Structure Formation and Cosmology with high-z Clusters

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
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 \( M_{<10\text{Mpc}} = \Omega_{\text{av}} \cdot 4/3\pi (10 \text{ Mpc})^3 \approx 10^{15} M_\odot \Omega_M h^{-2} \).
(Left) Locally, one can determine the $\sigma_8-\Omega_m$ relation ($\sigma_8\Omega_m^{0.5} \approx 0.5$), because only the amplitude on a given scale $R \approx (M/\Omega_m \rho_{\text{crit}})^{1/3}$ 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 $\Omega_m$, weakly on $\Omega_\Lambda$ at $z<1$.

r.m.s density fluctuation within a top-hat sphere of $8h^{-1}\text{Mpc}$ radius $\Rightarrow$ Amplitude of $P(k)$
Evolution of cluster abundance (DM only)

$\Omega_m = 1 - \Omega_\Lambda = 0.3$

EdS ($\Omega_m = 1$)

Normalized to cluster abundance at $z=0$; circles: clusters with $T>3$ keV, size $\propto T$ (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 mostly in the cores

• 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?

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

Geometry
- Observed (robust for X-ray selection)
- Empirical (scaling relations), Hydro-simulations (uncertainties due to complex cluster physics)

Volume effect
- \( \Omega_m=0.3 \)
- \( \Omega_m=0.3 \) and \( \Omega_\Lambda=0.7 \)

Growth effect

MF evolution: robust prediction from large N-body simulations

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

Need \( <X>(M,z) \) and \( \sigma_X(M,z) \)
How to compute the cluster mass function

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

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

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

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

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

(Springel et al. 2005)

Borgani 06
How to compute the cluster mass function

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

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

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

Geometry
from FRW metric

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

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

\[ H^2(z) = H_0^2[\Omega_M (1 + z)^3 + \Omega_\Lambda (1 + z)^{3(1+w)} + (1 - \Omega_0)(1 + z)] \]
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\[
\frac{d^3 N}{dM d\Omega dz} (M, z) = \frac{dn_M}{dM} (M, z) \cdot \frac{d^2 V_{\text{com}}}{dz d\Omega} (z)
\]

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

Geometry

from FRW metric

Several analytic approximations exist for the mass function (Press-Schechter; Sheth-Tormen; Jenkins)

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

\[
\frac{d^2 N}{dz d\Omega} (z) = \frac{d^2 V}{dz d\Omega} (z) N_{\text{com}} (z) = \frac{c}{H(z)} D_A^2 (1 + z)^2 \int_0^\infty dM f(M, z) \frac{dn}{dM} (M, z)
\]
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 a given mass, i.e. to estimate the evolution of the cluster mass function.

\[
\frac{dn}{dM}(M, z) = \frac{dn}{dX}(M, z) \frac{dX}{dM}(M, z)
\]

- **X**: observable proxy of the total mass
  \( (L_x, T, Y_{SZ}, Y_x, M_{gas}, M_{opt}, \sigma_{V}...) \)

- **Need**: \( <X>(M, z) \) and \( \sigma_X(M, z) \)

- **Observed**: (e.g. X-ray Luminosity Function)

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

**Mass calibration is critical**: \( L_x-M, T-M, Y_x-M, ... \)

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

**L_x-M relation**

(Reiprich & Boehringer 02)
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 $M_\Delta$: the matter contained in a spherical region of radius $r = R_\Delta$ whose mean density is $\Delta \times \rho_c(z)$, so that $M_\Delta(<r) = 4/3\pi R_\Delta^3 \Delta \rho_c(z)$

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

The virial mass is obtained taking $\Delta = \Delta_v \equiv 18\pi^2 + 82[\Omega_M(z) - 1] - 39[\Omega_M(z) - 1]^2$
The L-T and M-T relations in case of self-similarity and comparison with observations

From hydrostatic equilibrium \( M(R) = T \cdot R \),

\[ R_D \propto M^{1/3} E^{-2/3}(z) \]

**M-T relation**

\[ L_X \propto \int \epsilon_v dV \propto \rho_g^2 T^{1/2} M_{\Delta} / \rho_g = \rho_g M_{\Delta} T^{1/2} \propto T^2 E(z) \]

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

**L-T relation**

The L-T relation deviates from the self-similar case: \( L \sim T^2 \)

- 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 (\( M \sim T^{3/2} \)) 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: $Y_x = M_{\text{gas}} T$

Kravstov&Borgani 2012
Cluster abundance from X-ray Luminosity Function

The cluster XLF is modelled as a Schechter function:

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

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

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

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

$$V_{\text{max}} = \int_{0}^{z_{\text{max}}} S[f(L, z)] \left( \frac{d_L(z)}{1 + z} \right)^2 \frac{cdz}{H(z)}.$$

$S(f)$ is the sky coverage depending on the flux $f = L/(4\pi d_L^2)$.
X-ray Surveys Selection Functions

- 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 \( z \)).

