Cosmological and Large-Scale Structure Studies with X-ray Galaxy Clusters

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Overview

1. Galaxy Clusters in X-rays
2. Galaxy Clusters in the Large-Scale Structure
3. The CLASSIX Cluster Survey
4. Implication for Neutrino Masses
5. The Local Underdensity and the Hubble Constant
6. Magnetic Fields in Clusters
7. Conclusions

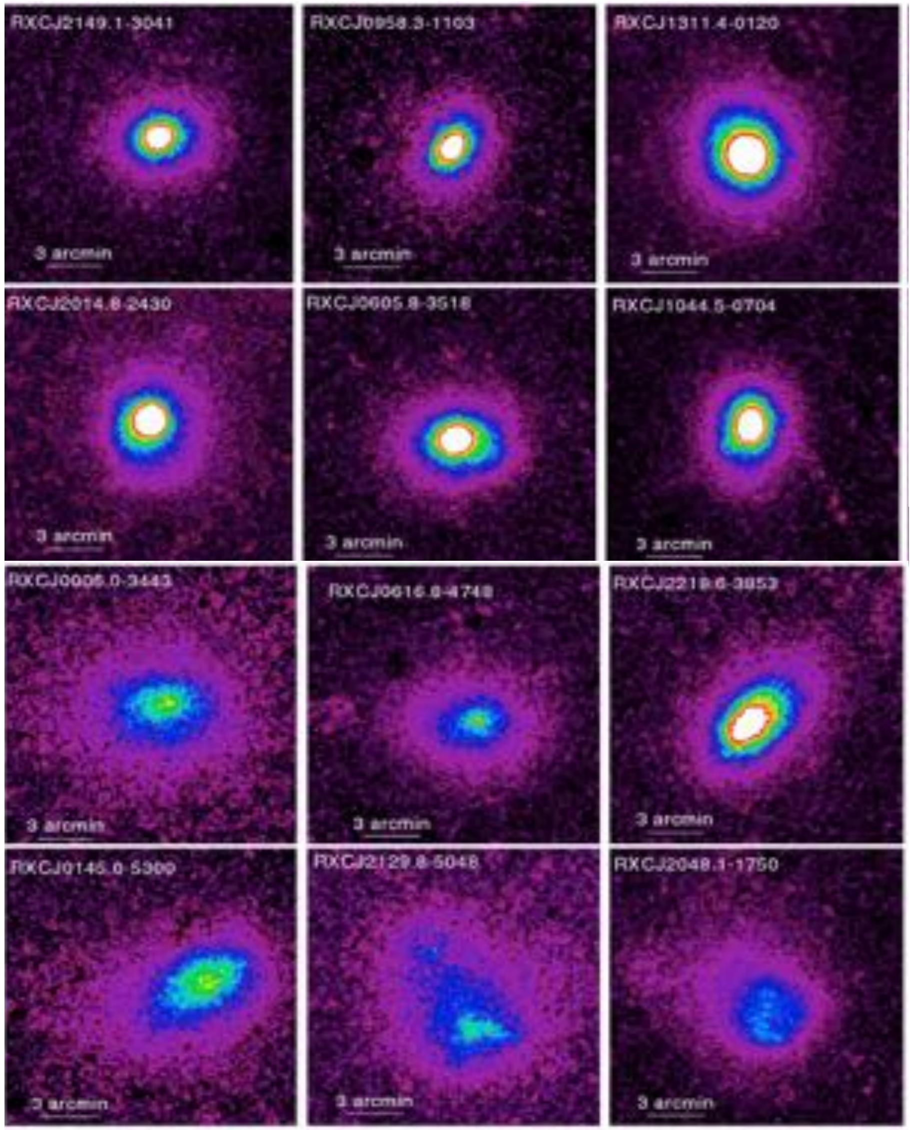
Optical and X-ray Image of the Coma Galaxy Cluster

Palomar Sky Survey and ROSAT-All Sky Survey

The X-ray emission origintes from a hot intracluster plasma with temperatures of a few 10 Million degrees.

Clusters of galaxies are the largest, clearly defined objects in our Universe

Structure and composition of galaxy clusters

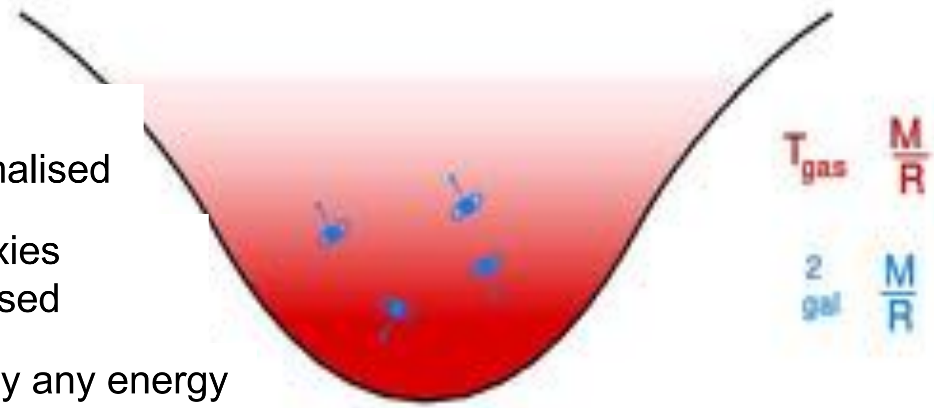


Clusters from REXCESS sample [Böhringer et al. 2007]

Gas thermalised

Galaxies virialised

Hardly any energy dissipation



Mass from hydrostatic equation:

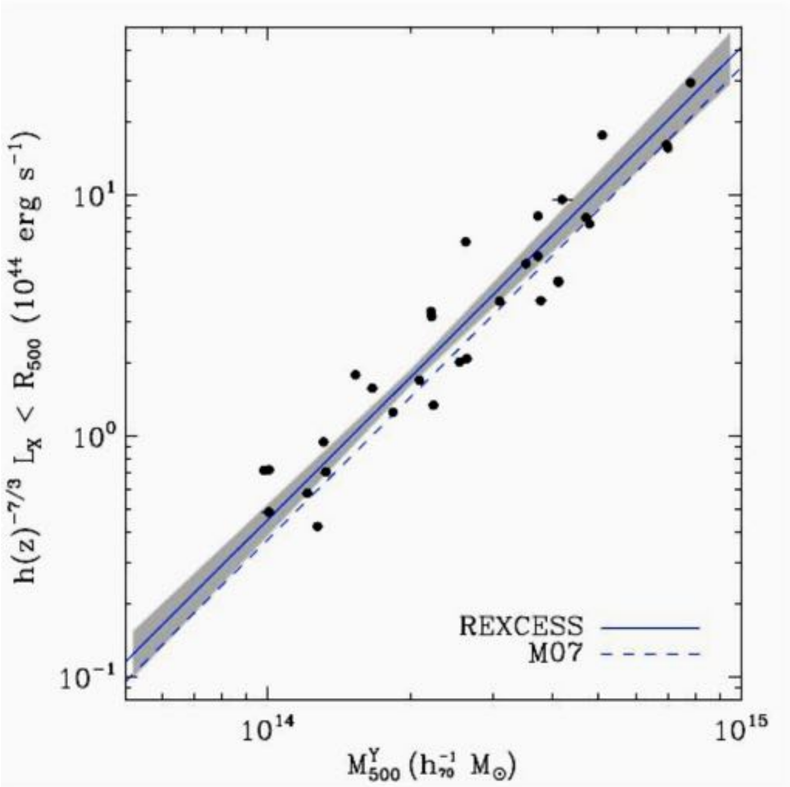
$$\frac{1}{\rho}\frac{dP}{dr} = -\frac{GM(r)}{r^2}$$

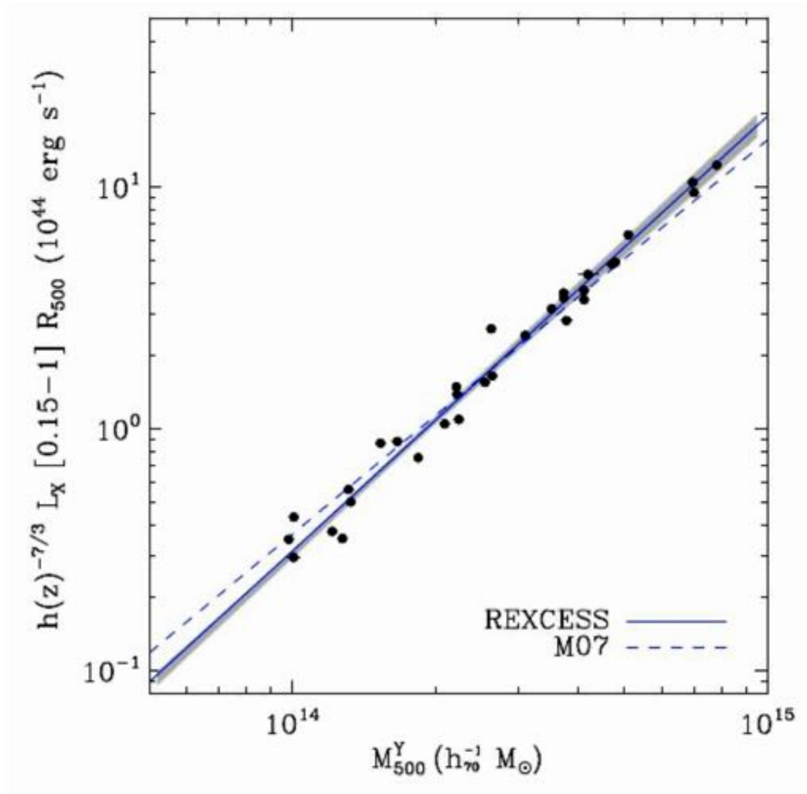
$$M(r) = -\frac{kT\,r}{G\,\mu m_p}\left(\frac{d\ln\rho}{d\ln r} + \frac{d\ln T}{d\ln r}\right)$$

Matter composition:

Dark Matter	~	84%
Gas	~	14%
Galaxies	~	2%

L_X – M Relation for REXCESS Clusters





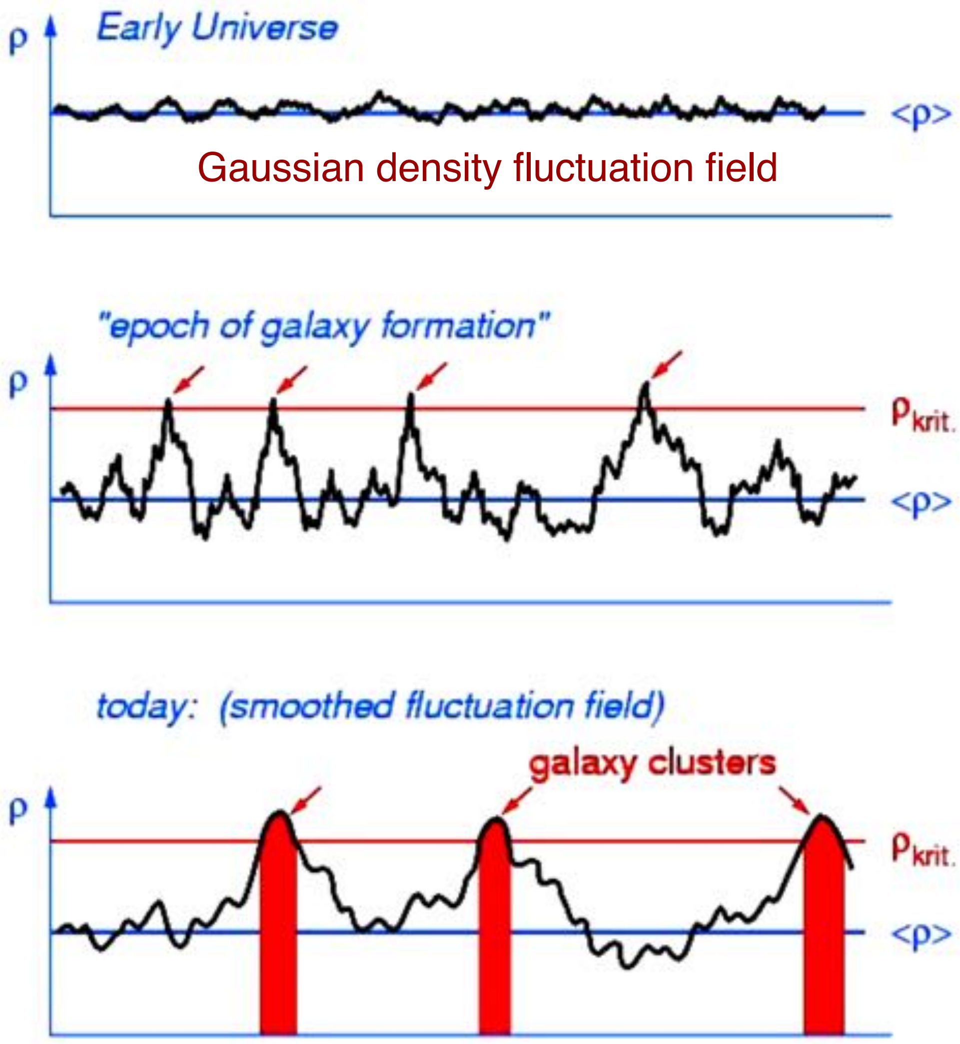
M estimated from Y_X

Scatter ~ 40%

Scatter ~ 18%

Pratt, H.B., et al. 2009

Formation of Galaxy Clusters



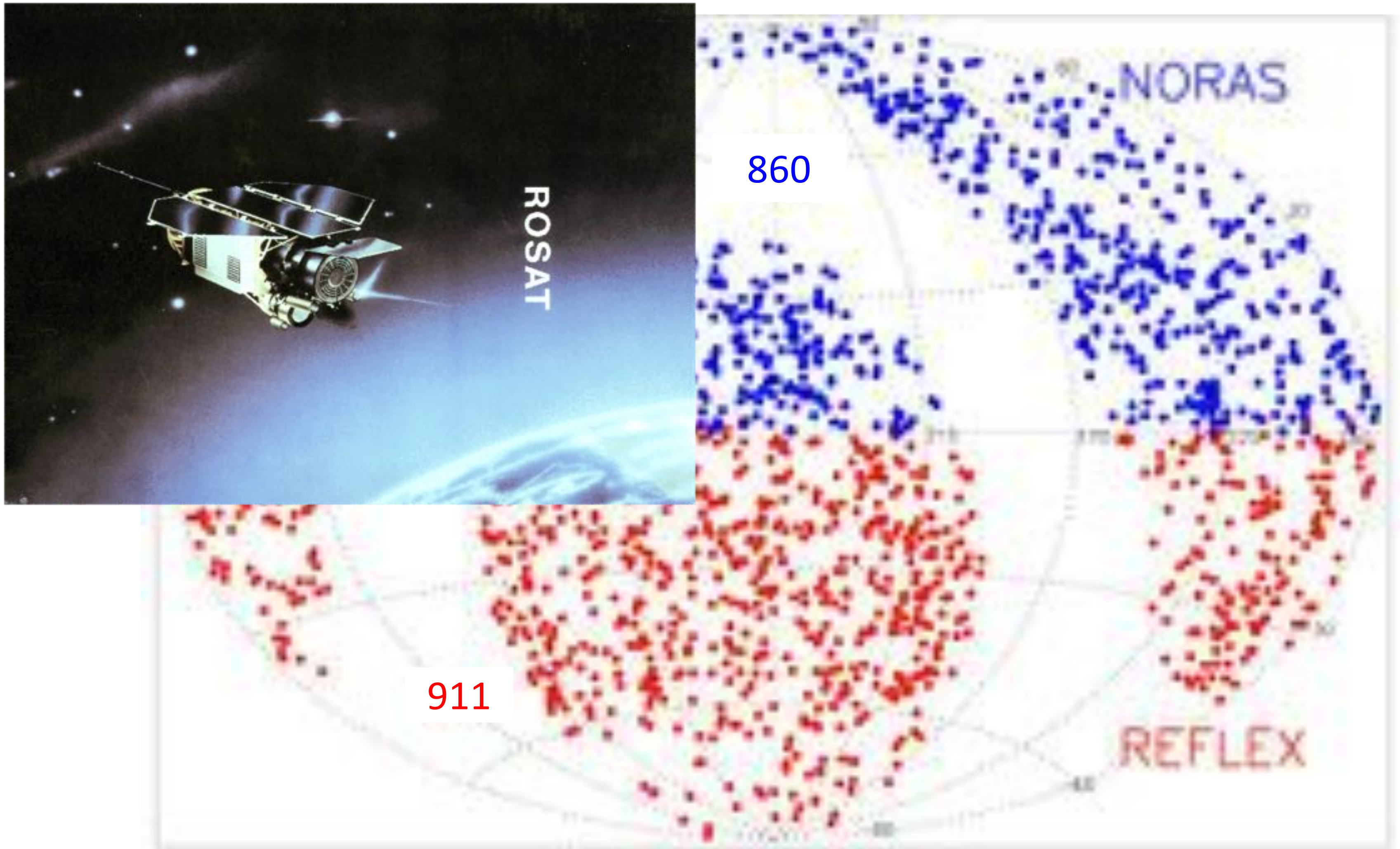
Mass of galaxy clusters ~10^{14} – 10^{15} M_{sun}

- Galaxy clusters form from peaks in the density fluctuation field.
- The number density and the spatial distribution of the density peaks in a Gaussian fluctuation field can be calculated statistically → prediction for the number density of galaxy clusters

