Humboldt Kolleg – Kitzbühel 2019

Cosmology with Clusters of Galaxies

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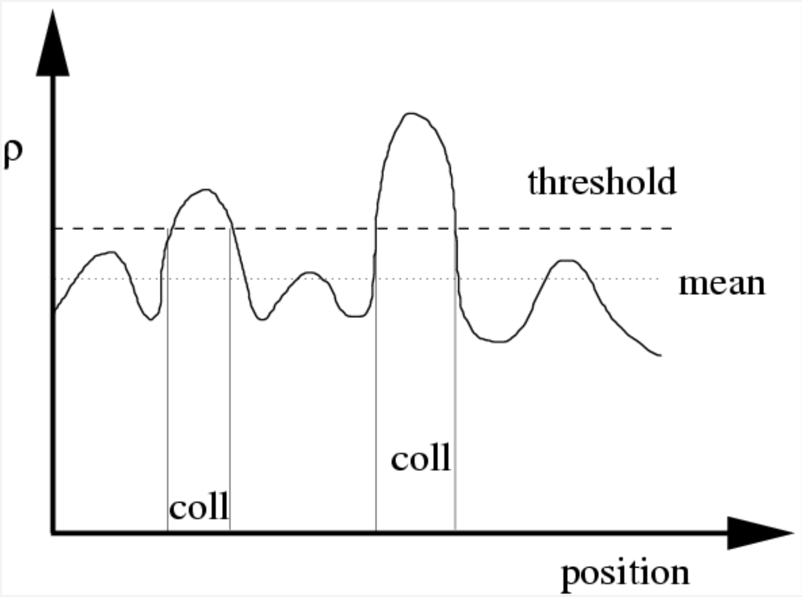
Excellence Cluster Origins

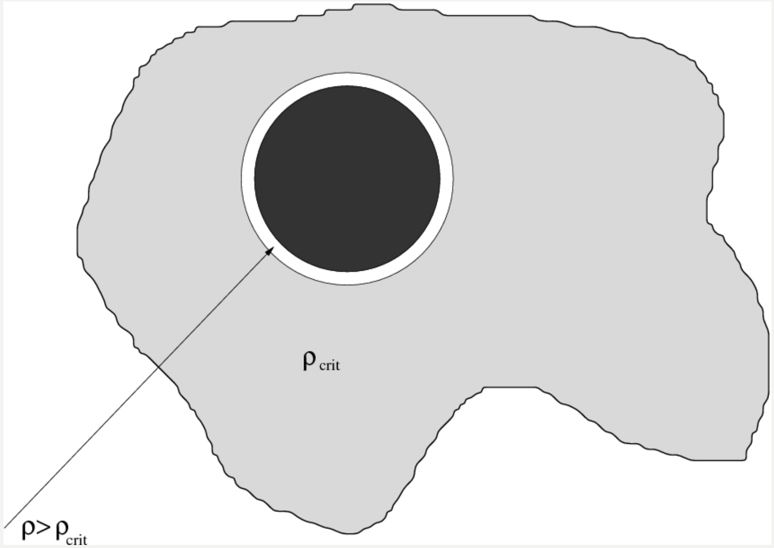


- If linear density perturbation exceeds threshold density the region will collapse and form a cluster
- Mass function; density of clusters at a given mass and redshift
- Mass function sensitive to amplitude of perturbations (σ_8) and mass contents of the Universe (Ω_m); but also other cosmological parameters.

- Simple: assume Gaussian distributed density fluctuations
- calculate probability that region with overdensity δ larger than some critical density δ_c is found
- Normalize to account for total mass-density in the Universe: fudge factor 2
- Press-Schechter mass function (Press, Schechter 1974)
- Suffers from cloud-in-cloud problem; can be properly addressed by excursion sets (Bond, Cole, Efstathiou and Kaiser; 1990): Get automatically factor of 2

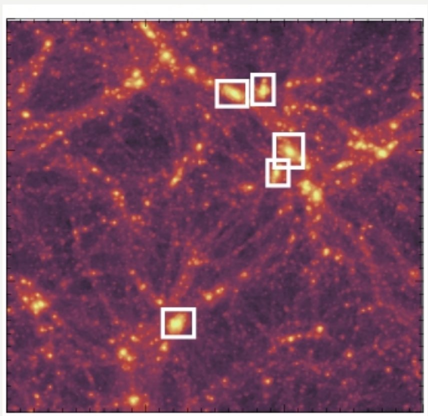
The Calculation of the Threshold

- Assume local overdensity spherical collapse of overdense region
- linearize dynamics
- calculate overdensity at collapse
  - In flat matter dominated Universe: $\delta_c = 1.686$
  - can be calculated for other cosmologies
  - mild cosmology dependence
- Feed into mass function of haloes
- Extension to ellipsoidal collapse (Sheth & Tormen 2002)

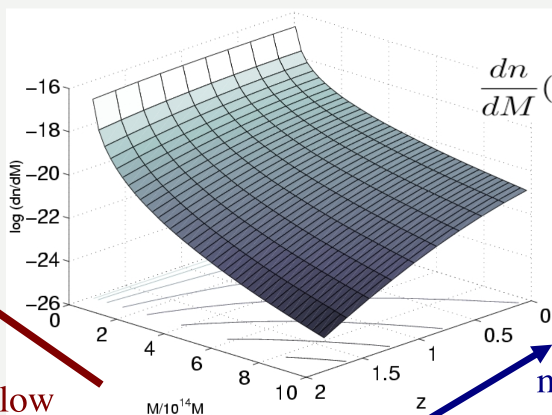


Overcoming Analytical Uncertainties: Counting Halos in Simulations !

- Count halos in N-body simulations
- Measure "universal" mass function - density of cold dark matter halos of given mass



$$\frac{dn}{dM}(z,M) = -0.316\frac{\rho_{m,0}}{M}\frac{d\sigma_M}{dM}\frac{1}{\sigma_M}\exp\left\{-\left|0.67-\log[D(z)\sigma_M]\right|^{3.82}\right\}$$

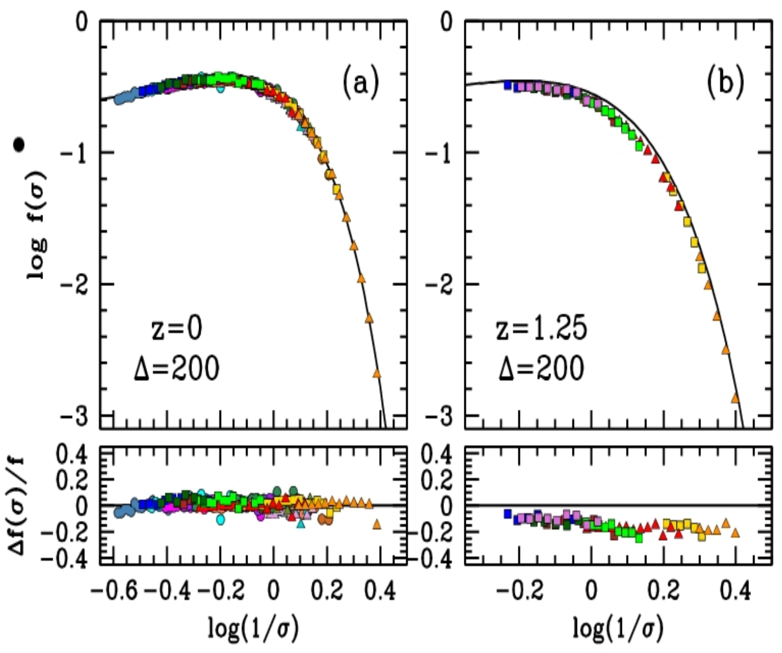


more low mass clusters

more low redshift clusters

Universality of the Mass Function - I

- Almost universal parameterization in terms of linear fluctuation σ(M)
- Tinker et al. 2008 find additional redshift dependence (strongest effect in amplitude, but also shape)
- This effect can be included in parameterization



Tinker et al. 2008

The parameterization of the mass function

$$\frac{dn}{dM} = f(\sigma)\frac{\bar{\rho}_m}{M}\frac{d\ln\sigma^{-1}}{dM}$$

$$f(\sigma) = A\left[\left(\frac{\sigma}{b}\right)^{-a} + 1\right]e^{-c/\sigma^2}$$

$$\sigma^2 = \int P(k,z)\hat{W}(kR)k^2dk$$

$$P(k,z) = P(k,z=0)D^2(z)$$

- Dependence on mass density

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- Dependence on mass density
- Power Law Dependence on fluctuation amplitude

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$$\sigma^2 = \int P(k,z)\hat{W}(kR)k^2 dk$$

$$P(k,z) = P(k,z=0)D^2(z)$$

- dependence on mass density
- power law dependence on fluctuation amplitude
- strong power law dependence on growth of structures

Predicting Cluster Number Counts

$$\Delta N(z, M) = \Delta\Omega \int_{z-\Delta z}^{z+\Delta z} dz \frac{dV}{dz d\Omega} \int_{M-\Delta M}^{M+\Delta M} \frac{dn}{dM} dM$$

- Survey sky coverage
- Redshift bins
- Volume element
- Limiting mass of survey (redshift dependent)
- Cosmology dependence driven by volume element and mass function

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- Survey sky coverage
- Redshift bins
- Volume element
- Mass bin (mass-observable relation)
- Cosmology dependence driven by volume element and mass function

