Observational cosmology with X-ray luminous galaxy clusters

First Lecture: Cosmology, Clusters and Gas Mass Fraction

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General outline for the two lectures

- Overview of current cosmological experiments and results

- Detailed examples of data analyses

- Paradigms and approaches in present-day cosmology including concrete examples

Observational cosmology

Underlying standpoints of data analysis to take home from the lectures:

- Deep understanding of astrophysical processes and objects
- Careful design of observations
- Justify and continuously revised assumptions
- Account properly for covariances between parameters, instrumental and astrophysical systematic uncertainties and biases
- Simultaneous fits of all the relevant astrophysical and cosmological parameters

Structure of the lectures

First Lecture:

- Introduction to cosmological analyses
- Expansion history measurements and cosmological results
- Detailed data analysis: gas mass fraction experiment

Second Lecture:

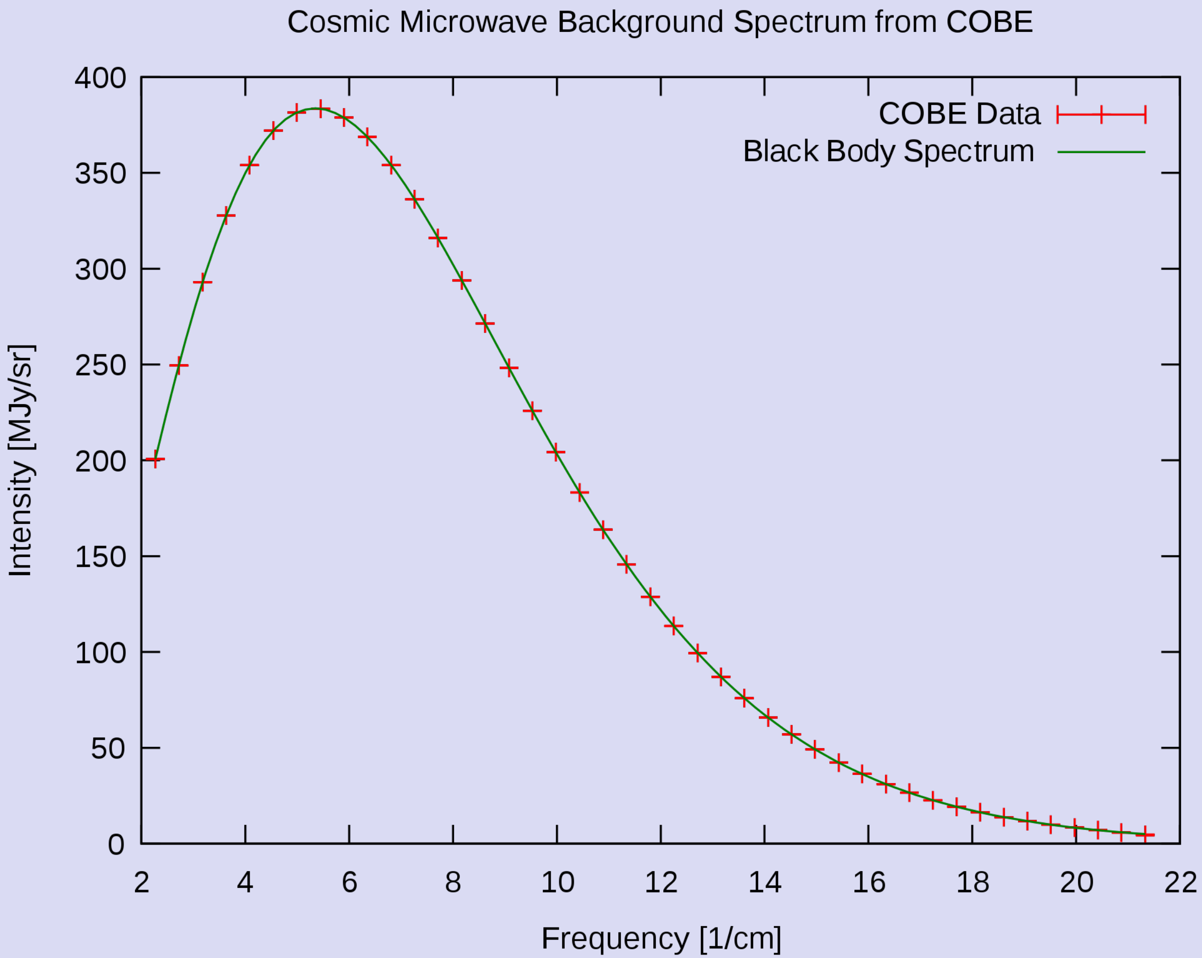
- Cosmological models and modeling
- Growth history measurements and cosmological results
- Detailed data analysis: cluster abundance experiment

Recent discoveries and current results

Cosmic Microwave Background (CMB)

Nobel Prize in Physics 1978: Arno Penzias & Robert Wilson (CMB discovery in 1965) [Pyotr Kapitsa (Low-temperature physics)]

Nobel Prize in Physics 2006: John Mather & George Smoot (CMB blackbody and anisotropy)



