The Dark Energy Survey (DES): status, recent results, and mocks.

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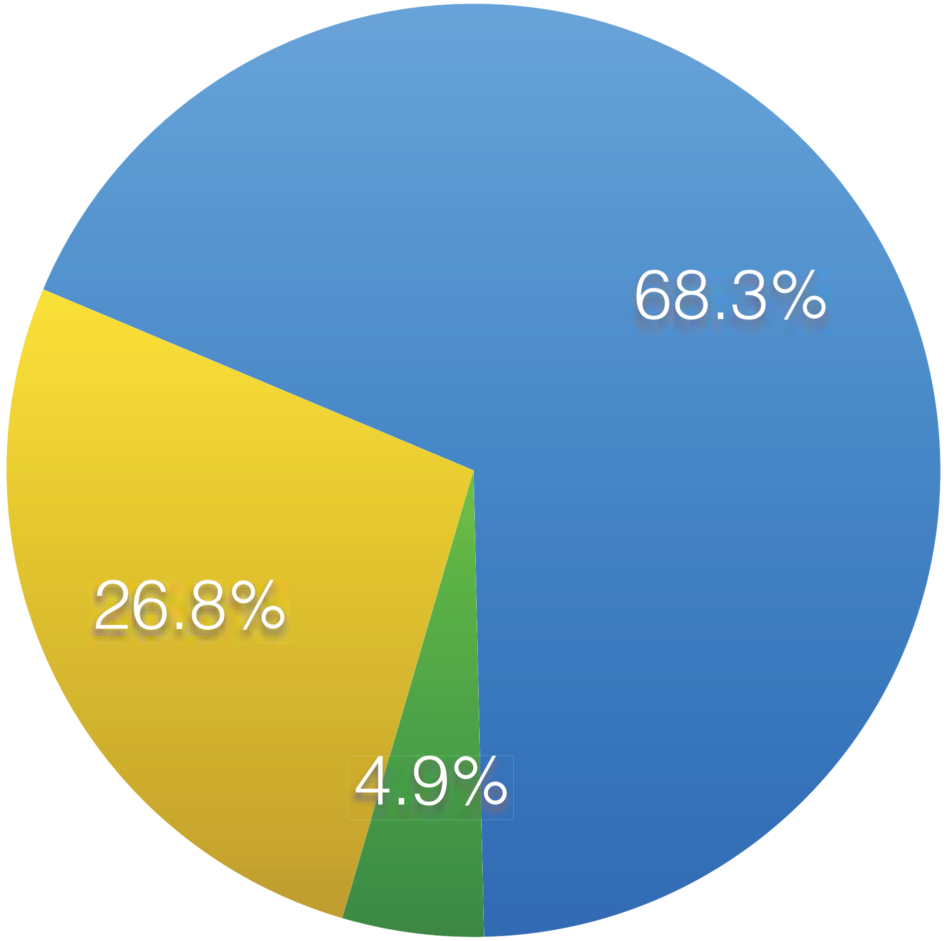
28th Jan 2016

OUTLINE

- Motivation
- The Dark Energy Survey
  Recent Results
- Mock Galaxy Catalogues

MOTIVATION: What is Dark Energy?

(maximally boring universe?)



Plank Results (2015)

- The expansion of the universe is accelerating.
- Dark Energy is about ~70% of the energy-density of the universe.
- What is it ?!

MOTIVATION: What is Dark Energy?

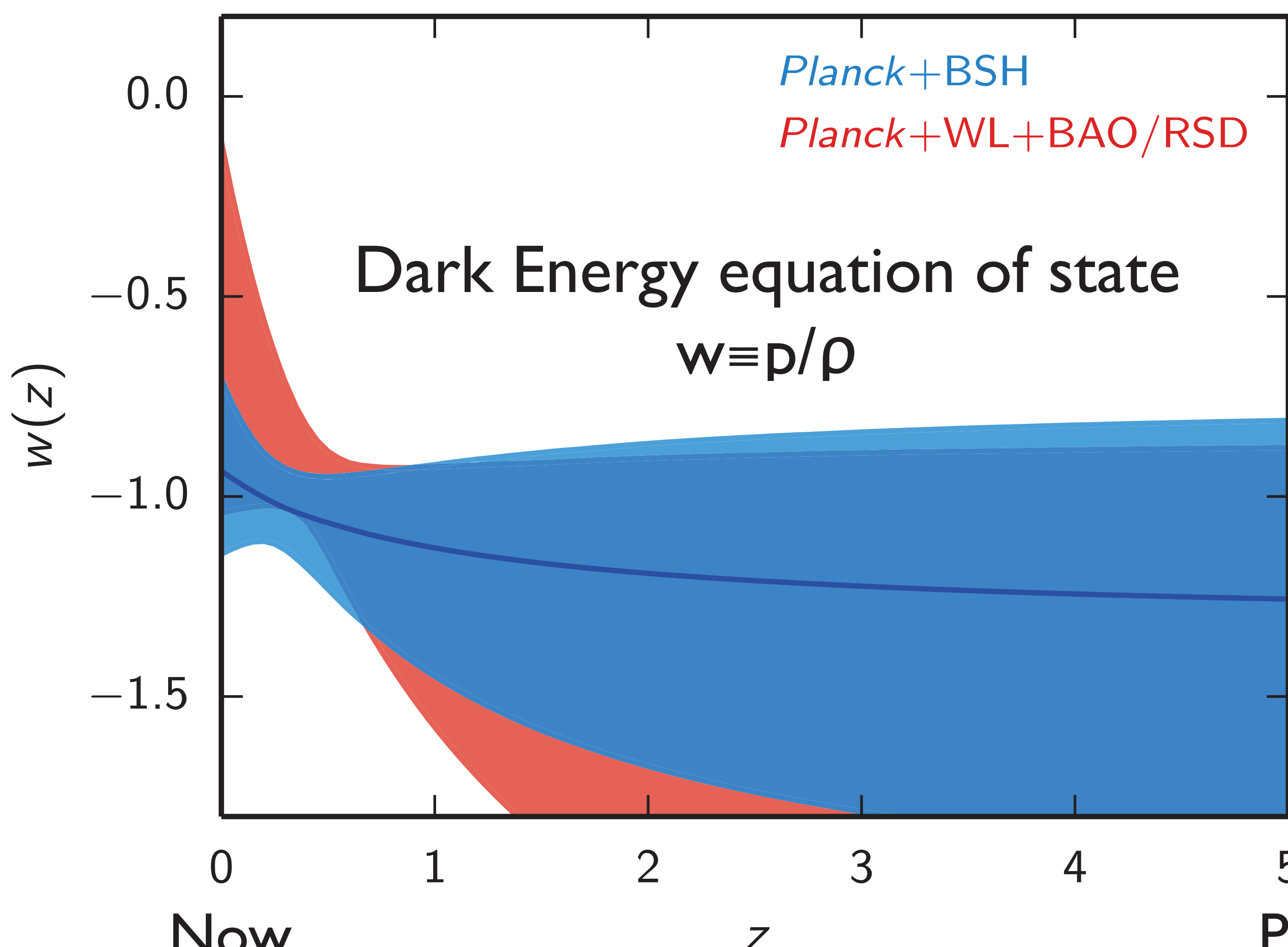
(OBSERVATIONAL STATUS)

* DE is consistent with "cosmological constant"

but:

- ✦ value of Λ not natural
- ✦ Time evolution?
- ✦ Modified gravity?

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

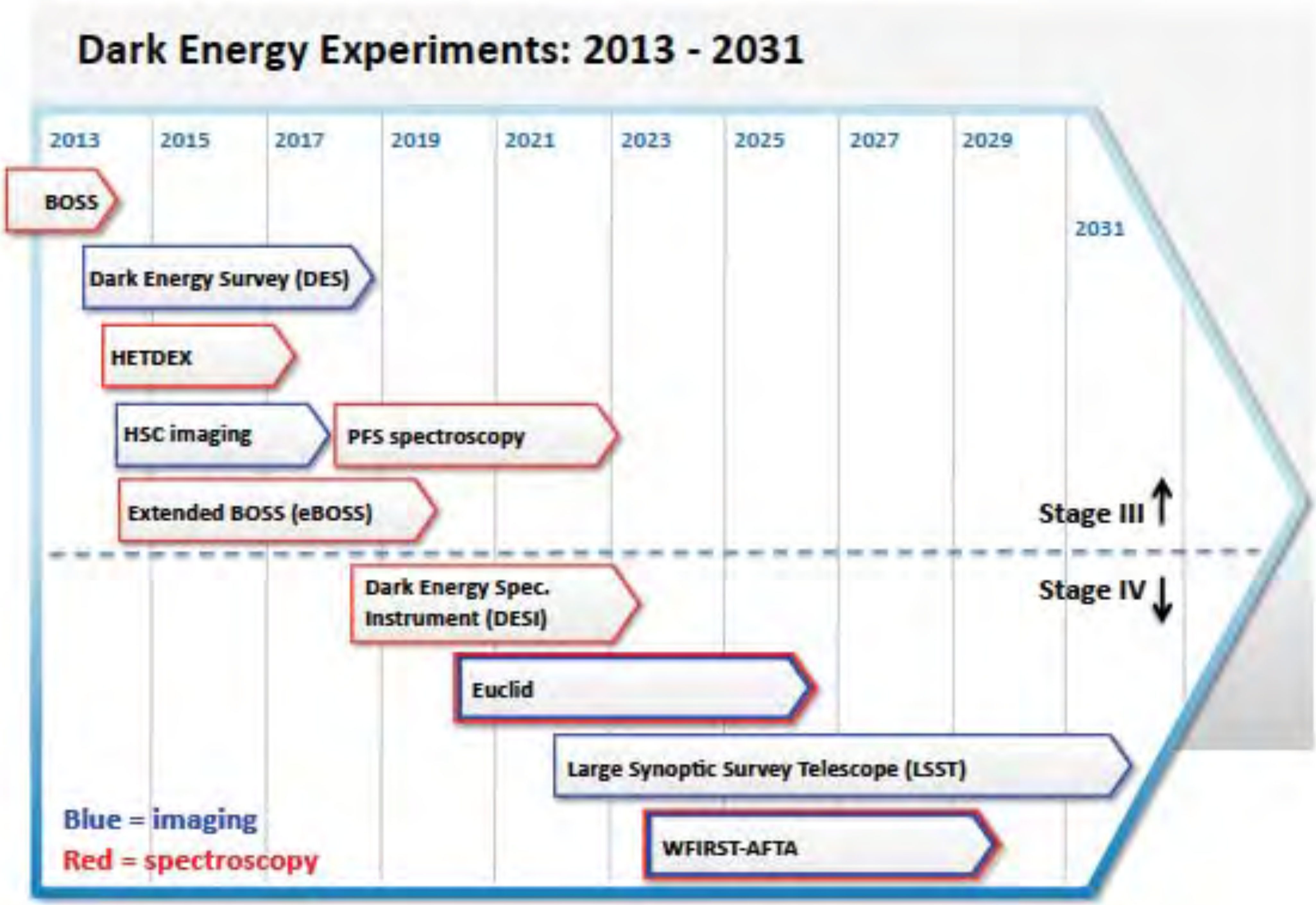


Now　　　　Past

redshift →
distance, time,

Planck Collaboration paper XIV

MOTIVATION: What is Dark Energy?



Measuring Dark Energy

(STRATEGY: LOOK AT ITS EFFECTS)

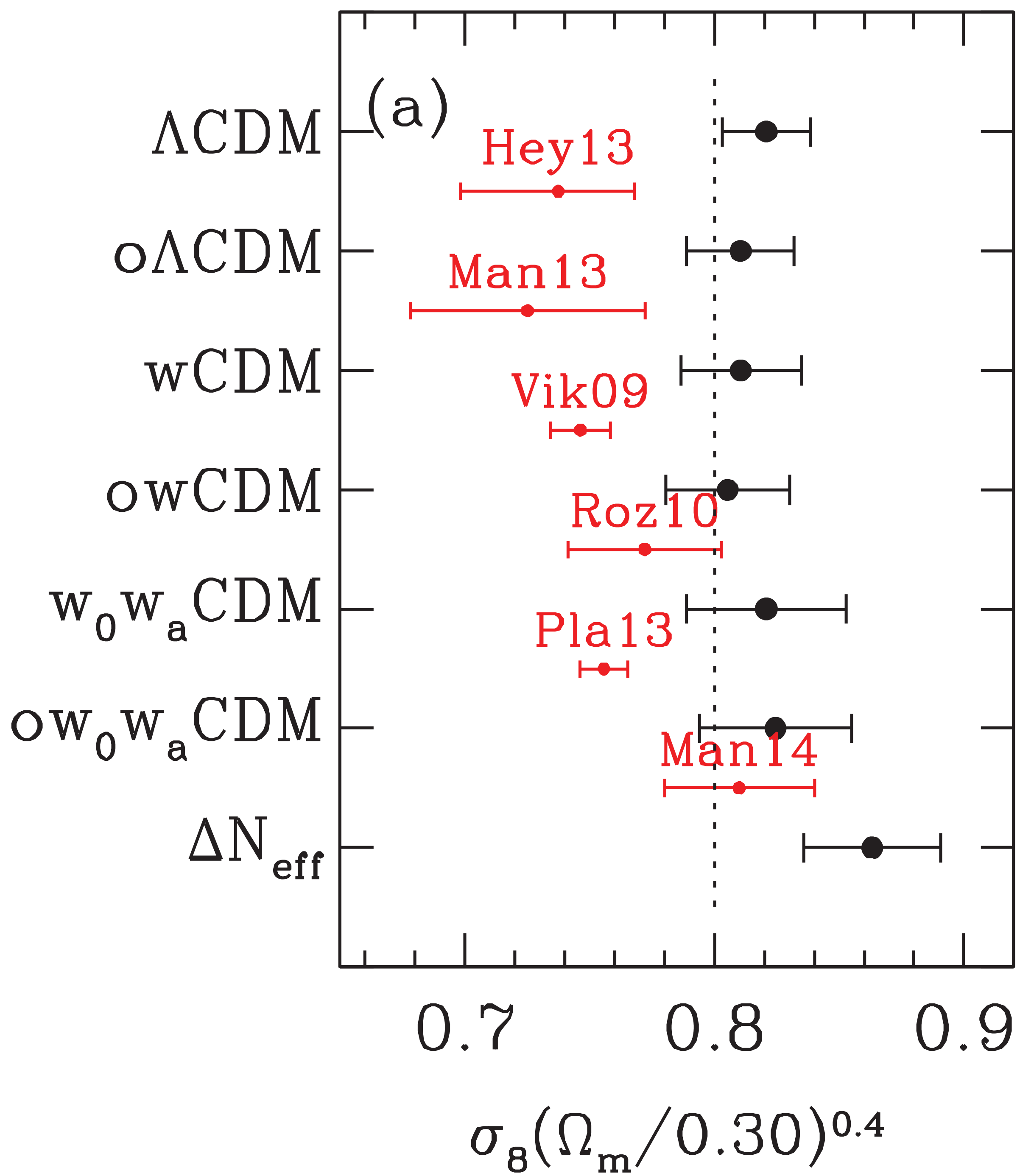
- Geometry: distance vs. redshift
  - redshift tells degree of expansion
  - light-travel distance = time

- Dynamics: structure growth
  - growth rate depends on matter density
  - evolution in matter density ↔ evolution in dark energy density

Measuring Dark Energy

(Tension btw geometrical and structure growth measurements)

Red points: Structure growth measurements

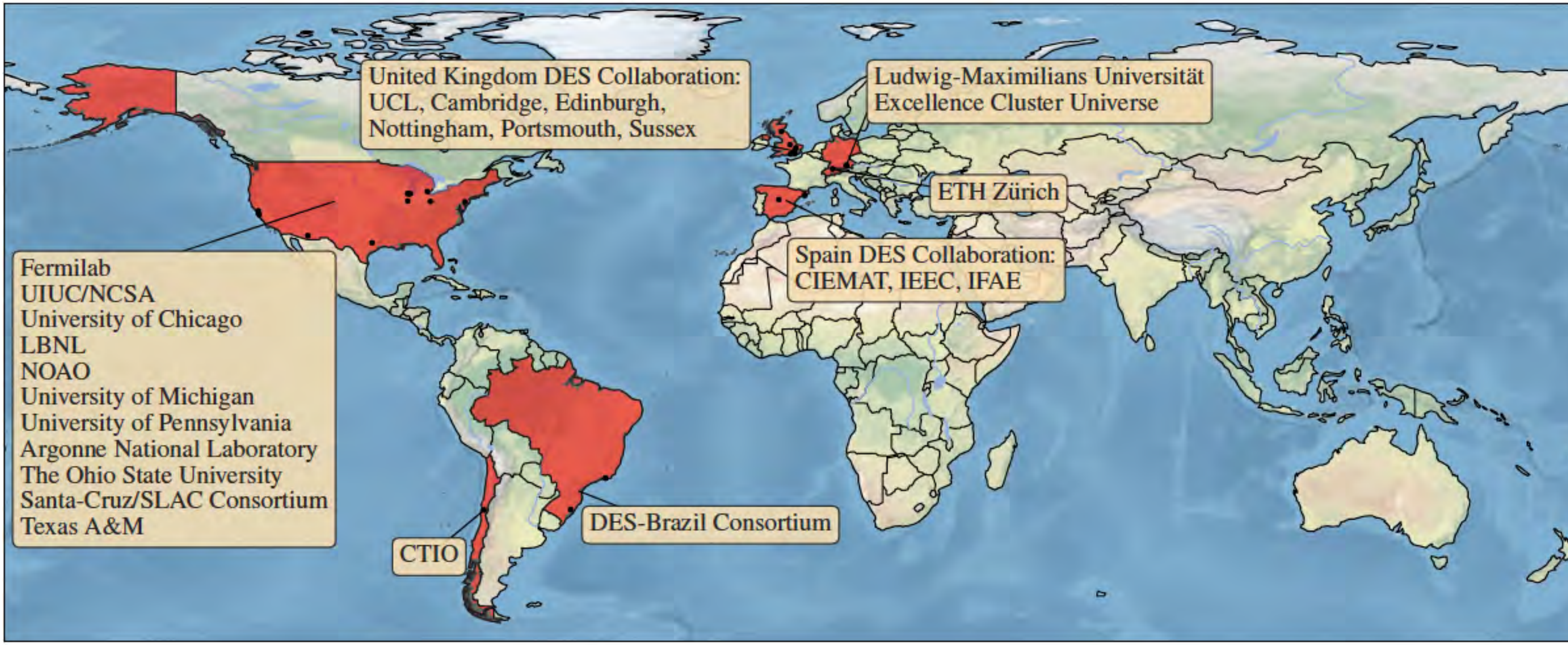


Black points: Derived from geometrical measurements for DE model

Aubourg et al. (2014)

THE DARK ENERGY SURVEY

Collaboration



~450 scientists

28 institutions

Director: Josh Frieman

Instrumentation lead: Brenna Flaugher

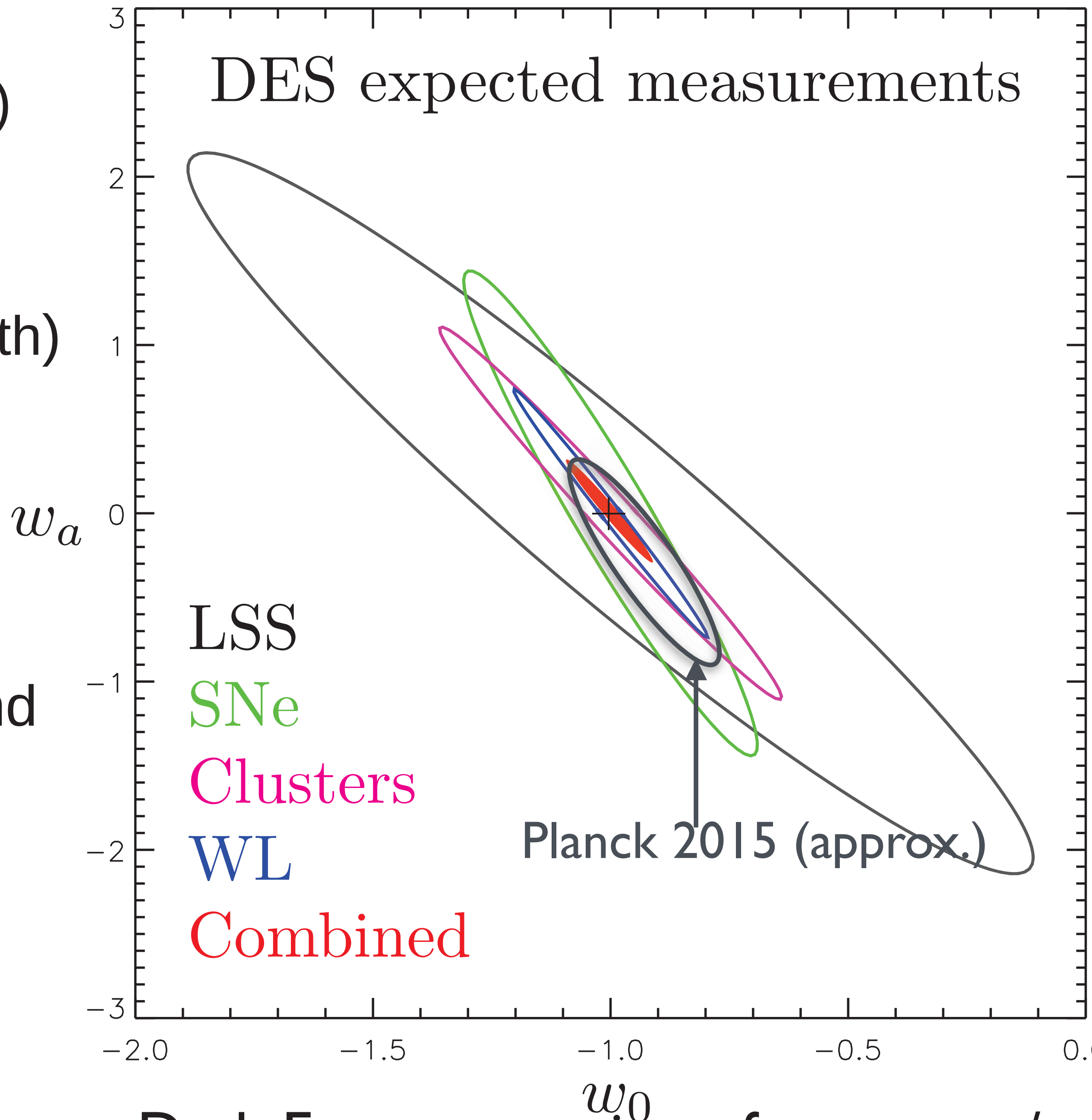
THE DARK ENERGY SURVEY
4-ways to constrain dark energy

Weak lensing (distance, structure growth)
 shape and measurements of 200 millions galaxies

Galaxy clusters (distance, structure growth)
 ten of thousands of clusters up to z~1
 synergies with SPT, VHS

Large Scale Structure (distance)
 standard ruler
 300 millions galaxies to z=1 and beyond

Type Ia supernovae (distance)
 standard candles
 3500 SNIa to z~1



Dark Energy equation of state $w \equiv p/\rho$

$$w(a) = w_0 + (1-a) w_a$$

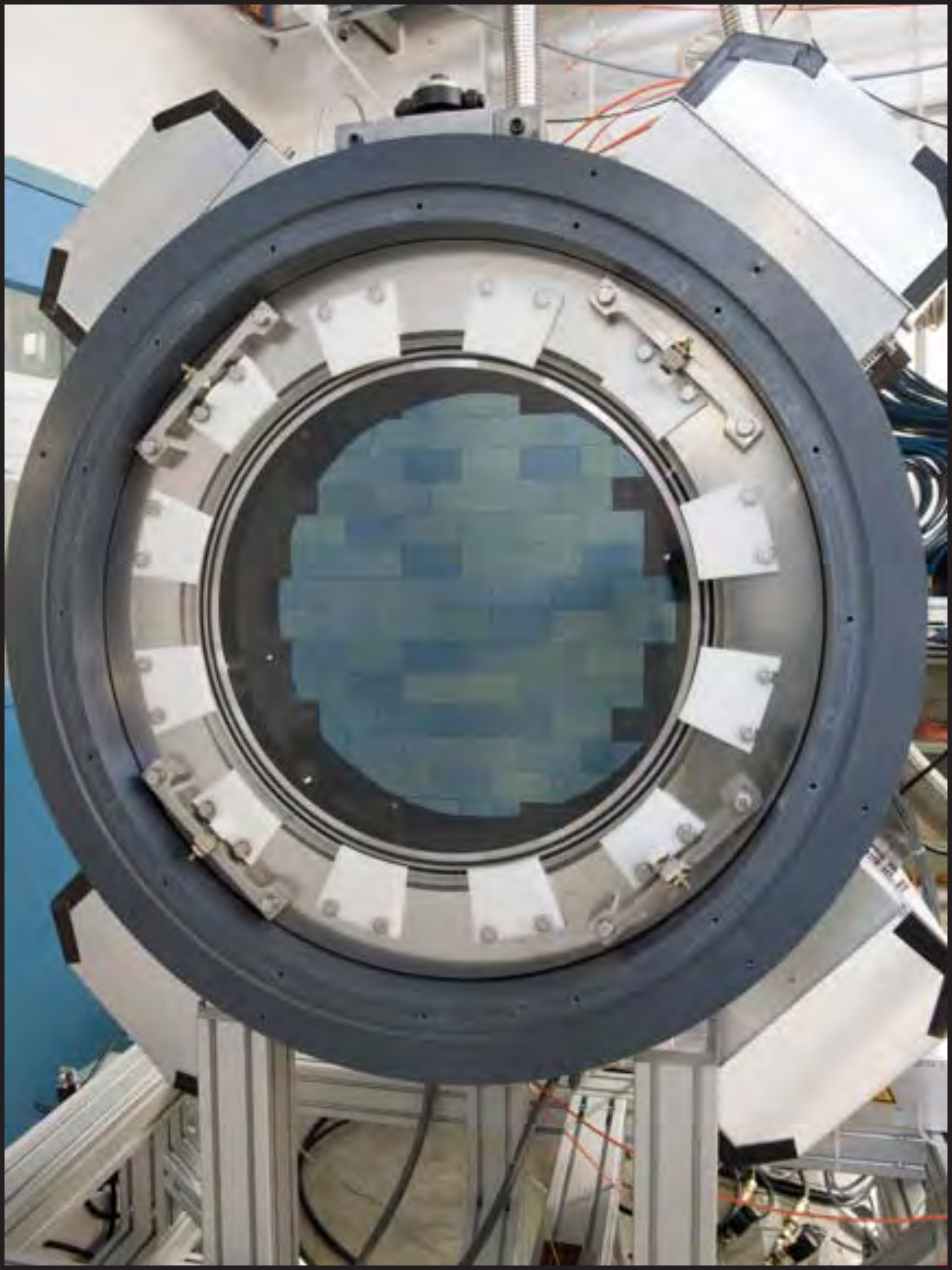
OUTLINE: DES & First Results

- The Dark Energy Survey
  - Telescope
  - Camera
  - Observing status
- Dark Energy Science
  - Weak lensing
  - Galaxy clusters
  - Large-Scale Structure
  - Supernovae
- non Dark Energy Science
  - Discoveries!