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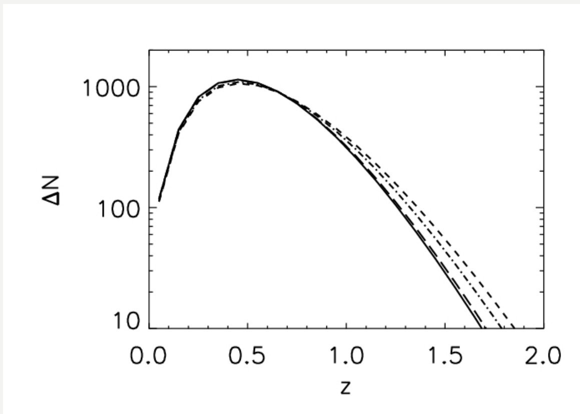
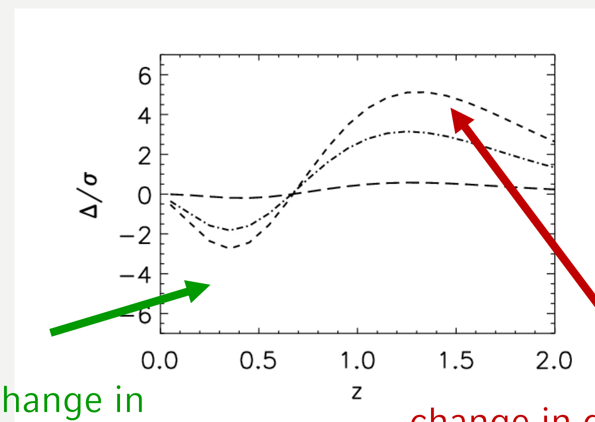
- Redshift bins
- Volume element
- Mass bin
- Cosmology dependence driven by volume element and mass function

Cosmology Dependence of Number Counts





change in volume

change in growth factor

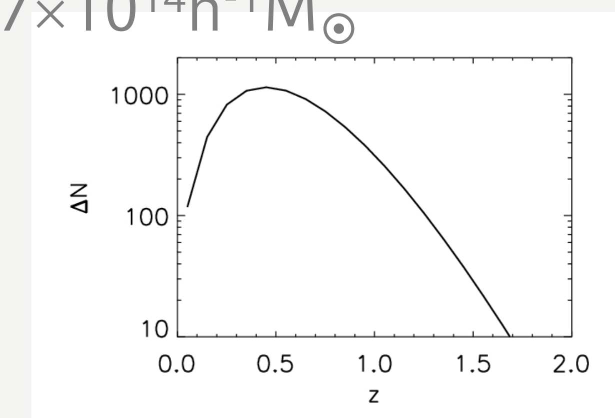
concordance cosmology:

$\Omega_m = 0.3$;

$\sigma_8 = 0.78$; $n=1$, $h=0.72$;

$w=-1$, $\Delta\Omega = 4.000\ \mathrm{deg}^2$

$M_{lim} = 1.7\times10^{14} h^{-1} M_\odot$



$\Omega_m = 0.4$

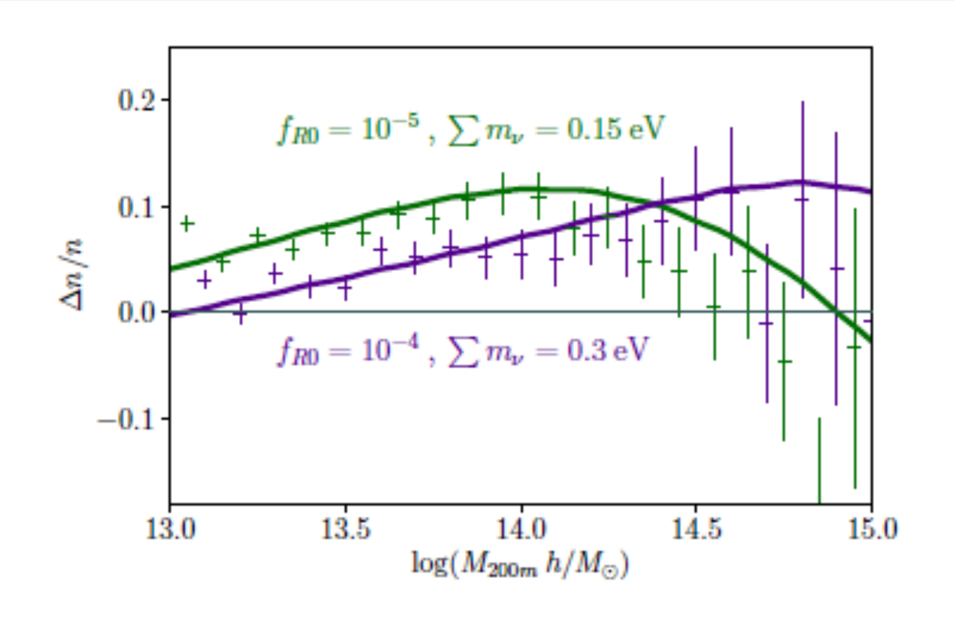
$\sigma_8 = 0.85$

$w = -0.8$

$w = -0.7$

$w = -1+0.2(1-a)$

$p_{DE} = w\rho_{DE}$



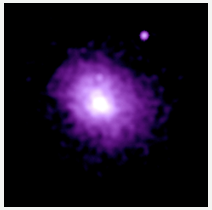
Hagstotz et al. 2018

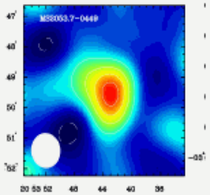
- Large Scale Extensions of Einstein Gravity – for example scalar tensor theories – f(R)
- Massive Neutrino

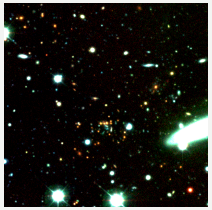
$$S = \int d^4x \sqrt{-g} \left(\frac{R + f(R)}{16\pi G} + \mathcal{L}_m \right)$$

$$f(R) \approx -2\Lambda - f_{R0} \frac{R_0^2}{R}$$

$$f_{R0} \equiv -2\Lambda m^2 / R_0^2$$







- x-ray signature of intra-cluster gas
- Sunyaev-Zel'dovich decrement in effective temperature of cosmic microwave background photons
- weak and strong lensing
- Member galaxies
  - counting
  - spectroscopy

- assign likelihood for observed mass for a true mass $p(M_{obs} \mid M)$ with a bias and a scatter included; allow to differ in redshift and mass bins
- completely free form does not allow cosmology fit (Lima & Hu)
- e.g. $\ln M_{bias} = A + n \ln(1+z)$
  - better form for particular selections, see later
  - e.g. $\sigma_{\ln M}^2 = A + Bz + Cz^2 + \ldots$
  - this is ad hoc

General form:

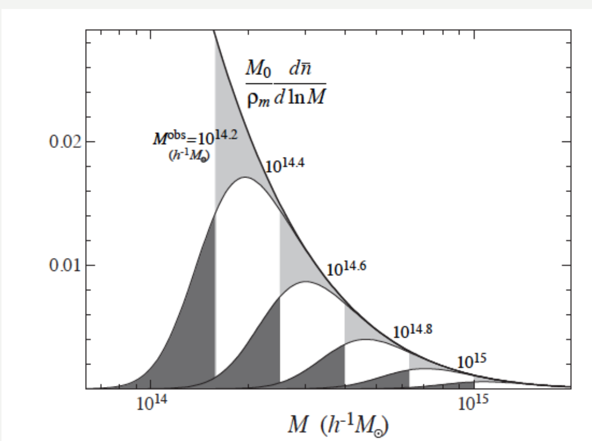
$$n_i = \int_{M^i_{obs}}^{M^{i+1}_{obs}} \frac{dM_{obs}}{M_{obs}} \int \frac{dM}{M} \frac{dn}{d\ln M} p(M_{obs}|M)$$

Simple Scatter Analysis

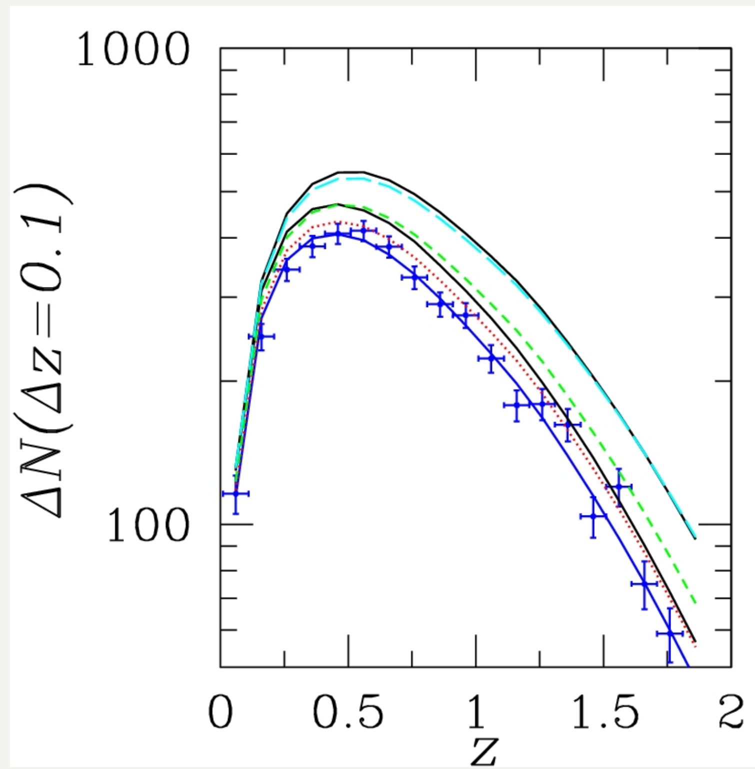
$$\frac{dN}{dz} = \Delta\Omega \frac{dV}{dz d\Omega}(z) \int_0^\infty \phi(M,z) \frac{dn}{dM} dM$$

$$\phi(M,z) = \frac{1}{2}\left\{ erf\left[\frac{M - M_{lim}(z)}{\delta M_{lim}(z)}\right] + 1 \right\}$$

