The bright and the dark side of gravitational lensing

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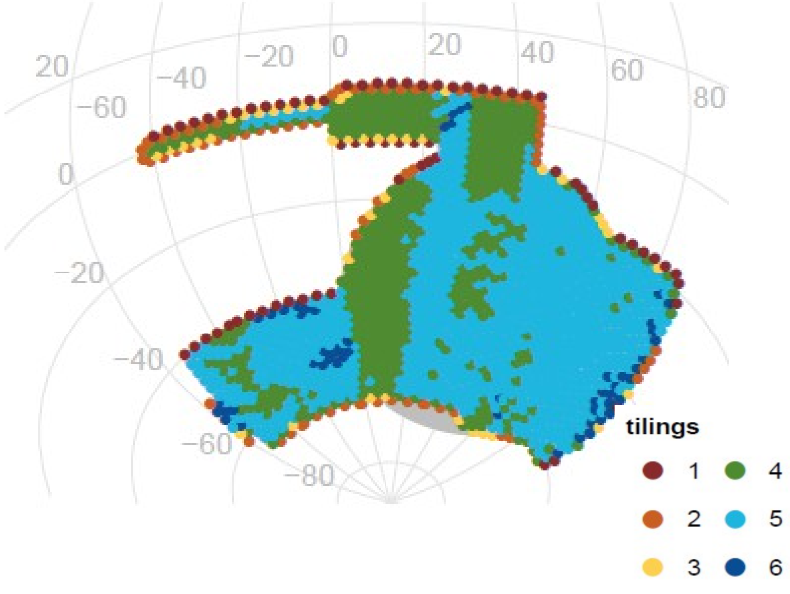
with Steve Allen, Joe DeRose, Oliver Friedrich, Stefan Hilbert, Elisabeth Krause, Tom McClintock, Peter Melchior, Eduardo Rozo, Eli Rykoff, Erin Sheldon, Tamas Varga, Risa Wechsler, … and the DES Weak Lensing, Simulations, and Theory working groups

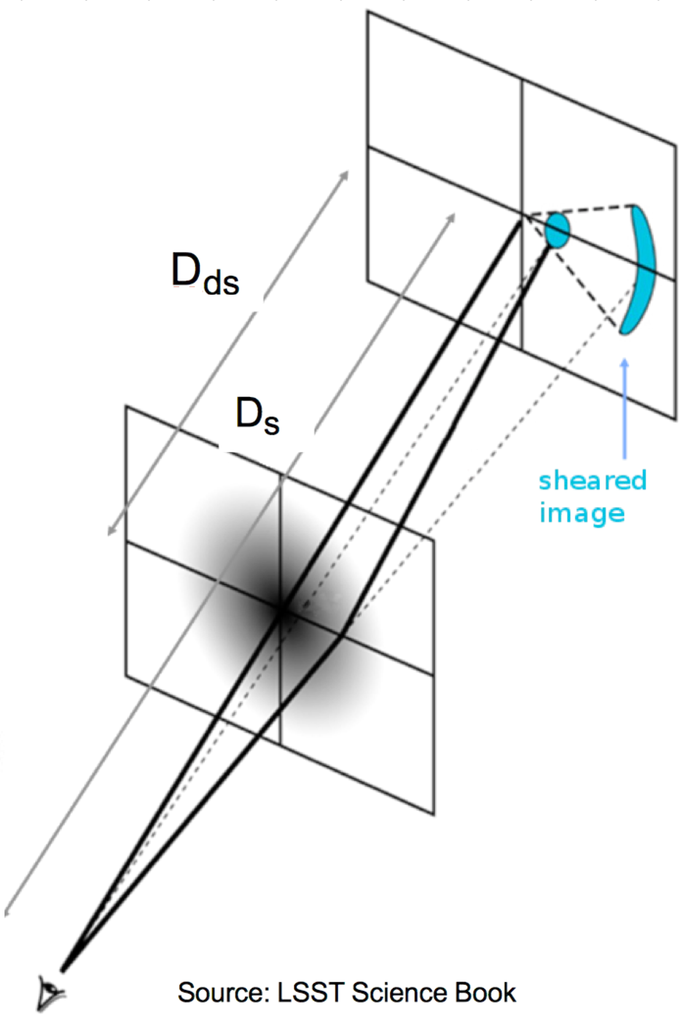
The Dark Energy Survey

- 5000 sq. deg. survey in grizY from Blanco @ CTIO, 10 exposures, 5 years, >300 scientists, 28 institutions
- Primary goal: dark energy equation of state
- Probes: Large scale structure, Supernovae, Cluster counts, **Gravitational lensing**
- Status:
  - SV (150 sq. deg, full depth):
    data understood, most science done,
    catalogs at http://des.ncsa.illinois.edu
  - Y1 (1500 sq. deg, 40% depth):
    data processed, science coming soon
  - Y3 (5000 sq. deg, 50% depth):
    data being processed



Gravitational lensing

- Matter (also dark) bends space-time (and therefore light rays)
- This causes **shifting**, and **magnification**, and **shearing** of the galaxy image and, in extreme cases, **multiple images**
- tangential distortion ~ overdensity



