Constraining cosmological models with surveys of galaxy clusters

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Excellence Cluster Universe of Munich

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Cosmology with clusters of galaxies

Galaxy clusters as cosmological probes

- Growth tests
- Geometrical tests

Forecasts from future surveys

- The importance of the observable mass calibration
- Combination of power spectrum and number density
- Dark Energy constraints
- Non Gaussian constraints

Cosmological constraints from current cluster surveys

- Massive high-redshift clusters
- High-redshift ($z>0.8$) mass function

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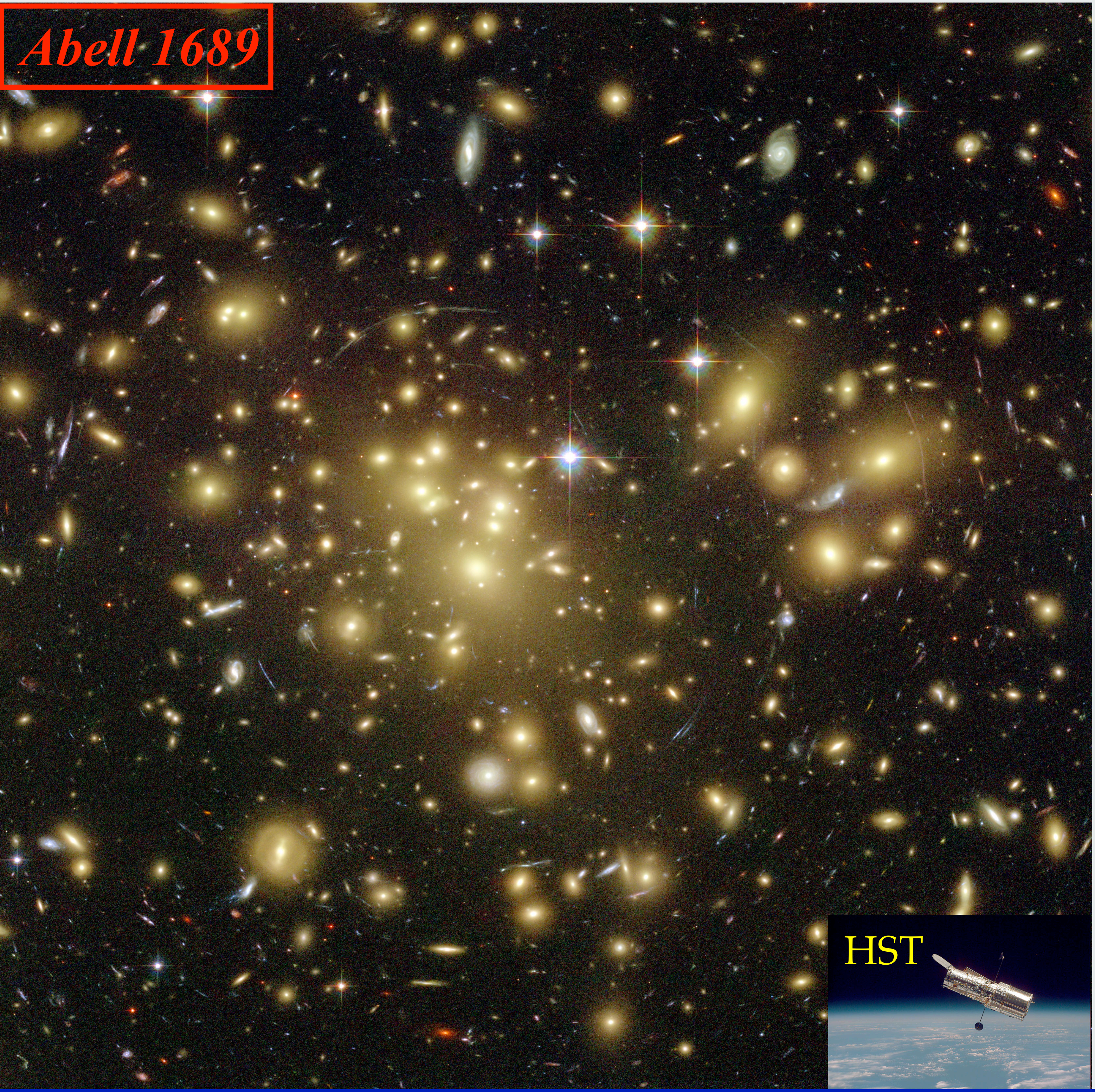
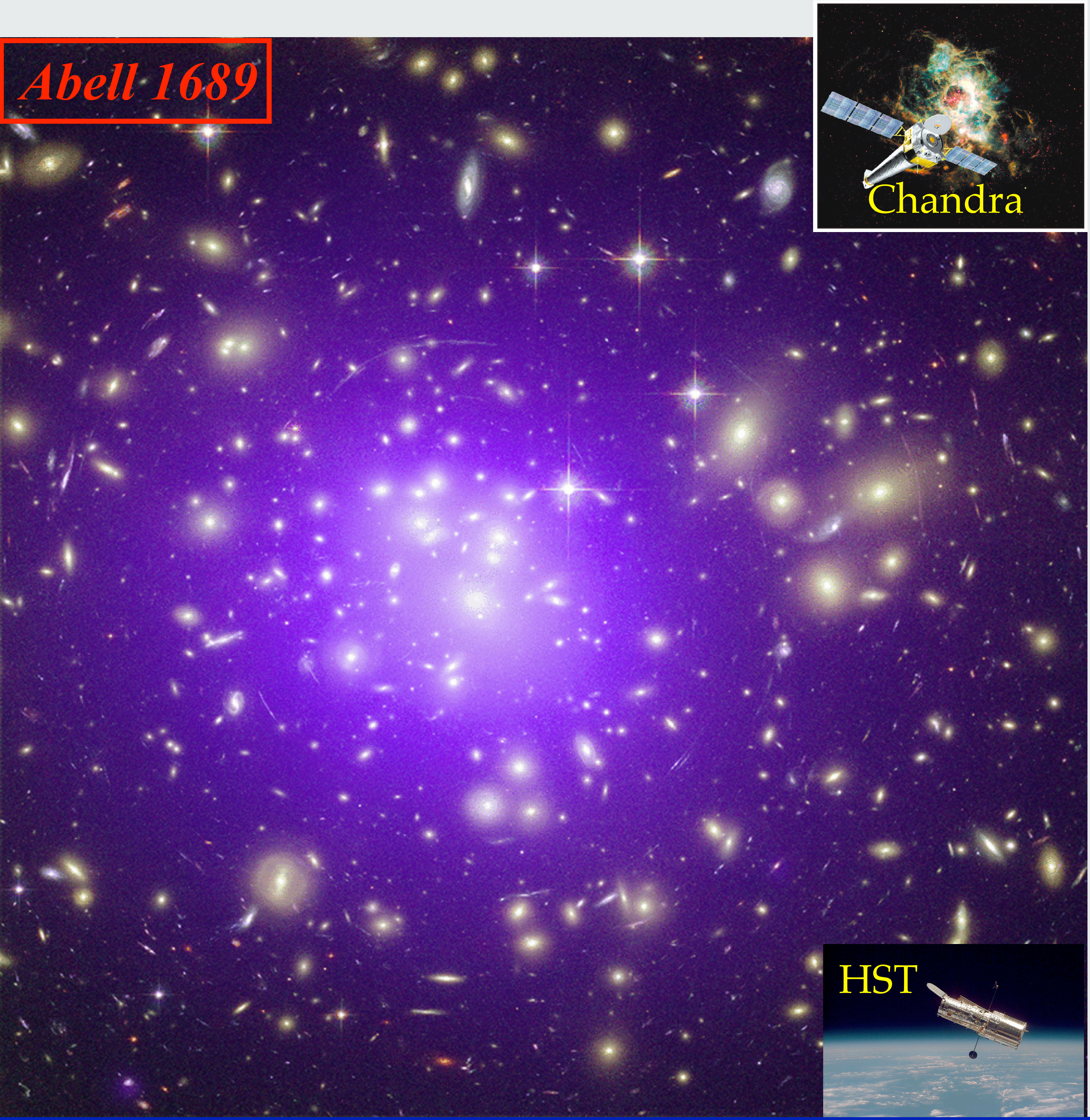


Observing a galaxy cluster

- Concentration of ~103 galaxies
- σ_v~500-1000 km s^{-1}
- Size: ~1-2 Mpc
- Mass: ~10^{14} $M_\odot$



Observing a galaxy cluster

- Concentration of
  ~103 galaxies

- σ_v~500-1000 km s^{-1}

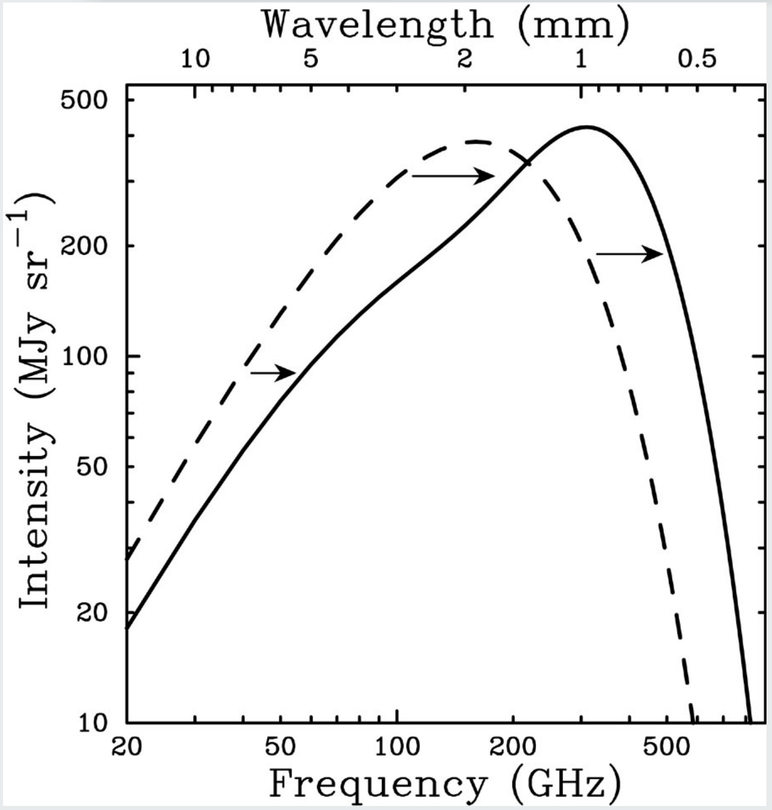
- Size: ~1-2 Mpc

- Mass: ~10^{14} $M_\odot$

- ICM temperature:
  T_X ~ 2-10 keV
  fully ionized plasma;

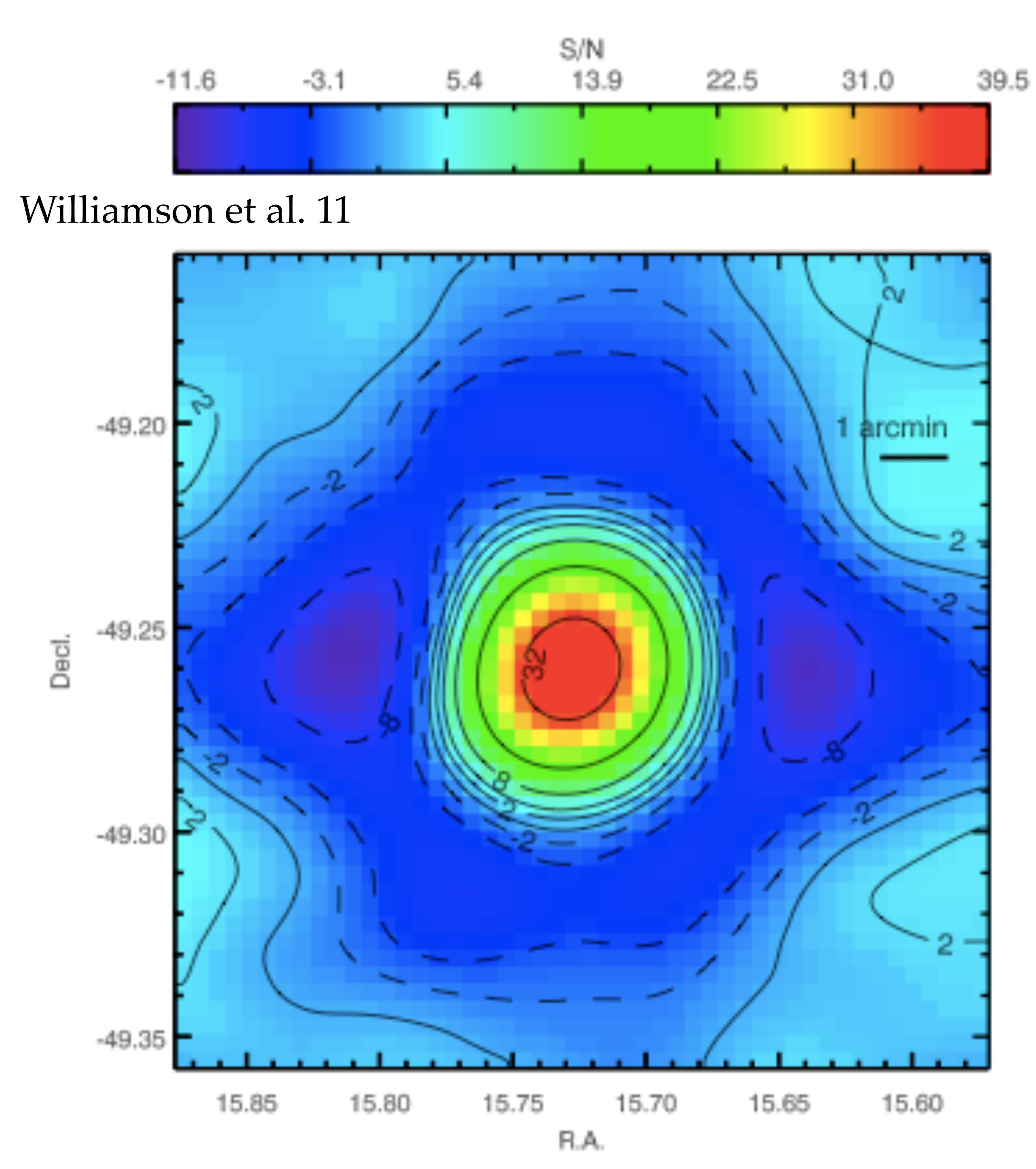
- Therm bremsstrahlung:
  n_e~10^{-2}-10^{-4} cm^{-3}
  L_X~10^{45} erg s^{-1}

Observations of the Sunyaev-Zeldovich Effect



Inverse Compton scattering of CMB photons off the ICM electrons

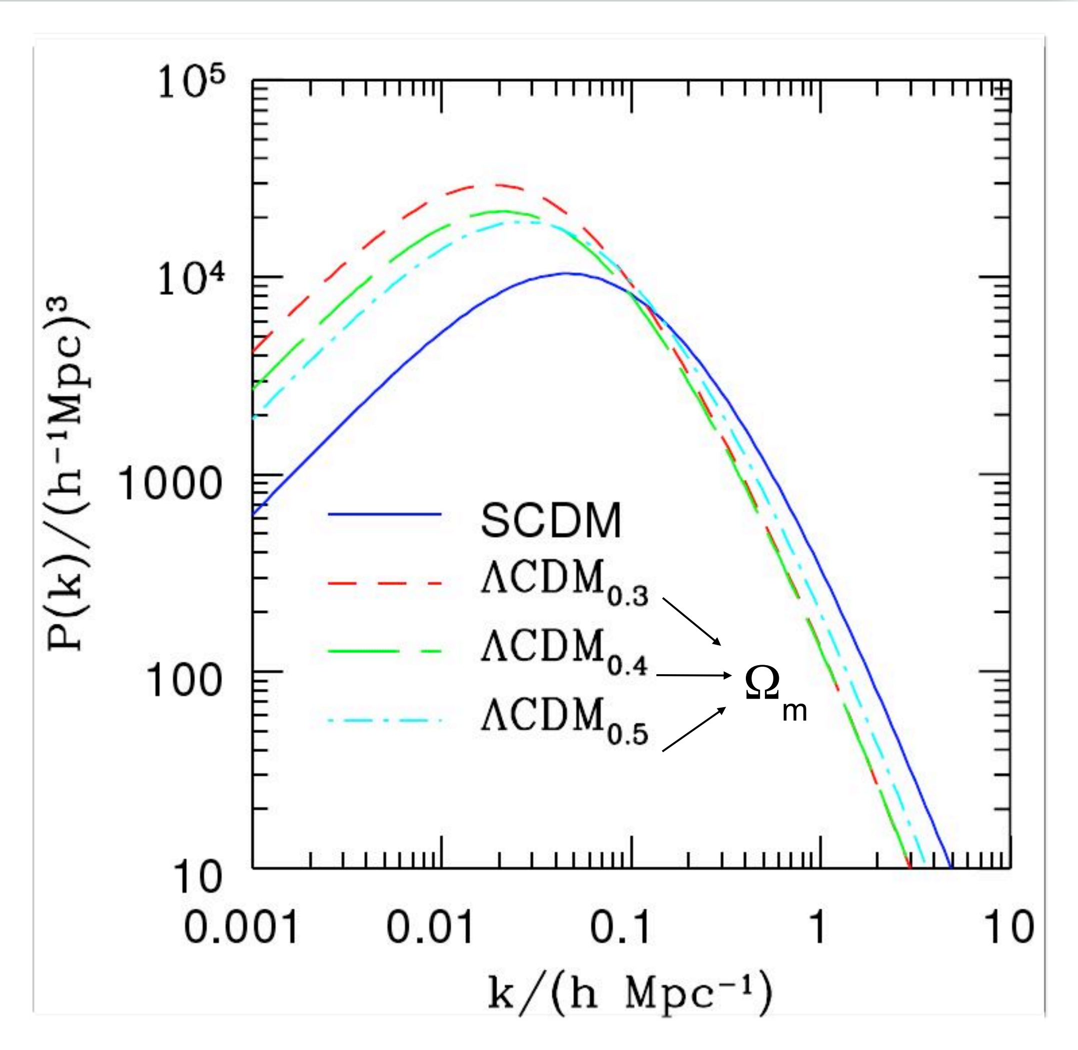
SPT cluster z=0.78



- Signal virtually independent of redshift.
- Proportional to the l.o.s. integration of $n_e T_e$ ~ pressure
- Survey for cluster detection are now producing results (e.g. ACT, SPT, Planck).

