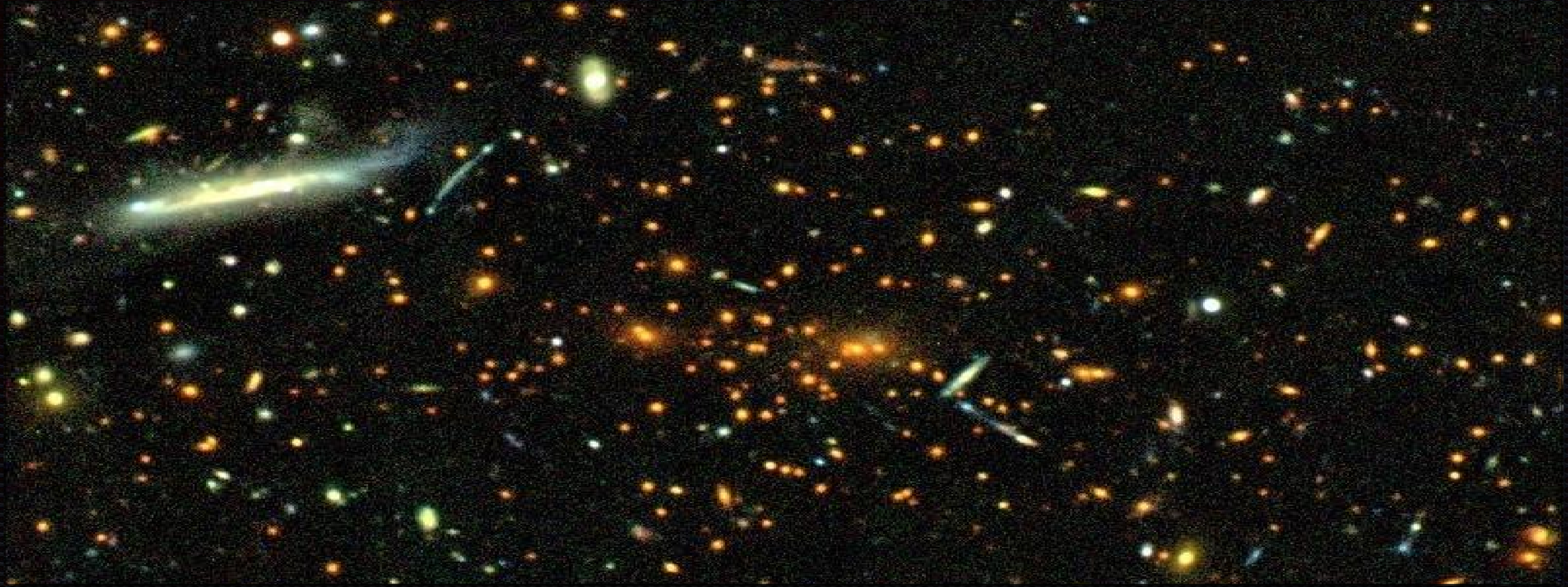


Using Galaxy Clusters to constrain Dark Energy

David Gilbank, South African Astronomical Observatory

NRF | SAAO
National Research Foundation
South African Astronomical Observatory

Edo van Uitert, UCL and the RCS-2 Collaboration

gilbank@saao.ac.za

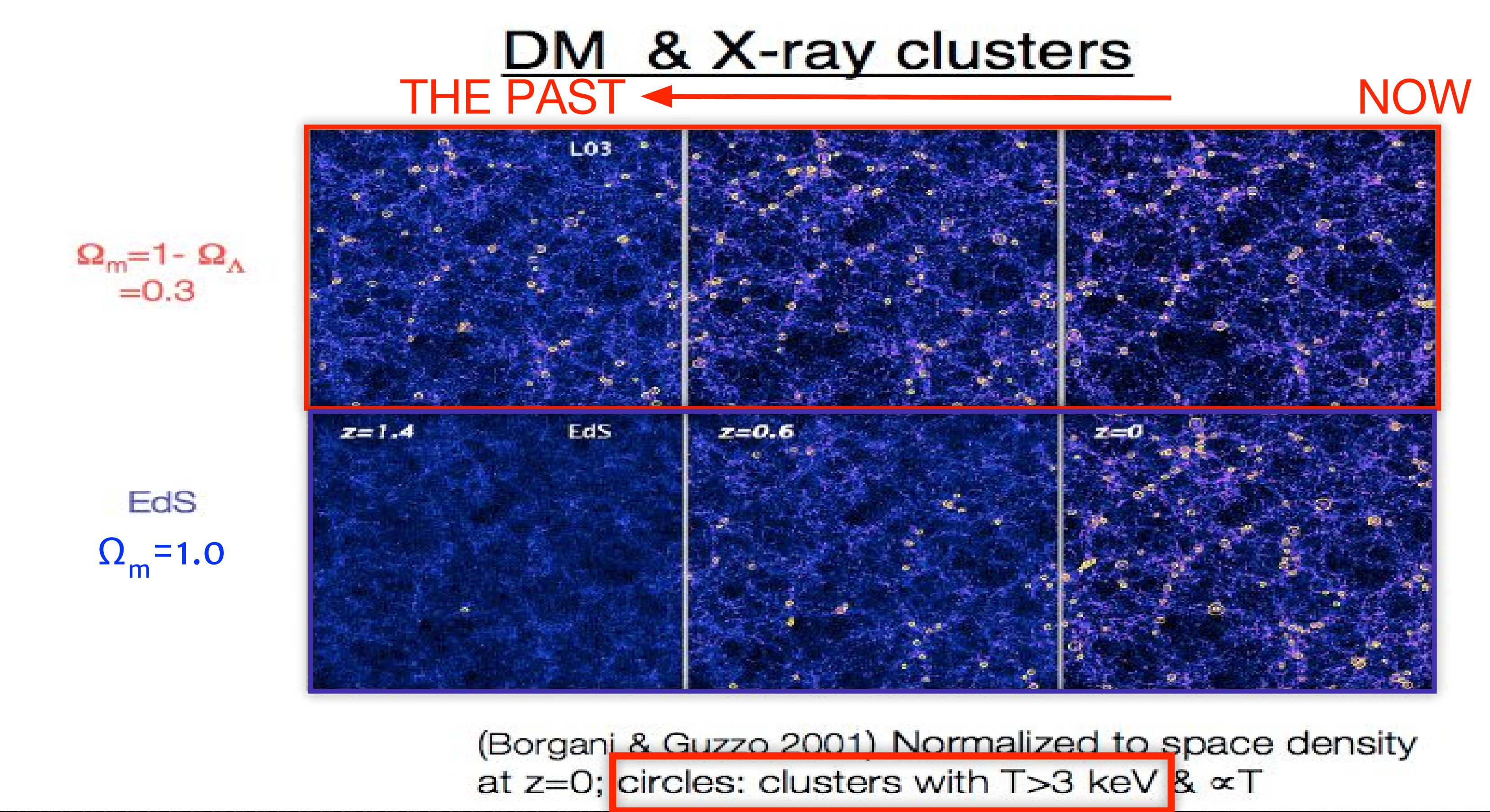
Cosmology with Large Surveys, Durban 2016

Outline

- Using Galaxy Cluster abundances to constrain Cosmological Parameters
- The Red-sequence Cluster Survey-2 (RCS-2)
- Calibration of the Mass--Richness Relation

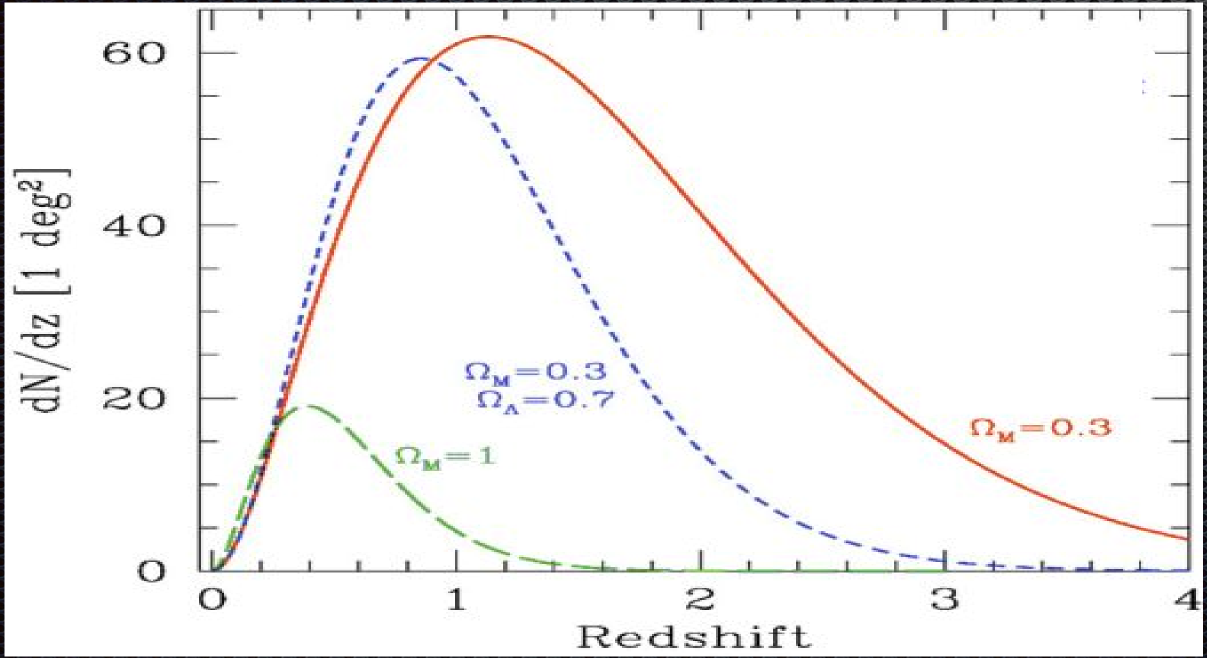
van Uitert, Gilbank et al. 2016, A&A, 586, 43

Cluster abundance



Cluster abundance

$$\frac{dN(z)}{dz\,d\Omega} = \frac{dV}{dz\,d\Omega} n(z) = \frac{c}{H(z)} d_A^2 (1+z)^2 \int_0^\infty dM\, f(M) \frac{dn(M,z)}{dM}$$



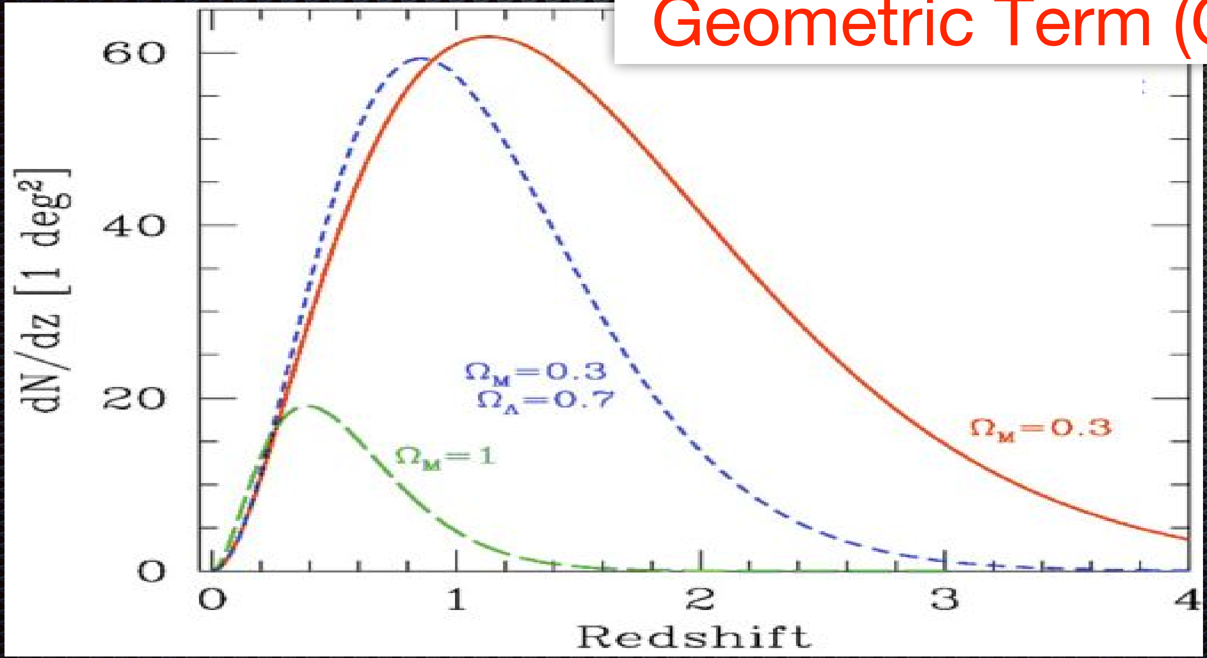
Cluster counts require:

- ***redshift*** of each cluster
- ***mass*** of each cluster

Cluster abundance

$$\frac{dN(z)}{dz\,d\Omega} = \frac{dV}{dz\,d\Omega}\,n(z) = \boxed{\frac{c}{H(z)}d_A^2(1+z)^2}\int_0^\infty dM\; f(M)\,\frac{dn(M,z)}{dM}$$

Geometric Term (GR)



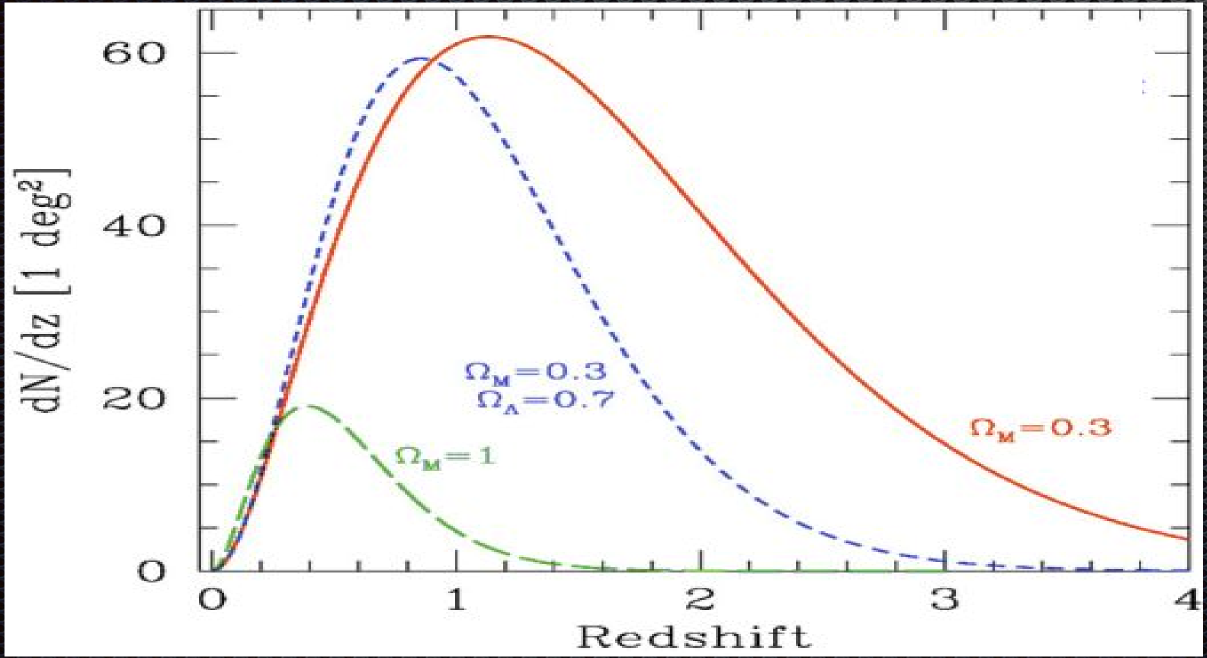
...er counts require:

- ***redshift*** of each cluster
- ***mass*** of each cluster

Cluster abundance

$$\frac{dN(z)}{dz\,d\Omega} = \frac{dV}{dz\,d\Omega} n(z) = \frac{c}{H(z)} d_A^2 (1+z)^2 \boxed{\int_0^\infty dM\, f(M) \frac{dn(M,z)}{dM}}$$

Growth of structure term

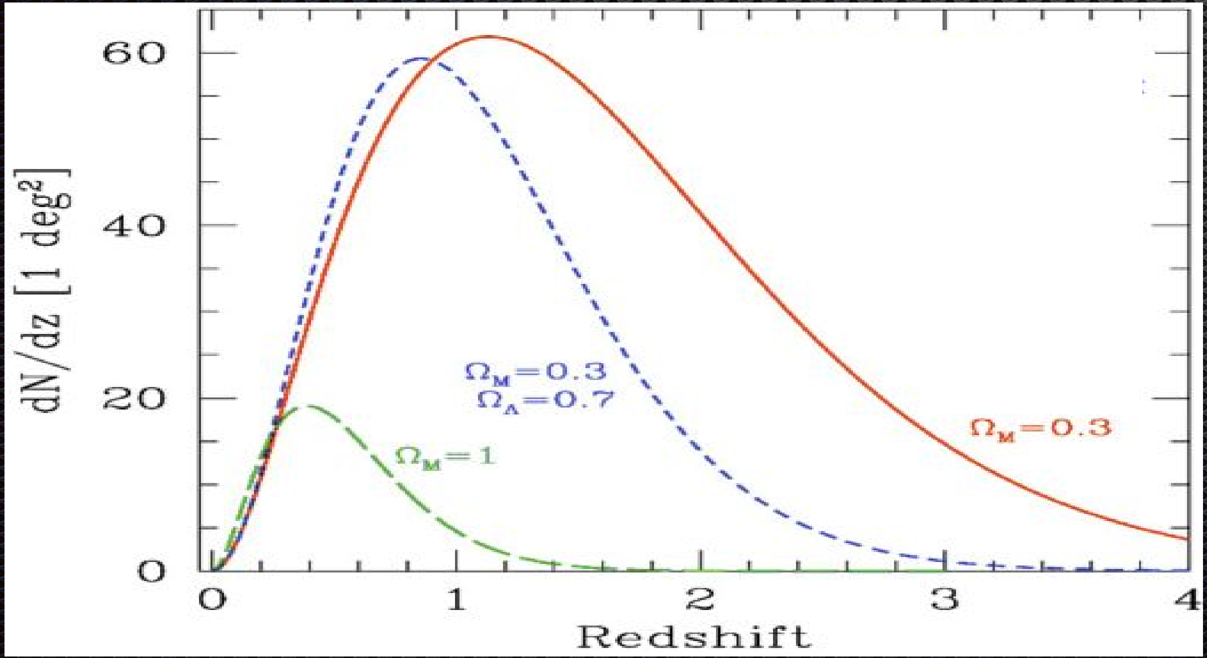


Clus

- ***redshift*** of each cluster
- ***mass*** of each cluster

Cluster abundance

$$\frac{dN(z)}{dz\,d\Omega} = \frac{dV}{dz\,d\Omega} n(z) = \frac{c}{H(z)} d_A^2 (1+z)^2 \int_0^\infty dM\ f(M) \frac{dn(M,z)}{dM}$$



Cluster counts require:

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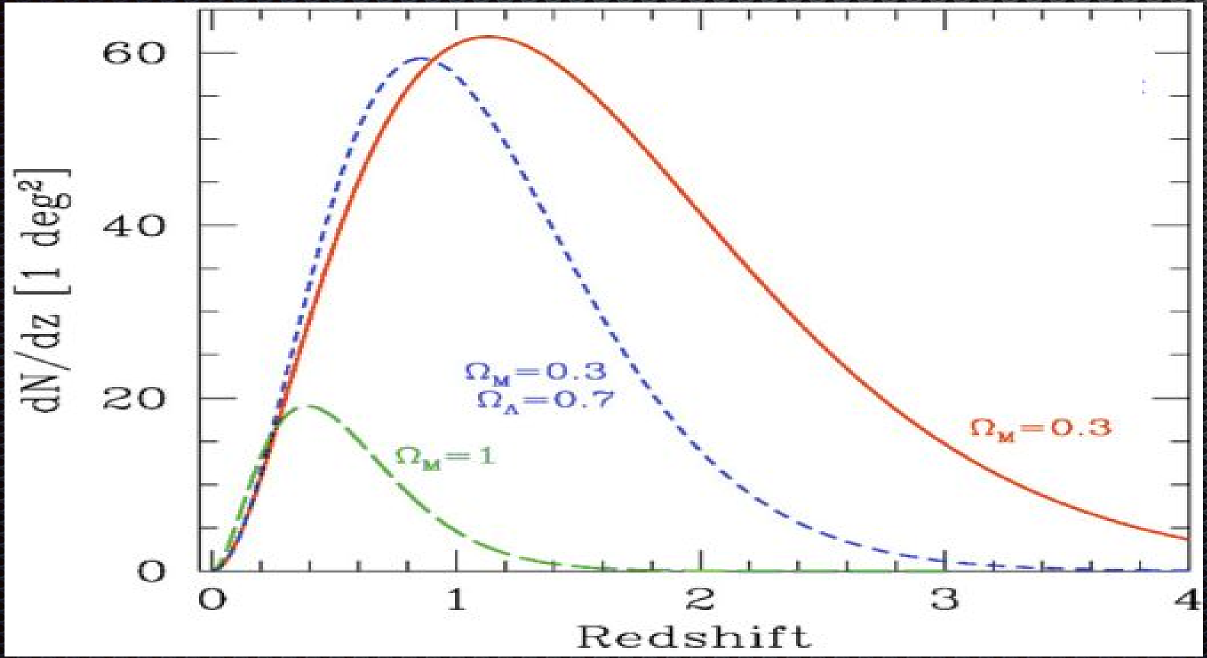
Cluster abundance

$$\frac{dN(z)}{dz\,d\Omega} = \frac{dV}{dz\,d\Omega}\,n(z) = \frac{c}{H(z)}\,d_A^2(1+z)^2 \int_0^\infty dM\; f(M)\,\frac{dn(M,z)}{dM}$$



Cluster counts require:

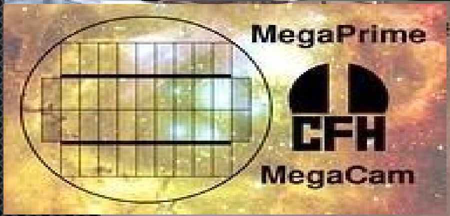
- ***redshift*** of each cluster
- ***mass*** of each cluster

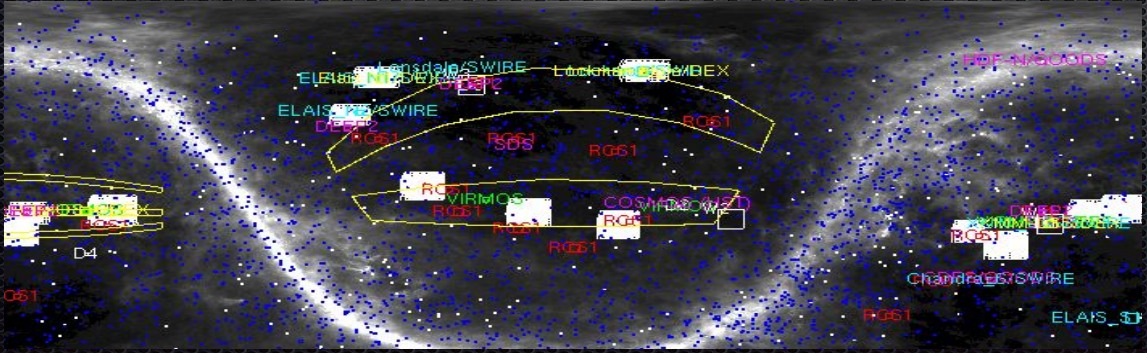
via **mass--observable** relation, f(M)
(selection function incorporating scatter)

Red-sequence Cluster Surveys

Find clusters out to z~1 with red-sequence technique

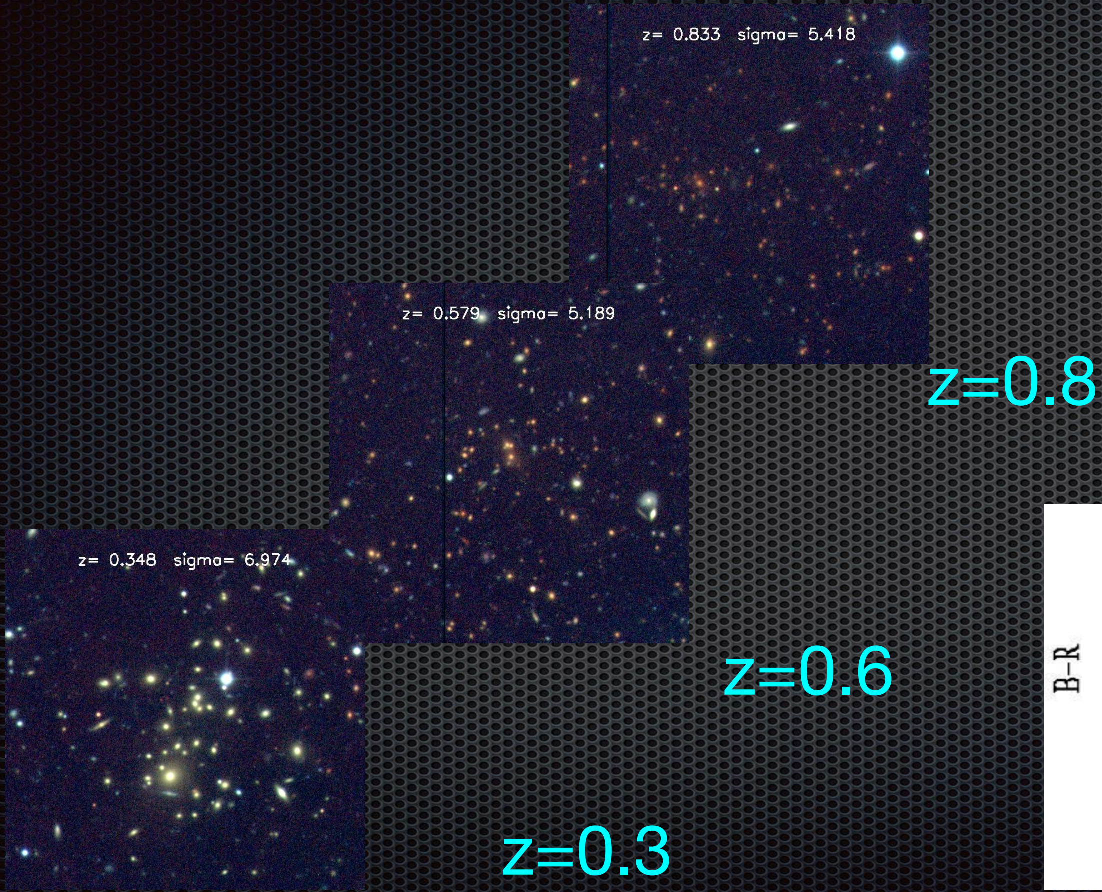
- RCS-2 Gilbank, Gladders, Yee, Hsieh
- 2011 AJ, 141, 94
  - Imaged ~1000 deg^2 in g', r', i', z'
    - with exquisite resolution (~0.6 - 0.8″)
  - Discovered ~10 000 clusters