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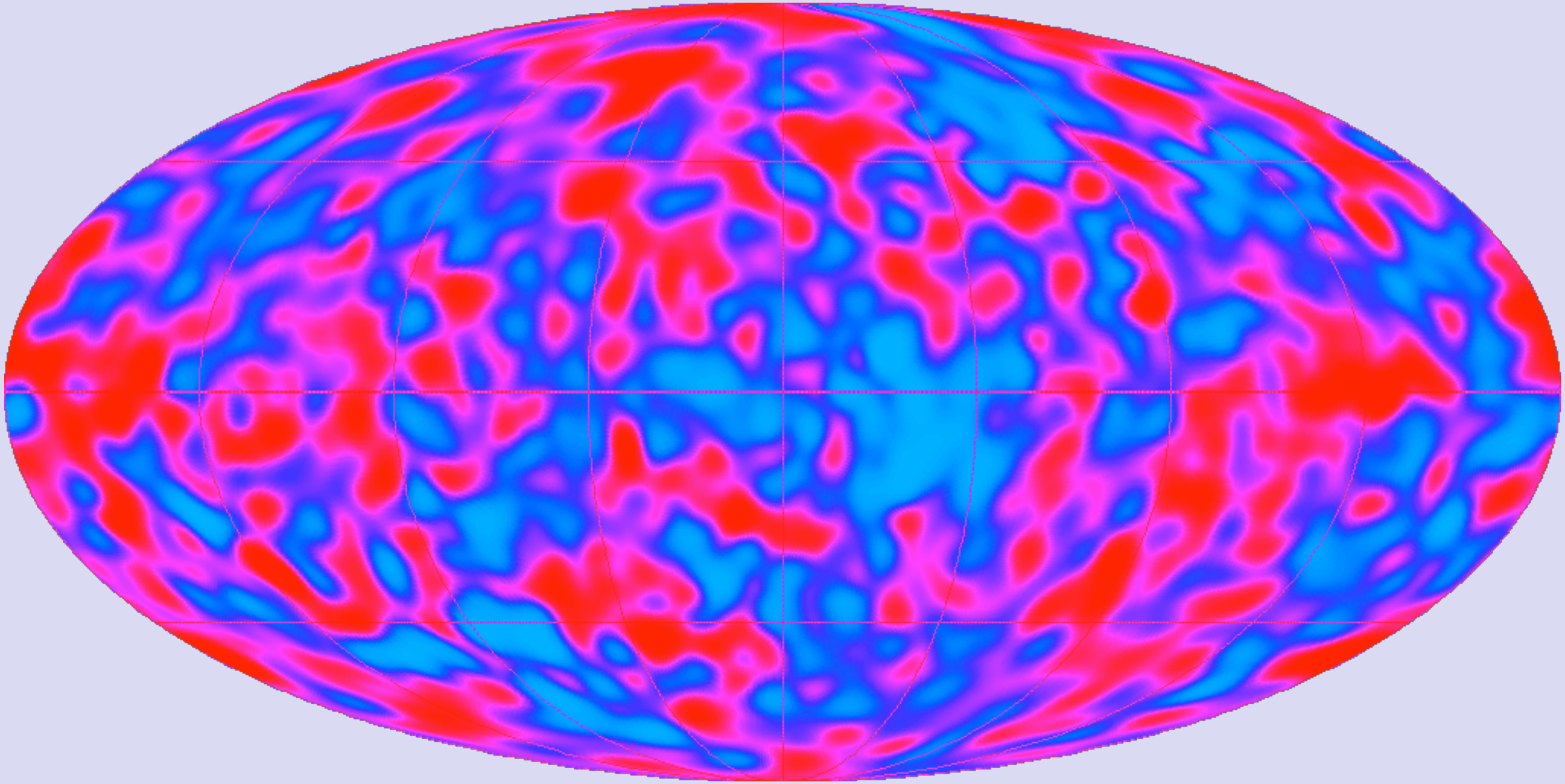
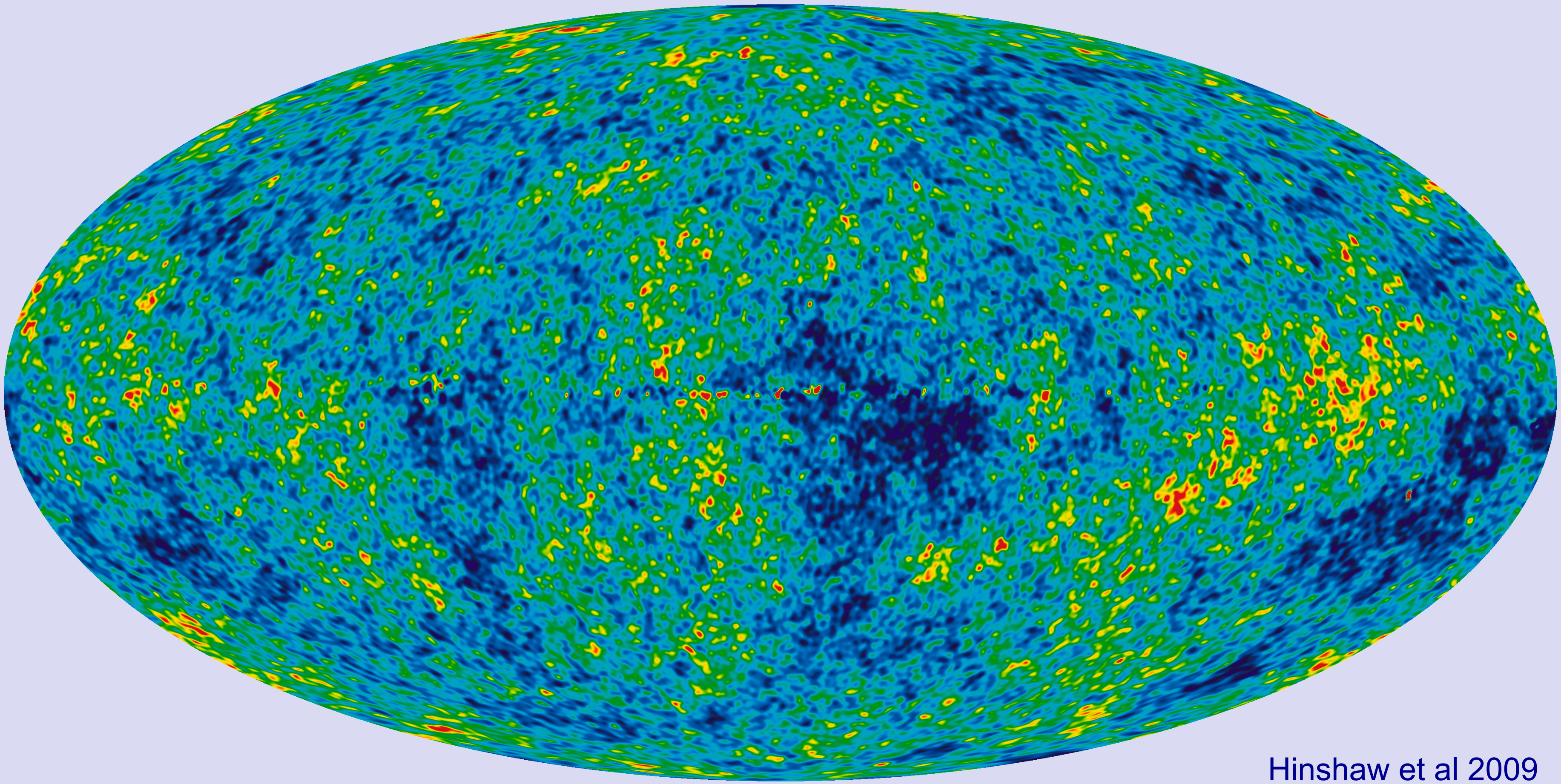
From NASA's COBE satellite



