# Constraining Models of Cosmic Acceleration with Galaxy Cluster Surveys

Jochen Weller

University Observatory Ludwig-Maximilians University

Excellence Cluster Universe

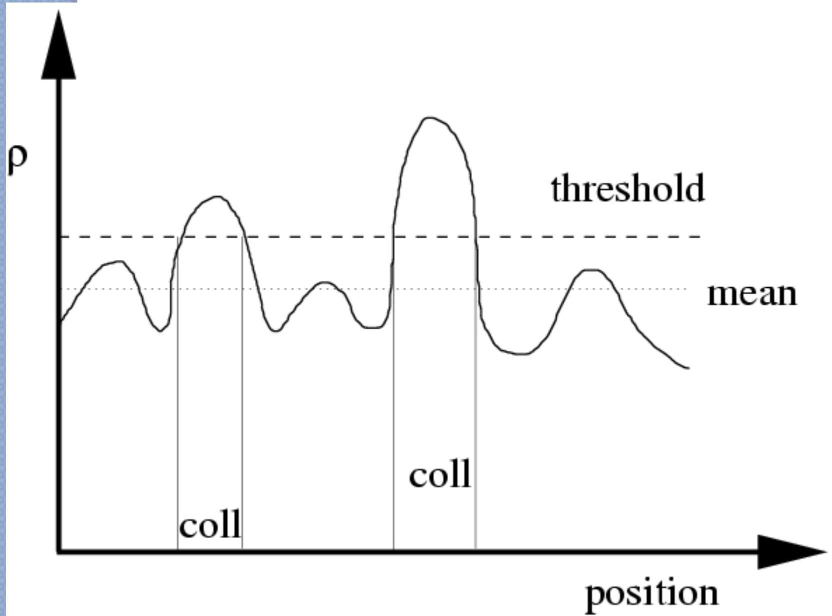
Max-Planck-Institute for Extraterrestrial Physics

TUM

LMU

Excellence Cluster Universe

# Galaxy Clusters as a Probe of Structure Formation in the Universe



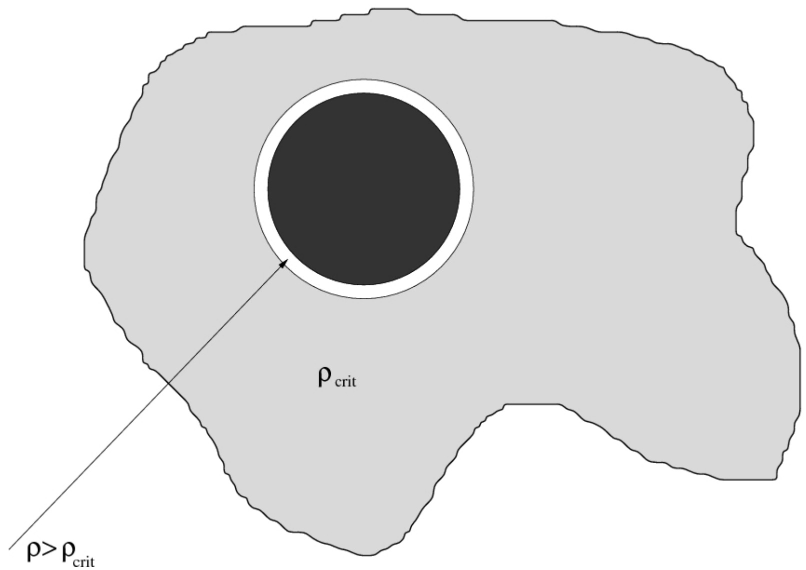

- If linear density perturbation exceeds threshold density the region will collapse and form a cluster
- Mass function; density of clusters at a given mass and redshift
- Mass function sensitive to amplitude of perturbations ($\sigma_8$) and mass contents of the Universe ($\Omega_m$); but also other cosmological parameters (w) !

# The Distribution of Dark Matter Haloes

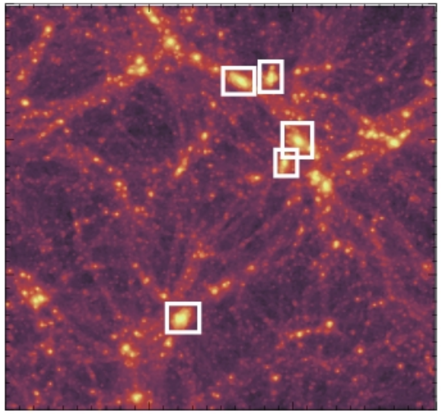
- Simple: assume Gaussian distributed density fluctuations
- calculate probability that region with overdensity $\delta$ larger than some critical density $\delta_c$ is found
- Normalize to account for total mass-density in the Universe: fudge factor 2
- Press-Schechter mass function (Press, Schechter 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)

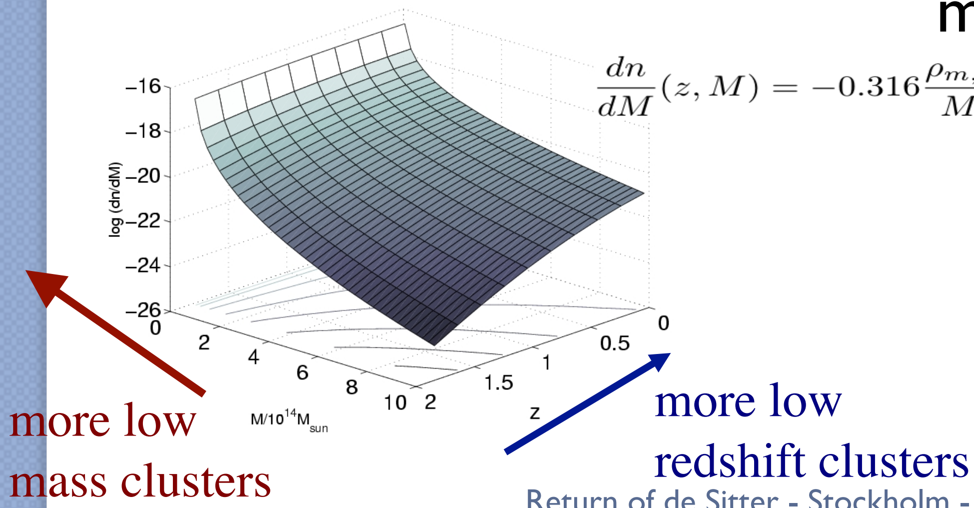


# Overcoming Analytical Uncertainties: Counting Halos in Simulations !



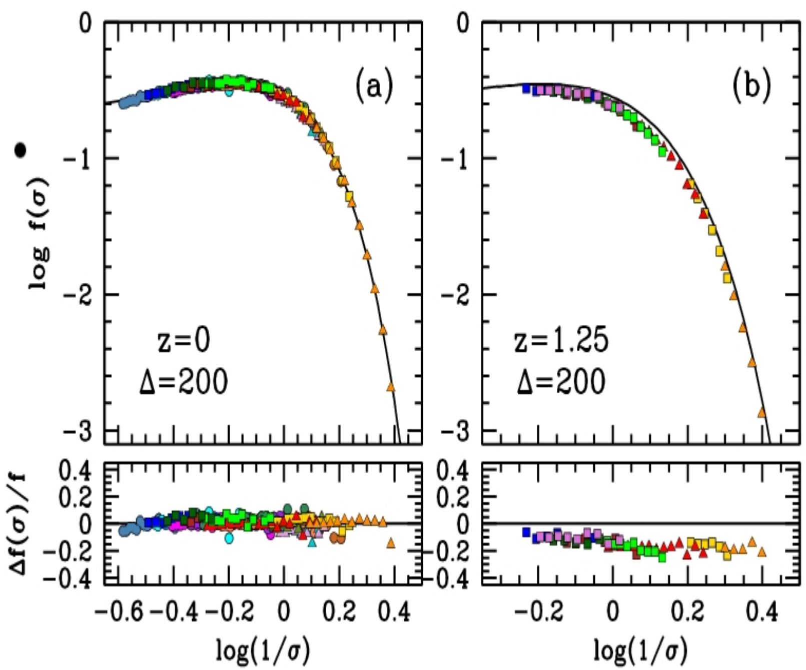
- Count halos in N-body simulations
- Measure "universal" mass function - density of cold dark matter halos of given mass