The CLASSIX Galaxy Cluster Survey

Cosmic Large-Scale Structure in X-rays cluster survey

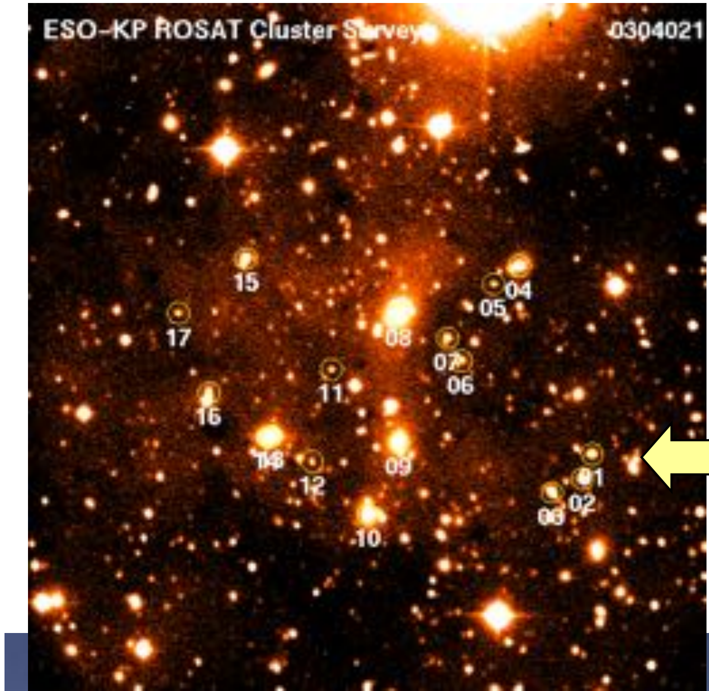
REFLEX & NORAS Cluster Survey

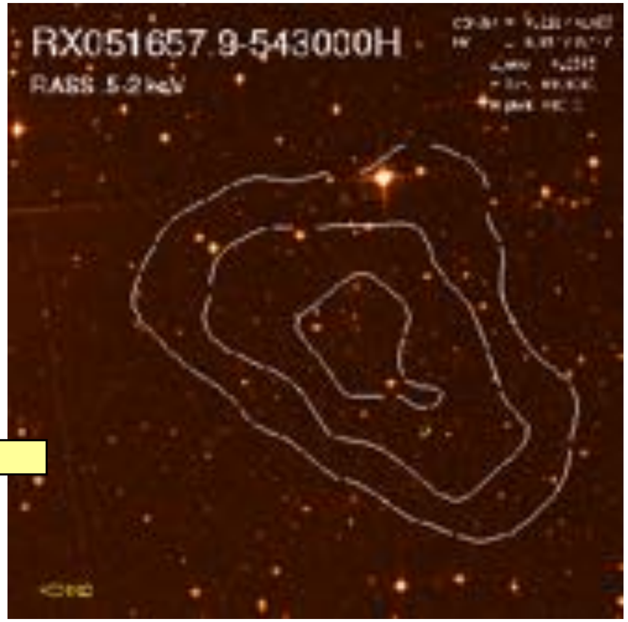


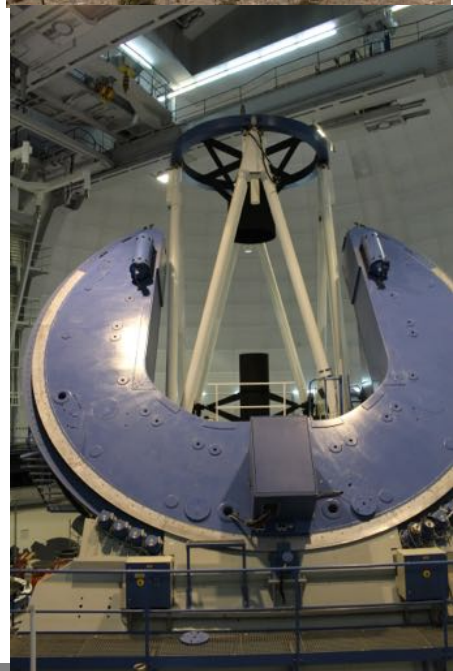
REFLEX II 911 clusters, NORAS II 860 clusters $F > 1.8\ 10^{-12}$ erg s^{-1} cm^{-2}

(Böhringer et al. 2000, 2001, 2004, 2013, 2014 Chon & HB 2012)

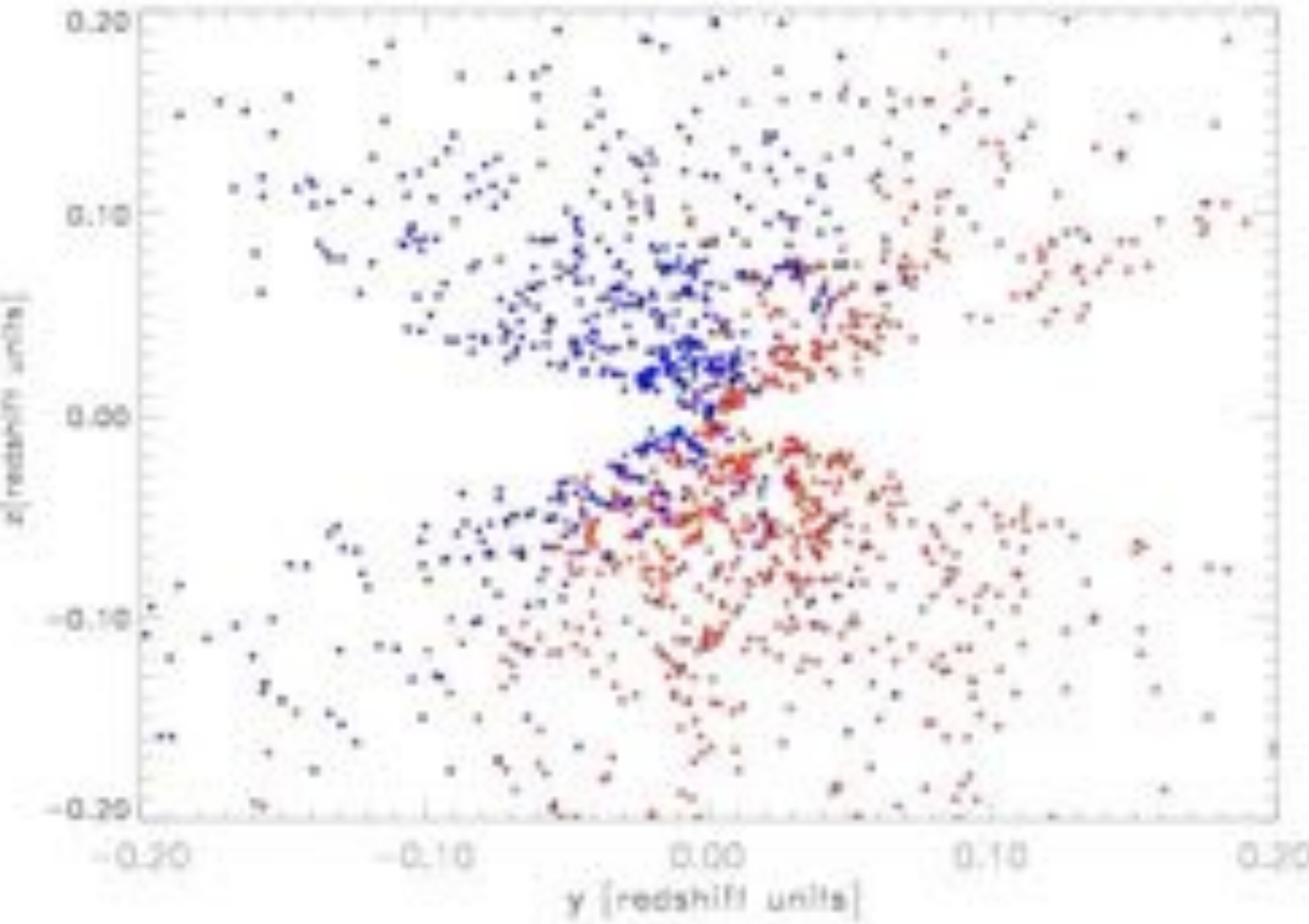
ESO – Key Program @ La Silla 1992 - 99 (II) – 2012
Observing Program at Calar Alto (Spain) 1995 - 2017





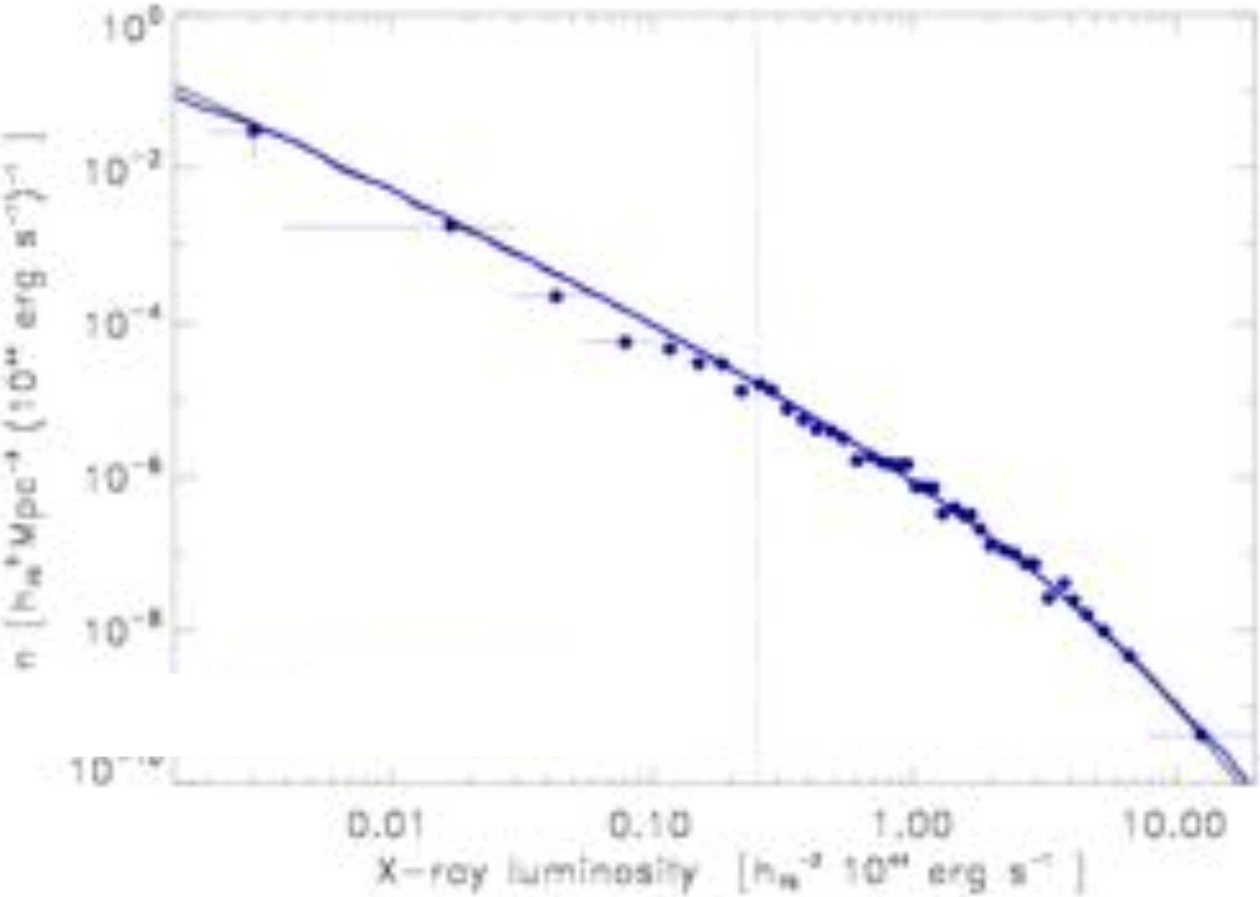


3-dimensional distribution of the REFLEX/NORAS clusters



X-ray luminosity function obtain from CLASSIX Survey

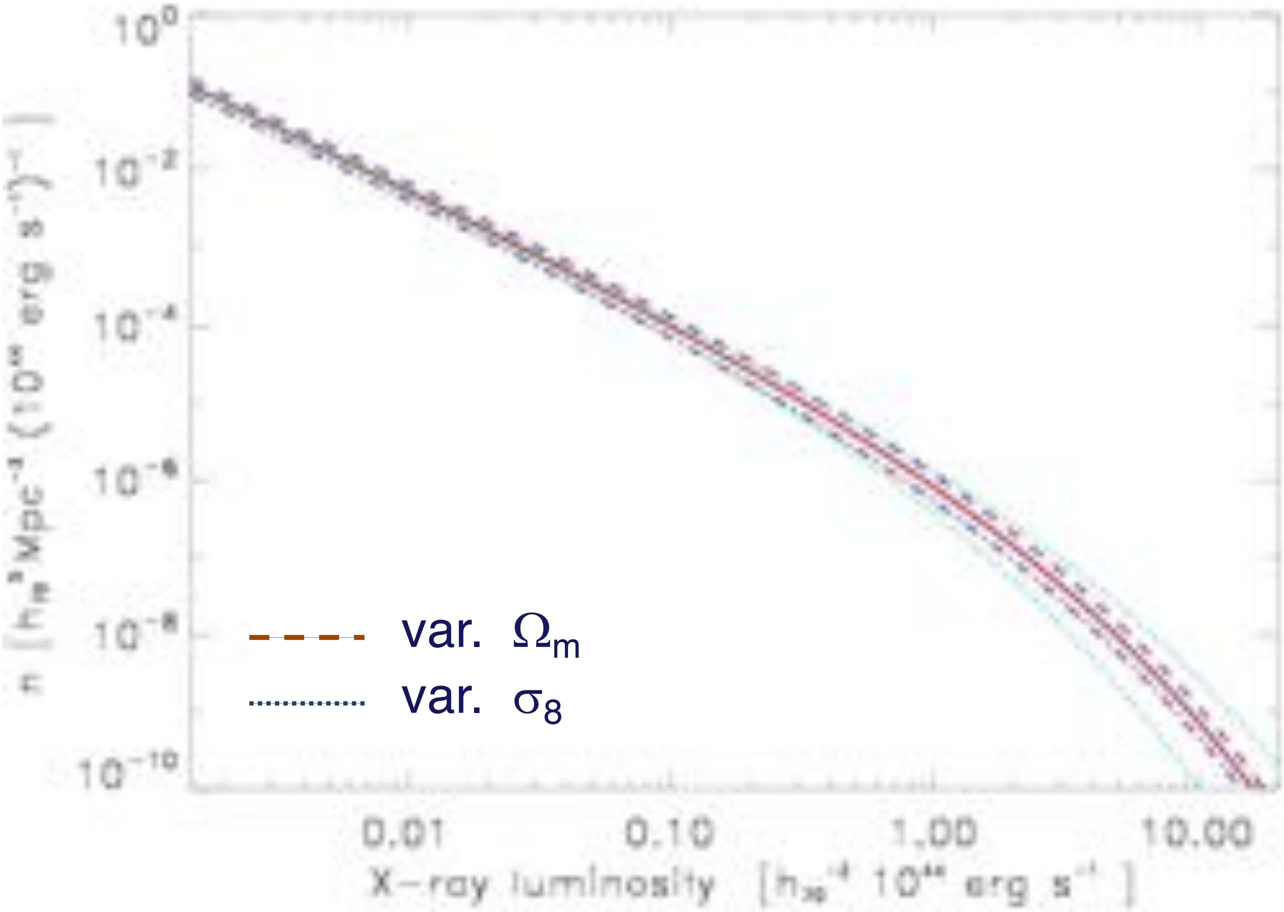
Prediction for a flat ΛCMD model $\Omega_m = 0.27$ and $\sigma_8 = 0.80$



Böhringer et al. 2014

model predicted X-ray luminosity function

Flat ΛCMD model with variation of Ω_m (15%) and σ_8 (12%)

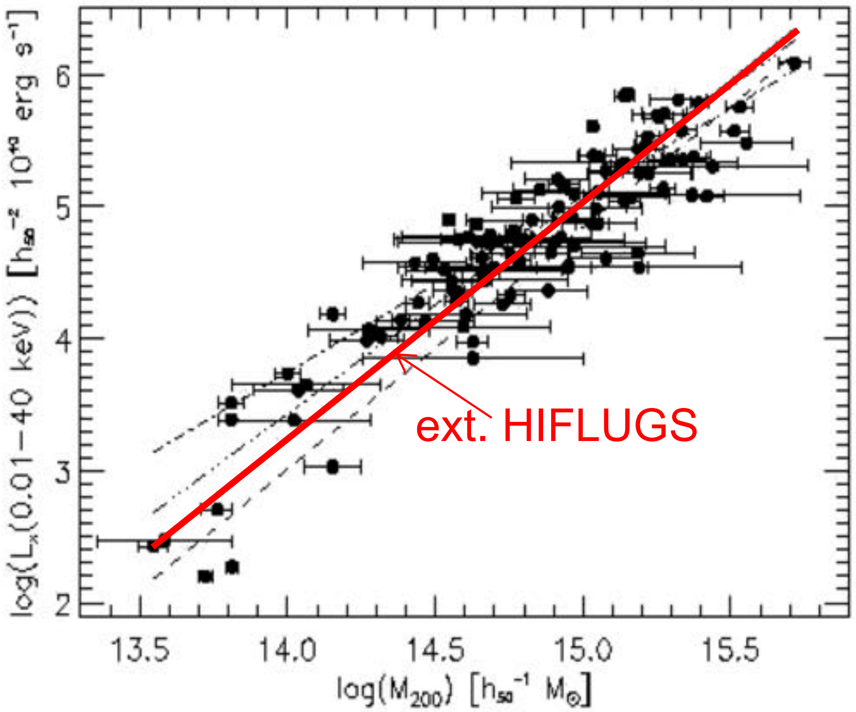


initial fluctuations
↓
homogeneous cosmology
↓
structure growth P(k)
↓
Mass function (Tinker)
↓
L_X- mass relation
↓
X-ray luminosity function

Böhringer et al. 2014

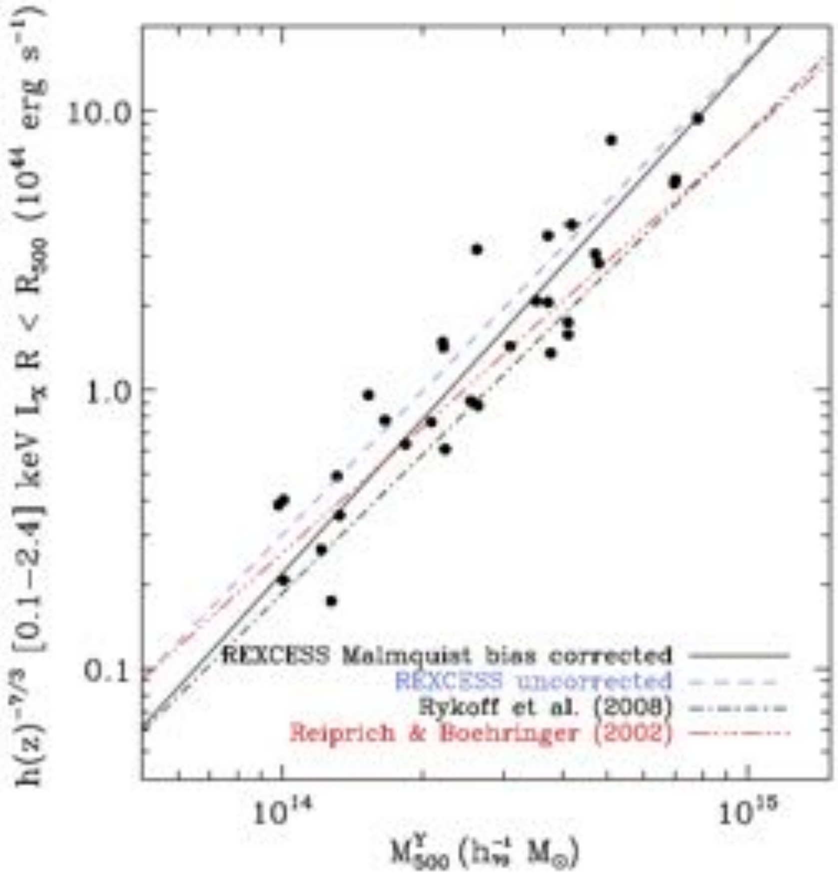
L_X – M scaling relations

HIFLUGCS sample



Reiprich & Böhringer 2002

REXCESS sample



Böhringer et al. 2007
Pratt, HB, et al. 2009

Mass determination from X-ray observations (assumption: hydrostatic)