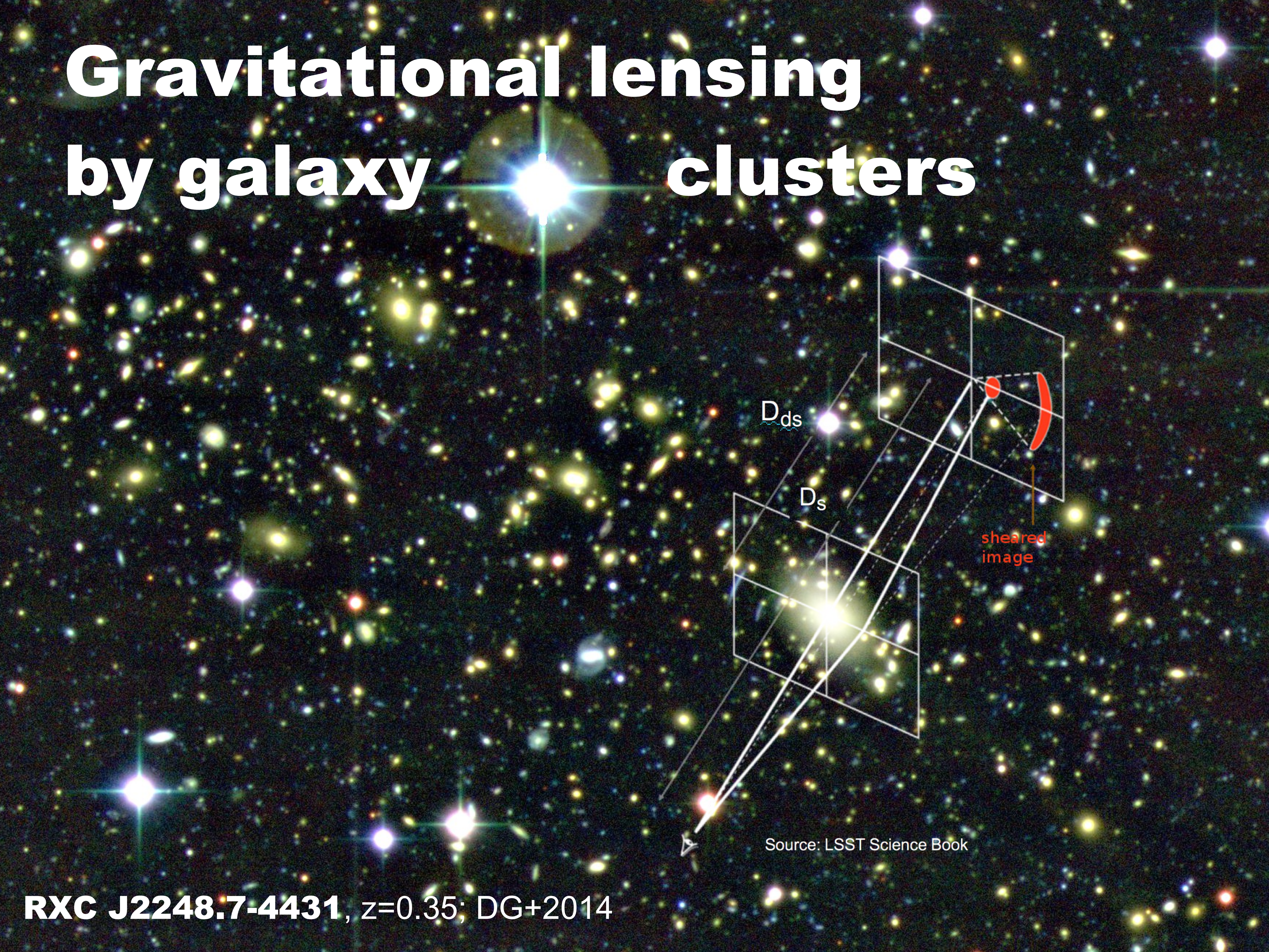
Source: LSST Science Book

Tangential shear $\gamma_t(\theta) = \langle\kappa(\theta')\rangle_{\theta'<\theta} - \kappa(\theta)$

Convergence (surface mass density) $\kappa = \Sigma / \left[\frac{c^2}{4\pi G}\frac{D_s}{D_d D_{ds}}\right]$

- measure masses / growth of structure w/o 'dirty' astrophysics

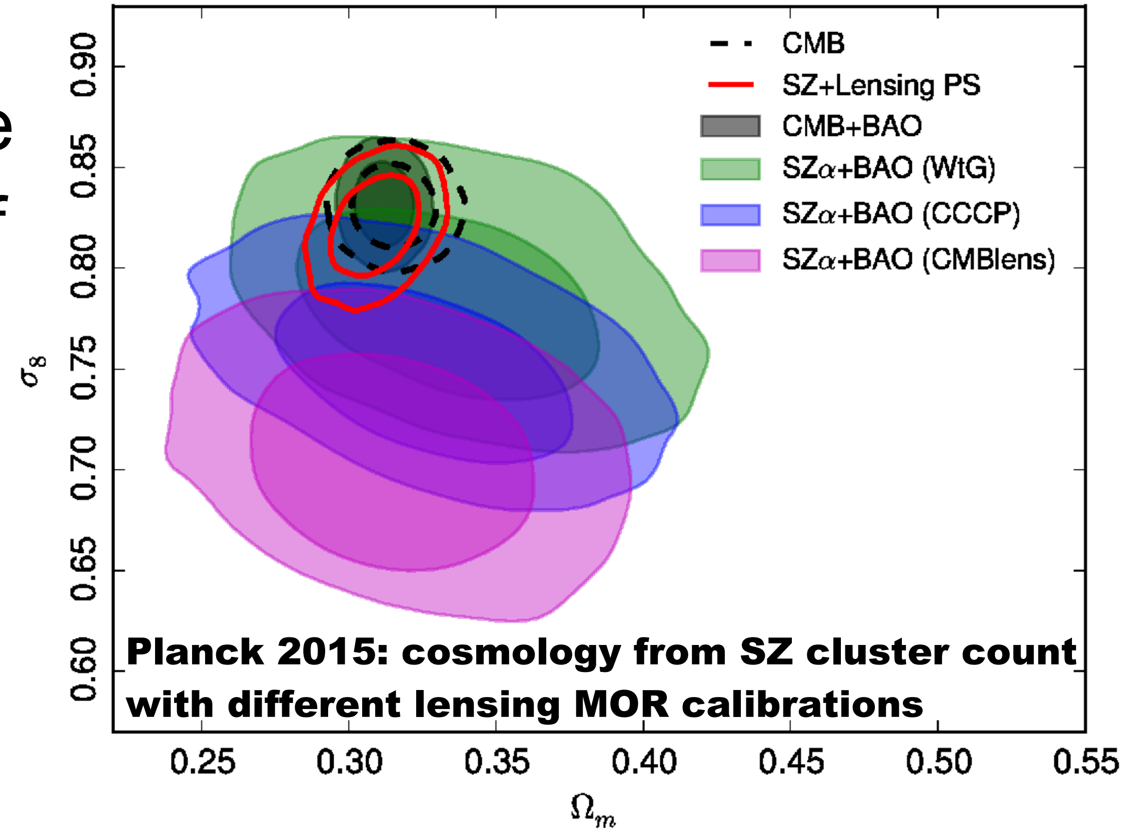
Gravitational lensing by galaxy clusters



RXC J2248.7-4431, z=0.35; DG+2014

Gravitational lensing constrains galaxy cluster scaling relations

- # of massive clusters above threshold in some observable is function of
  - Cosmology
  - Mass-observable relation (MOR)
  - Scatter in MOR



- calibration of MOR w/o astrophysics is possible with weak lensing
- full treatment of systematics required

Weak-lensing mass calibration of redMaPPer galaxy clusters in Dark Energy Survey Science Verification data

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… on the arXiv ~ this Friday