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



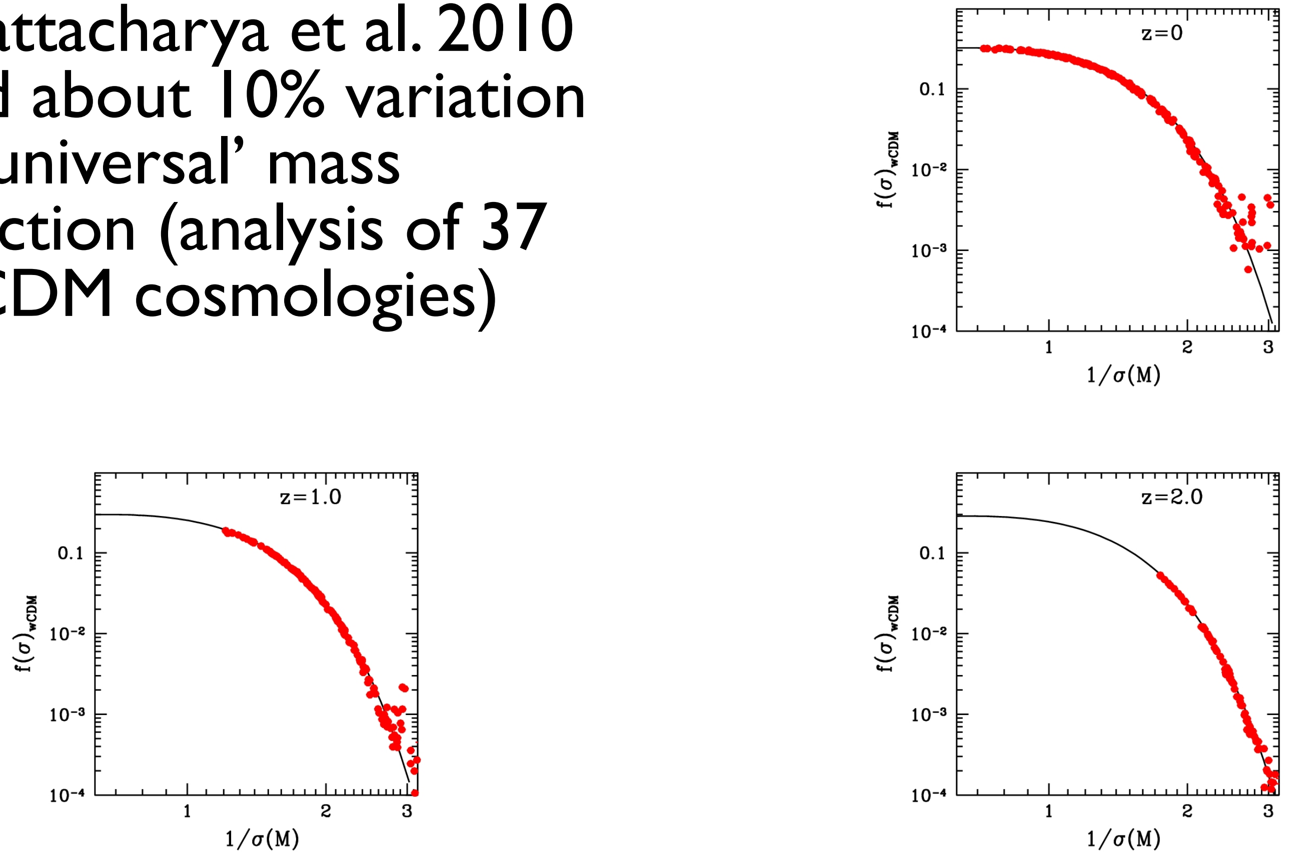
# Universality of the Mass Function - I

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



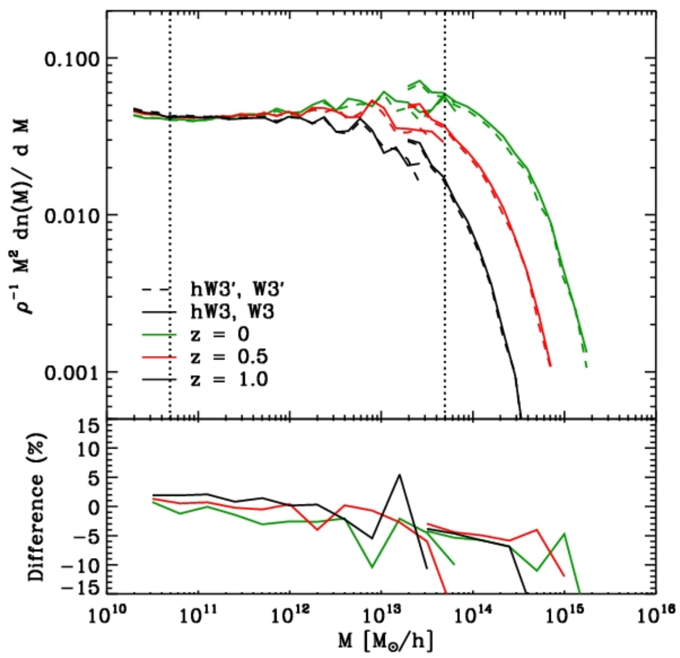
# Universality of the Mass Function - II

- Bhattacharya et al. 2010 find about 10% variation in 'universal' mass function (analysis of 37 wCDM cosmologies)



# One Simulation to Fit them All ?

- In order to do measure cosmological parameters, require fast way to do calculate mass function for a lot of cosmological models
- Idea:  Scale original simulation (masses, length, velocities)
  - possible drawback, only works close to simulated model
- Alternative: Simulate a few models  and then interpolate between them or a neural network approach – emulate: Heitman et al. 2009




Angulo & White 2009

# Cosmology Dependence of the Mass Function

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

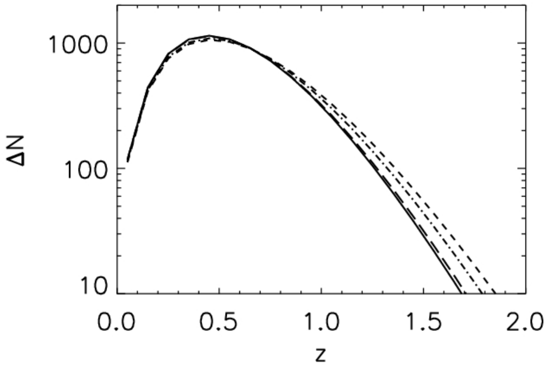
- mass density
- power law dependence on fluctuation amplitude
- strong power law dependence on growth factor

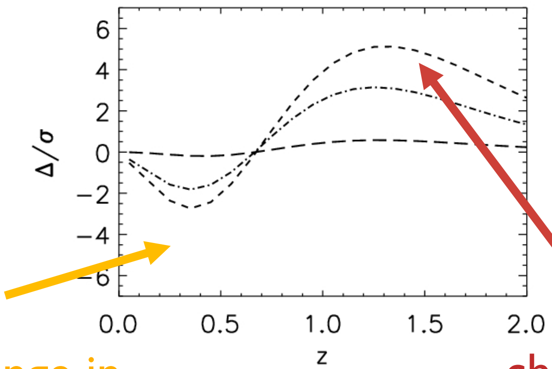
# Predicting Cluster Number Counts

$$\Delta N(z) = \Delta\Omega \int_{z-\Delta z/2}^{z+\Delta z/2} dz \frac{d^2V}{d\Omega dz} \int_{M_{\rm lim}}^{\infty} \frac{dn}{dM}\, dM$$

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

# Cosmology Dependence of Number Counts

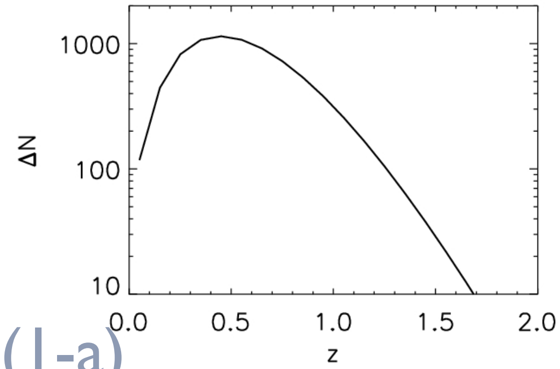


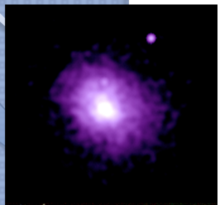
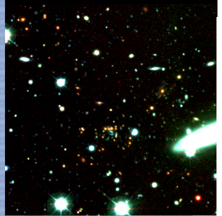
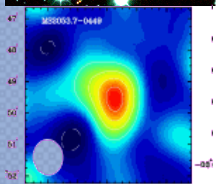
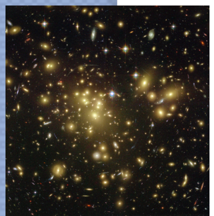

change in volume

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 $deg^2$ $M_{lim} = 1.7\times10^{14}h^{-1}M_\odot$
- $\Omega_m = 0.4$
- $\sigma_8 = 0.85$
- w = - 0.8
- w = - 0.7
- w = -1+0.2(1-a)

