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Ministero dell'Università e della Ricerca

Italiadomani
PIANO NAZIONALE DI RIPRESA E RESILIENZA

INAF
OSSERVATORIO ASTRONOMICO DI TRIESTE

Weak Lensing and Cosmology

Lucie Baumont

Outline

Part I

Conceptual Overview

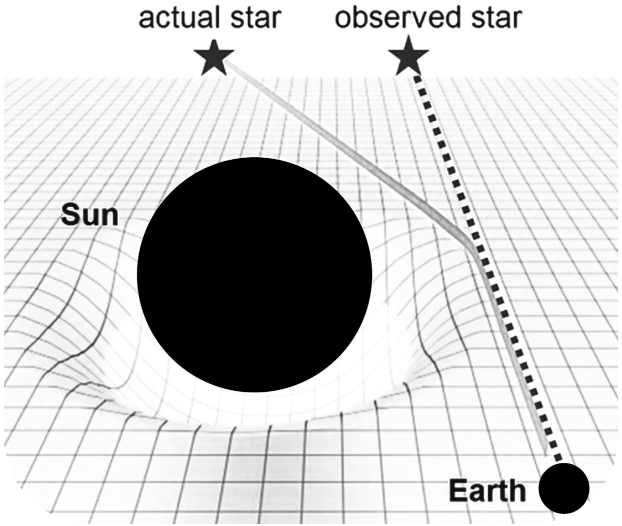
1915: Einstein predicts lensing from general relativity

Mass bends spacetime

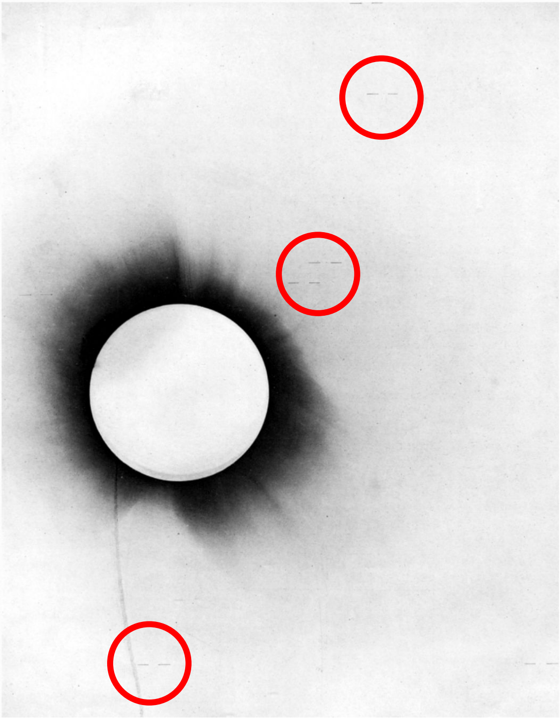
Light travels along null geodesics

→Mass deflects light rays

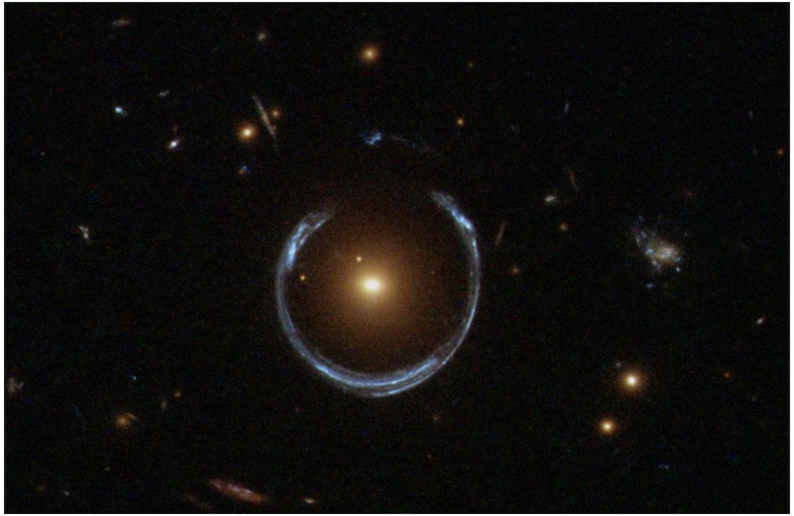
Predicts deflection angle is twice the newtonian prediction



1919: Edditington Measures deflection angle



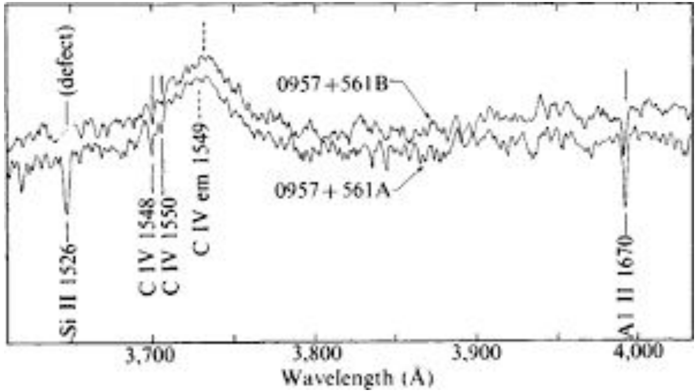
A Brief Timeline of Gravitational Lensing



Chwolson (1924), Einstein (1936): Ring structure as image possible

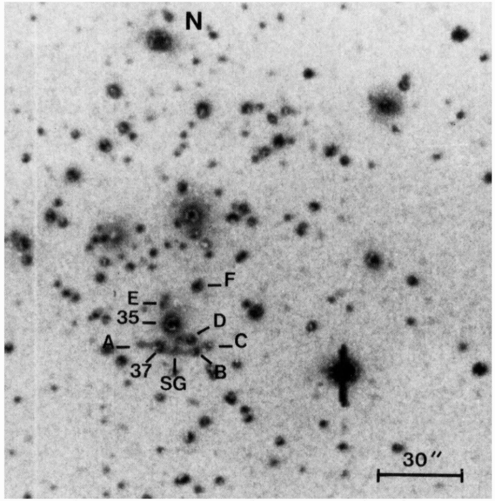
1937: Zwicky- galaxy clusters could be lenses

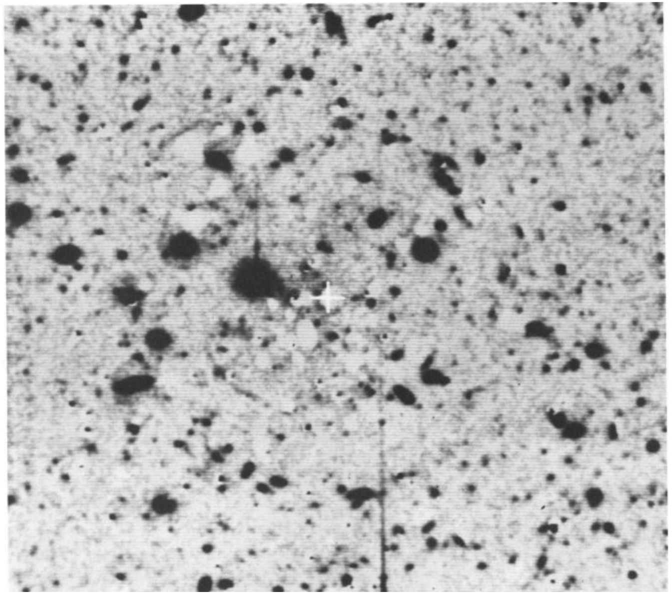
1979 Walsh et al. detect first double image of a lensed quasar.



A Brief Timeline of Gravitational Lensing

1987: Soucail et al. find strongly distorted “arcs” of background galaxies behind galaxy cluster

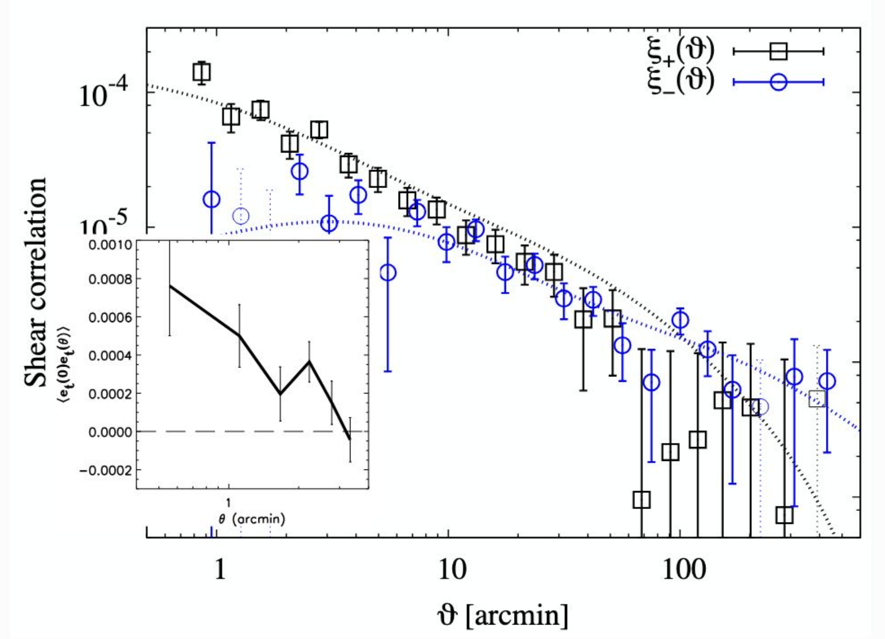




1990: Tyson et al. find tangential alignment of galaxies around clusters.

A Brief Timeline of Gravitational Lensing

2000: cosmic shear detected- weak lensing in blind fields, by 4 groups (Edinburgh,Hawai’i, Paris, Bell Labs/US). Some 10, 000 galaxies on few square degree on the sky area



A Brief Timeline of Gravitational Lensing

2012: von der Linden et al. (Weighing the Giants) use weak lensing masses to calibrate halo mass function for cluster cosmology

2016-present: CFHTLenS, DES, KiDS, HSC provide competitive constraints on cosmology. Factor 100 increase: Millions of galaxies over 100s of degree area. Many other improvements: Multi-band observations, photometric redshifts, image and N-body simulations

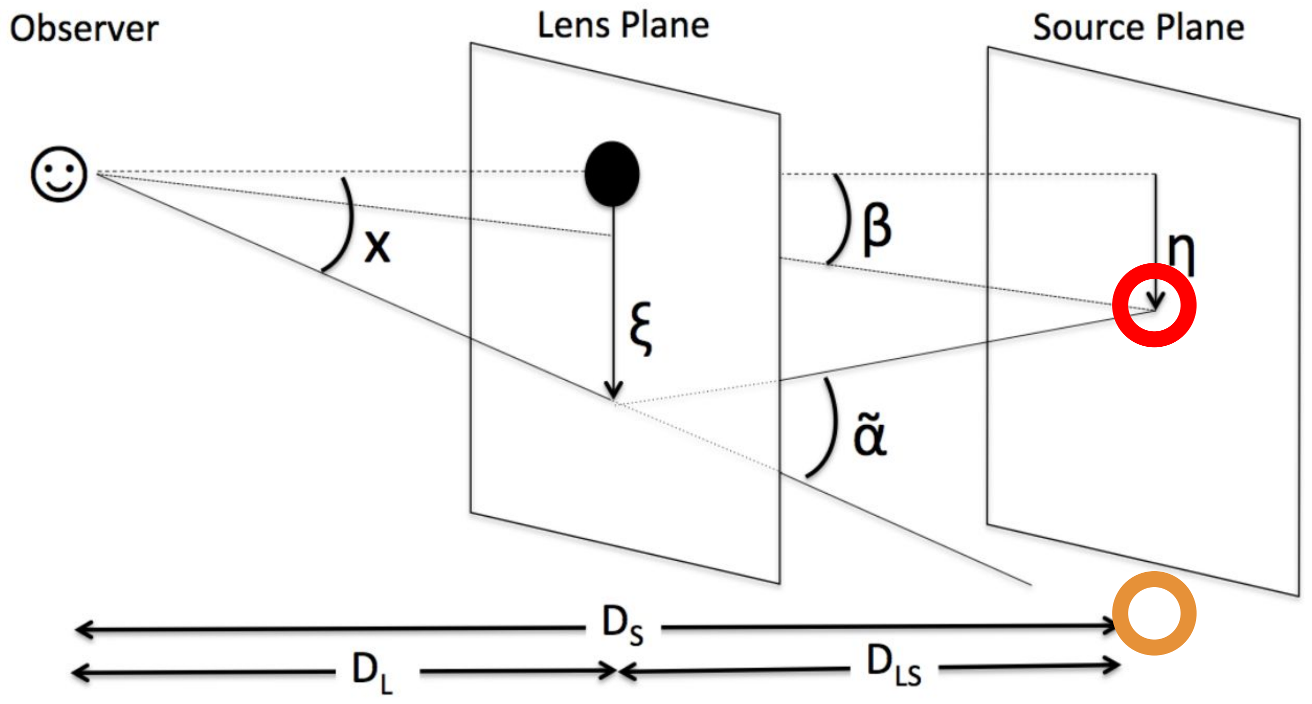
Present day: Euclid Space Telescope is measuring lensing from space, Vera Rubin telescope is in commissioning, Nancy Grace Roman telescope is scheduled to launch this fall. Soon a billion galaxies will have measured shapes

Lensing Geometry

True Position: β

Measured Position: x

Lens equation: $\beta = x - \alpha(x)$



Hoekstra 2013

Lensing Geometry

$$\boldsymbol{\alpha}(\boldsymbol{\theta}) = \frac{1}{\pi} \int_{\mathbb{R}^2} \mathrm{d}^2\theta' \, \kappa(\boldsymbol{\theta}') \, \frac{\boldsymbol{\theta} - \boldsymbol{\theta}'}{|\boldsymbol{\theta} - \boldsymbol{\theta}'|^2}$$

Deflection angle depends

1. 2-d Mass distribution of the lens
2. Distance Geometry

$$\kappa(\boldsymbol{\theta}) := \frac{\Sigma(D_\mathrm{d}\boldsymbol{\theta})}{\Sigma_\mathrm{cr}} \quad \text{with} \quad \Sigma_\mathrm{cr} = \frac{c^2}{4\pi G} \frac{D_\mathrm{s}}{D_\mathrm{d} \, D_\mathrm{ds}} \, ,$$

Use the identity $\nabla \ln |\boldsymbol{\theta}| = \boldsymbol{\theta}/|\boldsymbol{\theta}|^2$

to write deflection angle interms of a potential:

$$\boldsymbol{\alpha} = \nabla \psi$$

$$\nabla^2 \psi = 2\kappa$$

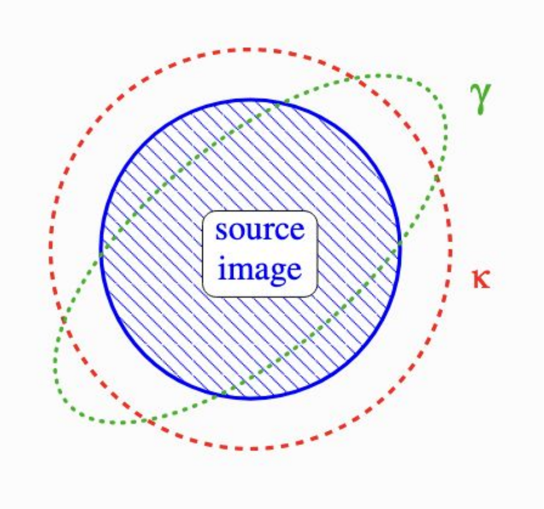
Weak Gravitational Lensing

Lensing conserves surface brightness (no photon gets lost)

$$I(\boldsymbol{\theta}) = I^{(\mathrm{s})}[\boldsymbol{\beta}(\boldsymbol{\theta})]$$

Linearize distortion of a surface brightness

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



$$\mathcal{A}(\boldsymbol{\theta}) = \frac{\partial \boldsymbol{\beta}}{\partial \boldsymbol{\theta}} = \left(\delta_{ij} - \frac{\partial^2 \psi(\boldsymbol{\theta})}{\partial \theta_i \partial \theta_j}\right) = \begin{pmatrix} 1-\kappa-\gamma_1 & -\gamma_2 \\ -\gamma_2 & 1-\kappa+\gamma_1 \end{pmatrix}$$

$$\gamma_1 = \frac{1}{2}(\psi_{,11} - \psi_{,22}), \quad \gamma_2 = \psi_{,12}$$

Kappa and gamma are not independent

convergence and shear are functions of a single scalar potential

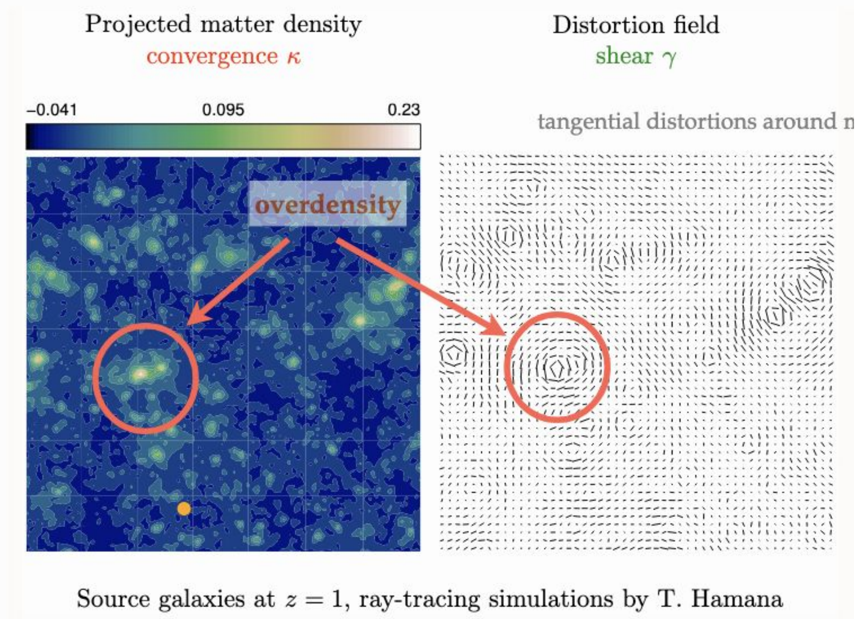
→ Shear components are related

Define the reduced shear

$$g \equiv \frac{\gamma}{1-\kappa}$$

In the weak lensing limit,

$$\kappa \ll 1, |\gamma| \ll 1$$



Definition: Galaxy shape

The **sizes** and **shapes** are defined in terms of the second moments of the surface brightness profile

$$T = I_{xx} + I_{yy}$$

$$e = e_1 + ie_2 = \frac{I_{xx} - I_{yy} + 2iI_{xy}}{I_{xx} + I_{yy} + 2\sqrt{I_{xx}I_{yy} - I_{xy}^2}}$$

where the moments are defined as

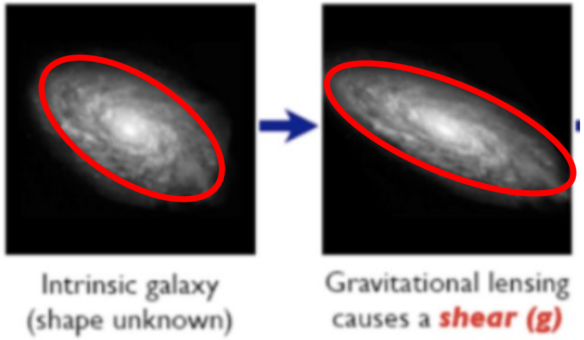
$$I_{\mu\nu} = \frac{\int \mathrm{d}x\mathrm{d}y I(x,y)(\mu - \bar{\mu})(\nu - \bar{\nu})}{\int \mathrm{d}x\mathrm{d}y I(x,y)}.$$

