Image of the galaxy before gravitational shear

Propagation of photons through the Universe

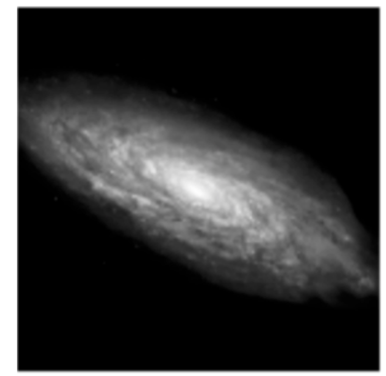


Image of gravitationally sheared galaxy

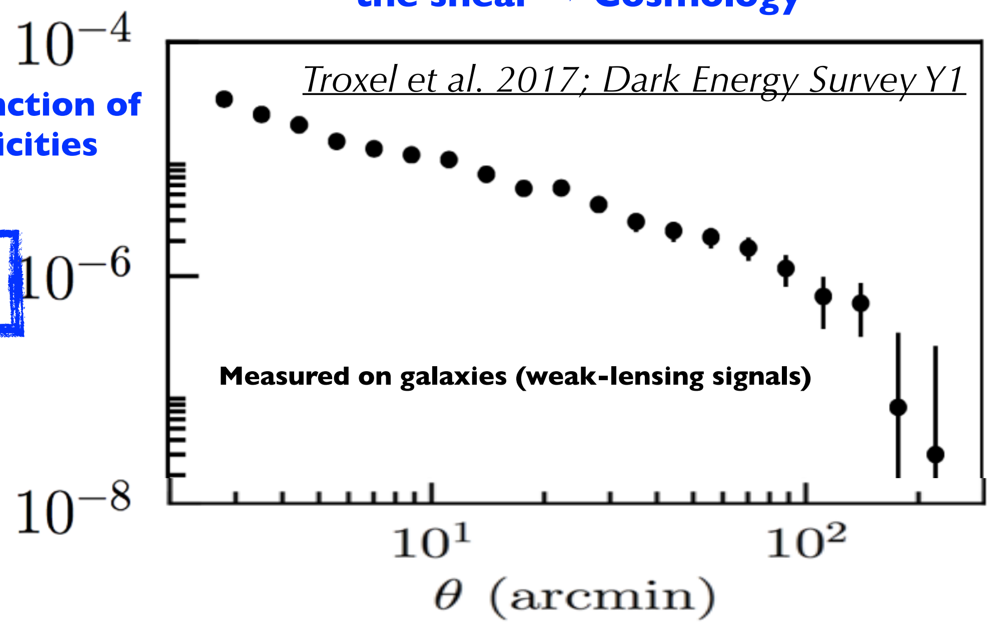
Introduction: Cosmic shear and the Large Synoptic Survey Telescope (LSST)

Cosmic shear, what is it?

Spatial correlation of the shear → Cosmology

correlation function of galaxies' ellipticities

$\boxed{\xi_+}$



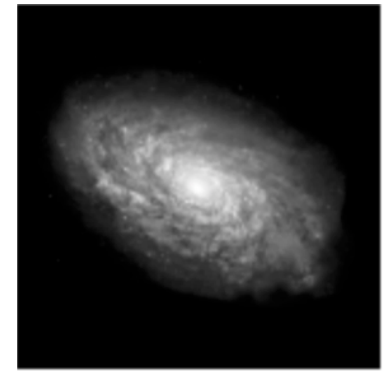


Image of the galaxy before gravitational shear

Propagation of photons through the Universe

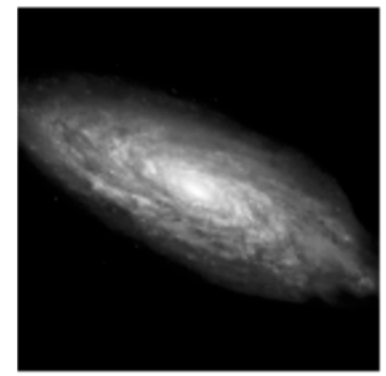


Image of gravitationally sheared galaxy

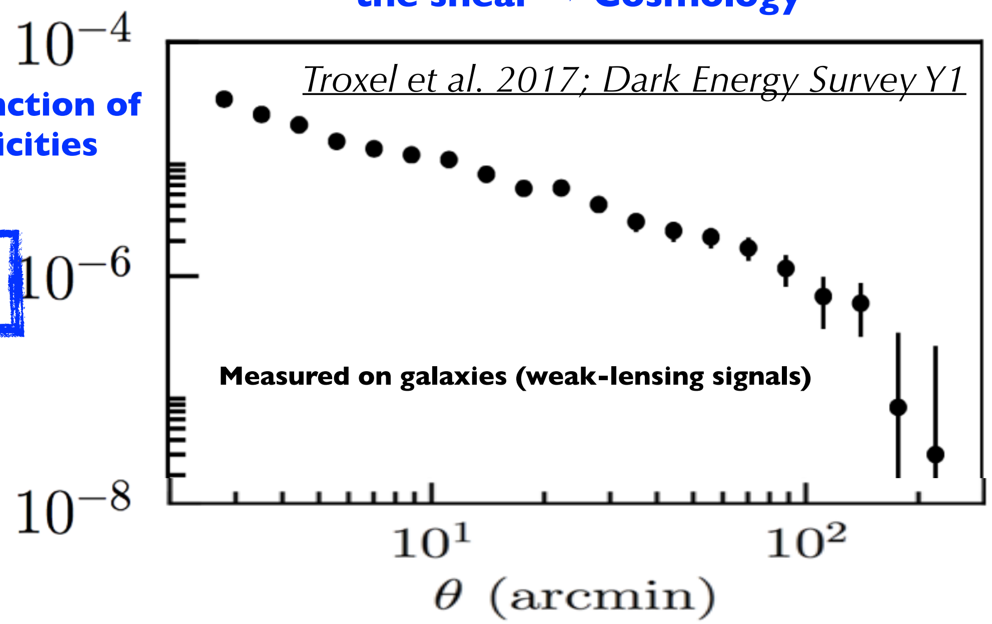
Introduction: Cosmic shear and the Large Synoptic Survey Telescope (LSST)

Cosmic shear, what is it?

Spatial correlation of the shear → Cosmology

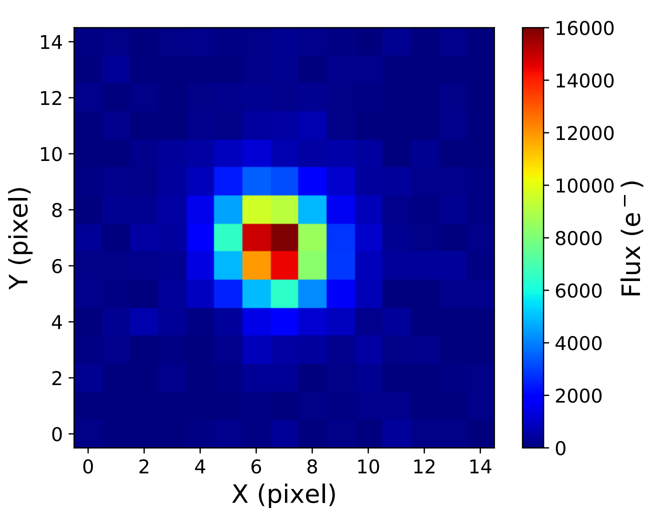
correlation function of galaxies' ellipticities

$\boxed{\xi_+}$



Star shape → PSF

Star → PSF



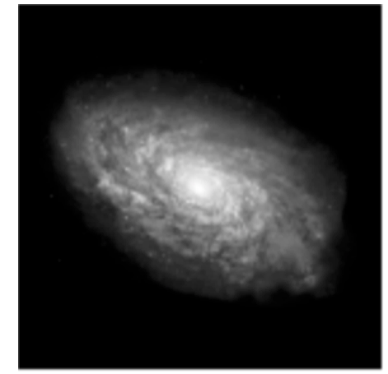


Image of the galaxy before gravitational shear

↓ *Propagation of photons through the Universe*

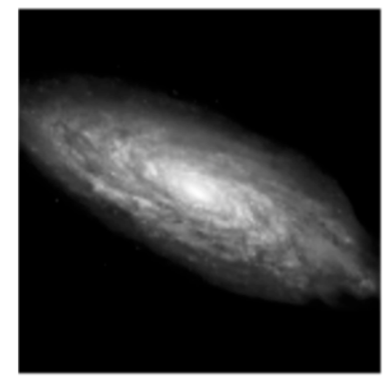


Image of gravitationally sheared galaxy

↓ *Propagation of photons through the atmosphere and telescope optics*

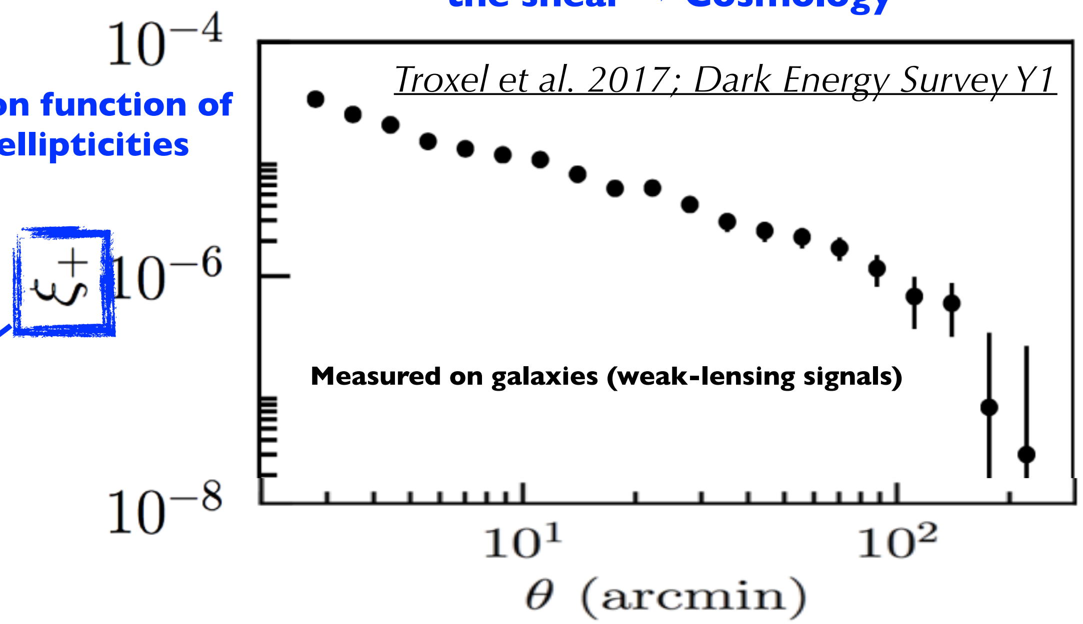
Convolution with a function that describes atmospheric turbulences and optical aberrations (PSF)

Introduction: Cosmic shear and the Large Synoptic Survey Telescope (LSST)

Cosmic shear, what is it?

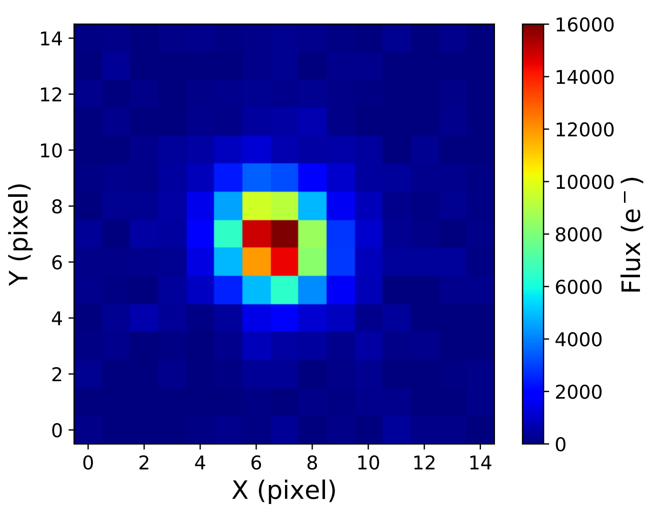
Spatial correlation of the shear → Cosmology

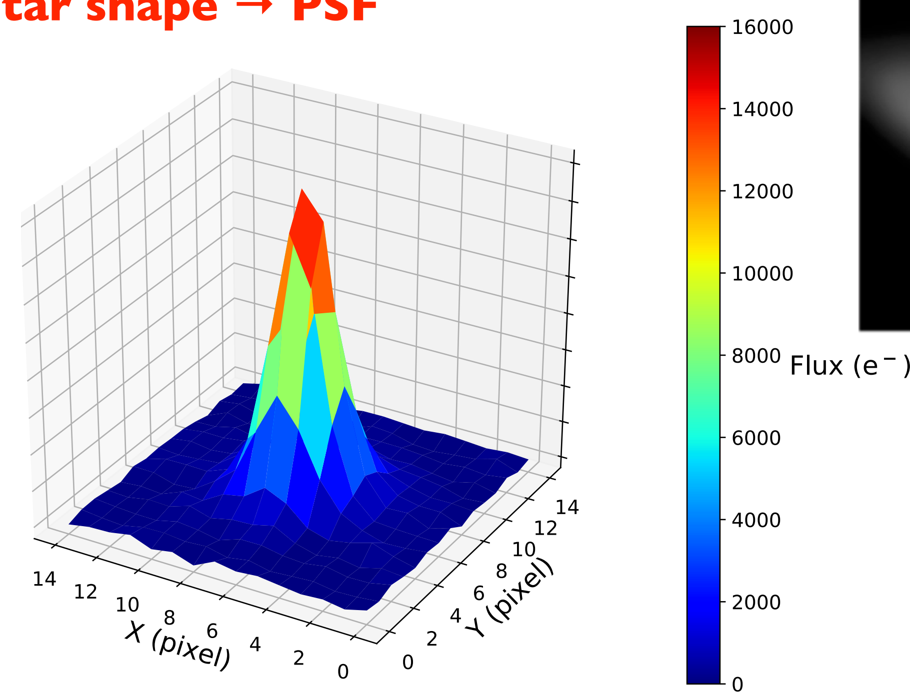
correlation function of galaxies' ellipticities



Star shape → PSF

Star → PSF





PSF → light spreads due to optics and the atmosphere

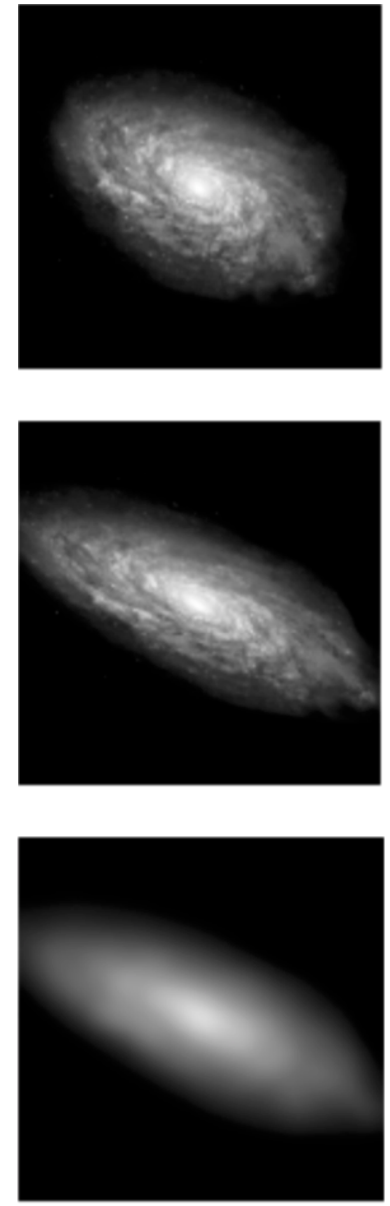


Image of the galaxy before gravitational shear

Propagation of photons through the Universe

Image of gravitationally sheared galaxy

Propagation of photons through the atmosphere and telescope optics

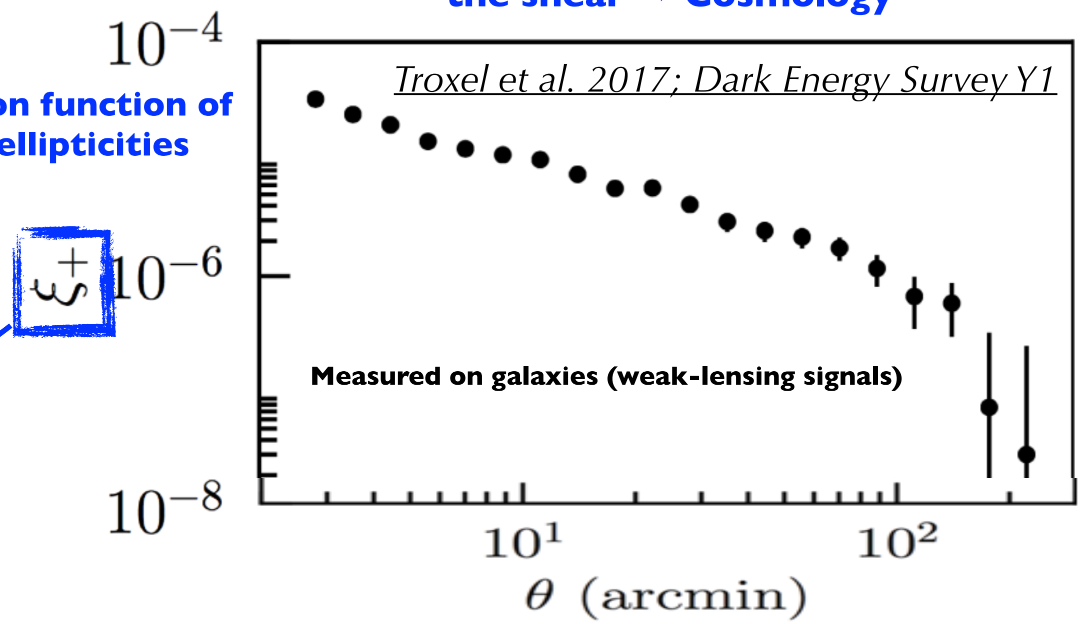
Convolution with a function that describes atmospheric turbulences and optical aberrations (PSF)

Introduction: Cosmic shear and the Large Synoptic Survey Telescope (LSST)

Cosmic shear, what is it?