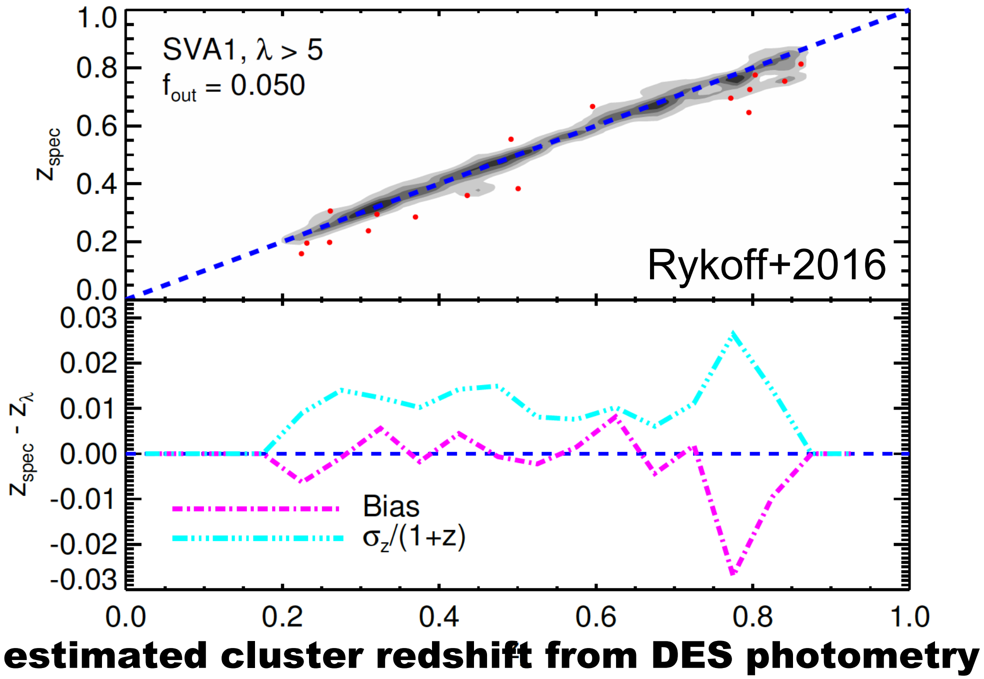
ABSTRACT

We use weak-lensing shear measurements to determine the mean mass of optically selected galaxy clusters in Dark Energy Survey Science Verification data. In a blinded analysis, we split the sample of more than 8,000 redMaPPer clusters into 15 subsets, spanning ranges in richness $5 \leqslant \lambda \leqslant 180$ and redshift $0.2 \leqslant z \leqslant 0.8$, and fit the averaged mass density contrast profiles with a model that accounts for seven distinct sources of systematic uncertainty: shear measurement and photometric redshift errors; cluster-member contamination; miscentering; deviations from the NFW halo profile; halo triaxiality; and line-of-sight projections. We combine the inferred cluster masses to estimate the joint scaling relation between mass, richness and redshift, $\mathcal{M}(\lambda, z) \propto M_0 \lambda^F (1+z)^G$. We find $M_0 \equiv \langle M_{200\mathrm{m}} \,|\, \lambda = 30, z = 0.5 \rangle = \left[2.34 \pm 0.17\,(\mathrm{stat}) \pm 0.12\,(\mathrm{sys})\right] \cdot 10^{14}\,\mathrm{M}_\odot$, with $F = 1.12 \pm 0.16\,(\mathrm{stat}) \pm 0.04\,(\mathrm{sys})$ and $G = 0.11 \pm 0.58\,(\mathrm{stat}) \pm 0.12\,(\mathrm{sys})$. The amplitude of the mass–richness relation is in excellent agreement with the weak-lensing calibration of redMaPPer clusters in SDSS by Simet et al. (2016) and with the Saro et al. (2015) calibration based on abundance matching of SPT-detected clusters. Our results extend the redshift range over which the mass–richness relation of redMaPPer clusters has been calibrated with weak lensing from $z \leqslant 0.3$ to $z \leqslant 0.8$. Calibration uncertainties of shear measurements and photometric redshift estimates dominate our systematic error budget and require substantial improvements for forthcoming studies.

How to calibrate the richness-mass relation with weak lensing...

- optically select clusters

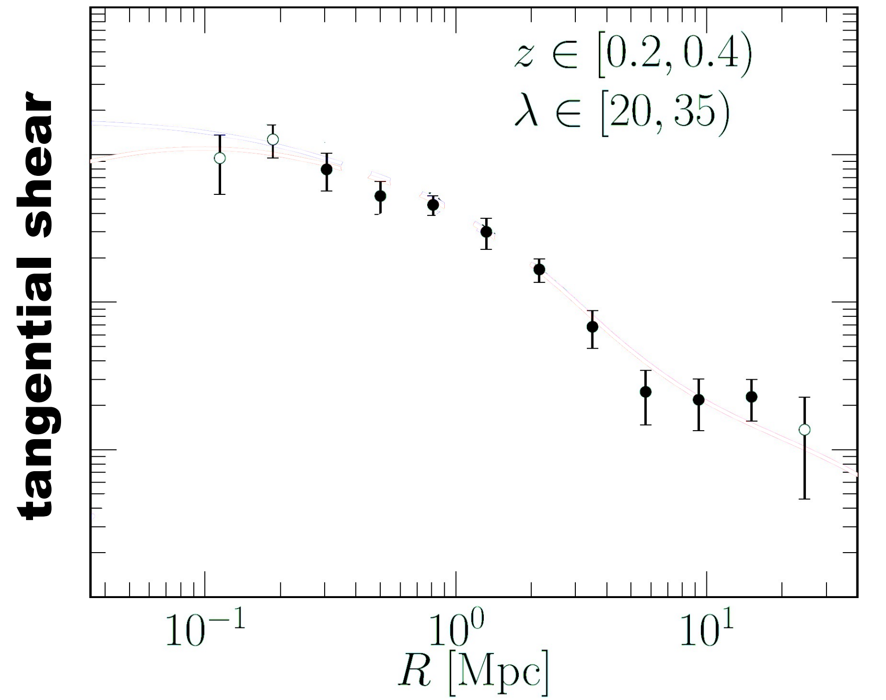
- redMaPPer algorithm (Rykoff+2014,2016)
- excellent photo-z, low scatter in richness λ = # of galaxies