Intrinsic scatter in distribution of galaxy ellipticity “shape noise” ~0.3

Shapes change under shear

Statistically we can use galaxy shapes to find gravitational shear

$$\epsilon^{\text{obs}} = \frac{\epsilon^{\text{orig}} + g}{1 + g^* \epsilon^{\text{orig}}} \approx \epsilon^{\text{orig}} + \gamma,$$



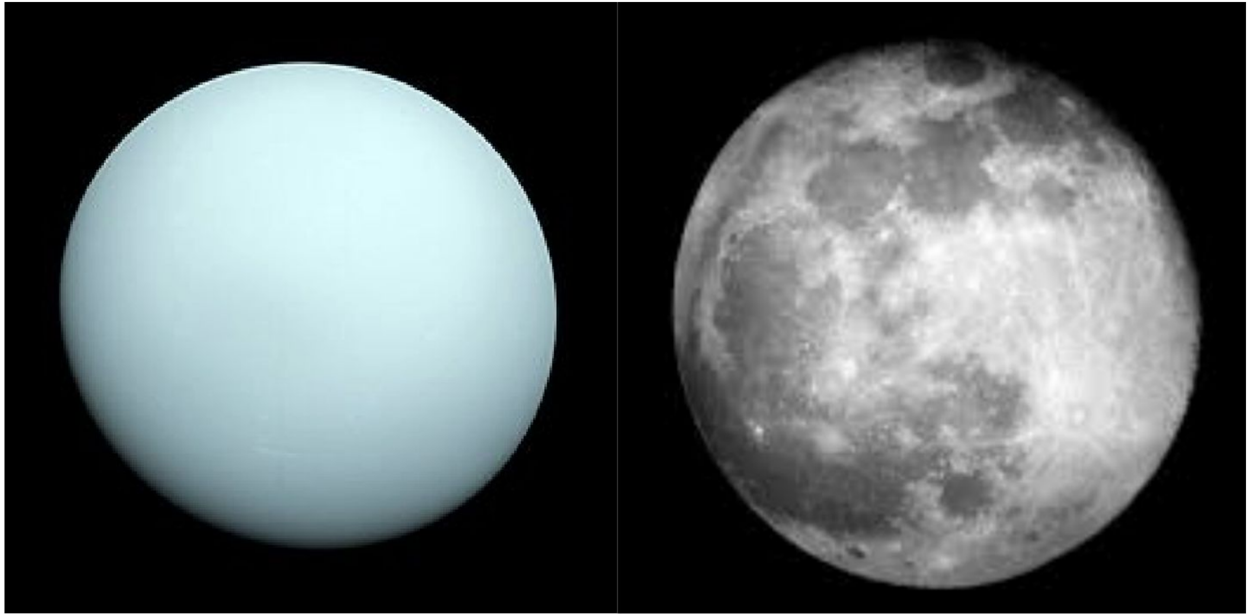
One common estimator for gravitational shear:

$$\langle \varepsilon \rangle = g$$

Assume $\langle \epsilon^{\text{orig}} \rangle = 0$
Otherwise, model *intrinsic alignment*

In reality…

Percent level ellipticity changes are smaller than difference between the ellipticity of uranus and the moon



Gravitational lensing as a cosmological probe

Cosmology can enter in two places:

1. Angular diameter distance
2. Mass distribution

The convergence power spectrum

in the lowest-order approximation, the 3-D cosmological mass distribution can be considered, as an effective surface mass density κ, just like in ordinary lensing

Variance in $\langle \kappa(\boldsymbol{\vartheta} + \boldsymbol{\theta}) \kappa(\boldsymbol{\vartheta}) \rangle = \langle \kappa\kappa \rangle(\theta)$ is related to variance in density contrast $\langle \delta\delta \rangle$ by Limber's Equation:

$$\langle \hat{\kappa}(\boldsymbol{\ell}) \hat{\kappa}^*(\boldsymbol{\ell}') \rangle = (2\pi)^2 \delta_{\mathrm{D}}(\boldsymbol{\ell} - \boldsymbol{\ell}') P_\kappa(\ell)$$

$$\left\langle \hat{\delta}(\boldsymbol{k}) \hat{\delta}^*(\boldsymbol{k}') \right\rangle = (2\pi)^3 \delta_{\mathrm{D}}(\boldsymbol{k} - \boldsymbol{k}') P_\delta(k)$$

$$P_\kappa(\ell) = \int \mathrm{d}\chi \, G^2(\chi) P_\delta \left(k = \frac{\ell}{\chi} \right)$$

The convergence power spectrum

initial conditions, growth of structure

$$P_\kappa(\ell) = \int \mathrm{d}\chi \, G^2(\chi) P_\delta\left(k = \frac{\ell}{\chi}\right)$$

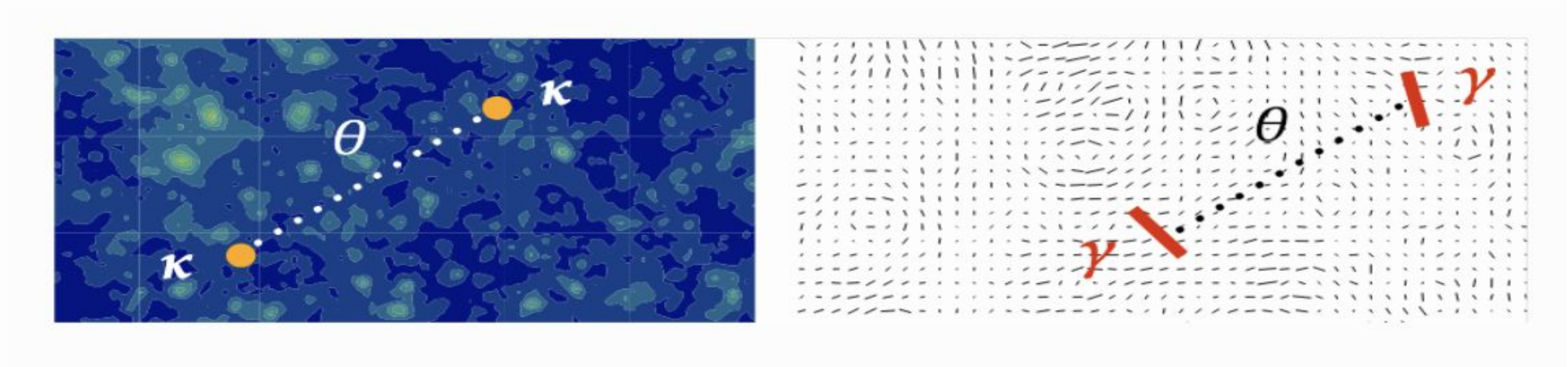
$$G(\chi) = \frac{3}{2}\left(\frac{H_0}{c}\right)^2 \frac{\Omega_\mathrm{m}}{a(\chi)} \int_\chi^{\chi_\mathrm{lim}} \mathrm{d}\chi' \, p(\chi') \frac{\chi' - \chi}{\chi'}$$

matter density

redshift distribution of source galaxies

geometry

Correlations of two shears



- Lensing/convervence power spectrum depends on cosmology
- Provides theory model prediction correlation of κ or γ in Fourier space.

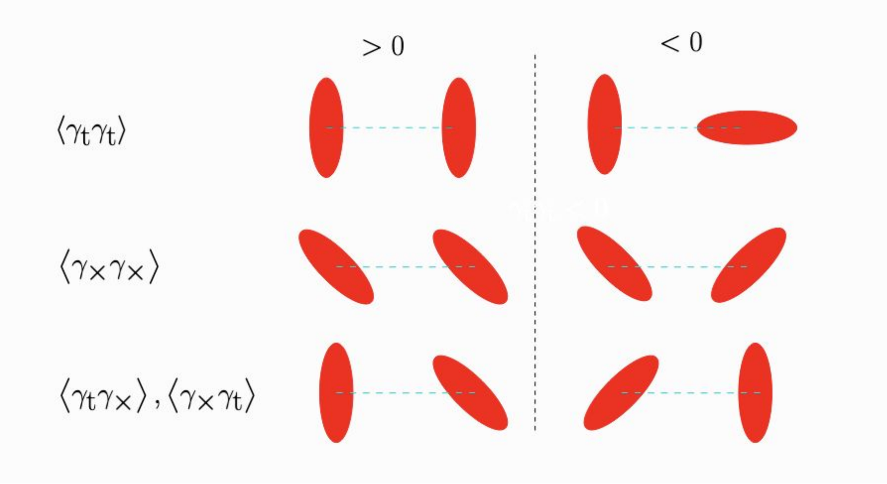
However we measure shear (ellipticity) in real space.

Two options:

1. Fourier-transform data. Square to get power spectrum.
2. Calculate correlations in real space. Inverse-Fourier transform theory Pκ.

Correlations of two shears

We can correlate in 4 ways



$$\xi_+(\vartheta) = \langle\gamma_t\gamma_t\rangle(\vartheta) + \langle\gamma_\times\gamma_\times\rangle(\vartheta)$$
$$\xi_-(\vartheta) = \langle\gamma_t\gamma_t\rangle(\vartheta) - \langle\gamma_\times\gamma_\times\rangle(\vartheta)$$

What about the mixed term?

The shear comes from the derivatives of a potential. This cannot take arbitrary form because the divergence of a curl is zero.

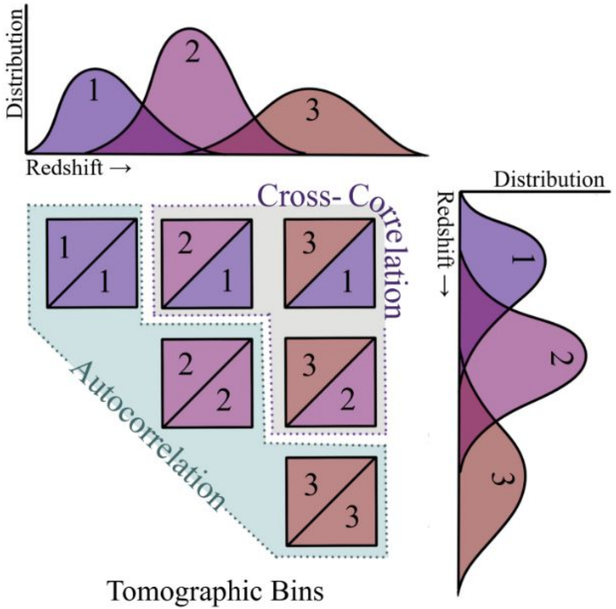
Theoretically, the “b-mode” should be zero

Measuring a non-zero B-mode in observations is usually seen as indicator of residual systematics in the data processing

Tomographic Analysis

Break sample up into redshift bins

This provides constraint on w

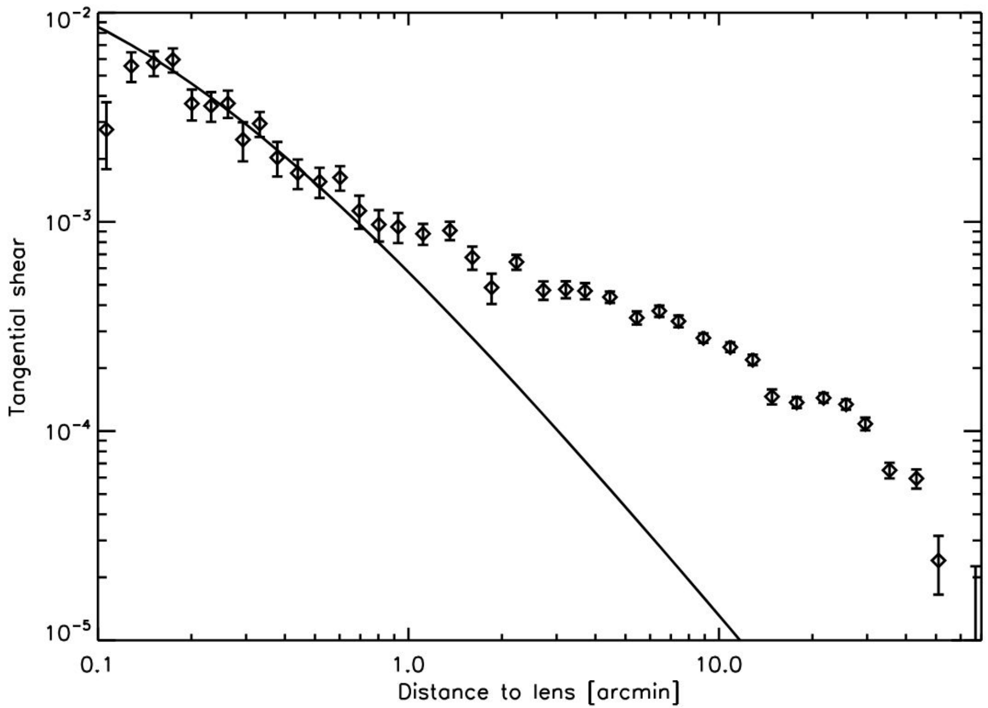


Lensing by galaxies (galaxy-galaxy lensing)

correlates shapes of high-z galaxies with positions of low- z galaxies

Get excess projected mass within an aperture of low-z sample

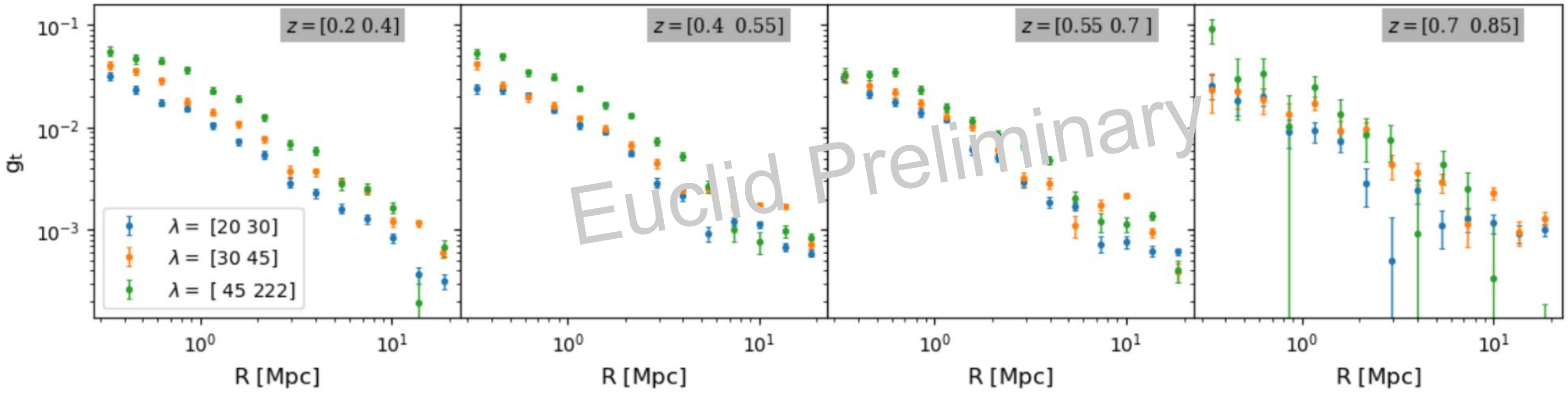
→ Combines with other tracers to constrain galaxy bias



Cluster Masses

Why use weak lensing for cluster masses?

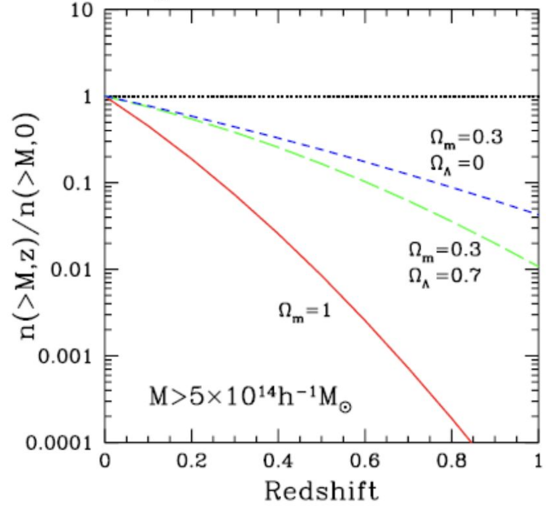
- Measures entire mass, including dark matter
- No equilibrium assumptions
- Noisy measurement, but unbiased on average



Cluster Masses anchor Cluster Cosmology

Calibrate Mass-Observable relation in cluster counts

Borgani et al. 2004



Calibrate the total mass for gas mass fraction test

$$f_{gas} = \frac{M_{gas}}{M_{tot}} = \Upsilon \frac{\Omega_b}{\Omega_m}$$

Cluster Masses

Lensing due to Galaxy Clusters and LSS is not the same:

- higher shear signal (factor of 10)
- higher object density (blending)
- fewer background galaxies for a single cluster (by a factor of 10^4!)