The Dark Energy Survey: telescope

The Blanco 4-meter at CTIO Chile

DES Field of View & Focal Plane



1st light: 12 Sept. 2012

Fornax cluster

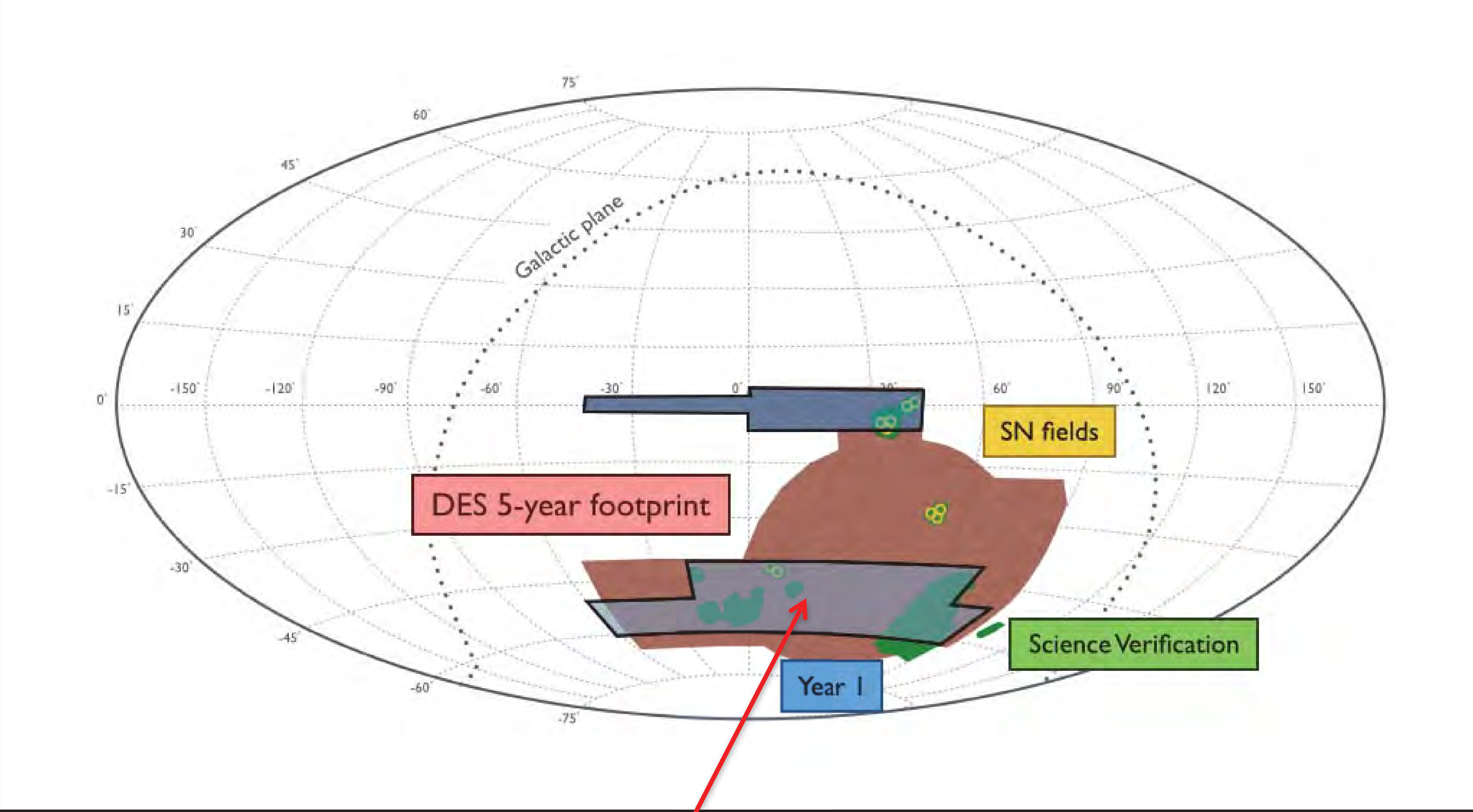
DES Early Data

...moment of zen...

The Dark Energy Survey

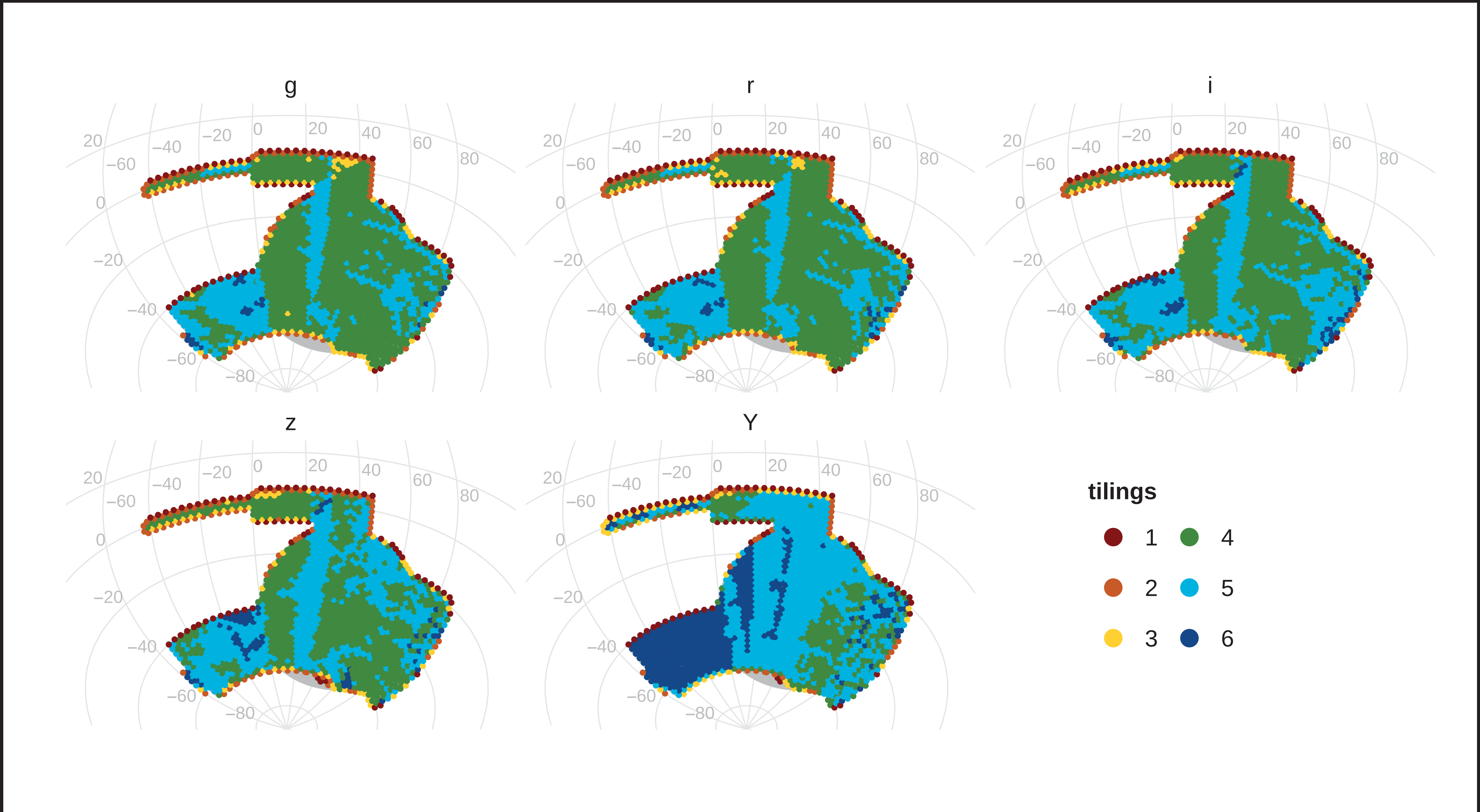
- Cerro Tololo Inter-American Observatory Blanco 4-meter telescope
- First light Sept. 12, 2012
- Survey 2013-2018, 525 nights
- DECam: 570 Mpix, 3 deg^2 FOV, griZY filters
- 5000 deg^2 survey footprint, to mag 24 (redshift ~1.5) + 30 deg^2 deep SN fields

Survey Footprint



Overlap with the South Pole Telescope Survey (SPT)

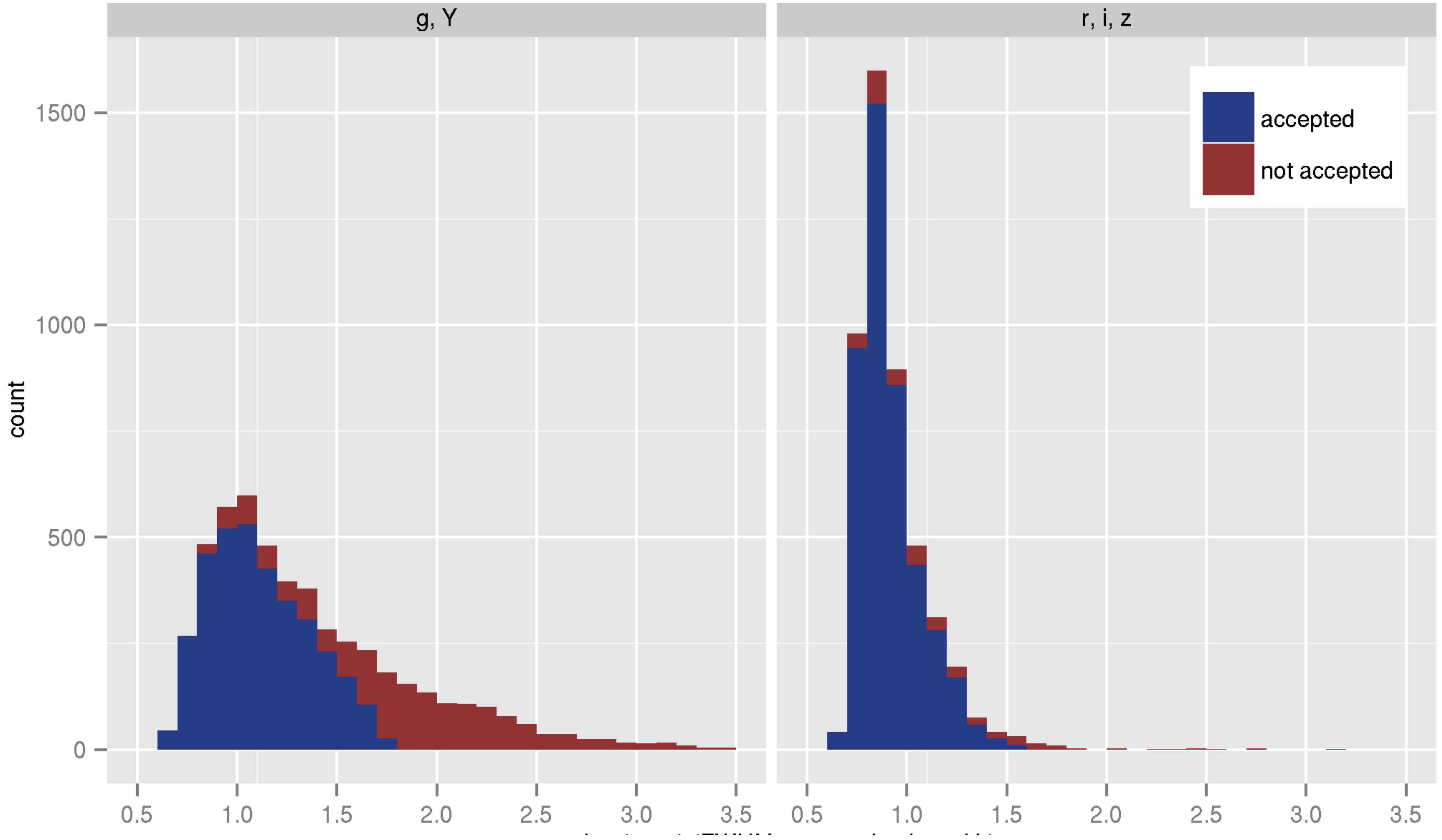
Survey Progress (Y1+Y2+Y3 as of 01/05/2016)



DARK ENERGY SURVEY

DES SEEING

The median delivered image quality in Y1 is approx FWHM 0.94 arcsec in filters riz (cf. 0.90 arcsec in WL science requirement) Improvements at telescope are underway (Y3 gives 0.89’’ in z_band).



Dark Energy Survey

DARK ENERGY SURVEY

Weak lensing (distance, structure growth)
shape and measurements of 200 millions galaxies

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Large Scale Structure (distance)
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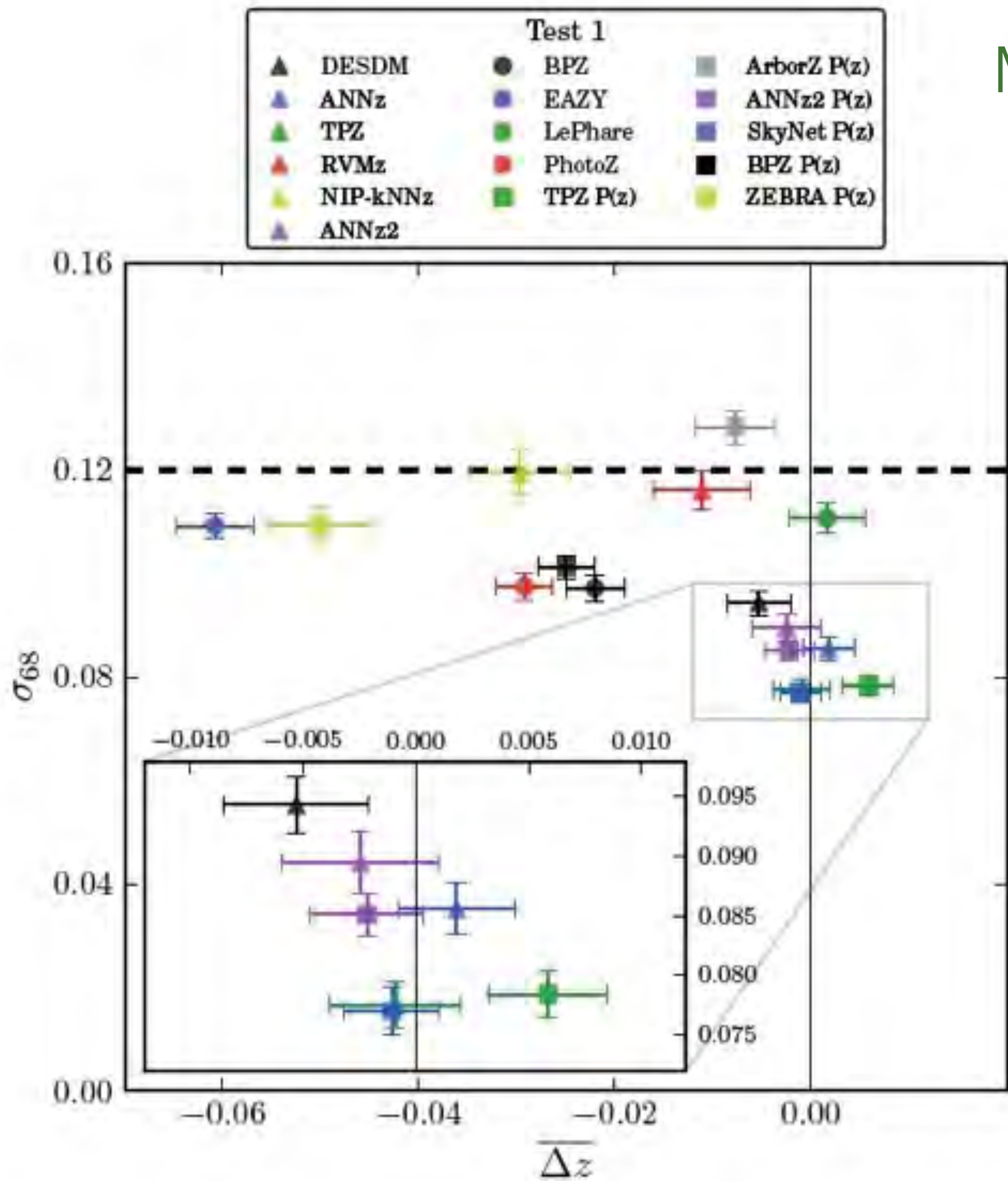
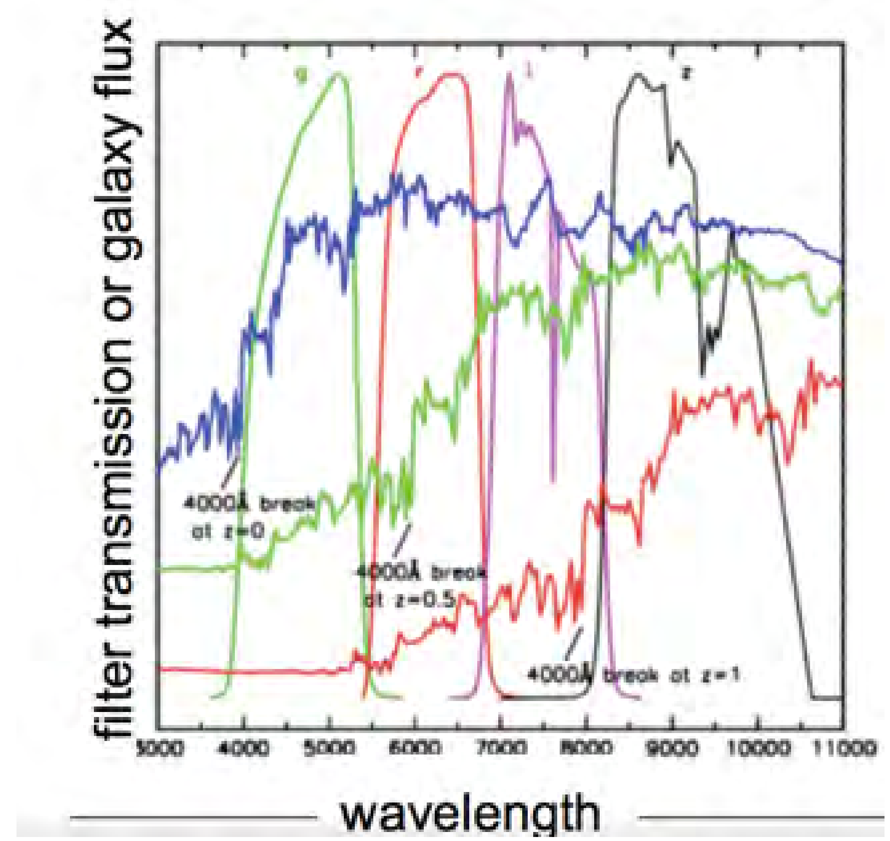
Type Ia supernovae (distance)
standard candles
3500 SNIa to z~1

} shared photometry/footprint

Results from Science Verification Data: Photometric Redshifts



Many codes already meet requirements



Carles Sanchez et al., MNRAS 445 1482 (2014)

OUTLINE: DES & First Results

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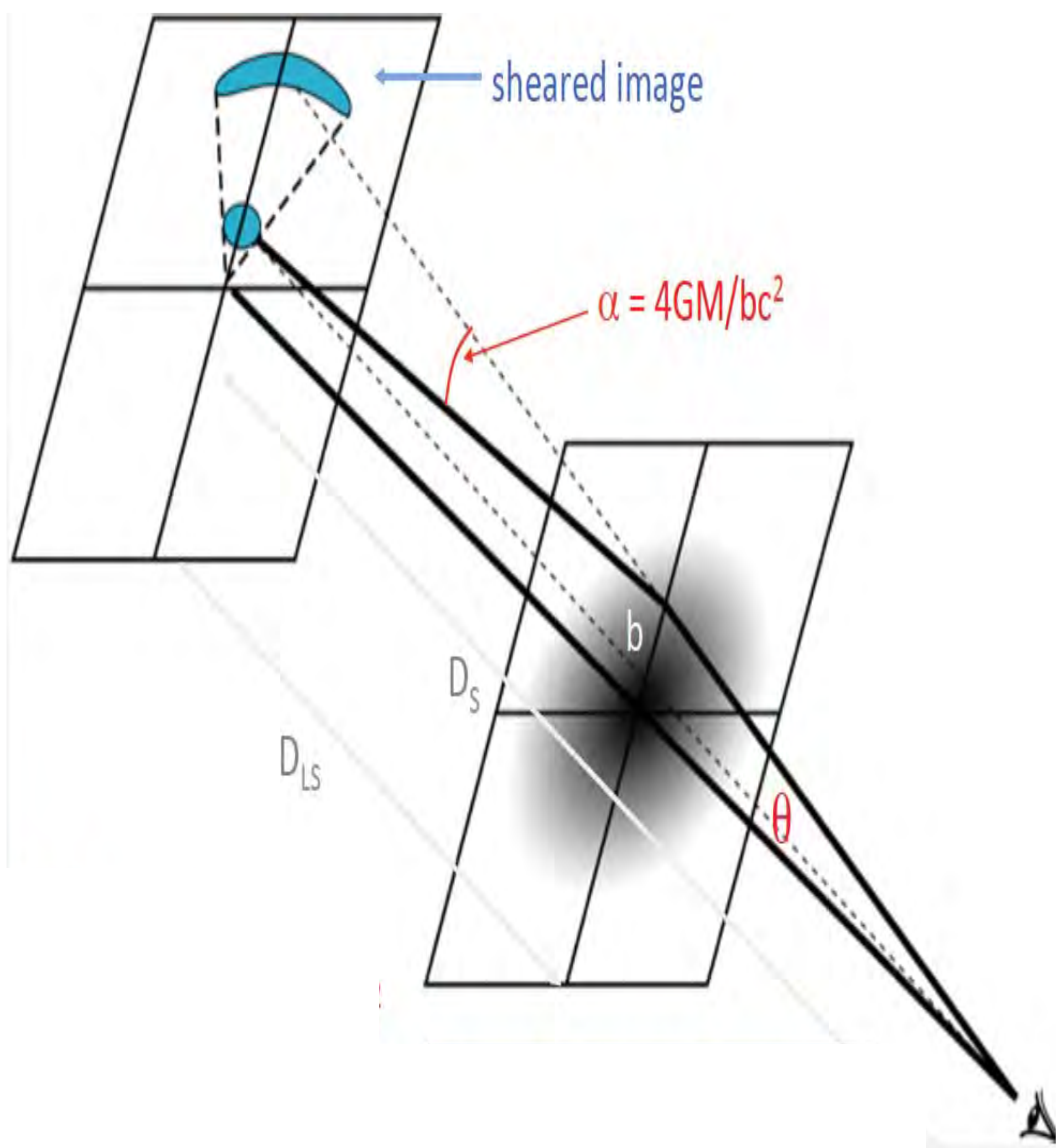
THE DARK ENERGY SURVEY

