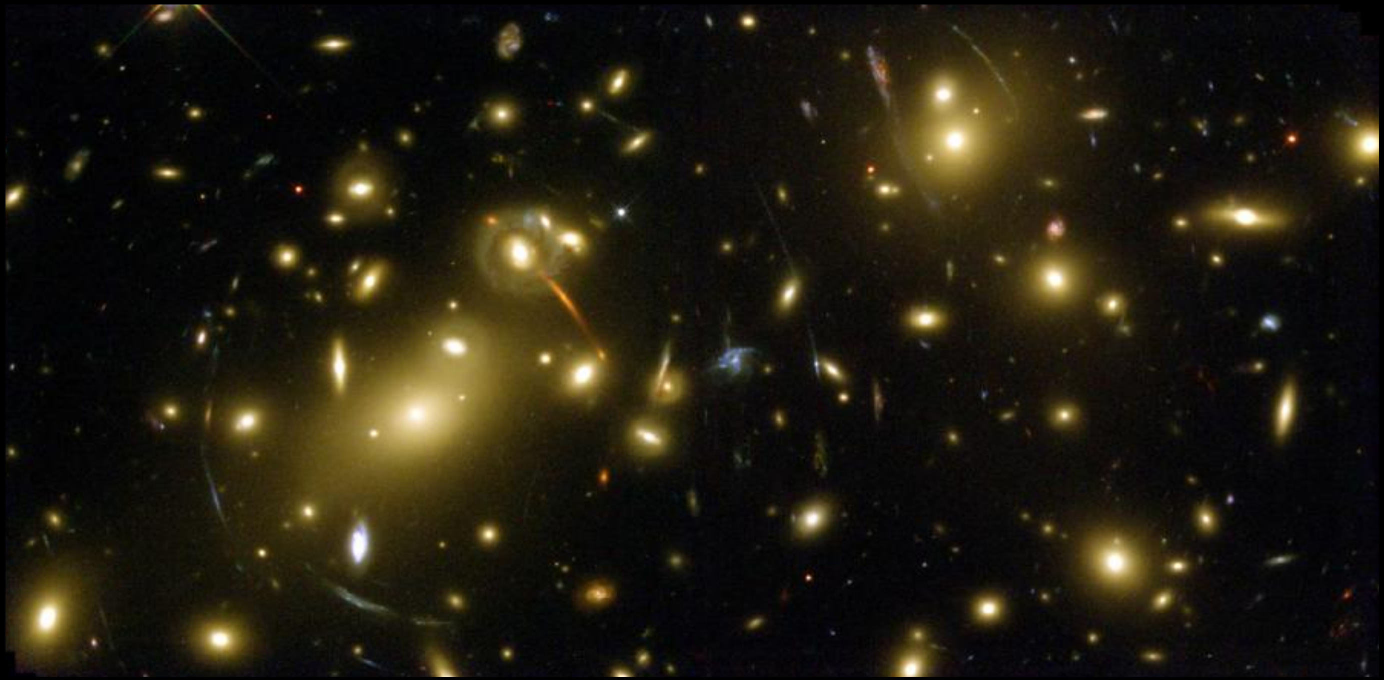
Weak Lensing in the next Decade

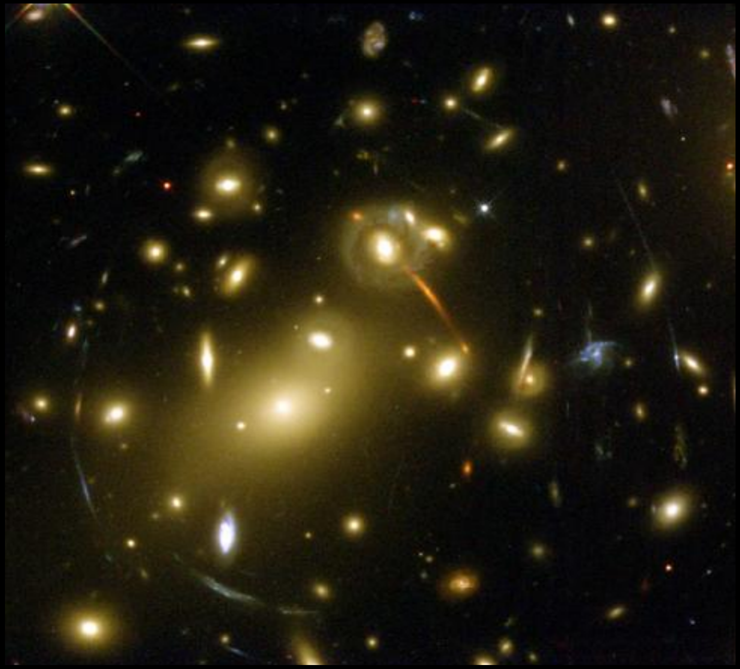


Sarah Bridle
University of Manchester

MANCHESTER 1824
The University of Manchester

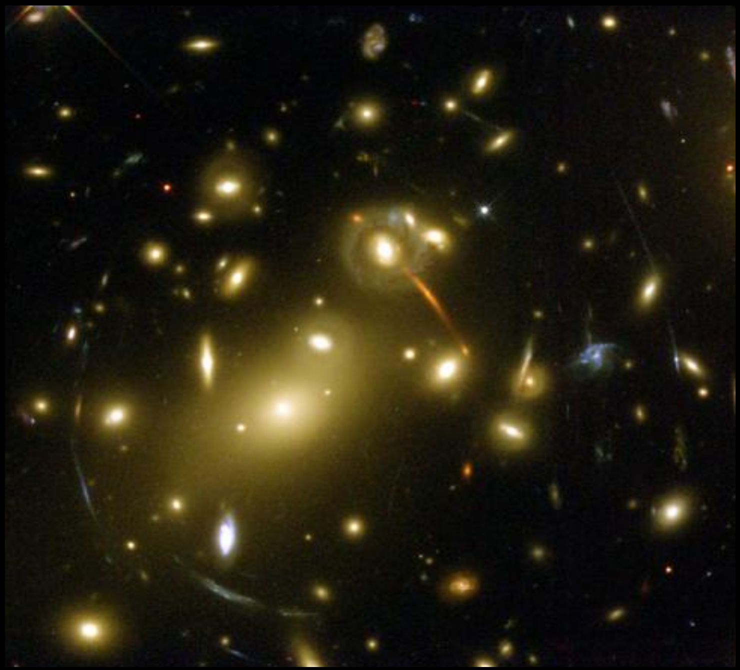
Weak Lensing in the next Decade

- Introduction to Cosmic Shear for dark energy
- Potential limitations
  - Shear measurement
  - Intrinsic alignments
  - Photozs
- Future surveys



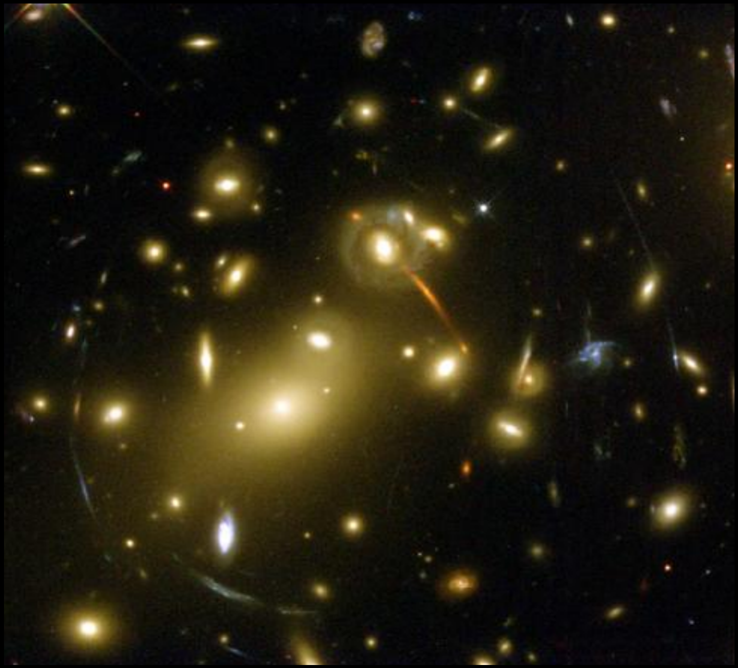
Weak Lensing in the next Decade

- Introduction to Cosmic Shear for dark energy
- Potential limitations
  - Shear measurement
  - Intrinsic alignments
  - Photozs
- Future surveys



Weak Lensing in the next Decade

- Introduction to Cosmic Shear for dark energy
- Potential limitations
  - Shear measurement
  - Intrinsic alignments
  - Photozs
- Future surveys



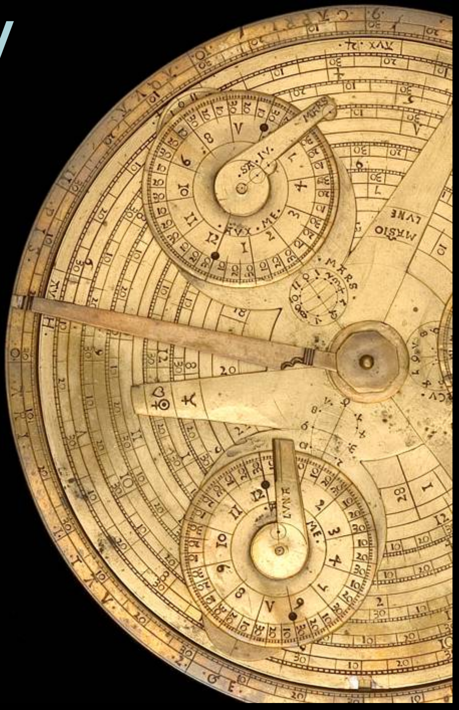
Why is the Universe Accelerating?

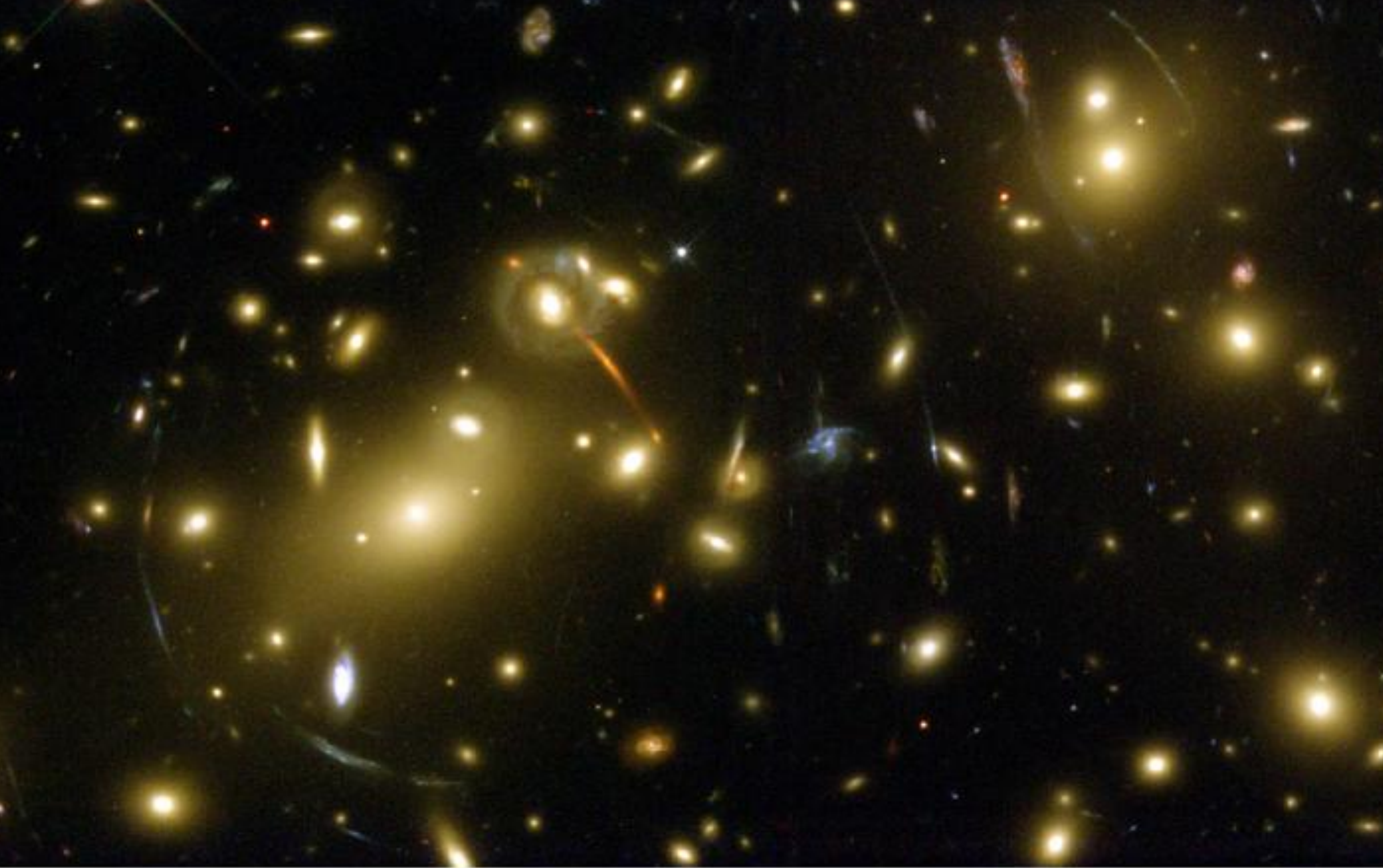
- Einstein's cosmological constant

$$R_{\mu\nu} - \frac{1}{2}R\,g_{\mu\nu} + \Lambda\,g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

- A new fluid called Dark Energy
    - Equation of state $w = p/\rho$

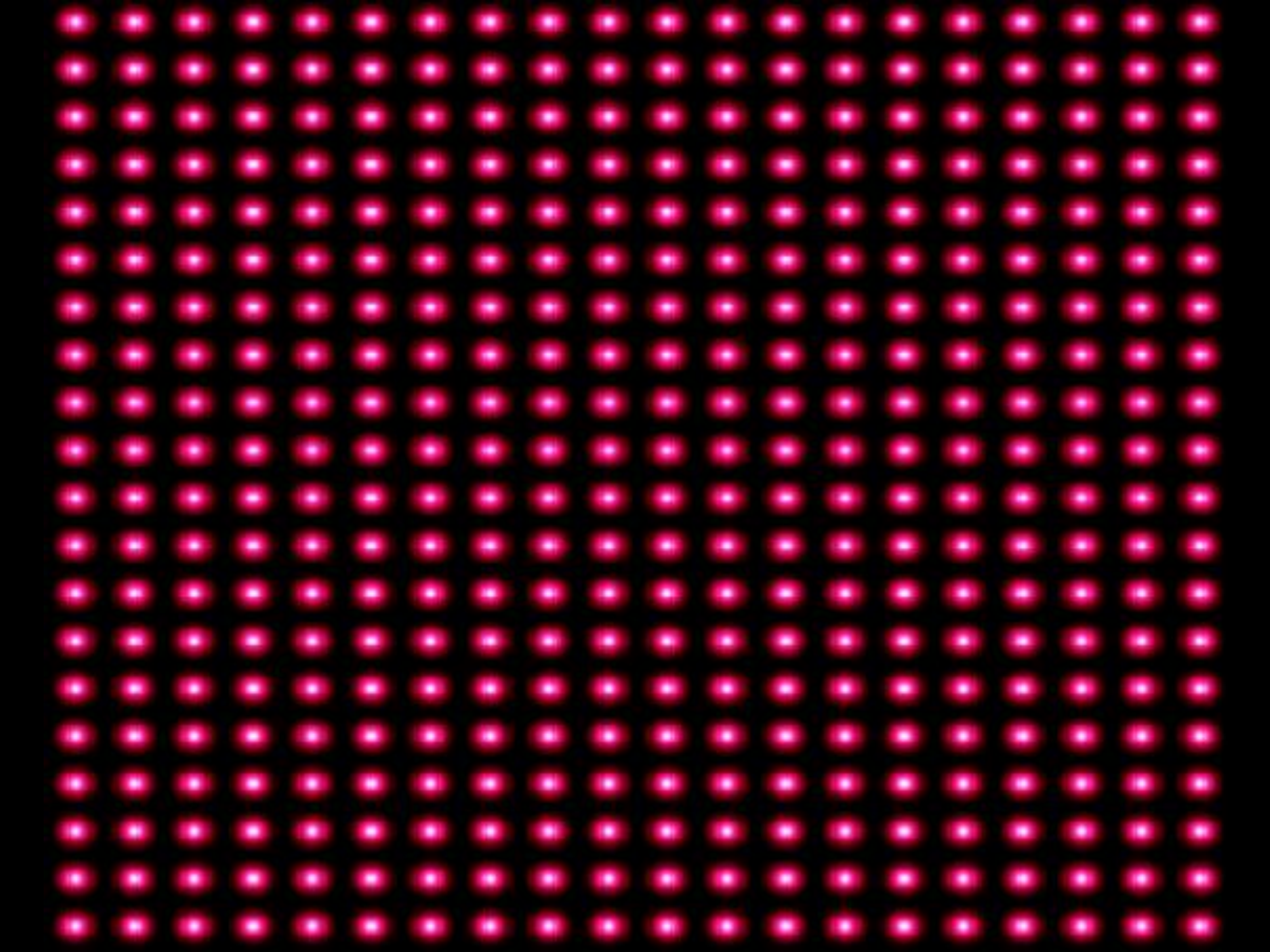
- General Relativity is wrong

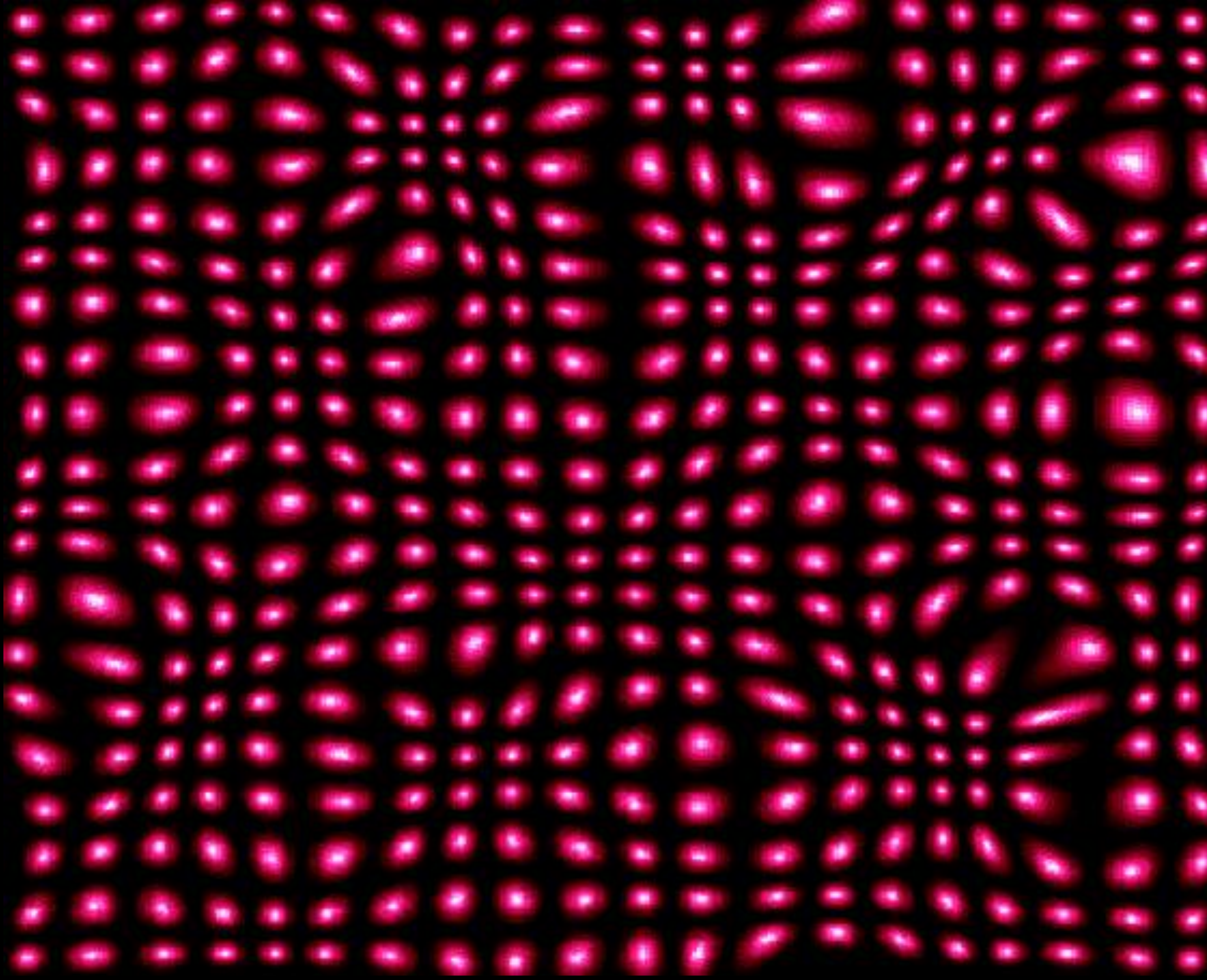




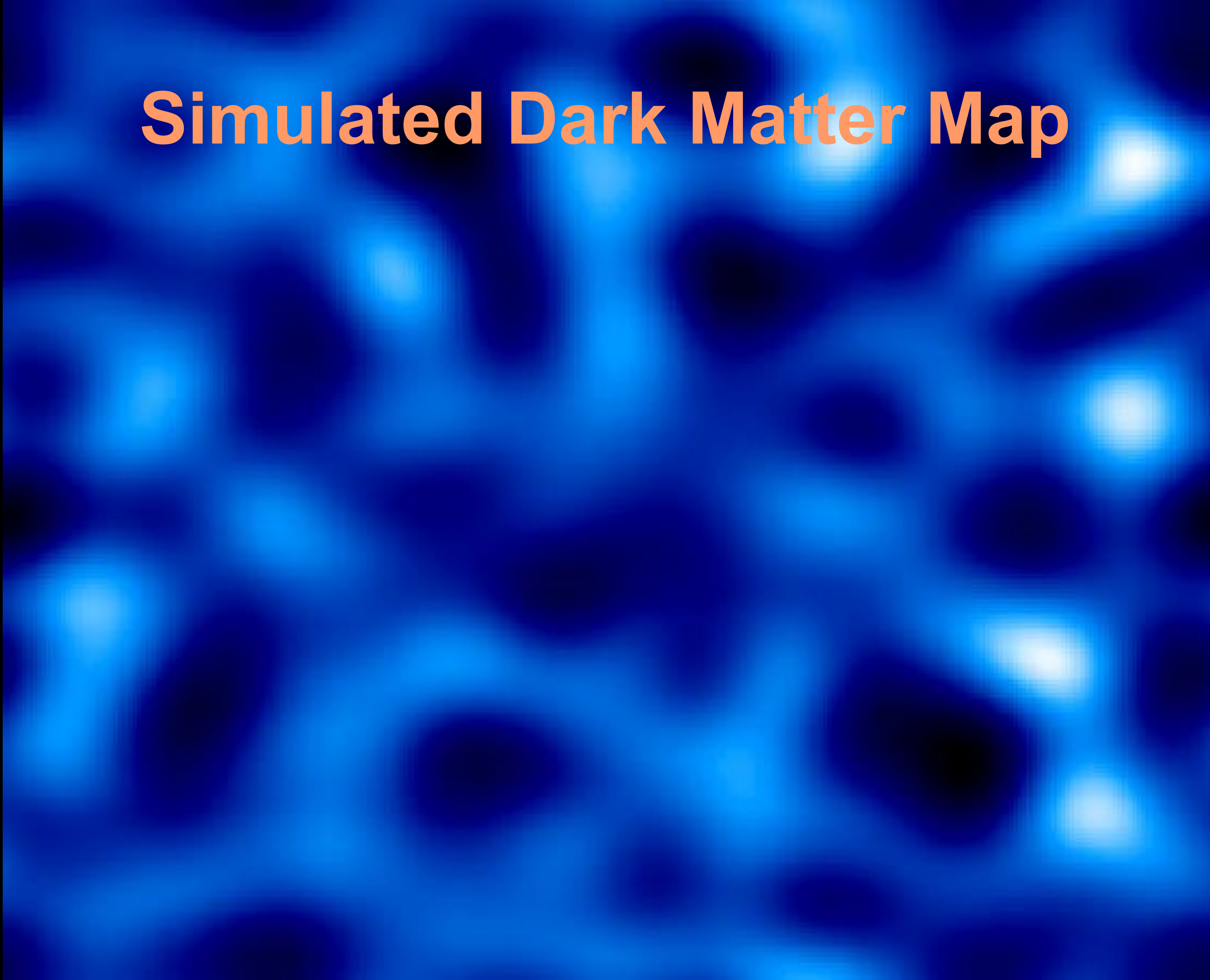
Galaxy Cluster Abell 2218

Hubble Space Telescope • WFPC2

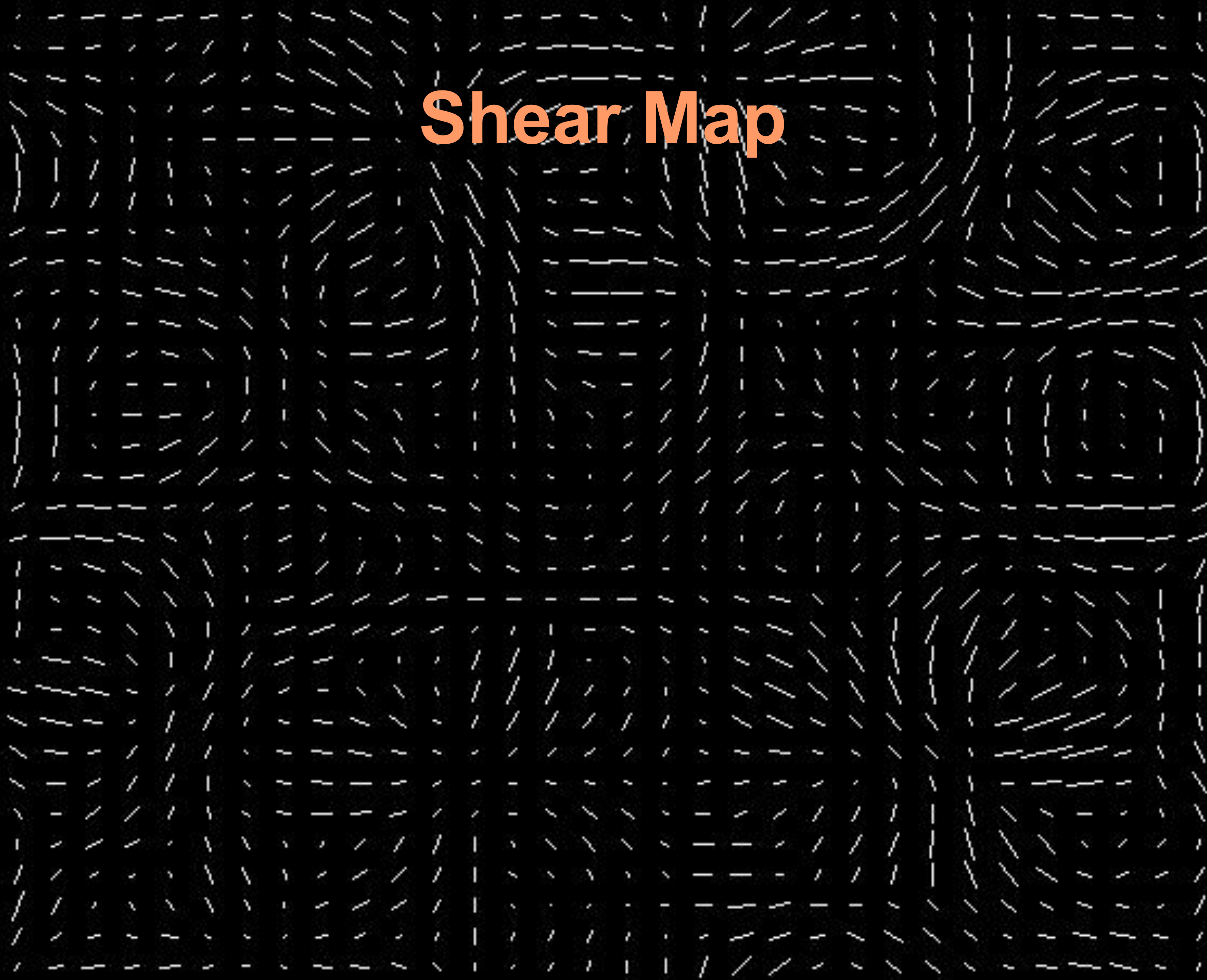


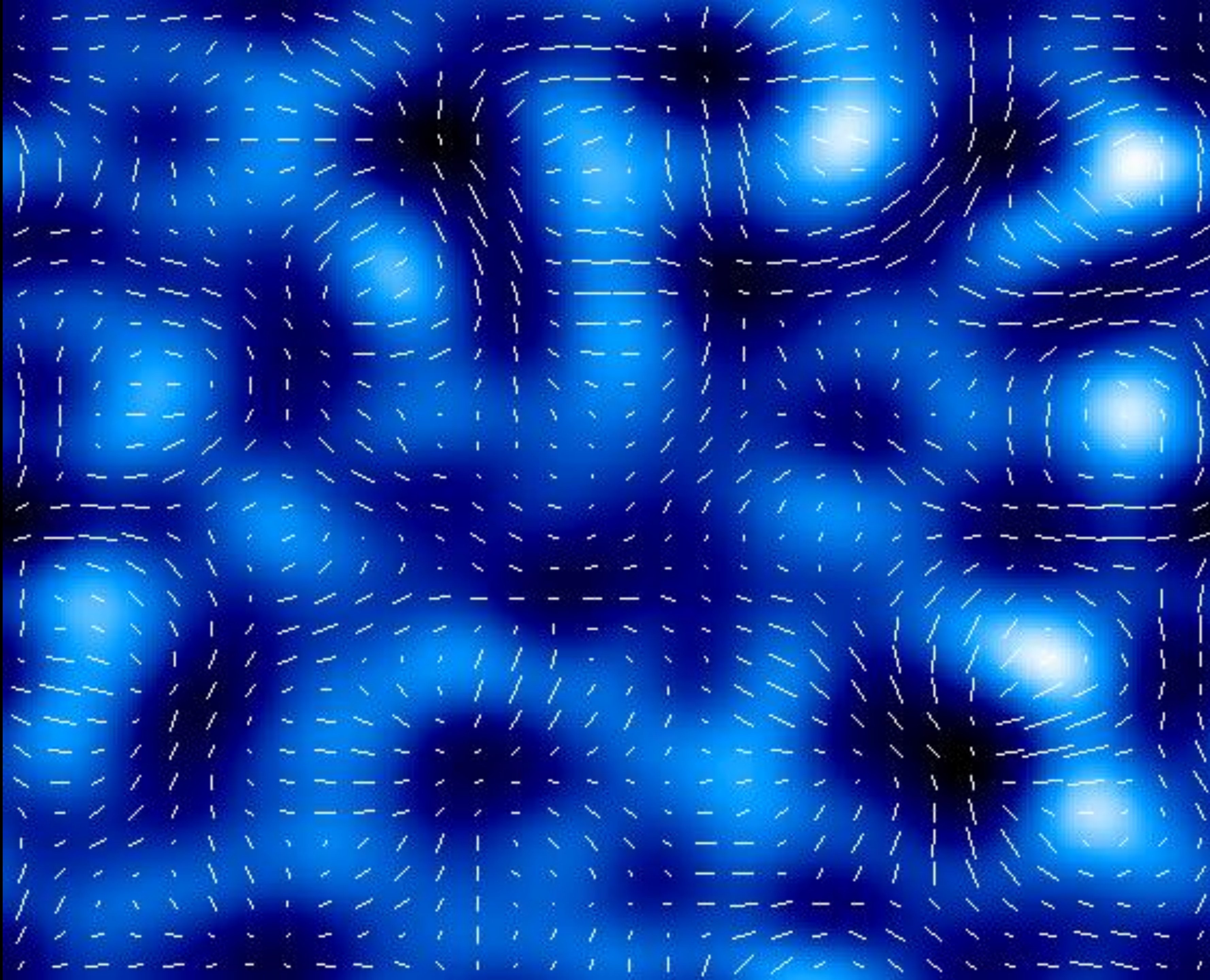


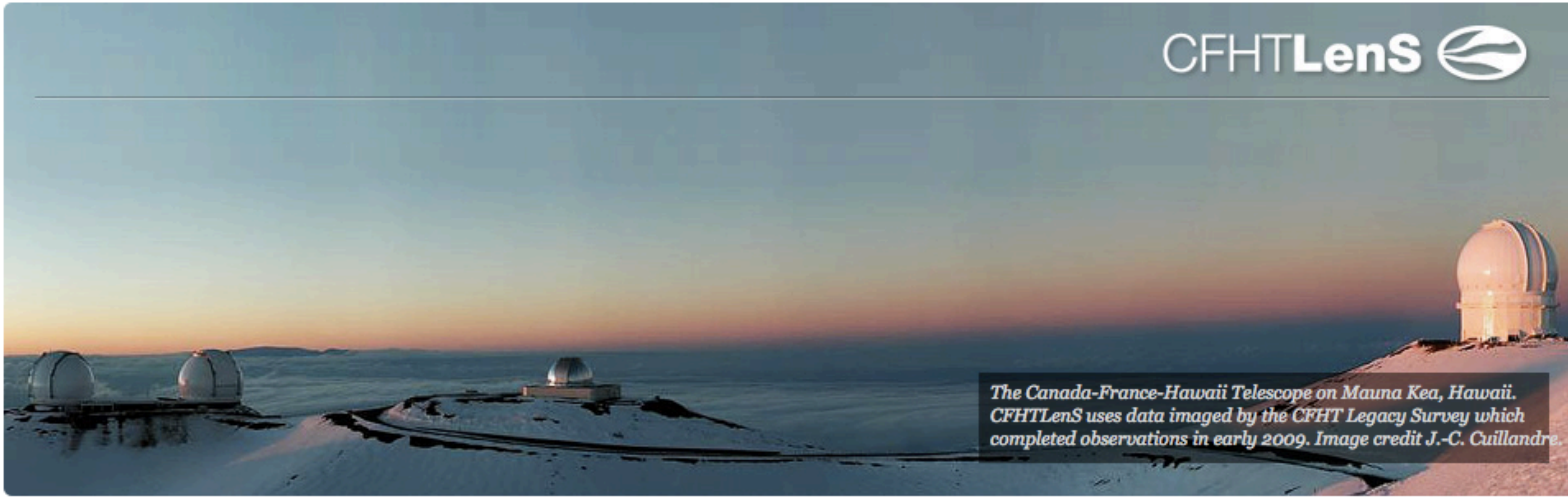
Simulated Dark Matter Map



Shear Map







- Home
- CFHTLenS

Information for Astronomers

- Team
- Images and Catalogues
- Cluster Catalogue

The CFHT Lensing Survey

Welcome to the Astronomer section of the website for the Canada-France Hawaii Telescope Lensing Survey: CFHTLenS.

