Structure Formation and Cosmology with high-z Clusters

Piero Rosati (ESO)

Outline

L1 : Introduction, observational techniques
- Observational definition, observable physical properties
- Methods for cluster searches - Cluster surveys
- Multi-wavelength observations of distant clusters

L2: Clusters as Cosmological Tools
- Constraining cosmological parameters with clusters
- The new population of high-z clusters

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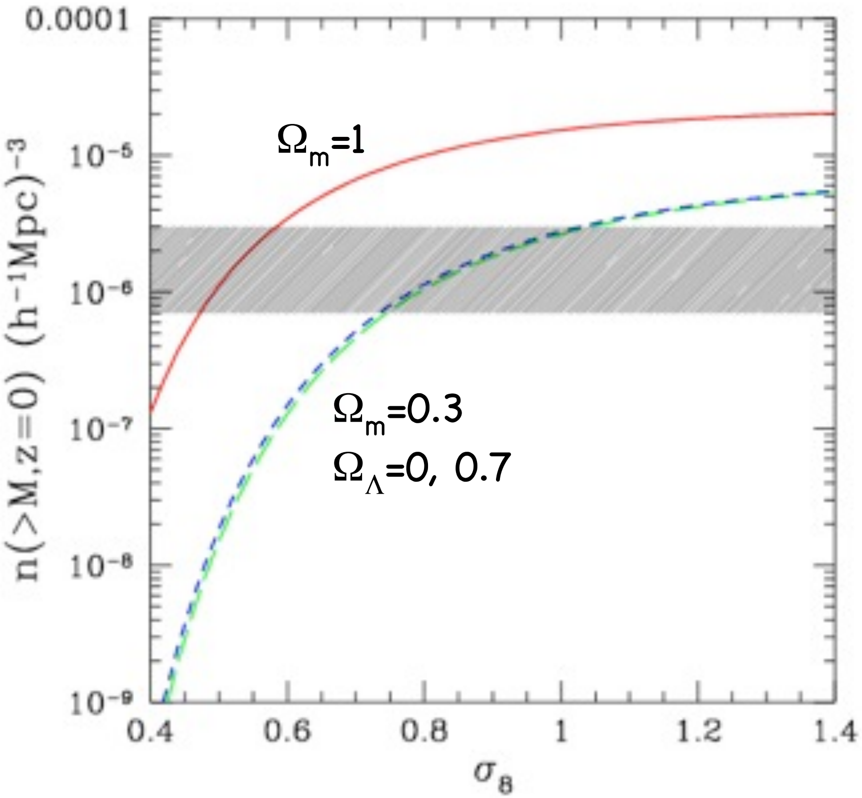
Role of Clusters in Cosmology

- Clusters arise from the gravitational collapse of rare peaks of primordial density perturbations in the hierarchical formation of cosmic structure
- Clusters are so large and massive that their evolution is dominated by gravity thus avoiding complex gas physics except for the cores
- Their abundance and spatial distribution keeps the imprint of original conditions, background cosmology and law of gravity
- Their space density in the local Universe can be used to measure the amplitude of the density perturbations on ~10 Mpc scales ($M_{<10\mathrm{Mpc}} = \varrho_{av} \cdot 4/3\pi\,(10\ \mathrm{Mpc})^3 \approx 10^{15}\,M_\odot\,\Omega_M\,h^{-2}$)

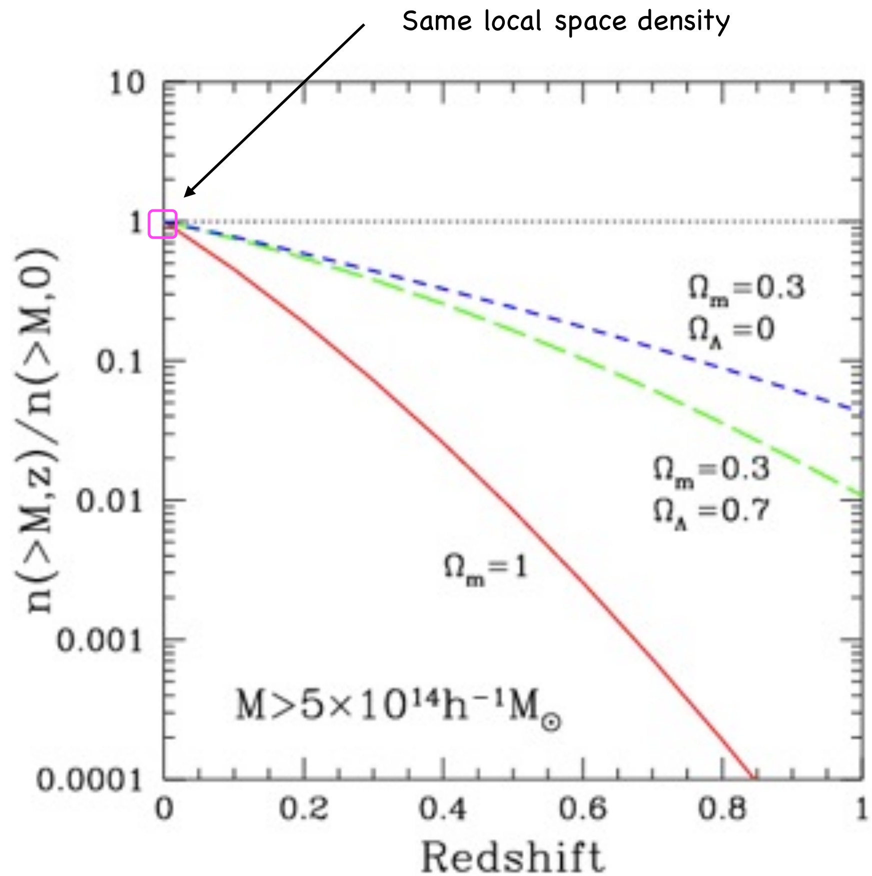
Constraining Cosmological Parameters with the Cluster Mass Function

(Left) Locally, one can determine the σ_8-Ω_m relation ($\sigma_8\Omega_m^{0.5} \approx 0.5$), because only the amplitude on a given scale $R \approx (M/\ \Omega_m\ \rho_{crit})^{1/3}$ can be measured.

(Right) the degeneracy can be broken measuring the evolution of n(M), due to the dependence of the growth factor primarily on Ω_m , weakly on Ω_Λ at



r.m.s density fluctuation within a top-hat sphere of $8h^{-1}$Mpc radius
⇔ Amplitude of P(k)

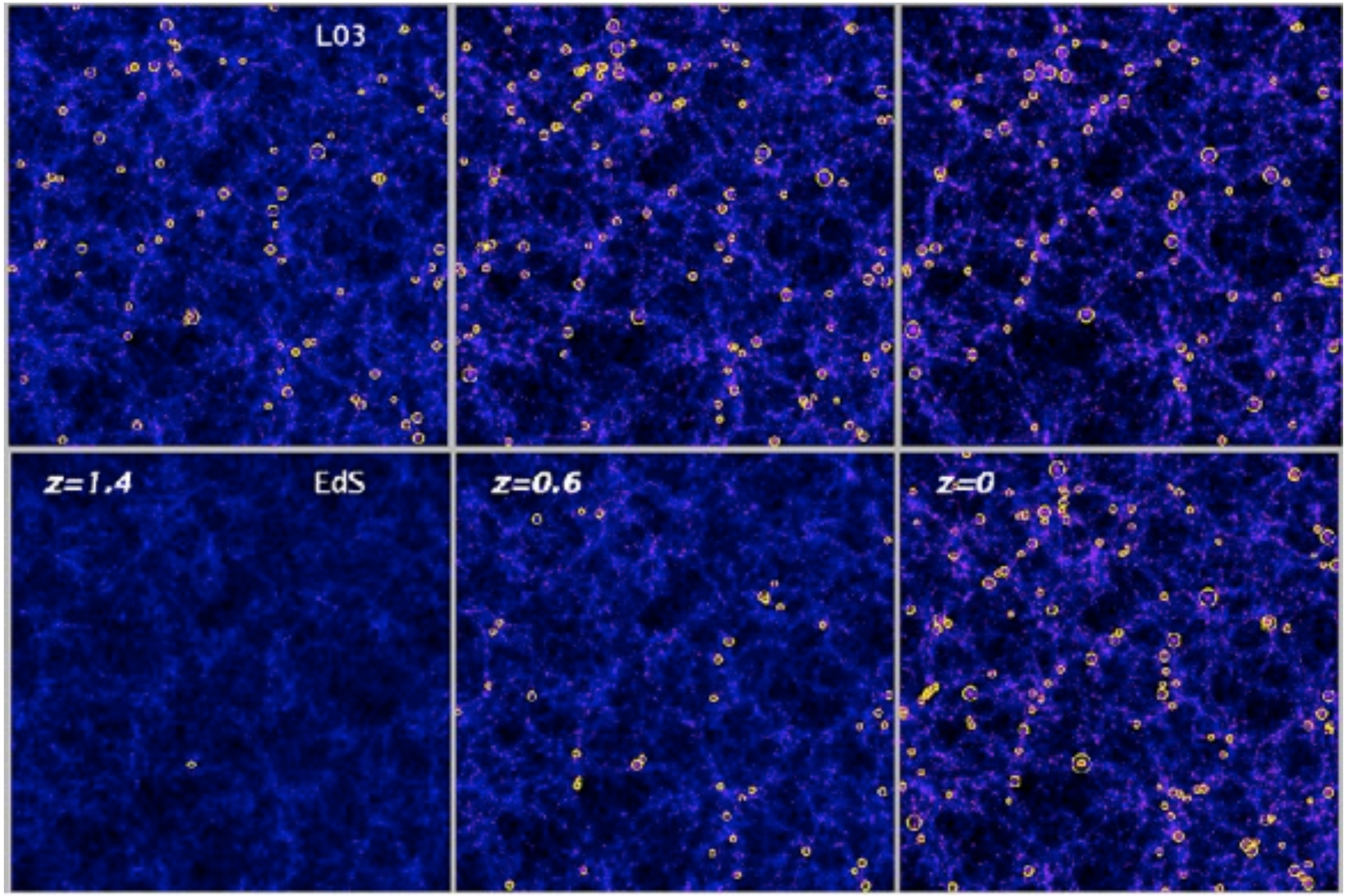


Rosati, Borgani & Norman 03

Evolution of cluster abundance (DM only)

Ω_m=1- Ω_Λ=0.3

EdS
(Ω_m=1)



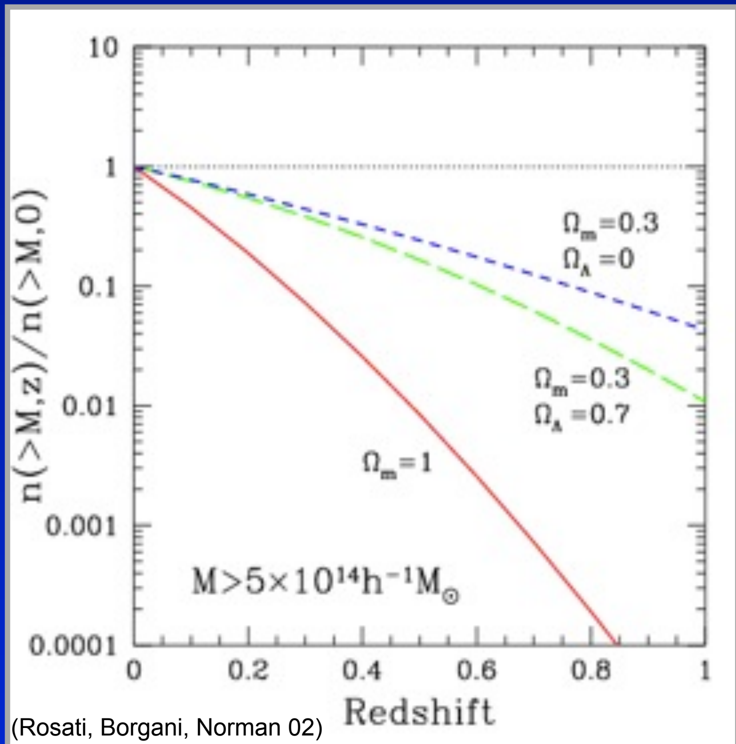
Normalized to cluster abundance at z=0; `circles`**: clusters with T>3 keV, size∝T** (Borgani & Guzzo 2001)

Theory vs Observations

- Current numerical simulation accurately reproduce the behaviour of the dominant (80-90% in mass) dark component (pure gravitational interactions)
- Current models finds it difficult to accurately predict the observed behaviour of the baryonic component <u>mostly in the cores</u>
- Galaxy formation alters the state of the cluster's ICM in a way difficult to model:
  - cold and hot phases of the baryonic component are interlinked via "feedback" from stellar and black hole accretion (AGN) processes
  - relations to derive masses from observations of baryons (hot gas, galaxies) are affected by this difficult physics

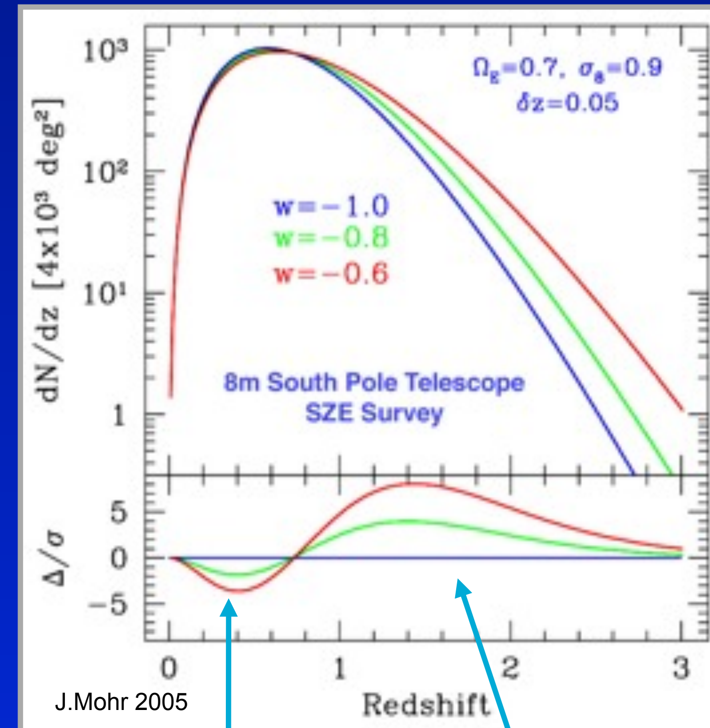
➡ Linking cluster masses in simulations with observations is the main source of uncertainty when using clusters for precision cosmology

Precision Cosmology from Cluster Abundance ?



(Rosati, Borgani, Norman 02)

Methodology



J.Mohr 2005

Volume effect

Growth effect

Geometry

$$\frac{d^3N}{dM\,d\Omega\,dz}(M,z) = \frac{dn_M}{dM}(M,z)\cdot\frac{d^2V_{\rm com}}{dz\,d\Omega}(z)$$

MF evolution:
robust prediction from
large N-body simulations

$$\frac{dn_M}{dM}(M,z) = \frac{dn_X}{dX}(M,z)\cdot\frac{dX}{dM}(M,z)$$

X: observable proxy of the total mass
(L_X, T, Y_{SZ}, Y_X, M_{gas}, M_{opt}, σ_V..)

☛ Need $\langle X\rangle(M,z)$ and $\sigma_X(M,z)$

Observed
(robust for X-ray selection)

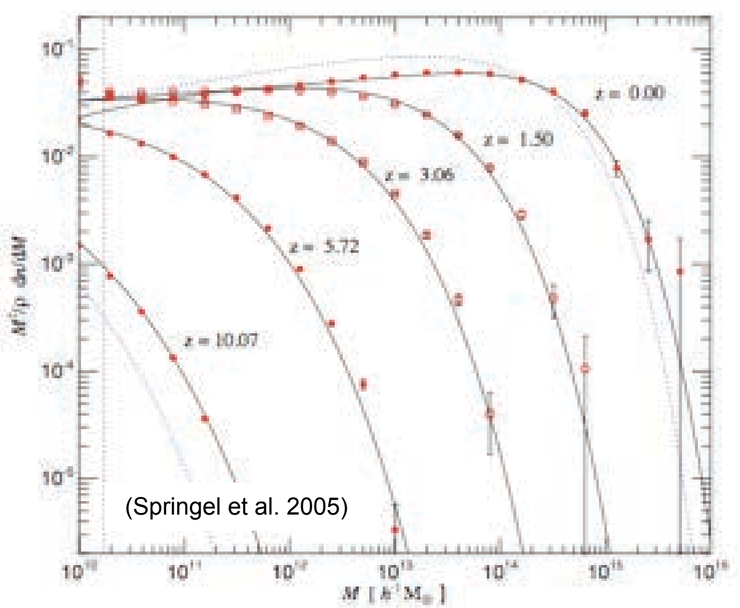
Empirical (scaling relations), Hydro-simulations
(uncertainties due to complex cluster physics)

Methodology: matching predicted with observed quantities, marginalizing over a set of cosmological parameters $\{\sigma_8, \Omega_M, \Omega_\Lambda, (\Omega_{DE}, w), w', ...\}$ and astrophysical (“nuisance”) parameters $\{\alpha_1, \alpha_2, ...\}$

How to compute the cluster mass function

$$\frac{d^3N}{dM\,d\Omega\,dz}(M,z) = \frac{dn_M}{dM}(M,z) \cdot \frac{d^2V_{\rm com}}{dz d\Omega}(z)$$

Growth of perturbations: robust prediction from large N-body simulations



Borgani 06

Geometry

$$\frac{dV}{d\Omega dz} = \frac{c}{H(z)} D_A^2(z)(1+z)^2$$

from FRW metric

$$\mathrm{H}^2(z) = H_0^2[\Omega_M(1+z)^3 + \Omega_\Lambda(1+z)^{3(1+w)} + (1-\Omega_0)(1+z)]$$

Several analytic approximations exists for the mass function (Press-Schecter; Sheth-Tormen; Jenkins)

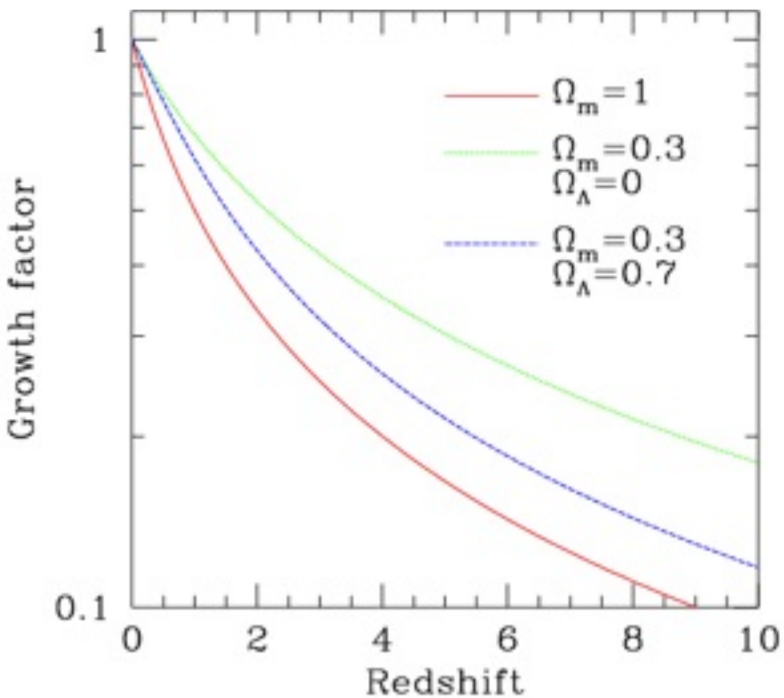
How to compute the cluster mass function

$$\frac{d^3N}{dM\,d\Omega\,dz}(M,z) = \frac{dn_M}{dM}(M,z)\cdot\frac{d^2V_{\rm com}}{dz d\Omega}(z)$$

Growth of perturbations:
robust prediction from
large N-body simulations

Geometry

$$D_+(z) = \frac{5}{2}\,\Omega_m E(z)\int_z^\infty \frac{1+z'}{E(z')^3}\,dz'$$



$$\frac{\partial^2\delta}{\partial t^2} + 2H(t)\frac{\partial\delta}{\partial t} - 4\pi G\bar{\rho}\delta = 0\,.$$

$$\frac{dV}{d\Omega dz} = \frac{c}{H(z)}D_A^2(z)(1+z)^2$$

from FRW metric

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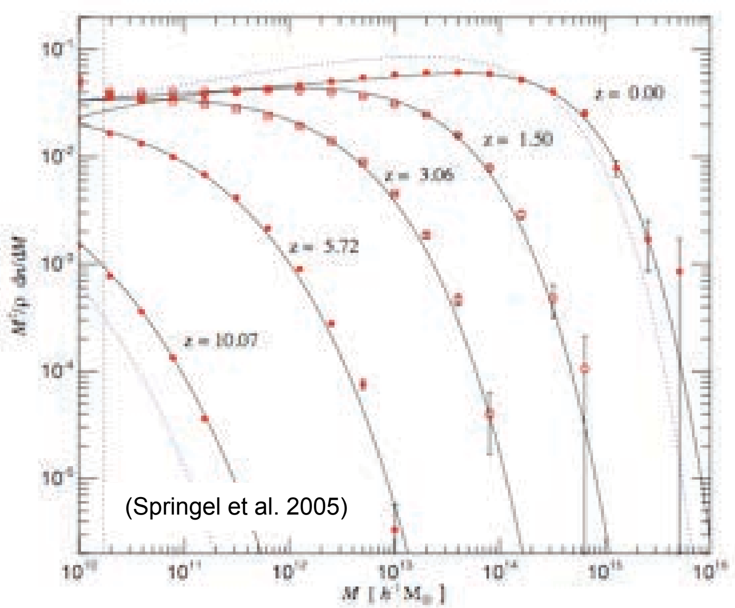

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The redshift distribution of clusters per unit solid angle is obtained by integrating the MF weighted by the survey selection function *f(M,z)*

Geometry   Selection fnct   Growth

$$\frac{d^2N}{dz\,d\Omega}(z) = \frac{d^2V}{dz\,d\Omega}(z)\,N_{com}(z) = \frac{c}{H(z)}D_A^2(1+z)^2\int_0^\infty dM\,f(M,z)\frac{dn}{dM}(M,z)$$

How to determine the mass function from observations

X-ray selection has provided the best way so far to trace the evolution of the space density of clusters of <u>a given mass</u>, i.e. to estimate the evolution of the cluster mass function

$$\frac{dn_M}{dM}(M,z) = \frac{dn_X}{dX}(M,z)\,\frac{dX}{dM}(M,z)$$

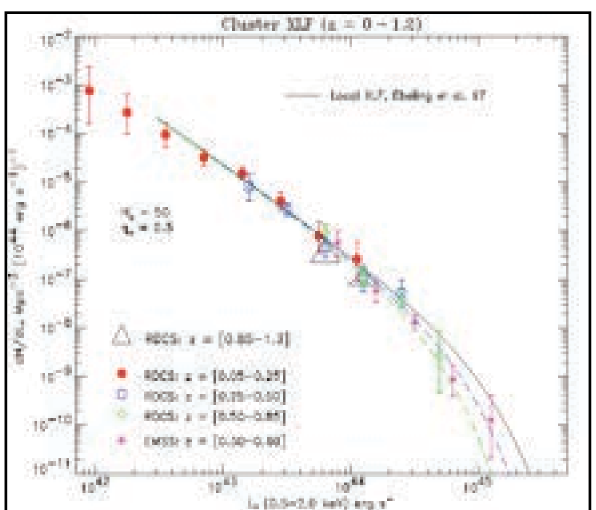
Observed
(e.g. X-ray Luminosity Fnct)

X: observable proxy of the total mass
(L_x, T, Y_{SZ}, Y_x, M_{gas}, M_{opt}, σ_V..)