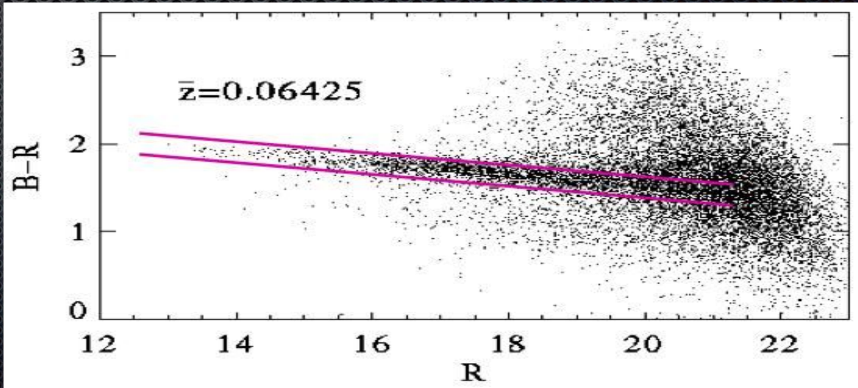


http://www.rcs2.org

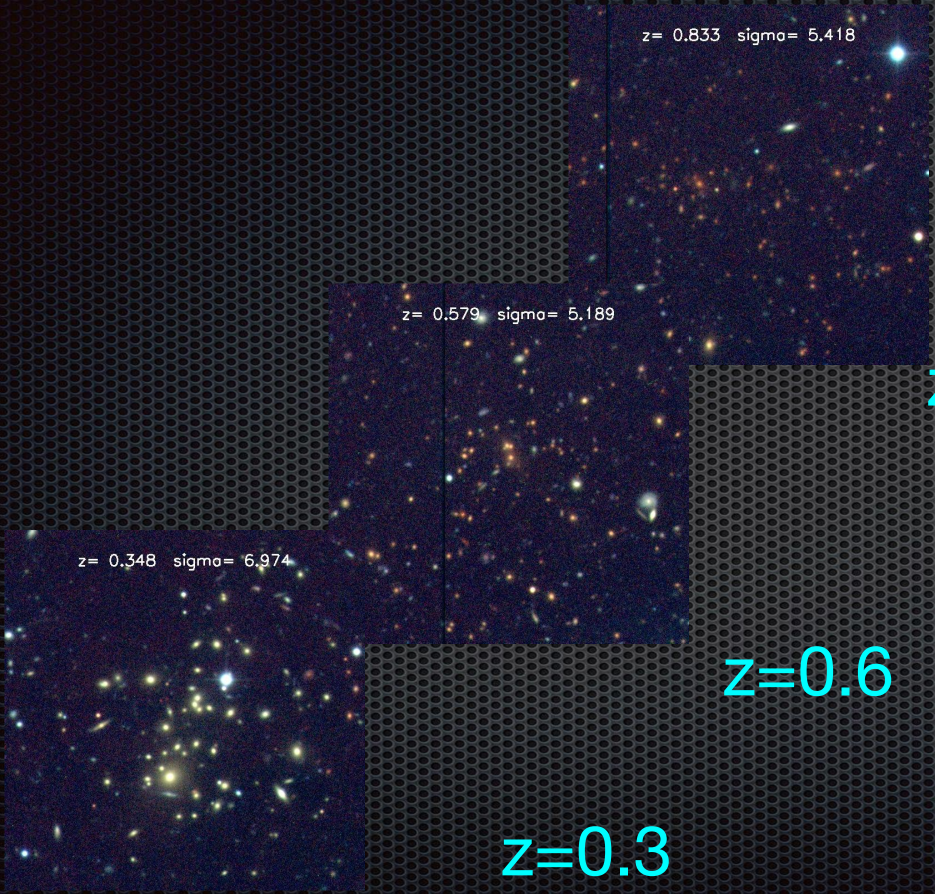
Using the Red-sequence to find Clusters



- Colour of red-sequence gives **redshift**
  - accurate to dz~0.03!
- Number of galaxies on red-sequence gives richness   Proxy for mass



Using the Red-sequence to find Clusters

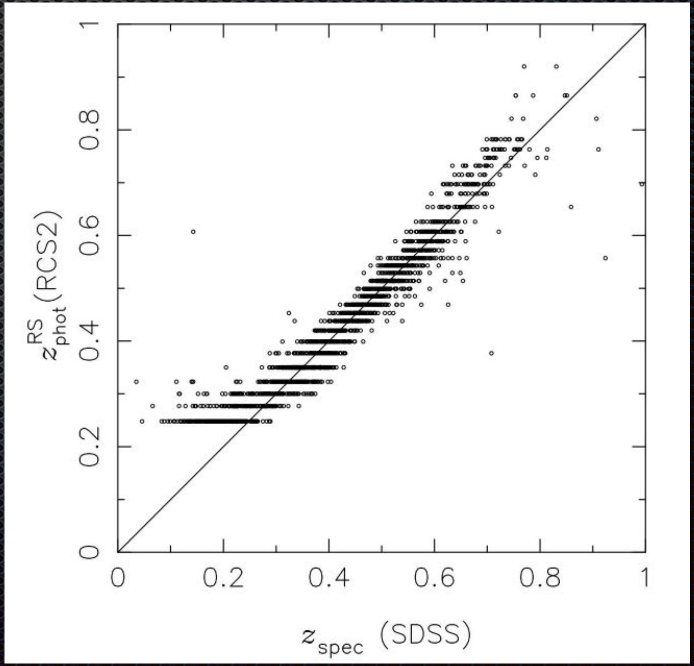


z=0.8

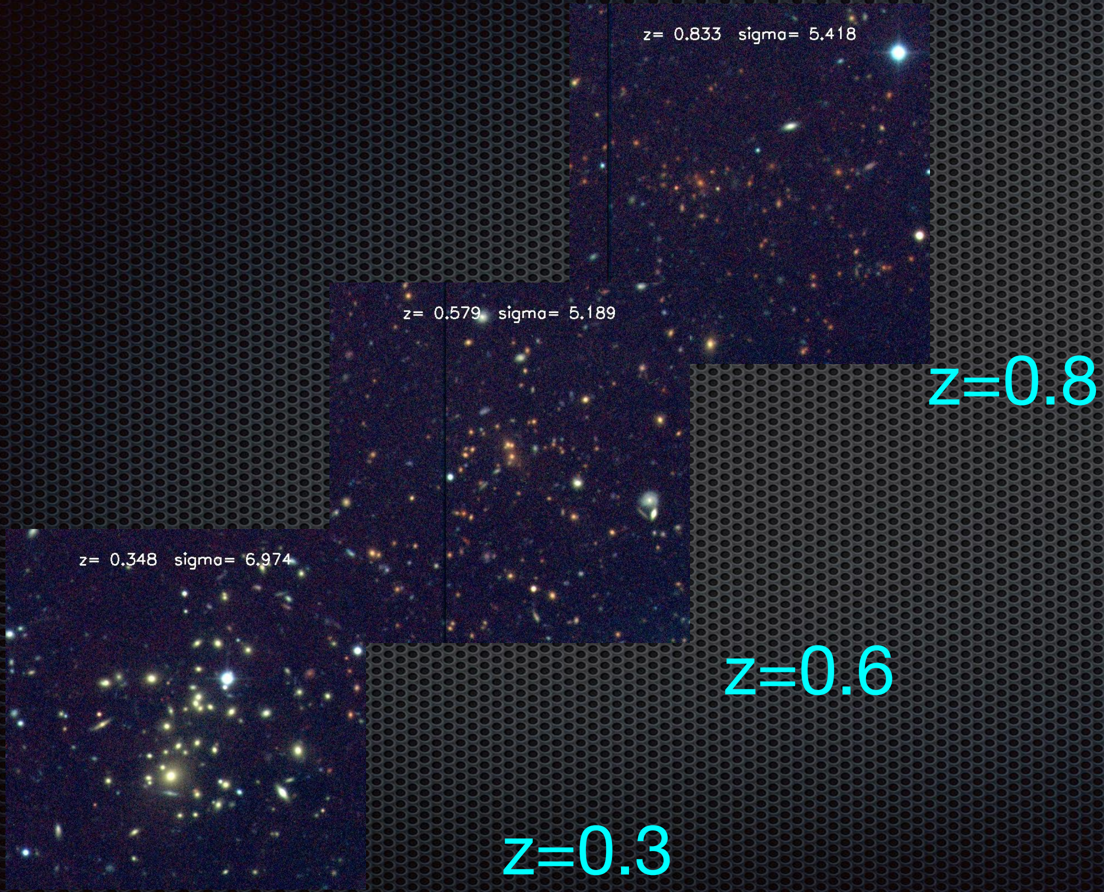
z=0.6

z=0.3

- Colour of red-sequence gives **redshift**
  - accurate to dz~0.03!



Using the Red-sequence to find Clusters

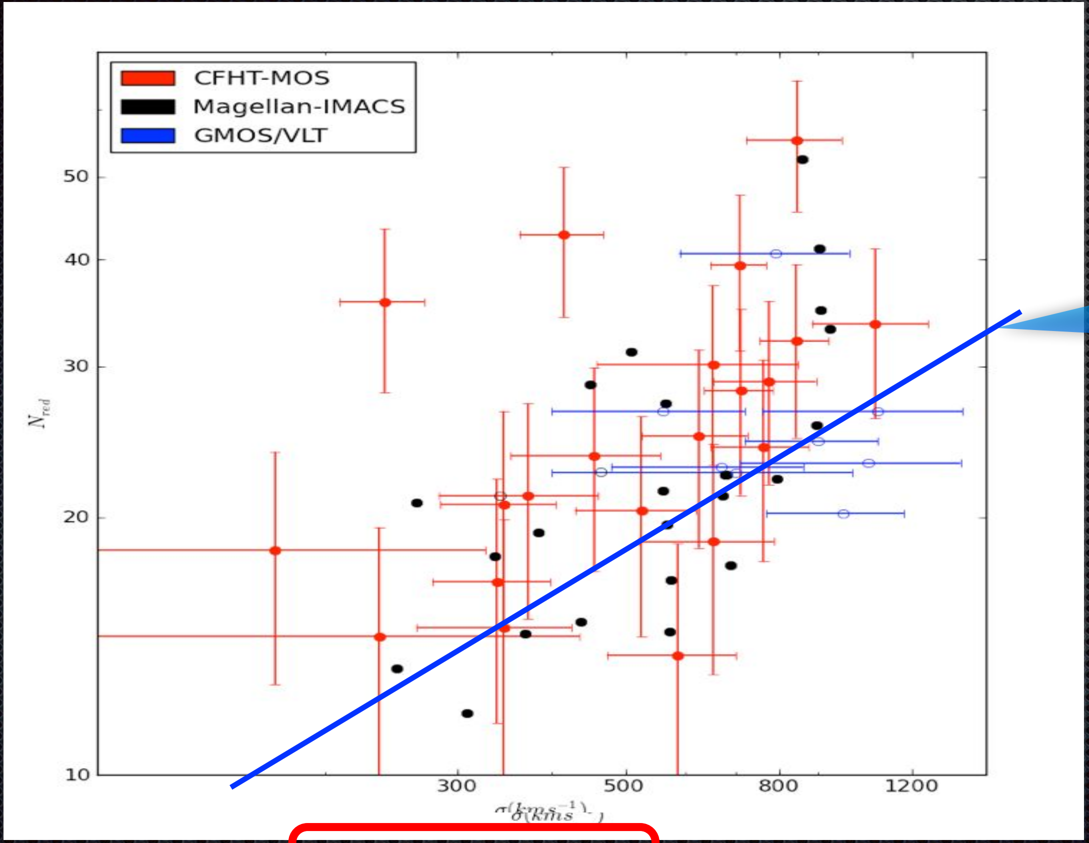


- Colour of red-sequence gives **redshift**
  - accurate to dz~0.03!
- Number of galaxies on red-sequence gives richness Proxy for mass

Need to calibrate!

Mass--Richness Relation

Optical richness



Dynamical Mass

Naive model :

$\sigma \propto N_{red}^{1.89}$

$0.1 < z < 1.1$

spectroscopy

Gilbank et al. in prep,
Ellingson et al. in prep

Alternative: use all the survey data themselves

Stacked Weak Lensing Analysis

van Uitert, Gilbank et al. 2016, A&A, 586, 43

Method

- Find cluster centre (BCG)

- Measure richness:
  - N_{gal}: $M<M^{*}+1$;

    $r < 1\mathrm{Mpc}$
  - N_{200}: $M<M^{*}+1$;

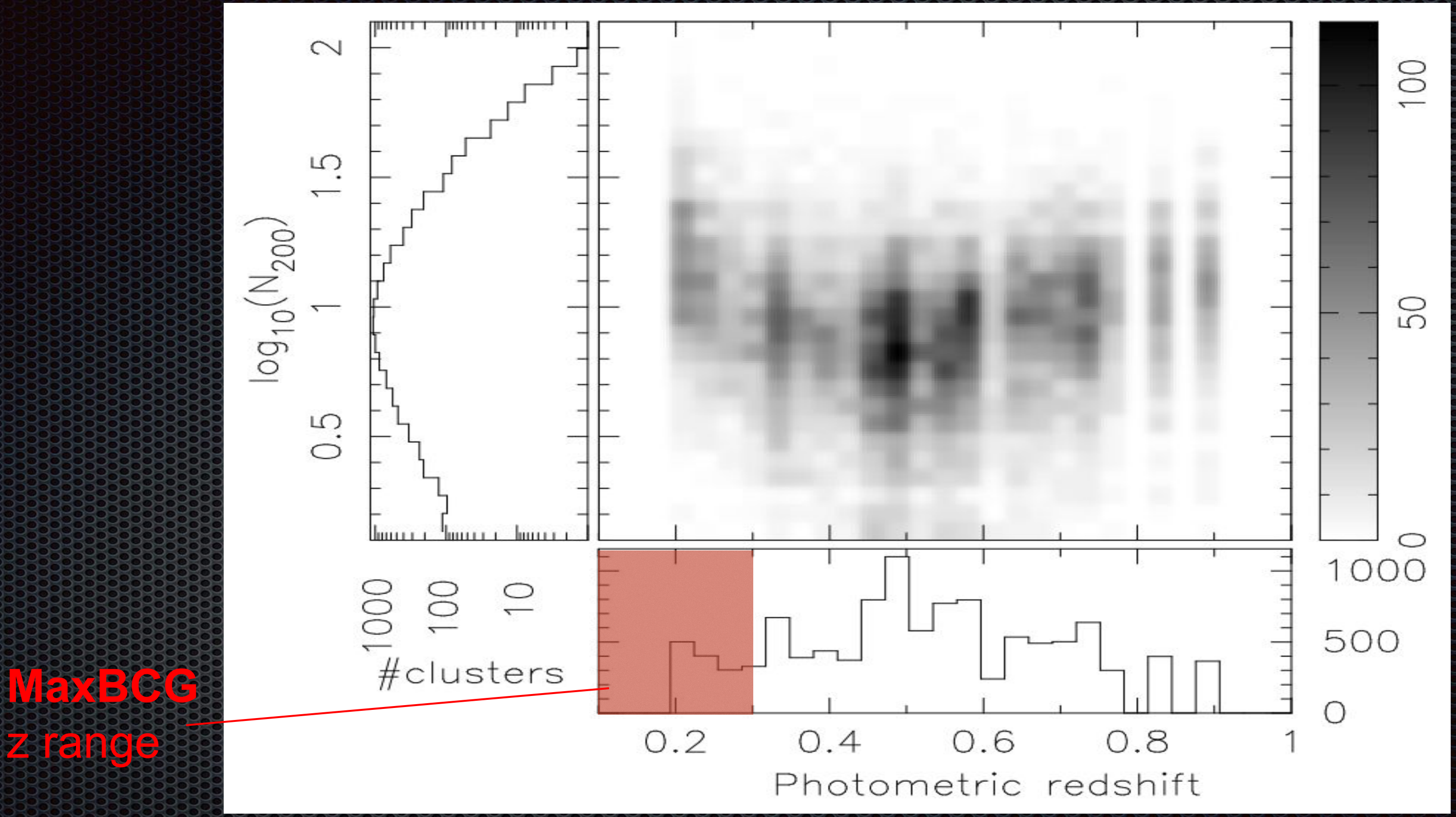
    $r < r_{200}$ + Statistical background subtraction

$$r_{200} = 0.156\, N_{gal}^{0.6}\ \mathrm{Mpc}$$

From simulations

MaxBCG SDSS sample (Hansen et al. 2005)

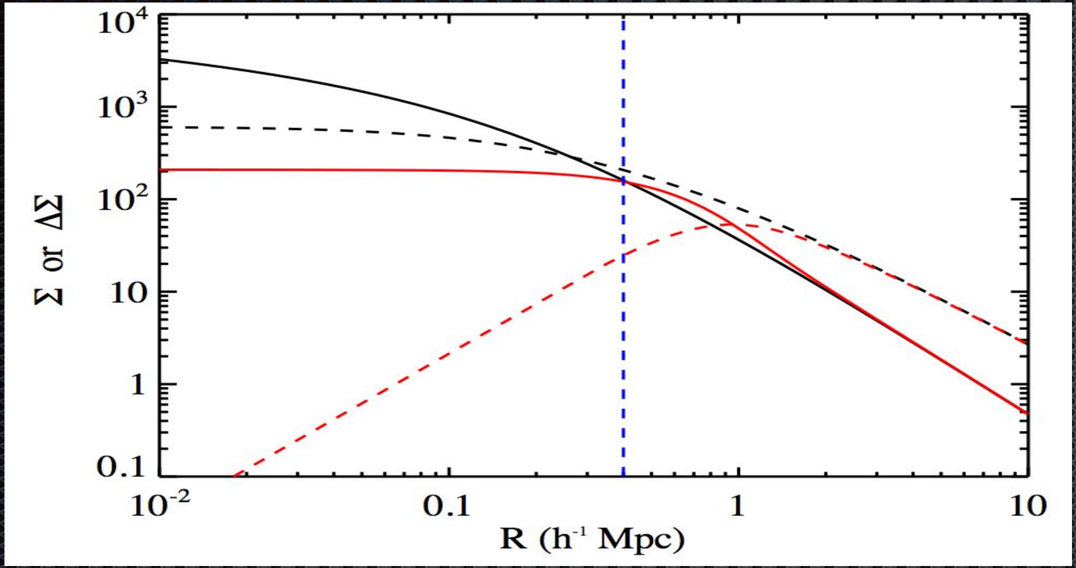
~10 000 clusters



Determine average tangential shear for lens bins of z, N_{200}

Use **halo model** (Johnston et al. 07)

- Fraction of clusters will not be correctly centred

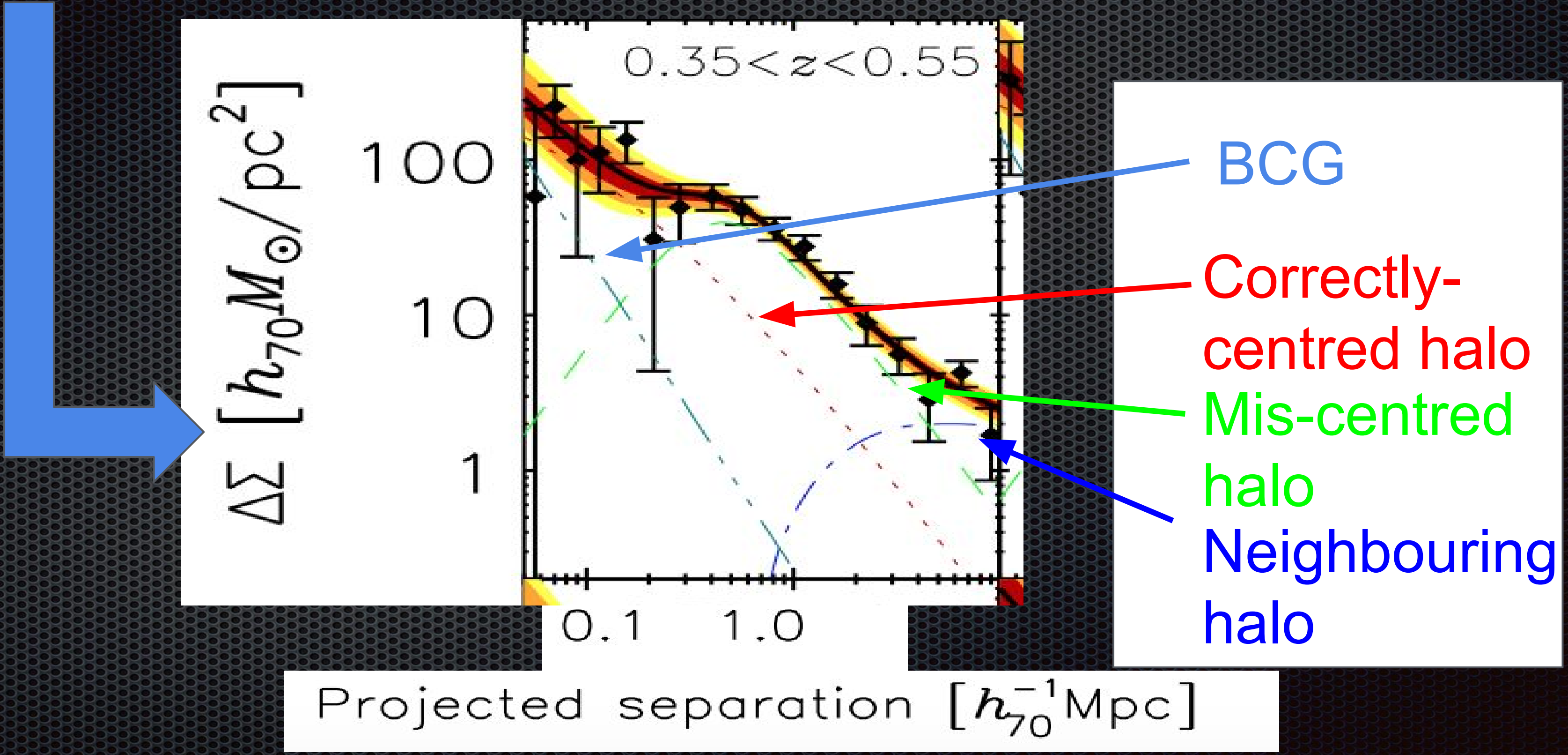


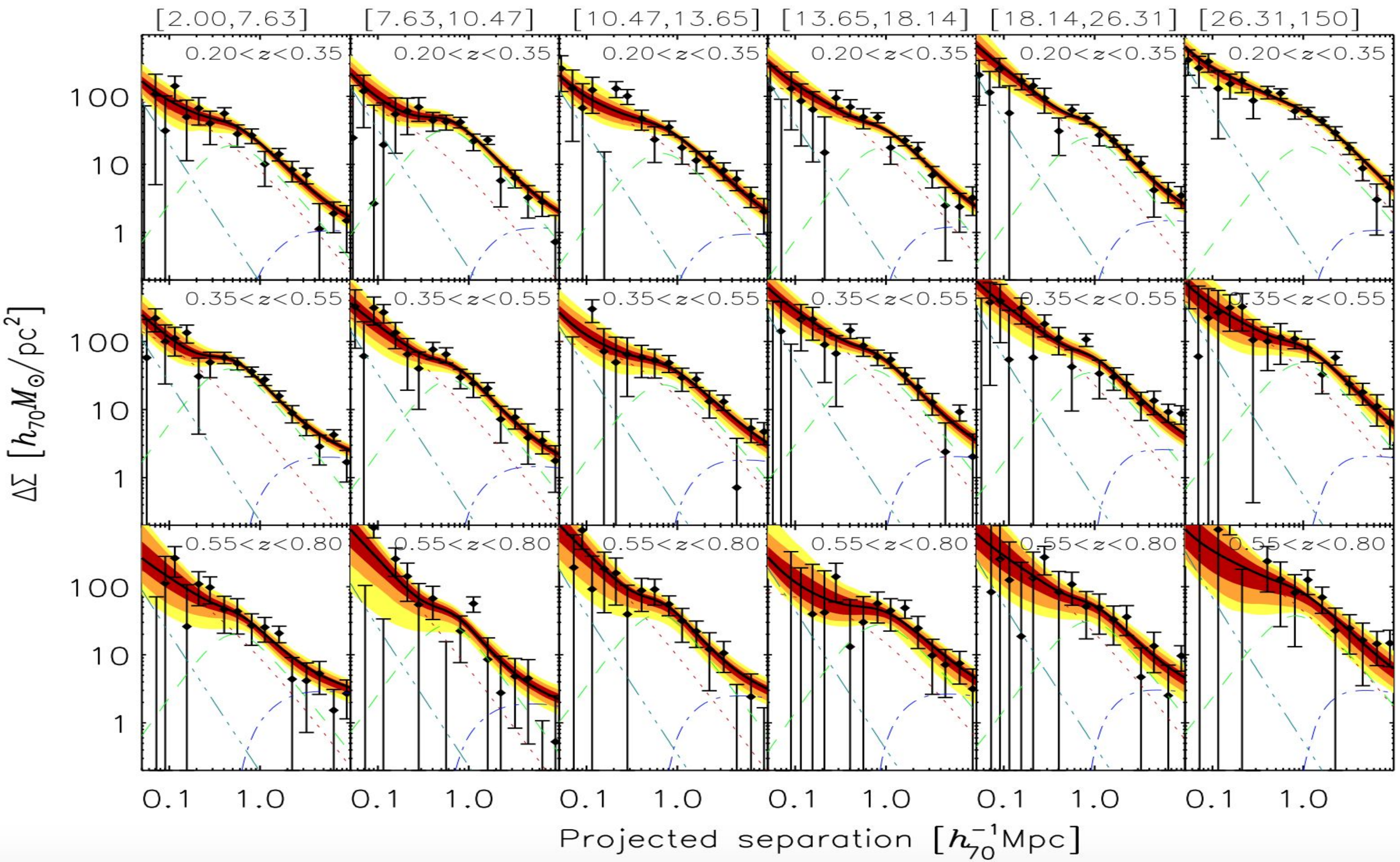
- r_{200}=1 Mpc
- c=5
- 2D-Gaussian, dispersion σ_s=0.5 Mpc
- dashed=lensing signal
- black=cent; red=miscent