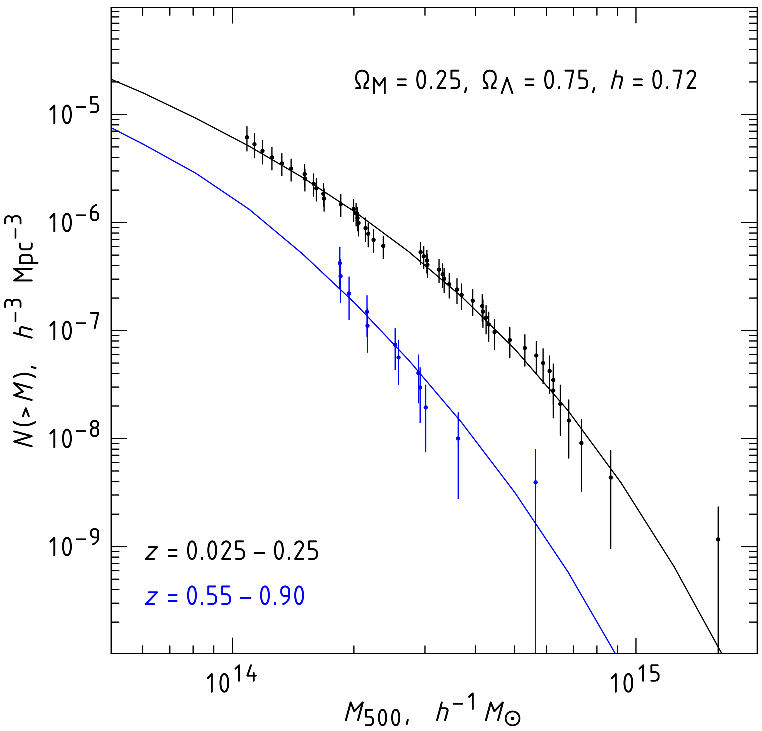


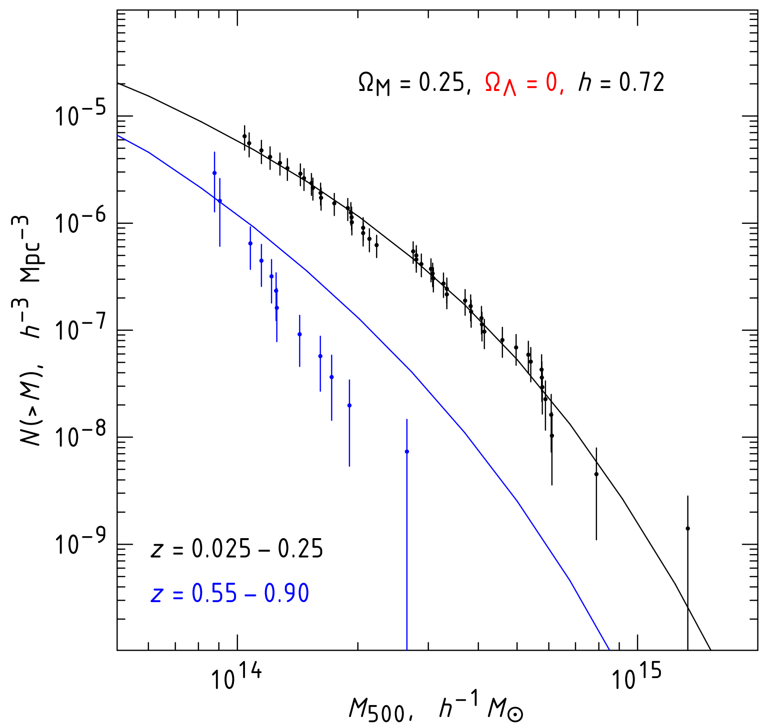
# Observation of Galaxy Clusters

- 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

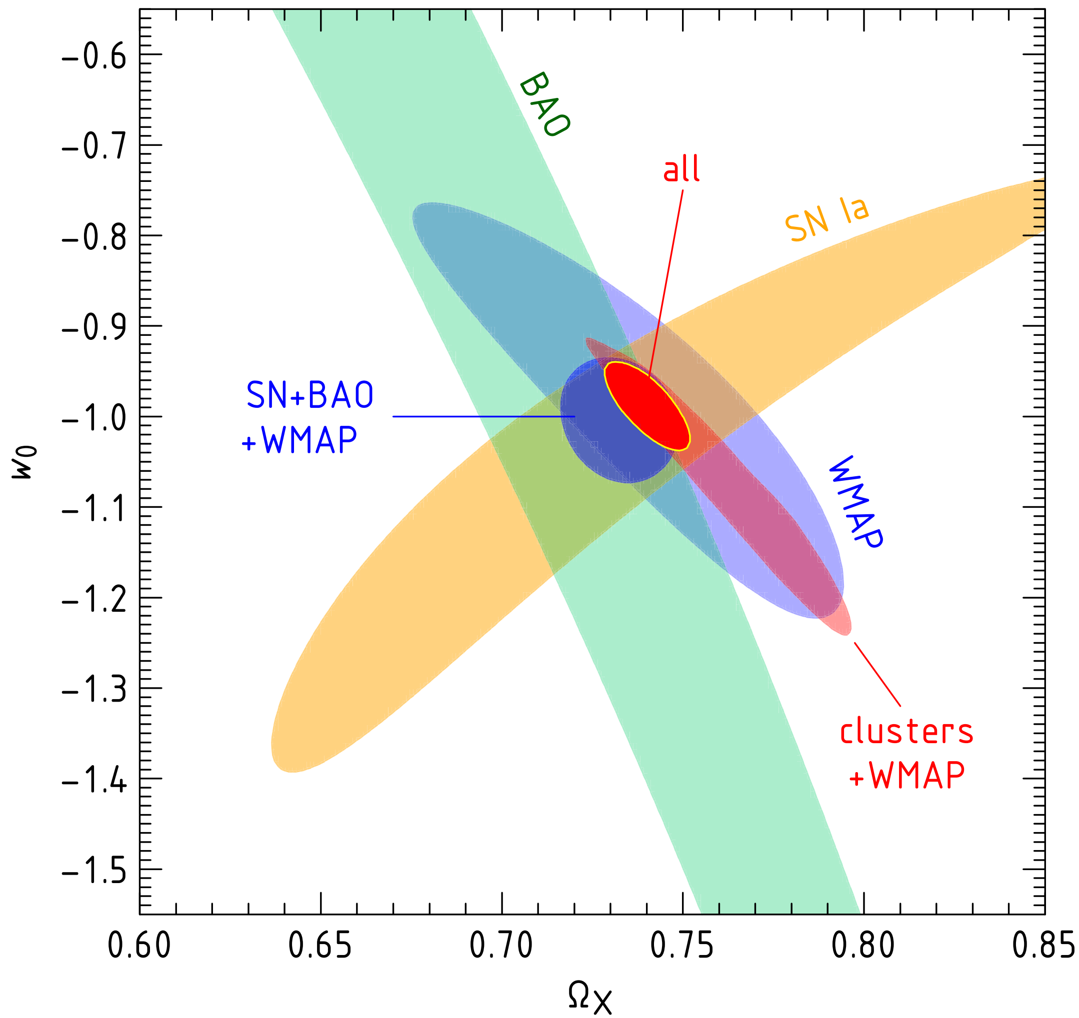
# Number counts from x-ray observations




37 Chandra clusters at high redshift
49 low redshift clusters with ROSAT
Vikhlinin et al. 2009

# Cosmological Constraints with Chandra




Vikhlinin et al. 2009

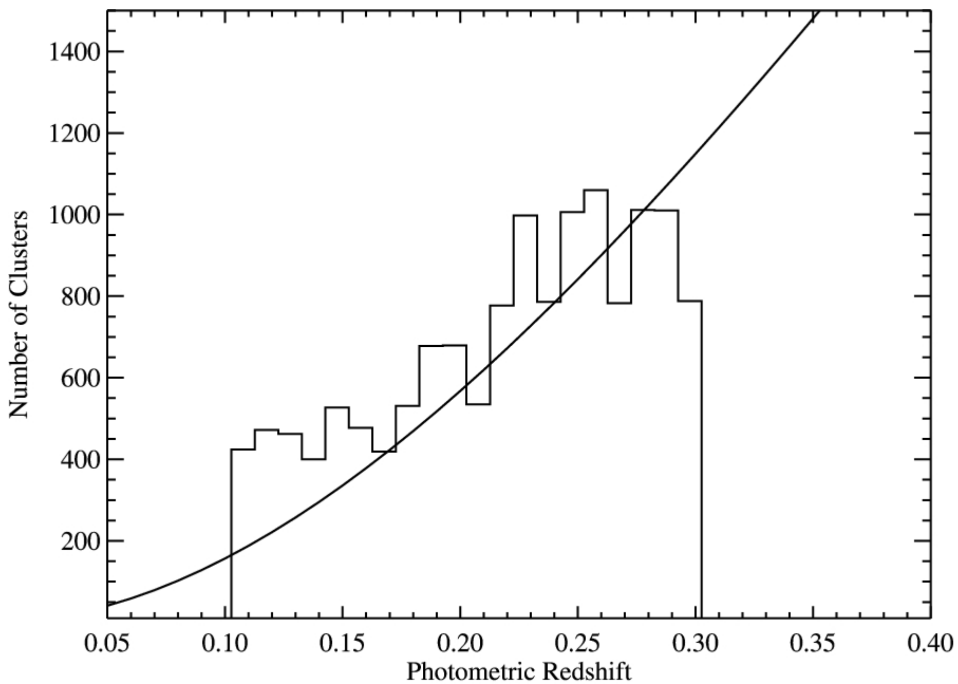
# Example: maxBCG Catalog of the SDSS

- Koester et al. 2007
  - over 13,000 clusters with $\sigma > 400$ km/s
  - redshift range $0.1<z<0.3$
- maxBCG exploits three features of clusters
  - 1/r decrease of spatial clustering in clusters (2D projection)
  - most luminous galaxies in clusters occupy tight sequence (E/S0 ridgeline) in color-magnitude diagram
  - Brightest Cluster Galaxy resides in ridgeline (≈at center of cluster)
  - maxBCG provides redshift estimate (photometric of the cluster center) and a scaled richness $N_{gals}^{r200}$
- For $N_{gals}>20$ better than 90% completeness

# The Algorithm

1. Using the likelihood function, each object in an input galaxy catalog is tested at an array of redshifts for the likelihood that it is a cluster center.
2. Each object is assigned the redshift which maximizes this likelihood function.
3. The objects are ranked by these maximum likelihoods.
4. The object with the highest likelihood in the list becomes the first cluster center. All other objects within z = ±0.02 (the typical $\sigma z$ on a red galaxy), a scaled radius r200, and lower maximum likelihood are removed from the list of potential centers.
5. The next object in the list is handled similarly, and the process is continued, flagging other potential cluster centers within that object's neighborhood which have lower likeli- hoods.
6. All unflagged objects at the end of this percolation are kept, and are taken as BCGs identifying clusters in the final cluster list.

# The SDSS maxBCG Catalog




Koester et al. 2007

# From Richness to Mass

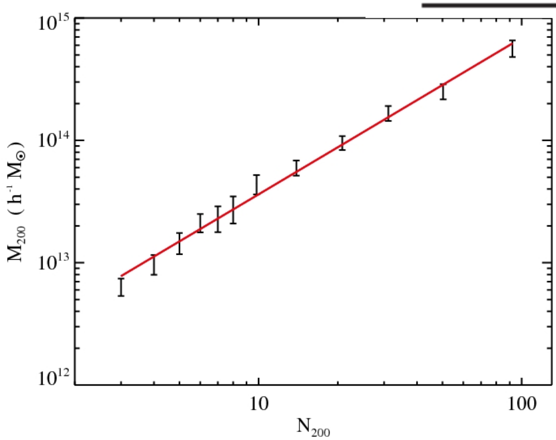
- Estimate mass with weak lensing (Sheldon et al. 2007, Johnston et al. 2007)
  - stacked over richness bins

ABUNDANCE OF MAXBCG CLUSTERS

| Richness | No. of Clusters |
|---|---|
| 11-14 | 5167 |
| 14-18 | 2387 |
| 19-23 | 1504 |
| 24-29 | 765 |
| 30-38 | 533 |
| 39-48 | 230 |
| 49-61 | 134 |
| 62-78 | 59 |
| 79-120 | 31 |

MEAN MASS OF MAXBCG CLUSTERS

| Richness | No. of Clusters | $\langle M_{200b} \rangle$ [$10^{14}$ $M_\odot$] |
|---|---|---|
| 12-17 | 5651 | 1.298 |
| 18-25 | 2269 | 1.983 |
| 26-40 | 1021 | 3.846 |
| 41-70 | 353 | 5.475 |
| 71+ | 55 | 13.03 |




Rozo et al. 2009

Johnston et al. 2007

# Uncertainty in Mass Limit

- Mean mass observable relation
  - scaling laws dependent on method – not entirely determined: redshift and mass dependence
  - different methods can be used for cross calibration
- individual scatter in mass observable relation
  - how behave the tails
    - high redshift, low mass, high mass, etc.
  - degenerate with cosmology
  - can also be estimated by surveys
    - Rozo et al.: optical, x-ray and weak lensing find 0.45±0.20

# General Form for Scaling and Scatter

- assign likelihood for observed mass for a true mass p ($M_{obs}$ | M ) with a bias and a scatter included; allow to differ in redshift and mass bins

$$p(M_{obs}|M) = \frac{1}{\sqrt{2\pi\sigma^2_{\ln M}}} \exp\left[-x^2(M_{obs})\right]$$

$$x(M_{obs}) = \frac{\ln M_{obs} - \ln M - \ln M_{bias}}{\sigma_{\ln M}}$$

- completely free form does not allow cosmology fit (Lima & Hu)
- $\ln M_{bias} = A + n \ln(1+z)$
  - better form for particular selections possible
- $\sigma_{\ln M}{}^2 = A + Bz + Cz^2 + \ldots$
  - so far this is ad hoc

# Self-Calibration

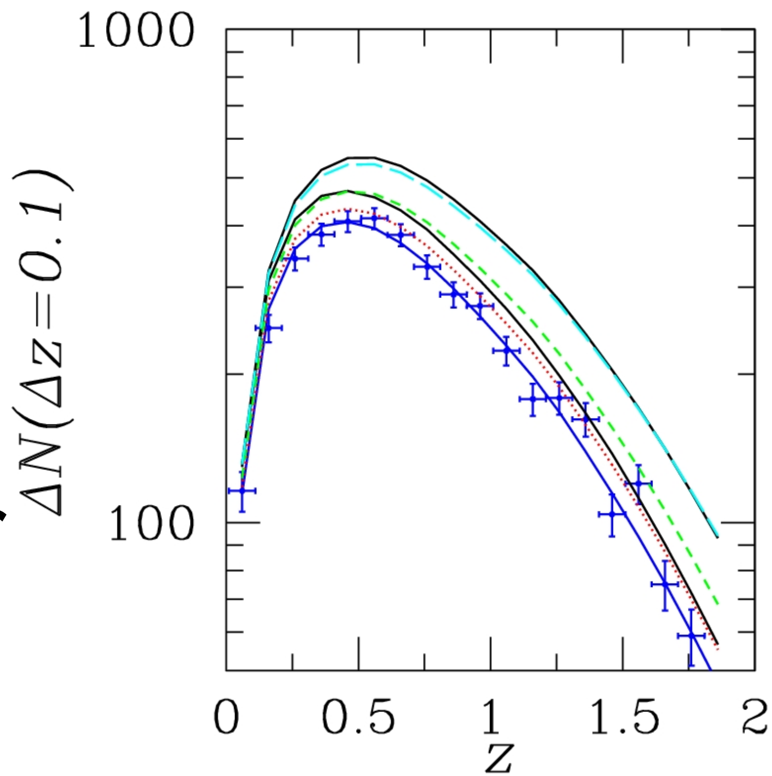
$$n_i = \int_{M_{obs}^{i}}^{M_{obs}^{i+1}} \frac{dM_{obs}}{M_{obs}} \int \frac{dM}{M} \frac{dn}{d\ln M} p(M_{obs}|M)$$