Quick link: Access the CFHTLenS Shear and Photometric Redshift catalogues here

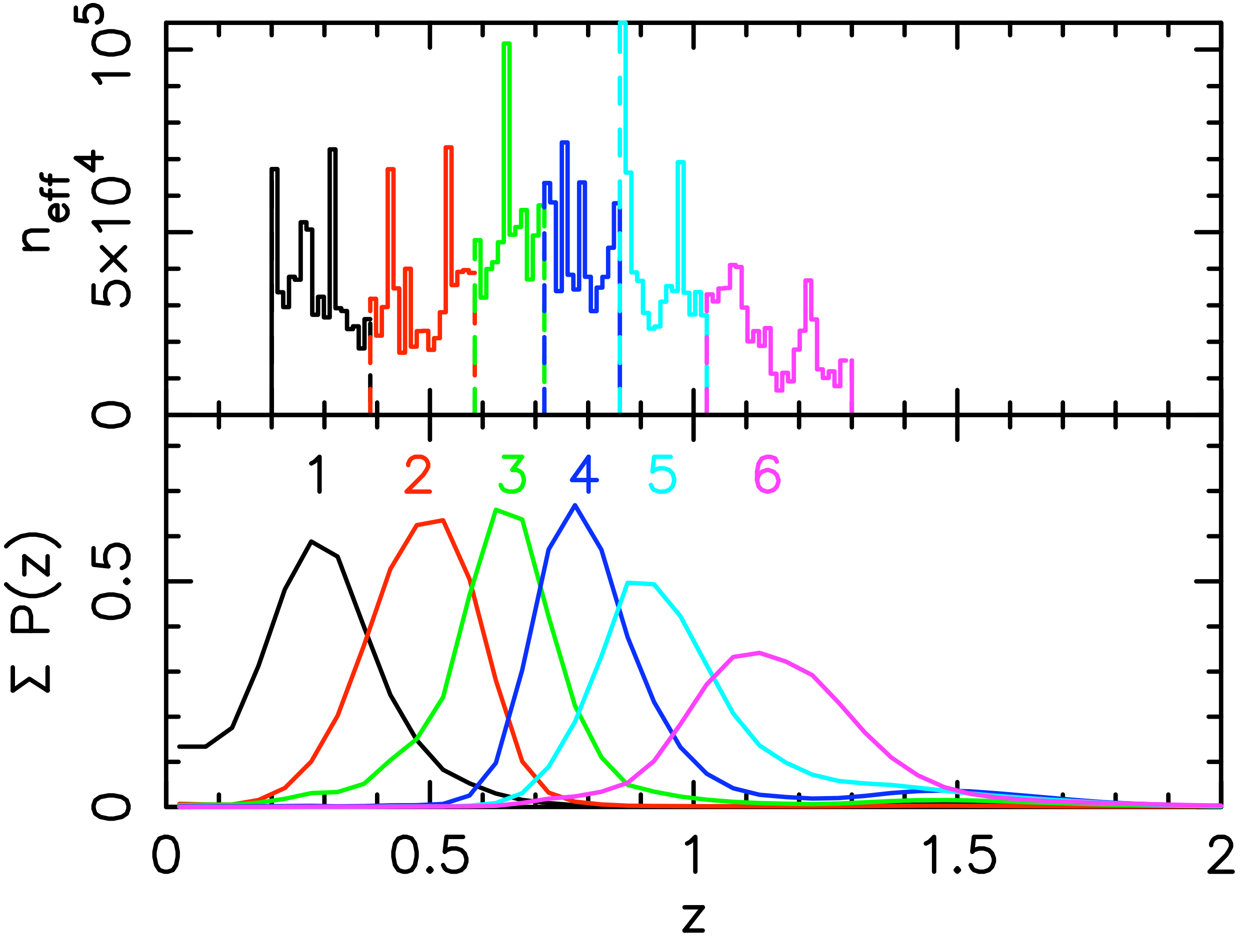
CFHTLenS is a 154 square degree multi-colour optical survey in *ugriz* incorporating all five years worth of data from the Wide, Deep and Pre-survey components on the CFHT Legacy Survey. The CFHTLS was optimised for weak lensing analysis with the deep *i*-band data taken in optimal sub-arcsecond seeing conditions. For a general overview of the survey see Erben et al 2012 and Heymans et al 2012

Useful links

- THELI: Data Reduction
- BPZ: Redshifts
- RCSLenS: Sister Survey
- CFHTLS: Survey
- MegaCam: at CFHT
- CADC: Archive

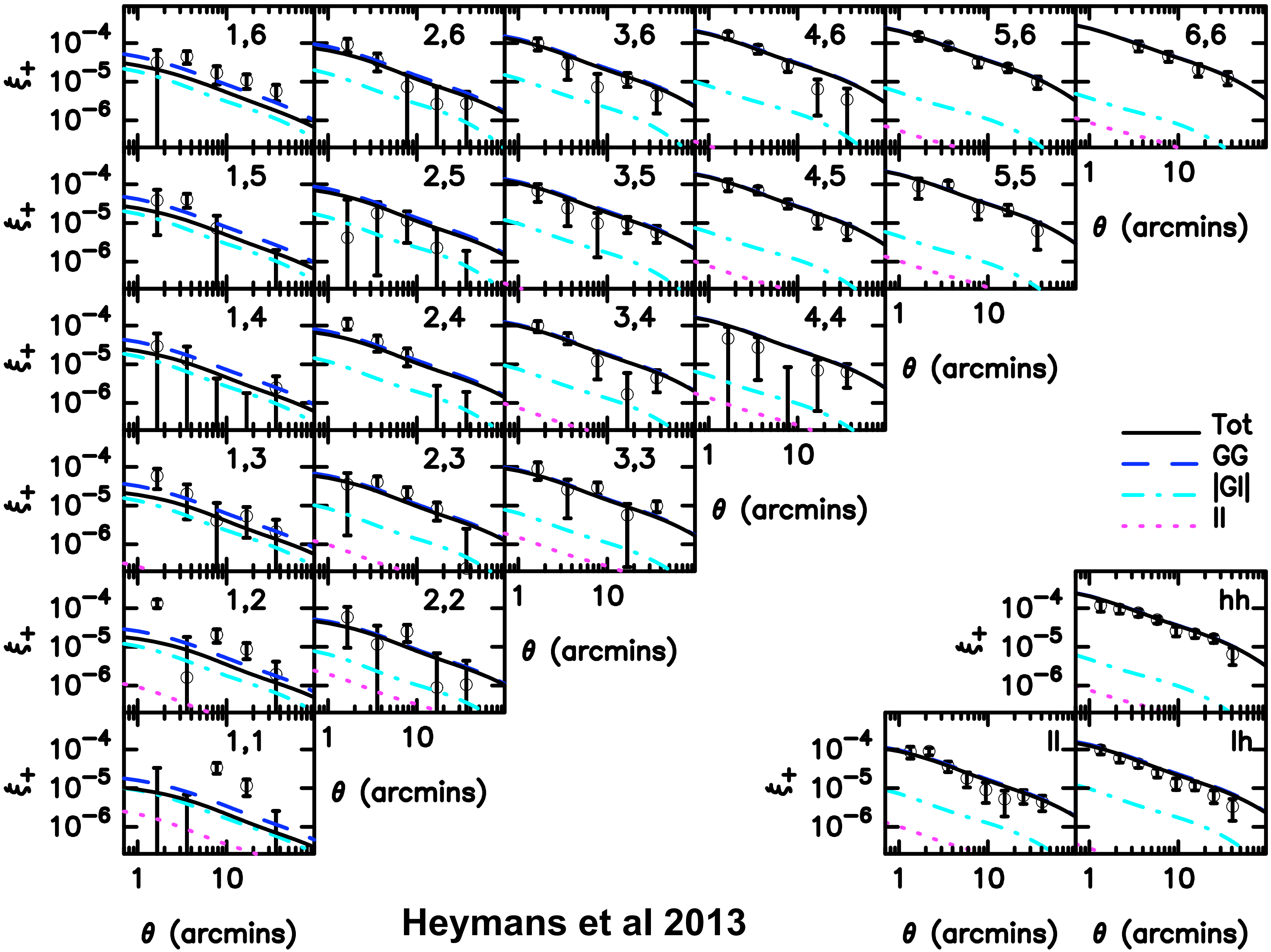
http://www.cfhtlens.org/

CFHTLenS Results



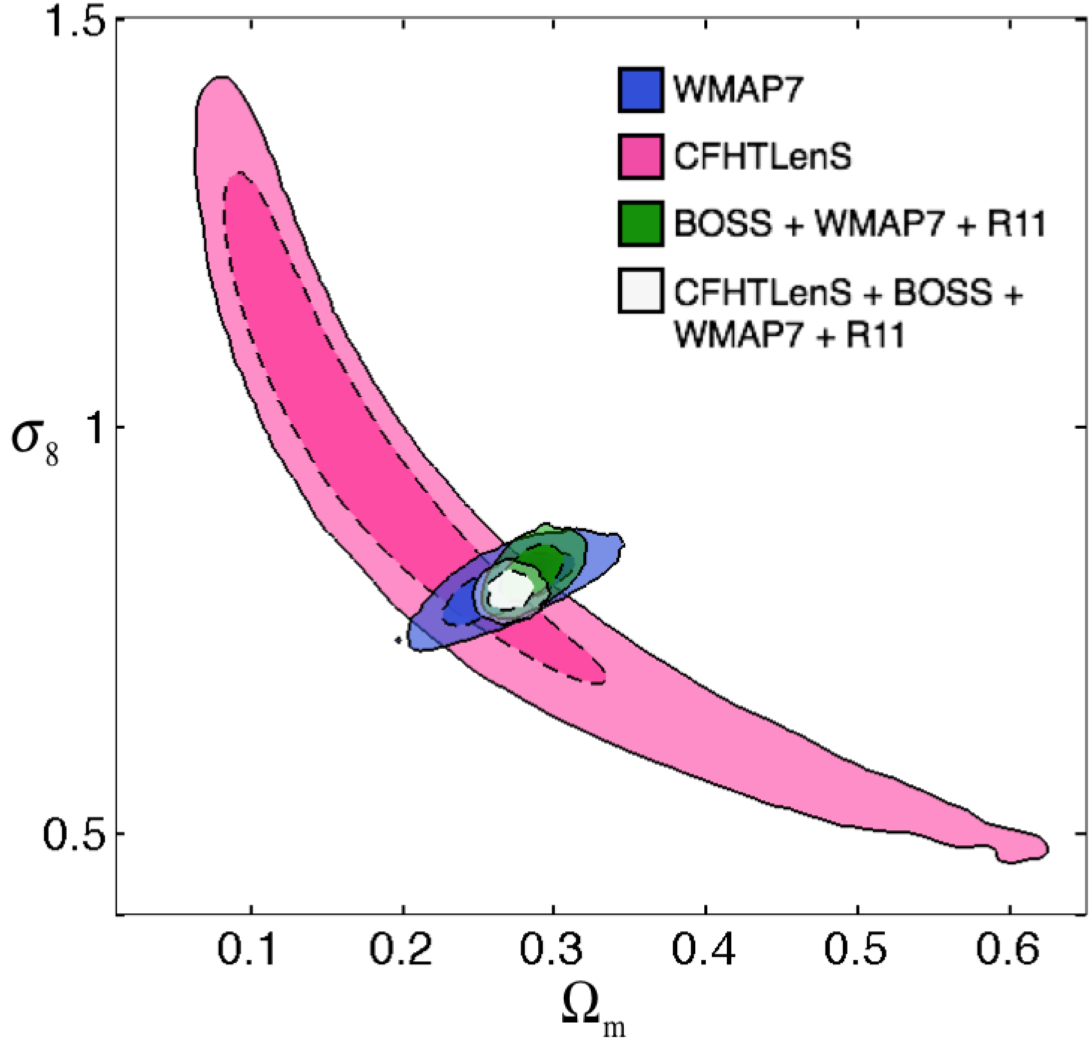
Heymans et al 2013

CFHTLens Results



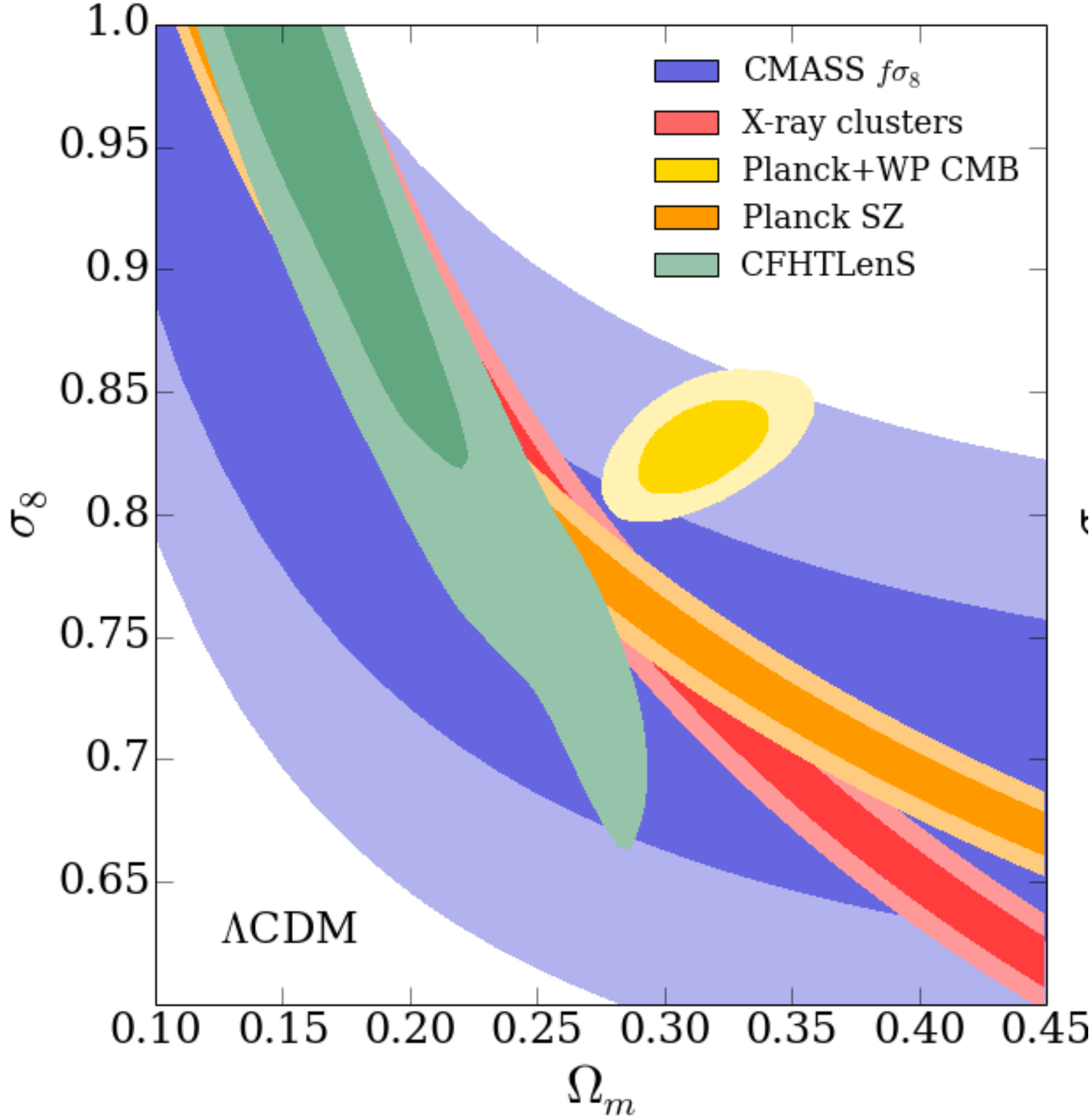
Heymans et al 2013

CFHTLenS Results



Heymans et al 2013

Context of other data



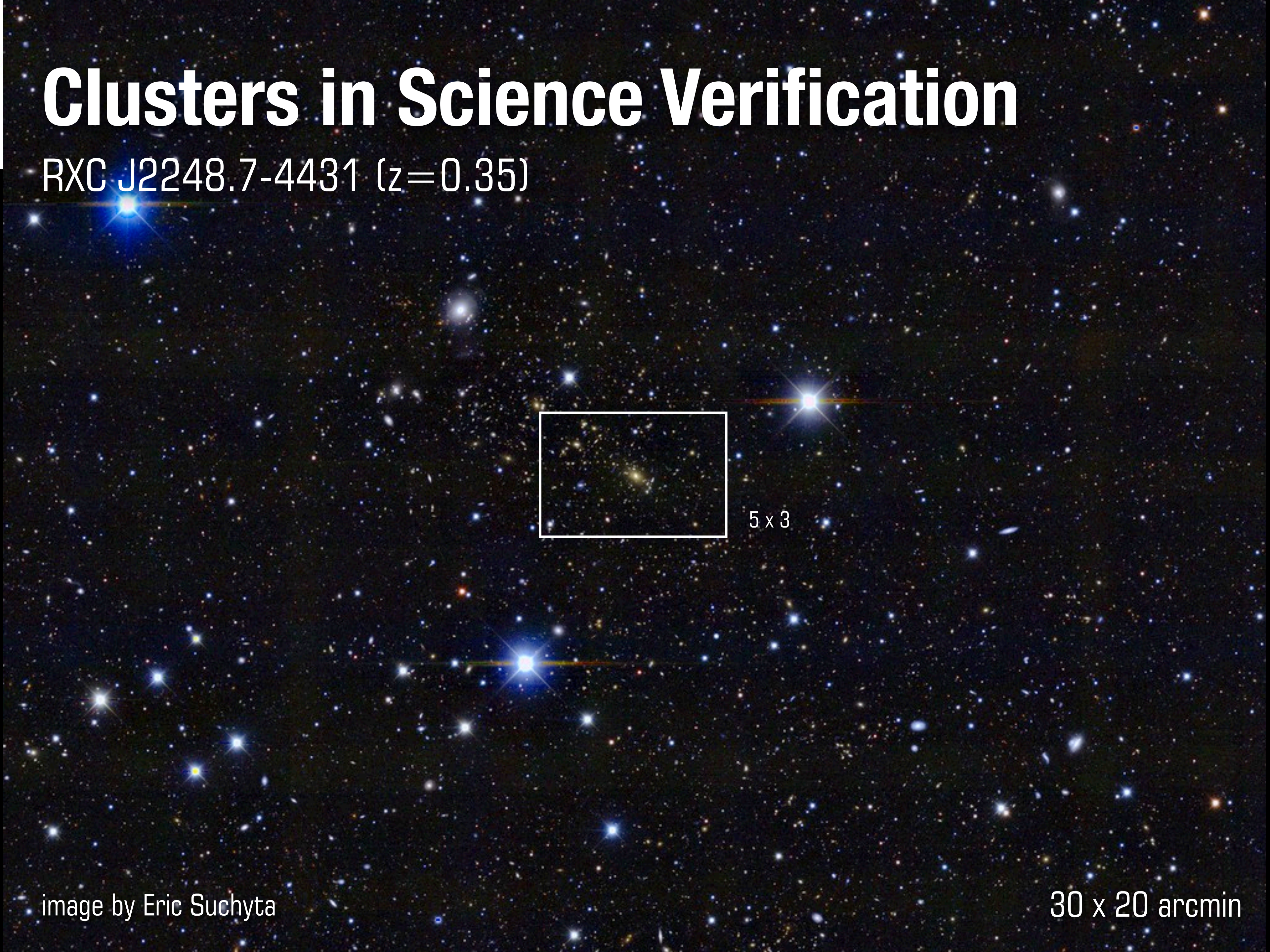
MacCrann, Zuntz, Bridle, Jain, Becker 2014

The Dark Energy Survey

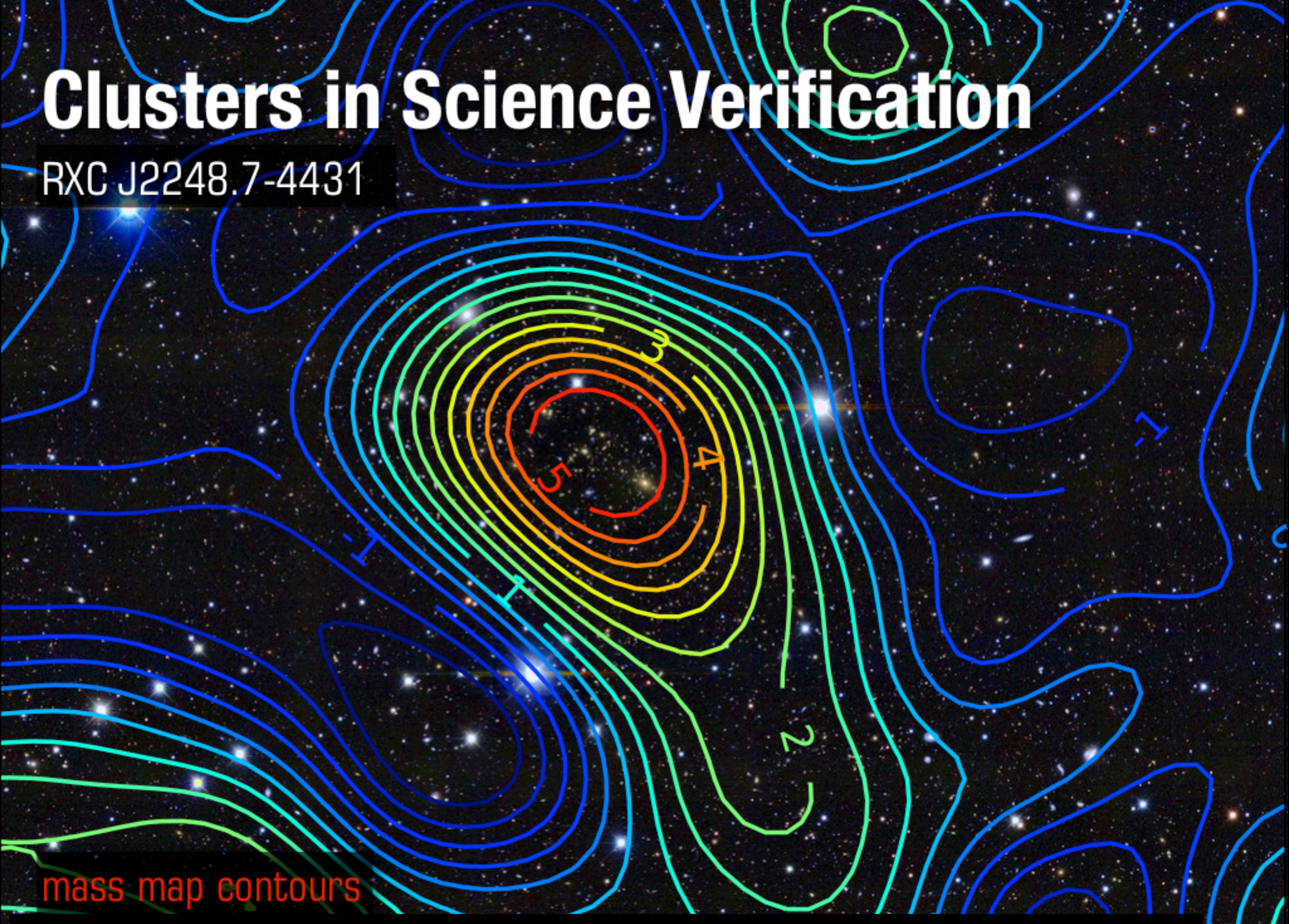
DARK ENERGY SURVEY

Blanco 4-meter at CTIO

- Survey project using 4 complementary techniques:
  - I. Cluster Counts
  - II. Weak Lensing
  - III. Large-scale Structure
  - IV. Supernovae
- Two multiband surveys:
  - 5000 deg^2 *grizY* to 24th mag
  - 30 deg^2 repeat (SNe)
- Build new 3 deg^2 FOV camera and Data management system
  - Survey 2013-2018 (525 nights)
  - Facility instrument for Blanco


Clusters in Science Verification
RXC J2248.7-4431 (z=0.35)
5 x 3
image by Eric Suchyta
30 x 20 arcmin

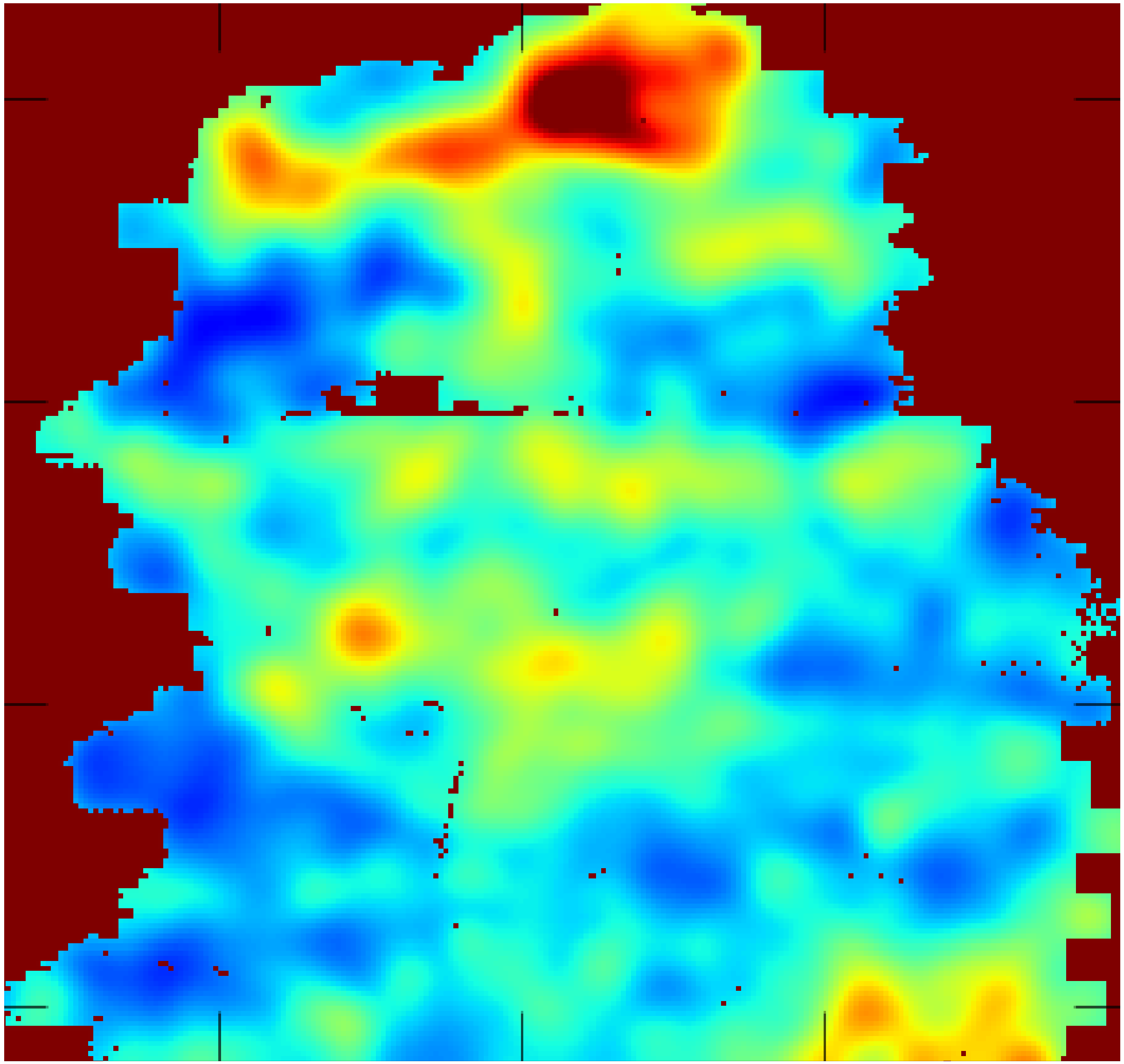
Clusters in Science Verification



Melchior, Suchyta, Huff, Hirsch, Kacprzak, Rykoff, Gruen et al (DES Collab) 2014

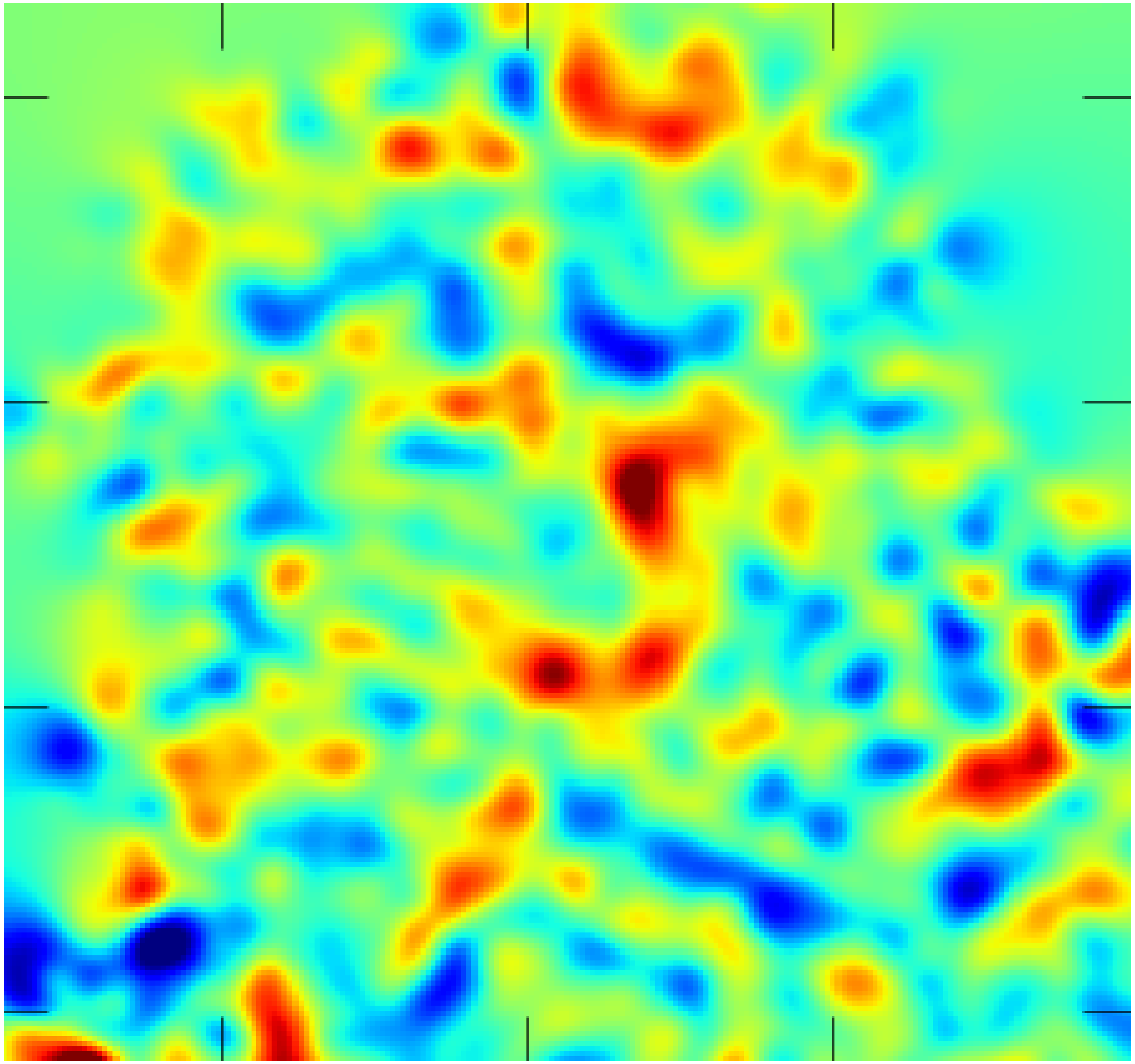

Clusters in Science Verification
RXC J2248.7-4431

Science Verification Data: Galaxies



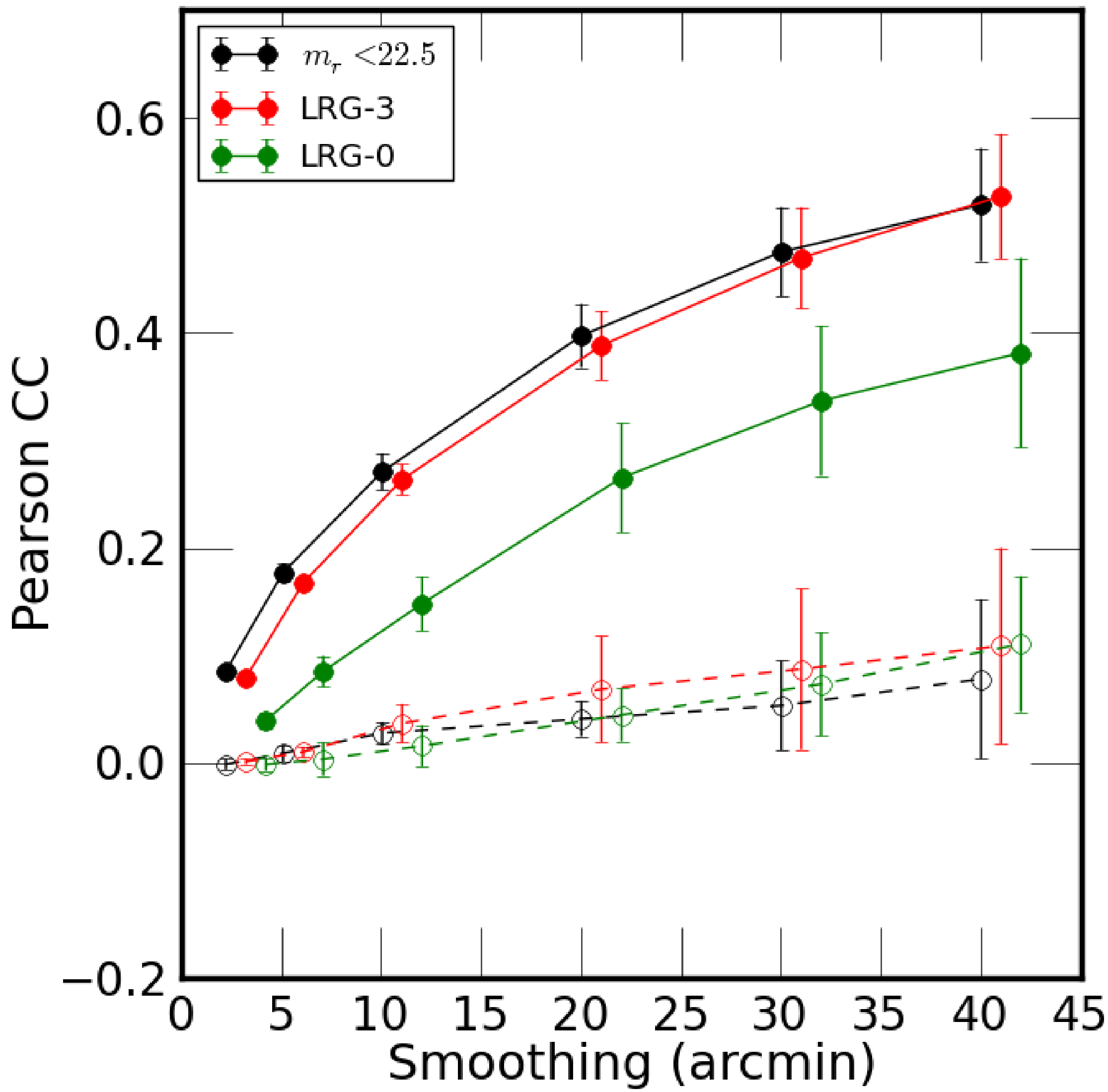
Vikram, Chang, Jain, Bacon et al (DES Collaboration) in prep

Mass map from lensing



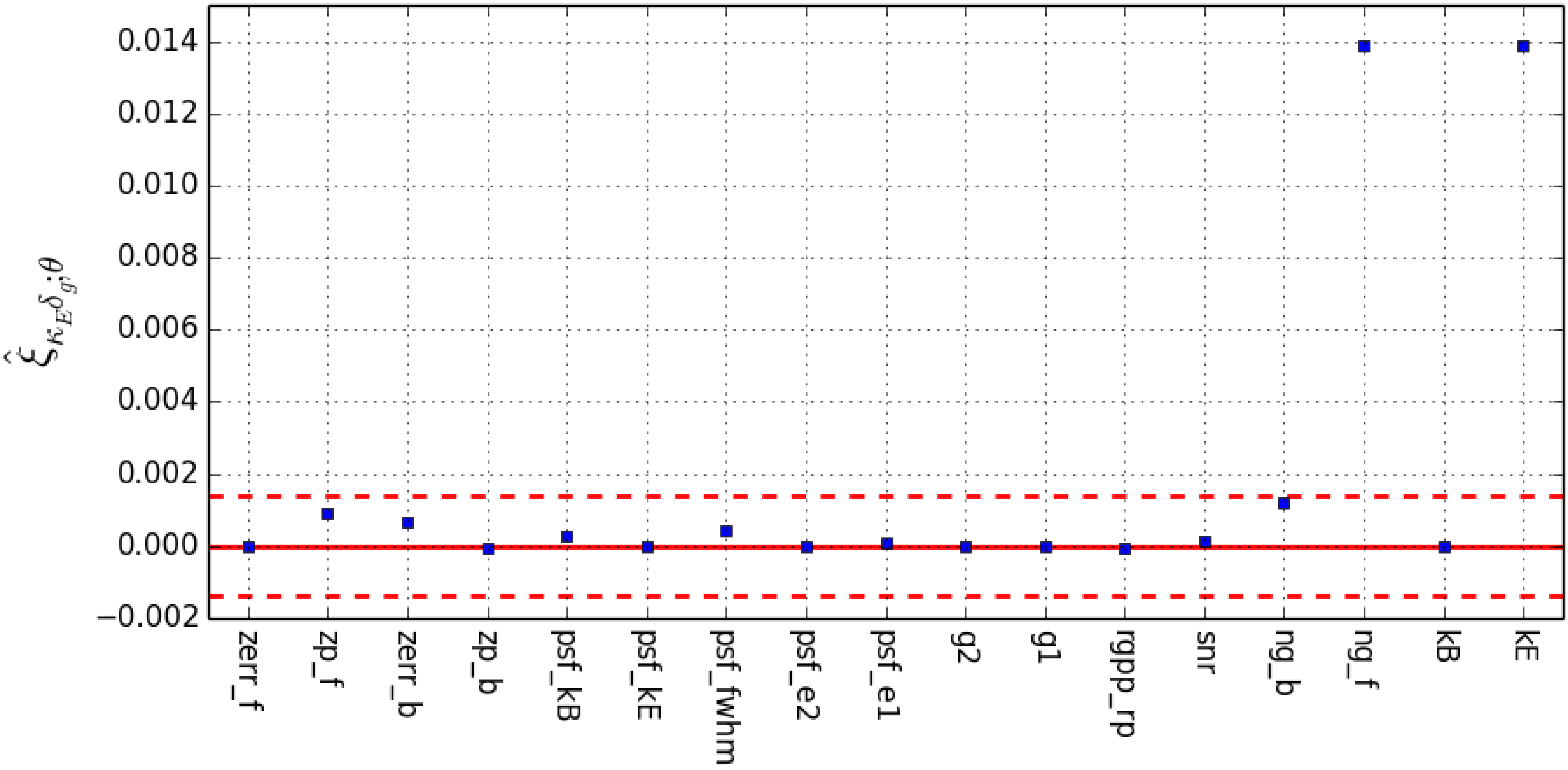
Vikram, Chang, Jain, Bacon et al (DES Collaboration) in prep

Cross-correlation between mass and light



Vikram, Chang, Jain, Bacon et al (DES Collaboration) in prep

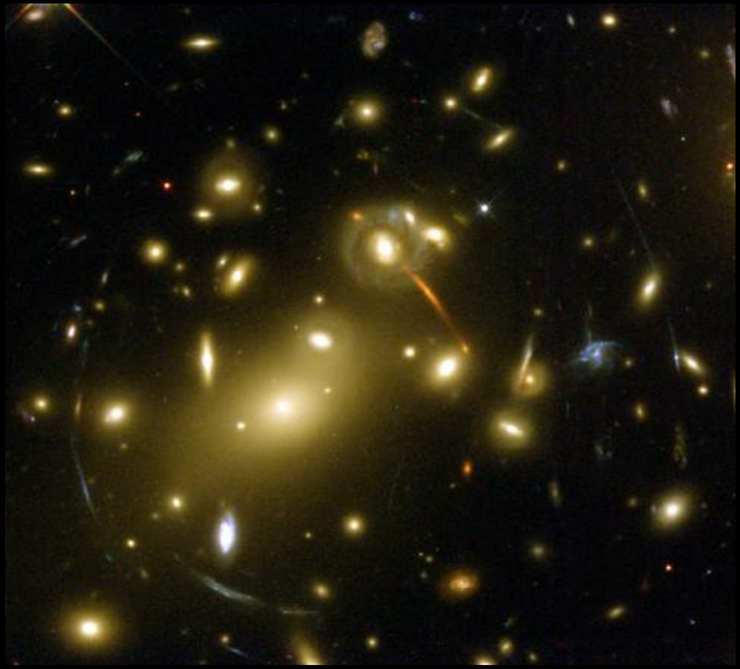
Contributions from potential systematics