Constrain cosmological parameters with power spectrum

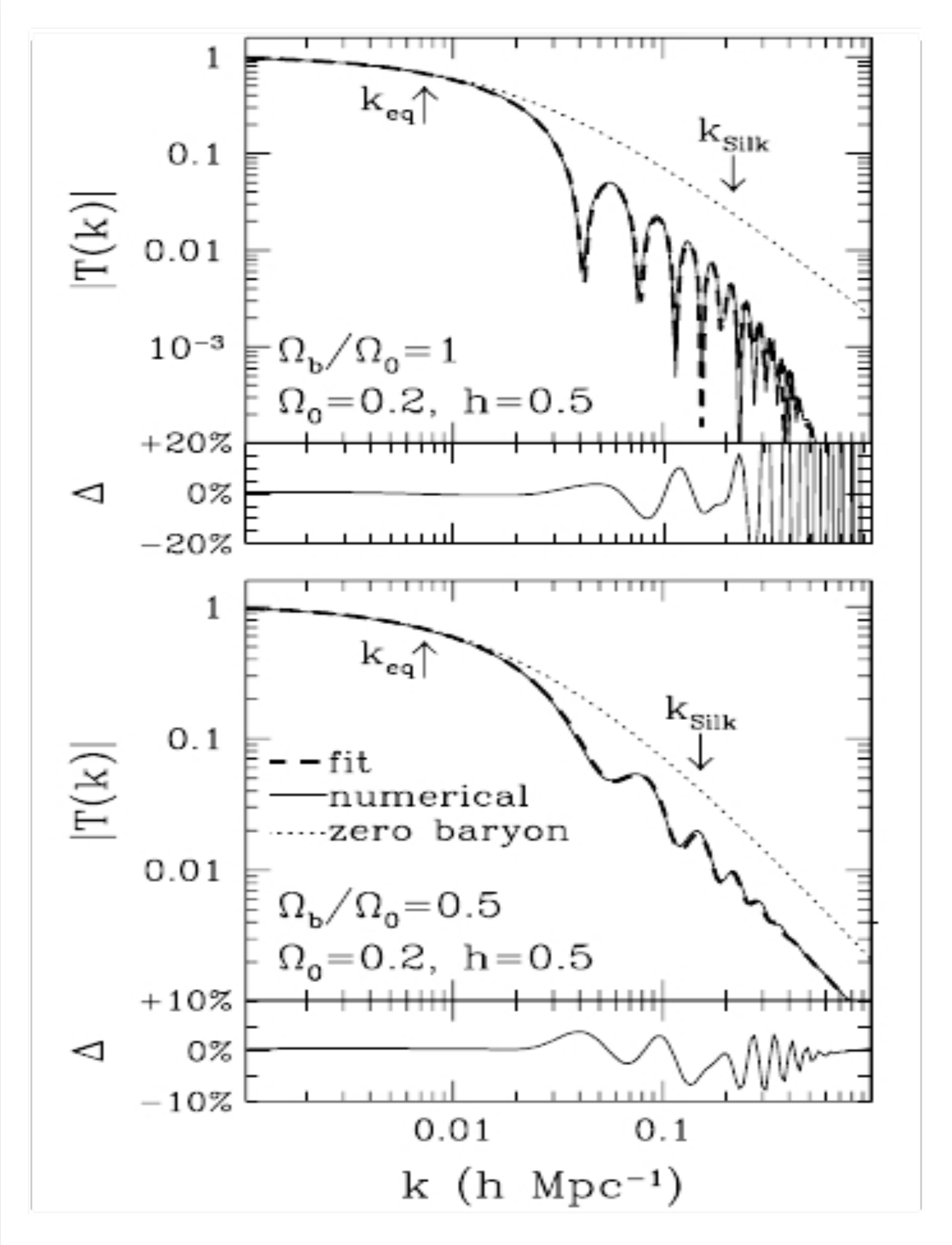
Power spectrum shape



$$P(k,z) = T^2(k)\,D^2(z)\,P_{in}(k)$$

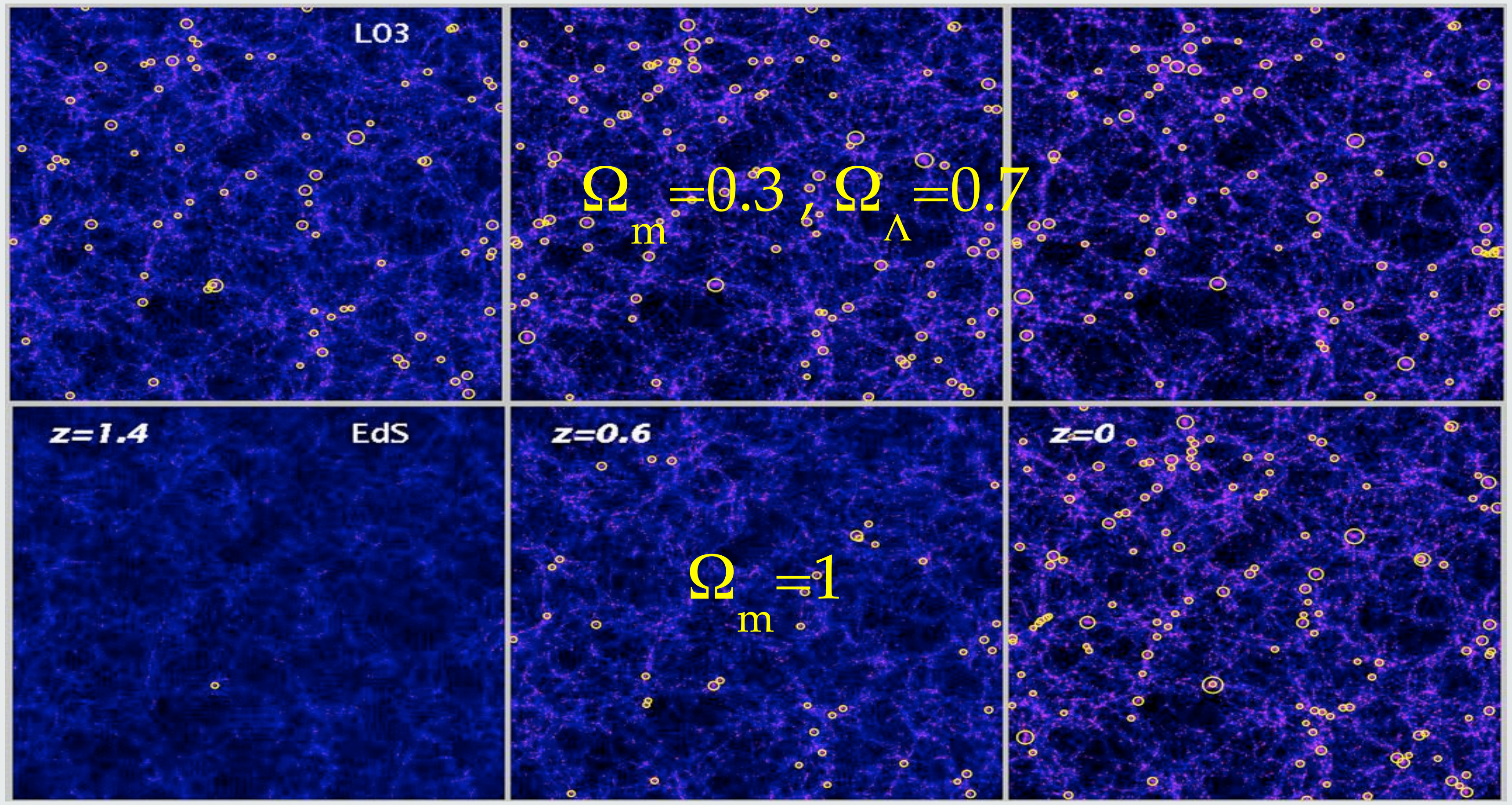
Borgani et al 1997

Barionic Acoustic Oscillations

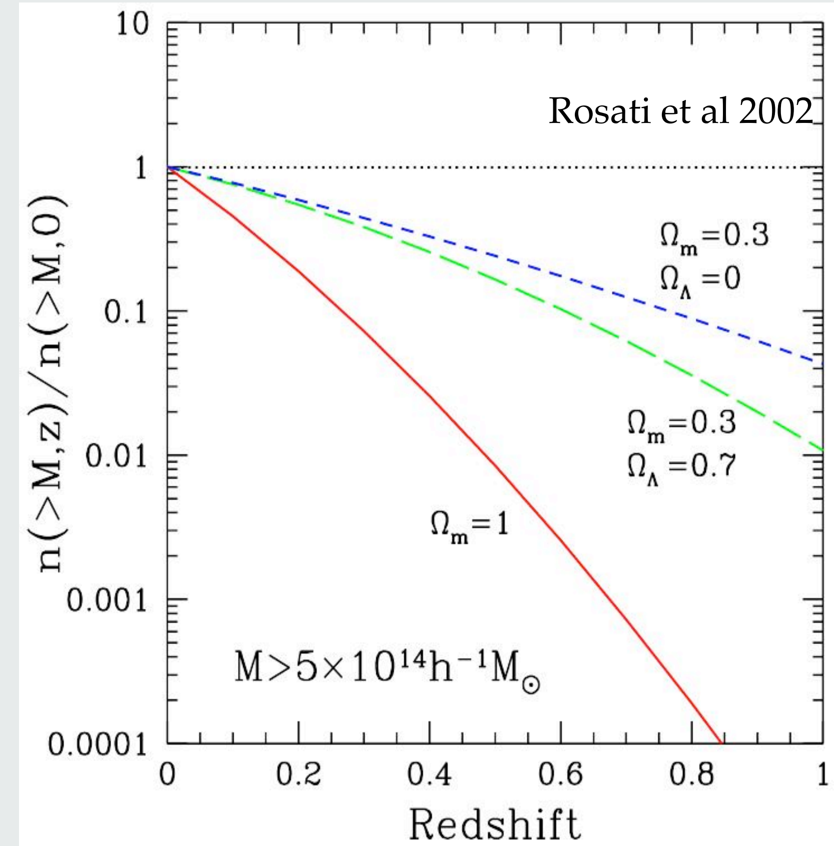


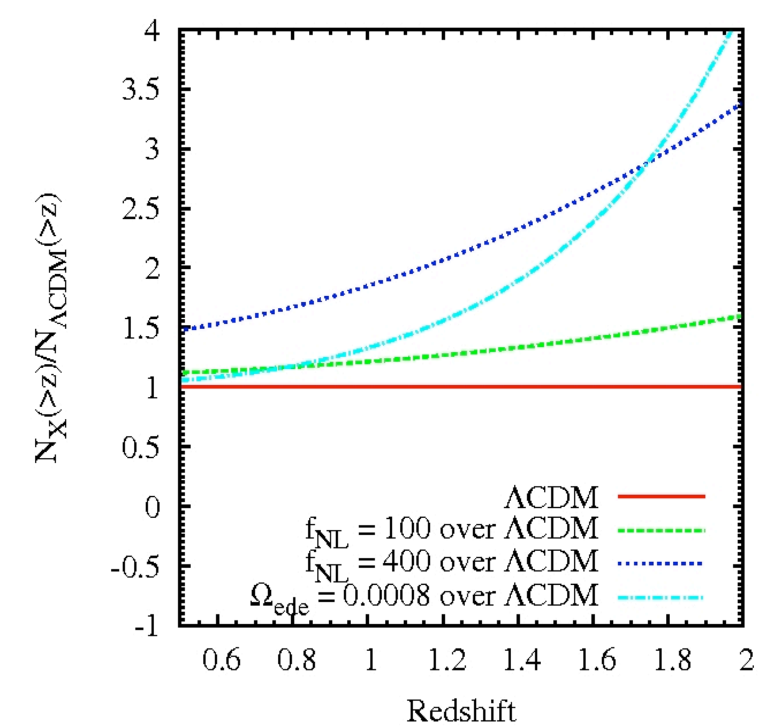
Eisenstein & Hu 1998

Constrain cosmological parameters with clusters number density



Borgani&Guzzo 2001





$$N_{l,m} = \Delta\Omega \int_{z_l}^{z_{l+1}} dz \, \frac{dV}{dz d\Omega} \int_{M^{ob}_{l,m}}^{M^{ob}_{l,m+1}} dM^{ob} \int_0^\infty dM \, n(M,z) \; p(M^{ob}||M) \, .$$

Cosmological information from cluster number density

$$\frac{dN(X;z)}{dXdz}$$

Number of clusters of given observable X and redshift z within the survey area

- Friedmann background: $\frac{dV}{dz}$

Priors on cosmological parameters Ω_i from CMB, SnIa, ….

- Growth history: $\frac{dn(M,z,\Omega_i)}{dM}$

Calibrated with N-body simulations

- Astrophysics: $\frac{dM}{dX}$

Priors on “mass parameters” p_j from follow-up observations and/or cosmological simulations

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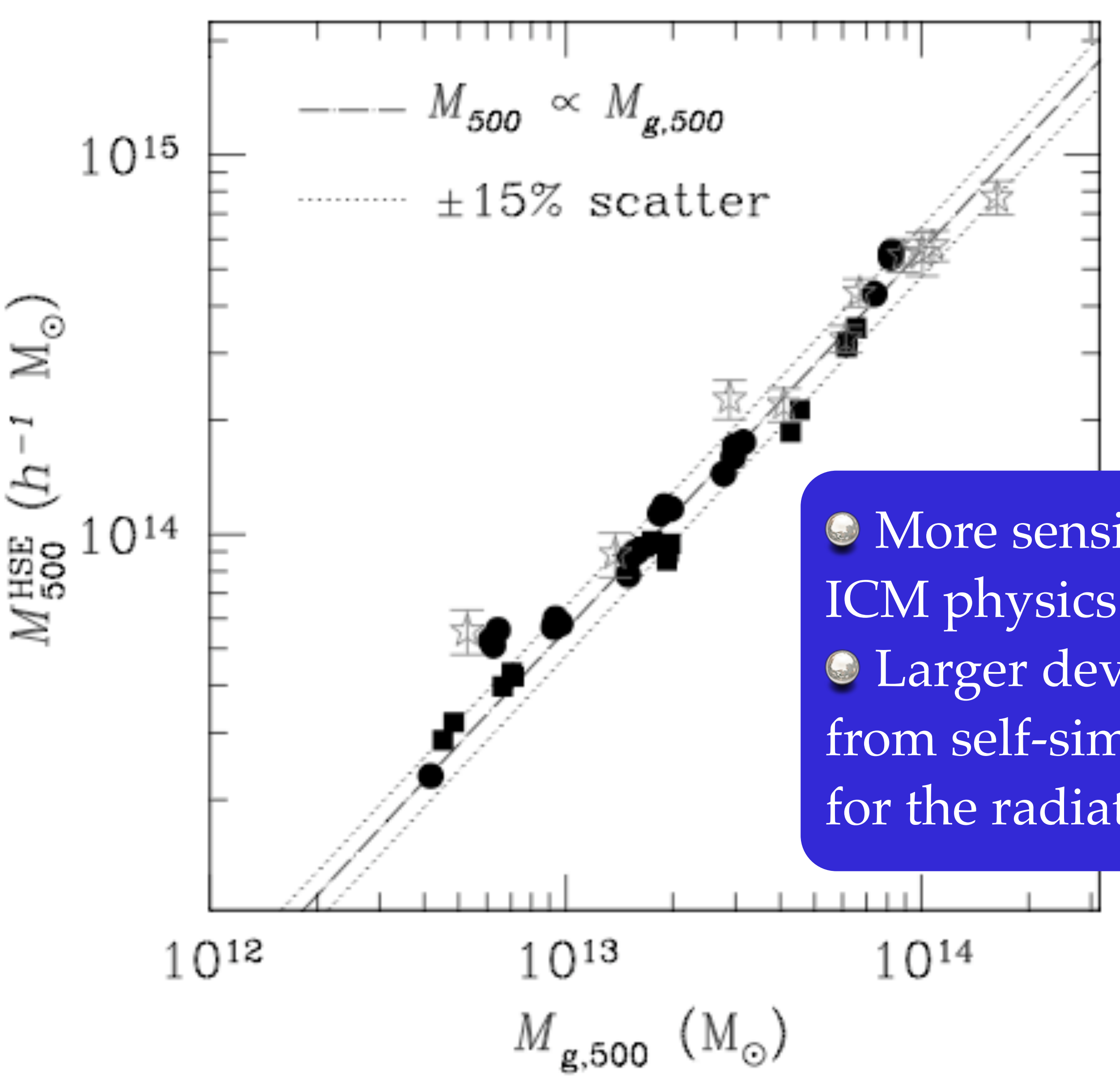
Observable - mass relations

Self-similar Gas-Cluster Mass relation from simulations



Nagai, Kravtsov & Vikhlinin 2007

- More sensitive to ICM physics
- Larger deviations from self-similar slope for the radiative runs

<u>Assumptions:</u>

• ICM evolves in gravitational potential of DM:

$$f_{\rm gas} = \frac{M_{\rm gas}}{M_{200}}$$

• ICM is hydrostatic equilibrium → Virial Theorem

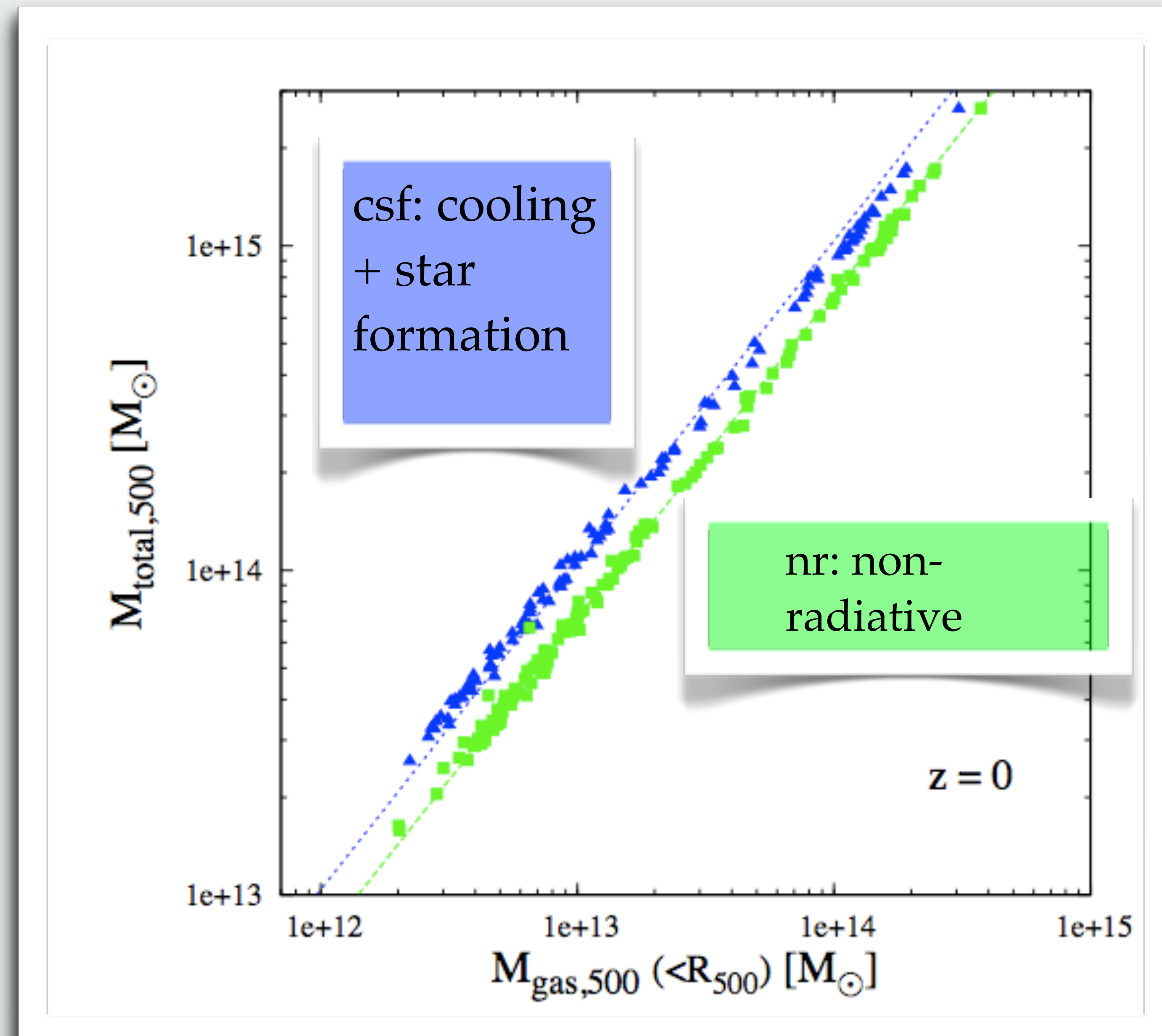
$$M_{200} \propto h^{-1}(z) T^{3/2}$$

• bremsstrahlung emission

$$L_X \propto h(z) T^2$$

Observable - mass relations

Self-similar Gas-Cluster Mass relation from simulations



Fabjan et al 2011

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e runs

Assumptions:

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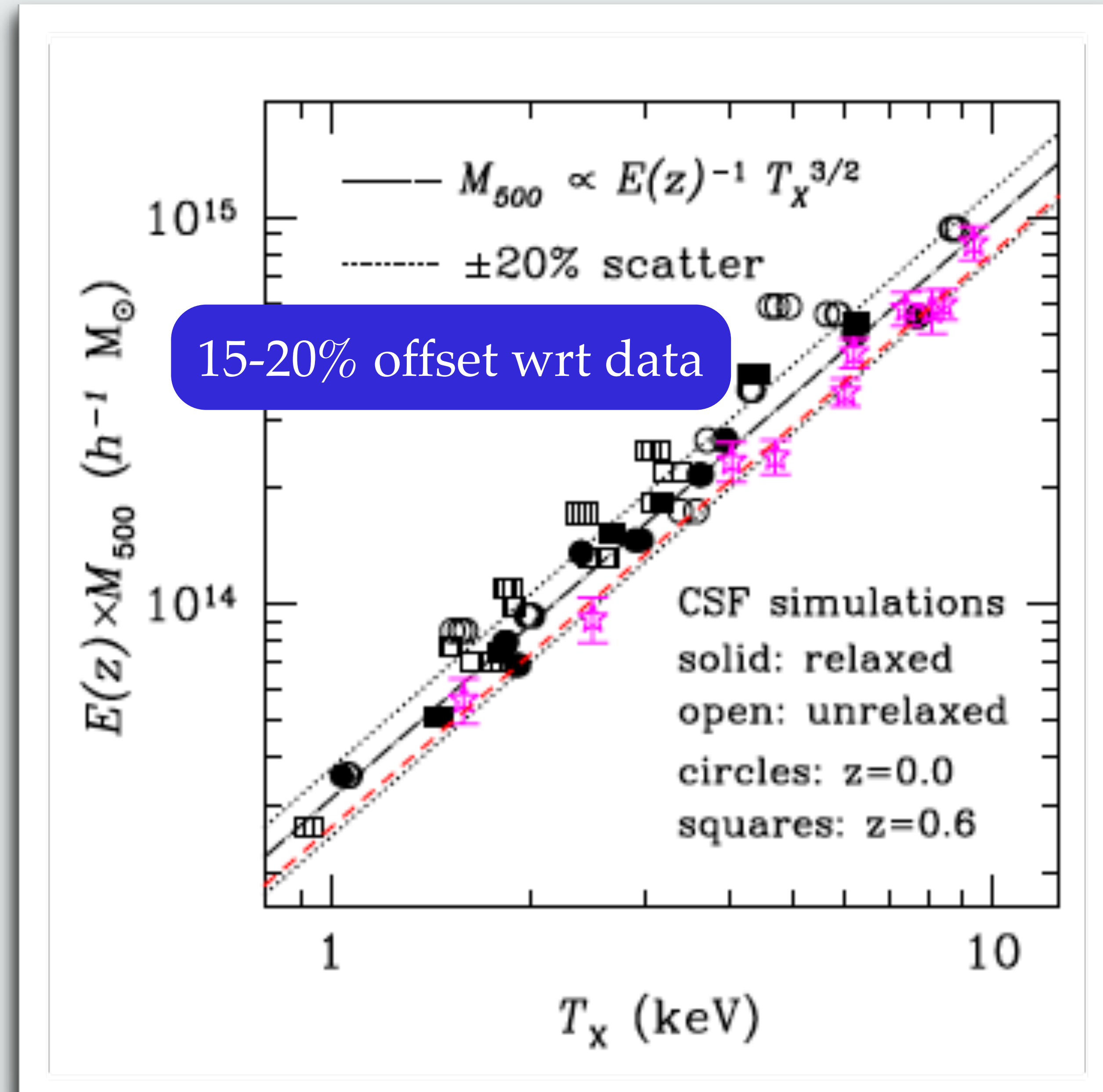
$$M_{200} \propto h^{-1}(z) T^{3/2}$$

- bremsstrahlung emission

$$L_X \propto h(z) T^2$$

Observable - mass relations

Self-similar Mass-Temperature relation from simulations



15-20% offset wrt data

Nagai, Kravtsov & Vikhlinin 2007

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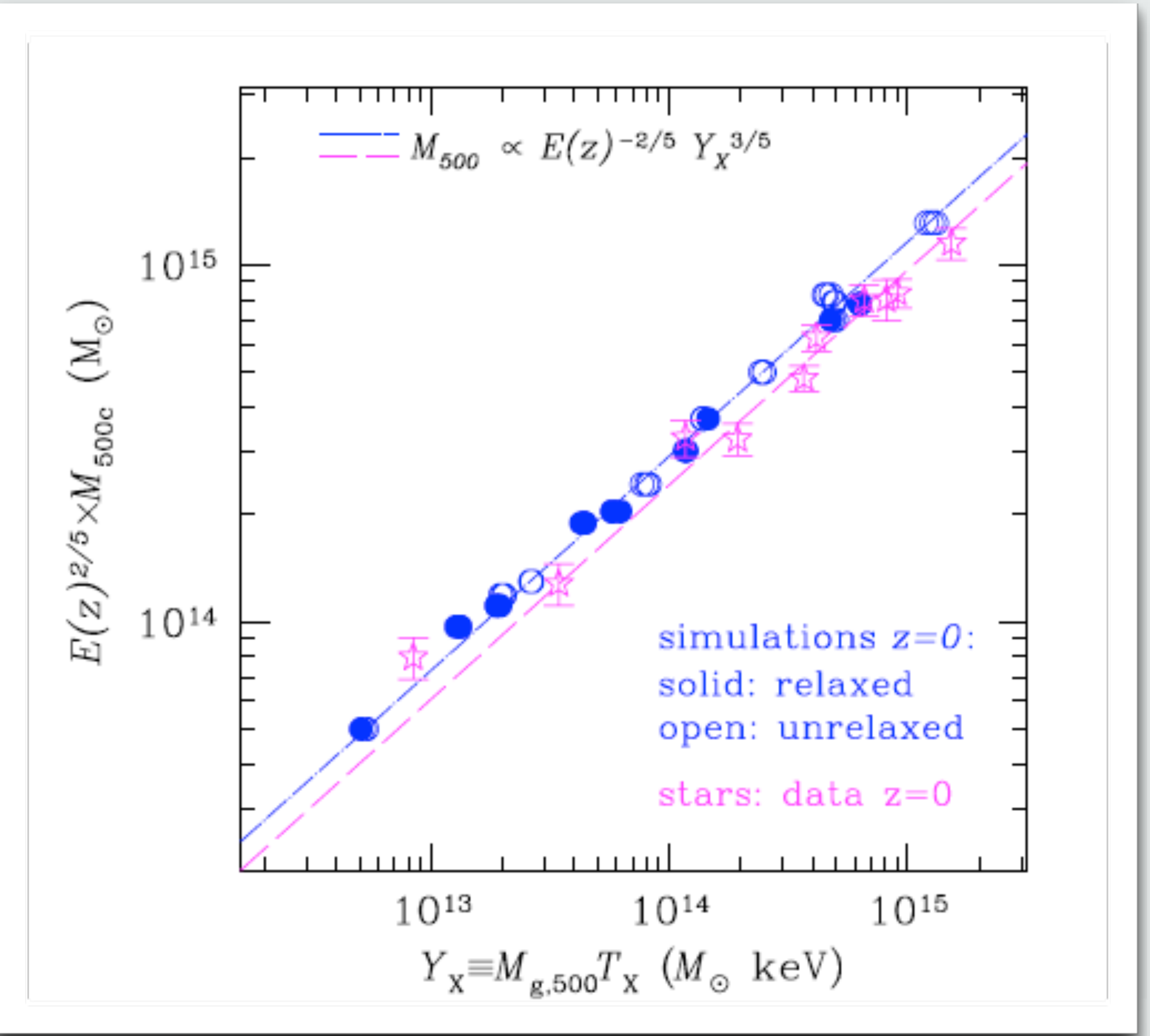
Observable - mass relations

Self-similar Mass-Y_X relation from simulations



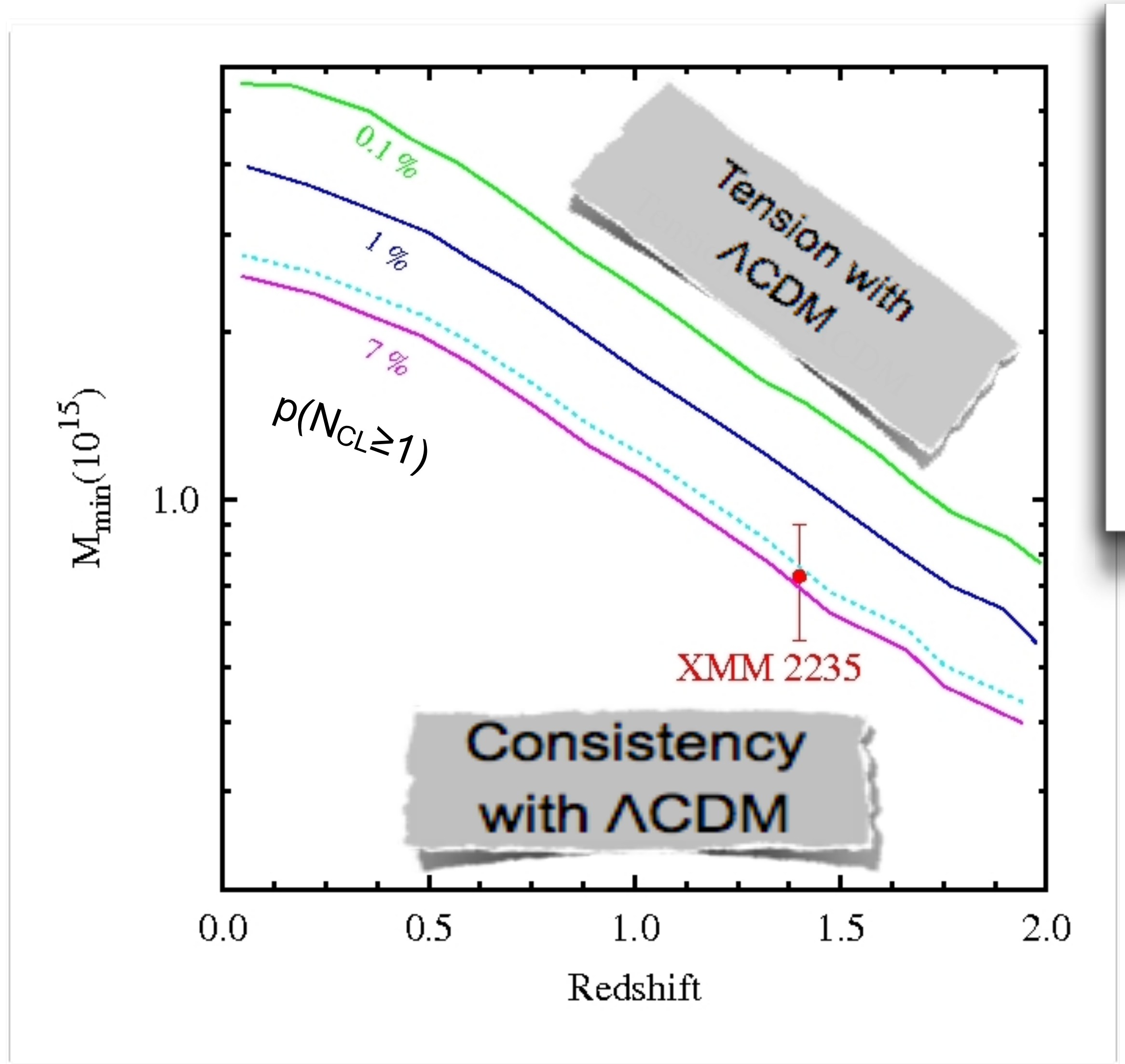
X-ray "pressure":

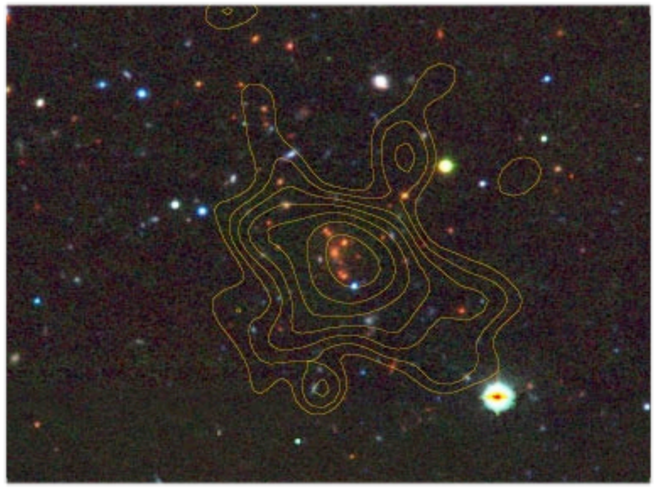
$Y_X = M_{gas} T_X$

- Similar to Compton-y from SZ observations.
- Weaker sensitivity to ICM physics
- Always close to self-similar prediction
- Very small intrinsic scatter: ~ 5-7 % !
- About 15 % offset wrt Chandra results.

Kravtsov, Nagai & Vikhlinin '06

The most massive distant clusters in the Universe and their impact on Cosmology





XMMU-J2235.3 cluster (Jee et al. 2009) z~1.4

Probability of finding at least one cluster with a given redshift and mass

XDCP (50 deg^2 to 10^{-14} erg/cm^2/s)

$M_L = 7.3 \pm 1.7 \times 10^{14} M_\odot / h_{70}$

Accurate (<10% errors) $M_{200,c}$ measurements needed

Sartoris et al. 2012 (in prep)

Parameters defining the mass - observable realtions

number density of cluster

$$N_{l,m} = \Delta\Omega \int_{z_l}^{z_{l+1}} dz \frac{dV}{dz d\Omega} \int_{M_{l,m}^{ob}}^{M_{l,m+1}^{ob}} dM^{ob} \int_0^\infty dM\, n(M,z)\, p(M^{ob}||M)\,.$$

Probability of assigning a mass M_{obs} to a cluster of "true" mass M:

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

$$x(M_{ob}) = \frac{\ln M_{ob} - B_M - \ln M}{(2\sigma^2_{\ln M})^{1/2}}$$

B_M: intrinsic bias in mass estimates (e.g. violation of hydrostatic equilibrium)

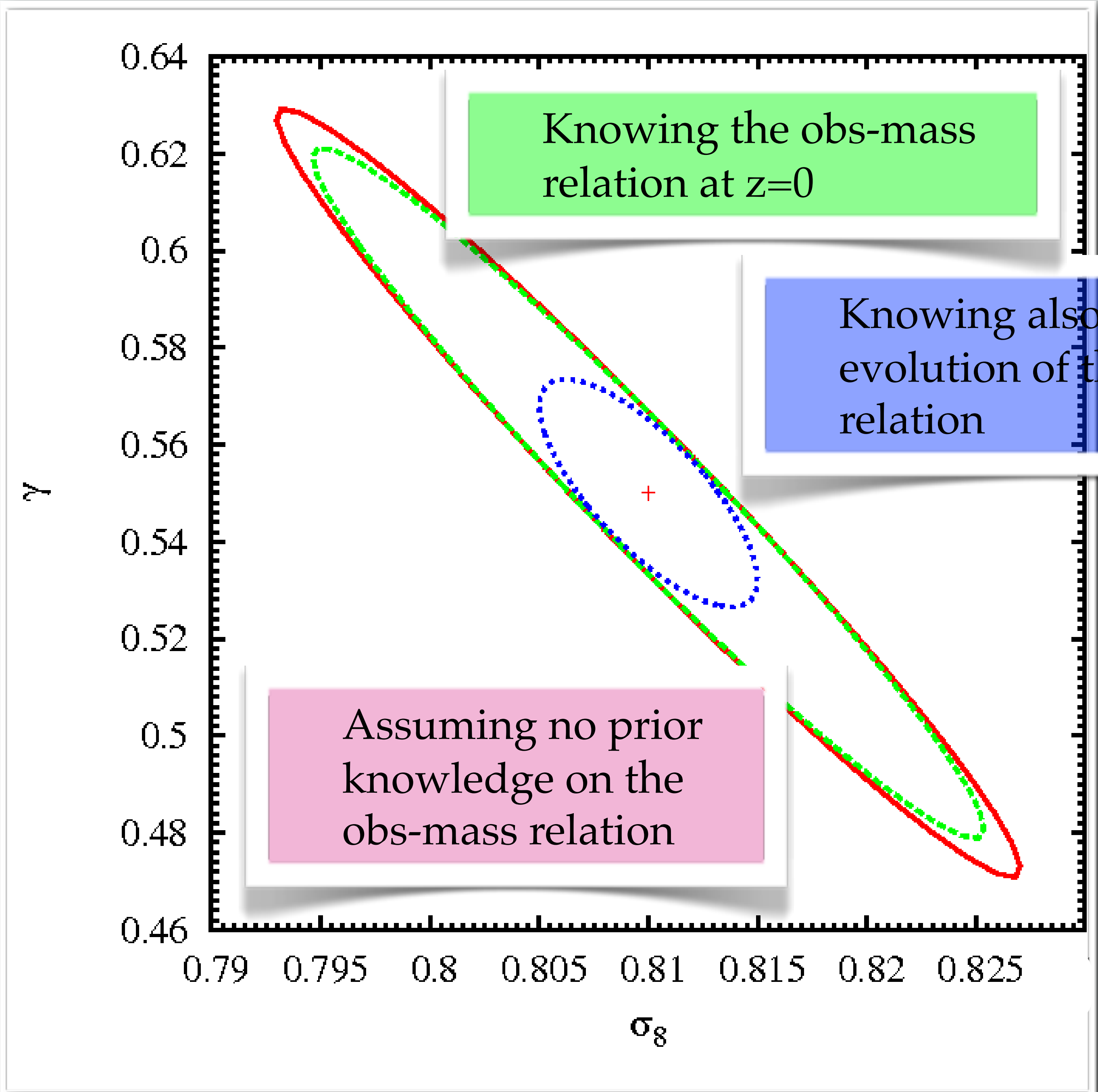
$$B_M(z) = B_{M,0}(1+z)^\alpha$$
$$\sigma_{\ln M}(z) = \sigma_{\ln M,0}(1+z)^\beta$$

4 "mass-parameters" : $B_{M,0}$, α, $\sigma_{\ln M,0}$, β

Majumdar & Mohr 03,04; Lima & Hu 04,05;

Sartoris et al. 2010 MNRAS 407,2339

Constraints on cosmological parameters
Importance of mass accuracy



- Parameterize deviations from GR with:

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

$\gamma=0.55$: standard GR

$\gamma=0.68$: DGP brane-world model

- Freeze expansion to ΛCDM and constrain dynamics: σ_8 and γ (Ω_m marginalized)

$$\begin{aligned} B_M(z) &= B_{M,0}(1+z)^\alpha \\ \sigma_{\ln M}(z) &= \sigma_{\ln M,0}(1+z)^\beta \end{aligned}$$

The Fisher Matrix method

Fisher matrix:

$$F_{ij} \equiv - < \frac{\partial^2 \ln \mathcal{L}}{\partial p_i \partial p_j} >$$

$$F^N_{\alpha\beta} = \sum_{l,m} \frac{\partial N_{l,m}}{\partial p_\alpha} \frac{\partial N_{l,m}}{\partial p_\beta} \frac{1}{N_{l,m}}$$

+

$$F_{\alpha\beta} = \frac{1}{8\pi^2} \sum_{l,m,i} \frac{\partial \ln \bar{P}_{cl}(\mu_i, k_m, z_l)}{\partial p_\alpha} \frac{\partial \ln \bar{P}_{cl}(\mu_i, k_m, z_l)}{\partial p_\beta} V^{eff}_{l,m,i} k^2_m \Delta k \Delta \mu$$

number density of cluster

cluster power spectrum

$$N_{l,m} = \Delta\Omega \int_{z_l}^{z_{l+1}} dz \frac{dV}{dz d\Omega} \int_{M^{ob}_{l,m}}^{M^{ob}_{l,m+1}} dM^{ob} \int_0^\infty dM\, n(M, z)\; p(M^{ob} || M) \,.$$

$$\bar{P}^{cl}_{l,m,i}(\mu, k, z_l) = \frac{\int_{z_l}^{z_{l+1}} dz \frac{dV}{dz} N^2(z)\, \tilde{P}_{damp}(\mu, k, z)}{\int_{z_l}^{z_{l+1}} dz \frac{dV}{dz} N^2(z)}$$

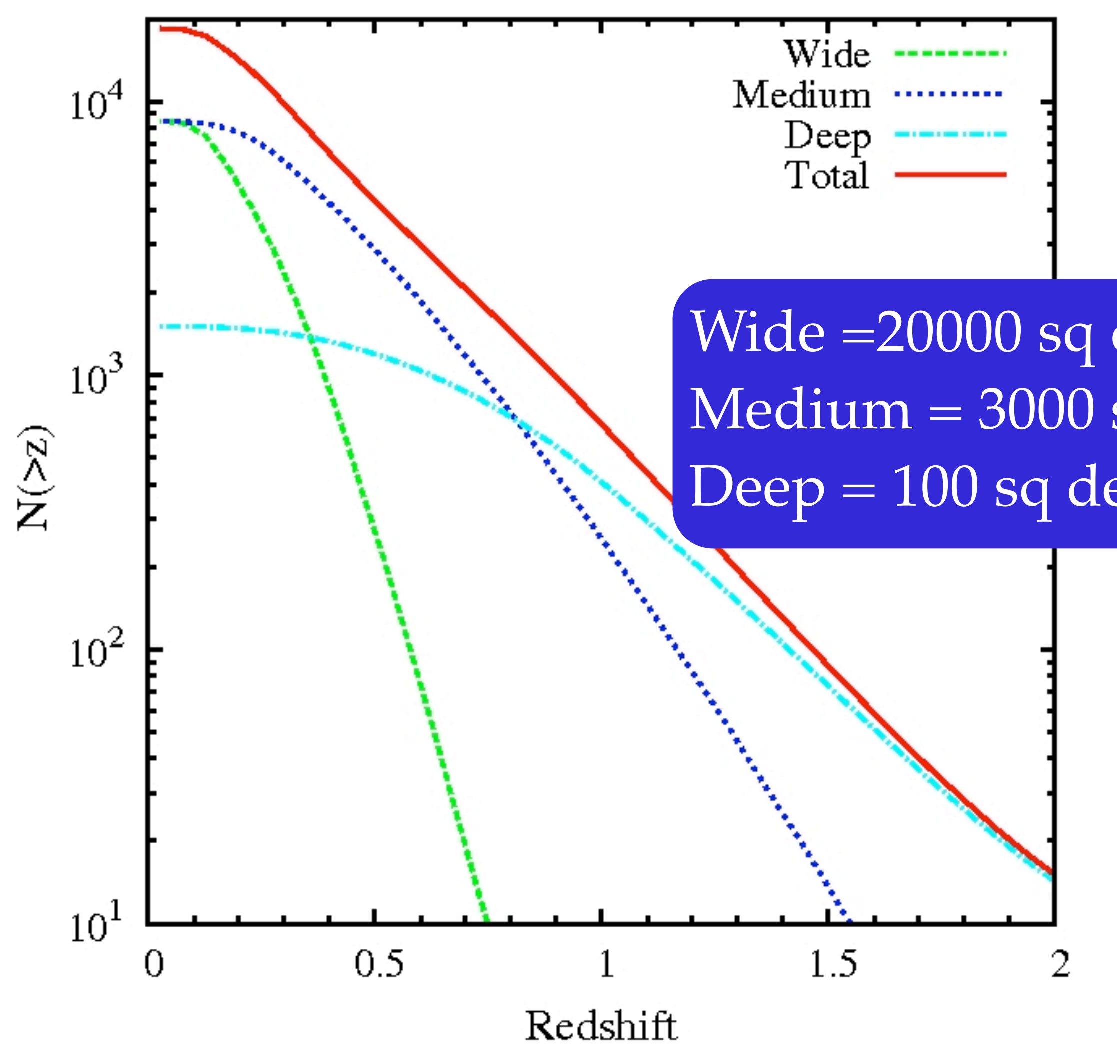
Majumdar & Mohr 2003, Tegmark et al. 1997