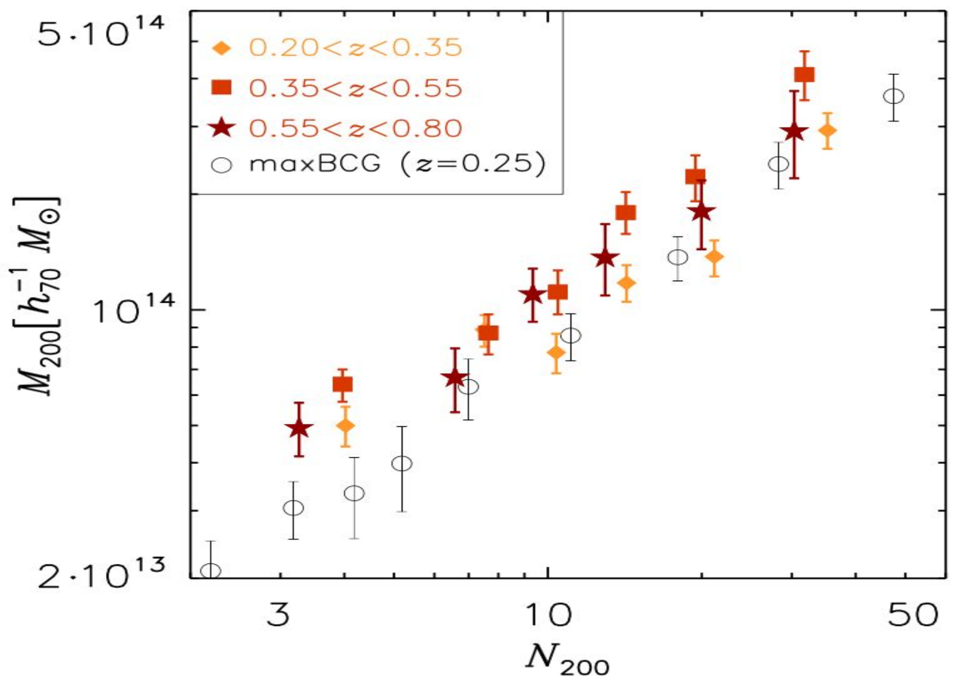
- Far from lens, neighbouring structures add to signal
- Scatter in richness-mass

→ not accounting for this biases results

Tangential shear




[2.00,7.63]
[7.63,10.47]
[10.47,13.65]
[13.65,18.14]
[18.14,26.31]
[26.31,150]
0.20<z<0.35
0.35<z<0.55
0.55<z<0.80
$\Delta\Sigma\ [h_{70}M_\odot/\mathrm{pc}^2]$
100
10
1
0.1
1.0
Projected separation $[h_{70}^{-1}\mathrm{Mpc}]$



$$M_{200} = A(N_{200}^{\mathrm{corr}}/20)^{\alpha}$$

Bin	A $[10^{13}h_{70}^{-1}M_\odot]$	α
$0.20<z<0.35$	15.0 ± 0.8	0.73 ± 0.07
$0.35<z<0.55$	22.5 ± 1.7	0.86 ± 0.08
$0.55<z<0.80$	18.7 ± 2.2	0.78 ± 0.11
maxBCG ($3<N_{200}<50$)	18.3 ± 1.1	0.98 ± 0.07

- Decrease in amplitude towards low-z suggests build-up of Red Sequence
- Similar trend seen in X-ray & vel. disp for maxBCG (Becker et al. 2007, Rykoff et al. 2008)

Conclusions

- Analysed ~10 000 clusters up to <z> ~0.7
- Combined shear and clus-sat corr. measurements, interpreted using halo model (Johnston et al. 2007 ++)
- N_{200}-- M_{200} relation evolves, likely due to build-up of red-sequence
- 35% BCGs at centre DM halo, rest follows 2D-Gaussian with 0.2-0.4 Mpc width
- Plus results on concentration, bias as fn(M_{halo}), see:
  van Uitert, Gilbank, et al. 2016 A&A, 586, 43

Halo model (extension of Johnston et al. 2007)

4 terms:

- point source [fixed by M_{NFW} via relation]
- centred term [M_{NFW}, c, p_c]
- miscentred term [(M_{NFW}, c, 1-p_c), σ_s]
- 2-halo term [b]
- $\xi_{cs} = A_{gal} \Sigma [(M_{NFW}, p_c, \sigma_s, b), c_{gal}, A_{gal}]$

+ convolve with log-normal distribution [$\sigma_{\ln M|N200}$]

8 fit parameters, use uninformative priors except for $\sigma_{\ln M|N200}$

We have catalogues of RS candidates

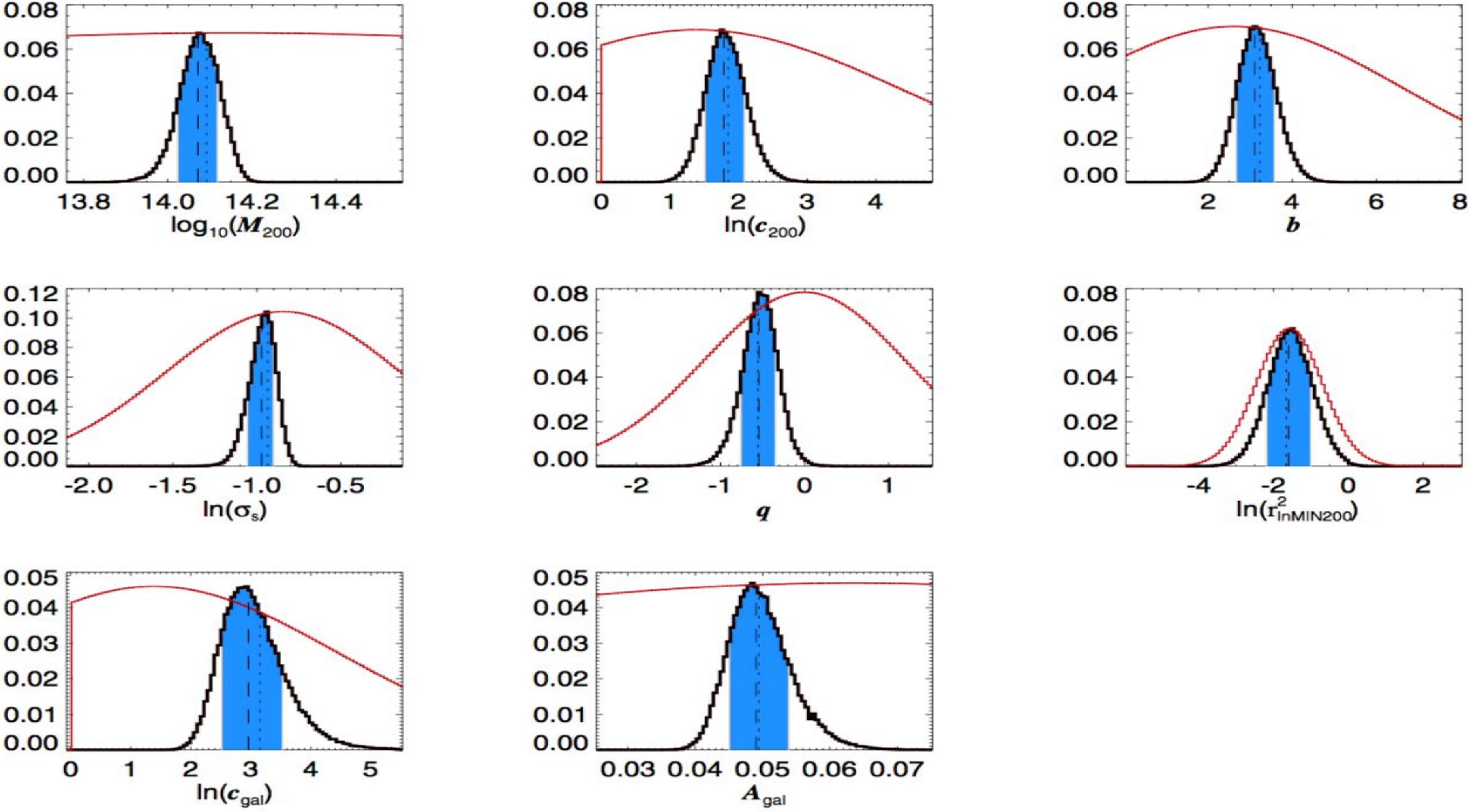
→ determine cluster-satellite correlation ξ_{cs}

(satellites defined as all RS members brighter than M*+1 at cluster-z)

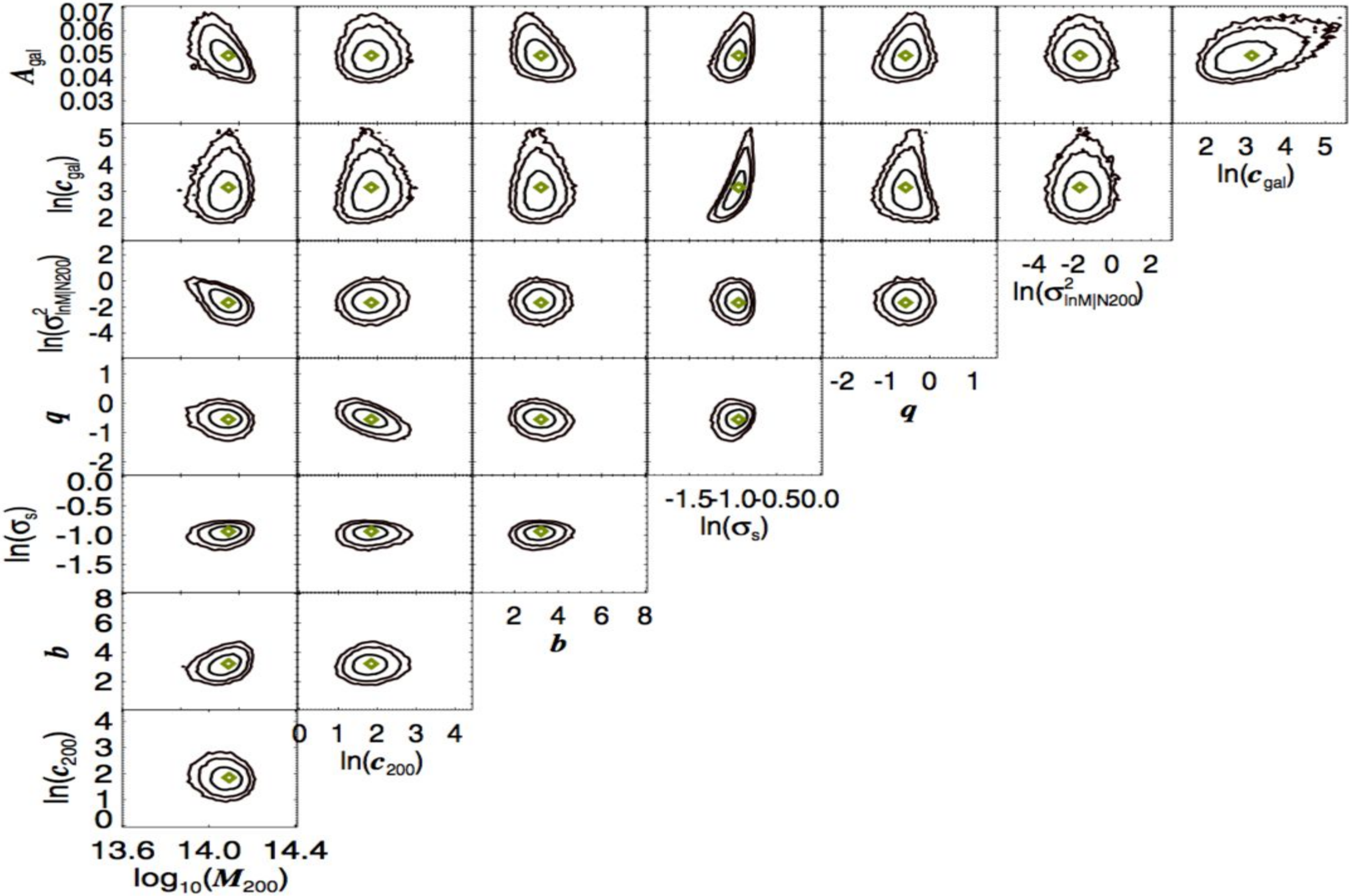
Assuming that satellites follow DM (but allowing for a different concentration) → ξ_{cs} similarly affected by miscentring as shear (see also Hikage+13)

Smaller effect of miscentring on Σ outweighed by larger S/N in measurement?

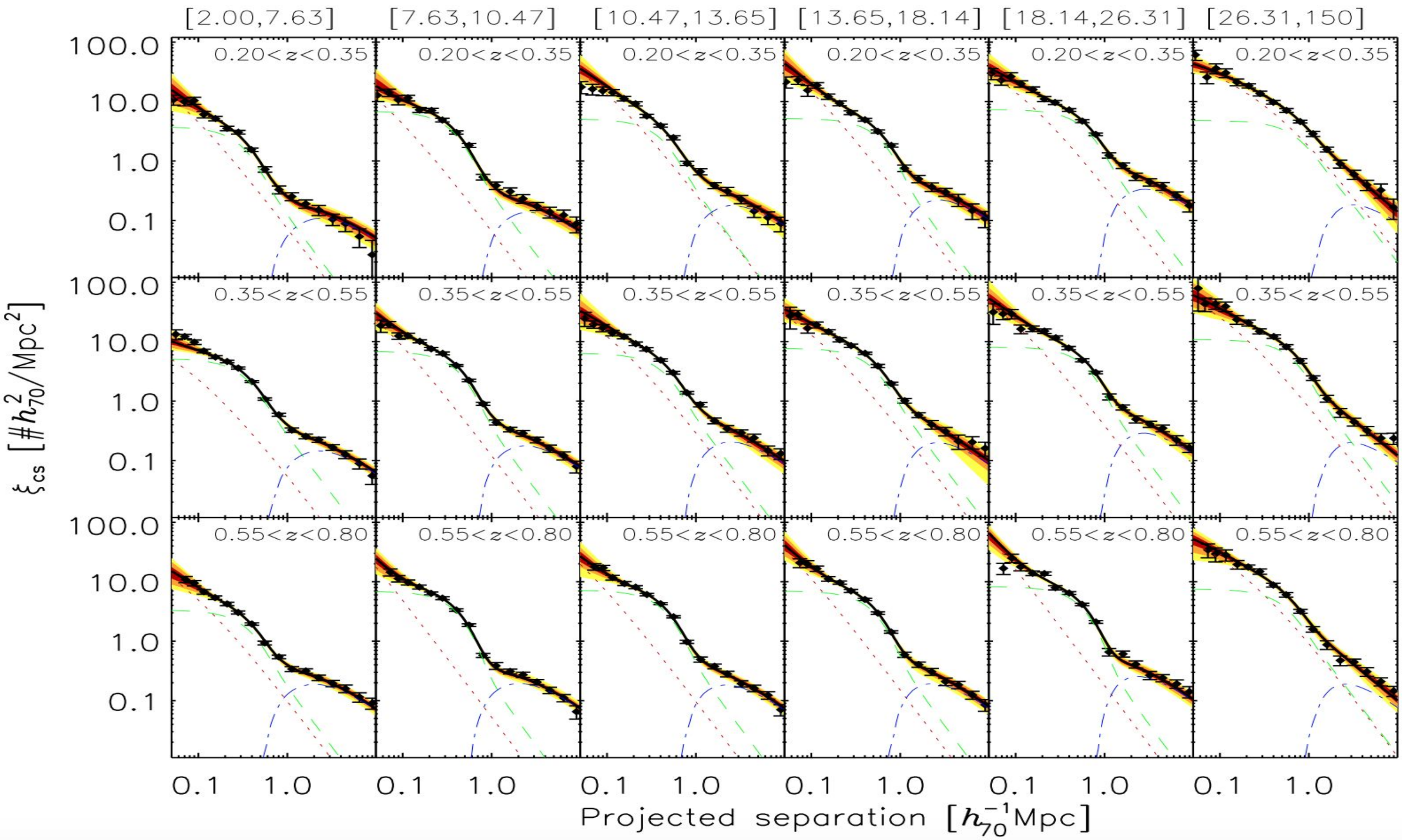
Fit together with the lensing signal using halo model



0.08
0.06
0.04
0.02
0.00
13.8
14.0
14.2
14.4
log10(M200)
0
1
2
3
4
ln(c200)
6
8
b
0.12
0.10
-2.0
-1.5
-1.0
-0.5
ln(σs)
-2
-1
q
-4
ln(r²lnMIN200)
0.05
0.03
0.01
5
ln(cgal)
0.07
Agal



A_{gal}
0.07
0.06
0.05
0.04
0.03
$\ln(c_{gal})$
$\ln(\sigma^2_{\ln M|N200})$
q
$\ln(\sigma_s)$
b
$\ln(c_{200})$
$\log_{10}(M_{200})$
13.6
14.0
14.4



[2.00,7.63]
[7.63,10.47]
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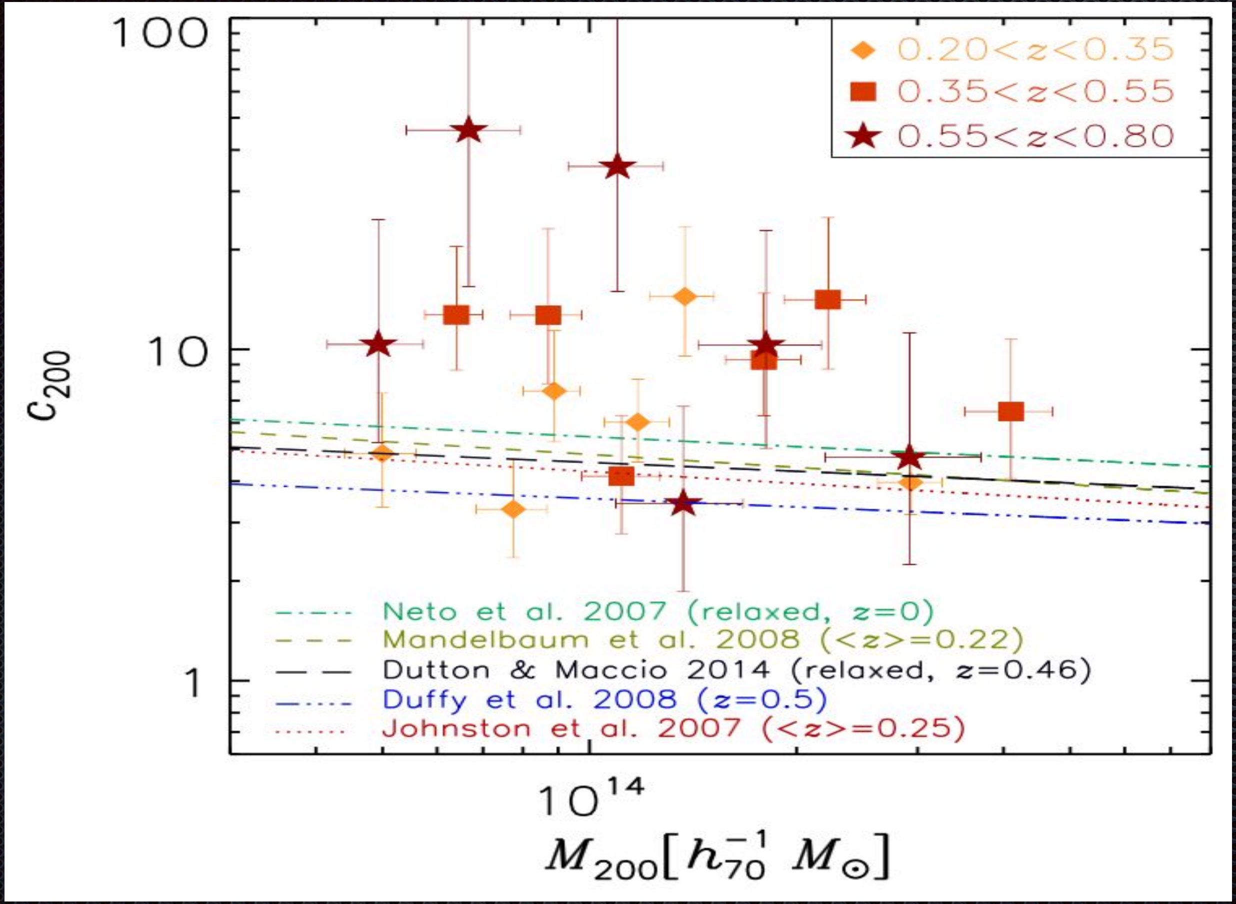
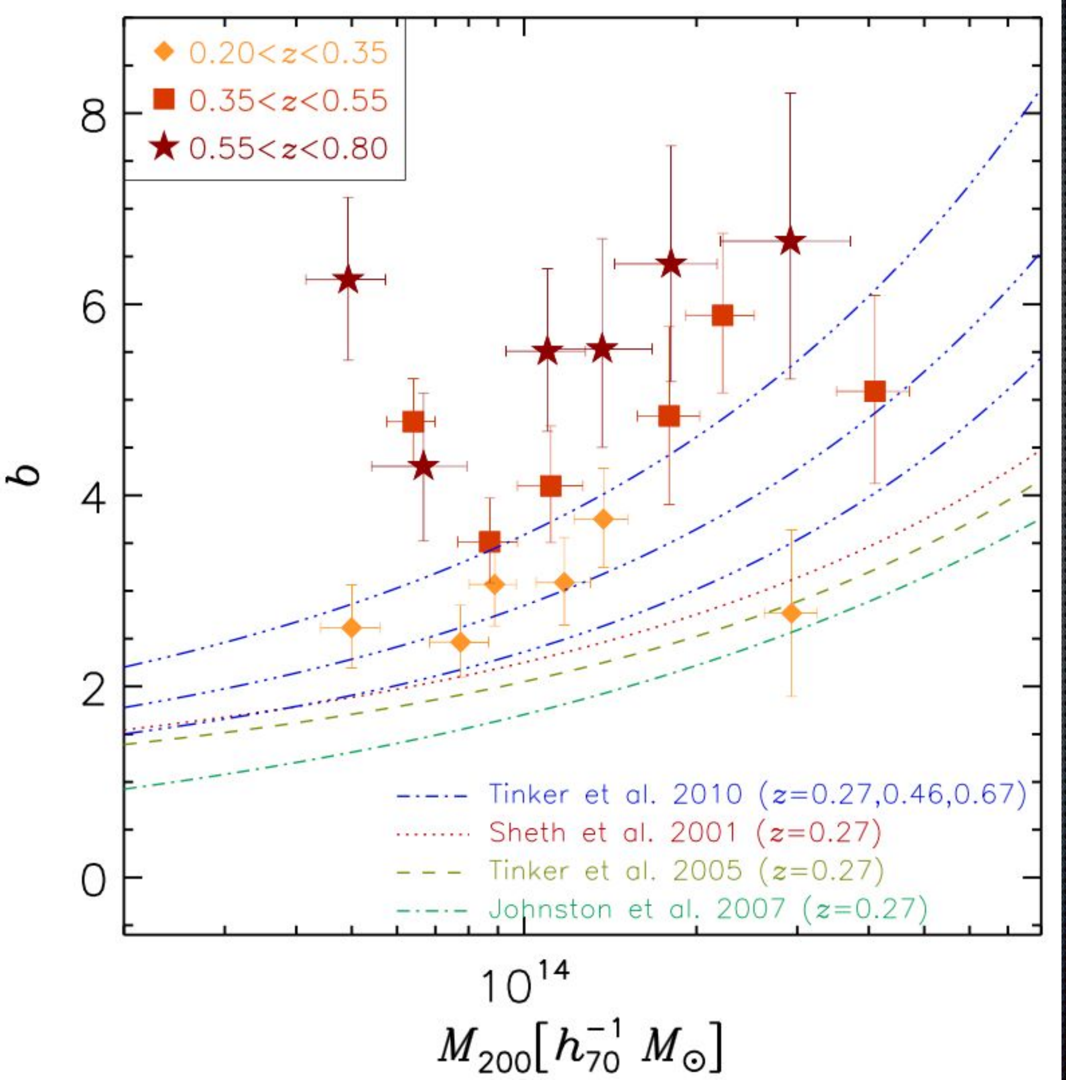
[13.65,18.14]
[18.14,26.31]
[26.31,150]
0.20<z<0.35
0.35<z<0.55
0.55<z<0.80
100.0
10.0
1.0
0.1
ξ_{cs} [$\#h_{70}^2$/Mpc^2]
0.1
1.0
Projected separation [h_{70}^{-1}Mpc]



- Good agreement low-z
- Higher normalisation intermediate-z
- Possibly selection and projection effects
- Need to check with simulations



0.20<z<0.35
0.35<z<0.55
0.55<z<0.80
b
8
6
4
2
0
10^{14}
$M_{200}[h_{70}^{-1}\ M_\odot]$
Tinker et al. 2010 (z=0.27,0.46,0.67)
Sheth et al. 2001 (z=0.27)
Tinker et al. 2005 (z=0.27)
Johnston et al. 2007 (z=0.27)

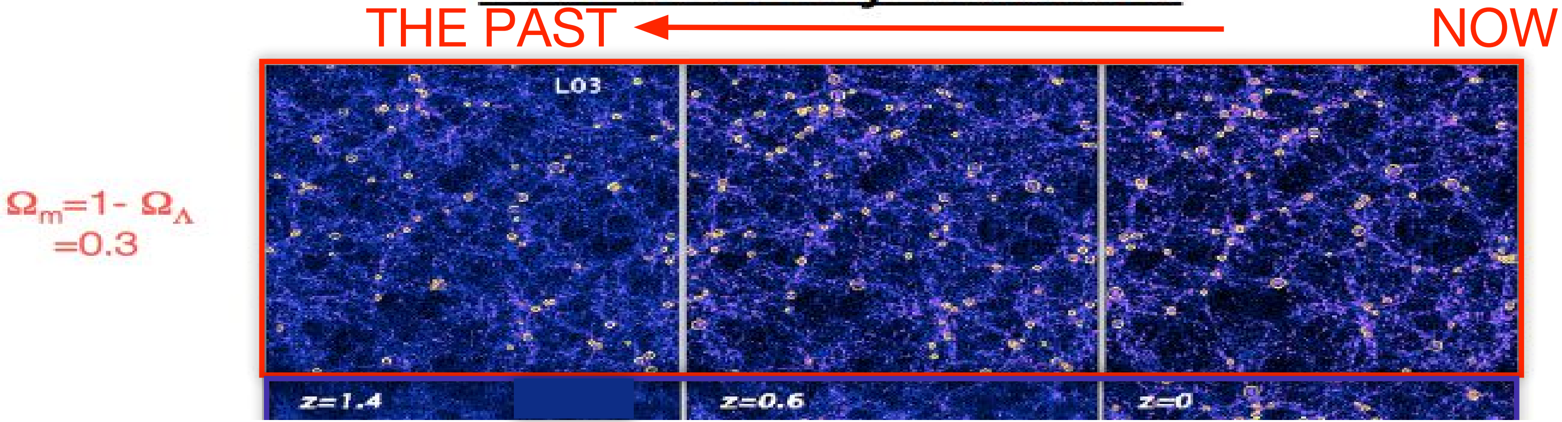
Method

- Find cluster centre (BCG)

+

Cluster abundance

DM & X-ray clusters



(Borgani & Guzzo 2001) Normalized to space density at z=0; circles: clusters with T>3 keV & ∝T