- off-centering, projection effects

Weak-lensing mass calibration of redMaPPer galaxy clusters in DES SV

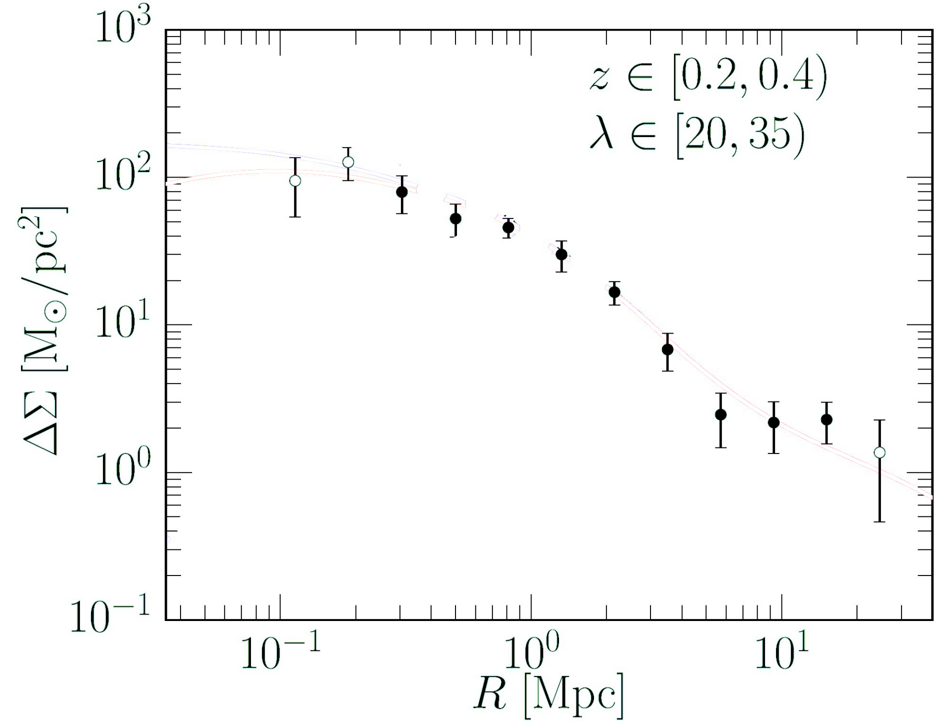
- optically select clusters
- measure shapes of background galaxies



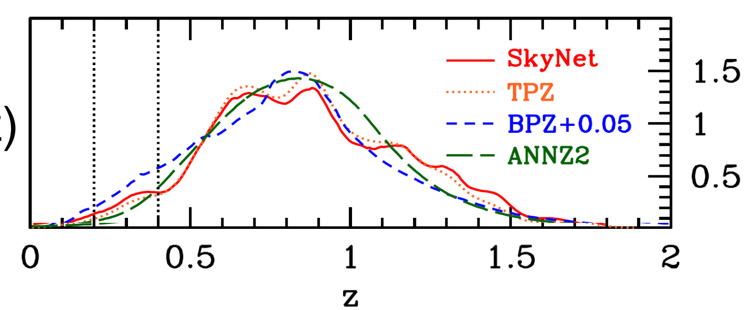
Weak-lensing mass calibration of redMaPPer galaxy clusters in DES SV

- optically select clusters
- measure shapes of background galaxies
- convert to mass density

$$\Delta\Sigma \equiv \overline{\Sigma}(< R) - \overline{\Sigma}(R) = \Sigma_{\rm crit}\ \gamma^{\sf T}(R)$$



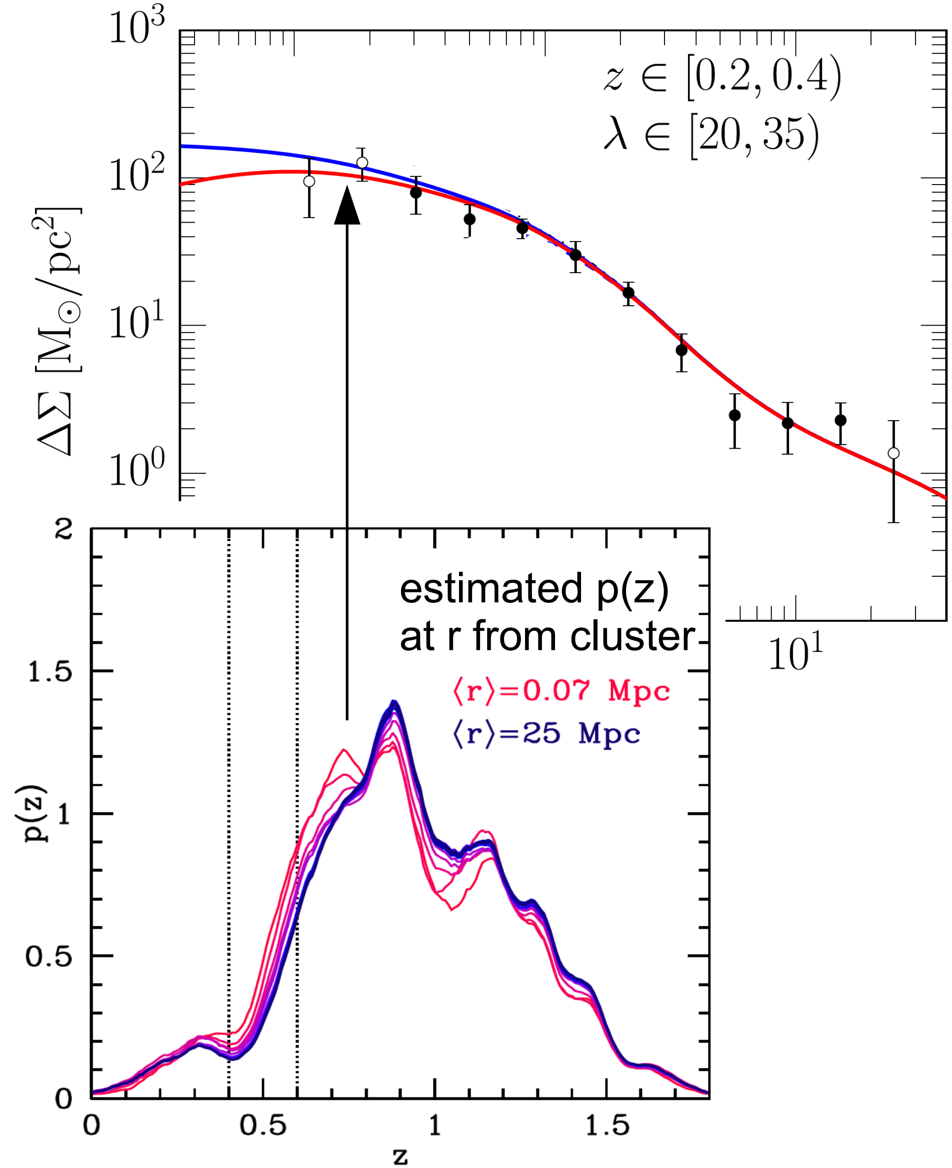
p(z)