- Exploit shape of mass function to calibrate for bias and scatter in constant mass bins
- Further use clustering of clusters (cross-correlated to other probes ? Not used here! )
- Result: scatter in mass-observable relation is not the problem: Increases number of clusters, hence better statistics
- Uncertainty in scatter is PROBLEM

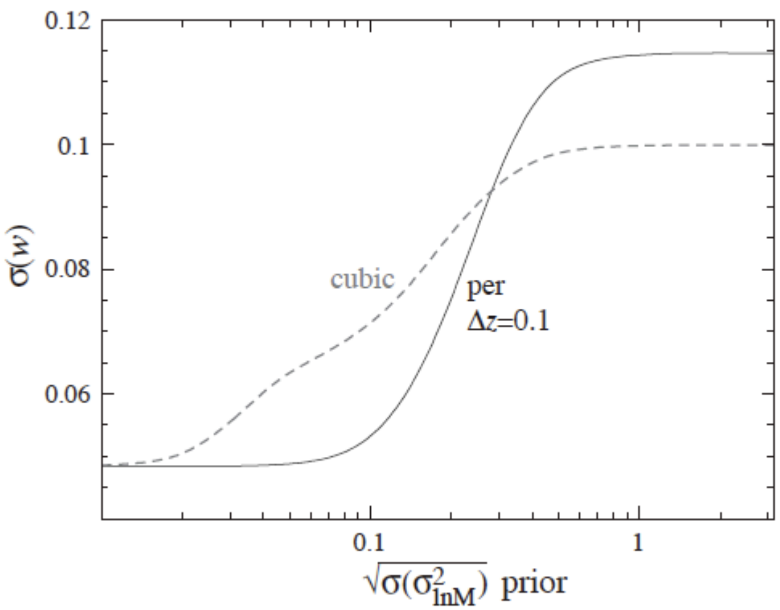
# Simple Scatter Analysis

$$\frac{dN}{dz} = \Delta\Omega \frac{dV}{dz d\Omega}(z) \int_0^\infty \phi(M,z) \frac{dn}{dM} dM \qquad \phi(M,z) = \frac{1}{2}\left\{erf\left[\frac{M - M_{lim}(z)}{\delta M_{lim}(z)}\right] + 1\right\}$$

- dashed and dotted lines $\delta$=20%, 30%, 40%
- did not marginalize over scatter - need prior



# Impact of Uncertainty in Scatter on Cosmological Parameter Estimation



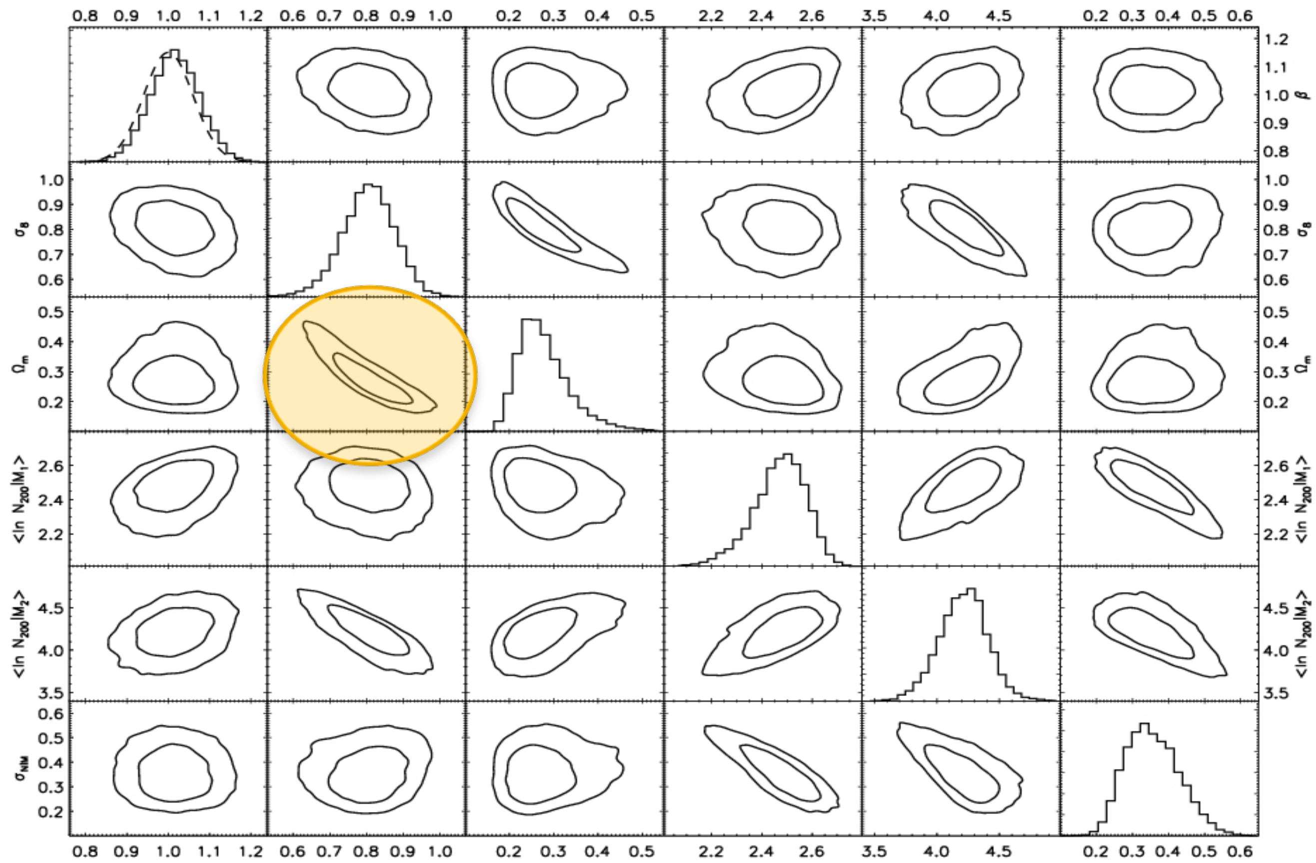

Lima & Hu 2004

- However: UNCERTAINTY IN SCATTER is problem
- Problem - mass - observable nuissance parameters are degenerate with cosmology (not included in the Lima & Hu free form fit)
- Prior on uncertainty in scatter required !

# Application to ‘Richness’ selected clusters

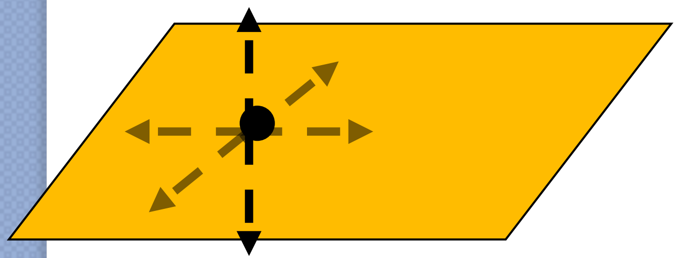
- assume $p(N_{200}|M)$ is log-normal distribution
- mean is linear in mass: 2 parameters
- one fixed scatter (prior range 0.1 … 1.5)
- include purity and completeness of sample (95%); errors added in quadrature
- allow for bias of weak lensing mass estimates

# Cosmology from SDSS maxBCG catalog



Rozo et al. 2009

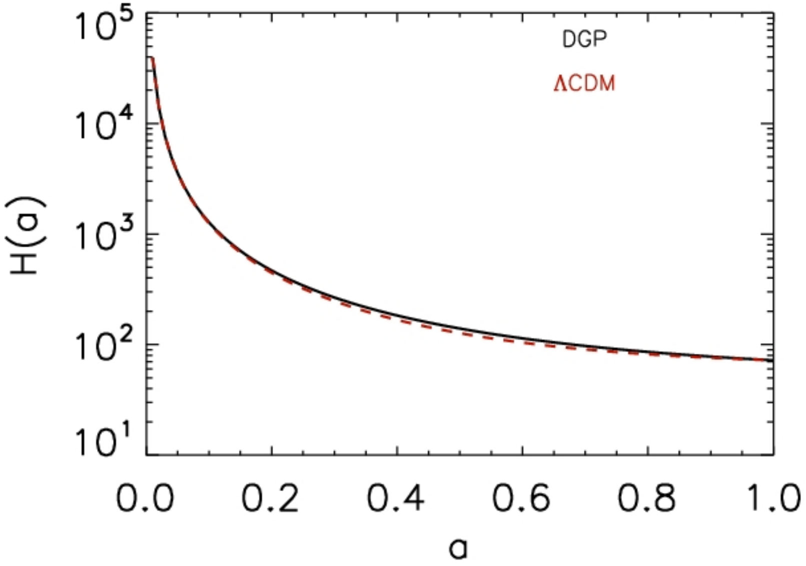
# Accelerated Expansion from Modified Gravity Model – Example: DGP



Dvali, Gabadadze, Porrati 2000

- Brane-world inspired scenario
- large extra dimension
- Standard model confined to the brane
- Gravity can leak of the brane into 5th dimension - cross over scale $r_c$
- Modification of Friedman equations
- has maybe intrinsic problems
- is ruled out by data (at least flat case)
- Better models see Appleby talk

# Modified Friedman Equation in DGP Model



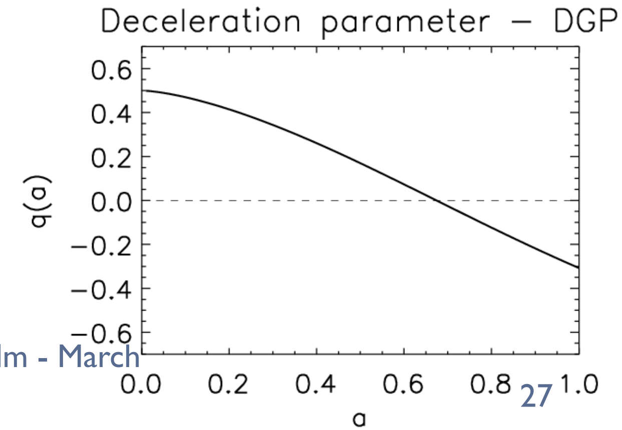

- modified equation

$$H^2 - \frac{H}{r_c} = \frac{8\pi G}{3}\rho_m$$

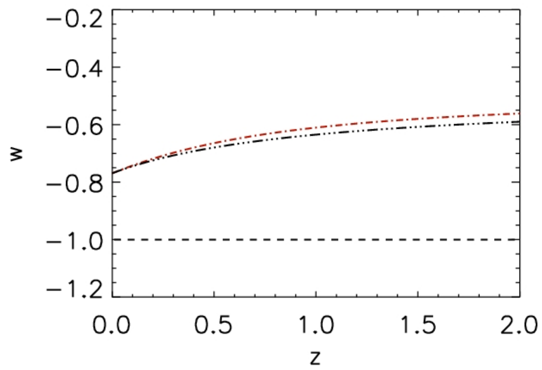
- accelerated branch as a solution

For flat Universe, condition:

$$\frac{1}{H_0 r_c} = 1 - \Omega_m$$



# Effective Equation of State of DGP Model




$$w = \frac{p}{\rho}$$

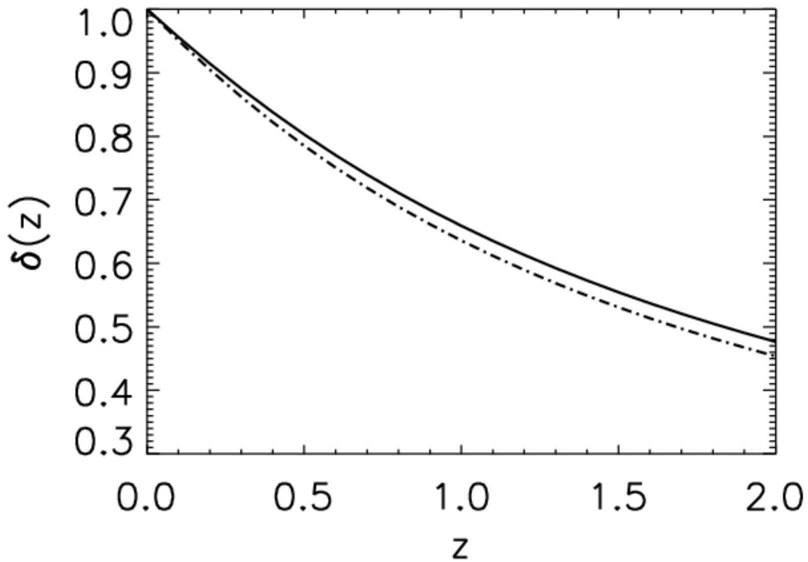
- Comparison to dark energy component

$$w(a) = -1 + \frac{\Omega_{\mathrm{m}} a^{-3}}{\left[(r_c H_0)^{-1} + 2\eta\right]\eta}$$

$$\eta = \sqrt{\Omega_{\mathrm{m}} a^{-3} + 1/(2r_c H_0)^2}$$

- parameterization: w(a)=-0.77+0.27(1-a)

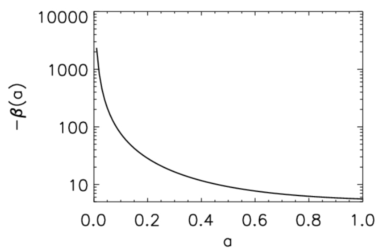
# The Growth Factor



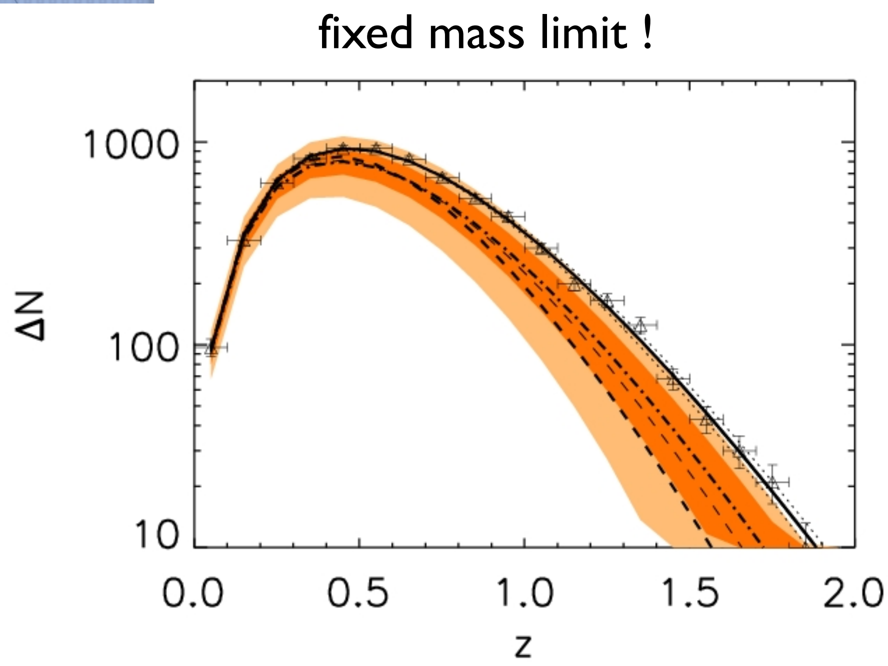

- From 5D perturbations (Maartens & Koyama 2006)
- For β→∞: std gravity mimic DE model
- significant difference

$$\delta'' + \delta' \left[\frac{3}{a} + \frac{H'}{H}\right] = \frac{3}{2}\frac{H_0^2}{H^2} a^{-5} \left(1 + \frac{1}{3\beta}\right) \Omega_{\rm m} \delta$$

$$\beta = 1 - \frac{2}{3} H r_c a \left[\frac{3}{a} + \frac{H'}{H}\right]$$



# Cluster Counts in DGP Model




significant difference between mimic DE and DGP: >1$\sigma$

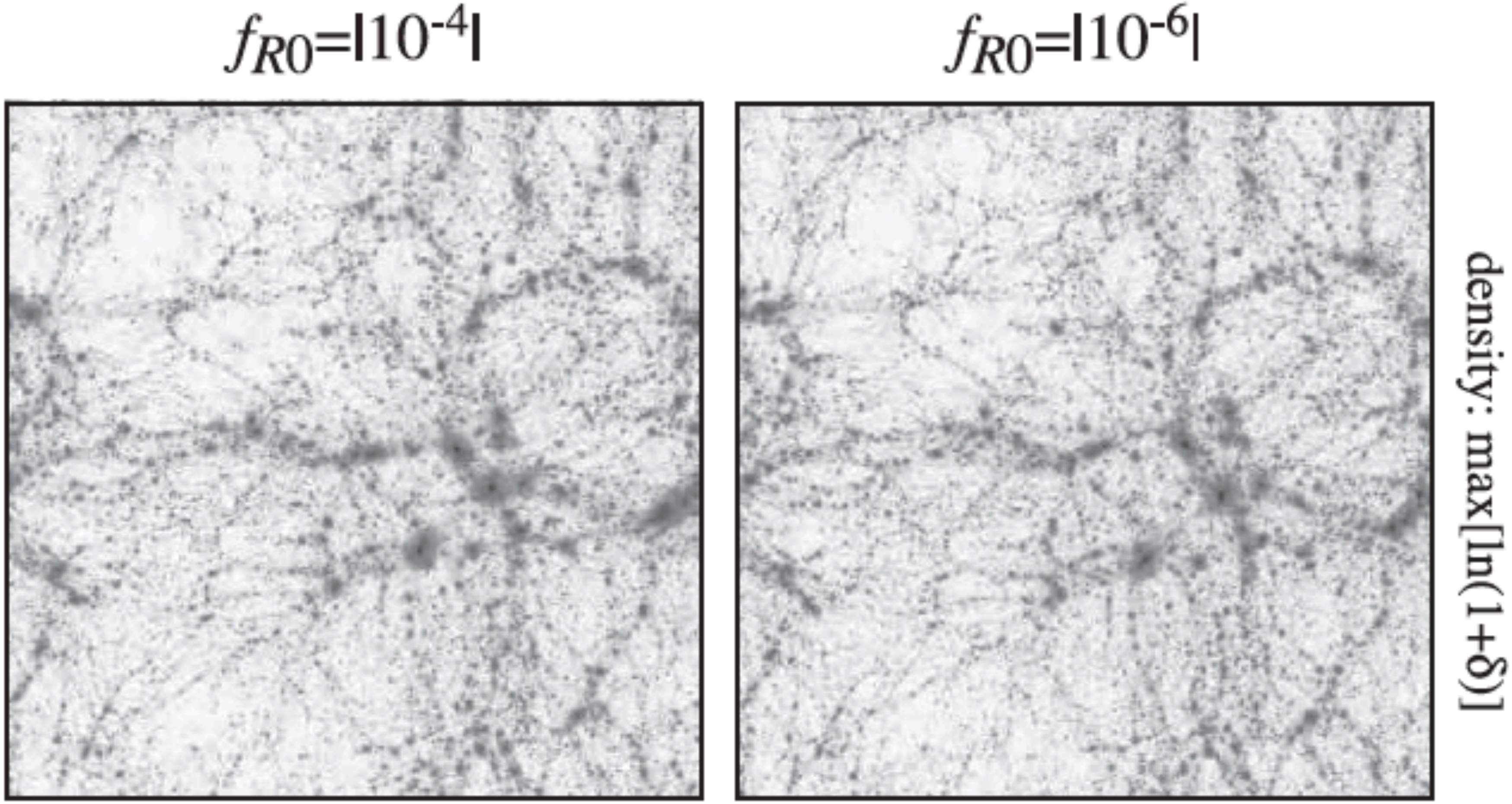
- DGP number counts for $\sigma_8$ = 0.75, n=1, $M_{lim}$=1.7×$10^{14}h^{-1}M_\odot$(from 'SPT')
- mock data assuming Poisson errors
- mimic DE model
- different $r_c$
- Error's from Supernovae observations with 2000 SNe $\delta w_0$=0.05; $\delta w_a$=0.2; $\delta\Omega_m$=0.03; $\delta\sigma_8$=0.03 (WMAP3+SDSS)
- $\delta\sigma_8$=0.01 (Planck+LSS)
- $\Lambda$CDM
- w=-0.8

# But: Be careful, things could go wrong – need to start from scratch

- What is mass function in DGP model ?
- Need either new analytical approach (spherical collapse, excursion sets, …)
- or better: Numerical Simulation, universality test, scaling, …
- performed 1st time for a modified gravity model: Oyaizu 2008