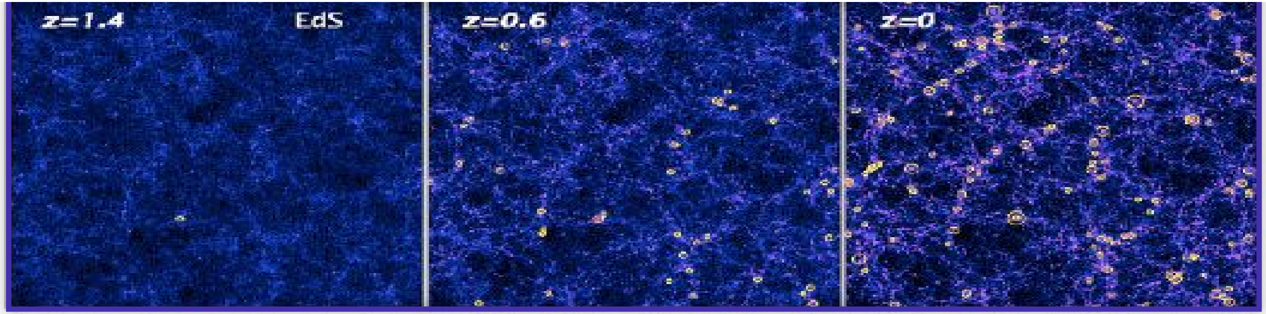
Cluster abundance

DM & X-ray clusters

THE PAST ← NOW

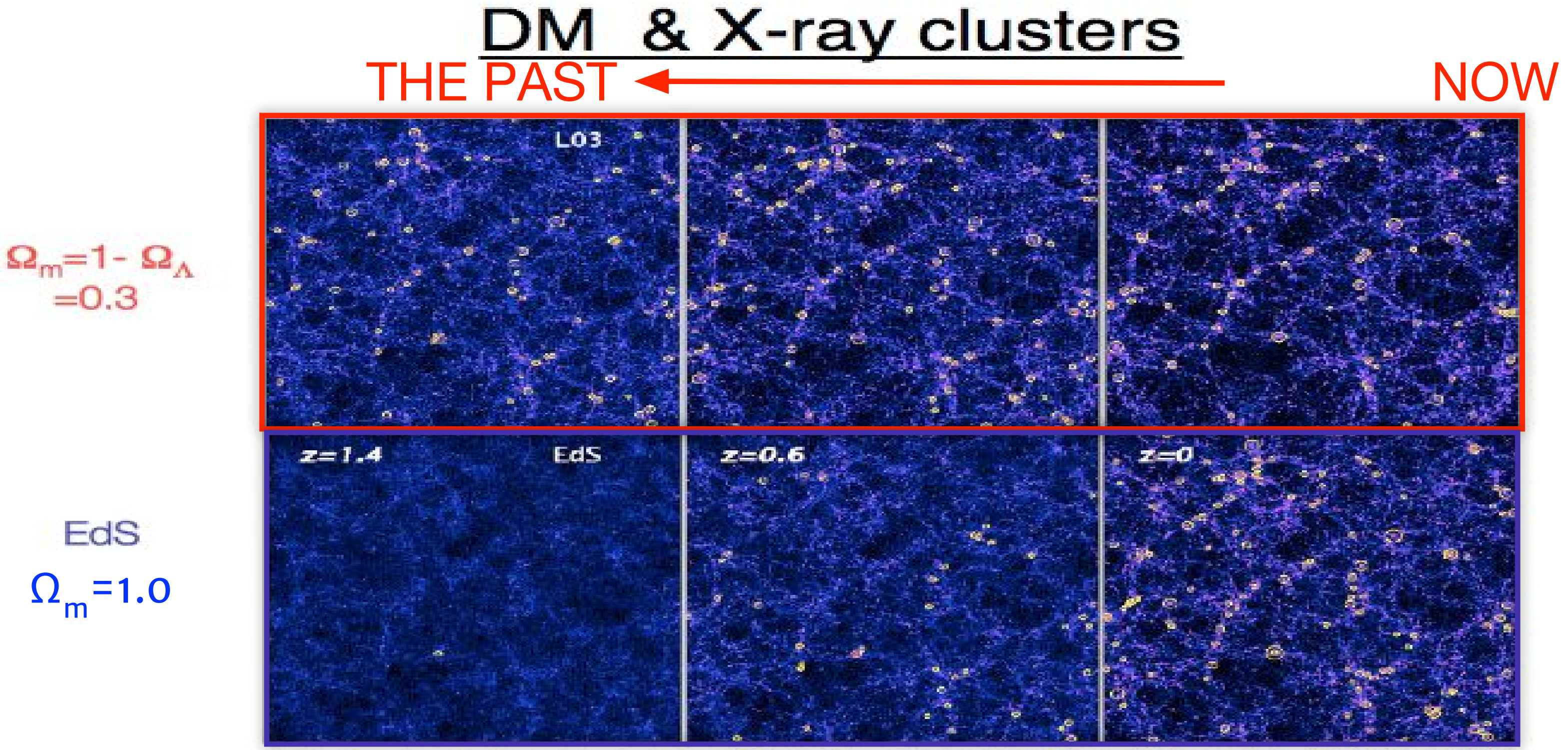
EdS

Ω_m=1.0



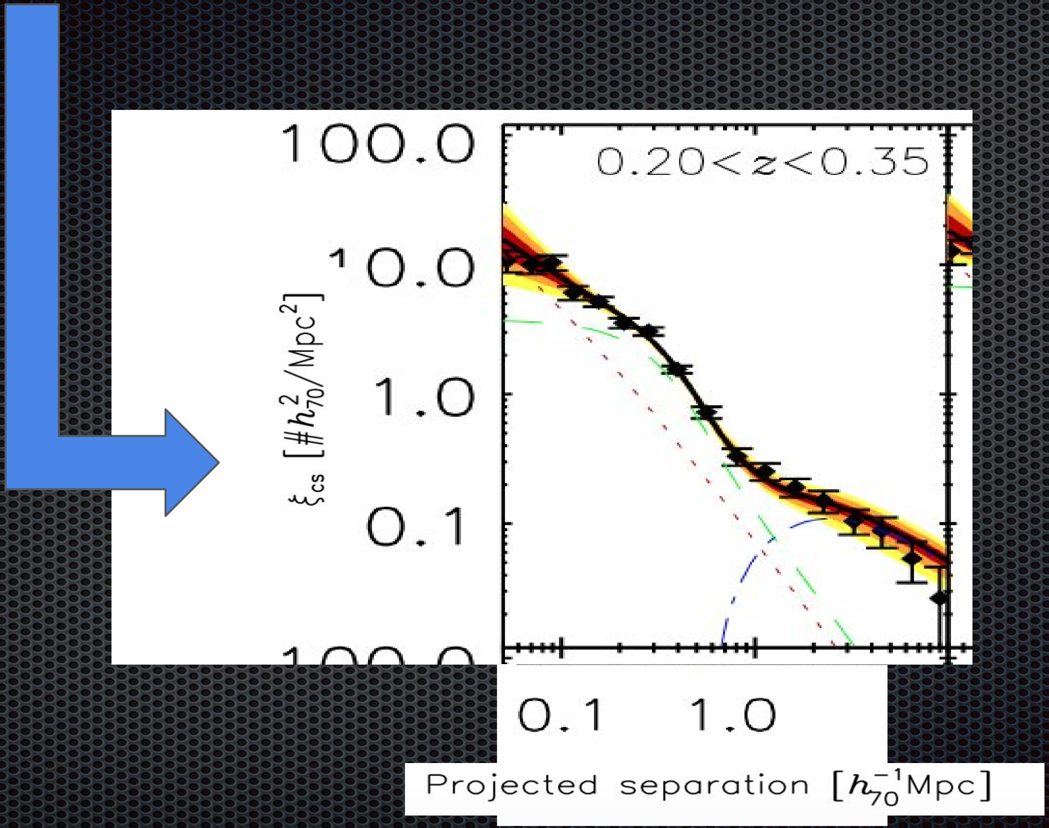
(Borgani & Guzzo 2001) Normalized to space density at z=0; circles: clusters with T>3 keV & ∝T

Cluster abundance

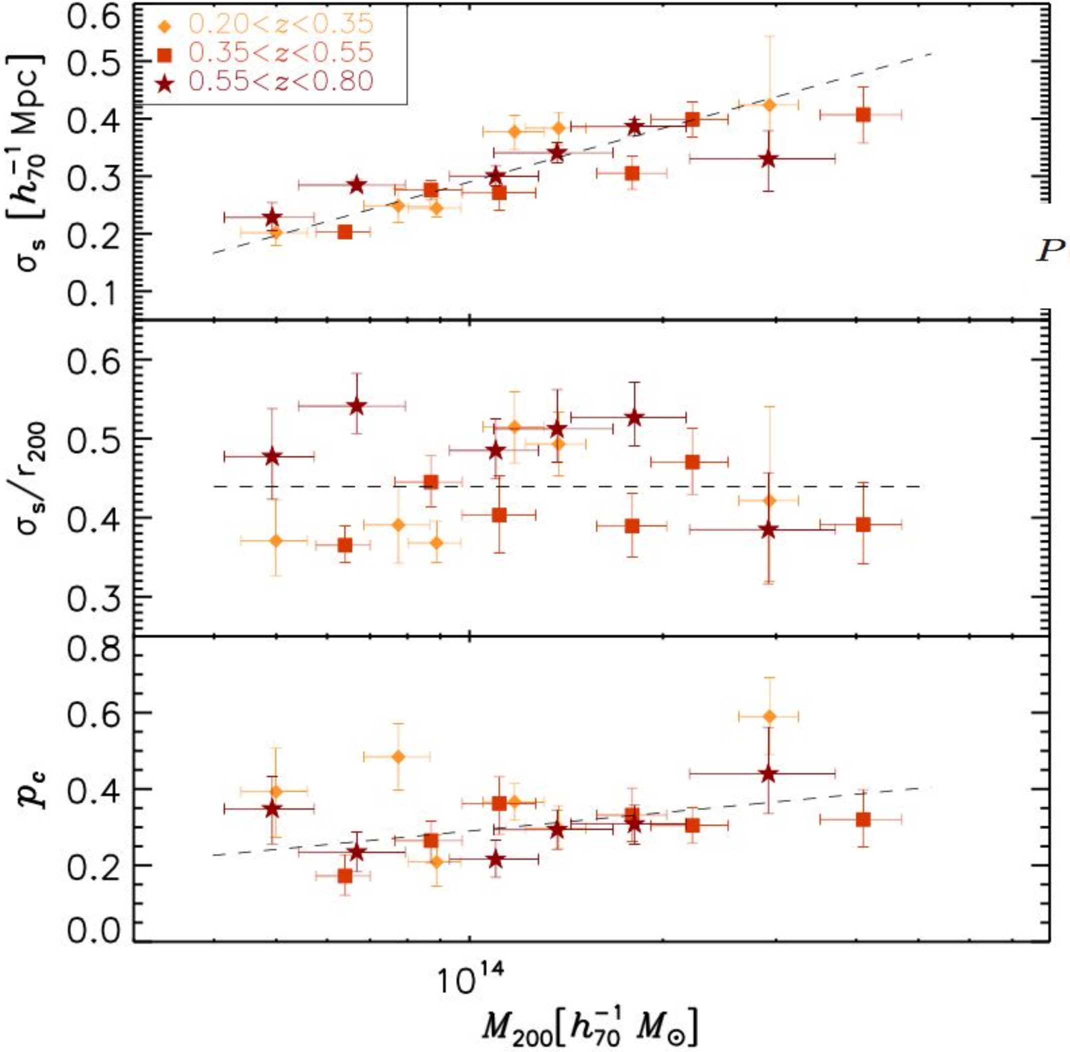


(Borgani & Guzzo 2001) Normalized to space density at z=0; circles: clusters with T>3 keV & ∝T

Cluster--satellite correlation function



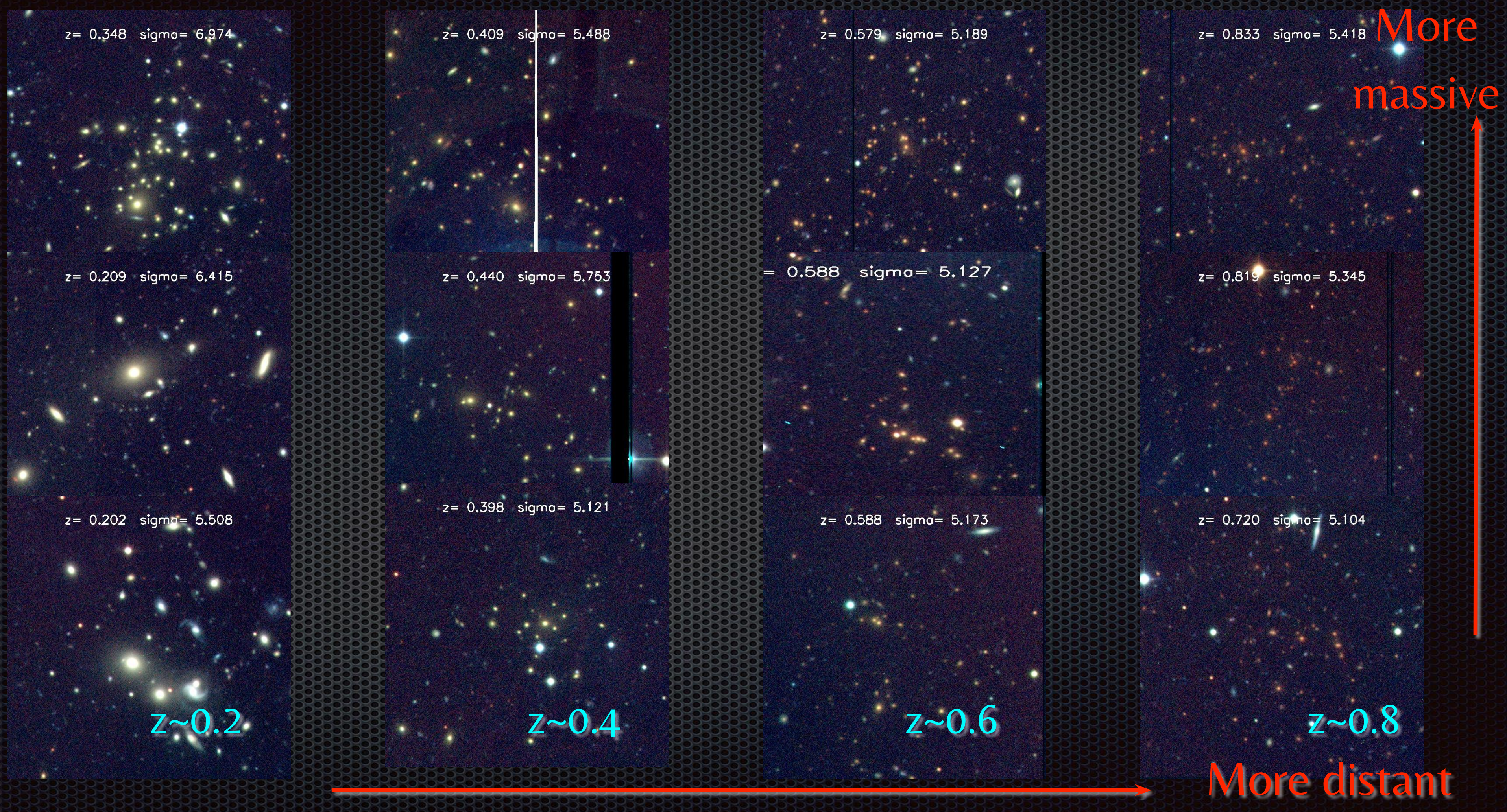
Width



$$P(r_{\rm mis}) = \frac{r_{\rm mis}}{\sigma_s^2}\exp\left(-\frac{1}{2}(r_{\rm mis}/\sigma_s)^2\right)$$

Centering fraction

maxBCG: p_c 60-80%
σ_s = 0.5 Mpc


z= 0.348 sigma= 6.974
z= 0.409 sigma= 5.488
z= 0.579 sigma= 5.189
z= 0.833 sigma= 5.418
More massive
z= 0.209 sigma= 6.415
z= 0.440 sigma= 5.753
= 0.588 sigma= 5.127
z= 0.819 sigma= 5.345
z= 0.202 sigma= 5.508
z= 0.398 sigma= 5.121
z= 0.588 sigma= 5.173
z= 0.720 sigma= 5.104
z~0.2
z~0.4
z~0.6
z~0.8
More distant

METHOD: Determine cluster’s centre: find BCG

Two-step approach

- brightest RS-member within 500 kpc from luminosity centre

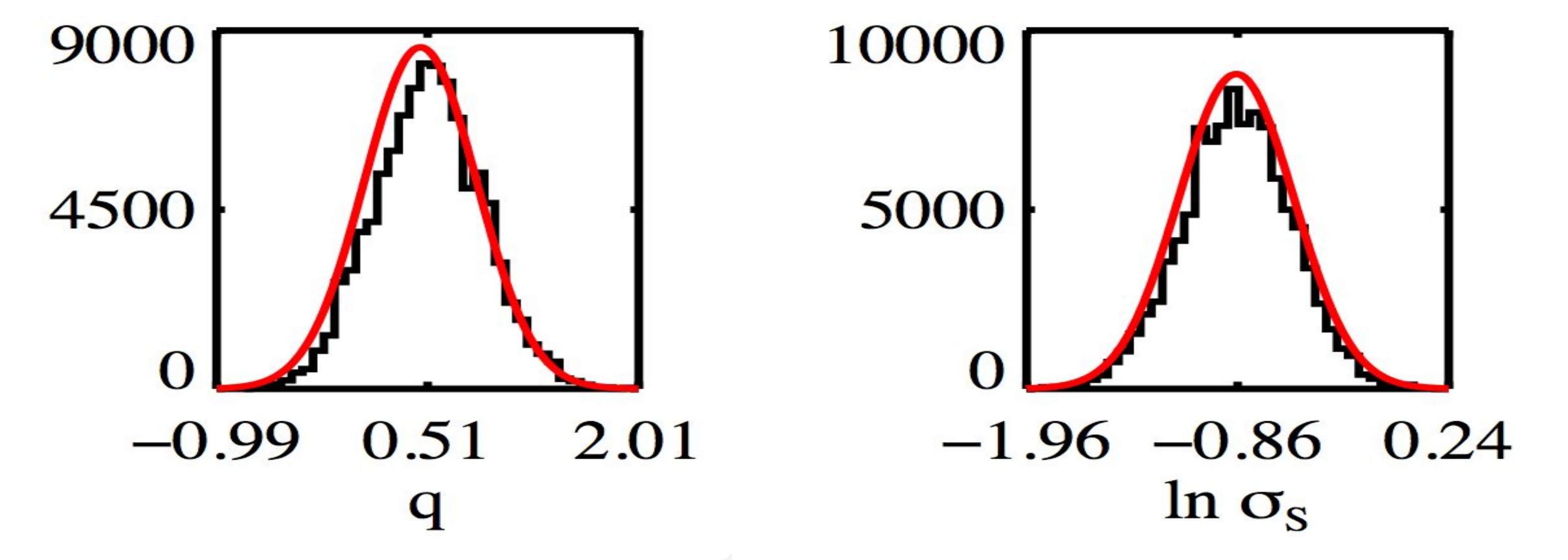
- second brightest gal. if at most 0.5 mag fainter, but 100 kpc closer to lum. centre

Compute mass proxy *richness* from RS-member list

- N_{gal}: # of RS brighter than M^*+1 within 1 Mpc
- estimate r_{200} via $r_{200}^{\rm gal} = 0.156 N_{\rm gal}^{0.6}$ Mpc (Hansen et al. 2005)
- counting within r_{200} gives N_{200}
- subtract <background>

(note: SDSS-maxBCG papers use range of slightly different definitions)

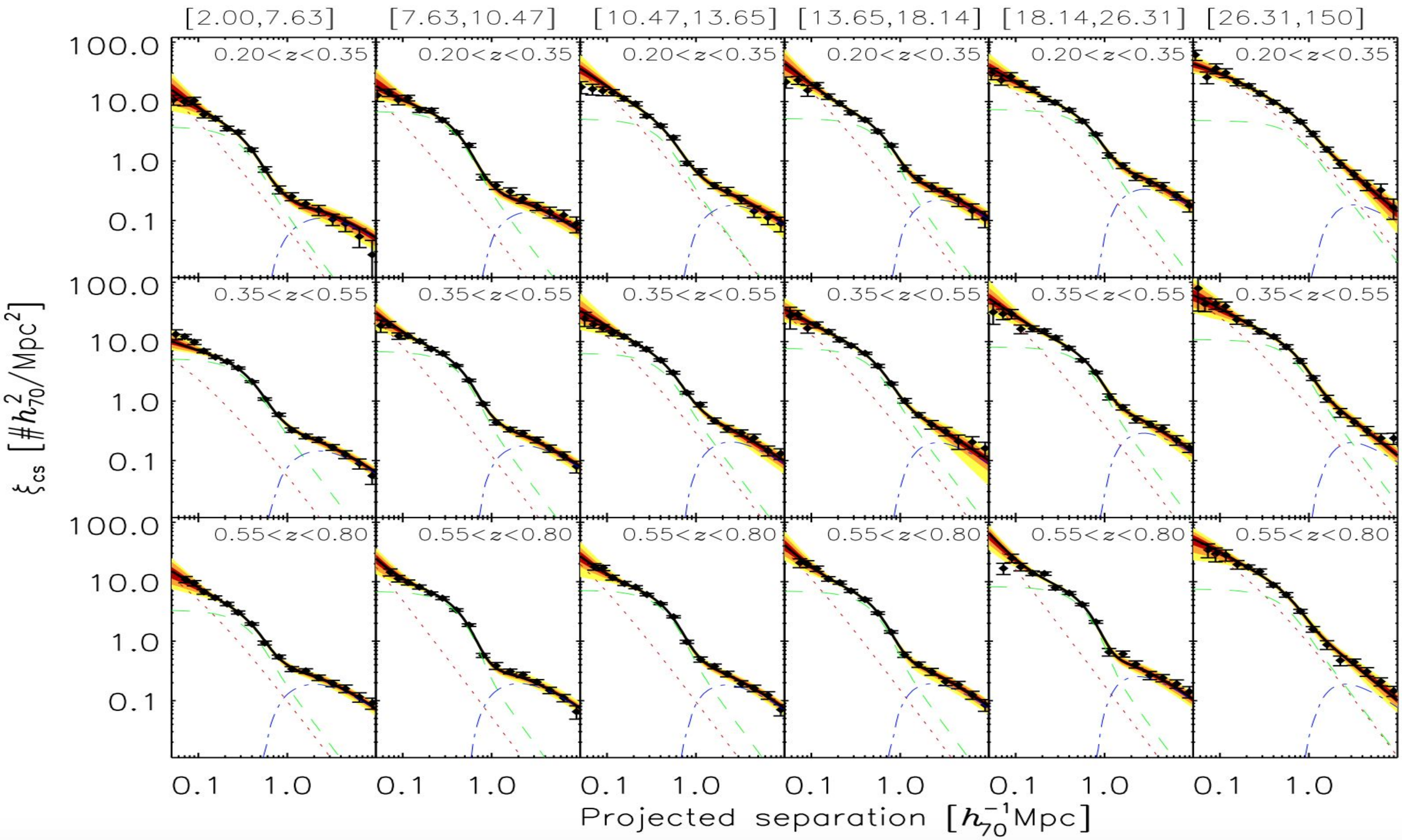
Problem: miscentring distribution not constrained by lensing alone



$p_c=(1+\exp(-q))^{-1}$

maxBCG used simulations to get priors

The risk: wrong priors can bias results



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[26.31,150]
0.20<z<0.35
0.35<z<0.55
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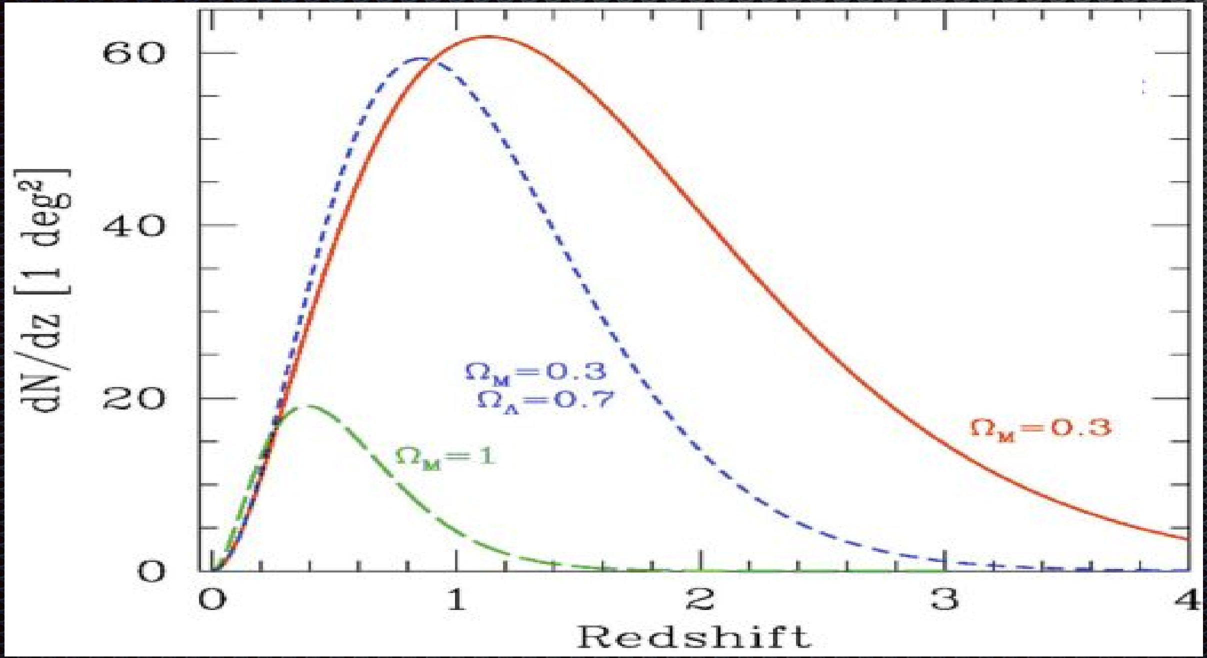
100.0
10.0
1.0
0.1
ξ_{cs} [# h_{70}^2/Mpc^2]
Projected separation [h_{70}^{-1}Mpc]

Cluster abundance

$$\frac{dN(z)}{dz\,d\Omega} = \frac{dV}{dz\,d\Omega} n(z) = \frac{c}{H(z)} d_A^2 (1+z)^2 \int_0^\infty dM\, f(M) \frac{dn(M,z)}{dM}$$