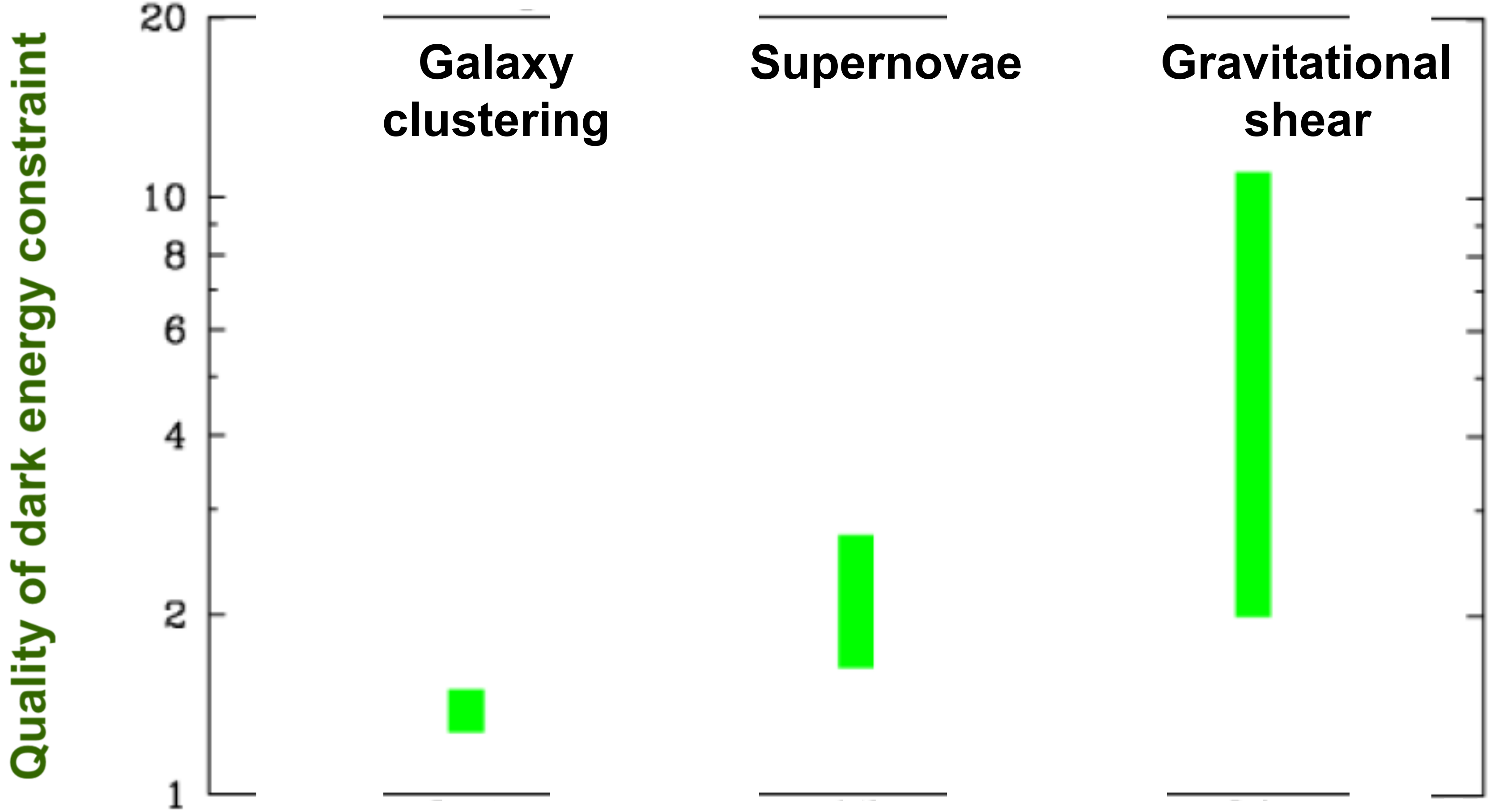
Vikram, Chang, Jain, Bacon et al (DES Collaboration) in prep

Weak Lensing in the next Decade

- Introduction to Cosmic Shear for dark energy
- Potential limitations
  - Shear measurement
  - Intrinsic alignments
  - Photozs
- Future surveys

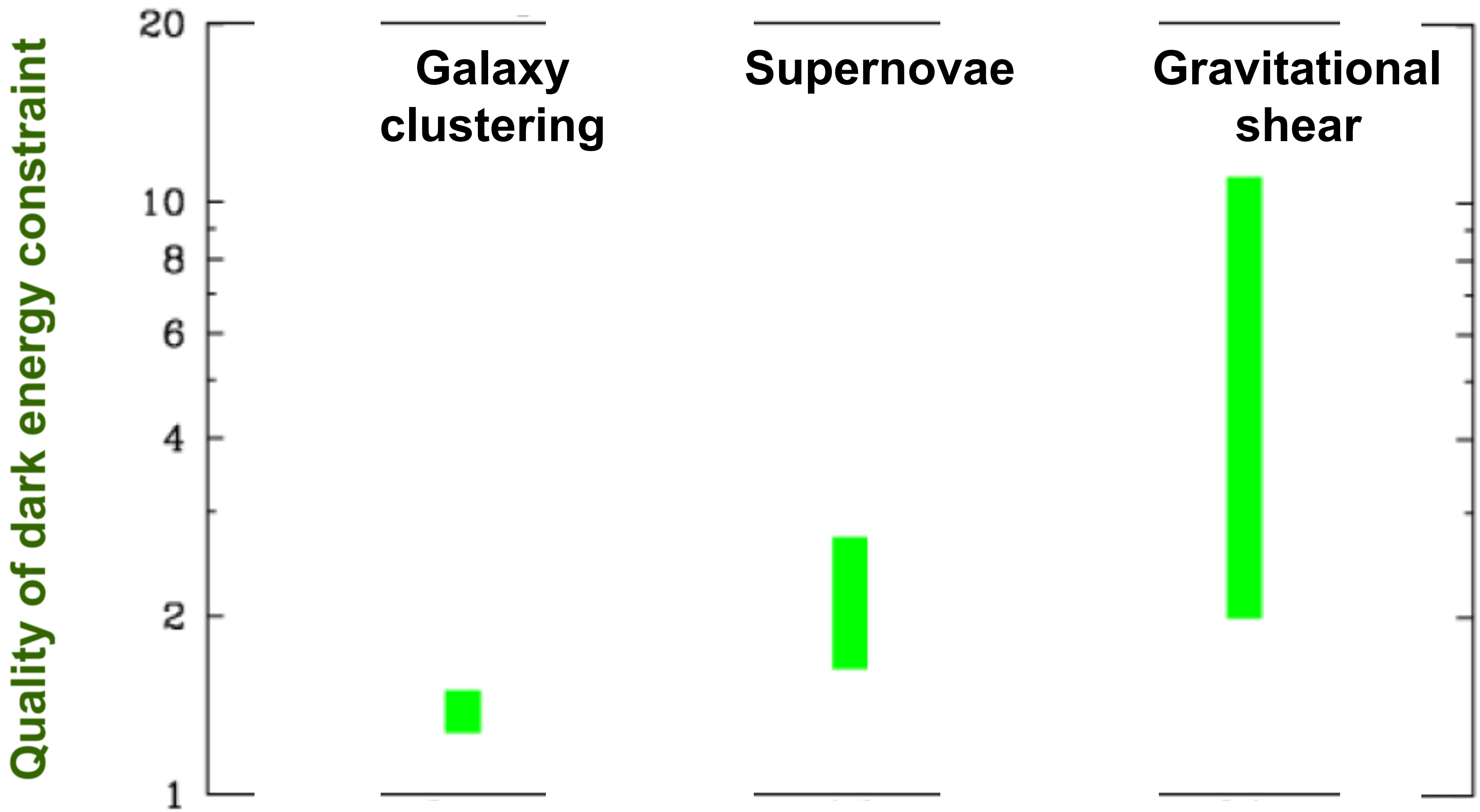


Comparison of different methods



Example for optical ground-based surveys
Dark Energy Task Force report astro-ph/0609591

Comparison of different methods



Example for optical ground-based surveys
Dark Energy Task Force report astro-ph/0609591

Cosmic Shear: Potential systematics

Shear measurement

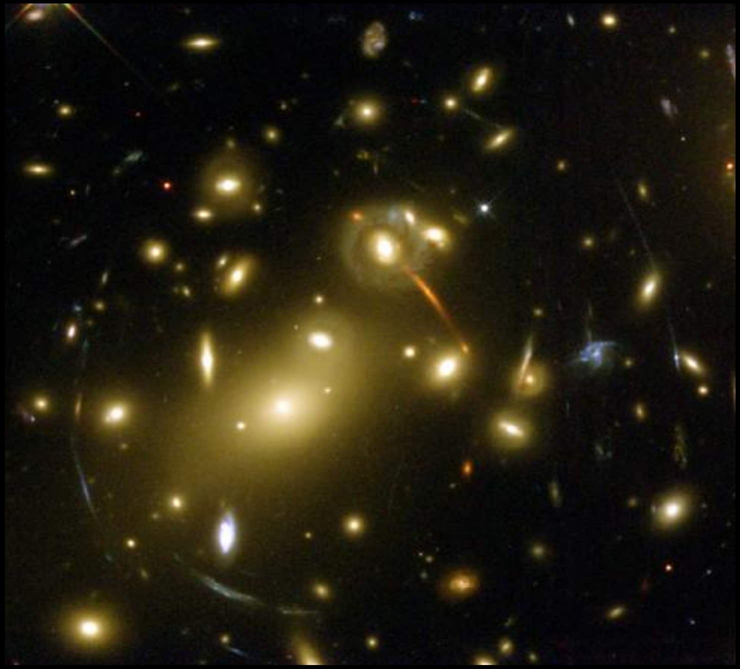
Photometric redshifts

Intrinsic alignments

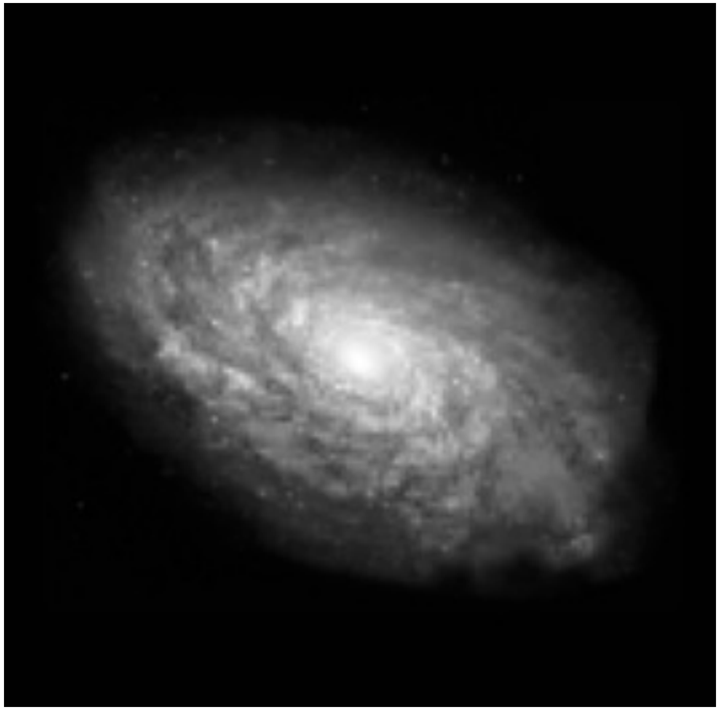
Accuracy of predictions

Weak Lensing in the next Decade

- Introduction to Cosmic Shear for dark energy
- Potential limitations
  - Shear measurement
  - Intrinsic alignments
  - Photozs
- Future surveys



Cosmic Shear

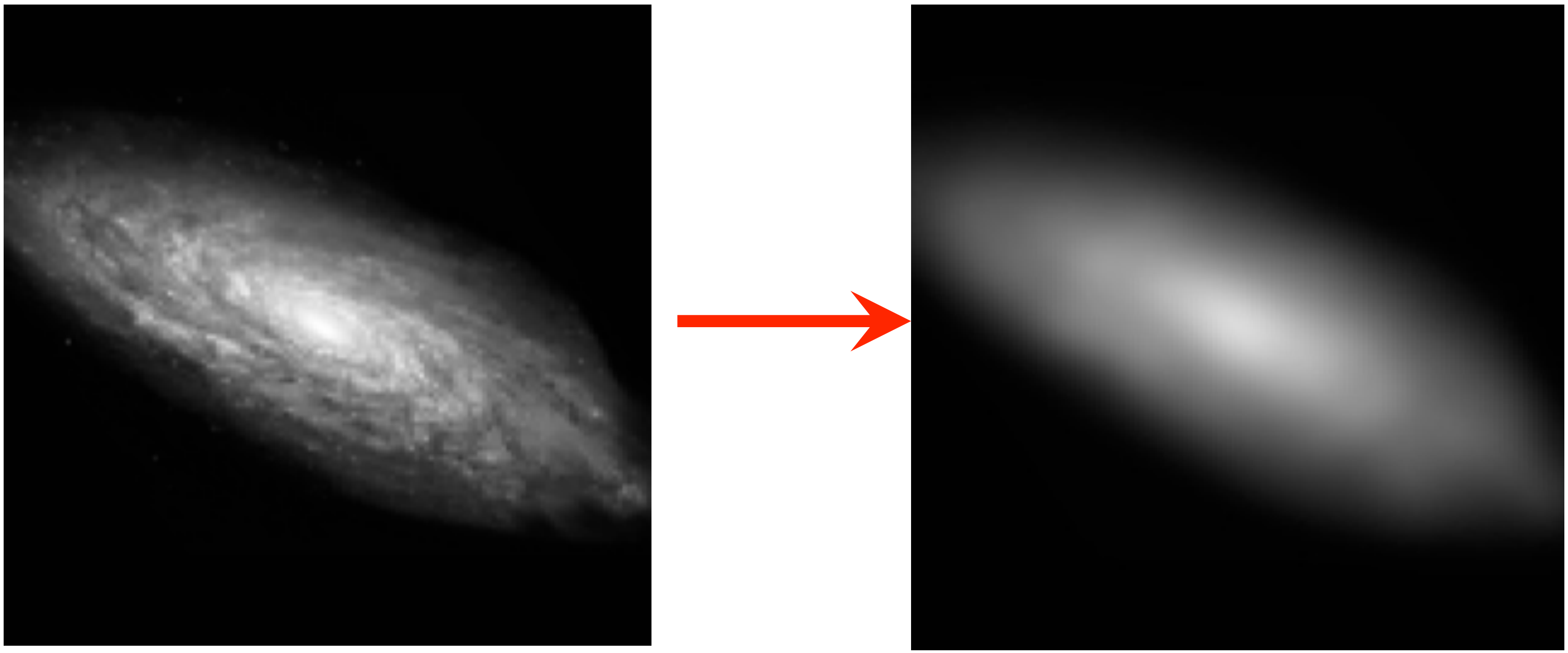


g_i~0.2

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

Real data:
g_i~0.03

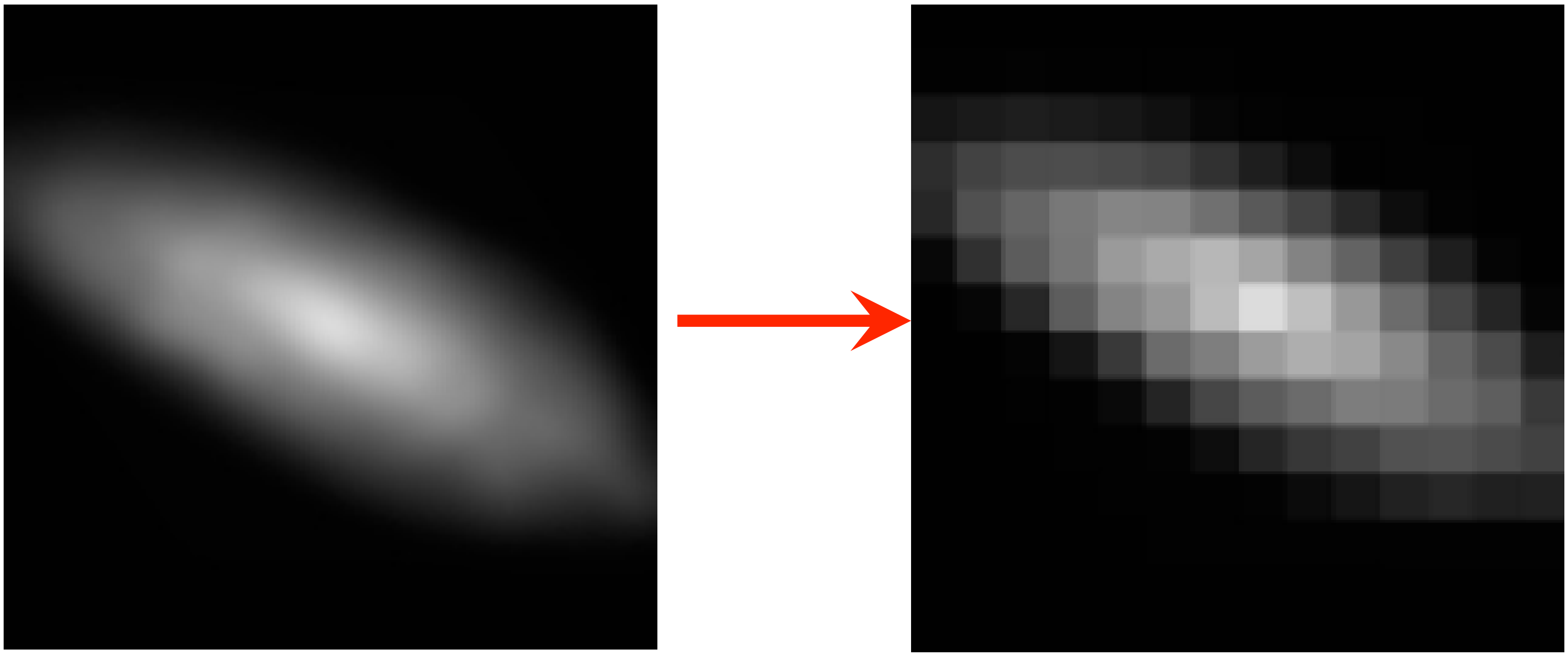
Atmosphere and Telescope



Convolution with kernel

Real data: Kernel size ~ Galaxy size

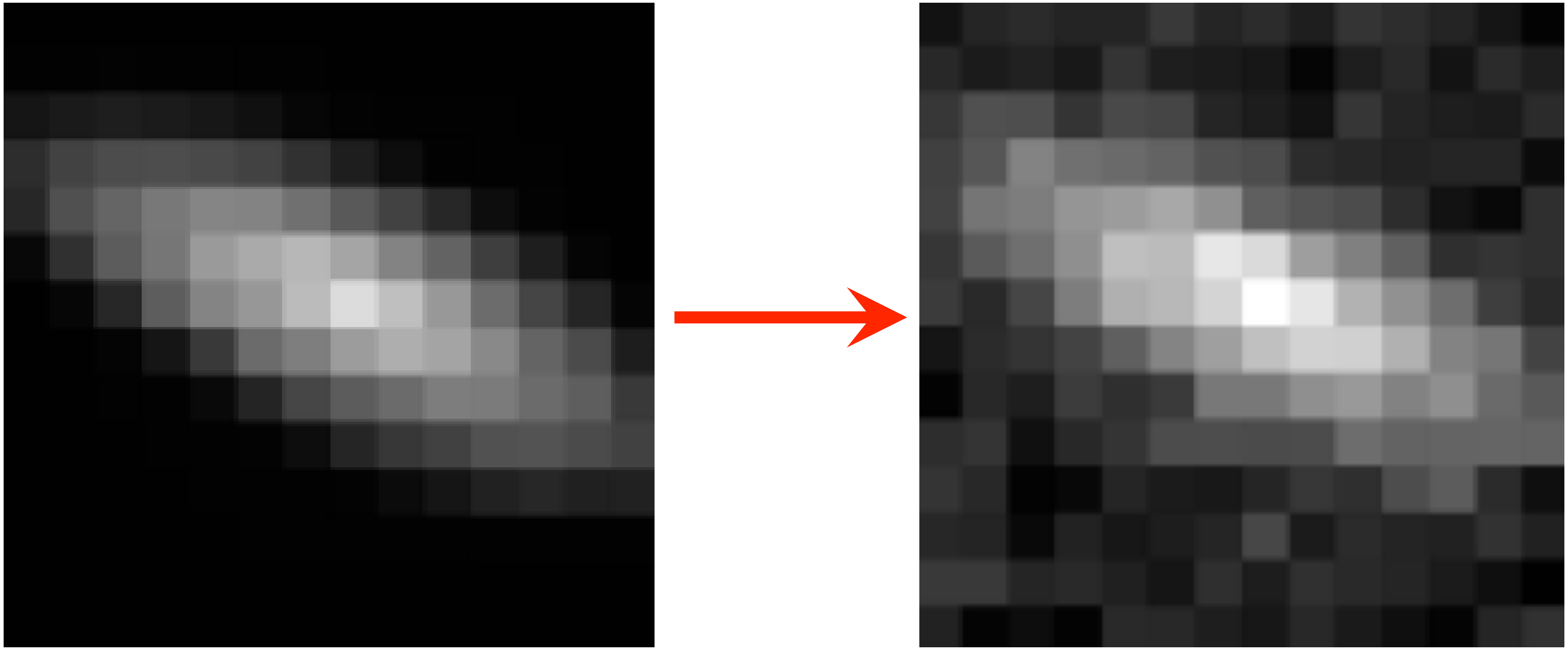
Pixelisation



Sum light in each square

Real data: Pixel size ~ Kernel size /2

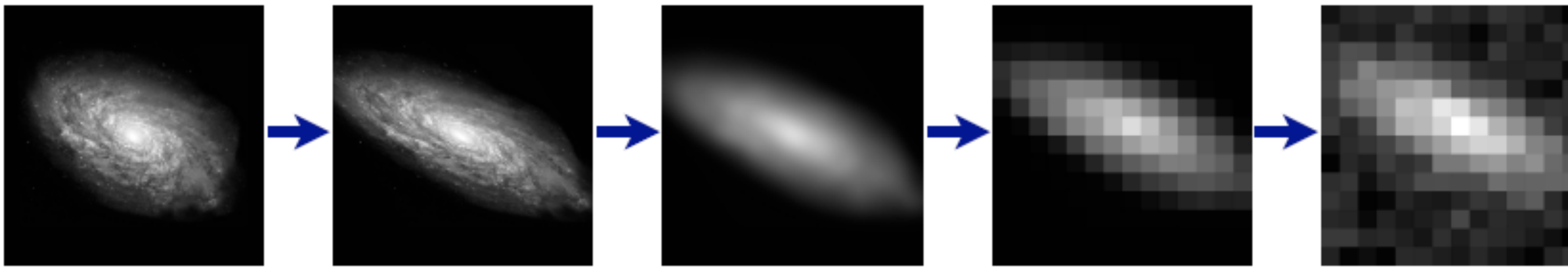
Noise



Mostly Poisson. Some Gaussian and bad pixels.
Uncertainty on total light ~ 5 per cent

The Forward Process.

Galaxies: Intrinsic galaxy shapes to measured image:



Intrinsic galaxy (shape unknown)

Gravitational lensing causes a ***shear (g)***

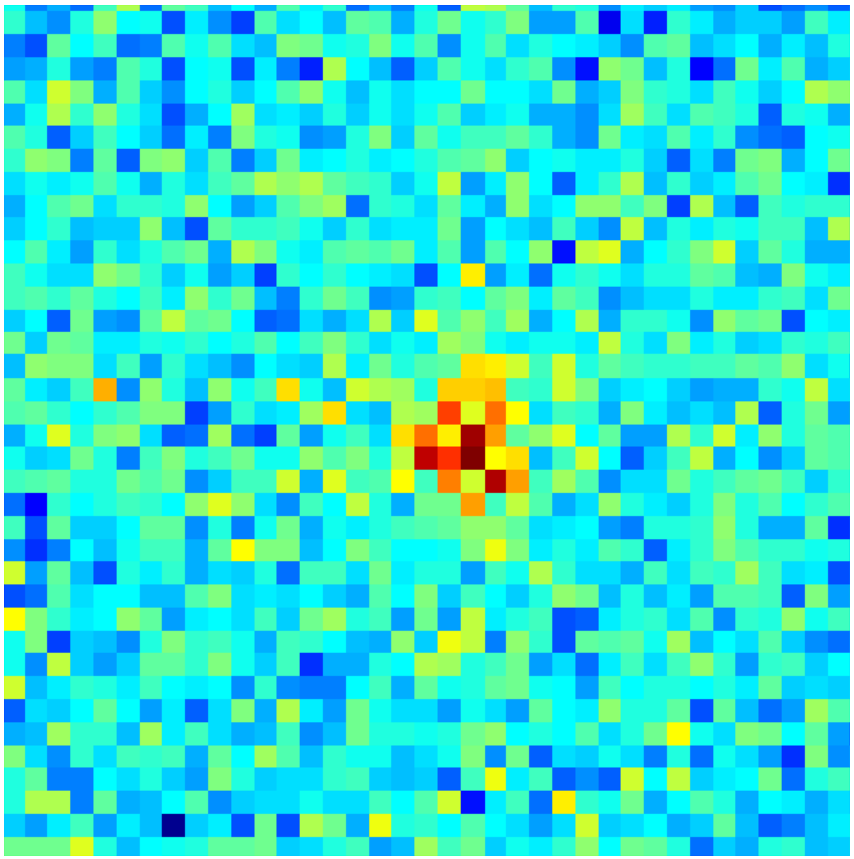
Atmosphere and telescope cause a convolution

Detectors measure a pixelated image

Image also contains noise

Bridle et al 2010

A typical galaxy image for cosmic shear



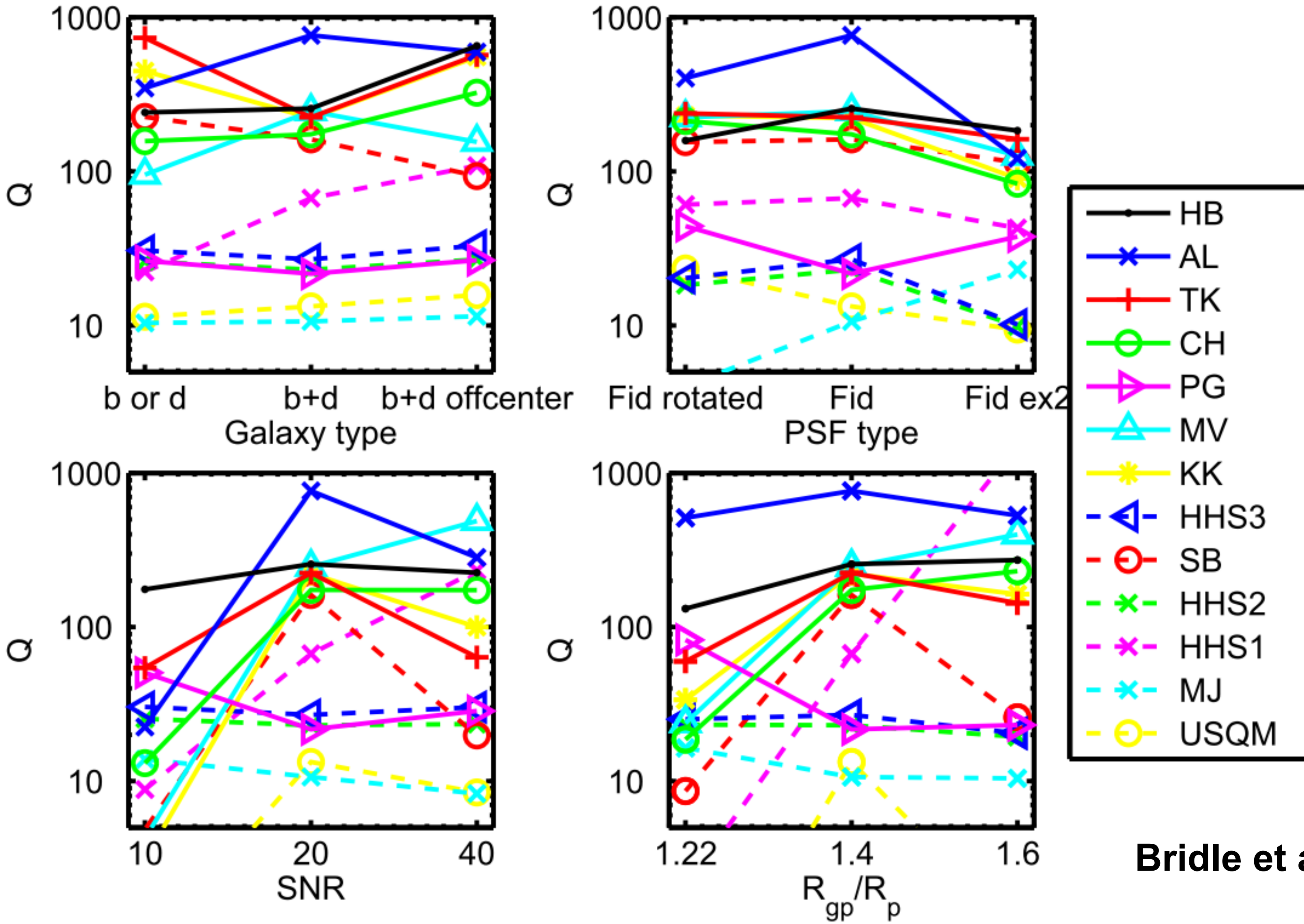
Intrinsic galaxy shape
b/a ~ 0.5

Uncertainty due to noise
σb/a ~ 0.5

Modification due to lensing
Δb/a ~ 0.05

Effect of changing w by 1%
δb/a ~ 0.0005

GREAT08 Results in Detail

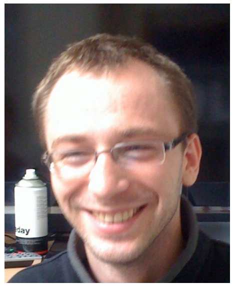


Bridle et al 2010

See also GREAT10 Kitching et al, and GREAT3 Rowe, Mandelbaum et al

im3shape Shear Measurement Code

Joe Zuntz



Tomek Kacprzak

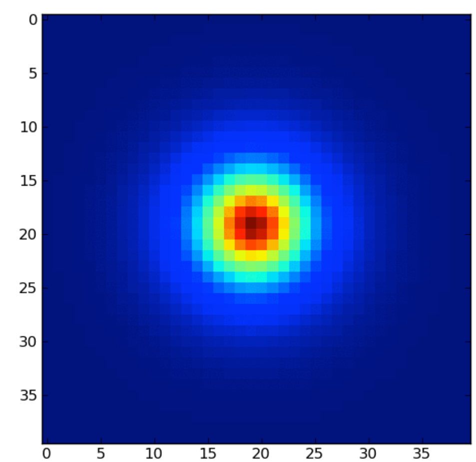
Barney Rowe

Lisa Voigt

Michael Hirsch

Sarah Bridle

- Forward model and fit
- Default: Galaxy is sum of two co-elliptical Sersics; PSF is Moffat
- Default: Maximum Likelihood.
- Takes about 1 second per galaxy



Zuntz, …, SB et al 2013

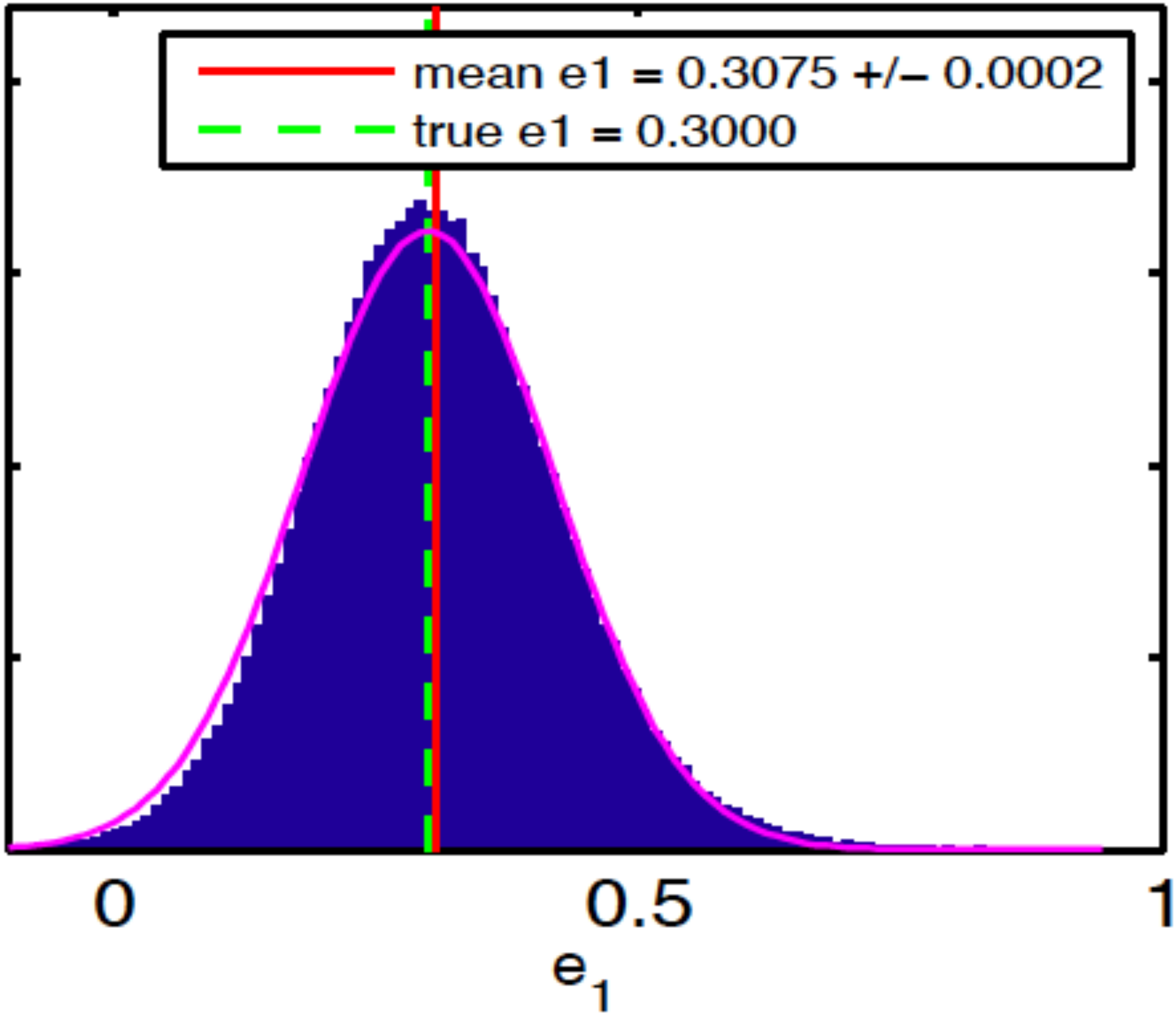
What causes the bias?
For model fitting methods

- Noise bias
  - Refregier, SB et al; Kacprzak, SB et al 2012
  - Maximum likelihood methods are biased
  - Calibration works well enough

- Model bias
  - Voigt & Bridle 2009
  - e.g use wrong profile in fit
  - e.g. use elliptical isophote model in fit

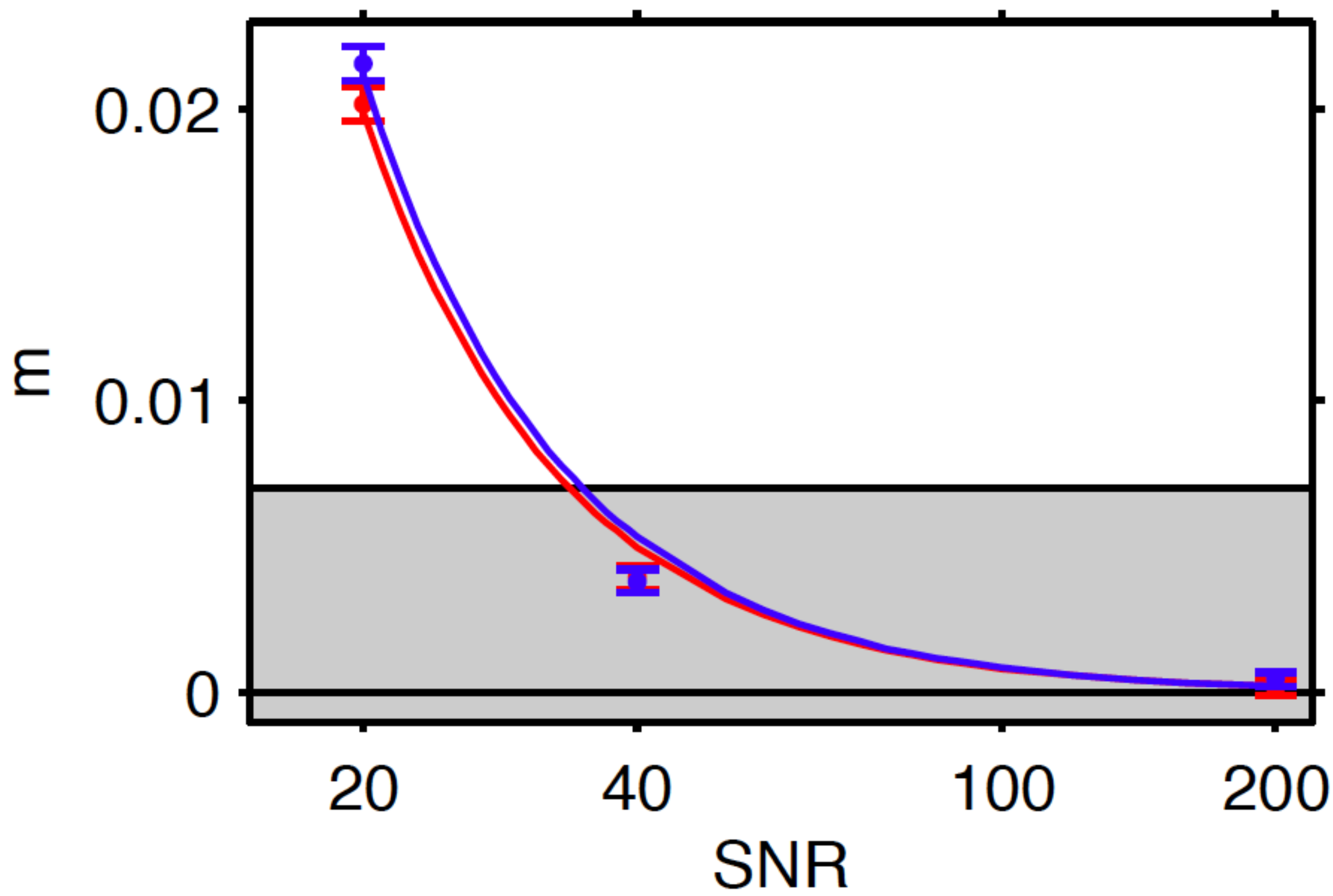
Noise Bias

Many identical images with different noise



Kacprzak, Zuntz, Rowe, Bridle et al 2012

Bias disappears at high S/N
Above requirements at low S/N



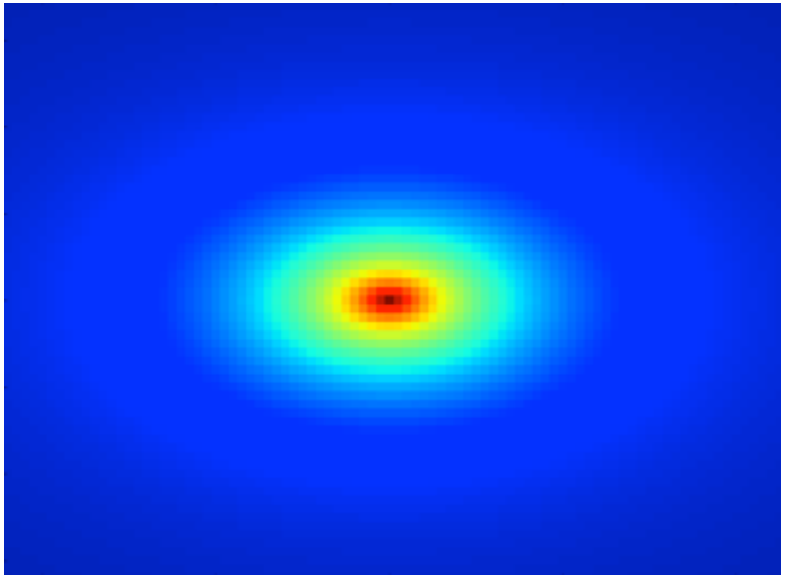
Refregier, Kacprzak, Amara, Bridle, Rowe 2012
Kacprzak, Zuntz, Rowe, Bridle et al 2012