Weak-lensing mass calibration of redMaPPer galaxy clusters in DES SV

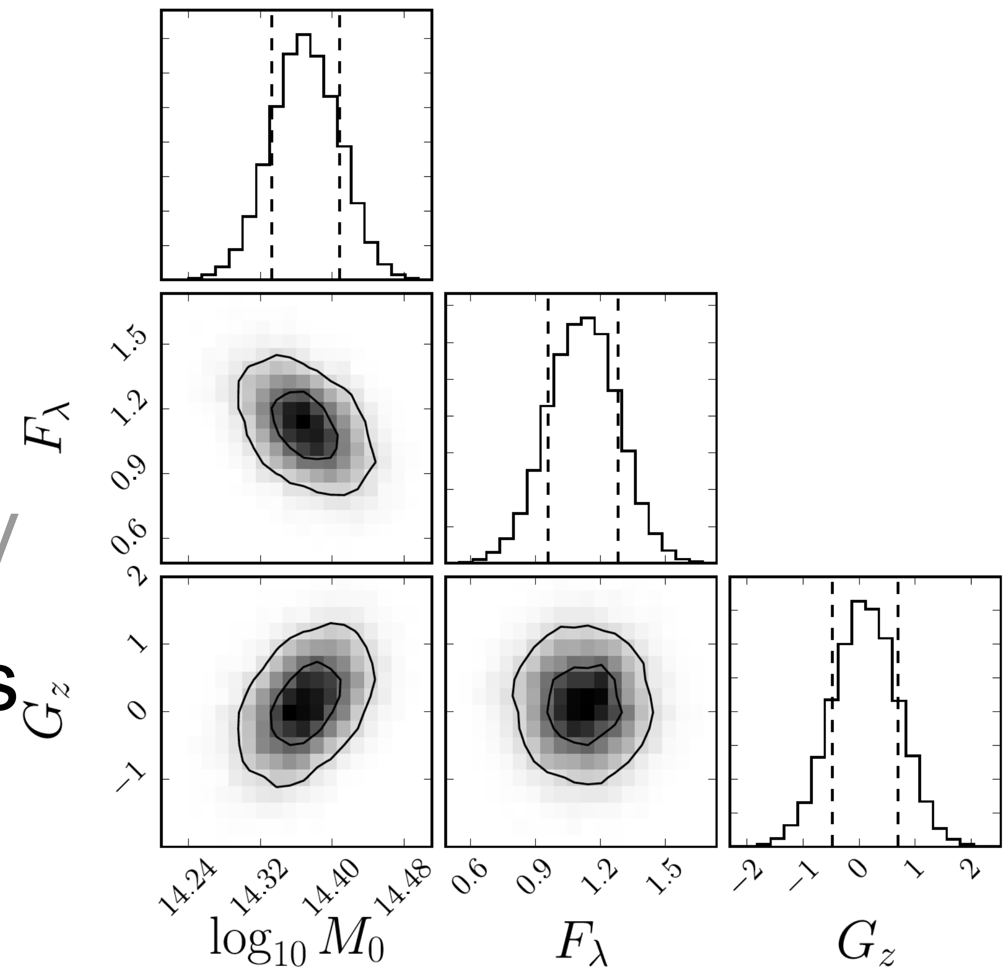
- optically select clusters
- measure shapes of background galaxies
- convert to mass density

  accounting for cluster members



Weak-lensing mass calibration of redMaPPer galaxy clusters in DES SV

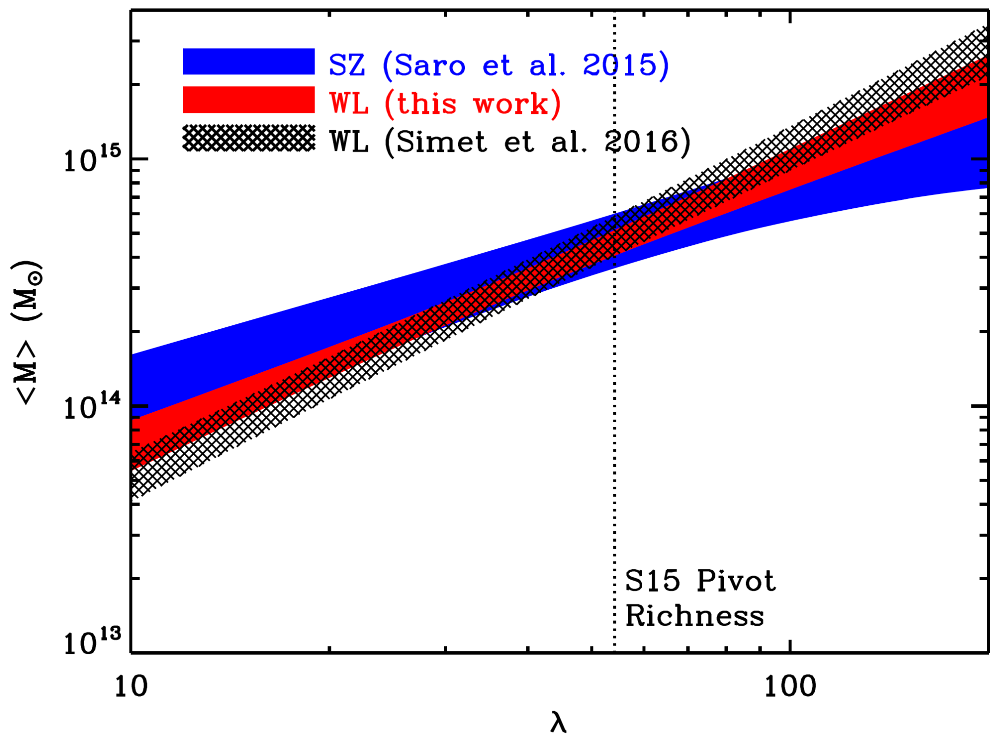
- optically select clusters
- measure shapes of background galaxies
- convert to mass density
- estimate mass-richness relation