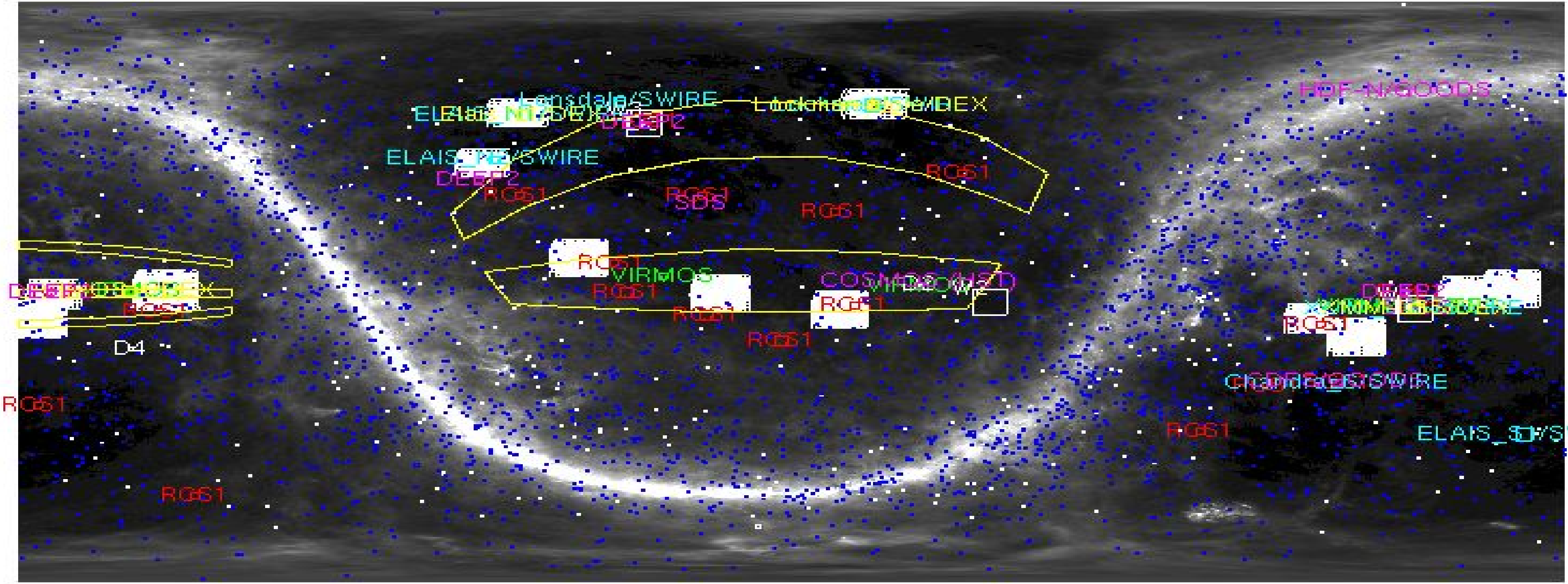


Cluster counts require:

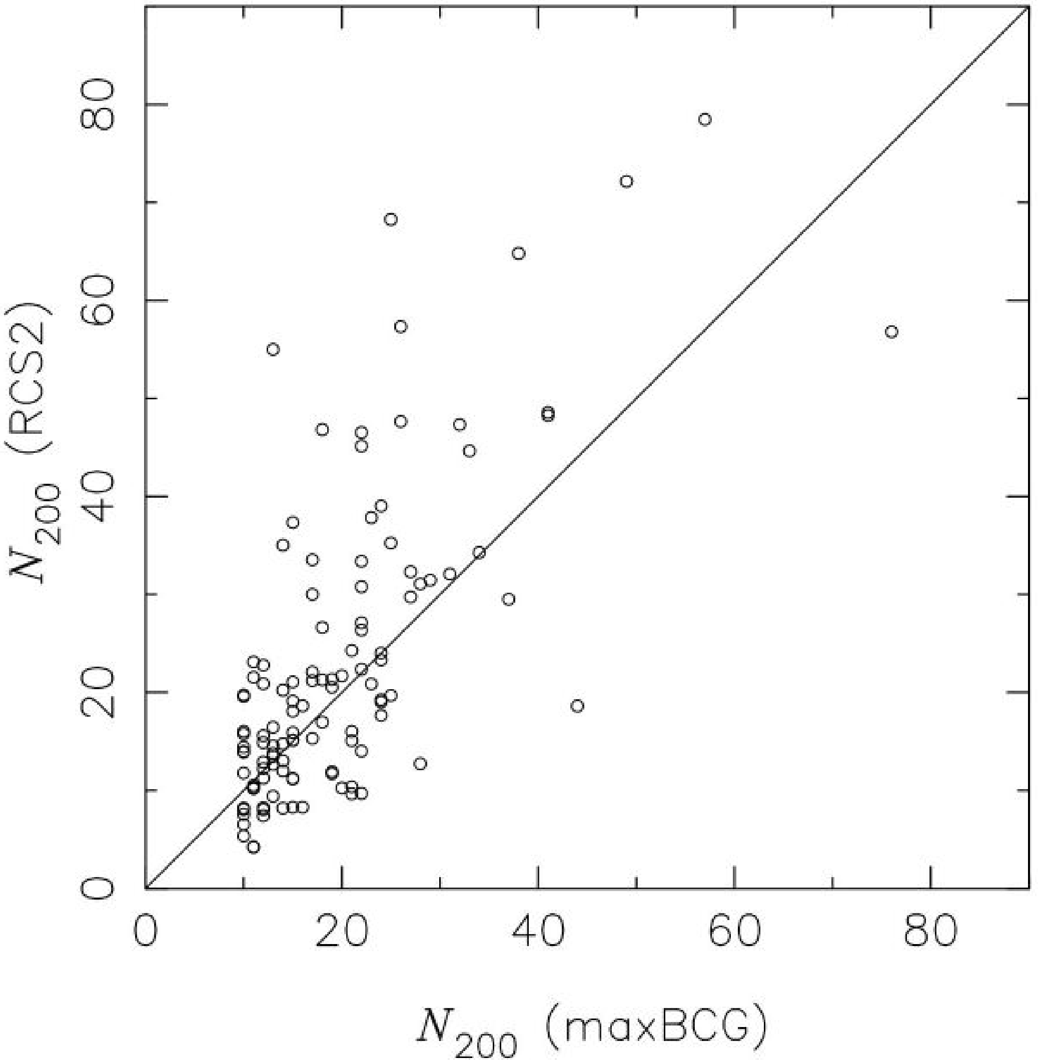
- ***redshift*** of each cluster
- ***mass*** of each cluster

via **mass--observable** relation, f(M)
(selection function
incorporating scatter)

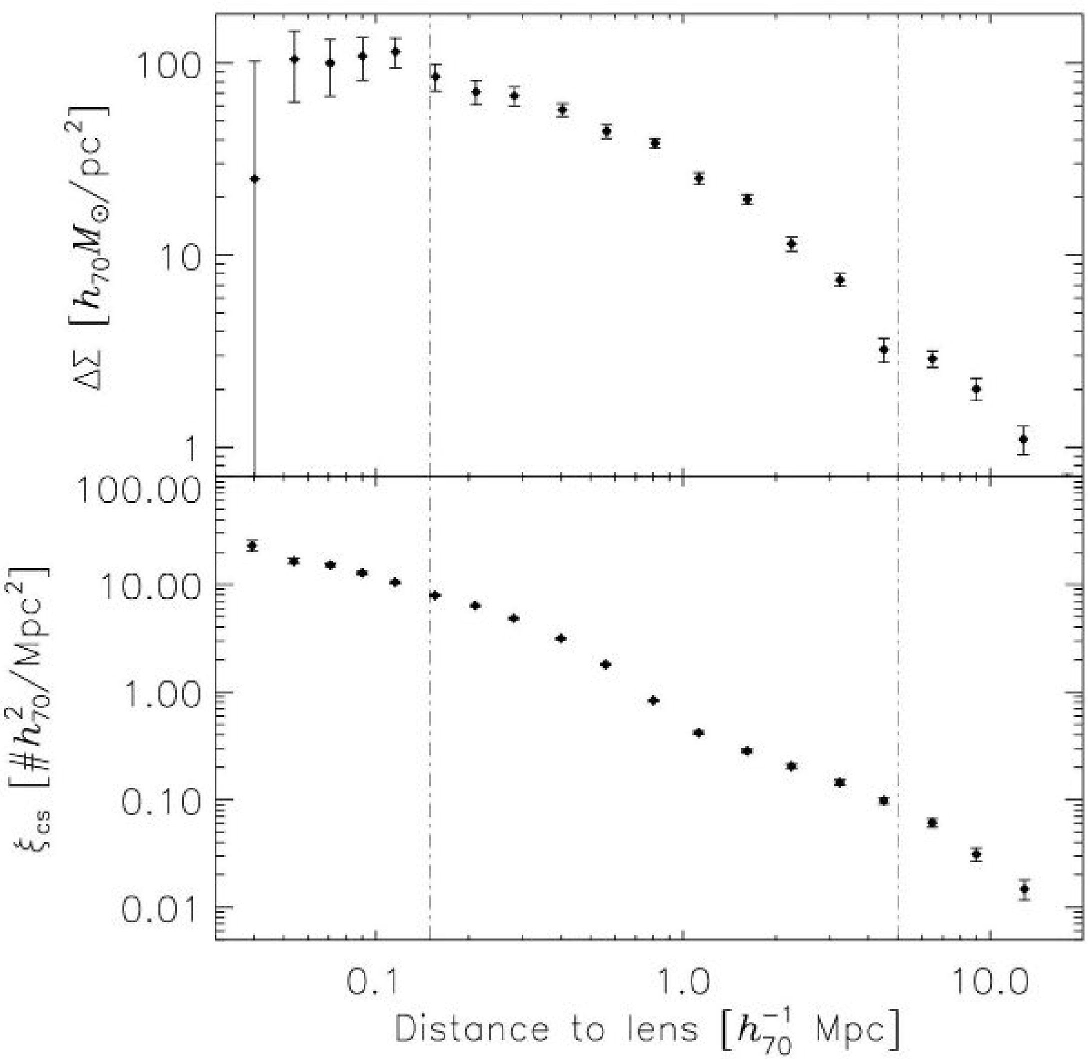
RCS-2



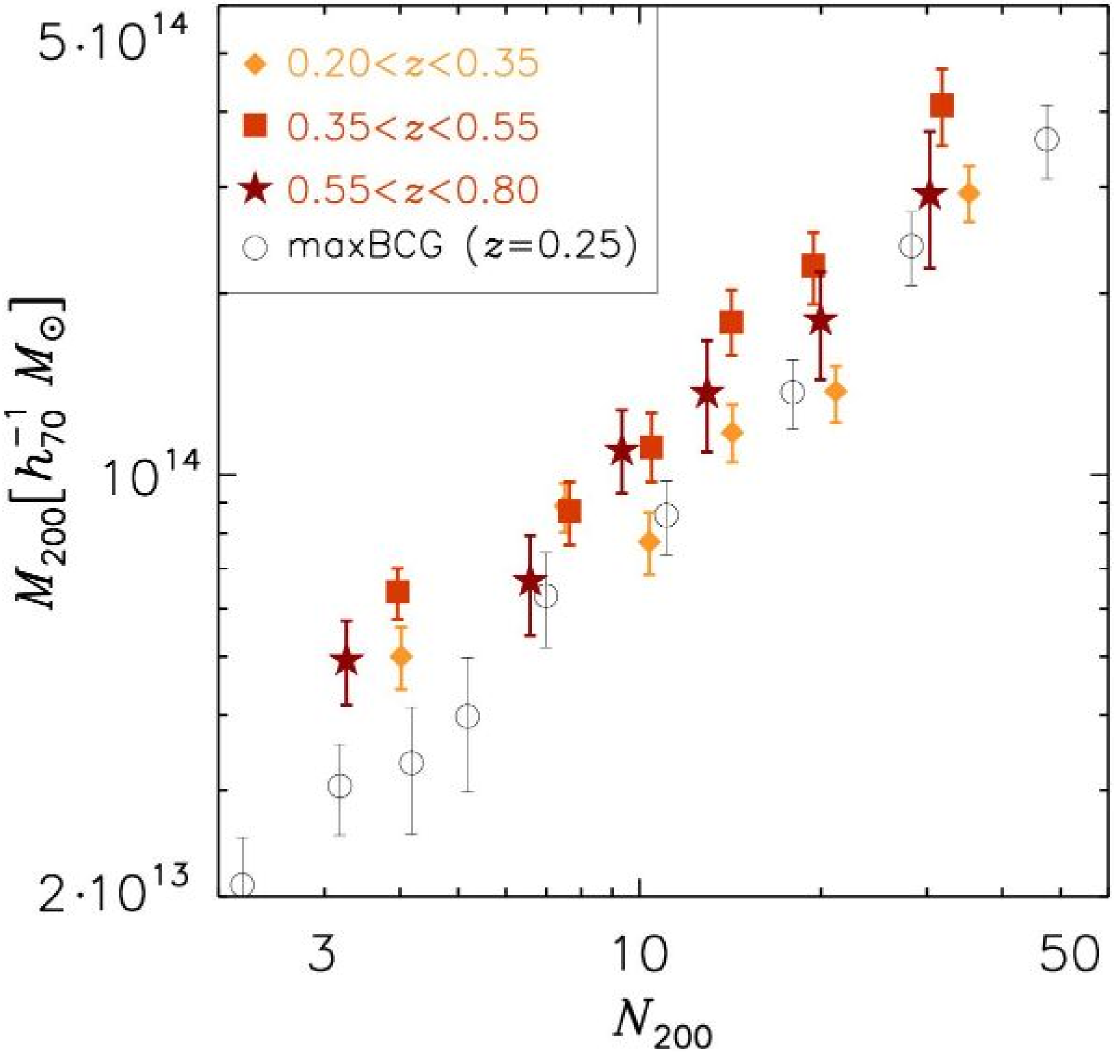
http://www.rcs2.org



0
20
40
60
80
N_{200} (RCS2)
N_{200} (maxBCG)

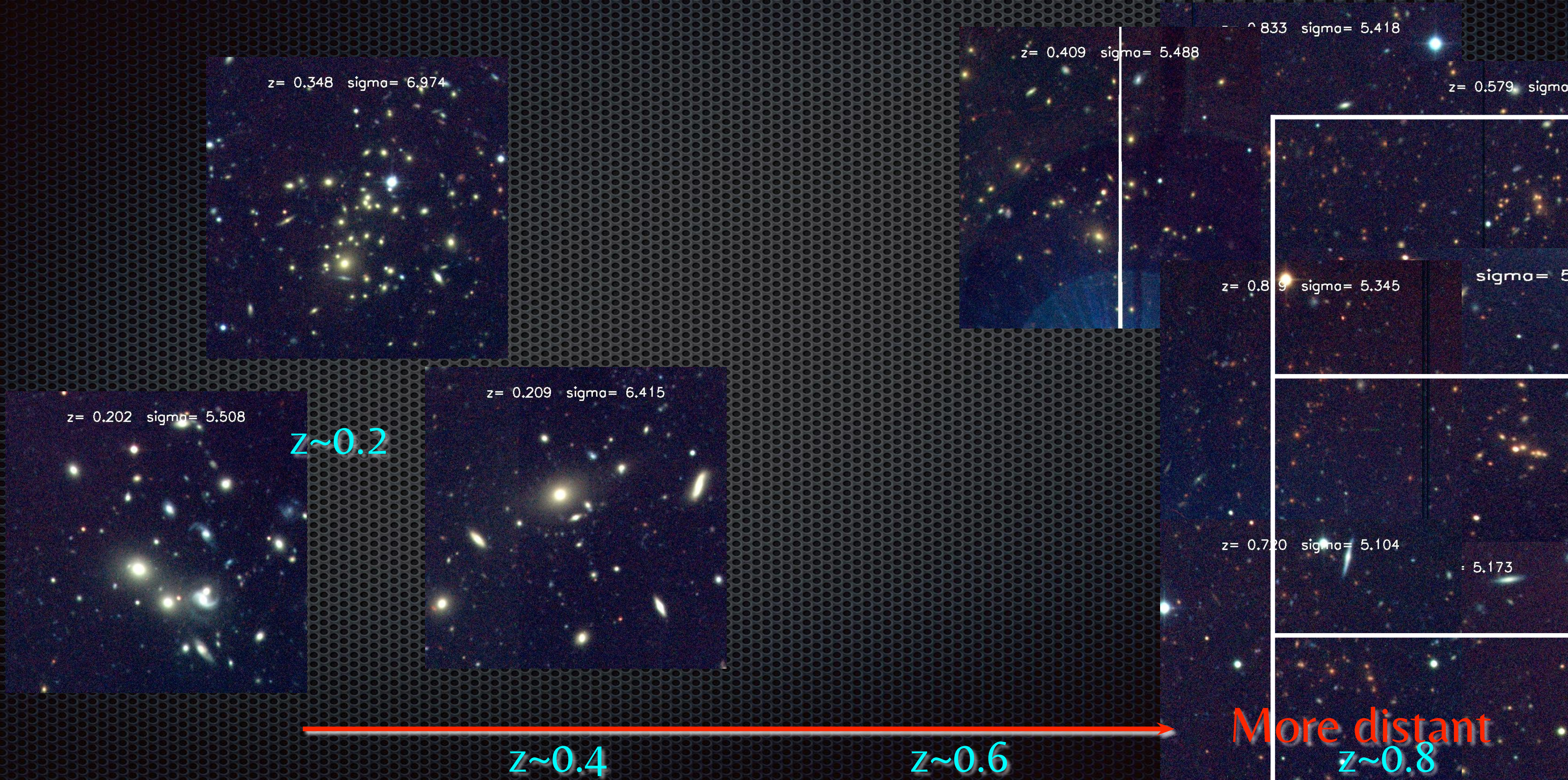


100
10
1
$\Delta\Sigma$ [$h_{70}M_\odot/\mathrm{pc}^2$]
100.00
10.00
1.00
0.10
0.01
ξ_{cs} [$\#h_{70}^2/\mathrm{Mpc}^2$]
0.1
1.0
10.0
Distance to lens [h_{70}^{-1} Mpc]



0.20<z<0.35
0.35<z<0.55
0.55<z<0.80
maxBCG (z=0.25)
$M_{200}[h_{70}^{-1}\ M_\odot]$
$5\cdot10^{14}$
10^{14}
$2\cdot10^{13}$
3
10
50
N_{200}

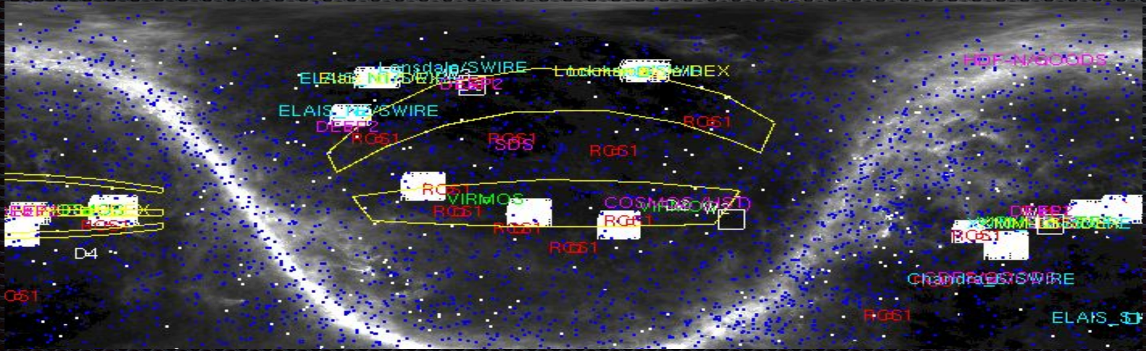
Properties of Cluster Galaxies



Red-sequence Cluster Surveys

Find clusters out to z~1 with red-sequence technique

- RCS-2 Gilbank, Gladders, Yee, Hsieh 2
  AJ, 141, 94
  - Imaged ~1000 deg^2 in g', r', z'
  - Discovered ~10 000 clusters!



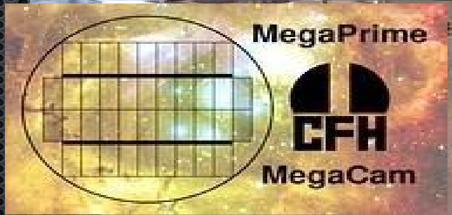
http://www.rcs2.org

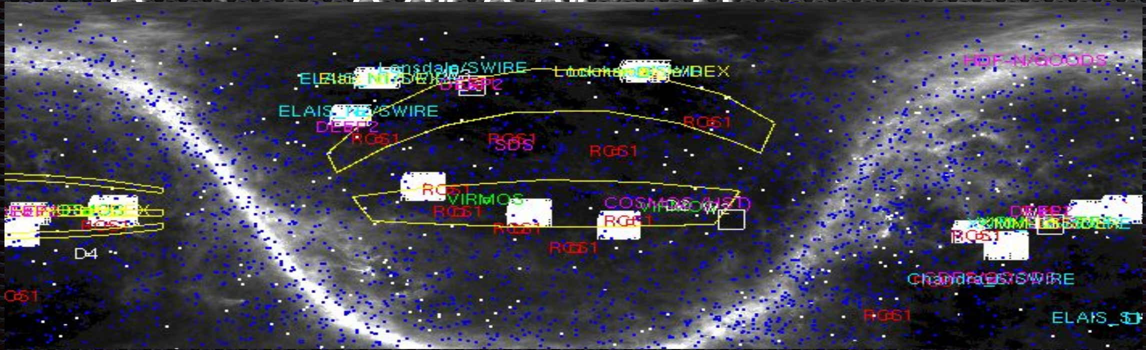
Red-sequence Cluster Surveys

- RCS-2 Gilbank, Gladders, Yee, Hsieh 2011 AJ, 141, 94

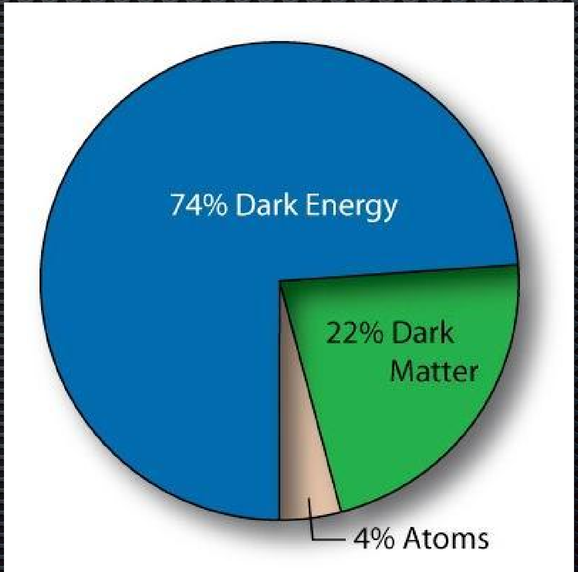
Find clusters out to z~1 with red-sequence technique

- imaging completed -- 785 deg^2 in **g**, ***r'***, *i'*, ***z'*** with CFHT MegaCam (g~25.3, ***r*~24.8**, z~22.5, **AB**)
- +171 deg^2 CFHTLS Wide