☛ Need $\langle X\rangle(M,z)$ and $\sigma_X(M,z)$

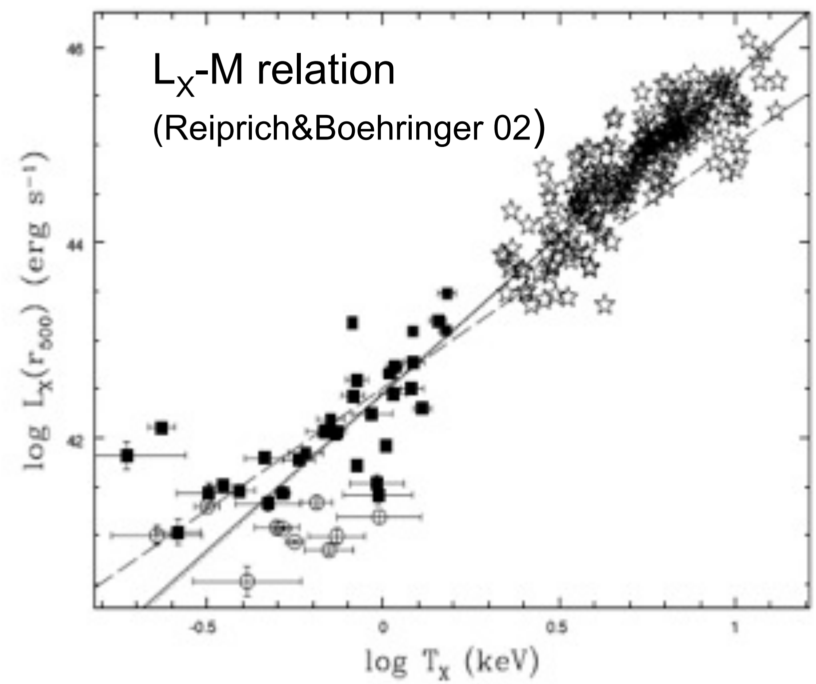
Empirical (scaling relations), Hydro-simulations
(uncertainties due to complex cluster physics)

Observed space density of clusters (i.e. XLF)



Mass calibration is critical:

L_x–M, T–M, Y_x–M, ...



Cluster scaling relations

Mass ↔ Thermodynamical quantities

- **Astrophysics**: deviations from self-similar model, impact of galaxy formation on ICM
- **Cosmology**: calibration of "mass-proxy" (observable)-mass relation

The simple self-similar model (Kaiser 1986) assumes that gravitational collapse is scale free (in an EdS universe) and that the density and T distribution of ICM are independent of cluster mass.

To link the observations to theoretical models is convenient to define the cluster mass as M_Δ : the matter contained in a spherical region of radius $r = R_\Delta$ whose mean density is $\Delta \times \rho_c(z)$, so that $M_\Delta(<r) = 4/3\pi\, R_\Delta^3\, \Delta\, \rho_c(z)$

$$\rho_c(z) = \frac{3H^2(z)}{8\pi G} = \rho_c(0)E^2(z) \qquad E^2(z) = [\Omega_M(1+z)^3 + (1-\Omega_M-\Omega_\Lambda)(1+z)^2 + \Omega_\Lambda]$$

The virial mass is obtained taking $\Delta = \Delta_v \cong \underbrace{18\pi^2}_{178} + 82[\Omega_M(z)-1] - 39[\Omega_M(z)-1]^2$

The L-T and M-T relations in case of self-similarity and comparison with observations

From hydrostatic equilibrium M(R)=T • R, $R_\Delta \propto M_\Delta^{1/3} E^{-2/3}(z)$

$$\Rightarrow \quad T \propto \frac{M}{R} \propto M_\Delta^{2/3} E^{-2/3}(z)$$ **M-T relation**

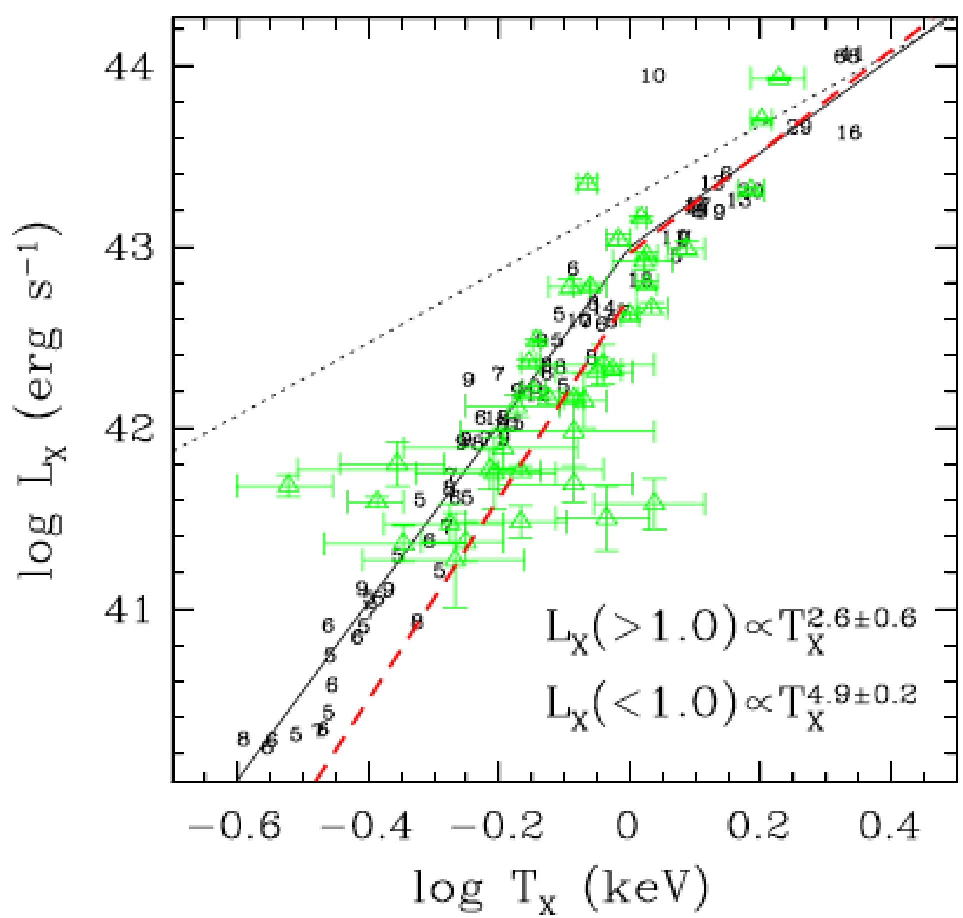
$$L_X \propto \int \epsilon_\nu dV \propto \rho_g^2 T^{1/2} M_\Delta / \rho_g = \rho_g M_\Delta T^{1/2} \propto T^2 E(z)$$ **L-T relation**

$$L_X \propto M^{4/3} E(z)^{7/3}$$

The L-T relation deviates from the self-similar case: L ~ T ^{2}

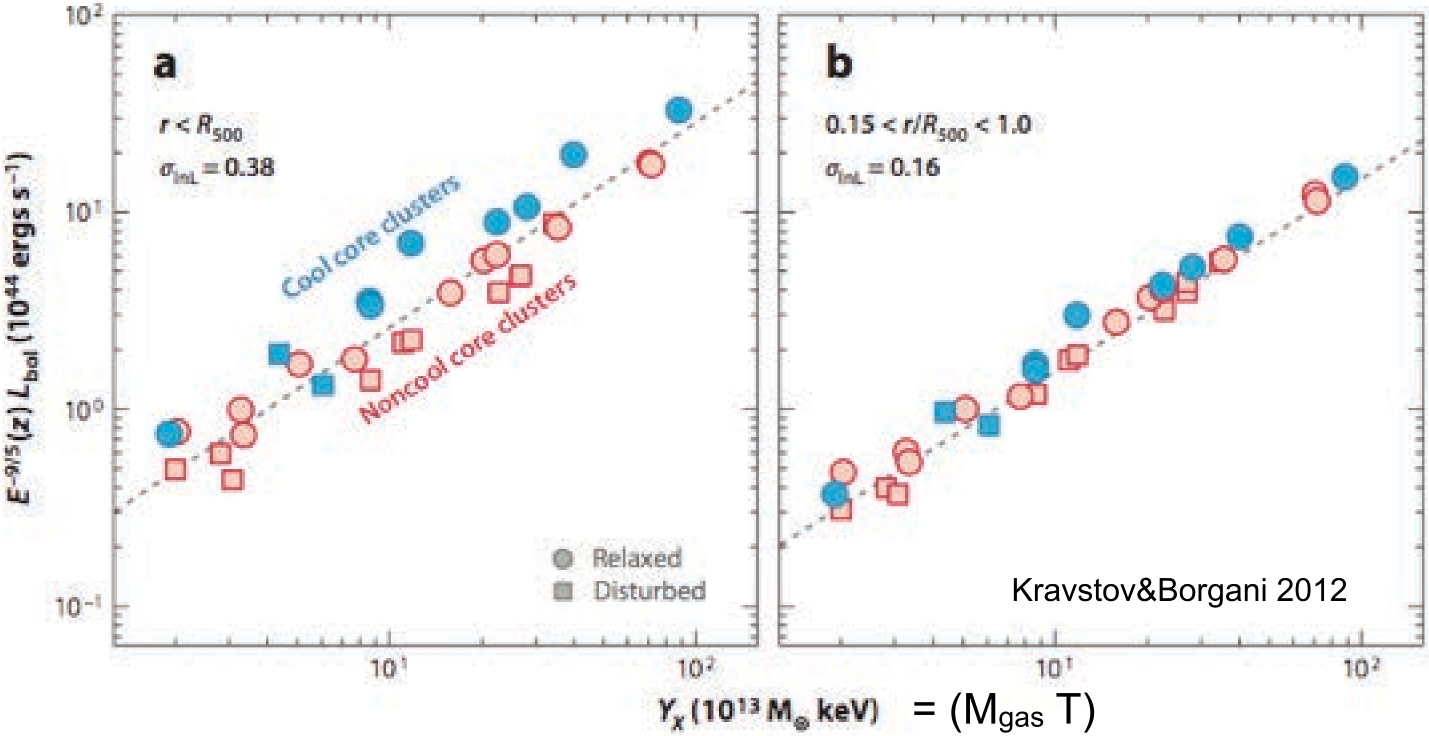
- On group scales non-gravitational effects dominate (elevated entropy makes it harder to compress the gas)
- For massive clusters (gravity dominates) self-similar relations are recovered, with the exception of their cores

The M-T relation is found to have the self-similar slope (M~T$^{3/2}$) but a 40% lower normalization



Cluster scaling relations

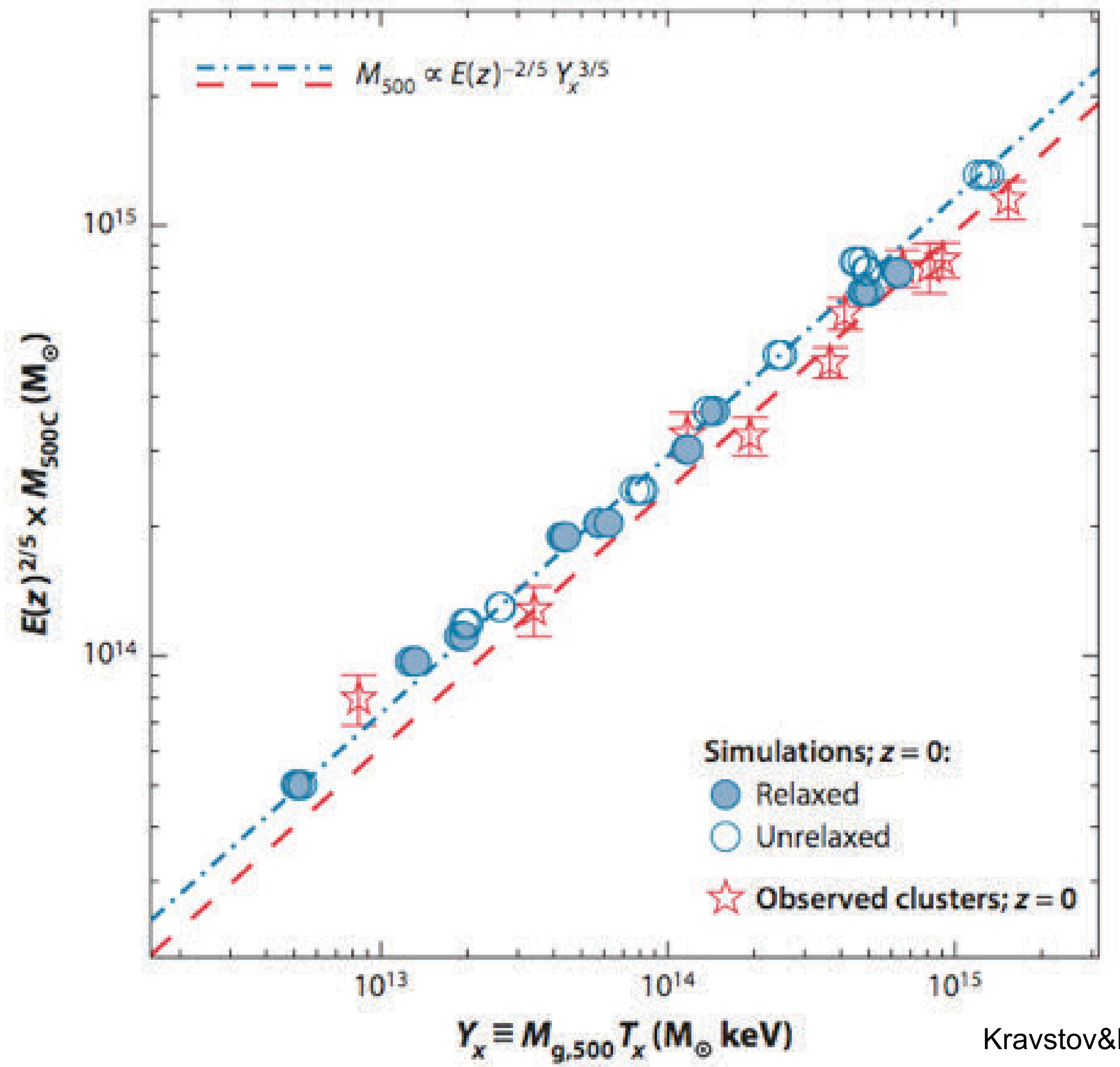
Solution: remove the cores !



- Correlation of X-ray observable quantities with total mass becomes tight when cores are excised. Need to have adequate resolution to do it at high-z.
- Clusters show remarkable regularities, we do understand cluster physics after all !

Cluster scaling relations

A popular mass proxy: $Y_X = M_{gas}\,T$



Kravstov&Borgani 2012

Cluster abundance from X-ray Luminosity Function

The cluster XLF is modelled as a Schechter function:

$$\phi(L_X)dL_X = \phi^* \left(\frac{L_X}{L_X^*}\right)^{-\alpha} \exp(-L_X/L_X^*)\,\frac{dL_X}{L_X^*},$$

A binned representation used to derive the LF from a flux-limited cluster sample is:

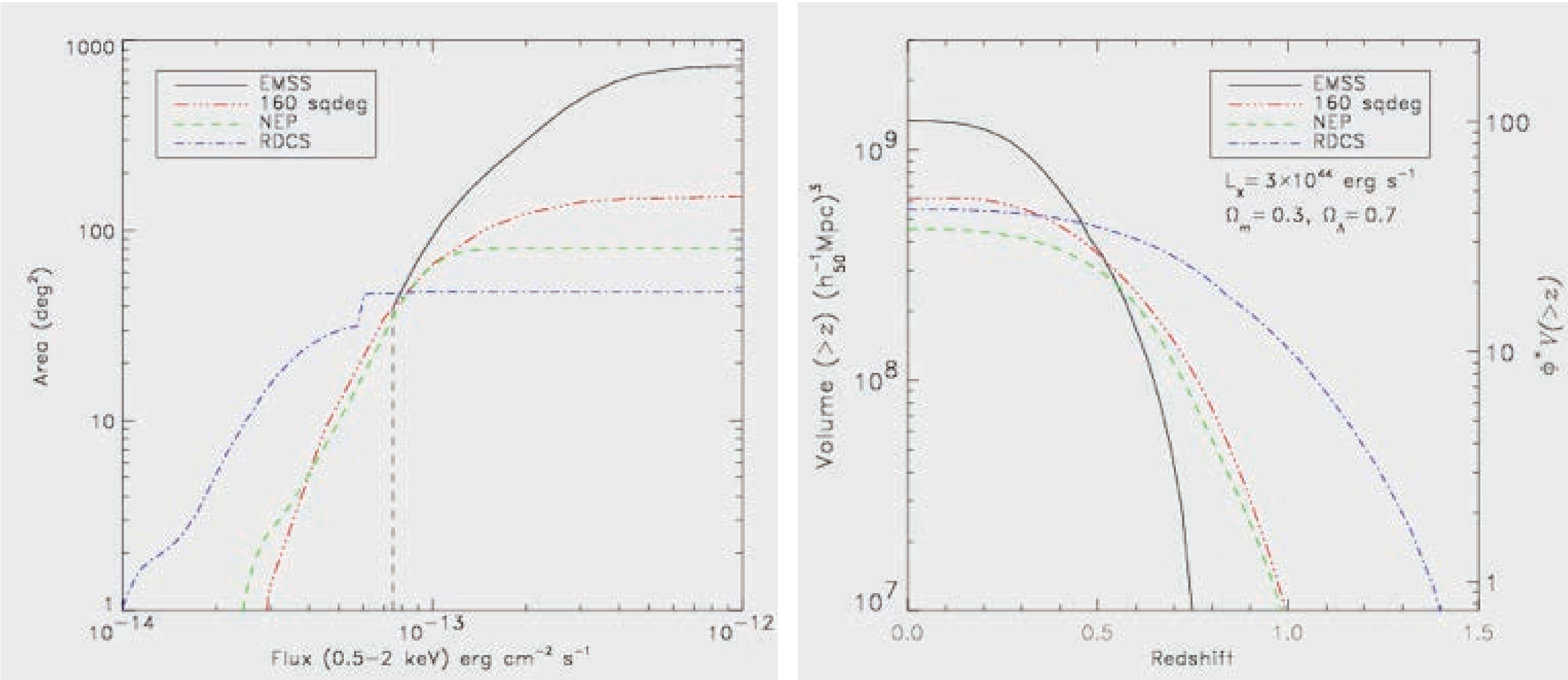
$$\phi(L_X) = \left(\frac{1}{\Delta L_X}\right) \sum_{i=1}^{n} \frac{1}{V_{max}(L_i,\, f_{lim})},$$

where V_{max} is the total search volume defined as

$$V_{max} = \int_0^{z_{max}} S[f(L,z)] \left(\frac{d_L(z)}{1+z}\right)^2 \frac{c\,dz}{H(z)}.$$

S(f) is the sky coverage depending on the flux $f = L/(4\pi d_L^2)$

X-ray Surveys Selection Functions

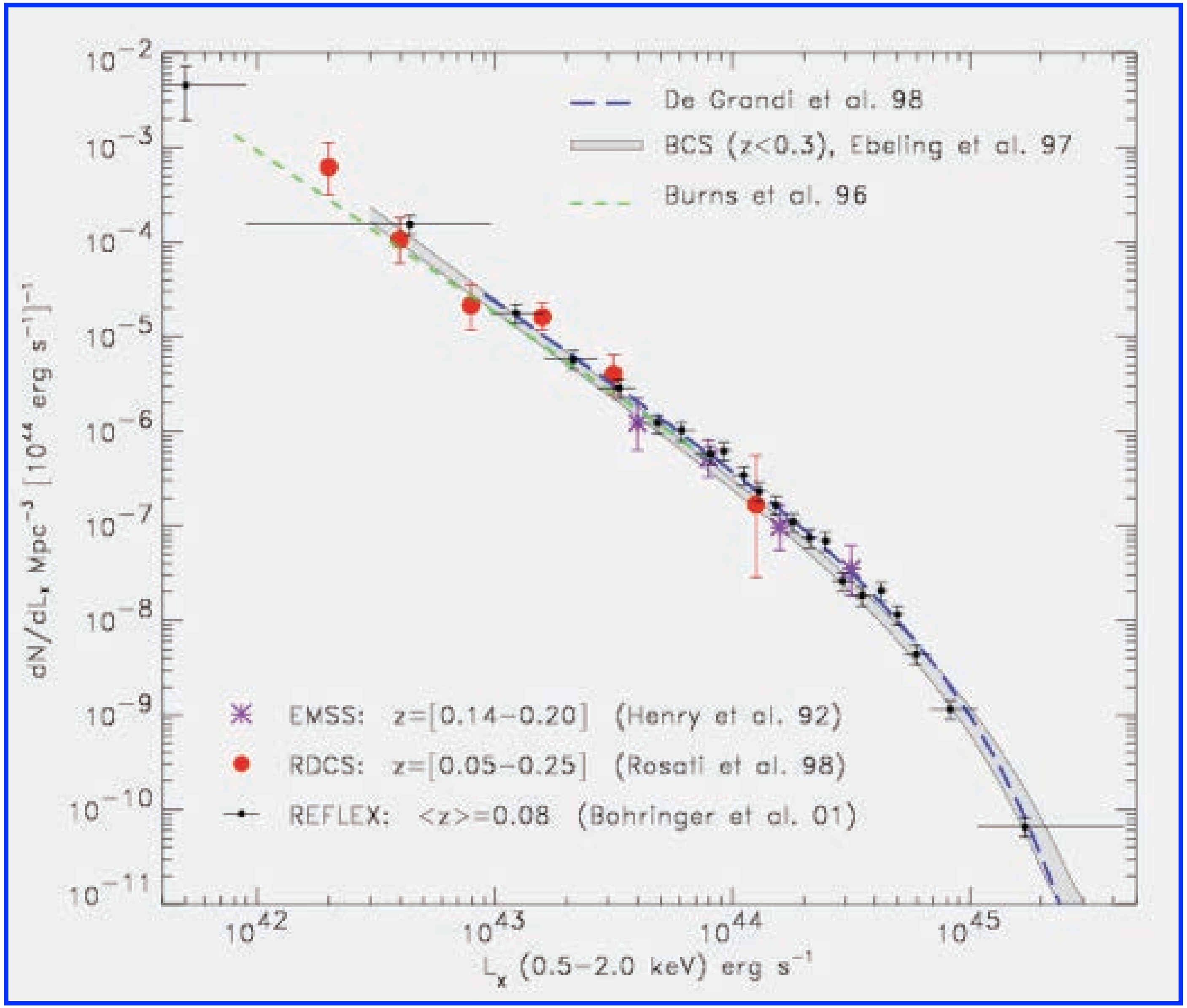


(RBN 2002)

- Area and Depth determine the sensitivity to distant clusters and the probed range of the XLF, i.e. the expected f(M,z) distribution for given evolution of the mass function
- Complementary surveys need to be used to adequately range the demographics of the entire cluster population (as a funct. of M,and z)

Local Space Density of Clusters

$$\phi(L_X)dL_X = \phi^*\left(\frac{L_X}{L_X^*}\right)^{-\alpha}\exp(-L_X/L_X^*)\frac{dL_X}{L_X^*},$$

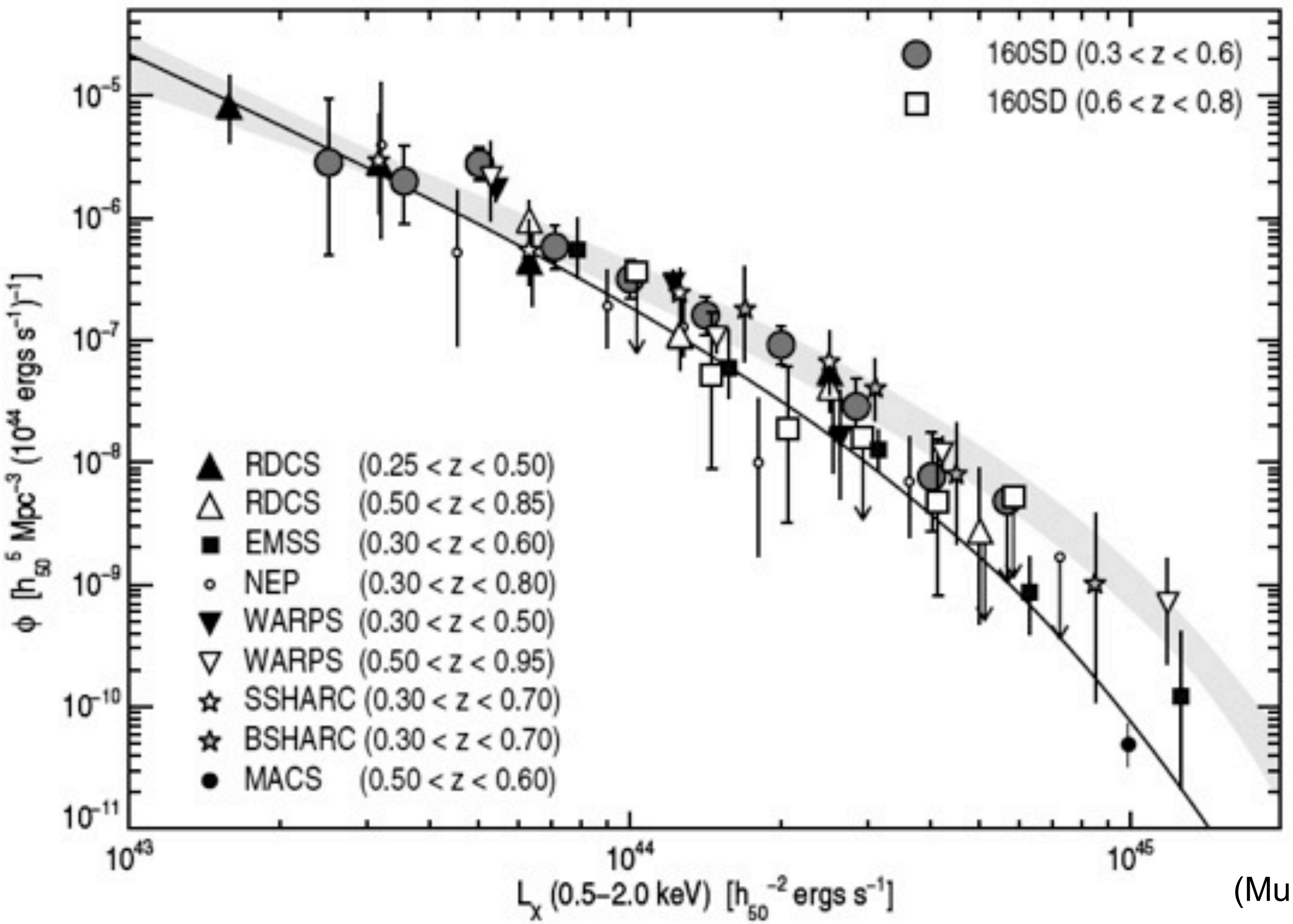


(RBN 2002)

- Different surveys, using independent methods, same results!