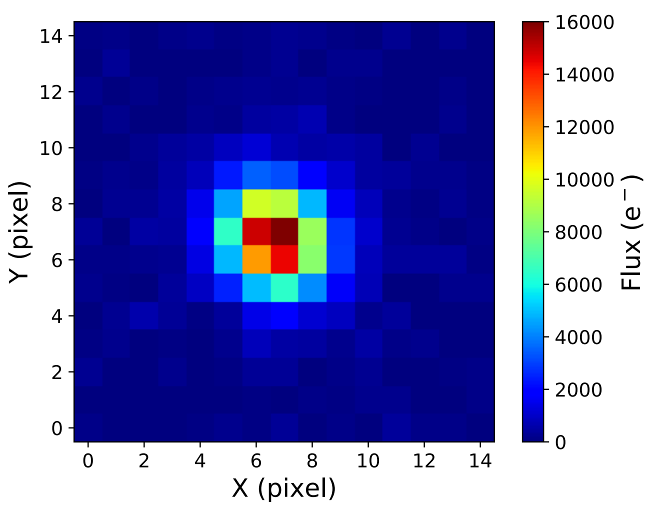
Spatial correlation of the shear → Cosmology

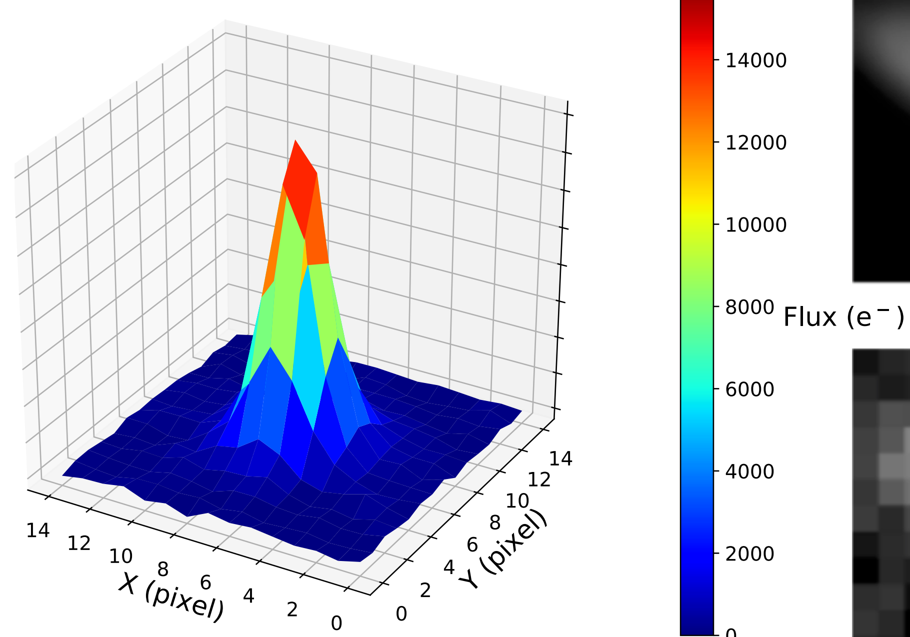
correlation function of galaxies' ellipticities



Star shape → PSF

Star → PSF





PSF → light spreads due to optics and the atmosphere

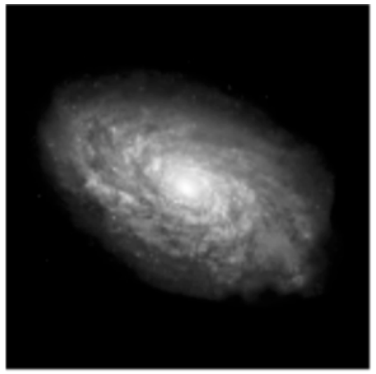


Image of the galaxy before gravitational shear

↓ *Propagation of photons through the Universe*

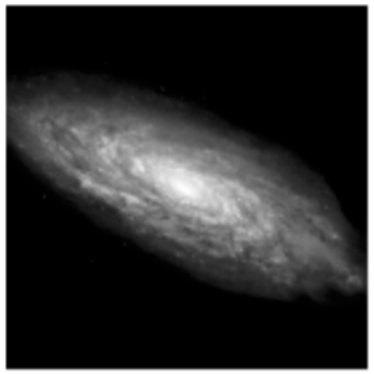
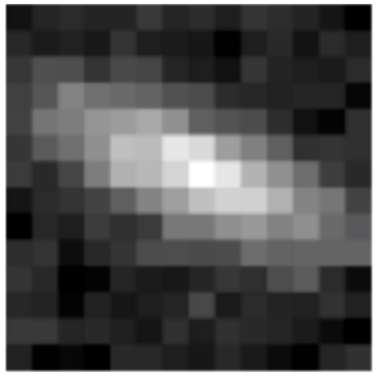


Image of gravitationally sheared galaxy

↓ *Propagation of photons through the atmosphere and telescope optics*

Convolution with a function that describes atmospheric turbulences and optical aberrations (PSF)

↓ *Digitalization of the image by the telescope camera*



Final image that must be used to measure the cosmic shear signal

Introduction: Cosmic shear and the Large Synoptic Survey Telescope (LSST)

Spatial correlation of galaxies' ellipticities
==
Cosmology

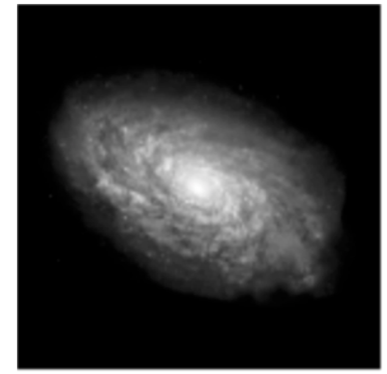


Image of the galaxy before gravitational shear

Propagation of photons through the Universe

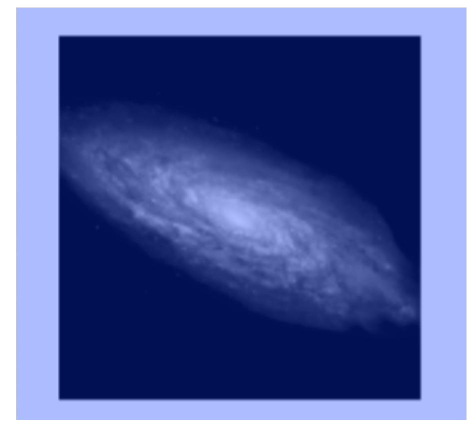
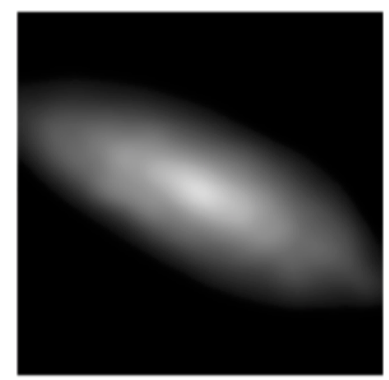


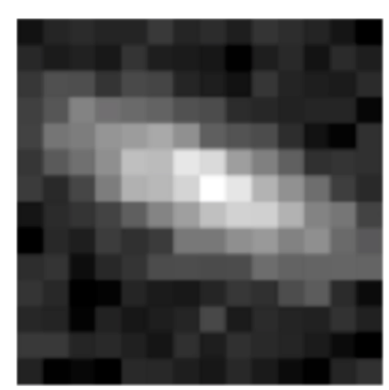
Image of gravitationally sheared galaxy

Propagation of photons through the atmosphere and telescope optics



Convolution with a function that describes atmospheric turbulences and optical aberrations (PSF)

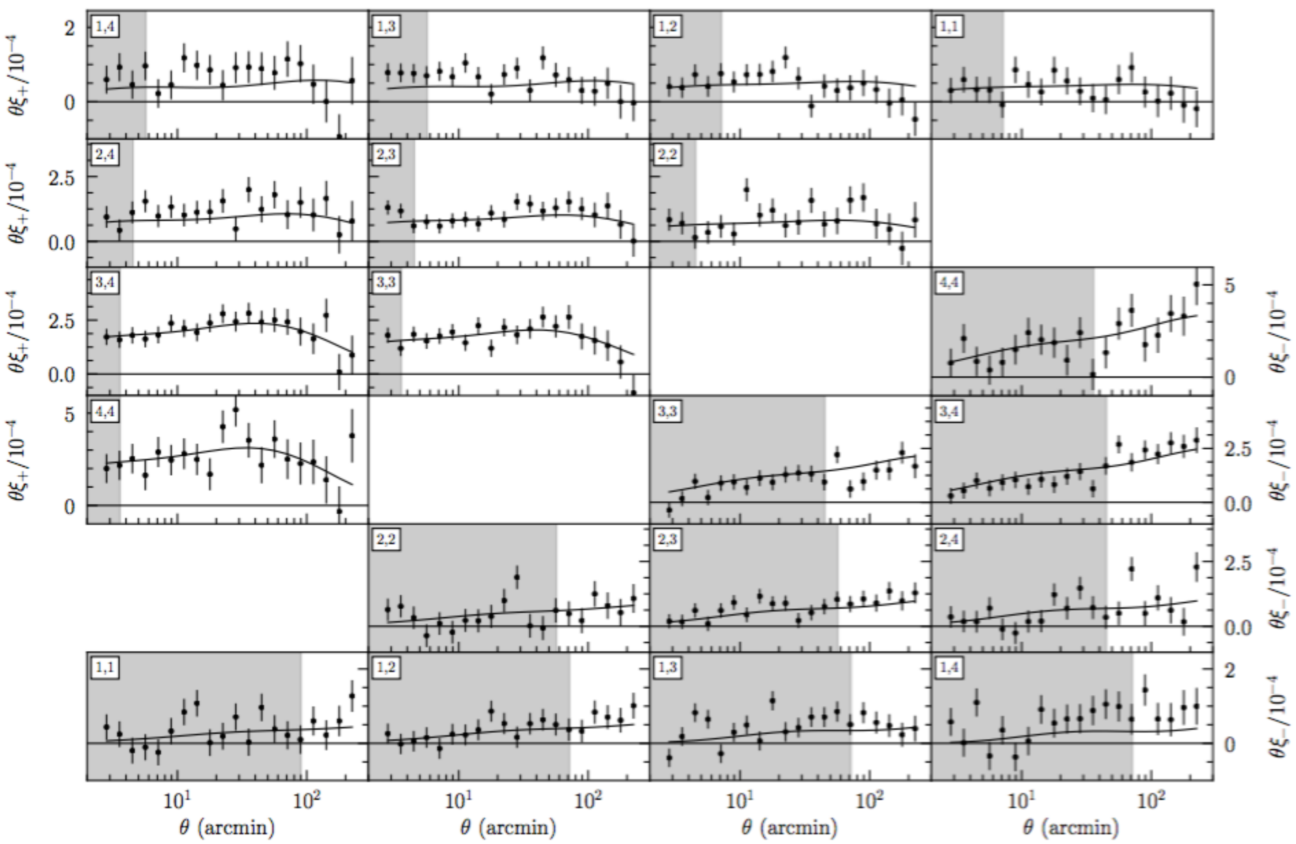
Digitalization of the image on the telescope camera



Final image that must be used to measure the cosmic shear signal

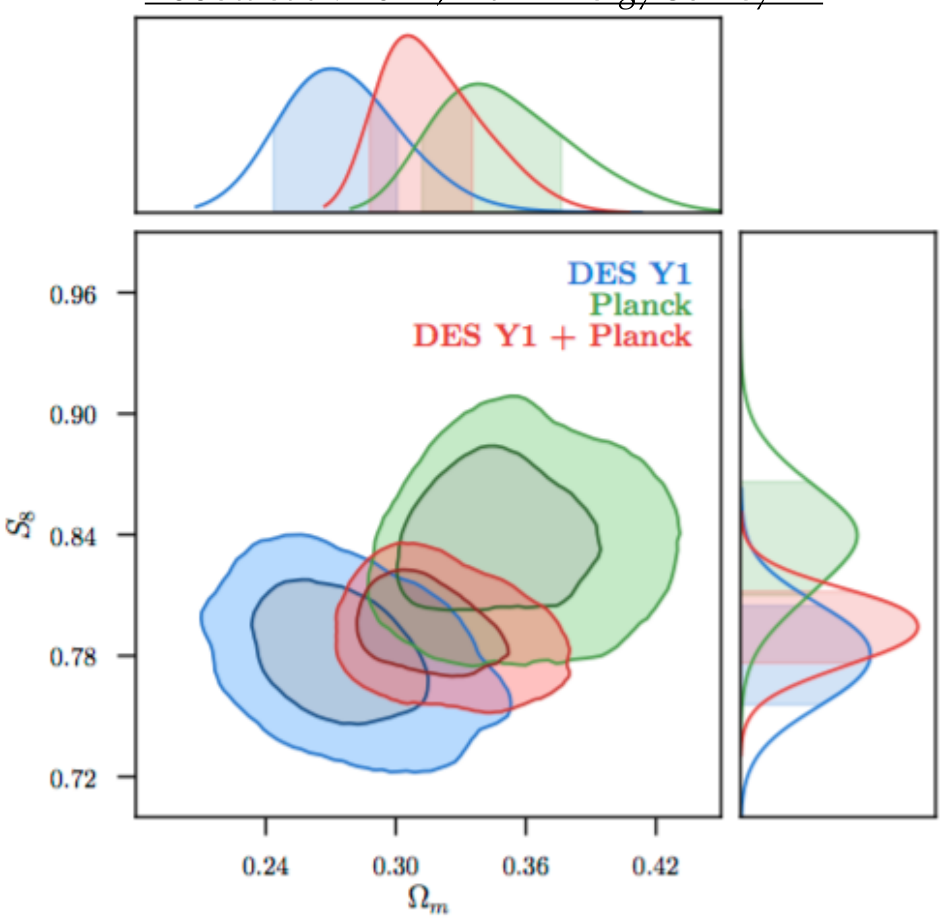
Introduction: Cosmic shear and the Large Synoptic Survey Telescope (LSST)

Troxel et al. 2017; Dark Energy Survey Y1



- With the 2-point correlation function of galaxy shape, cosmological parameters are measured ($\boldsymbol{\Omega}_{m}$, $\mathbf{S_8}$, **...**)
- Cross-correlation between different redshift bins provides more information

Abbott et al. 2017; Dark Energy Survey Y1



- For DES Y1, the 3X2-point correlation function (cosmic shear + galaxy-galaxy lensing + galaxy clustering) produced cosmological parameters with uncertainties comparable to the Planck results!