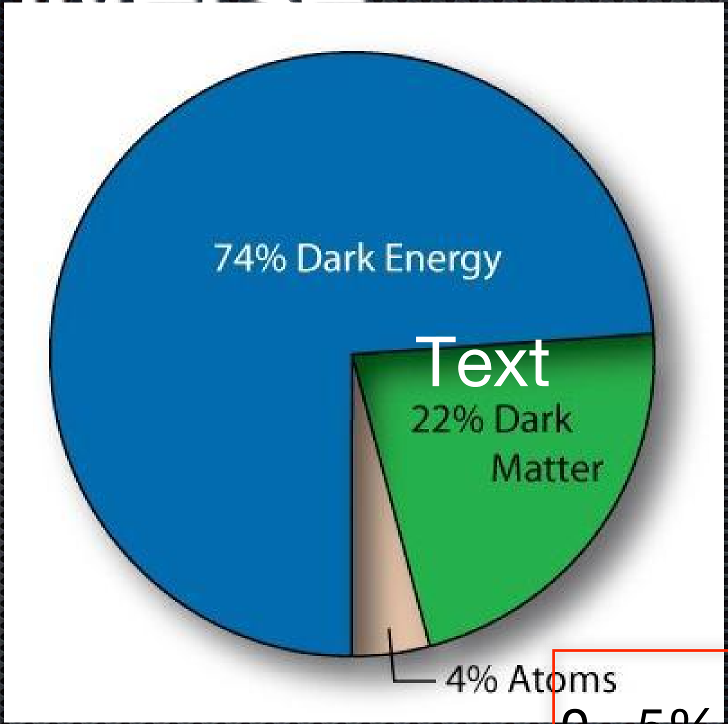




http://www.rcs2.org


74% Dark Energy
22% Dark Matter
4% Atoms

The Universe



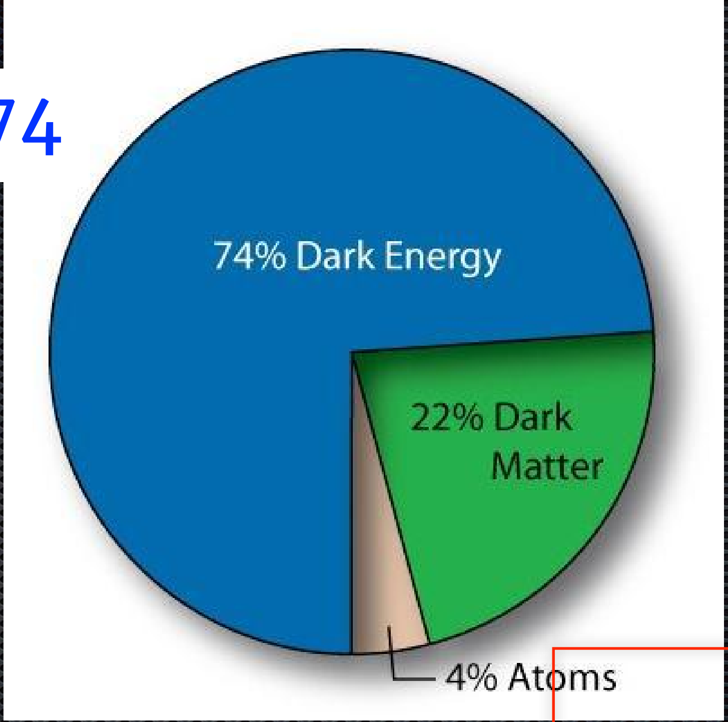
0. ~5% stars
rest is mostly H,He

The Universe

$\Omega_\Lambda = 0.74$

$P = w\rho$

Equation of state of dark energy



$\Omega_m = 0.26$

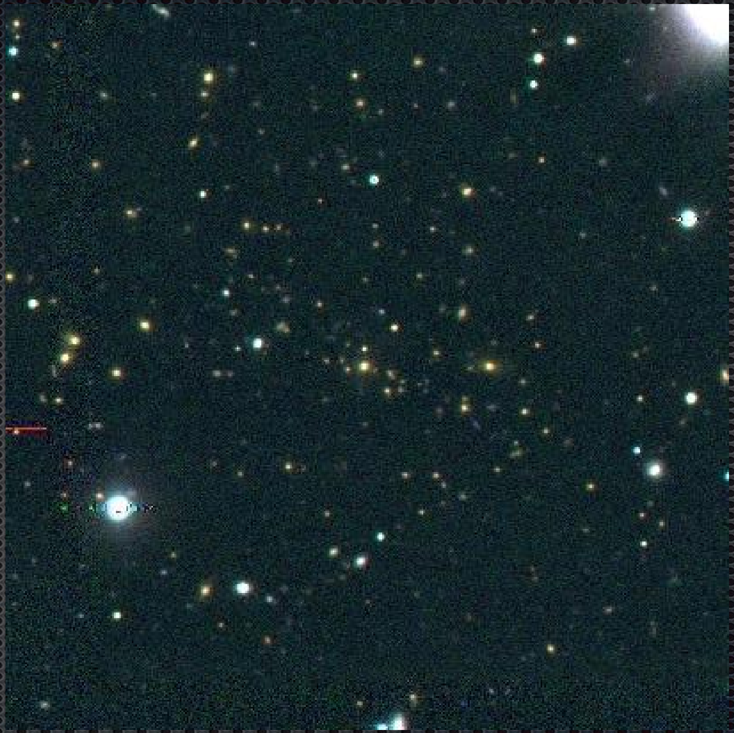
~0.5% stars
rest is mostly H,He

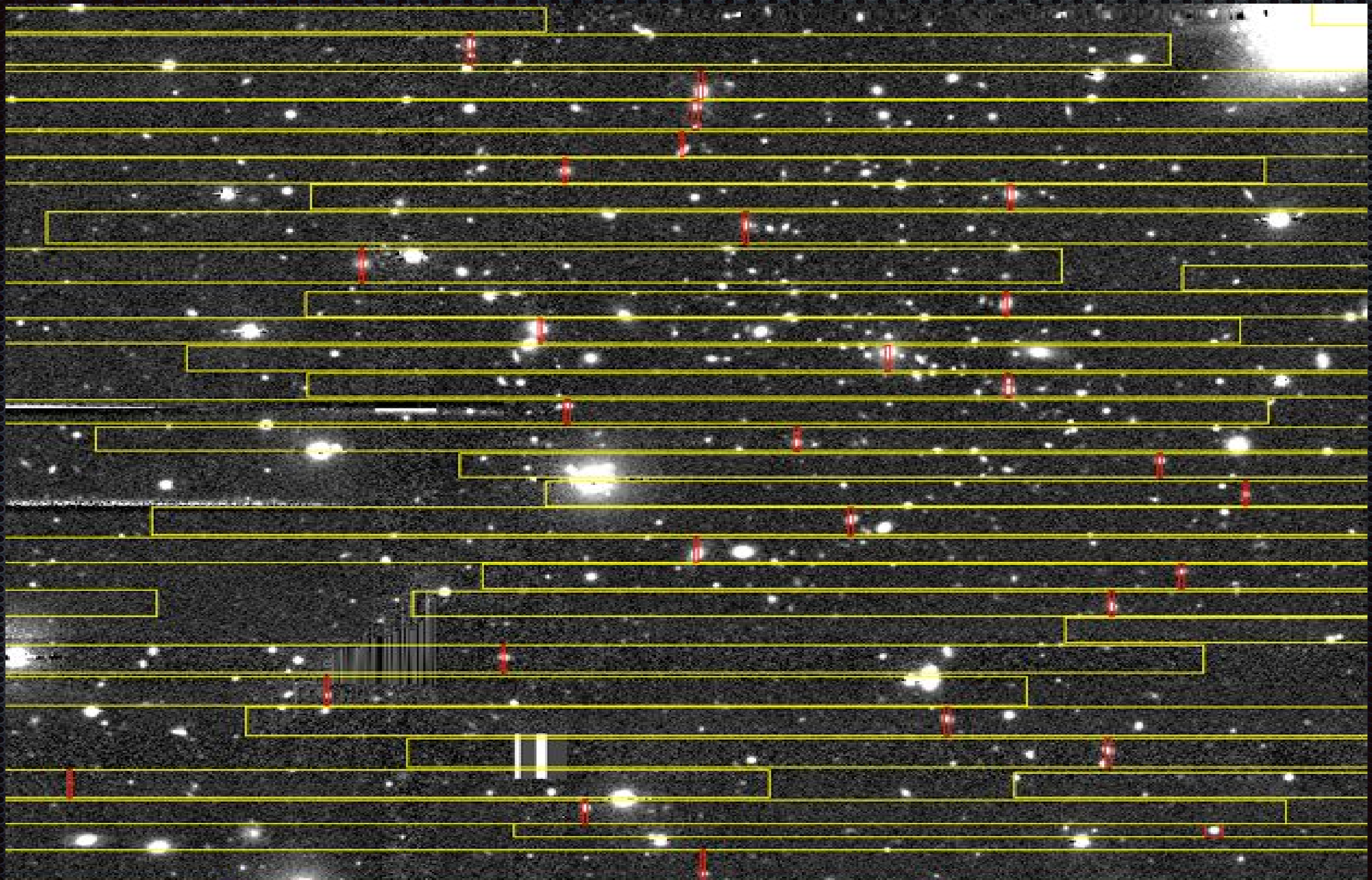
Spectroscopic Follow-up

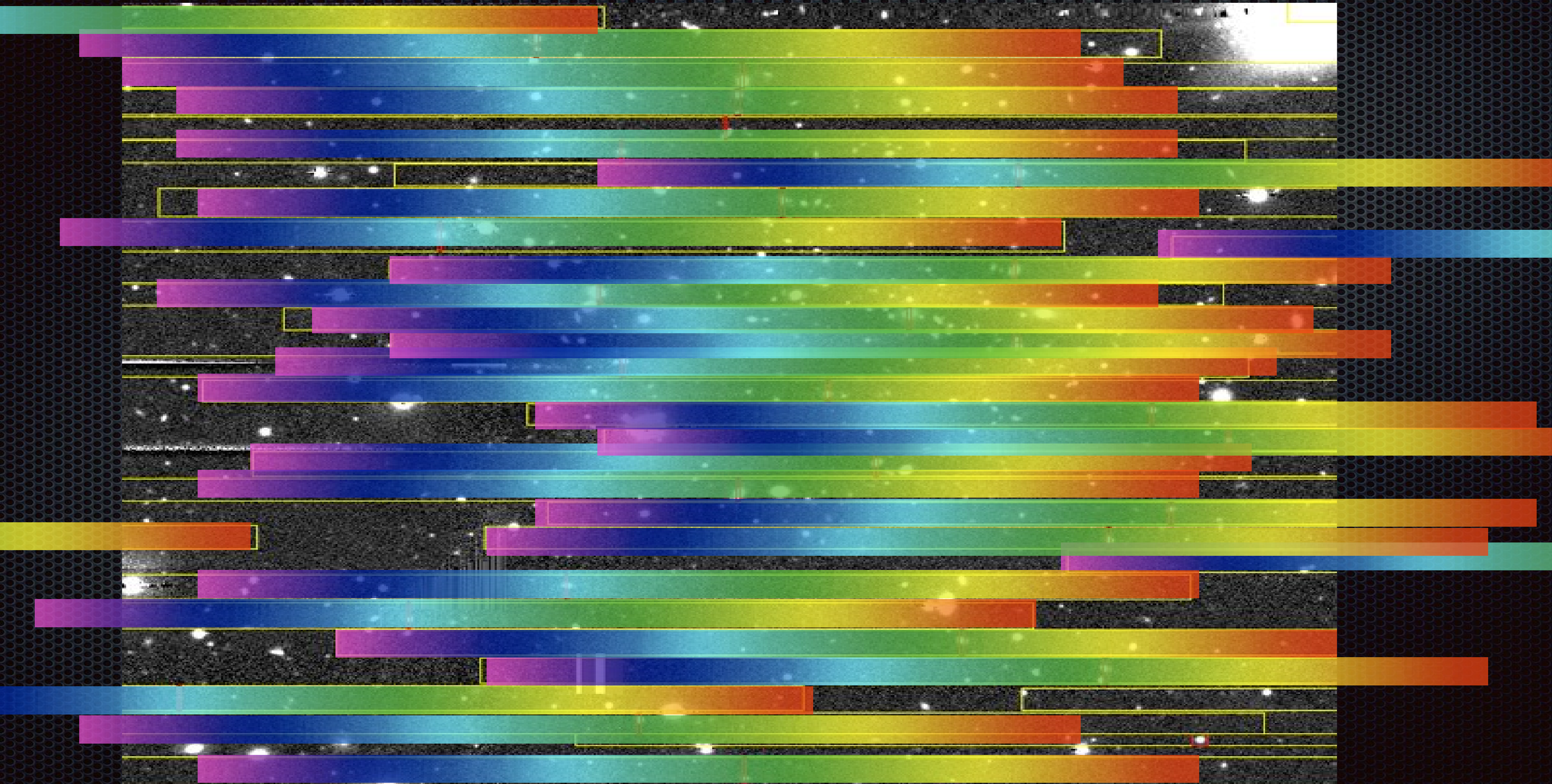
- 10 year+ campaign to follow-up well-defined subsample of clusters for **mass calibration**

Spectroscopic Follow-up

- 10 year+ campaign to follow-up well-defined subsample of clusters for **mass calibration**
- CFHT-MOS, K. Blindert PhD Thesis (U. Toronto, 2006)
- 6.5-m Magellan LDSS-3, IMACS; 8-m Gemini GMOS-N,S; 8-m VLT FORS2 (Gilbank et al. 2007, 2008, in prep.)
- In addition to dynamical masses from optical Multi-Object Spectroscopy (MOS):
  - strong and weak gravitational lensing, X-ray, SZ, ...







RCS-2 Science Drivers

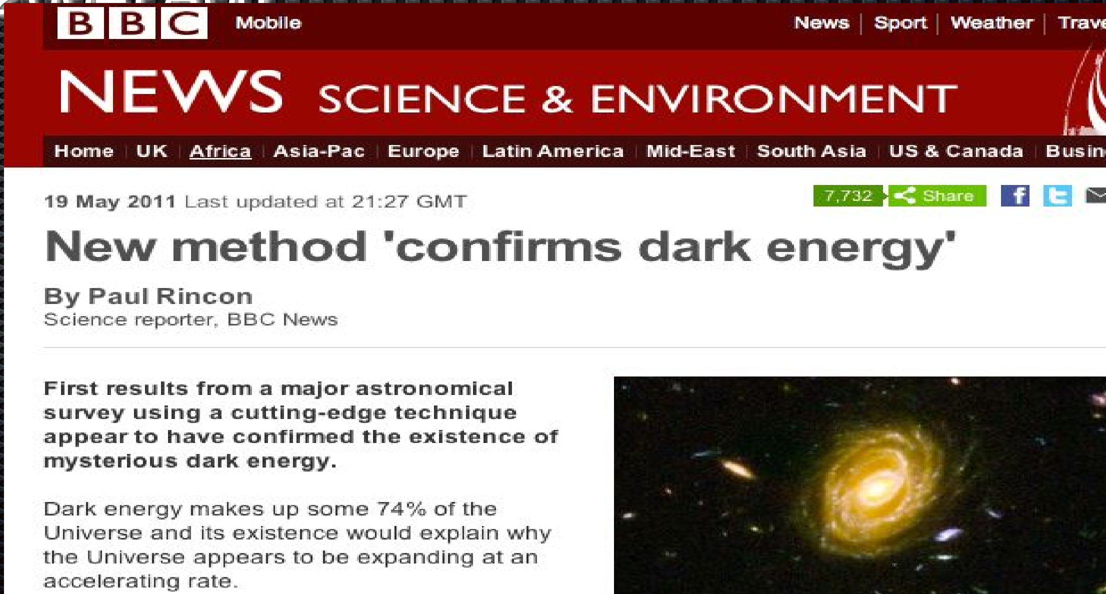
- Cosmology: measure the Dark Energy equation of state parameter, w, to an accuracy of 0.1 using RCS-2 alone, or 0.05 when combined with SNe/CMB

- Discover ~50-100 high surface brightness, strongly-lensed, distant galaxies, with which to study in detail representative galaxies in the high redshift universe

- Produce a sample of ~20 000 - 30 000 clusters in the redshift range 0.1-1.0 with which to study cluster galaxy evolution

Measuring Cosmological Parameters with RCS-2

- Cluster abundance
  - e.g., Majumdar & Mohr (2004) ApJ 613, 41
- BAO with WiggleZ
  - Blake et al. (2011) arXiv1



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19 May 2011 Last updated at 21:27 GMT

7,732 Share

New method 'confirms dark energy'

By Paul Rincon
Science reporter, BBC News

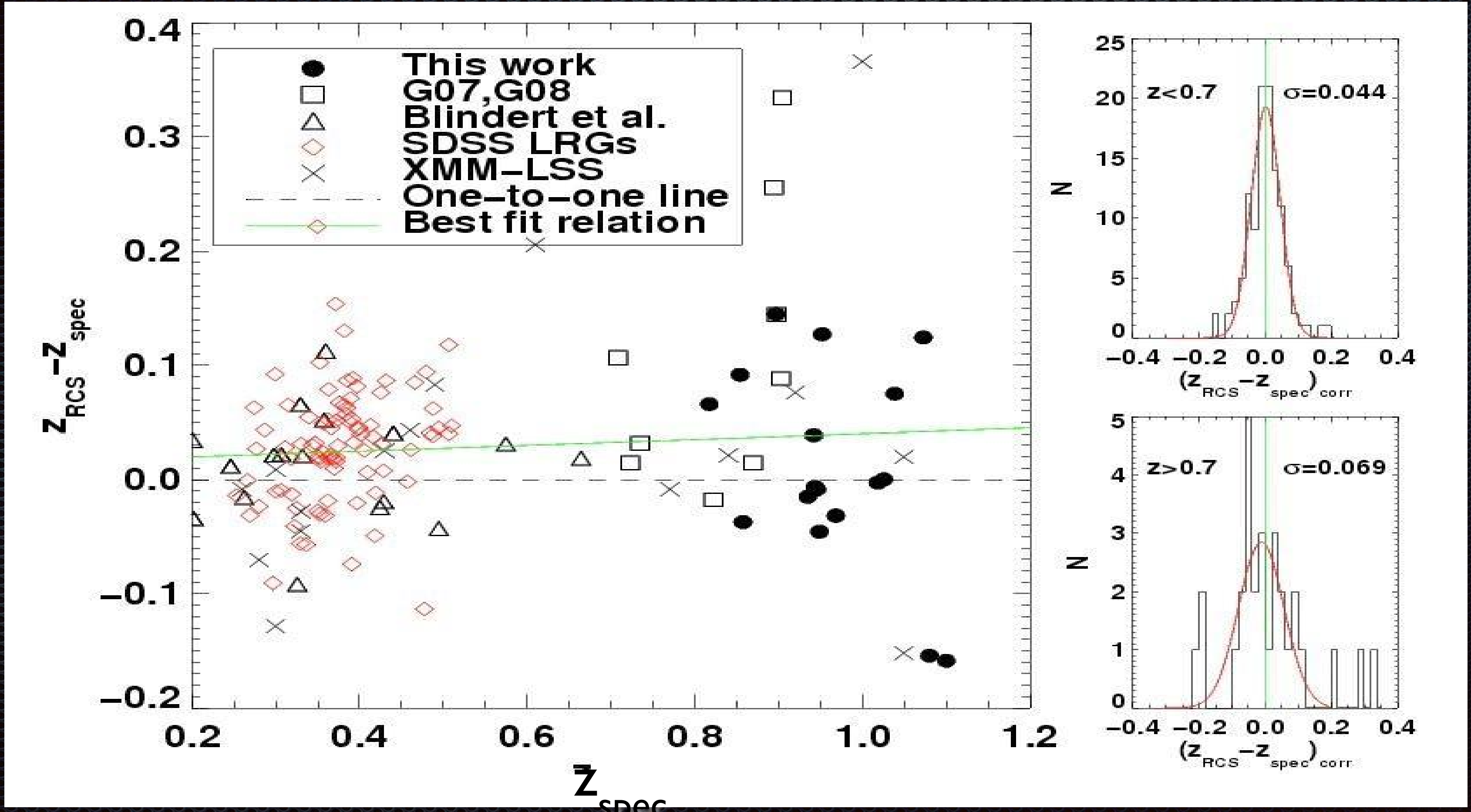
First results from a major astronomical survey using a cutting-edge technique appear to have confirmed the existence of mysterious dark energy.

Dark energy makes up some 74% of the Universe and its existence would explain why the Universe appears to be expanding at an accelerating rate.

Measuring Cosmological Parameters with RCS-2

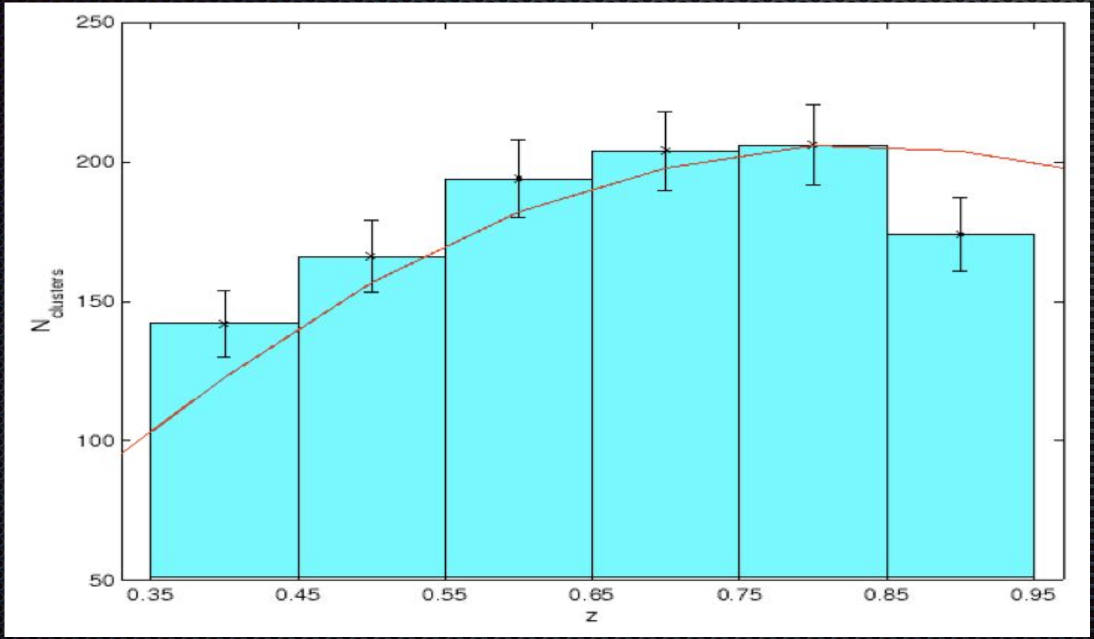
- Cluster abundance
  - e.g., Majumdar & Mohr 2004 ApJ 613, 41
- Strong lens statistics
- BAO with WiggleZ
  - Glazebrook et al., astro-ph/0701876

Red-sequence redshift accuracy



Cluster counts from RCS-1

Proof of concept



Gladders et al. 2007

ApJ, 655, 128

found:

Ω_m=0.31+/−0.10

σ_8=0.67+/−0.17

using self-calibration

- fit for cosmological parameters and unknown mass--richness relation

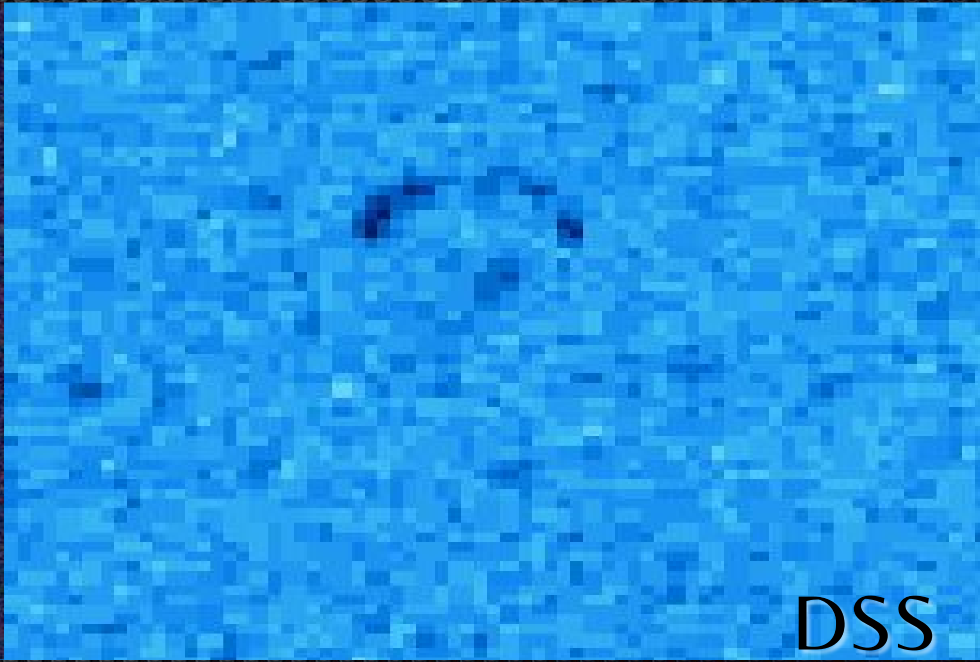
Example Strong Lensing Clusters

lensing cluster at z_{est}=0.59 with giant arc

lensing cluster at z_{est}=0.58 with multiple bright arcs

Images from the RCS-2 g′, r′, z′ survey data

Example Strong Lensing Clusters



lensing cluster at z_{est}=0.59 with giant arc

Images from the RCS-2 g', r', z' survey data

Example Strong Lensing Clusters

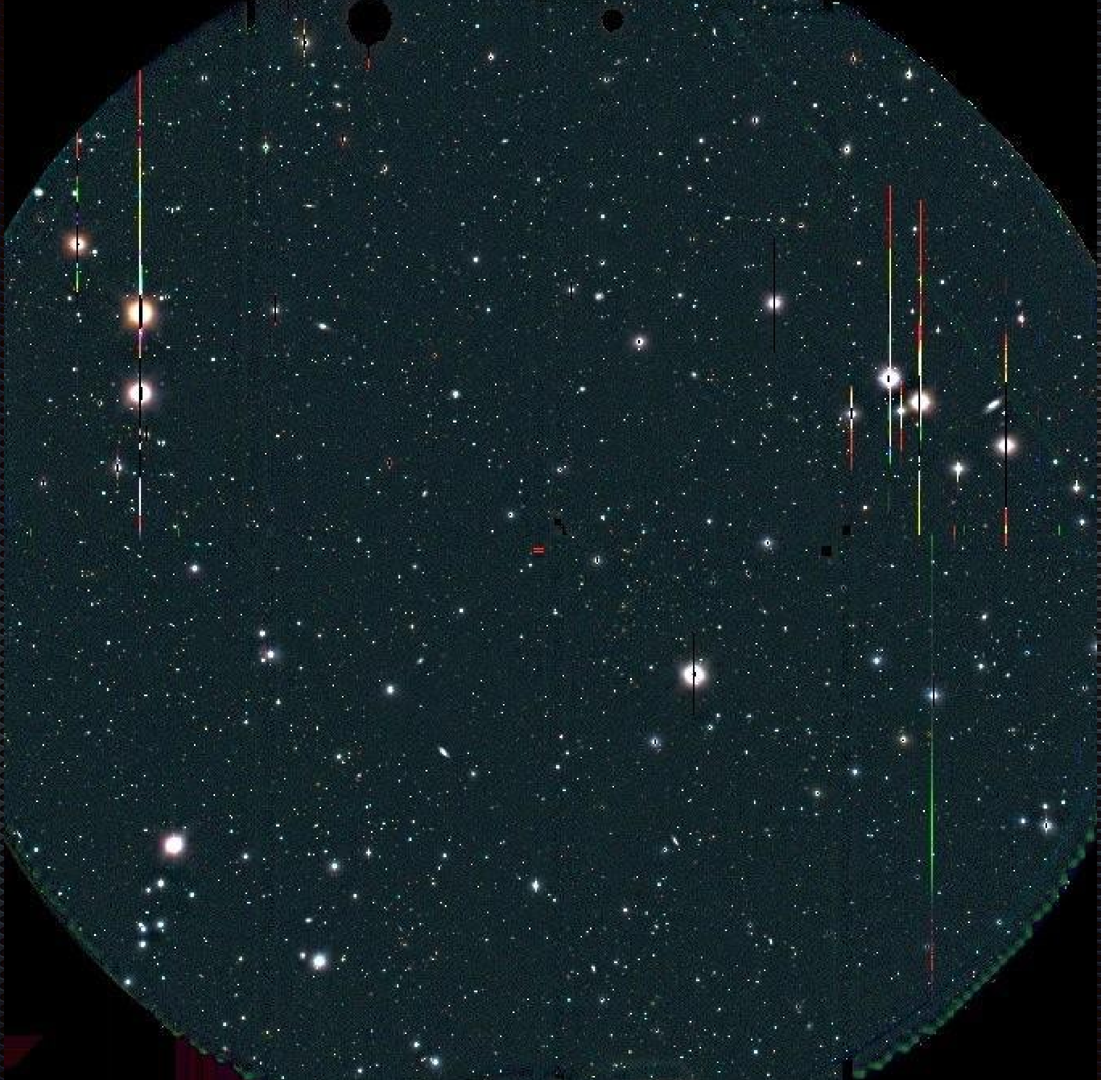
lensing cluster at z_{est}=0.59 with giant arc