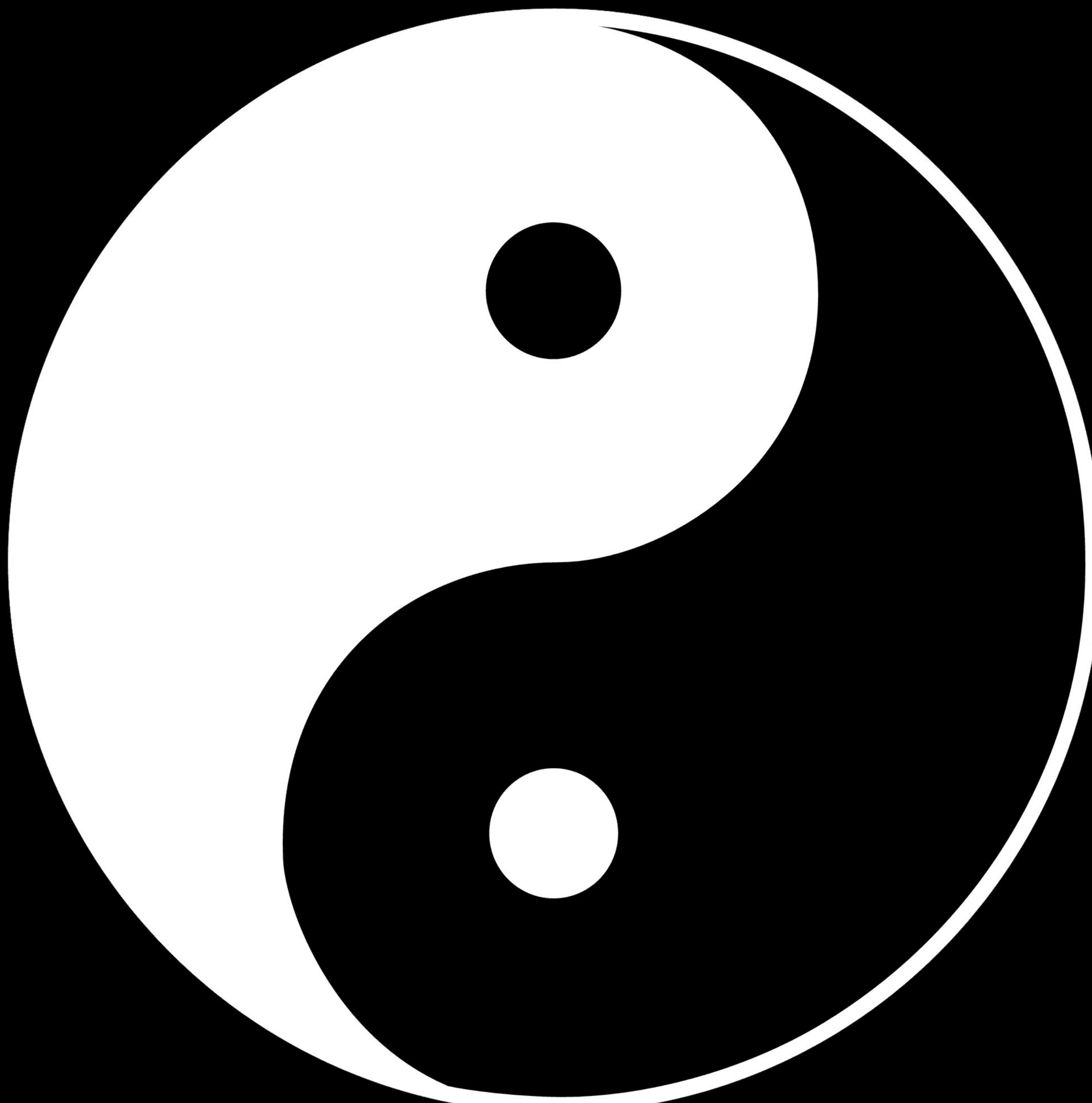
$$\langle M \mid \lambda, z \rangle = M_0 \left(\frac{\lambda}{\lambda_0} \right)^{F_\lambda} \left(\frac{1+z}{1+z_0} \right)^{G_z}$$