(RBN 2002)
Different surveys, using independent methods, same results!

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

$\sigma_8 = 0.72 \pm 0.05 \ (\pm 0.05)$ for $\Omega_M = 0.3$

Conversion of observables to cluster mass:
- L-T slope: $L \sim T^\alpha$
- L-T evolution: $L \sim (1+z)^\Lambda$
- M-T normalization $\beta$
- L-M intrinsic scatter $\Delta_{M-L}$

Cluster Power Spectrum

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

$\sigma_8 = 0.71 \pm 0.03 \ (\pm 0.08)$

$\Omega_M = 0.34 \pm 0.03 \ (\pm 0.1)$

($\Omega_T = 1, \Omega_b h^2 = 0.020, n_s = 1$)
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 $z\sim 1.4$
  - 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 ($M_{\text{gas}}, Y_X$)
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- Vikhlinin et al. 09: 85 ROSAT clusters at $z<0.9$ with follow-up Chandra data for robust mass proxies ($M_{\text{gas}}, Y_X$)
- Cosmological constraints from clusters to date provide useful complementary probes, not highly competitive today but they are based on $\sim 10^2$ clusters only!
- High yield, large area surveys are needed to explore and control multi-parameter systematics

Also: Allen et al. 08 ; Henry et al. 09; ....
**Precision Cosmology from Cluster Abundance?**

**Key properties**
- **X-ray**
- **Opt/NIR SZ**

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<th>Key properties</th>
<th>X-ray</th>
<th>Opt/NIR</th>
<th>SZ</th>
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<tr>
<td><strong>Sample size</strong></td>
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<td><strong>Mass calibration</strong></td>
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<td><strong>Extension to high-z</strong></td>
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**Score card**

- **Mantz et al. 09**
- **Vikhlinin et al. 09**

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

**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)**

⇒ stronger constraints on $\sigma_8$, $\Omega_M$, $\Omega_{DE}$, $w$, $w'$, ...
Power Spectrum of the distribution of Clusters

- Clusters have a clustering amplitude much larger than galaxies (corr. length for clusters \( r_0 \approx 20 \text{h}^{-1} \text{Mpc} \approx 4 \) times \( r_{0,\text{gal}} \approx 5 \text{h}^{-1} \text{Mpc} \))

- 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” = \( \frac{\delta \rho / \rho_{\text{xray}}}{\delta \rho / \rho_{\text{mass}}} \) easier to compute for clusters using the \( L_{\text{x}} - M \) 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 ($\Omega_t = 1$)

- $\Omega_M = 0.3$
- $\Omega_M = 0.5$

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- “bias factor” = $(\delta \rho / \rho)_\text{X-ray} / (\delta \rho / \rho)_\text{mass}$ easier to compute for clusters using the $L_X - M$ relation $\implies P(k)$ can be predicted for a given cosmological model

Borgani & Guzzo 01

(Tegmark + Schuecker 04)
Constraining $\Omega_M$ and other parameters with the cluster gas fraction
(White et al. 1993, Ettori et al., Allen et al.)

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

$\Rightarrow \Omega_M = b / f_{\text{gas}} (1 + f_{\text{star}} / f_{\text{gas}}) = 0.9 \times 0.044 / 0.11(1 + 0.16) = 0.27 (\pm 0.05)$

2) $f_{\text{gas}} \propto D_A(z, h, \Omega_M, \Omega_\Lambda)$, if $f_{\text{gas}}(z) = \text{const} \Rightarrow f_{\text{gas}}$ is like a standard rod
A glimpse of science from future cluster surveys?

Testing deviations from GR

Two models have the same expansion history

2000 clusters (20 bins with 100 each) with good mass determinations to $z \sim 2$

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\(^2\) (\(M_{\text{lim}} \sim 2 \times 10^{14} M_\odot\)); ACT: \(455\) deg\(^2\) (\(M_{\text{lim}} \sim 2x\) higher)
  - X-ray (serendipitous) surveys (almost only XMM)
High-z X-ray clusters: the importance of resolution (and background)

- Tremendous progress in sensitivity and angular resolution...