Images from the RCS-2 g', r', z' survey data

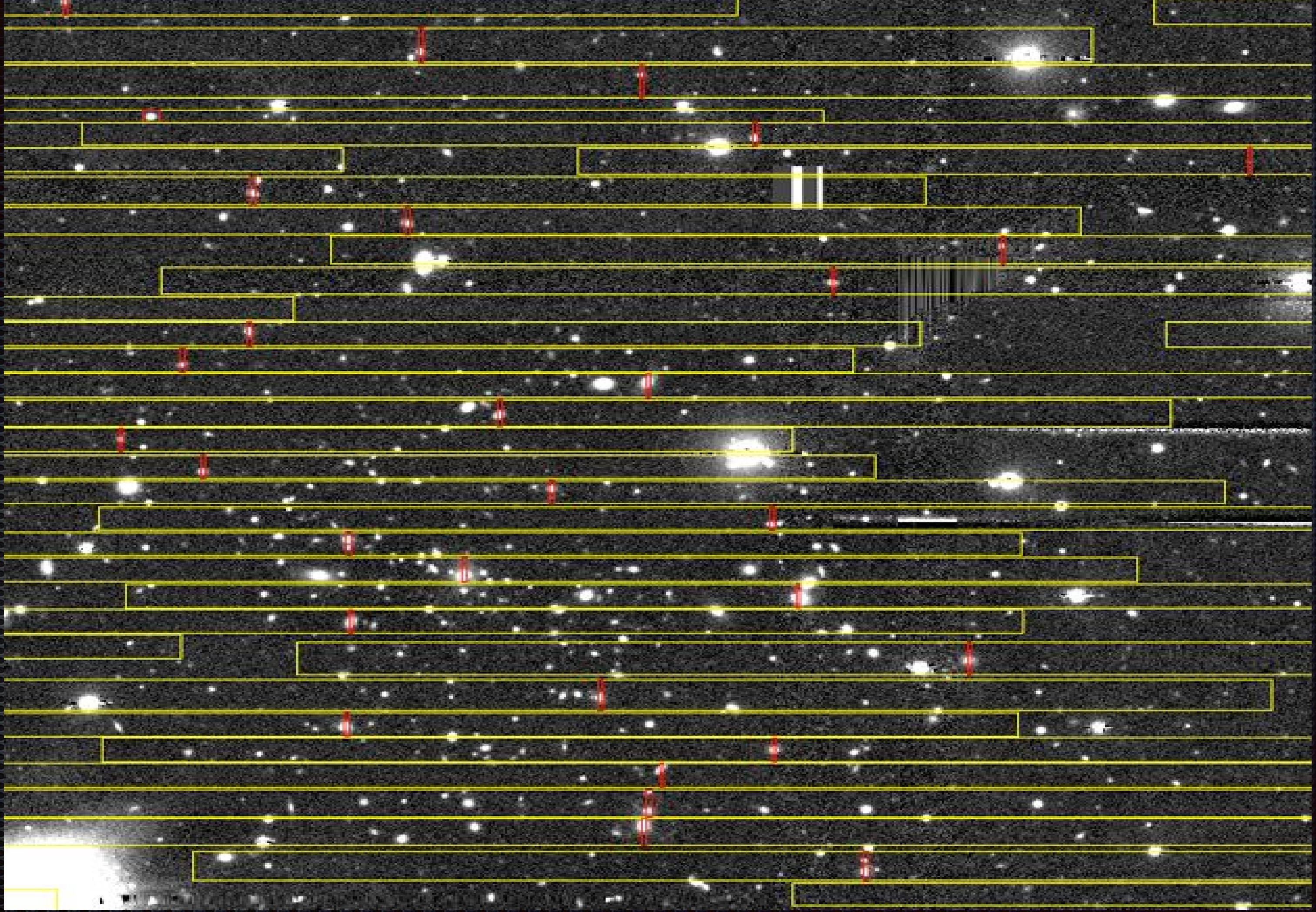
- Properties of lensed galaxy studied in Wuyts et al. (2010) ApJ, 724, 1182
- Larger sample: Wuyts, Rigby, Gilbank, Gladders (2011) in prep

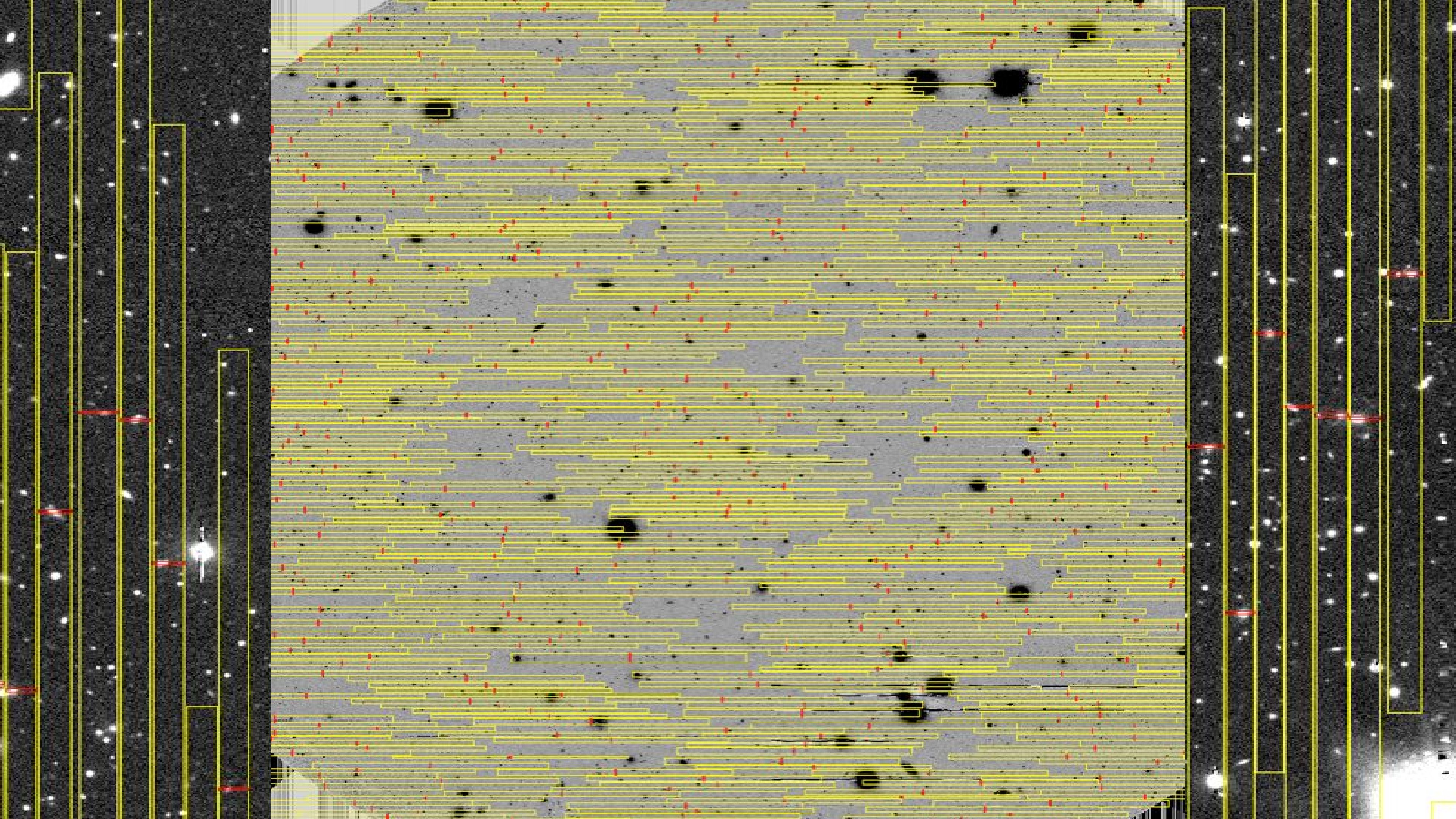

~1/2 degree
IMACS

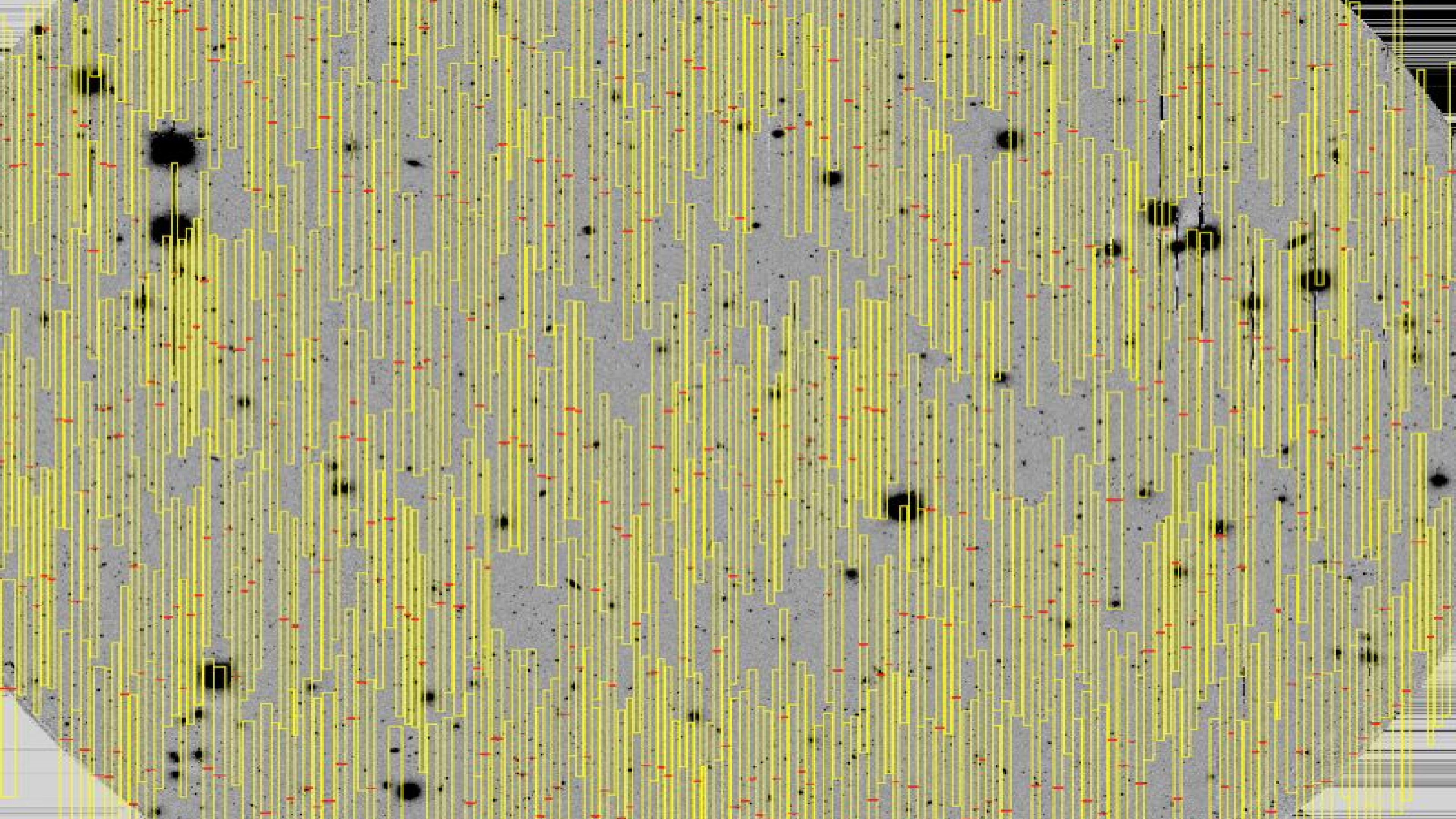
~1/2 degree



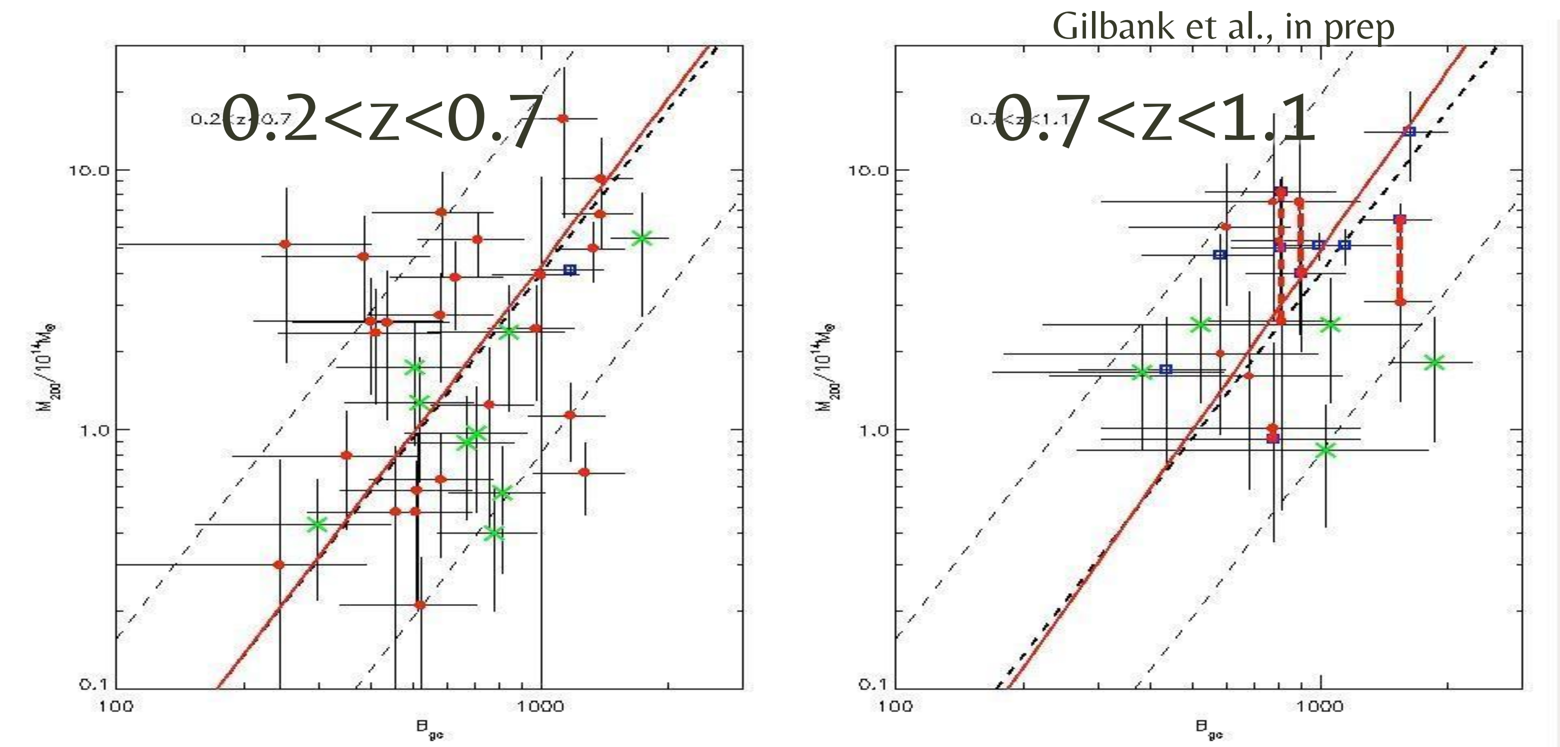
IMACS







mass--richness relation



mass estimates:

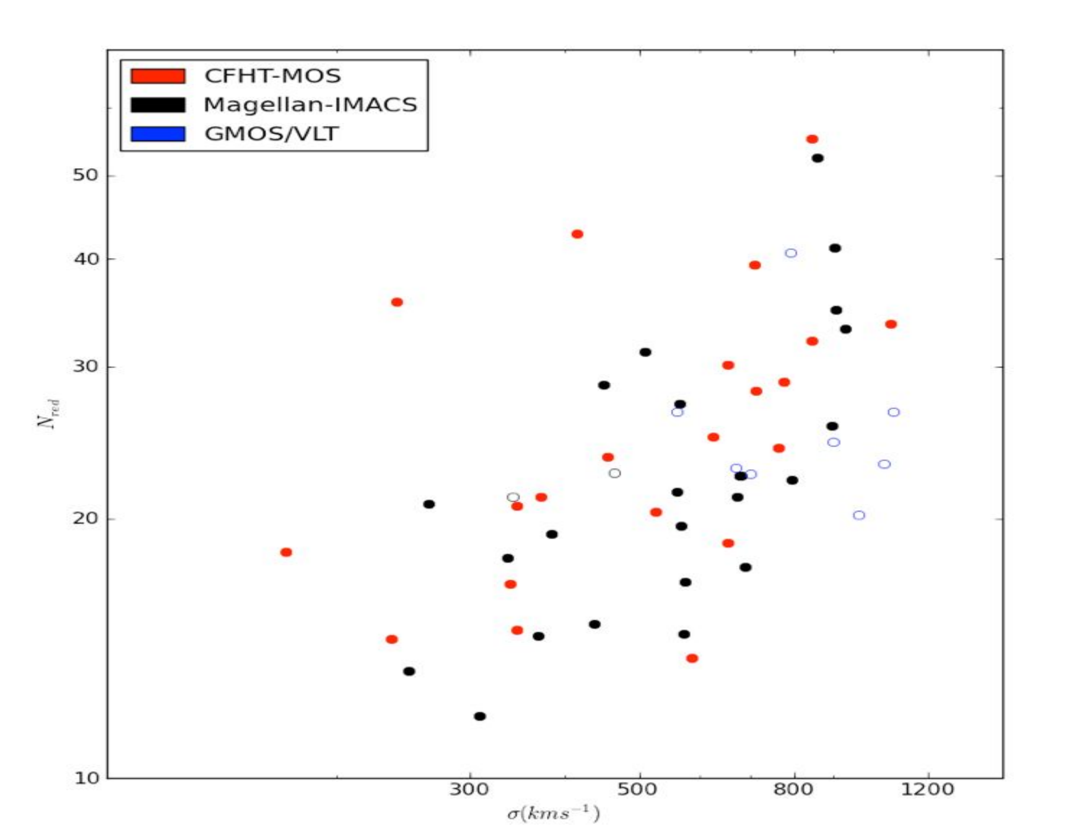
dynamical
Blindert et al., ApJS submitted

Chandra
Hicks et al., astro-ph/0710.5513

XMM-LSS

log(σ)~0.6,
c.f. Lx--M scatter (Nord et al. 2008)

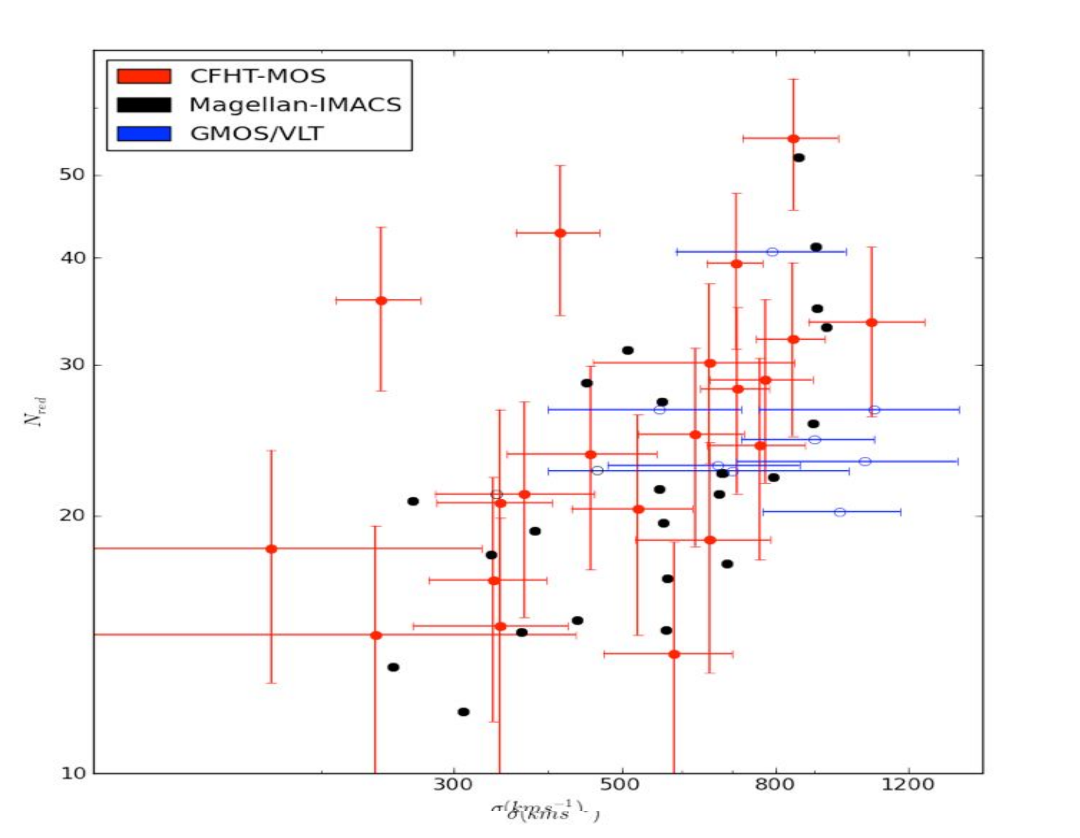
Mass--Richness Relation



Optical richness

Dynamical Mass

Mass--Richness Relation



Optical richness

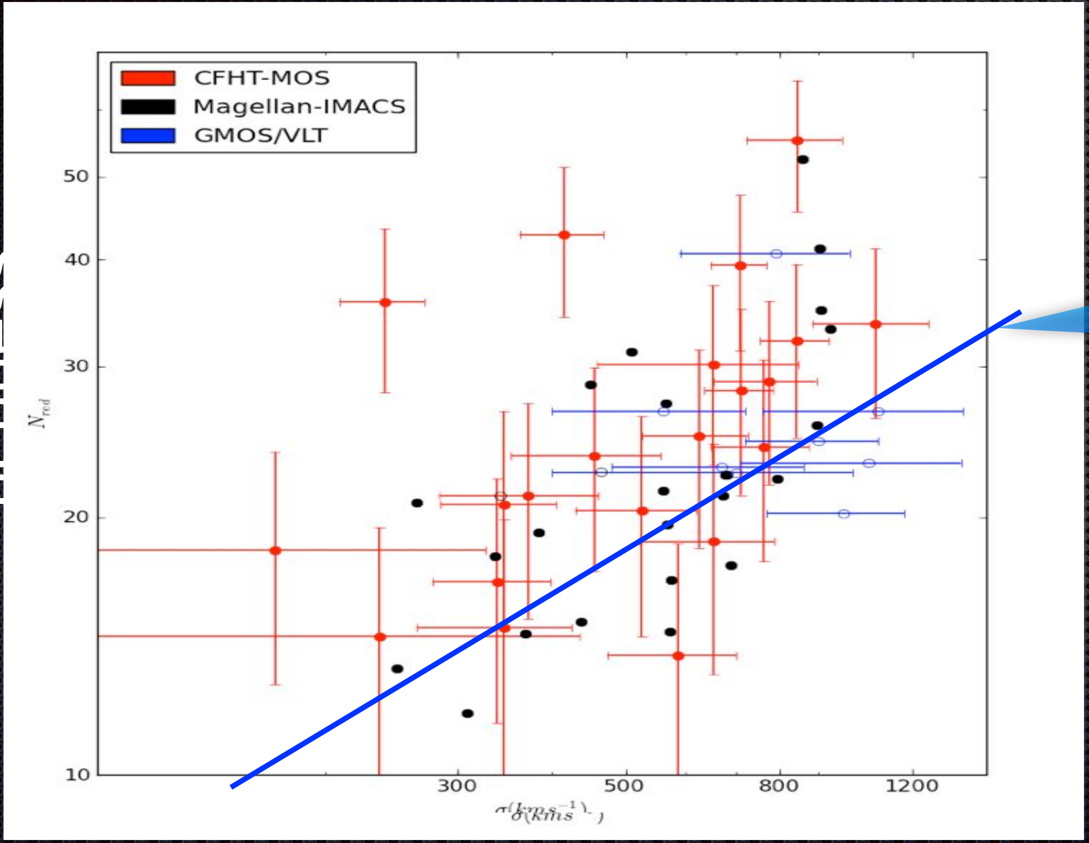
Dynamical Mass

$0.2 \lesssim z \lesssim 1.1$

Gilbank et al. in prep,
Ellingson et al. in prep

Mass--Richness Relation

Optical richness



Dynamical Mass

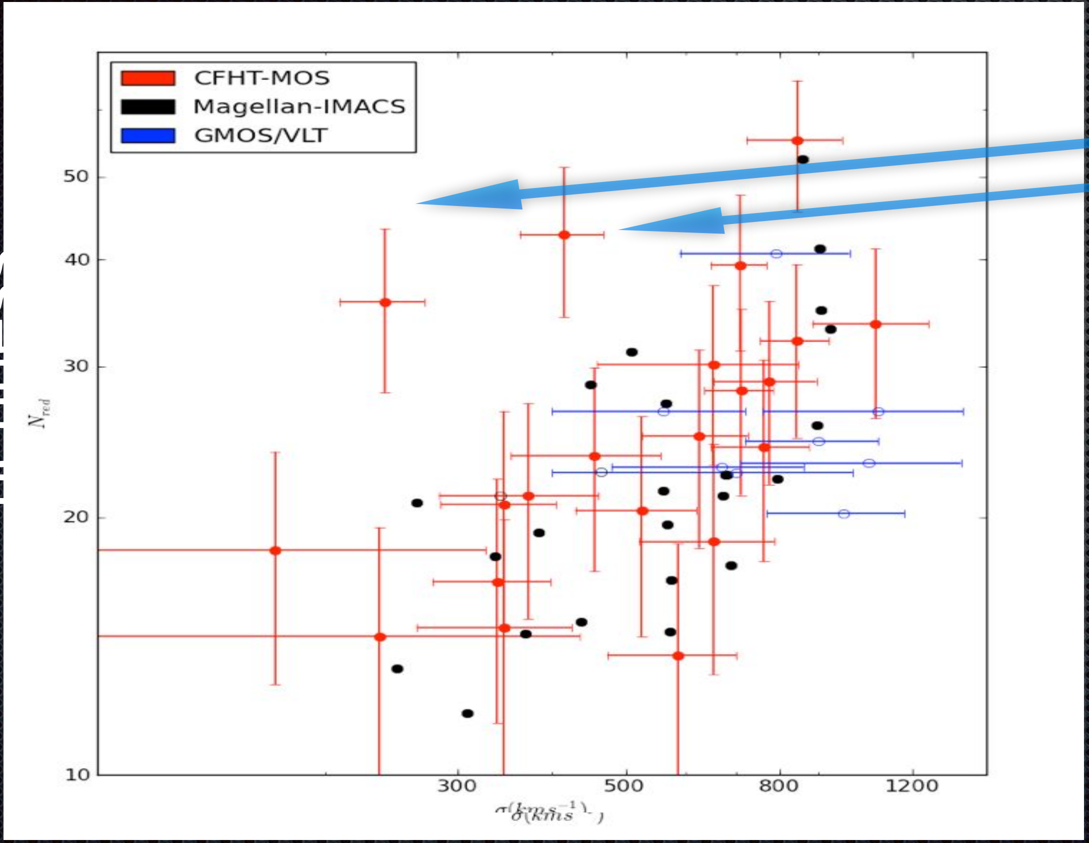
Naive model :