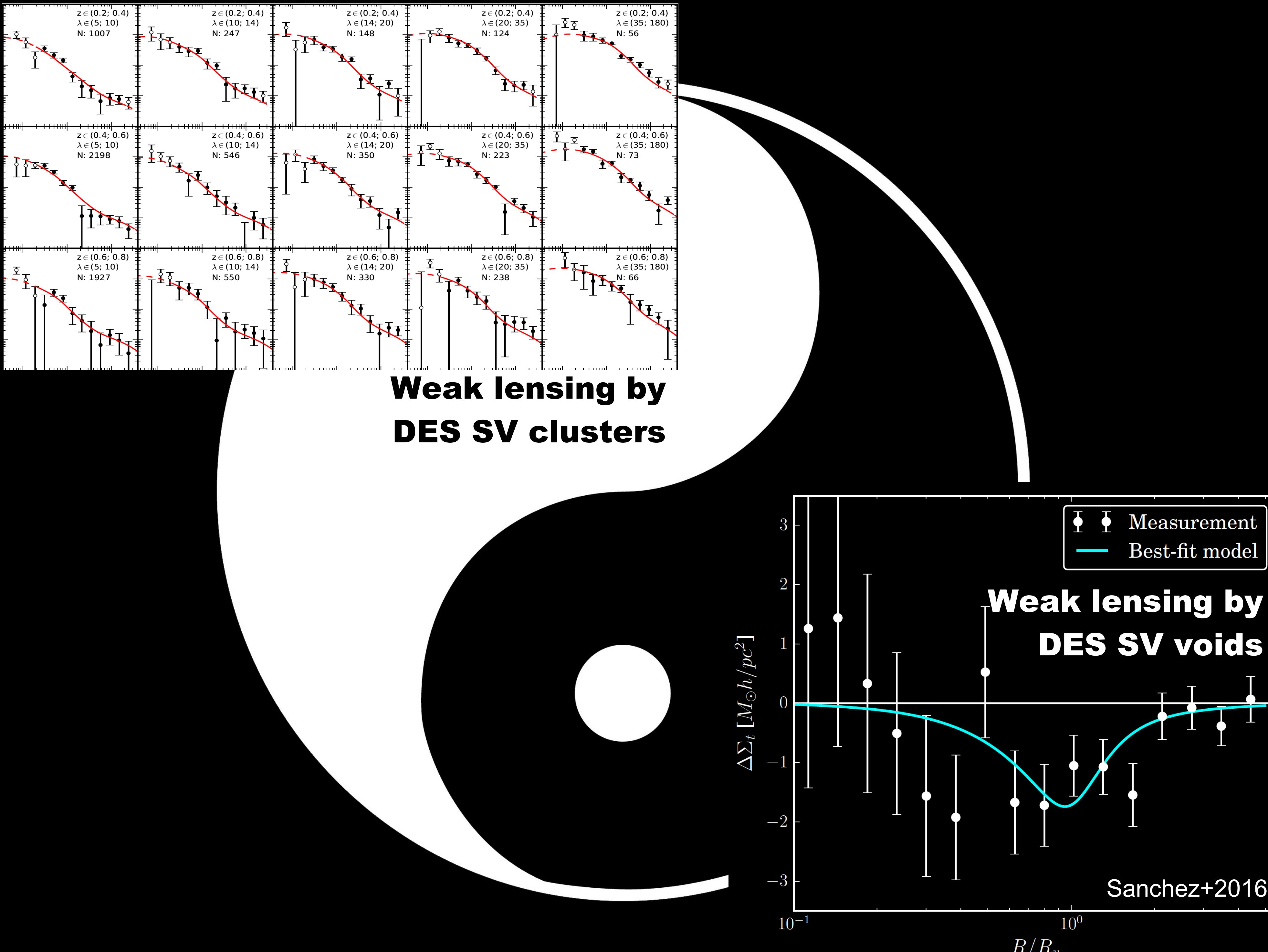
redMaPPer in SV: Conclusions

- consistent, competitive calibration compared to SDSS lensing (Simet+2016) and SPT SZ (Saro+2015) of redMaPPer clusters
- consistent with $M \propto \lambda$, $\langle M|\lambda,z\rangle = \langle M|\lambda\rangle$
- absolute mass calibration with 9% statistical and 6% systematic error



Source of systematic	
Shear measurement	4%
Photometric redshifts	3%
Modeling systematics	1% (2%)
Cluster triaxiality	1% (2%)
Line-of-sight projections	1% (2%)
Membership dilution + miscentering	$\leqslant$ 1%
Total	**5.1%** (6.1%)





z ∈ (0.2; 0.4)
λ ∈ (5; 10)
N: 1007
z ∈ (0.2; 0.4)
λ ∈ (10; 14)
N: 247
z ∈ (0.2; 0.4)
λ ∈ (14; 20)
N: 148
z ∈ (0.2; 0.4)
λ ∈ (20; 35)
N: 124
z ∈ (0.2; 0.4)
λ ∈ (35; 180)
N: 56
z ∈ (0.4; 0.6)
λ ∈ (5; 10)
N: 2198
z ∈ (0.4; 0.6)
λ ∈ (10; 14)
N: 546
z ∈ (0.4; 0.6)
λ ∈ (14; 20)
N: 350
z ∈ (0.4; 0.6)
λ ∈ (20; 35)
N: 223
z ∈ (0.4; 0.6)
λ ∈ (35; 180)
N: 73
z ∈ (0.6; 0.8)
λ ∈ (5; 10)
N: 1927
z ∈ (0.6; 0.8)
λ ∈ (10; 14)
N: 550
z ∈ (0.6; 0.8)
λ ∈ (14; 20)
N: 330
z ∈ (0.6; 0.8)
λ ∈ (20; 35)
N: 238
z ∈ (0.6; 0.8)
λ ∈ (35; 180)
N: 66
Weak lensing by
DES SV clusters
Measurement
Best-fit model
Weak lensing by
DES SV voids
Sanchez+2016
3
2
1
0
−1
−2
−3
$\Delta\Sigma_t\ [M_\odot h/pc^2]$
10^{-1}
10^0
R/R_v