What causes the bias?
For model fitting methods

- Noise bias
  - Refregier, SB et al; Kacprzak, SB et al 2012
  - Maximum likelihood methods are biased
  - Calibration works well enough

- Model bias
  - Voigt & Bridle 2009
  - e.g use wrong profile in fit
  - e.g. use elliptical isophote model in fit

But galaxies aren't simple…

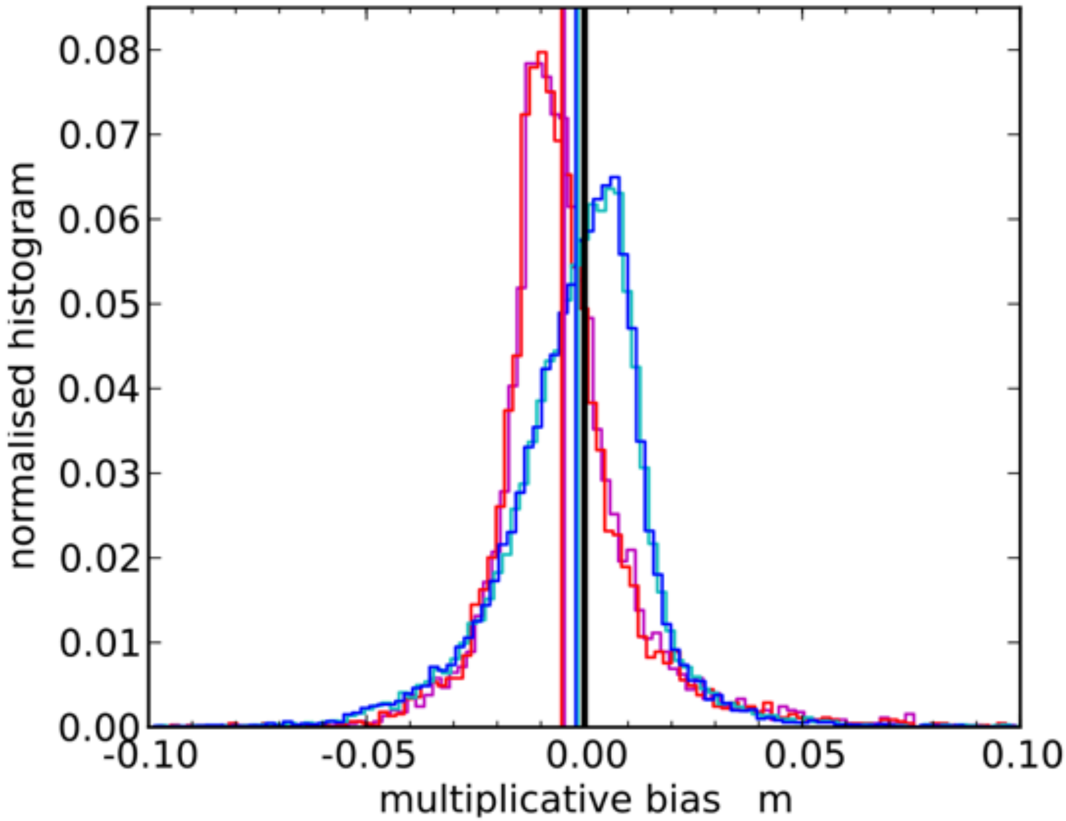


Model galaxy

Actual galaxy

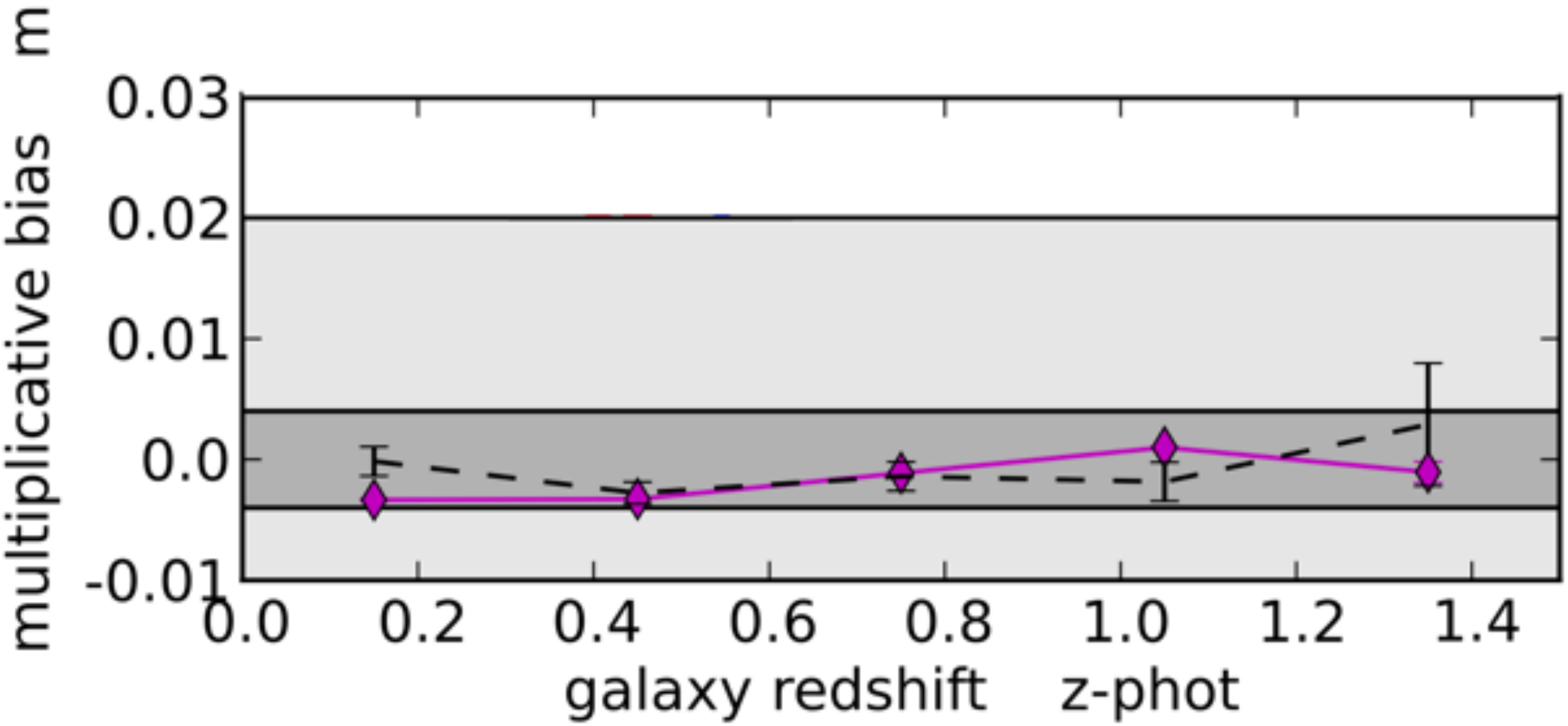
The effect of realistic galaxy shapes

- Measure with sims from HST data
- Bias for red and blue galaxies shown
- DES 5-year requires mean m < 0.005



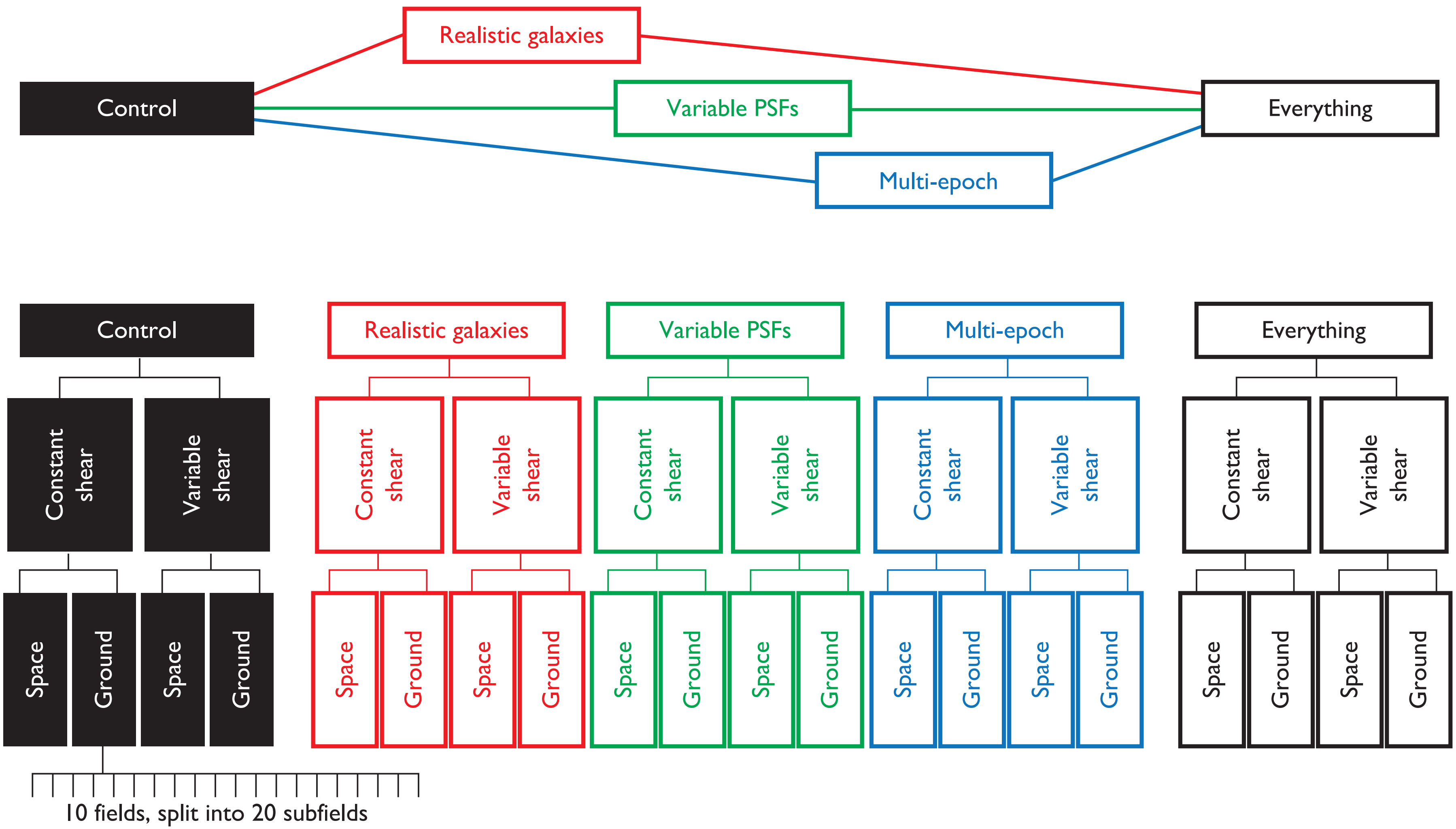
Plots from Tomasz Kacprzak

Impact on dark energy constraints



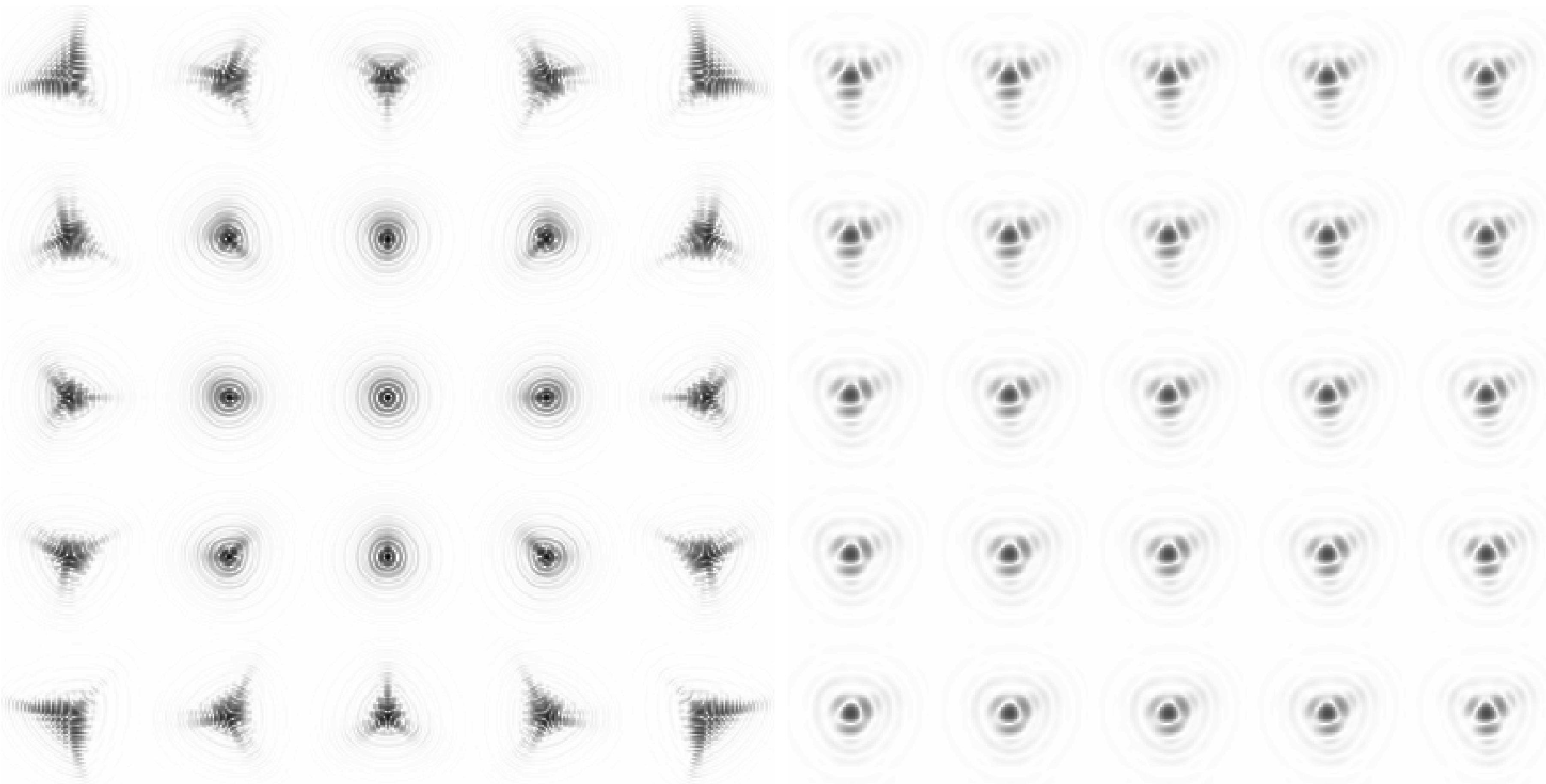
Kacprzak, SB, et al 2013

The GREAT3 Challenge



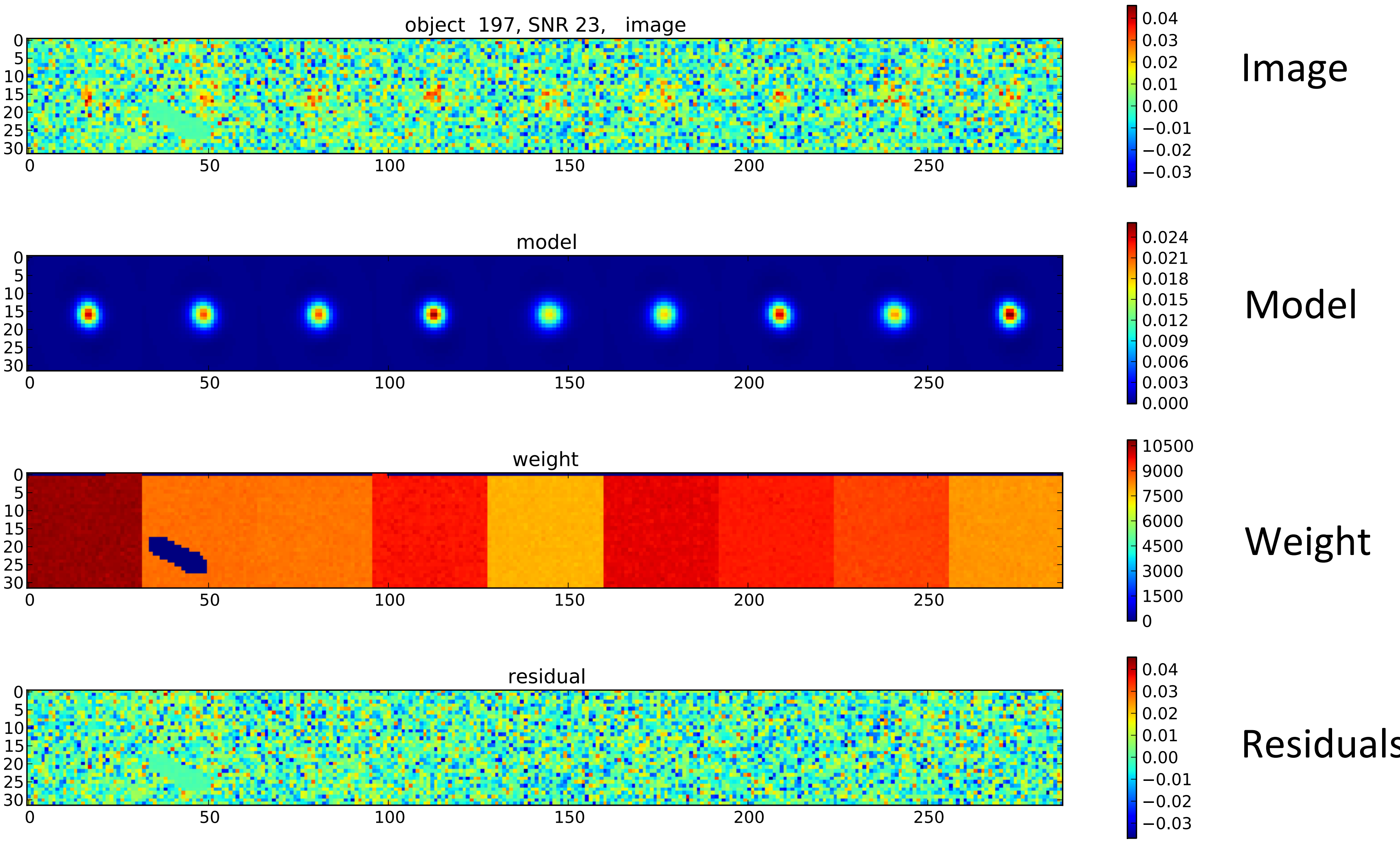
From the GREAT3 Challenge Handbook (Mandelbaum, Rowe, et al 2013)

The GREAT3 Challenge



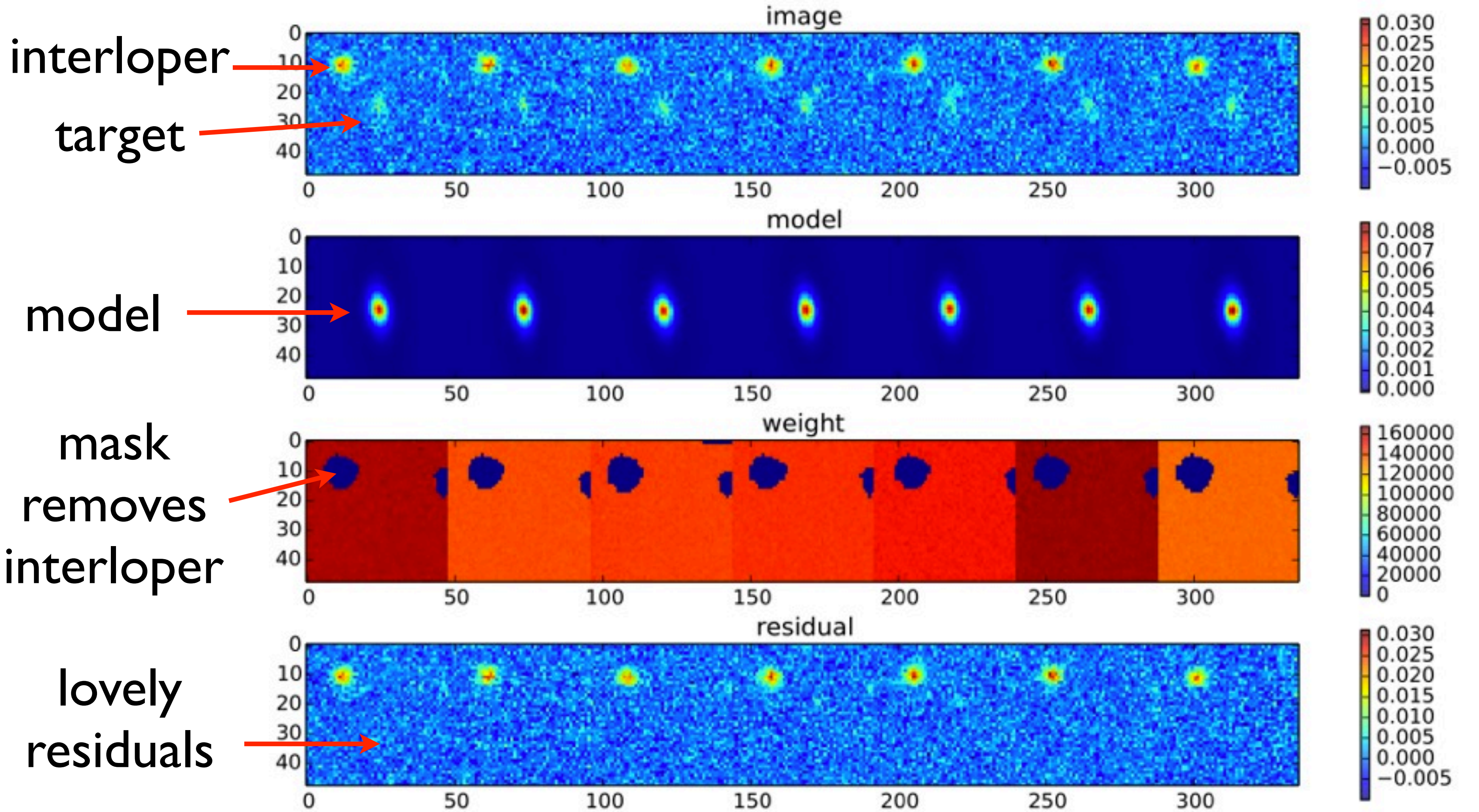
From the GREAT3 Challenge Handbook (Mandelbaum, Rowe, et al 2013)

Typical DES data – multiple exposures



DESDM data, PSFs; im3shape fit (Zuntz, Hirsch, Kacprzak, Rowe, MacCrann, Bridle)

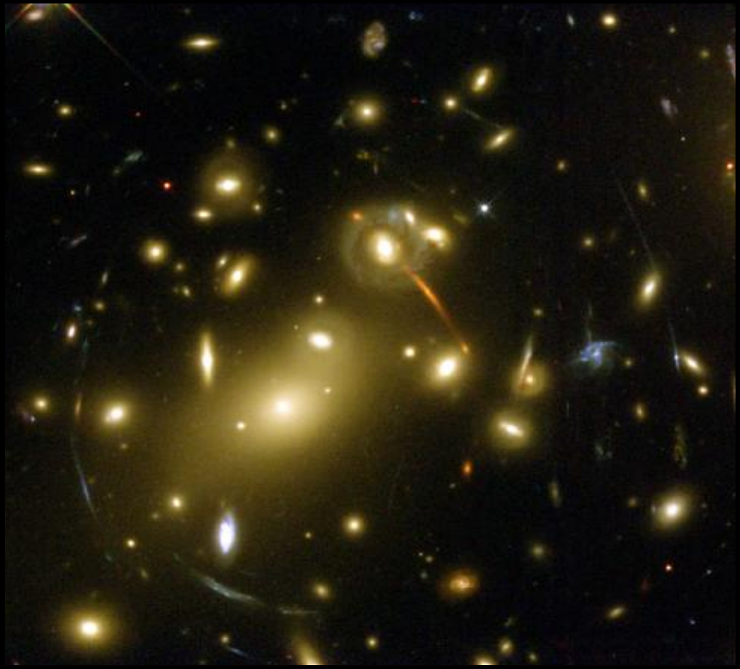
How to deal with overlaps?



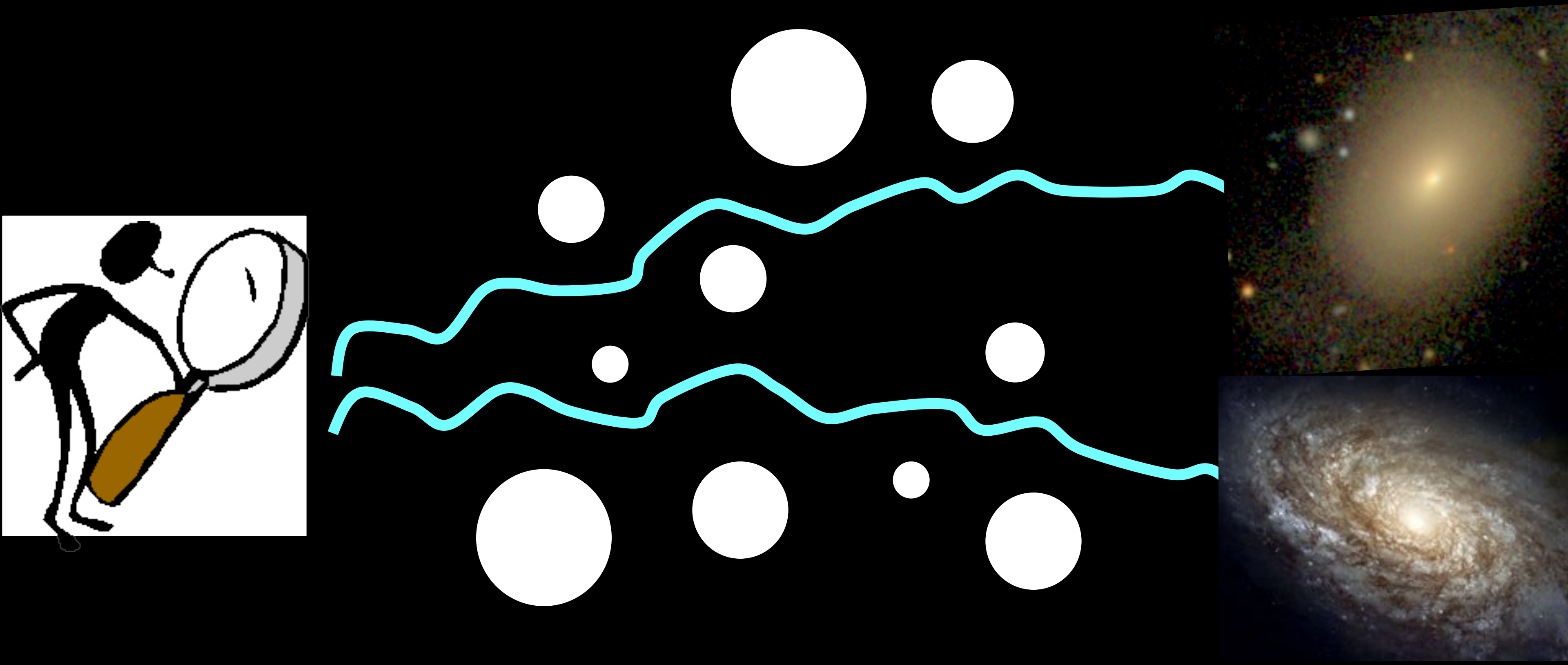
DESDM data, PSFs; im3shape fit (Zuntz, Hirsch, Kacprzak, Rowe, MacCrann, Bridle)

Weak Lensing in the next Decade

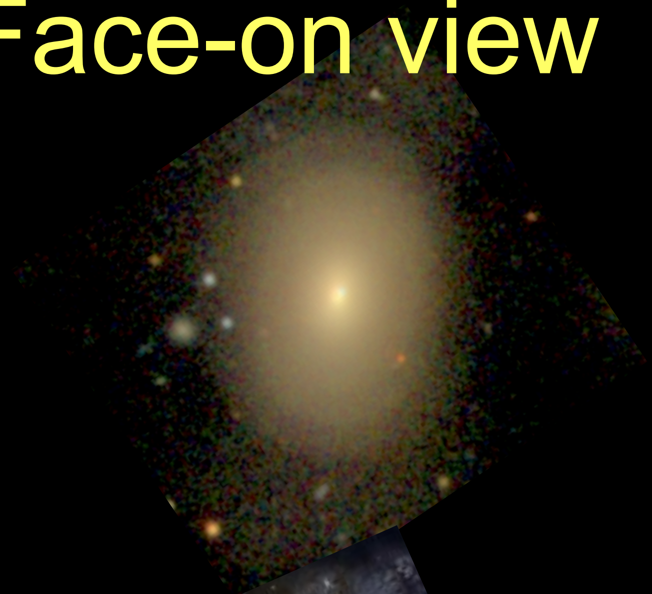
- Introduction to Cosmic Shear for dark energy
- Potential limitations
  - Shear measurement
  - Intrinsic alignments
  - Photozs
- Future surveys



Cosmic shear



Cosmic shear
Face-on view

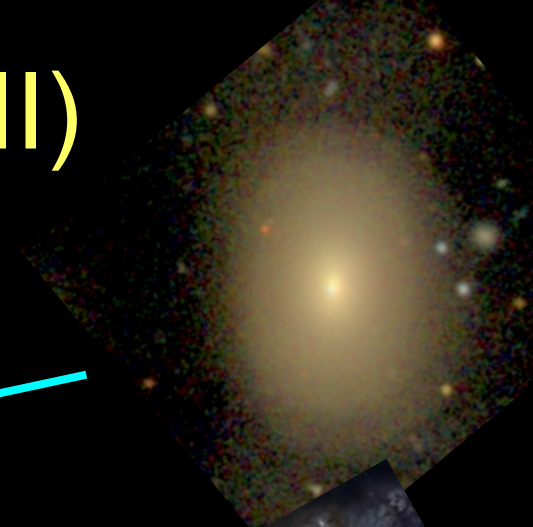


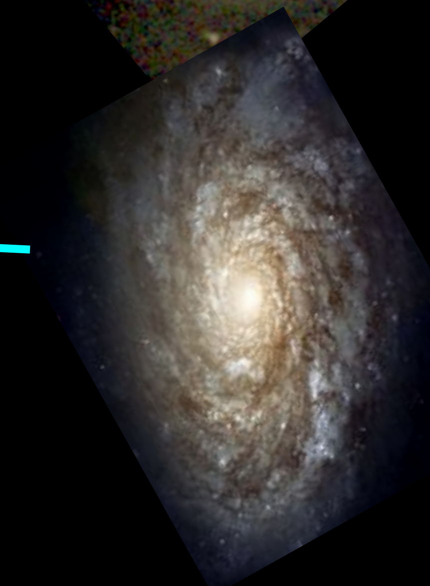
Gravitationally sheared

Gravitationally sheared

Lensing by dark matter causes galaxies to appear aligned

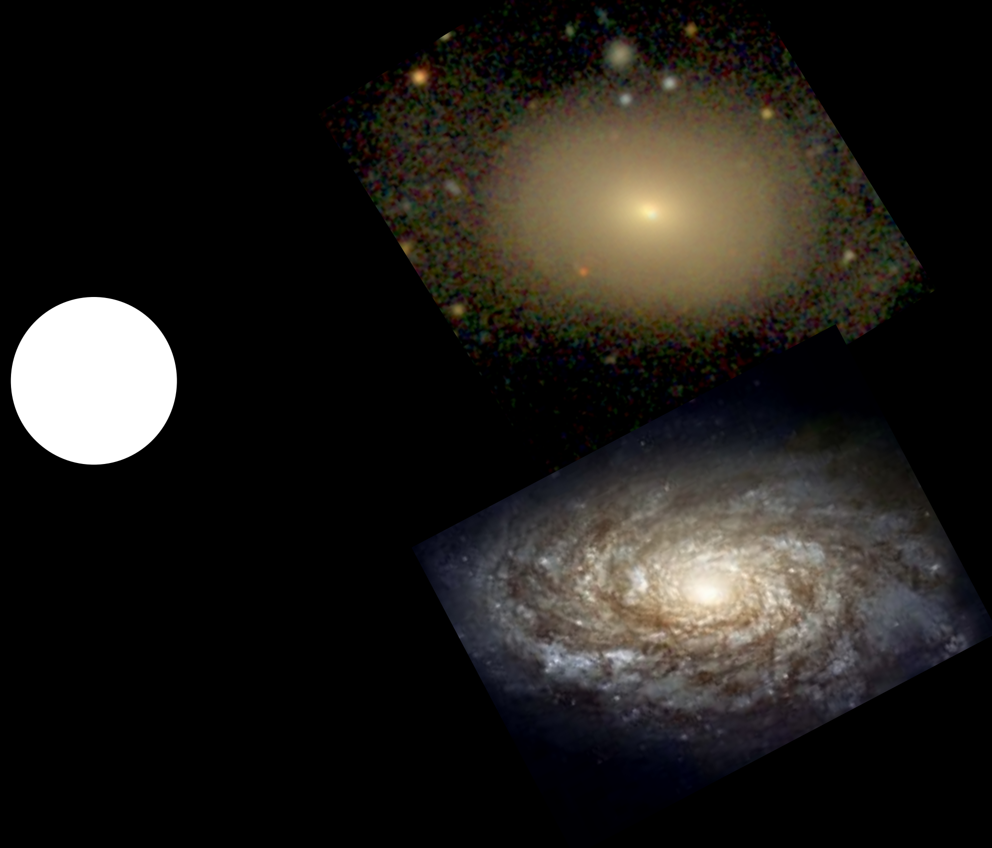
Intrinsic alignments (II)





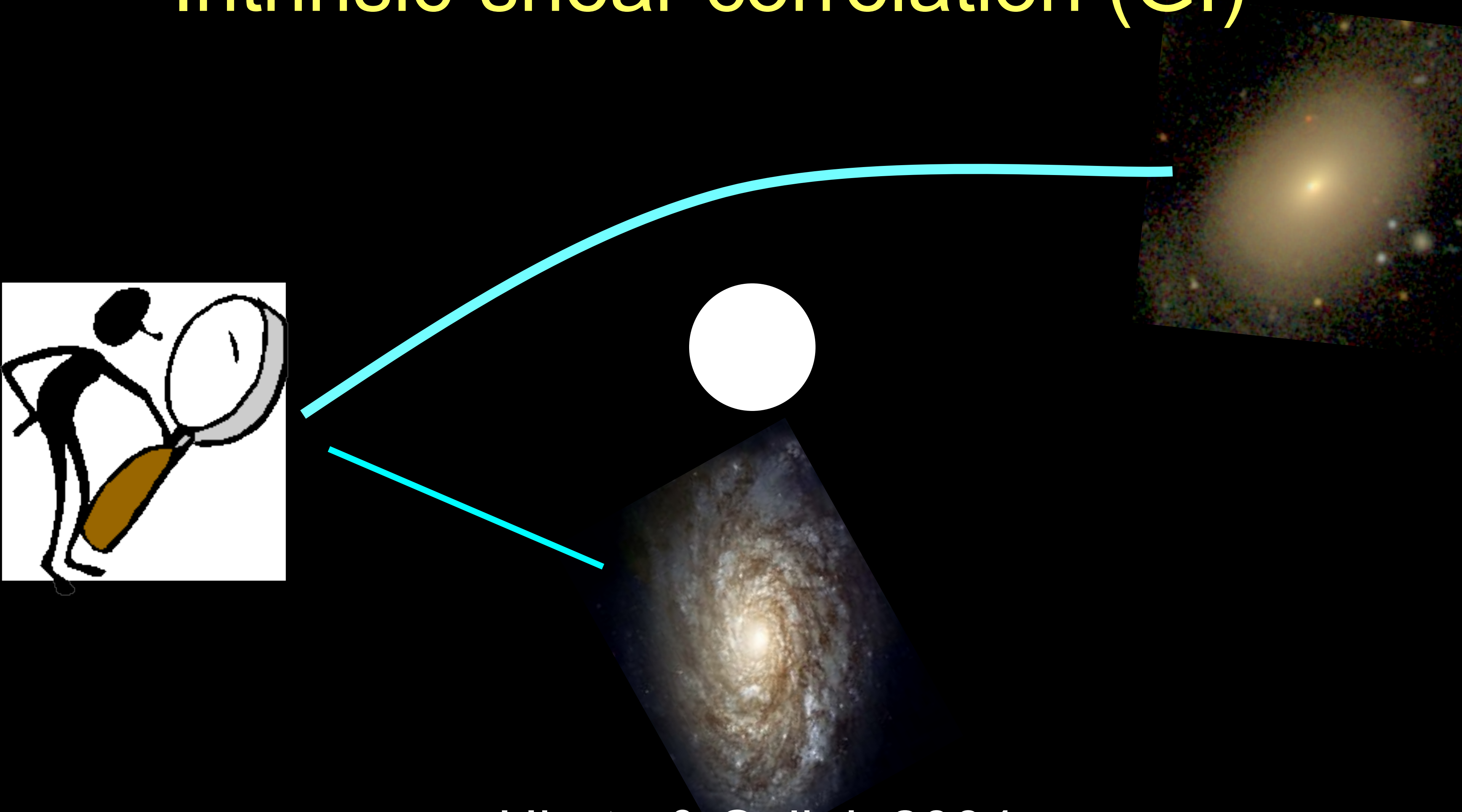
Lensing contaminant pointed out by Croft & Metzler 2000; Heavens e
l 2000; Catelan et al 2001 then investigated by Crittenden et al 2001
Mackey et al. 2002; Jing 2002; Hui & Zhang 2002