Other WL summary statistics

Statistics	Tomo	Systematics	Params	Forecasts (with II order)	Real data	Survey	References
Summary statistics employed in the analysis	If a tomographic analysis was performed	m = multiplicative bias c = additive bias photo-z = photometric redshifts bar = baryonic effects IA = intrinsic alignment	The cosmological parameters that are constrained	Improvement w.r.t 2PCF %=single parameter Number = 2D FoM	Constraining power > = better ~ = similar < = worst	Survey specs, name or sky coverage + galaxy number density	First author + year.
PDF	no	m, c	Ω_m, σ_8	2		DES-Y1	Patton + 2017
	yes	no	M_ν, A_s	35%, 61%		LSST	Liu, J.+ 2018
	no	no	M_ν, w_0	27%,40%+Planck		Euclid	Boyle+ 2020
Bispectrum	yes	no	$\sigma_8, w_a, w_0, \Omega_\Lambda$	3		4000 deg^2, 100 arcmin^{-2}	Takada+ 2005
	yes	no	Ω_m, σ_8	2		Euclid	Bergé+ 2010
	yes	no	M_ν, Ω_m, A_s	32%, 13%, 57%		LSST	Coulton+ 2019
MF	yes	no	Ω_m, σ_8, w_0	11%, 14%, 14%		LSST	Kratochvil+ 2012
	no	photo-z, m, c	Ω_m, σ_8		biased (syst.)	CFHTLenS	Petri+2015
	yes	no	M_ν, Ω_m, A_s	4		LSST	Marques+2018
	yes	IA, photo-z, m	Ω_m, σ_8	4.2		DES	Zürcher+ 2021
Moments	no	photo-z, m, c	Ω_m, σ_8		> 2PCF	CFHTLenS	Petri+ 2015
	yes	m, c	Ω_m, σ_8	2		3500 deg^2, 27 arcmin^{-2}	Vicinanza+ 2018
	yes	bar, IA, photo-z, m	S_8	20%		DES-Y3	Gatti+ 2019
Peaks	yes	photo-z, m, c	Ω_m, σ_8		~ 2PCF	CS82	Liu X.+ 2015
	yes	photo-z, m, c	Ω_m, σ_8		> 2PCF (2)	CFHTLenS	Liu J.+ 2015
	no	m,c, IA, boost, photo-z	Ω_m, σ_8		~ 2PCF	DES-Y1	Kacprzak+ 2016
	yes	m,c, IA, photo-z, bar	S_8		> 2PCF (20%)	KiDS-450	Martinet+ 2017
	yes	no	M_ν, Ω_m, A_s	39%, 32%, 60%		LSST	Li Z.+ 2018
	yes	no	M_ν, Ω_m, A_s	63%, 40%, 72%		Euclid	Ajani+ 2020
Minima	yes	IA, photo-z, m	Ω_m, σ_8	2.8		DE	Zürcher+ 2021
Minima+Peaks	yes	bar	M_ν, Ω_m, A_s	44%, 11%, 63%		LSST	Coulton+ 2020
Voids	no	no	Ω_m, S_8, h, w_0	$\gtrsim$ 2PCF		LSST	Davies+ 2020
1D M_{ap}	yes	no	Ω_m, S_8, w_0	57%, 46%, 68%		Euclid	Martinet+2020
M. Learning	no	no	Ω_m, σ_8	5		3500 deg^2, no noise	Gupta+ 2018
	no	no	Ω_m, σ_8	~45% (dep. noise)		KiDS-450	Fluri 2018
	yes	photo-z, m, c, IA	S_8		> 2PCF (30%)	KiDS-450	Fluri 2019
Scattering T.	yes	no	M_ν, Ω_m, w_0	40%, > 2PCF		LSST	Cheng S.+ 2021
Starlet ℓ_1- norm	yes	no	M_ν, Ω_m, A_s	72%, 60%, 75%		Euclid	Ajani+ 2021

Summary of part I

Lensing deflection depends on distance geometry and mass distribution

We can use Galaxy ellipticities to estimate the gravitational shear signal, but we need an ensemble of galaxies

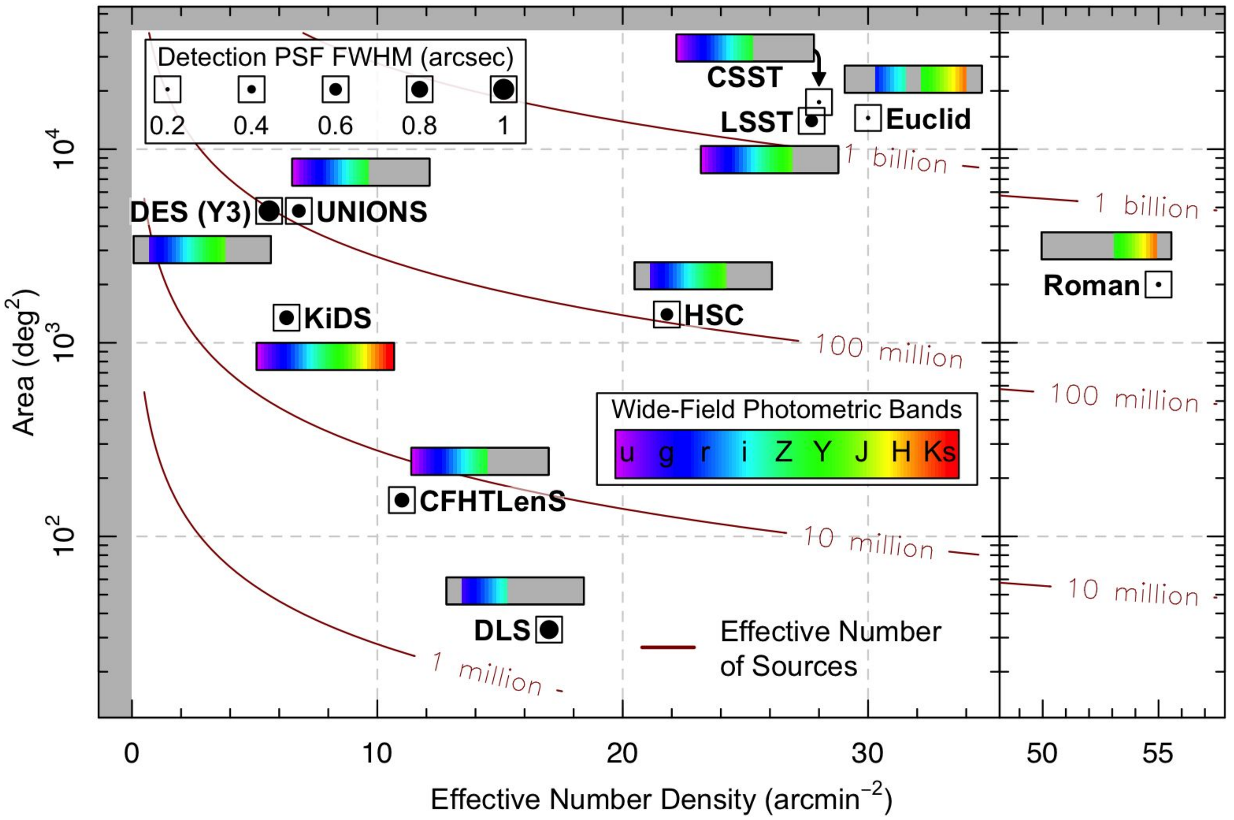
To constrain cosmology we can use

1. Weak lensing around clusters to calibrate cluster masses
2. Weak lensing around galaxies
3. Weak lensing of large scale structure

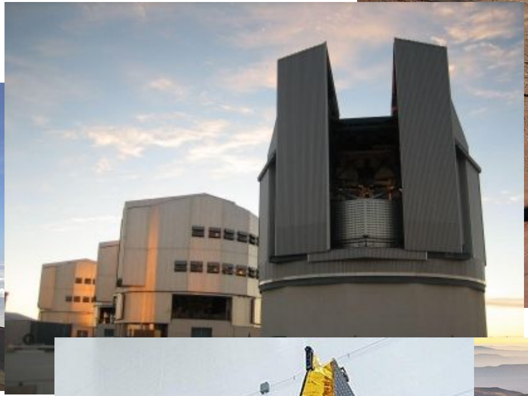
Part II

Making the catalogs

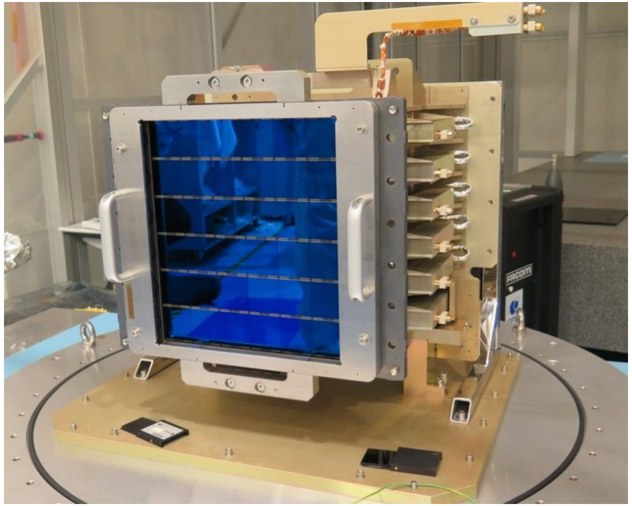
We need to measure many galaxy shapes and distances



Wide field telescopes



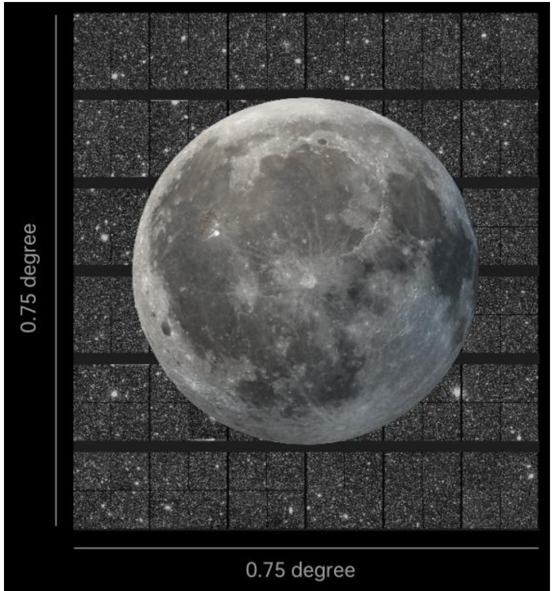
Multi-Chip CCD Camera

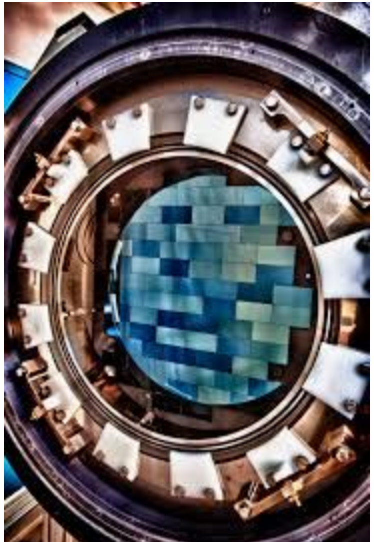


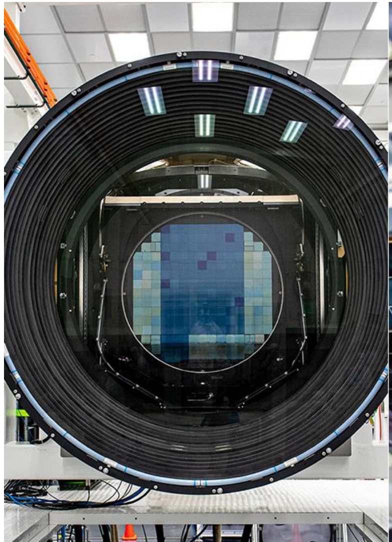
With a huge FOV, readout causes problems

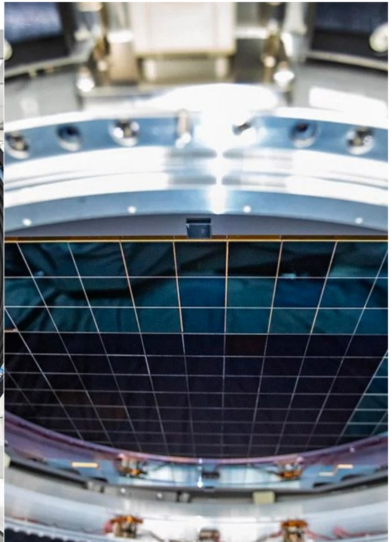
- Increased noise
- Takes a lot of time

→Break into multiple chips ~ 8-16 Mpixels each





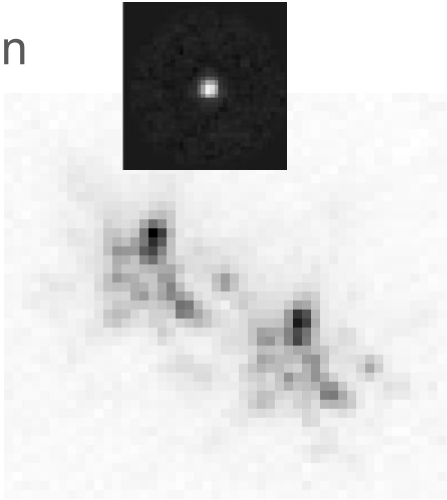


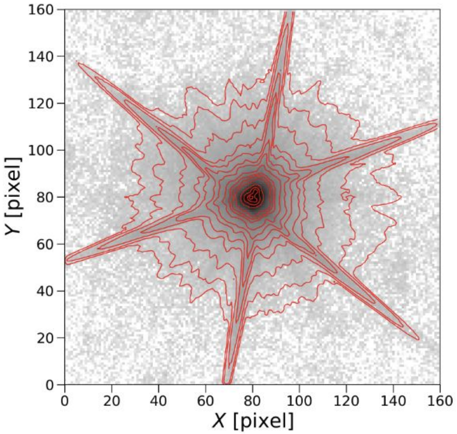


Good Observing Conditions

Galaxy shape is convolved with instrument point spread function

- On the ground, this depends on the atmosphere (seeing)
  - Turbulence in the atmosphere causes stars to “twinkle”
  - Mitigate with high altitude, dry areas, dark nights with no moon
  - (Figure: short exposure of a binary star)
  - Typical size 0.6-1 arcsec
  -
- In space, we are diffraction limited
  - PSF is smaller and more stable
  - Typical size 0.1 arcsec
  - PSF is very complicated





Lensing Survey Telescopes and Cameras

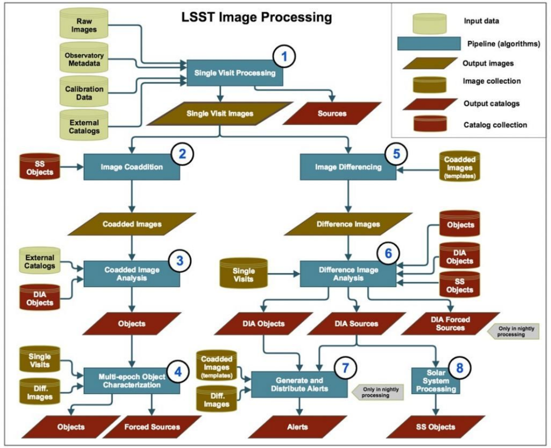
Telescope	Mirror diameter (m)	Location	Camera	Chips	FOV (sq. deg)
Euclid	1.2	L2, space	VIS	36	0.56
VST	2.6	Cerro Paranal, Chile	OmegaCam	32	1
CFHT	3.6	Mauna Kea, Hawaii	MegaCam	40	1
Victor Blanco	4	Cerro Tololo, Chile	DECam	62	2.2
Subaru	8.2	Mauna Kea, Hawaii	Hyper SuprimeCam	104	1.8
Vera Rubin	8.4	Cerro Pachon, Chile	LSSTCam	189	9.6

Computing Power

We need to process terabytes of image data (Rubin: 20 Tb per night, 80Pb in total)

EUCLID: CC-IN2P3 (France), AMONRA (Italy), ++

Rubin: NERSC (USA), CC-IN2P3 (France), LIneA (Brazil), ++

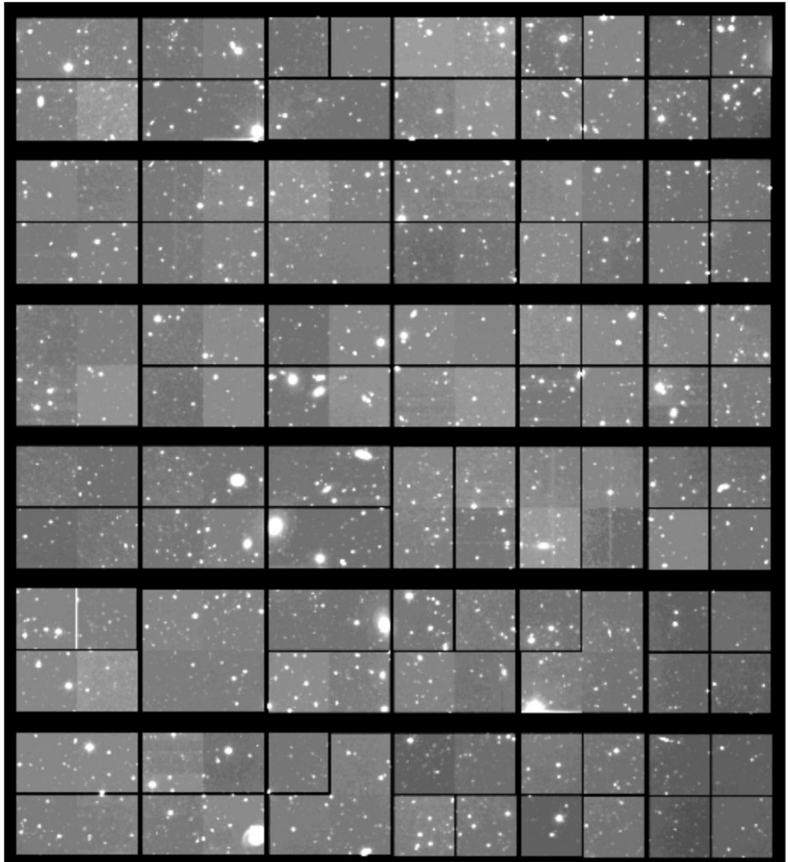


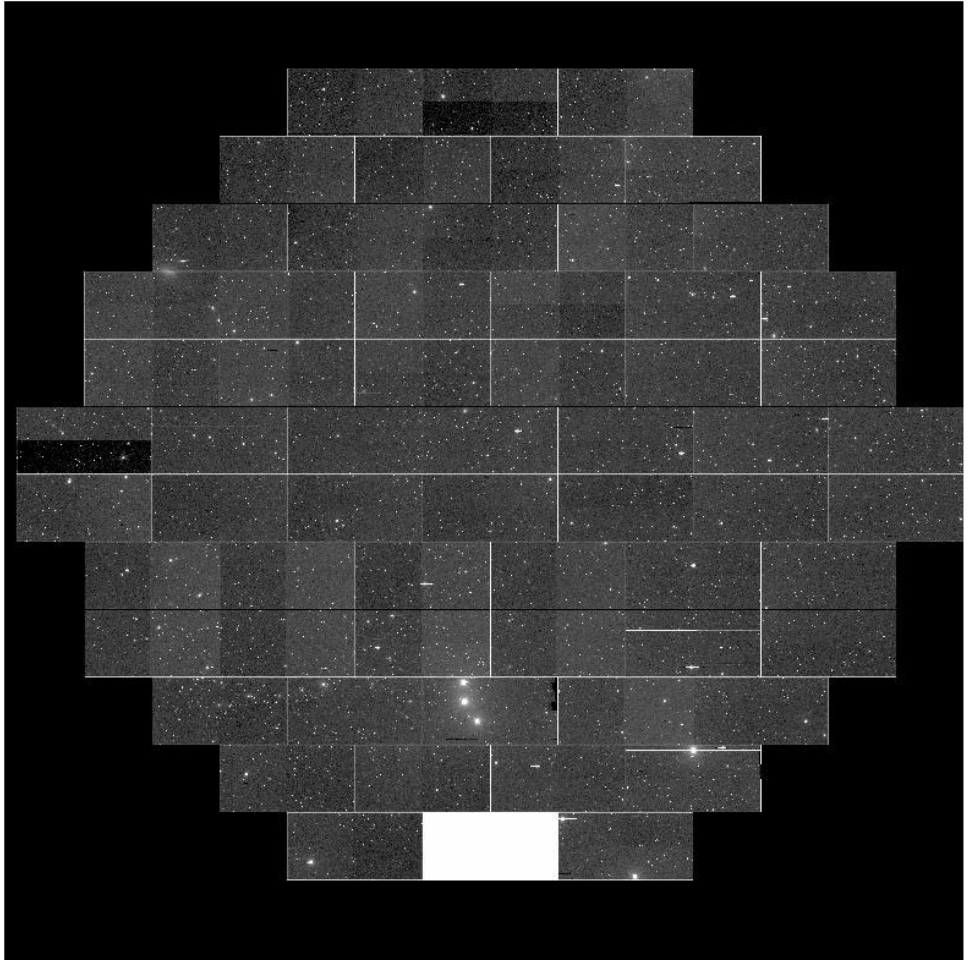
Pixel level processing

Ideal image:

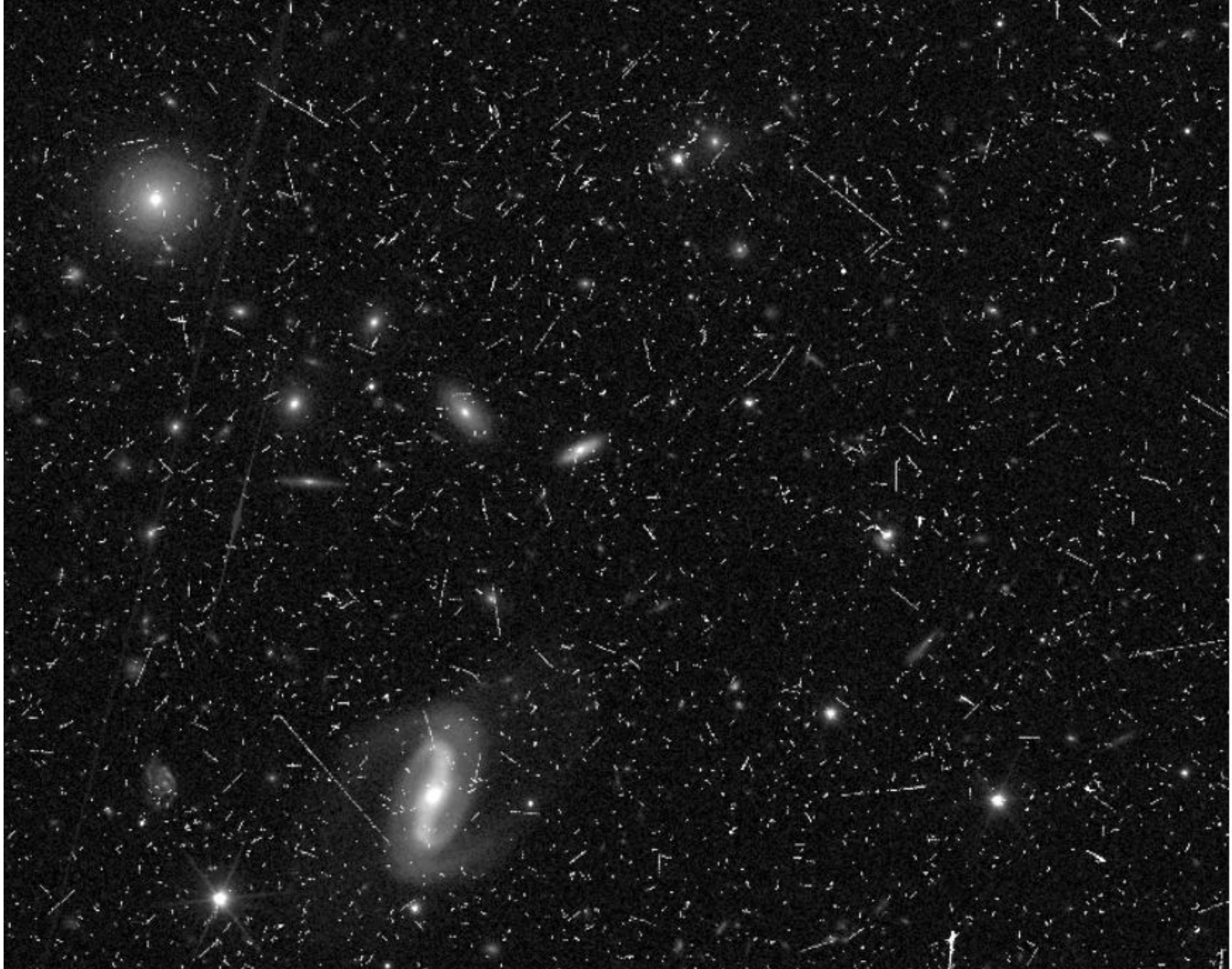
- equal-sized pixels with linear response
- pixels are independent
- PSF (Point Spread Function) independent of object's flux
- only image astronomical sources of interest
- Pixels are on consistent flux scale in all ccds

Real images





Real Images

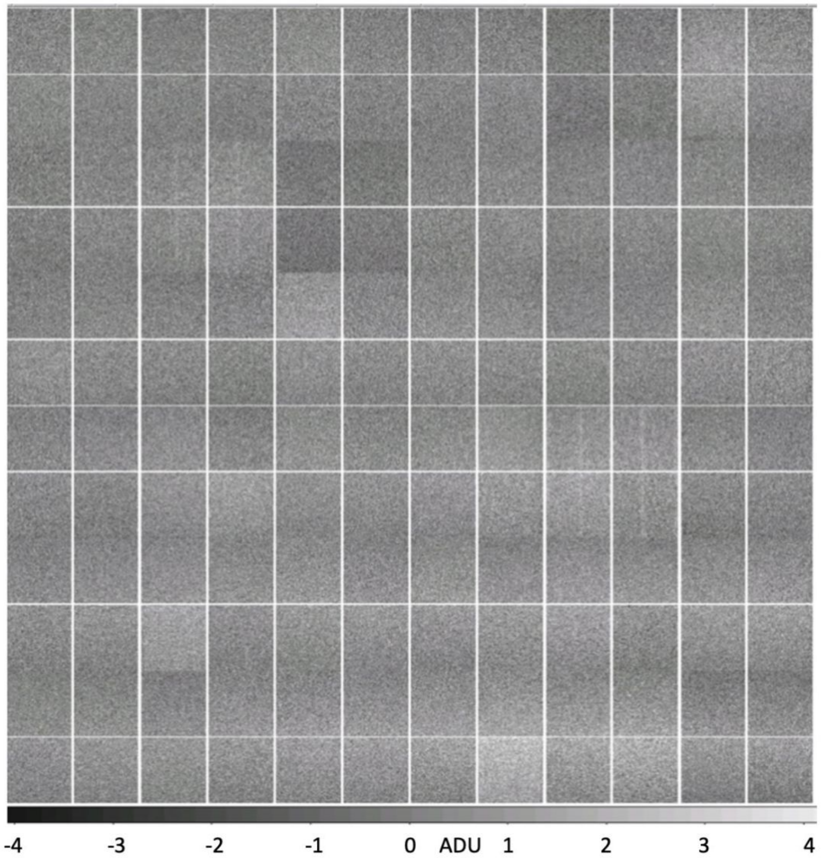


Bias

CCDs have a voltage offset

Take zero-second exposure to remove inherent sensor noise

“Readout noise”

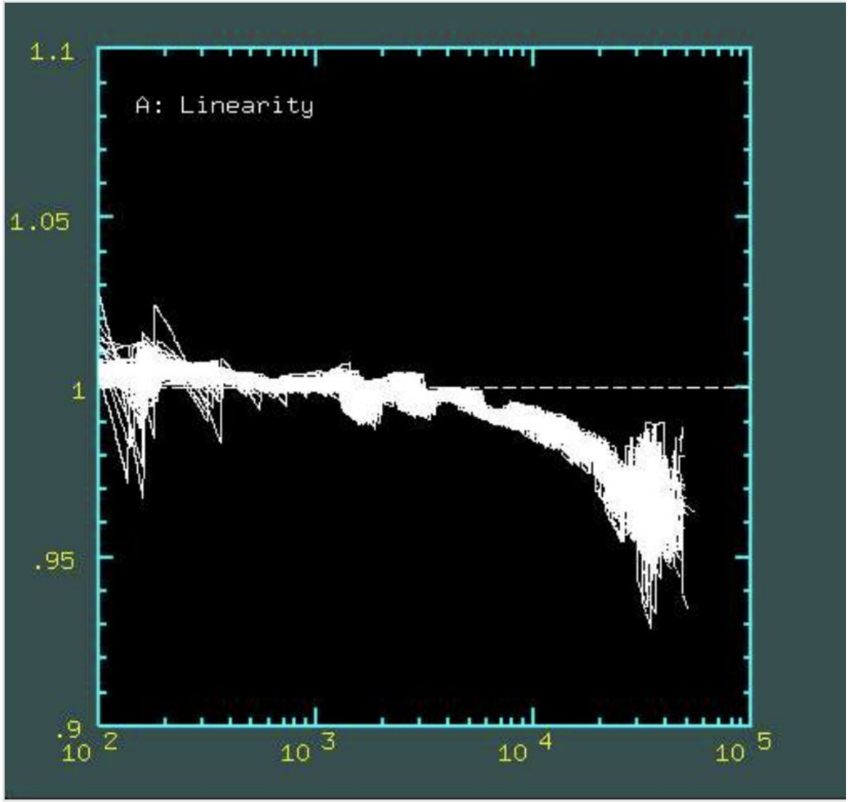


Bias frame from VIS

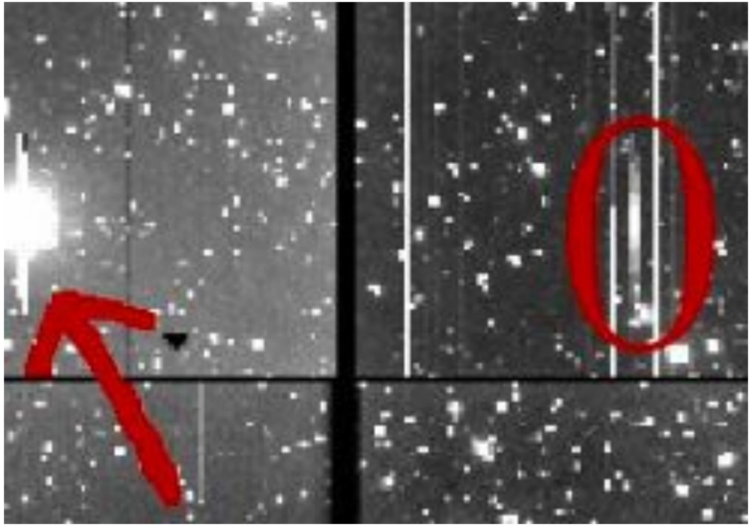
Non-linearity

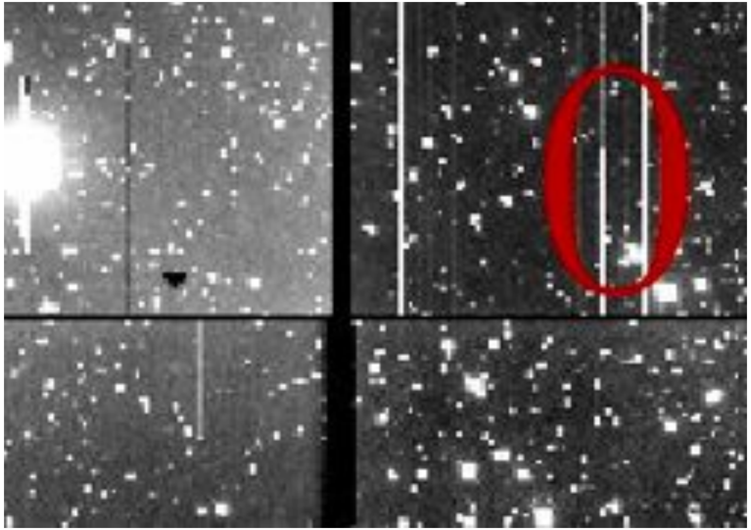
Counts should be proportional to photons for image to be calibrate-able

Calibrate by taking exposures of a uniform screen for an increasing about of time

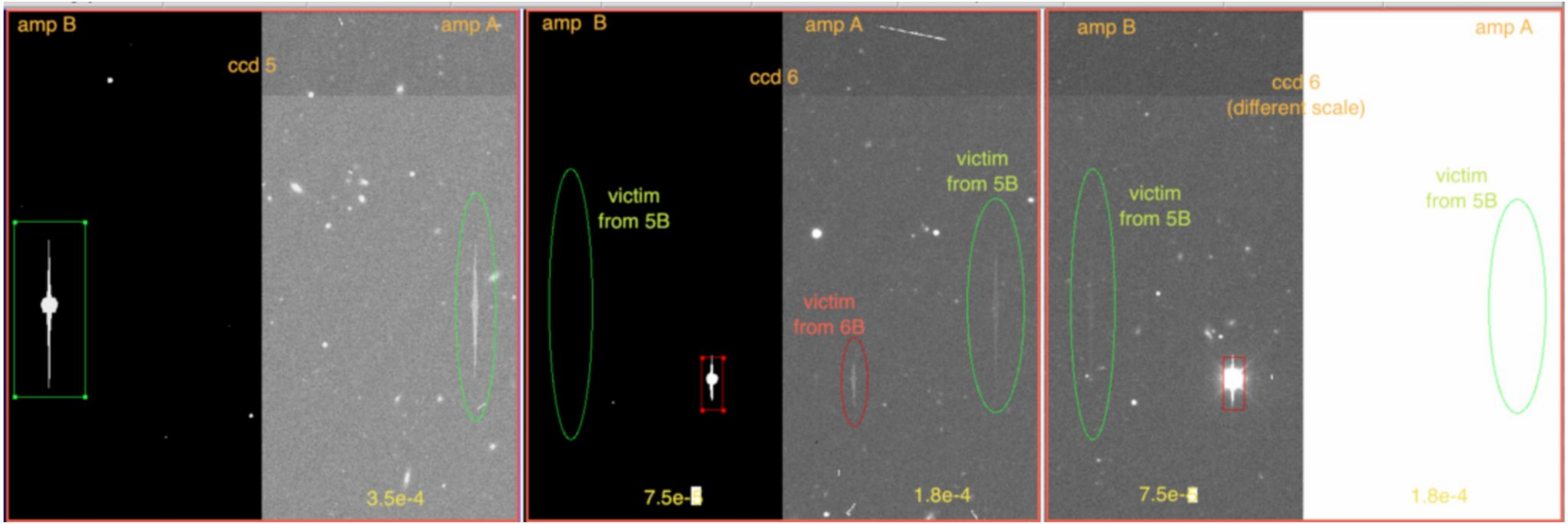


Crosstalk

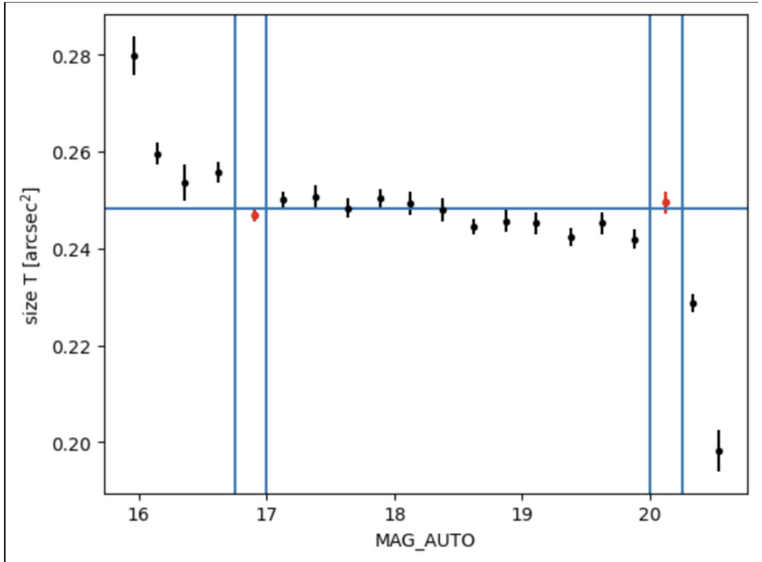


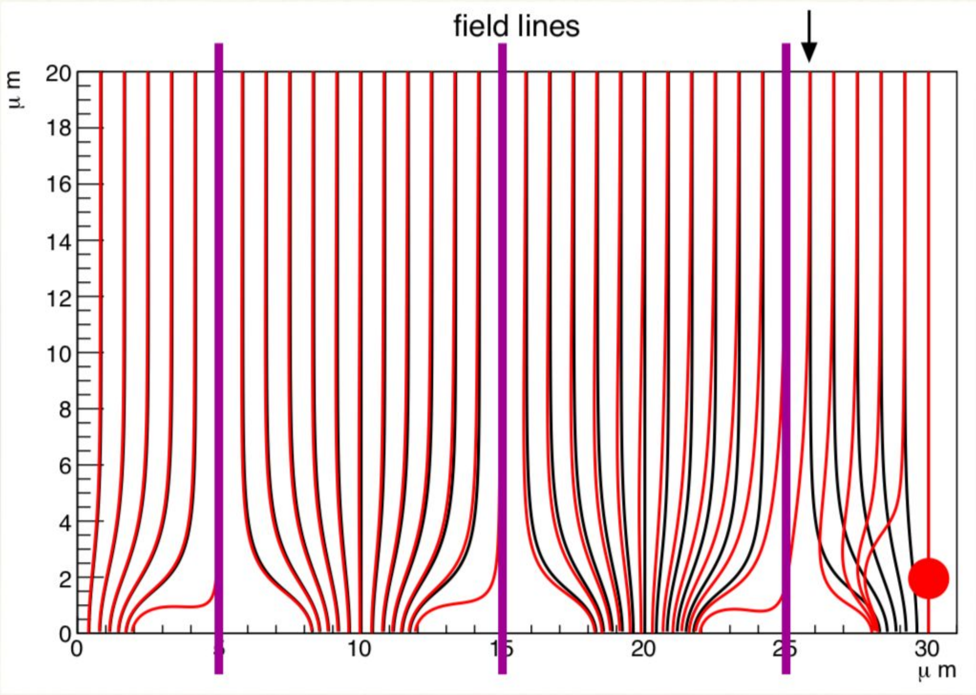


More Crosstalk



Brighter fatter effect





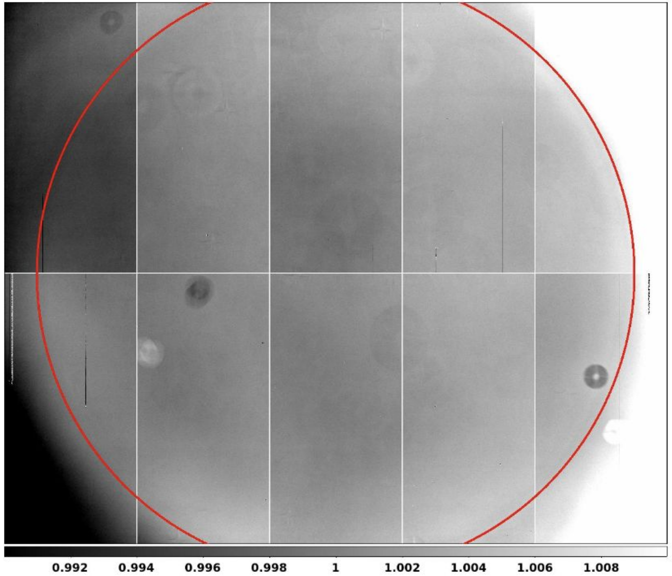
Want to measure psf from stars, but psf slightly depends on magnitude