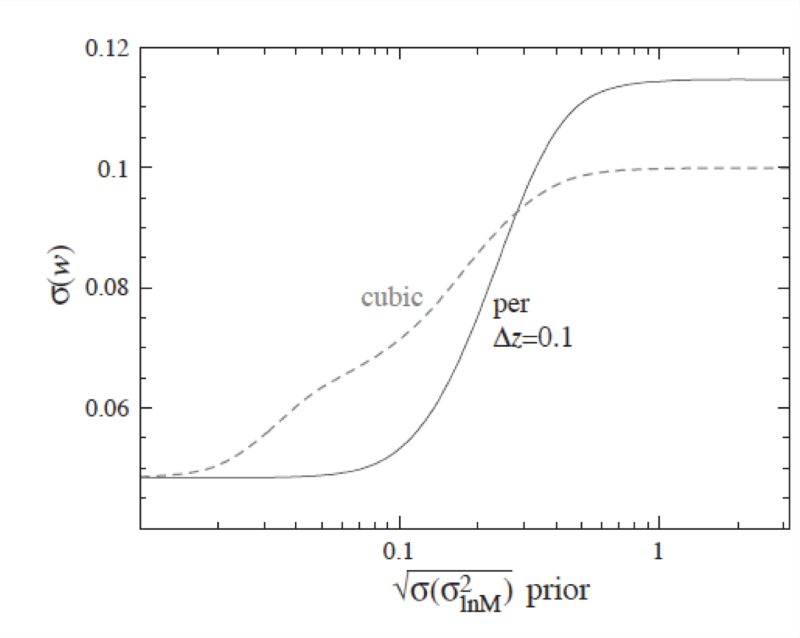
- dashed and dotted lines δ=20%, 30%, 40%



Lima & Hu 2005



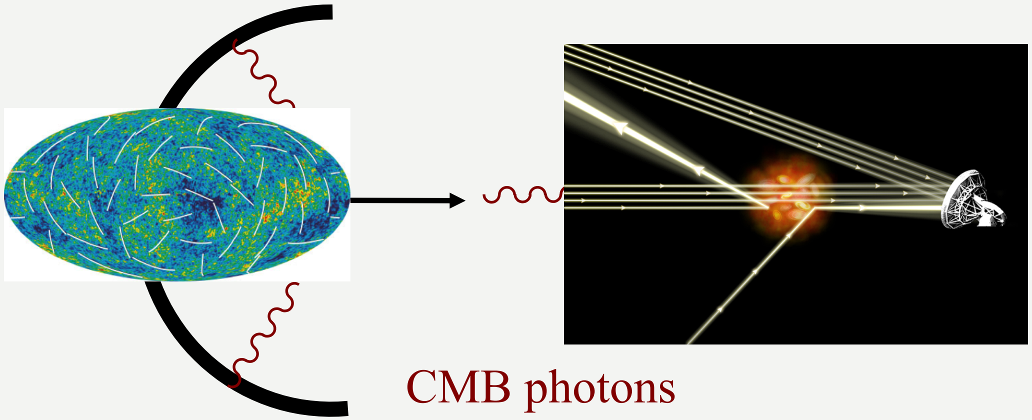
Impact of Uncertainty in Scatter

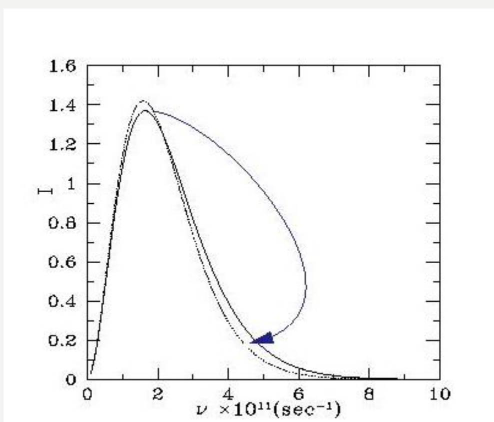


Lima & Hu 2005

- However: UNCERTAINTY IN SCATTER is problem
- Problem - mass - observable nuissance parameters are degenerate with cosmology
- Prior on uncertainty in scatter required !

SUNYAEV-ZEL'DOVICH EFFECT

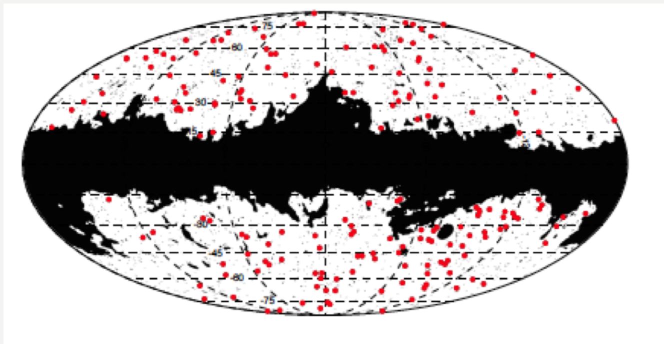


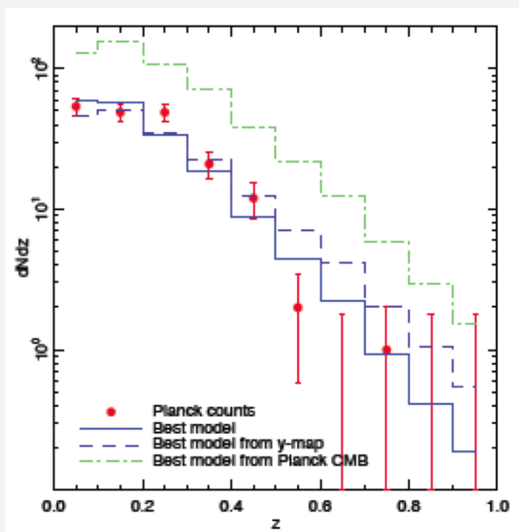


(Sunyaev+Zel'dovich: 1970)

- Compton Scattering: $e^- + \gamma \rightarrow e^- + \gamma$
- Conservation of overall number of photons
- Decrease in flux or temperature in Rayleigh - Jeans part of the spectrum
- Decrement independent of redshift. Cosmic diming $\sim(1+z)^{-4}$ is balanced by larger density of photons $\sim(1+z)^4$ which are (inverse) Compton scattered.
- First detection: Coma cluster by Parijskji 1972
- First unequivocal: Birkinshaw et al. 1984

The Planck 2013 Cluster Sample





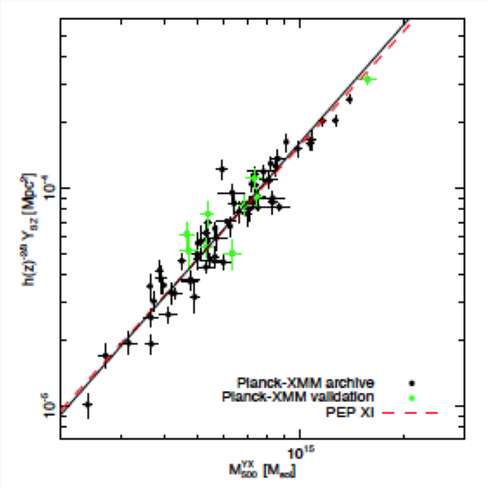
- Trade-off between purity and large sample
- 189 with S/N>7
- 188 with redshifts (184 spectroscopic)
- 71 used for scaling calibration

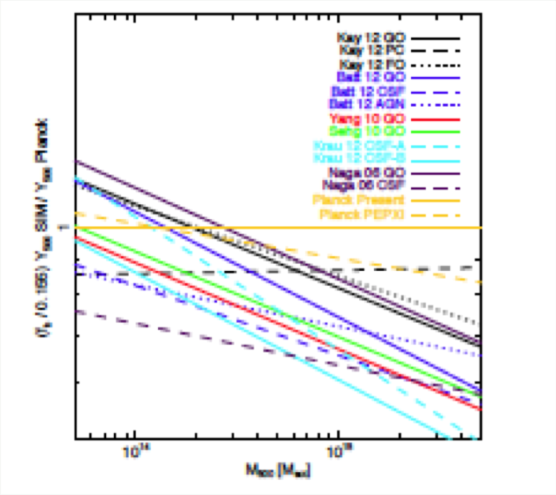
$$\frac{dN}{dz} = \int d\Omega dM_{500} \hat{\chi}(z, M_{500}, l, b) \frac{dN}{dz dM_{500} d\Omega}$$

- Mass function: Tinker et al.
- Scaling relation: Y-M from 71 Clusters
- Selection Function: Planck Noise Maps
- Sample: 189 PSZ Clusters