Cosmic Microwave Background (CMB)

Measurements from current NASA's WMAP satellite (five-years)

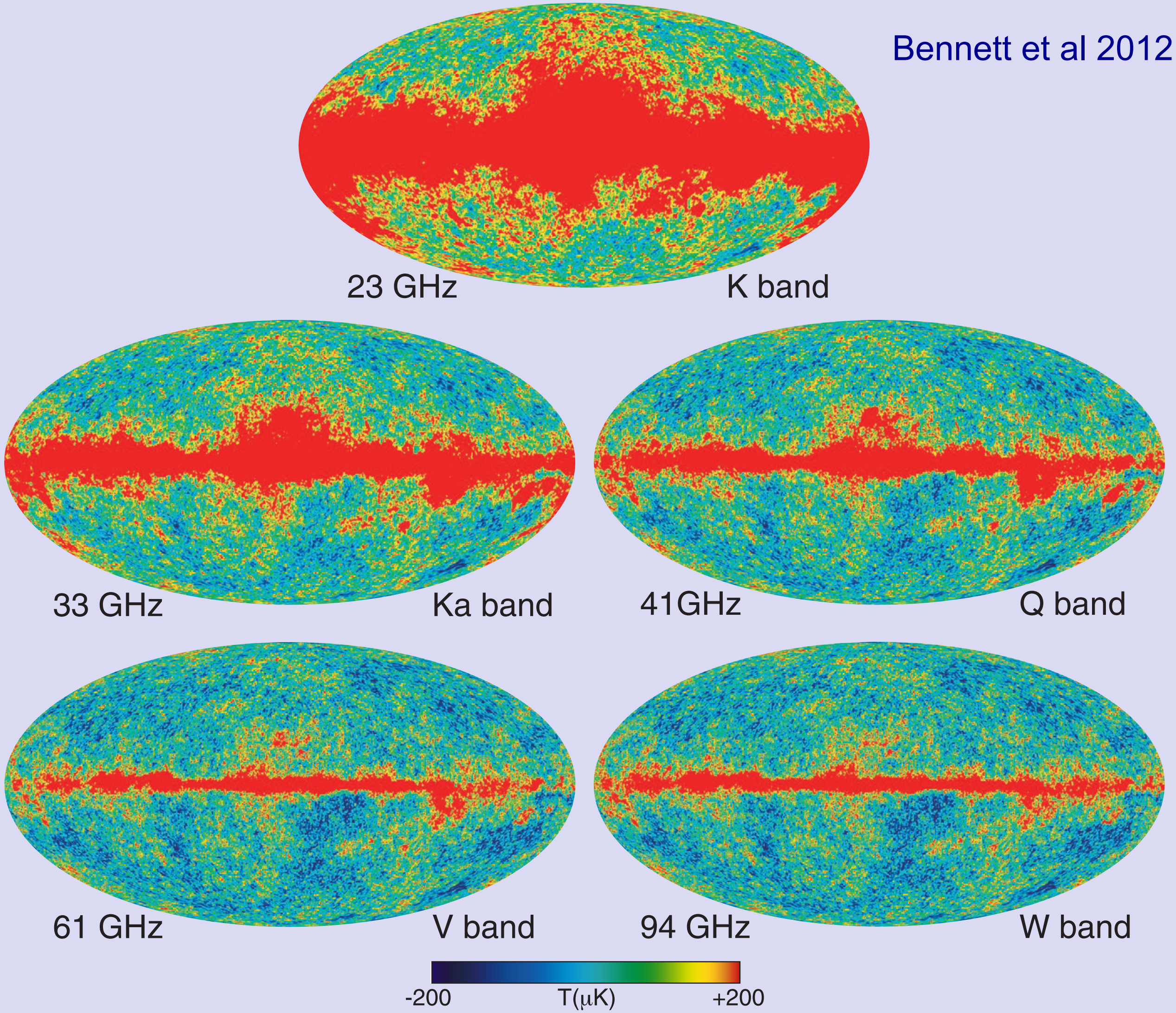


Hinshaw et al 2009

Cosmic Microwave Background (CMB)