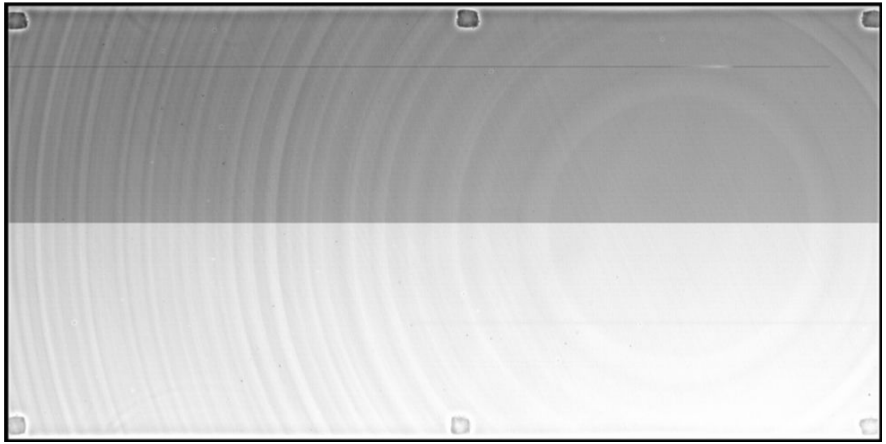
Flat Field

Von der Linden 2012

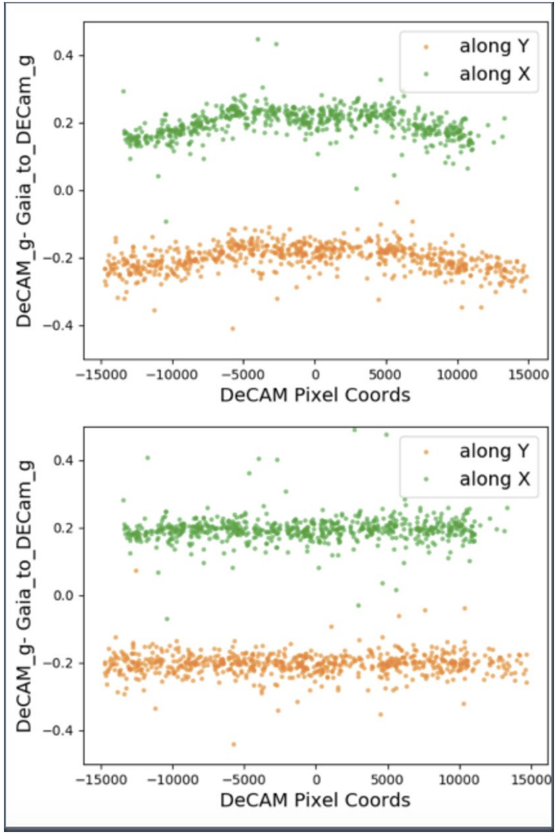
Pixels have different responses- we need to normalize them to the same level

Divide by “domeflat”



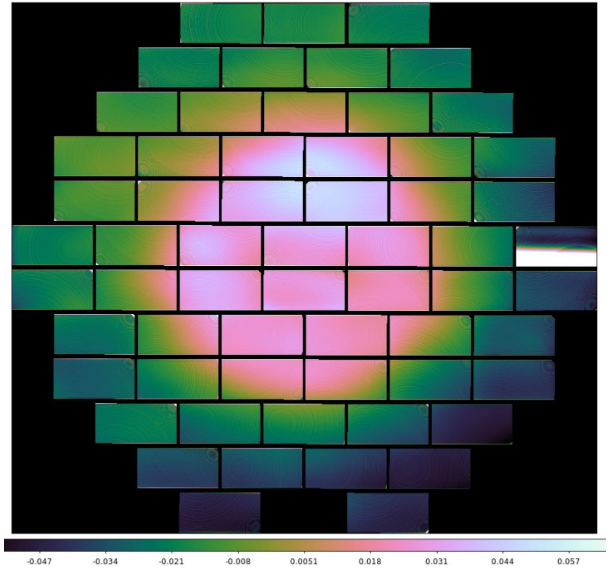


Starflat



- ~10% correction across focal plane
- does not assume uniform pixel size
- response to focused starlight, not scattered light

Take dithered exposures and ensure the same star has the same flux anywhere on the focal plane



Sky Subtraction

Large-scale variations across focal plane are removed and produce a background mean of zero

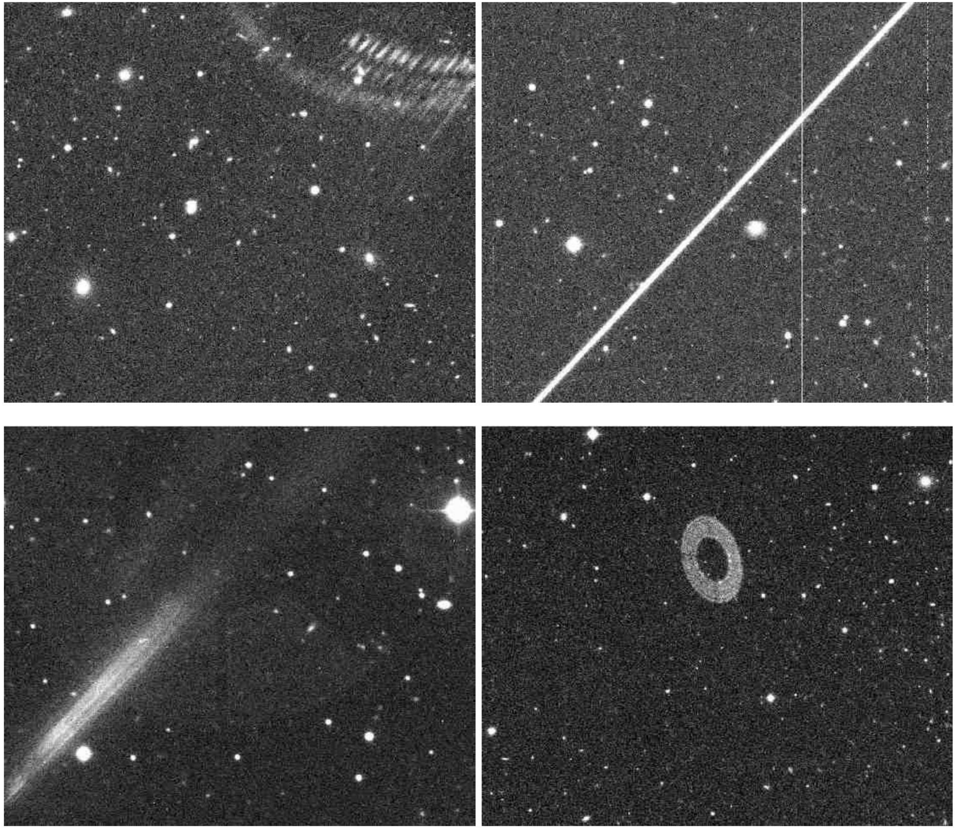
What is sky background: light in the image even where no sources are present

Ground based- light diffusion from the atmosphere “airglow”, scattered moonlight and starlight

Space based- scattered starlight, zodiacal light

Why do we need sky subtraction?

Masking



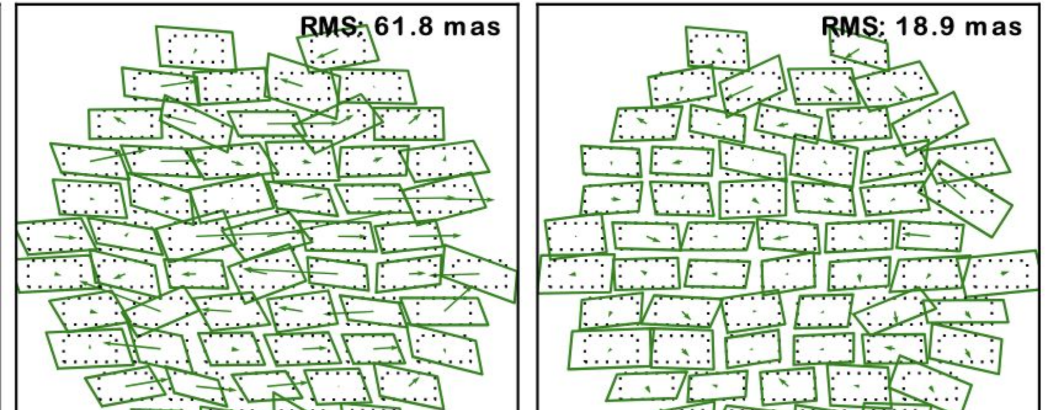
Erben 2006

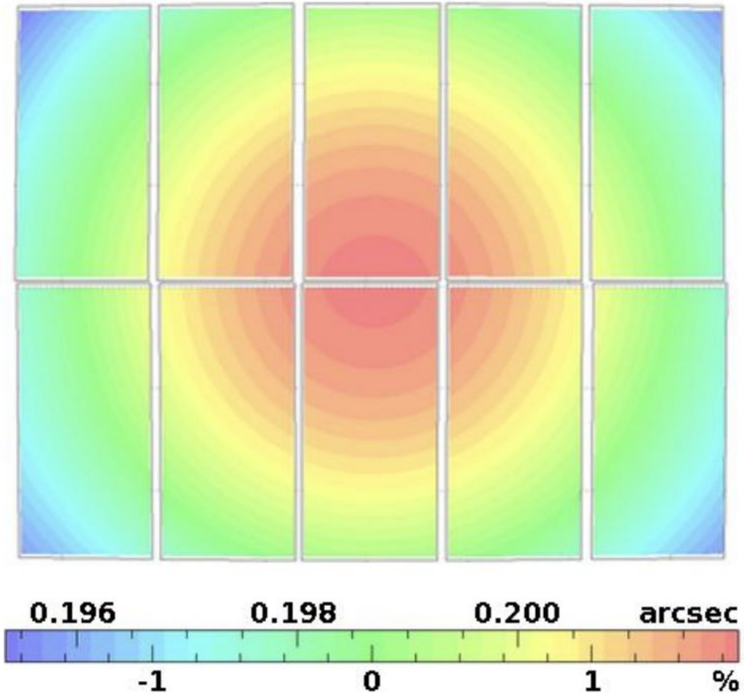
Astrometric calibration

Astrometry: map from pixels to sky coordinates

Consistency in positions between images **and** with external data

Constrain model using stellar positions





Von der linden 2012

Photometric Calibration

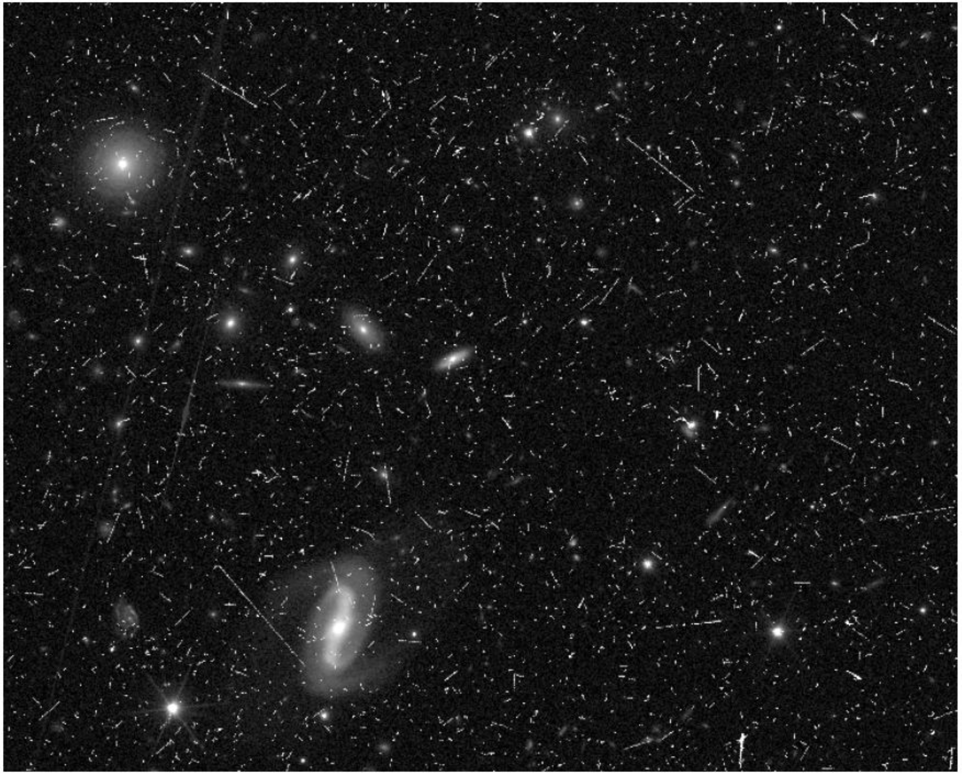
$Mag = -2.5\log(flux) + zero\ point$

Kinds of photometric calibration

1. Relative calibration between exposures
2. Color calibration between different filters
3. Absolute flux calibration

Photometric calibration sets relative zero points across ccds and exposures

Stacking (Coaddition)



One euclid VIS imag vs a stack of 42 images

Stacking (Coaddition)

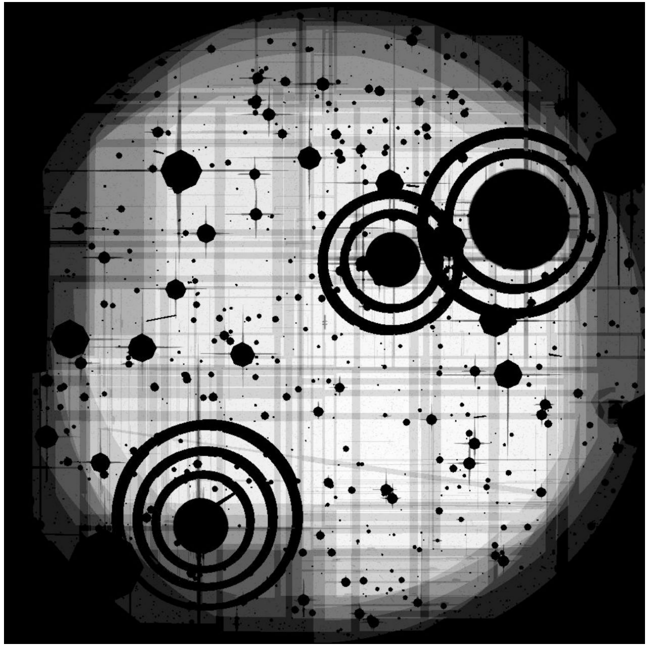
Resample pixels onto a common grid, then combine

Why stack?

- Cover chip gaps
- Increase SNR
- Remove transient objects (median stack)
- Save processing time measuring on coadd

Why not stack?

- Resampling correlates noise
- The psf will have discontinuities unless you make a cell-based coadd



Weight map of a stacked image

How often do we need to calibrate?