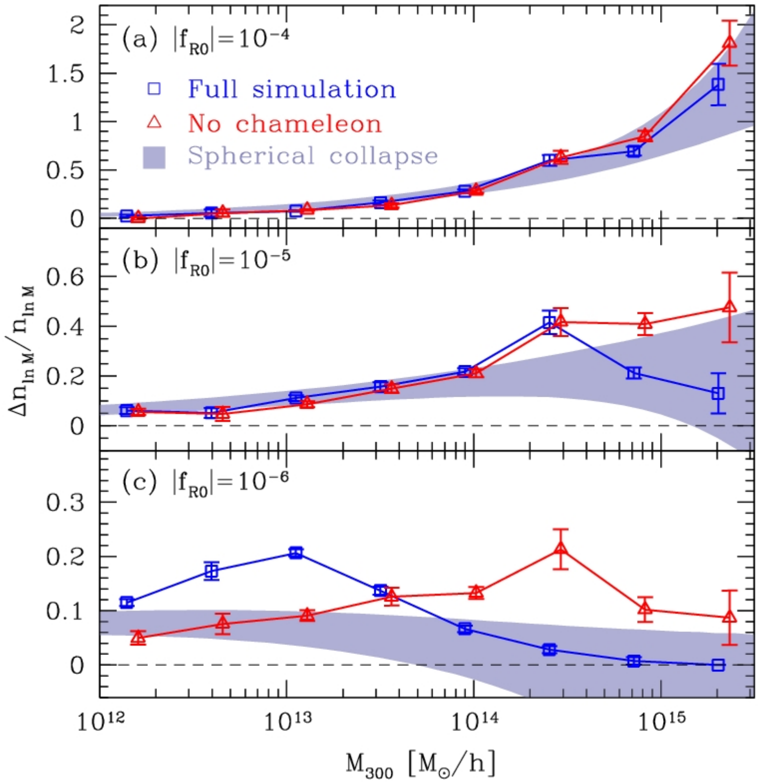
# Simulating a f(R) Chameleon

$$f(R) = -16\pi G\rho_\Lambda - f_{R0}\frac{\bar{R}_0^2}{R}$$




Oyaziu et al. 2008

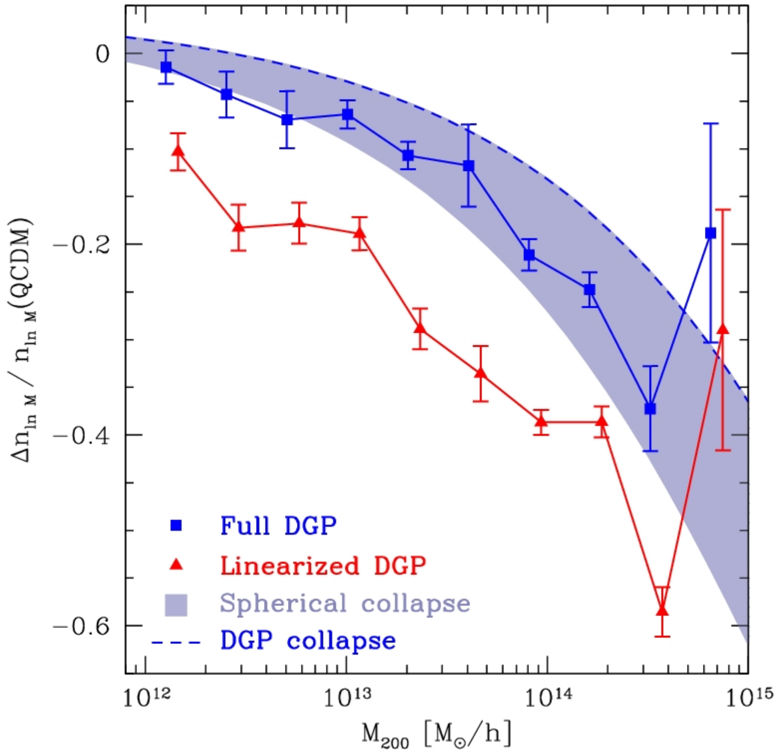
# The Mass Function in Modified f(R) Gravity




Schmidt et al. 2009

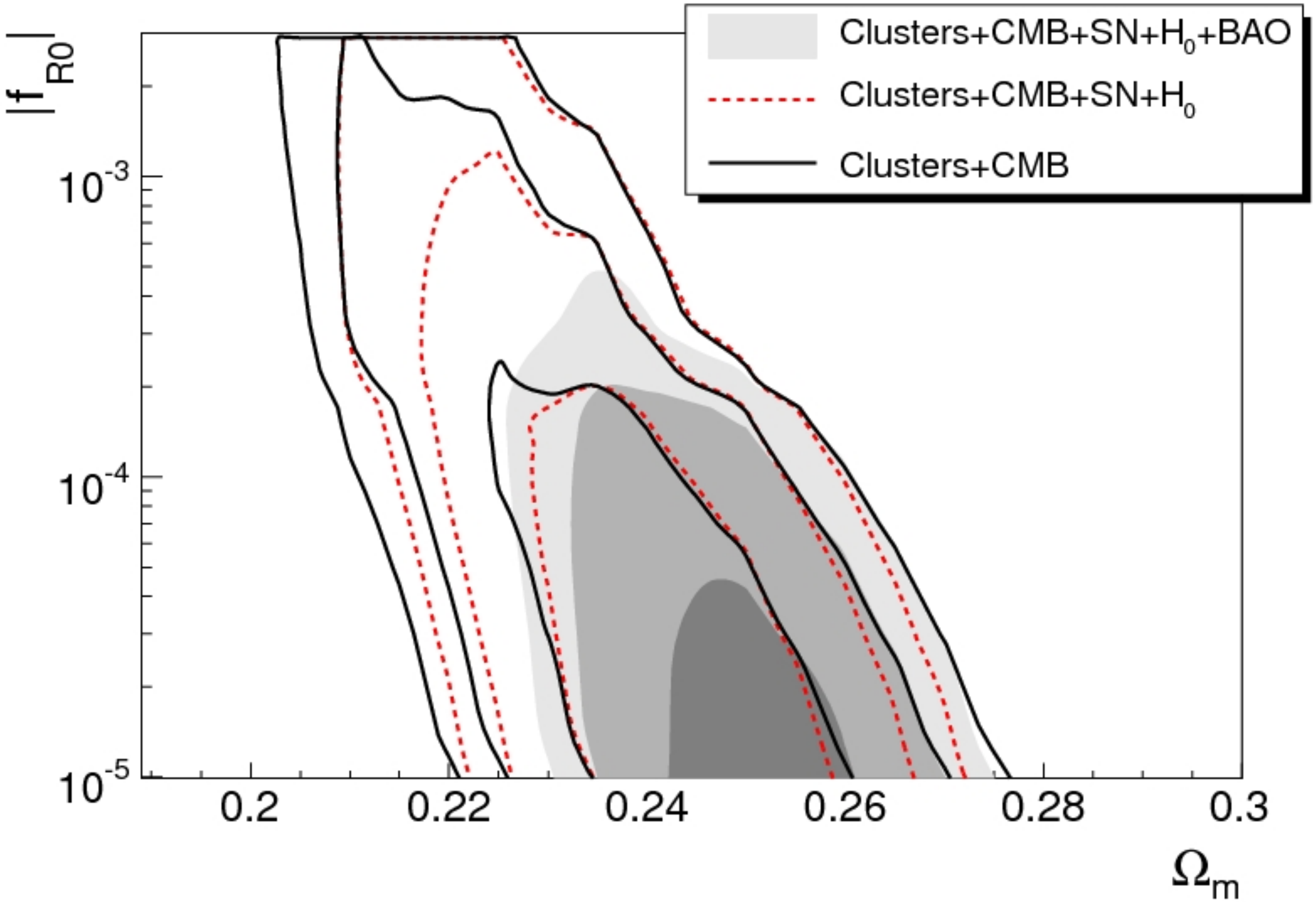
- shaded region: adapted spherical collapse and Sheth and Tormen for large and small field limit
- Large field: enhanced gravitational forces inside the halo enhance the abundance of these objects

# The Mass Function in the DGP Model




Schmidt et al. 2010

# Constraints on f(R) from X-ray Data




Schmidt et al. 2009

# The Promise of Cluster Abundance

| Parameters | $f(R)$ | | $f(R)$ (with gISW) | | $f(R)$ (with $E_G$) | |
|---|---|---|---|---|---|---|
| $100\Omega_b h^2$ | $2.223 \pm 0.053$ | $2.206$ | $2.225 \pm 0.054$ | $2.253$ | $2.224 \pm 0.054$ | $2.206$ |
| $\Omega_c h^2$ | $0.1123 \pm 0.0036$ | $0.1109$ | $0.1117 \pm 0.0036$ | $0.1133$ | $0.1125 \pm 0.0036$ | $0.1131$ |
| $\theta$ | $1.0403 \pm 0.0027$ | $1.0392$ | $1.0403 \pm 0.0027$ | $1.0416$ | $1.0403 \pm 0.0027$ | $1.0394$ |
| $\tau$ | $0.083 \pm 0.016$ | $0.082$ | $0.084 \pm 0.016$ | $0.090$ | $0.083 \pm 0.016$ | $0.083$ |
| $n_s$ | $0.954 \pm 0.012$ | $0.950$ | $0.954 \pm 0.012$ | $0.965$ | $0.954 \pm 0.013$ | $0.952$ |
| $\ln[10^{10} A_s]$ | $3.212 \pm 0.040$ | $3.215$ | $3.209 \pm 0.039$ | $3.200$ | $3.213 \pm 0.039$ | $3.221$ |
| $100B_0$ | $< 315$ | $28$ | $< 43.2$ | $0.0$ | $< 319$ | $30$ |
| $\Omega_m$ | $0.272 \pm 0.016$ | $0.268$ | $0.269 \pm 0.016$ | $0.272$ | $0.273 \pm 0.016$ | $0.279$ |
| $H_0$ | $70.4 \pm 1.4$ | $70.4$ | $70.7 \pm 1.3$ | $70.7$ | $70.3 \pm 1.3$ | $69.6$ |
| $10^3 \lvert f_{R0} \rvert$ | $< 350$ | $46$ | $< 69.4$ | $0.0$ | $< 353$ | $51$ |
| $-2\Delta \ln L$ | -1.104 | | 1.506 | | -0.696 | |

TABLE III: Same as Tab. I, but for $f(R)$ gravity. $-2\Delta \ln L$ is quoted with respect to the corresponding maximum likelihood flat $\Lambda$CDM model. Limits on $B_0$ and $|f_{R0}|$ indicate the one-sided 1D marginalized upper 95% C.L. Note that as $B_0 \to 0$ reproduces $\Lambda$CDM predictions, the slightly poorer fits of $f(R)$ gravity should be attributed to sampling error in the MCMC runs.

SNe, BAO, Hubble
CMB, WL, galaxy flows
Cluster Abundance:
-galaxy-galaxy lensing of MaxBCG clusters and groups: three mass bins and two redshift bins

| Parameters | $f(R)$ (with CA) | | $f(R)$ (with $E_G$&CA) | | $f(R)$ (all) | |
|---|---|---|---|---|---|---|
| $100\Omega_b h^2$ | $2.209 \pm 0.054$ | $2.204$ | $2.213 \pm 0.054$ | $2.235$ | $2.216 \pm 0.054$ | $2.210$ |
| $\Omega_c h^2$ | $0.1064 \pm 0.0032$ | $0.1112$ | $0.1073 \pm 0.0029$ | $0.1108$ | $0.1076 \pm 0.0028$ | $0.1104$ |
| $\theta$ | $1.0390 \pm 0.0027$ | $1.0398$ | $1.0392 \pm 0.0027$ | $1.0413$ | $1.0394 \pm 0.0027$ | $1.0398$ |
| $\tau$ | $0.077 \pm 0.016$ | $0.080$ | $0.077 \pm 0.015$ | $0.084$ | $0.079 \pm 0.015$ | $0.075$ |
| $n_s$ | $0.953 \pm 0.012$ | $0.951$ | $0.954 \pm 0.012$ | $0.956$ | $0.954 \pm 0.012$ | $0.951$ |
| $\ln[10^{10} A_s]$ | $3.175 \pm 0.0038$ | $3.209$ | $3.179 \pm 0.037$ | $3.203$ | $3.182 \pm 0.0037$ | $3.193$ |
| $100B_0$ | $< 0.333$ | $0.000$ | $< 0.152$ | $0.000$ | $< 0.112$ | $0.001$ |
| $\Omega_m$ | $0.247 \pm 0.014$ | $0.268$ | $0.251 \pm 0.012$ | $0.261$ | $0.252 \pm 0.012$ | $0.264$ |
| $H_0$ | $72.2 \pm 1.4$ | $70.3$ | $71.9 \pm 1.3$ | $71.4$ | $71.9 \pm 1.2$ | $70.8$ |
| $10^3 \lvert f_{R0} \rvert$ | $< 0.484$ | $0.001$ | $< 0.263$ | $0.000$ | $< 0.194$ | $0.002$ |
| $-2\Delta \ln L$ | 0.802 | | 0.264 | | 0.926 | |

Lombriser, Slosar, Seljak & Hu 2010

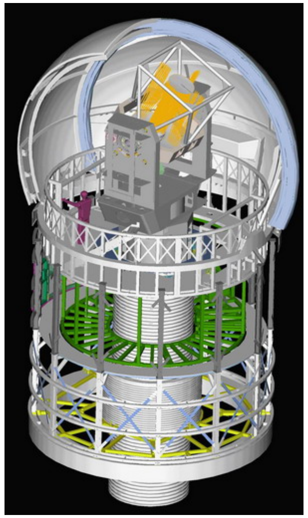
TABLE IV: Same as Tab. II, but for $f(R)$ gravity. See also Tab. III.