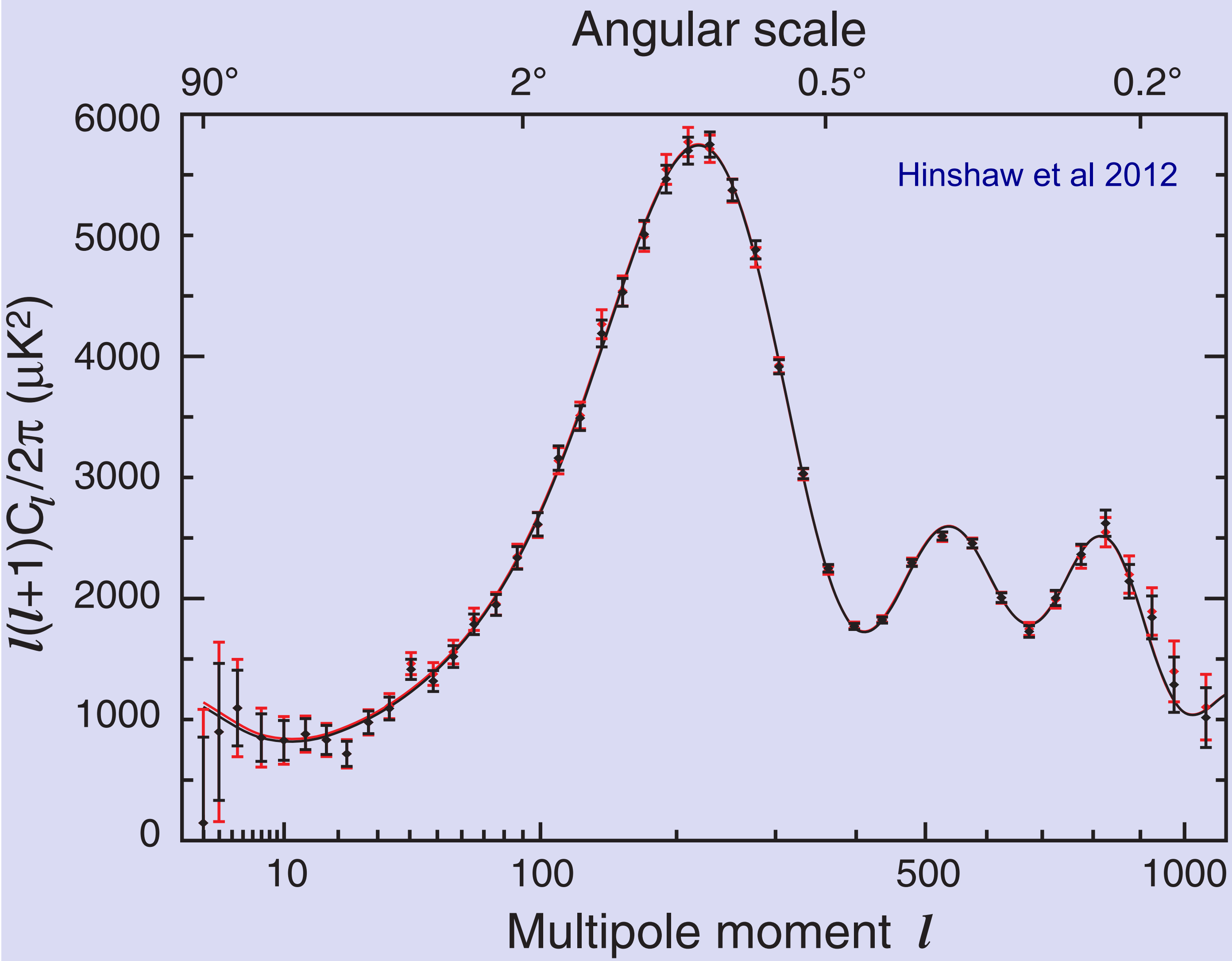
Final WMAP (nine-years) measurements

Bennett et al 2012



Cosmic Microwave Background (CMB)

Final WMAP (nine-years) measurements



Red symbols (binned data) and line (best fit): Using the previous WMAP MASTER-based power spectrum

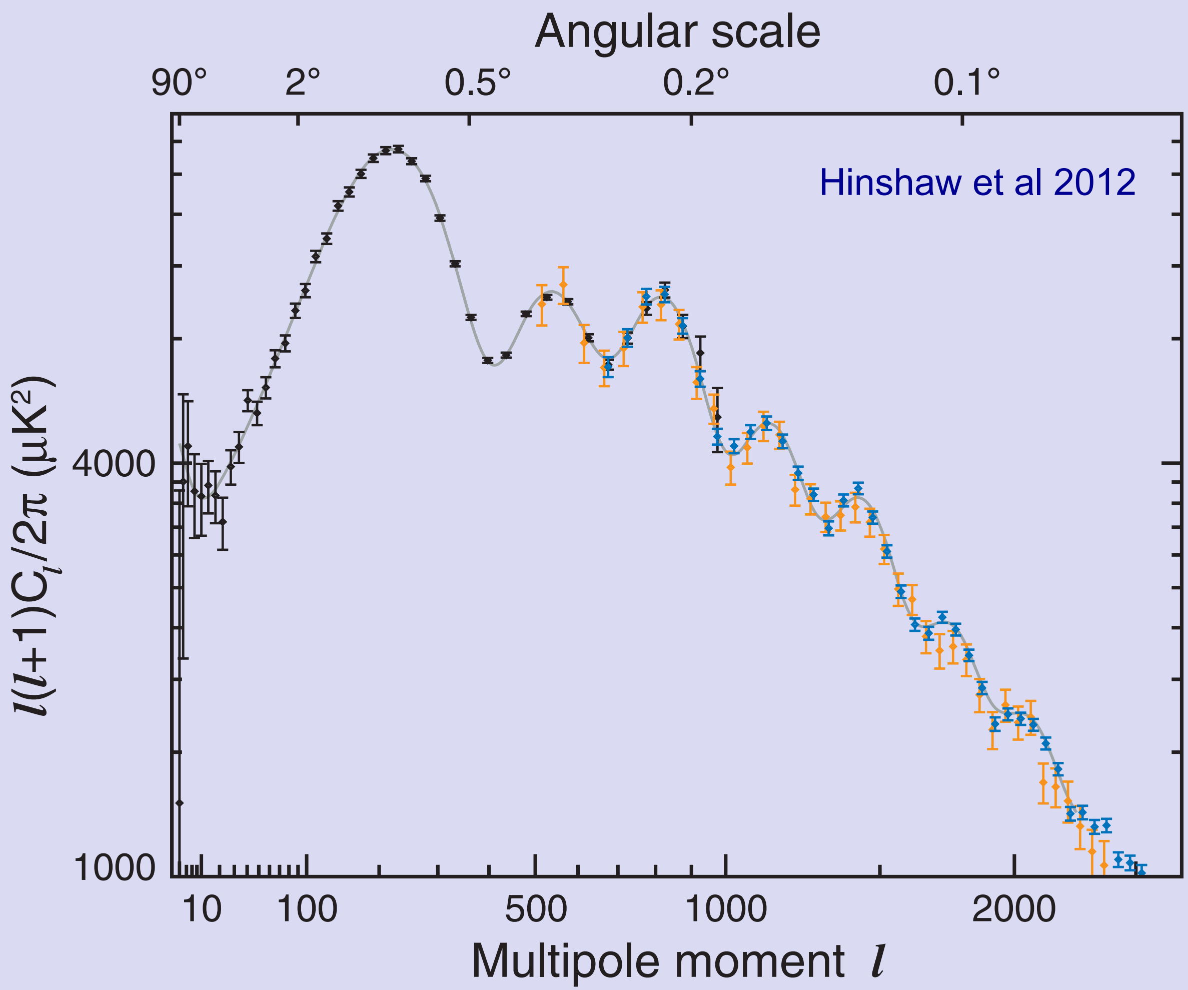
Black symbols (binned data) and line (best fit): Using the new WMAP C^{-1}-weighted power spectrum

Up to 5% difference in the vicinity of l~50. This affects mainly n_s.