Influence of the scaling relation on cosmological constraints

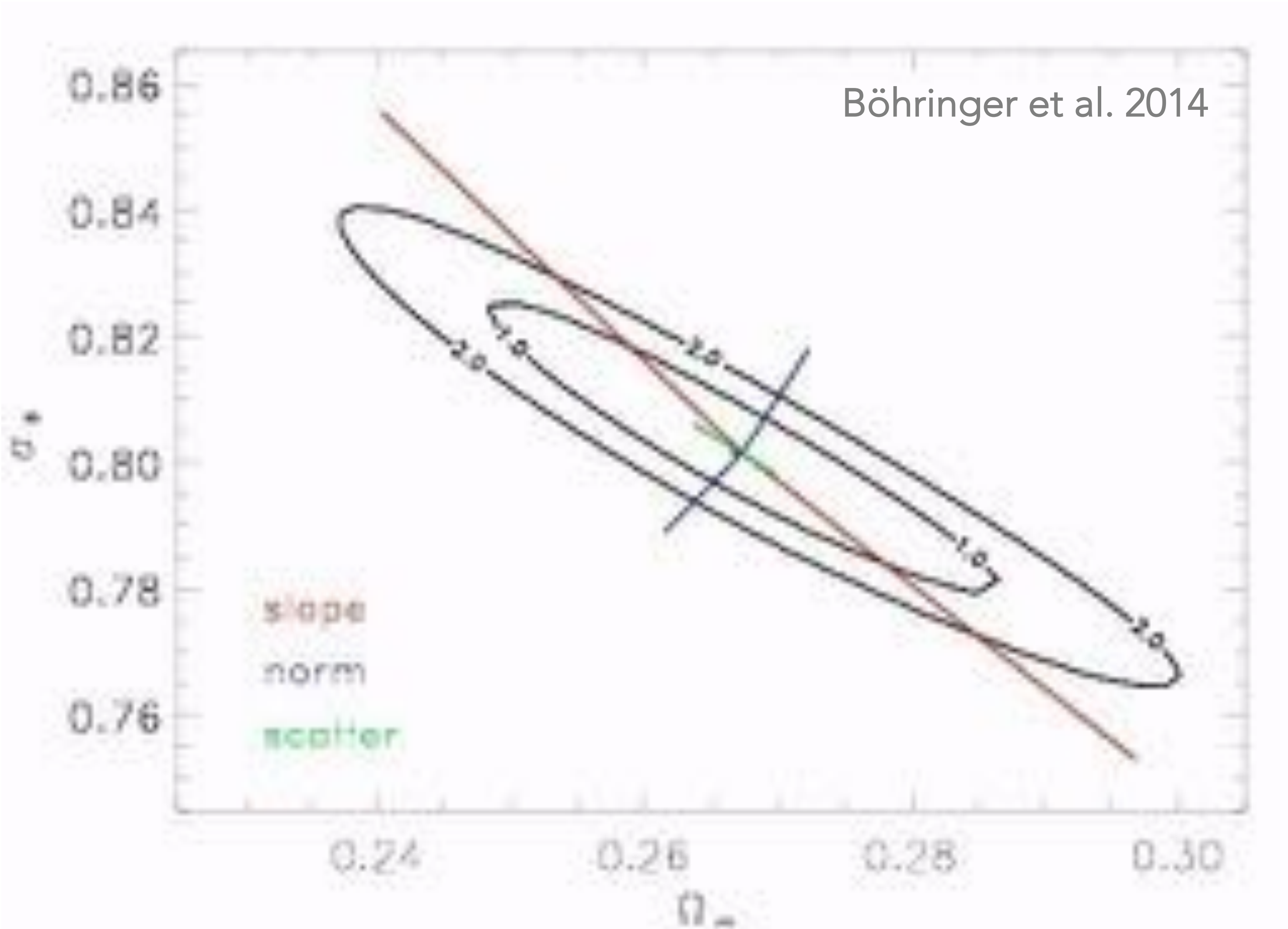
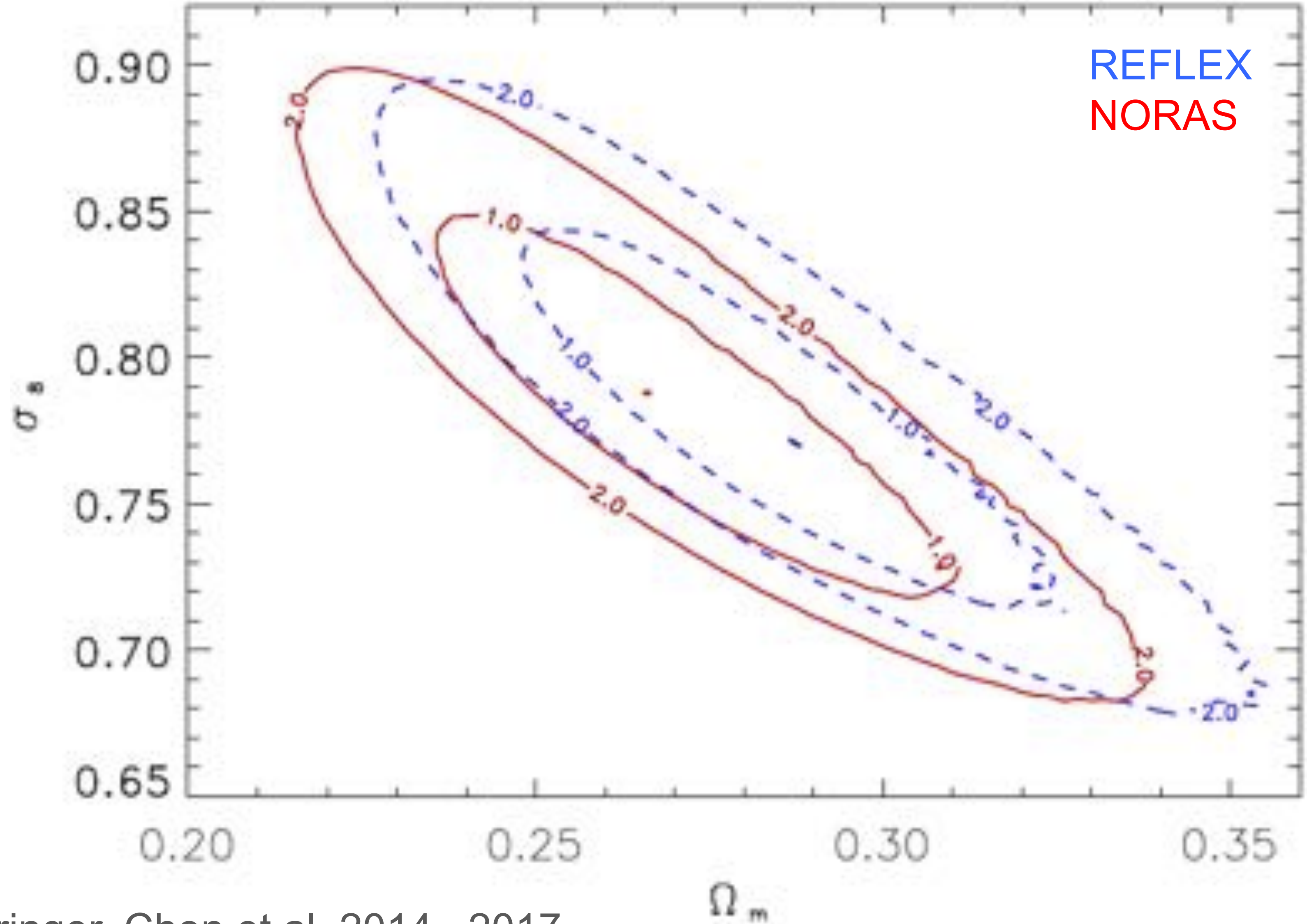


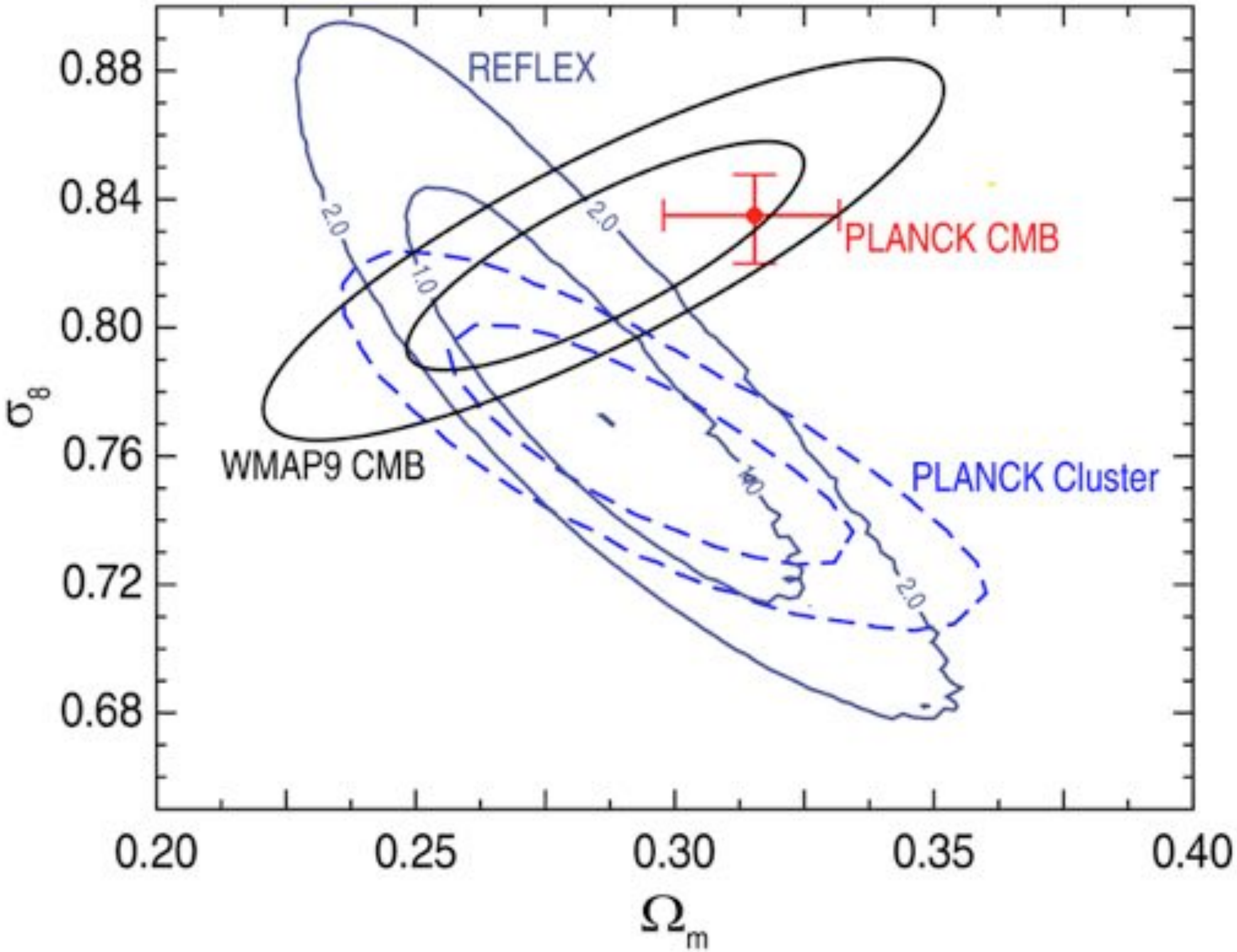
Figure: slope +- 5%, normalization +- 10%, scatter +- 10%
Marginalization: slope +- 7%, normalization +- 14%, scatter 30%
Assume hydrostatic mass bias of -10%

Cosmological constraints by REFLEX and NORAS



Böhringer, Chon et al. 2014, 2017

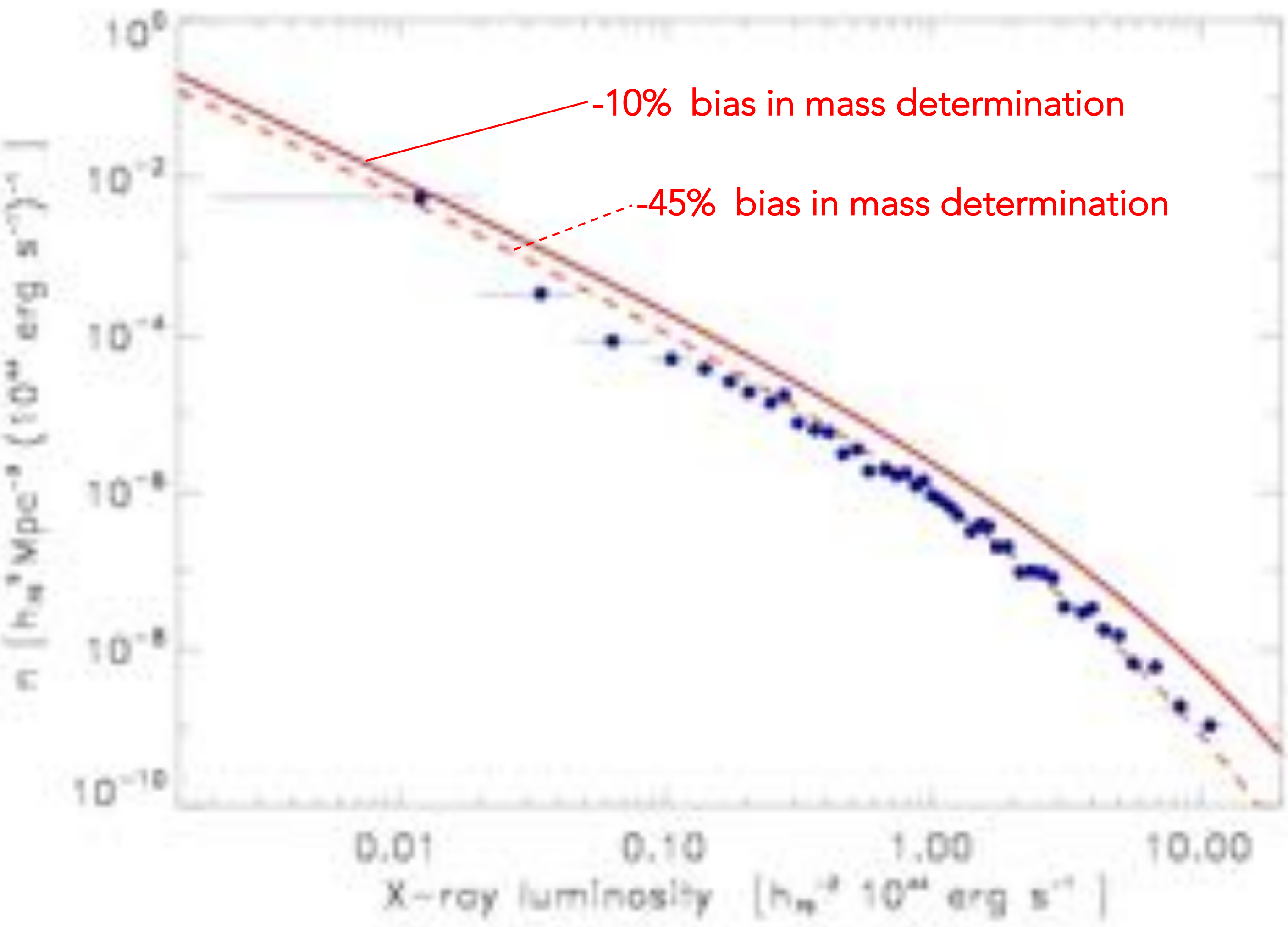
Cosmology: REFLEX and PLANCK Galaxy Clusters as well as PLANCK and WMAP CMB Results



Planck Collaboration 2013
Hinshaw et al. 2013

Böhringer et al. 2014

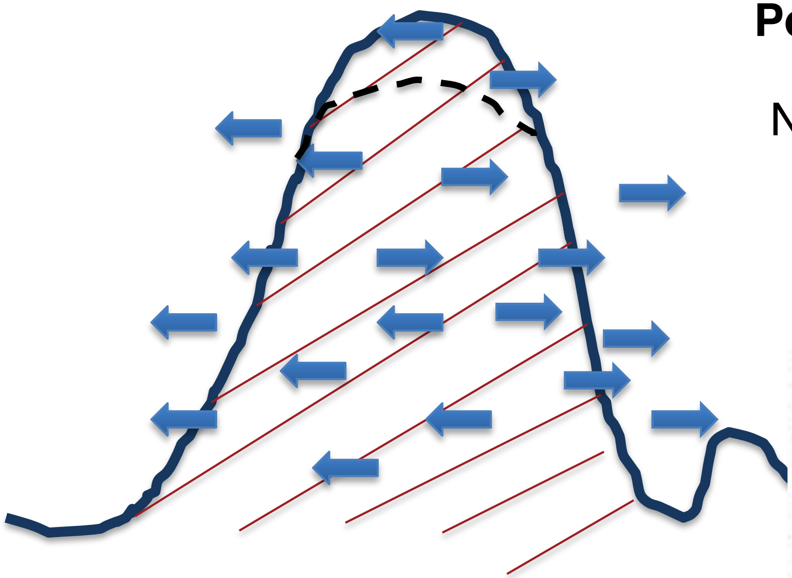
X-ray luminosity function for Planck Cosmology