Introduction: Cosmic shear and the Large Synoptic Survey Telescope (LSST)

Spatial correlation of galaxies' ellipticities
==
Cosmology

- LSST will be systematic limited and not statistic limited:
  - ~ 6 galaxies / arcmin^2 for current survey
  - ~ 40 galaxies / arcmin^2 for LSST

- Systematic uncertainties related to the shear measurement (will) matter:
  - PSF
  - Model bias
  - Noise bias
  - Blending

- Need an **unbiased** estimation of the shear (understand shear calibration to the ‰ level)

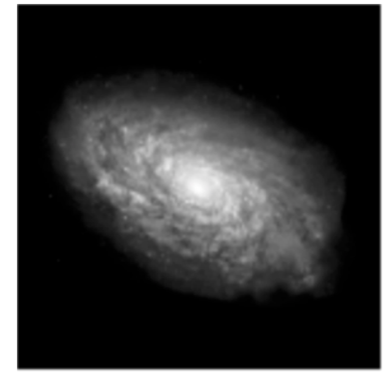


Image of the galaxy before gravitational shear

Propagation of photons through the Universe

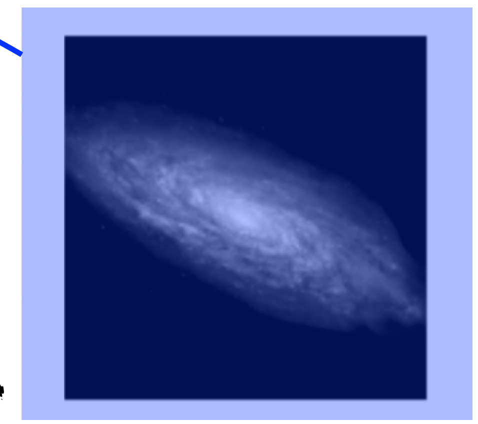
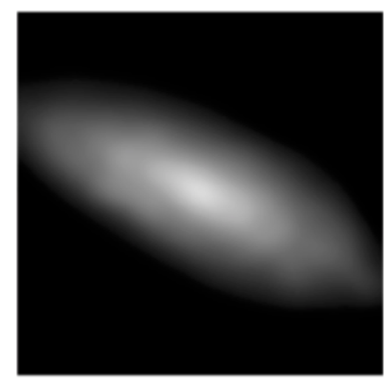


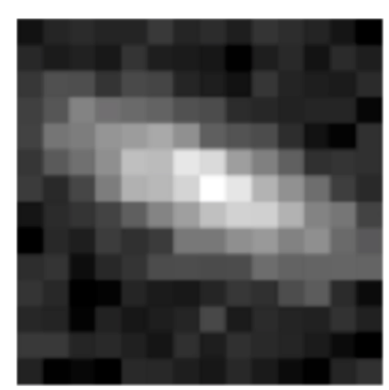
Image of gravitationally sheared galaxy

Propagation of photons through the atmosphere and telescope optics



Convolution with a function that describes atmospheric turbulences and optical aberrations (PSF)

Digitalization of the image by the telescope camera

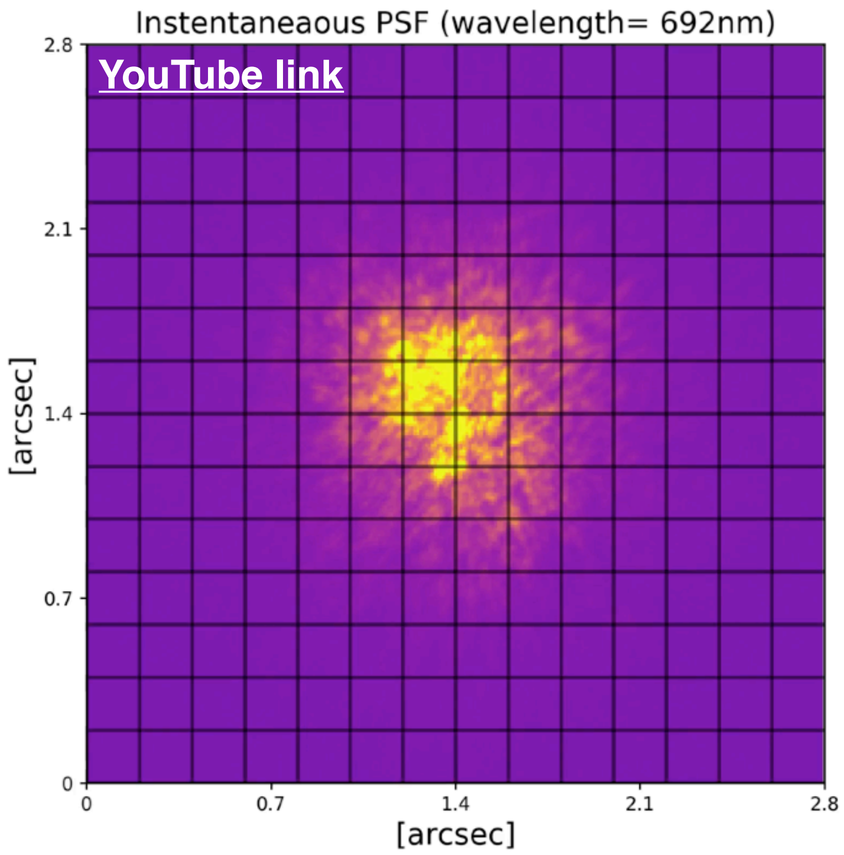


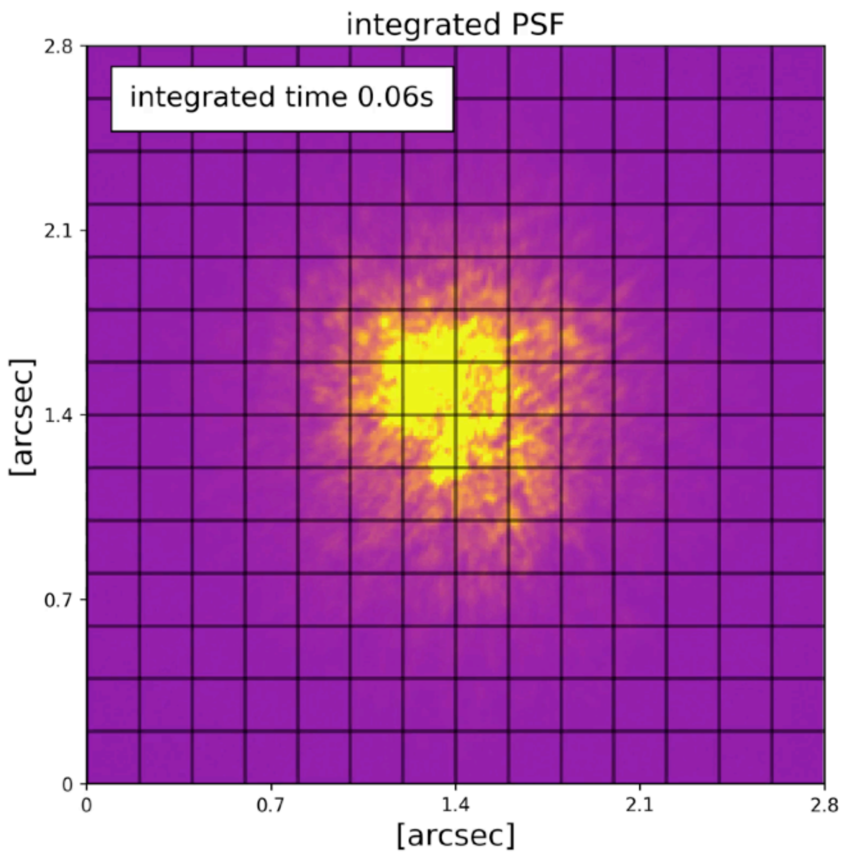
Final image that must be used to measure the cosmic shear signal

Shear measurement systematics: The Point Spread Function

- PSF ~ How a light point source reacts once it goes through all of these:
  - The Atmosphere
  - The Optics of the Telescope
  - The Sensors

Shear measurement systematics: The Point Spread Function



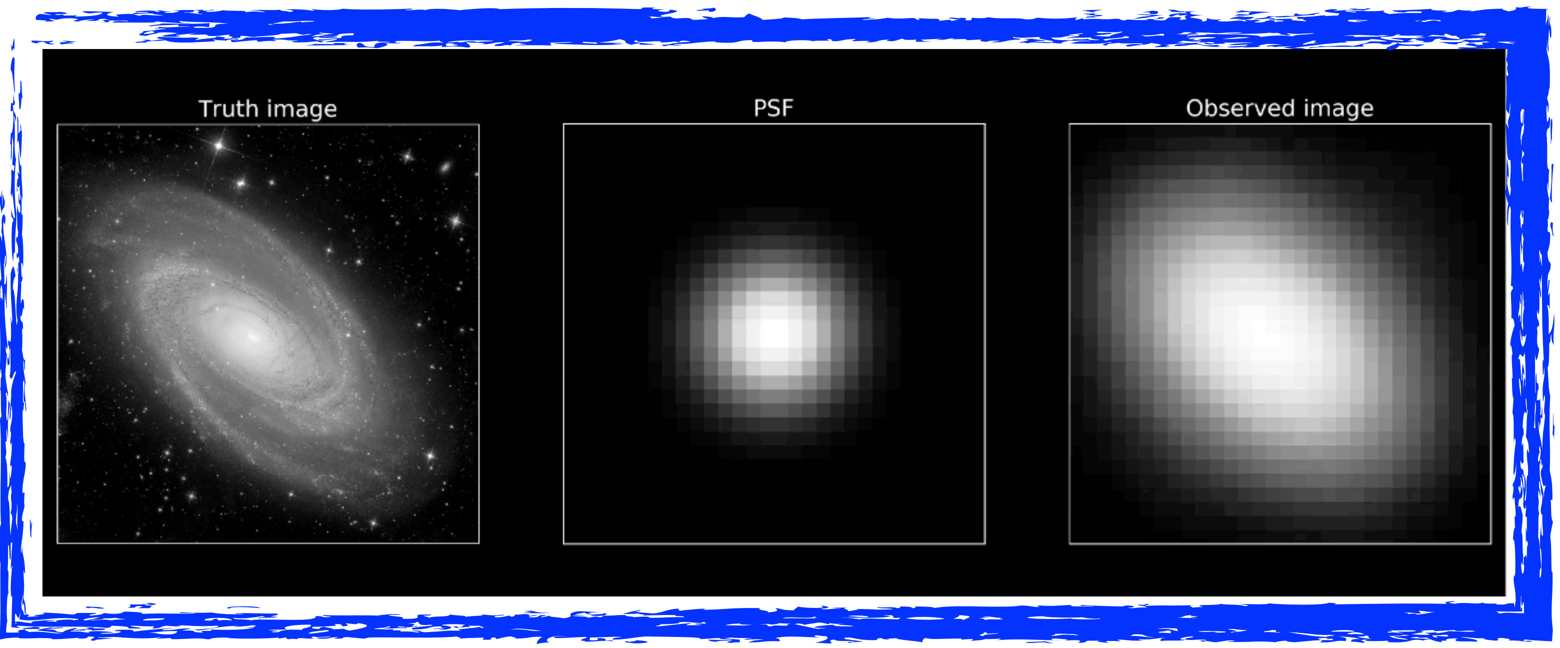


- PSF ~ How a light point source reacts once it goes through all of these:
  - The Atmosphere
  - The Optics of the Telescope
  - The Sensors

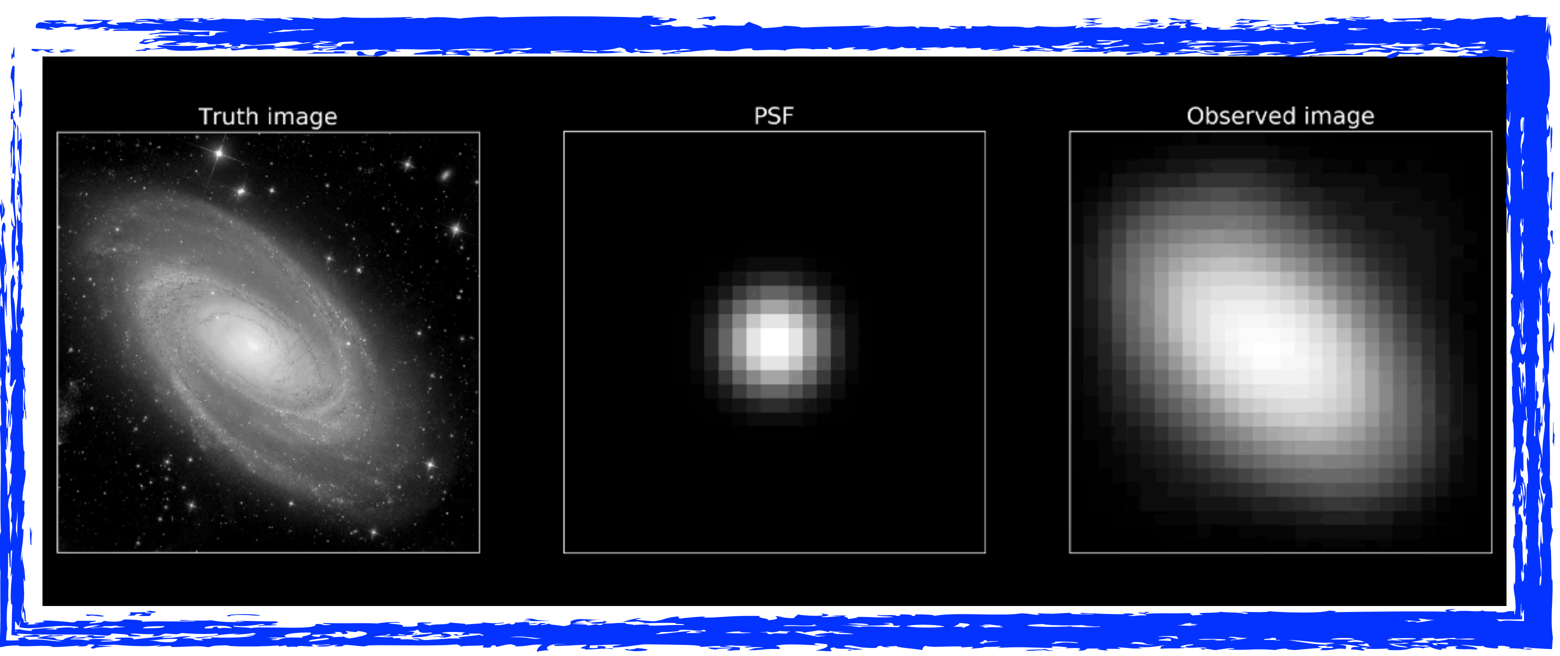
- What does the PSF really look like ?
- High definition movies of bright stars taken on Gemini South with the Differential Speckle Survey Instrument
- 0.011 arcsec / pixel (LSST 0.2 arcsec / pixel)
- Exposure time of 60 ms with 2 ms of readout
- See Hébert et al. 2018

Shear measurement systematics: The Point Spread Function

Changing PSF size (**YouTube link**):