Gravitational Lensing

DARK ENERGY SURVEY



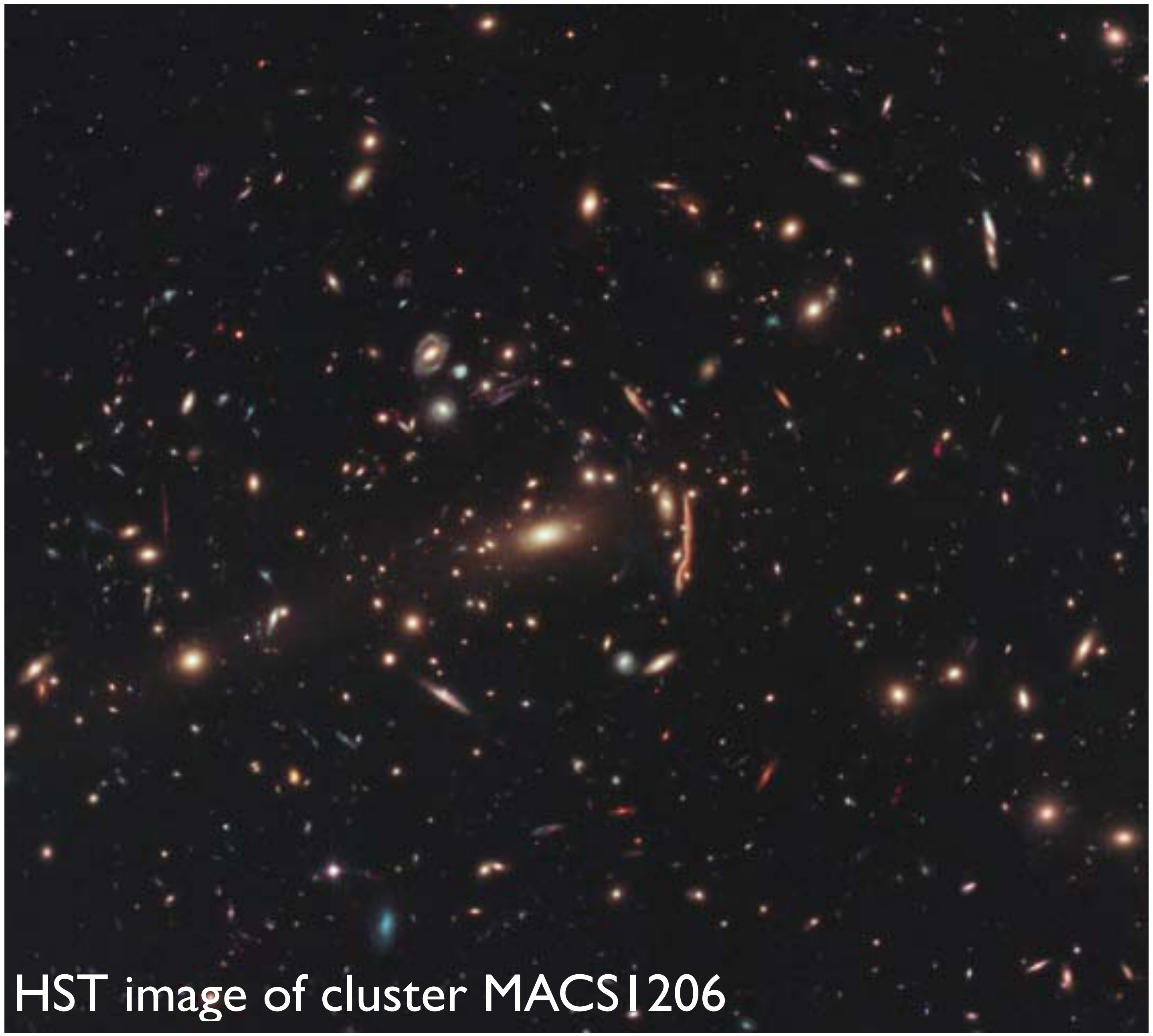
- Matter bends light and distorts galaxy shapes
- DES found 6 strong gravitational lensing systems (Three of which were unknown Nord et al. arXiv:1512.03062.)

$$A = (1-\kappa)\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} - \gamma \begin{bmatrix} \cos 2\phi & \sin 2\phi \\ \sin 2\phi & -\cos 2\phi \end{bmatrix}$$

$$\gamma = \gamma_1 + i\gamma_2 = \frac{1}{2}(\psi_{,11} - \psi_{,22}) + i\psi_{,12}.$$

$$\kappa = \frac{1}{2}\nabla^2\psi;$$

Gravitational Lensing



HST image of cluster MACS1206

$$\kappa(\theta, r) = \frac{3H_0^2\Omega_m}{r} \int_0^r dr' \frac{r'(r-r')}{r} \frac{\delta(\theta, r')}{a(r')}$$

- Matter bends light and distorts galaxy shapes
- DES found 6 strong gravitational lensing systems (Three of which were unknown Nord et al. arXiv:1512.03062.)
- Unbiased tracer of matter distribution
- measure shapes to obtain "shear" catalog

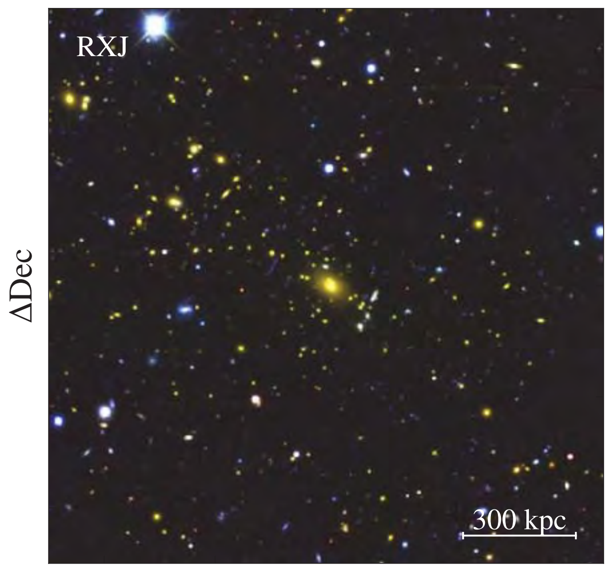
$$\gamma = \gamma_1 + i\gamma_2 = \frac{1}{2}(\psi_{,11} - \psi_{,22}) + i\psi_{,12}.$$

$$\kappa = \frac{1}{2}\nabla^2\psi;$$

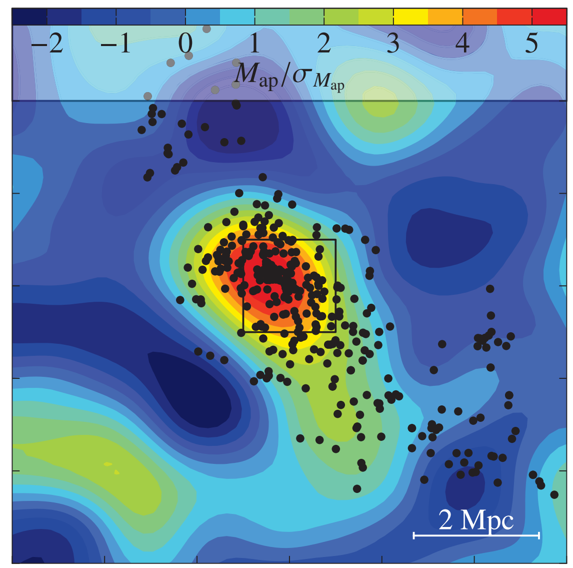
DES Clusters: *Mass and galaxy distributions of four massive galaxy clusters*

Melchior et al. (2014)

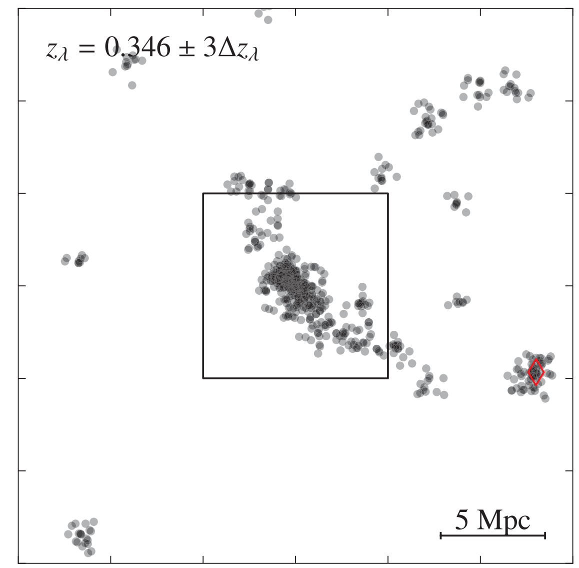
DES Image



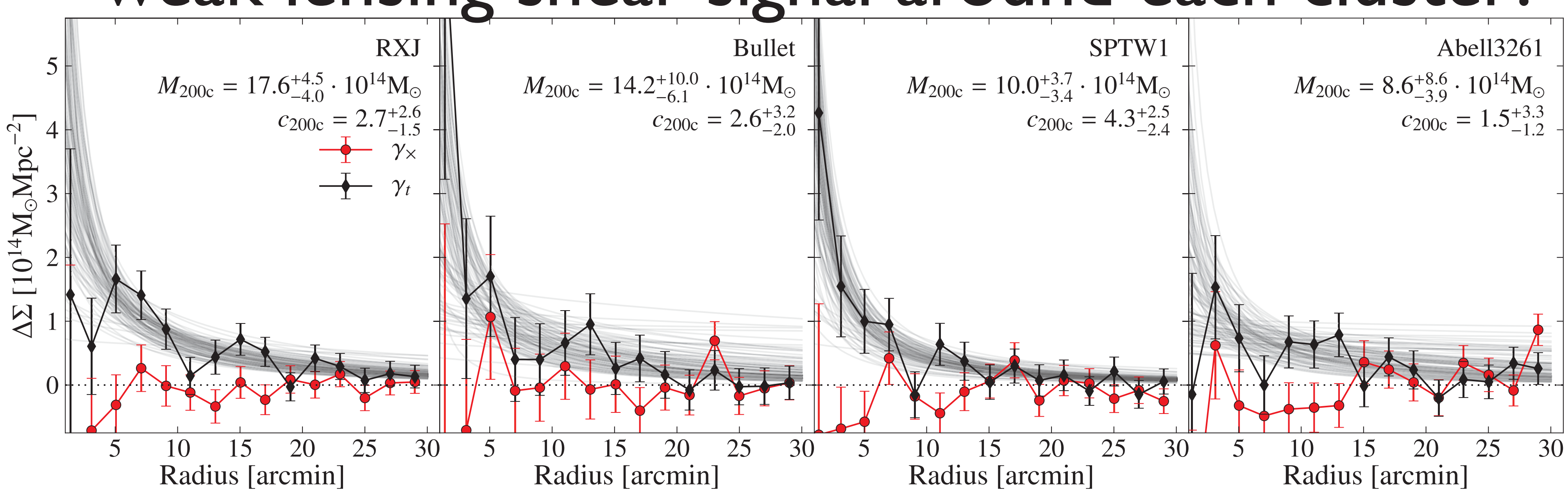
Lensing map
+cluster galaxies



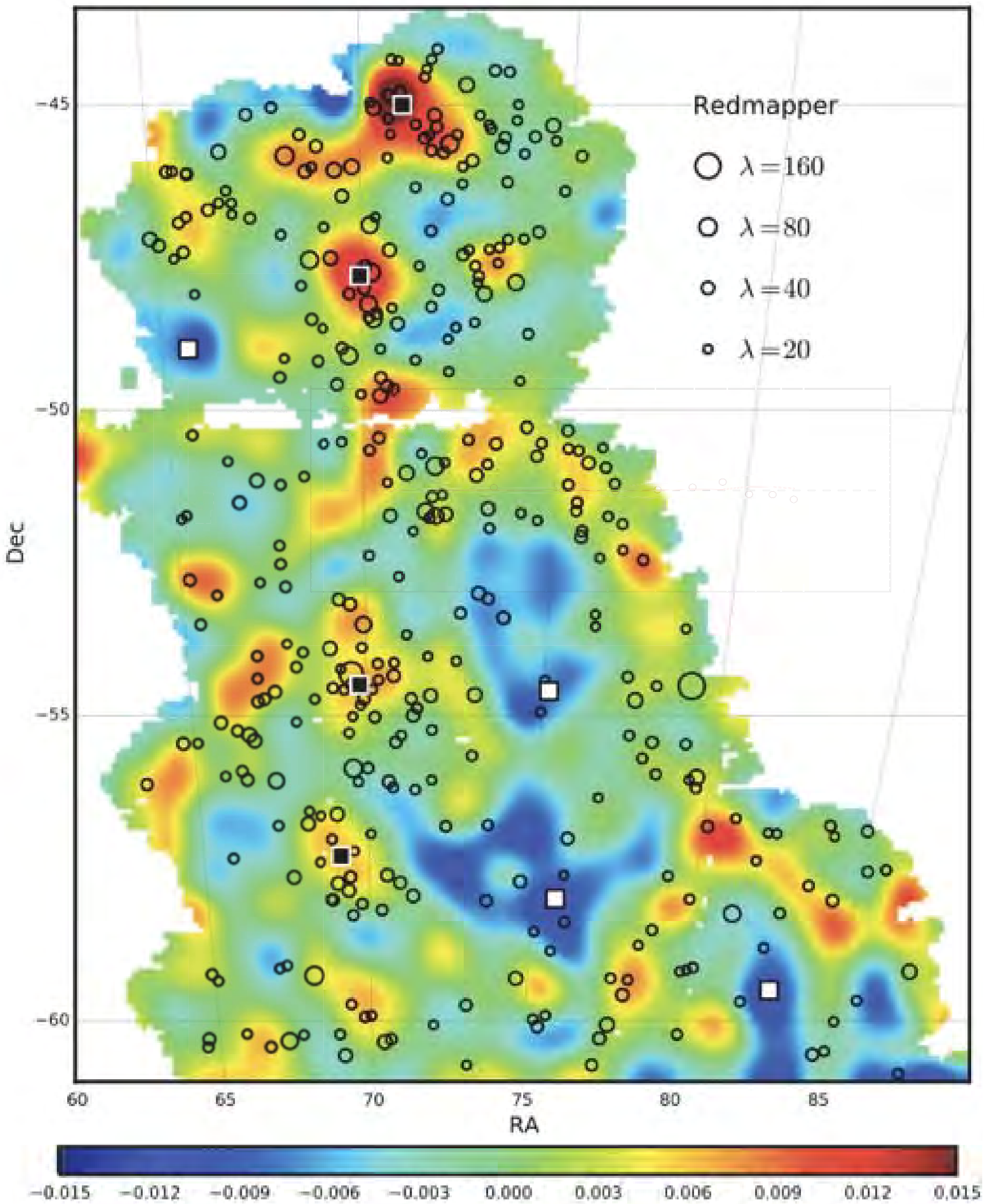
Cluster galaxies;
zooming out



weak lensing shear signal around each cluster:



Weak Lensing: Mass mapping

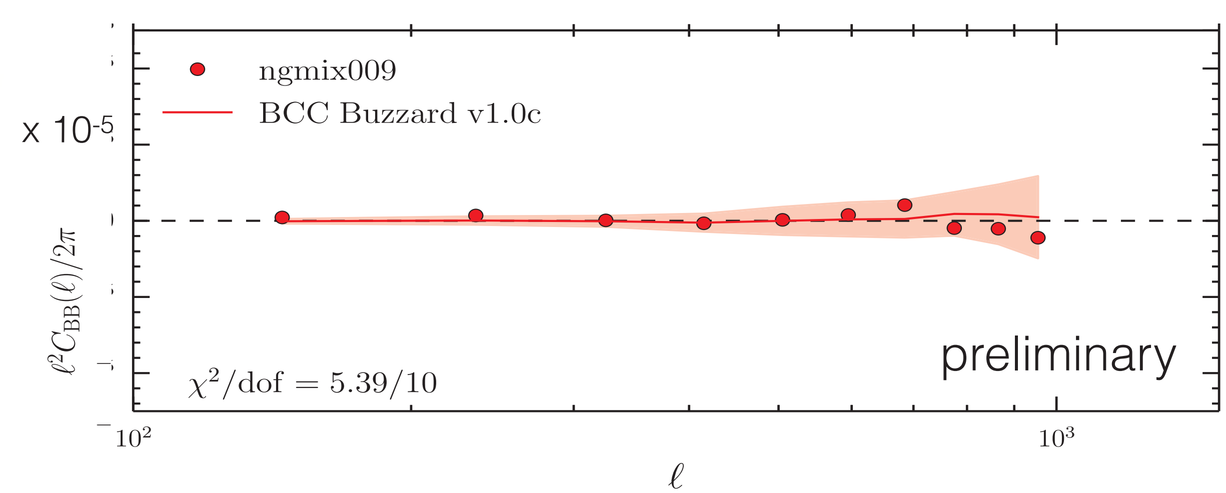


Convergence (mass) map from galaxy shear measurements

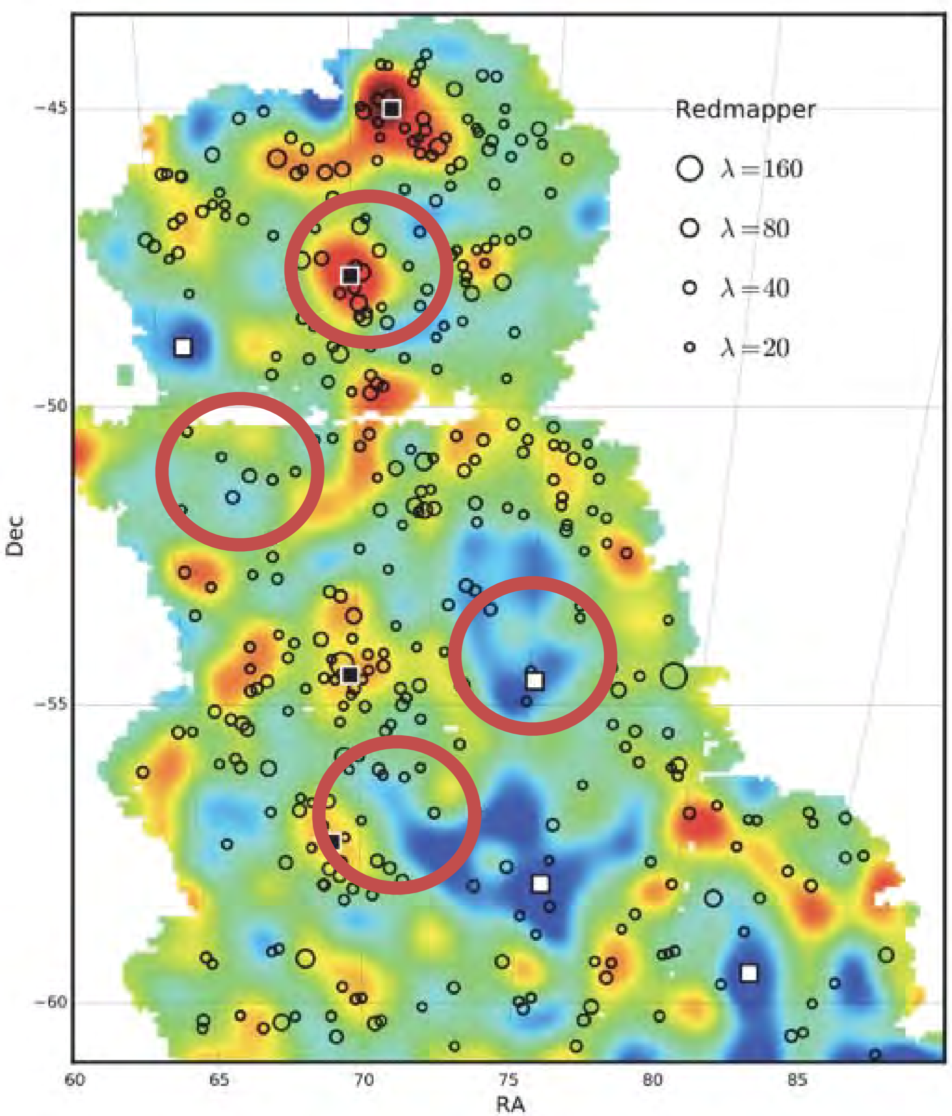
Map of projected mass distribution for z < 0.5

Vikram, Chang, Jain, Bacon et al. (2015)

Galaxy groups plotted on top. Test with simulations kB=0



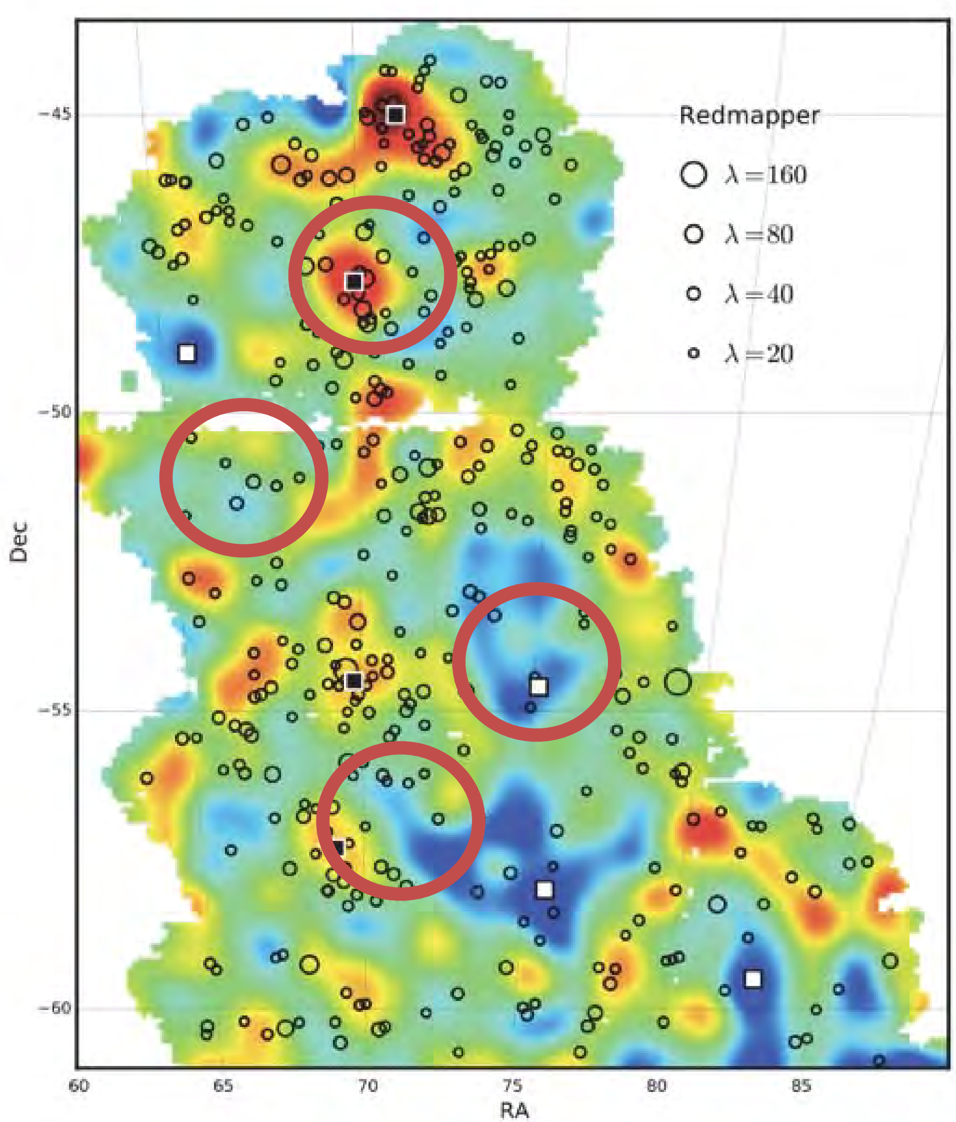
Weak lensing and galaxy statistics



DES WL kappa and cluster map
Chang, Vikram, Jain et al 2015.

- **Investigate the correlation between galaxies and the weak lensing field.**
- Count in cells: we throw circles randomly and obtain galaxy counts and average values of kappa, and kappa_gal.
- Test the log-normality of each field separately, as well as jointly (cf Wild et al.)
- Check the validity of the log-normal model: compare the results from those measured directly from data.
- Get estimation of galaxy bias and compare it with clustering results.

Data



DES WL kappa and cluster map
Chang, Vikram, Jain et al 2015.

- Galaxies: Benchmark
  - 18.0 < i <22.5
  - 0 < g–r < 3 and 0< r–i < 2 and 0 < i–z < 3.
  - (not confusted with stars) modest class = 1
  - 60 < ra < 95 and –62 < dec < –40 (SPT-E)
  - 0 < z < 0.5; photoz from skynet
- Lensing:
  - s
  - kappa maps as in chang et al. using Kaiser-Squires

- We use circles with radius from 10 to 40 arcminutes
- We test our methodology with MICE simulations

Why log-normal

Right shape

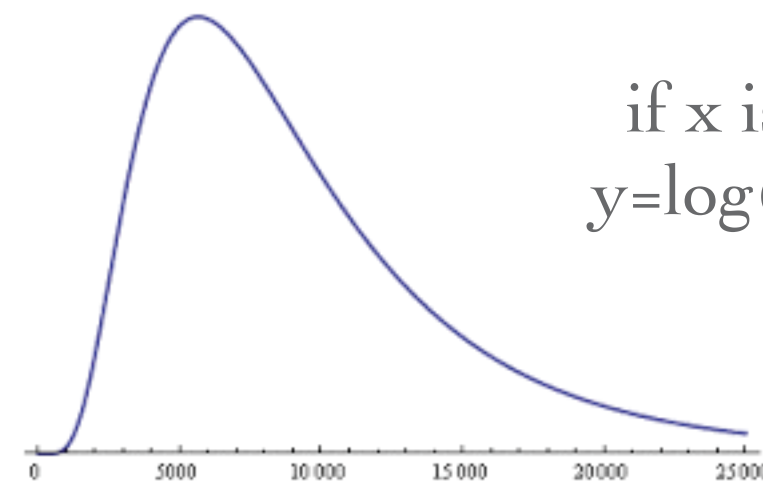
- Bounded at zero
- Skewed

Galaxies

- Hubble 1934
- Coles & Jones 1991
- Kayo & Suto 2001
- Wild et al 2005 etc…

Kappa

- Taruya et al. 2001
- Hilbert et al. 2011
- Joachimi et al. 2011



if x is lognormal
y=log(x) is normal

"The lognormal model applies to non-linear processes in the same way the normal distribution does to linear ones.