Overall, WMAP9 wrt WMAP7 improve the parameters an average of ~10%, with almost 20% for $\Omega_c h^2$ and Ω_Λ, with about 10% from the new power spectrum.

Cosmic Microwave Background (CMB)

Final WMAP (nine-years) measurements



Black: WMAP9
(Hinshaw et al 2012)

Blue: SPT
(Keisler et al 2011)

Orange: ACT
(Das et al 2011)

Next: results from ESA's Planck satellite are coming soon this year…

Discovery of cosmic acceleration

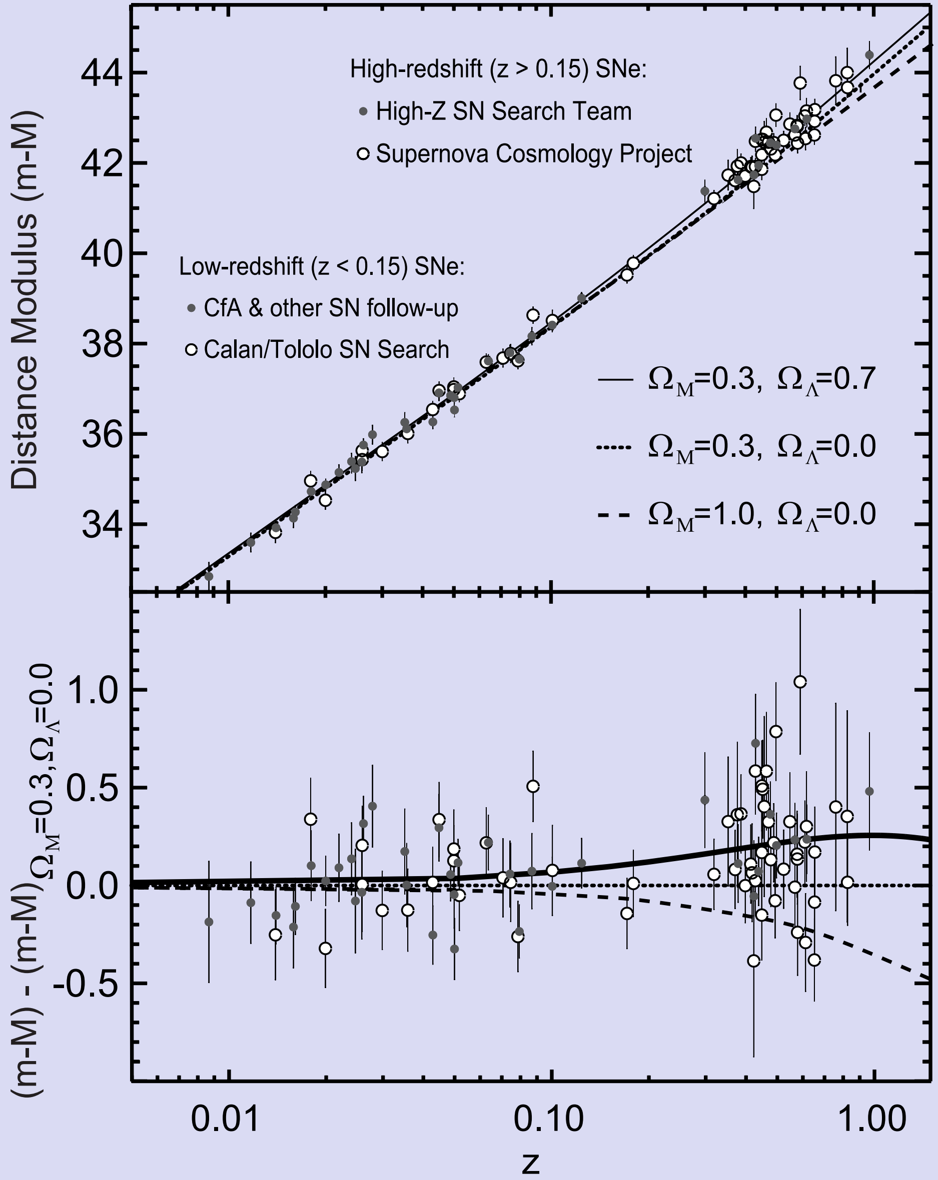


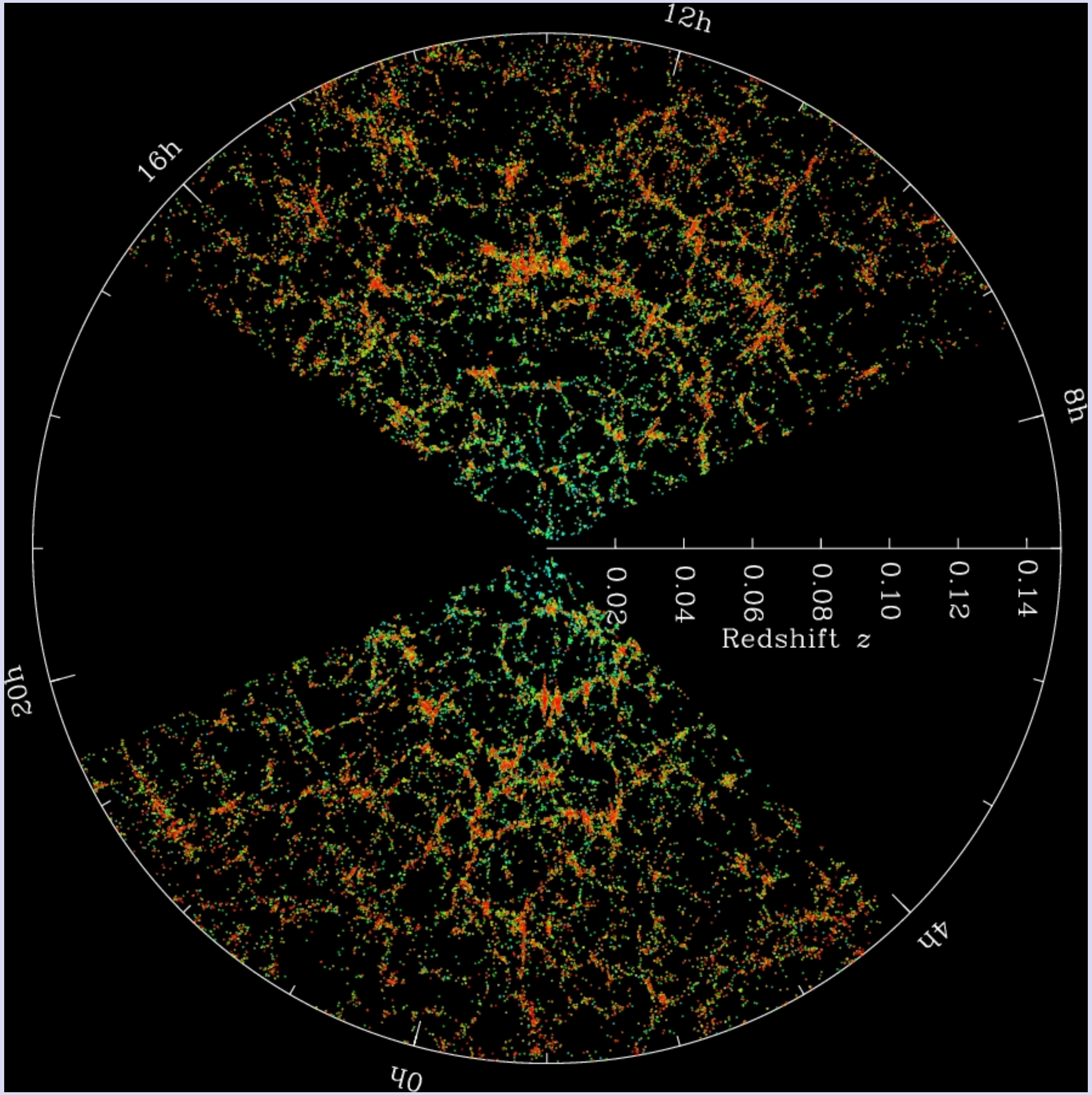
Figure from the dark energy review of Frieman, Turner & Huterer, 2008, ARA&A., 46, 385

-High-Z SN Search Team (HZT): Riess et al 1998