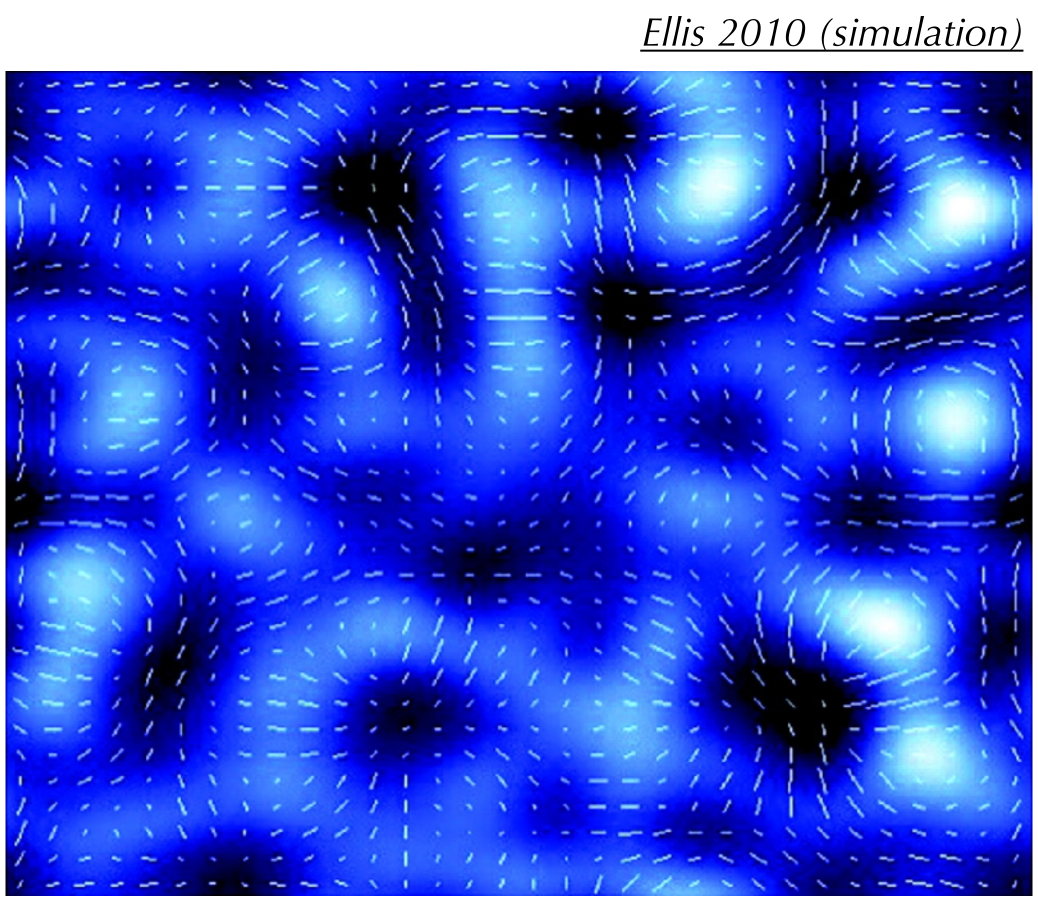
Changing PSF ellipticity (**YouTube link**):

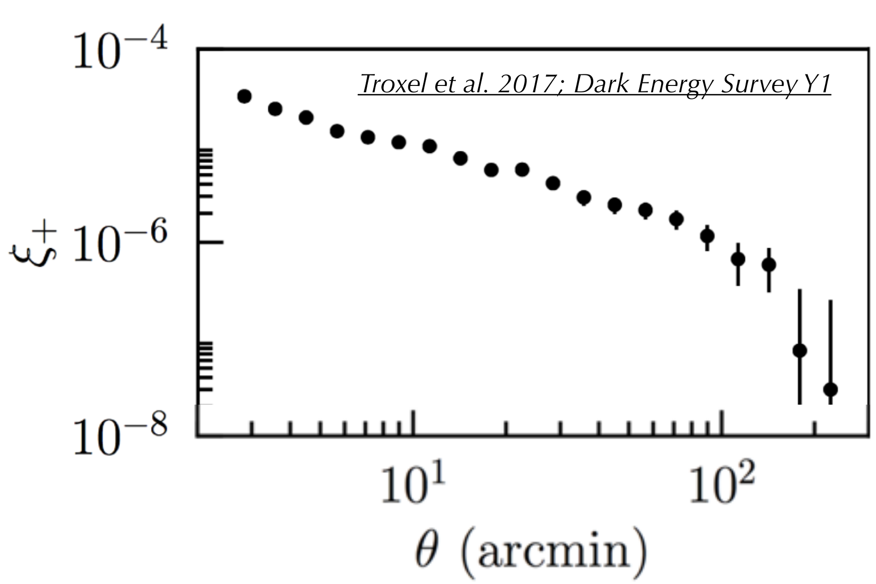


- Understanding the PSF is fundamental for measuring the shear
- Changing the PSF size/ellipticity, changes galaxy ellipticity
- Wrong PSF size/ellipticity, involves bias in the shape measurement of individual galaxies
- For LSST, PSF size should be known at 0.1%
- However, a wrong PSF is not the real problem, the real issue is that the PSF is spatially correlated like the cosmic shear signal…

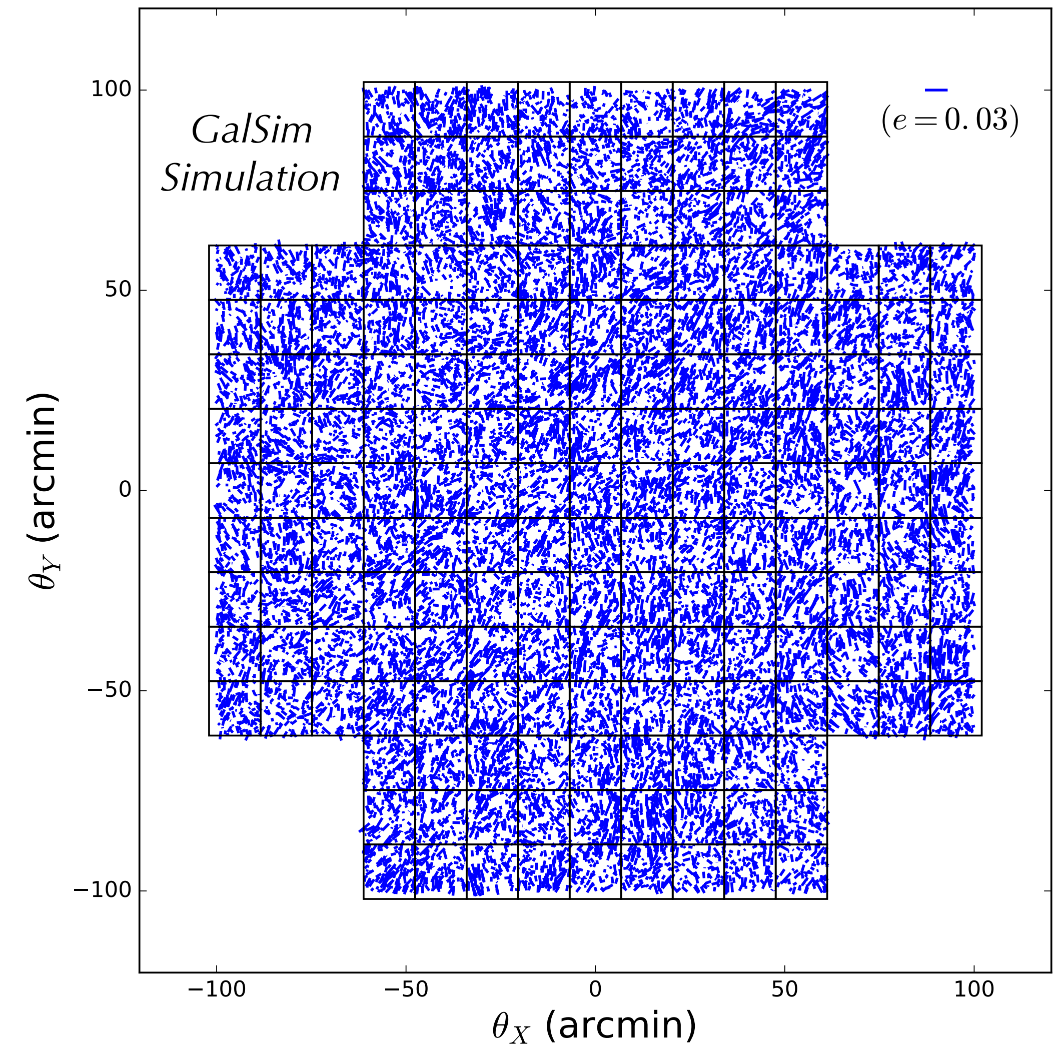
Shear measurement systematics: The Point Spread Function

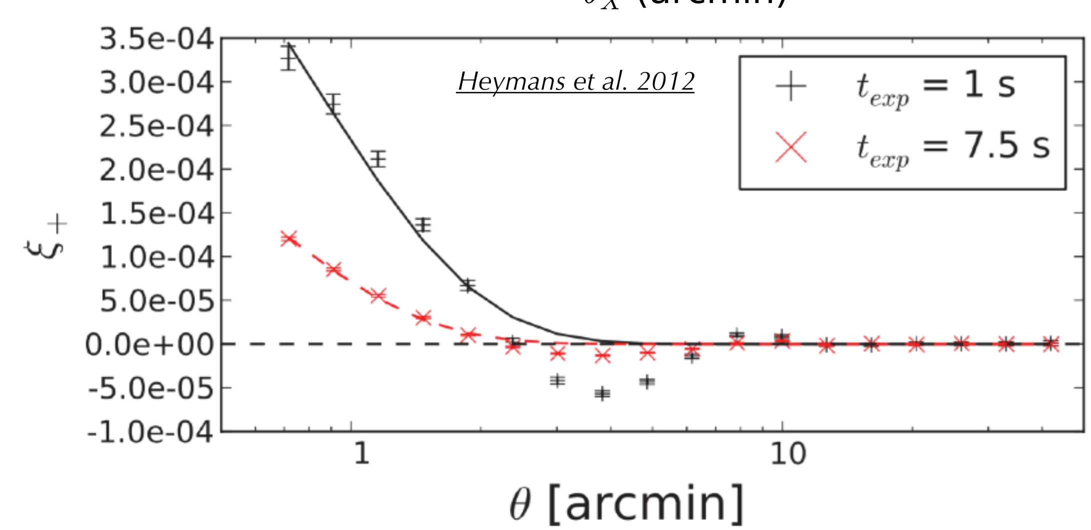
Weak lensing signal





Point Spread Function ellipticity





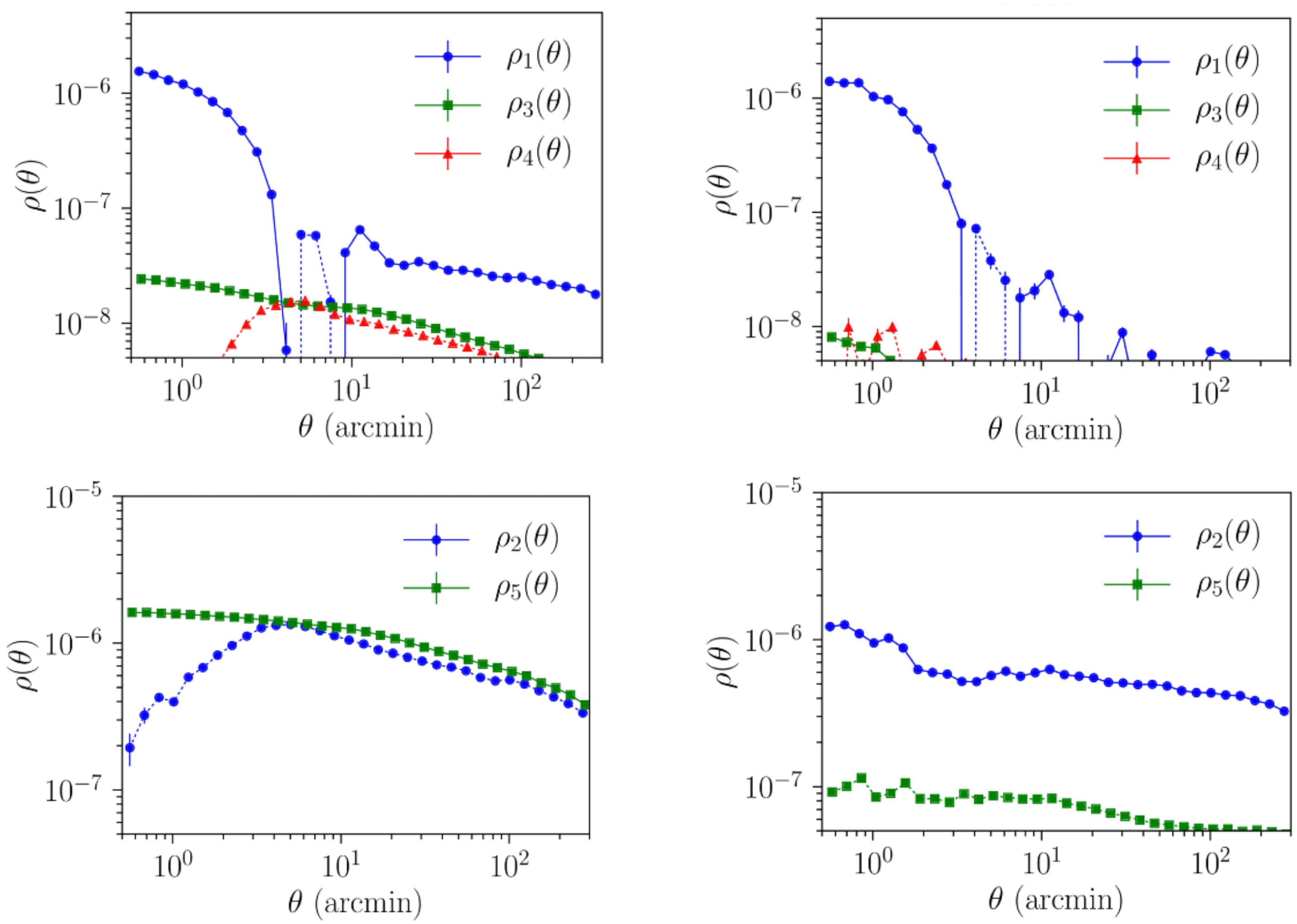
PSFs In the Full FoV (Piff) package

- Piff is a new python software for PSF estimation developed initially to replace PSFex in DES and now also developed for LSST
- Modular package where it is easy to implement new PSF modeling and interpolation scheme over the FoV
- Package with unit testing and code review
- Will be used for the Weak-Lensing analysis of DES Y3
- Contributors:

Mike Jarvis, Chris Davis, Pierre-François Léget, Erin Sheldon, Josh Meyers, Gary Bernstein, Aaron Roodman, Pat Burchat, Daniel Gruen, Ares Hernandez, Andres Navarro, Flavia Sobreira, Reese Wilkinson, Joe Zuntz, Sarah Burnett