  → The determination of the local cluster abundance is **solid** today

Summary of Cluster XLFs of Distant Clusters



(Mullis et al. 04)

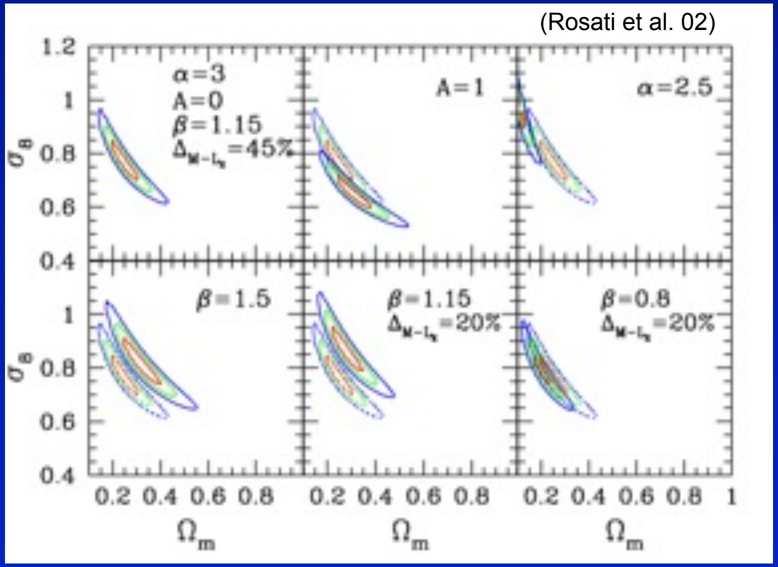
- The determination of the cluster space density out to z=0.9, for systems at (0.1-5)L*, is rather solid today

Cosmological constraints (early results)

Cluster abundance

Borgani et al. 2002: combining XLF evolution with scaling relations $L_X \rightarrow T \rightarrow M$ using 81 RDCS clusters

$\sigma_8=0.72\pm0.05$ (±0.05)
for $\Omega_M=0.3$

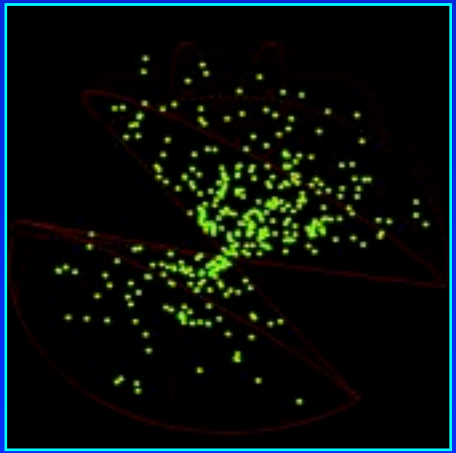


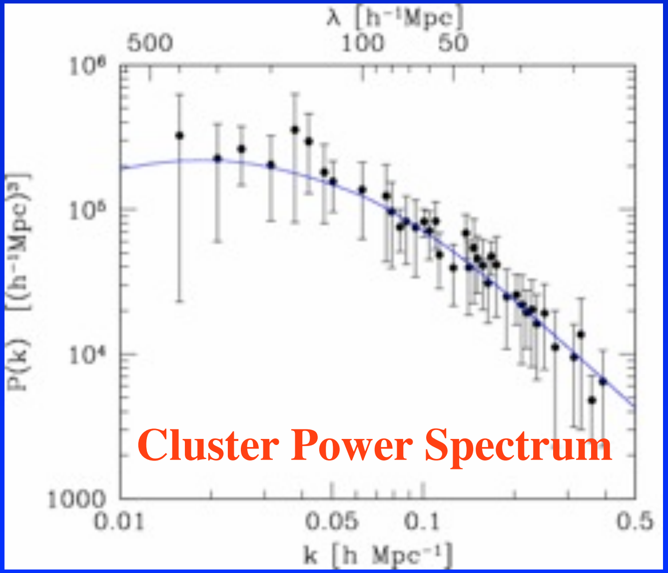
Conversion of observables to cluster mass:

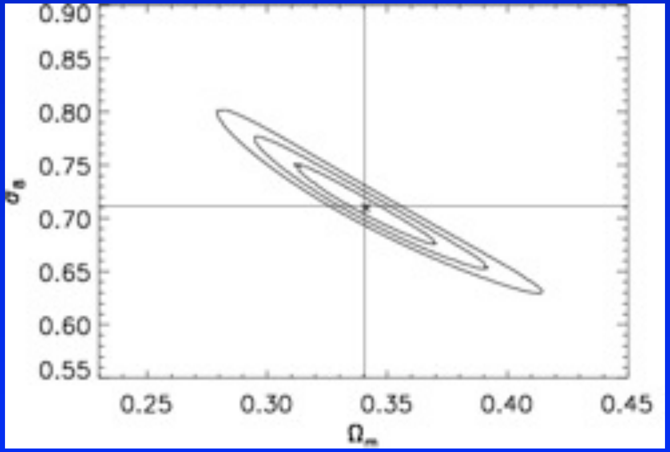
- L-T slope: L~T $^{\alpha}$
- L-T evolution: L~$(1+z)^{A}$
- M-T normalization β
- L-M intrinsic scatter Δ_{M-L}

Cluster Power Spectrum

Schuecker et al. 2003: combining cluster abundance (XLF) with Power Spectrum (clustering) using 452 REFLEX clusters

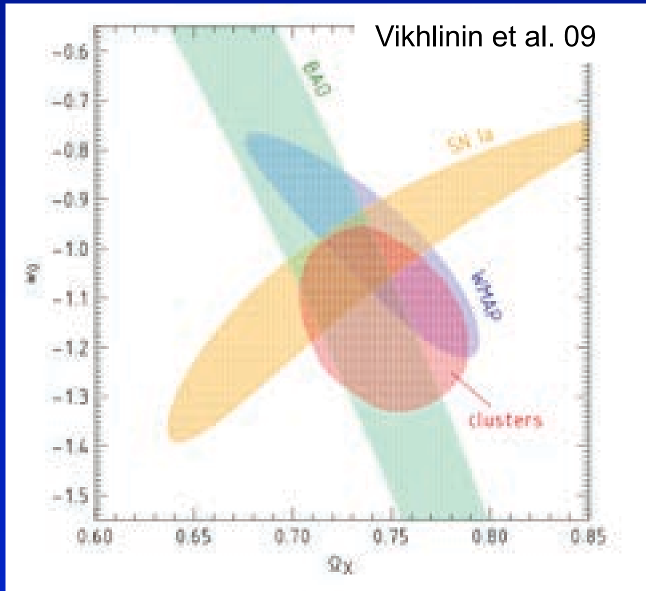




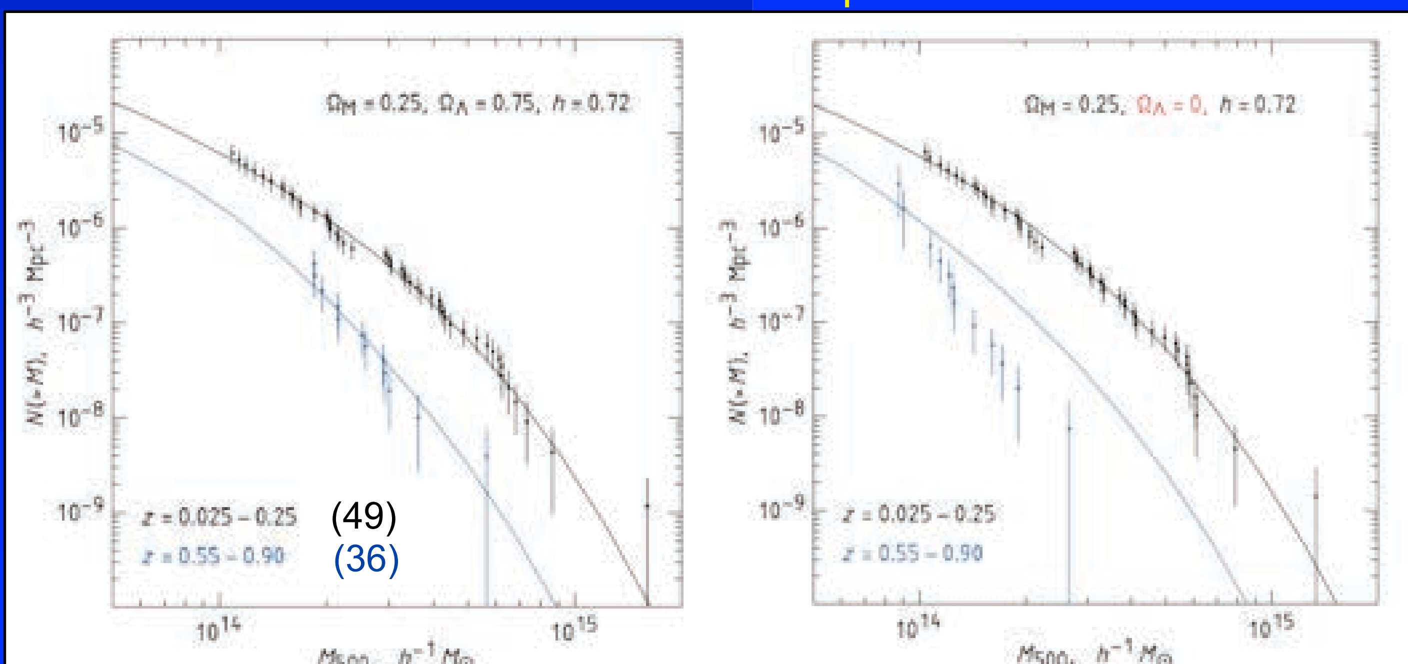


$\sigma_8=0.71\pm0.03$ (±0.08)
$\Omega_M=0.34\pm0.03$ (±0.1)
($\Omega_T=1$, $\Omega_b h^2=0.020$, $n_s=1$)

Cosmological constraints from Cluster evolution (latest work)



- X-ray clusters samples have not changes in the last 10-15 years (still ROSAT based, sample size~100)
- All studies in last decade have focused on mass calibration, i.e. reducing systematics:
  - follow-up Chandra and XMM observations and weak lensing of 50-100 clusters out to z~1.4
  - large investments of cosmological simulations and theoretical studies to model scaling relations, and quantify systematics (robustness of mass proxies)
- Vikhlinin et al. 09: 85 ROSAT clusters at z<0.9 with follow-up Chandra data for robust mass proxies (M_{gas}, Y_X)



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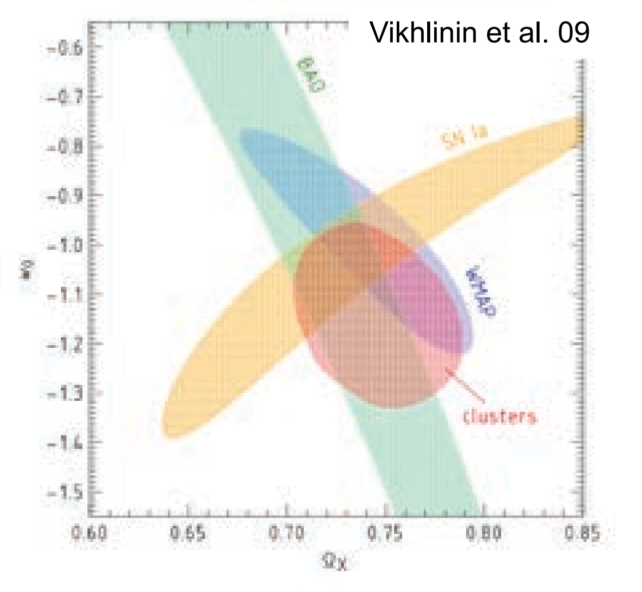

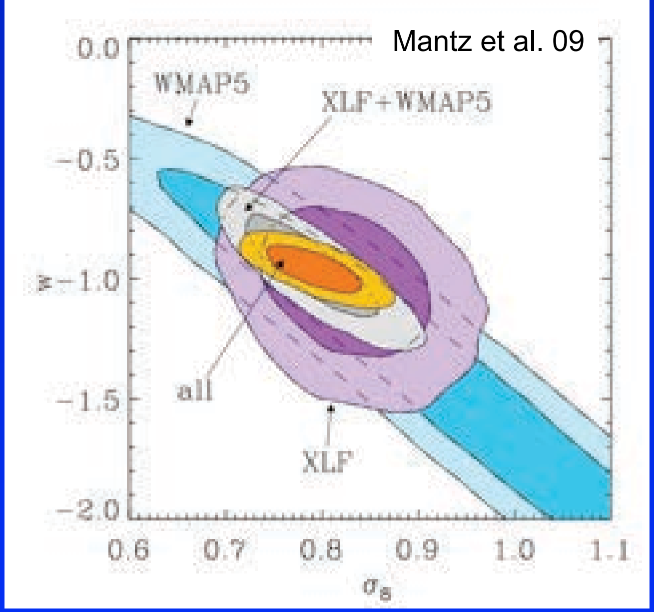

Also: Allen et al. 08 ; Henry et al. 09; ....

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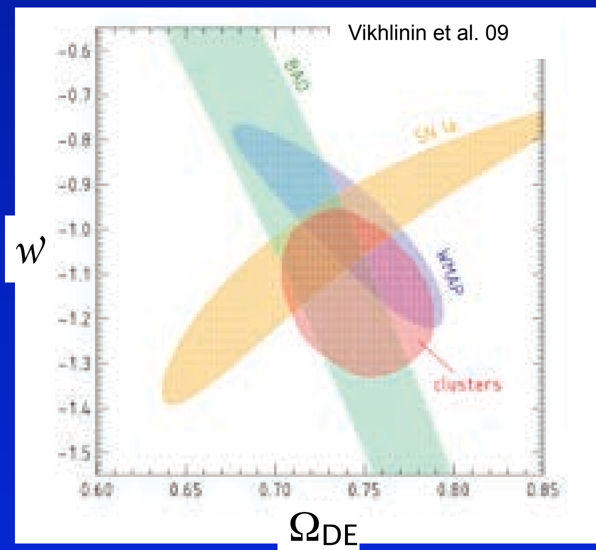
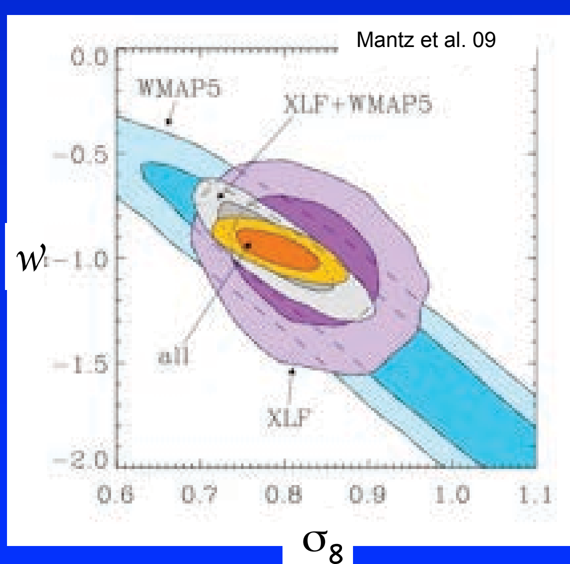
- Vikhlinin et al. 09: 85 ROSAT clusters at z<0.9 with follow-up Chandra data for robust mass proxies (M_{gas}, Y_X)
- Cosmological constraints from clusters to date provide useful complementary probes, not highly competitive today but they are based on ~10^2 clusters only!
- High yield, large area surveys are needed to explore and control multi-parameter systematics

Precision Cosmology from Cluster Abundance ?

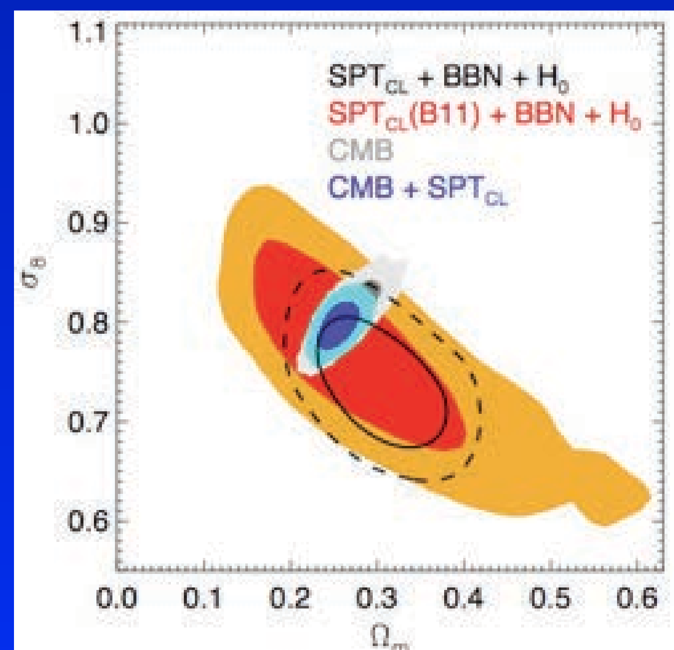
X-ray: small (N~100) ROSAT based samples !
L_x linked to M with caveats





Score card

Key properties	X-ray	Opt/NIR	SZ
Sample size			
Mass calibration			
Selection function			
Extension to high-z			



First results from SZ cluster samples, still early days..

The Y-M relation needs to be calibrated!

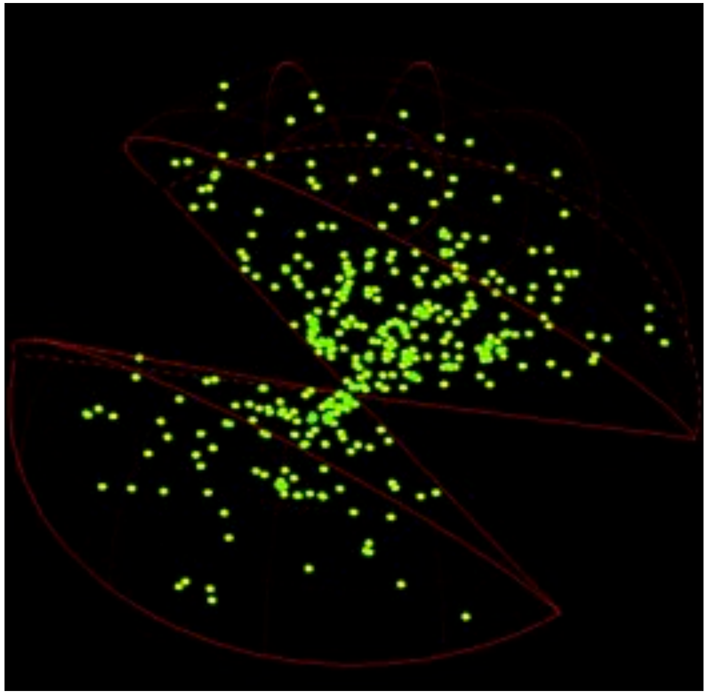
Y is directly linked to M but is a noisy measure

SZ surveys will soon combined cluster abundance with Power Spectrum)

$\Rightarrow$ stronger constraints on σ_8, Ω_M, Ω_{DE}, w, w', ...