Uses SDSS maxBCG catalog

# Application to Future Surveys

- PanStarrs, DES(+SPT), Planck, EUCLID

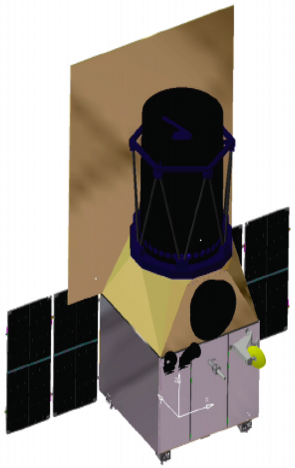
Panstarrs



Dark Energy Survey

Planck CMB Satellitt


EUCLID



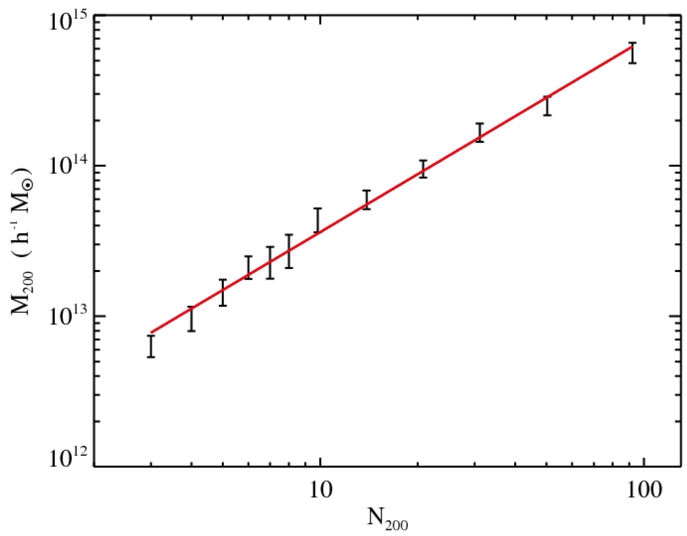
# EUCLID an ESA Cosmic Vision Proposal

- 20,000 deg
- Weak Lensing
  - Diffraction limited galaxy shape measurements in one broad visible R/I/Z band.
  - Redshift determination by Photo-z measurements in 3 YJH NIR bands to H(AB)=24 mag
- BAO
  - Spectroscopic redshifts (NIR) for 33% of all galaxies brighter than H(AB)=22 mag, $\sigma_z$<0.001
- Constraints
  - Aperture: max 1.2 m diameter
  - Limited numbers of NIR detectors
  - Mission duration: max ~5 years

# Selection Clusters with Euclid

- Weak lensing: e.g. peak statistics
- Galaxy overdensities
  - maxBCG
  - Voronoi Tesselation
  - Matched filters
  - Counts in Cells
  - Percolation Algorithms (FoF)
  - smoothing kernels
  - surface brightness enhancements
  - …
- Strong Lensing

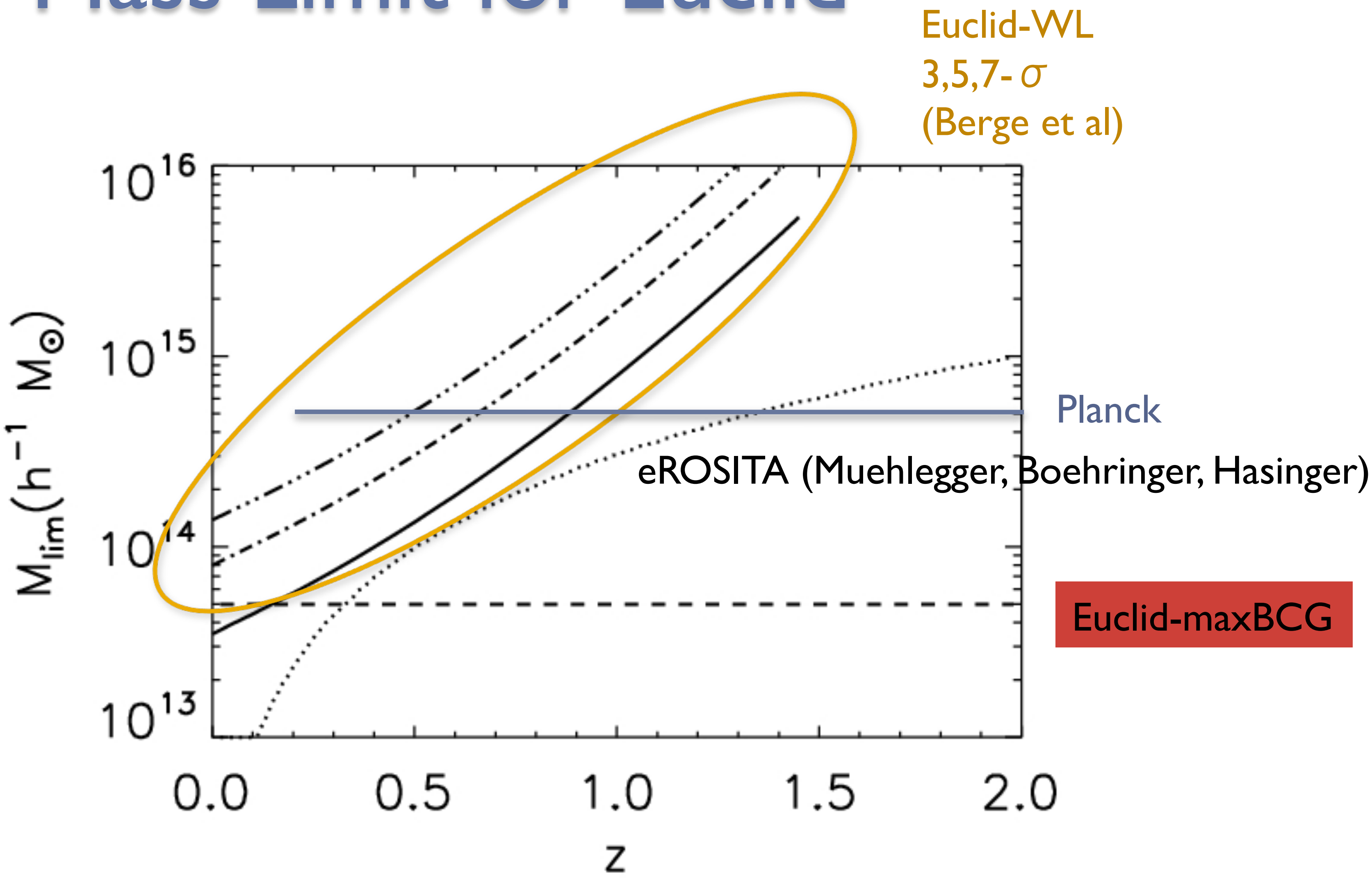
# maxBCG Selection SDSS: A Lesson for Euclid ?



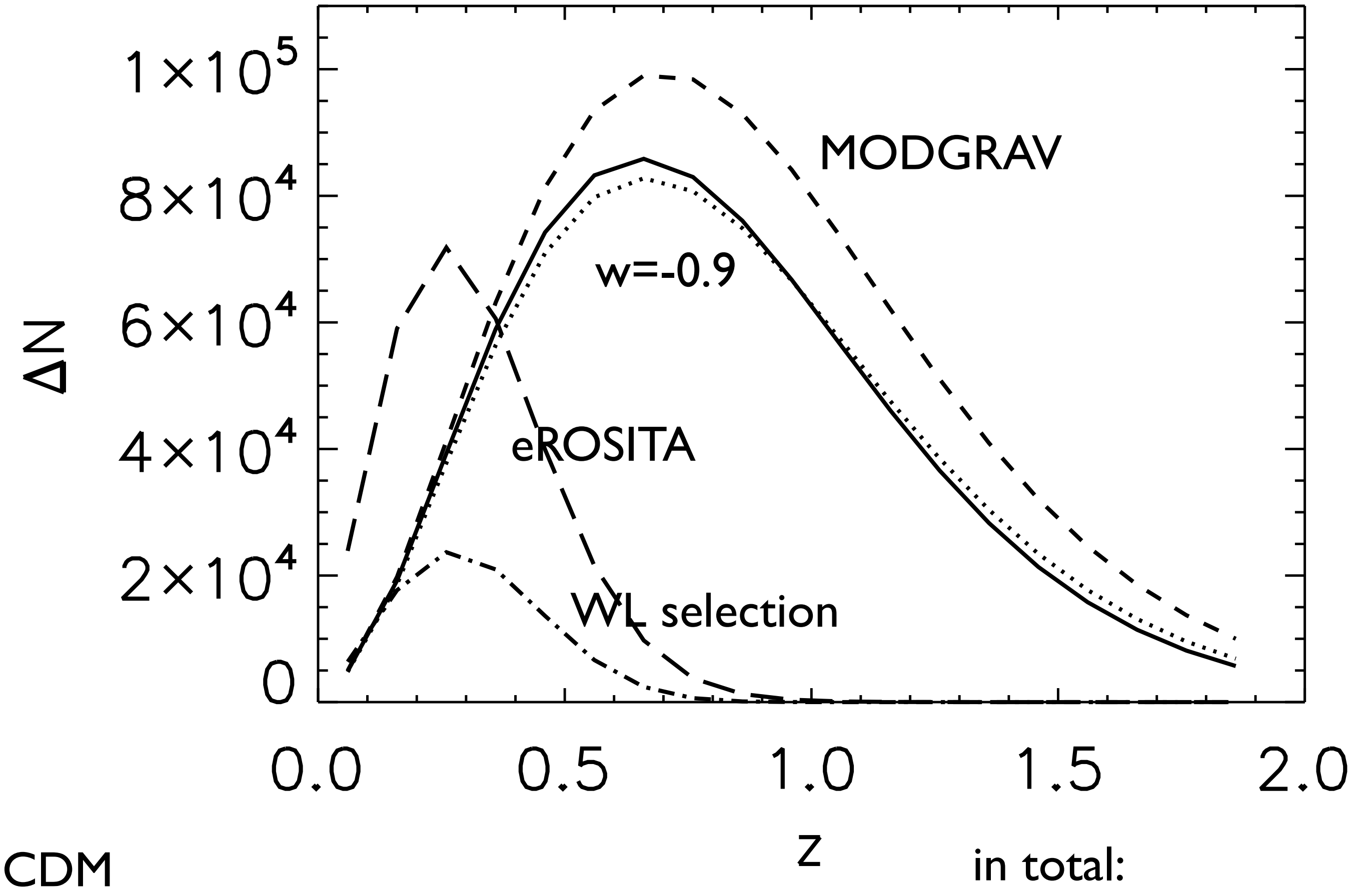

Johnston et al. 2007

- Mass – Richness relation
  - calibrated with statistical weak lensing measurements (for 130,000 groups)
  - Johnston et al. 2007
- Good purity and completeness to about: $M \sim 10^{13.5}\ h^{-1} M_{\odot}$
- however for SDSS only to: z ~ 0.3
- depth of Y, J and H filters
  - should be able to find ridgeline galaxies out to z=1.3-2.0
  - how far out do we find robust red sequence ?
- calibration with internal and external spectroscopy in EUCLID !
- Need mock catalogs, to study this question: in process