Shear measurement systematics: The Point Spread Function

PSFex Piff



Rowe statistics:

$$\rho_1(\theta) \equiv \left\langle \Delta e^*(x) \Delta e(x+\theta) \right\rangle$$

$$\rho_3(\theta) \equiv \left\langle \left(e^* \frac{\Delta T}{T} \right)(x) \left(e \frac{\Delta T}{T} \right)(x+\theta) \right\rangle$$

$$\rho_4(\theta) \equiv \left\langle \Delta e^*(x) \left(e \frac{\Delta T}{T} \right)(x+\theta) \right\rangle$$

$$\rho_2(\theta) \equiv \left\langle e^*(x) \Delta e(x+\theta) \right\rangle$$

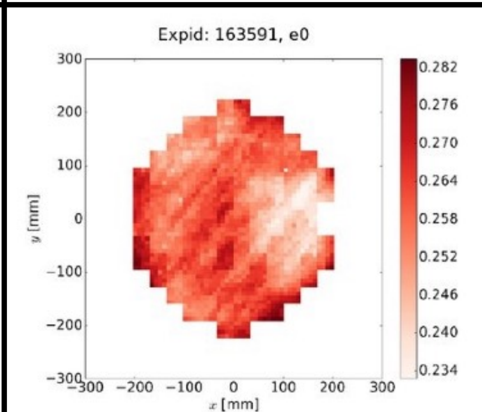
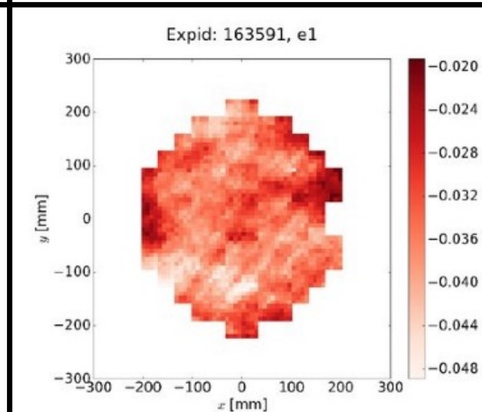
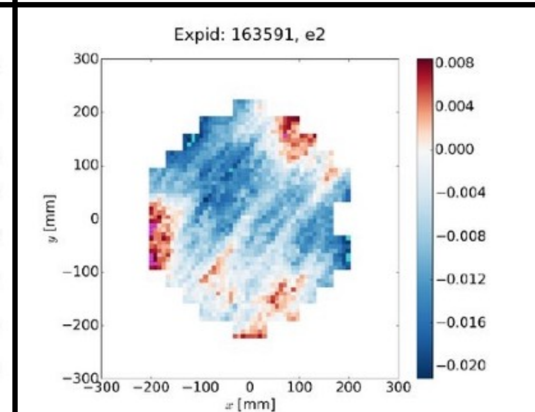
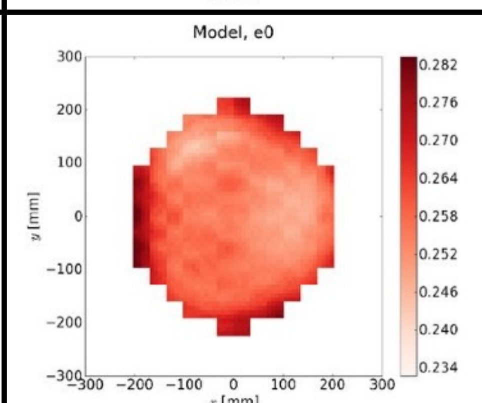
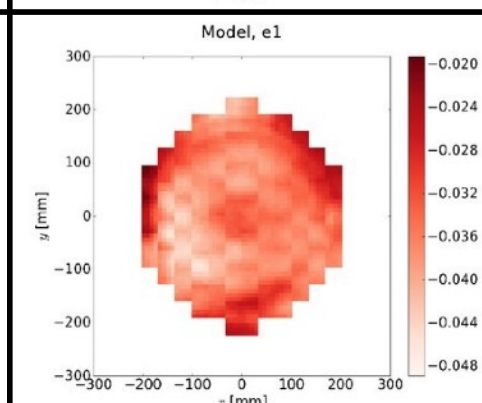
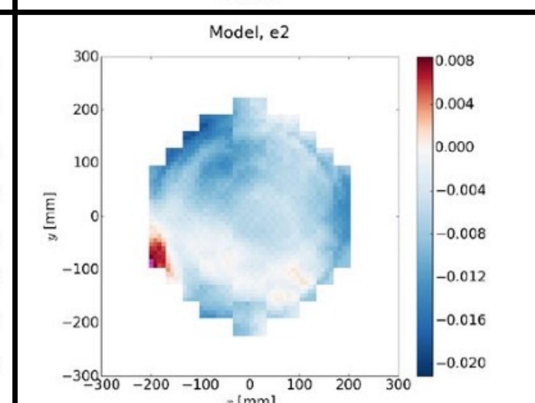
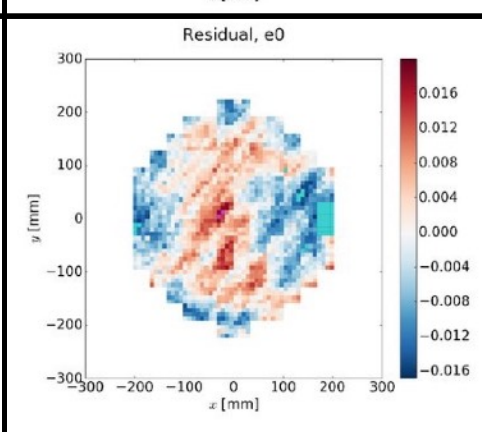
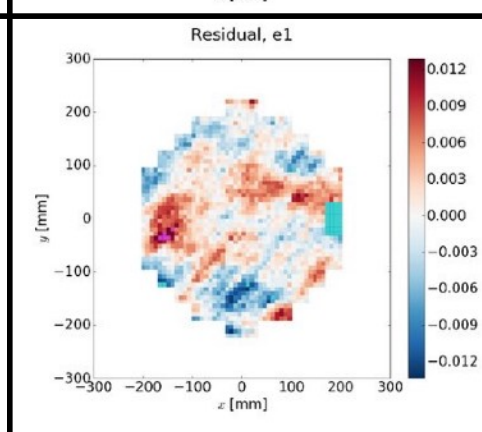
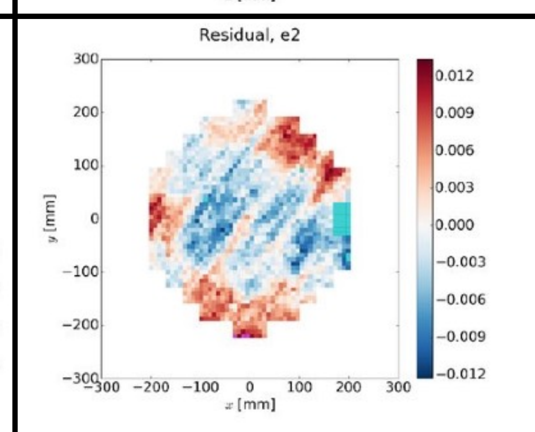
$$\rho_5(\theta) \equiv \left\langle e^*(x) \left(e \frac{\Delta T}{T} \right)(x+\theta) \right\rangle$$

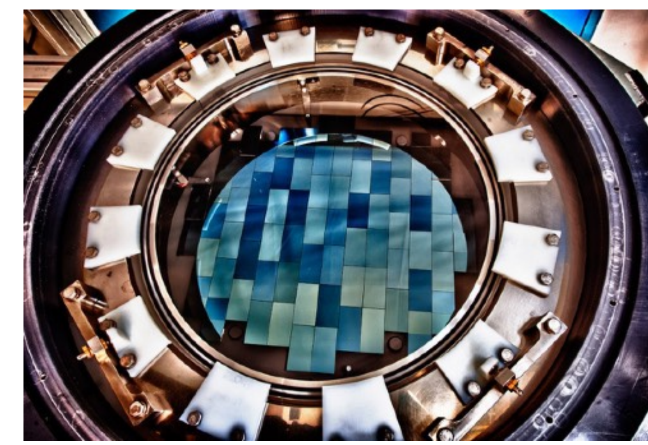
- Piff and PSFex are applied on ~50% of DES Y3 data
- Both used the same 'Pixel Basis' model of the PSF
- Both used a Polynomial interpolation per CCD chip
- The main difference is the coordinate system
- Rowe statistics is computed to compare both
- Analysis and plots done by Mike Jarvis

Shear measurement systematics: The Point Spread Function

Piff ++: An optical and an Atmospheric description of the PSF

For a given exposure

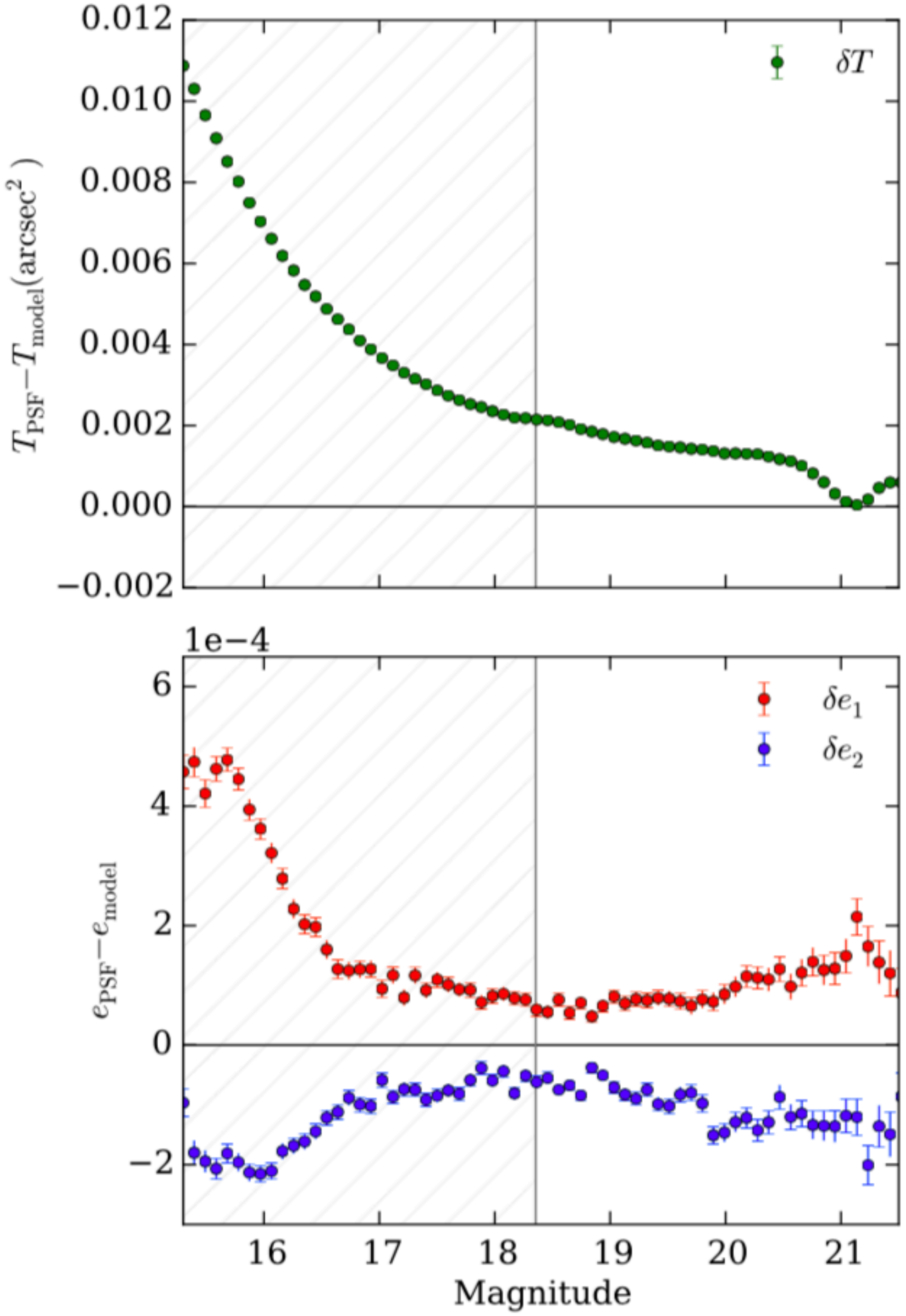
Davis et al. 2016	PSF size	PSF ellipticity 1	PSF ellipticity 2
Total PSF			
Optical PSF			
Atmospheric PSF			



Dark Energy Camera

Shear measurement systematics: The PSF & Brighter-Fatter

Jarvis et al. 2016



Guyonnet et al. 2015

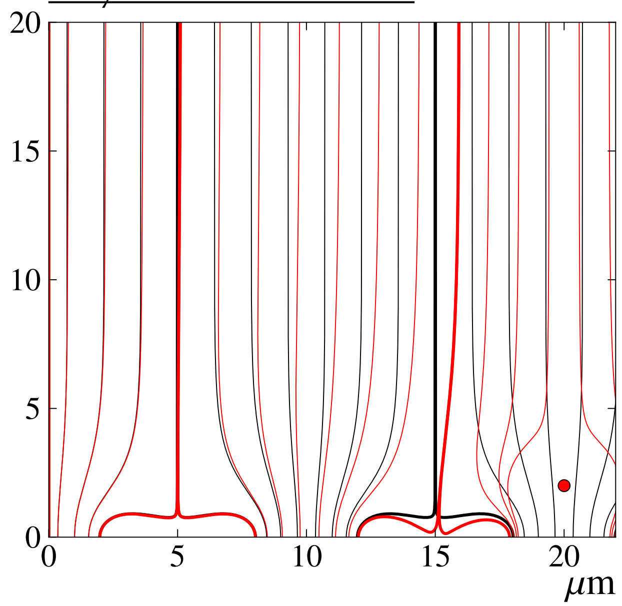
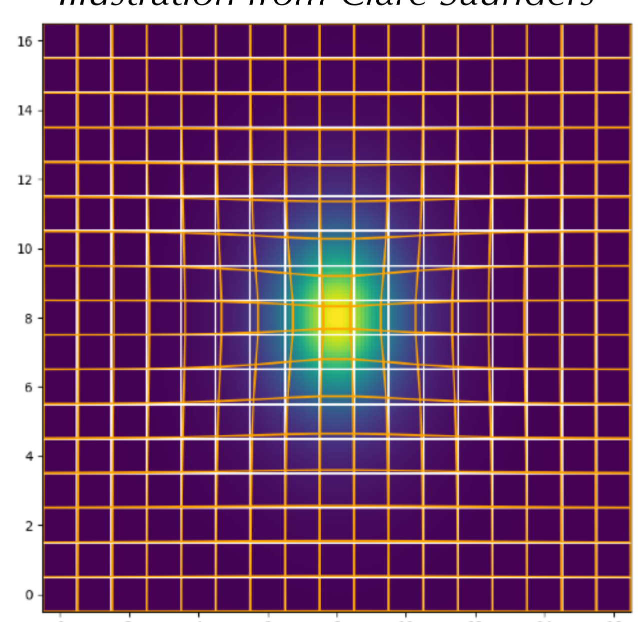
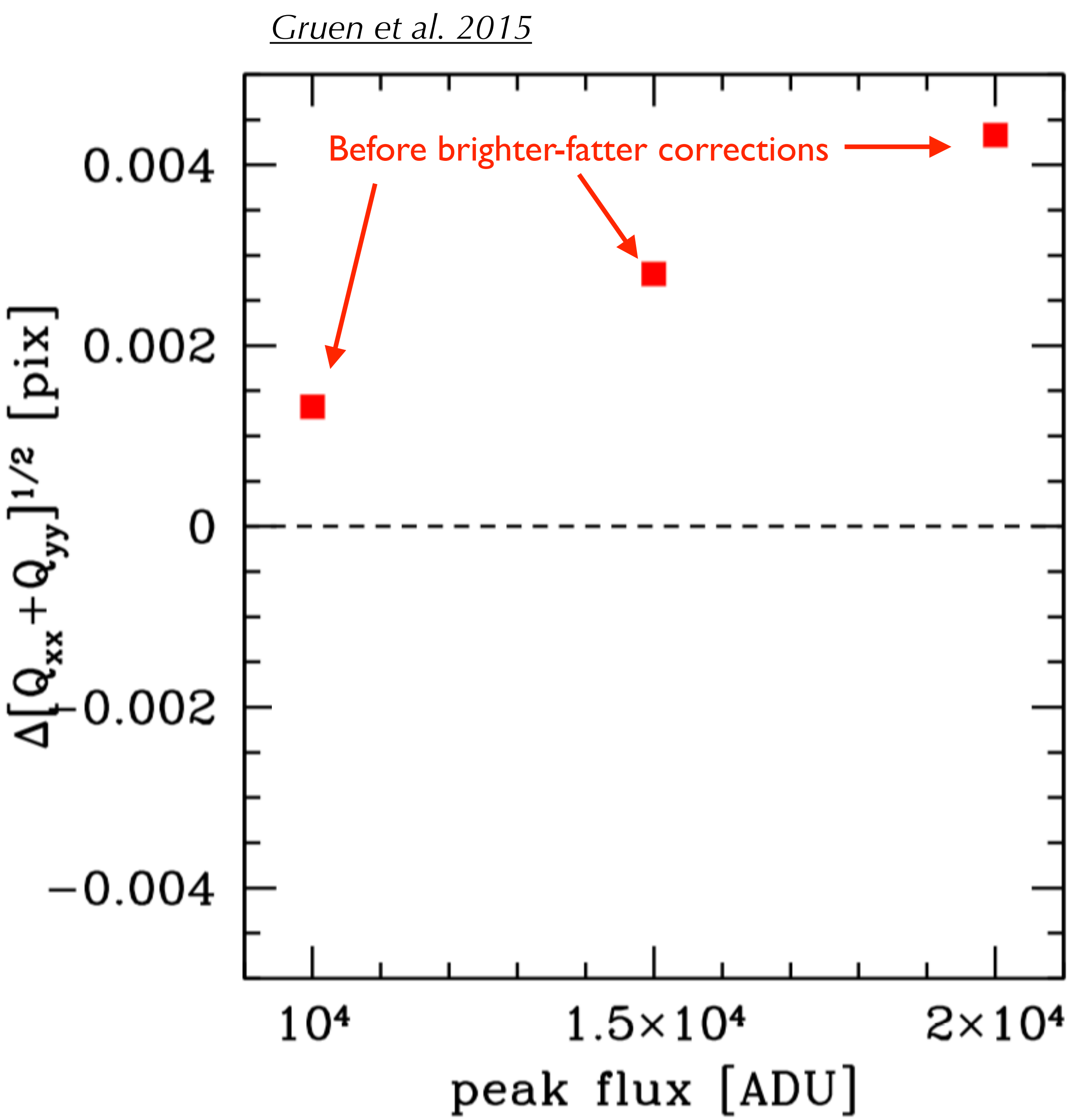