Scaling Relation

Planck 2013





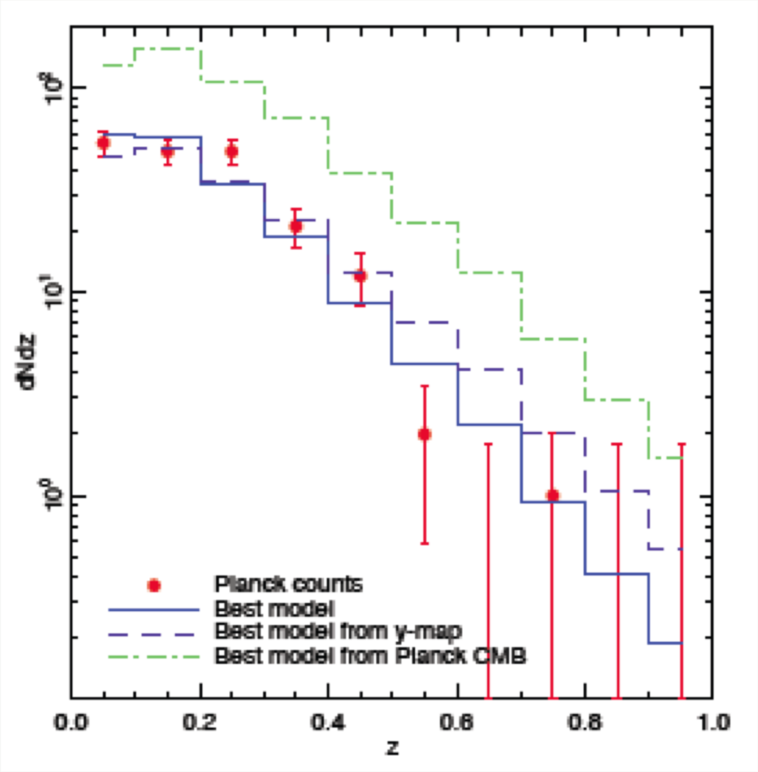
- 71 Clusters with XMM-Newton Data
- Scaling Y_{SZ}

$$E^{-\beta}(z)\left[\frac{d_A^2(z)\bar{Y}_{500}}{10^{-4}Mpc^2}\right] = Y_*\left[\frac{h}{0.7}\right]^{-2+\alpha}\left[\frac{(1-b)M_{500}}{6\times 10^{14}M_\odot}\right]^{\alpha}$$

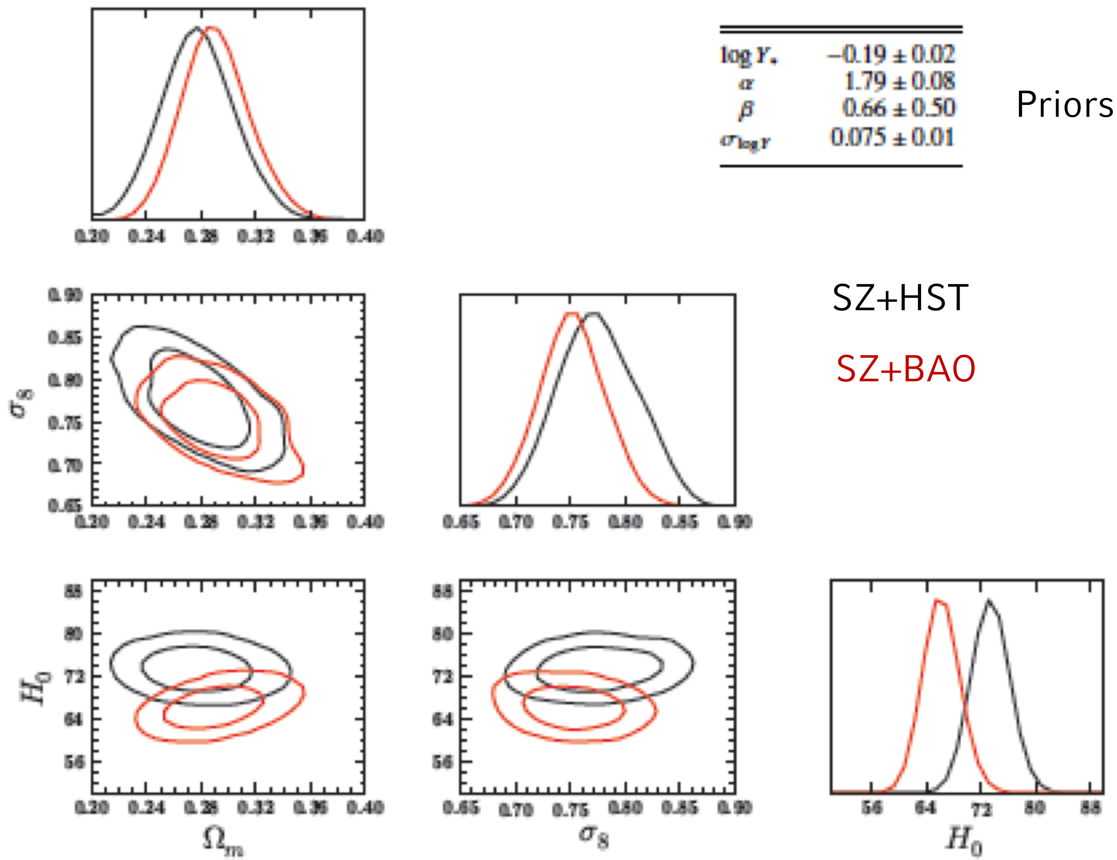
- log-normal scatter on Y
- allowed bias in scaling relation (compare to simulations): (1-b)=0.8 or [0.7-1.0]

The Number Counts of the 2013 Planck Sample

Planck 2013



Cosmological Constraints from the 2013 Sample

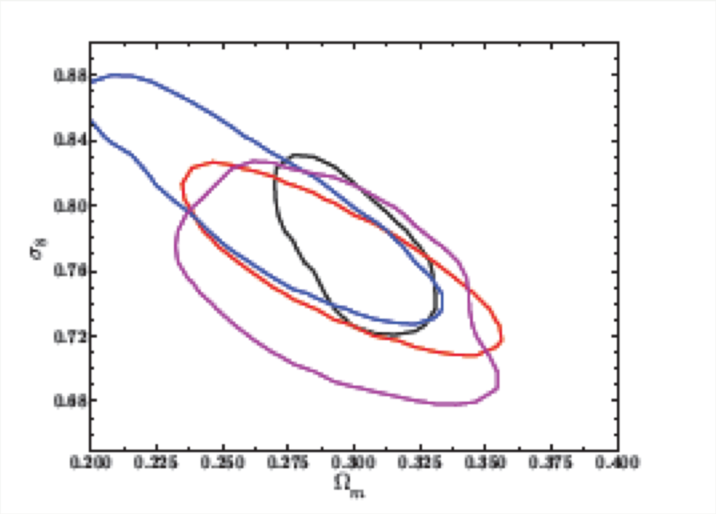


$\log Y_*$	-0.19 ± 0.02
α	1.79 ± 0.08
β	0.66 ± 0.50
$\sigma_{\log Y}$	0.075 ± 0.01

Planck 2013

n_s, Ω_b, Y_*, $\alpha\sigma_{Y500}$ marginalized (1-b)=0.8 fixed

BBN prior

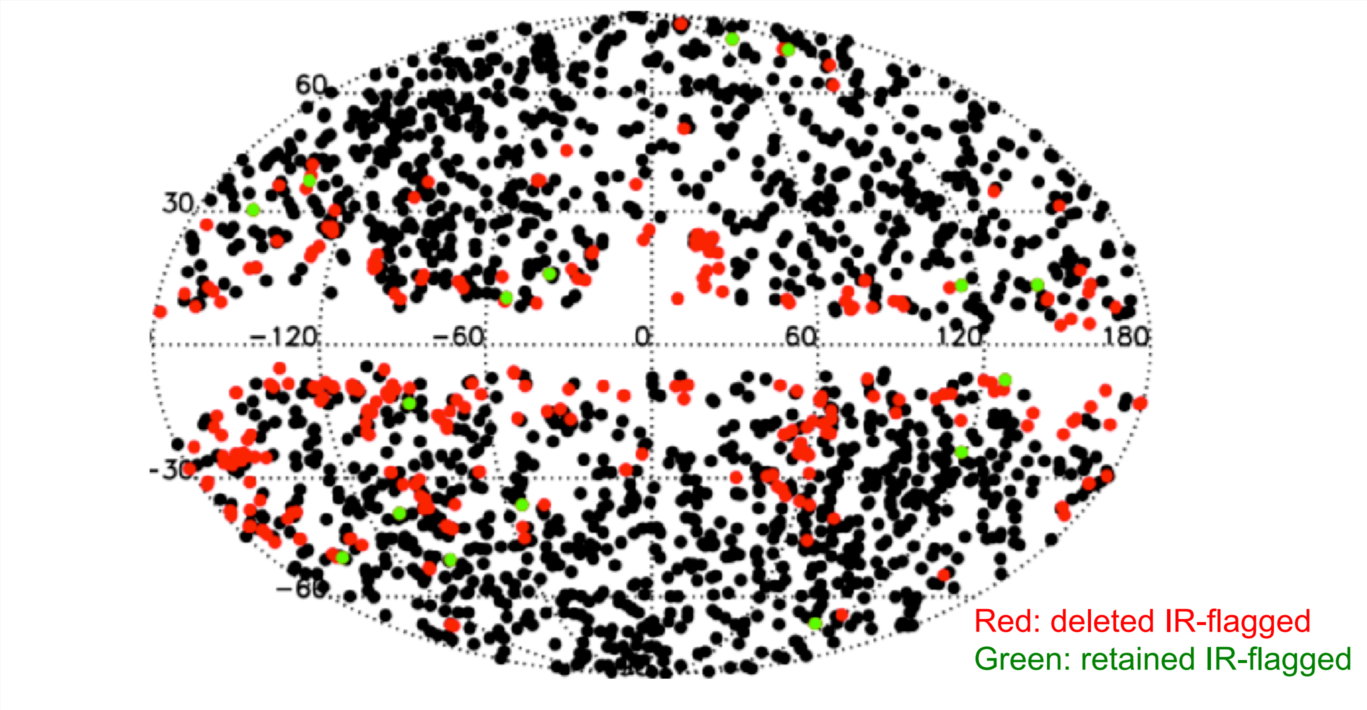


Planck 2013

- Standard Analysis
- Redshift evolution of scaling relation (β)
- Mass Function (Watson et al.)
- (1-b) in [0.7-1.0]