If you have a quantity Y which is the sum of n independent effects, Y=X1+X2+…+Xn, the distribution of Y tends to be normal by virtue of the Central Limit Theorem regardless of what the distribution of the Xi is

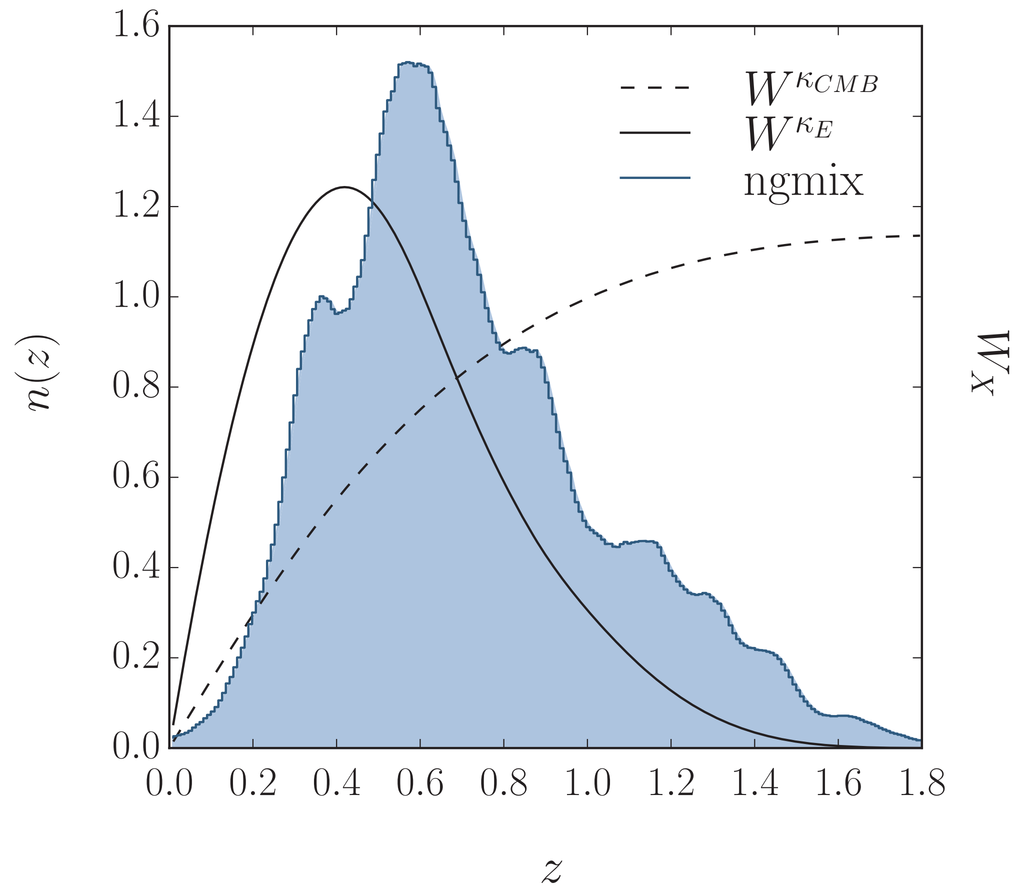
If the process is multiplicative so Y=X1×X2×…×Xn, since log Y = log X1 + log X2 + …+log Xn, the Central Limit Theorem makes log Y normal.

The lognormal is a good distribution for things produced by multiplicative processes, such as hierarchical fragmentation or coagulation processes: e.g distribution of sizes of the pebbles on a beach. "

Basic Equations

The convergence is an integrated quantity of the matter density weighted by a geometrical lensing function.

$$\kappa(\boldsymbol{\theta}, r) = \frac{3H_0^2\Omega_m}{2} \int_0^r \mathrm{d}r' \frac{r'(r-r')}{r} \frac{\delta(\boldsymbol{\theta}, r')}{a(r')}.$$



Noise:
galaxy and kappa field have a contribution from noise, which is taken into account.

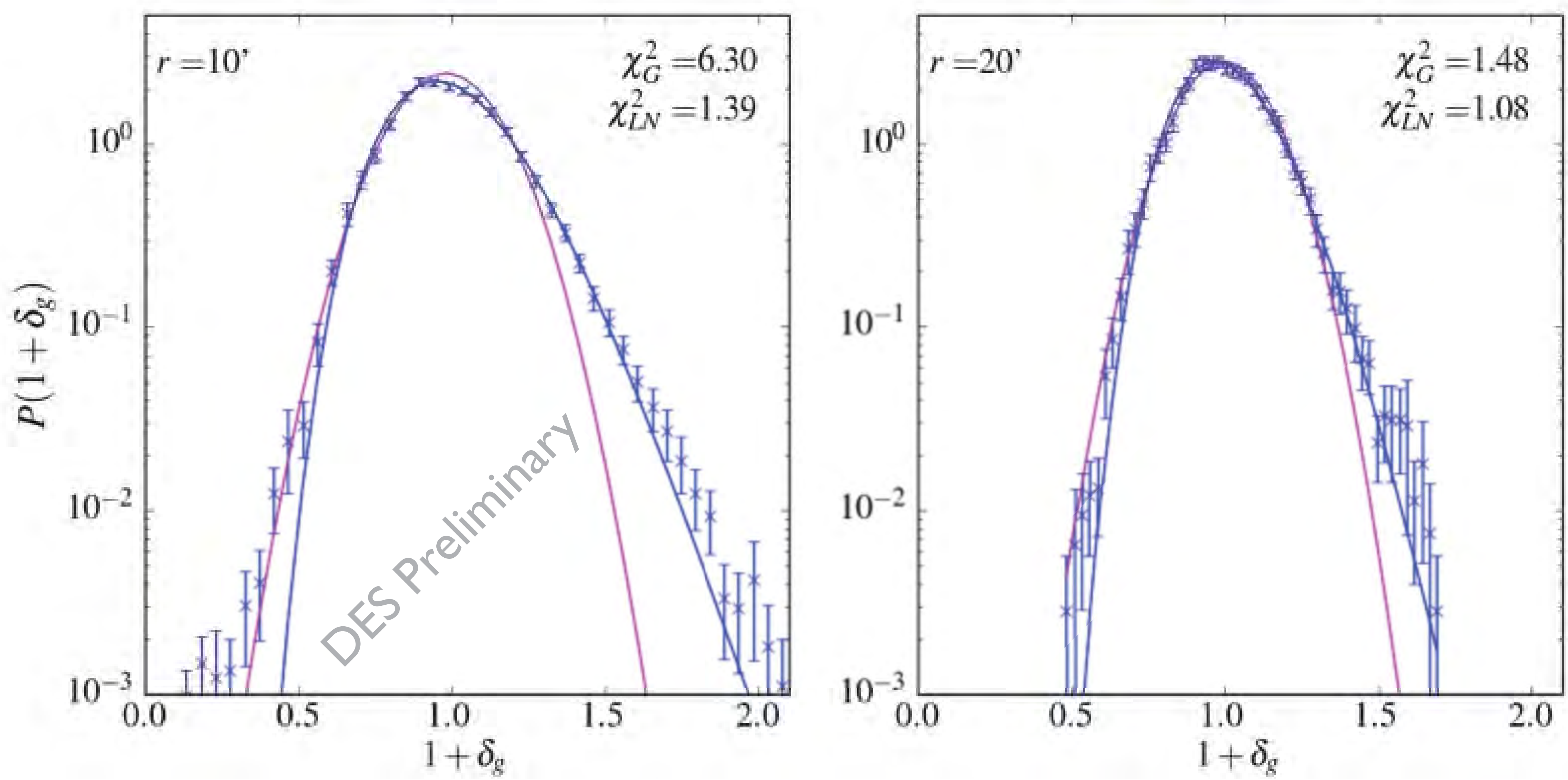
$$P(\kappa) = \frac{1}{\sqrt{2\pi}\sigma} \int_{-1}^{\infty} \exp\left[-\frac{(\kappa-\kappa')^2}{2\sigma^2}\right] f(\kappa) d\kappa'$$

shape noise

$$P(N) = \int_{-1}^{\infty} \frac{\bar{N}^N (1+\delta)^N}{N!} e^{-\bar{N}(1+\delta)} f(\delta) d\delta$$

shot-noise

Log-normal galaxy fits as a function of scale

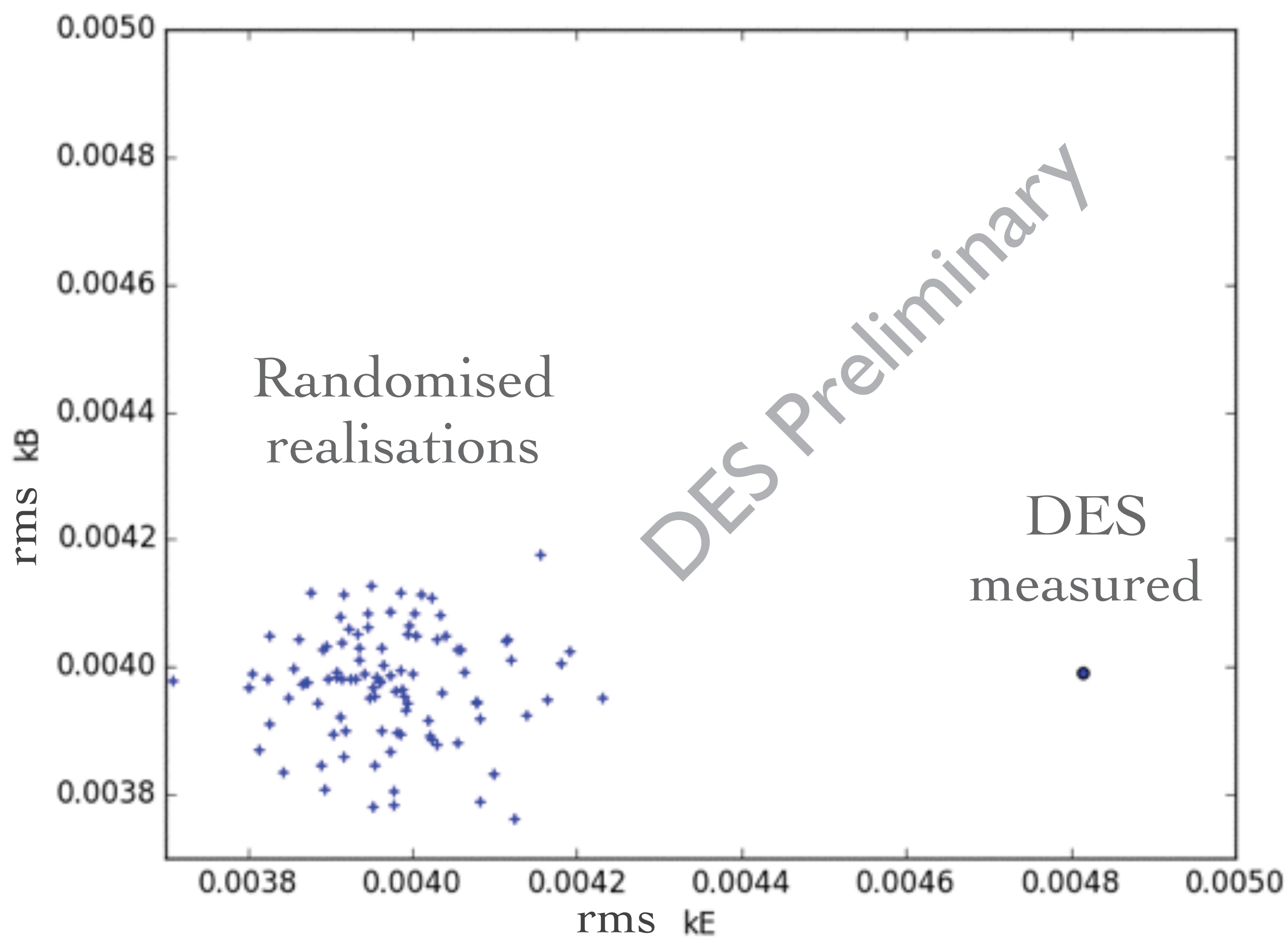


The distribution of galaxies becomes more gaussian as the counts in cells radius increases.

Clerkin, Kirk, MM, Lahav et al. (in prep)

10' -> 4.6 Mpc @ z=0.8

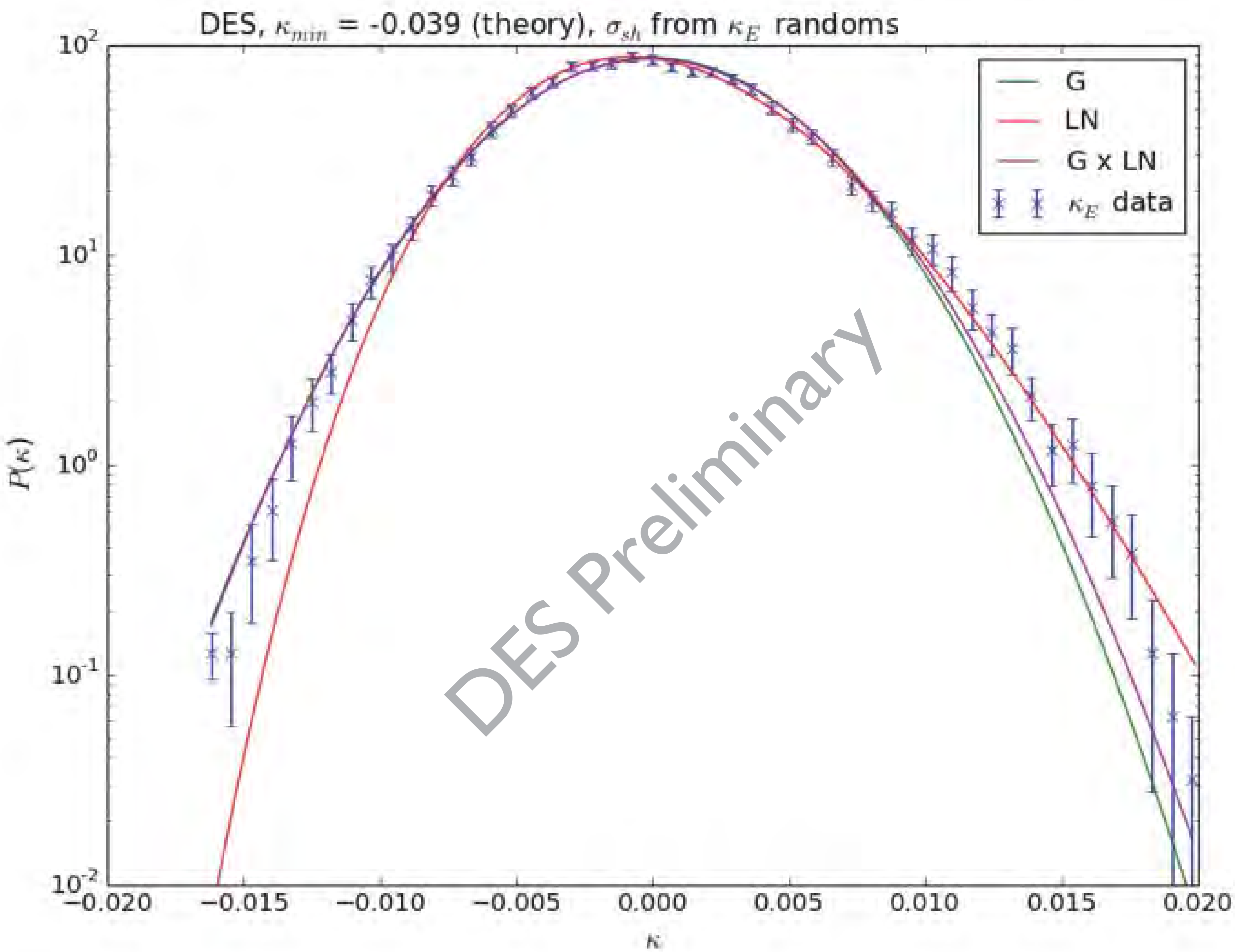
Noise contribution to kappa



$$P(\kappa) = \frac{1}{\sqrt{2\pi}\sigma} \int_{-1}^{\infty} \exp\left[-\frac{(\kappa - \kappa')^2}{2\sigma^2} \right] f(\kappa) d\kappa'$$

- The noise contribution to the kappa maps is evaluated from 100 realisations where the shear was randomised.
- Both kB and the mean of random kE maps give the same result. This is a test for observational systematics

Noise contribution to kappa



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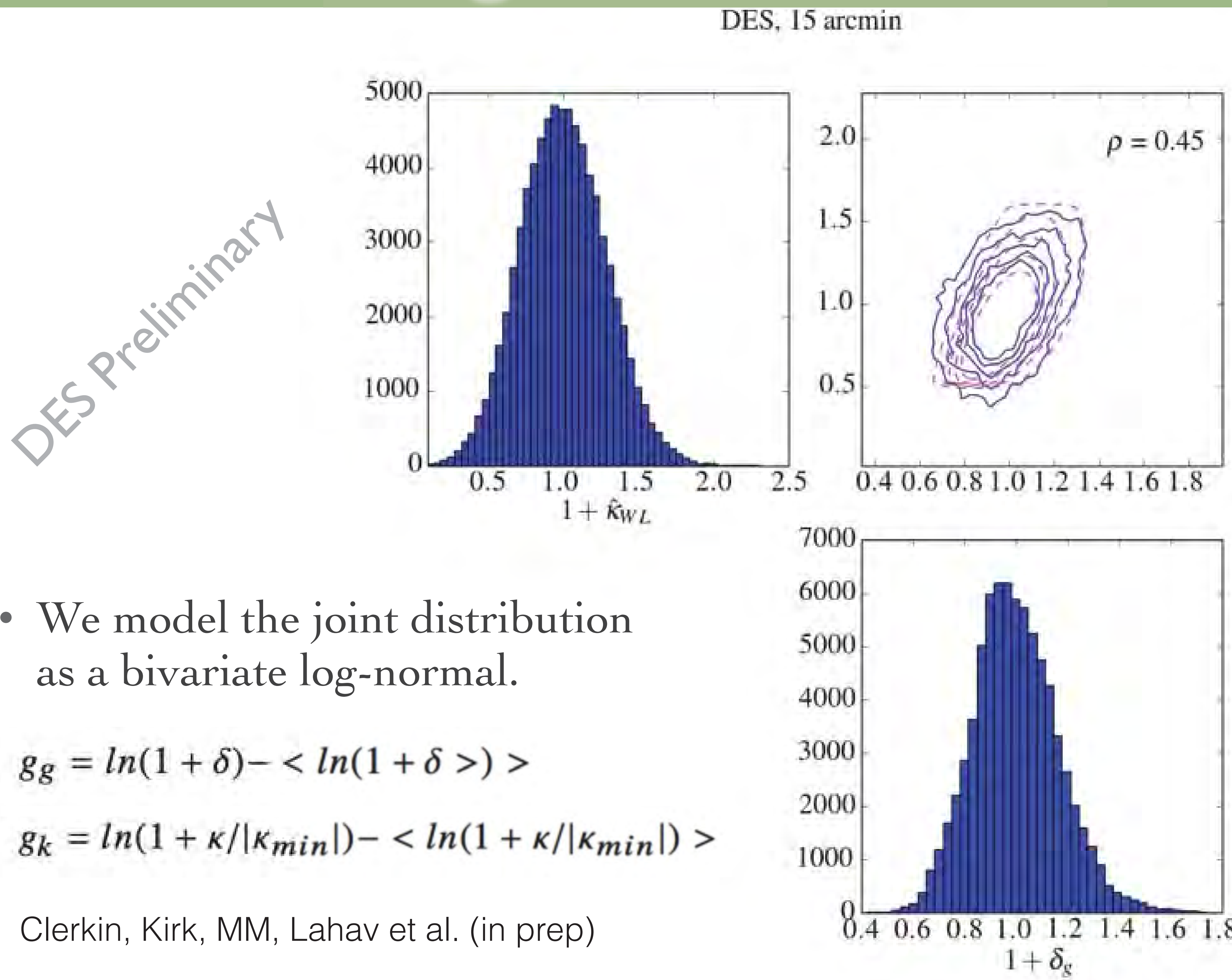
Log-normal fits



- We model the joint distribution as a bivariate log-normal.

$$g_g = ln(1+\delta) - < ln(1+\delta >) >$$

$$g_k = ln(1+\kappa/|\kappa_{min}|) - < ln(1+\kappa/|\kappa_{min}|) >$$

Clerkin, Kirk, MM, Lahav et al. (in prep)

Bias from different estimators

The relationship between galaxies and the underlying field is a complex, non-local, non-linear, stochastic phenomenon that depends also on environment and history.

$$\delta_g(x) = F[\delta(x)] = b_1\delta(x) + \frac{1}{2}b_2\delta_g^2(x) + \cdots$$

simplification: linear and local bias $\delta_g(x) = b\delta(x)$

* Bias from 1-point statistics : eg., lensing kappa

$$\kappa(\theta, r) = \frac{3H_0^2\Omega_m}{r}\int_0^r dr' \frac{r'(r-r')}{r}\frac{\delta(\theta, r')}{a(r')} \qquad \kappa_g(\theta, r) = \frac{3H_0^2\Omega_m}{r}\int_0^r dr' \frac{r'(r-r')}{r}\frac{\delta_g(\theta, r')}{a(r')}$$

* Bias from 2-point statistics : eg., galaxy clustering

$$\xi_g(r) =< \delta_g\delta_g >= b^2 < \delta\delta >= b^2\xi(r)$$

Bias from different estimators

$$\delta_g(x) = F[\delta(x)] = b_1\delta(x) + \frac{1}{2}b_2\delta_g^2(x) + \cdots$$

simplification: linear bias $\delta_g(x) = b\delta(x)$

Bias from comparing lensing and galaxies integrated on the line of sight:

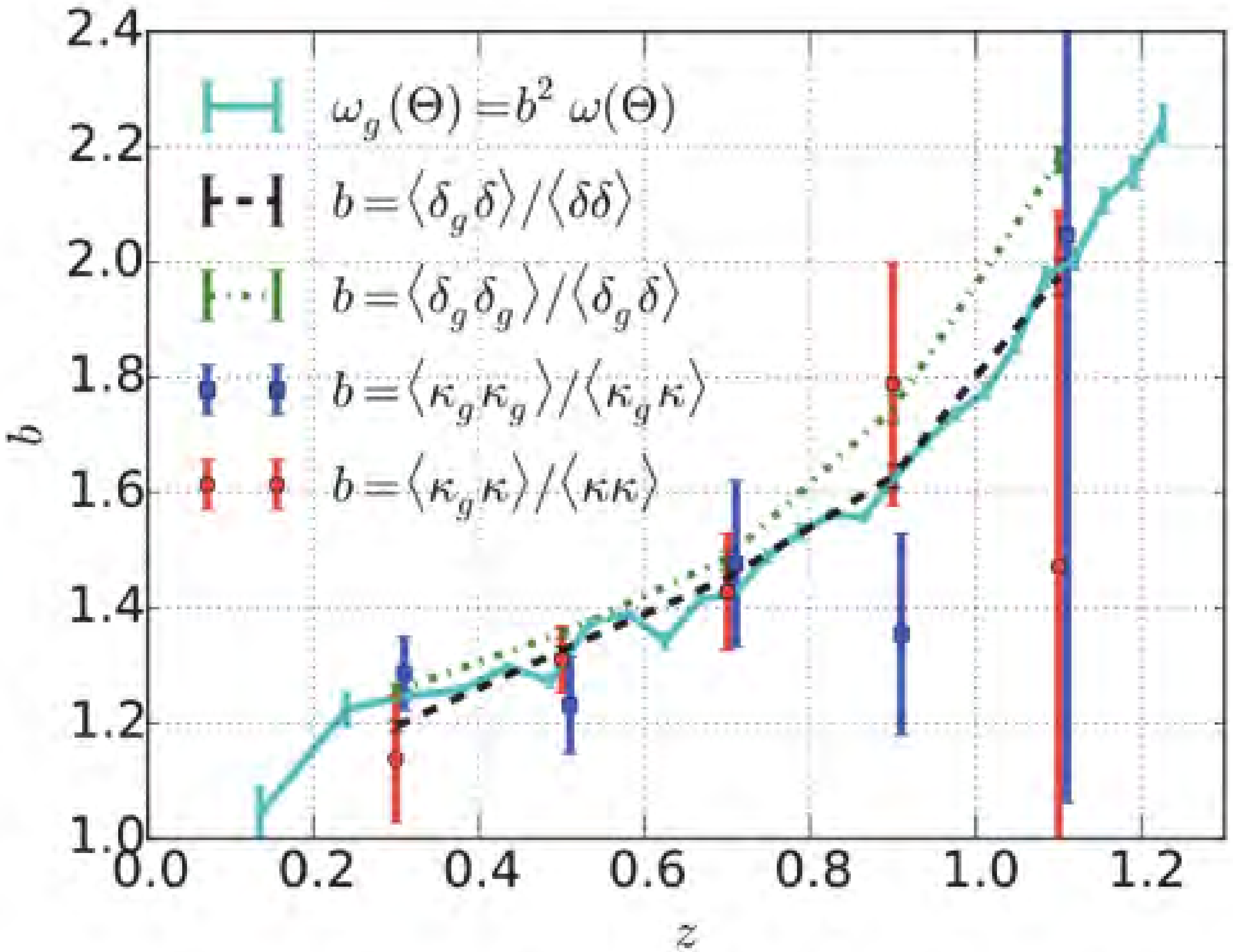
$$\kappa(\theta, r) = \frac{3H_0^2\Omega_m}{r}\int_0^r dr' \frac{r'(r-r')}{r}\frac{\delta(\theta, r')}{a(r')}$$