Illustration from Clare Saunders



- Since 2014, PSF was supposed to be flux independent (i.e. PSF parameters do not depend on flux)
- This is wrong due to sensor/electrostatic effects.
- Pixels' size shrink as it gathers electrons due to changes of the electric fields == makes PSF « fatter » as the PSF becomes « brighter »
- This is the « brighter-fatter » effect and involves bias in shape measurements
- PSF is estimated on bright stars, and weak-lensing on faint galaxies…

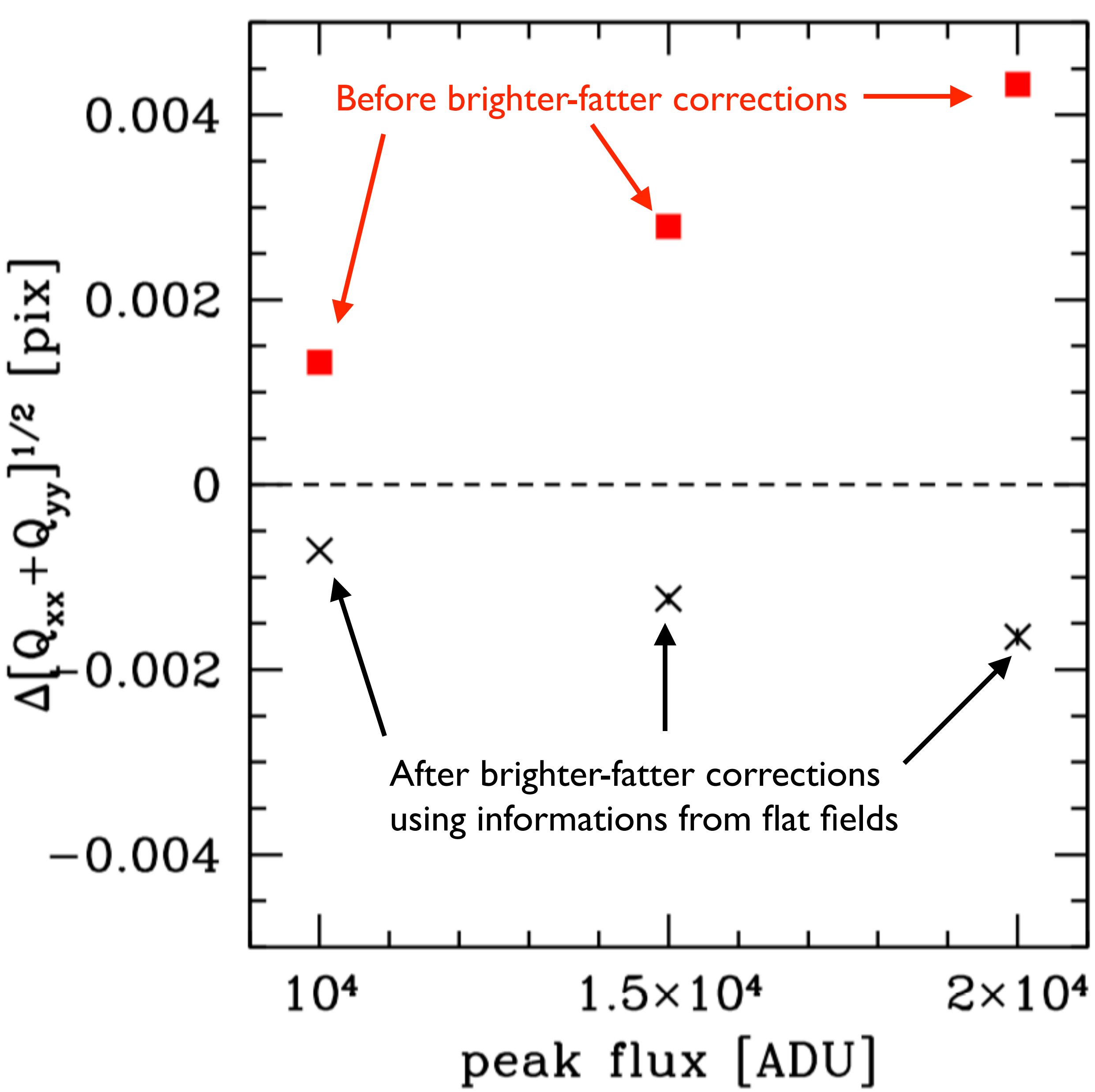
Shear measurement systematics: The PSF & Brighter-Fatter



- Current solution implements what was presented in Antilogus et al. 2014 ; Guyonnet et al. 2015
- See Gruen et al. 2015 for DES or Coulton et al. 2018 for HSC as examples
- Measured spatial correlation of the effects from flat fields and apply linear corrections on pixels.

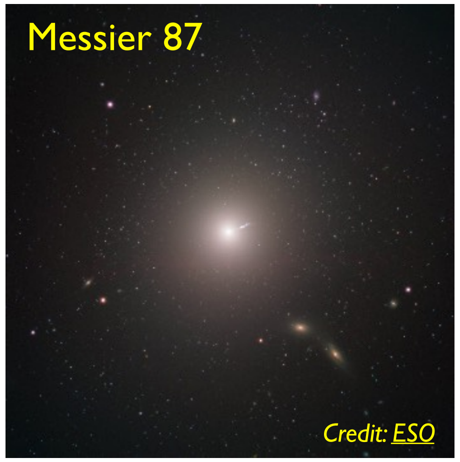
Shear measurement systematics: The PSF & Brighter-Fatter

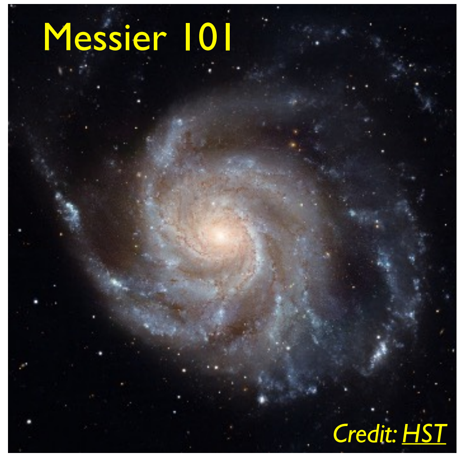
Gruen et al. 2015



- Current solution implements what was presented in Antilogus et al. 2014 ; Guyonnet et al. 2015
- See Gruen et al. 2015 for DES or Coulton et al. 2018 for HSC as examples
- Measured spatial correlation of the effects from flat fields and apply linear corrections on pixels.
- ~ 10 % percent of the effect remain
- Astier et al. 2019 proposed to go to higher order description of the covariances and this model better describes the shape of covariances in terms of the flux!

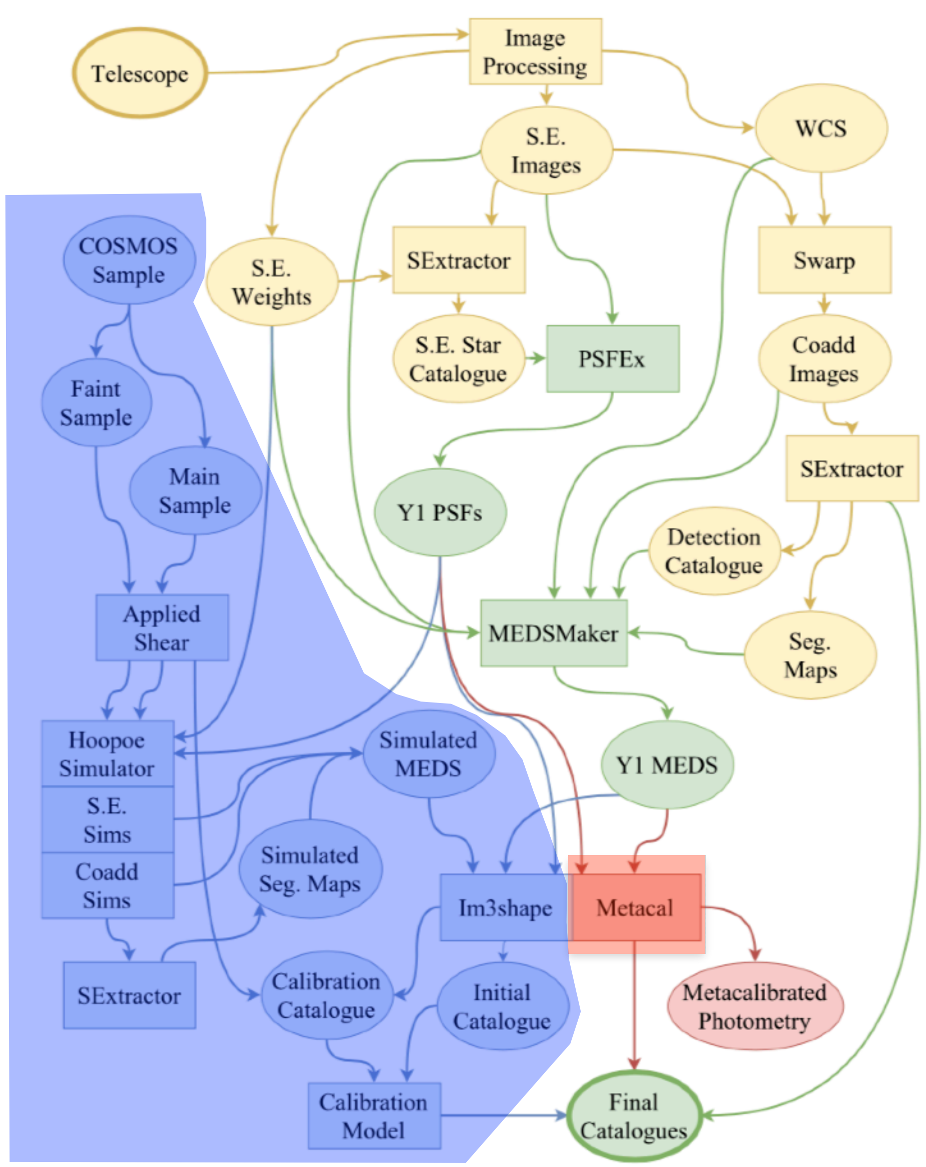
Shear measurement systematics: Model bias





→ Galaxies don't follow an elliptical profile…

Zuntz et al. 2017



- All shear estimators are biased because there is not a general model for estimating galaxy shape
- One solution: use realistic simulation to calibrate your shear estimator
  - e.g.: im3shape in DES Y1 (bulk+flow model using Sérsic profile)
- Other solution: Use only the observed images and try to self-calibrate it
  - e.g.: Metacalibration in DES Y1

Shear measurement systematics: Model bias

The idea of Metacalibration (Huff et al. 2017; Sheldon et al. 2017; Zuntz et al. 2017):

Shear measurement systematics: Model bias

The idea of Metacalibration (Huff et al. 2017; Sheldon et al. 2017; Zuntz et al. 2017):

$$\boldsymbol{e} = \boldsymbol{e}|_{\gamma=0} + \left.\frac{\partial \boldsymbol{e}}{\partial \boldsymbol{\gamma}}\right|_{\gamma=0} \boldsymbol{\gamma} + \ldots$$

Shear measurement systematics: Model bias

The idea of Metacalibration (Huff et al. 2017; Sheldon et al. 2017; Zuntz et al. 2017):

$$\boxed{\boldsymbol{e} = \boldsymbol{e}|_{\gamma=0} + \left.\frac{\partial \boldsymbol{e}}{\partial \boldsymbol{\gamma}}\right|_{\gamma=0} \boldsymbol{\gamma} + \ldots}$$

Taylor expansion of the measured ellipticity around null shear

Shear measurement systematics: Model bias

The idea of Metacalibration (Huff et al. 2017; Sheldon et al. 2017; Zuntz et al. 2017):

$$\begin{aligned}\boldsymbol{e} &= \boldsymbol{e}|_{\gamma=0} + \left.\frac{\partial \boldsymbol{e}}{\partial \boldsymbol{\gamma}}\right|_{\gamma=0} \boldsymbol{\gamma} + \ldots \\ &\equiv \boldsymbol{e}|_{\gamma=0} + \boxed{\boldsymbol{R}_{\gamma}}\boldsymbol{\gamma} + \ldots\end{aligned}$$

Shear response

Shear measurement systematics: Model bias

The idea of Metacalibration (Huff et al. 2017; Sheldon et al. 2017; Zuntz et al. 2017):

$$
\begin{aligned}
\boldsymbol{e} &= \boldsymbol{e}|_{\gamma=0} + \left.\frac{\partial \boldsymbol{e}}{\partial \boldsymbol{\gamma}}\right|_{\gamma=0} \boldsymbol{\gamma} + \ldots \\
&\equiv \boldsymbol{e}|_{\gamma=0} + \boxed{\boldsymbol{R_\gamma}}\,\gamma + \ldots
\end{aligned}
$$

$$\boldsymbol{R_\gamma}_{i,j} = \frac{e_i^+ - e_i^-}{\Delta\gamma_j}$$

Compute directly on the image by introducing artificial shear

Shear response

Shear measurement systematics: Model bias

The idea of Metacalibration (Huff et al. 2017; Sheldon et al. 2017; Zuntz et al. 2017):

$$\boldsymbol{e} = \boldsymbol{e}|_{\gamma=0} + \left.\frac{\partial \boldsymbol{e}}{\partial \boldsymbol{\gamma}}\right|_{\gamma=0} \boldsymbol{\gamma} + \ldots$$
$$\equiv \boldsymbol{e}|_{\gamma=0} + \boldsymbol{R}_{\gamma}\boldsymbol{\gamma} + \ldots$$

$$\boldsymbol{R}_{\boldsymbol{\gamma}\,i,j} = \frac{e_i^+ - e_i^-}{\Delta\gamma_j}$$

Compute directly on the image by introducing artificial shear

$$\langle\boldsymbol{\gamma}\rangle_w \approx \langle\boldsymbol{R}_\gamma\rangle^{-1}\langle\boldsymbol{R}_\gamma\boldsymbol{\gamma}\rangle \approx \langle\boldsymbol{R}_\gamma\rangle^{-1}\langle\boldsymbol{e}\rangle \quad \equiv$$

Unbiased estimate of the average shear using the Metacalibration process

Shear measurement systematics: Model bias

The idea of Metacalibration (Huff et al. 2017; Sheldon et al. 2017; Zuntz et al. 2017):

$$\begin{aligned} \boldsymbol{e} &= \boldsymbol{e}|_{\gamma=0} + \left.\frac{\partial \boldsymbol{e}}{\partial \boldsymbol{\gamma}}\right|_{\gamma=0} \boldsymbol{\gamma} + \ldots \\ &\equiv \boldsymbol{e}|_{\gamma=0} + \boldsymbol{R_\gamma}\boldsymbol{\gamma} + \ldots \end{aligned}$$