The Planck SZ2 Catalogue

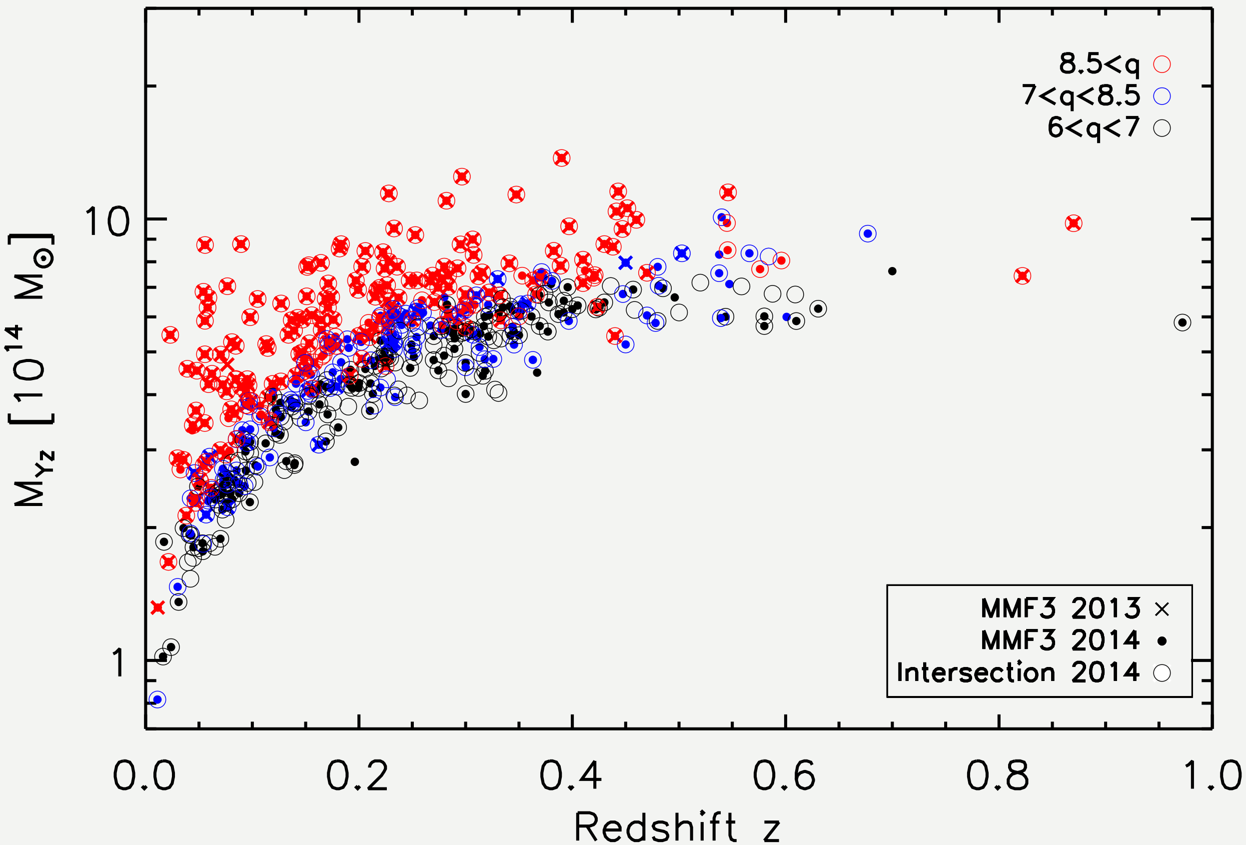
1653 sources
with S/N > 4.5



Planck 2015: XXVII
Corresponding author: D. Sutton

The Mass-Redshift Distribution of the Planck 2015 Sample

Planck 2015



Using Counts in Redshift and Observable

Observation: $$\frac{dN}{dzdq}$$

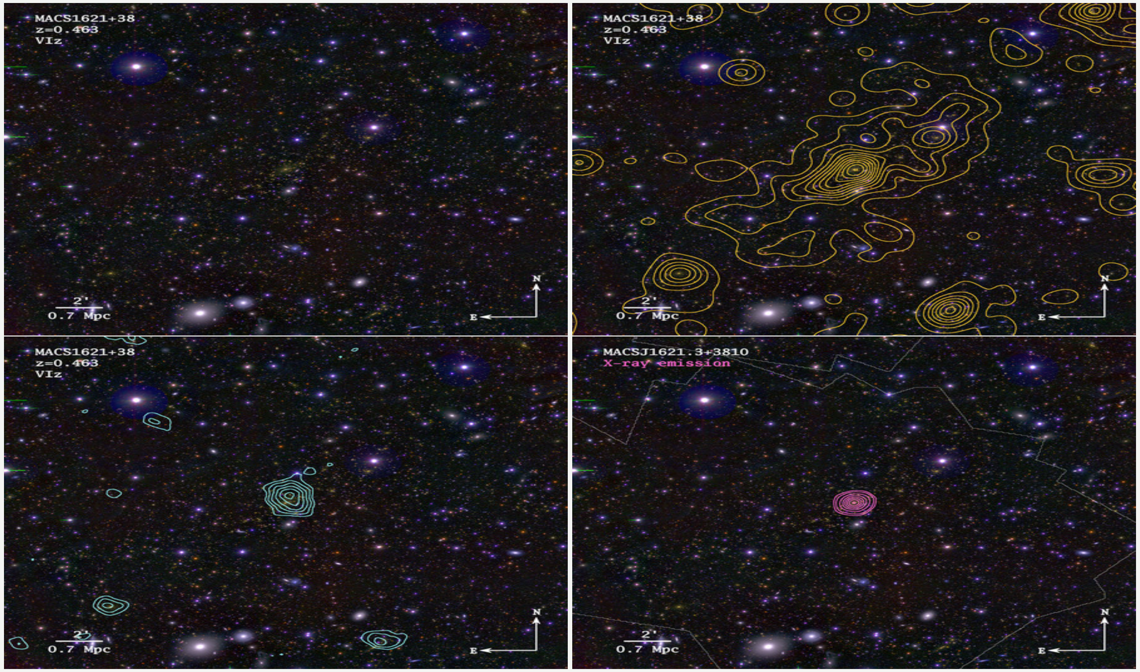
Theory: $$\frac{dN}{dzdq} = \int d\Omega_{\rm mask} \int dM_{500} \frac{dN}{dzdM_{500}d\Omega} P[q|\bar{q}_m(M_{500}, z, l, b)]$$

Mass function

Scaling law
completeness

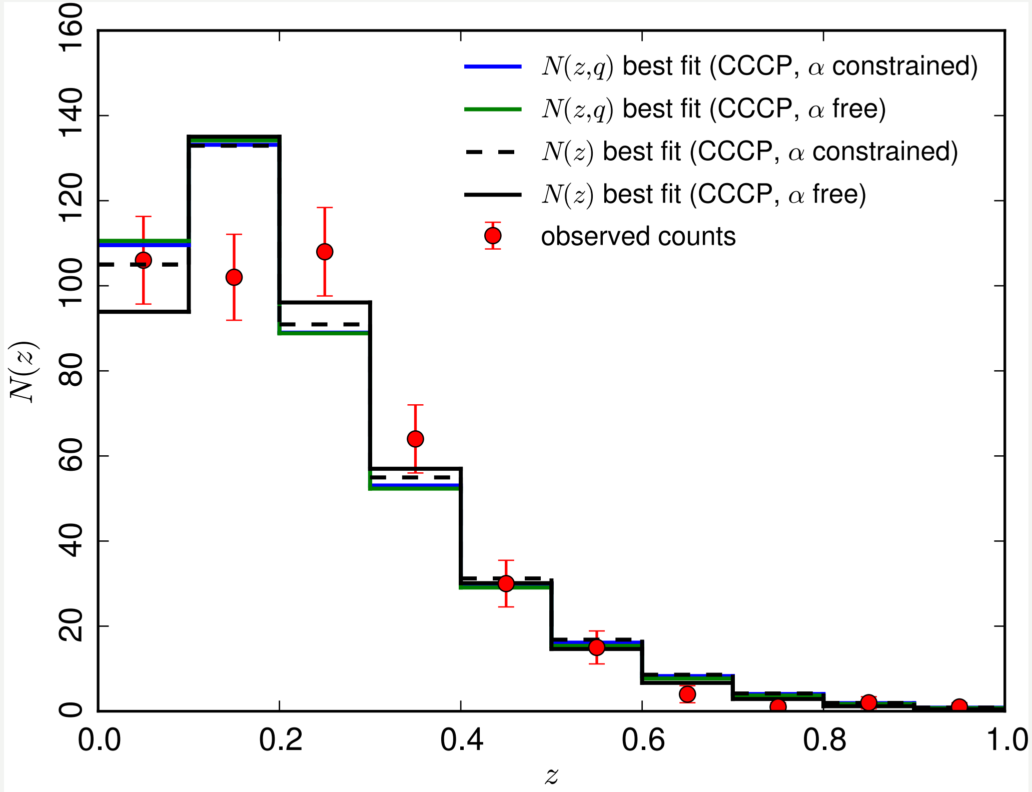
Different Mass Priors

Prior name	Quantity	Value & Gaussian errors
Weighing the Giants (WtG)	$1 - b$	0.688 ± 0.072
Canadian Cluster Comparison Project (CCCP)	$1 - b$	0.780 ± 0.092
CMB lensing (LENS)	$1/(1 - b)$	0.99 ± 0.19
Baseline 2013	$1 - b$	$0.8\,[-0.1, +0.2]$