Sartoris et al. 2010 MNRAS 407,2339

Survey redshift range

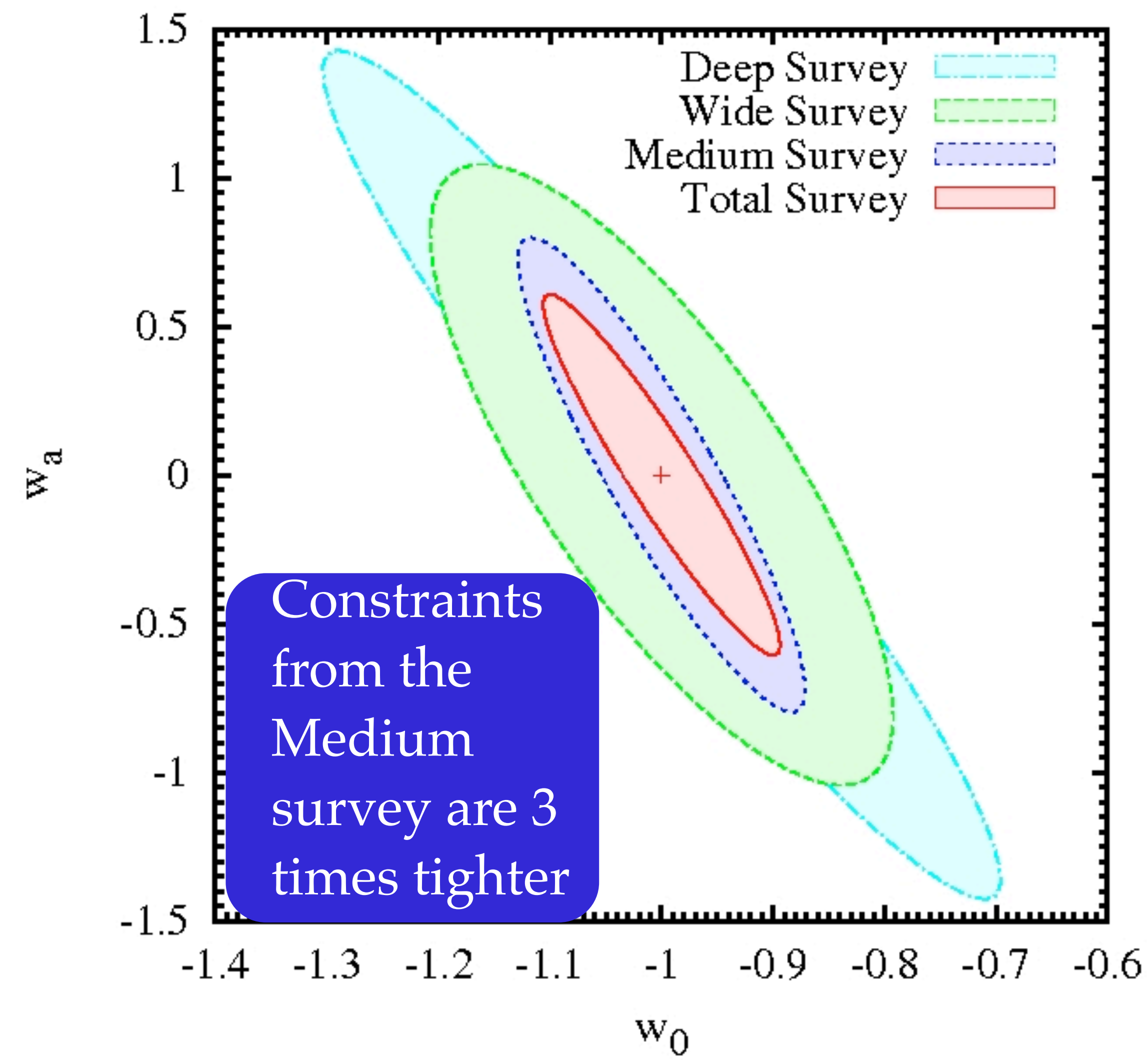
Cumulative redshift distribution

$$w(a) = w_0 + w_a(1 - a)$$



Wide =20000 sq deg
Medium = 3000 sq deg
Deep = 100 sq deg

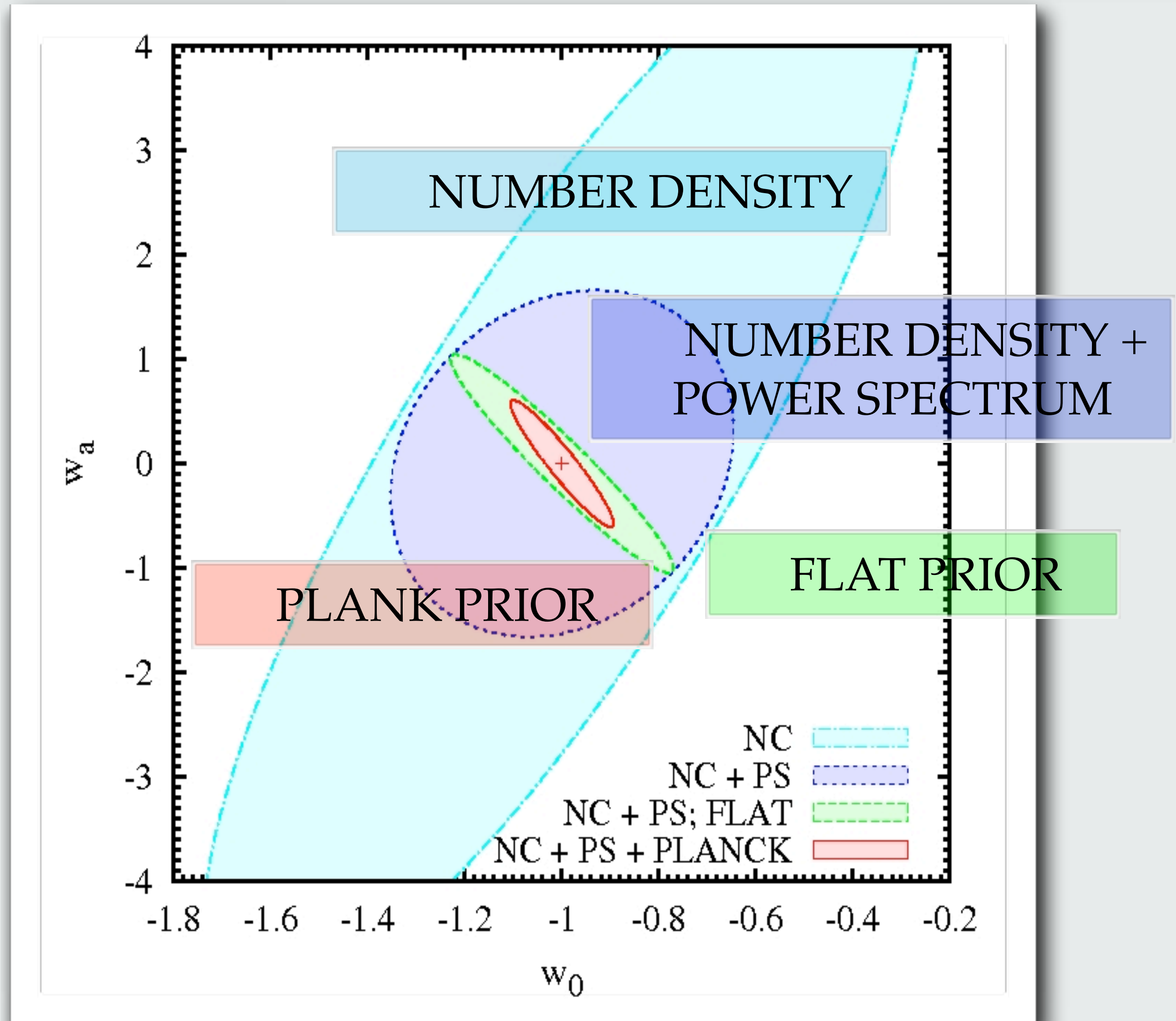
Sartoris et al. 2012 MNRAS



Constraints from the Medium survey are 3 times tighter

Constraints: 68 % level

Constraints on cosmological parameters
Combining Cluster abundance and Power spectrum



$$w(a) = w_0 + w_a(1-a)$$

$FoM_{DEFT} = (\det [Cov(p_i,p_j)])^{-1/2}$

Constraints: 68 % level

$\Delta w_0 = 0.046$
$\Delta w_a = 0.14$
FoM = 106

Sartoris et al. 2012 MNRAS

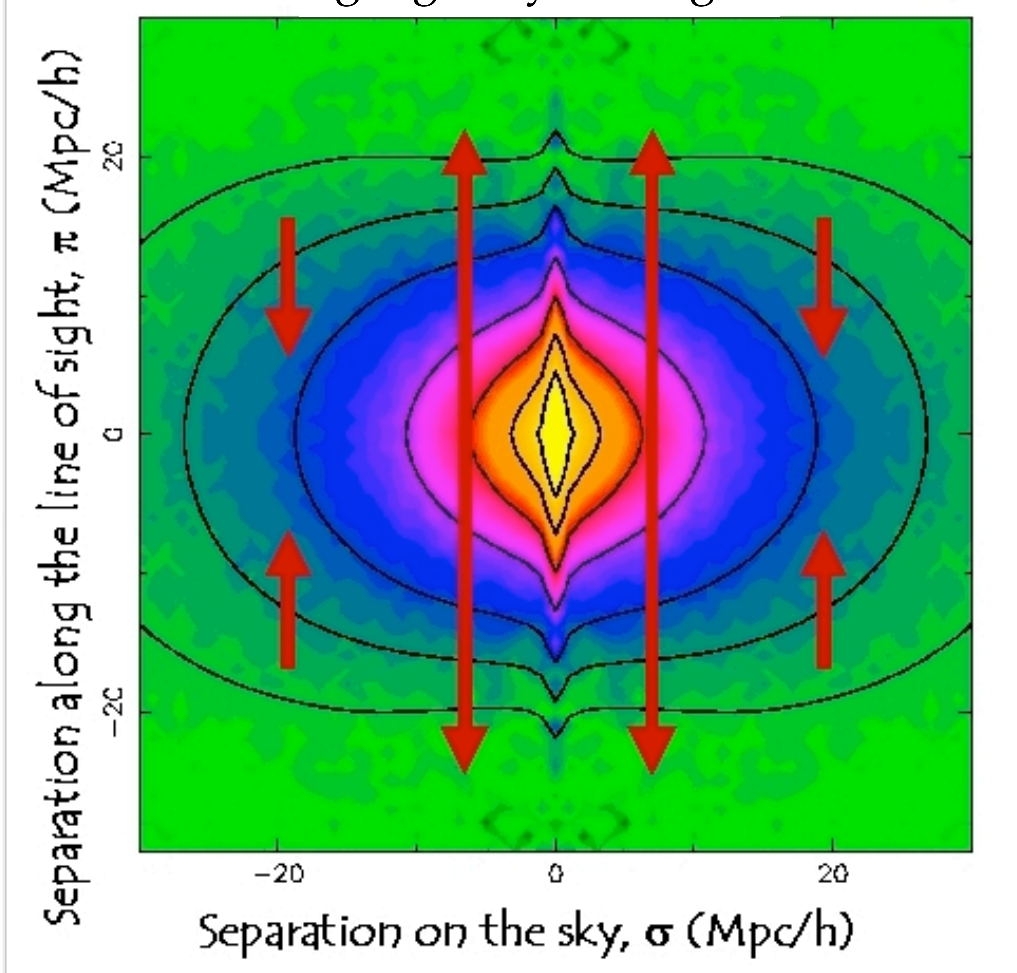
Constraints on cosmological parameters from the Redshift Space Distortions

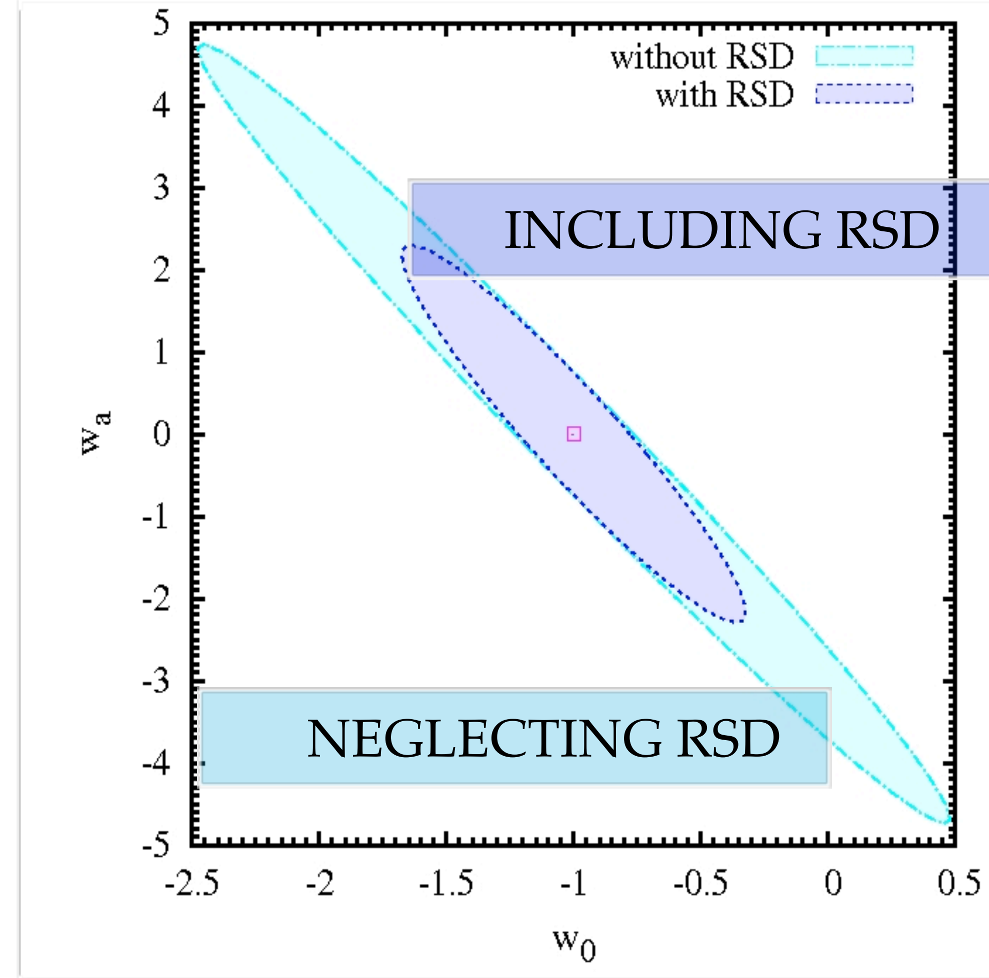
$z_{obs} = z_{true} + v_{pec}/c$ where $v_{pec} \propto \Omega^{0.6}\, \delta\rho/\rho = (\Omega^{0.6}/b)\, \delta n/n$ (b: bias)

$$\tilde{P}(k,\mu) = (b + f\mu^2)^2 P(k)$$

$$f = \frac{d\ln D}{d\ln a}$$

2gF galaxy catalogue



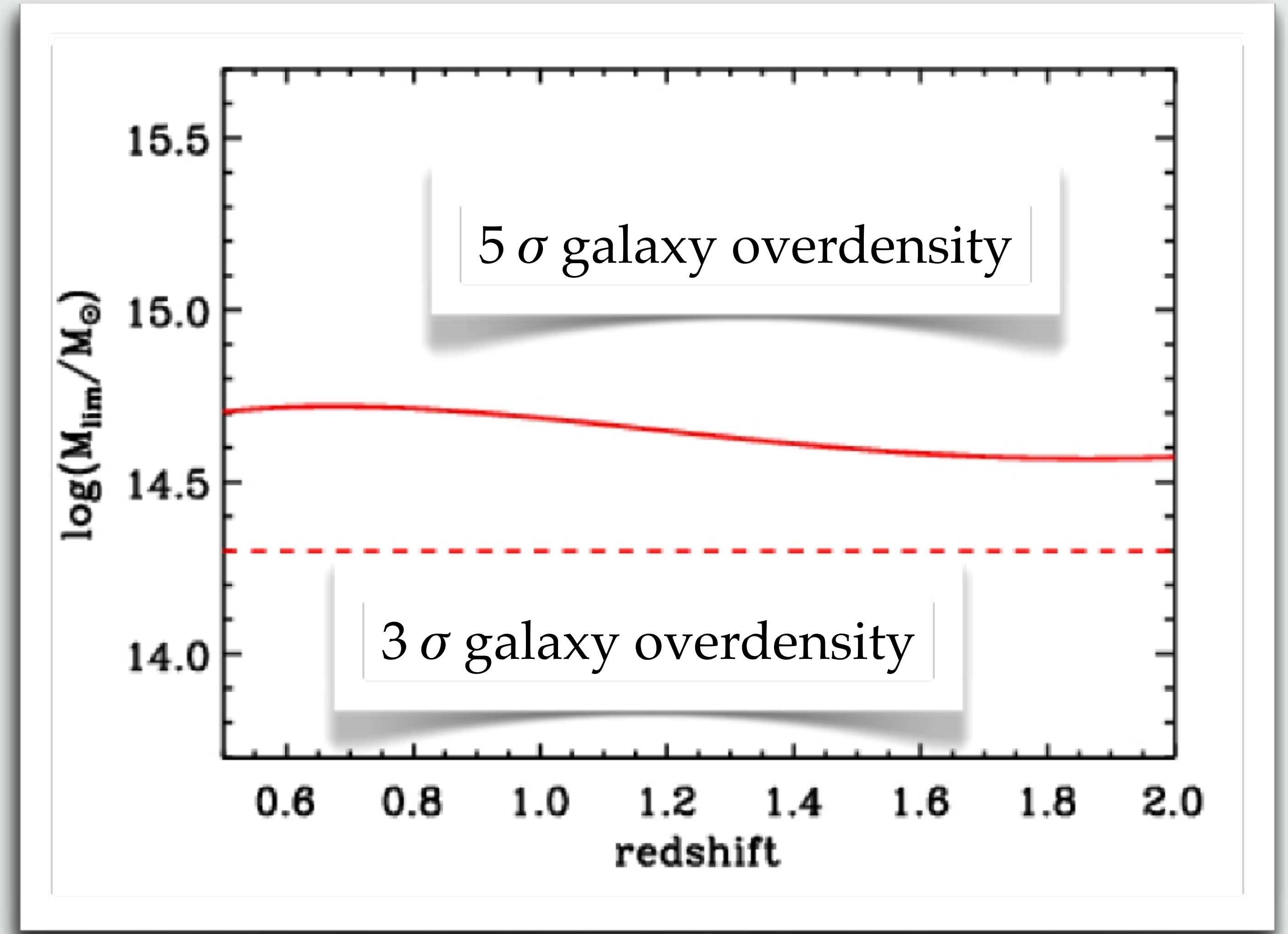


$FoM_{RSD} / FoM_{noRSD} = 2$

Sartoris et al. 2012 MNRAS

Constraints at 68 % level

DE forecast from future optical near-IR Euclid survey



Mission approved by ESA with the primary aim to study the origin of the Universe expansion (measure of w) from BAO+WL cosmic shear