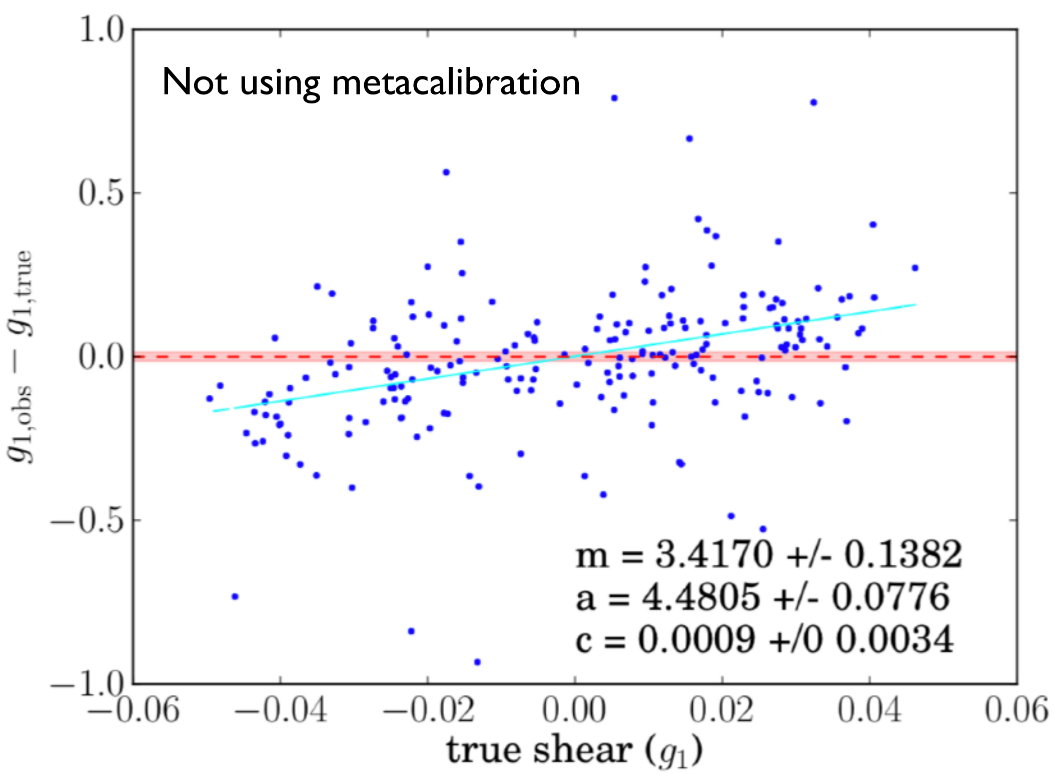
$$\boldsymbol{R_\gamma}_{i,j} = \frac{e_i^+ - e_i^-}{\Delta\gamma_j}$$

Compute directly on the image by introducing artificial shear

$$\langle\boldsymbol{\gamma}\rangle_w \approx \langle\boldsymbol{R_\gamma}\rangle^{-1}\langle\boldsymbol{R_\gamma}\boldsymbol{\gamma}\rangle \approx \langle\boldsymbol{R_\gamma}\rangle^{-1}\langle\boldsymbol{e}\rangle \quad \equiv$$

Unbiased estimate of the average shear using the Metacalibration process

Huff et al. 2017



Shear measurement systematics: Model bias

The idea of Metacalibration (Huff et al. 2017; Sheldon et al. 2017; Zuntz et al. 2017):

$$\boldsymbol{e} = \boldsymbol{e}|_{\gamma=0} + \frac{\partial \boldsymbol{e}}{\partial \boldsymbol{\gamma}}\bigg|_{\gamma=0} \boldsymbol{\gamma} + \ldots$$
$$\equiv \boldsymbol{e}|_{\gamma=0} + \boldsymbol{R}_\gamma \boldsymbol{\gamma} + \ldots$$

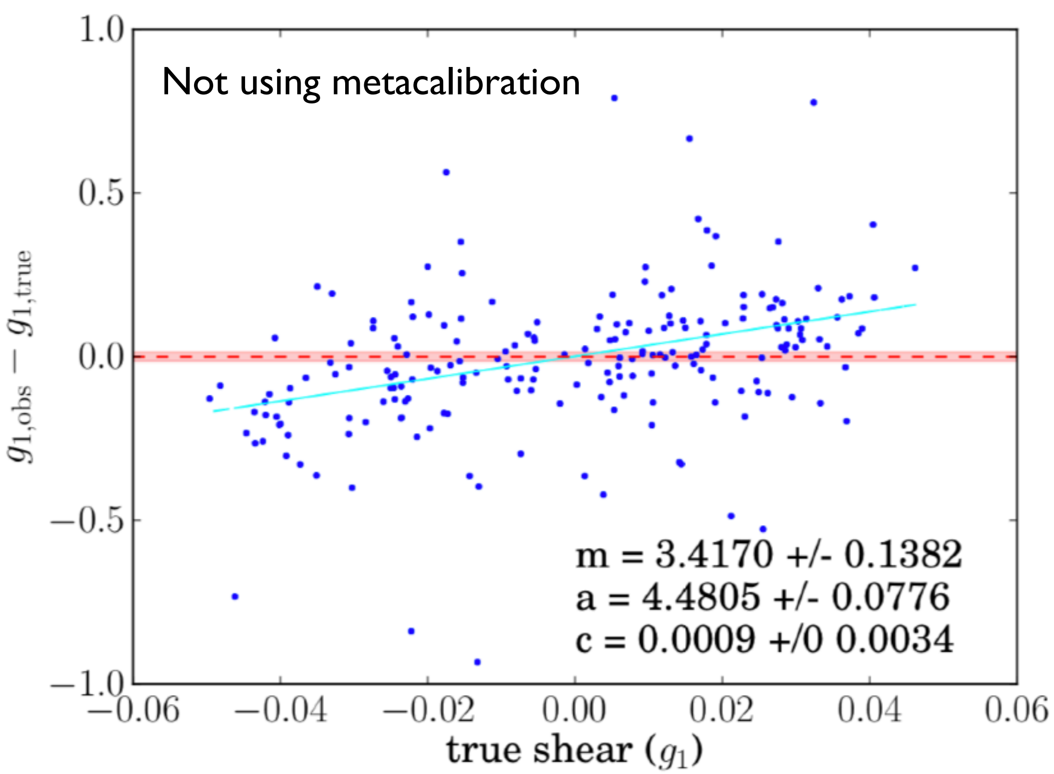
$$\boldsymbol{R}_{\gamma\, i,j} = \frac{e_i^+ - e_i^-}{\Delta\gamma_j}$$

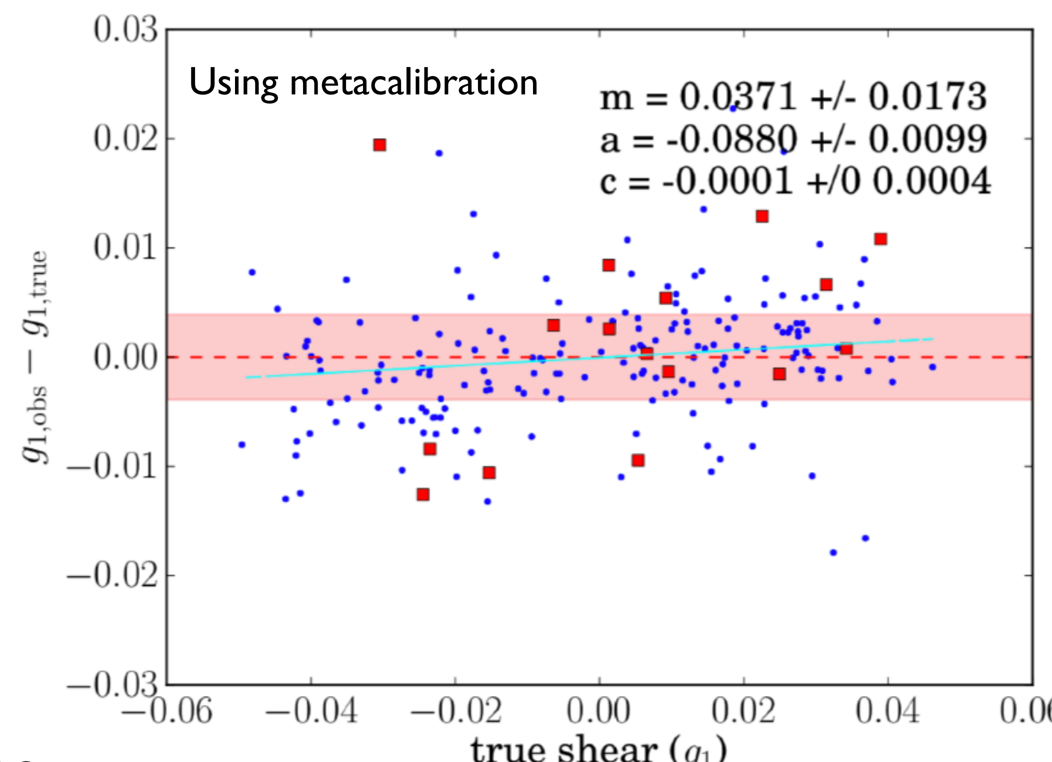
Compute directly on the image by introducing artificial shear

$$\langle \boldsymbol{\gamma} \rangle_w \approx \langle \boldsymbol{R}_\gamma \rangle^{-1} \langle \boldsymbol{R}_\gamma \boldsymbol{\gamma} \rangle \approx \langle \boldsymbol{R}_\gamma \rangle^{-1} \langle \boldsymbol{e} \rangle \quad \equiv$$

Unbiased estimate of the average shear using the Metacalibration process

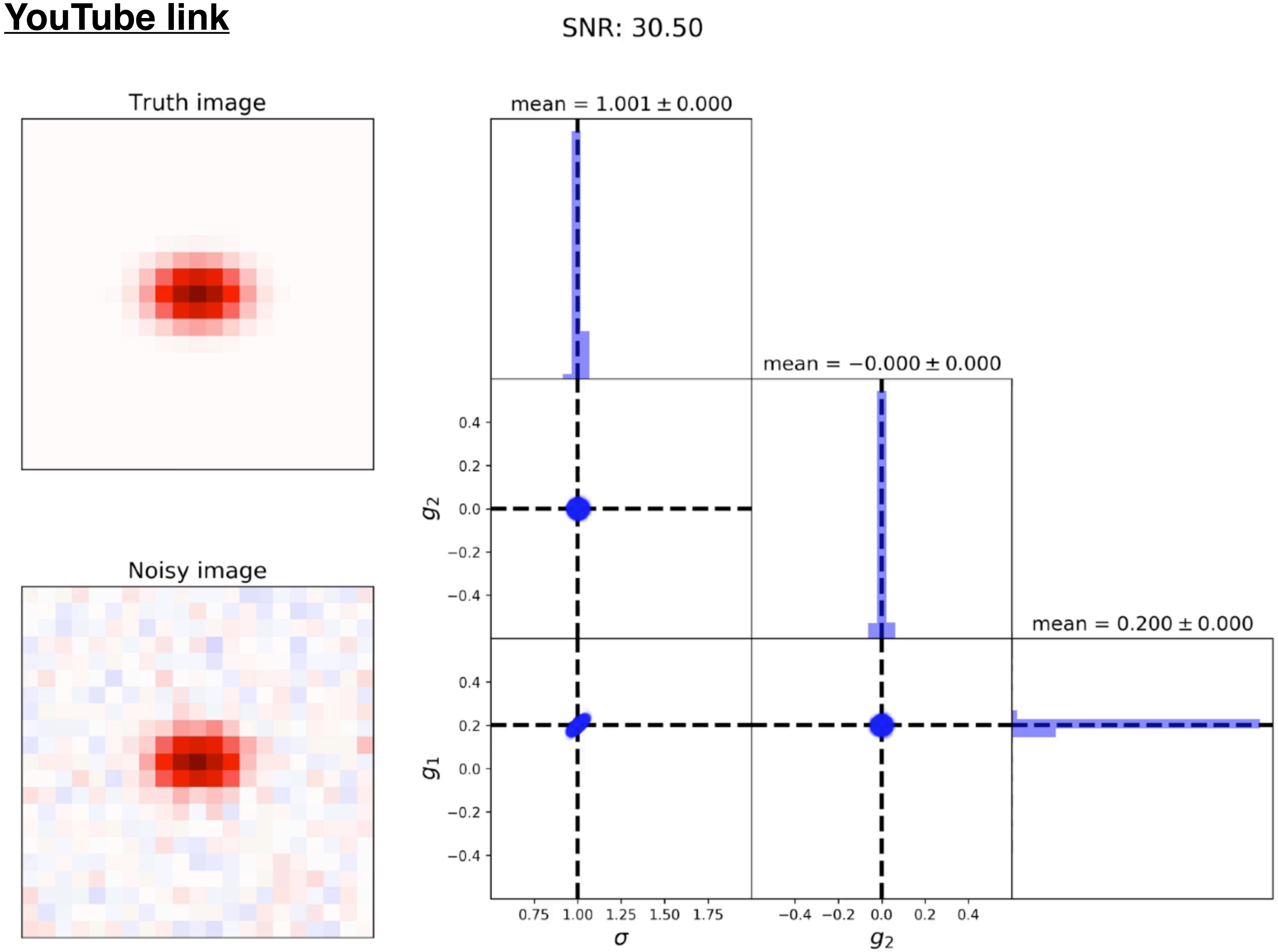
Huff et al. 2017





Shear measurement systematics: Noise bias

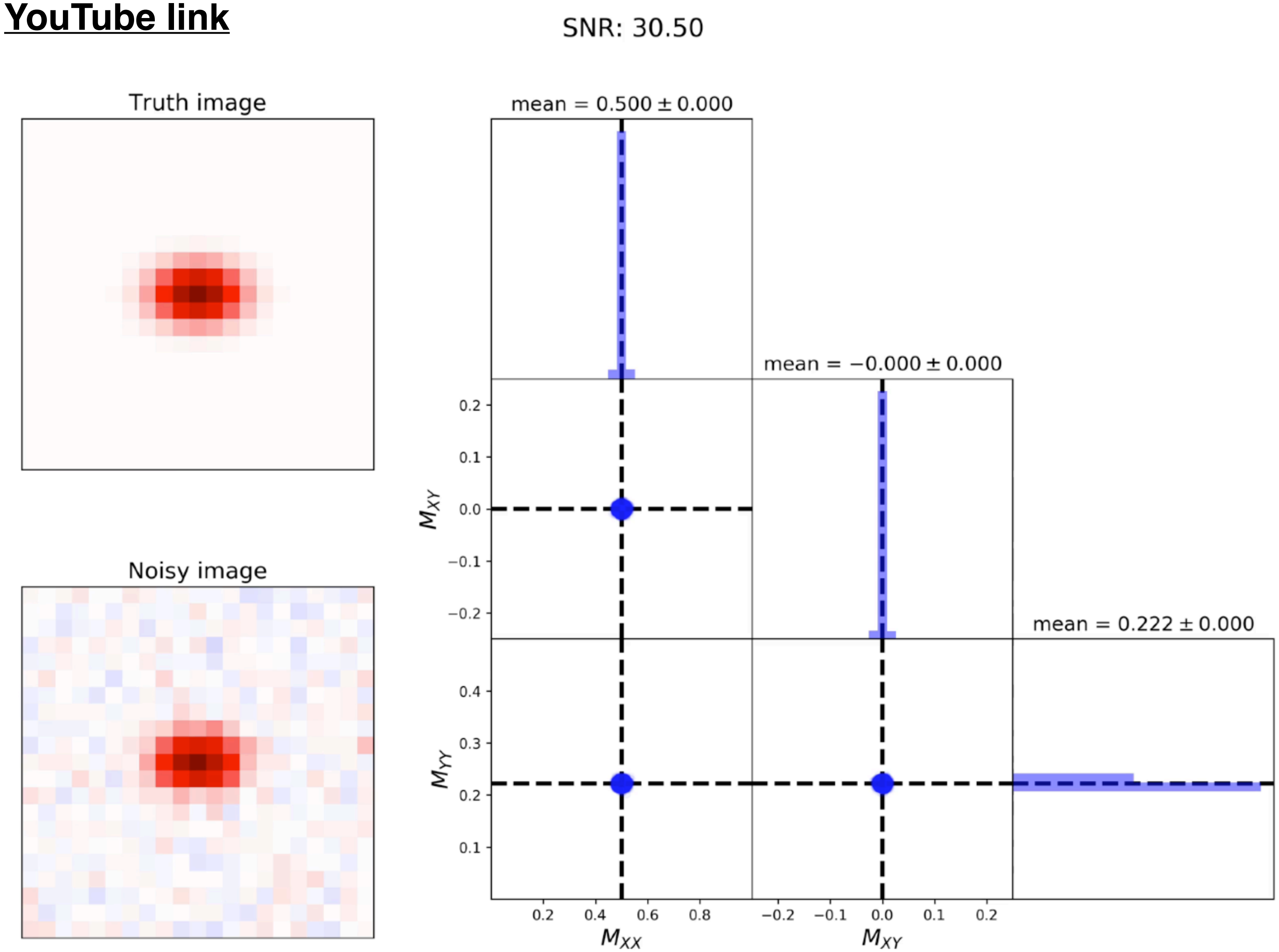
[YouTube link]()