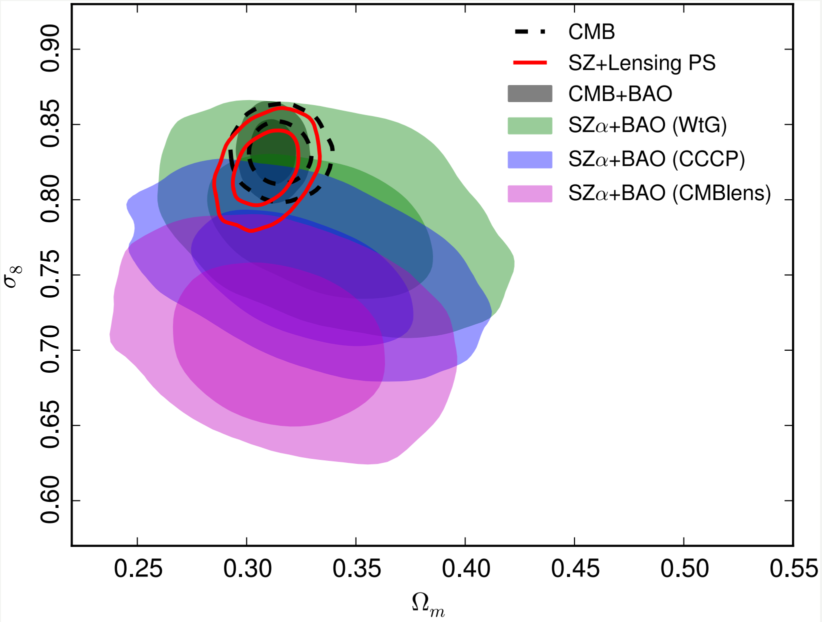


Best Fit Number Counts

Planck 2015

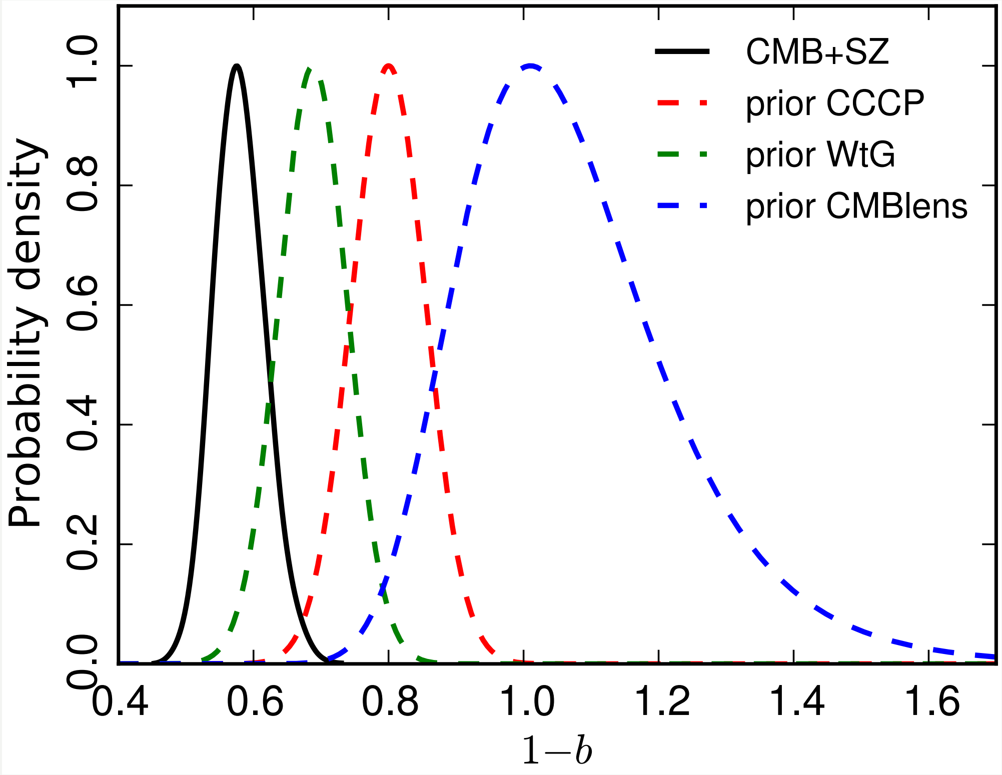


Cosmological Constraints



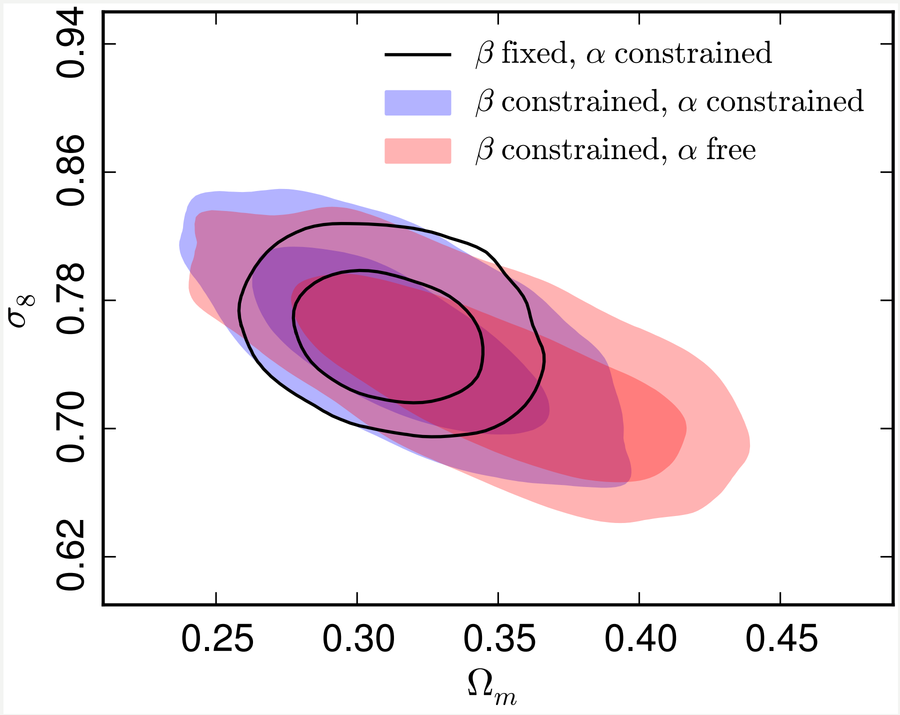
Planck 2015: XXIV
Corresponding Author's: A. Bonaldi and M. Roman