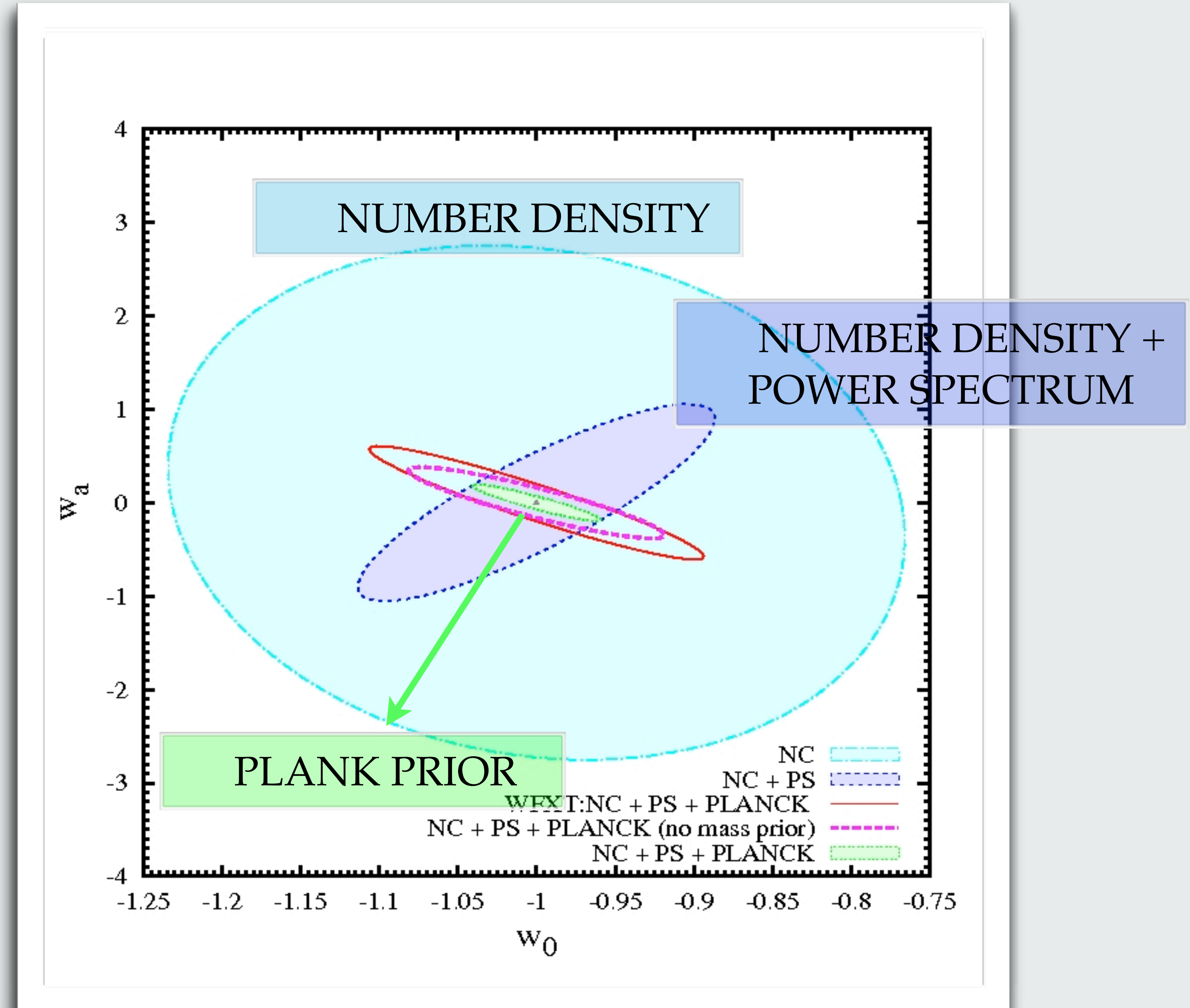
- optical band: 550- 900 nm with a resolution of <0.2 arcsec
- NIR band: 920-2000 nm

Combination with ground experiments Pan-STARRS and LSST.

20000 sq deg.

Euclid cluster sample: 3000 clusters detected via photometry with WL mass measurements.

DE forecast from future optical near-IR Euclid survey



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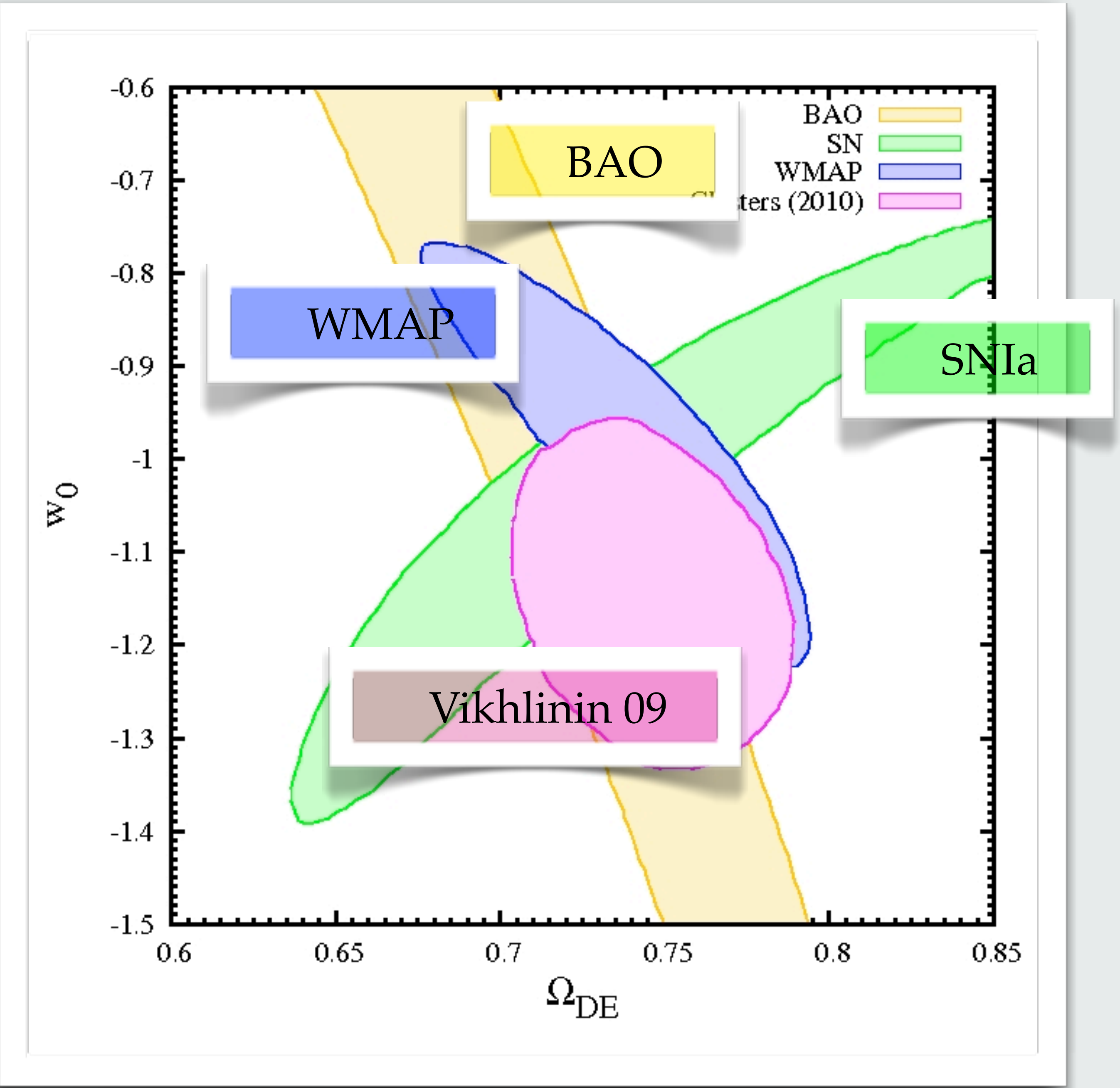
- NIR band: 920-2000 nm

Combination with ground experiments Pan-STARRS and LSST.

20000 sq deg.

Euclid cluster sample: 30000 clusters detected via photometry with WL mass measurements.

Dark Energy constraints from clusters current data



Vikhlinin et al 2009

→ Flat universe

→ Constant DE EoS

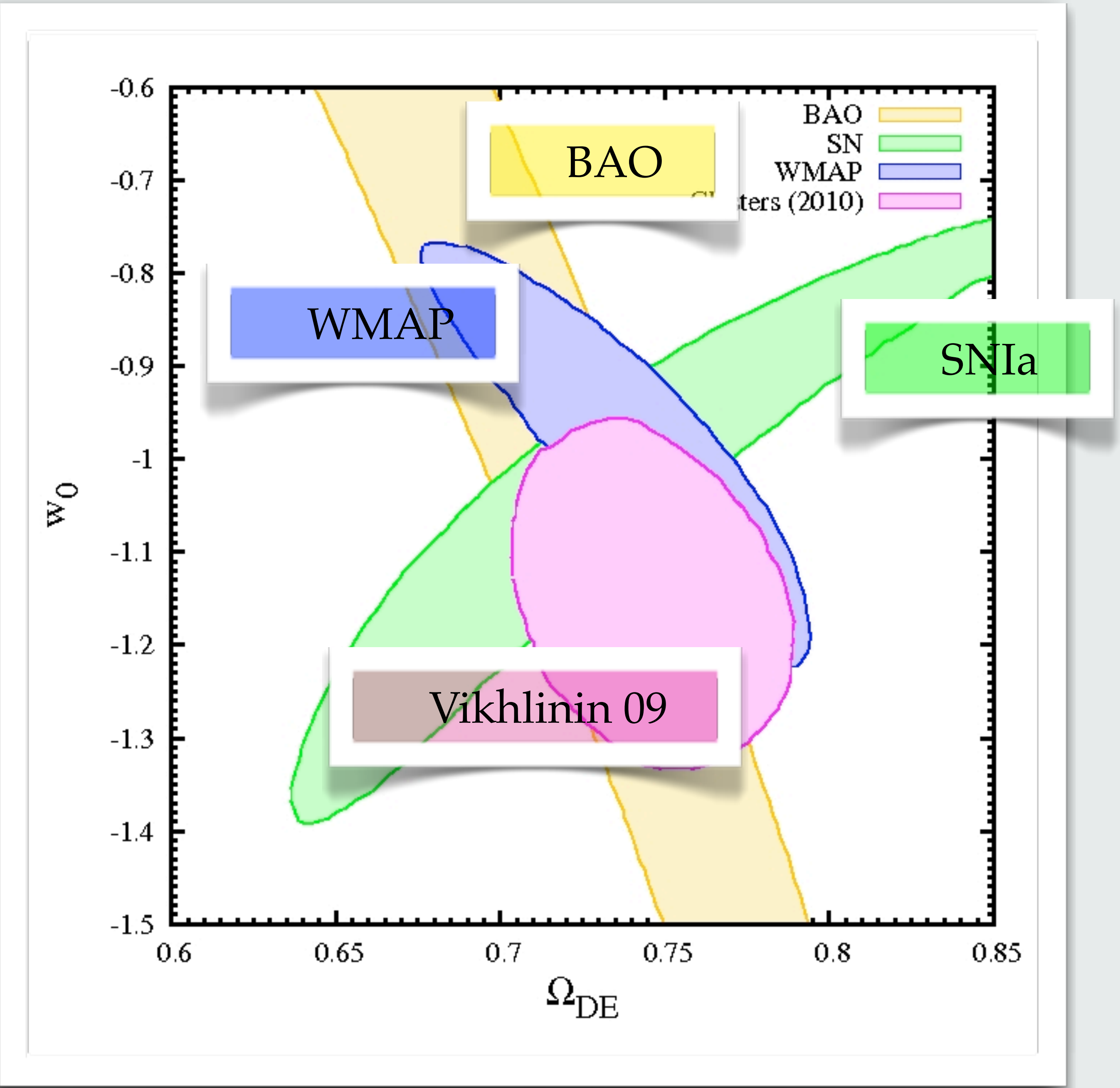
- Constraints from galaxy clusters:

$w_0 = -1.1 \pm 0.2$
$\Omega_{DE} = 0.75 \pm 0.04$

- Joint constraints:

$w_0 = -0.99 \pm 0.05$
$\Omega_{DE} = 0.74 \pm 0.02$

Dark Energy constraints from clusters current data



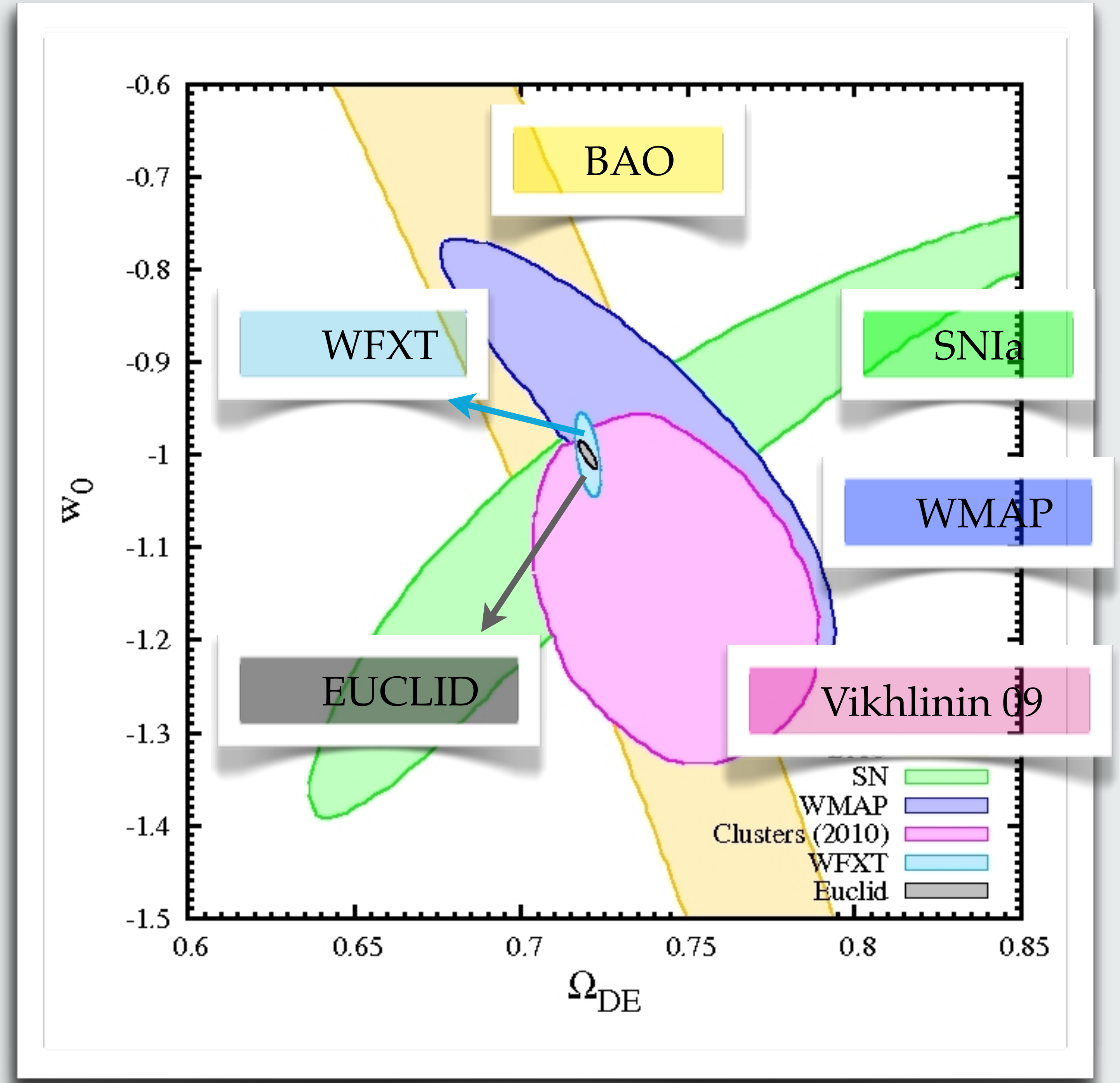
Vikhlinin et al 2009

Constraints from clusters number density obtained with:

- 49 brightest clusters at $z \approx 0.05$ detected in the X-ray ROSAT All-Sky Survey
- 37 clusters ($\langle z \rangle = 0.55$) derived from 400 sq. Deg. X-ray ROSAT serendipitous survey

Follow up observations of all clusters with Chandra.

Dark Energy constraints from clusters current and future survey



→ Flat universe

→ Constant DE EoS

- Constraints from clusters (2010):

$w = -1.1 \pm 0.2$

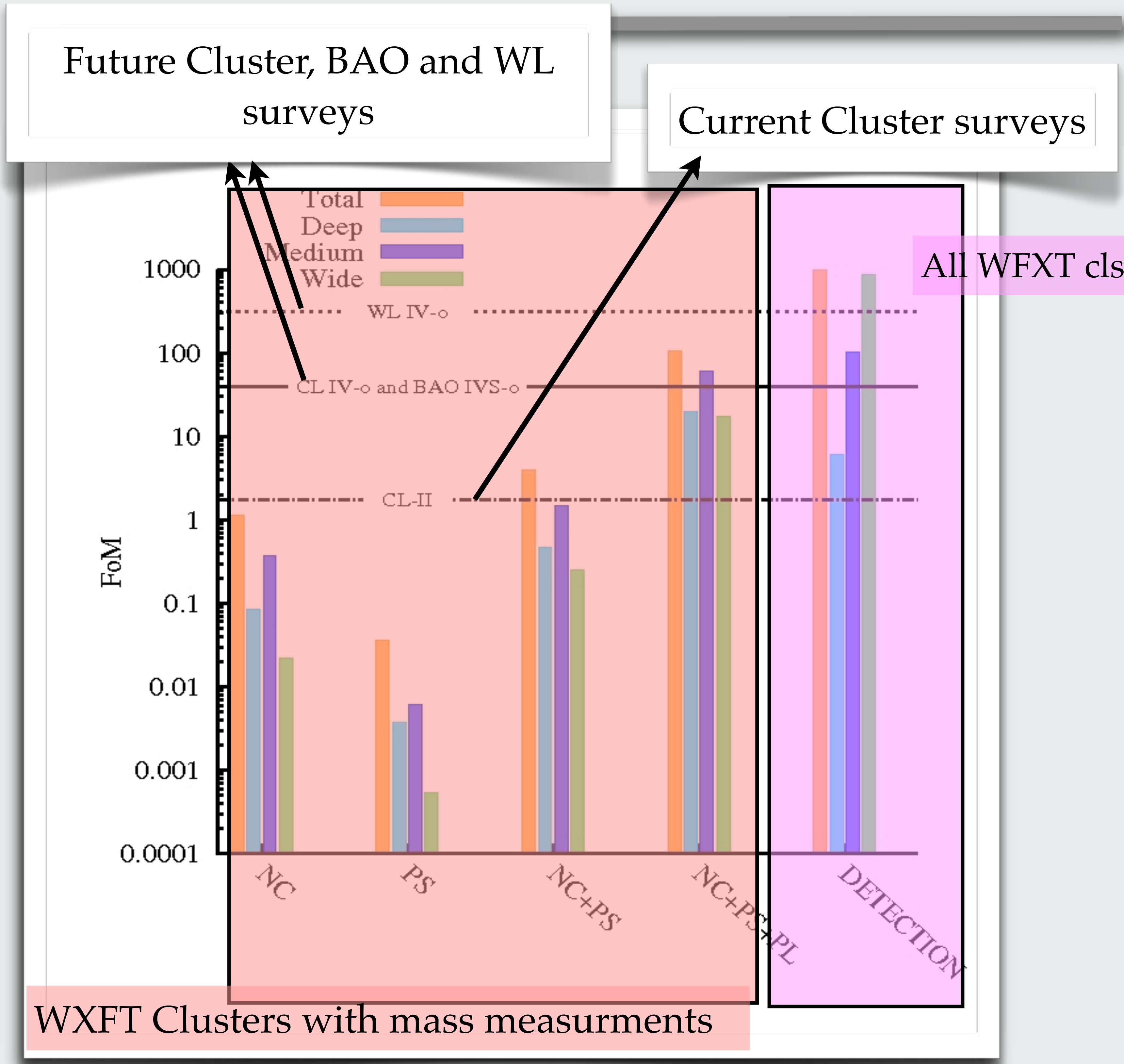
$\Omega_{DE} = 0.75 \pm 0.04$

- Constraints from EUCLID:

more than one order of magnitude tighter.