Böhringer et al. 2014

Effect of Massive Neutrinos

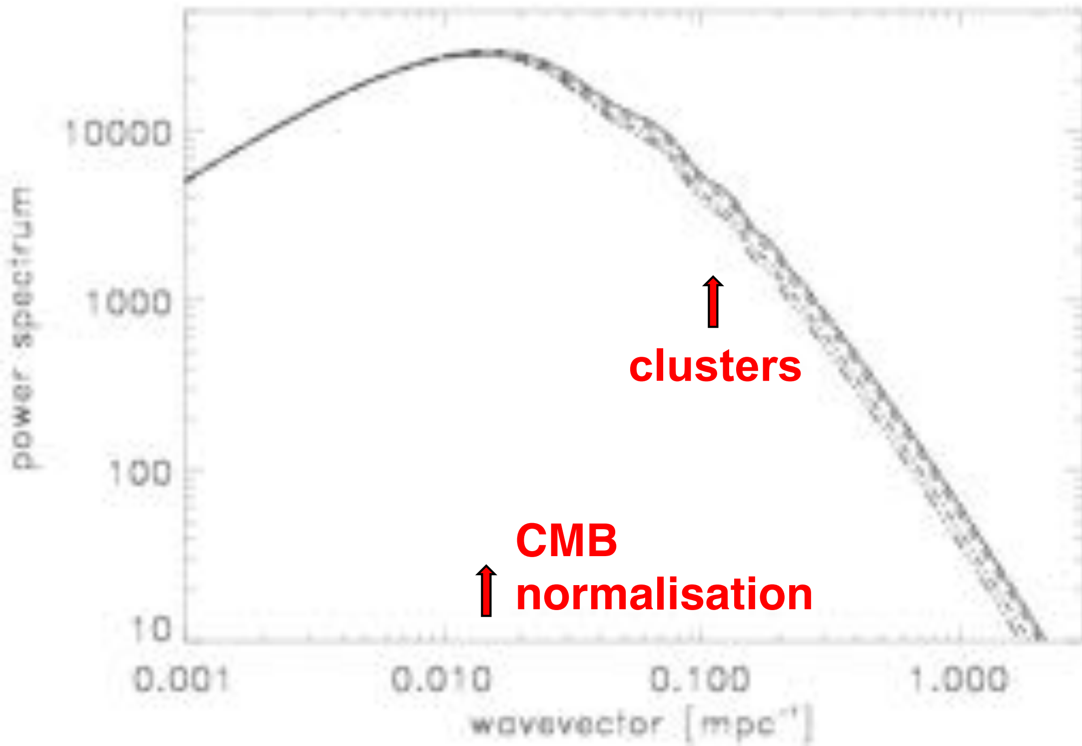
Damping of the density fluctuations by the relativistic neutrinos



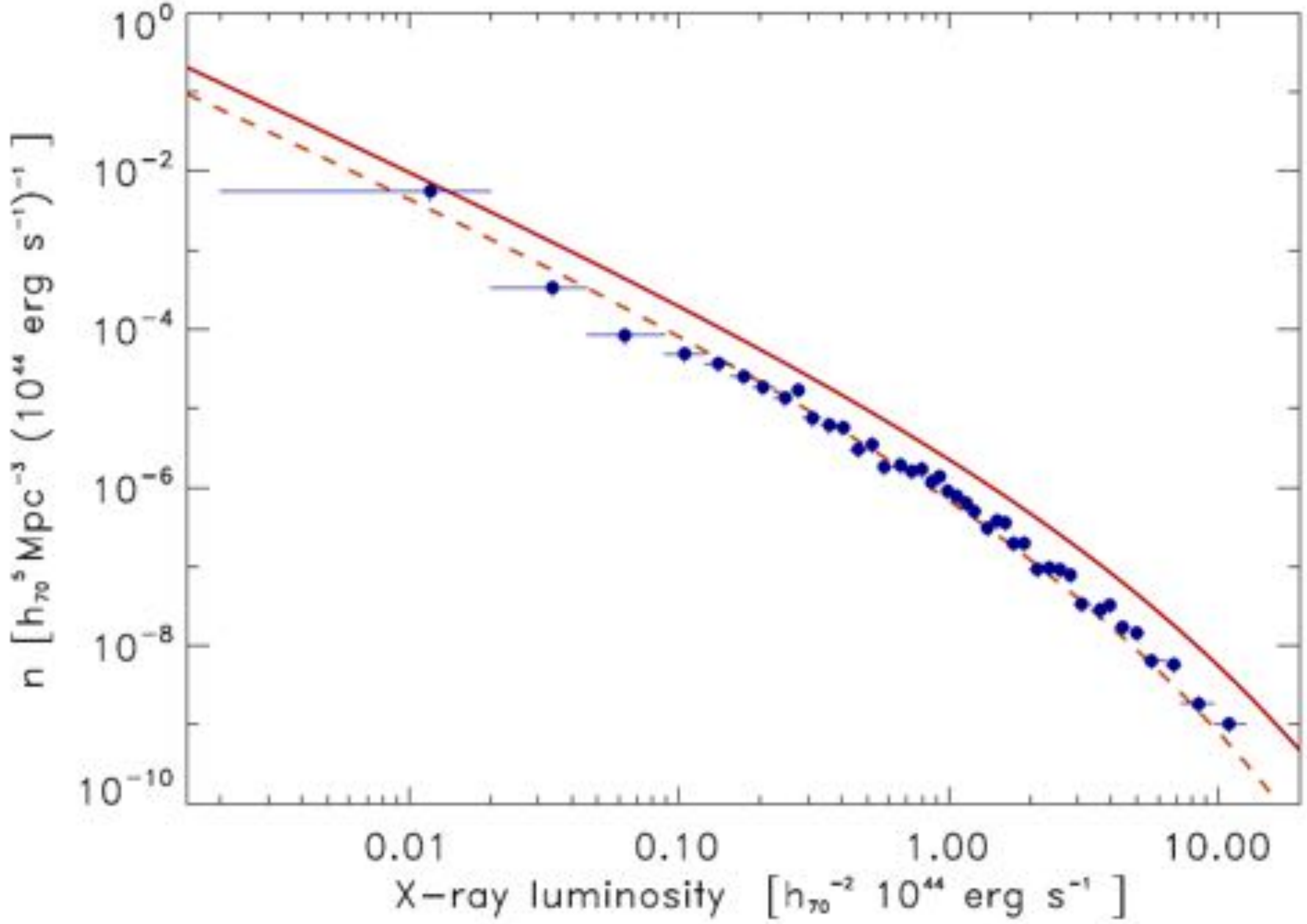
Relativistic neutrinos can diffuse out the density fluctuations (peaks)

Power spectrum of the matter density fluctuations

Neutrino mass: $\Sigma(m_{\nu})$ = 0, 0.06, 0.17, 0.4, 0.6 eV



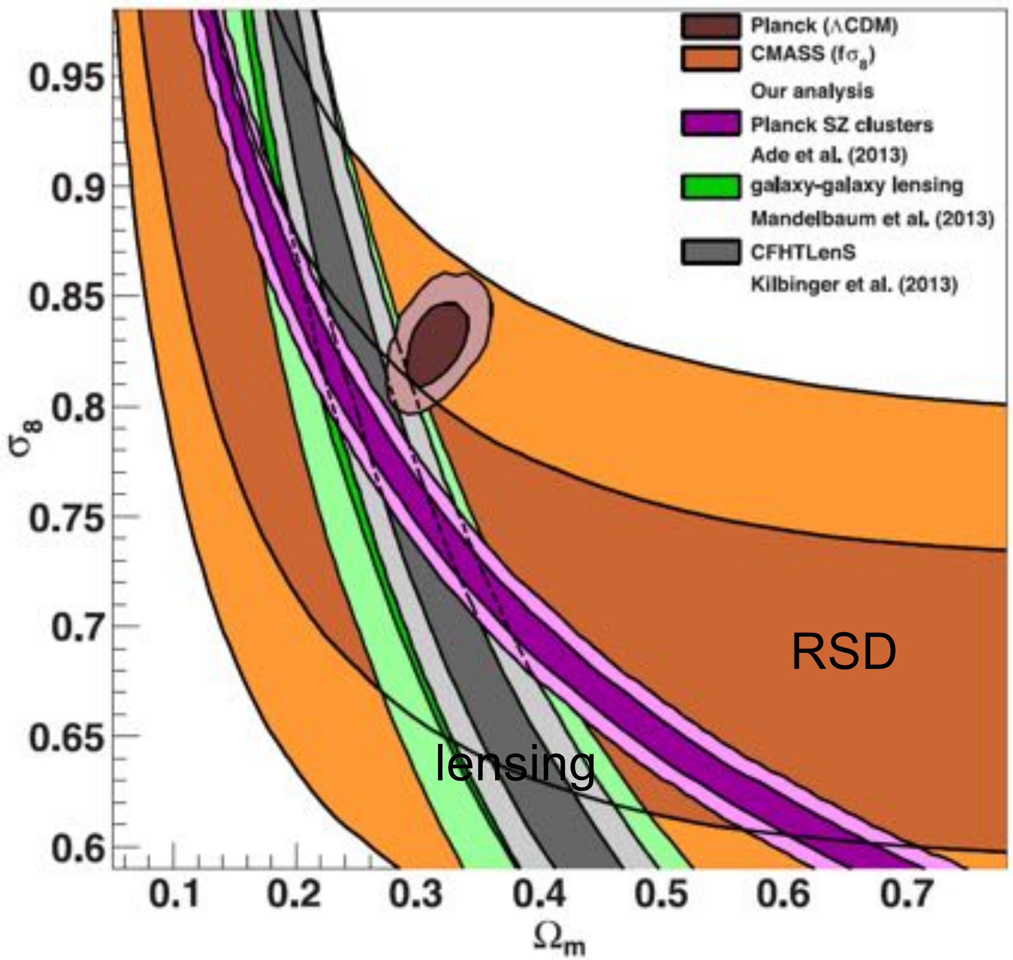
Fit to the observations for M_ν = 0.17 eV (and mass bias = 24%)

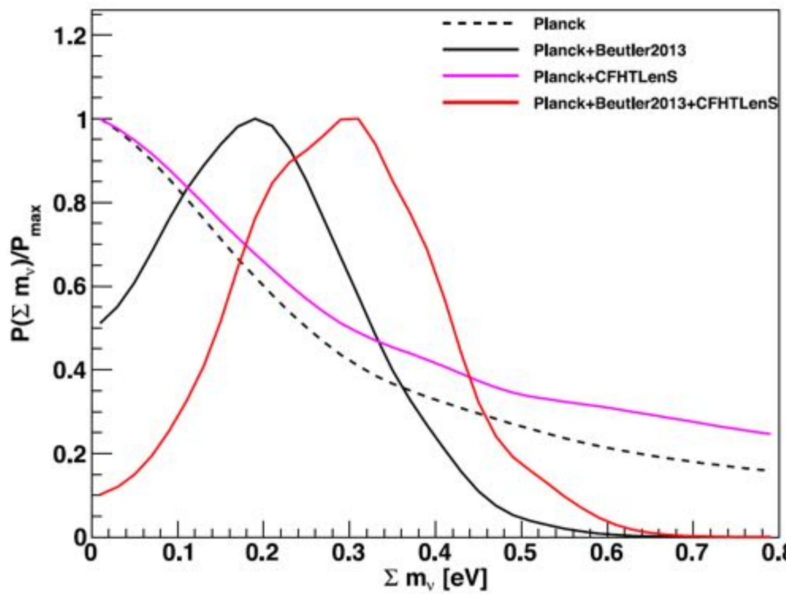


Formal consistency for M_ν = 0.17 – 0.7 eV

Böhringer & Chon 2015; Böhringer 2018

Neutrino mass constraints from redshift space distortions and lensing

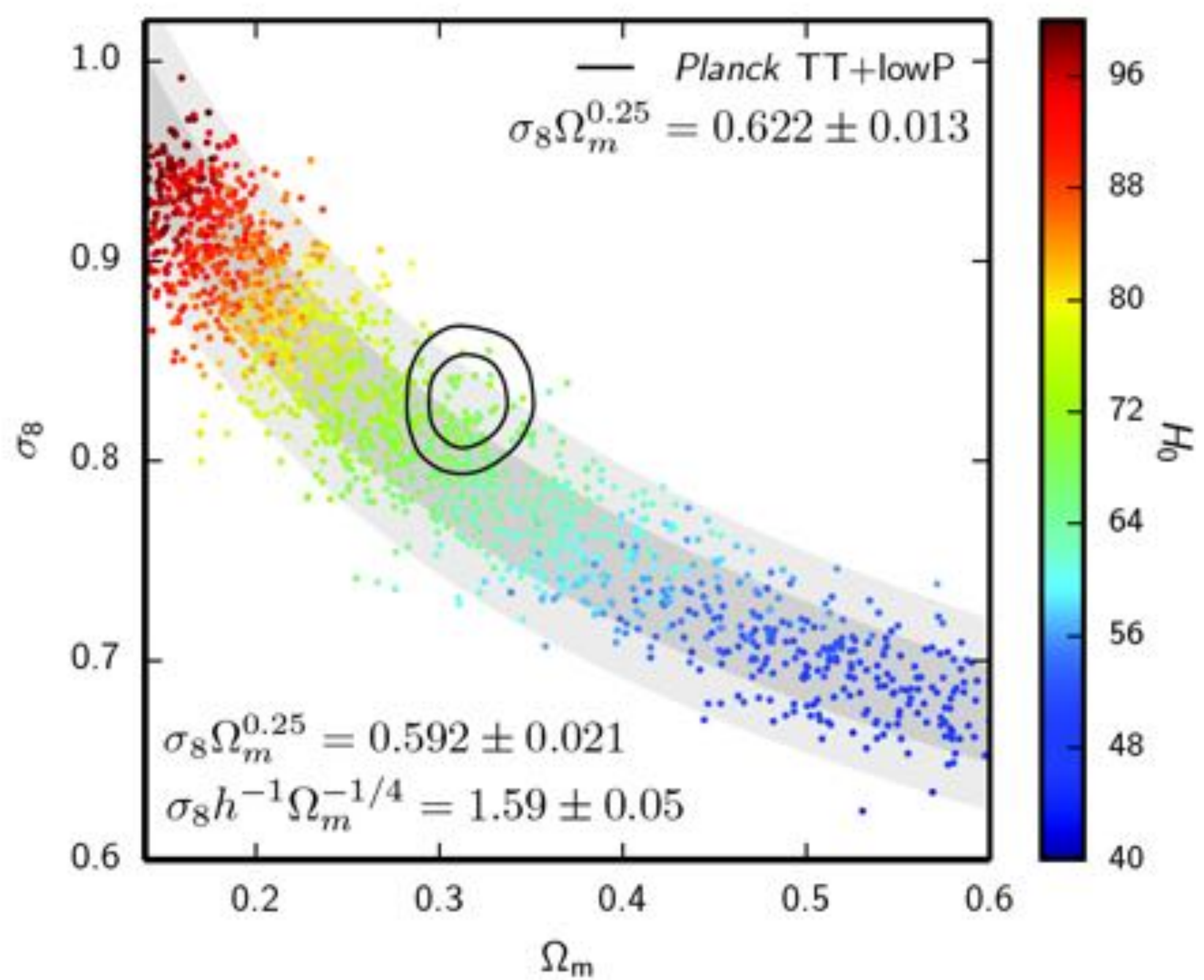




Beutler et al. 2014

Redshift space distortions (brown) and gravitational lensing (green & grey) also show a lower amplitude of the density fluctuations than expected