-Supernova Cosmology Project (SCP): Perlmutter et al et al. 1999

Nobel Prize Award in Physics 2011:
Saul Perlmutter (SCP)
Brian Schmidt & Adam Riess (HZT)

Large scale distribution of galaxies



Sloan Digital Sky Survey
(from the SDSS website)

Slice of a 3D map of galaxies

Galaxies are colored according to the ages of their stars: the redder, the more strongly cluster since are made of older starts.

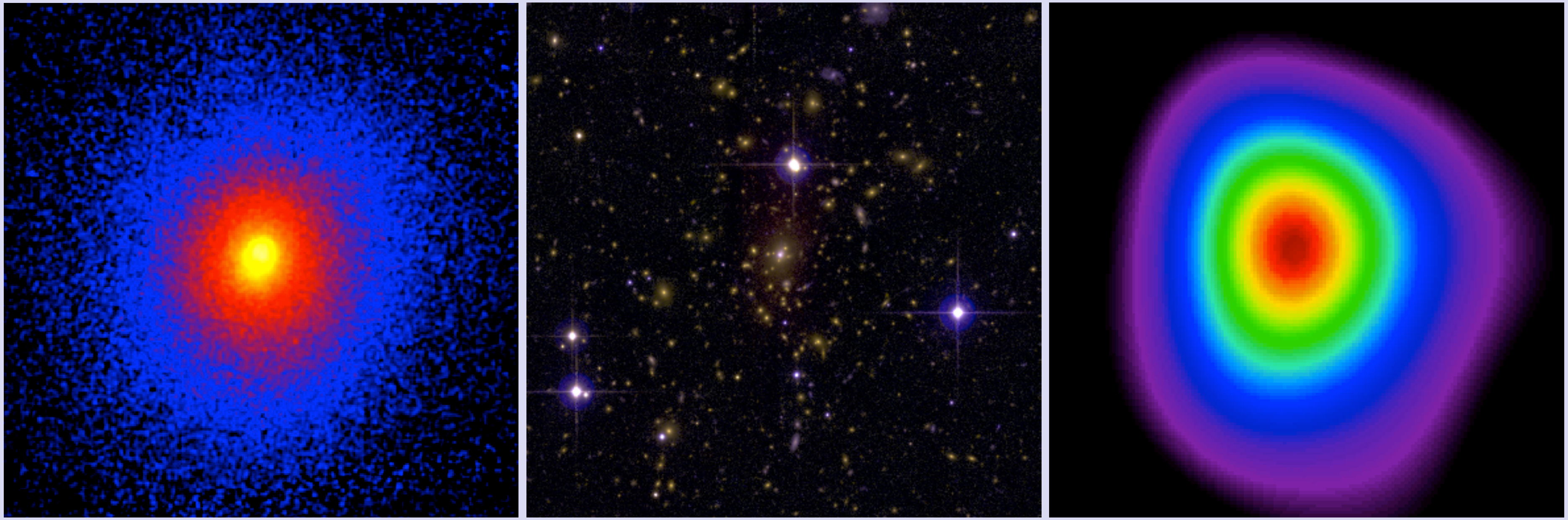
Outer circle: about two billion light years old

>930000 galaxies

Cluster cosmology

Cluster cosmology

Figure from Allen, Evrard & Mantz 11 (credits X-ray/Mantz; Optical/von der Linden et al; SZ/Marrone)