Power Spectrum of the distribution of Clusters

- Clusters have a clustering amplitude much larger than galaxies (corr. length for clusters $r_0 \approx 20h^{-1}$ Mpc $\approx$ 4 times $r_{0,gal} \approx 5h^{-1}$Mpc)
- Strong clumpiness: clusters trace only the high-density peaks of underlying mass density field (more "biased" tracers of the mass distribution than galaxies)
- "bias factor" = $(\delta\rho/\rho)_{Xray}/ (\delta\rho/\rho)_{mass}$ easier to compute for clusters using the L_X-M relation $\Rightarrow$ P(k) can be predicted for a given cosmological model



- Fluctuations out to 500 Mpc scales can be probed with large cluster surveys
- "Concordance model" best fits the observed P(k) from the REFLEX survey (Schueker et al. 01)

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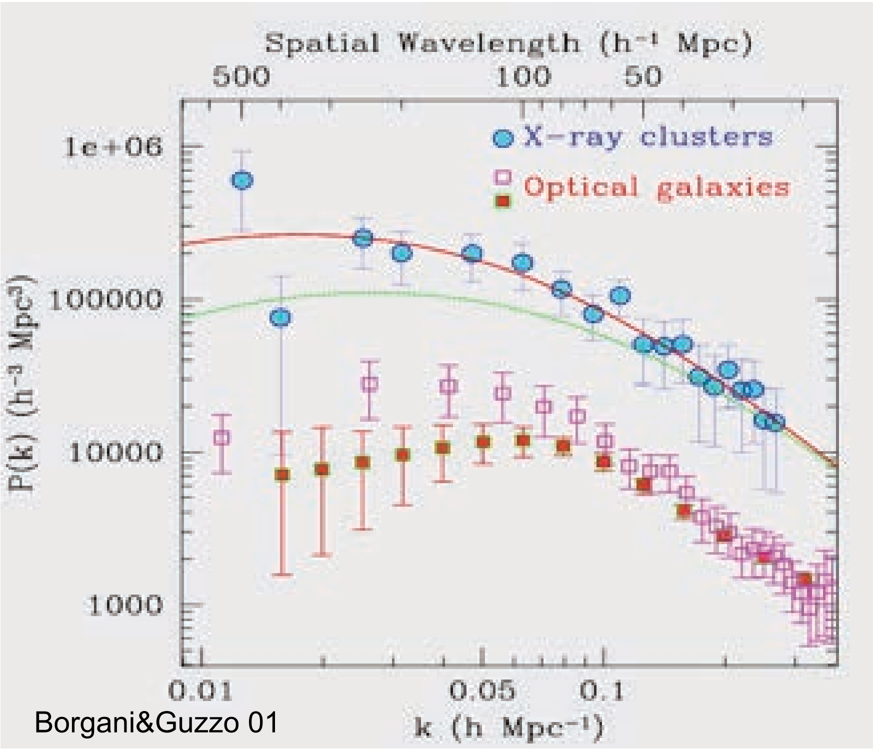

Flat models (Ω_T=1)

Ω_M=0.3

Ω_M=0.5

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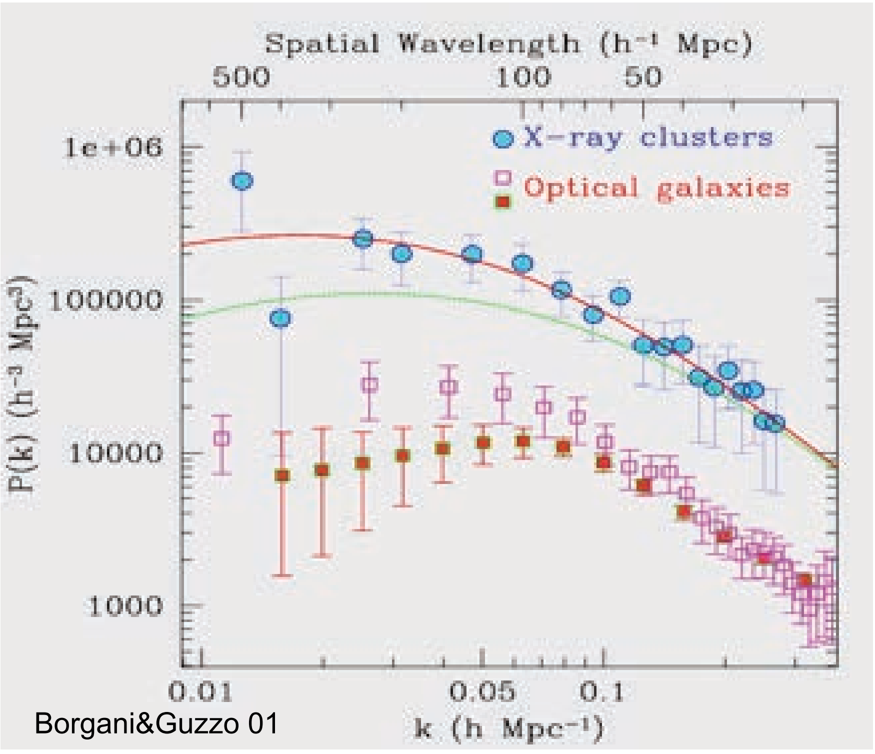
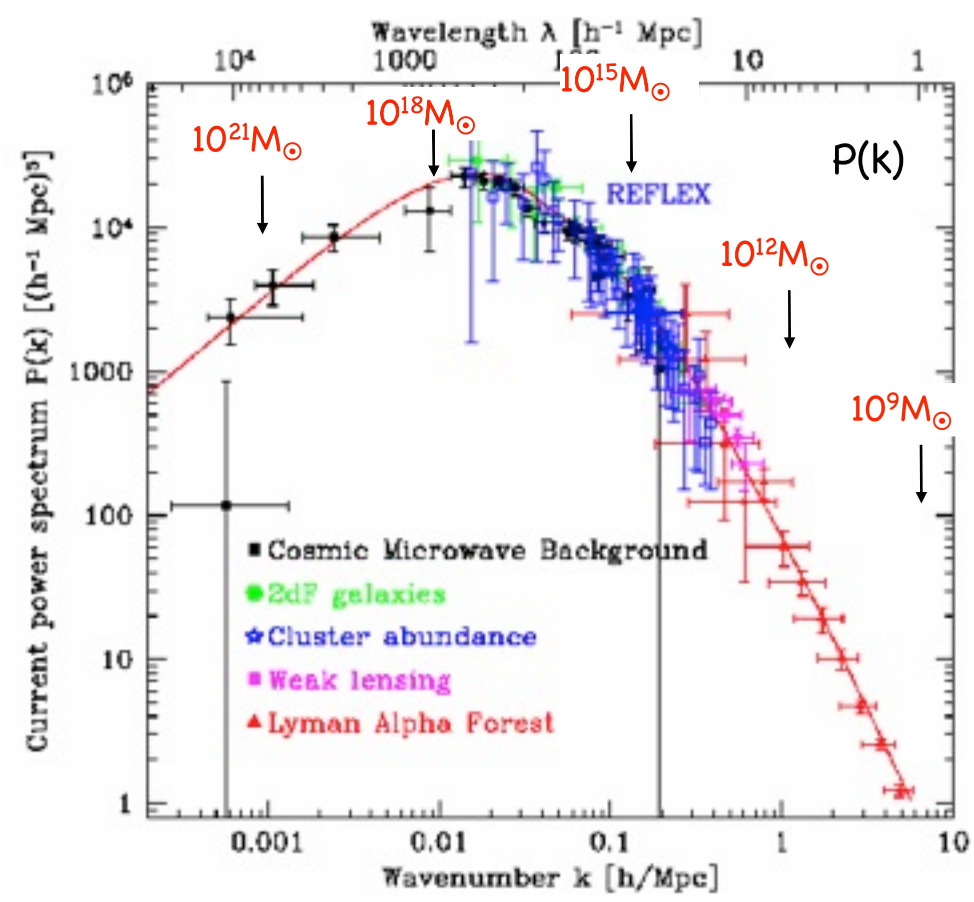


Borgani&Guzzo 01



(Tegmark + Schuecker 04)

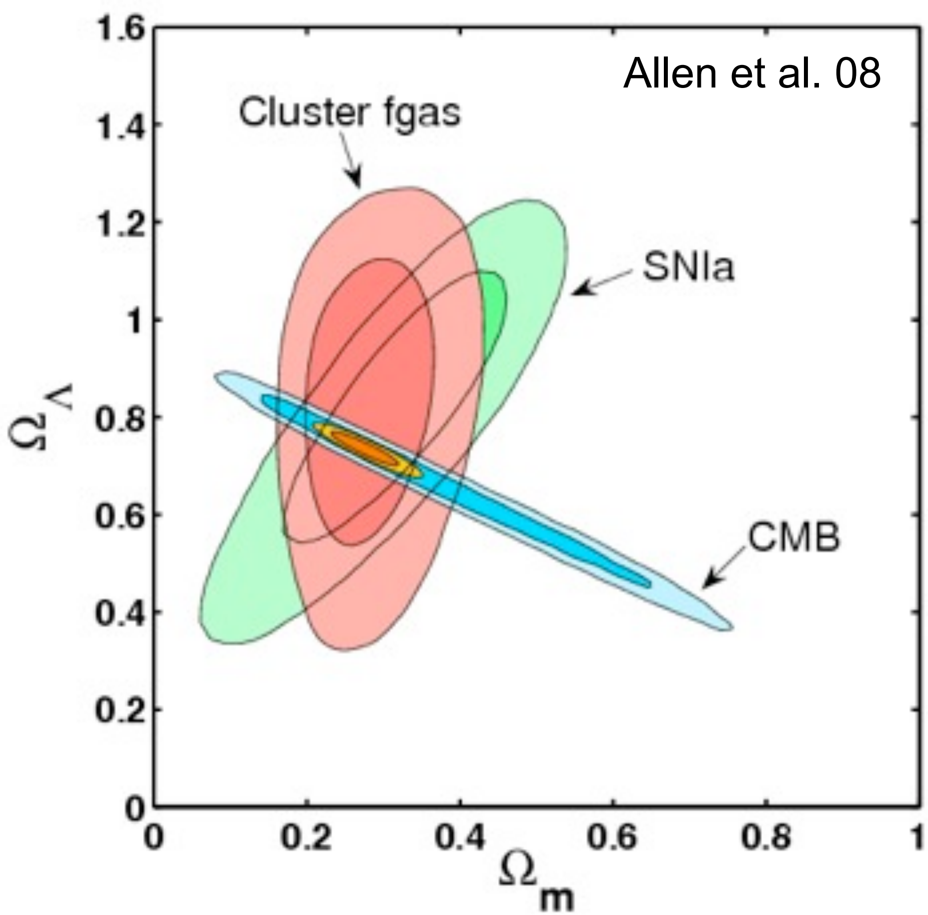
Constraining Ω_M and other parameters with the cluster gas fraction

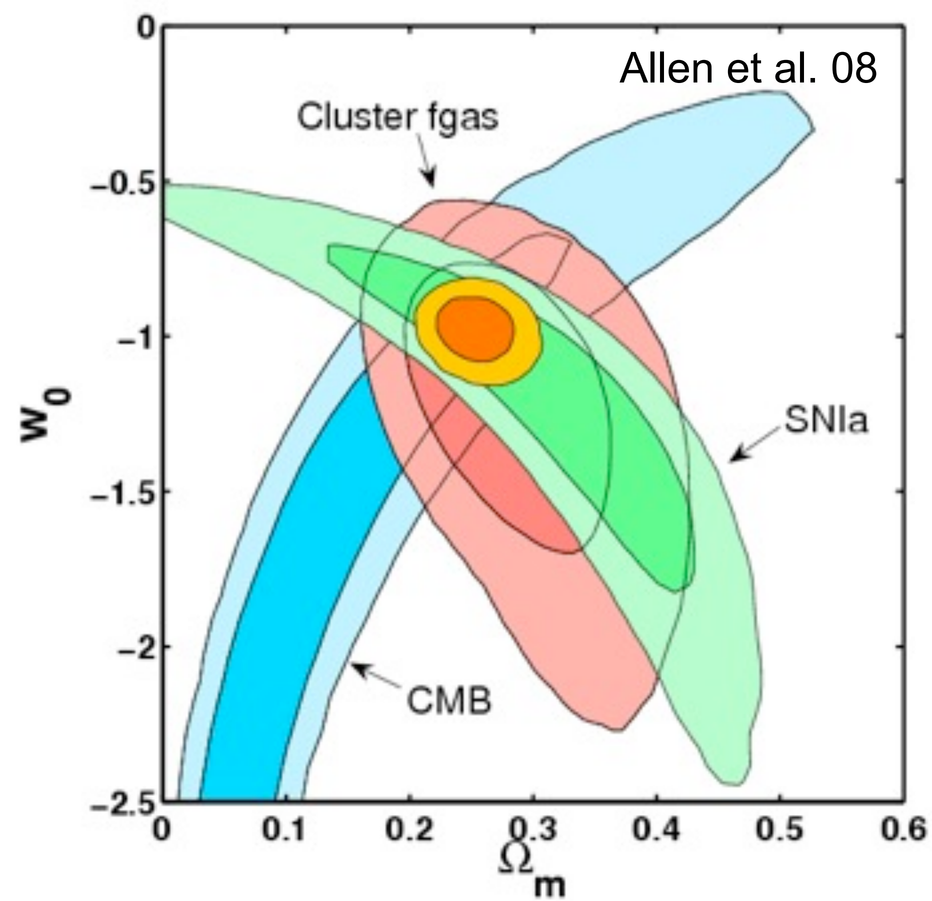
(White et al. 1993, Ettori et al. , Allen et al.)

1) $f_{bar} = b \cdot \Omega_b / \Omega_M$, $f_{bar} = f_{gas} + f_{star}$, $f_{star}=0.16\ h_{70}^{-1} f_{gas}$, $f_{gas}=0.11\ h_{70}^{-1.5}$

→ $\Omega_M = b\ \Omega_b / f_{gas}(1+f_{star}/f_{gas}) = 0.9*0.044/0.11(1+0.16) =$ **0.27 (±0.05)**

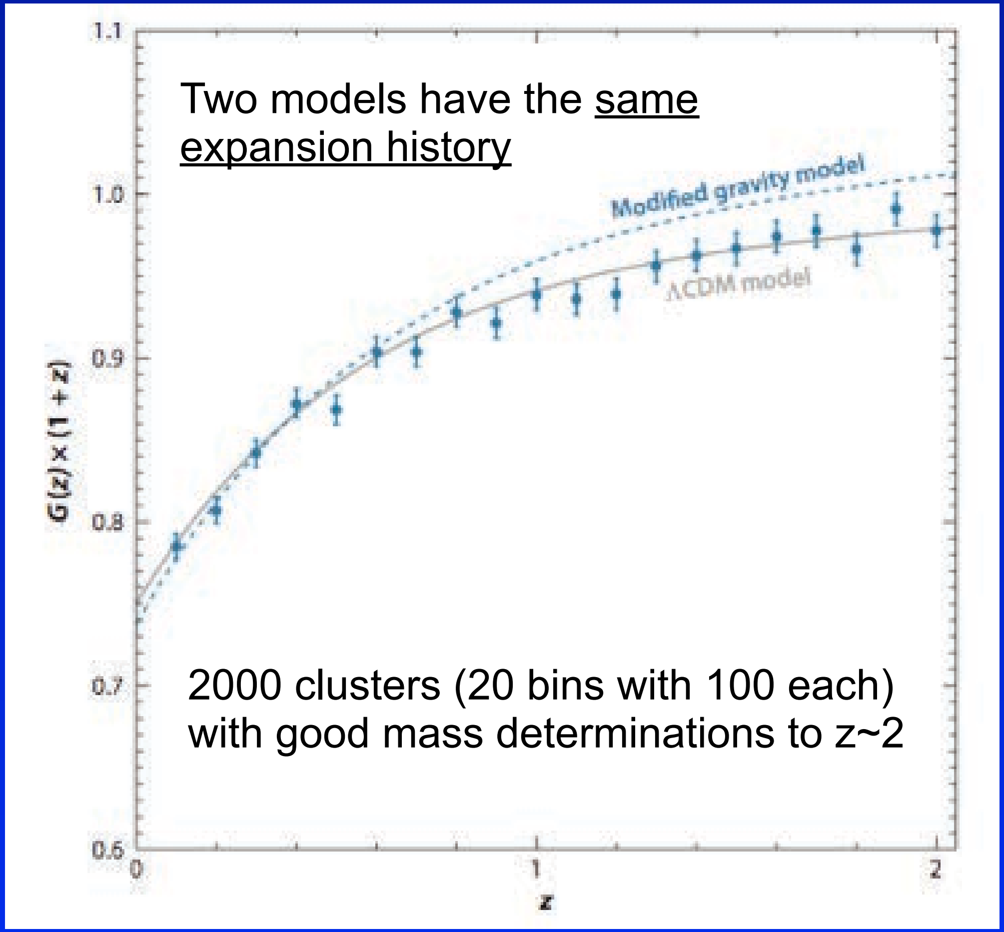
2) $f_{gas} \propto D_A(z,h,\Omega_M,\Omega_\Lambda)$, if $f_{gas}(z)$=const → f_{gas} is like a standard rod



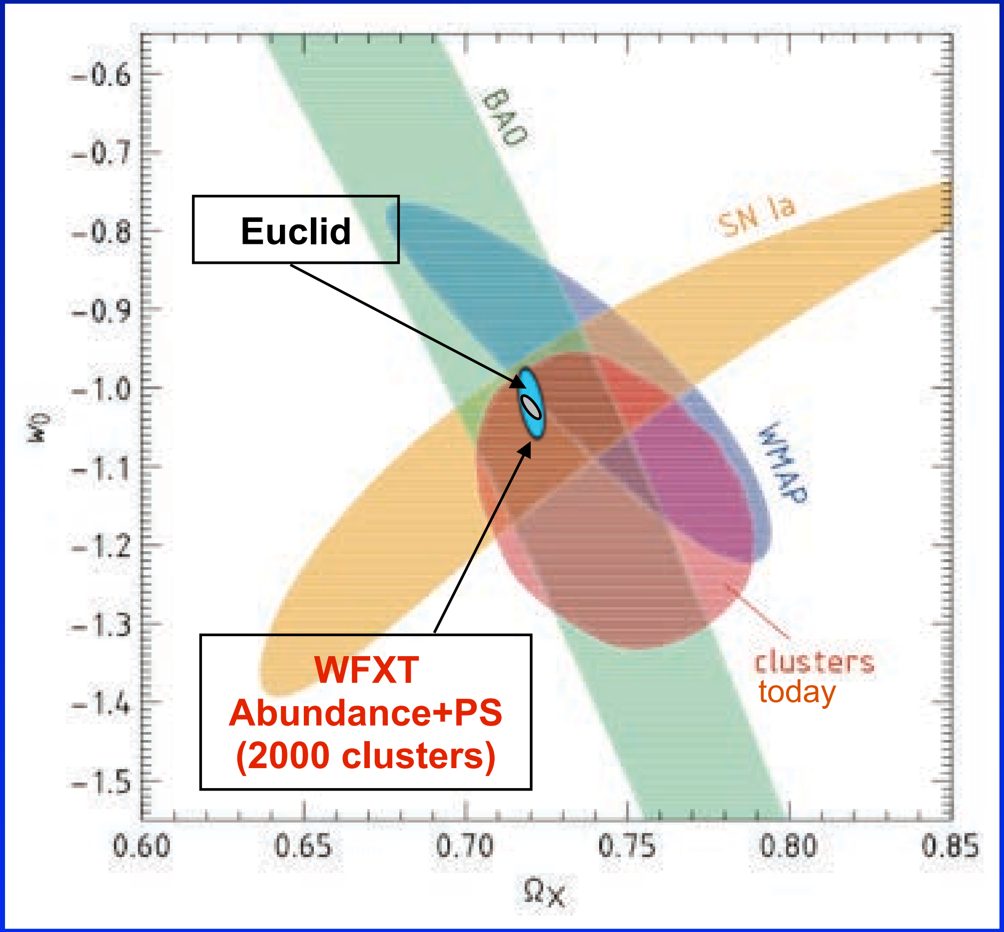


A glimpse of science from future cluster surveys ?

Testing deviations from GR



Vikhlinin et al. 2009



Sartoris et al. 2012

The special role of most distant clusters

- The most distant clusters provide a strong leverage:
  - ➡ on Dark Energy (w, w') probing growth rate at z>1
    in principle even a single very massive cluster at z>1 could create tension with LCDM scenario
  - ➡ on the formation of stellar populations in massive galaxies, mass assembly history, ICM enrichment and energy input

- Tremendous progress over the last 5 years thanks to a combination of
  - NIR: wide area Spitzer/IRAC +Optical
  - SZ: SPT: 2500 deg^2 (M_{lim}~$2x10^{14}$ $M_{\odot}$); ACT: 455 deg^2 (M_{lim} ~2x higher)
  - X-ray (serendipitous) surveys (almost only XMM)

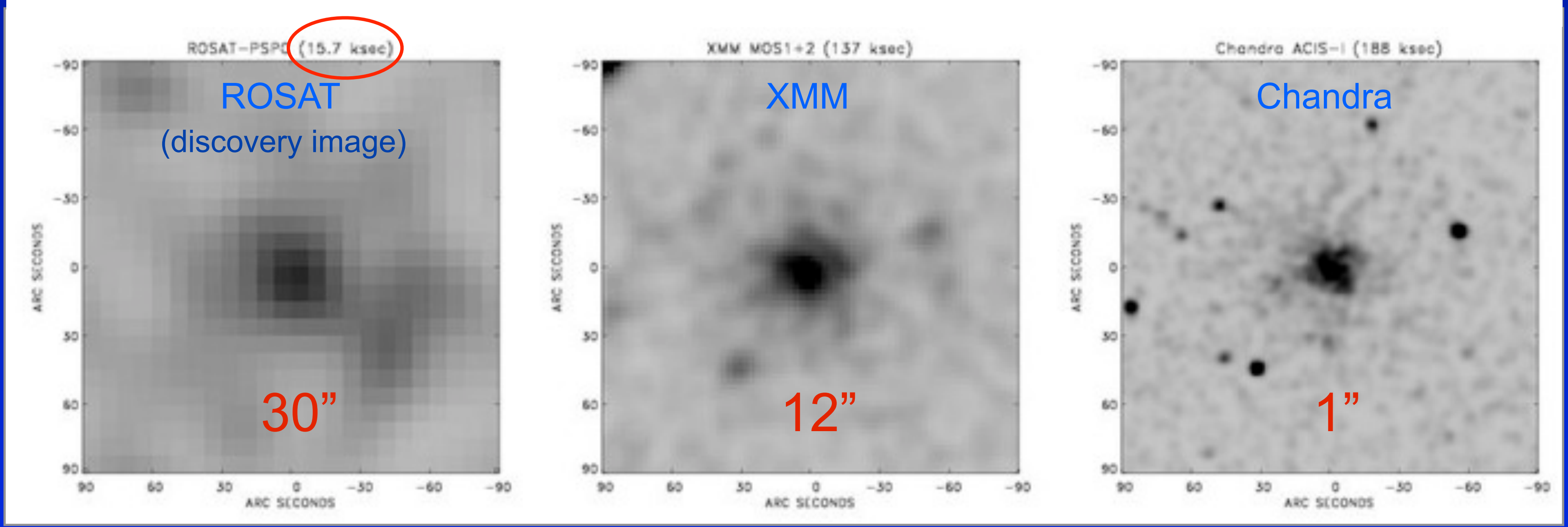
Progress in X-ray searches of distant clusters

High-z X-ray clusters: the importance of resolution (and background)

- Tremendous progress in sensitivity and angular resolution...