$\sigma \propto N_{red}^{1.89}$

Gilbank et al. in prep,
Ellingson et al. in prep

Mass--Richness Relation

Optical richness

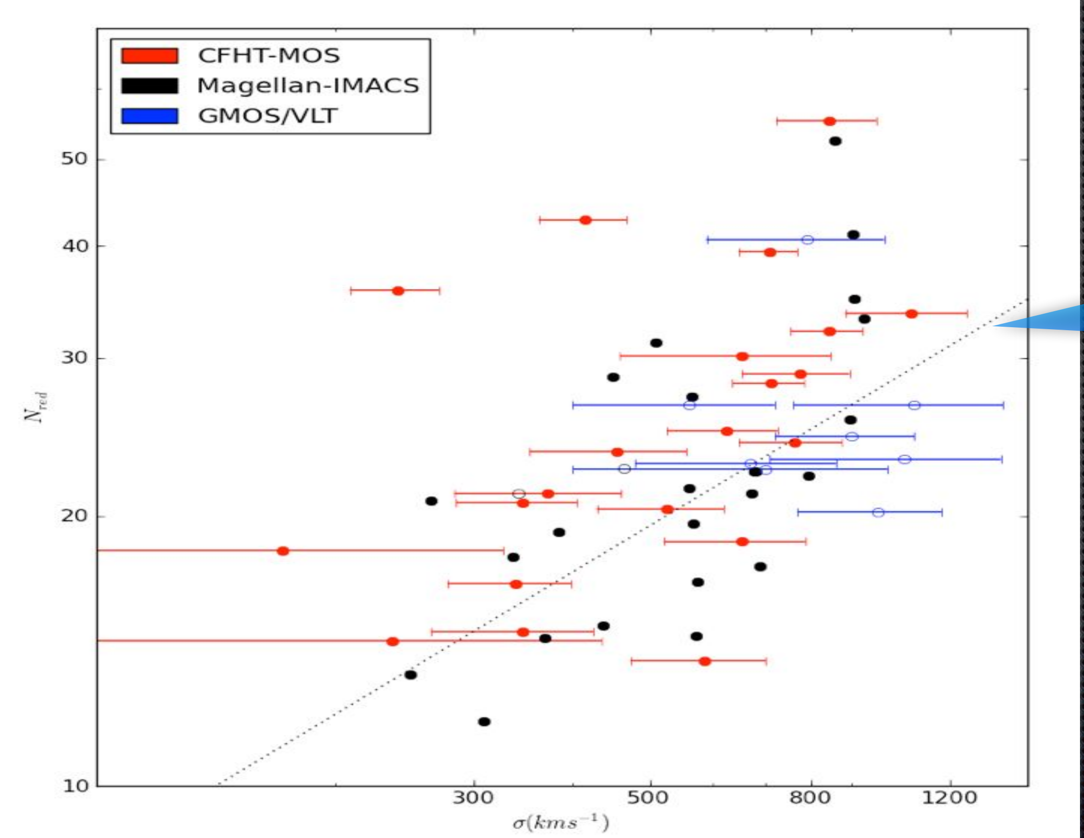


Dynamical Mass

“Fried Eggs”

Gilbank et al. in prep,
Ellingson et al. in prep

Mass--Richness Relation



Optical richness

Dynamical Mass

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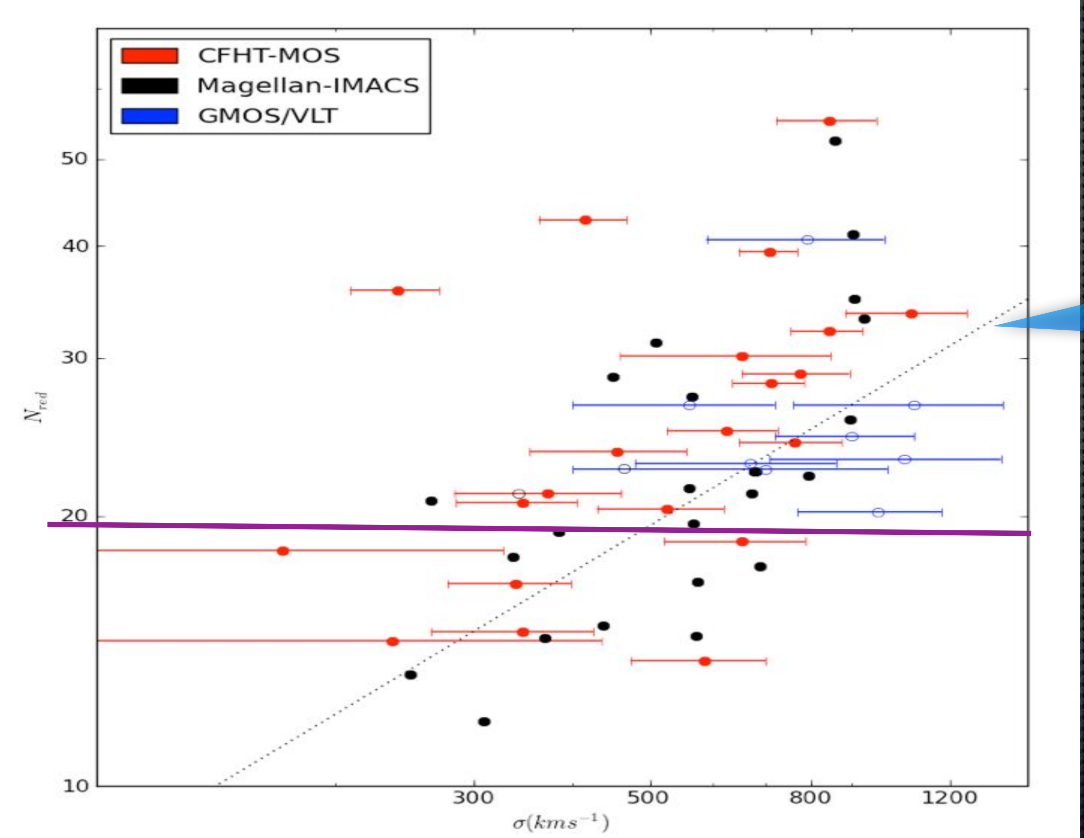

Optical richness

Dynamical Mass

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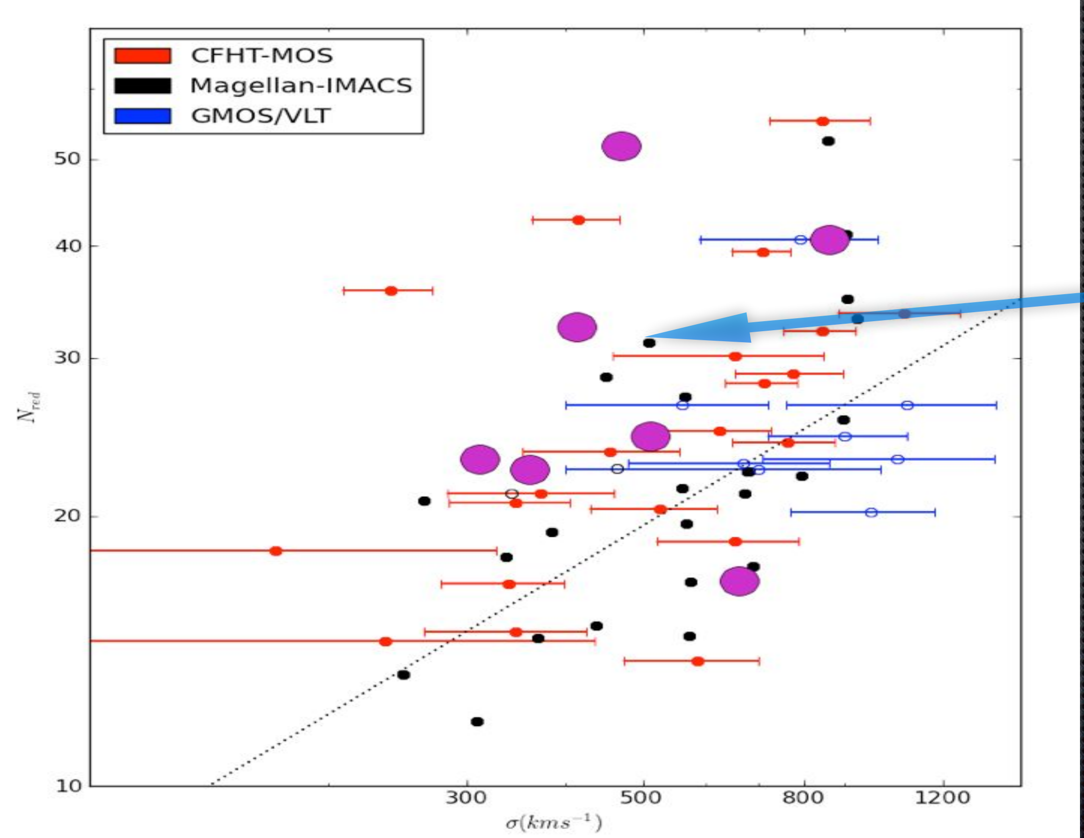
Gilbank et al. in prep,
Ellingson et al. in prep

Mass--Richness Relation

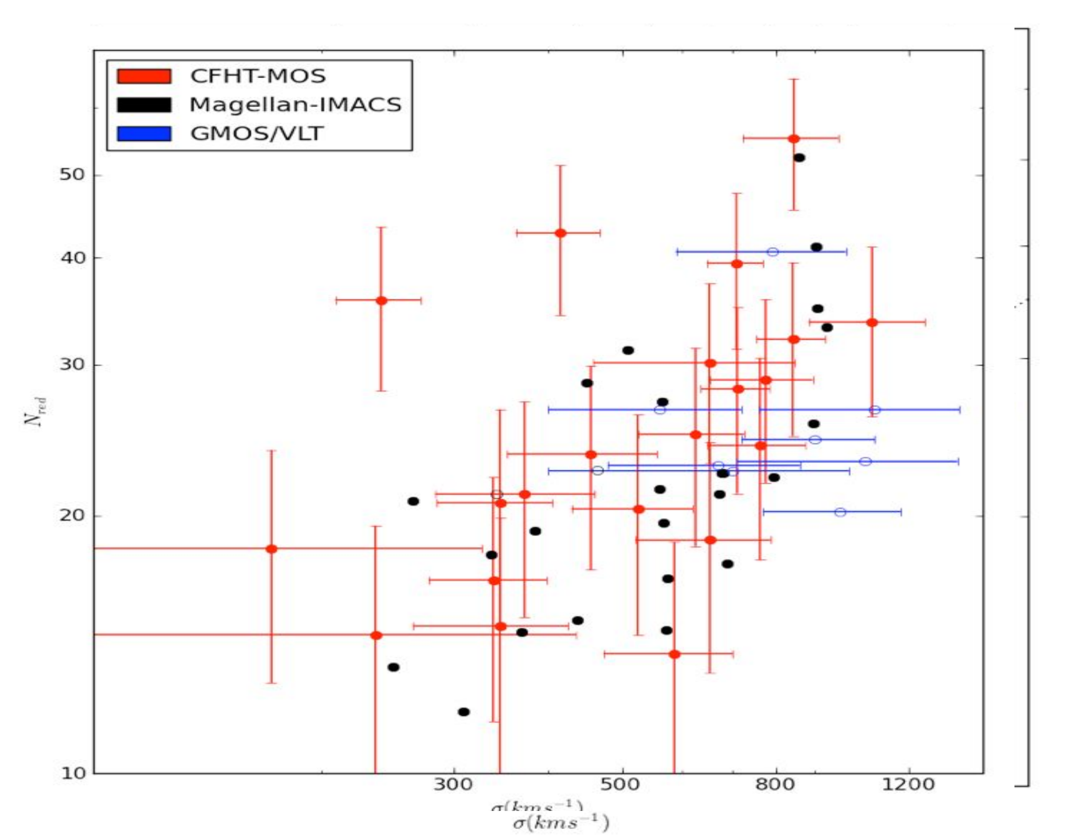


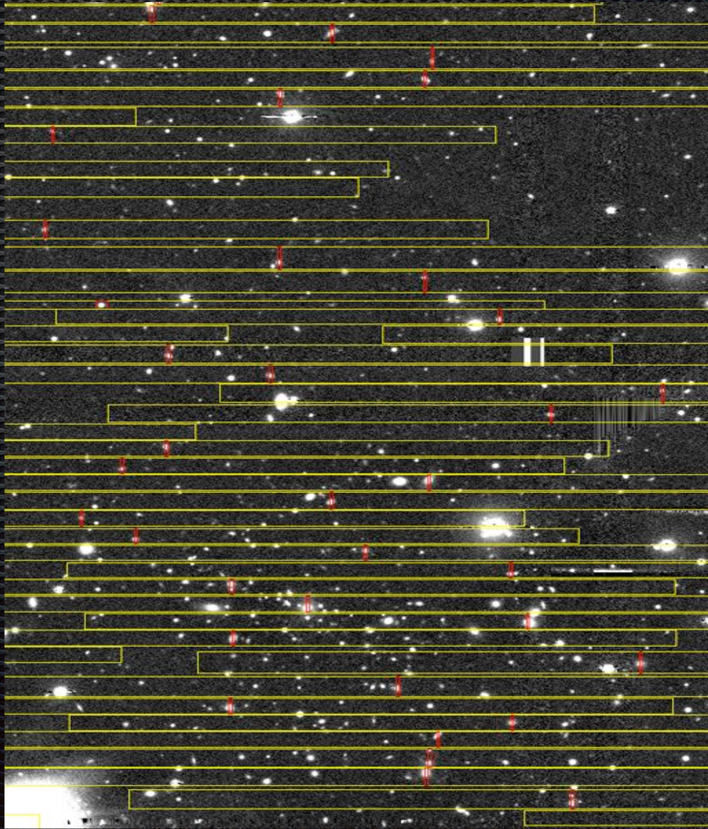
Optical richness

Dynamical Mass

Chandra X-ray masses

Mass--Richness Relation



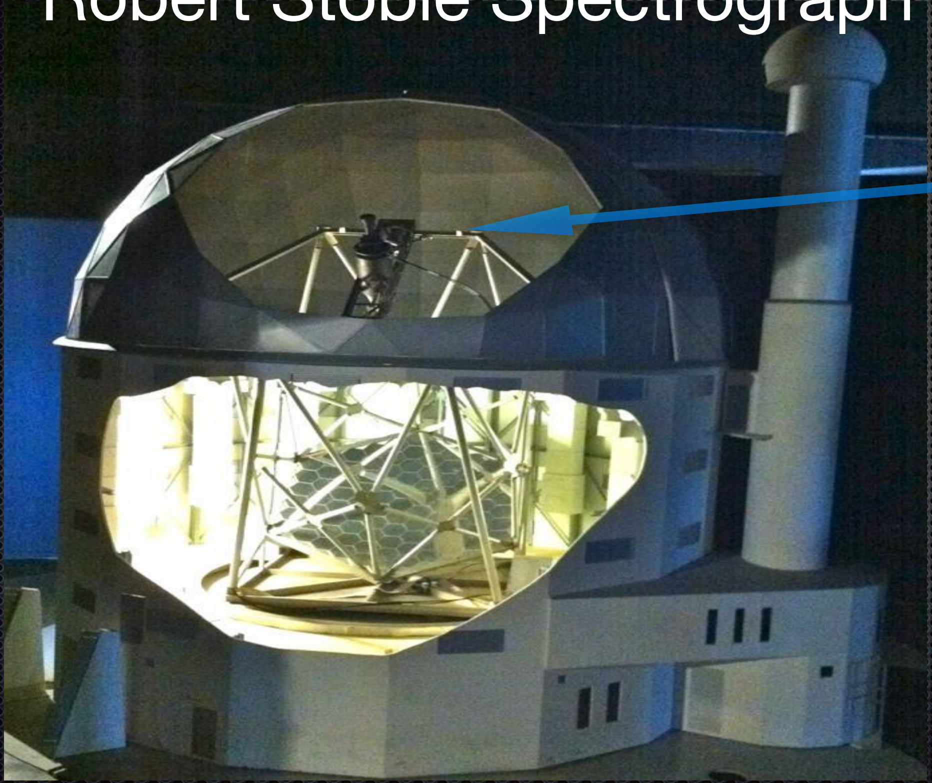


Optical richness

Dynamical Mass

RSS on SALT

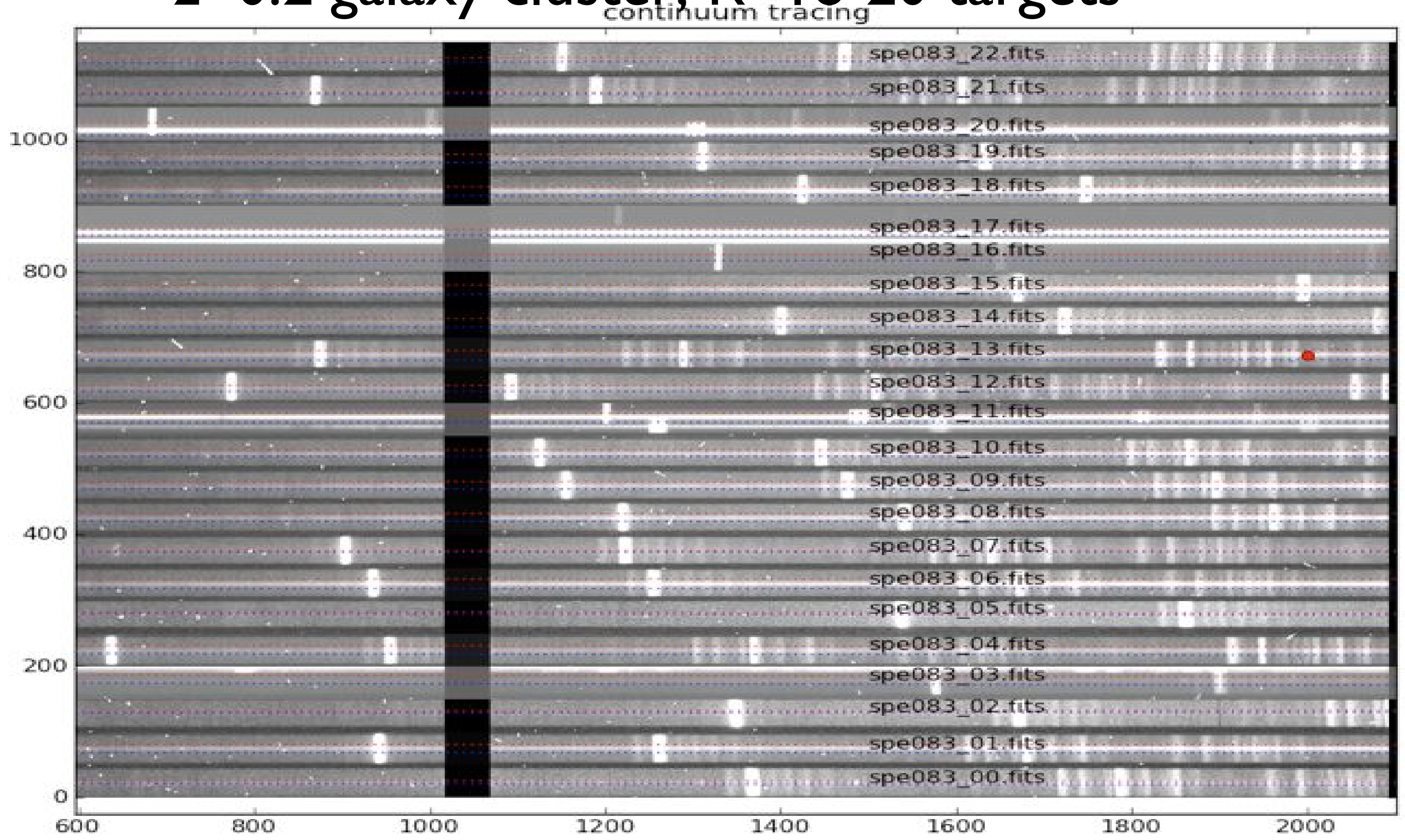
Robert Stobie Spectrograph



First MOS data
March 2012!

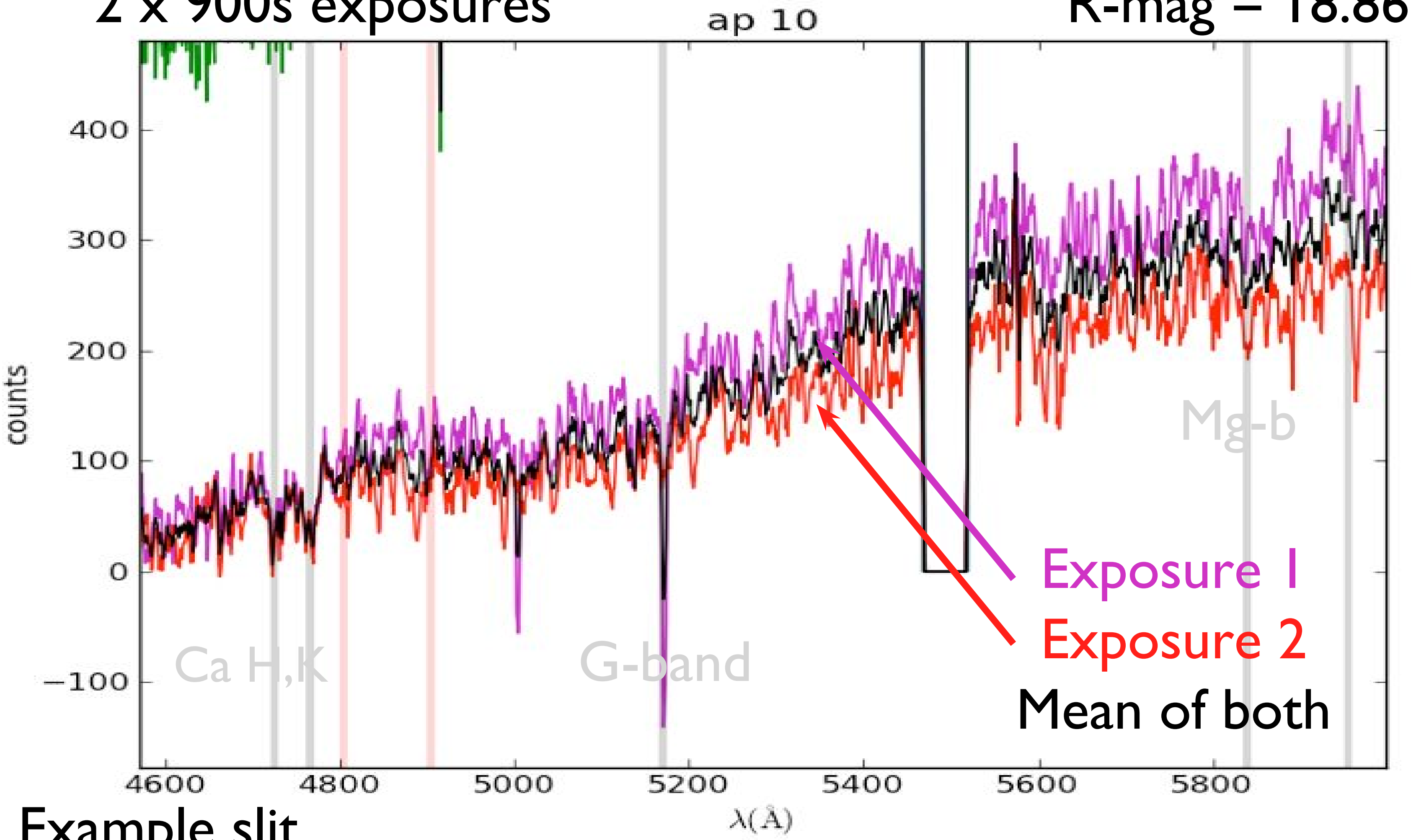
Example MOS mask

z~0.2 galaxy cluster, R~18-20 targets



2 x 900s exposures

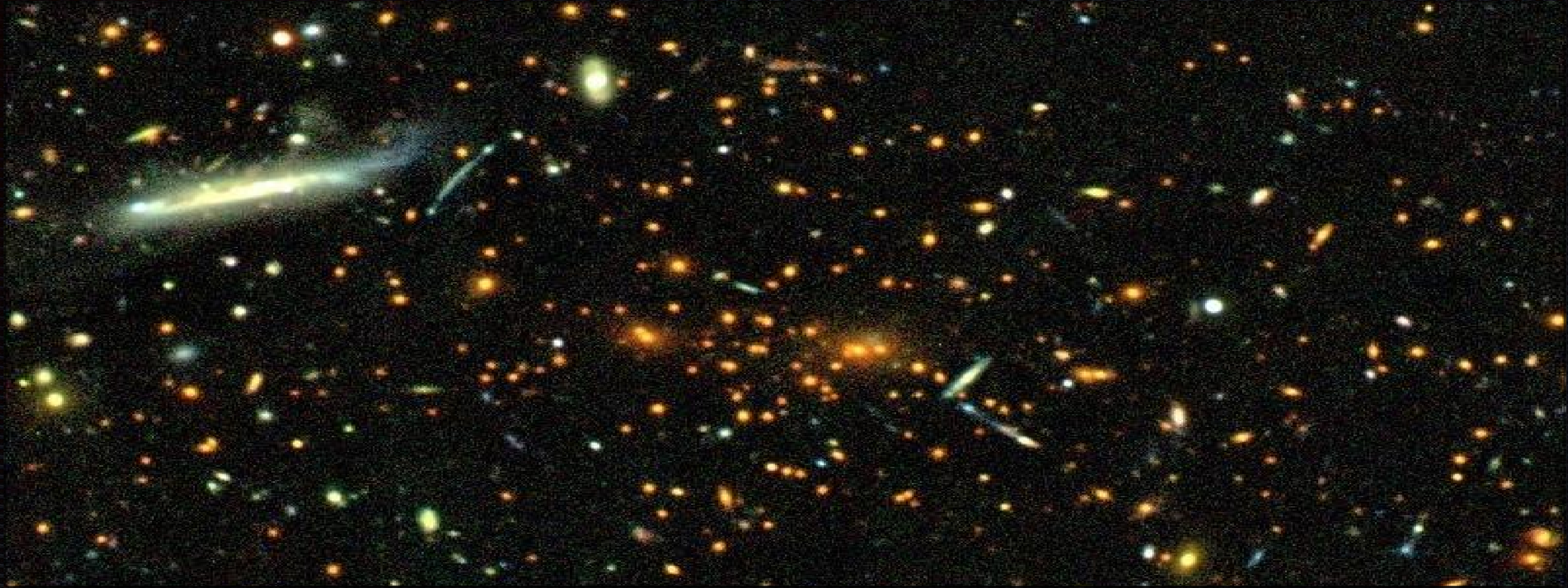
R-mag = 18.86



Example slit

Summary

- **Cosmological parameters** can be measured by counting galaxy clusters
- RCS-2 1000 deg^2 survey, **~10 000 clusters**
    - should be able to measure **w to ±10%** using RCS-2 alone, or ±5% when combined with SNe/CMB
- Calibration of the **mass--richness** observable is essential!
    - Dynamical masses from **optical spectroscopy** is an efficient method



Calibrating Mass Observables for Optical Surveys

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Edo van Uitert, UCL

gilbank@saao.ac.za

NRF National Research Foundation | SAAO South African Astronomical Observatory

van Uitert, Gilbank et al. 2016, A&A, 586, 43

Cosmology with Large Surveys, Durban 2016