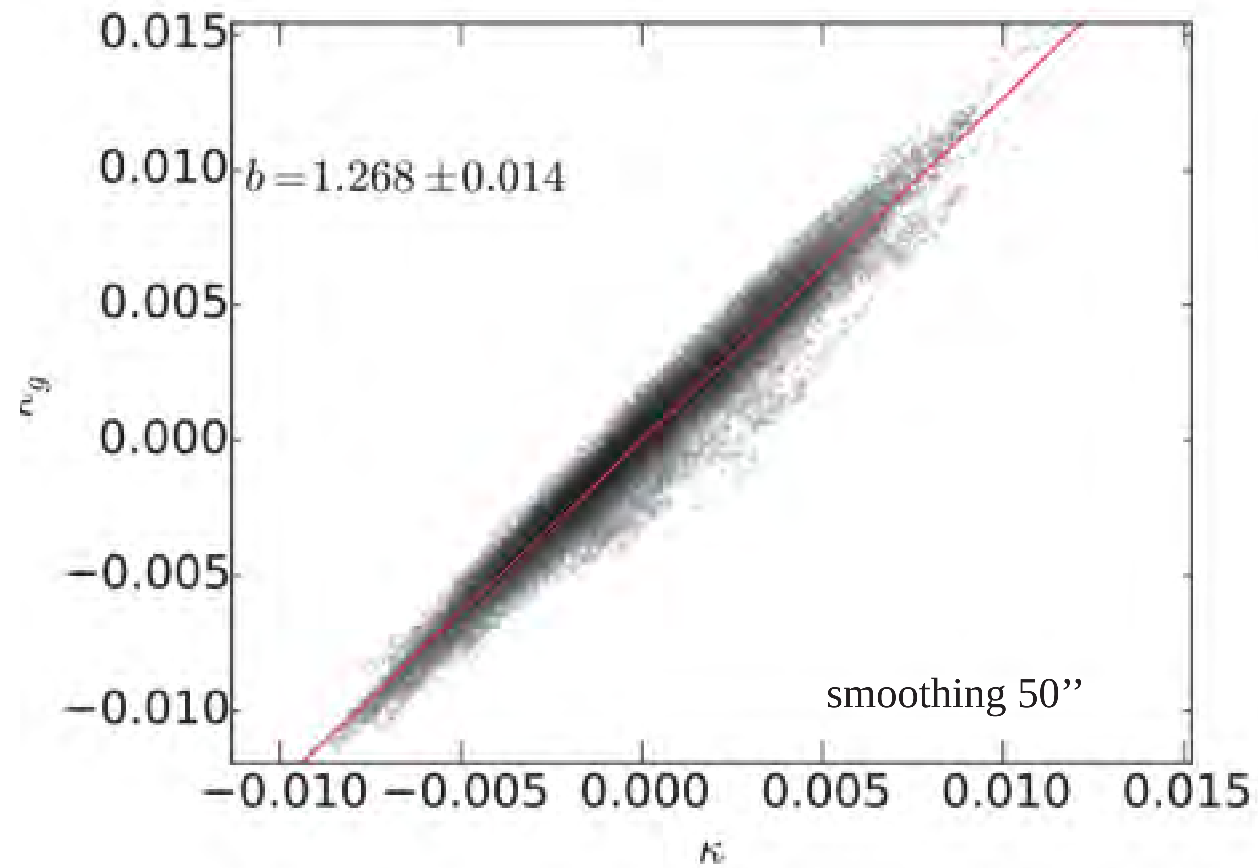
$$\kappa_g(\theta, r) = \frac{3H_0^2\Omega_m}{r}\int_0^r dr' \frac{r'(r-r')}{r}\frac{\delta_g(\theta, r')}{a(r')}$$

Bias from correlation of galaxies comparing with theory

$$\xi_g(r) =< \delta_g\delta_g >= b^2 < \delta\delta >= b^2\xi(r) \qquad w_g(\theta) = b^2\, w(\theta)$$

Bias from simulations

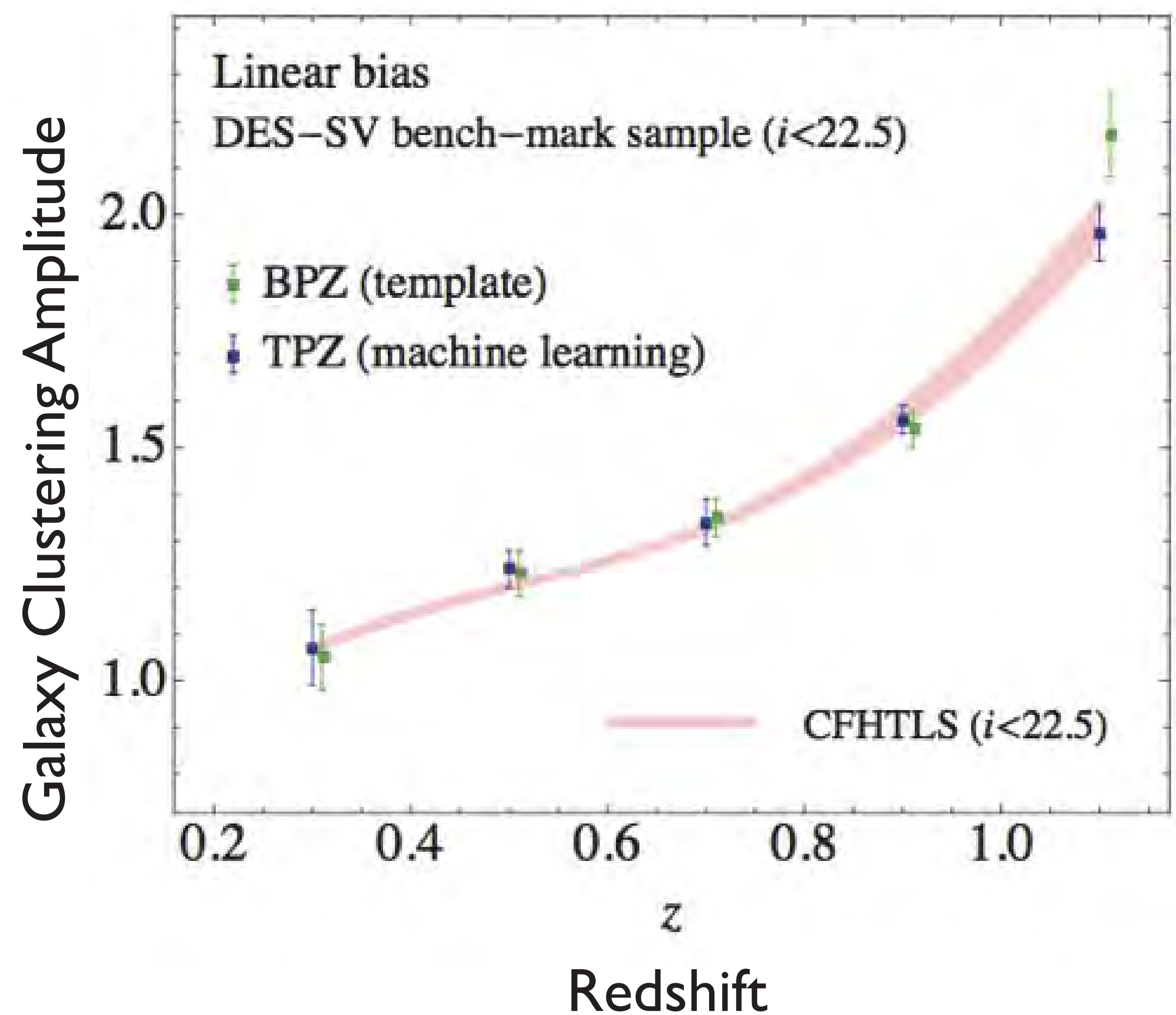




Pujol et al. 2015 arXiv:1601.00160

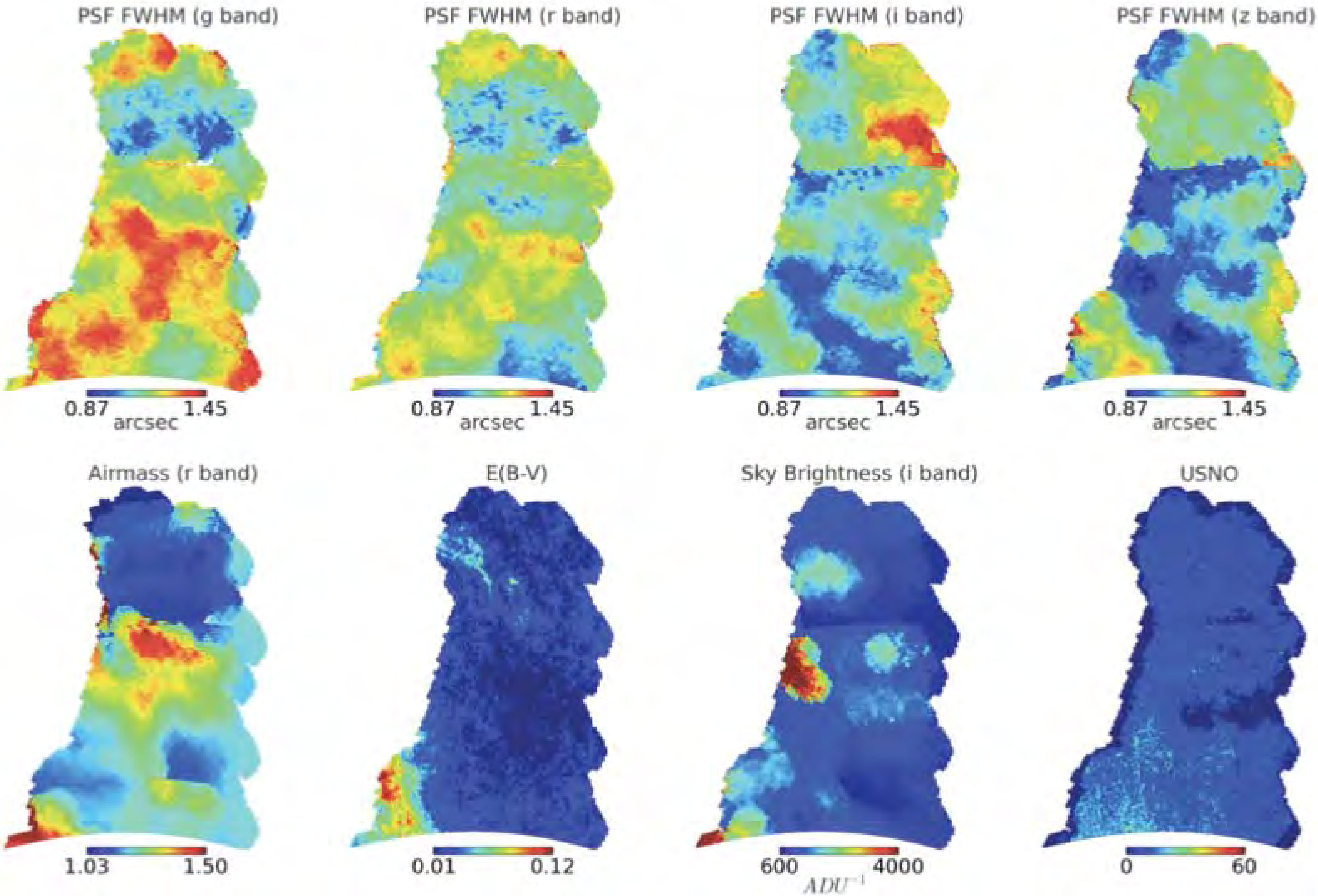
Bias from 2-point correlation

- Clustering measured in Science Verification data (~130 deg^2)
- Compares well to state of the art at same sensitivity
- (Thorough investigation of systematics)



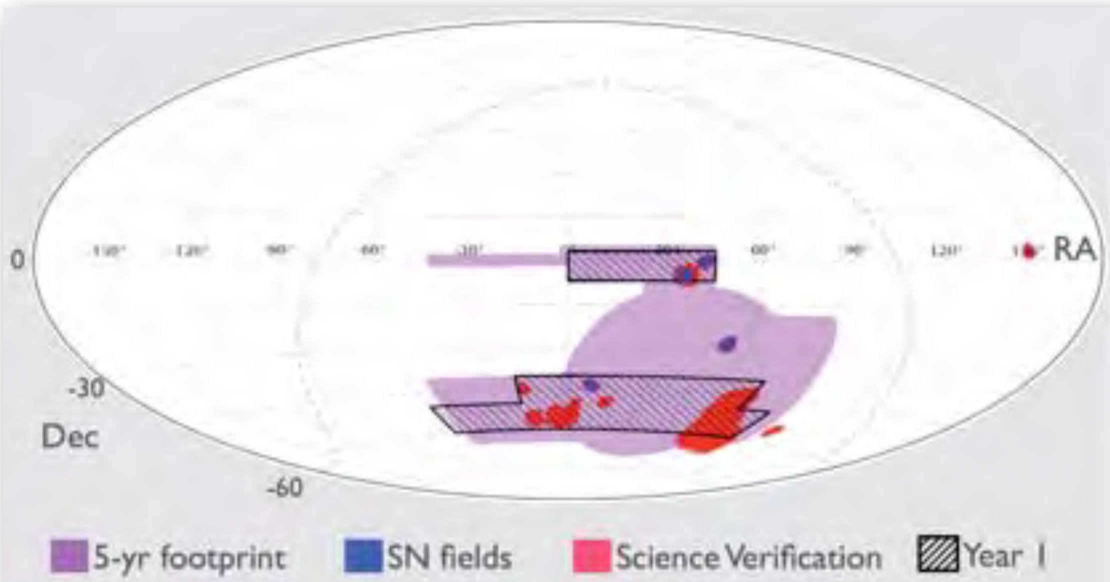
Crocce et al. 2015 MNRAS 455

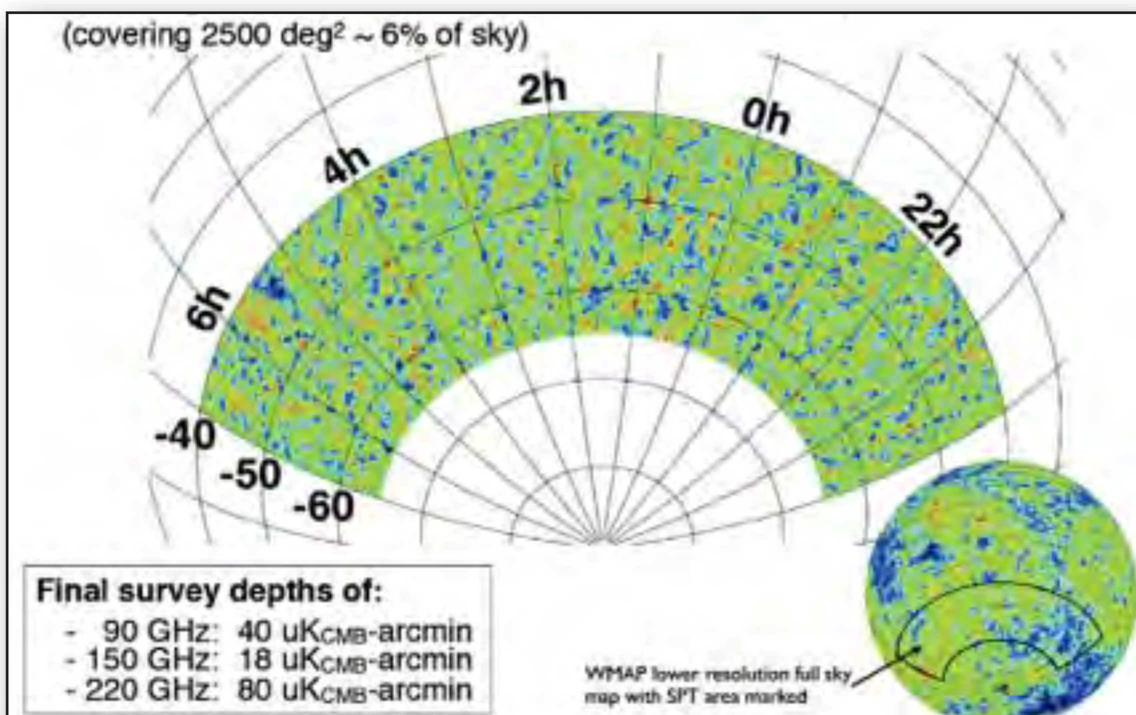
Systematics

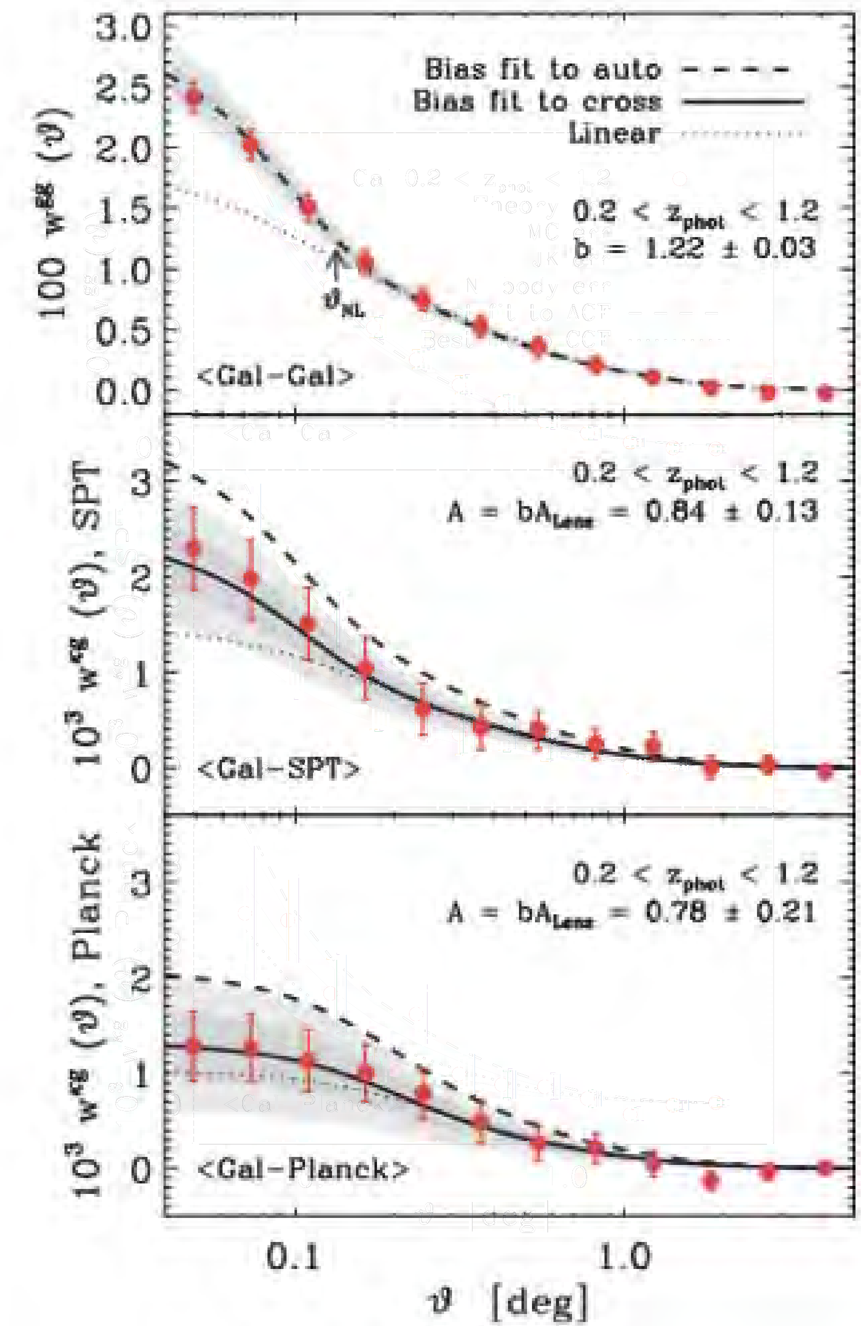


Crocce et al. (2015), Leisted et al. (2015) Suchyta et al. (2015)

Bias from CMB x DES



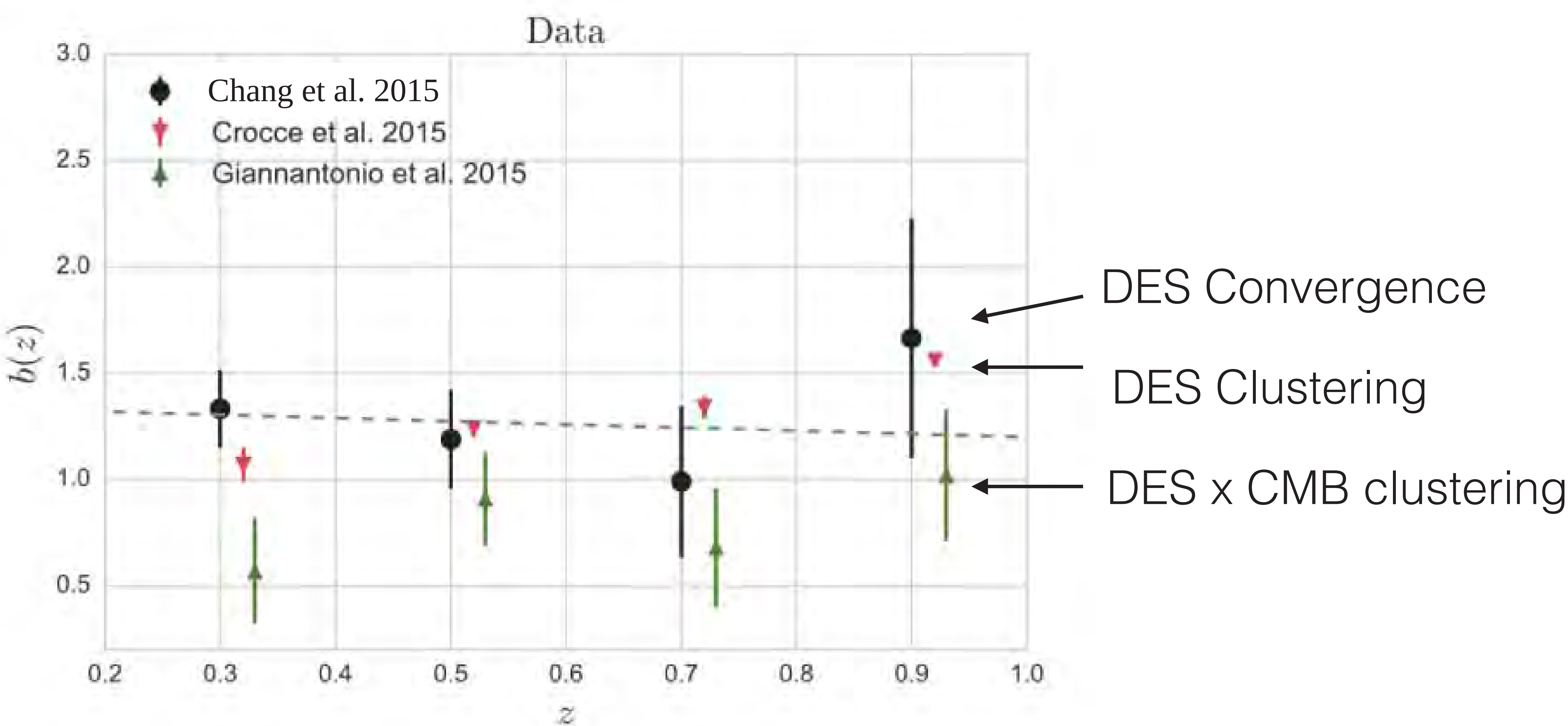




Giannantonio, Fosalba 2016 MNRAS 456

(also evolution in redshift)