Massive ($6\times10^{14} M_{\odot}$) cluster at z=1.24

(RDCS1252, Rosati et al. 04)

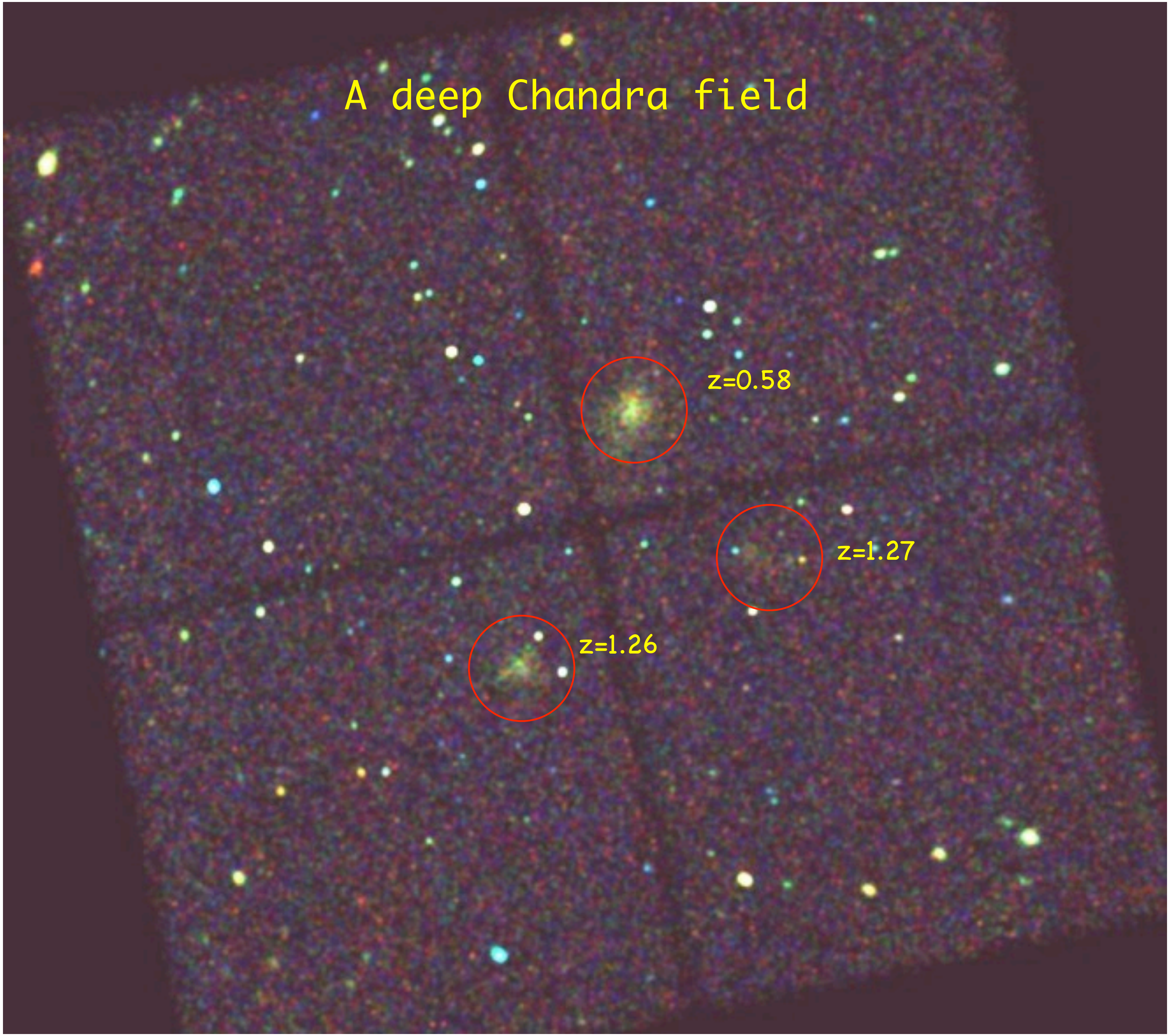


... but very little progress in survey area (*grasp*) over the years, due the lack of an X-ray mission dedicated to surveys with wide-field optimized optics

Survey discovery speed FoM = $A \cdot \Omega \cdot T \cdot (PSF)^{-2}$

➔ eROSITA survey will be a significant step forward (~30” resolution, z<~1.2)

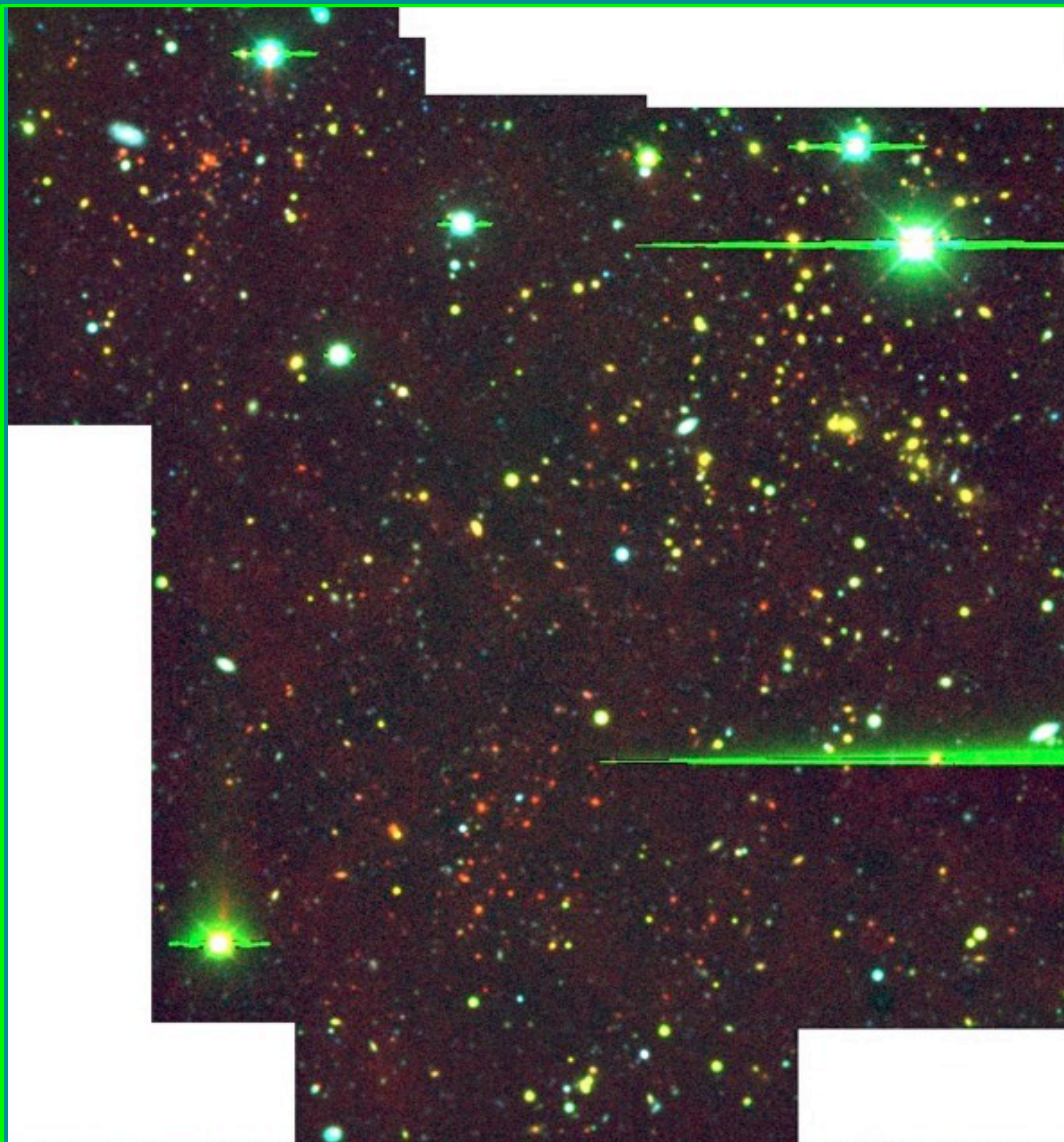
➔ **Motivation for a *Wide Field X-ray Telescope* mission** (FoM 10^2 x higher)


A deep Chandra field
z=0.58
z=1.27
z=1.26

Lynx field: B I K image

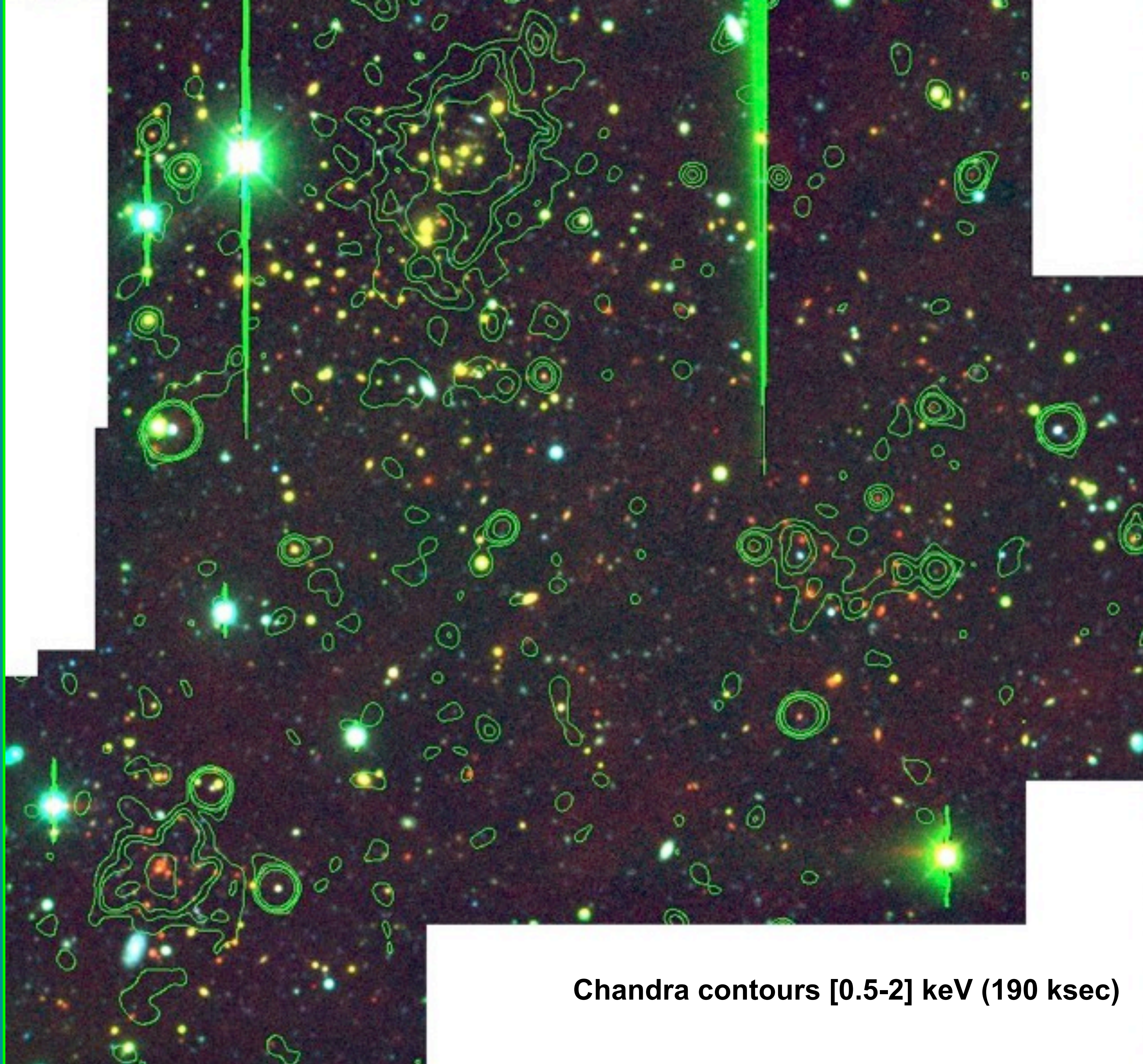
1 Mpc/h_{50}

2 arcmin



(Stanford et al. 97, Rosati et al. 99)
SPICES field

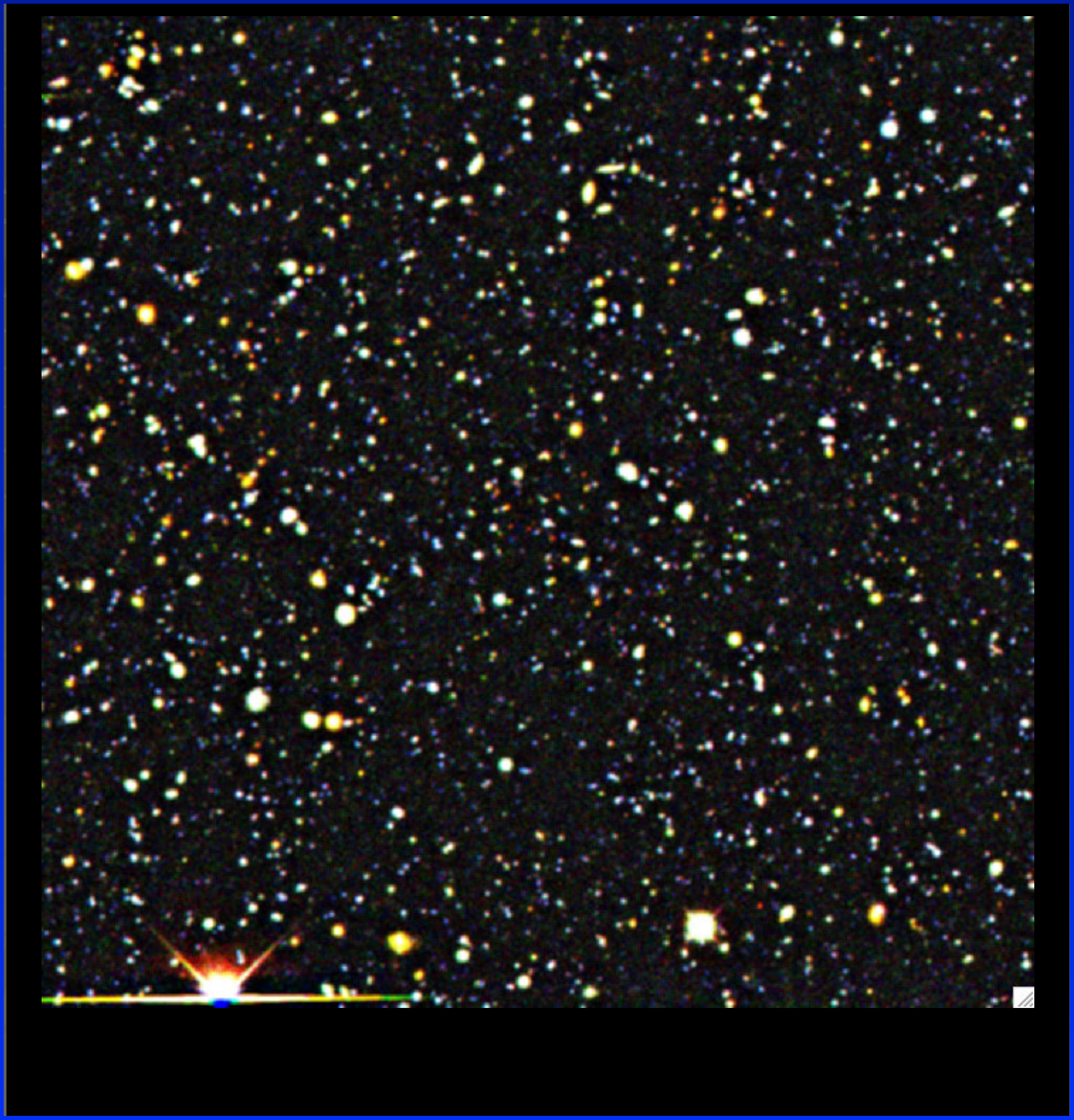
Lynx field: B I K image



1 Mpc/h_{50}
2 arcmin

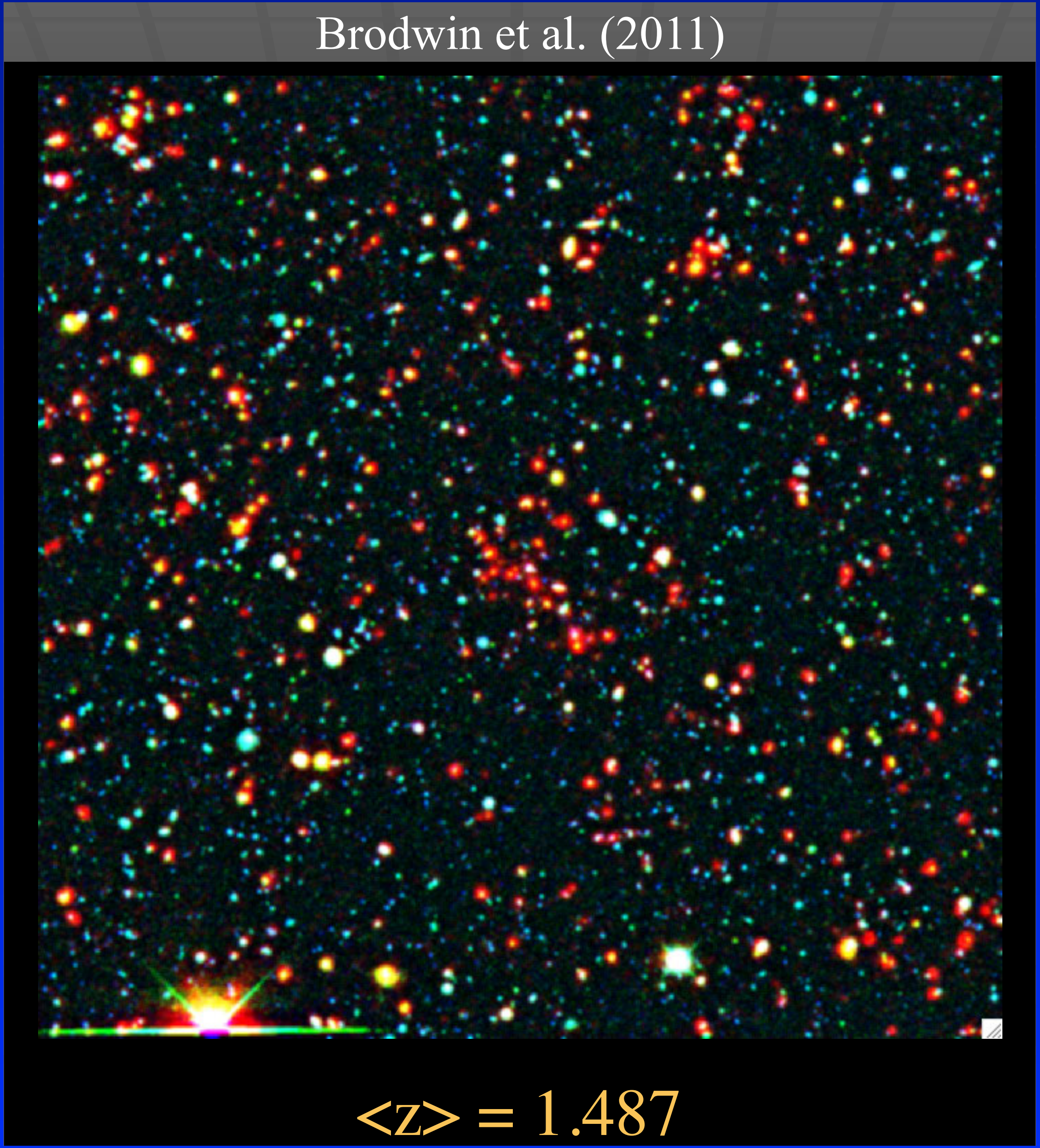
(Stanford et al. 97, Rosati et al. 99)
SPICES field

Progress in optical/IR searches of distant clusters



IRAC Cluster Surveys

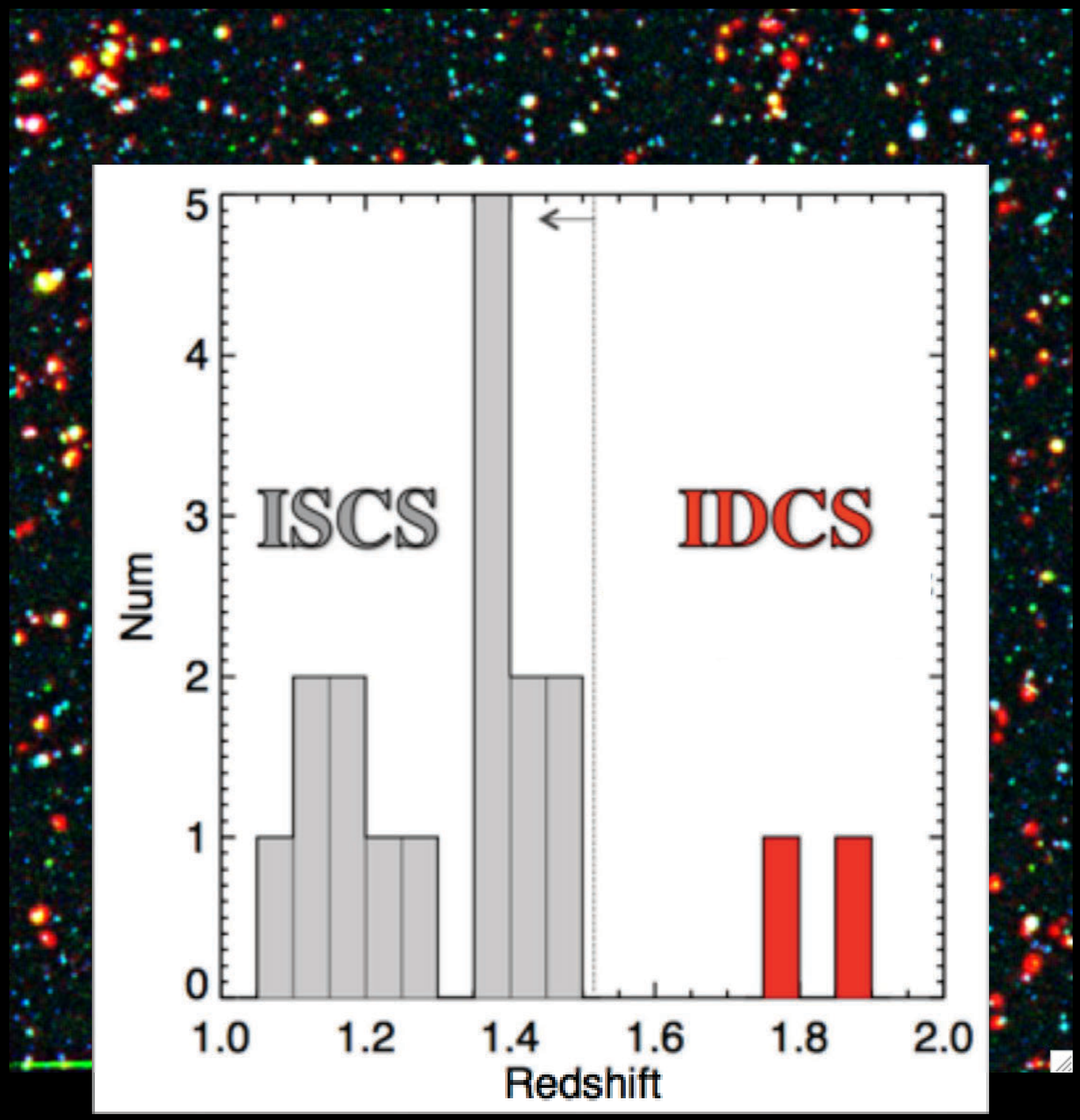
Progress in optical/IR searches of distant clusters



IRAC Cluster Surveys

Progress in optical/IR searches of distant clusters

Brodwin et al. (2011)