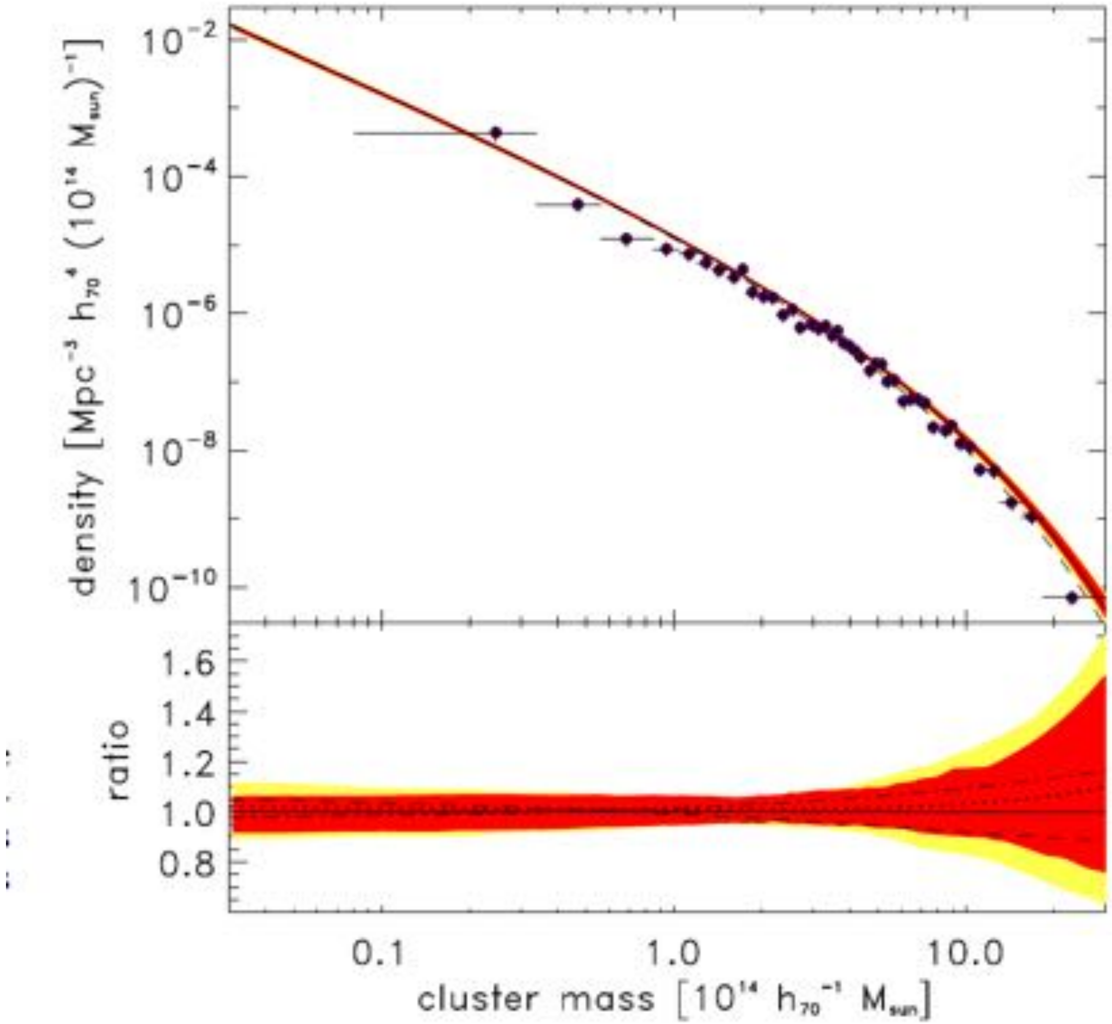
Planck CMB lensing



Planck Collaboration 2015

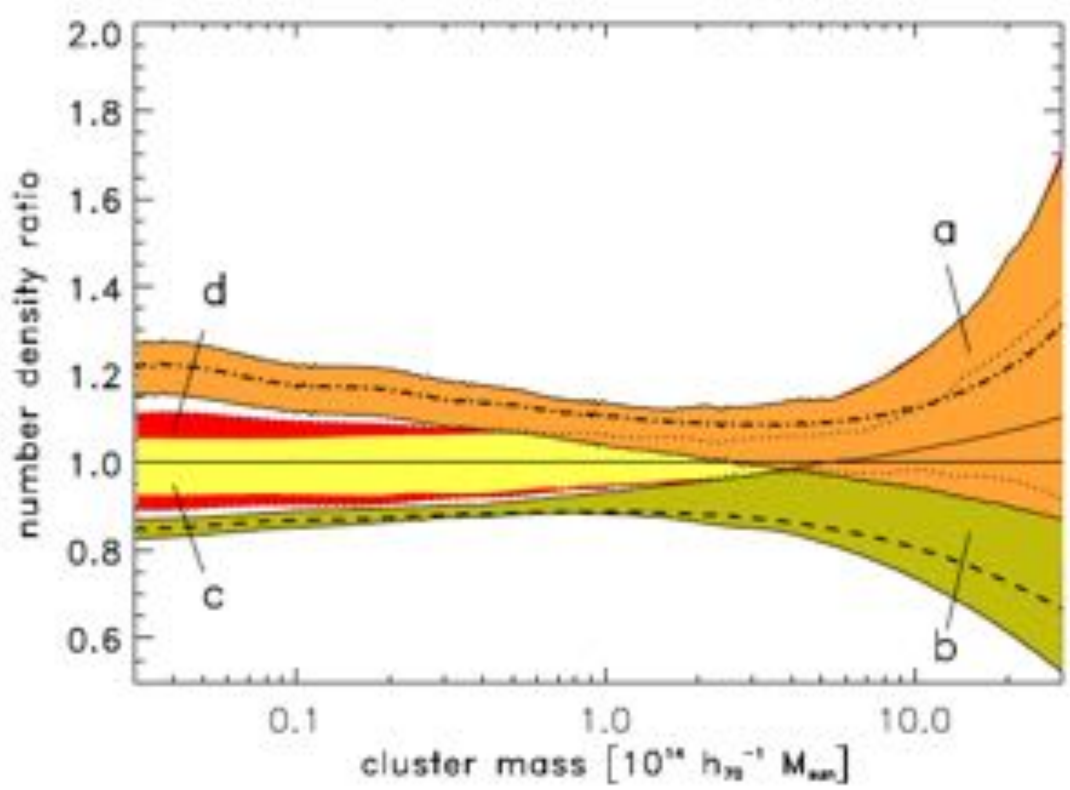
Aspects of Large-Scale Structure

Cluster Mass Function



Böhringer, Chon, Fukugita 2017

Cluster Mass Function and Mass Fraction using different parametrised recipes



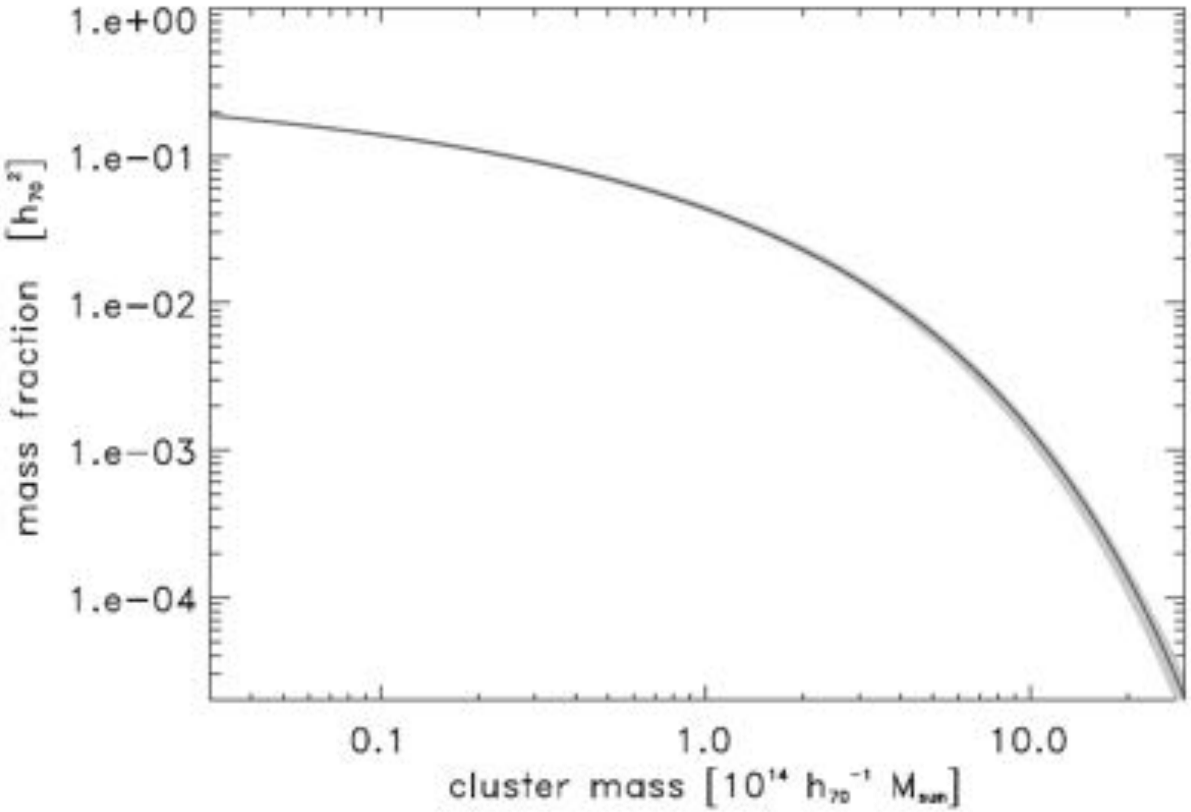
a = Despali et al. 2016
b = Watson et al. 2013

c = Tinker et al. 2008
with cosmological
marginalisation

d = Tinker et al. 2008
with marginalisation
and H_0 variation

Böhringer, Chon, Fukugita 2017

Cluster Mass Fraction of Cosmic Matter



14 +- 1% in groups and clusters $M_{200} > 10^{13}$ M_{sun}

4.4 +- 0.4% in clusters $M_{200} > 10^{14}$ M_{sun}

Fraction of Cosmic Matter in Collapsed Objects

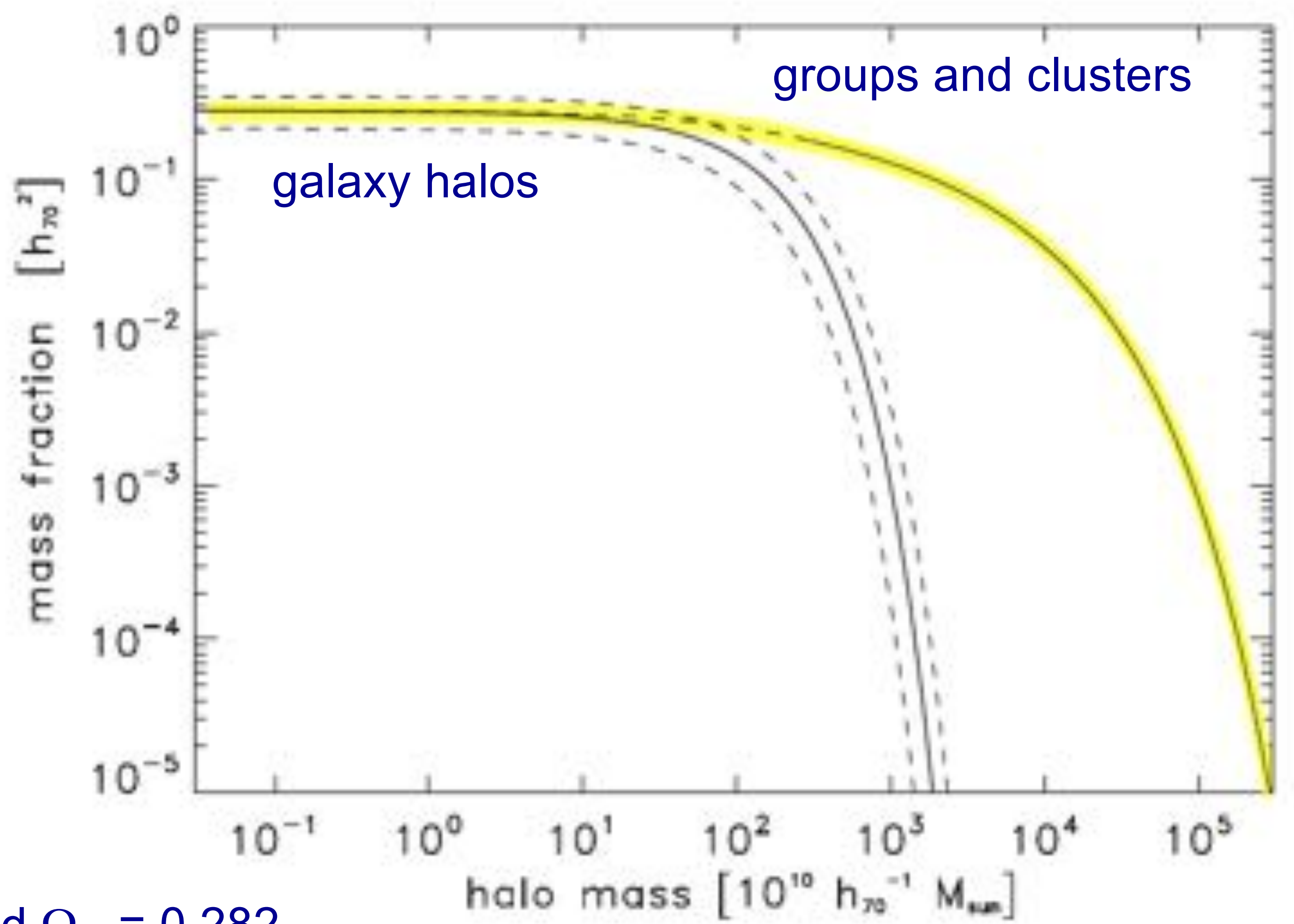
Using results from the Sloan Survey (SDSS) we compare the matter in clusters at larger scale to those in galaxy halos.

From galaxy number counts in SDSS we get the light density (Blanton et a. 2001, Masaki et al. 2012)

The mass-to-light ratio comes from lensing measurements in the halos of galaxies confirmed by similar results from galaxy dynamics (McKay et al. 2001, 2002)

$(M/L_r)|_{r200} = 90 \pm 20\ h^{-1}$

Fraction of Cosmic Matter in Collapsed Objects

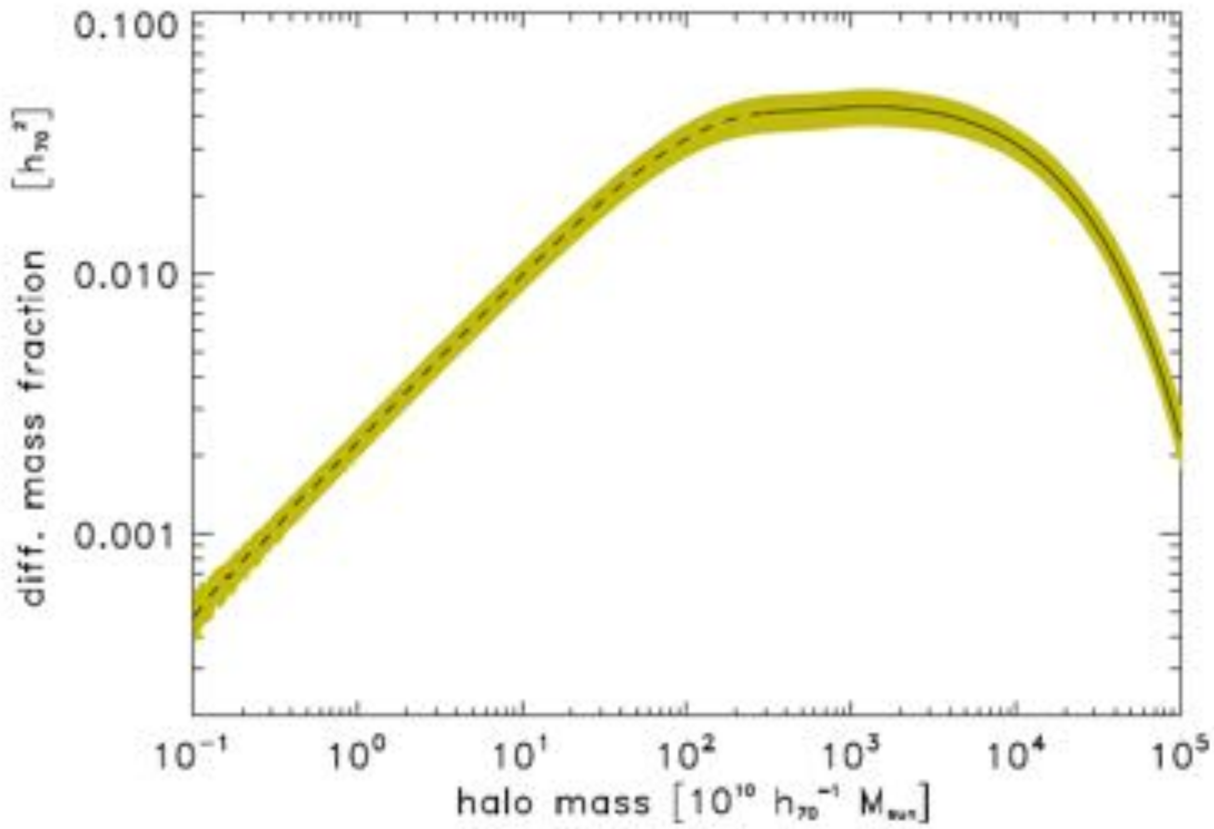


assumed Ω_m = 0.282

Asymtotic mass fraction = 28%

Fukugita & H.B. 2019

Differential Mass Fraction

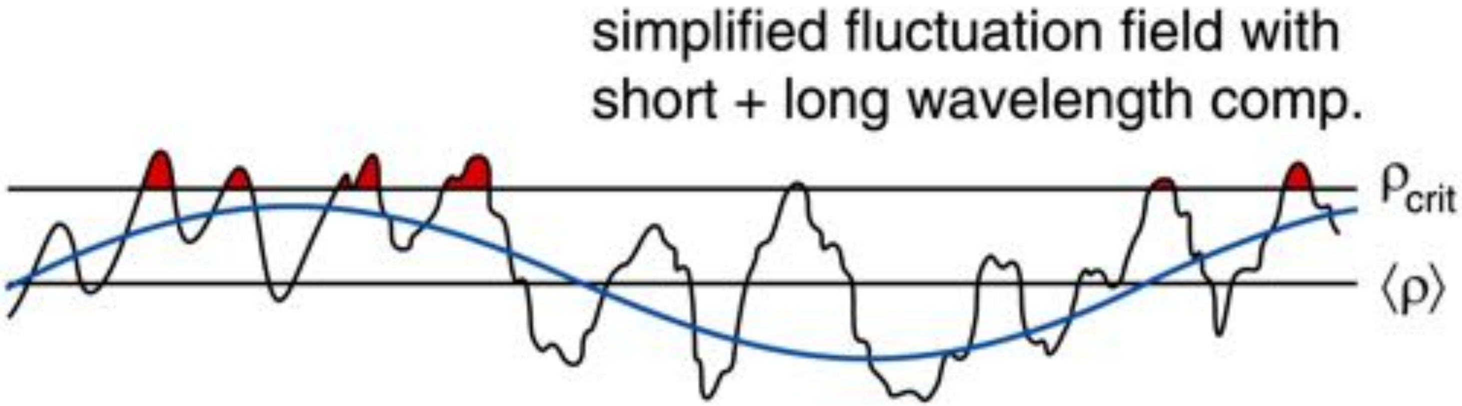


Most of the mass in Dark Matter halos is in the mass range $10^{12} – 10^{14}$ M_{sun}

Fukugita & H.B. 2019

Halo bias in large-scale structure

Spatial modulation of the density of peaks (clustering) :



→ The cluster distribution traces the matter distribution in a „biased" (amplified) way

Biasing : $$\widetilde{P}(k) = b^2 \cdot P_{DM}(k)$$

$$b(M,z) = 1 + \frac{\Delta_*}{\sigma^2(M,z)} - \frac{1}{\Delta_*}$$

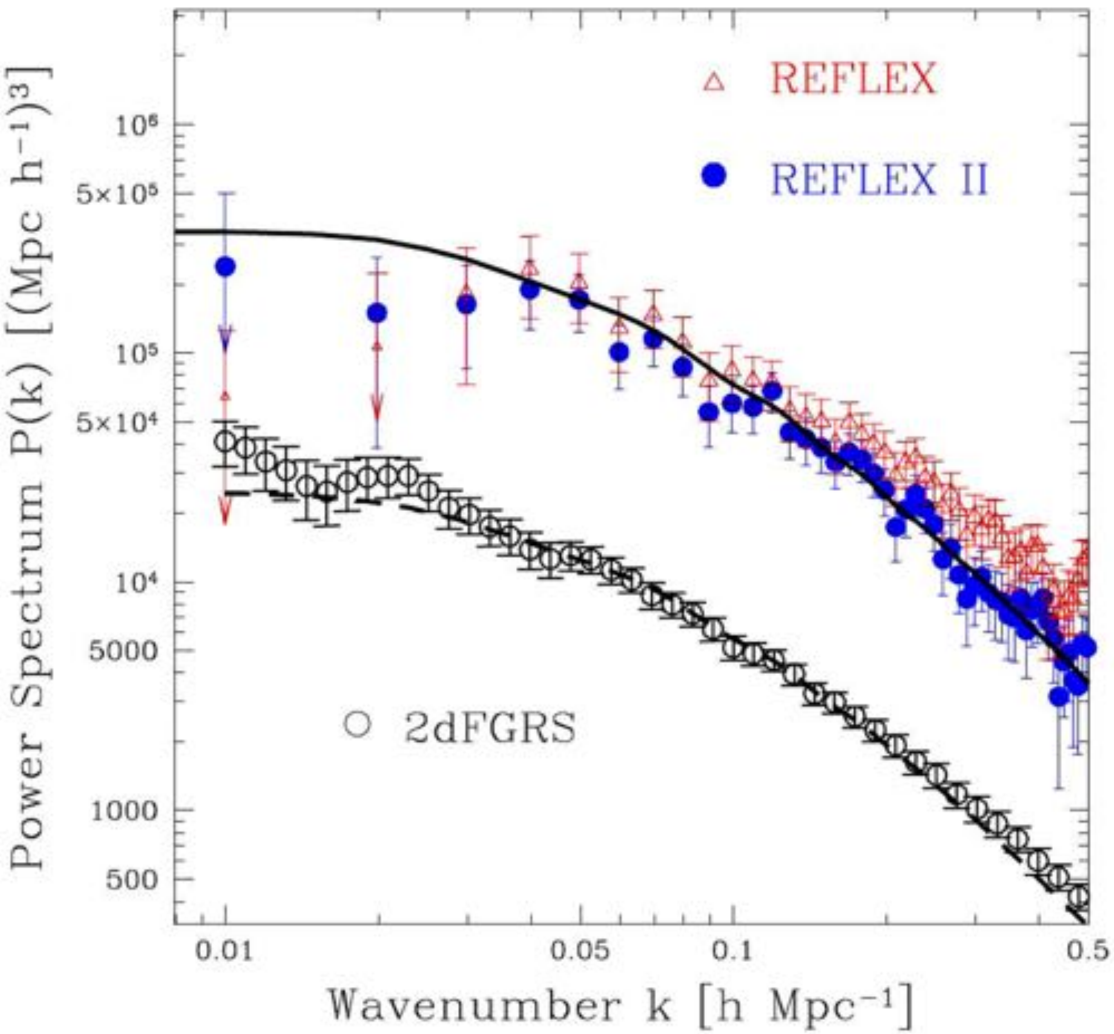
Mo & White 1996

Sheth & Tormen 1999

Tinker et al. 2010

➡ biased (amplified) probe of very large scales

REFLEX II power spectrum (ΛCDM cosmology)