... 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  $F_{\text{OM}} = A \cdot \Omega \cdot T \cdot (\text{PSF})^{-2}$

- eROSITA survey will be a significant step forward (~30" resolution, $z<\sim1.2$)
- Motivation for a **Wide Field X-ray Telescope** mission (FoM $10^2$ x higher)
A deep Chandra field

$z=0.58$

$z=1.27$

$z=1.26$
1 Mpc/h₅₀
2 arcmin

Lynx field: B I K image

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

SPICES field
Chandra contours [0.5-2] keV (190 ksec)

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

Brodwin et al. (2011)

$\langle z \rangle = 1.487$

IRAC Cluster Surveys
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$\langle z \rangle = 1.487$
The highest SZ cluster confirmed so far: $z=1.31$
The increasing population of distant clusters

Only a few clusters known at $z>1$
The increasing population of distant clusters

Massive cluster formation?

proto-clusters around RGs/AGN

SPT 0205-5829  z=1.31

IDCS 14626+36  z=1.75

2012

(XMM serendip survey, Fassbender 2011 et al.)

(Gobat et al. 2011)

(z=2.07)

(Santos et al. 2011)

(z=1.579)

(Stanford et al. 2012)
Cluster detection and abundance at high-z

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

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

$\sigma_v=(802\pm155)$ km/s

Rosati et al. 09

ACS(i+z) - WFC3(J+H) - HAWKI-K$_s$

color composite
Chandra Observations of XMM2235 (190 ksec)

- Global fit:
- Core fit (r=7.5''=60 kpc):

\[ kT = 8.7^{+1.4}_{-1.2} \text{ keV}, \text{ and } Z = 0.32^{+0.19}_{-0.22} Z_\odot \]

\[ kT = 6.9^{+1.5}_{-1.1} \text{ keV}, \text{ and } Z = 0.59^{+0.29}_{-0.37} Z_\odot \]

Rosati et al. 09
Hottest (most massive) cluster to date at $z>1$ with a prominent cool core:

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

The ICM is already enriched at local values at $z=1.4$
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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, i775 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): $M_{200}(<1.1 \text{ Mpc}) = (7.1 \pm 1.3) \times 10^{14} \text{ M}_\odot / h_{70}$

• Such massive cluster is a rare event ($p \approx 5\%$) in the X-ray survey volume, is there any tension with $\Lambda$CDM ?
  ➞ 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 $M \sim 10^{15} \text{ M}_\odot$ clusters in SZ surveys (SPT) at $z \gtrapprox 1$
Early work by N. Bahcall in the mid-nineties MS1054 at z=0.83 to argue for a low $\Omega_M$ Universe
The most massive distant clusters in the Universe and their impact on Cosmology

- 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.

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

Accurate (<~10% errors) $M_{200}$ measurements needed!
Exclusion probability for $\Lambda$CDM using extreme clusters

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

Extreme value contours for $\Lambda$CDM ($f_{\text{sky}}=1$)

ACT-CL J0102–4915, $z=0.87$

SPT-CL J2106-5844, $z=1.13$

most likely maximum mass

(Menenteau et al. 2011)

(Foley et al. 2011)
Clusters as Cosmological Probes

N(M,z) from evolution of cluster abundance:
\[ \sigma_8, \Omega_M, \Omega_{\Lambda}(w) \]

Clustering, \( \xi_{\text{CL}}(r) \), or P(k): \( \sigma_8, \Omega_M, \Omega_{\Lambda} \)

### Parameter Accuracy *

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Accuracy</th>
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<tbody>
<tr>
<td>( \sigma_8 )</td>
<td>3-5%</td>
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<tr>
<td>( \Omega_M )</td>
<td>5-10%</td>
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<tr>
<td>( \Omega_{\Lambda} ), ( w )</td>
<td>40-60%</td>
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* with current (ROSAT) samples

Note: \( \sigma_8 = 0.7-0.8 \) consistently from clusters

\[ \sigma_8 = 0.92 \pm 0.10 \Rightarrow 0.77 \pm 0.05 \Rightarrow 0.81 \pm 0.02 \]

WMAP1    WMAP3    WMAP7
+BAO + H_0

Gas fraction, \( f_B, f_B(z) \)

\[ \Omega_M h, (\Omega_{\Lambda}, w) \]
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)

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

**Mass function and distribution of DM halos** (∼ Gpc scale)

- REFLEX collaboration

**Millennium simulations** (Springel et al. 2005)

- CDM 23%
- Dark Energy 73%
- 4%