Constraints at 68 % level

Dark Energy Task Force FoM



$\mathrm{FoM}_{\mathrm{DEFT}} = (\det [Cov(p_i,p_j)]\,)^{-1/2}$

$$w(a) = w_0 + w_a(1-a)$$

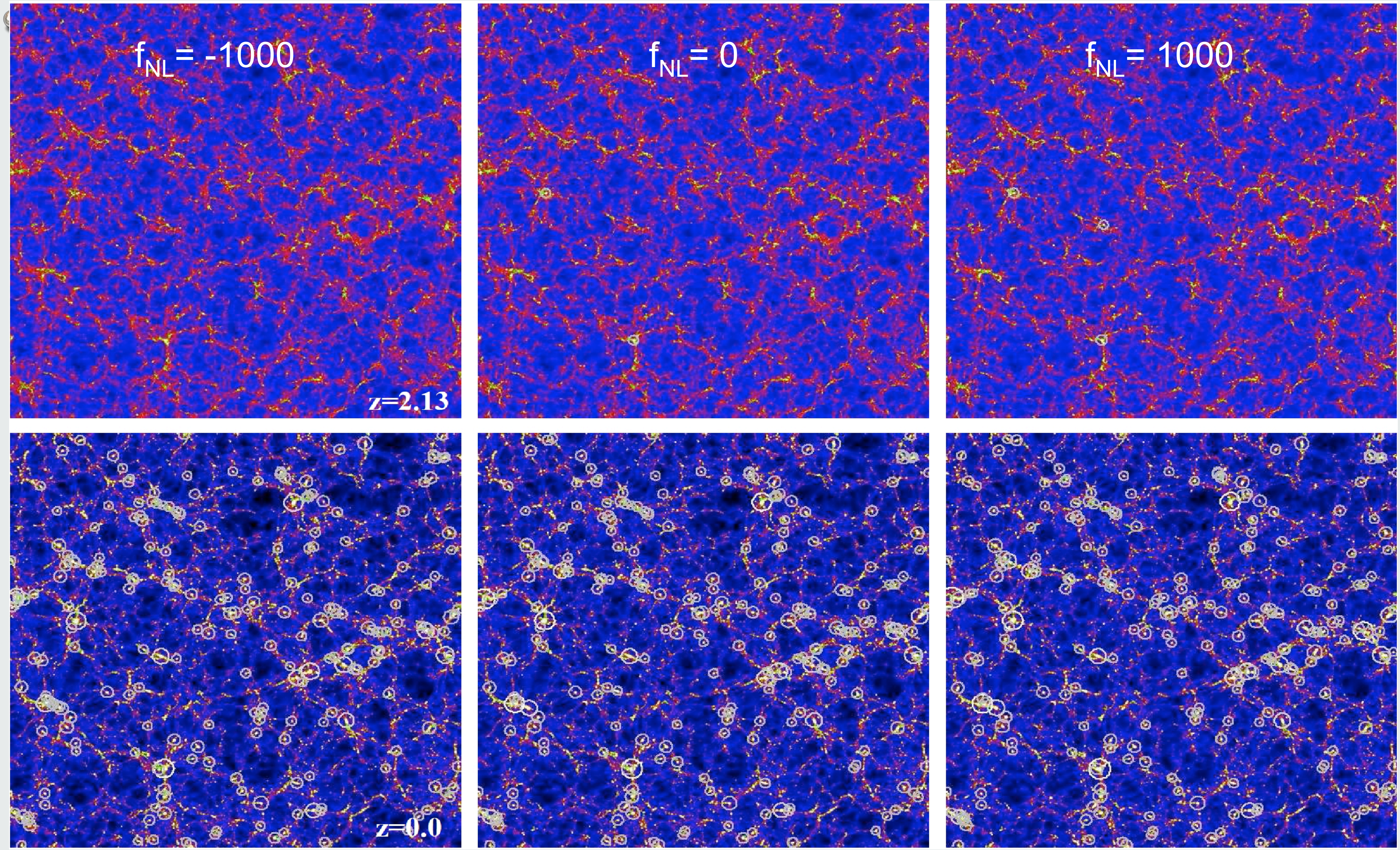
Constaitns from 2 x 10^4 WXFT clusters with direct mass measurments:

$\Delta w_0 = 0.046$
$\Delta w_a = 0.14$
FoM = 106

Sartoris et al. 2012 MNRAS

Non-Gaussian evolution of clusters

Grossi et al. 2007



Non Gaussian initial conditions

- Parametrize deviations from Gaussian initial fluctuations:

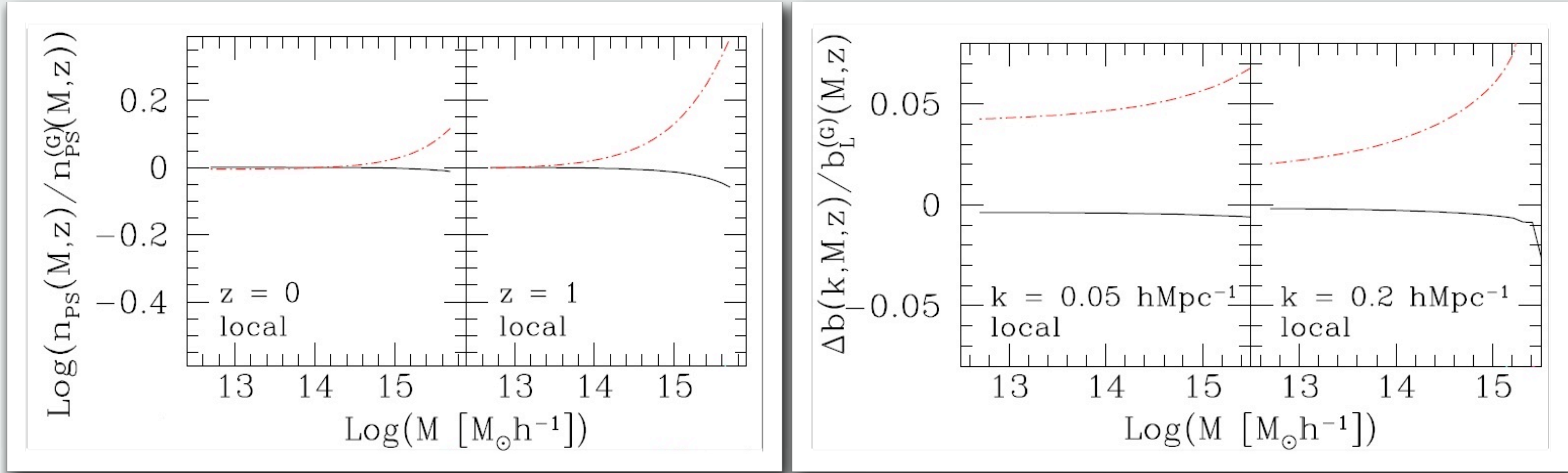
$$\Phi = \Phi_G + f_{NL} * \left(\Phi_G^2 - \langle \Phi_G^2 \rangle\right)$$

f_{NL}=0 standard cosmology

Positive skewness: collapse of halos at higher z, for fixed σ_8.

$$n(M,z) = n^{(G)}(M,z)\frac{n_{PS}(M,z)}{n_{PS}^{(G)}(M,z)}$$

$$b(M,z,k) = 1 + b_L^{(G)}(M,z)\left[1 + \frac{\Delta b(M,z,k)}{b_L^{(G)}(M,z)}\right]$$

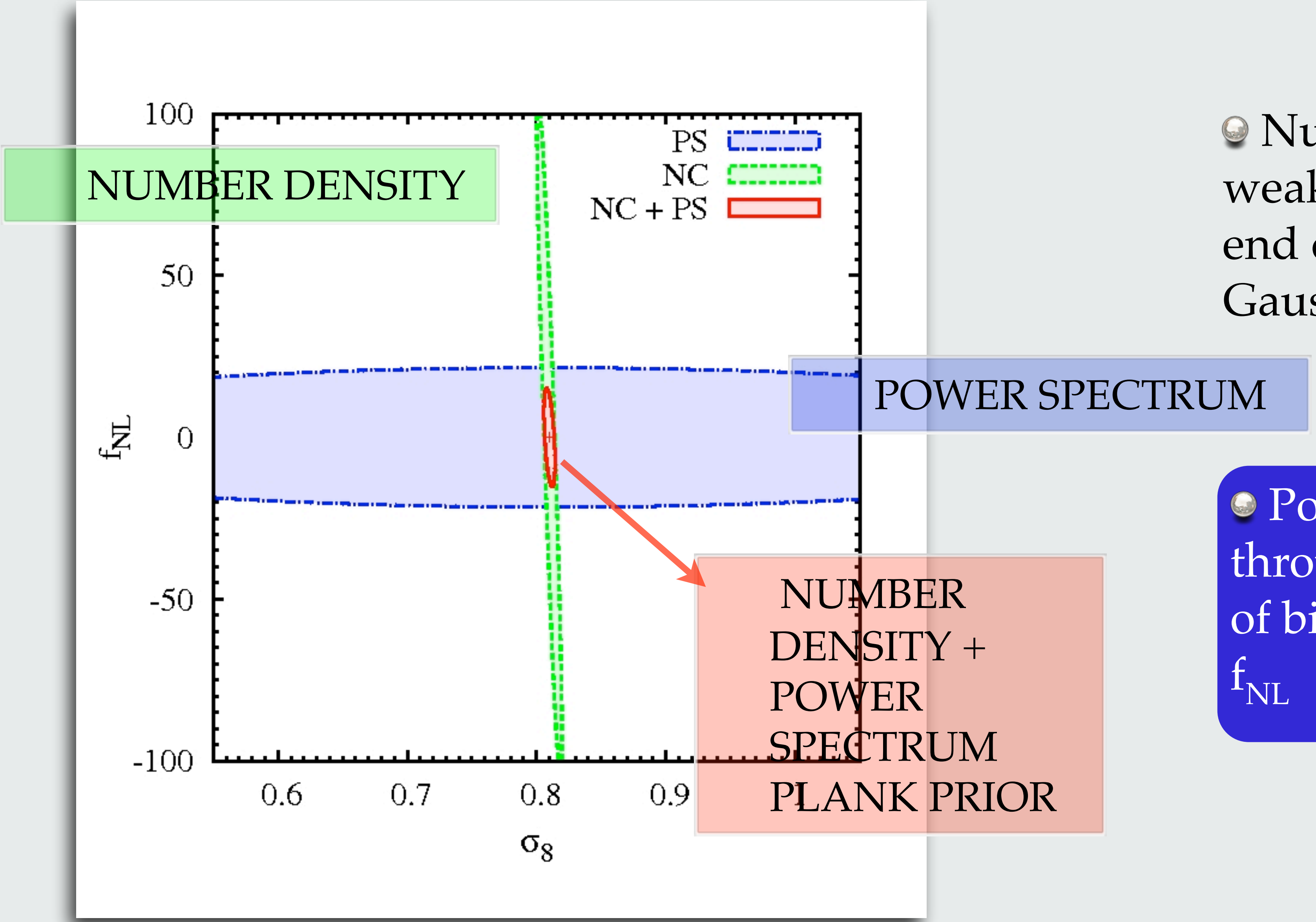


Fedeli et al. 2009

Red for f_{NL}=145; Black for f_{NL}= -12

Constraints on Non-Gaussianity

Strong complementarity NC and PS to constrain σ_8 and f_{NL}.



- Number Counts: weakly sensitive of the high end of the mass function to non Gaussianity and so on f_{NL}.

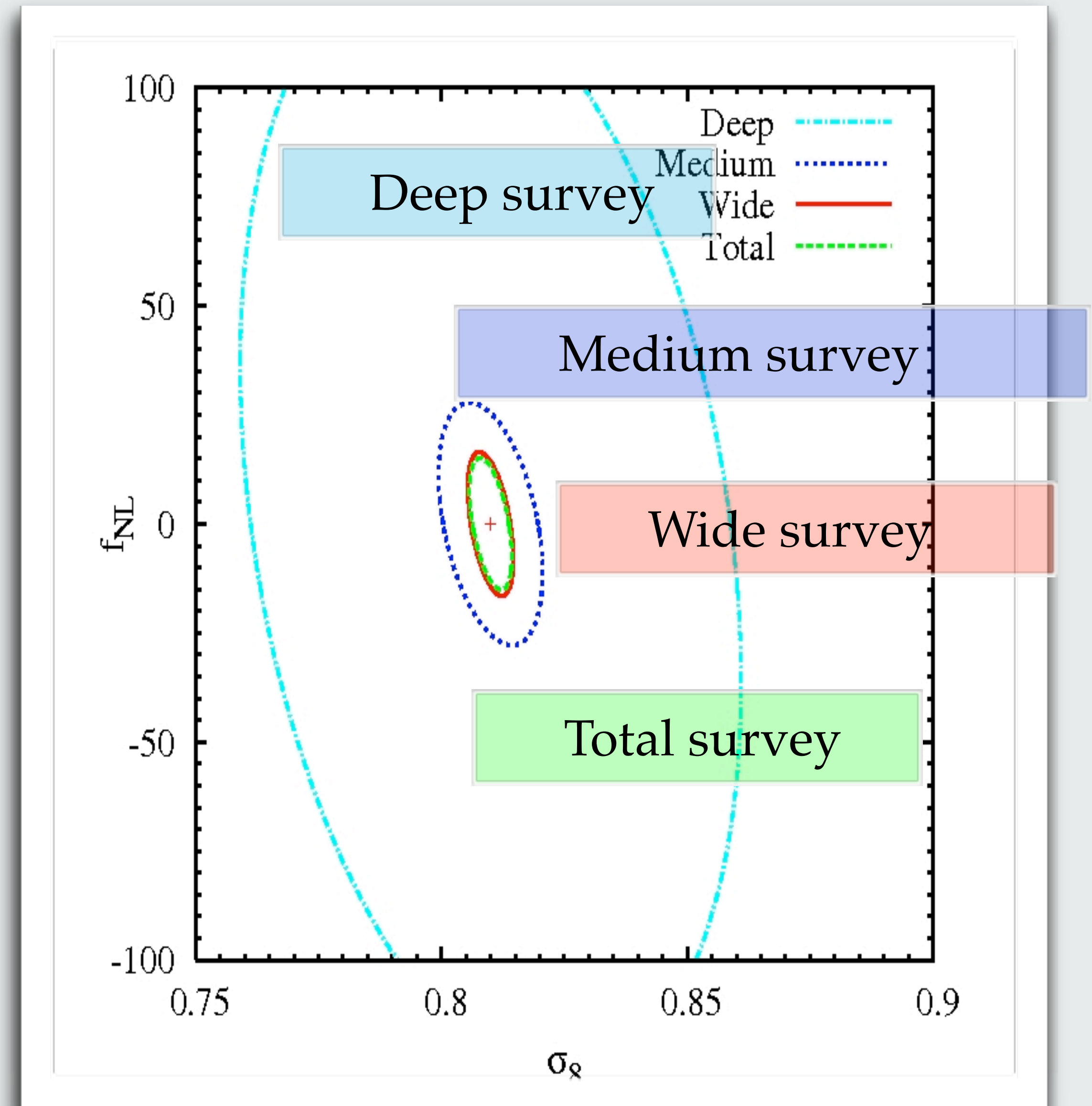
- Power Spectrum: through the scale-dependence of bias strong constraints on f_{NL}

Constraints at 68 % level

Sartoris et al. 2010 MNRAS 407,2339

Constraints on Non-Gaussianity

Combine all the information obtainable from the three WXFXT surveys



Most of the constraining power from Wide survey:

➡ larger statistics out to z ≃ 1

➡ better sample long-wavelength modes

- Constraints from WFXT: $\Delta f_{NL} \simeq 12$

- Current constraints from CMB (WMAP-7):

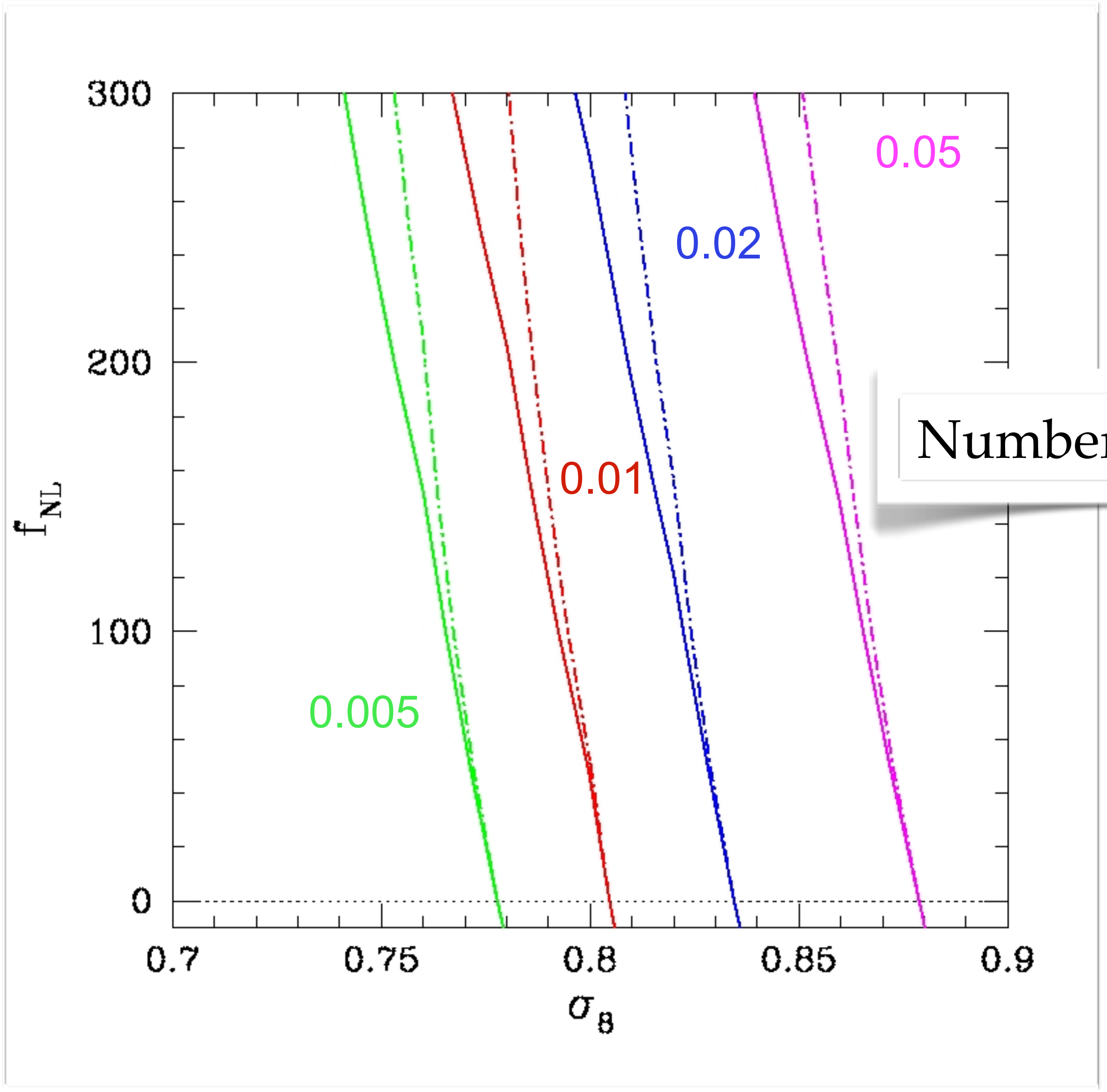
$-9 < f_{NL}^{CMB} < 111$ (95% C.L.) (Komatsu et al. 09)

Constraints at 68 % level

Sartoris et al. 2010 MNRAS 407,2339

Using high-z massive clusters to constrain Non-Gaussianity

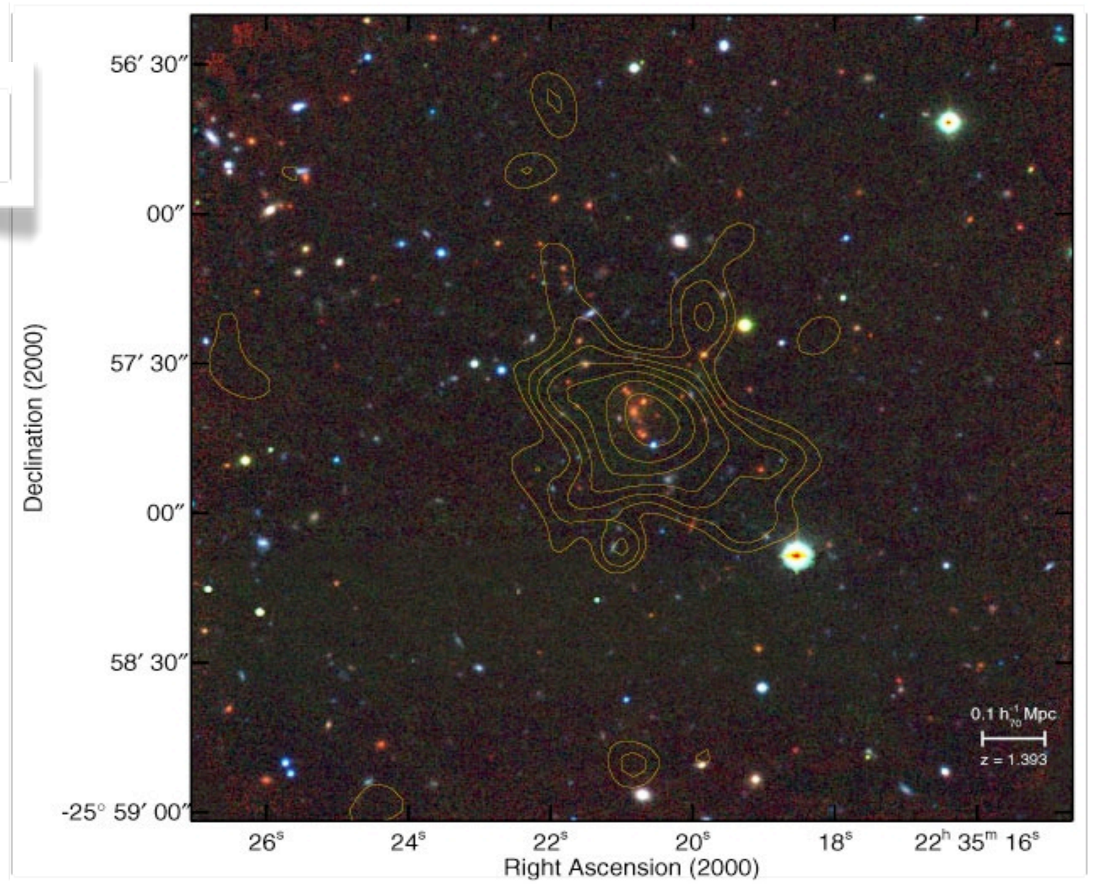
XMMU-J2235.3 cluster (Jee et al. 2009) z~1.4, M= 5 x $10^{14}M_o$ detected in 11 sq.deg.