<z> = 1.487

IRAC Cluster Surveys

Progress in SZ detections

The highest SZ cluster confirmed so far: **z=1.31**

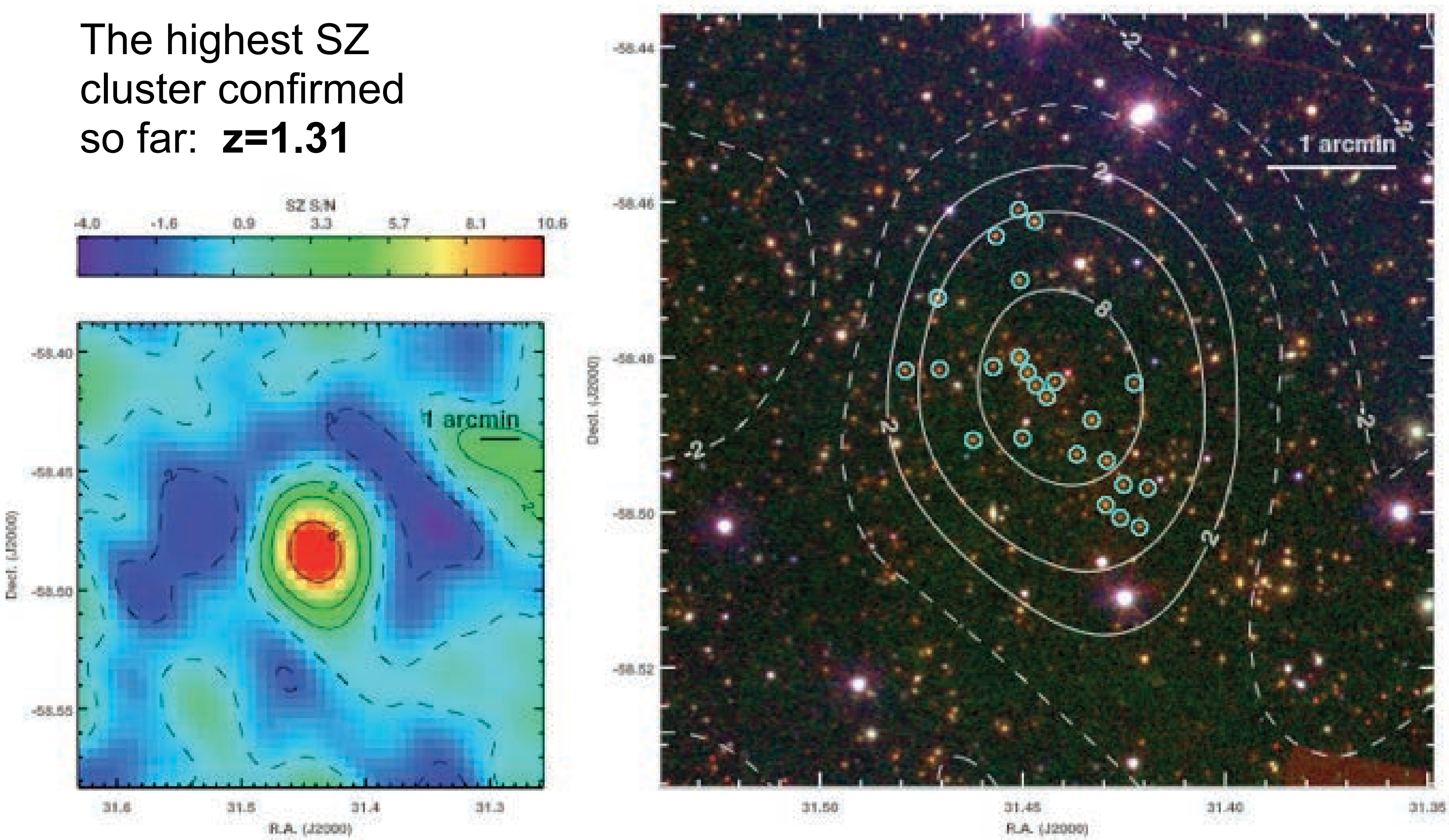
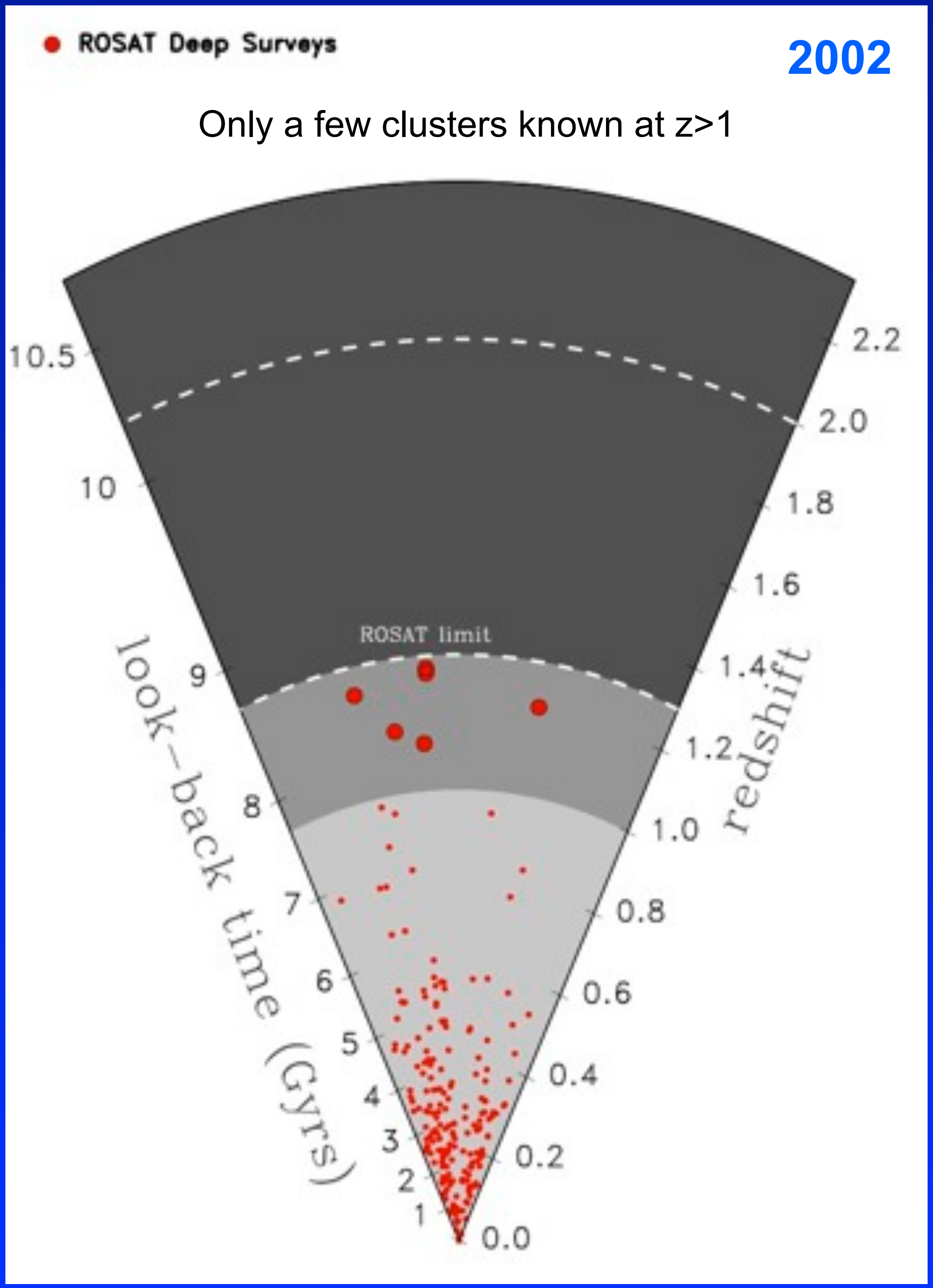
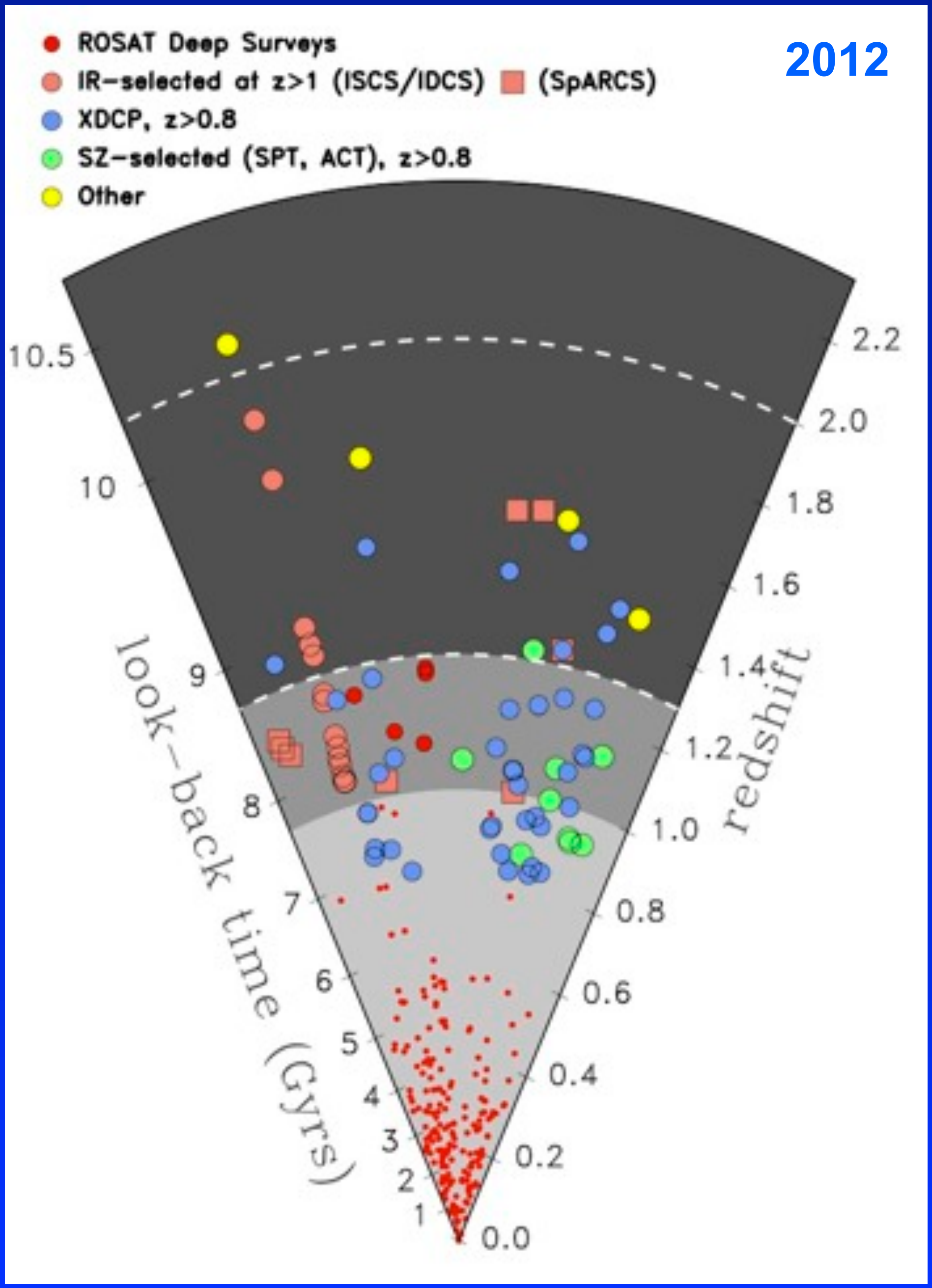


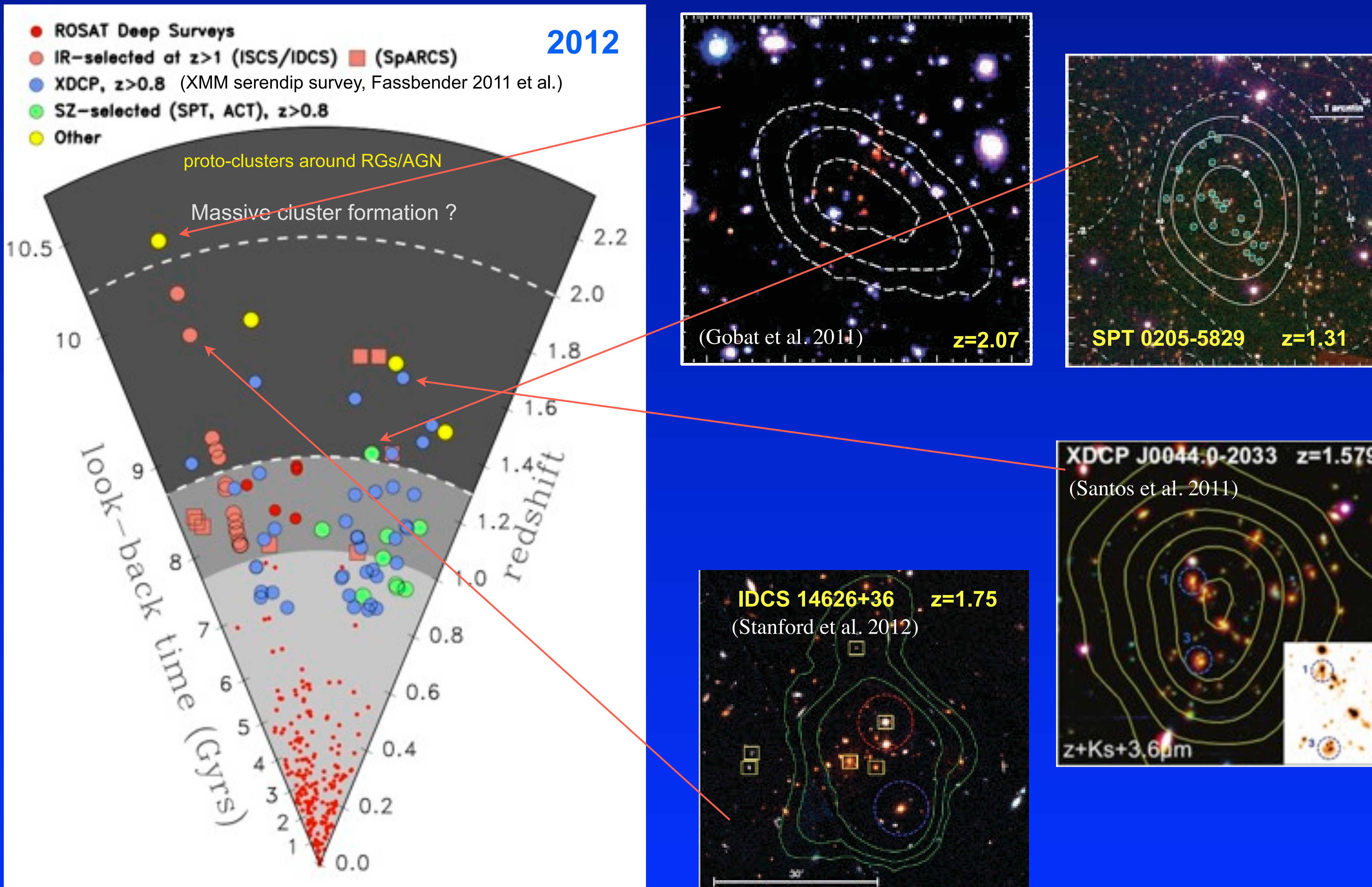
Fig. 1.— (Left) The filtered SPT-SZ significance map of SPT-CL J0205-5829. The negative trough surrounding the cluster is an artifact of the filtering of the time ordered data and maps. (Right) Color image from IMACS i, NEWFIRM K_S, Spitzer/IRAC [3.6], with SPT-SZ contours overlayed in white and red sequence galaxies indicated in cyan.

The increasing population of distant clusters

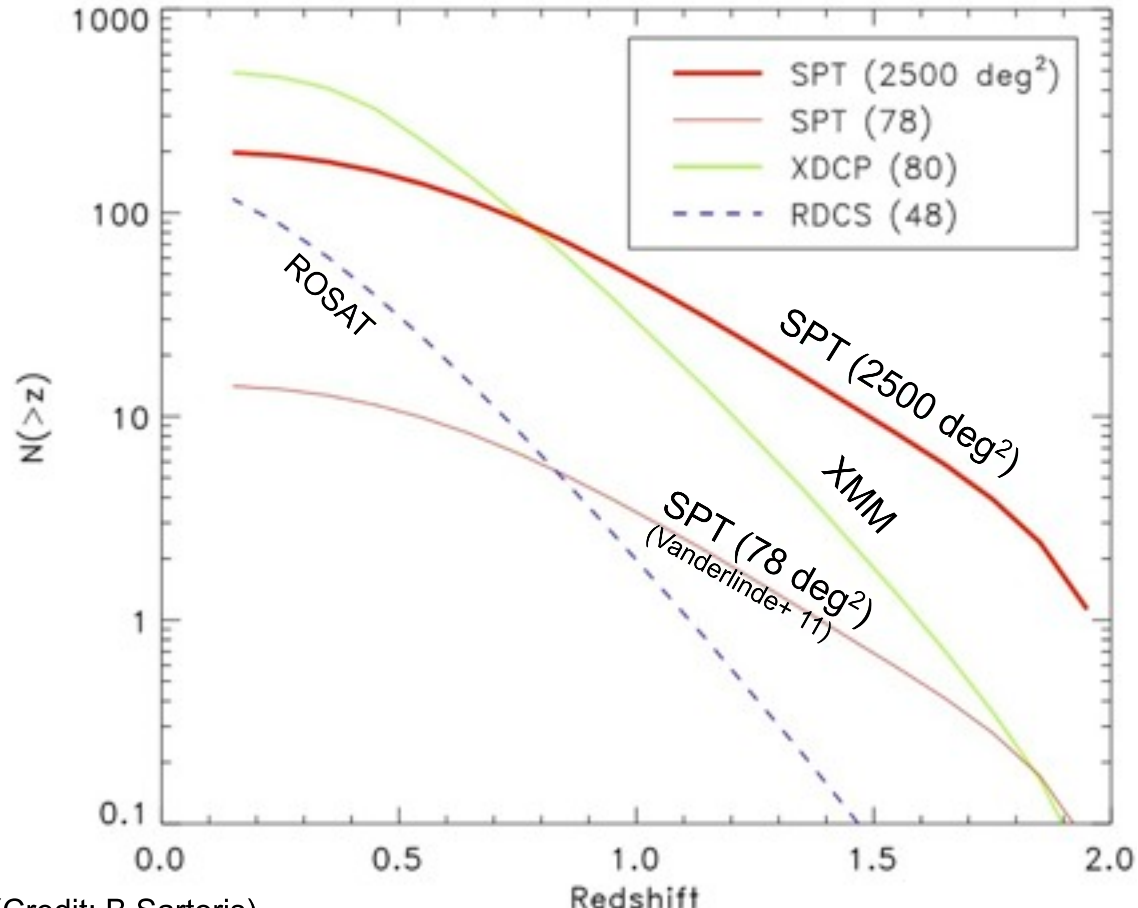




The increasing population of distant clusters

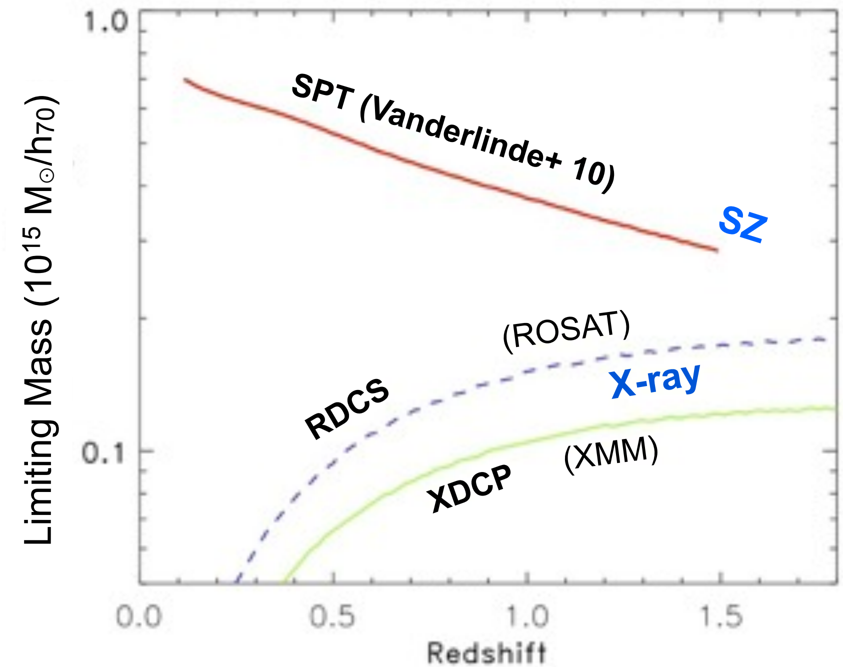


Cluster detection and abundance at high-z



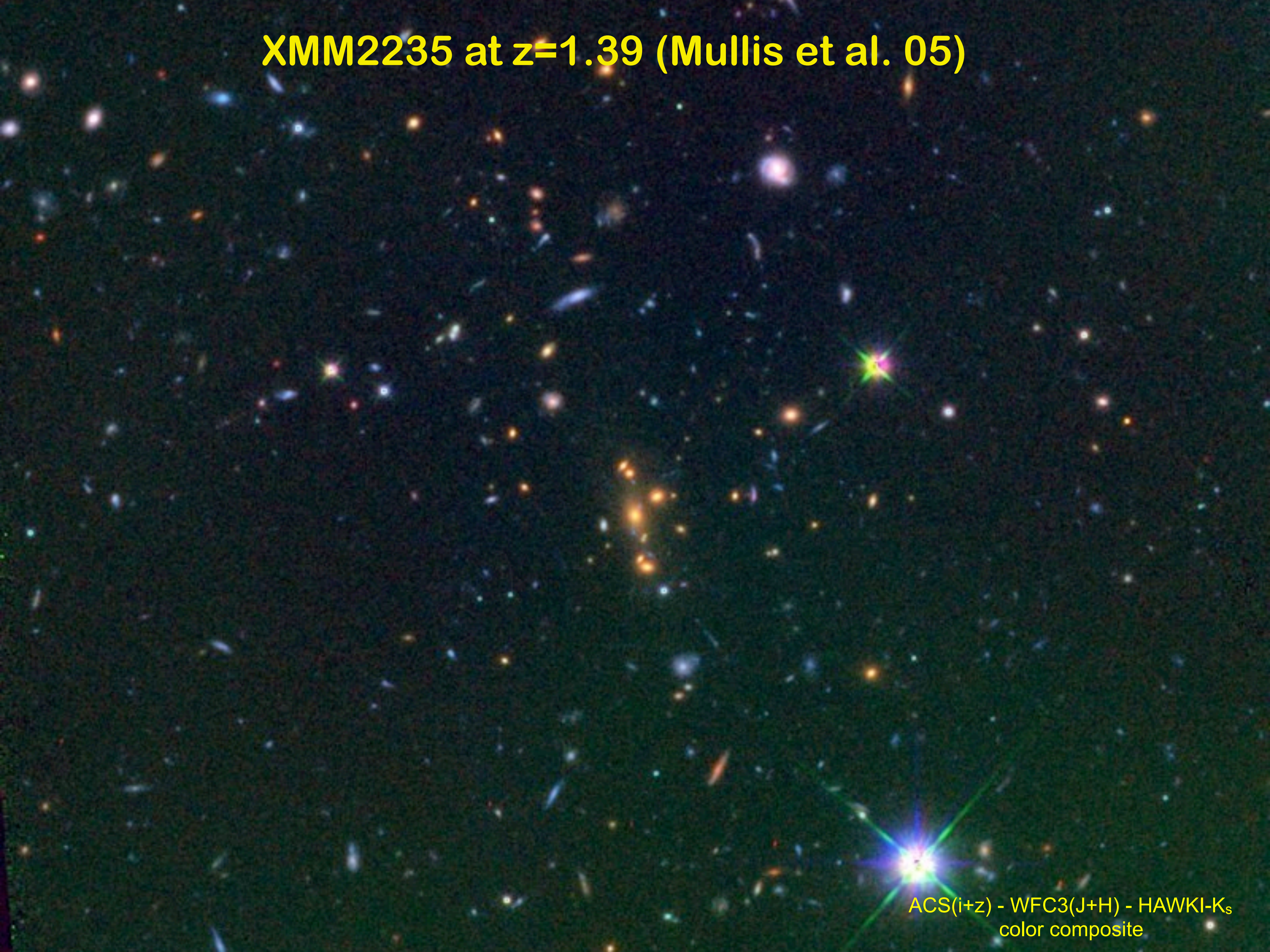
(Credit: B.Sartoris)

Mass detection limit



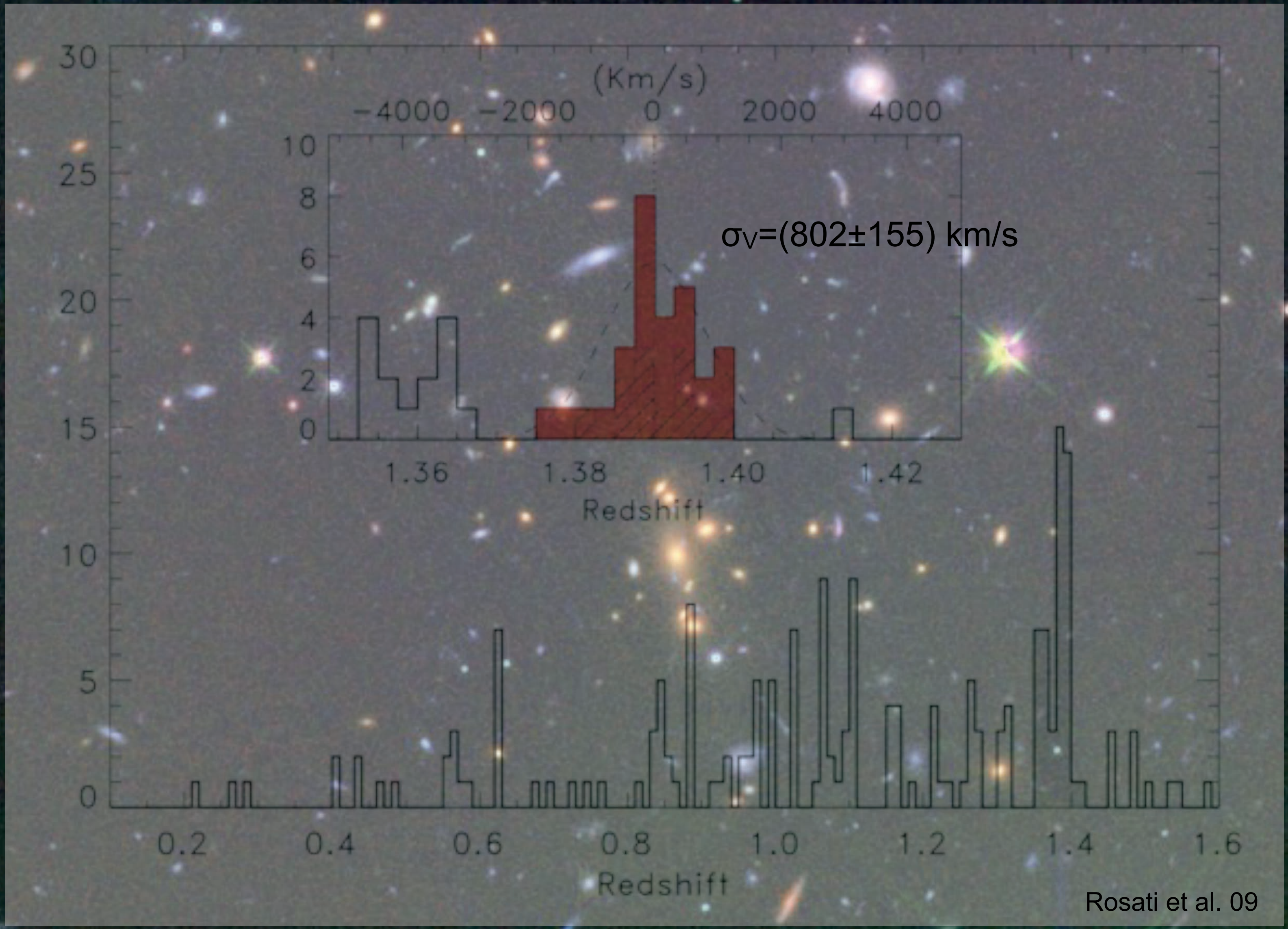
- The completion of the SPT (and ACT) survey will cover enough volume to unveil most massive clusters at z>1, but we are still in need of X-ray follow-up! (several Chandra/XMM Ms invested)
- XMM serendip surveys, IR (Spitzer) and radio source driven searches will continue to unveil less massive clusters out to z~2, critical to study progenitors of lower-z massive clusters