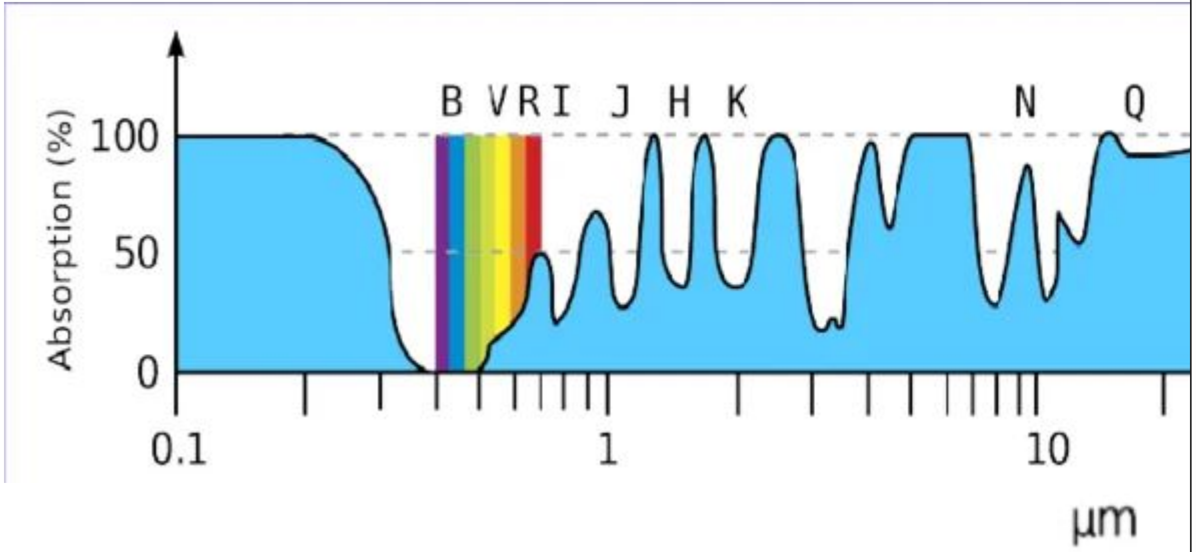
Some corrections are **static** (crosstalk, non-linearity, brighter-fatter)

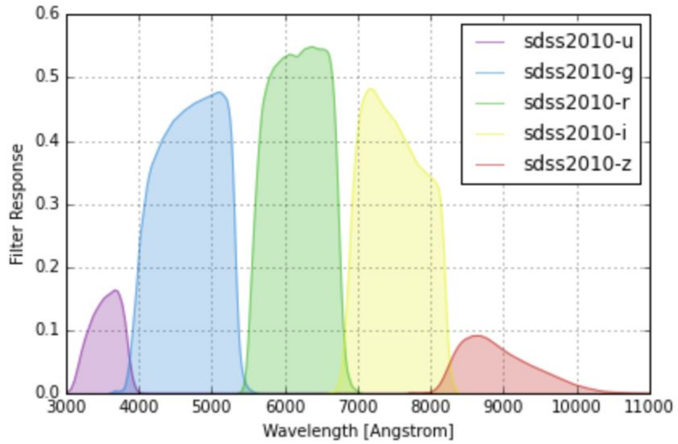
Some corrections need to be recalibrated **whenever the camera is adjusted** on the instrument (starflat)

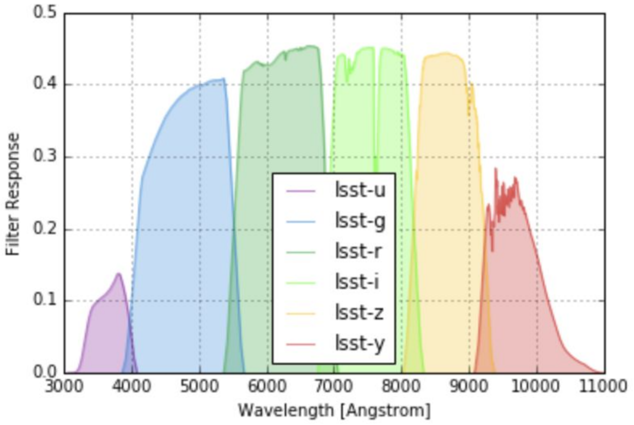
Domeflats are usually taken **every day**

Ground-based data is processed together in ~2 week chunks and flats and bias exposures are averaged over this period

Bonus: Broadband photometric filters







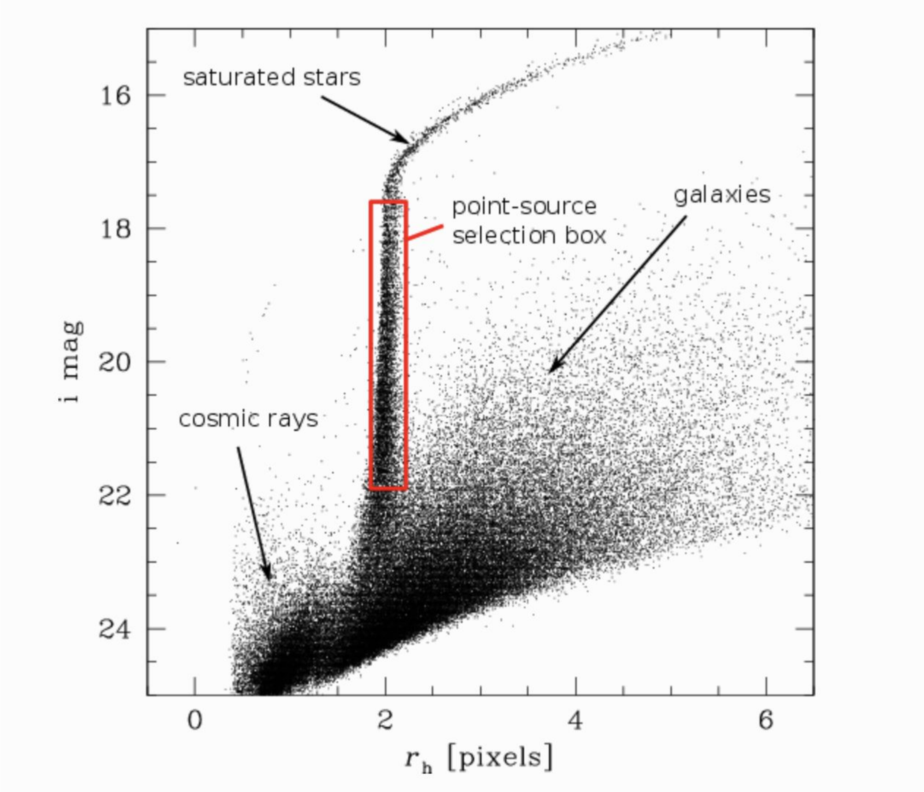
Finally, we can produce catalogs!

Source Detection and Classification

Perform detection on deepest image

Often use SExtractor (Bertin 1996)

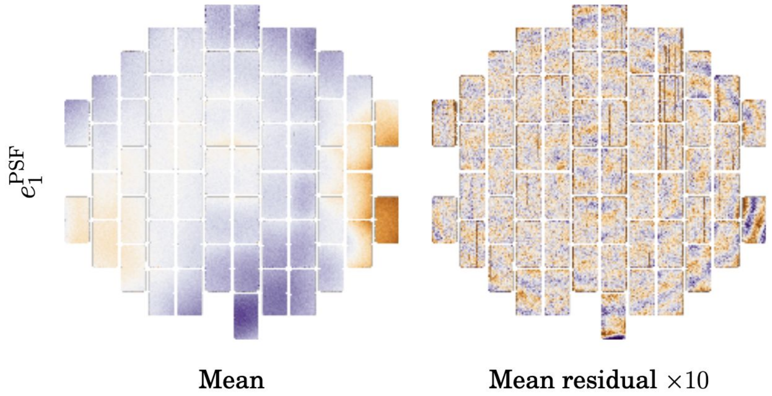
Using median image reduces detection of spurious objects



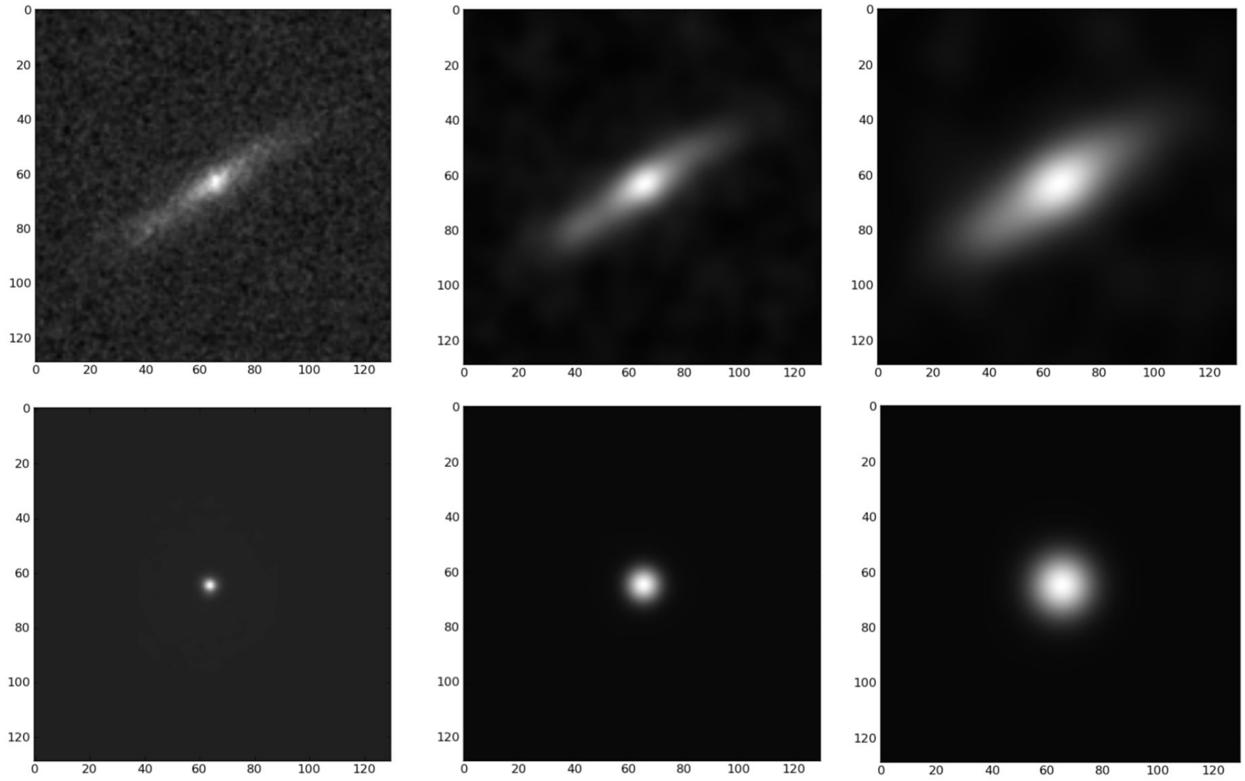
Point Spread Function (PSF) Modeling

Image is convolved with the PSF, which comes from the instrument and atmosphere

- varies with position on the focal plane and time- fit per exposure
- Stars are point sources- use them to model PSF
- Select stars, measure psf and interpolate to get a model for the whole ccd



How does psf affect shear estimation?



How does psf affect shear estimation?

1. Blurring and rounding light profile
2. Imprint coherent shear that depends on psf shape
   a. PSF size error can induce an multiplicative bias on the shear
   b. PSF shape error can lead to additive bias

Point Spread Function Modeling

Look at quality of interpolation

"Rho statistics"

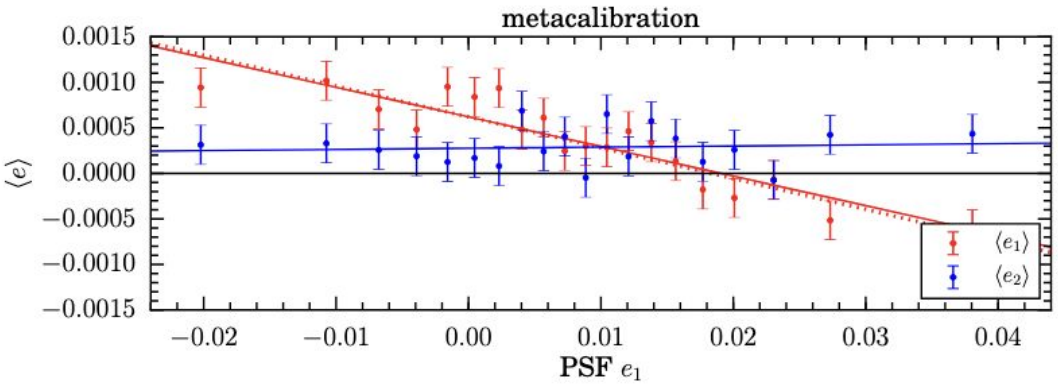
$$\rho_1(\theta) \equiv \langle \delta e^*_{\rm PSF}(\mathbf{x}) \delta e_{\rm PSF}(\mathbf{x}+\boldsymbol{\theta}) \rangle$$
$$\rho_2(\theta) \equiv \langle e^*_{\rm PSF}(\mathbf{x}) \delta e_{\rm PSF}(\mathbf{x}+\boldsymbol{\theta}) \rangle$$

1. Derive additive correction from psf
2. Minimize this correction

Look at psf contribution to shear

$$e_{\rm gal} = e_{\rm true} + \alpha e_{\rm PSF} + c.$$

"PSF leakage"



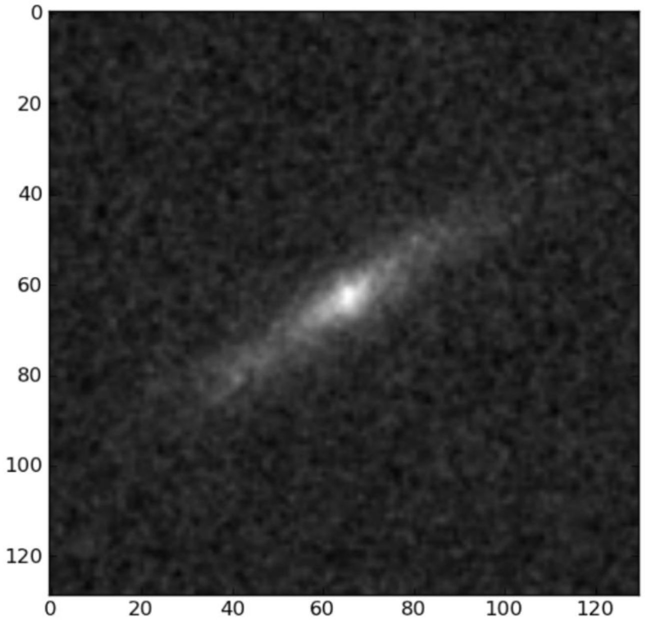
Zuntz 2016

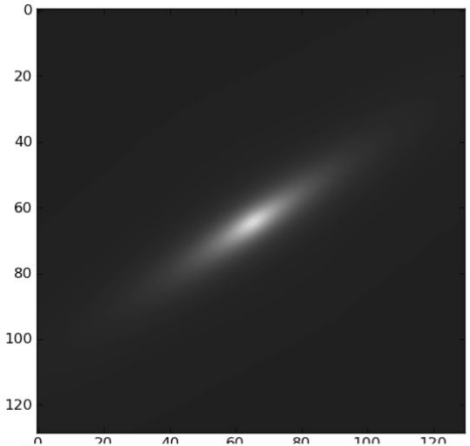
Shape Measurement: Model fitting

Model fitting: forward-modelling methods

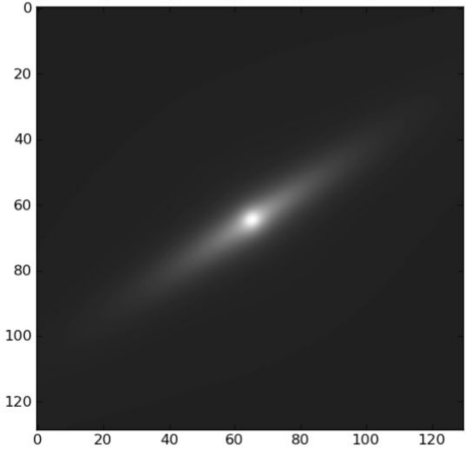
- Generate parametric models of galaxy images $g(x_1,x_2)$ (e.g. Gaussian, Sersic, bulge + disk)
- Get psf model from the data $P(x_1,x_2)$
- Compare $g(x_1,x_2) \otimes P(x_1,x_2)$ to data to fit galaxy parameters

Example: HST i-band image



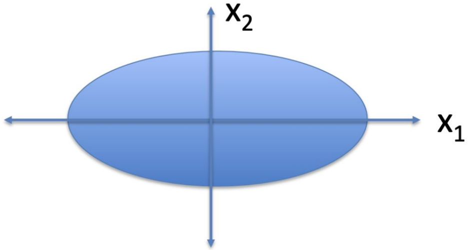


Model: Sersic
Flux, n, shape,
size, center
→7 parameters



Model: 2 flux 2 size
4 shape 4 centroid
→12 parameters

Shape measurement: Moments



What are moments?

Consider infinite SNR noise-free galaxy:

Zeroth moment: Flux

$$M_0 = \int I(x_1,x_2)\, dx_1 dx_2$$

First moment: Centroid

$$M_i = \int I(x_1,x_2)\, x_i\, dx_1 dx_2 \,/\, M_0$$

Second moment: Shape, size

$$M_{ij} = \int I(x_1,x_2)\, (x_i-M_i)(x_j-M_j)\, dx_1 dx_2 \,/\, M_0$$

Shape measurement: Moments

Real galaxies have noise, and the moments will diverge unless we add a weight function!

Moments: inverse methods

- Choose a weight function
    - Use a crude size estimate for a circular gaussian
    - Use iterative process “adaptive moments”
- measure second-order moments on the image data
- apply corrections to compensate for the effects of the psf

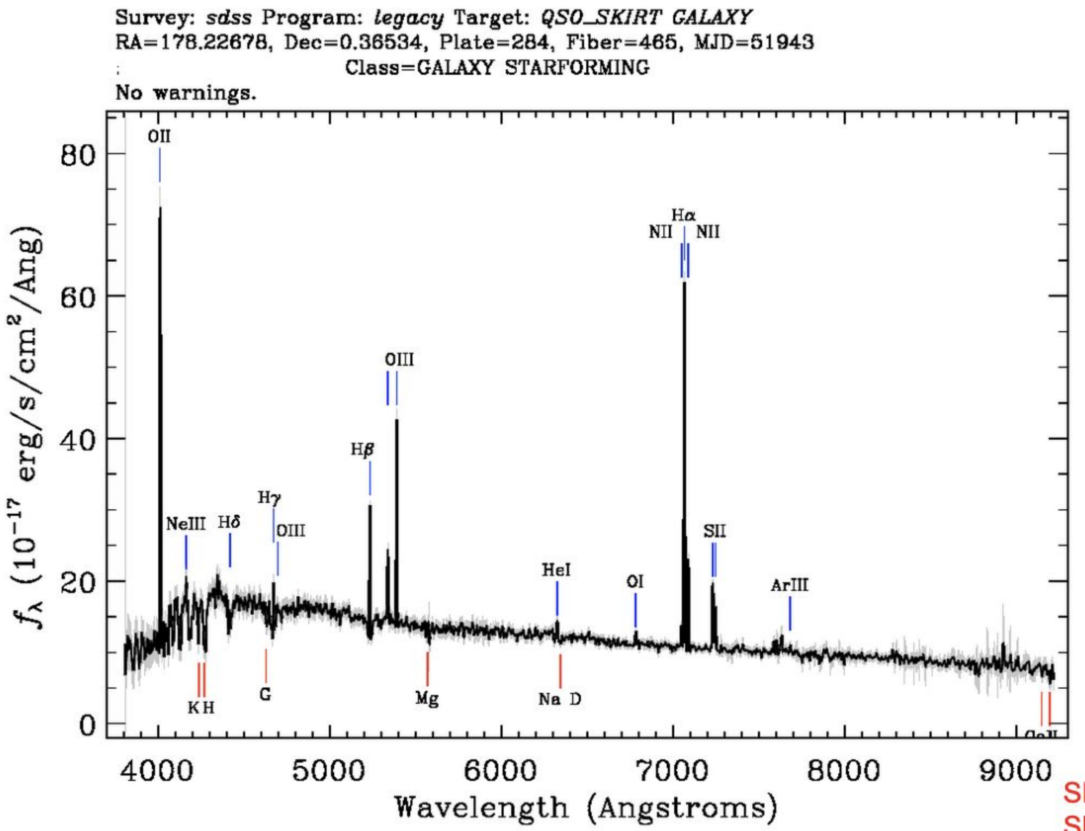
What about this galaxy?

Shape is not a well defined property for realistic galaxies!

However, we just need ensemble statistics of estimator to have a well defined response to shear

Note: we cannot meaningfully compare shapes directly from two different estimators, we can only compare ensemble statistics

How do we measure this galaxy’s redshift?