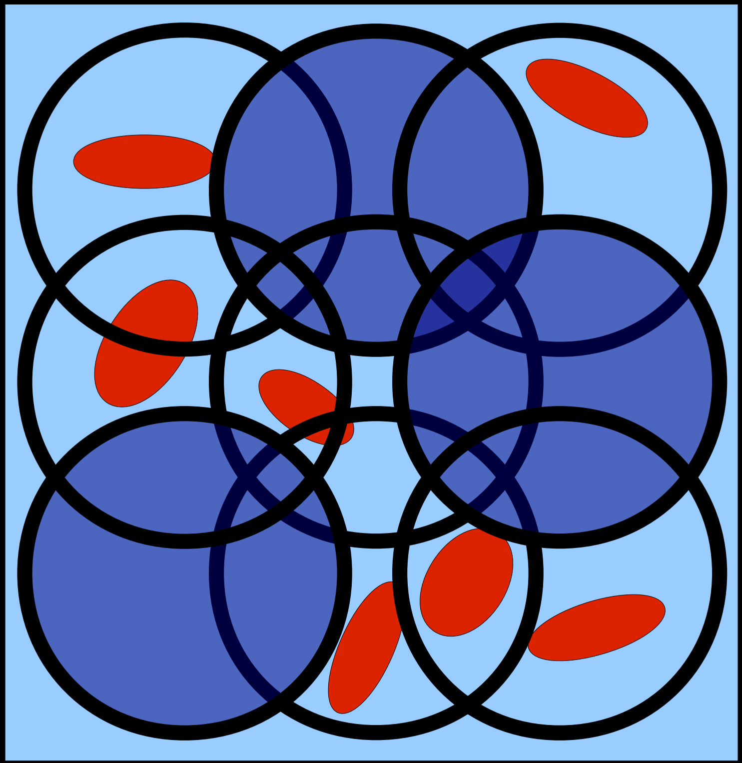
New statistic: Galaxy troughs

- Trough: (long) cylinder* with galaxy count below some percentile threshold

+ easy to find in photo-z, high S/N of lensing due to suppression of LSS noise,

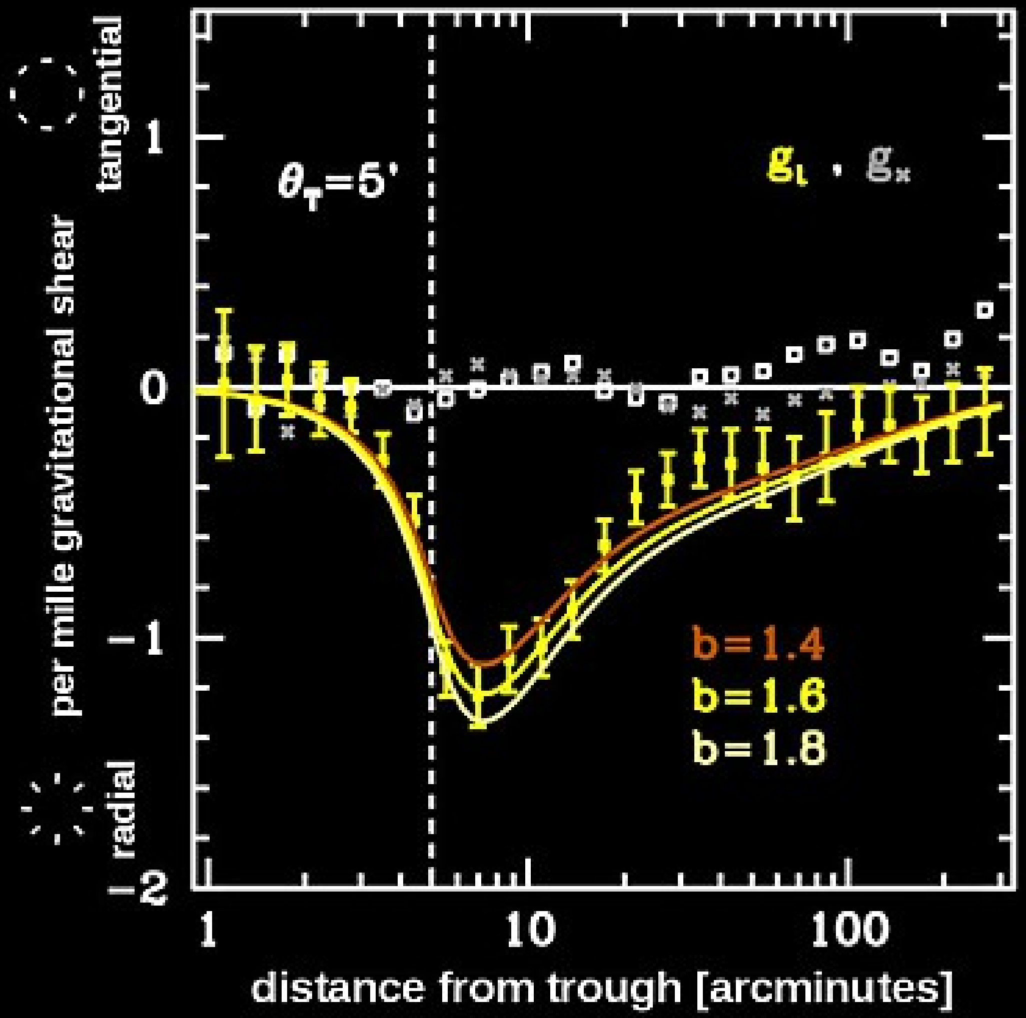
+ new way of probing structure and gravity in low density regime

+ in the limit of dense tracers, signal is easy to predict and independent of galaxy bias etc.



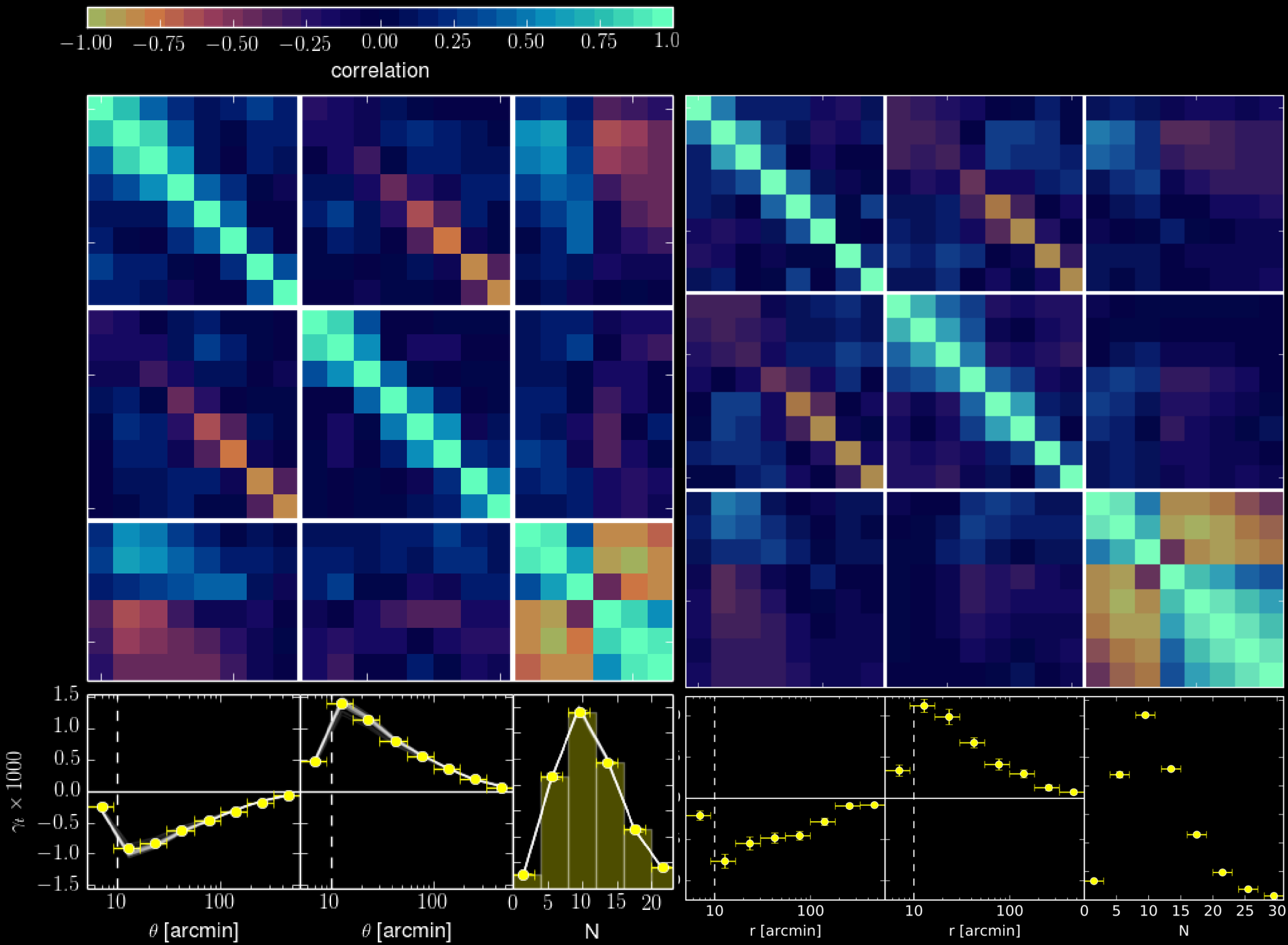
Measurement in DES SV

- tracers: Rykoff/Rozo redMaGiC galaxies, $0.2<z<0.5$, $L>0.5L^*$, 1/[1000 Mpc^3]
- troughs = lower quintile in galaxy count
- S/N ~ 15 >> void lensing
- consistent with simple model
- for large scales / tracer count: independent of galaxy bias



DG+2016

Troughs in simulations and Y1 data



simulated DES Y1, cosmic variance only

actual DES Y1, blinded and preliminary

Conclusions

- DES SV (3% of survey) has allowed competitive measurements of lensing statistics
  - calibration of optical cluster mass scaling
  - high S/N measurements of the low density Universe
- Focus on systematics control
  - new methods for estimating / marginalizing over lensing systematics
  - without improvements in shape and photo-z biases, these will be the limiting factor in future releases
- Final SV results out ~ this month, Y1 approaching