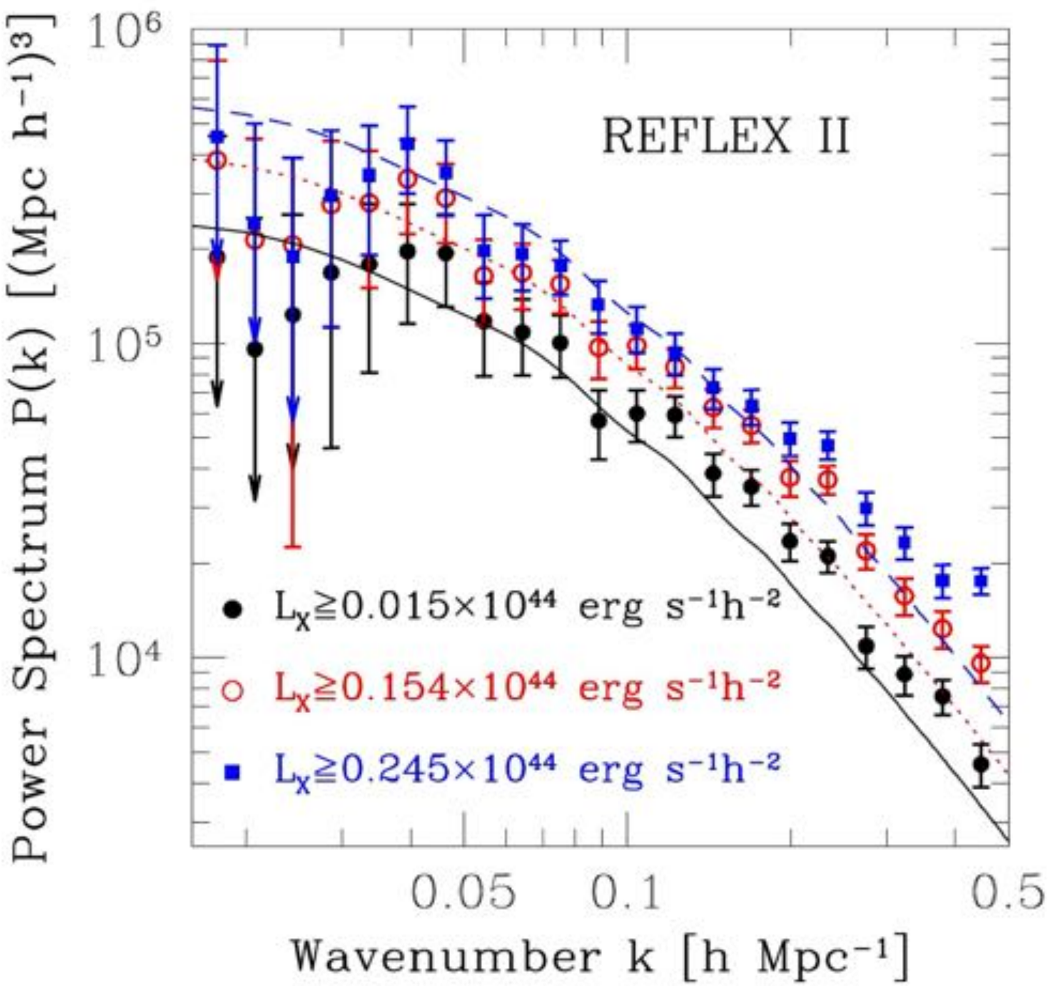


Balaguera-Antolinez et al. 2010

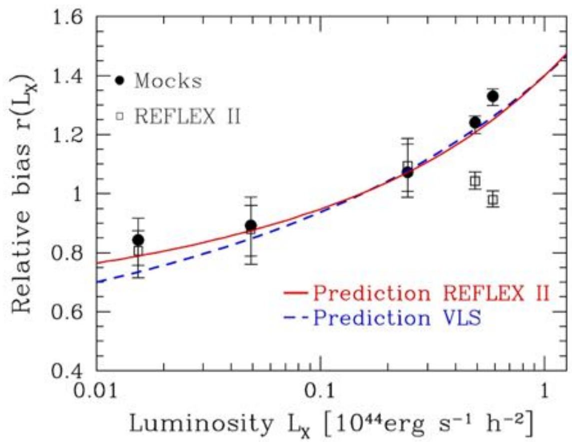
The lines give the prediction of the Concordance Cosmological Model with WMAP 5yr parameters.

REFLEX II power spectrum (biasing)

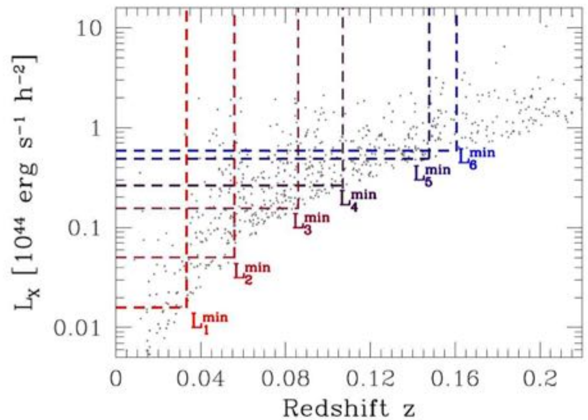
The amplitude of the P(k) increases with increasing lower mass limit



Balaguera-Antolinez et al. 2010



Increase of the amplitude (above) for 6 volume limited subsamples



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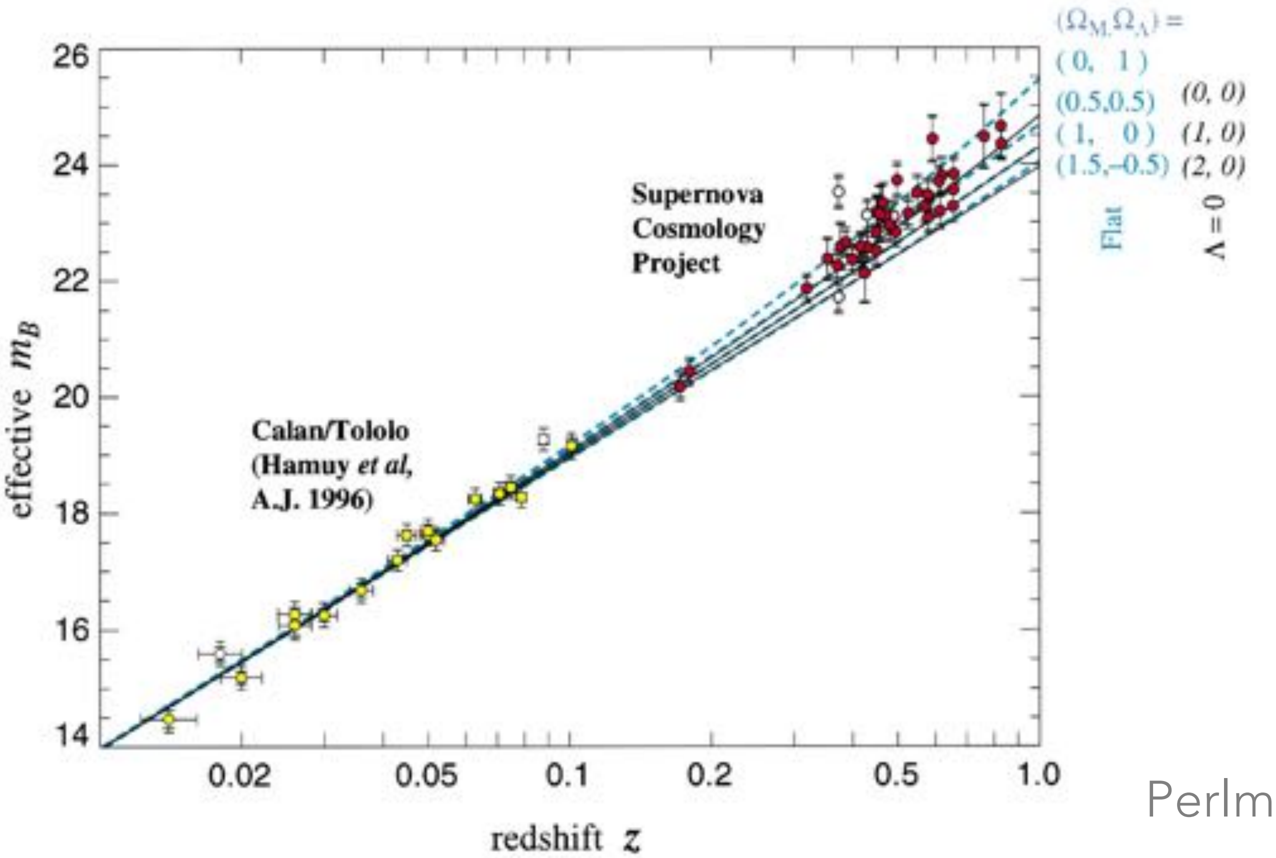
Local Cosmography

Mimicking an accelerating Universe

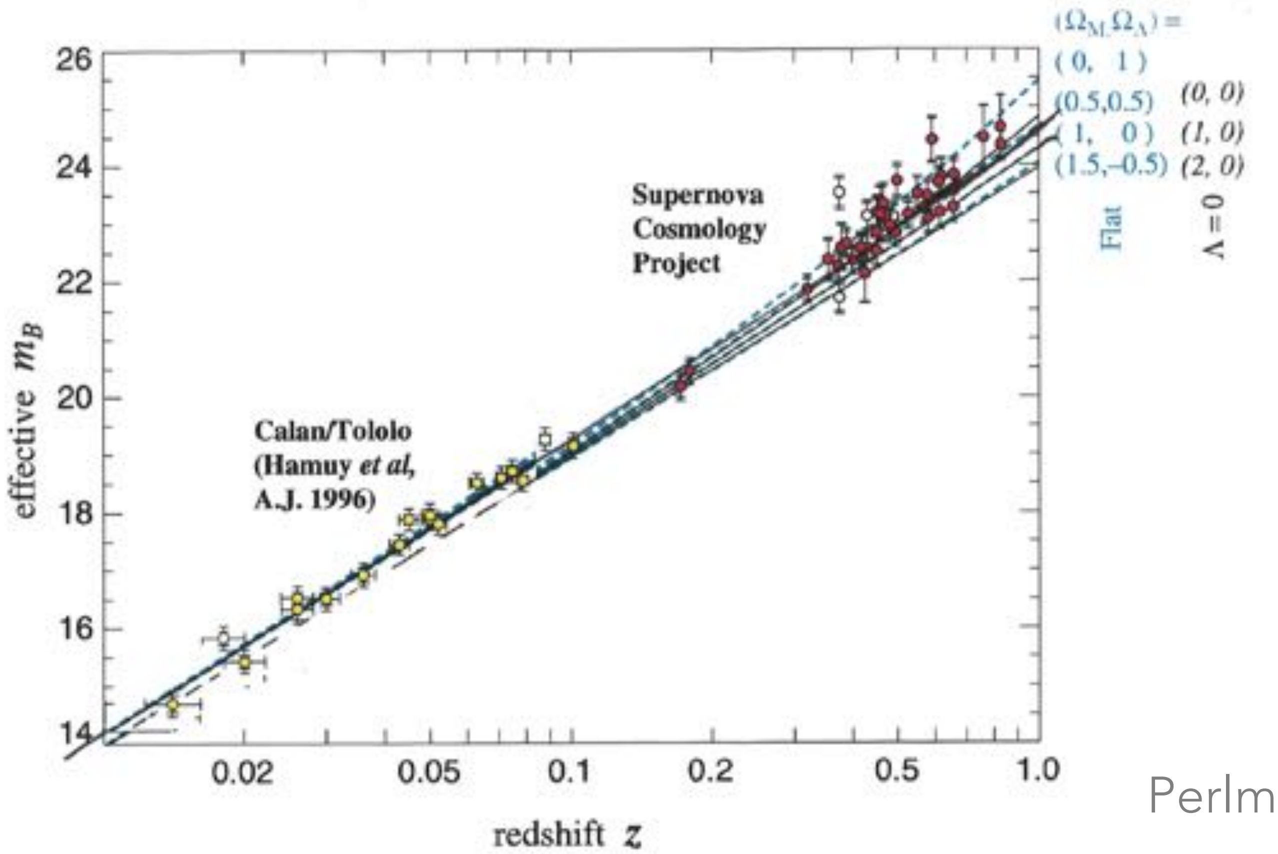


Perlmutter et al. 1999

SN Ia in the nearby Universe are closer and appear brighter for high H_0 for given z – correcting to higher magn. → less curvature in the plot → lower Λ

For Λ ~ 0 one would need an at least 300 Mpc large void with a density deficit of about 50% - our results shown in the following can rule this out !

Mimicking an accelerating Universe



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Different Hubble constants

Planck (2018) Hubble constant	67.4 +- 0.5	km/s/Mpc
Freedman et al. 2012 (HST-KP)	74.3 +- 1.5 +- 2.1	km/s/Mpc
Riess et al. 2011	73.8 +- 2.4	km/s/Mpc
Tully et al. 2014	75.2 +- 3.0	km/s/Mpc
Riess et al. 2018	73.24	km/s/Mpc
Riess et al. 2019	74.03 +- 1.42	km/s/Mpc

……………………………………………………………………………………

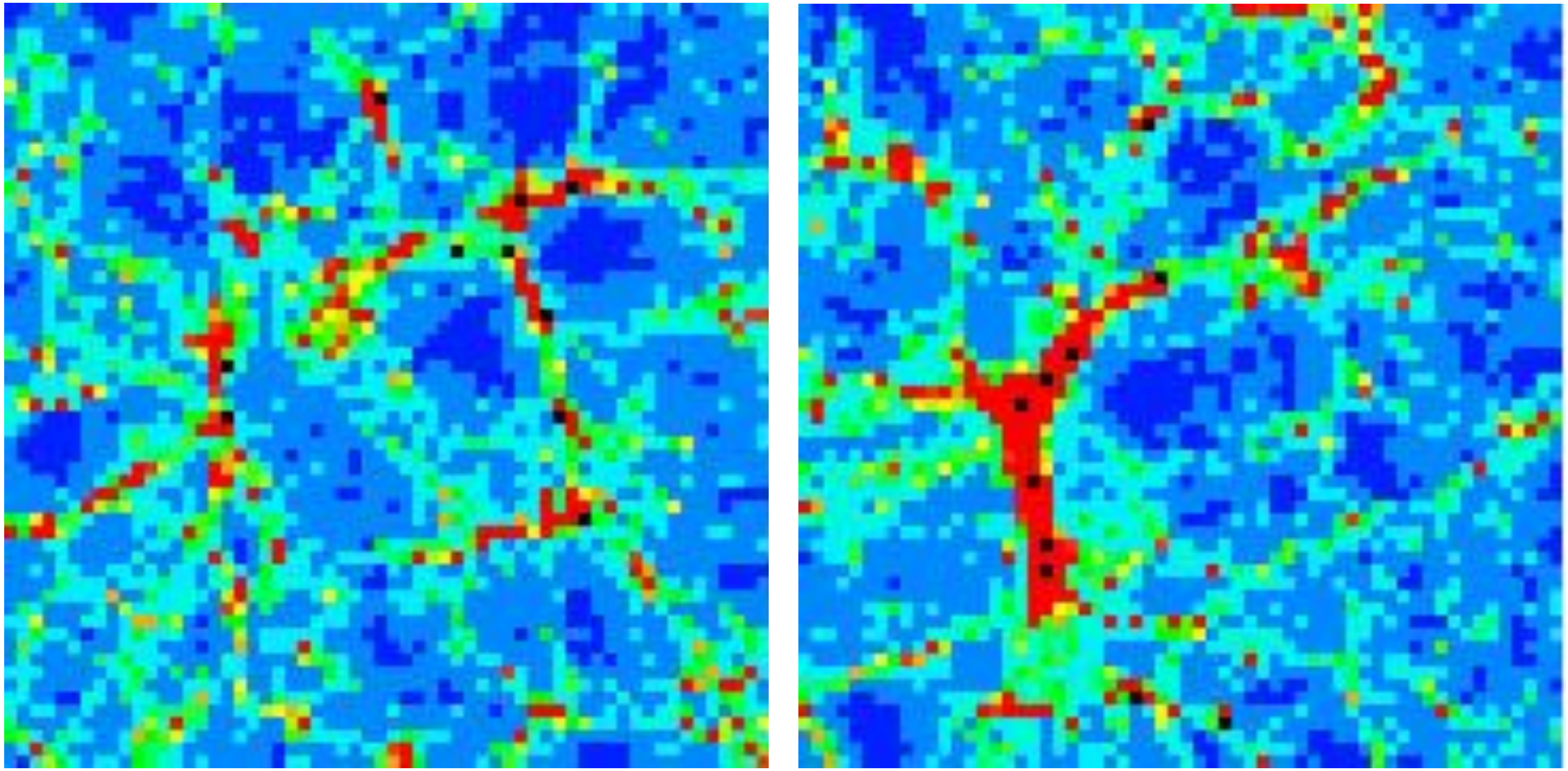
Currently hot debate between Riess et al. (2018,19) and Shanks et al. (2018, 19a,b):

Shanks: zero point offsets of Gaia Cepheid paralaxes
"calibrated" with AGN ΔH_0 ~4.7 %
local underdensity ΔH_0 ~1.8%
→ H0 = 73.4 → 68.9 km/s/Mpc

Riess: both claims are wrong, (complex dependence of zeropt. offsets)