Sartoris et al. 2010 MNRAS 407,2339

Number of clusters with mass M> 5 x $10^{14}M_o$, found in the redshift range 1.4 < z < 2 within 11 sq.deg.

Number of clusters



Mullis et al. 2005, Jee et al. 2009

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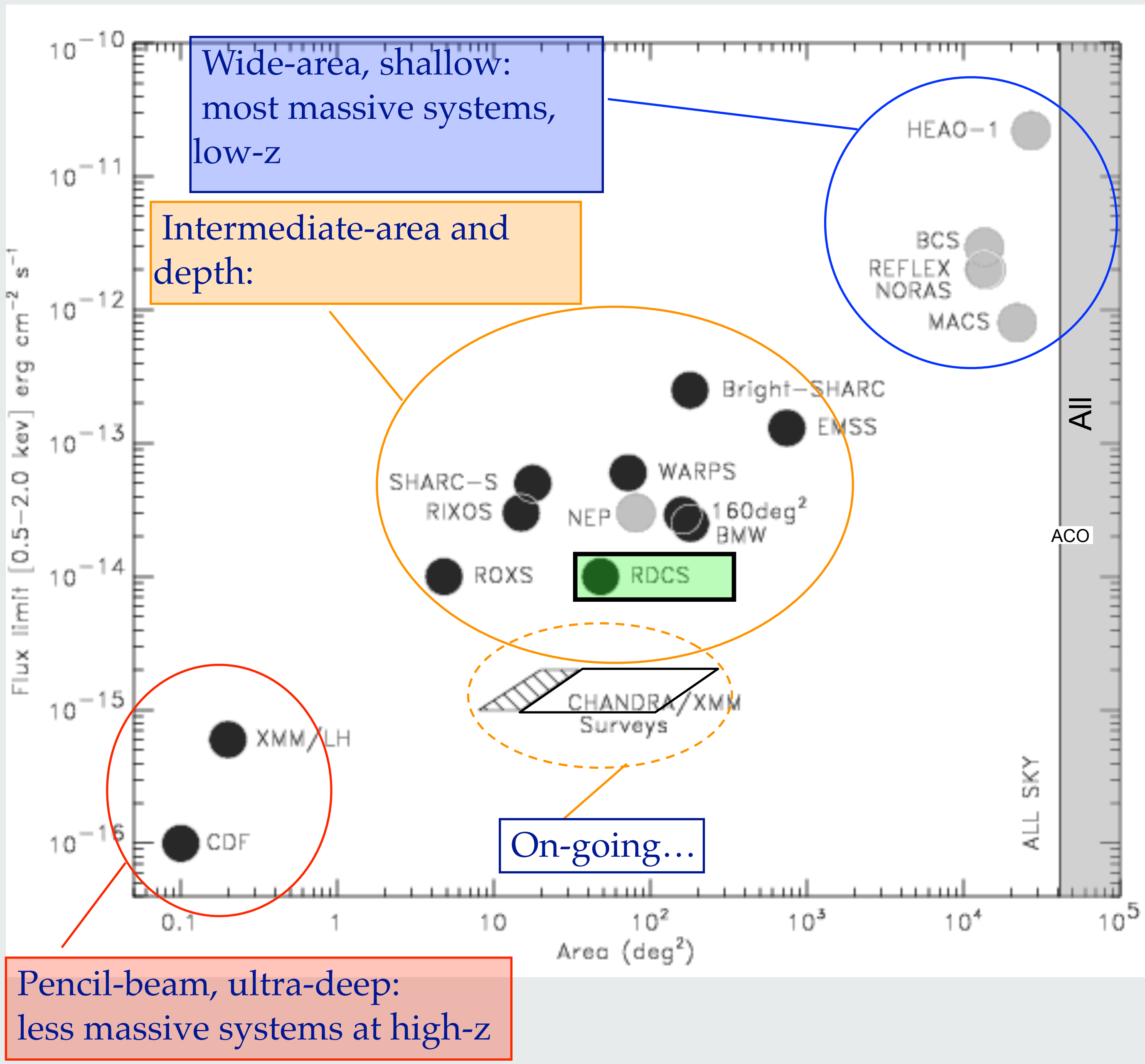
High-redshift (z>0.8) mass function

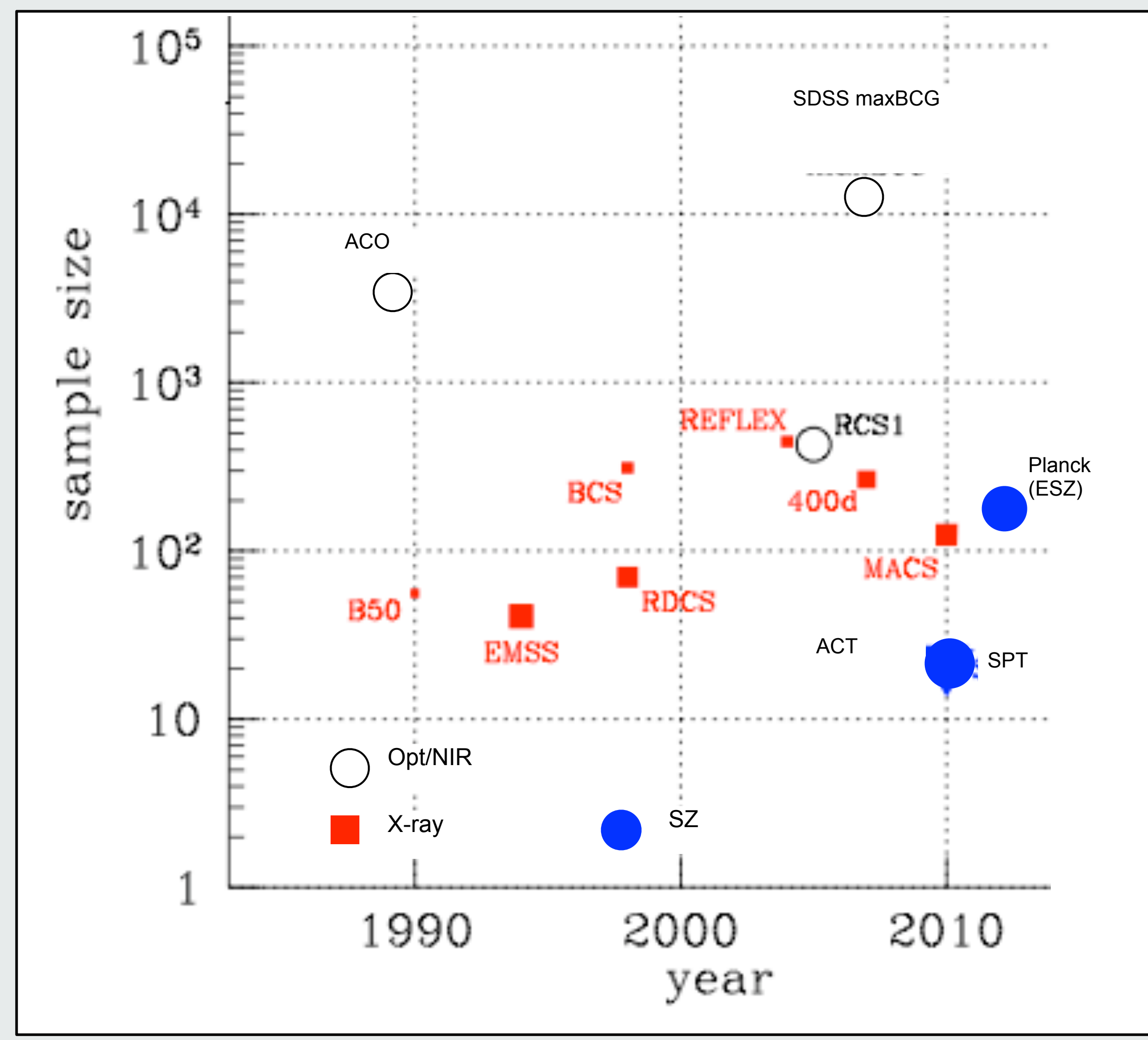
Cluster Surveys (1980 - 2010)

Solid angles and flux limits of X-ray cluster surveys

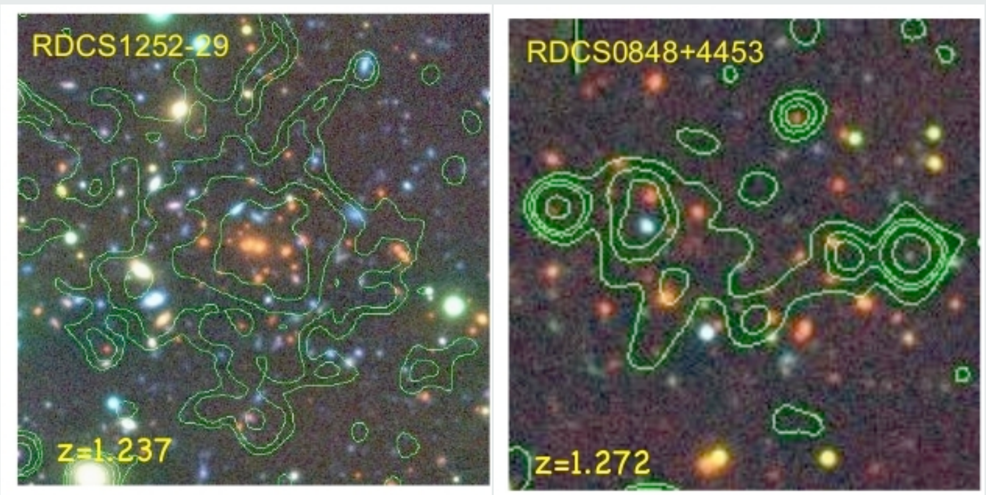


In order to obtain tight constraints we need :

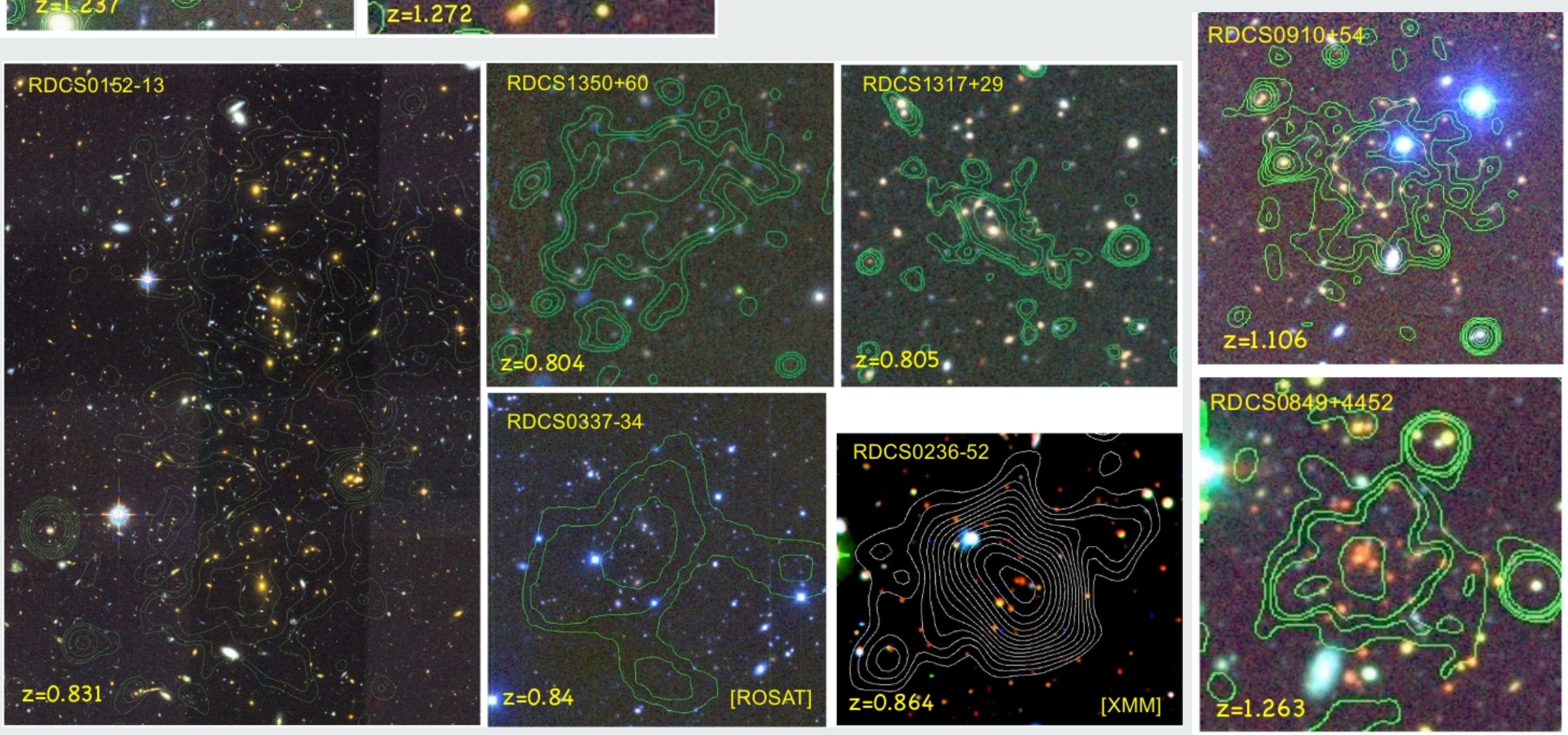
- a robust measurement of the mass proxies
- a large statistic of clusters (expecially at high redshifts)



ROSAT Deep Cluster Sample - RDCS



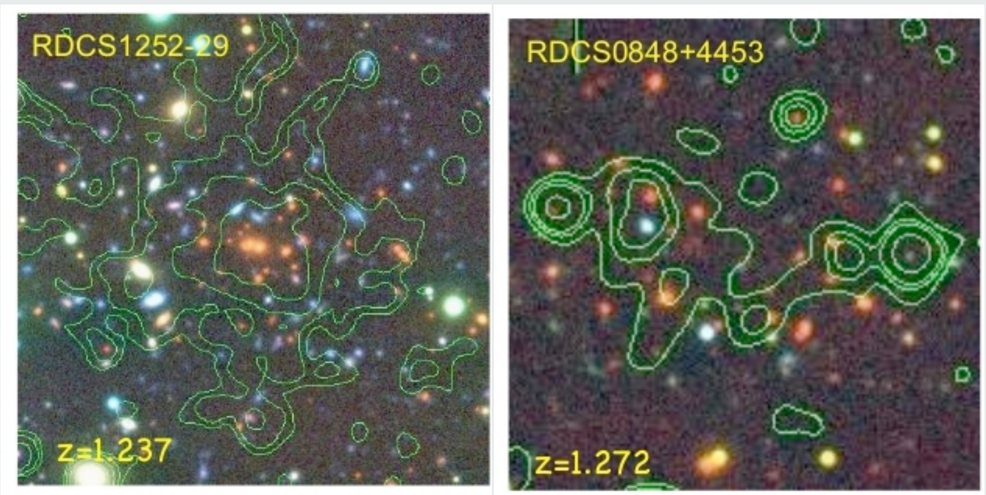
RDCS high-z sample
($f_{lim} = 10^{-14}$ erg/cm^2/s
[0.5 – 2]keV band)
0.8<z<1.3