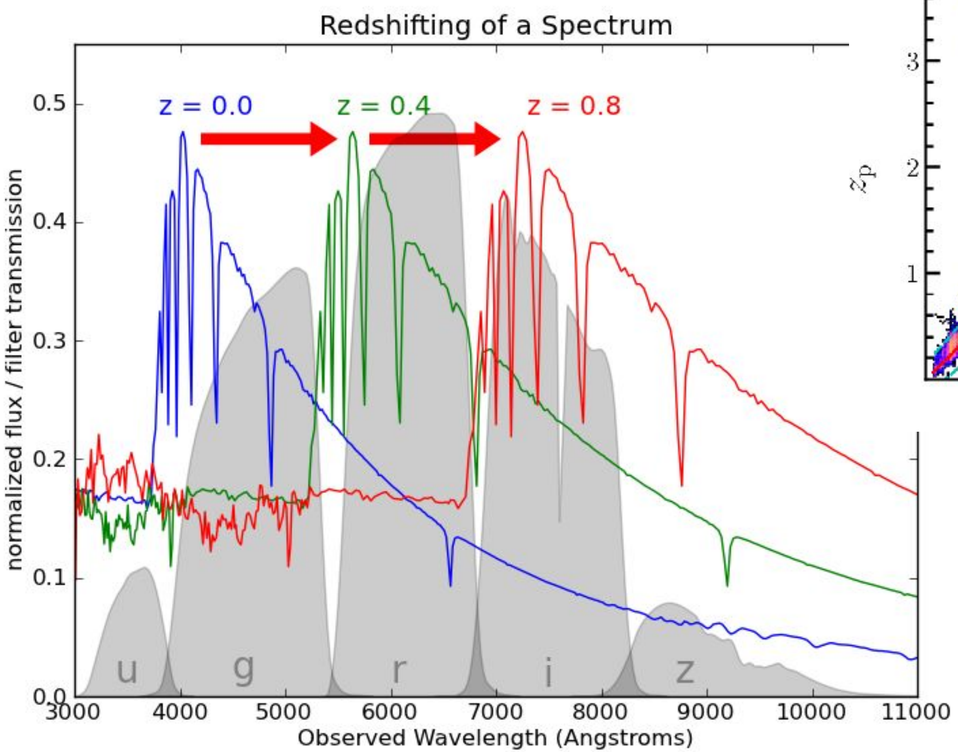
SDSS Skyserver

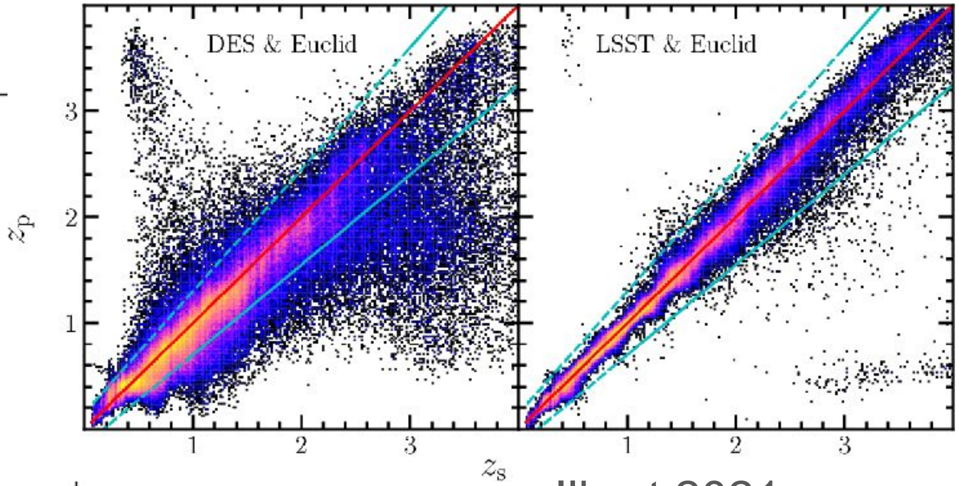
Bad news:

Galaxies where we measure shapes tend to be faint- getting spectra for these is very expensive

It would take forever to get spectra of all galaxies for even a small weak lensing survey

Measuring Redshifts: Photometric Redshifts





Ilbert 2021

Create ultra-low resolution spectra with broadband filters

Much less information per galaxy but many more galaxies!

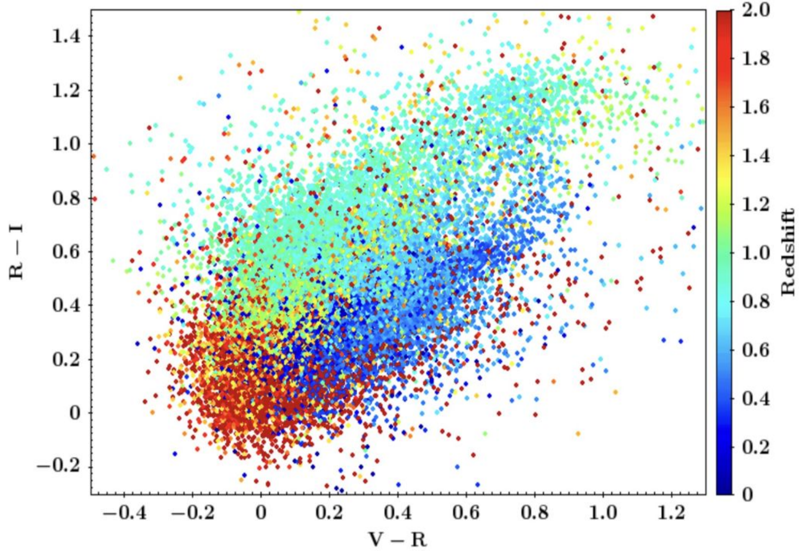
Measure flux in broadband filters

Aperture photometry: Convolve to worst “seeing” or psf, measure in apertures

Model fitting: in analogy to shape measurement, but we need to jointly fit the model across bands to preserve galaxy colors

→ Colors correlate with redshifts

- Get photo-z from photometry with template fitting or ML



Will Hartley

Shear Calibration

Galaxy shapes are estimator dependent, we want to find gravitational shear

we want to measure response of **ensemble statistics** of a shape estimator to shear

$$g_i = (1 + m_i) g_i^{\mathrm{tr}} + c_i$$

Two methods

1. Simulations: simulate galaxies, apply constant shear, and measure response of shape estimator
2. Apply external shear to the images directly and compute response: “metacalibration”

Where does m-bias come from

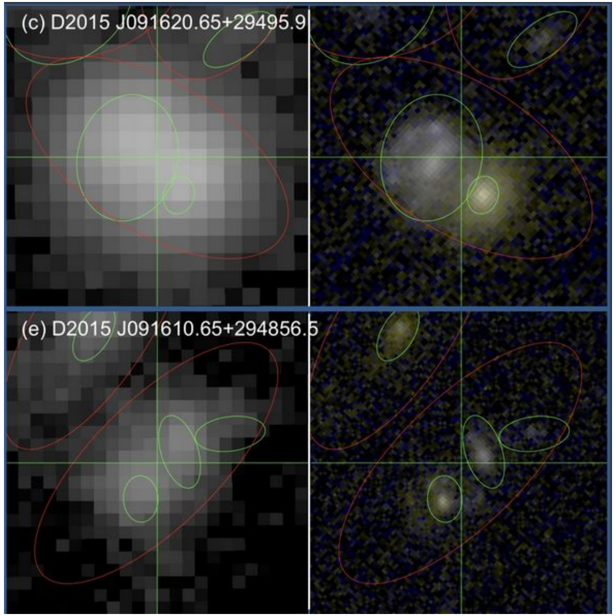
Model bias: model does not really fit galaxy

Noise Bias: Galaxy is pixelated

Blending

Selection effects: e.g. highly elliptical galaxies might not make snr threshold

PSF size errors

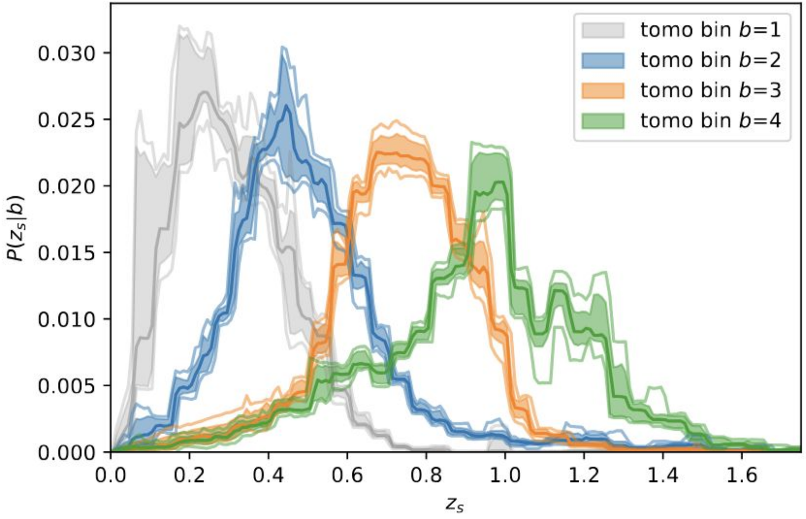


Dawson 2016

Photo-z Calibration

Most weak lensing measurements do not care about individual photo-zs, only on the ensemble N(z)

We can use spectroscopic redshifts to calibrate N(z)



DES Y3 N(z)
Grandis 24

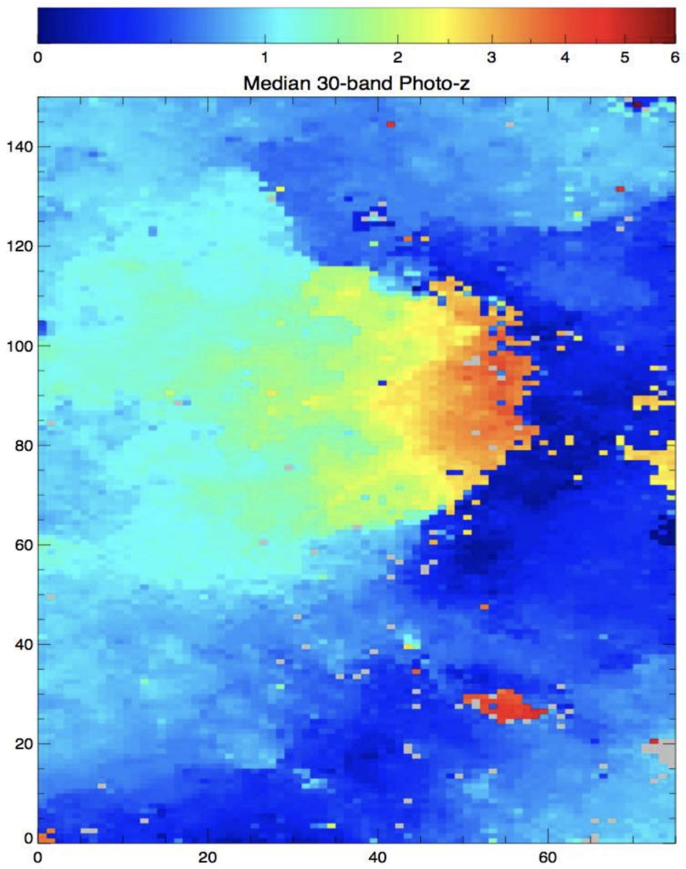
Photo-z Calibration

Direct method:

Reweight spectroscopic sample to look like photometric sample

Som:

Map colors to spec-z in training sample, assign this redshift to test galaxies with this color



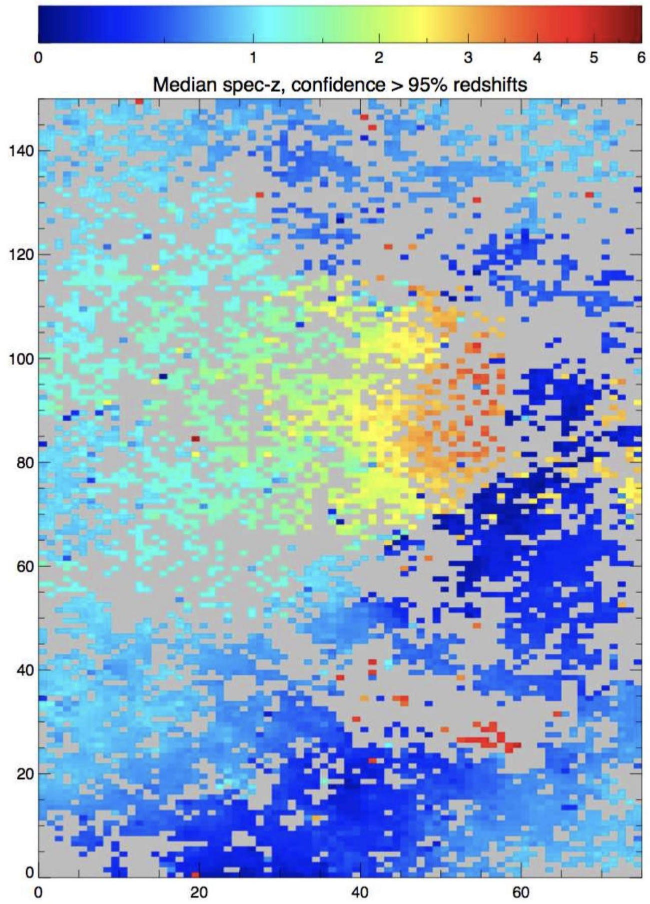
Masters 2015

Photo-z Calibration

Problem: missing spec-z

Interpolating is dangerous- discontinuities in map!

SOM is okay for DES and KiDS, but Euclid and Rubin have many faint galaxies, where there are no spectra



Masters 2015

Photo-z Calibration

Cross-correlation calibration: “clustering redshifts” or “clustering-z”

Use the fact that galaxies are embedded in shared LSS to recover their redshift distribution

Cross correlate sample with known (specz) redshifts and unknown sample. **Spec-z sample need not extend to faint magnitudes**! e.g. DESI, 4MOST

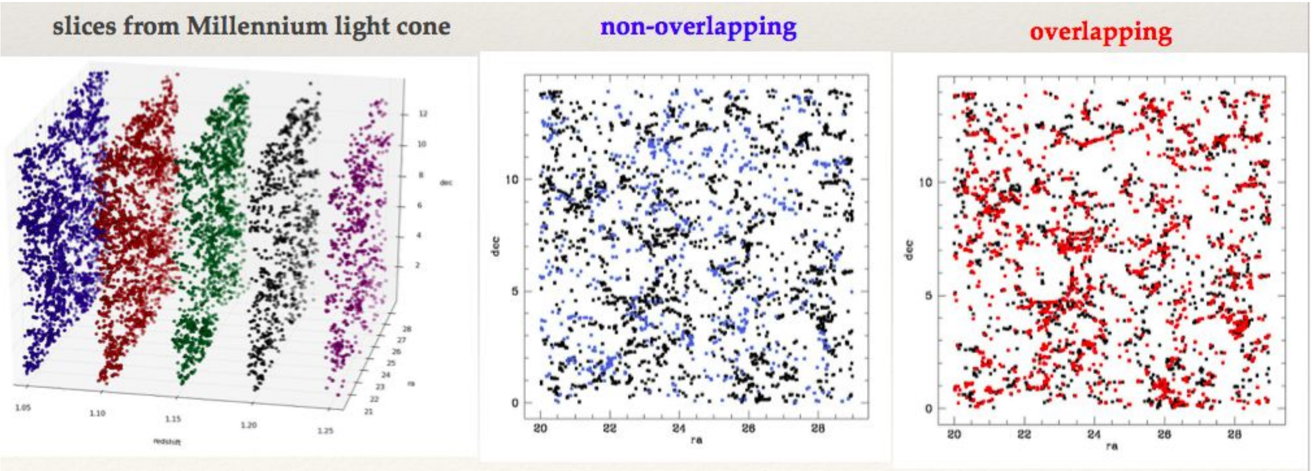
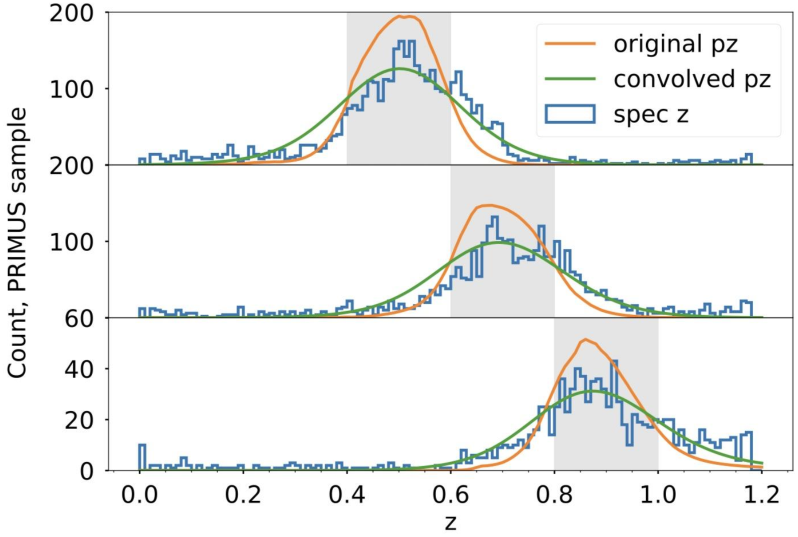
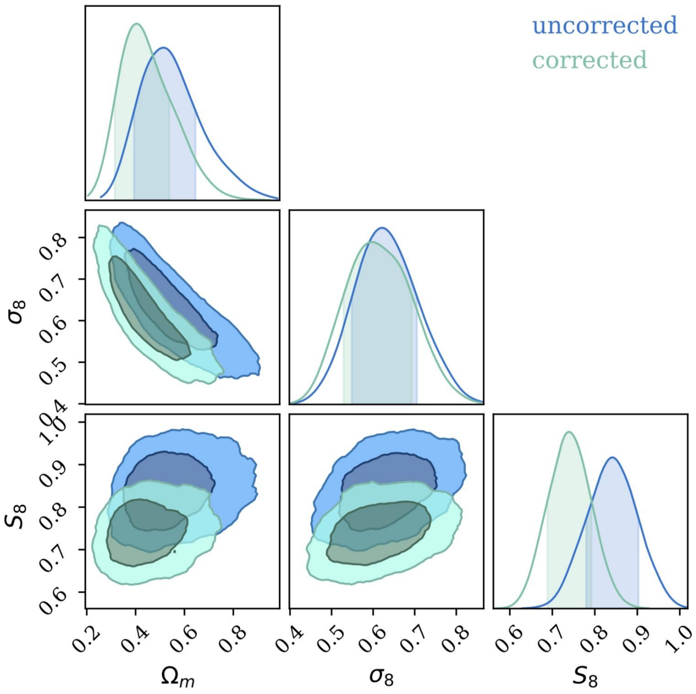


Photo-z Calibration

Hasan et al 2021: Deep Lens- small shifts in mean and width of N(z) change contours!