Intrinsic alignments (II)
Face-on view



Tidal stretching causes galaxies to align
Adds to cosmic shear signal

Intrinsic-shear correlation (GI)



Hirata & Seljak 2004

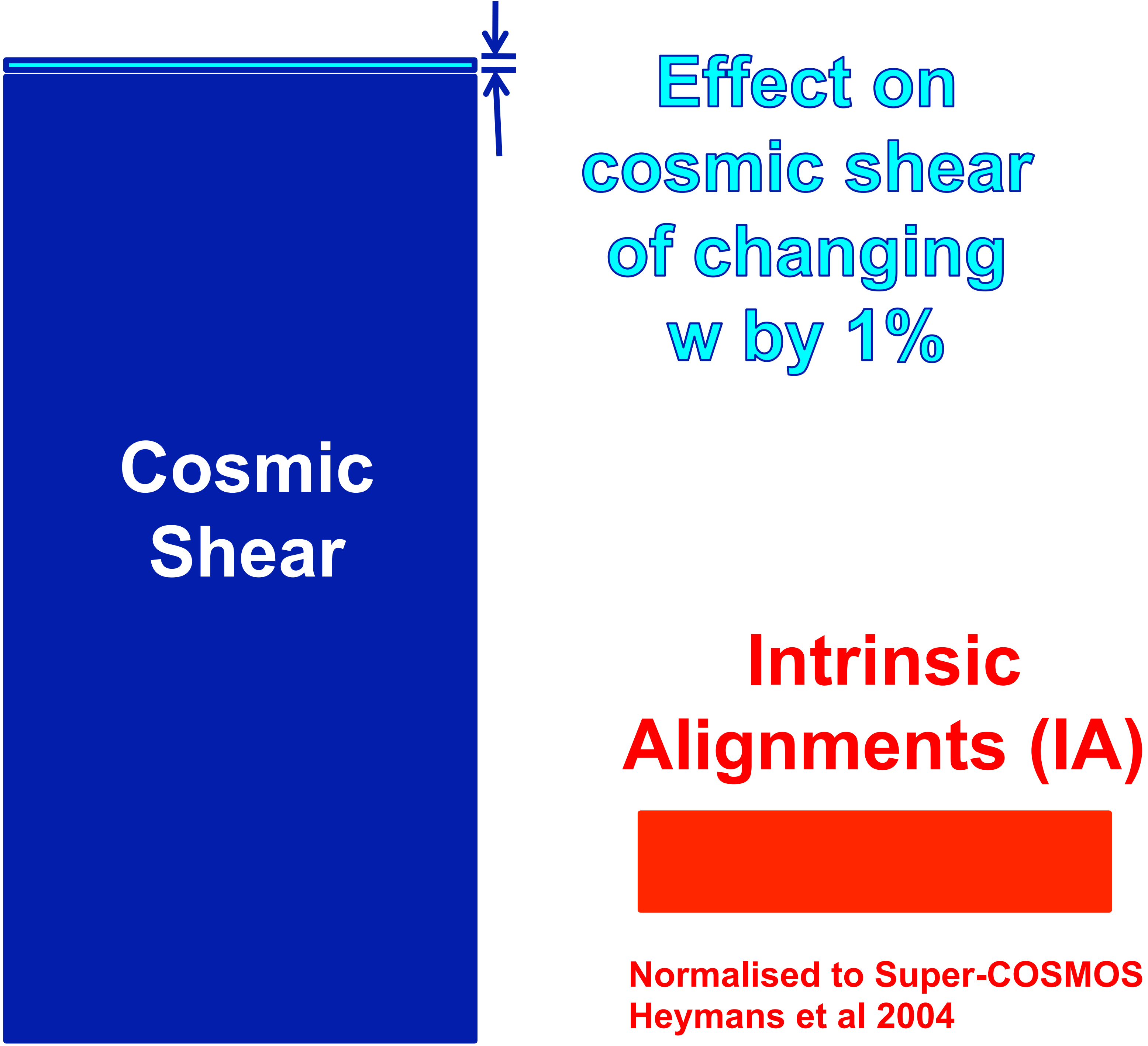
See also Heymans et al 2006, Mandelbaum et al 2006, Hirata et al 2007

Intrinsic-shear correlation (GI)
Face-on view

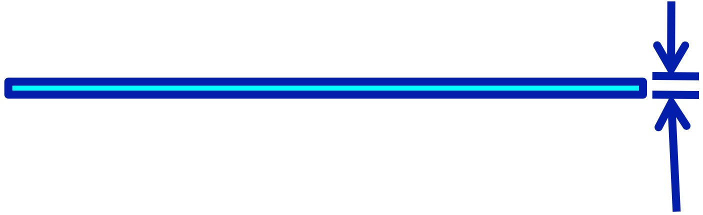
Gravitationally sheared (G)

Intrinsically aligned (I)

Galaxies point in opposite directions
Partially cancels cosmic shear signal



Effect on cosmic shear of changing w by 1%
Cosmic Shear
Intrinsic Alignments (IA)
Normalised to Super-COSMOS
Heymans et al 2004



Effect on cosmic shear of changing w by 1%

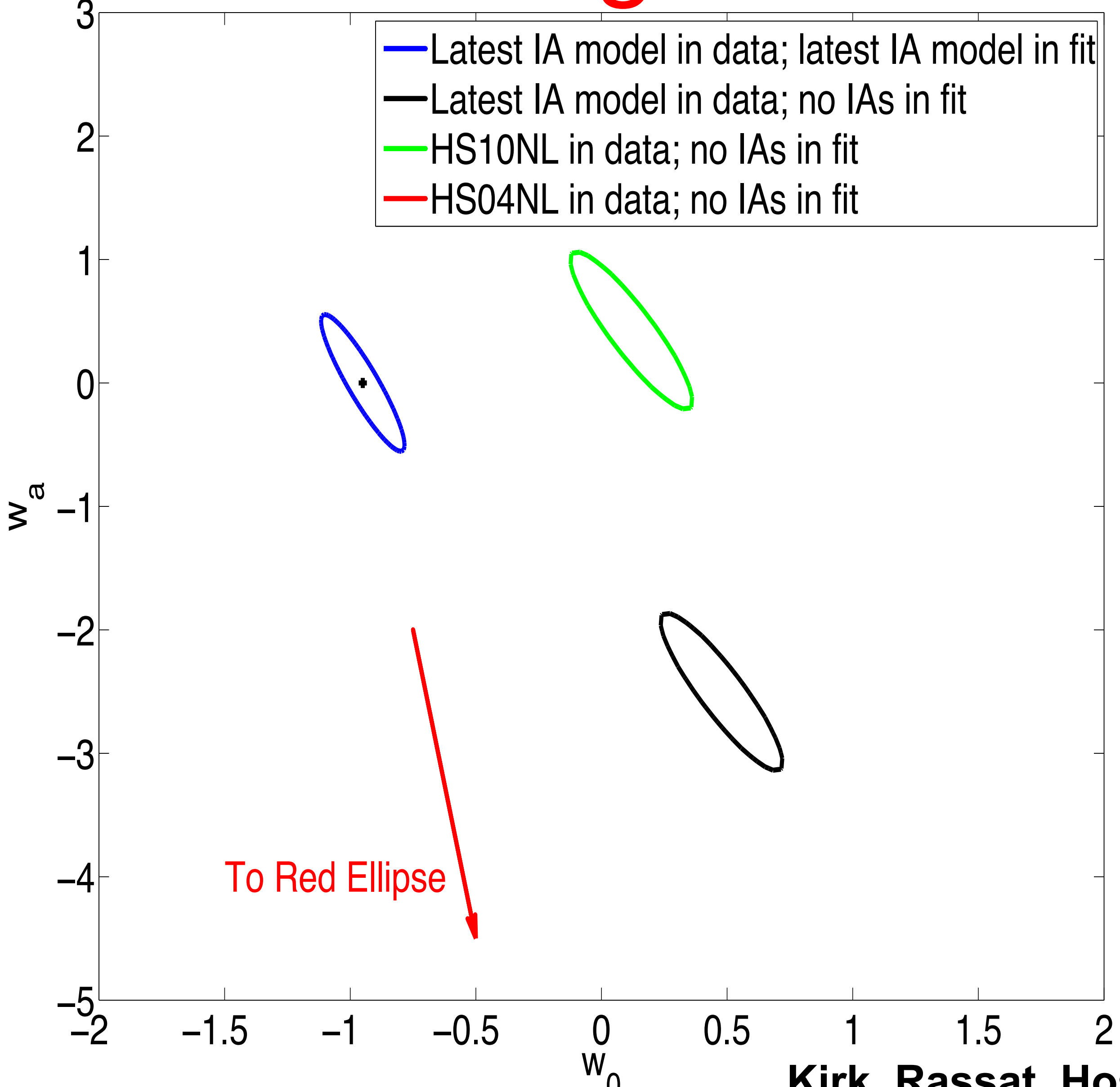
Bridle & King 2007

If consider only w then IA bias on w is ~10%

If marginalise 6 cosmological parameters then IA bias on w is ~100% (+/- 1 !)

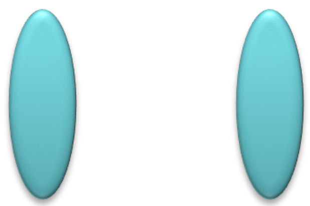
Intrinsic Alignments (IA)

We can't ignore IAs

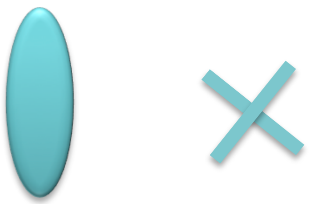


Kirk, Rassat, Host, Bridle 1112.47

Use of shear-position correlations



Shear-shear correlations
- Measure mostly dark matter



Shear-position correlations
- Measure mostly intrinsic alignments

Position-position correlations
- Traditional galaxy survey observable

Joint Constraints from Position 2-point Observables

Cosmic shear **Intrinsic Alignments**

$$C_{\epsilon\epsilon}^{(ij)}(\ell) = C_{\rm GG}^{(ij)}(\ell) + C_{\rm IG}^{(ij)}(\ell) + C_{\rm IG}^{(ji)}(\ell) + C_{\rm II}^{(ij)}(\ell)$$

$$C_{nn}^{(ij)}(\ell) = C_{\rm gg}^{(ij)}(\ell) + C_{\rm gm}^{(ij)}(\ell) + C_{\rm gm}^{(ji)}(\ell) + C_{\rm mm}^{(ij)}(\ell)$$

$$C_{n\epsilon}^{(ij)}(\ell) = C_{\rm gG}^{(ij)}(\ell) + C_{\rm gI}^{(ij)}(\ell) + C_{\rm mG}^{(ij)}(\ell) + C_{\rm mI}^{(ij)}(\ell)$$

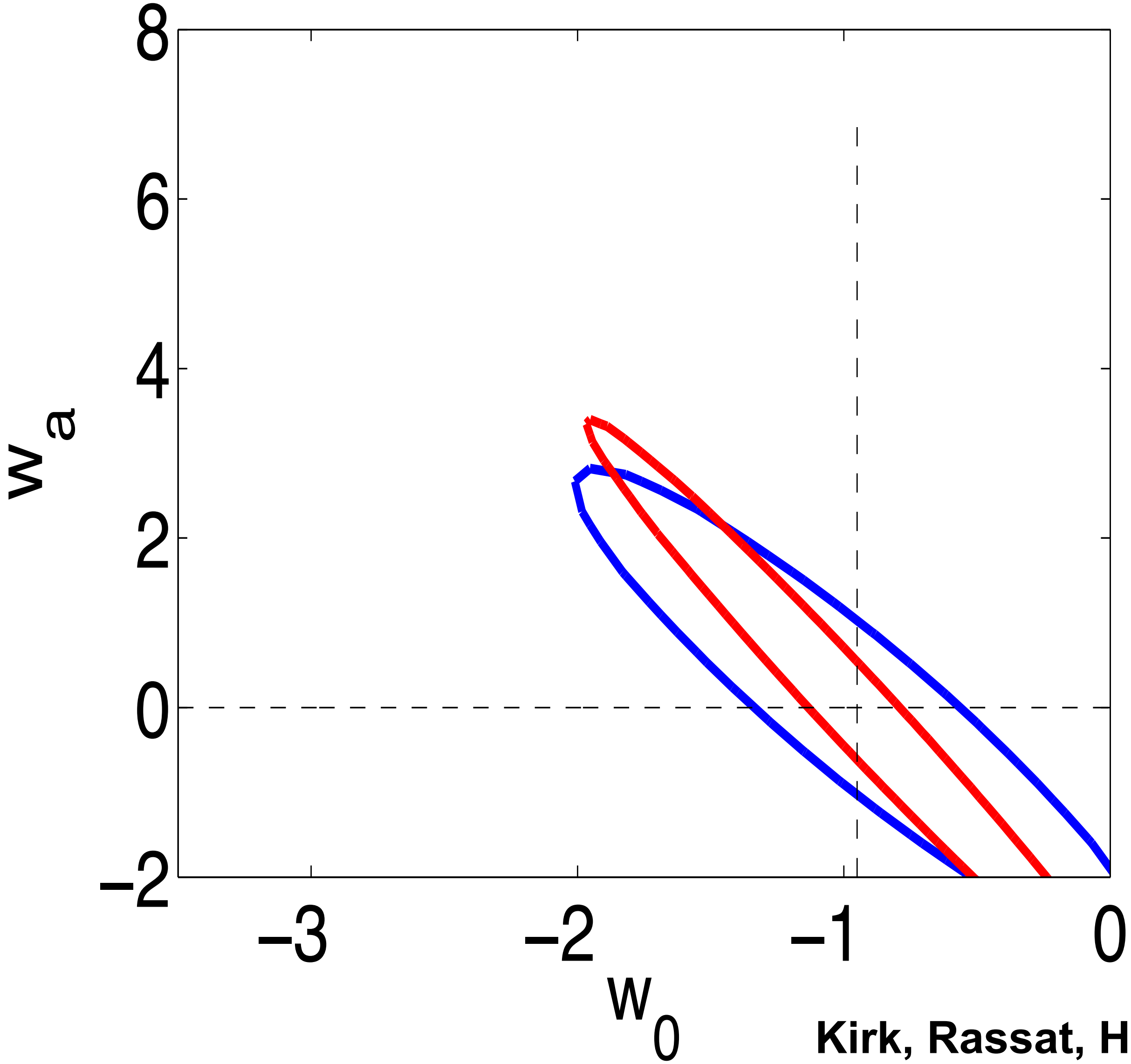
Galaxy clustering **Cosmic magnification**

Shear-position correlation function

Angular power spectra are sourced by underlying 3D power spectra: Dark matter P(k), galaxy P(k), IA P(k), galaxy-DM cross, IA-DM cross

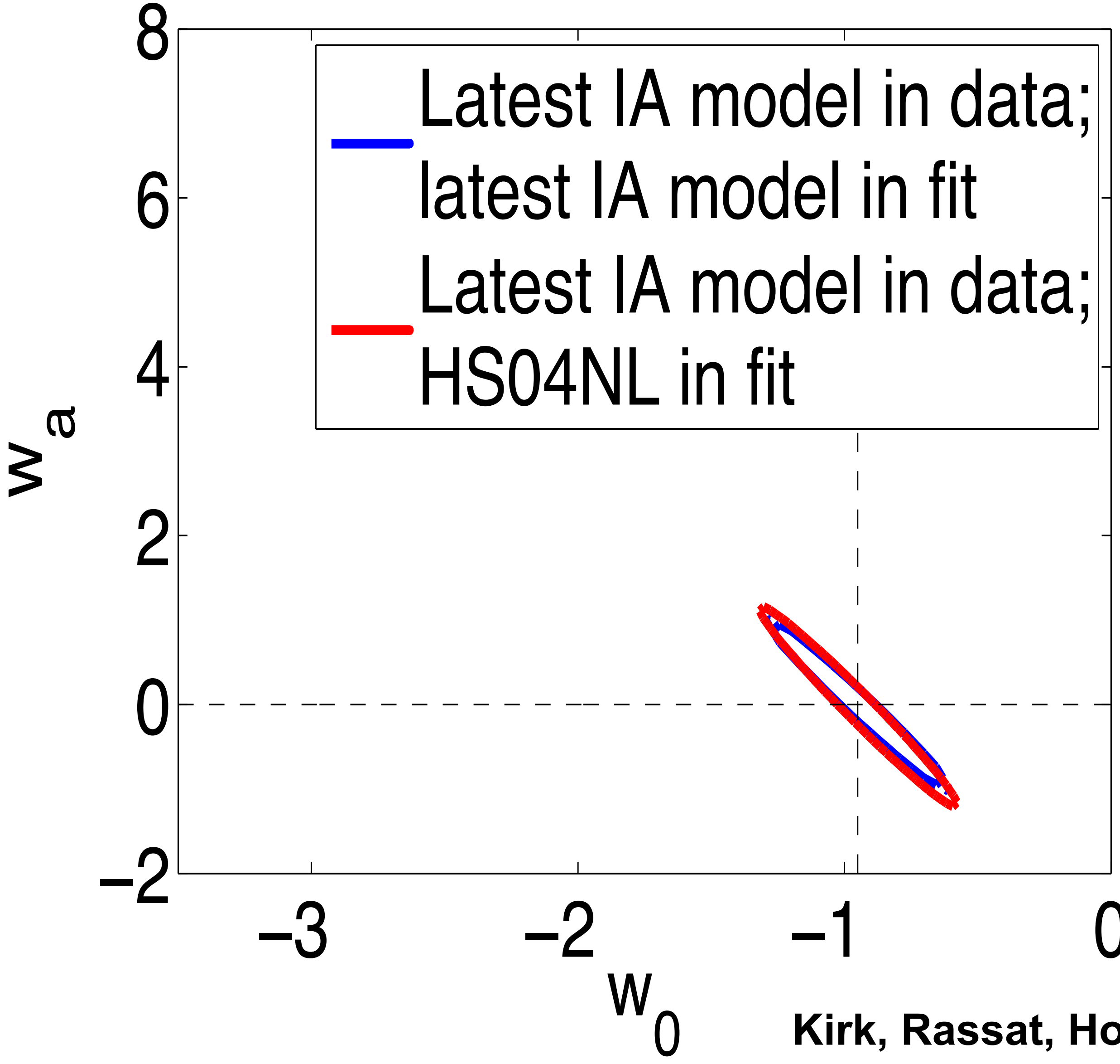
Bernstein 2009, Joachimi & Bridle 2010

Marginalised over 100 parameters

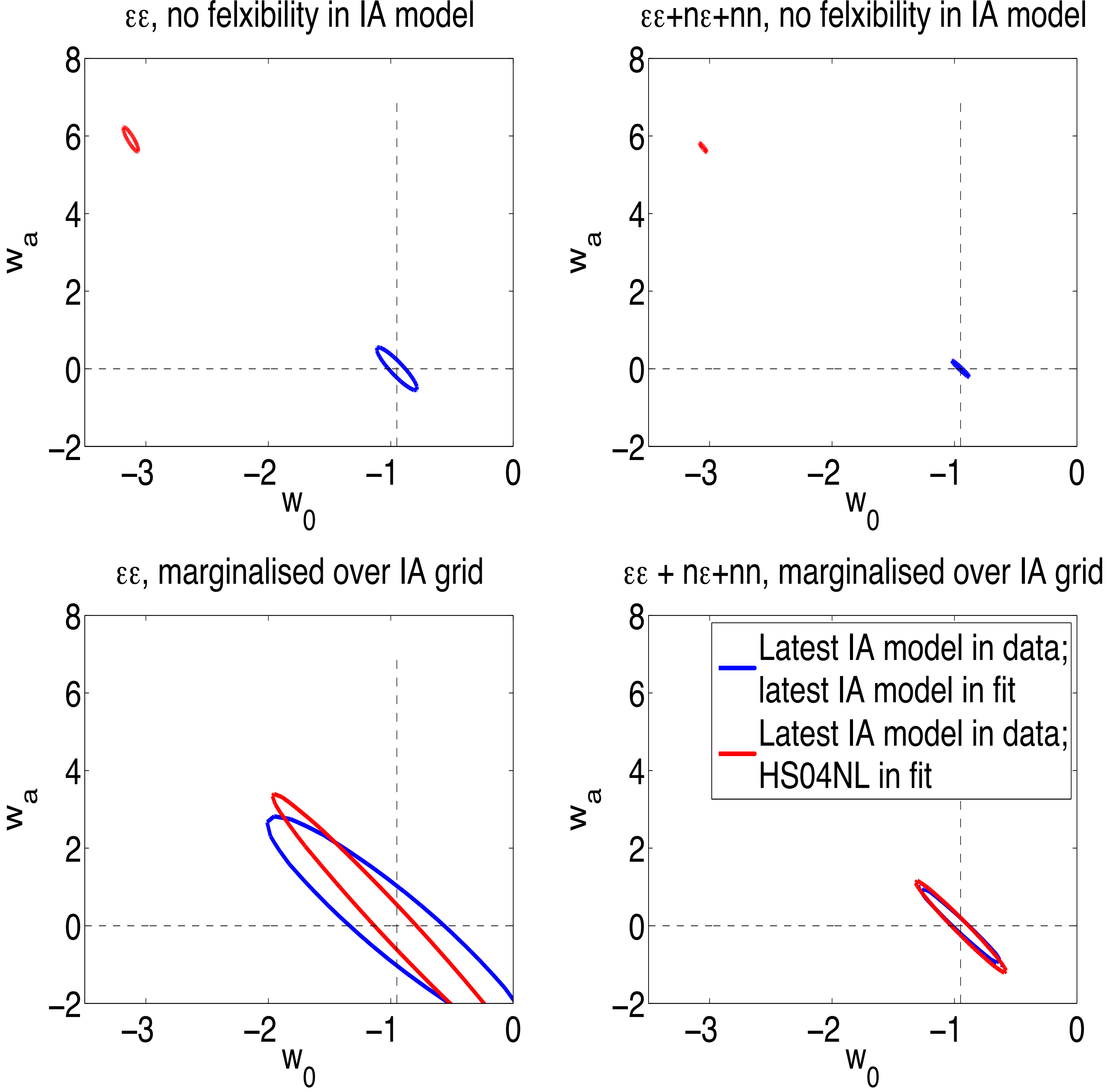


Kirk, Rassat, Host, Bridle 1112.47

Marginalised over 100 parameters
With shear-position correlations



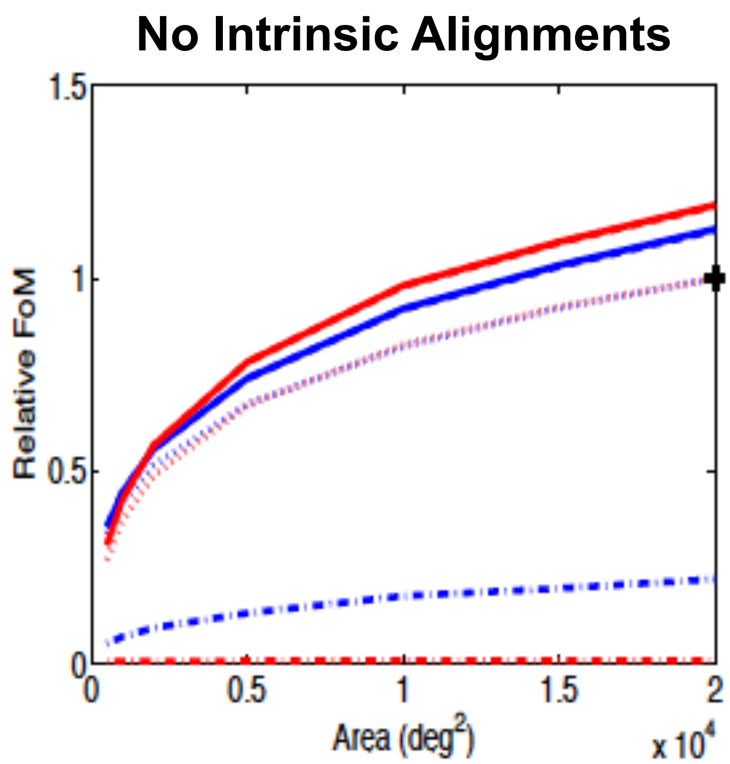
Kirk, Rassat, Host, Bridle 1112.47

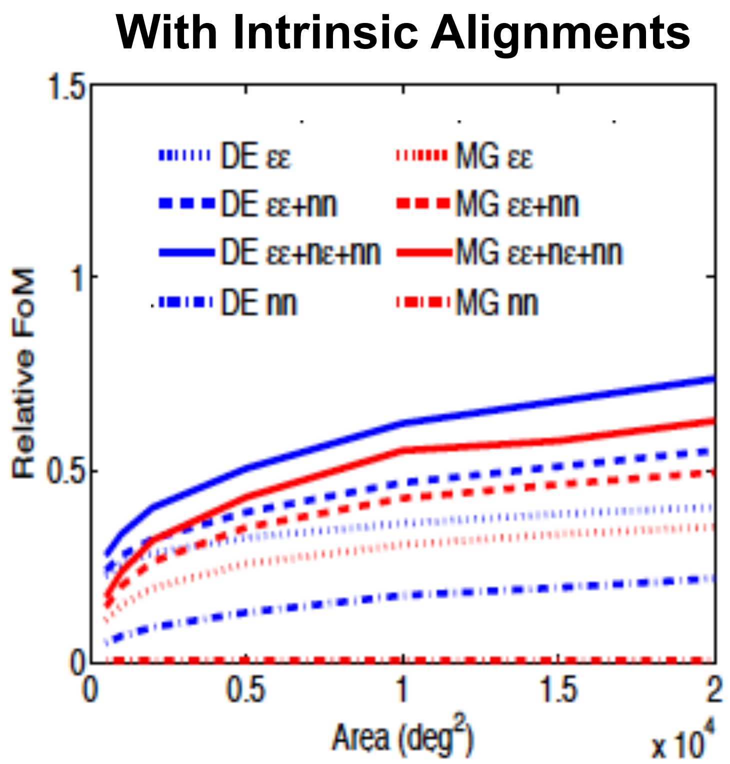


Realistic error bars lie somewhere between 0 and 100 IA parameters

Impact of Intrinsic Alignments on Survey Design

Figure of Merit



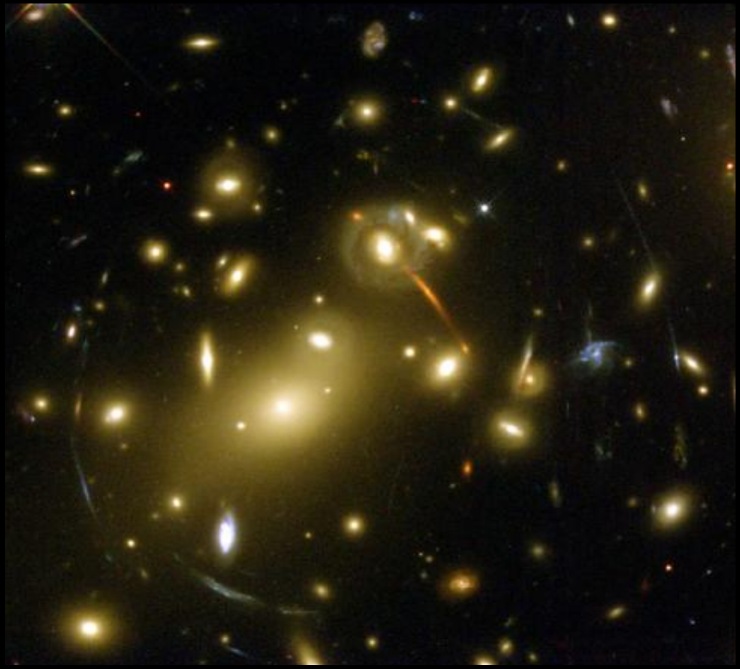


Flatter dependence on area
Because intrinsic alignments dominate at low redshift
Same conclusion for dark energy or modified gravity

Kirk, Laszlo, Bridle, Bean 2011

Weak Lensing in the next Decade

- Introduction to Cosmic Shear for dark energy
- Potential limitations
  - Shear measurement
  - Intrinsic alignments
  - Photozs
- Future surveys

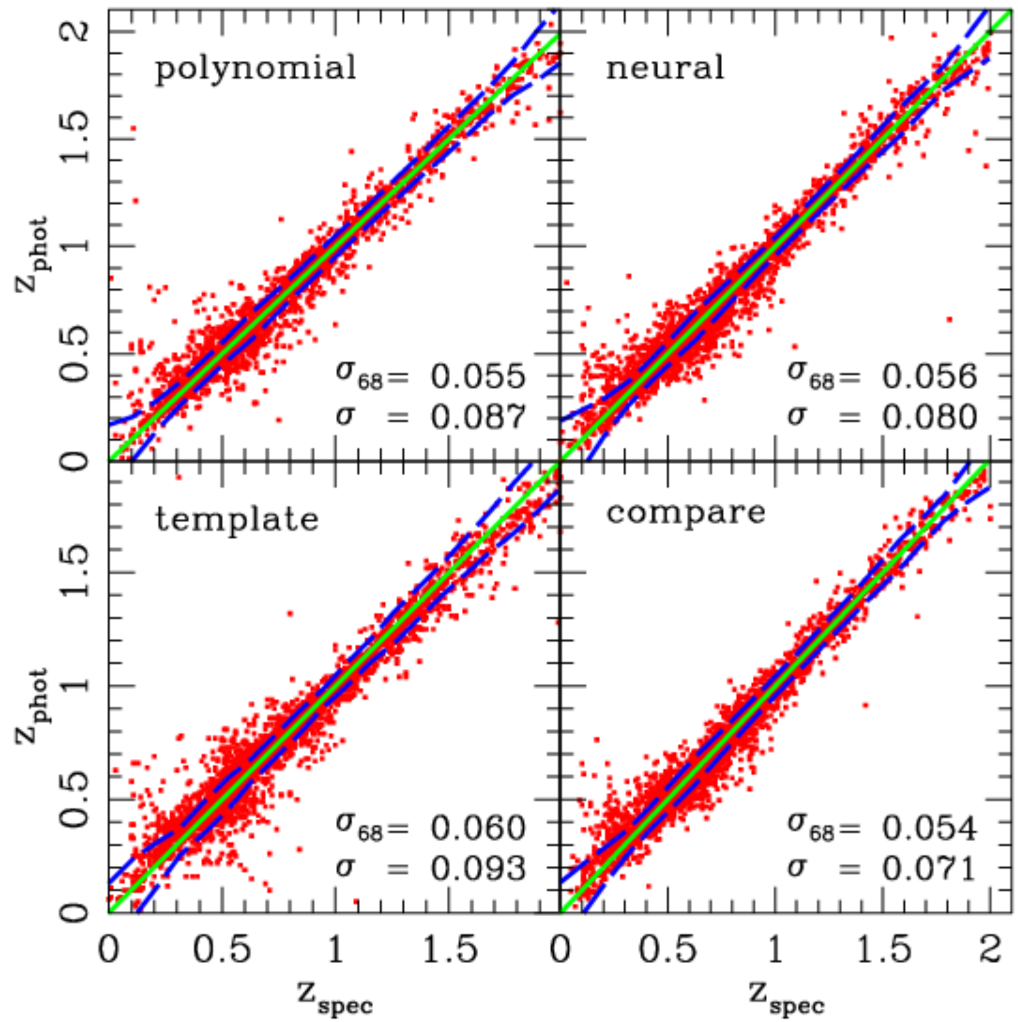


Field Galaxy Photo-z Results

DES + VISTA
griz+YJHKs filters

10σ Limiting Magnitudes

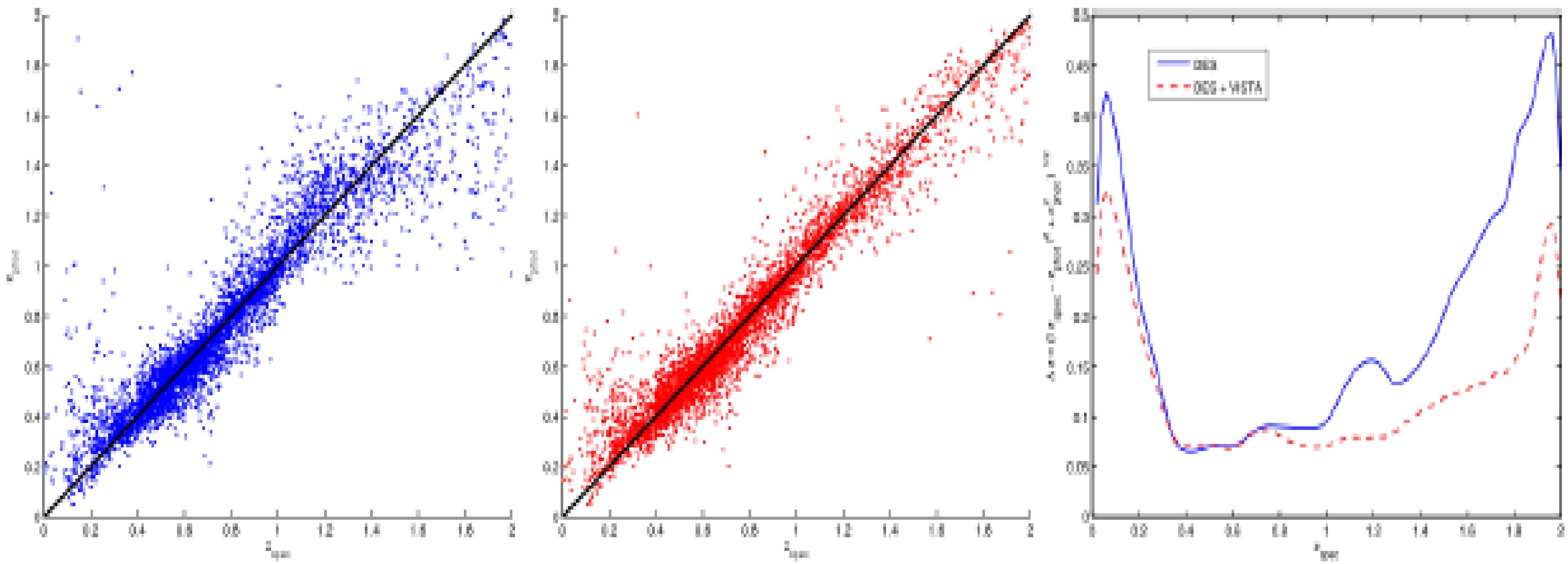
Y	22.45
J	22.15
H	21.65
Ks	21.15



Cunha, Lima, Collister, Lahav, Lin in prep

DES and VDES

DES (griz) ***DES+VISTA(JK)***



JK would improve photo-z by a factor of 2 for z> 1

F. B. Abdalla, J. Lalli, O. Lahav, et al.

How good to photozs have to be?

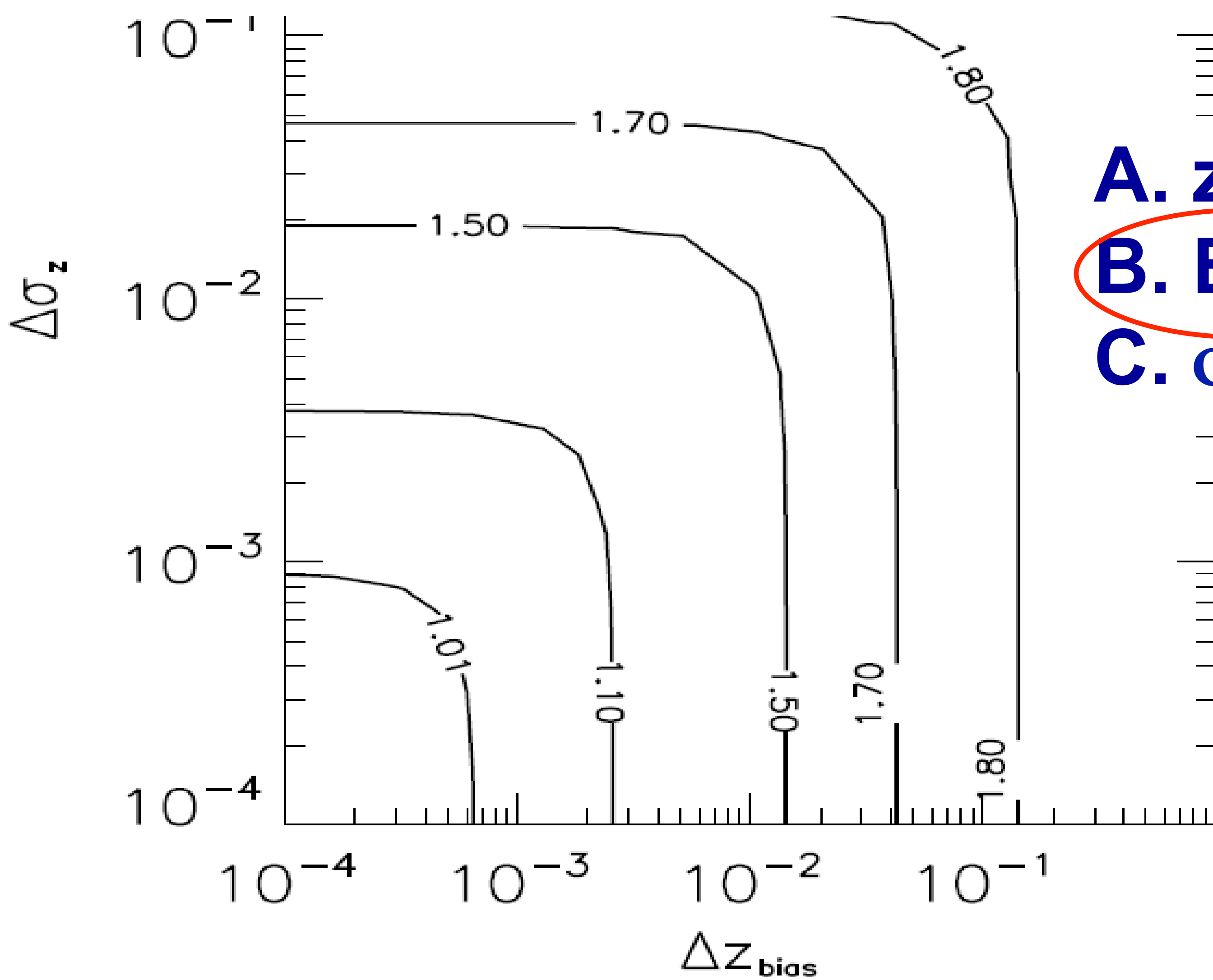
Huterer et al

$$P^\kappa \propto \Omega_{\rm DE}^{-3.5} \sigma_8^{2.9} z_{\rm s}^{1.6} |w|^{0.31}$$

- Measure P^κ
- If all other cosmological parameters fixed..