XMM2235 at z=1.39 (Mullis et al. 05)



ACS(i+z) - WFC3(J+H) - HAWKI-K_s
color composite

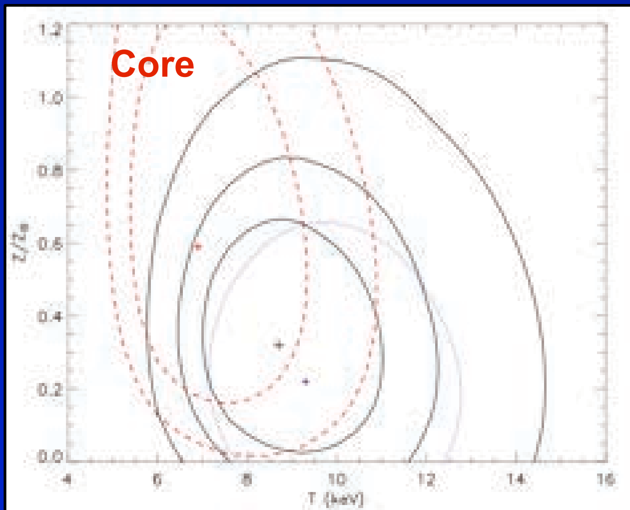
XMM2235 at z=1.39 (Mullis et al. 05)

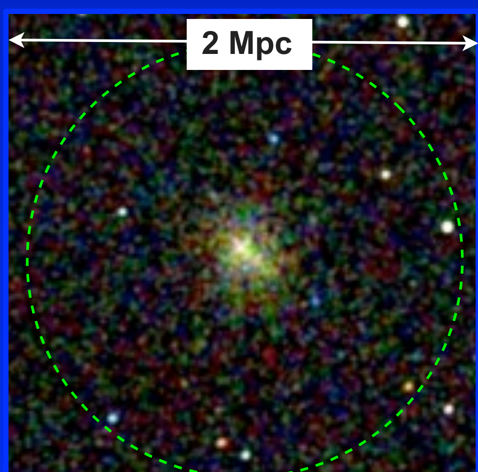


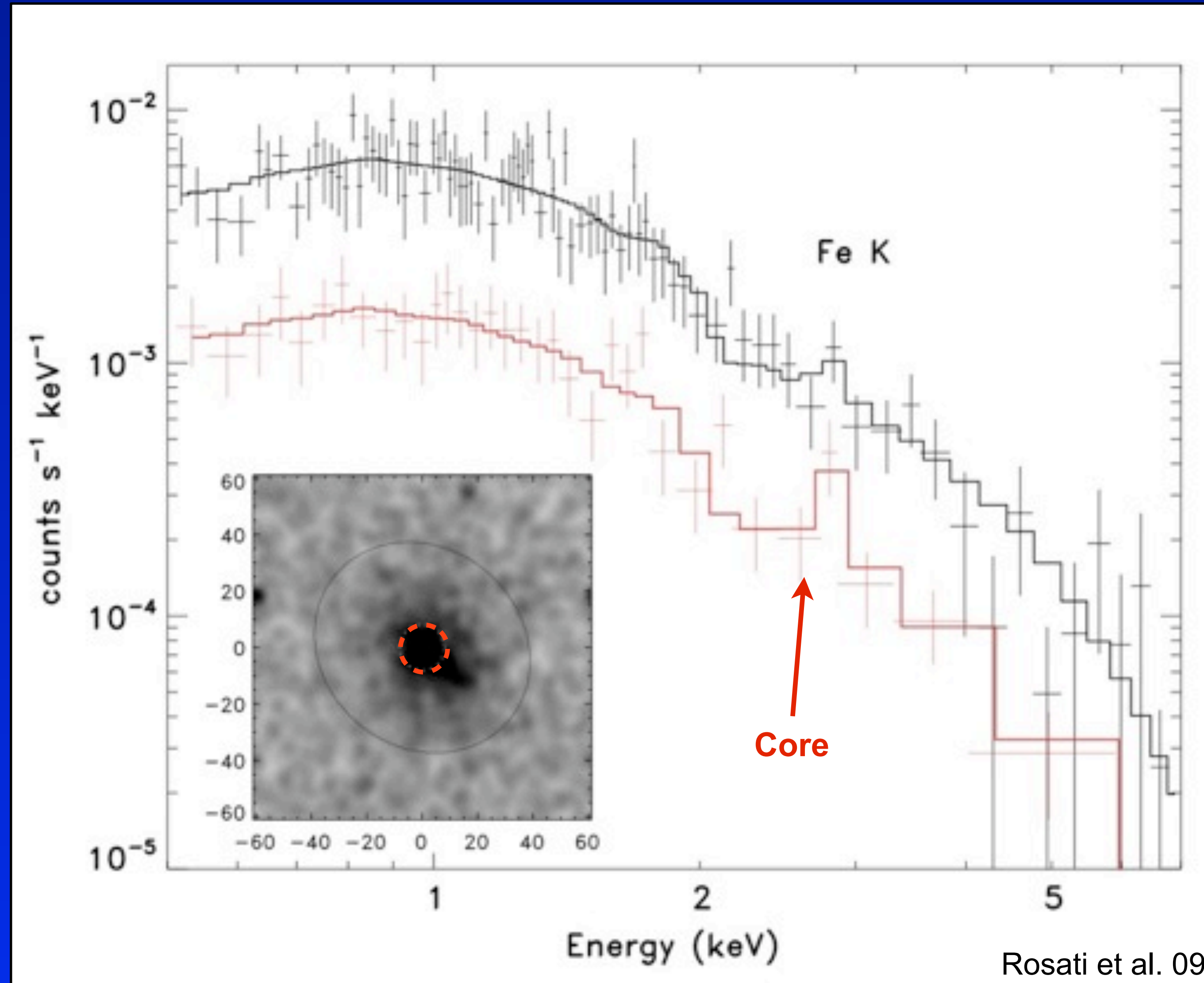
- Spectroscopic members (over 3 Mpc): 34 (22 passive, 12 star forming)
- >150 redshifts in the field

ACS(i+z) - WFC3(J+H) - HAWKI-K_s
color composite

Chandra Observations of XMM2235 (190 ksec)

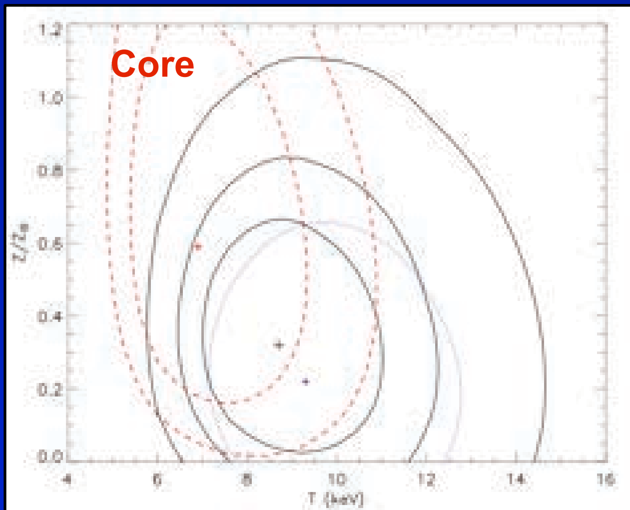


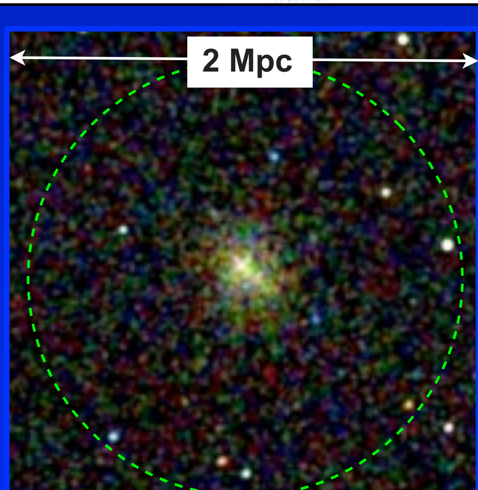


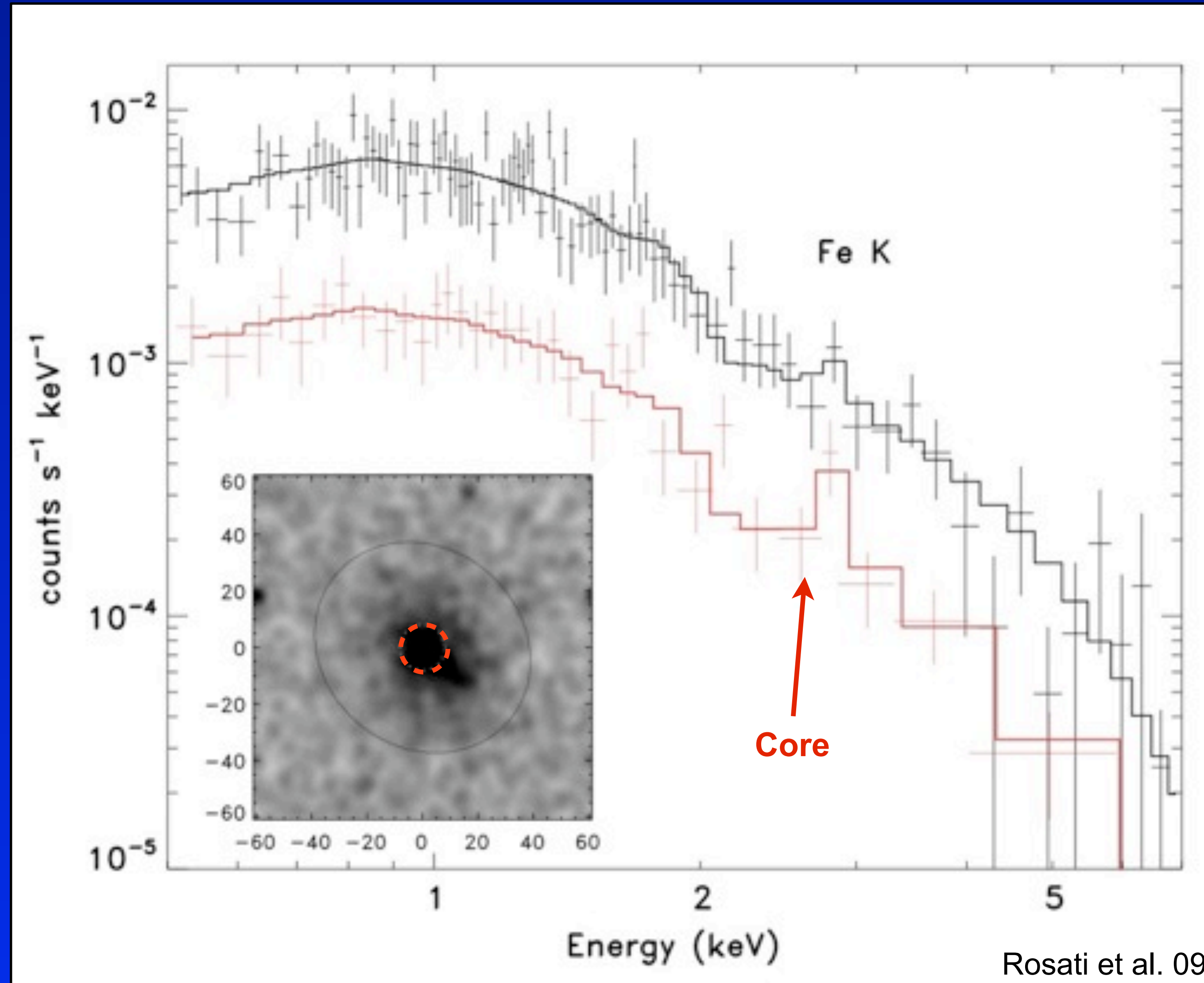


- Global fit: $kT = 8.7^{+1.4}_{-1.2}$ keV, and $Z = 0.32^{+0.19}_{-0.22}\,Z_\odot$
- Core fit (r=7.5"=60 kpc): $kT = 6.9^{+1.5}_{-1.1}$ keV, and $Z = 0.59^{+0.29}_{-0.37}\,Z_\odot$

Chandra Observations of XMM2235 (190 ksec)





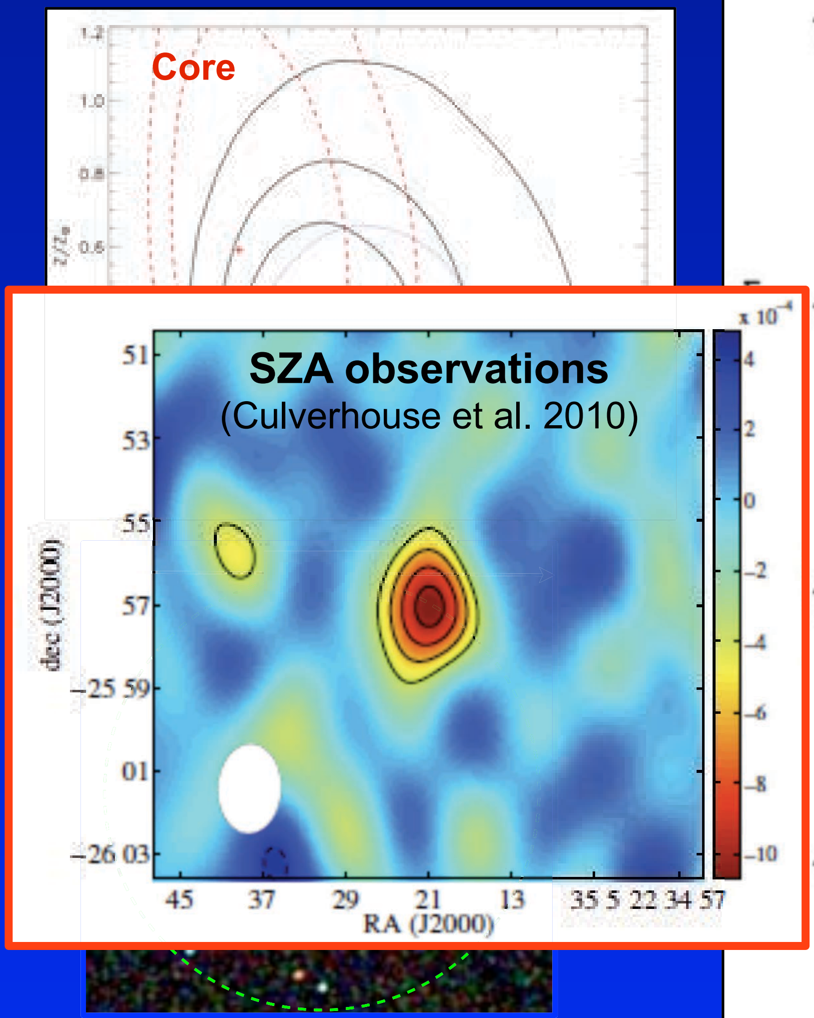


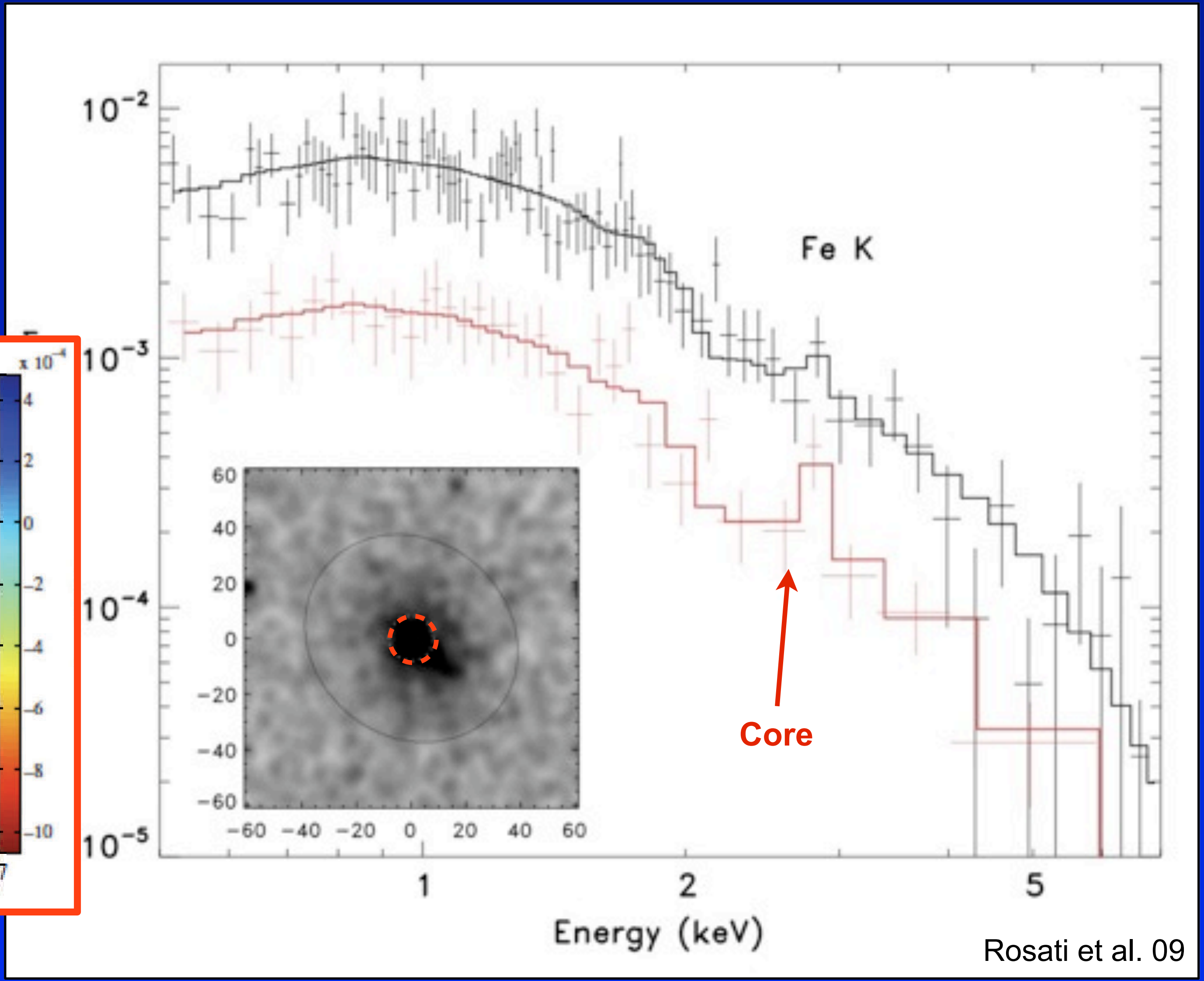
➡ Hottest (most massive) cluster to date at z>1 with a prominent cool core:

$M_{200}(<1.1\ \mathrm{Mpc}) = (7.3 \pm 1.3) \times 10^{14}\ M_\odot\ /\ h_{70}$

➡ The ICM is already enriched at local values at z=1.4

Chandra Observations of XMM2235 (190 ksec)





➡ Hottest (most massive) cluster to date at z>1 with a prominent cool core:

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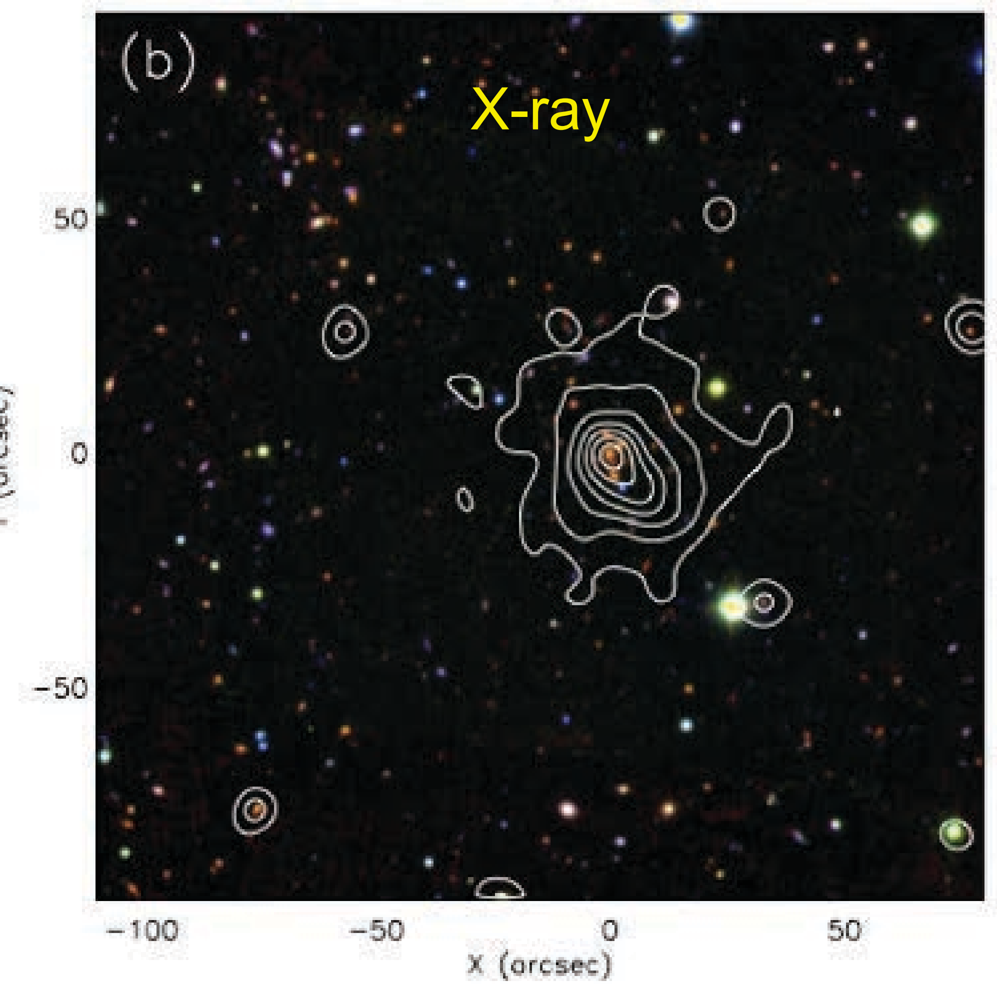
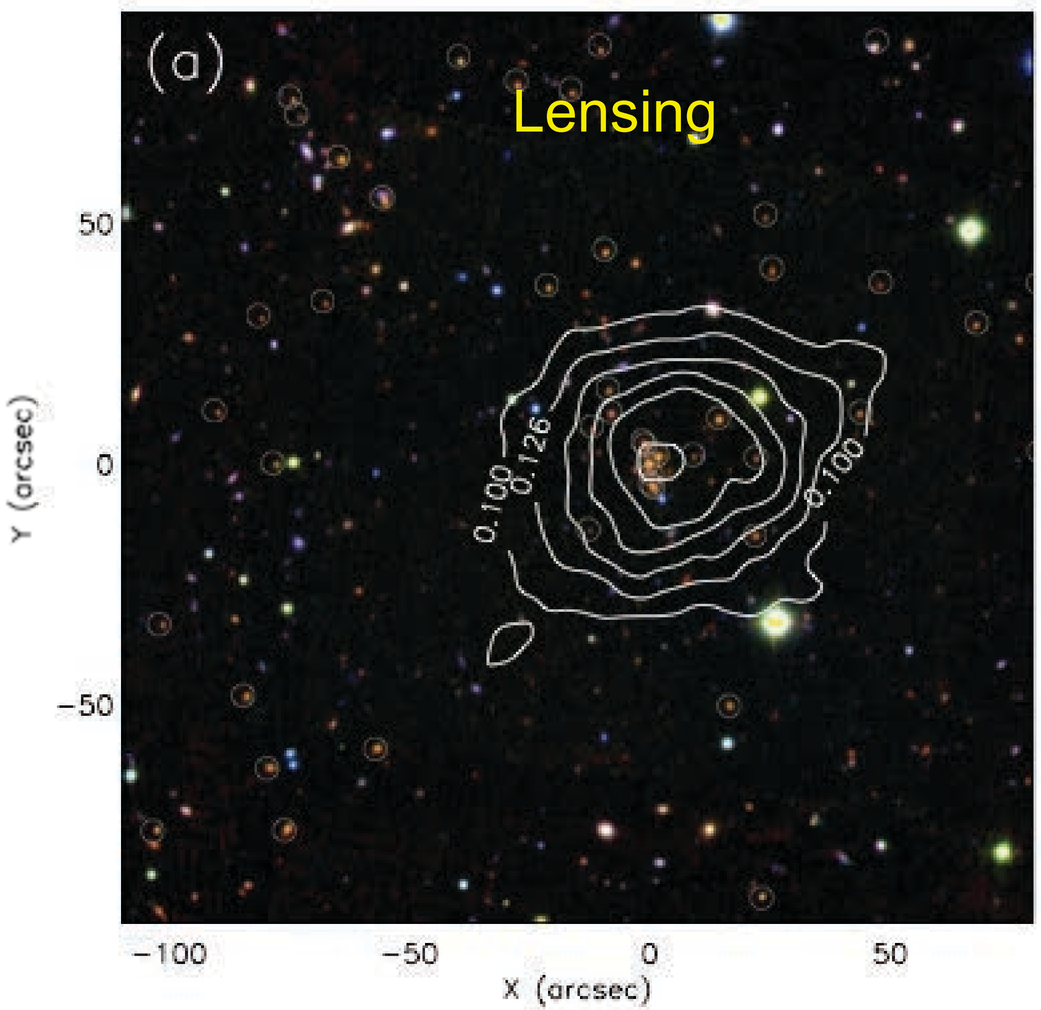
➡ The ICM is already enriched at local values at z=1.4

X-ray and Weak-lensing mass of XMM2235 at z=1.4

(Jee et al. 09, Rosati et al. 09)





- With ACS, shear detected out to ~1 Mpc (max >8σ), beyond Chandra (8150s exp, i_{775} band)
- X-ray and Weak Lensing based masses at r=1 Mpc agree within 10%
- Systematics in WL can be further reduced with SL features

Anatomy of a massive cluster at z=1.4
Too big ? too early ?