Hydrostatic Bias



Planck 2015: XXIV

Opening up the scaling relation



Planck 2015: XXIV

Update 2019: Counts and Cluster Powerspectra

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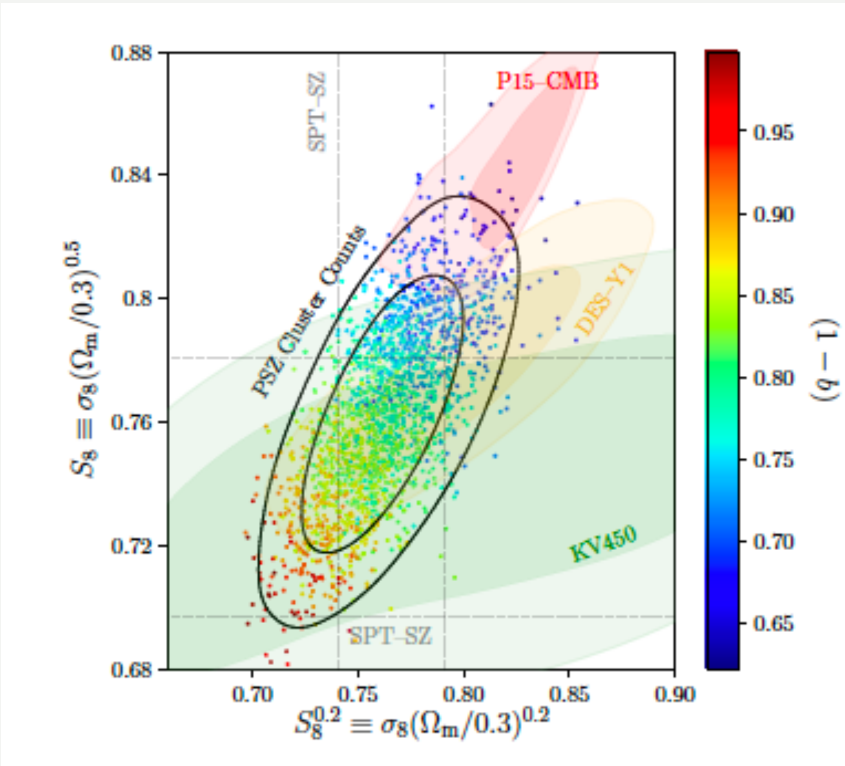
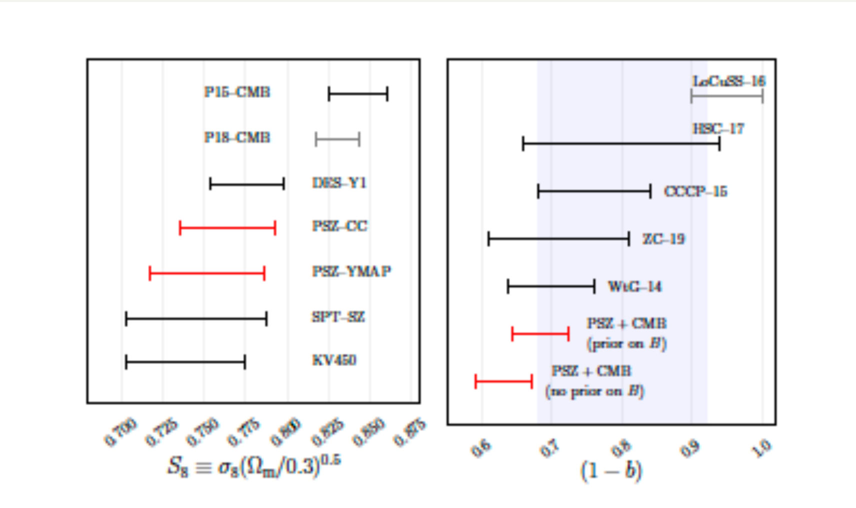
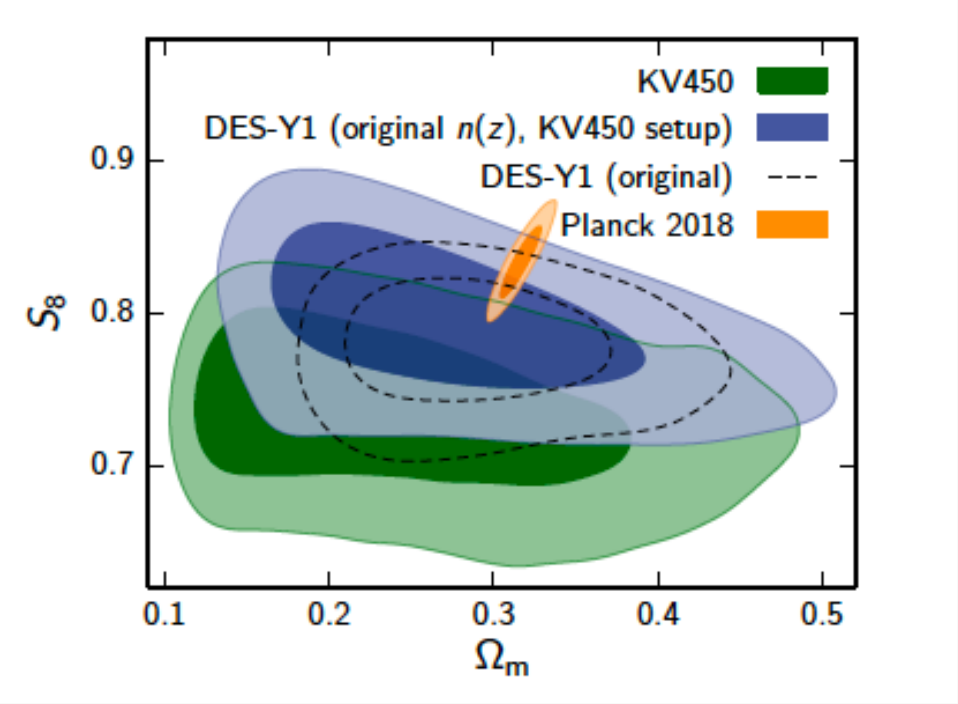




Bolliet et al. 2019

A note on Tensions: Weak Lensing

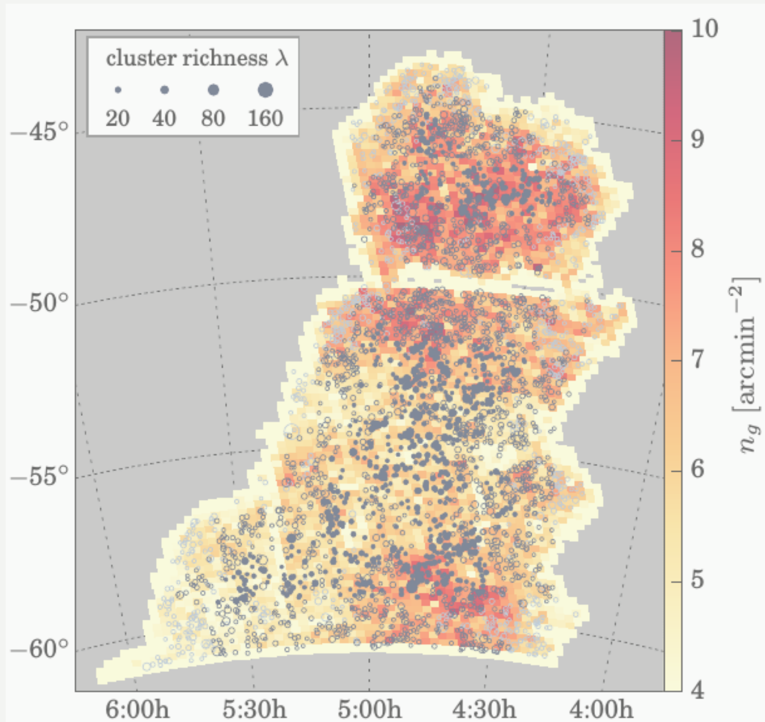


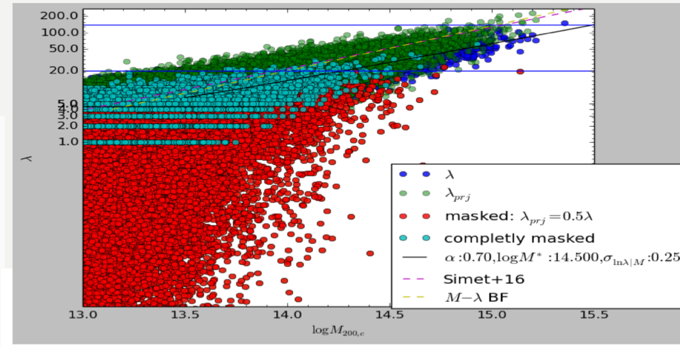
Joudaki et al. 2019

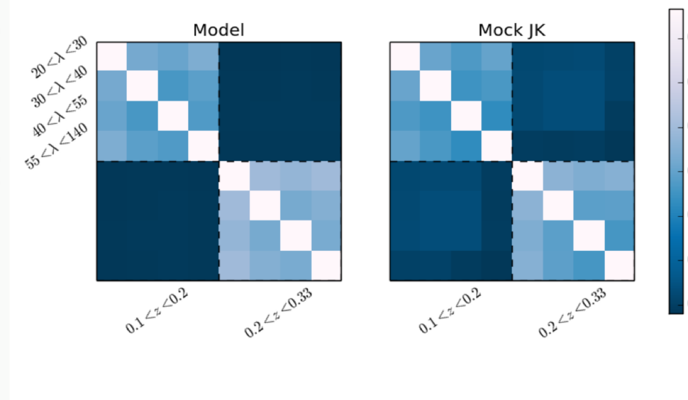
Analysis of optical selected cluster catalogs (SDSS, DES-SV) for cosmological parameter inference

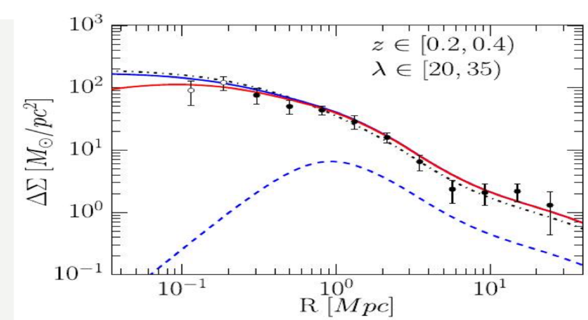
- Modeling of the observable-mass relation and cluster finder effects (masking, projection, etc etc)

- Modeling of the covariance matrix for cluster number counts analysis



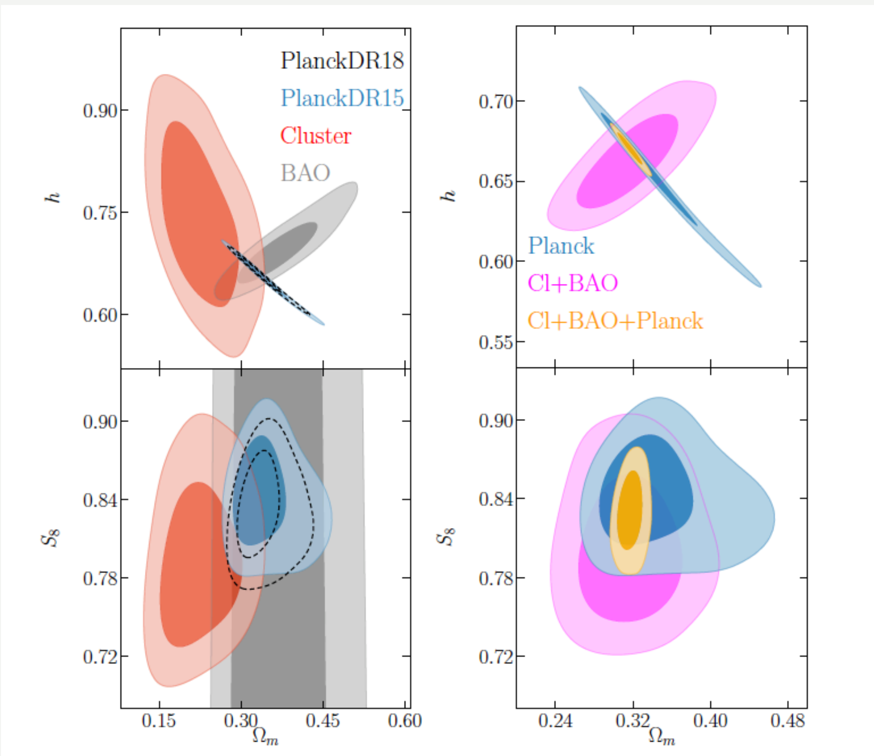






- Combining with cluster shear profile measurements to self-calibrate the observable-mass relation