  $|w| / z_s^{1.6 / 0.31} = z_s^5$
- If want |w| to 1 per cent accuracy, to what accuracy must z_s be known?
- $\Delta w = 5 \Delta z_s$
- $\Delta z_s = \Delta w / 5 = 0.01 / 5 = 0.002$

Which is more important z_{bias} or σ_z ?



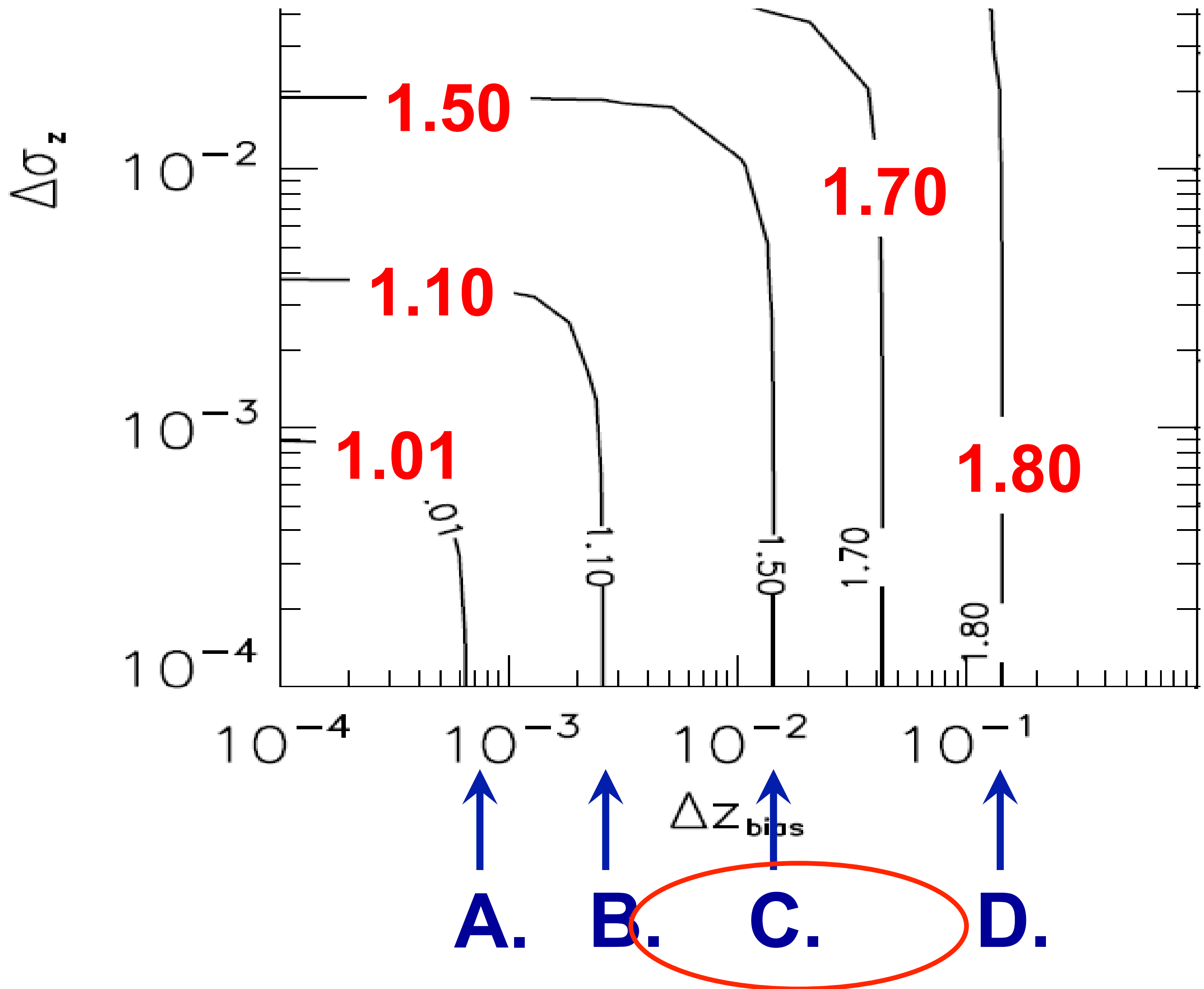
A. z_{bias}

B. Equal

C. σ_z

Ma, Hu

What Δz_{bias} is acceptable?



Ma, Hu & Huterer

How many spectra are needed?

$$\Delta z_{\rm bias}(z_\mu) = \sigma_z(z_\mu)\sqrt{1/N^\mu_{\rm spec}}$$

$$\Delta\sigma_z(z_\mu) = \sigma_z(z_\mu)\sqrt{2/N^\mu_{\rm spec}}$$

- $\Delta z_{bias} \sim 0.003$
- $\sigma_z \sim 0.1$
- N^{μ}_{spec} = number per redshift interval
  - A. 10 B. 100 C. 1000
- Total spectra ~ 10^4

Calculate # spectra for LSST

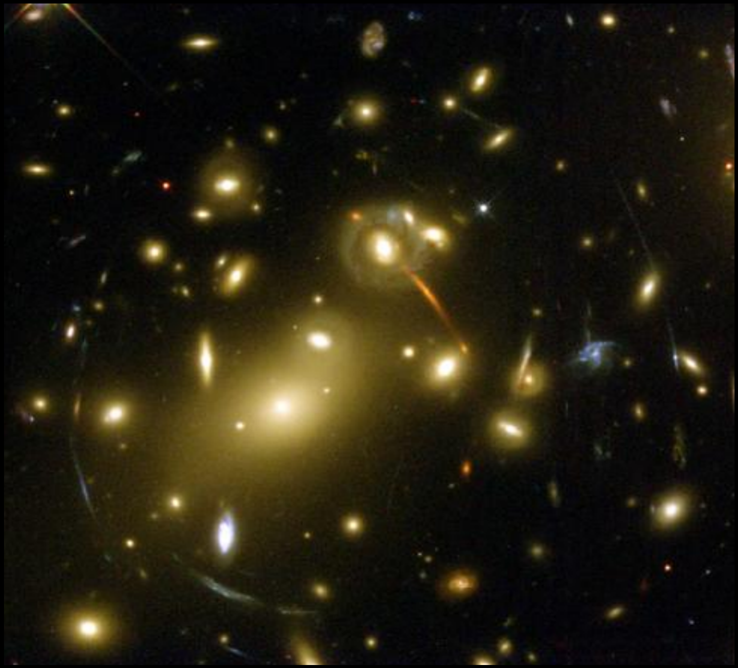
$$\Delta z_{\rm bias} = \sqrt{\frac{0.1}{f_{\rm sky}}} \times \left[1 + 0.6\left(\frac{55}{n^A} - 1\right)\right] \Delta z_{\rm bias}^{\rm fid}$$

$$\Delta z_{\rm bias}(z_\mu) = \sigma_z(z_\mu)\sqrt{1/N_{\rm spec}^{\mu}}$$

- n_A ~55
- f_{sky} ~ 0.75
- Δz_{bias} ~ 0.3 x 0.003 ~ 0.0001
- N per z interval ~ 10 000

Weak Lensing in the next Decade

- Introduction to Cosmic Shear for dark energy
- Potential limitations
  - Shear measurement
  - Intrinsic alignments
  - Photozs
- Future surveys



Upcoming weak lensing surveys

Survey	Start	End	Area / sq deg	# galaxies / sq arcmin
KIDS	2012	2016	1500	~12
DES	2013	2018	5000	~12
HSC	2014	2019?	1500	~20
Euclid	2020	2025	15 000	~30
LSST	2021	2031	>10 000	~30

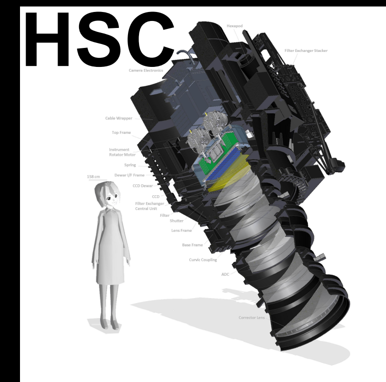
Also WFIRST and SKA

The Future

DARK ENERGY SURVEY

KiDS

HSC



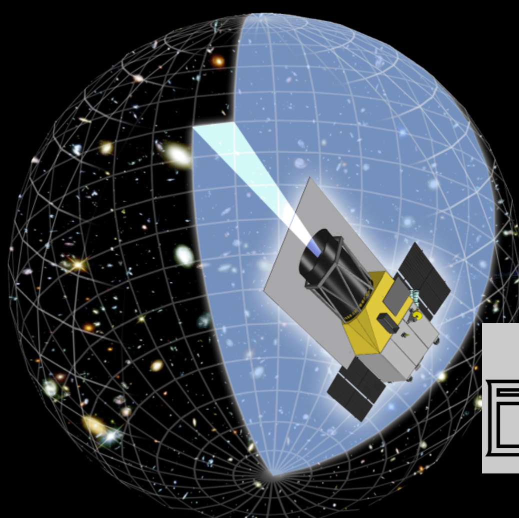
WFIRST

SKA

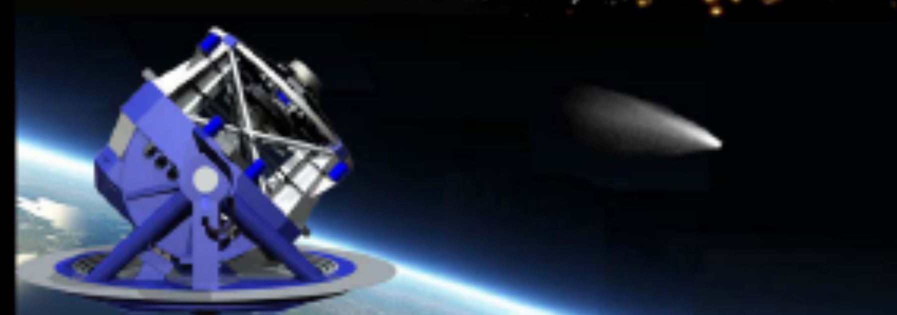
LSST

Large Synoptic Survey Telescope

DEM



EUCLID



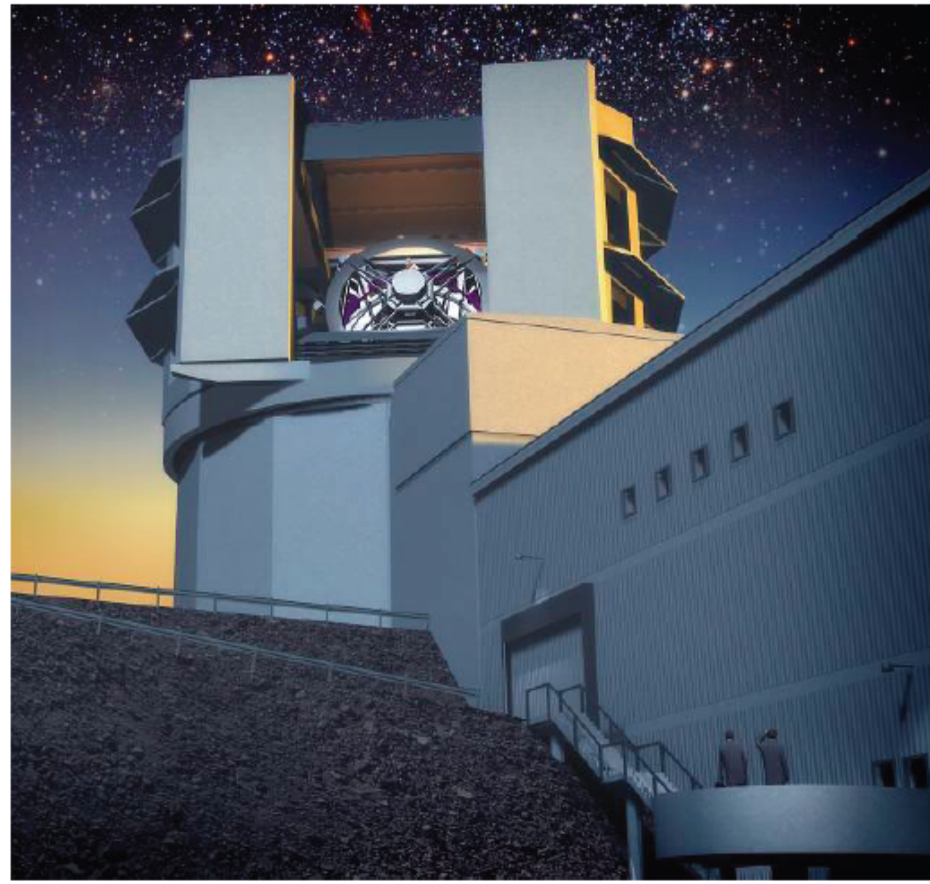
Upcoming Surveys: Different strengths & systematics

(based on publicly available data)

Stage IV	DESI	LSST	Euclid	WFIRST-AFTA
Starts, duration	~2018, 5 yr	2020, 10 yr	2020 Q2, 7 yr	~2023, 5-6 yr
Area (deg^2)	14,000 (N)	20,000 (S)	15,000 (N + S)	2,400 (S)
FoV (deg^2)	7.9	10	0.54	0.281
Diameter (m)	4 (less 1.8+)	6.7	1.3	2.4
Spec. res. $\Delta\lambda/\lambda$	3-4000 (N_{fib}=5000)		250 (slitless)	550-800 (slitless)
Spec. range	360-980 nm		1.1-2 μm	1.35-1.95 μm
BAO/RSD	20-30m LRGs/[OII] ELGs 0.6 < z < 1.7, 1m QSOs/Lya 1.9<z<4		~20-50m Hα ELGs Z~0.7-2.1	20m Hα ELGs z = 1–2, 2m [OIII] ELGS z = 2–3
pixel (arcsec)		0.7	0.13	0.12
Imaging/ weak lensing (0<z<2.)		~30 gal/arcmin^2 5 bands 320-1080 nm	30-35 gal/arcmin^2 1 broad vis. band 550– 900 nm	68 gal/arcmin^2 3 bands 927-2000nm
SN1a		10^4-10^5 SN1a/yr z = 0.–0.7 photometric		2700 SN1a z = 0.1–1.7 IFU spectroscopy

LSST

Large Synoptic Survey Telescope



8.4m primary mirror diameter
6.7m effective aperture
Engineered for fast, wide, deep surveys

Cerro Pachon, Chile

LSST slides from S. Kahn, etal

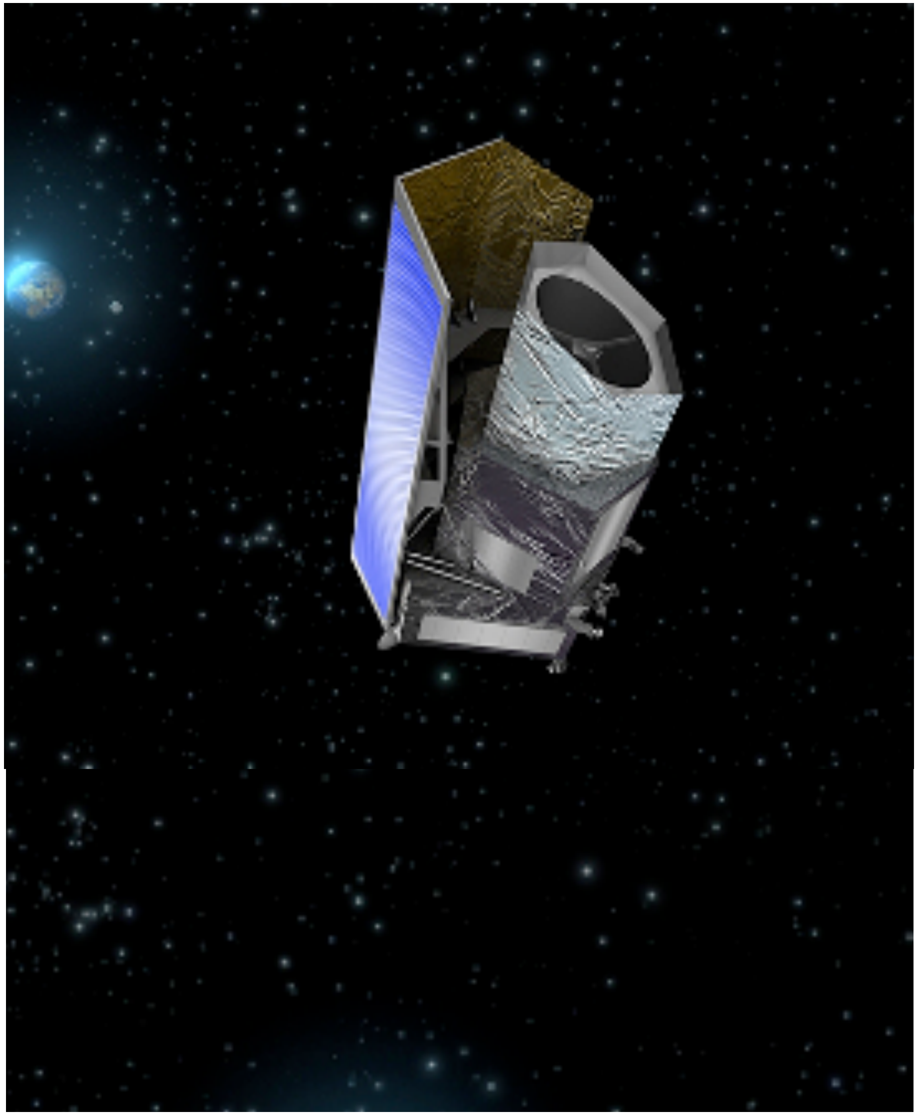
Summary of High Level Requirements

Survey Property	Performance
Main Survey Area	18000 sq. deg.
Total visits per sky patch	825
Filter set	6 filters (ugrizy) from 320-1050nm
Single visit	2 x 15 second exposures
Single Visit Limiting Magnitude	u = 23.9; g = 25.0; r = 24.7; I = 24.0; z = 23.3; y = 22.1
Photometric calibration	< 2% absolute, < 0.5% repeatability & colors
Median delivered image quality	~ 0.7 arcsec. FWHM
Transient processing latency	< 60 sec after last visit exposure
Data release	Full reprocessing of survey data annually

See LSST talk by Pierre Antiologus tomorrow morning

Euclid: ESA dark energy mission

Euclid Consortium



Euclid has been selected by ESA for a launch in 2020 to L2 from where it will survey the sky for 6 years. Its primary cosmology probes, which drive the design, are:

- Weak lensing by large scale structure
- Clustering of galaxies

Euclid will image the

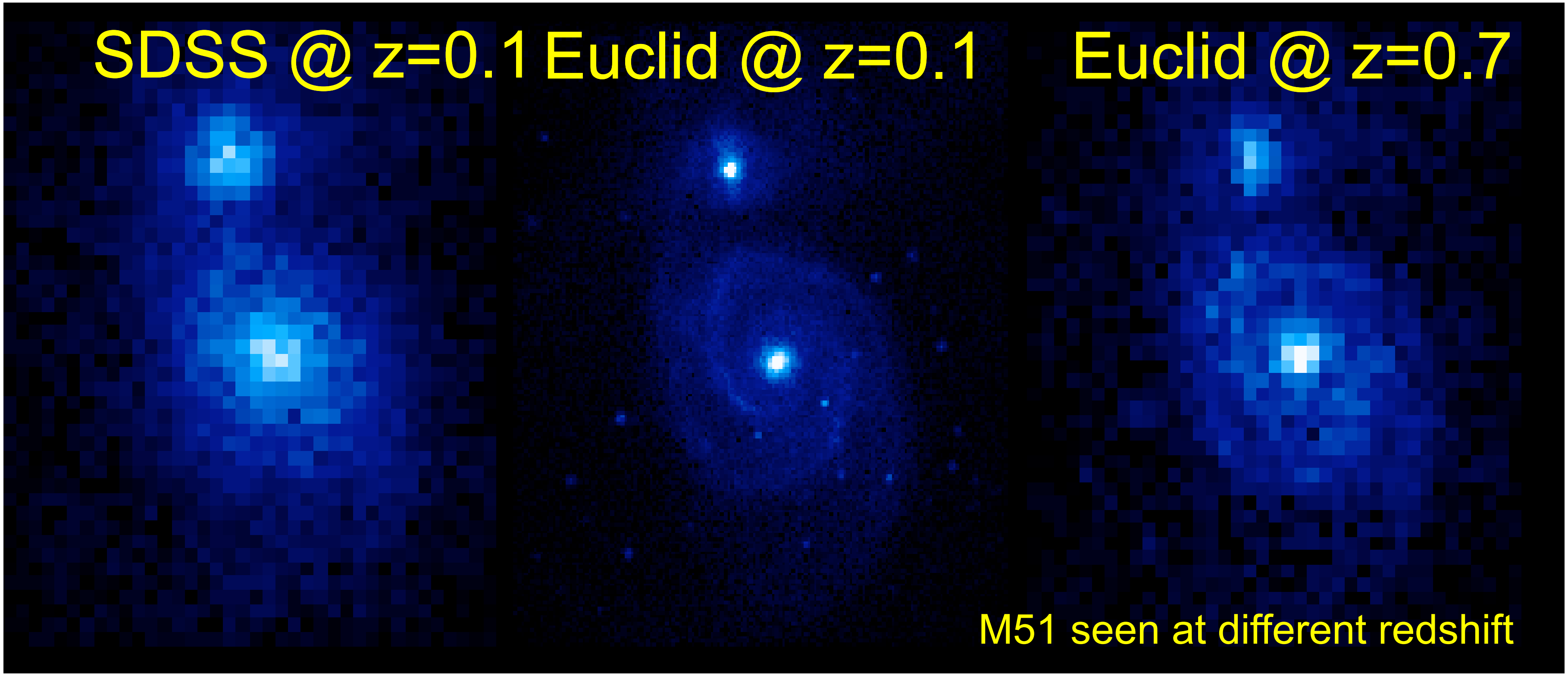
- best 1/3 of the sky (15000 deg^2)
- similar resolution at HST in optical
- NIR imaging in 3 filters (YJH)
- Images for $2x10^9$ galaxies

and carry out an unprecedented (slitless) redshift survey with

- NIR spectra for ~$2.5x10^7$ galaxies (0.9<z<1.8)
- Spectral resolution R~250 (1.25-1.80μm)

Slide from Henk Hoekstra. And see upcoming panel discussion with Yannick Mellier

Euclid is "SDSS" at z~1



Euclid images of *z*~1 galaxies will have the *same* resolution as SDSS images at *z*~0.05 and will be at least 3 magnitudes *deeper*.

Slide from Henk Hoekstra. And see upcoming panel discussion with Yannick Mellier

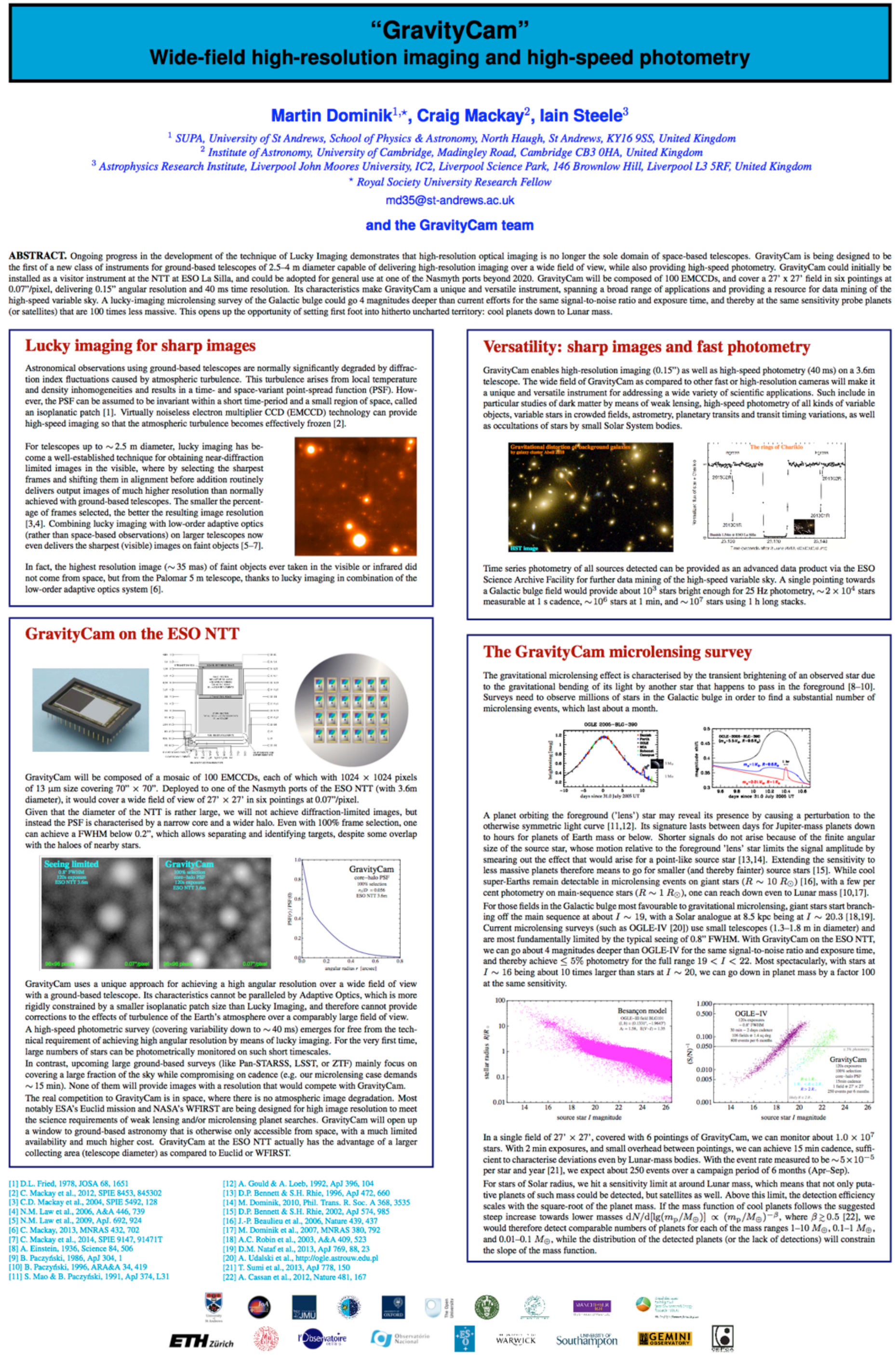
Weak gravitational lensing with the Square Kilometre Array

M. L. Brown*,[1] D. J. Bacon,[2] S. Camera,[1] I. Harrison,[1] B. Joachimi,[3] R. B. Metcalf,[4] A. Pourtsidou,[2] K. Takahashi,[5] J. A. Zuntz,[1] F. B. Abdalla,[3,6] S. Bridle,[1] M. Jarvis,[7] T. D. Kitching,[3] L. Miller,[7] P. Patel[8]

Survey	A_{sky} (deg^2)	n_{gal} (arcmin^{-2})	z_m
SKA1-early	1000	3.0	1.0
VST-KiDS	1500	7.5	0.6
SKA1	5000	2.7	1.0
DES	5000	6.0	0.6
SKA2	30940	10	1.6
Euclid	15000	30	0.9

See GravityCam Poster by Valentin Ivanov

Also here are other GravityCam team members Ivo Saviane, and Don Pollacco



"GravityCam"
Wide-field high-resolution imaging and high-speed photometry

Martin Dominik[1,*], **Craig Mackay**[2], **Iain Steele**[3]

[1] SUPA, University of St Andrews, School of Physics & Astronomy, North Haugh, St Andrews, KY16 9SS, United Kingdom
[2] Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, United Kingdom
[3] Astrophysics Research Institute, Liverpool John Moores University, IC2, Liverpool Science Park, 146 Brownlow Hill, Liverpool L3 5RF, United Kingdom
[*] Royal Society University Research Fellow
md35@st-andrews.ac.uk

and the GravityCam team

ABSTRACT. Ongoing progress in the development of the technique of Lucky Imaging demonstrates that high-resolution optical imaging is no longer the sole domain of space-based telescopes. GravityCam is being designed to be the first of a new class of instruments for ground-based telescopes of 2.5–4 m diameter capable of delivering high-resolution imaging over a wide field of view, while also providing high-speed photometry. GravityCam could initially be installed as a visitor instrument at the NTT at ESO La Silla, and could be adopted for general use at one of the Nasmyth ports beyond 2020. GravityCam will be composed of 100 EMCCDs, and cover a 27' x 27' field in six pointings at 0.07"/pixel, delivering 0.15" angular resolution and 40 ms time resolution. Its characteristics make GravityCam a unique and versatile instrument, spanning a broad range of applications and providing a resource for data mining of the high-speed variable sky. A lucky-imaging microlensing survey of the Galactic bulge could go 4 magnitudes deeper than current efforts for the same signal-to-noise ratio and exposure time, and thereby at the same sensitivity probe planets (or satellites) that are 100 times less massive. This opens up the opportunity of setting first foot into hitherto uncharted territory: cool planets down to Lunar mass.

Lucky imaging for sharp images

Astronomical observations using ground-based telescopes are normally significantly degraded by diffraction index fluctuations caused by atmospheric turbulence. This turbulence arises from local temperature and density inhomogeneities and results in a time- and space-variant point-spread function (PSF). However, the PSF can be assumed to be invariant within a short time-period and a small region of space, called an isoplanatic patch [1]. Virtually noiseless electron multiplier CCD (EMCCD) technology can provide high-speed imaging so that the atmospheric turbulence becomes effectively frozen [2].

For telescopes up to ~2.5 m diameter, lucky imaging has become a well-established technique for obtaining near-diffraction limited images in the visible, where by selecting the sharpest frames and shifting them in alignment before addition routinely delivers output images of much higher resolution than normally achieved with ground-based telescopes. The smaller the percentage of frames selected, the better the resulting image resolution [3,4]. Combining lucky imaging with low-order adaptive optics (rather than space-based observations) on larger telescopes now even delivers the sharpest (visible) images on faint objects [5–7].

In fact, the highest resolution image (~35 mas) of faint objects ever taken in the visible or infrared did not come from space, but from the Palomar 5 m telescope, thanks to lucky imaging in combination of the low-order adaptive optics system [6].

GravityCam on the ESO NTT

GravityCam will be composed of a mosaic of 100 EMCCDs, each of which with 1024 × 1024 pixels of 13 μm size covering 70" × 70". Deployed to one of the Nasmyth ports of the ESO NTT (with 3.6m diameter), it would cover a wide field of view of 27' × 27' in six pointings at 0.07"/pixel.

Given that the diameter of the NTT is rather large, we will not achieve diffraction-limited images, but instead the PSF is characterised by a narrow core and a wider halo. Even with 100% frame selection, one can achieve a FWHM below 0.2", which allows separating and identifying targets, despite some overlap with the haloes of nearby stars.

GravityCam uses a unique approach for achieving a high angular resolution over a wide field of view with a ground-based telescope. Its characteristics cannot be paralleled by Adaptive Optics, which is more rigidly constrained by a smaller isoplanatic patch size than Lucky Imaging, and therefore cannot provide corrections to the effects of turbulence of the Earth's atmosphere over a comparably large field of view.

A high-speed photometric survey (covering variability down to ~40 ms) emerges for free from the technical requirement of achieving high angular resolution by means of lucky imaging. For the very first time, large numbers of stars can be photometrically monitored on such short timescales.

In contrast, upcoming large ground-based surveys (like Pan-STARSS, LSST, or ZTF) mainly focus on covering a large fraction of the sky while compromising on cadence (e.g. our microlensing case demands ~15 min). None of them will provide images with a resolution that would compete with GravityCam.

The real competition to GravityCam is in space, where there is no atmospheric image degradation. Most notably ESA's Euclid mission and NASA's WFIRST are being designed for high image resolution to meet the science requirements of weak lensing and/or microlensing planet searches. GravityCam will open up a window to ground-based astronomy that is otherwise only accessible from space, with a much limited availability and much higher cost. GravityCam at the ESO NTT actually has the advantage of a larger collecting area (telescope diameter) as compared to Euclid or WFIRST.

Versatility: sharp images and fast photometry

GravityCam enables high-resolution imaging (0.15") as well as high-speed photometry (40 ms) on a 3.6m telescope. The wide field of GravityCam as compared to other fast or high-resolution cameras will make it a unique and versatile instrument for addressing a wide variety of scientific applications. Such include in particular studies of dark matter by means of weak lensing, high-speed photometry of all kinds of variable objects, variable stars in crowded fields, astrometry, planetary transits and transit timing variations, as well as occultations of stars by small Solar System bodies.

Time series photometry of all sources detected can be provided as an advanced data product via the ESO Science Archive Facility for further data mining of the high-speed variable sky. A single pointing towards a Galactic bulge field would provide about 10^3 stars bright enough for 25 Hz photometry, $\sim 2 \times 10^4$ stars measurable at 1 s cadence, $\sim 10^6$ stars at 1 min, and $\sim 10^7$ stars using 1 h long stacks.

The GravityCam microlensing survey

The gravitational microlensing effect is characterised by the transient brightening of an observed star due to the gravitational bending of its light by another star that happens to pass in the foreground [8–10]. Surveys need to observe millions of stars in the Galactic bulge in order to find a substantial number of microlensing events, which last about a month.

A planet orbiting the foreground ('lens') star may reveal its presence by causing a perturbation to the otherwise symmetric light curve [11,12]. Its signature lasts between days for Jupiter-mass planets down to hours for planets of Earth mass or below. Shorter signals do not arise because of the finite angular size of the source star, whose motion relative to the foreground 'lens' star limits the signal amplitude by smearing out the effect that would arise for a point-like source star [13,14]. Extending the sensitivity to less massive planets therefore means to go for smaller (and thereby fainter) source stars [15]. While cool super-Earths remain detectable in microlensing events on giant stars ($R \sim 10\ R_\odot$) [16], with a few per cent photometry on main-sequence stars ($R \sim 1\ R_\odot$), one can reach down even to Lunar mass [10,17].

For those fields in the Galactic bulge most favourable to gravitational microlensing, giant stars start branching off the main sequence at about $I \sim 19$, with a Solar analogue at 8.5 kpc being at $I \sim 20.3$ [18,19]. Current microlensing surveys (such as OGLE-IV [20]) use small telescopes (1.3–1.8 m in diameter) and are most fundamentally limited by the typical seeing of 0.8" FWHM. With GravityCam on the ESO NTT, we can go about 4 magnitudes deeper than OGLE-IV for the same signal-to-noise ratio and exposure time, and thereby achieve $\leq 5\%$ photometry for the full range $19 < I < 22$. Most spectacularly, with stars at $I \sim 16$ being about 10 times larger than stars at $I \sim 20$, we can go down in planet mass by a factor 100 at the same sensitivity.

In a single field of 27' × 27', covered with 6 pointings of GravityCam, we can monitor about 1.0×10^7 stars. With 2 min exposures, and small overhead between pointings, we can achieve 15 min cadence, sufficient to characterise deviations even by Lunar-mass bodies. With the event rate measured to be $\sim 5 \times 10^{-5}$ per star and year [21], we expect about 250 events over a campaign period of 6 months (Apr–Sep).

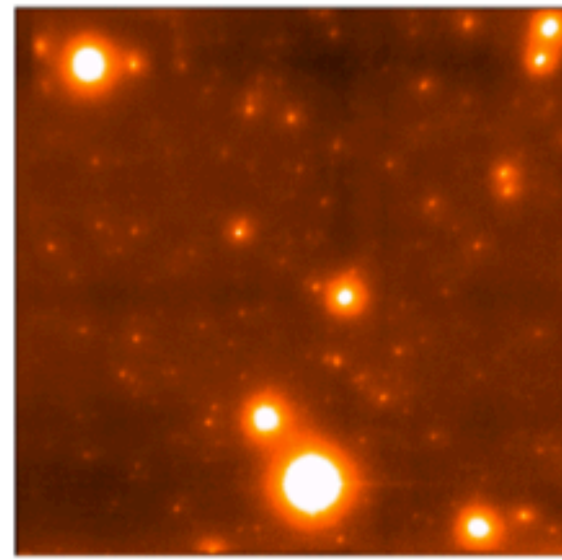
For stars of Solar radius, we hit a sensitivity limit at around Lunar mass, which means that not only putative planets of such mass could be detected, but satellites as well. Above this limit, the detection efficiency scales with the square-root of the planet mass. If the mass function of cool planets follows the suggested steep increase towards lower masses $\mathrm{d}N/\mathrm{d}[\lg(m_\mathrm{p}/M_\oplus)] \propto (m_\mathrm{p}/M_\oplus)^{-\beta}$, where $\beta \gtrsim 0.5$ [22], we would therefore detect comparable numbers of planets for each of the mass ranges 1–10 $M_\oplus$, 0.1–1 $M_\oplus$, and 0.01–0.1 $M_\oplus$, while the distribution of the detected planets (or the lack of detections) will constrain the slope of the mass function.

[1] D.L. Fried, 1978, JOSA 68, 1651
[2] C. Mackay et al., 2012, SPIE 8453, 845302
[3] C.D. Mackay et al., 2004, SPIE 5492, 128
[4] N.M. Law et al., 2006, A&A 446, 739
[5] N.M. Law et al., 2009, ApJ. 692, 924
[6] C. Mackay, 2013, MNRAS 432, 702
[7] C. Mackay et al., 2014, SPIE 9147, 91471T
[8] A. Einstein, 1936, Science 84, 506
[9] B. Paczyński, 1986, ApJ 304, 1
[10] B. Paczyński, 1996, ARA&A 34, 419
[11] S. Mao & B. Paczyński, 1991, ApJ 374, L31
[12] A. Gould & A. Loeb, 1992, ApJ 396, 104
[13] D.P. Bennett & S.H. Rhie, 1996, ApJ 472, 660
[14] M. Dominik, 2010, Phil. Trans. R. Soc. A 368, 3535
[15] D.P. Bennett & S.H. Rhie, 2002, ApJ 574, 985
[16] J.-P. Beaulieu et al., 2006, Nature 439, 437
[17] M. Dominik et al., 2007, MNRAS 380, 792
[18] A.C. Robin et al., 2003, A&A 409, 523
[19] D.M. Nataf et al., 2013, ApJ 769, 88, 23
[20] A. Udalski et al., http://ogle.astrouw.edu.pl
[21] T. Sumi et al., 2013, ApJ 778, 150
[22] A. Cassan et al., 2012, Nature 481, 167

Lucky imaging for sharp images

Astronomical observations using ground-based telescopes are normally significantly degraded by diffraction index fluctuations caused by atmospheric turbulence. This turbulence arises from local temperature and density inhomogeneities and results in a time- and space-variant point-spread function (PSF). However, the PSF can be assumed to be invariant within a short time-period and a small region of space, called an isoplanatic patch [1]. Virtually noiseless electron multiplier CCD (EMCCD) technology can provide high-speed imaging so that the atmospheric turbulence becomes effectively frozen [2].