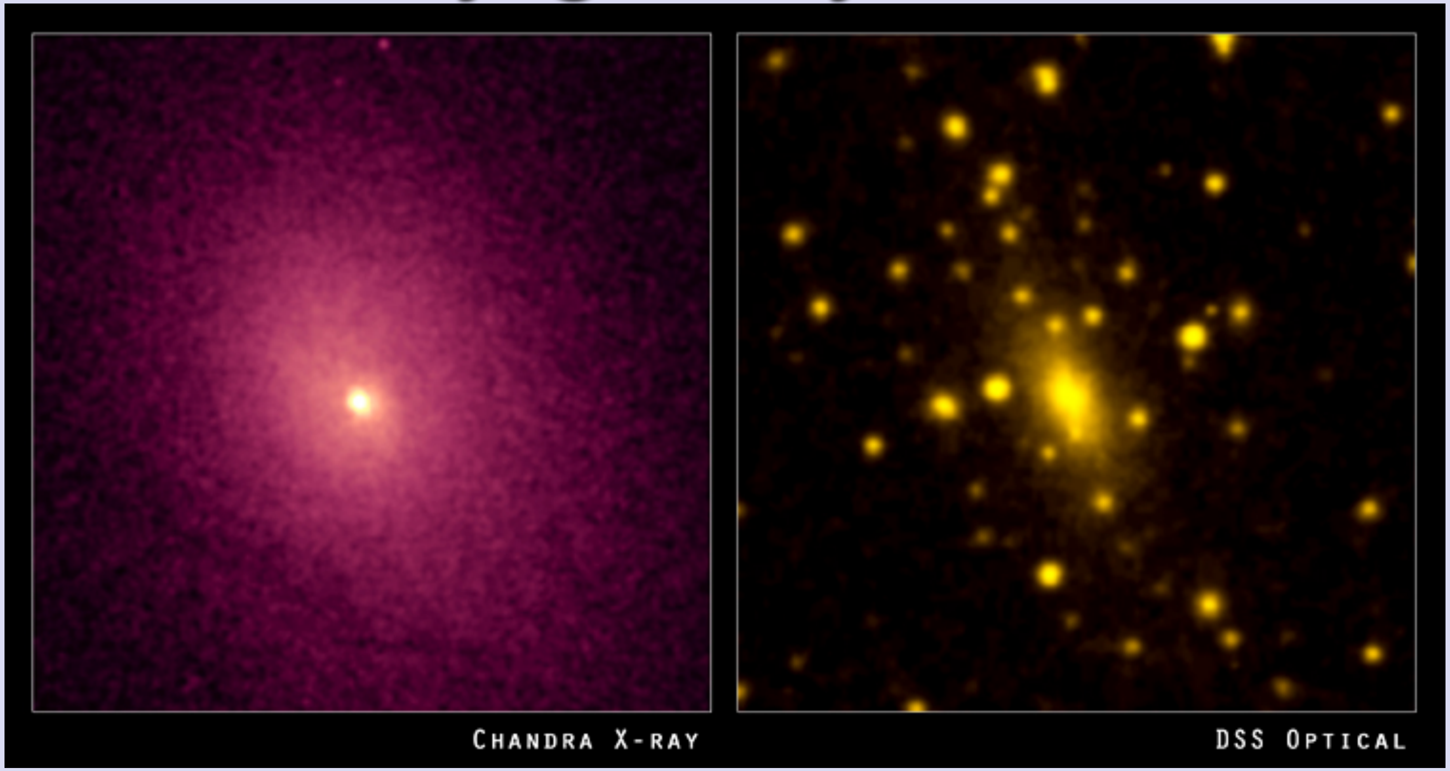


X-ray Optical Millimeter (SZ)

- Images of galaxy cluster Abell 1835 in different wavelength
- Cosmology with galaxy clusters using X-ray observations:
  - Gas mass fraction
  - Abundance of clusters and their observable-mass relations