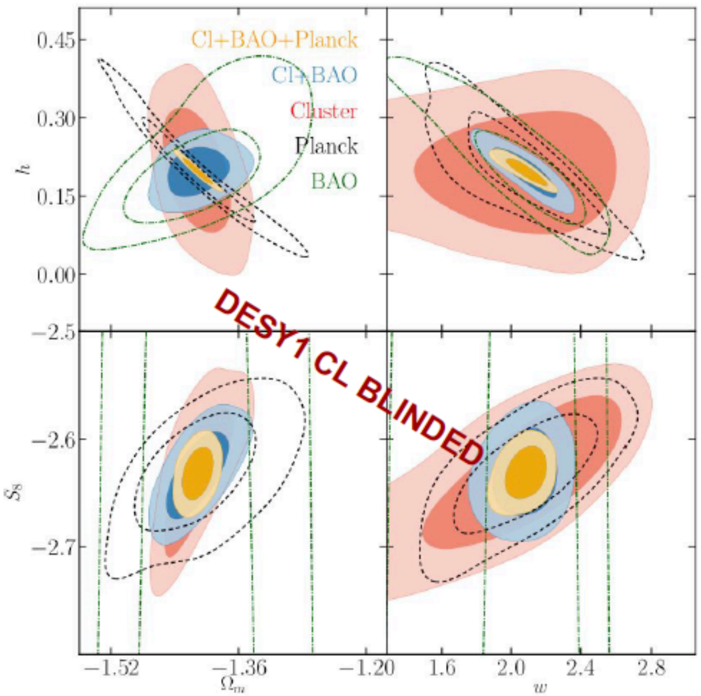
SDSS redMapper Cluster Cosmology

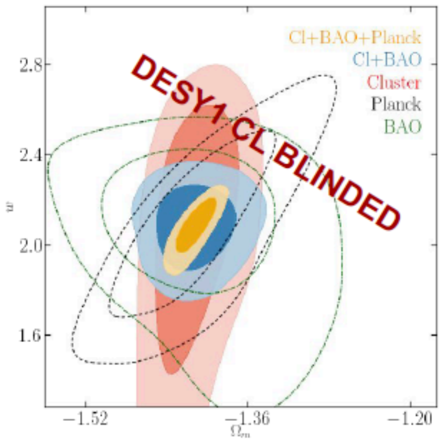


Costanzi et al. 2018

- $S_8 = \sigma_8 (\Omega_m / 0.3)^{0.5}$ Cluster Normalization\
- Abundance and Weak Lensing Mass calibration

Dark Energy Survey Results to come out soon



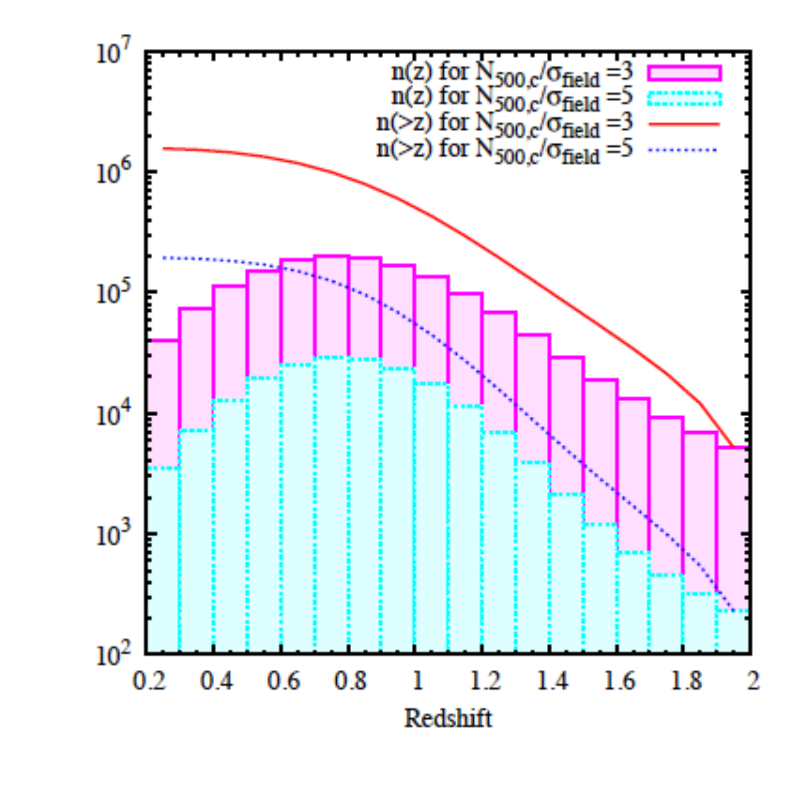


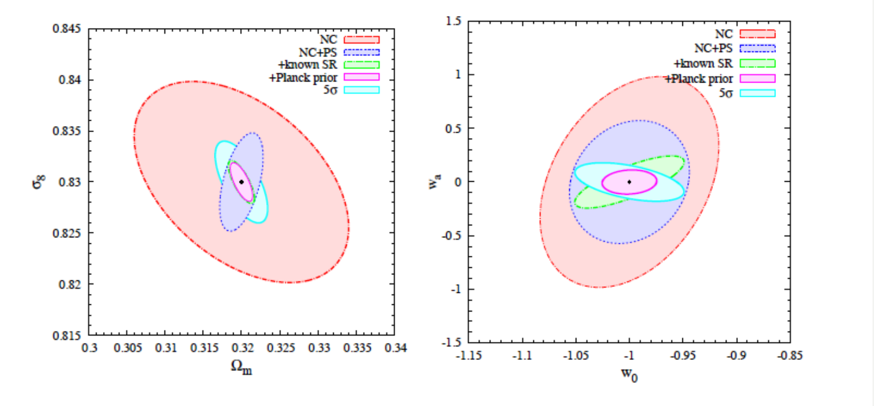
PRELIMINARY

	wCDM+ν	
	ΔS_8	Δw
Cl-only	0.045	0.35
Planck DR15	0.035	0.27
Cl+BAO	0.026	0.12

Costanzi, DES collaboration, to be released 2019

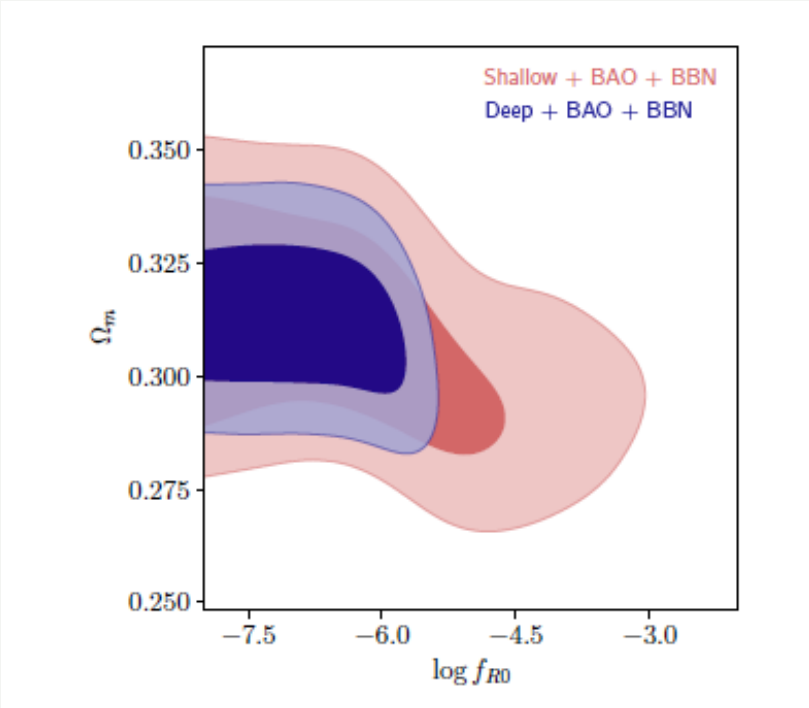
Euclid Satellite as a Cluster Finder





Sartoris et al. 2016

Potential Constraints on Scalar-Tensor Theories with Euclid like Survey



- Forecast: Constraints from a Euclid like survey on scalar-tensor theories

Hagstotz et al. 2018

Summary / Conclusions

- Clusters of Galaxies deliver interesting constraints on cosmological parameters
- From SZ Clusters tension with primary CMB constraints
  - Astrophysics of Clusters might need to be better understood
- Optically selected Clusters are beginning to deliver constraints
- Many more to come
  - Dark Energy Survey – DES – ongoing; paper out soon
  - eRosita – now launch July, 12th
  - EUCLID - 2022