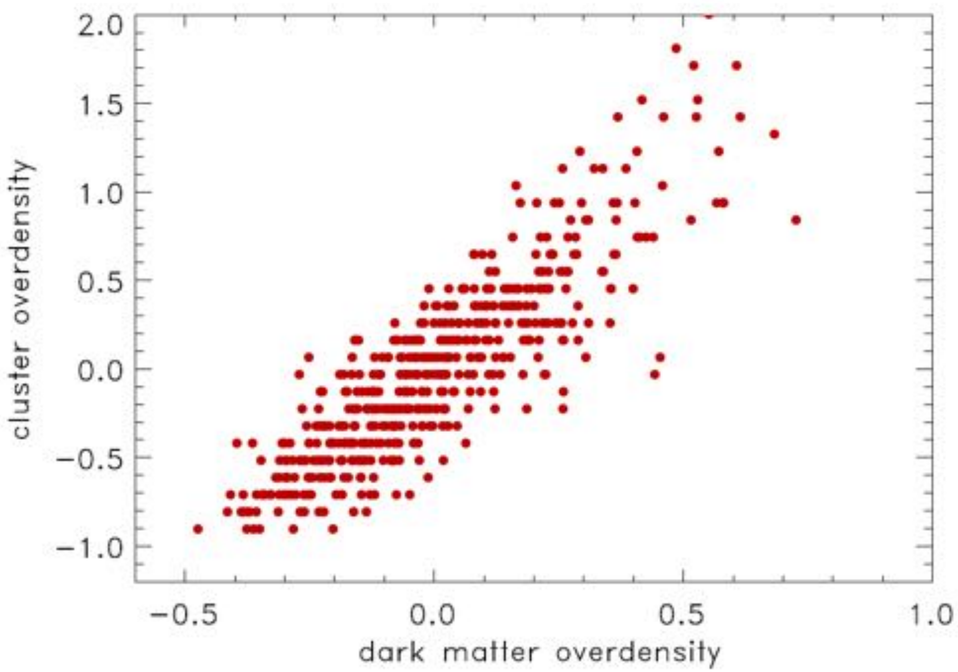
Galaxy clusters: excellent tracers of the large-scale matter distribution

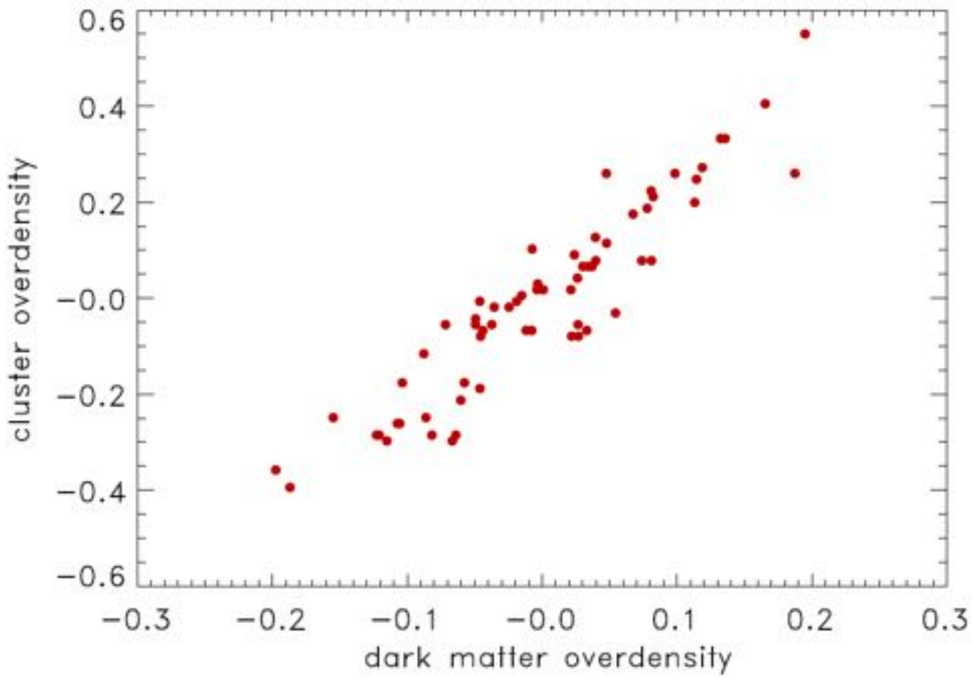
2 slices through the Millenium dark matter simulations
black points = clusters   colour scale = matter density



Cluster bias in the Millenium Simulation

Cluster bias in the Millenium simulation for counts in cells (L = 89.3 Mpc [left] and 178.6 Mpc [right]) for clusters with $M_{200} > 0.5\ 10^{44}\ M_{sun}$. Bias factor is about 2.1.

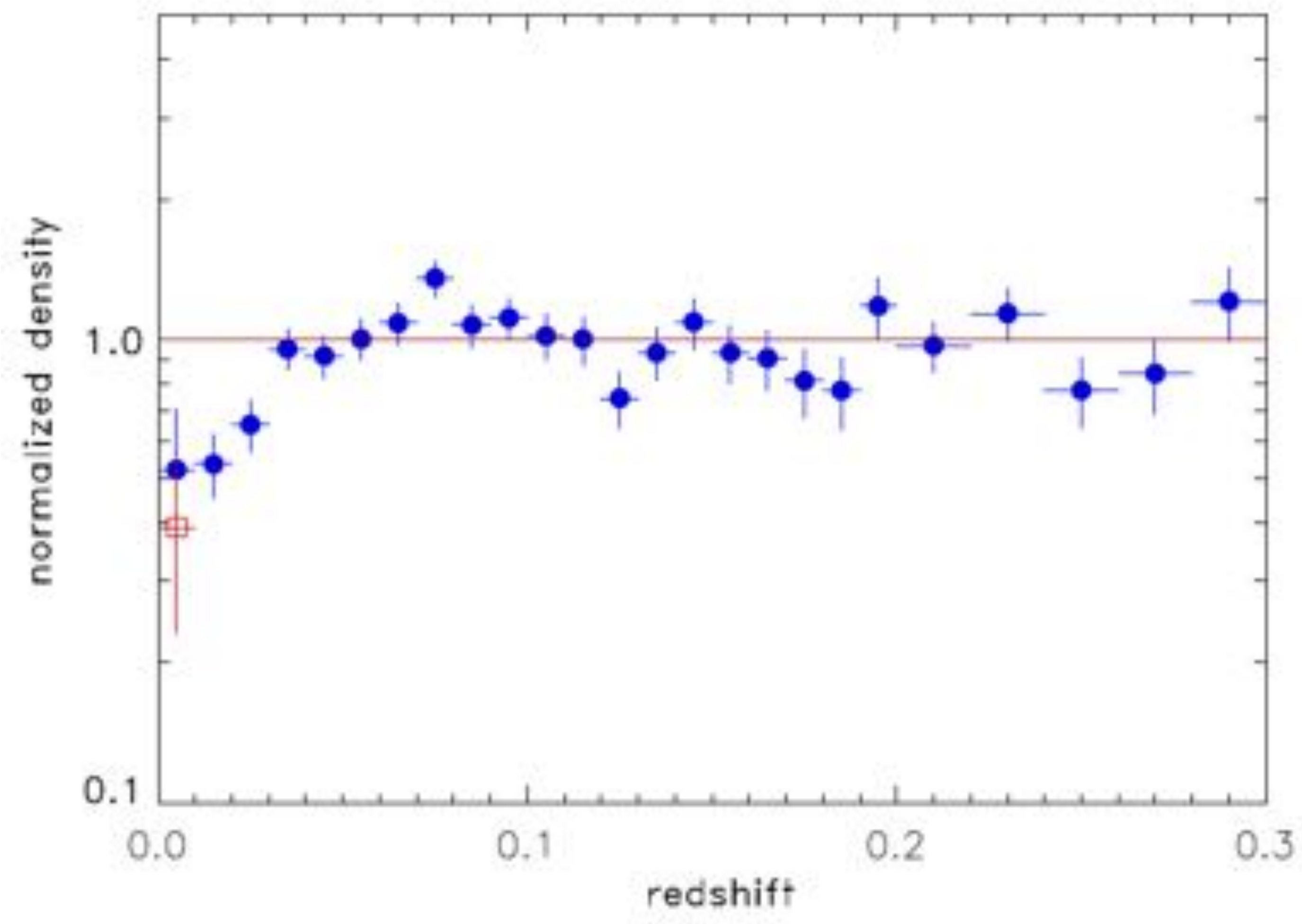




$$\text{Overdensity: } \Delta = \frac{\rho - \bar{\rho}}{\bar{\rho}}$$

Böhringer, Chon, et al. (2019)

CLASSIX (all extragal. Sky)



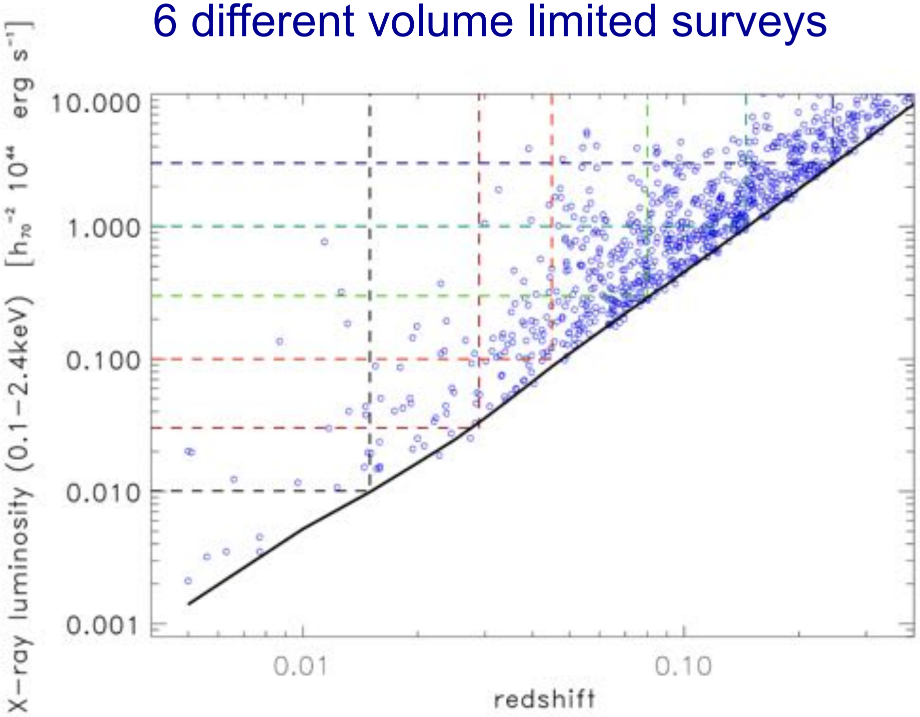
Red square: excluding the Virgo-cluster region

Böhringer, Chon, et al. 2019

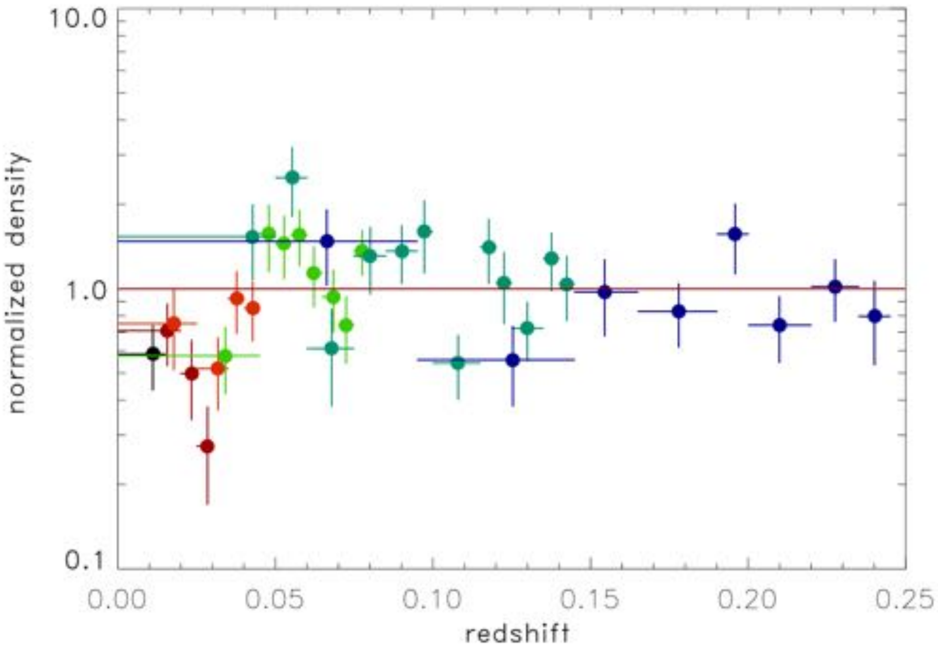
Cluster Density Distribution for different lower X-ray Luminosity Limits

We can avoid the ambiguity problem by constructing the density distribution for different volume limited sub-surveys:

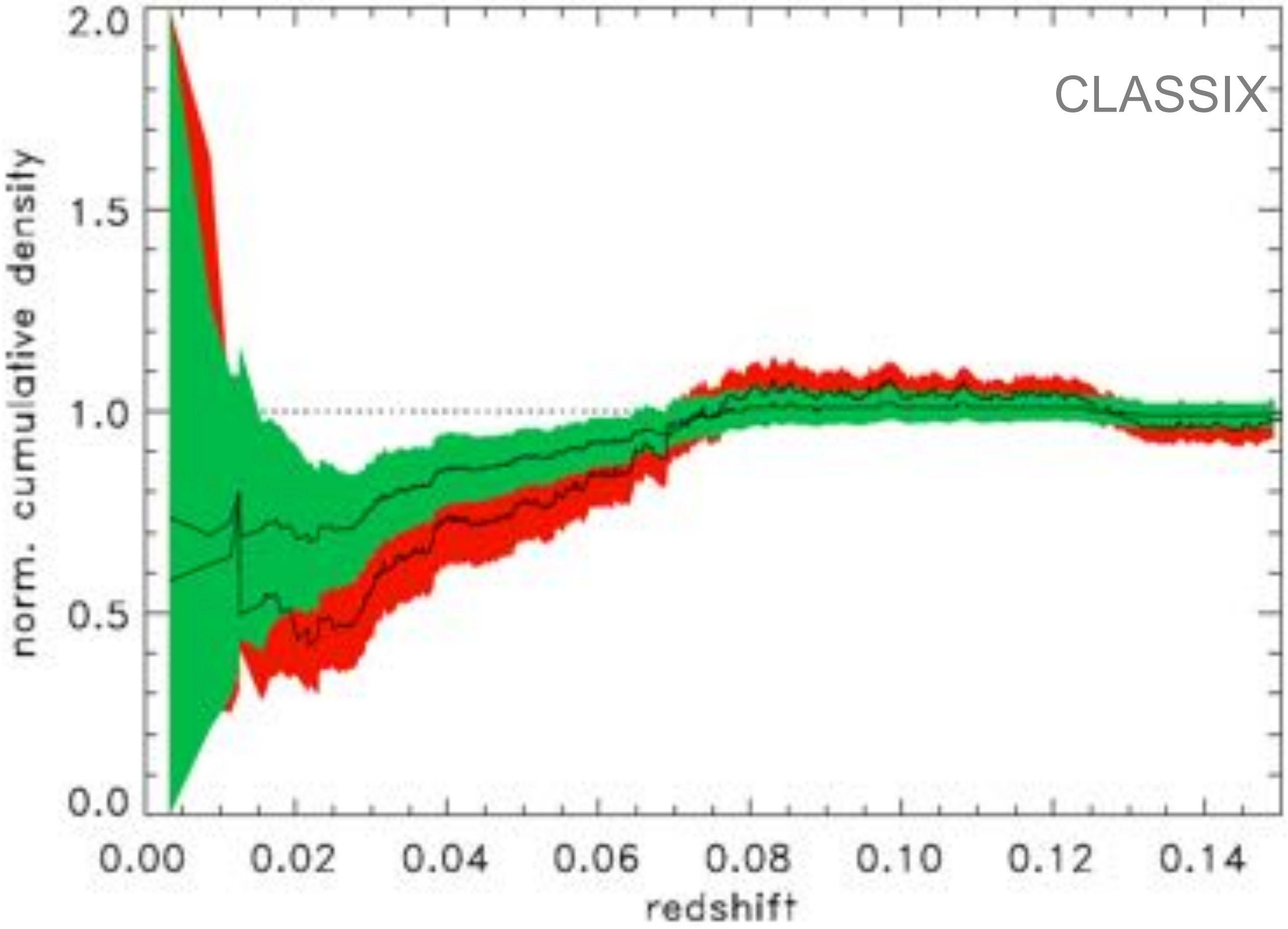
6 different volume limited surveys



Combined cluster density distribution



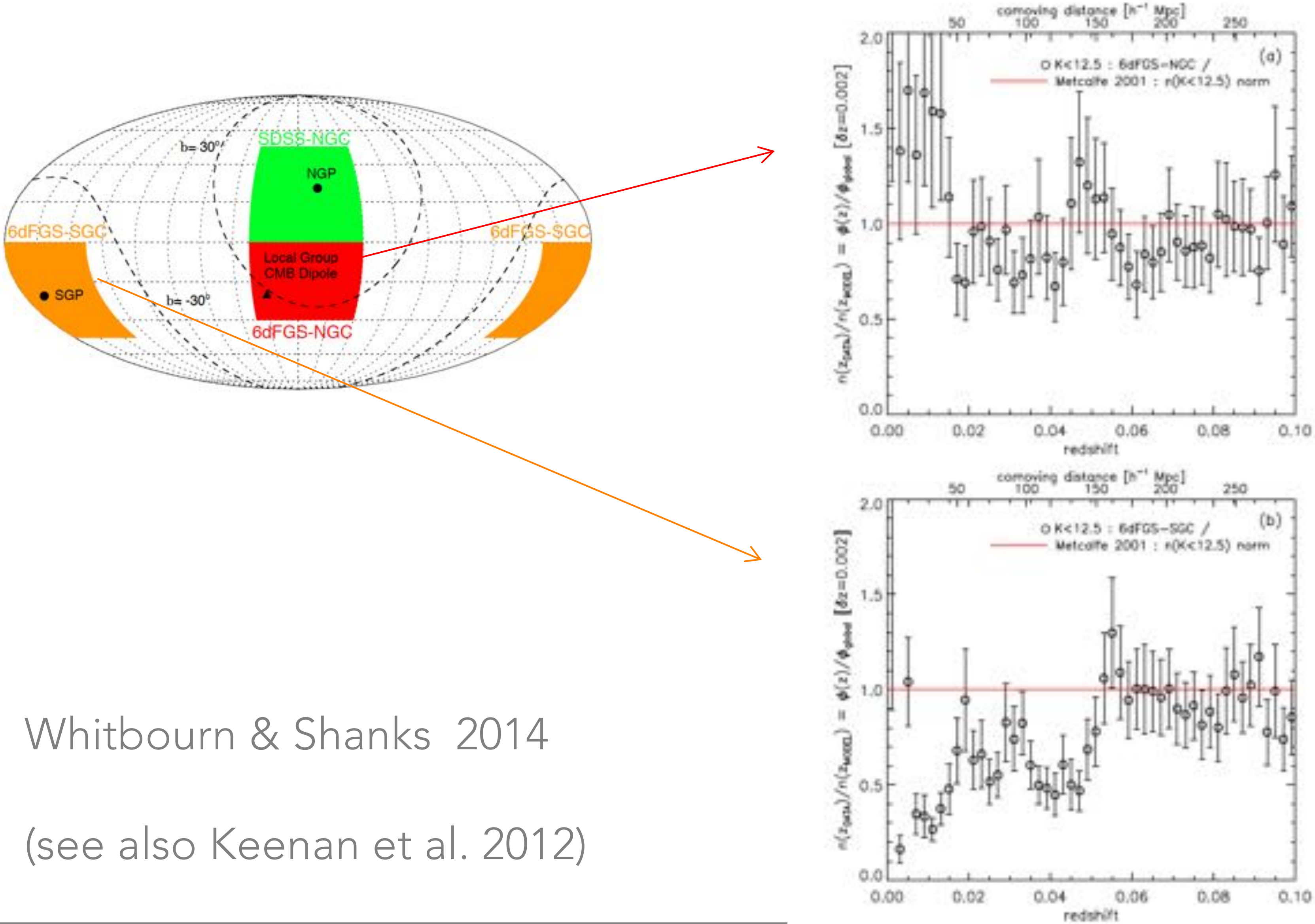
Cumulative density profile for cluster and matter