For telescopes up to $\sim$2.5 m diameter, lucky imaging has become a well-established technique for obtaining near-diffraction limited images in the visible, where by selecting the sharpest frames and shifting them in alignment before addition routinely delivers output images of much higher resolution than normally achieved with ground-based telescopes. The smaller the percentage of frames selected, the better the resulting image resolution [3,4]. Combining lucky imaging with low-order adaptive optics (rather than space-based observations) on larger telescopes now even delivers the sharpest (visible) images on faint objects [5–7].

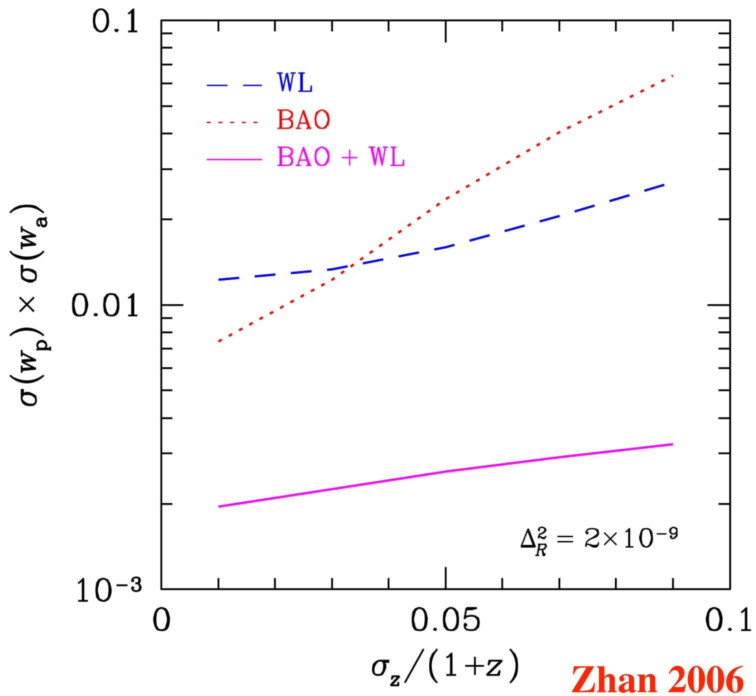


In fact, the highest resolution image ($\sim$35 mas) of faint objects ever taken in the visible or infrared did not come from space, but from the Palomar 5 m telescope, thanks to lucky imaging in combination of the low-order adaptive optics system [6].

See GravityCam poster by Valentin Ivanov

Two spectroscopic needs for photo-z work: training and calibration

- **Better training of algorithms using objects with spectroscopic redshift measurements shrinks photo-z errors and improves DE constraints, esp. for BAO and clusters**
  - **Training datasets will contribute to calibration of photo-z's. ~Perfect training sets can solve calibration needs.**



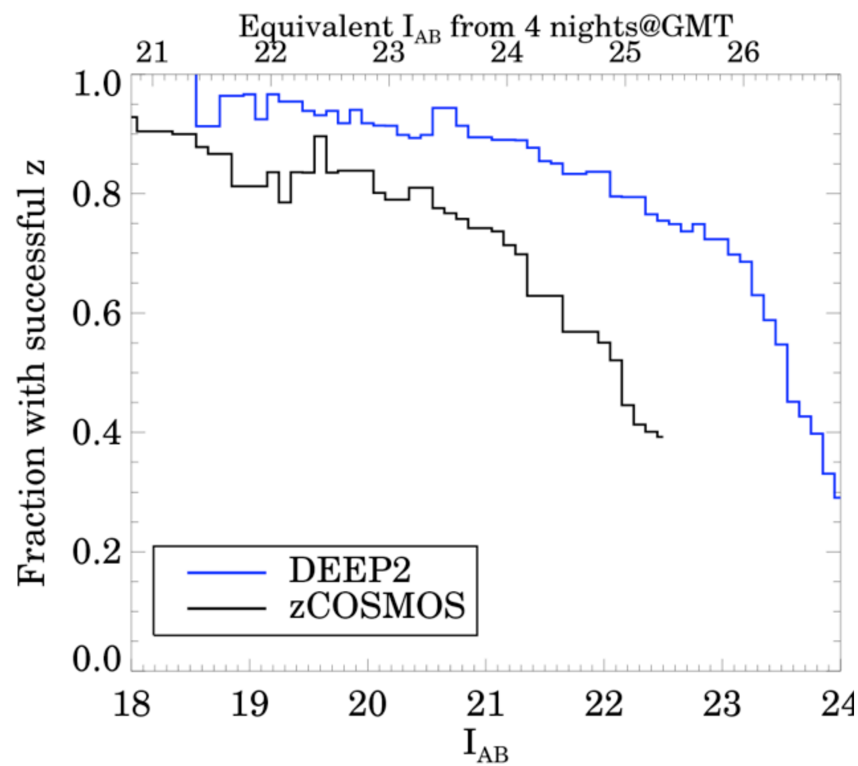
Zhan 2006

- **For weak lensing and supernovae, individual-object photo-*z*'s do not need high precision, but the calibration must be accurate - bias and errors need to be extremely well-understood**
  - ***uncertainty in* bias, $\sigma(\delta_z) = \sigma(<z_p - z_s>)$, and in scatter, $\sigma(\sigma_z) = \sigma(RMS(z_p - z_s))$, must both be <~0.002(1+*z*) for Stage IV**

Slide from Jeff Newman – see http://arxiv.org/abs/1309.5384 for more details

Biggest concern: incompleteness in training sets

- **In current deep redshift surveys (to i~22.5/R~24), 25-60% of targets fail to yield secure (>95% confidence) redshifts**
- **Redshift success rate depends on galaxy properties - losses are systematic, not random**
- **Estimated need 99-99.9% completeness to prevent systematic errors in calibration from missed populations**



Data from DEEP2 (Newman et al. 2013) and zCOSMOS (Lilly et al. 2009)

Slide from Jeff Newman – see http://arxiv.org/abs/1309.5384 for more details

What qualities do we desire in training spectroscopy?

- **Sensitive spectroscopy of ~30,000 faint objects (to i=25.3 for LSST)**
  - Needs a combination of large aperture and long exposure times
- **High multiplexing**
  - Required to get large numbers of spectra
- **Coverage of full ground-based spectral window**
  - Ideally, from below 4000 Å to ~1.5μm
- **Significant resolution ($R=\lambda/\Delta\lambda>$~4000) at red end**
  - Allows secure redshifts from [OII] 3727 Å line at $z>1$
- **Field diameters > ~20 arcmin**
  - Need to span several correlation lengths for accurate clustering
- **Many fields, >~15**
  - To mitigate sample/cosmic variance)

Slide from Jeff Newman – see http://arxiv.org/abs/1309.5384 for more details

3 Ways to address spectroscopic incompleteness – all may be feasible

I. Throw out objects lacking secure photo-*z* calibration
   - ID regions in e.g. *ugrizy* space where redshift failures occurred
   - Eliminating a fraction of sample has modest effect on FoM
     - Not yet known if sufficiently clean regions exist

II. Incorporate additional information
   - Longer exposure/wider wavelength range spectroscopy (JWST, etc.) for objects that fail to give redshifts in first try
     - Not yet known if will yield sufficient completeness
   - Develop comprehensive model of galaxy spectral evolution constrained by redshifts obtained
     - A major research program, not there now

III. Cross-correlation techniques

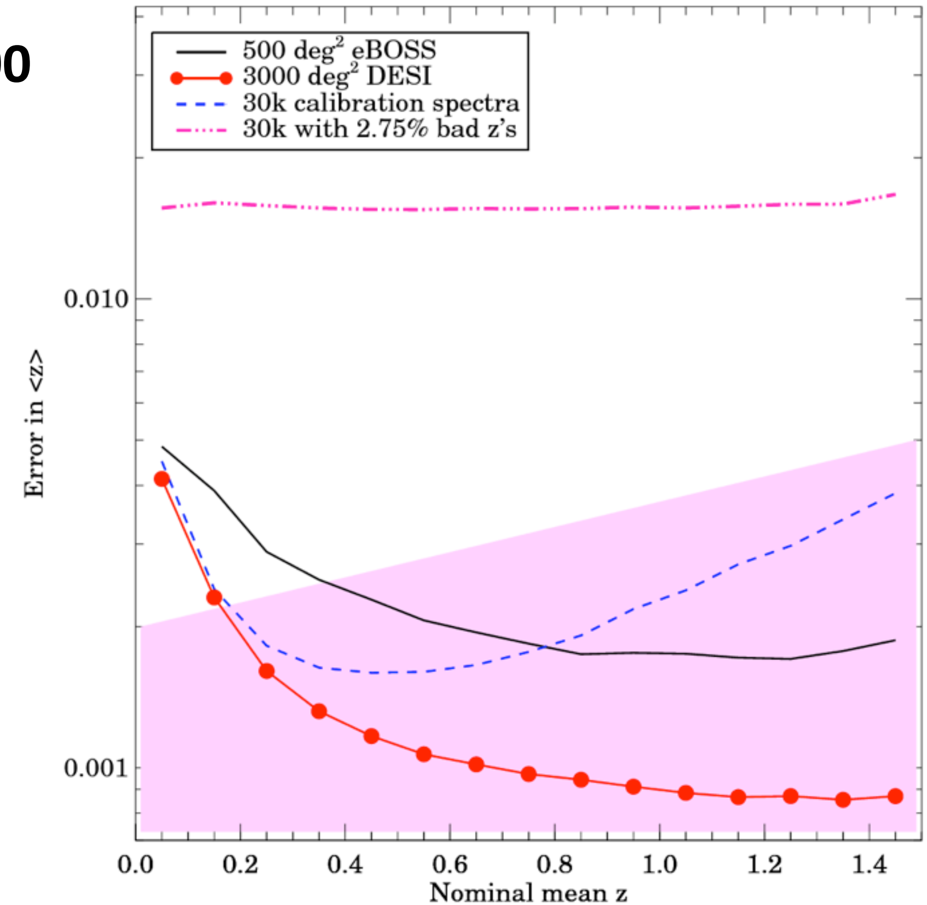
Slide from Jeff Newman – see http://arxiv.org/abs/1309.5384 for more details

Spectroscopic requirements for cross-correlation methods

- **Want >100k objects over >100 sq. degrees, spanning redshift range of photometric sample**

- **>500 square degrees of overlap with DESI-like survey sufficient for cross-correlation calibrations to Stage IV requirements**

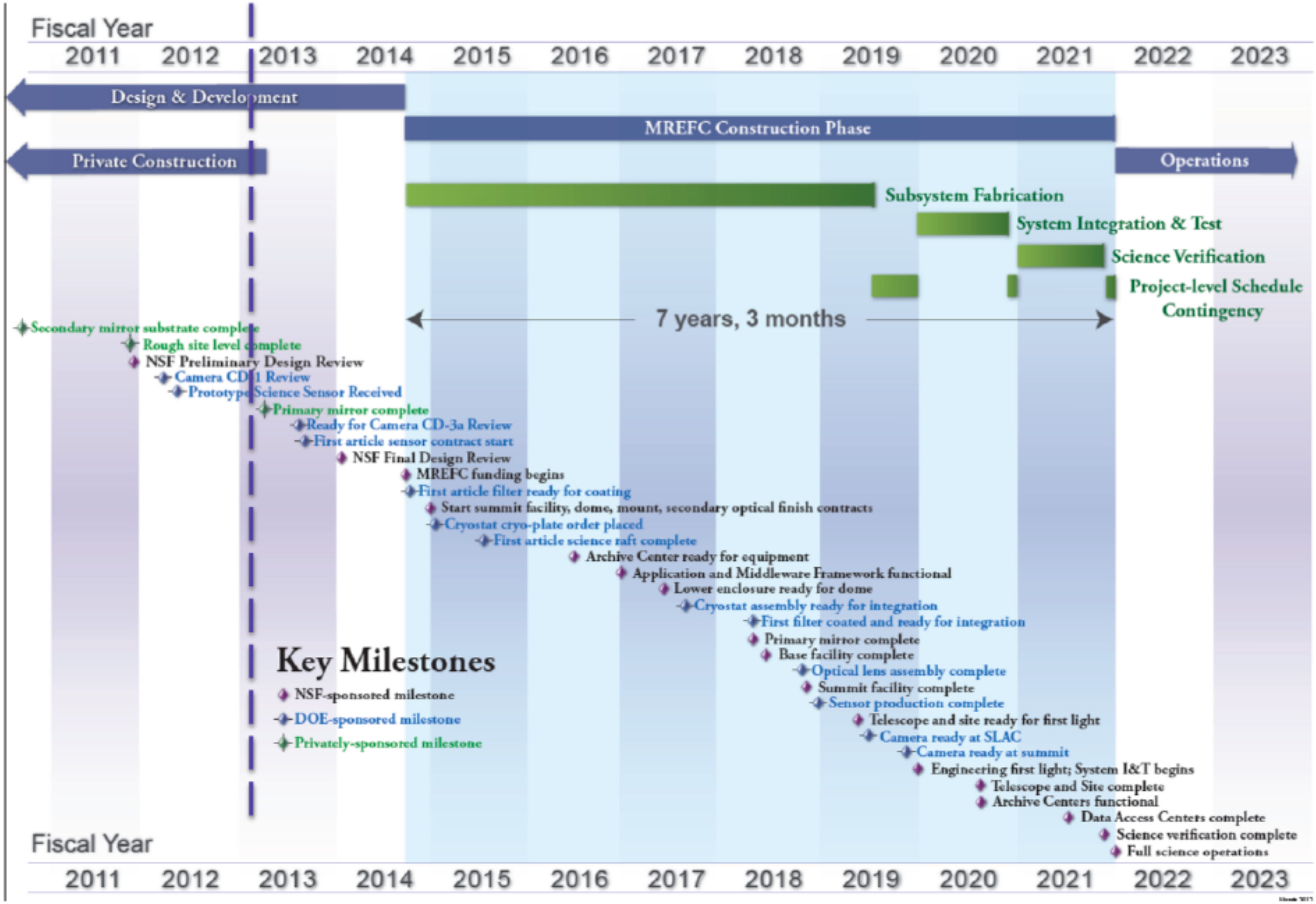
- **Expected ~3000 deg^2 overlap is comparable to 100% complete sample of 100k spectra with no false z's!**



Snowmass White Paper: Spectroscopic Needs for Imaging DE Experiments

Slide from Jeff Newman – see http://arxiv.org/abs/1309.5384 for more details

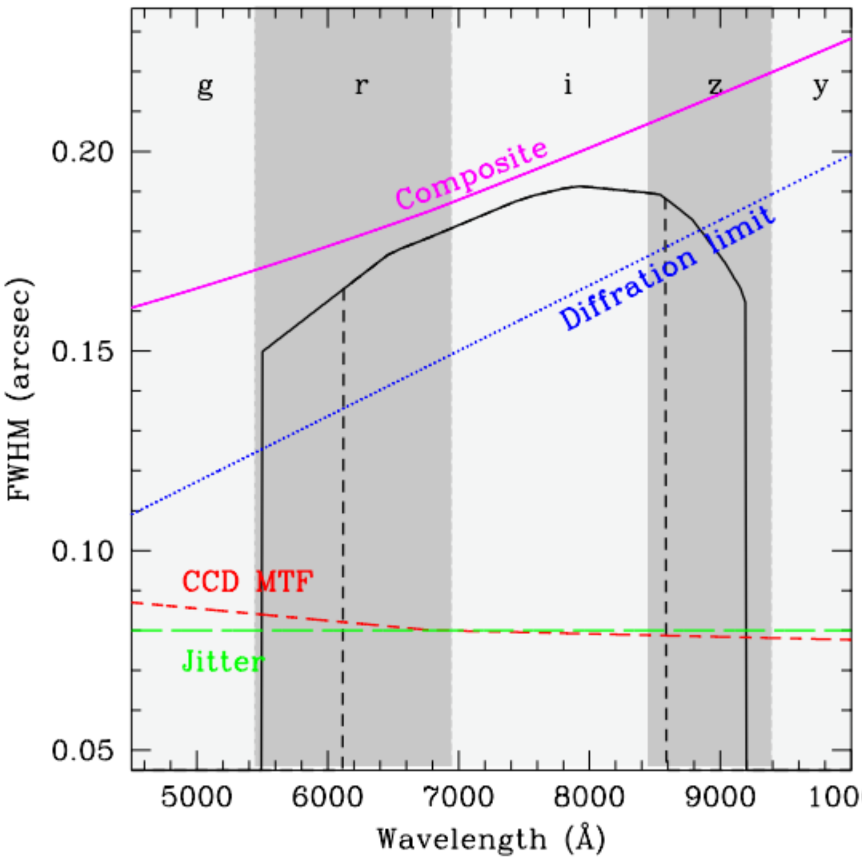
Project timeline enables "first light" in 2019, survey start 2022

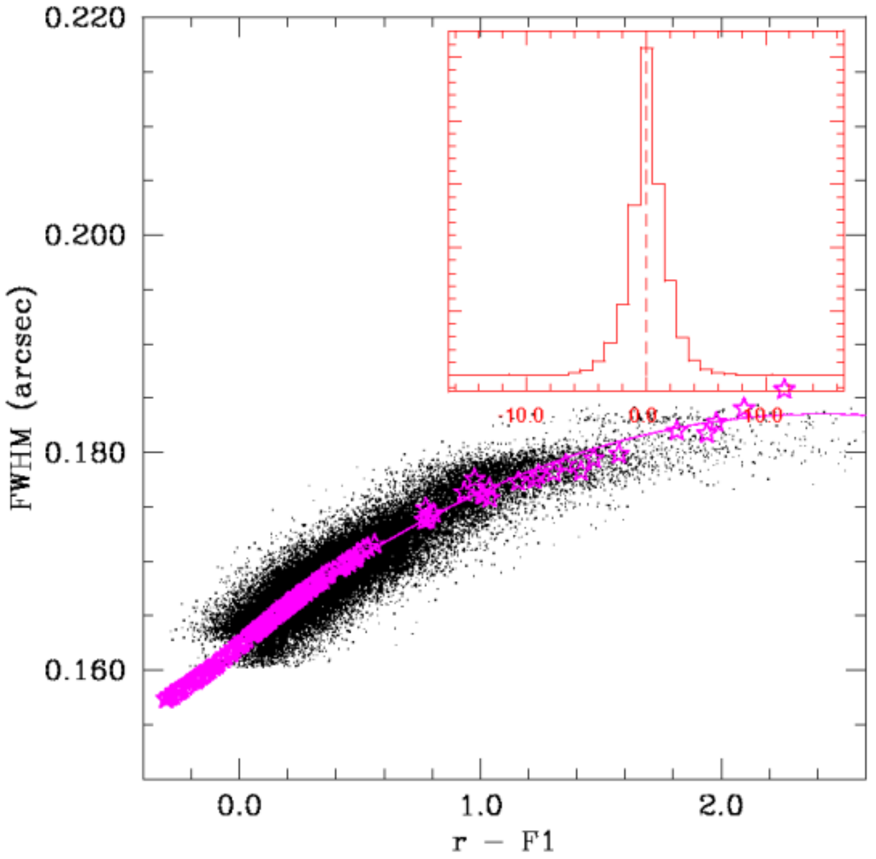


Conclusions

- Cosmic shear has the greatest potential to uncover nature of dark energy
- New field – challenging systematics
  - Shear measurement
  - Photoz measurement
- Very exciting decade for cosmic shear
  - LSST, Euclid, WFIRST
- Spectroscopic followup will extend the potential of these surveys

Wavelength Dependence of the PSF

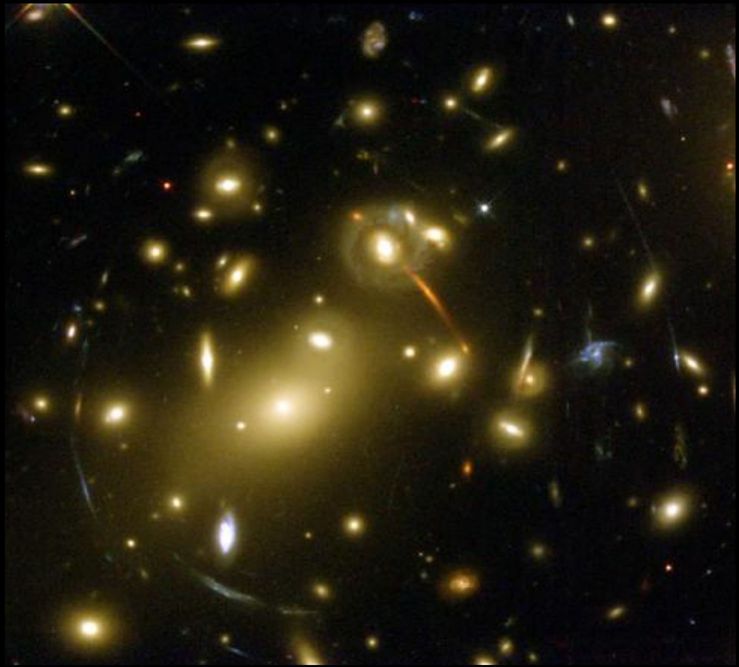




Cypriano, Amara, Voigt, Bridle et al 2010

Weak LAensing in the next Decade

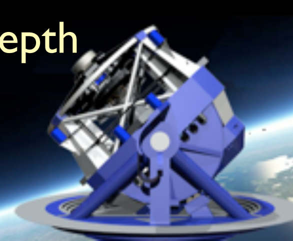
- Introduction to Cosmic Shear for dark energy
- Potential limitations
  - Shear measurement
  - Intrinsic alignments
  - Photozs
- Future surveys




http://www.lsst.org/News/enews/first-blast-201104.html

LSST Basics

- 8.4m mirror
- 9.6 sq deg FOV
- 20,000 deg of sky
- 1000 visits per field
- filters: ugrizY
- 320 - 1035 nm
- r ~24.7 in single visit, ~27.7 stacked depth
- 3.2 Gpix camera
- ~0.01 mag precision photometry



Big Collaboration – a subset in Tucson Arizona Aug 2014

Big Data Challenges in LSST

- Image simulations
- Real-time image processing -Transient alerts
- Rapid image processing
  - Imaging solar system objects
  - Supernovae, gamma-ray bursts, new objects
- High precision image processing
  - Weak lensing, photometric redshifts
- Catalogue search
  - Tidal streams falling into the Milky Way
  - New types of galaxy

Summary

- Cosmic shear the greatest potential of all for DE
- Discrepancy between CFHTLenS and Planck
- Shear measurement is hard
- Dark Energy Survey early data now in
- Large Synoptic Survey Telescope (LSST) now expanding internationally

The Dark Energy Survey

DARK ENERGY SURVEY

Blanco 4-meter at CTIO

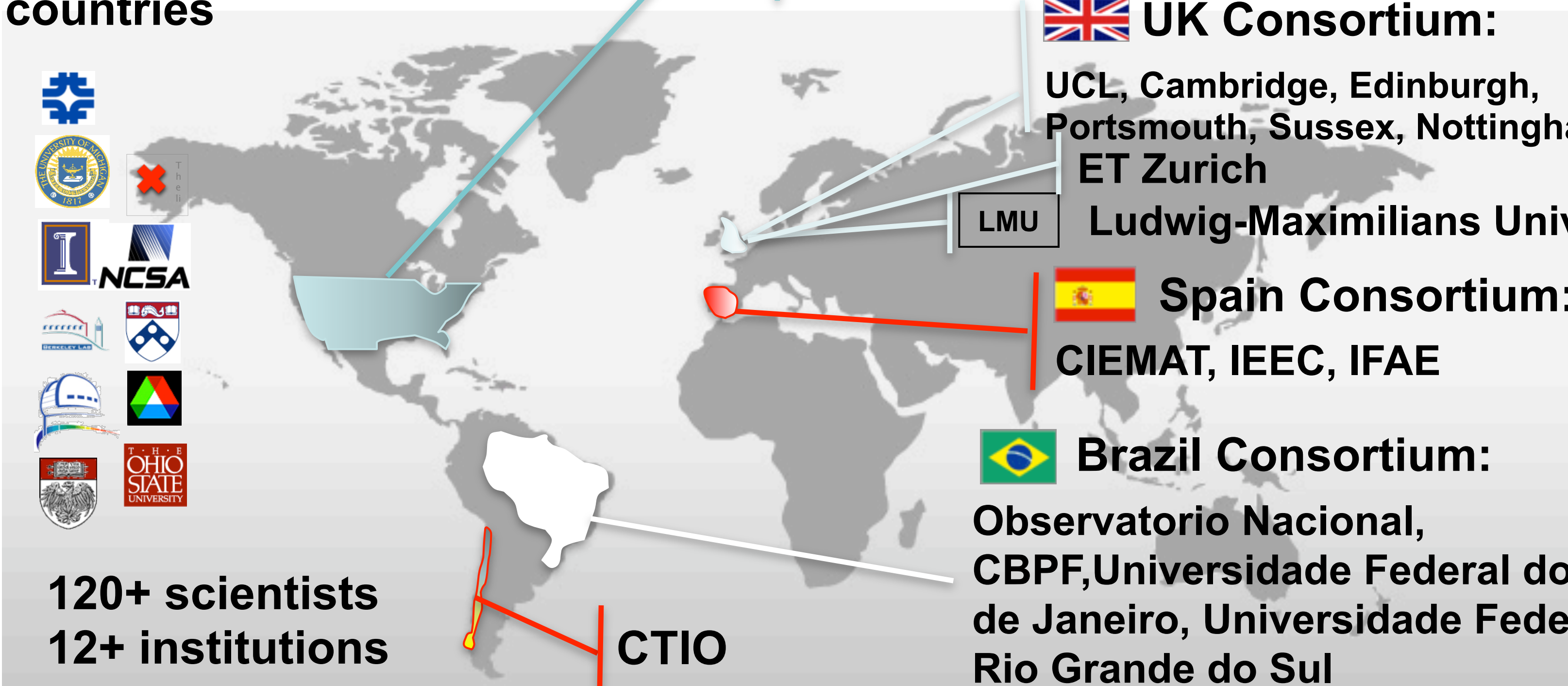
- Survey project using 4 complementary techniques:
  - I. Cluster Counts
  - II. Weak Lensing
  - III. Large-scale Structure
  - IV. Supernovae
- Two multiband surveys:
  - 5000 deg^2 *grizY* to 24th mag
  - 30 deg^2 repeat (SNe)
- Build new 3 deg^2 FOV camera and Data management system
  - Survey 2013-2018 (525 nights)
  - Facility instrument for Blanco

DES Collaboration

The DES is an international project to "nail down" the dark energy equation of state.

Funding from DOE, NSF and collaborating institutions and countries

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



UK Consortium:

UCL, Cambridge, Edinburgh, Portsmouth, Sussex, Nottingham

ET Zurich

Ludwig-Maximilians Universität

Spain Consortium:

CIEMAT, IEEC, IFAE

Brazil Consortium:

Observatorio Nacional, CBPF,Universidade Federal do Rio de Janeiro, Universidade Federal do Rio Grande do Sul

CTIO

120+ scientists
12+ institutions

THE DES COLLABORATION (~300 scientists from 6 countries)

Fermilab — The Fermi National Accelerator Laboratory

Chicago — The University of Chicago

NOAO — The National Optical Astronomy Observatory

United Kingdom DES Collaboration

- UCL - University College London
- Cambridge - University of Cambridge
- Edinburgh - University of Edinburgh
- Portsmouth - University of Portsmouth
- Sussex - University of Sussex
- Nottingham - University of Nottingham

DES-Brazil Consortium

- ON - Observatorio Nacional
- CBPF - Centro Brasileiro de Pesquisas Fisicas
- UFRGS - Universidade Federal do Rio Grande do Sul

UIUC/NCSA — The University of Illinois at Urbana-Champaign

LBNL — The Lawrence Berkeley National Laboratory

Spain DES Collaboration

- IEEC/CSIC - Instituto de Ciencias del Espacio,
- IFAE - Institut de Fisica d'Altes Energies
- CIEMAT - Centro de Investigaciones Energeticas, Medioambientales y Tecnologicas

Michigan — The University of Michigan

Pennsylvania — The University of Pennsylvania

ETH-Zuerich — Eidgenoessische Technische Hochschule Zuerich

OSU — The Ohio State University

TAMU — Texas A&M University

Munich—Universitäts-Sternwarte München

- Ludwig-Maximilians Universität
- Excellence Cluster Universe

ANL — Argonne National Laboratory

Santa Cruz-SLAC-Stanford DES Consortium

- Santa Cruz - University of California Santa Cruz
- SLAC - SLAC National Accelerator Laboratory
- Stanford - Stanford University

DES Science Committee

- SC Chair: O. Lahav, G. Bernstein
- Large Scale Structure: E. Gaztanaga & A. Ross
- Weak Lensing: S. Bridle & B. Jain
- Clusters: J. Mohr & C. Miller
- SN Ia: M. Sako & B. Nichol
- Photo-z: F. Castander & H. Lin
- Simulations: G. Evrard & A. Kravtsov
- Galaxy Evolution: D. Thomas & R. Wechsler
- QSO: P. Martini & R. McMahon
- Strong Lensing: L. Buckley-Geer & A. Amara
- Milky Way: B. Santiago & B. Yanny
- Theory & Combined Probes: S. Dodelson & J. Weller
- + Spectroscopic task force: F. Abdalla & A. Kim
- + Ad-hoc Committees

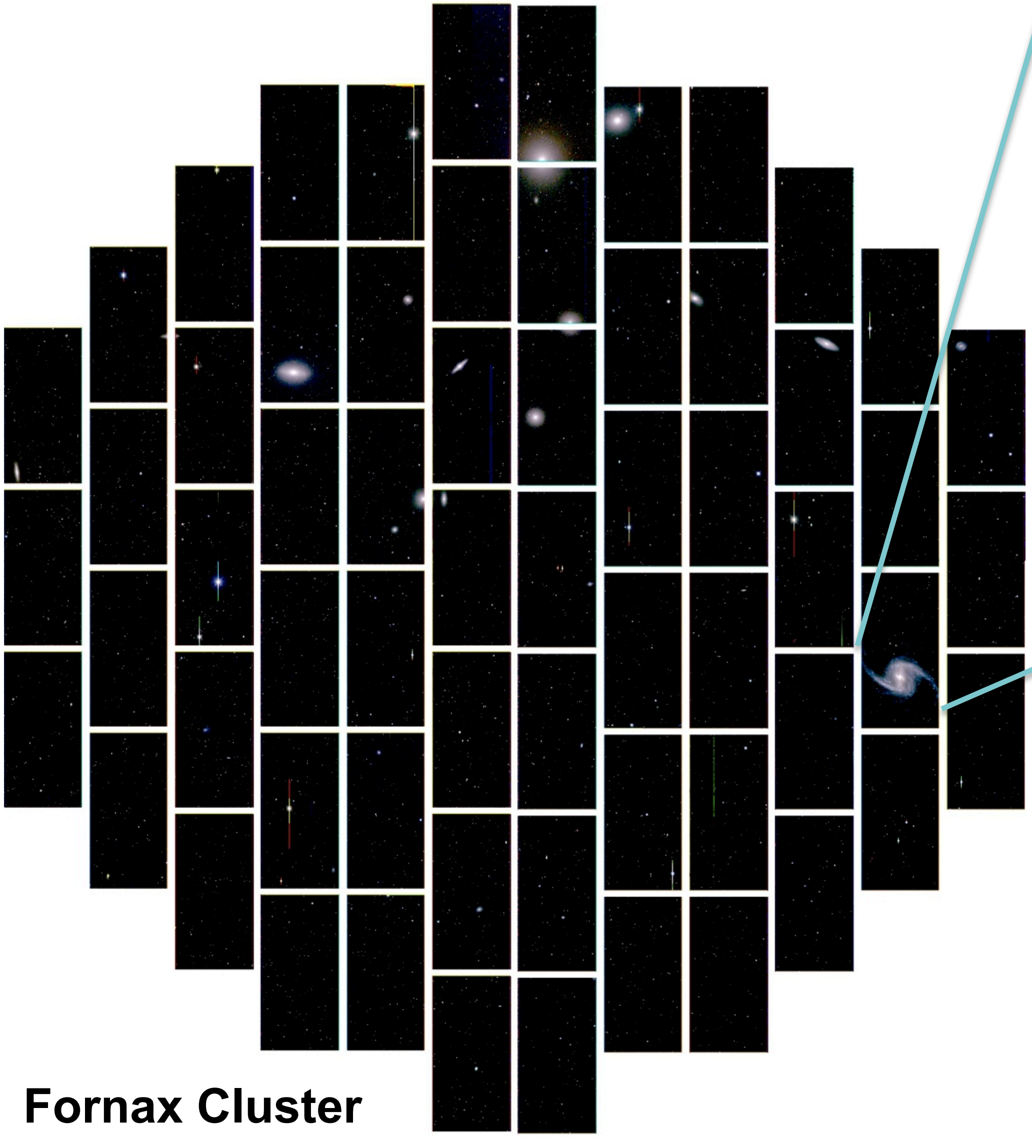
>200 Scientists across the world, in 23 institutes
1 year ago at Eden Roc

DARK ENERGY SURVEY

Optical corrector assembly at CTIO

Jan. 19, 2012

DES First Light

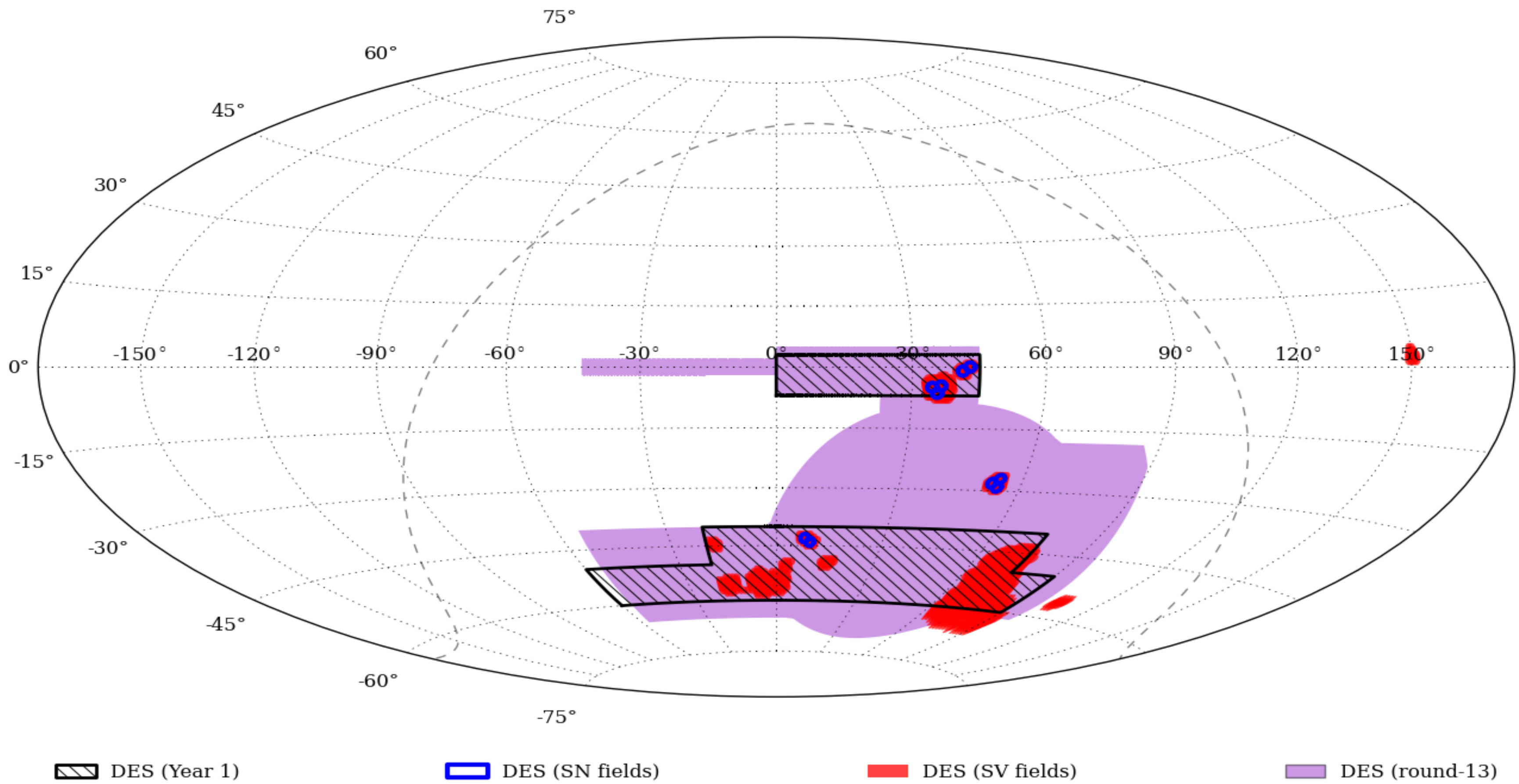


NGC 1365

0.8" images recorded within first few nights of first light!