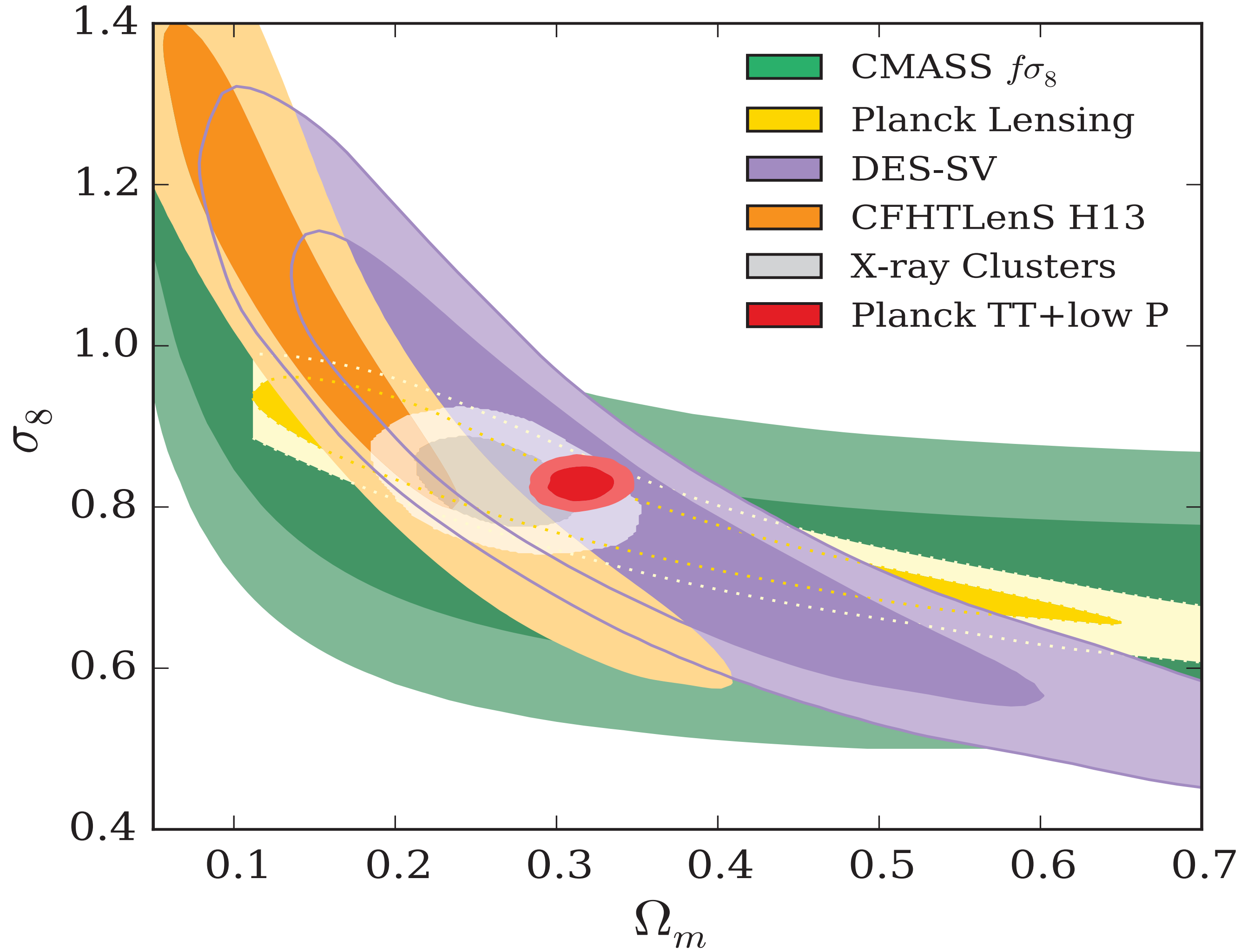
Bias comparison

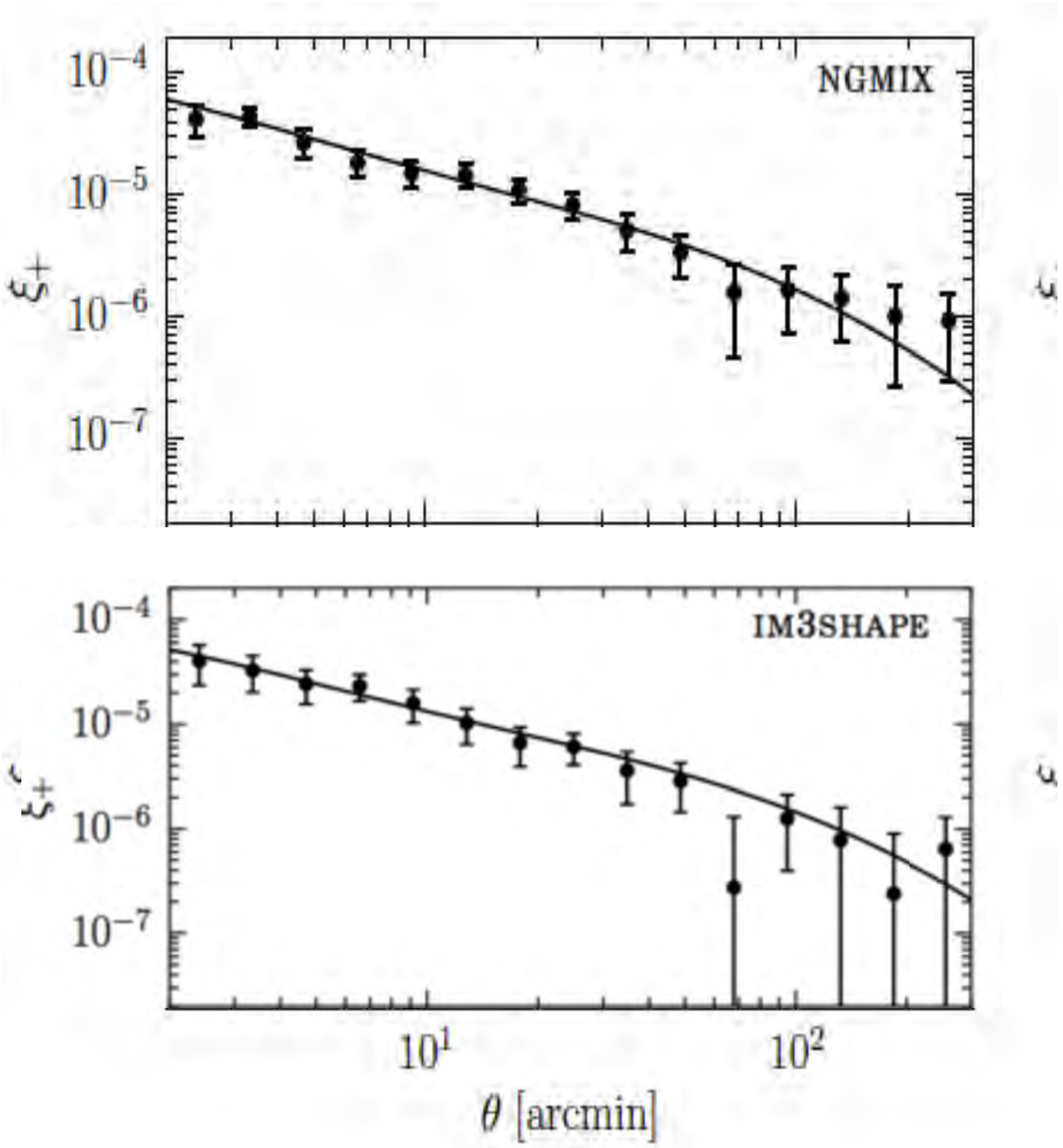


Chang et al. 2016 arXiv:1601.00450

Only with SV Data

Cosmology with WL-2pf





Cosmological parameters

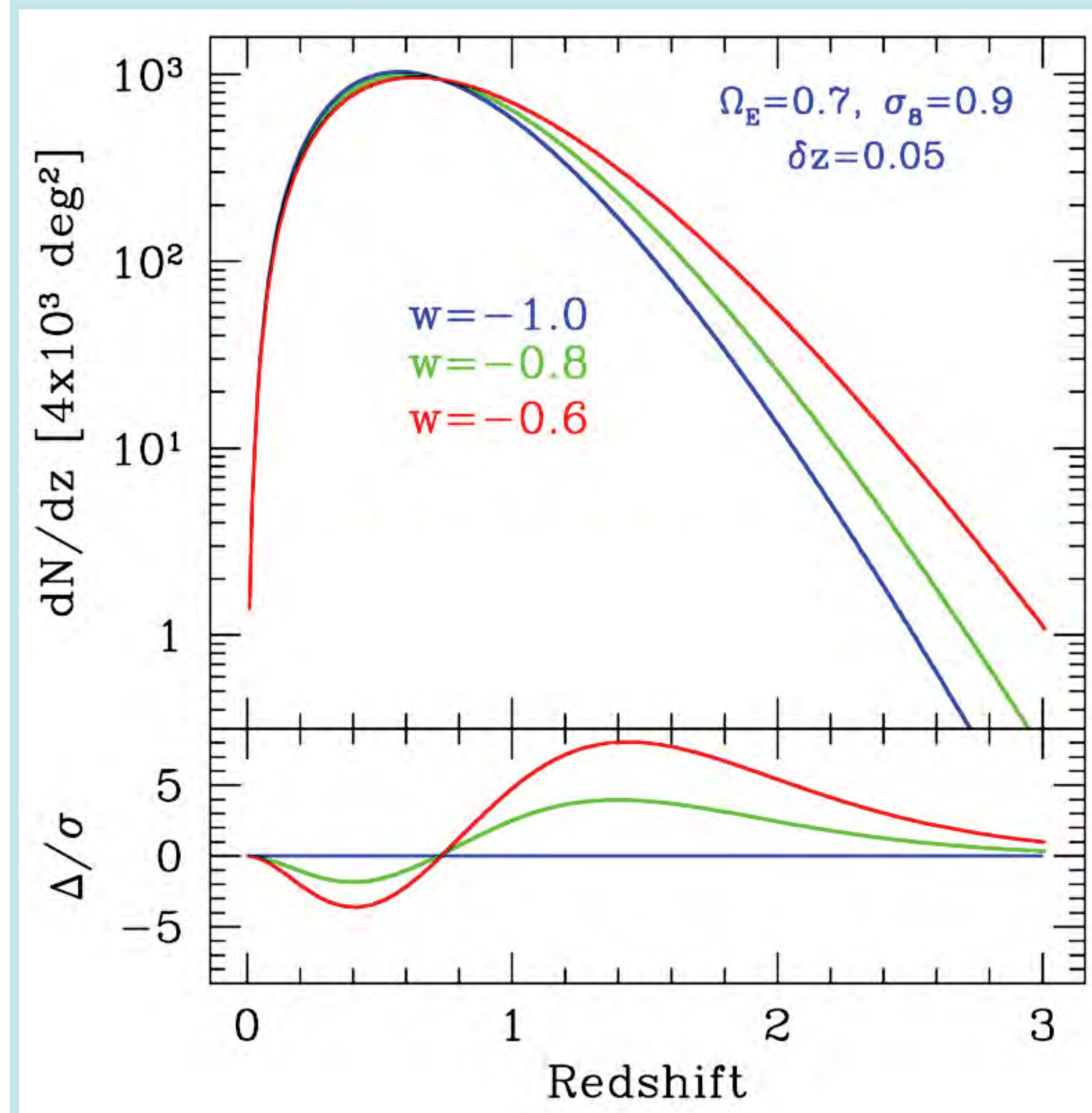
*The DES collaboration
(Bridle, McCrann, Zunz et al.)

Becker et al. astroph 2015,
Jarvis et al. arXiv 2015

2pt xi (+-) from two shear pipelines

Clusters

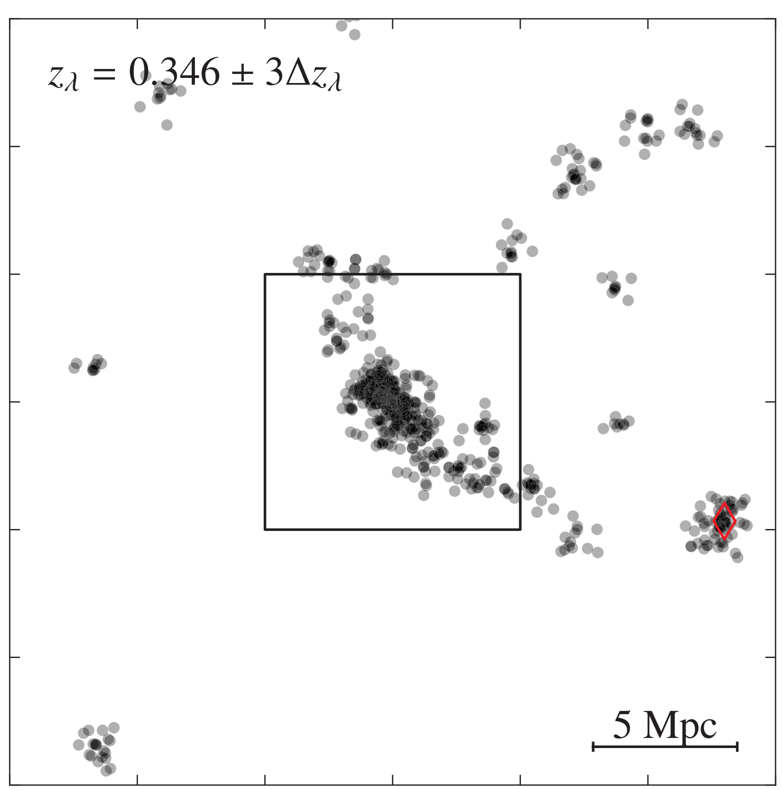
- ✦ Number of clusters as function of redshift sensitive to DE
- ✦ Accurate Mass calibration and redshift determination is vital

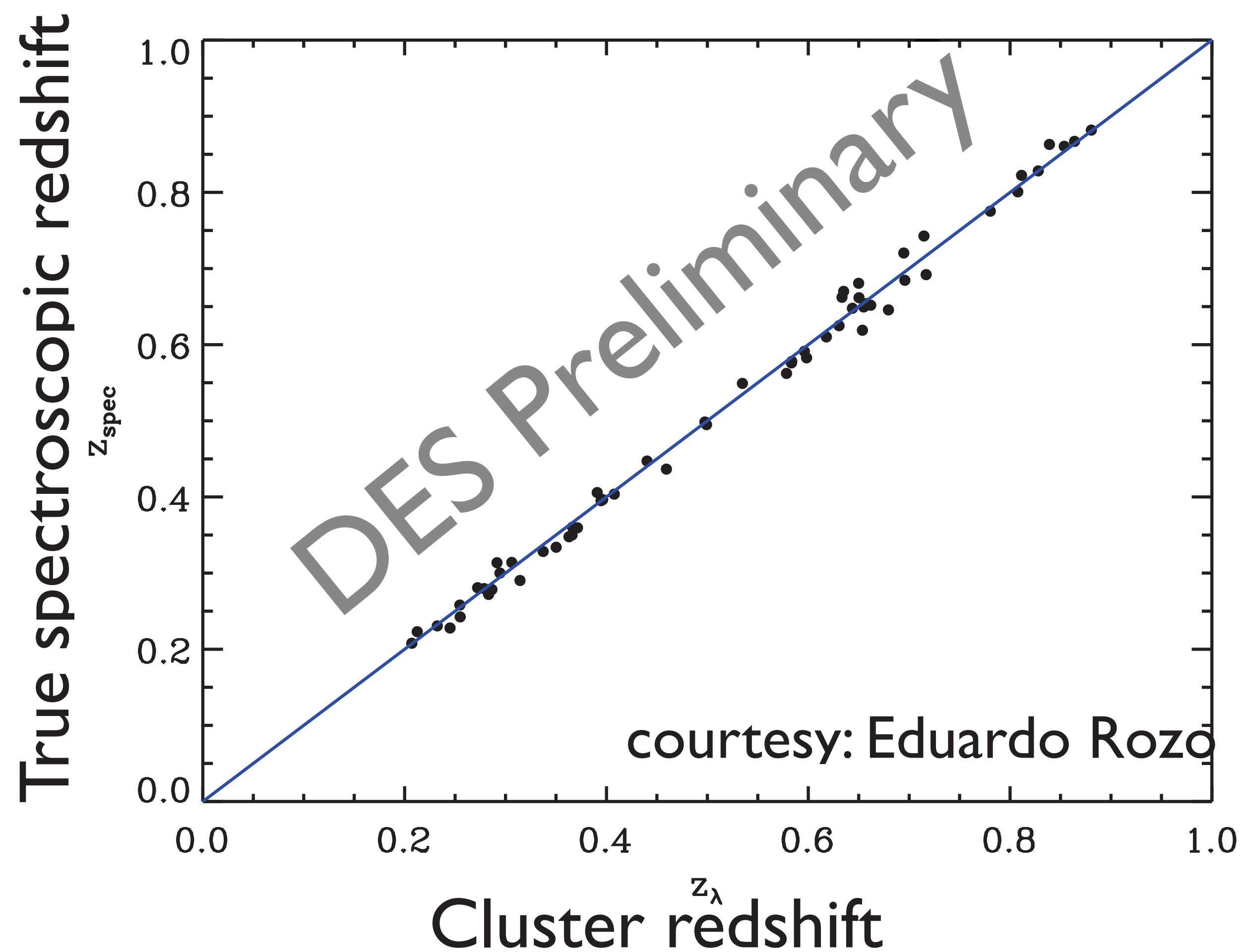


Number of clusters above $10^{14.5}$ solar masses, for a 4000 deg^2 survey

DES Clusters: redshift calibration

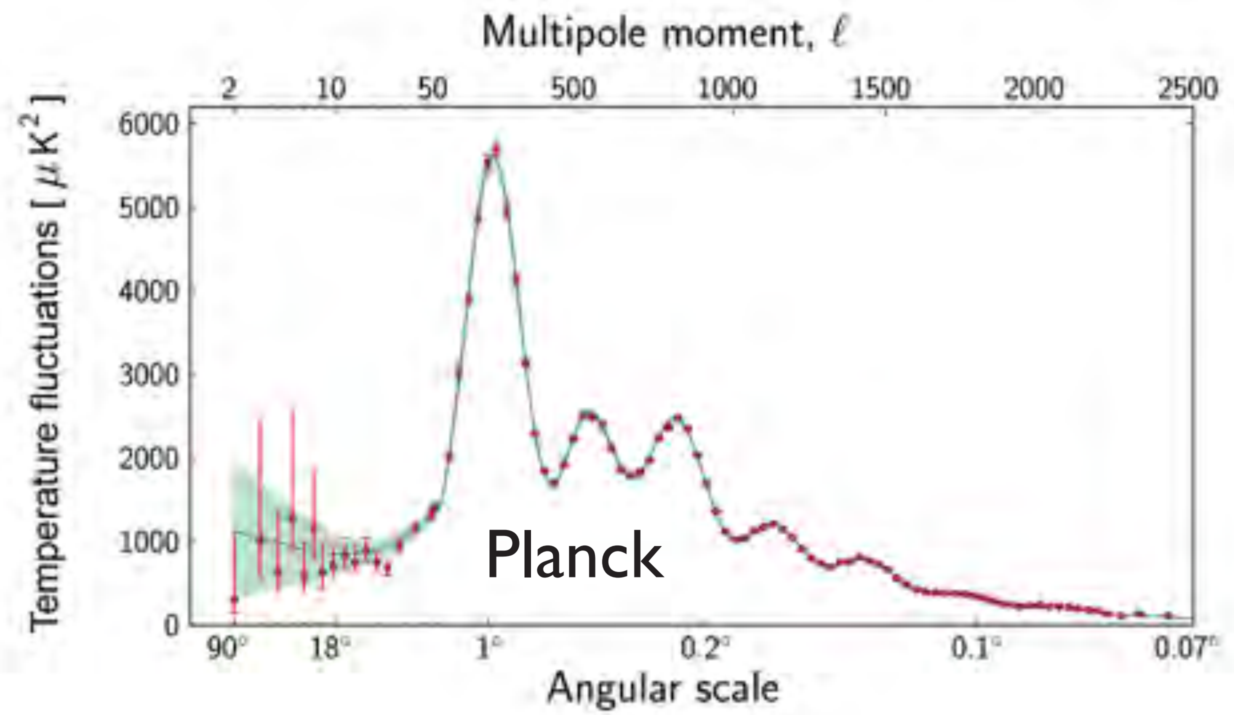
- 1% redshift accuracy
- Cluster cosmology should follow once we complete mass calibration