Matter density in CLASSIX: -30 +-15% for radius < 100 Mpc

Böhringer et al. 2019

Local underdensity in the galaxy distribution in the South Galactic Cap

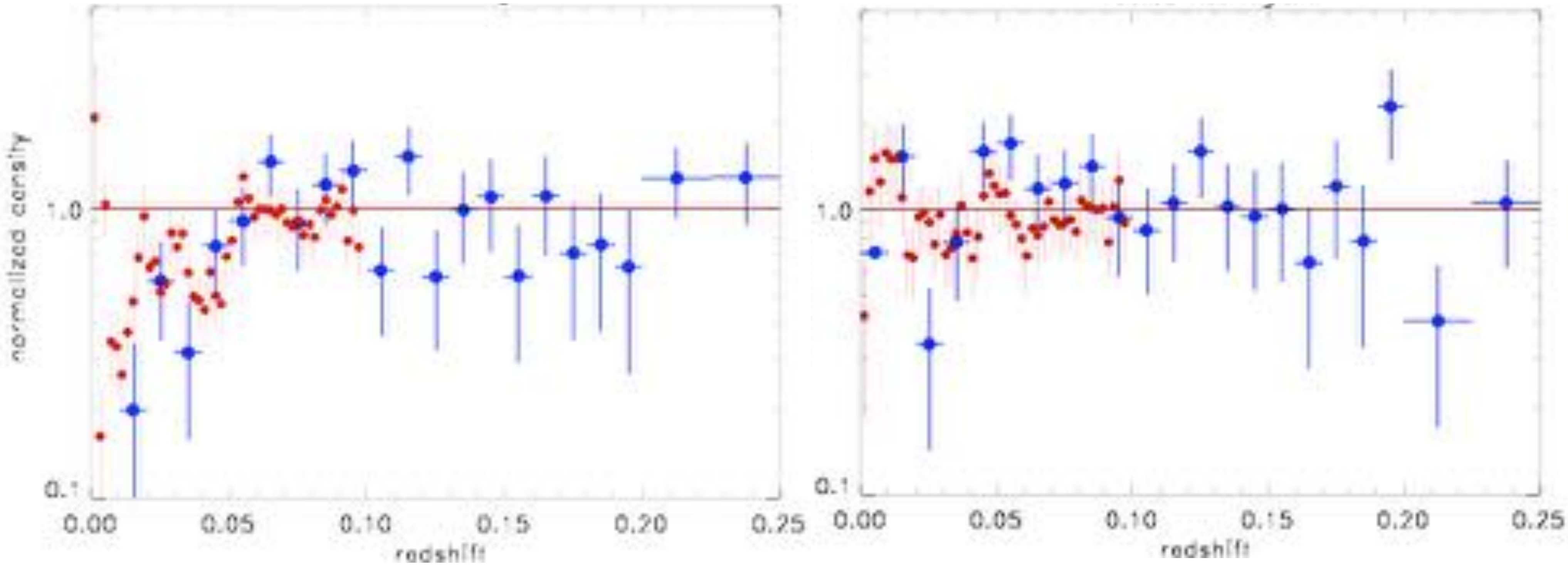


Whitbourn & Shanks 2014

(see also Keenan et al. 2012)

REFLEX cluster density distribution in the North and South Galactic Cap (in the southern sky)

South galactic cap region | North galactic cap region in South



Böhringer, Chon, et al. 2015

Change of H_0 with Underdensity

An underdensity of -30 % → change in Hubble parameter by 5.5 (+2.1 – 2.5)%

H_0 = 67.4 +- 0.5 → 71 (+- 1.5) km/s/Mpc <> 74.0 km/s/Mpc

Planck Collaboration 2016 Riess et al. 2019

Note: that the H_0 measurement of Riess et al. covers a larger volume, in which this effect is diluted (smaller)!

Size of the local underdensity: ~ 100 Mpc

in comoving coordinates ~ 90 Mpc

Variance at 90 Mpc („spherical top-hat") radius ~ 10 – 12

→ a -30 +- 15% underdensity is a 1. 3 – 3.7 sigma effect

Probing the Magnetic Field in Galaxy Clusters Through Faraday Rotation of Polarised Background Radio Sources

Hans Böhringer, Gayoung Chon,
Philipp Kronberg

Hans Böhringer sity 16. 1. 2020

Introduction

We probe magnetic fields through rotation measures in polarised radio signal of background radio sources.

$$\mathrm{RM} = 811.9 \left(\frac{n_e}{1\ \mathrm{cm}^{-3}}\right)\left(\frac{B_{\|}}{1\ \mu\mathrm{G}}\right)\left(\frac{L}{1\ \mathrm{kpc}}\right)\ \mathrm{rad\ m}^{-2}.$$

Galaxy cluster sample: CLASSIX (NORAS and REFLEX)

8.25 ster of the sky $|b_{II}| > 20$ deg

1722 clusters (flux limit 1.8 10^{-12} erg s^{-1} cm^{-2})

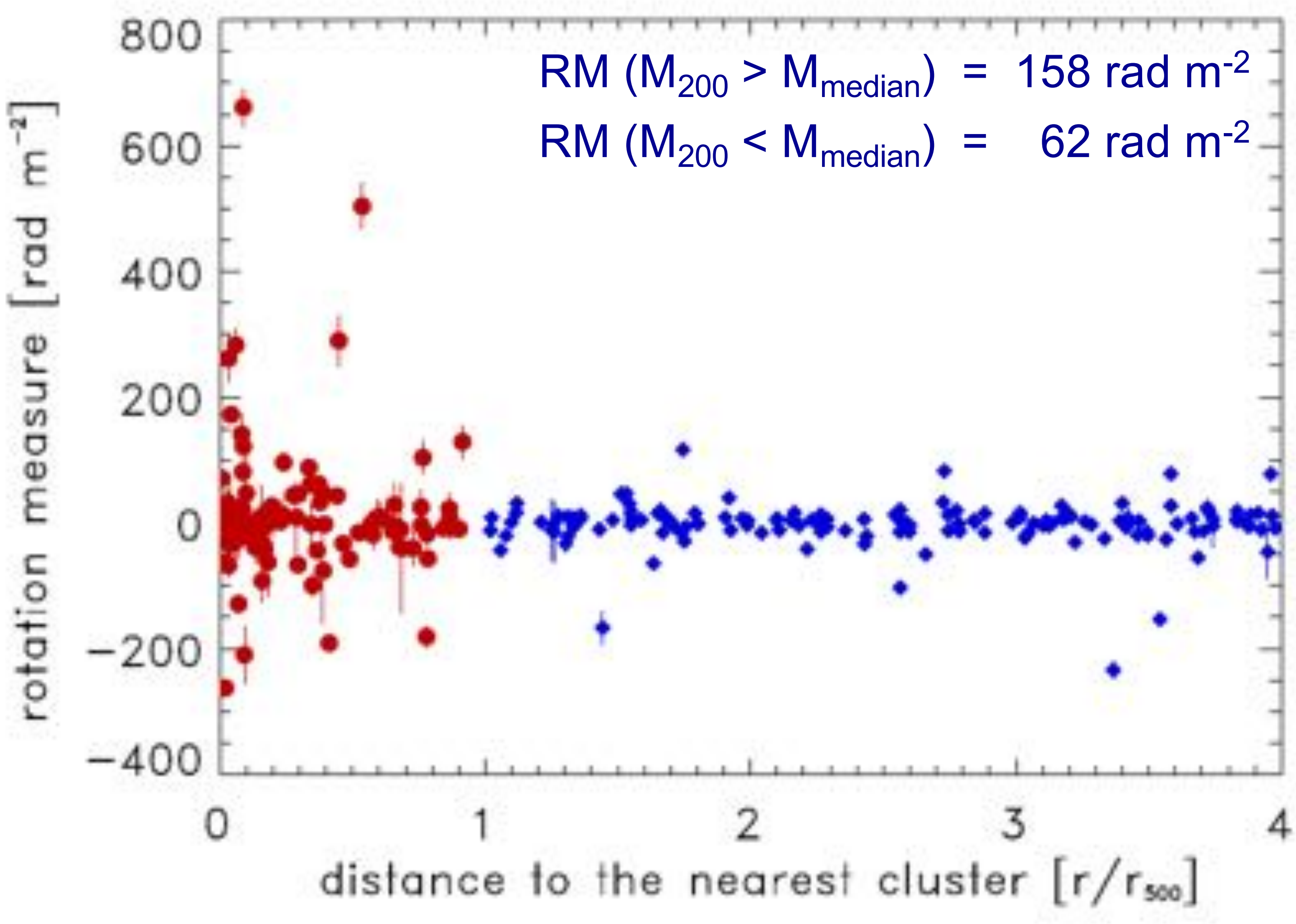
cluster mass = 0.02 - 19.1 x 10^{14} M_{sun}

total cross section ($<r_{500}$) = 208.3 deg^2

Radio source sample: 1383 RMs z > 0.05 (several frequencies)

92 Radio sources in the sightlines of 65 clusters ($r < R_{500}$)

Corrected RM as a Function of Scaled Cluster Radius

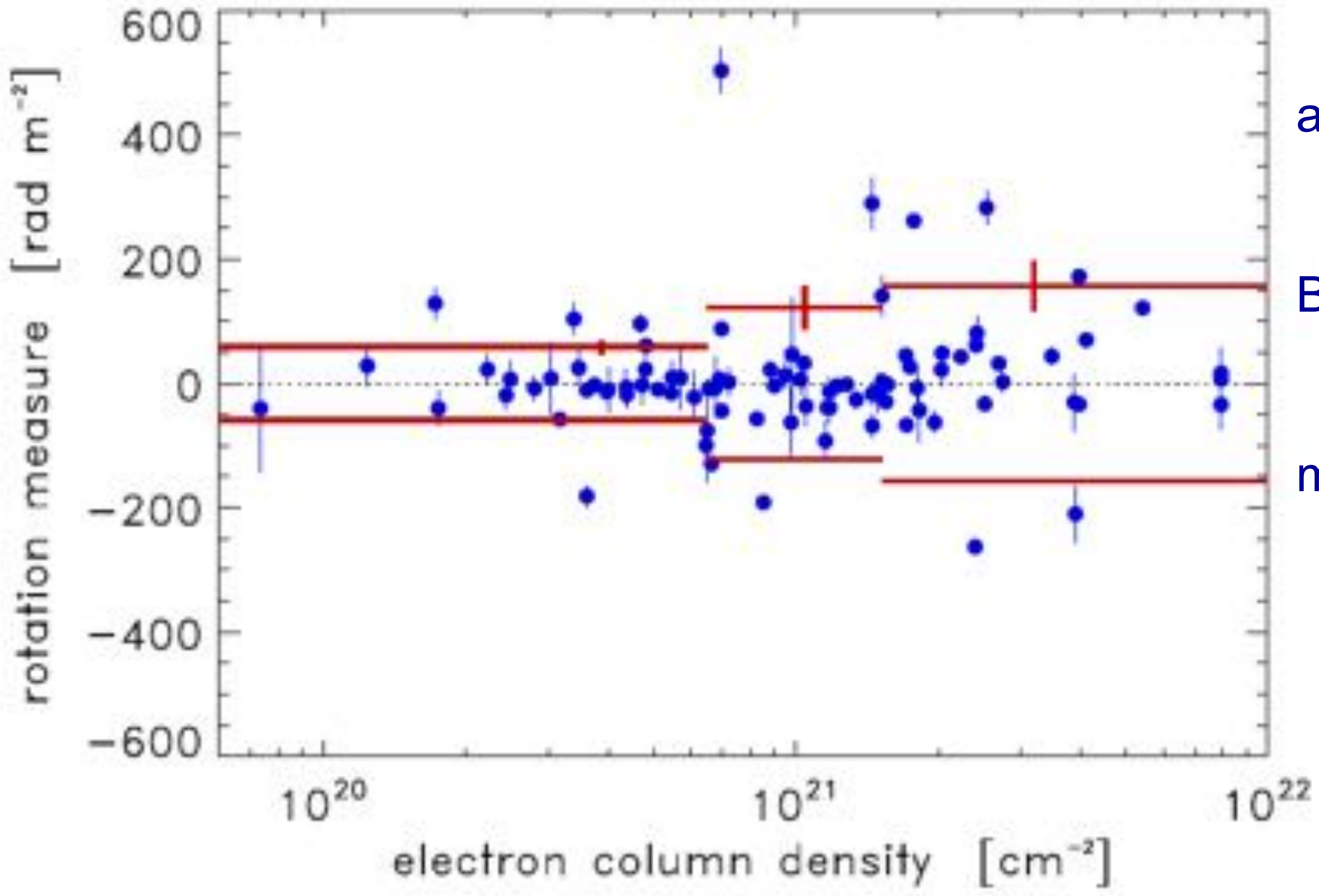


M_{200} (median) $= 1.4\ 10^{14}\ M_{sun}$

$$r_{500} = 0.957\ L_{X,500}^{0.207}\ E(z)^{-1}$$

Böhringer, Chon, Kronberg (2016)

RM as a Function of Electron Column Density



assuming L ~ 1 Mpc
l ~10 kpc

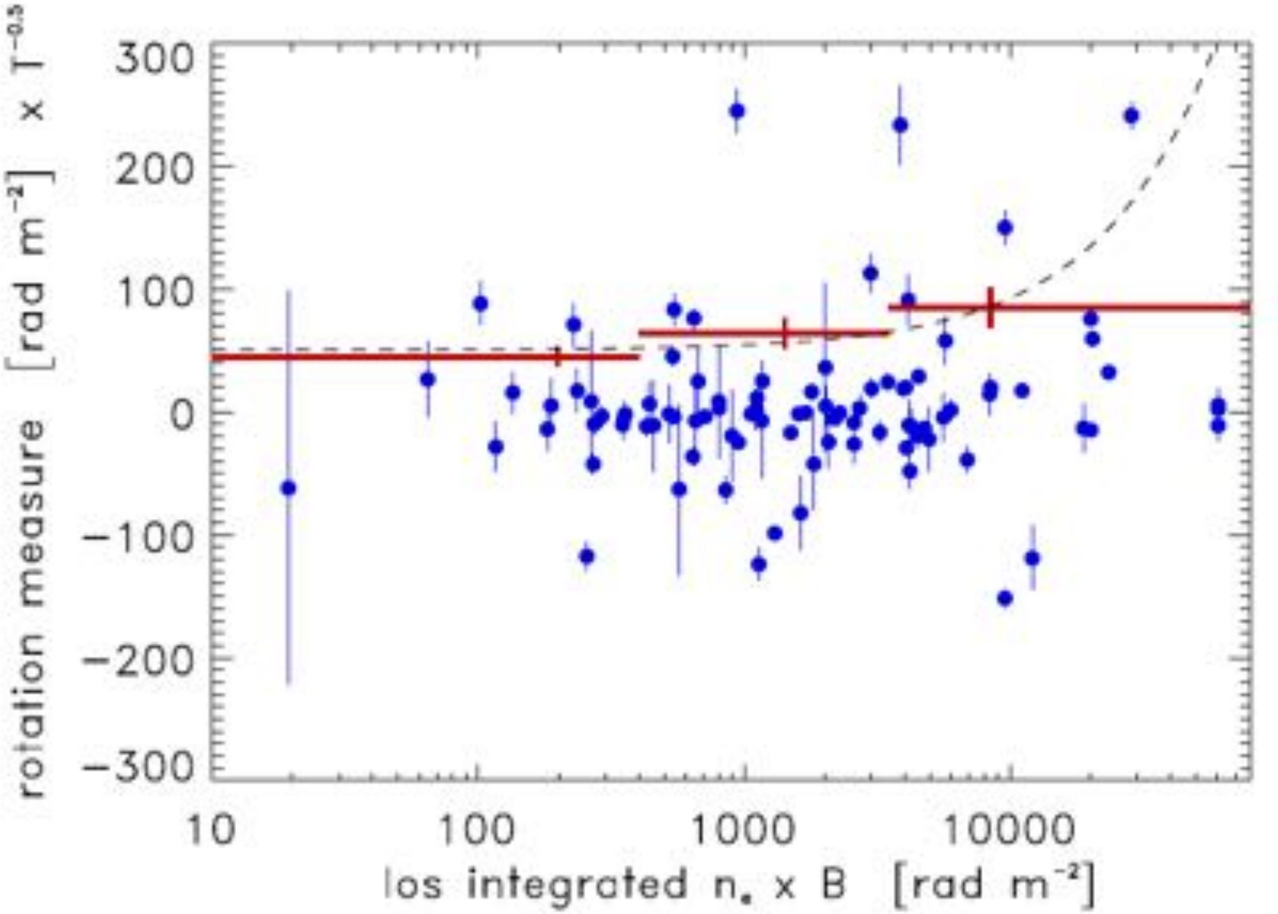
B ~ 0.18 (+-0.05) Λ μG

magnetic fields of few μG

$$\left(\frac{B_{||}}{1\ \mu\mathrm{G}}\right) = 3.801 \times 10^{18} \left(\frac{\sigma(RM)}{\mathrm{rad\ m^{-2}}}\right) \left(\frac{N_e}{\mathrm{cm^{-2}}}\right)^{-1} \Lambda \qquad \Lambda = (L/l)^{1/2}$$

Böhringer, Chon, Kronberg (2016)

RM as Function of los integrated n_e x B



$$\frac{B^2}{8\pi} = \eta \, \frac{3}{2} \, n \, k_B T$$

ratio of magnetic to thermal energy density in the ICM:

$3\text{–}10 \times 10^{-3} \, (l/10 \, \mathrm{kpc})^{-1/2}$

→ B-Field energy density is not much larger than 1% on average

Böhringer, Chon, Kronberg (2016)

Conclusion

- Galaxy Clusters are powerful probes for the study of the LSS and for cosmological tests
- Constraining Ω_m and σ_8 we find a discrepancy with the Planck results
- This may point to the effect of massive neutrinos
- We can reproduce the predicted halo mass function and biasing
- The cosmographical cluster distribution suggest a significant local underdensity of 100 – 140 Mpc size
- Magnetic fields contribute not much more than 1% on average to the energy content of the intracluster medium