# Mass Limit for Euclid



# Cluster Numbers for Euclid

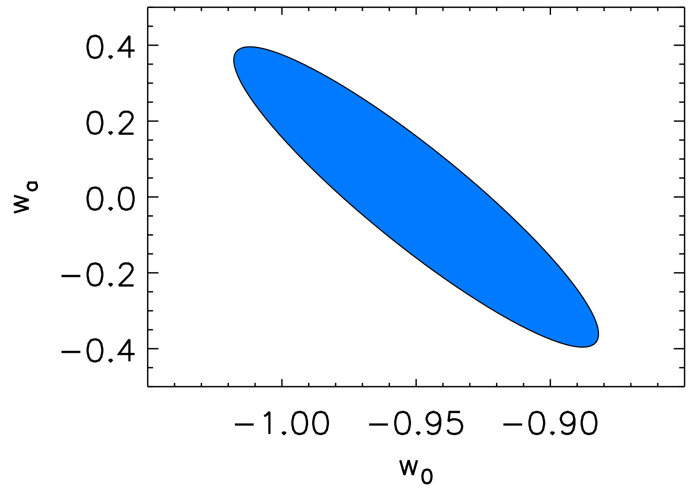


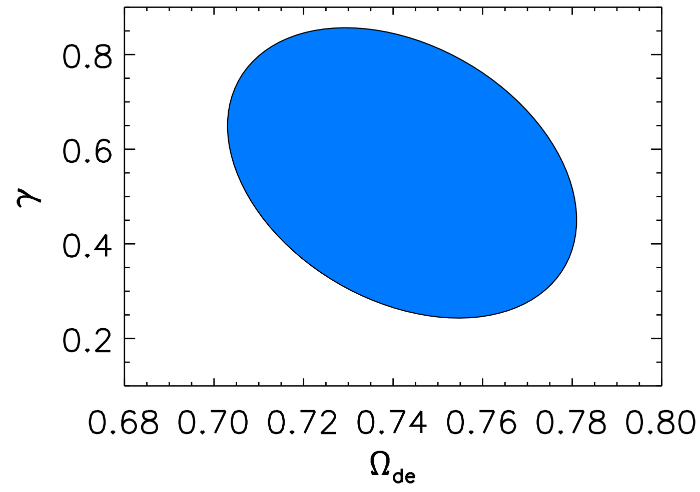

solid: $\Lambda$CDM

in total:
well over 750,000#

# Constraints from Euclid Cluster Counts (no spectroscopy included)

$$\frac{d\ln(\delta/a)}{d\ln a} = \Omega_m^\gamma - 1$$

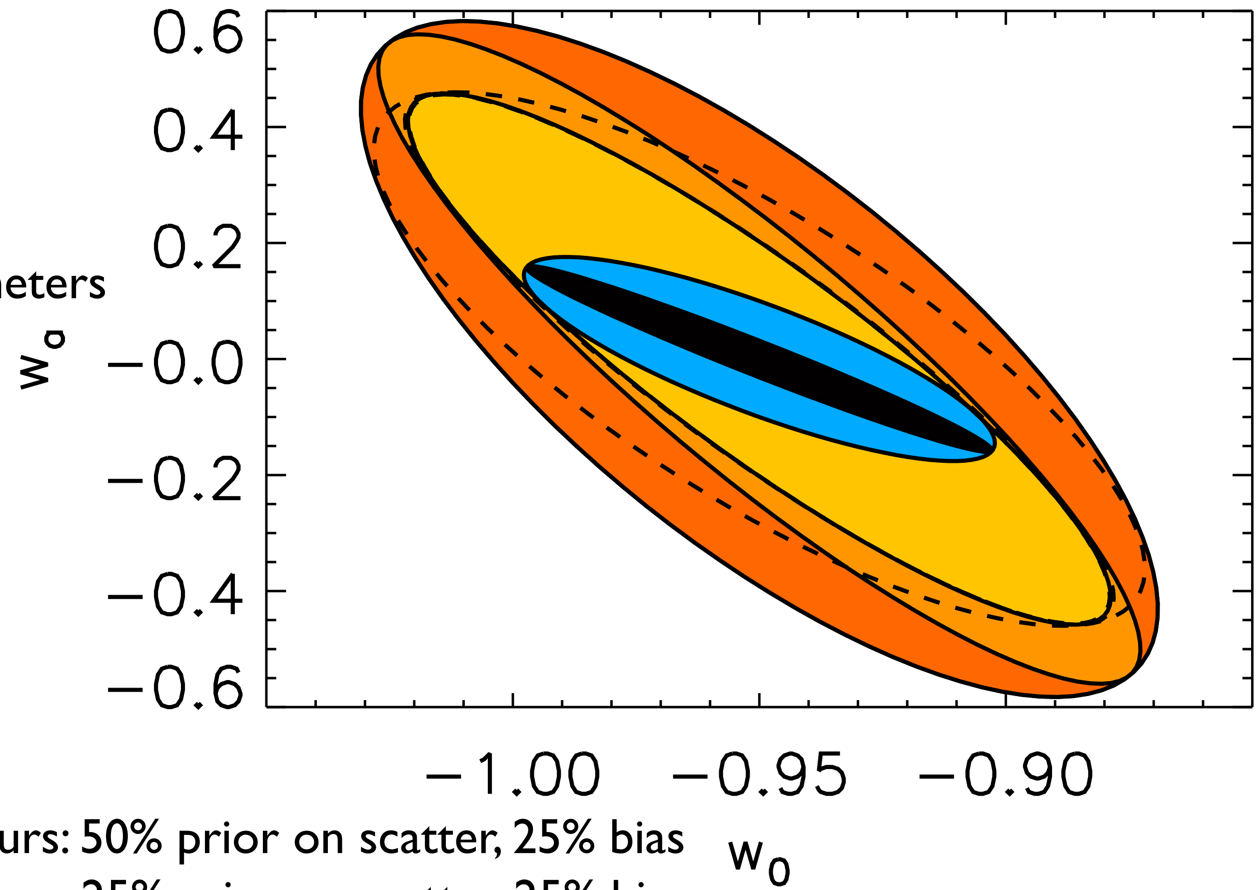



Including 5 cluster nuissance parameters; prior on scatter: 25%

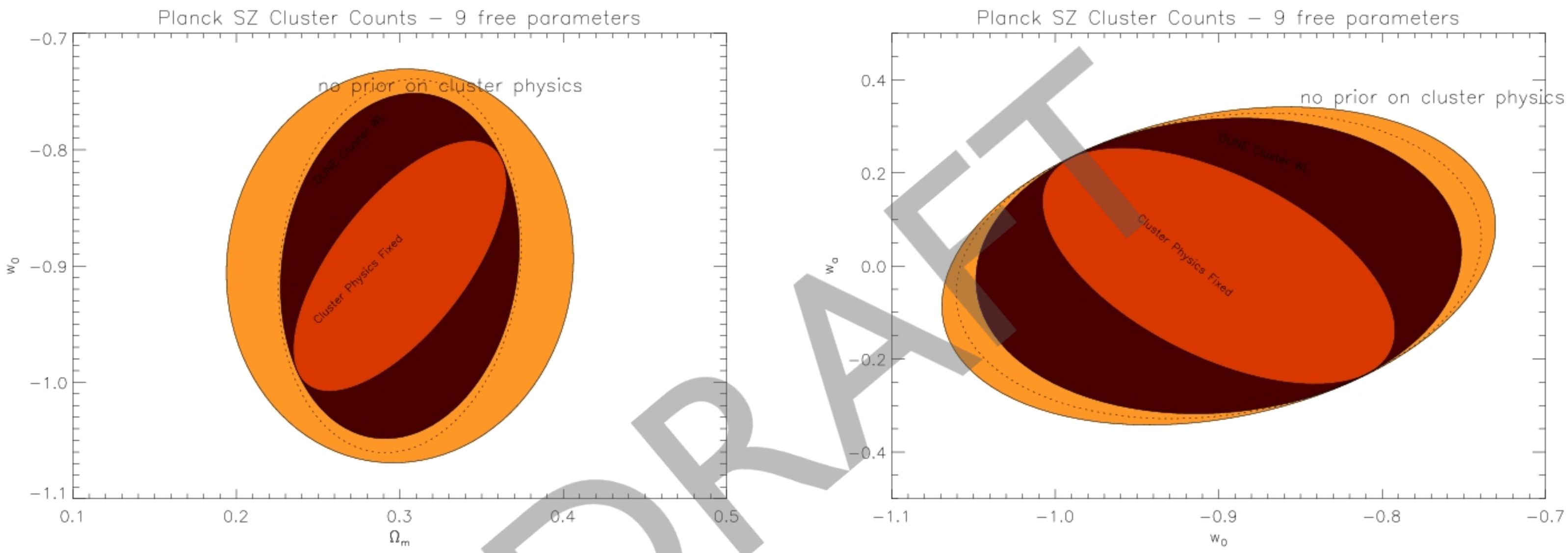
# Cosmology and Priors on the Mass – Observable Relation

1,2 and 3
scatter parameters




orange contours: 50% prior on scatter, 25% bias
dashed contours: 25% prior on scatter, 25% bias
blue contour: fixed scatter
dark contour: fixed scatter and bias

# How can Euclid help Planck-SZ Clusters – *Very Preliminary !*






NO SCATTER, see also Cunha et al., Wechsler et al.

But also vice versa: Improvement of FoM could be 50% from WL and x-ray

# Conclusions

- Clusters are extremely sensitive to the growth of structures
- Astrophysical uncertainties can be controlled by self- and cross-calibrating the uncertainties and detailed follow up of selected clusters (x-ray, SZ, WL, spectroscopy)
- 'Richness' methods now at a stage to give meaningful cosmological constraints
- SDSS maxBCG sample is currently providing the tightest cosmological constraints on f(R) models – might this also be true for future galaxy cluster counts vs. weak lensing, BAO, etc ???