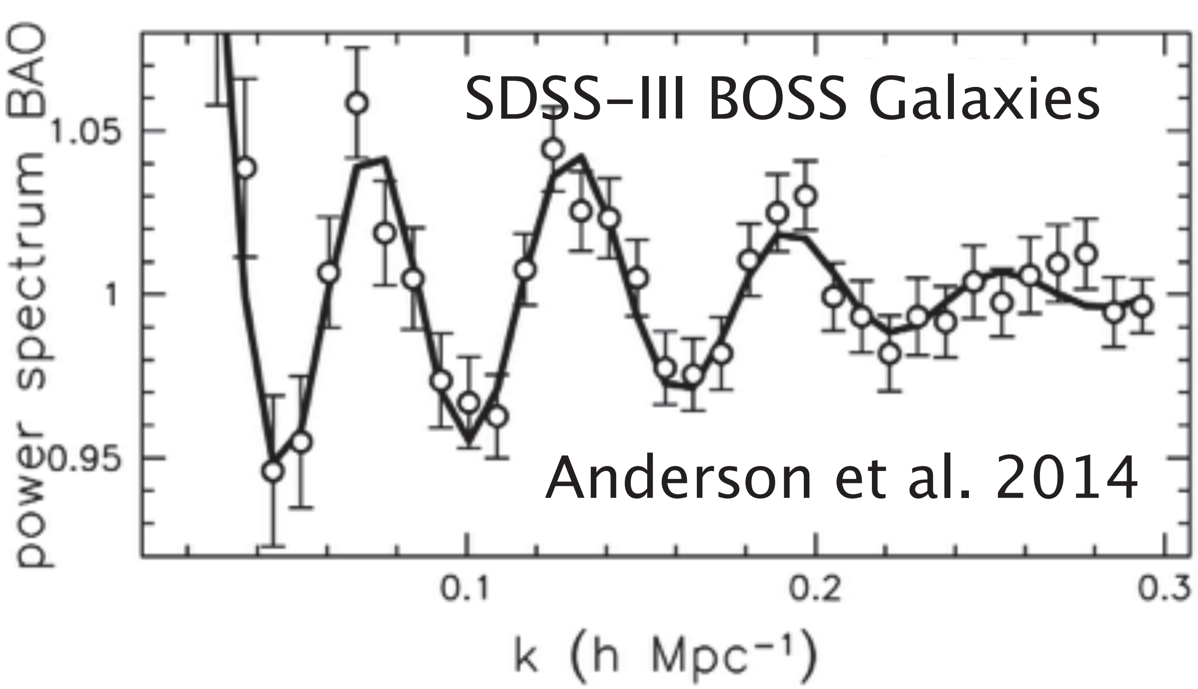


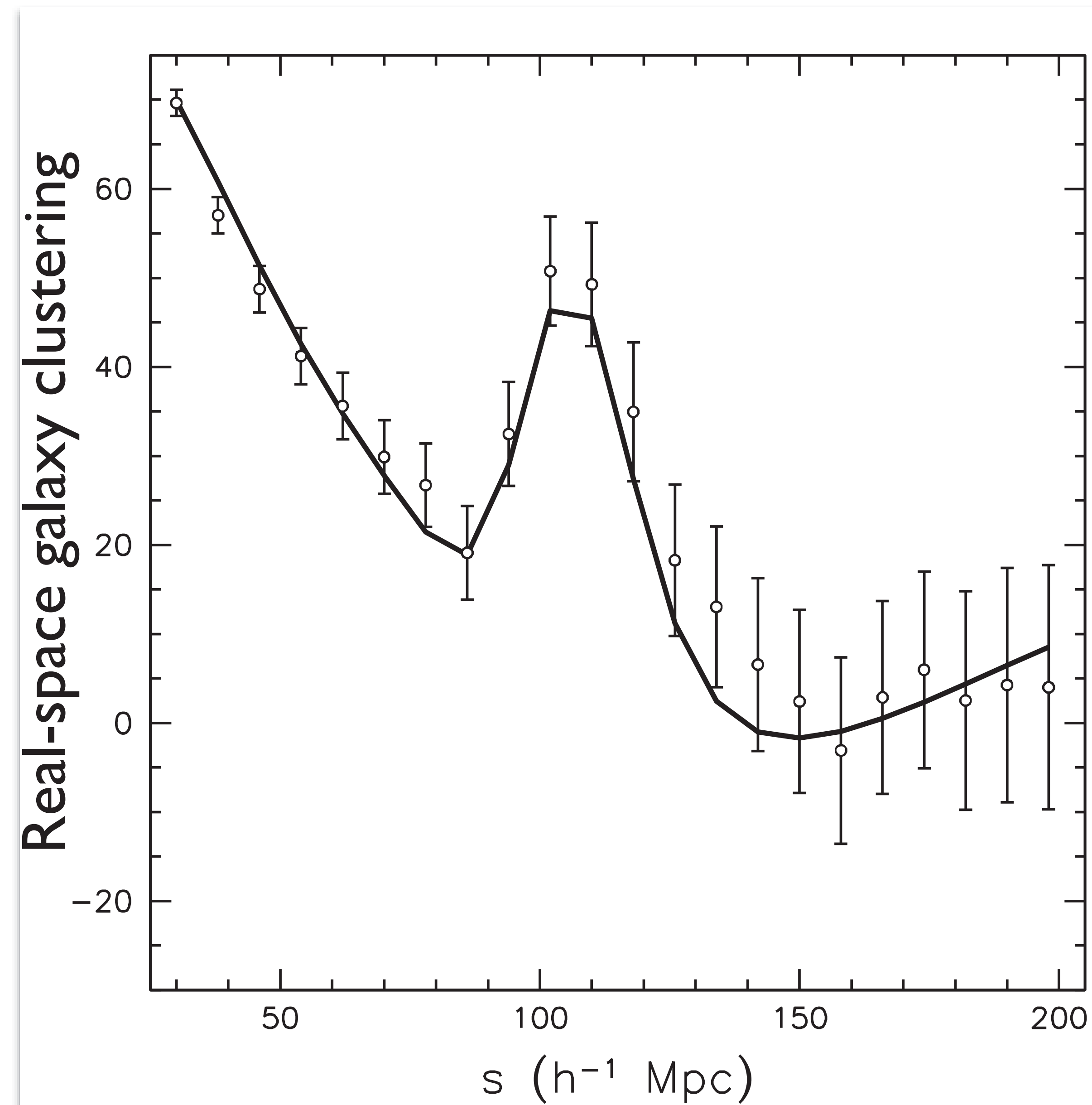


Large Scale Structure

- baryon acoustic oscillation feature gives "standard ruler", calibrated by CMB

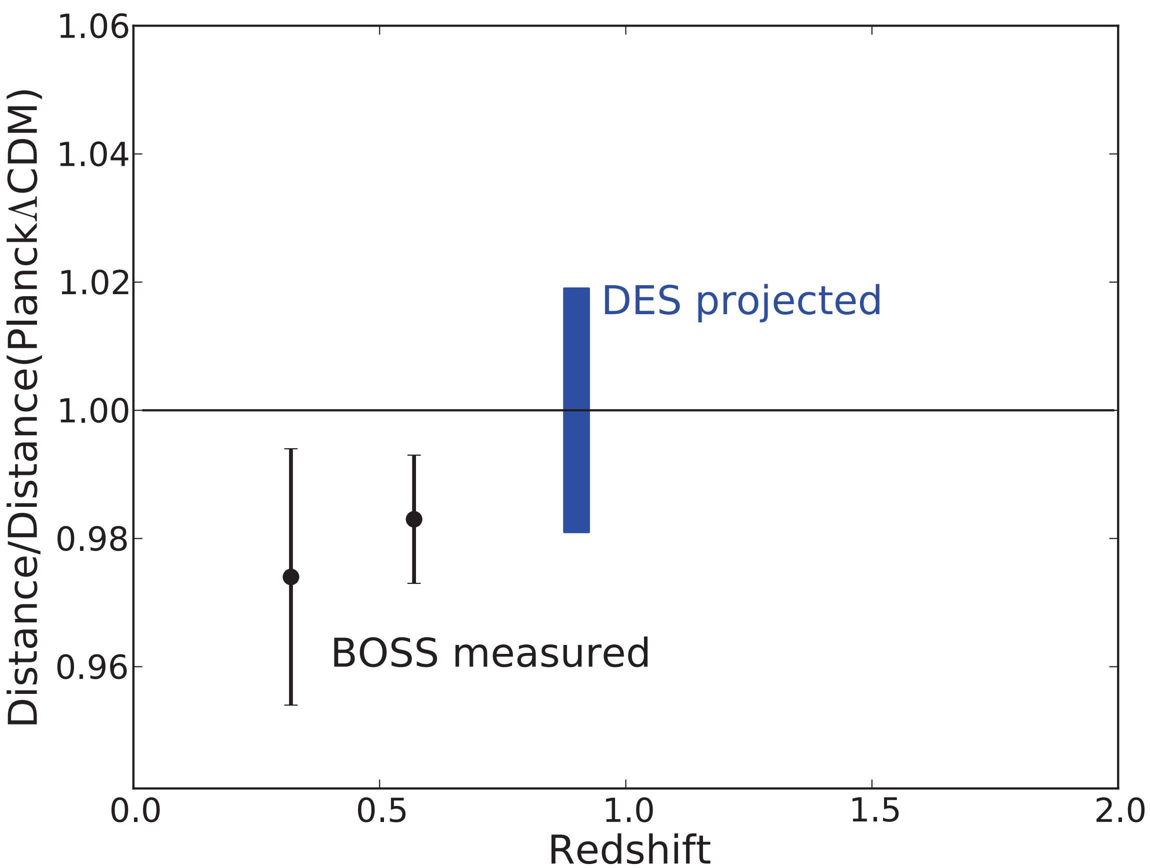


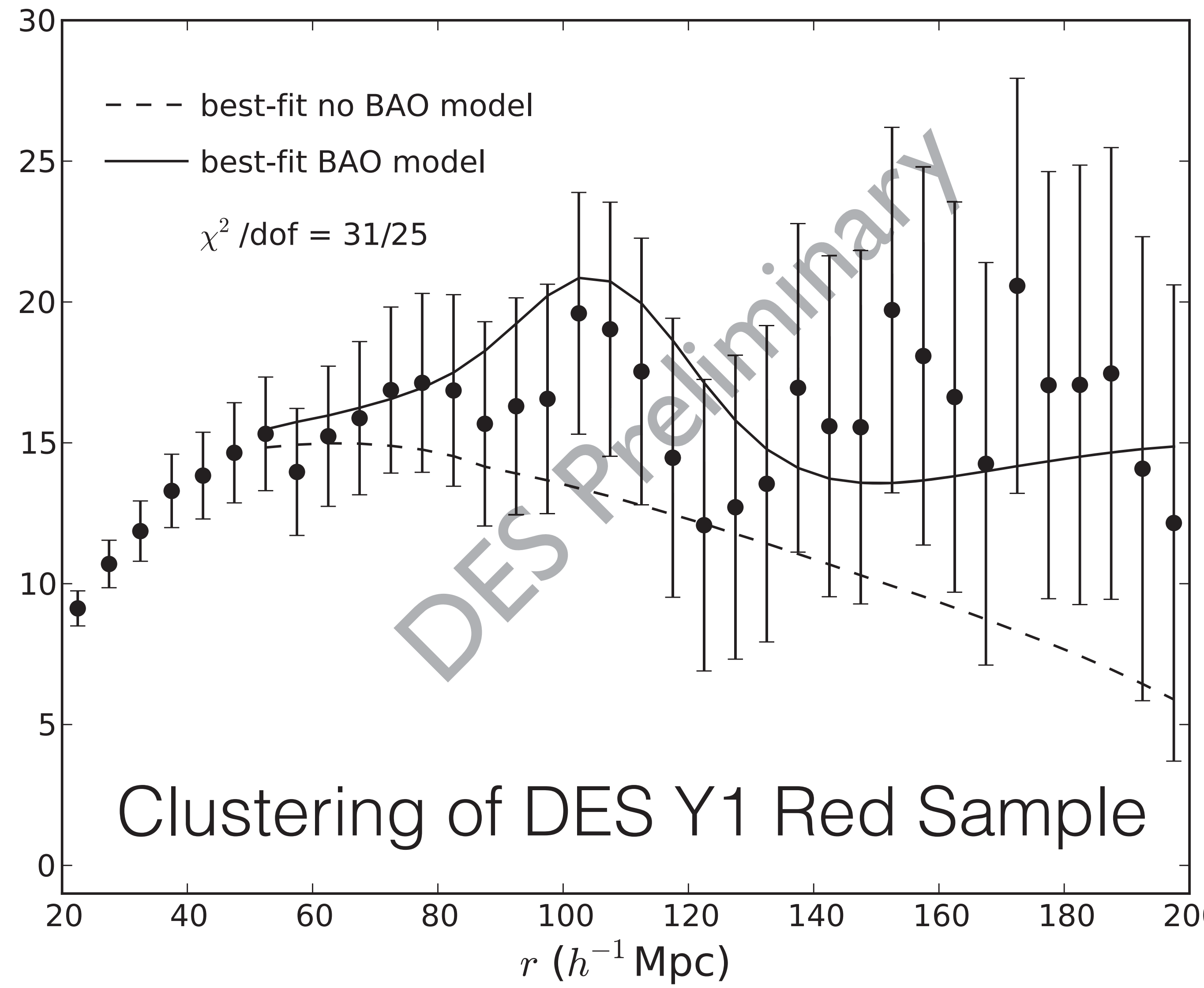




Large Scale Structure

✦ BAO extrapolation based on current data:





✦ Very preliminary
✦ Very encouraging

✦ Plot: 3D clustering, weighted heavily to transverse pairs
✦ Yielding better than 4% BAO measurement

Credit: Ashley Ross

OUTLINE: DES & First Results

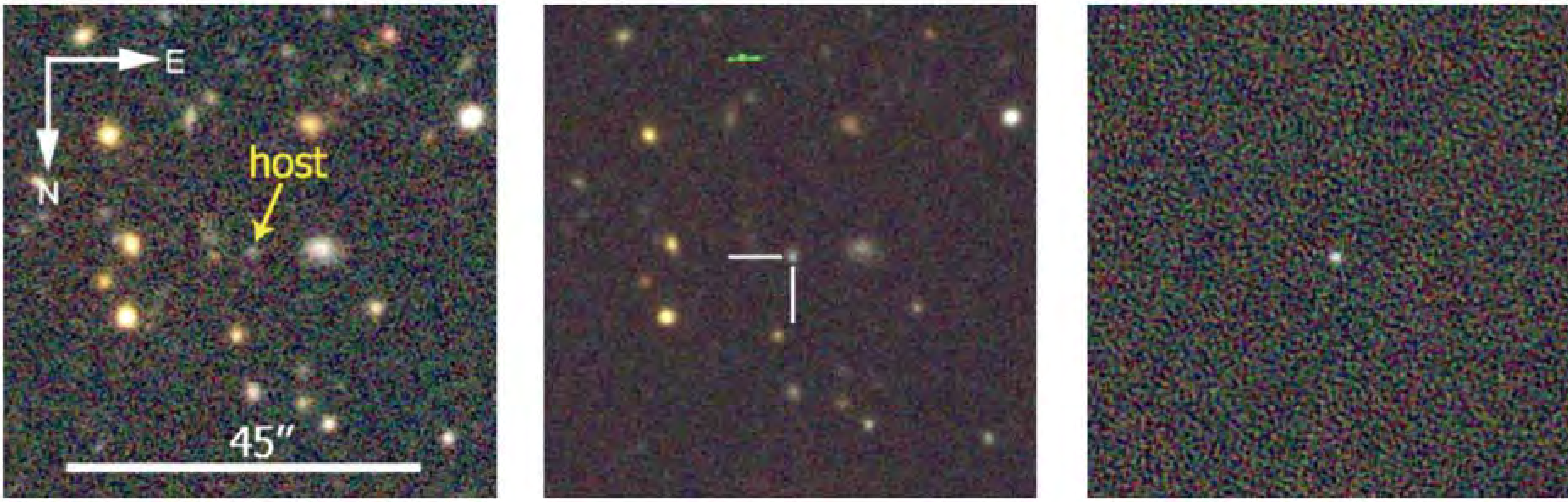
- The Dark Energy Survey
  - Telescope
  - Camera
  - Observing status
- Dark Energy Science
  - Weak lensing
  - Galaxy clusters
  - Large-Scale Structure
  - Supernovae
- non Dark Energy Science
  - Discoveries!

THE DARK ENERGY SURVEY

Results from Science Verification Data: SuperLuminous SuperNova

DARK ENERGY SURVEY

DES13S2cmm



Papadopoulos et al. 2015, Arxiv:1501.07232v2

- SLSN are 50 times brighter than typical SN.
- SLSN are rare objects. Only 14 are observed as well as this one.
- Spectroscopically confirmed SLSN with $z = 0.663 \pm 0.001$
- Located in a faint, low metallicity, low stellar-mass host galaxy.

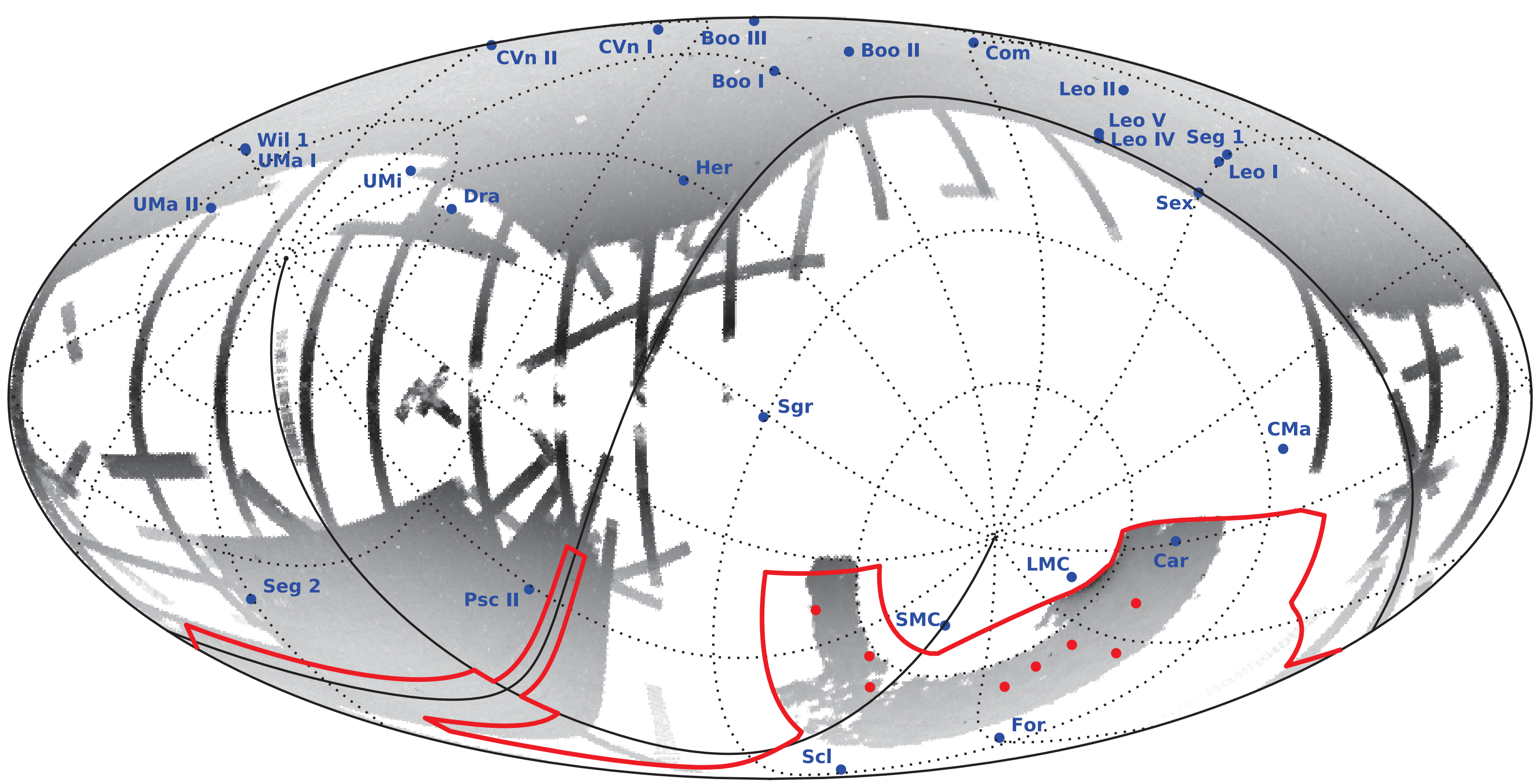
Milky Way Satellites

DARK ENERGY SURVEY

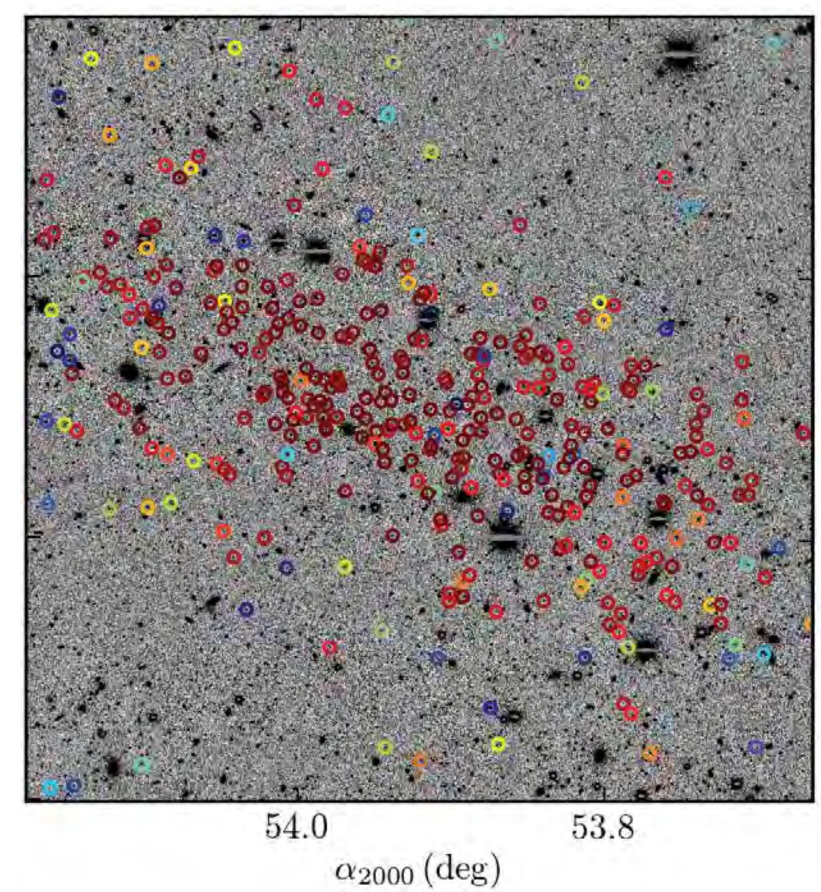
Bechtol et al. (2015)

- 8 new dwarf satellites!

Locations of Milky Way Satellites



DES J335.6

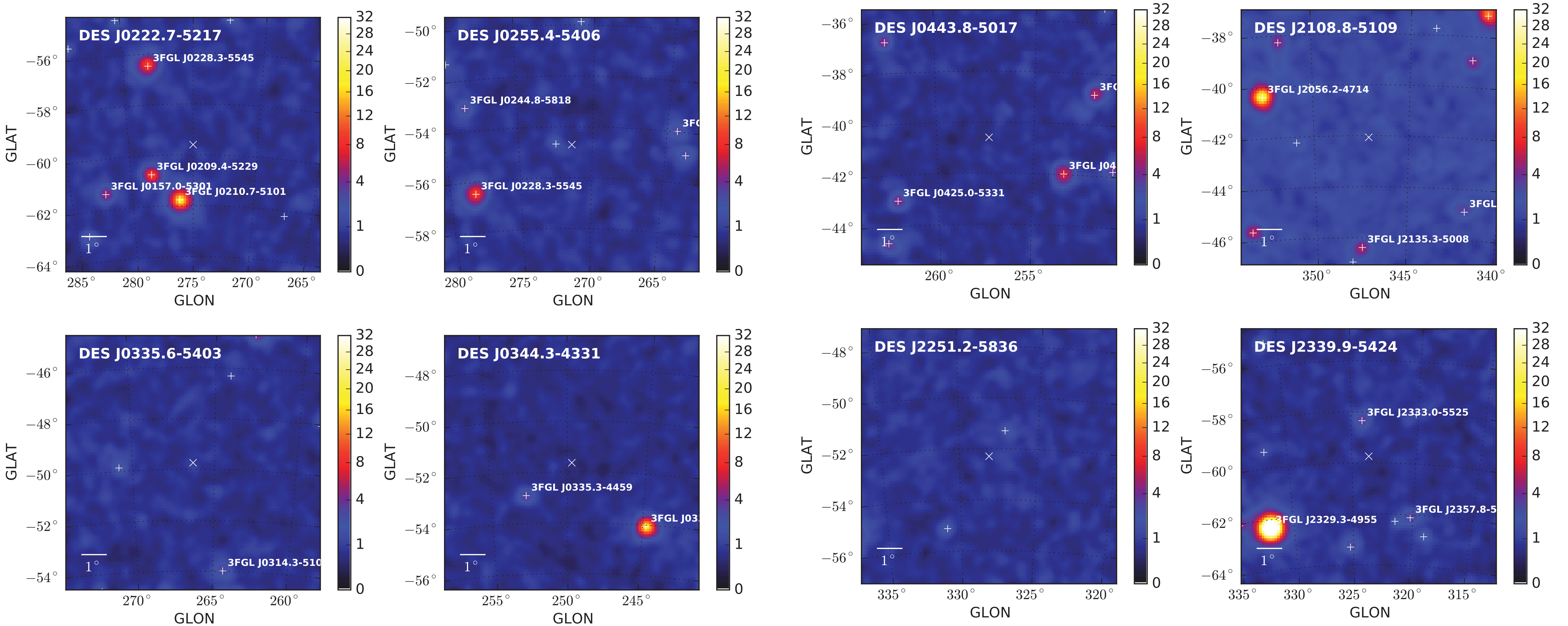


- From 1,800 deg^2 of optical imaging data (DES 1st year)
- Identified as statistically significant overdensity of stars

Milky Way Satellites

Drlica-Wagner et al. (2015)

- DES+Fermi LAT collaboration
- No detection of dark matter annihilation signature in gamma rays



OUTLINE

- Motivation
- The Dark Energy Survey & First Results
- Mock Galaxy Catalogues

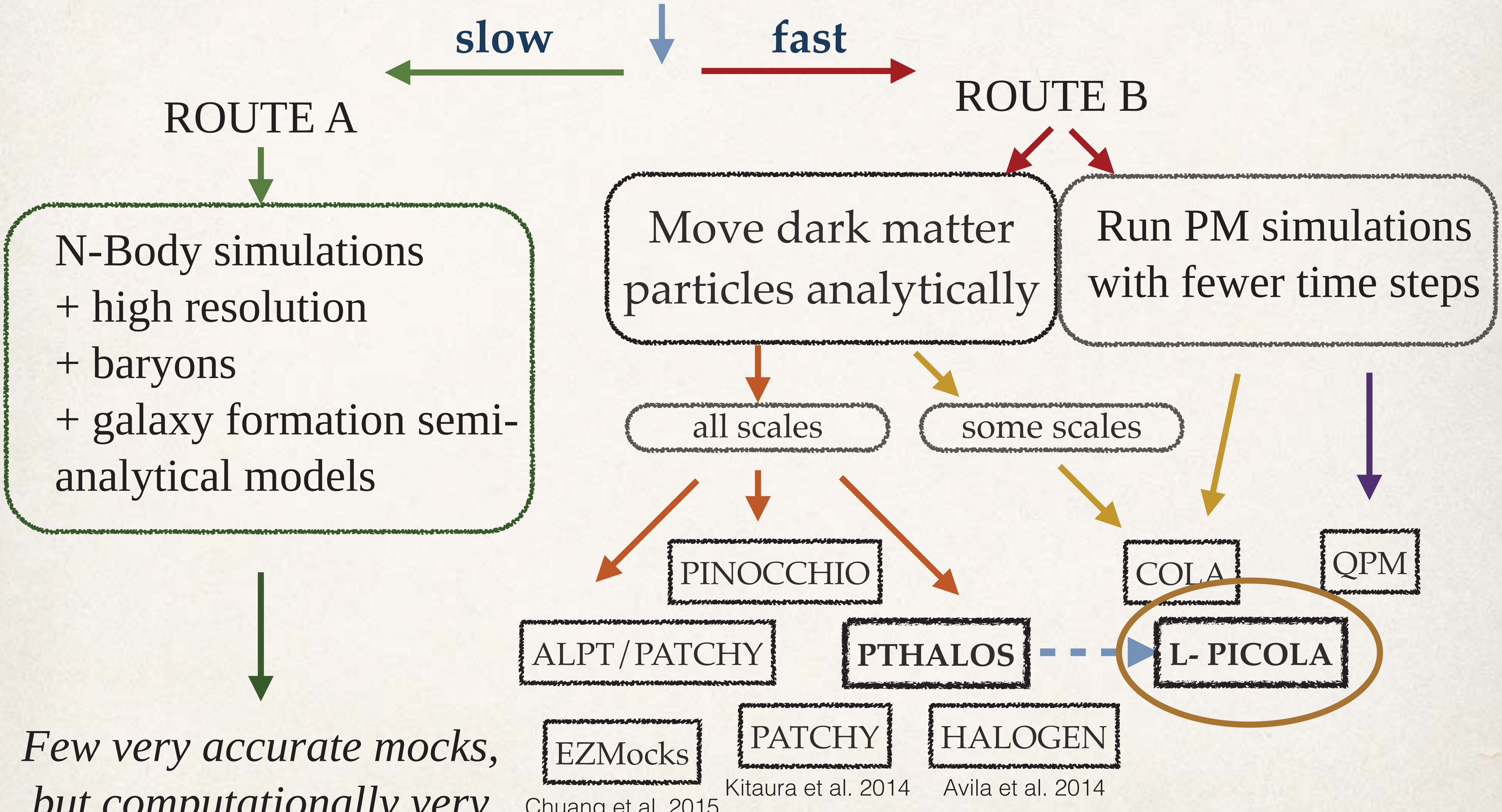
THE DARK ENERGY SURVEY

Why Mock Galaxy Catalogues?