Part IV

Modeling Choices

Intrinsic Alignment

$$\langle \varepsilon \rangle = g$$ → Assume $<\epsilon^{orig}> =0$
Otherwise, model *intrinsic alignment*

galaxies are subjected to tidal fields generated by their large-scale environment during formation and evolution

Models are often created for specific scales and galaxy type (spiral and elliptical)

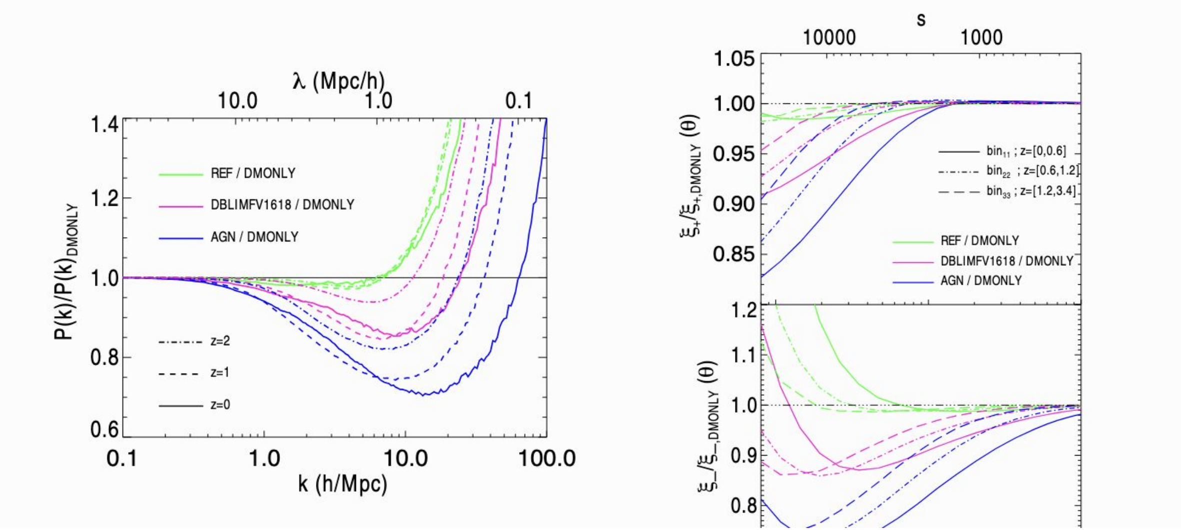
Good consistency test is to split sample into red and blue galaxies

Baryons

Universe is more than just dark matter!

Cosmological scale hydro sims are difficult, and the results depend on the prescription used

Semi-analytical “Baryonification models” parameterize baryonic effects on n-body predictions

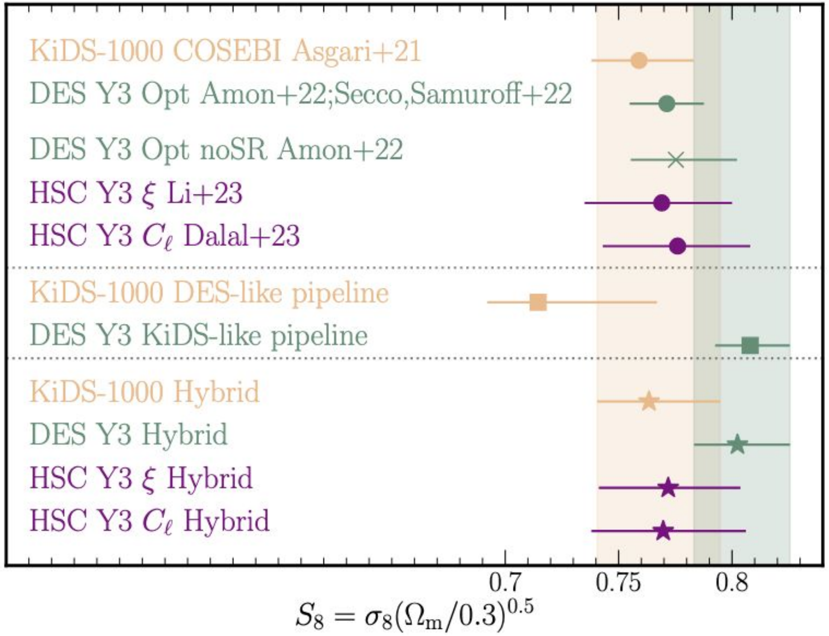


Sembolini 2011

Consequence of modeling problems:

DES and KiDS exchanged data and ran their cosmology pipeline with their respective modeling choices

arxiv:2305.17173



Part V

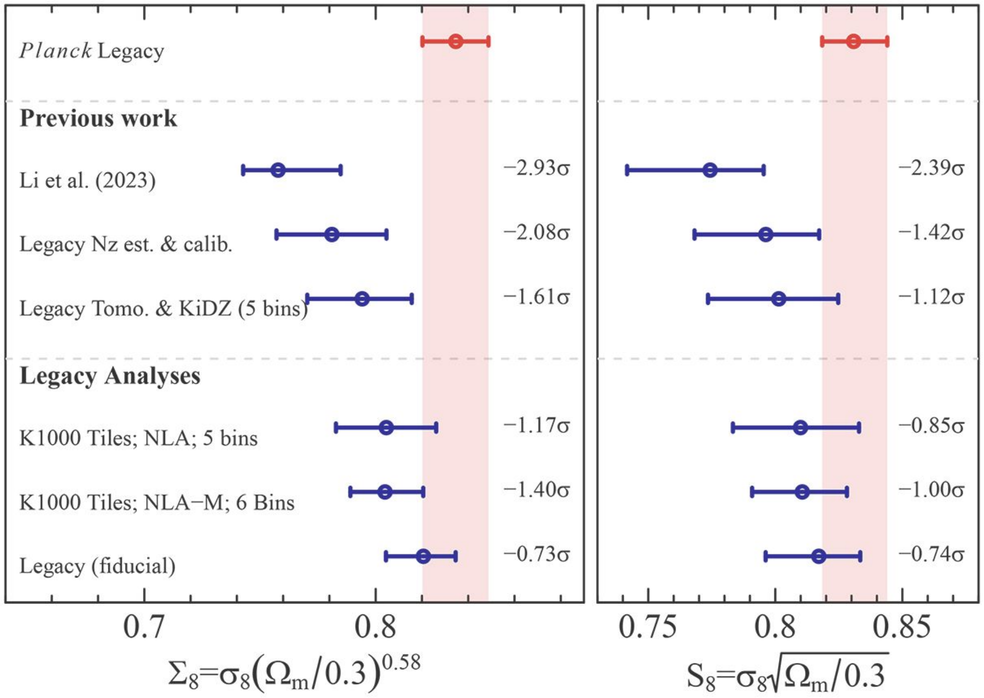
Contours!

Disclaimer: The following contour plots are the culmination of years of work by dozens of people, my comments are meant to show just how difficult this measurement is

KiDS Legacy vs KiDS 1000

Consistency with Planck changes between data releases mostly due to subtle changes in redshift calibration

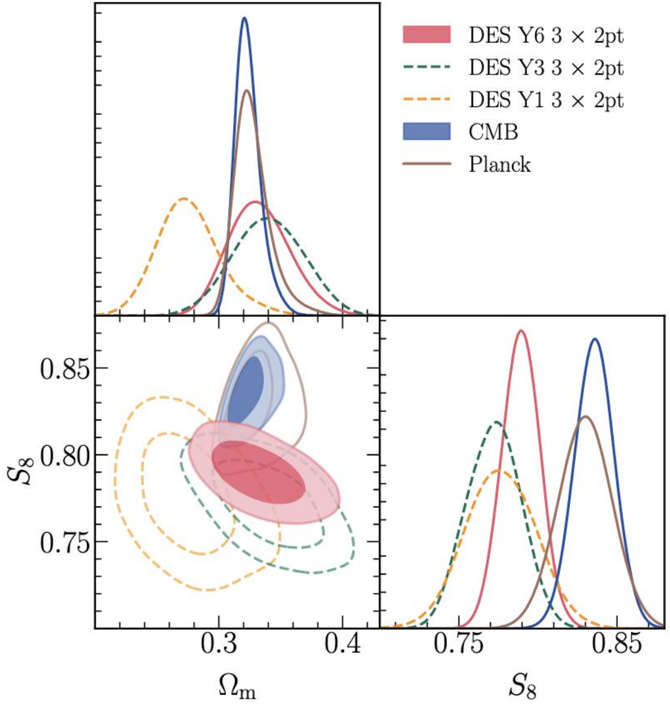
(Wright et al 2025)



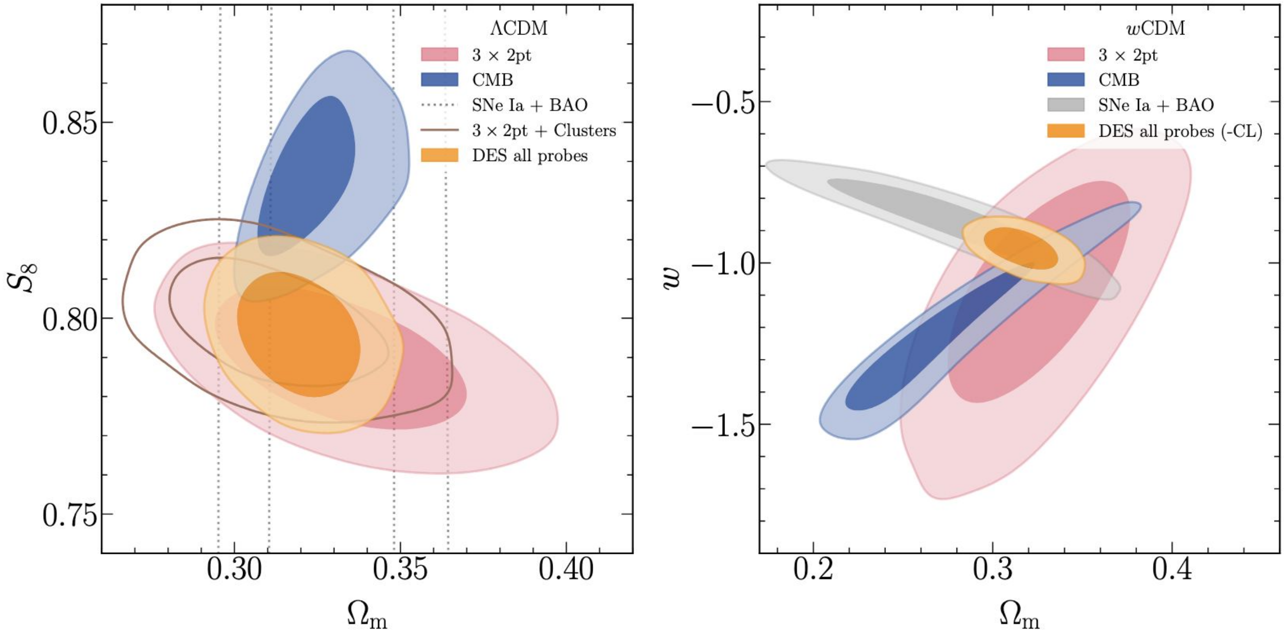
We are systematics limited

Parameter posteriors are not incredibly different between releases, despite big changes in area and depth

(DES Collaboration 2026)



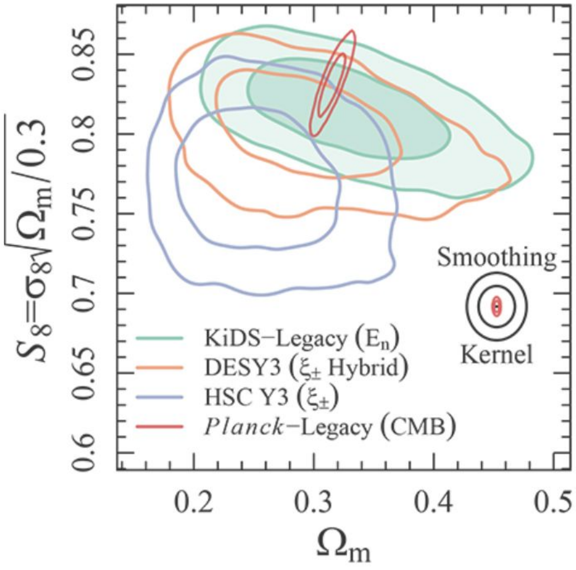
DES Constraints on w-cdm

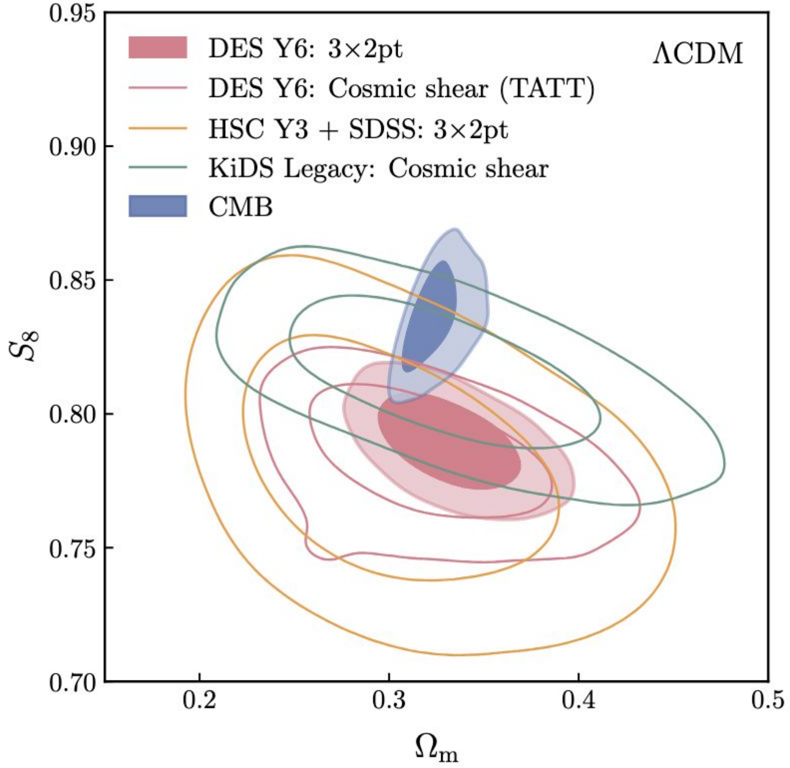


Comparison between different surveys

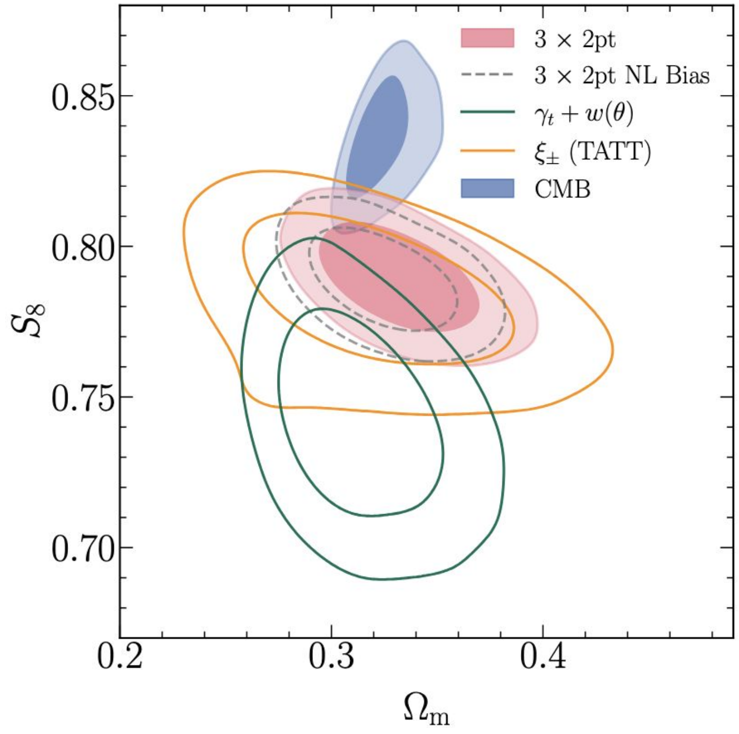
From DES Collaboration 2026

From Wright et al. 2026



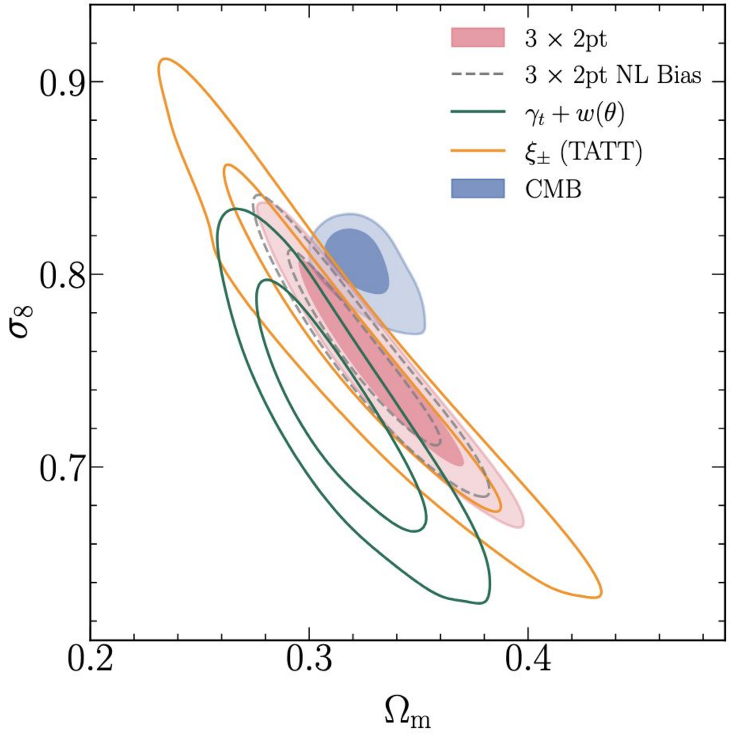


The "dark secret" of cosmic shear contours



$$S_8 \equiv \sigma_8 \sqrt{\Omega_{\rm m}/0.3}$$

The “dark secret” of cosmic shear contours



In conclusion

Weak lensing is a very complex statistical measurement

The contour plots are the culmination of years of work by dozens of people

We are systematics limited- getting a signal is not enough, we need to know how to model it to a high degree of precision

Many assumptions go into the analysis starting from the pixels

Many exciting and difficult data sets are on the way!

Some resources/ references

Cosmic shear lecture slides by Martin Kilbinger

Shape measurement lecture slides by Rachel Mandelbaum

Gravitation Lensing Lectures by Peter Schneider

Photometric Redshift lecture slides by Sam Schmidt