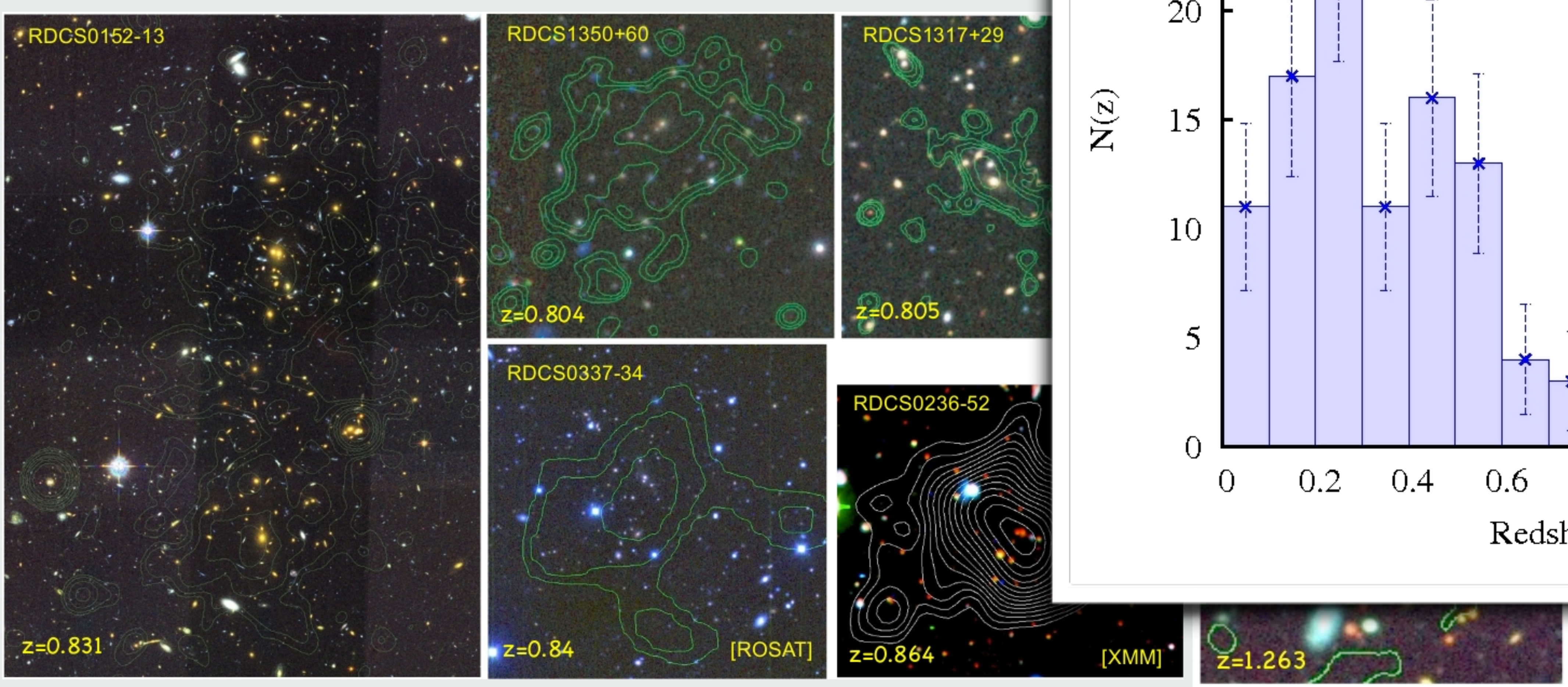
Rosati et al 1995

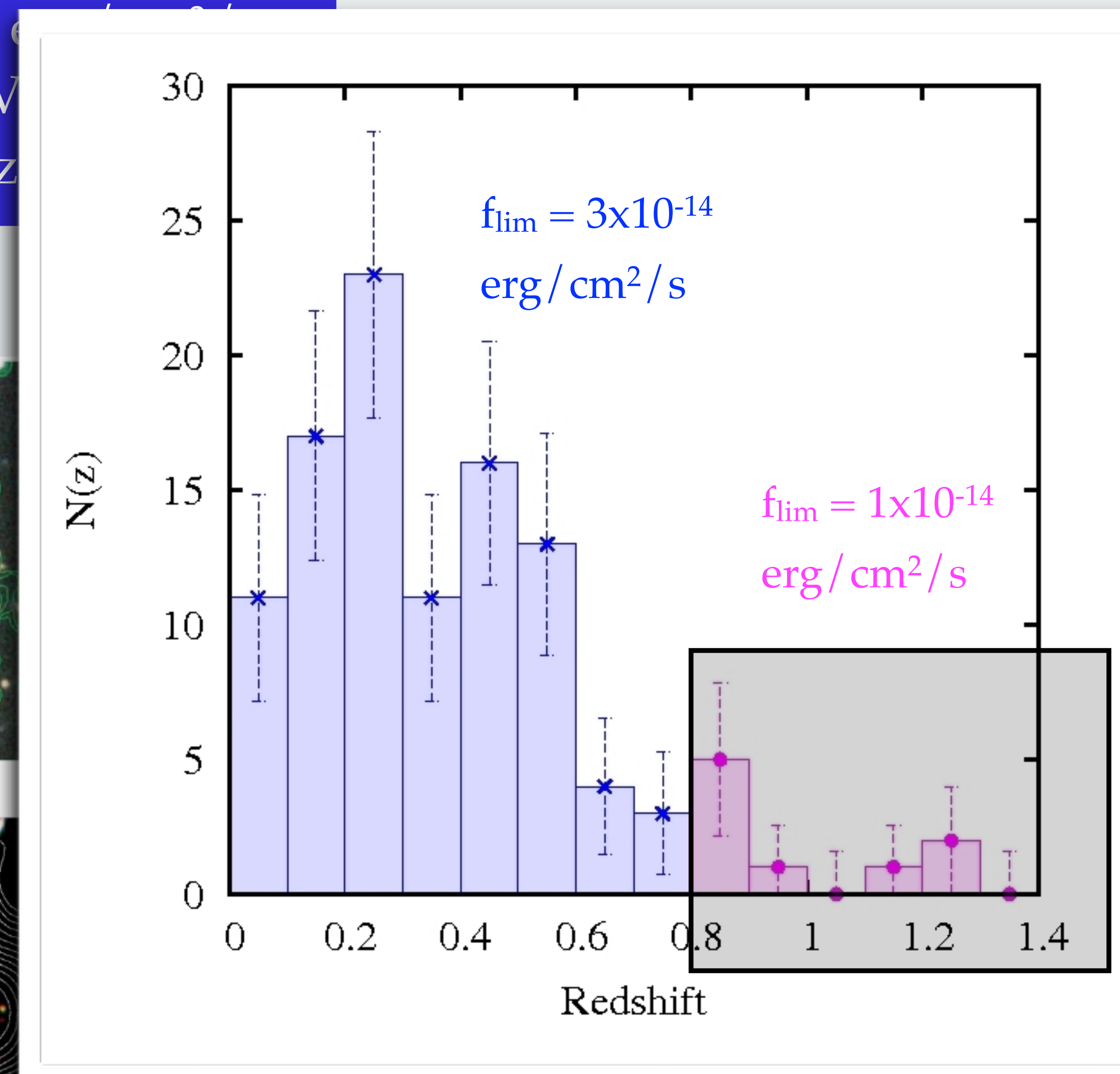
ROSAT Deep Cluster Sample - RDCS

RDCS redshift distribution (N_{cl}=106)



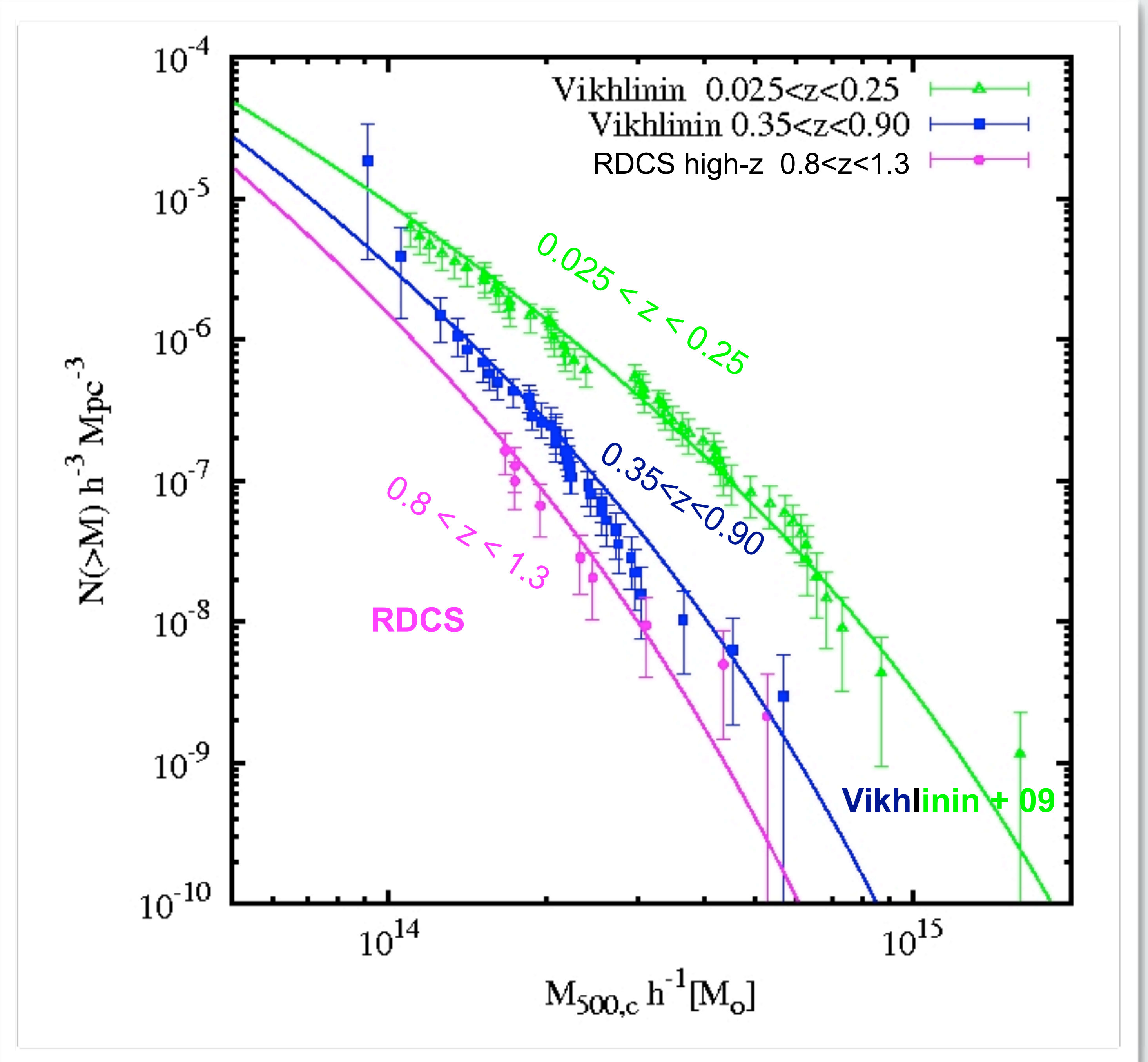
RDCS high-z sample
($f_{lim} = 10^{-14}$ ...
[0.5 – 2]keV ...
0.8<z ...





Rosati et al 1995

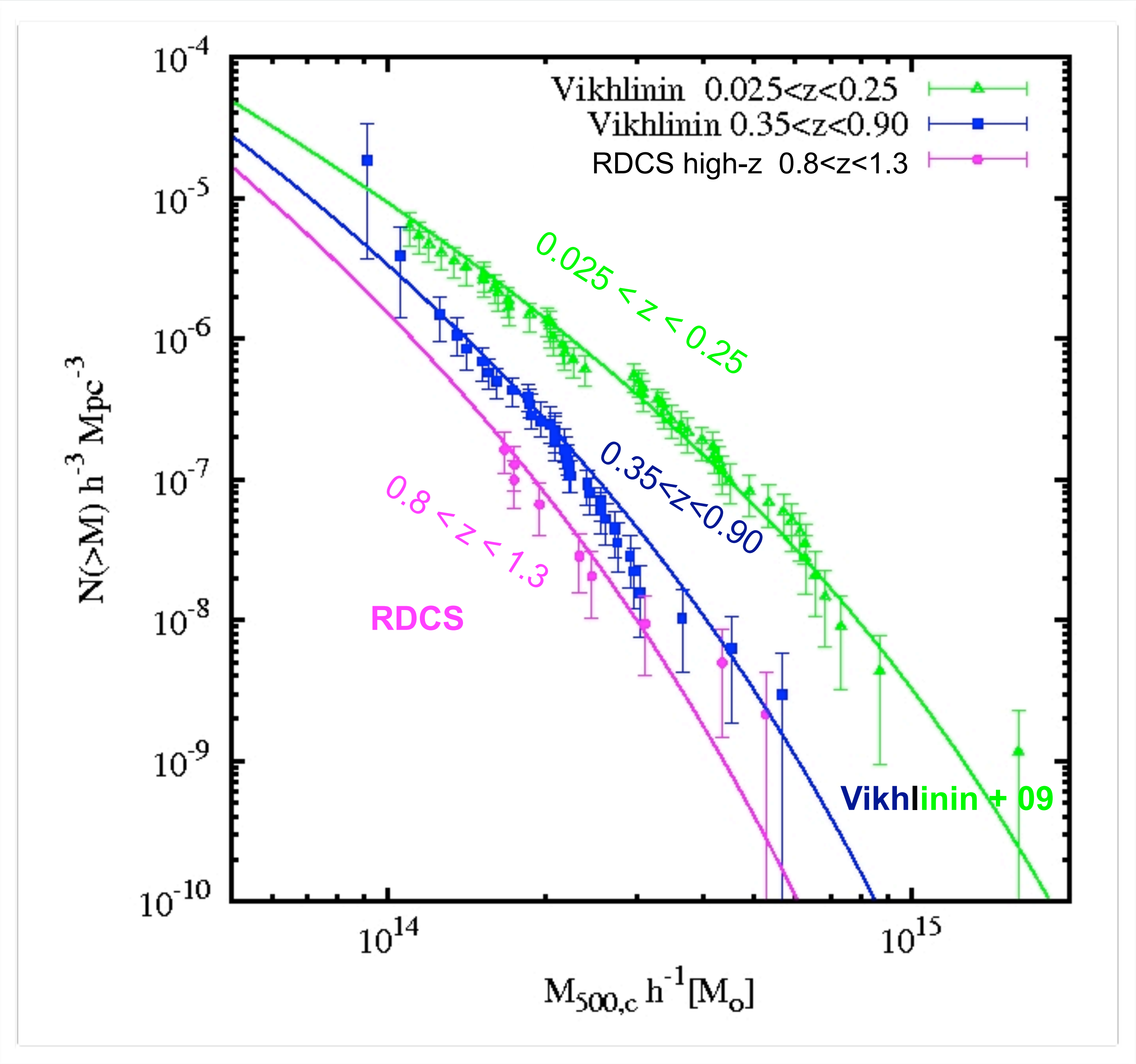
Cluster mass functions in three redshift ranges



Sartoris et al. 2012 in preparation

- Mass from WL for 5 clusters from HST observations. Error on mass between 12%< M_{WL} < 30%
- Mass from hydrostatic equilibrium for 7 clsuters. from Chandra observations. Error on mass between 20%< M_X < 50%
- Mass derived from the theoretical observable-mass relations for 2 clusters. Error on mass >50%

Cluster mass functions in three redshift ranges



Sartoris et al. 2012 in preparation

$$N(>M) = \sum_{M_i > M} V(M_i)^{-1}$$

Rosat Deep Cluster Survey

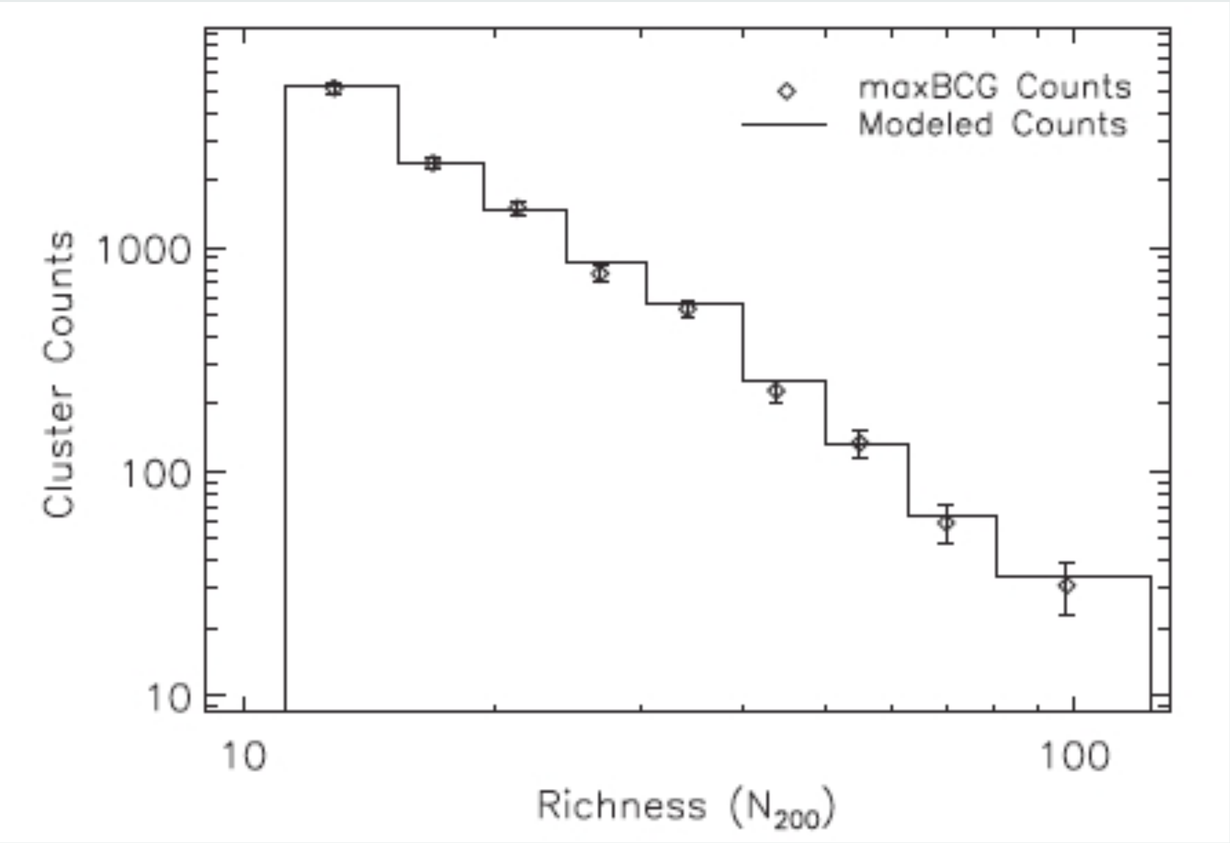
(f_{lim} = 10^{-14} erg/cm^2/s [0.5 – 2]keV band)

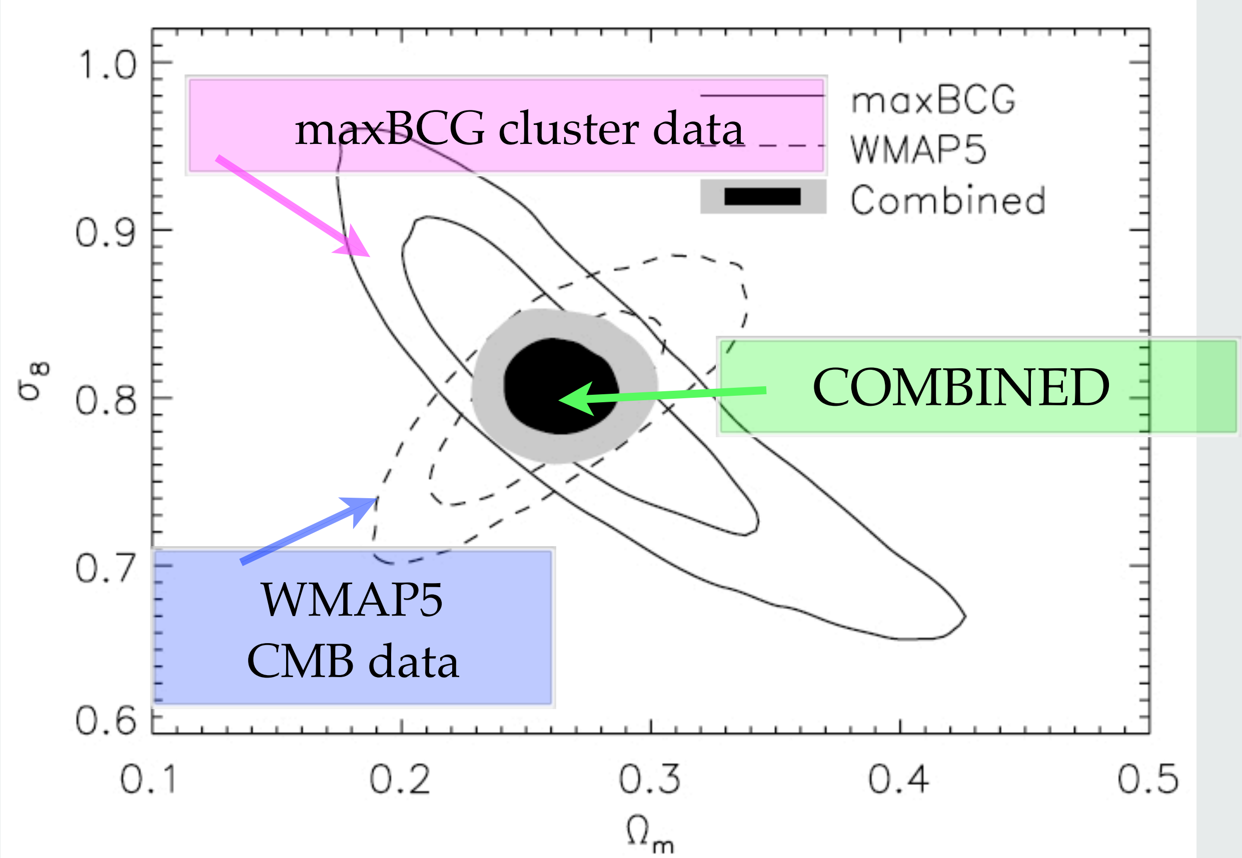
- Cluster mass function at <z = 0.9>. The observed evolution of the mass function as calculated from zRDCS-1 sample is in agreement with prediction of ΛCDM at high redshift.

Constraints from current optical survey: SDSS maxBCG

Rozo et al. (2010) derived cosmological constraints from the SDSS maxBCG cluster sample (Koester et al., 2007b) and the statistical weak lensing mass measurement from Johnston et al. (2007).

- SDSS maxBCG survey area: 7398 sq. deg.
- Photometric redshift range: [0.1, 0.3]
- More than 9 10^3 clusters





Conclusions

Forecast on DE EoS from future X-ray surveys:

- A robust measurement of the mass proxies and a large statistic of clusters are both important to obtain tight constraints.

Constraints deviation from Gaussian perturbation models with future X-ray surveys:

- NC and PS of galaxy clusters are highly complementary in providing constraints.
- PS is sensitive to deviations from Gaussianity, through the scale dependence of the bias.
- Wider area surveys better sample long-wavelength modes.

Tests of LCDM models with high redshift, massive cluster:

- Mass estimations from different methods are consistent and reduce possible systematic errors

Current X-ray cluster data:

- High-z mass function from current X-ray data confirm the LCDM scenario inferred from cluster samples at lower z. Waiting for cosmological constraints ...