- *Testing your pipelines*
- *Understanding Errors*
- *Computing covariances*

- *You know what has been included in the mocks, so one can work out what are the best estimators, and test systematics.*
- *As pipelines become complex they are more difficult to capture by theoretical modelling, and mocks are needed.*
- *Covariance matrix require a large number of realisations, the production of fast mock galaxy catalogues may provide them*
- *Large number of mocks allows for exploration of the parameter space.*

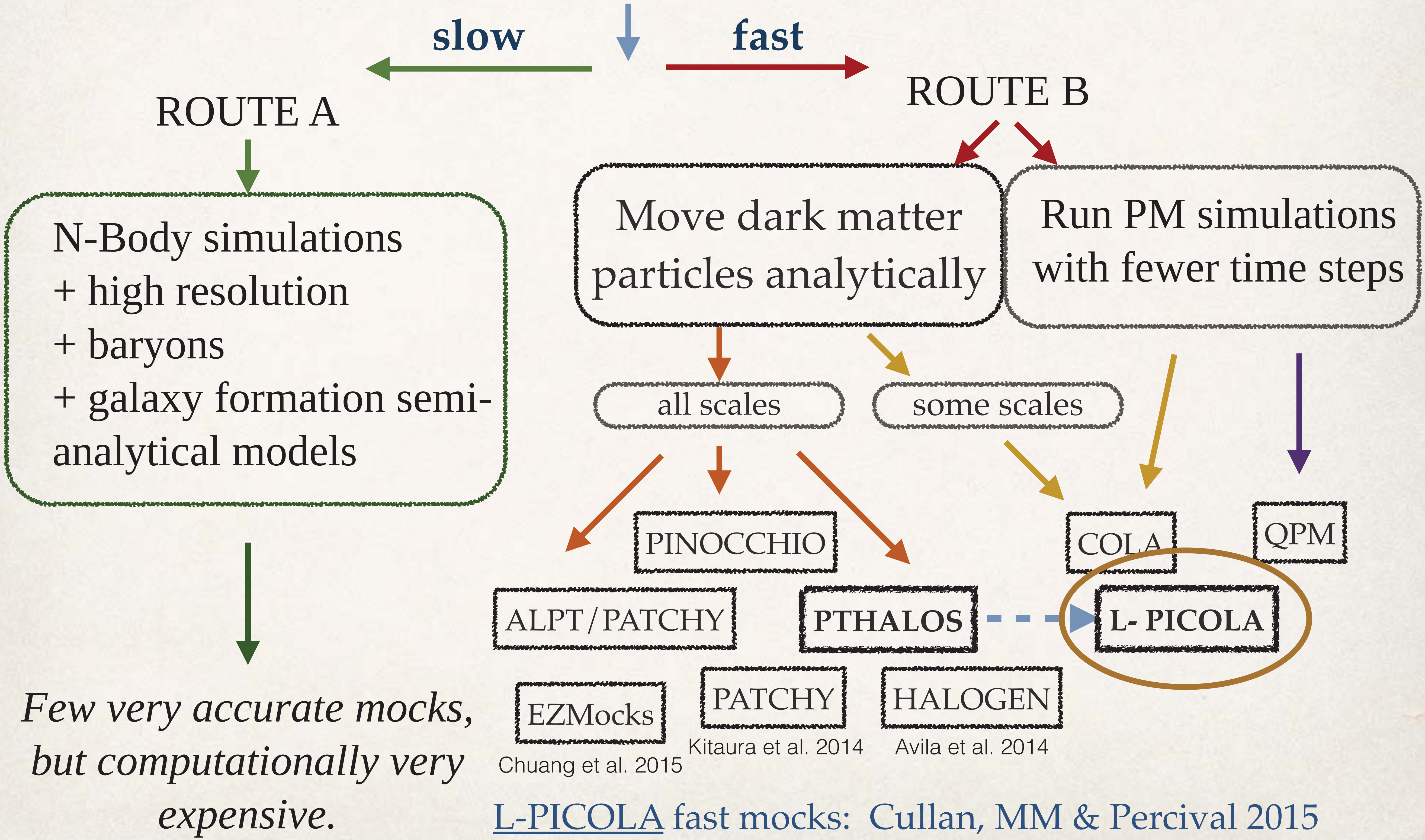
Mock Catalogues



Few very accurate mocks, but computationally very expensive.

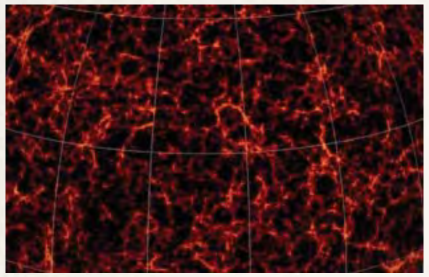
- *2-3 orders of magnitude faster than N-body runs*
- *decide how to define halos and populate galaxies*

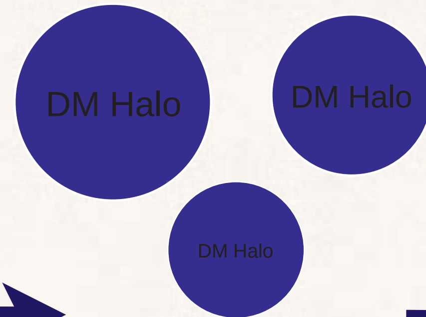
Mock Catalogues

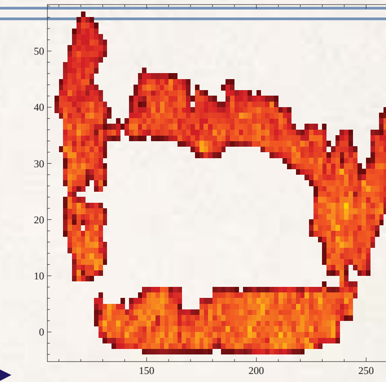


L-PICOLA fast mocks: Cullan, MM & Percival 2015
DES Fast Images on n-body: BCC & UFIS, Chang 2015

Matter fields: 2LPT

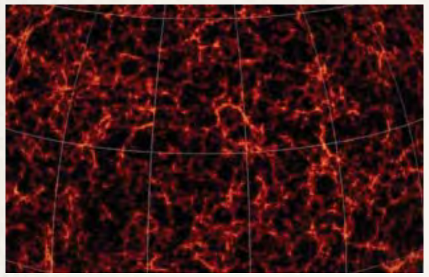




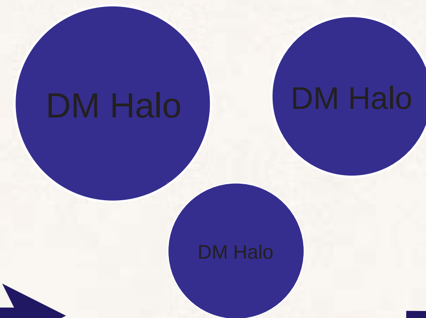


Dark Matter field *Halo field* *Galaxy field* *Mask and geometry*

Matter fields: 2LPT

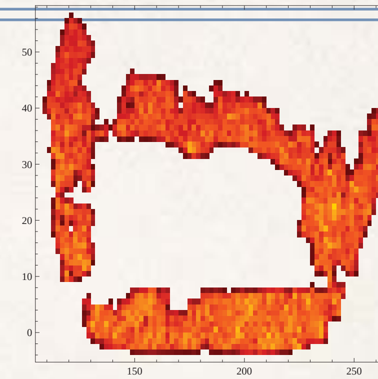


Dark Matter field



Halo field

Galaxy field



Mask and geometry

$$\vec{x}(\tau) = \vec{q} + \vec{\Psi}(\vec{q}, \tau) \qquad \vec{\Psi} = \vec{\Psi}^{(1)} + \vec{\Psi}^{(2)} + \ldots$$

$$\frac{d^2\vec{x}}{d\tau^2} + \mathcal{H}(\tau)\frac{d\vec{x}}{d\tau} = -\nabla\phi$$

Use the Poisson equation

$$J(\vec{q}, \tau)\nabla \cdot [\frac{d^2\vec{x}}{d\tau^2} + \mathcal{H}(\tau)\frac{d\vec{x}}{d\tau}] = \frac{3}{2}\Omega_m \mathcal{H}(J(\vec{q}, \tau) - 1)$$

Matter fields: 2LPT

Dark Matter field *Halo field* *Galaxy field* *Mask and geometry*

$$\vec{x}(\vec{q}) = \vec{q} - D_1 \nabla_q \phi^{(1)} + D_2 f_2 \nabla_2 \phi^{(2)}$$

$$\vec{u}(\vec{q}) = -D_1 f_1 \mathcal{H} \nabla_q \phi^{(1)} + D_2 f_2 \mathcal{H} \nabla_2 \phi^{(2)}$$

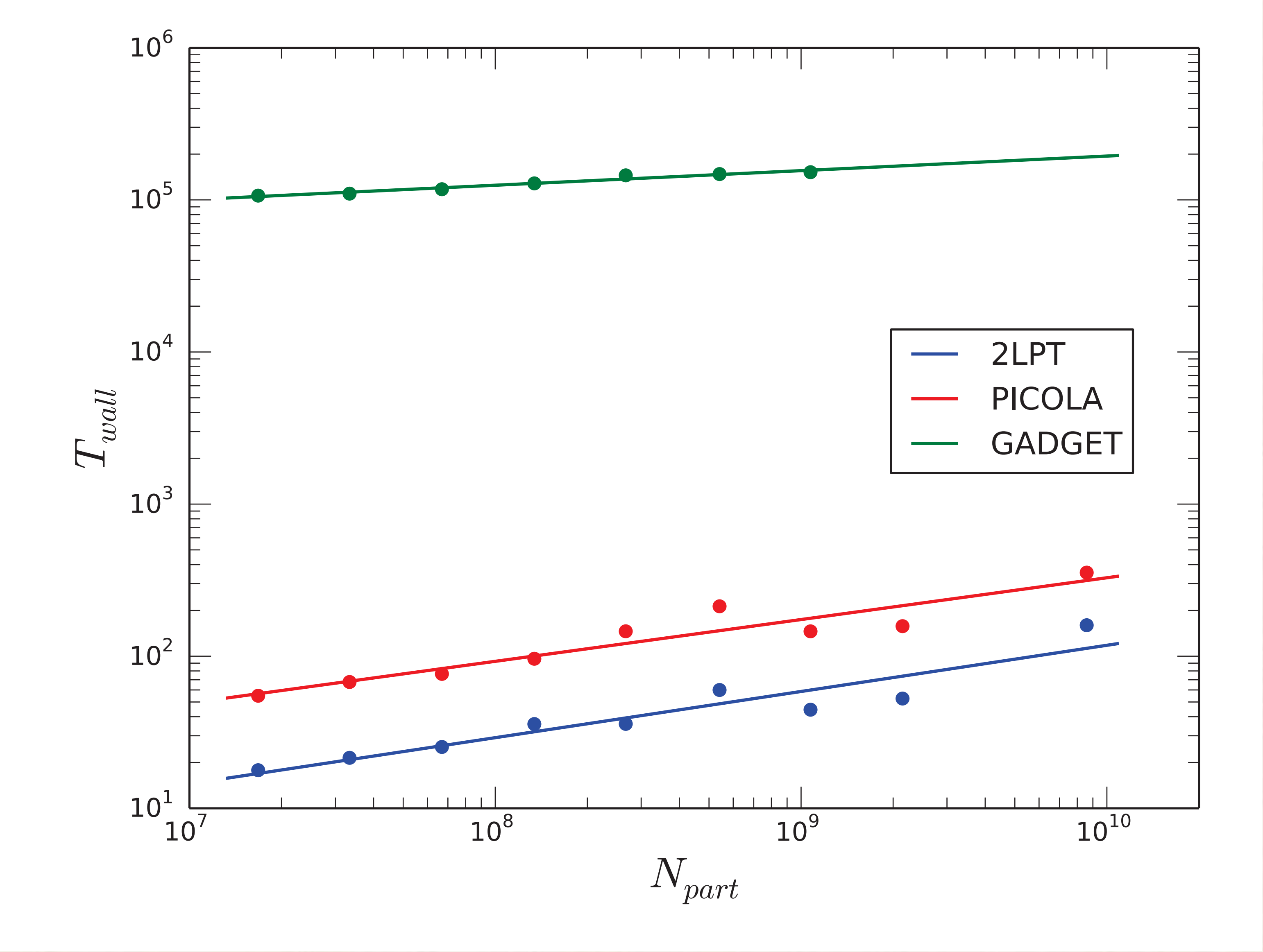
D and f are known, numerically and have very good analytical approximations.

$$f_i \equiv (dlnD_i)/(dlna)$$

One can separate large scales (2LPT) and small scales (PM)

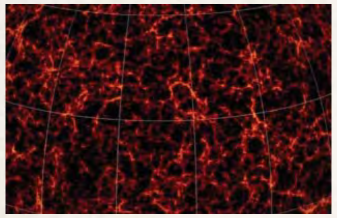
COLA (Tassev et al. 2013), also implemented in L-PICOLA (Howlett, MM, Percival 2015).

PICOLA performance

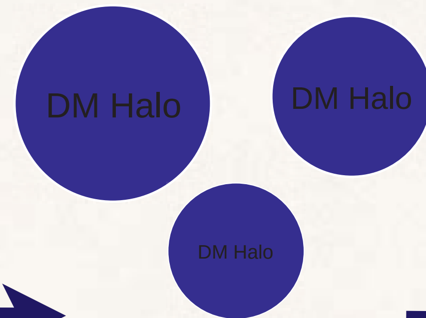


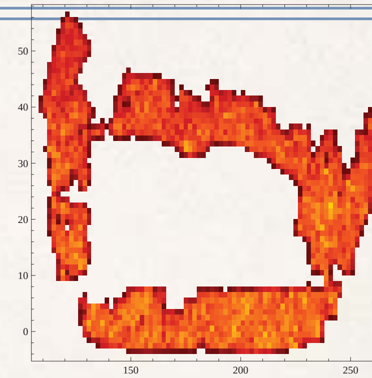
Howlett, MM, & Percival 2015

L-PICOLA mock catalogues



Dark Matter →



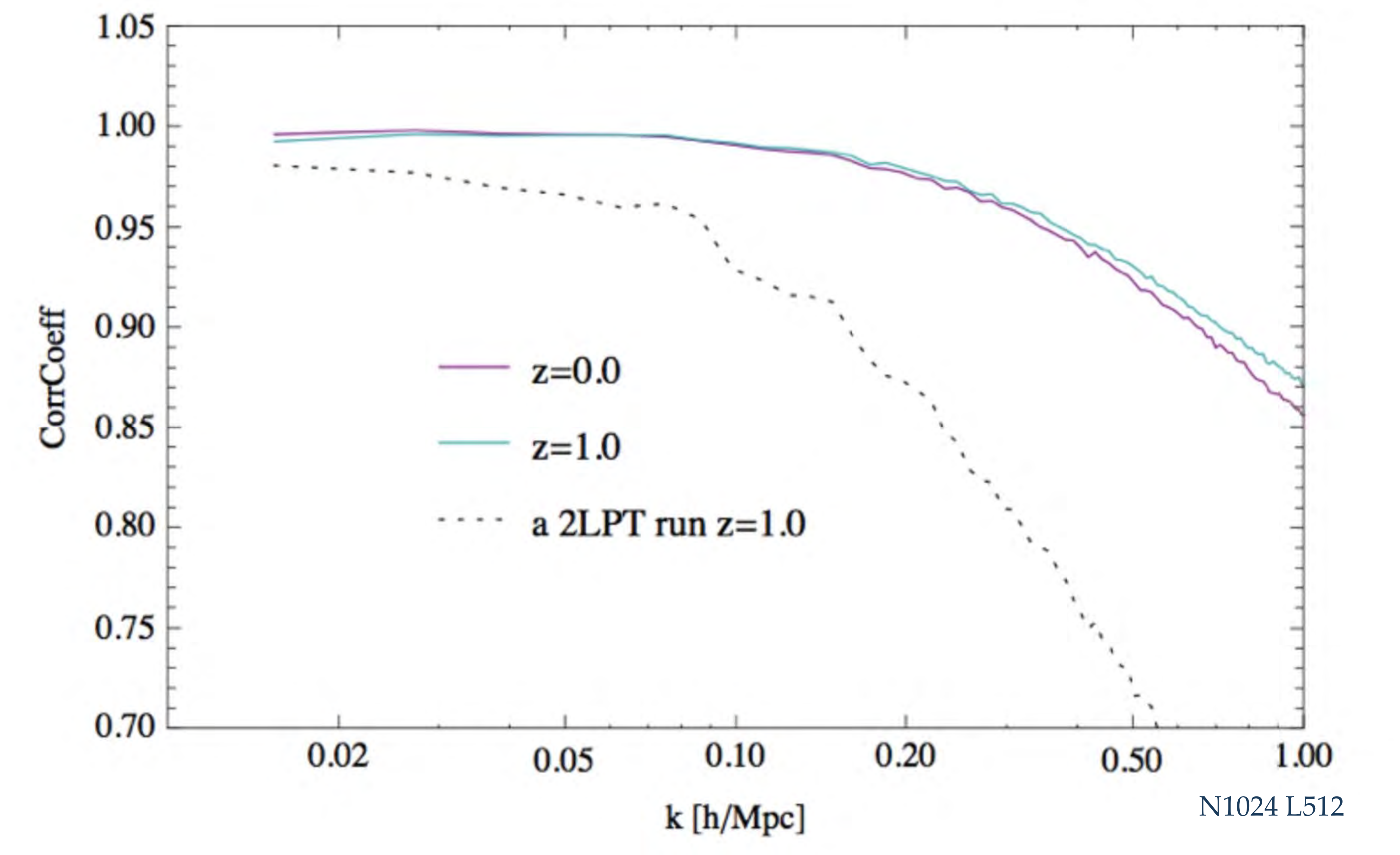


Halo field → *Galaxy field* → *Mask and geometry*

↑

For DES mocks we use Friends-of-Friends.
It is possible to use other schemes to place halos.

L-PICOLA performance

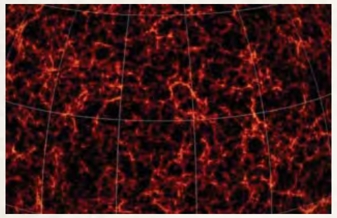


L=2048 Mpc/h   N=4096

Flat LCDM   Ωm= 0.317 s8= 0.83

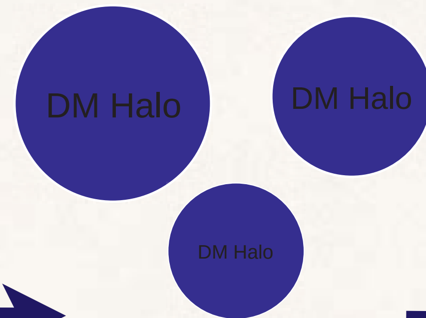
Howlett, MM, & Percival 2015

L-PICOLA mock catalogues



Dark Matter

L-PICOLA.
Lightcone
Mp = 10^{10} Mo/h
Run at COSMA

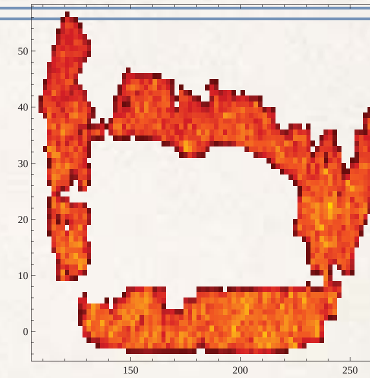


Halo field

Friends of Friends

Galaxy field

HOD and Halo abundance matching calibration.
Colours in five DES filters
Colour-Magnitude diagram



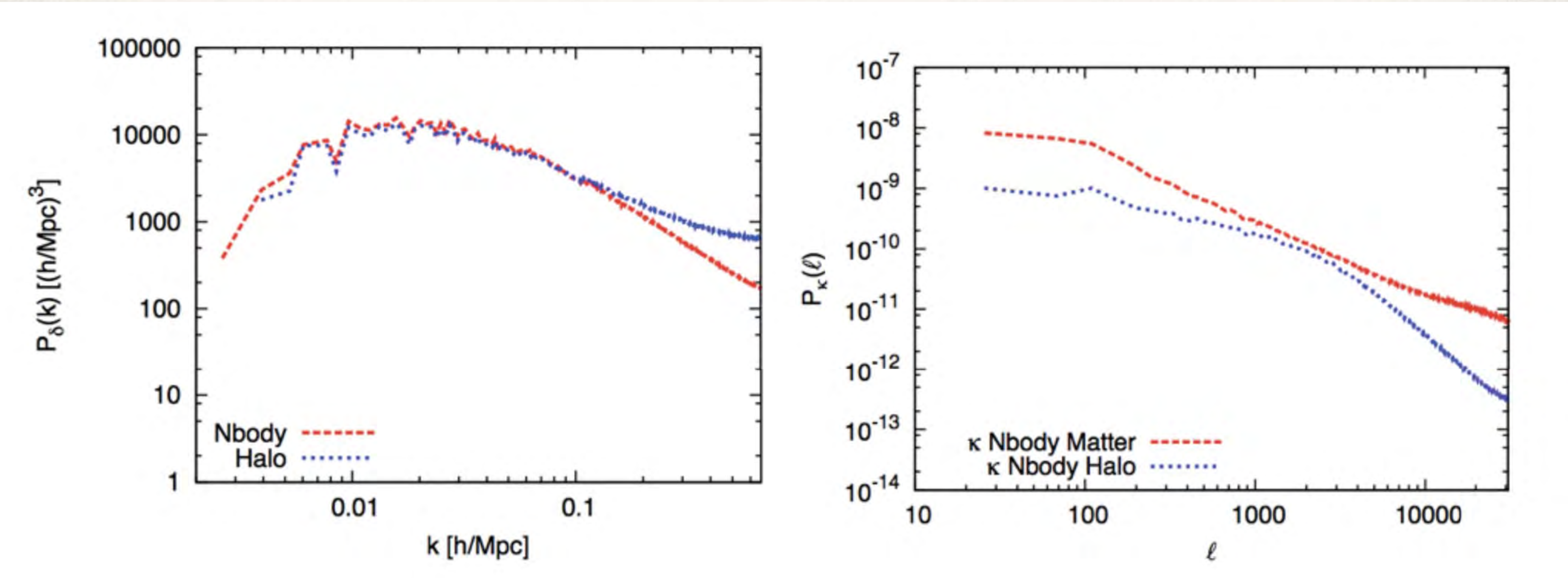
Mask and geometry

Pixelized masks with varying magnitude limits

Mocks for DES

Mock catalogues: cosmic web

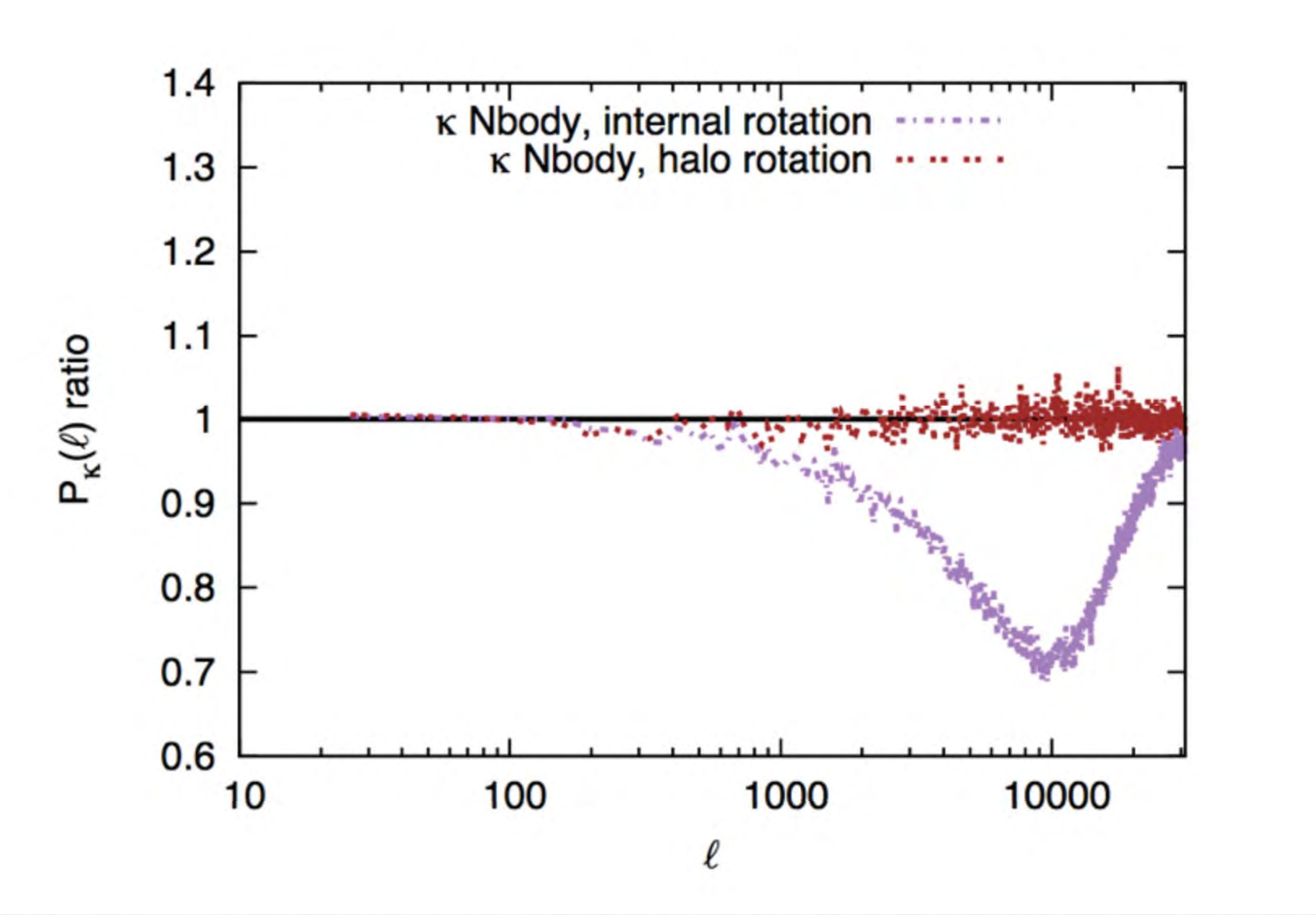
The importance of cosmic web on the power spectrum



The cosmic web contributes significantly to the convergence power spectrum.
Obtaining Pκ only from halos misses power.

Pace, MM, Bacon, Crittenden & Percival et al. 2015, arXiv:1503.04324

Mock catalogues: substructure



Pace, MM, Bacon, Crittenden & Percival et al. 2015, arXiv:1503.04324

Summary

DARK ENERGY SURVEY

- Initial Science Verification data already yielding high-quality results; photoz codes already comply with science requirements, and images are good for lensing.

- First results include: lensing of four massive clusters, mass maps, galaxy bias from different probes, discovery of 8 candidates for Milky Way dwarf galaxy satellites, superluminous supernova, etc: 50 papers from DES already out

- MUCH work ongoing within DES. Third year of observations just about to end! We already have a first taste of dark energy results and cosmology.

- Mock galaxy catalogues are essential for the analysis of galaxy clustering. Fast mocks can be done using L-PICOLA.

Thank you!

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28th Jan 2016

THE DARK ENERGY SURVEY