Fornax Cluster

DES survey footprint



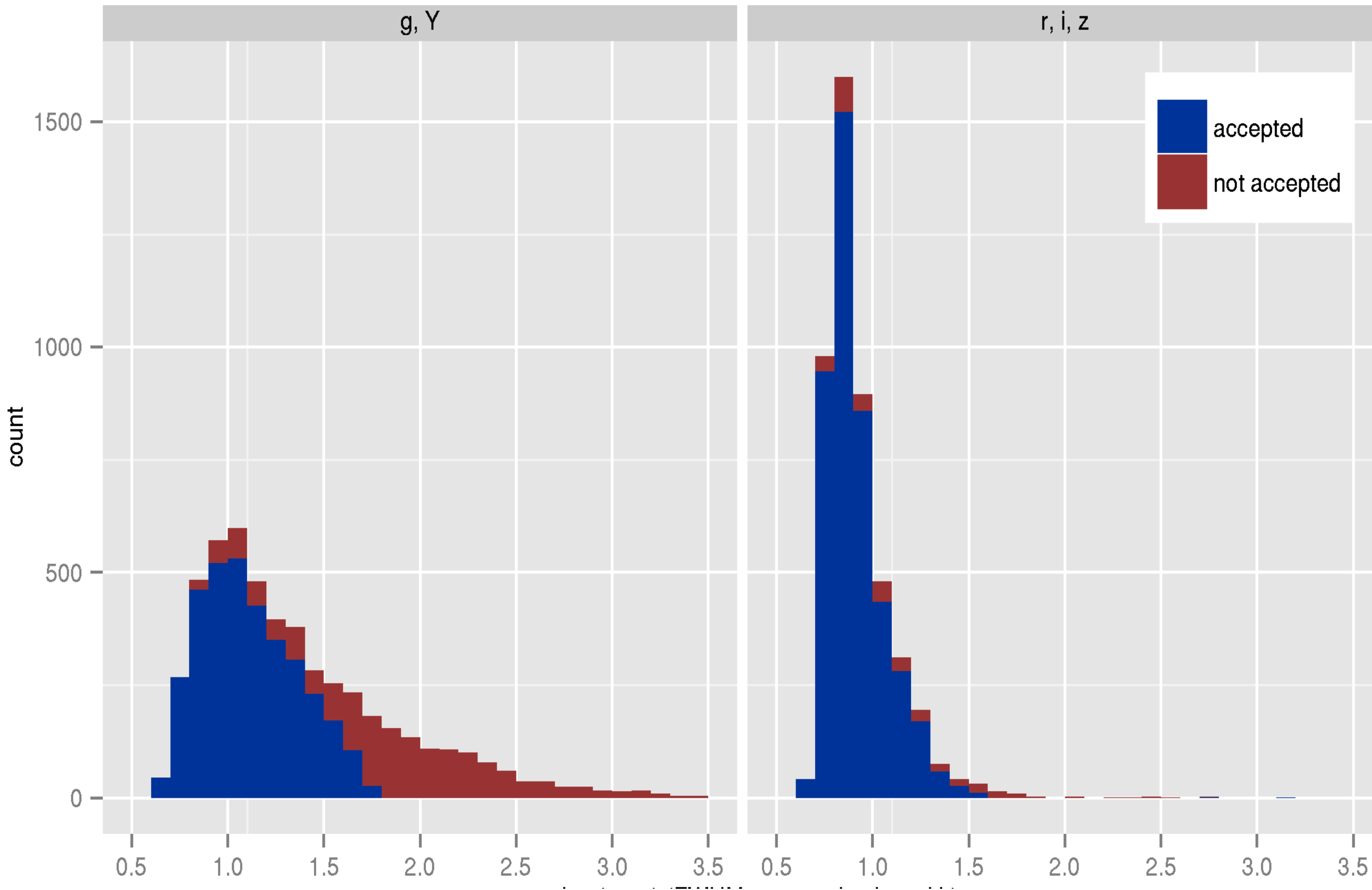
5000 sq deg survey to be covered: 1st year strategy is to cover ~2500 sq deg in 4 tilings overlapping SPT, VHS, BOSS

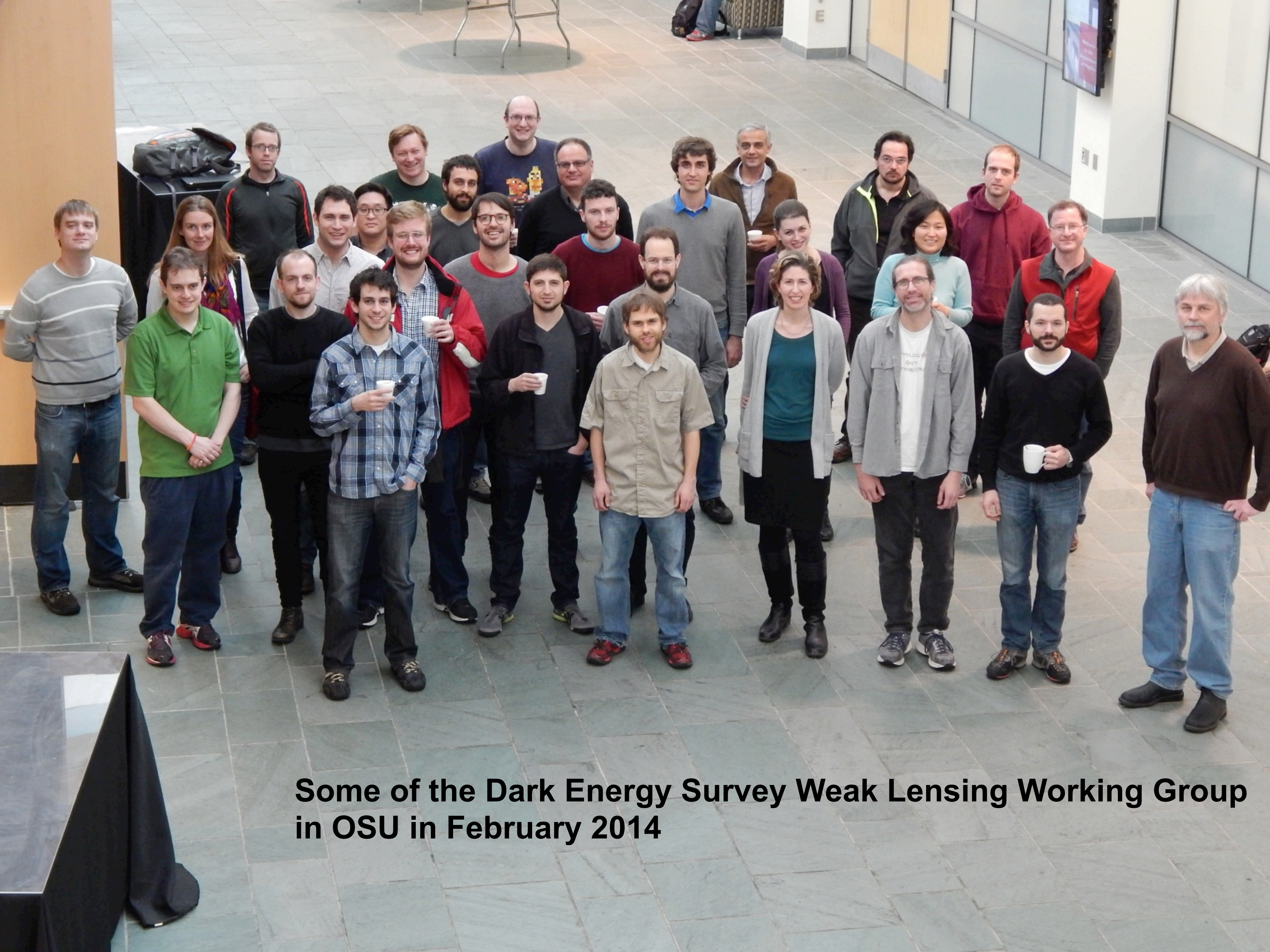
DES Seeing (mid Dec 2013)

Accepted median FWHM (arcsec)

1.09 (g), 0.89 (r), 0.85 (i) 0.82 (z), 1.07 (Y)

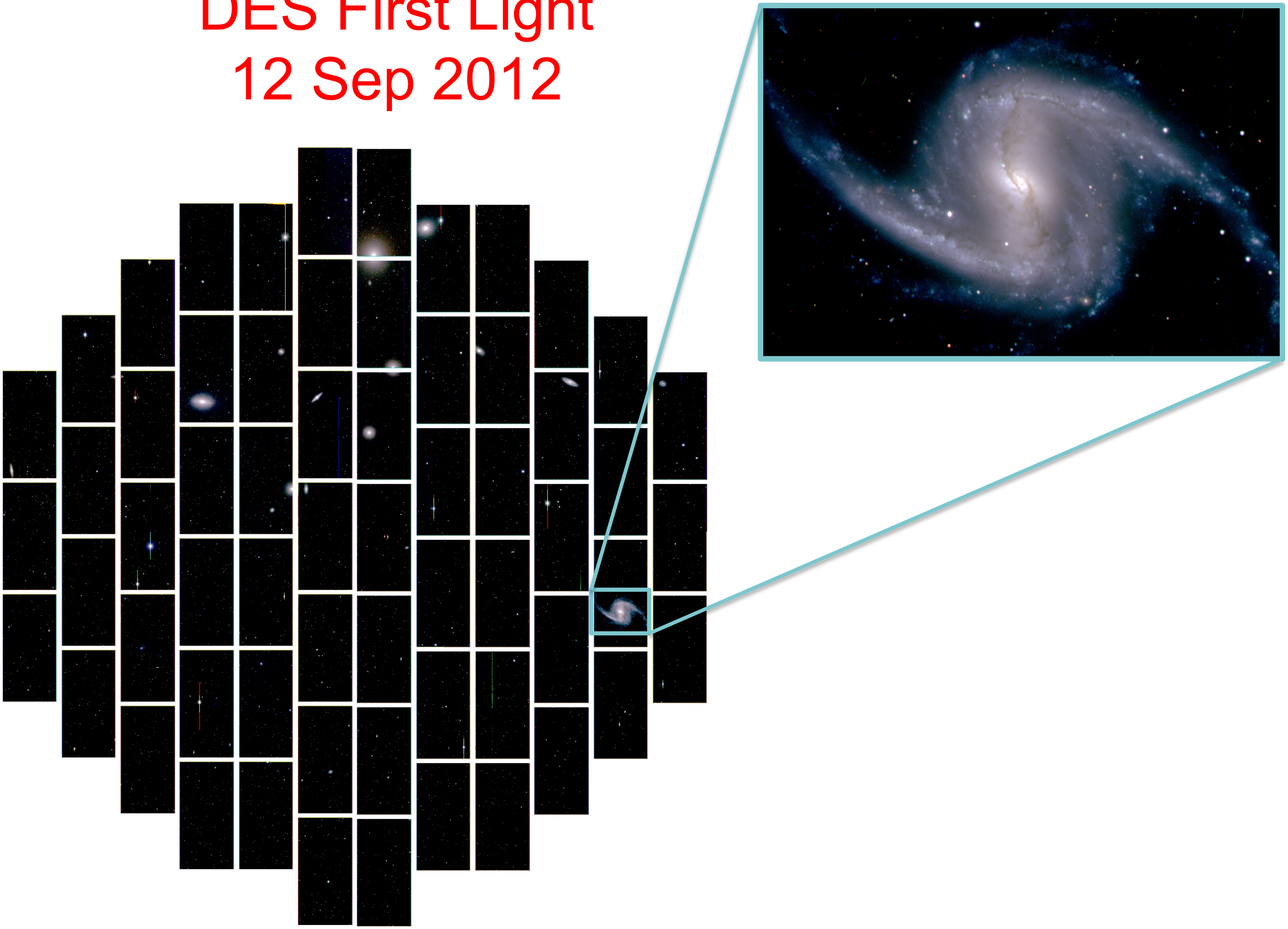
WL analysis in riz (required 0.9 arcsec)





Some of the Dark Energy Survey Weak Lensing Working Group in OSU in February 2014

DES First Light
12 Sep 2012



DARK ENERGY SURVEY

Clusters in Science Verification

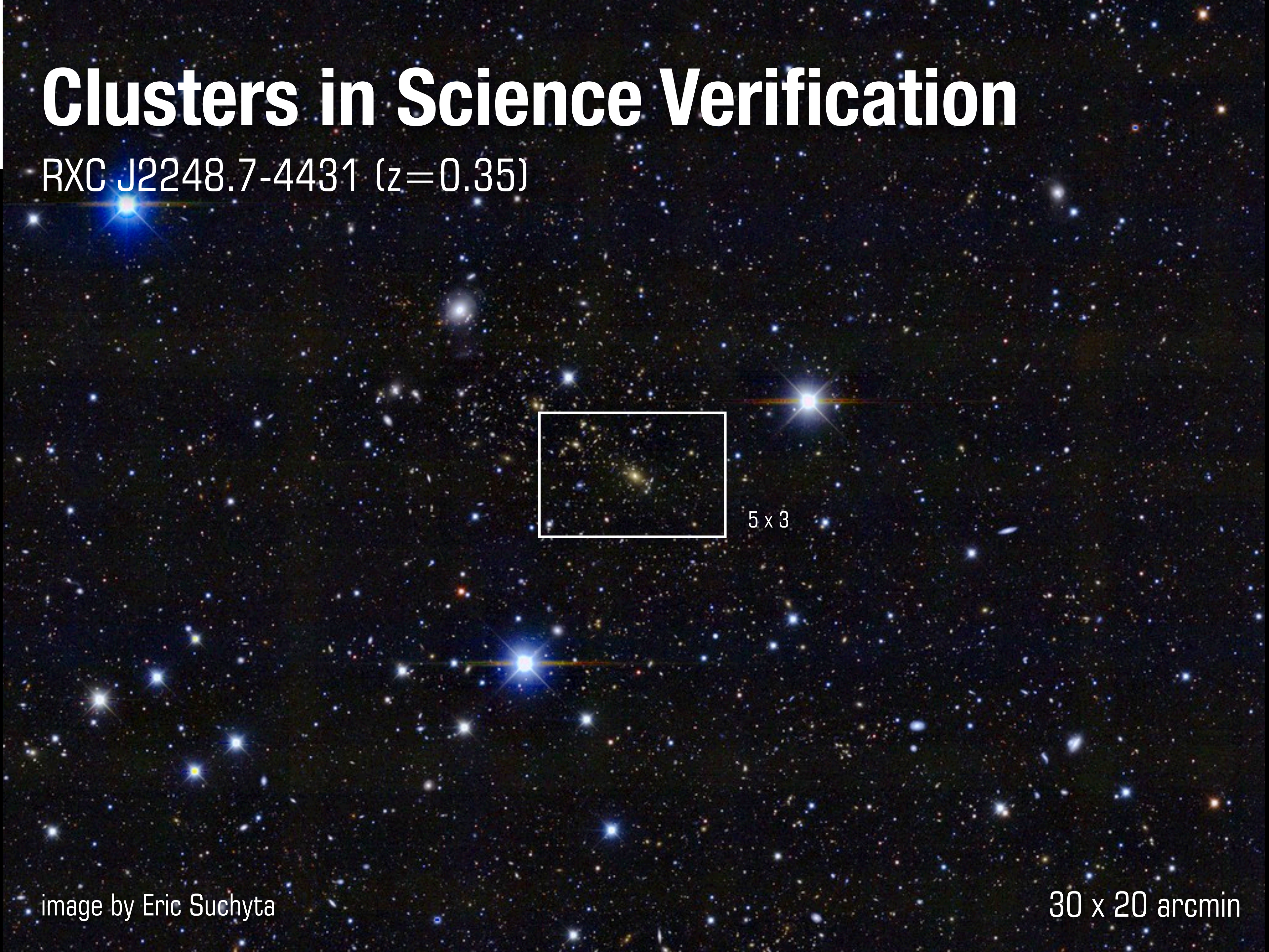
RXC J2248.7-4431 (z=0.35)

image by Eric Suchyta

5 x 3 arcmin

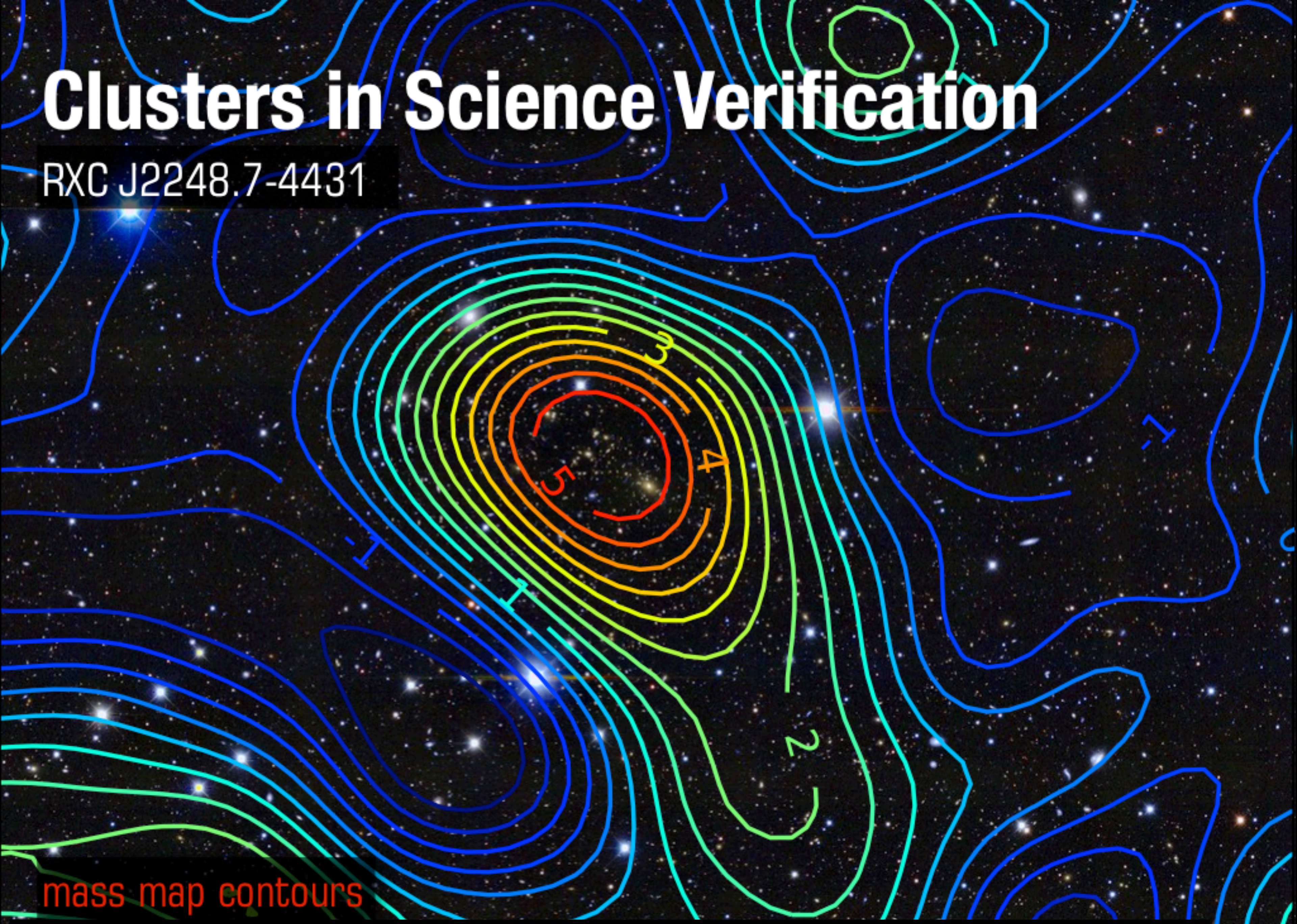
Clusters in Science Verification

RXC J2248.7-4431 (z=0.35)



Clusters in Science Verification

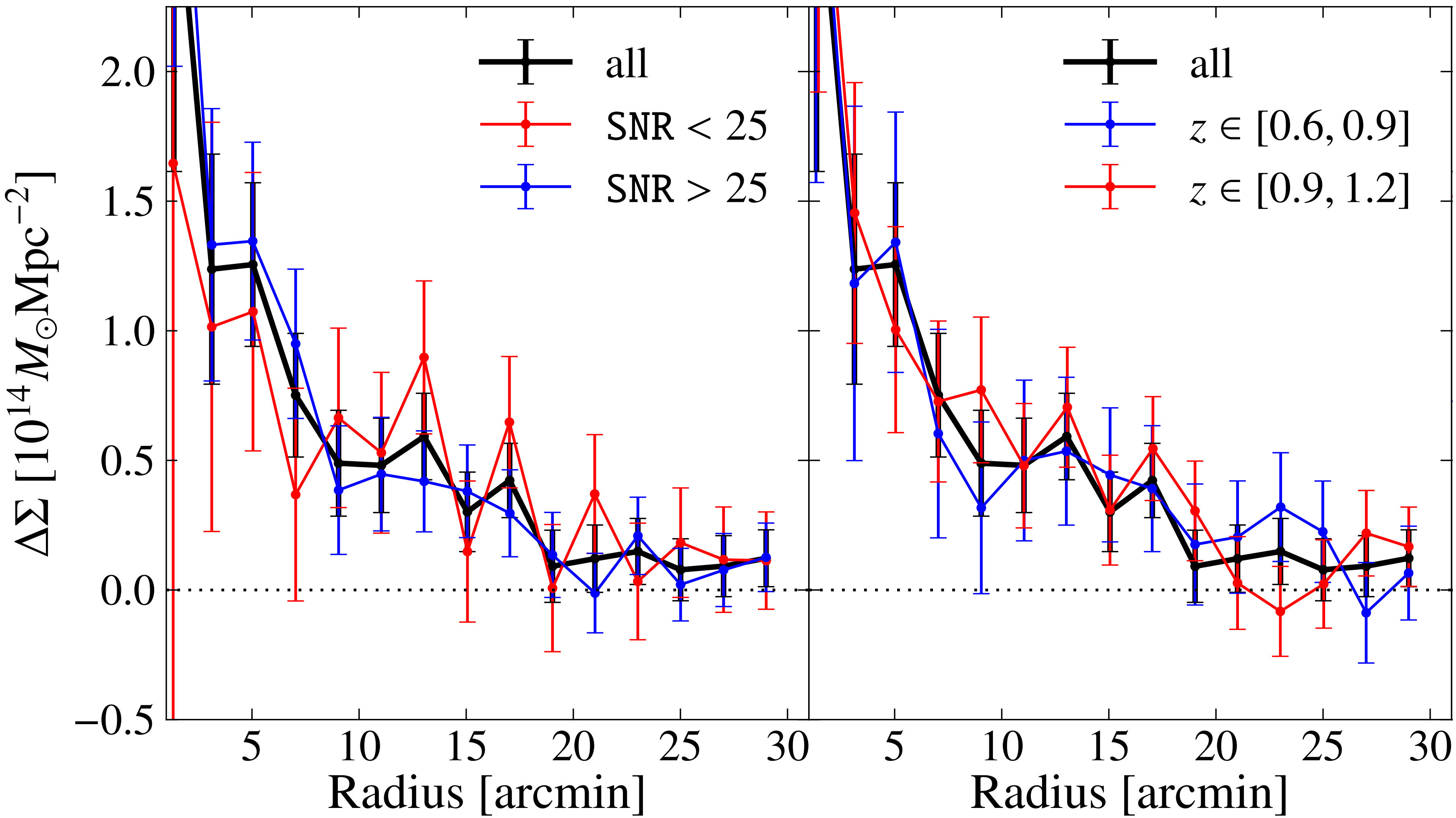
RXC J2248.7-4431



Melchior, Suchyta, Huff, Hirsch, Kacprzak, Rykoff, Gruen et al (DES Collab) 2014

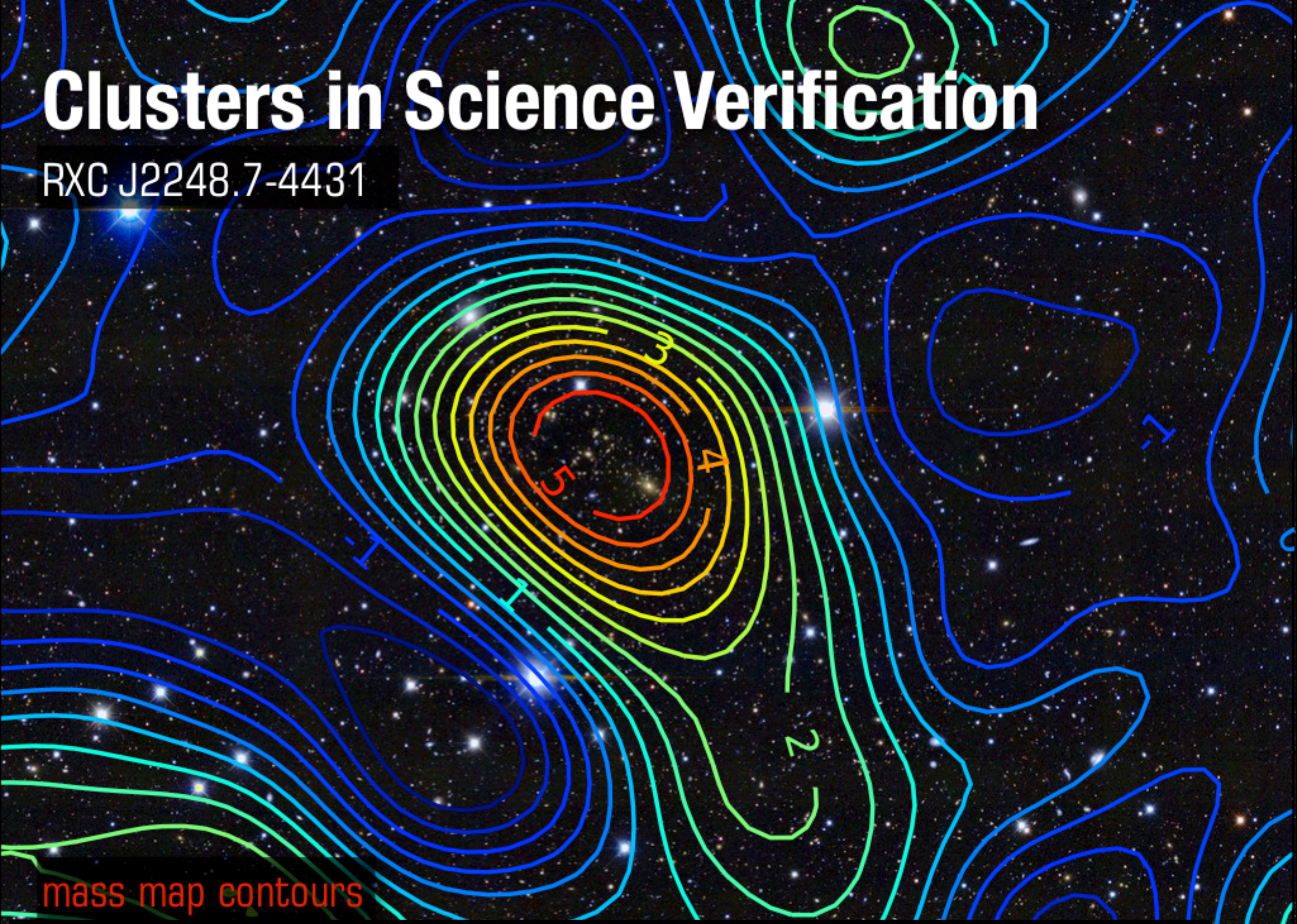
Consistency tests

Stacked lensing signal of 4 massive clusters



Melchior, Suchyta, Huff, Hirsch, Kacprzak, Rykoff, Gruen et al (DES Collab) 2014

Clusters in Science Verification



Melchior, Suchyta, Huff, Hirsch, Kacprzak, Rykoff, Gruen et al (DES Collab) 2014

Big Data from LSST

3.2G pixel camera
2000 exposures per night
-> 20TB per night

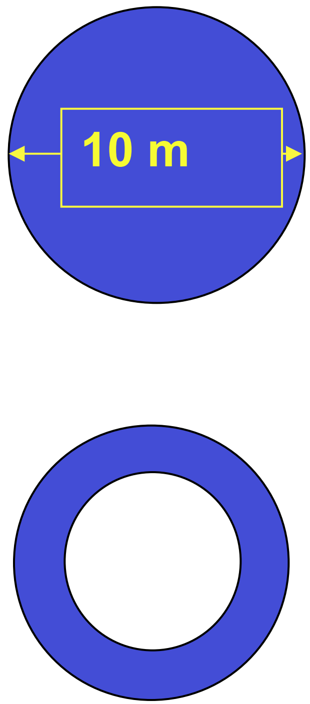
10 year survey
-> 100 PB data

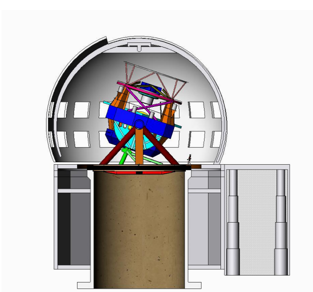
Why is the LSST unique?

Primary mirror diameter

Field of view
(full moon is 0.5 degrees)

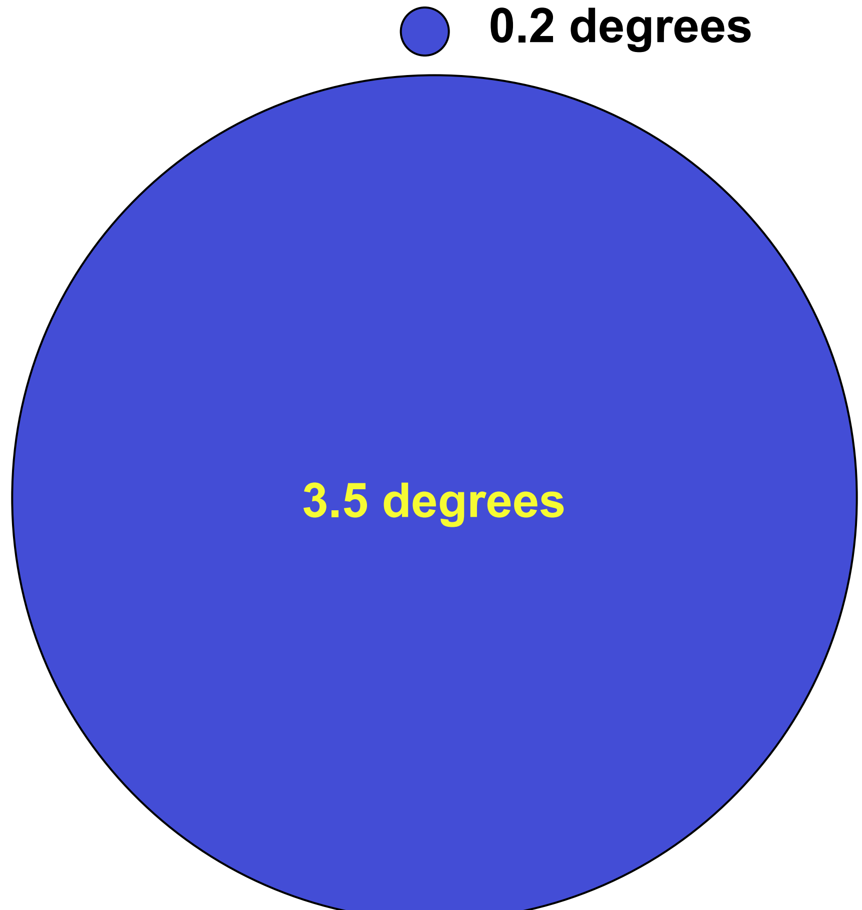
Keck Telescope



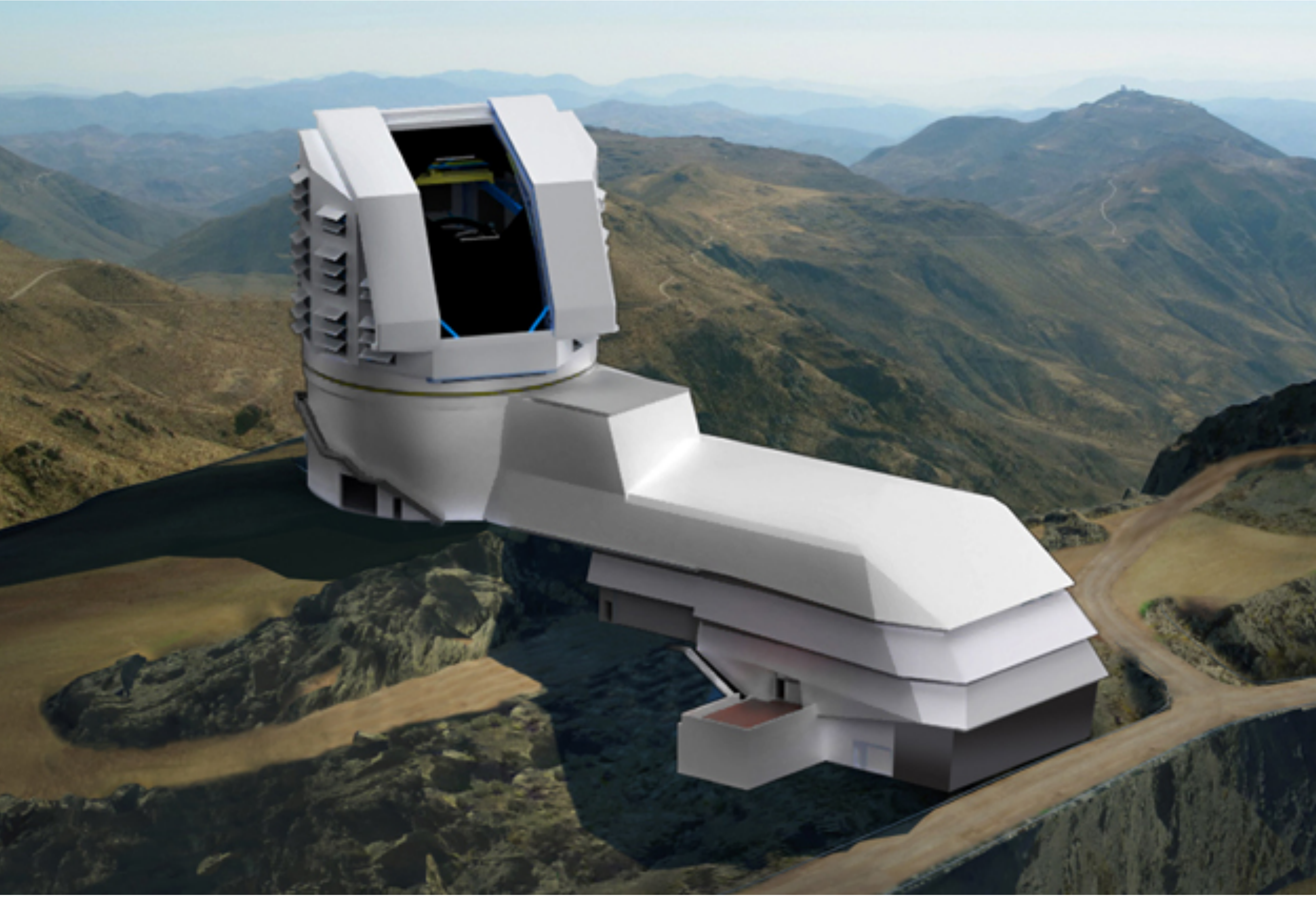


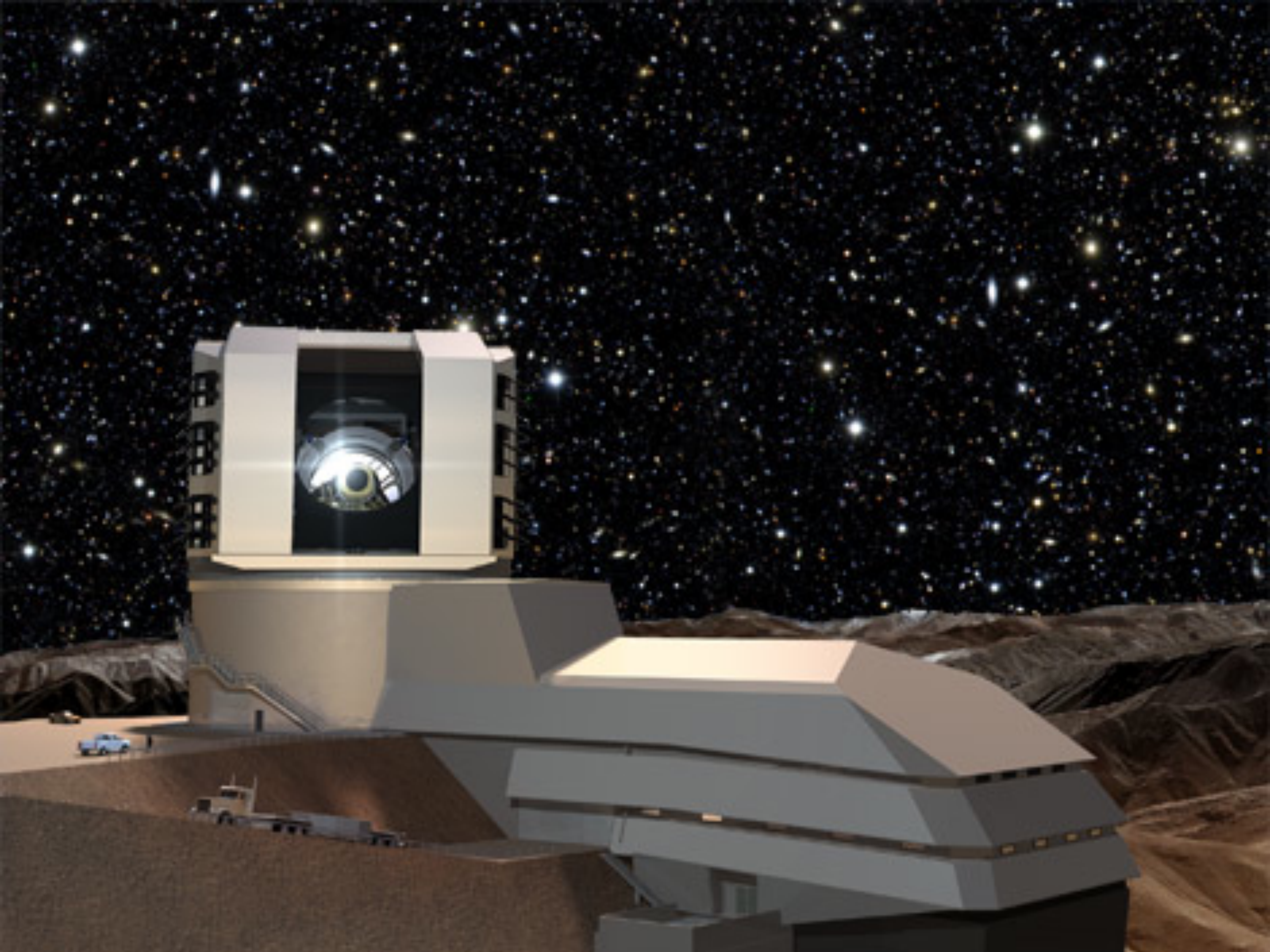
LSST

8.4m primary diameter
6.7m effective diameter




LSST Site
La Serena
Santiago





Big Data from LSST

- 800 images (movie) of the southern hemisphere in 6 colours
- ~100 000 alerts/ night worldwide, within 60 seconds
- 3 billion galaxies, 10 million supernovae

Project timeline enables "first light" in 2019, survey start 2022