- Maximum Likelihood estimator is biased at low signal to noise ratio (Refregier et al. 2012)
- Problem because a lot of the galaxy would be at low SNR
- A simple example of noise bias:
    - Elliptical gaussian with known flux and center and not convolved with a PSF (not fitted)
    - Fit ~8000 times using a **Maximum Likelihood** fit with different realization of the same SNR

Shear measurement systematics: Noise bias

[YouTube link]



- Other estimators, like the « moment based » method, don’t have this problem
- Simple example:
  - Elliptical gaussian with known flux and center and not convolved with a PSF (not fitted)
  - Fit ~8000 times using a **moment based** fit with different realization of the same SNR
- But this kind of estimator has other bias due to:
  - Weight function
  - Error on centroids

Shear measurement systematics: Noise bias

- Solutions for Noise bias applied to real data:
  - Use simulations to correct the effects.
    - e.g. : im3shape on DES Y1 (see Zuntz et al 2017)
  - Cut in SNR and use a method that corrects the bias introduced by the cut
    - e.g.: METACALIBRATION on DES Y1 (see Zuntz et al 2017)

Shear measurement systematics: Noise bias

- Solutions for Noise bias applied to real data:

  - Use simulations to correct the effects.
    - e.g. : im3shape on DES Y1 (see Zuntz et al 2017)

  - Cut in SNR and use a method that corrects the bias introduced by the cut
    - e.g.: METACALIBRATION on DES Y1 (see Zuntz et al 2017)

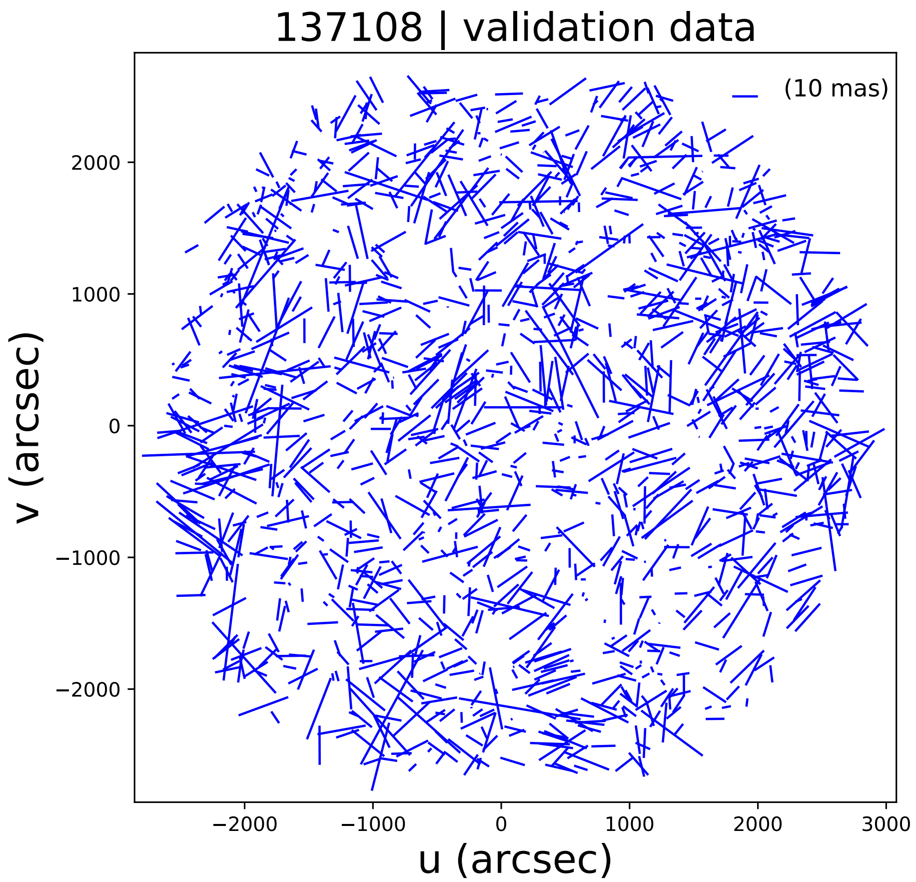
- Some thoughts on other solutions:

  - A « Metacalibration-like » method using a moment based estimator of the shear. But need to correct for centroids error!

Shear measurement systematics: Noise bias

- Solutions for Noise bias applied to real data:
  - Use simulations to correct the effects.
    - e.g. : im3shape on DES Y1 (see Zuntz et al 2017)
  - Cut in SNR and use a method that corrects the bias introduced by the cut
    - e.g.: METACALIBRATION on DES Y1 (see Zuntz et al 2017)
- Some thoughts on other solutions:
  - A « Metacalibration-like » method using a moment based estimator of the shear. But need to correct for centroids error!

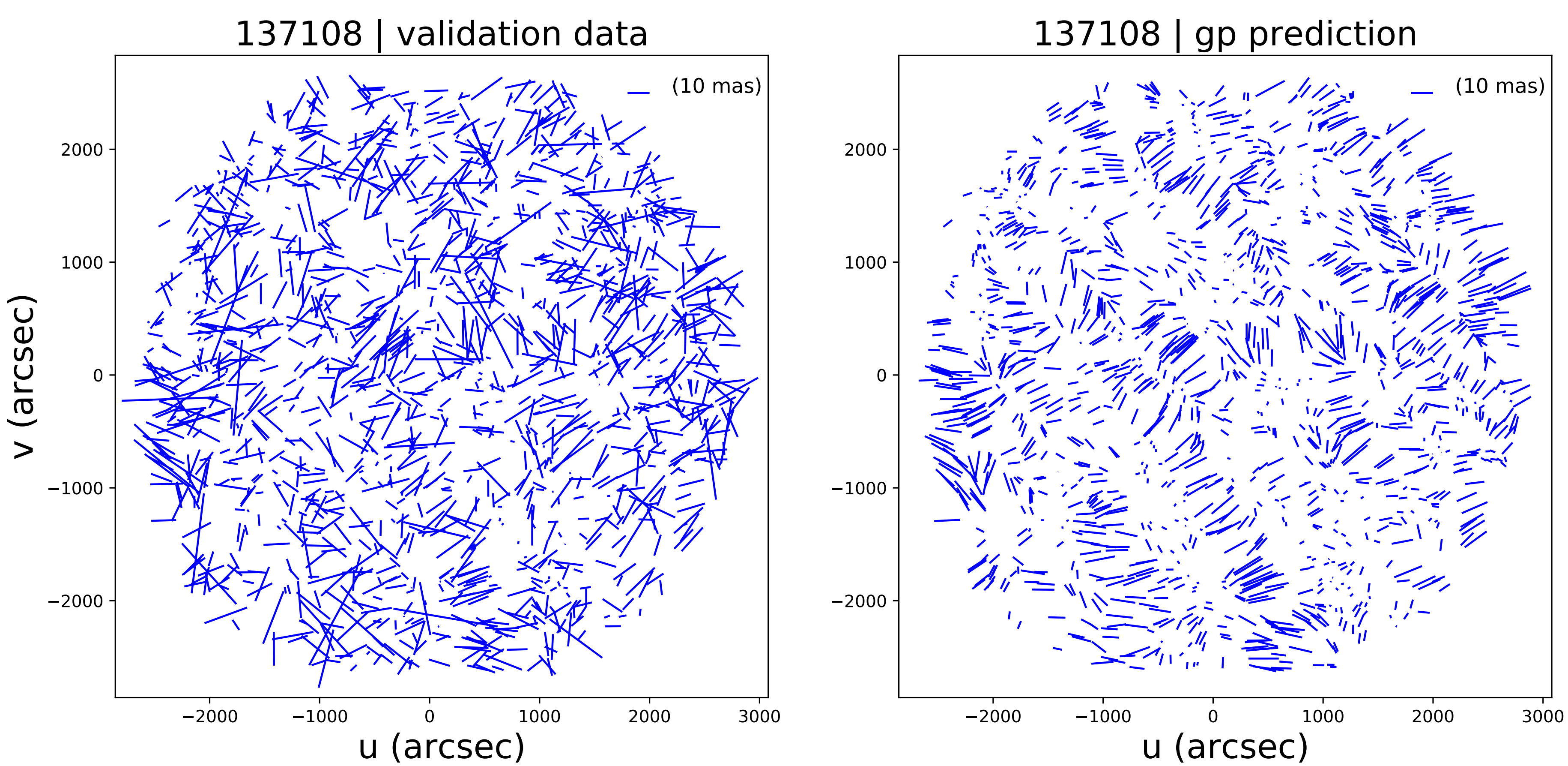
Subaru-HSC astrometric residuals for a single exposure



Shear measurement systematics: Noise bias

- Solutions for Noise bias applied to real data:
    - Use simulations to correct the effects.
        - e.g. : im3shape on DES Y1 (see Zuntz et al 2017)
    - Cut in SNR and use a method that corrects the bias introduced by the cut
        - e.g.: METACALIBRATION on DES Y1 (see Zuntz et al 2017)
- Some thoughts on other solutions:
    - A « Metacalibration-like » method using a moment based estimator of the shear. But need to correct for centroids error!

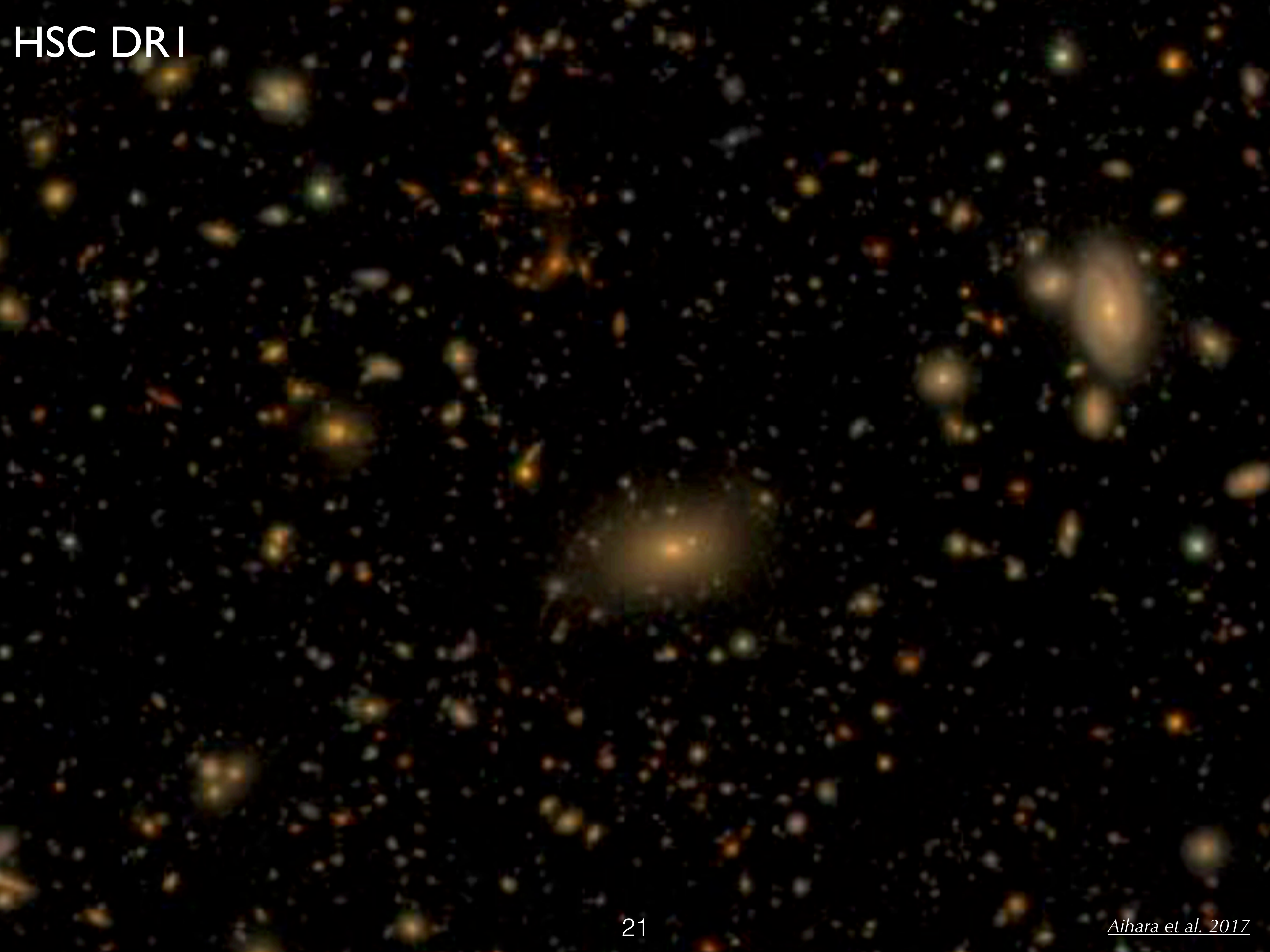
Subaru-HSC astrometric residuals for a single exposure



Atmospheric modeling of astrometric residuals using a Kolmogorov like correlation function

SDSS DR14

[sdss website link]


HSC DR1
Aihara et al. 2017

Shear measurement systematics: Blending

- From SUBARU-HSC (~LSST like depth) 58%-74% of objects are identified as blend (Bosch et al. 2017)

- Current techniques to deal with blending:

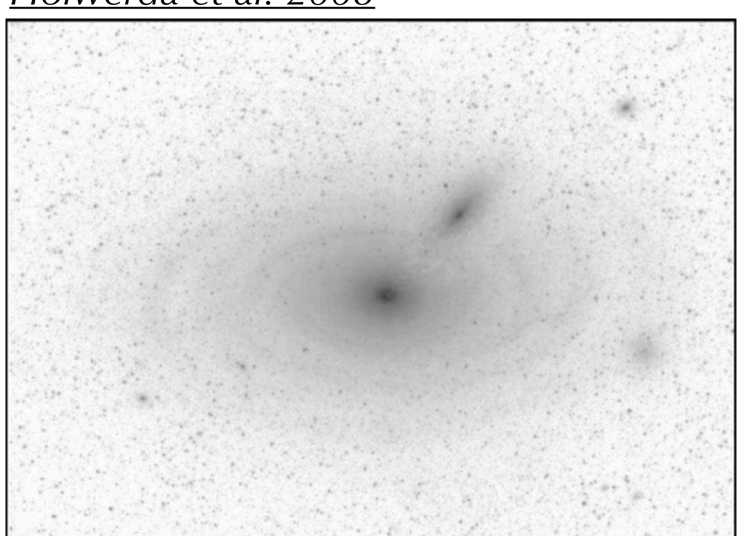
- Used simulations:
  - DES Y1 in3shape catalogue (Zuntz et al 2017)
  - HSC (Mandelbaum et al. 2017)

- Used an algorithm to identify common pixels:
  - DES Y1 metacalibration catalogue using a Multi Object Fitting (Zuntz et al 2017)

- In any of those methods you need a realistic simulation…

  - e.g. Blending is not linear due to dust extinction…

Holwerda et al. 2008



- Modeling dust of galaxies is complicated

  - Example of modeling dust properties of galaxies:
    - Chotard et al. 2011
    - Léget 2016 Ph.D., Léget et al. 2019 submitted

- But also a photo-z problem …

Conclusions:

- Shear measurements have a lot of systematics
- Some of them have a looks to have solutions which should be good enough for LSST
  - PSF / Brighter-Fatter
  - Model bias
  - Noise bias
- Blending looks really the most challenging
  - Having help from space experiment as Euclid may help (Rhodes et al. 2017)

MERCI !