- XMM2235 is in a surprisingly advanced evolutionary state at 2/3 T_U:
  - Old stellar pops, almost complete stellar mass assembly, early ICM metal enrichment, prominent cool core

- Accurate mass profile, very robust mass determination (multiple mass probes): $M_{200}(<1.1\ \mathrm{Mpc}) = (7.1\pm1.3)\times10^{14}\ M_\odot / h_{70}$

- Such massive cluster is a rare event (p≈5 %) in the X-ray survey volume, is there any tension with ΛCDM ?

  ➔ this stimulated a number of papers exploring also “exotic solutions”

  - *non-gaussian fluctuations* (Jimenez&Verde 09, Sartoris et al. 10, Hoyle et al. 10, Chongchitnan&Silk 2012)
  - *interacting dark energy (*Baldi & Pettorino 10, Mortonson et al. 10)
  - Holz&Perlmutter 10, Harrison&Coles 2011

- Recent discovery of more $M \sim 10^{15}\ M_\odot$ clusters in SZ surveys (SPT) at z≳1

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

Early work by N.Bahcall in
the mid-nineties MS1054 at z=0.83
to argue for a low Ω_M Universe

THE MOST MASSIVE DISTANT CLUSTERS: DETERMINING Ω AND σ_8

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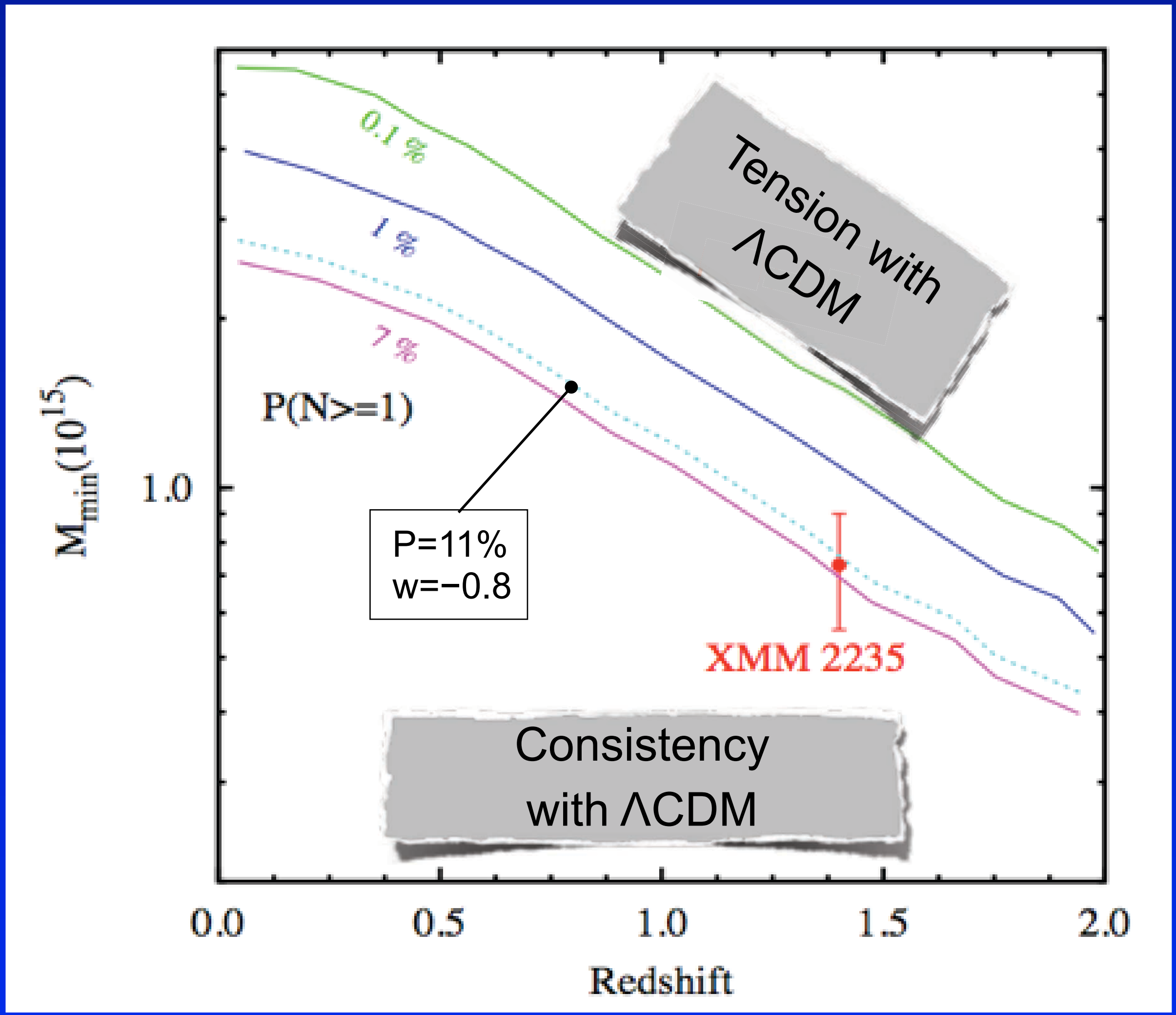
Received 1997 November 12; accepted 1998 April 6

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



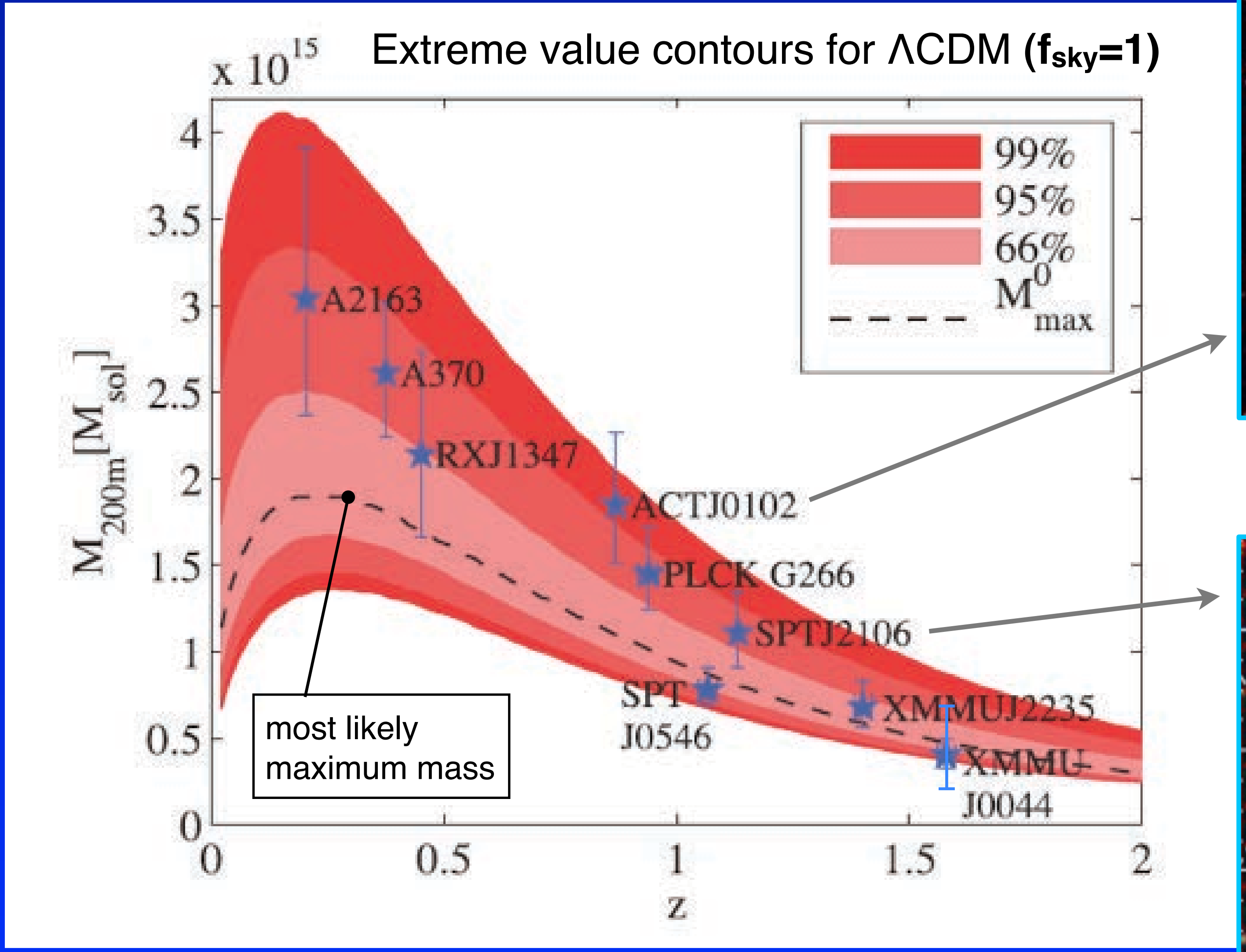
Probability of finding at least one cluster in XDCP (50 deg^2 to 10^{-14} erg/cm^2/s) using ΛCDM cluster MF *N(>M,>z)* (Sartoris et al. 11, Jee+ 09)

- selection function and completeness not critical
- weak and strong lensing very effective, all mass probes available
- high-end of cluster mass function from simulation at z>1 still uncertain..

☛ Accurate (<~10% errors) M_{200} measurements needed !

Exclusion probability for ΛCDM using extreme clusters

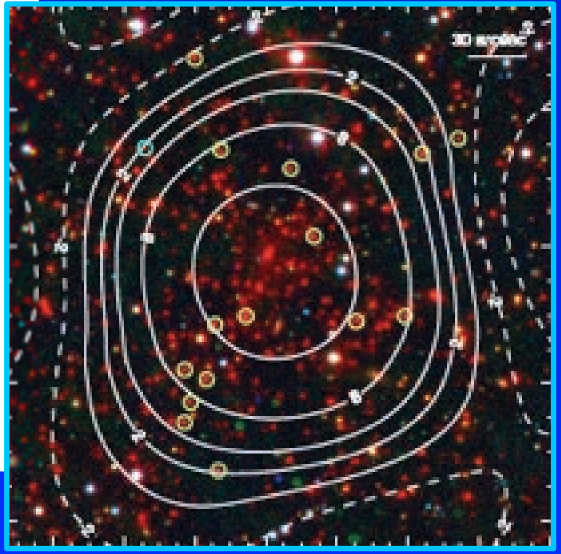
(Harrison&Coles 2012, also Mortonson et al. 2011)



ACT-CL J0102–4915, z=0.87

(Menenteau et al. 2011)

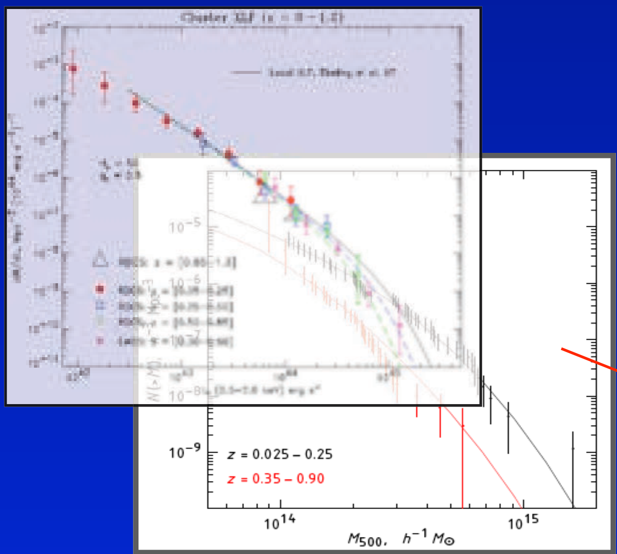
SPT-CL J2106-5844, z=1.13



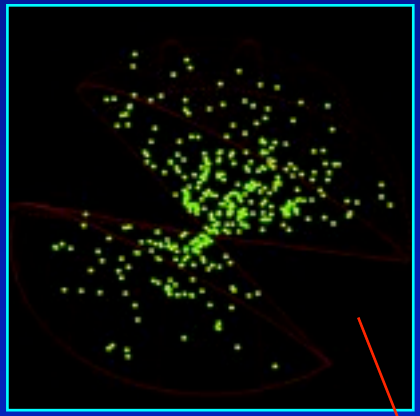
(Foley et al. 2011)

Clusters as Cosmological Probes

N(M,z) from evolution of cluster abundance:
σ_8, Ω_M, Ω_Λ (w)



Clustering, $\xi_{CL}(r)$, or $P(k)$: σ_8, Ω_M, Ω_Λ



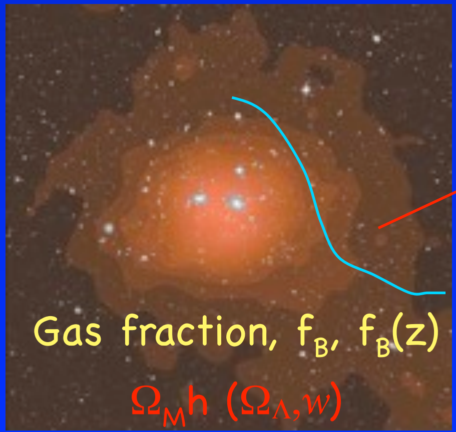
Parameter	Accuracy *
σ_8	3-5%
Ω_M	5-10%
Ω_Λ, w	40-60%

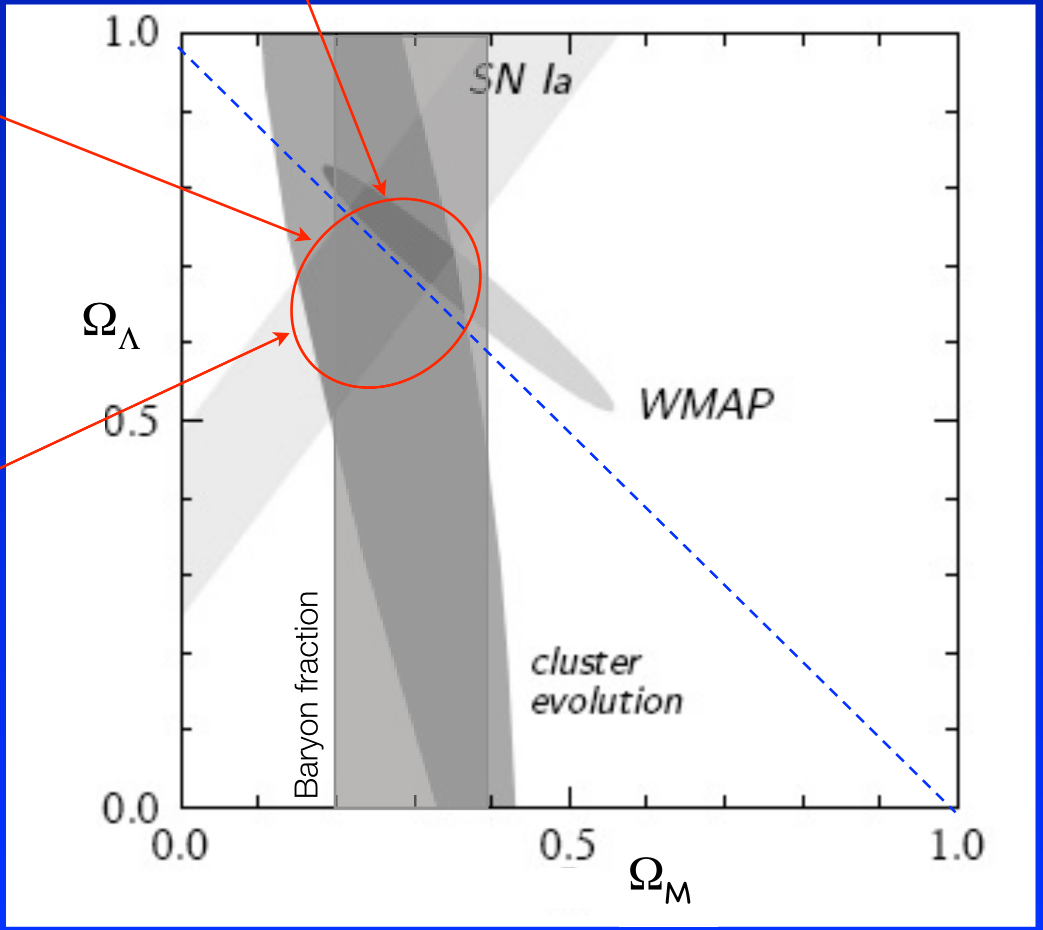
* with current (ROSAT) samples

Note: σ_8 =0.7-0.8 consistently from clusters

σ_8= 0.92 ± 0.10 ⟹ 0.77±0.05 ⟹ 0.81±0.02

WMAP1 **WMAP3** **WMAP7 +BAO + H_0**





Independent Probes of cosmological parameters

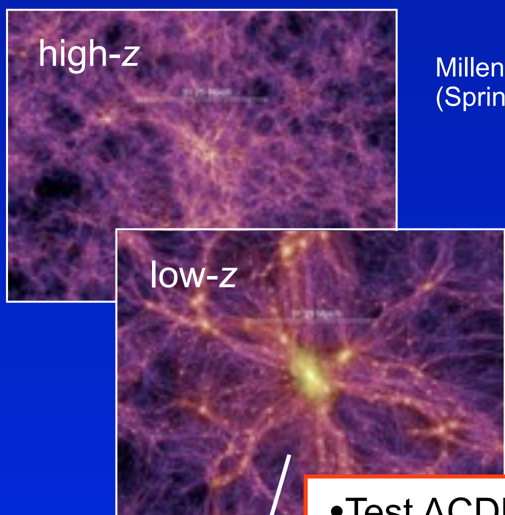
- Geometrical methods:
  - Type Ia Supernovae: comoving distance-redshift relation
  - Cosmic Microwave Background angular spectrum
  - Baryon Acoustic Oscillations (modulation of P(k)) from galaxy redshift surveys (galaxy clustering), act as standard rod

- Dynamical methods:
  - Number density of clusters: measure combination of growth factor, D(a), and expansion history (volume evolution)
  - Weak lensing tomography: trace the evolution of the growth rate, $f_g(a)=d\ln(D)/d\ln(a)$, of DM perturbations
  - Redshift-space distortions: measure the growth rate (derivative of growth factor) from z-distortions due to peculiar motions

Clusters are powerful probes of structure formation and cosmological models

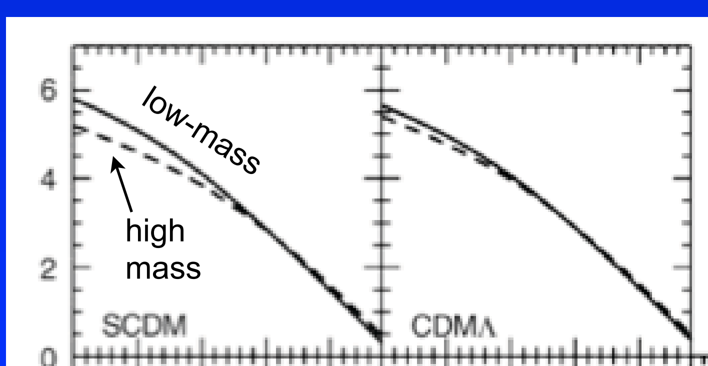
1) Sensitive probe of the **dark sector** of the Universe (DM+DE)

Structure of DM halos
(≲1 Mpc scale)

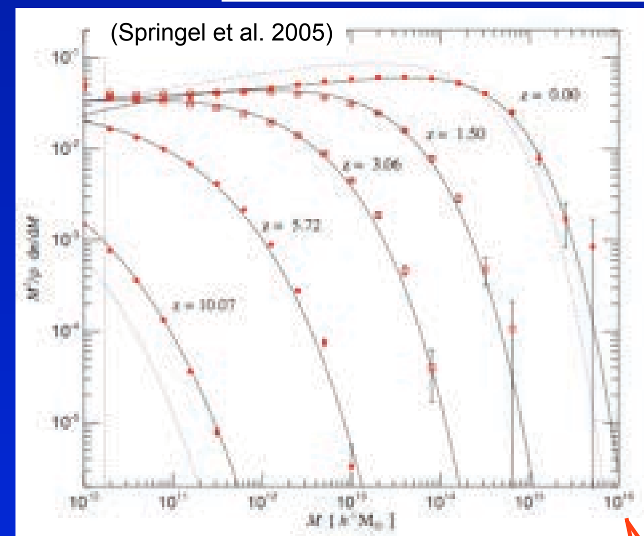


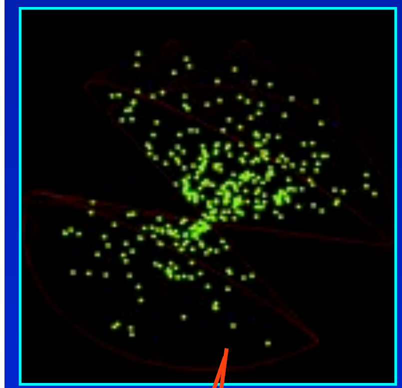
Millennium simulations
(Springel et al. 2005)

- Test ΛCDM predictions on DM density profiles
- Collision-less nature of DM?



Mass function and distribution
of DM halos (~ Gpc scale)





REFLEX collaboration

Test ΛCDM and GR:
<u>geometry</u> *vs* <u>growth</u>