Cluster cosmology review: Allen, Evrard & Mantz, 2011, ARA&A, 49, 409

X-ray galaxy cluster

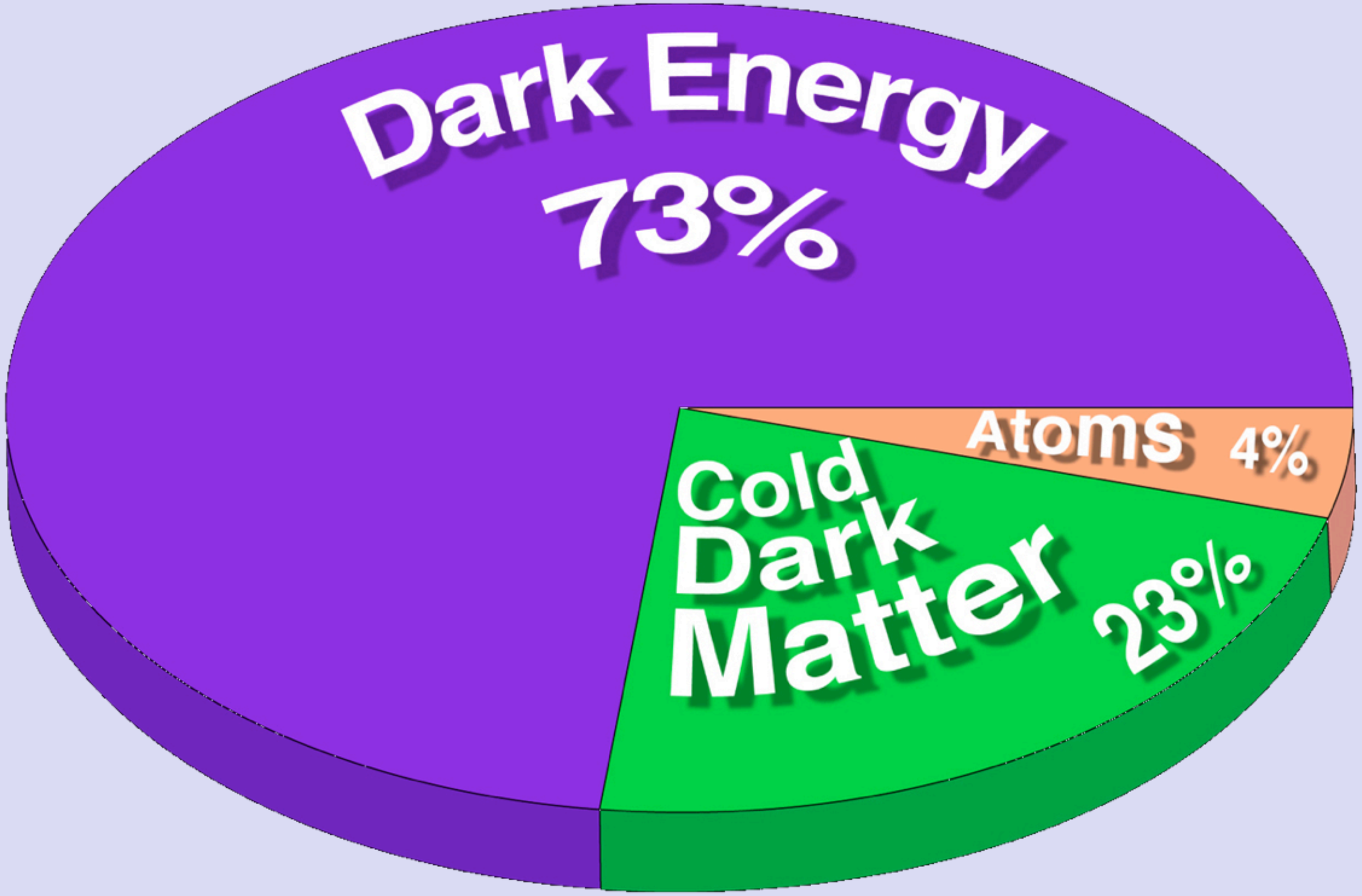


Galaxy cluster Abell 2029:
Thousands of galaxies optical (right panel)
Hot (multimillion Kelvin degrees) gas (left panel).
Dark matter (only gravitational interaction) >10^{15} solar masses.
In 1933 Fritz Zwicky proposed "missing matter" (dark matter) in clusters of galaxies
(Note: Central enormous elliptically shaped galaxy)

Basic cosmology

Peebles; Luchin & Mataresse; Peacock;
Dodelson; Weinberg ; Mukhanov; etc.

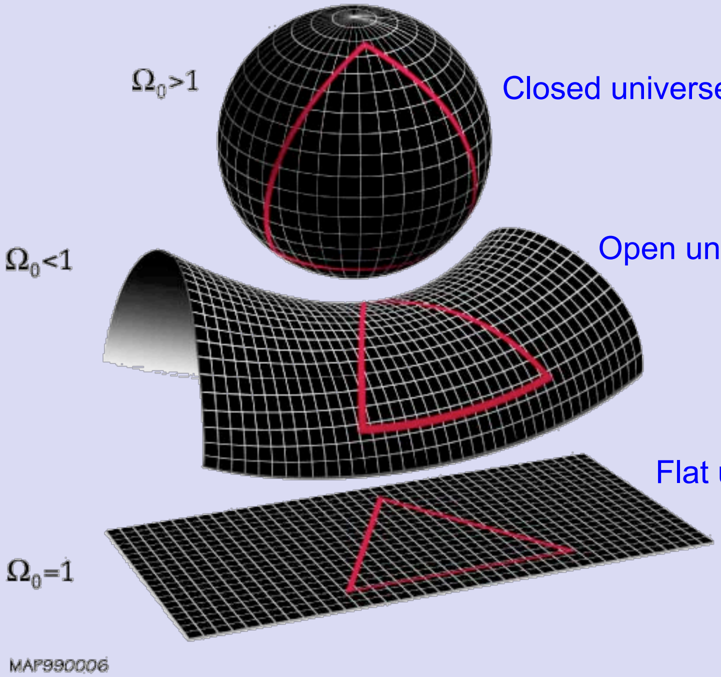
Cosmic pie: energy density of the Universe



Space-time metric of the Universe

Friedmann-Lemaitre-Robertson-Walker (FLRW) metric: for an isotropic and homogenous space-time (current data indicate that at large scale these assumptions are nearly valid)

$$ds^2 = dt^2 - a^2(t)\left[dr^2/(1-kr^2) + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2\right]$$

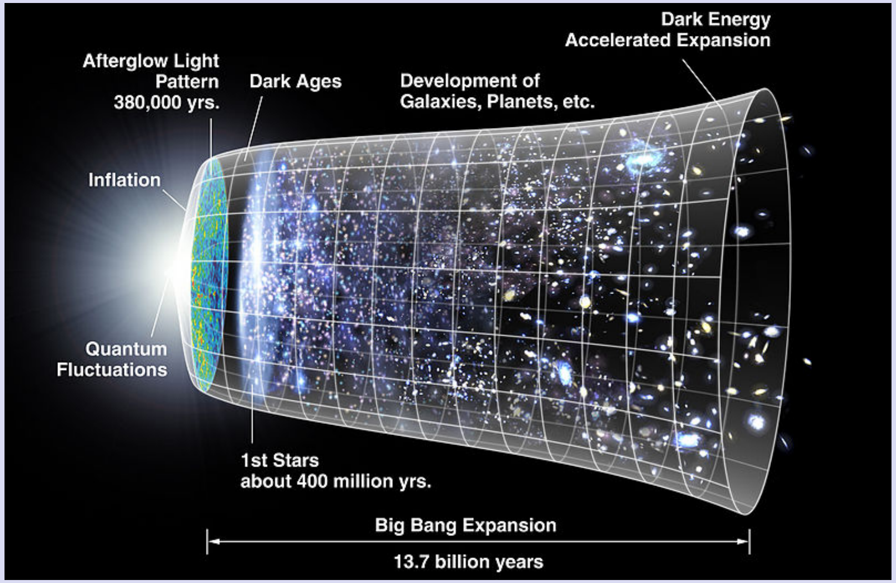


Closed universe: k>0

Open universe: k<0

Flat universe: k=0

Expansion history a(t)



Gravity and energy density

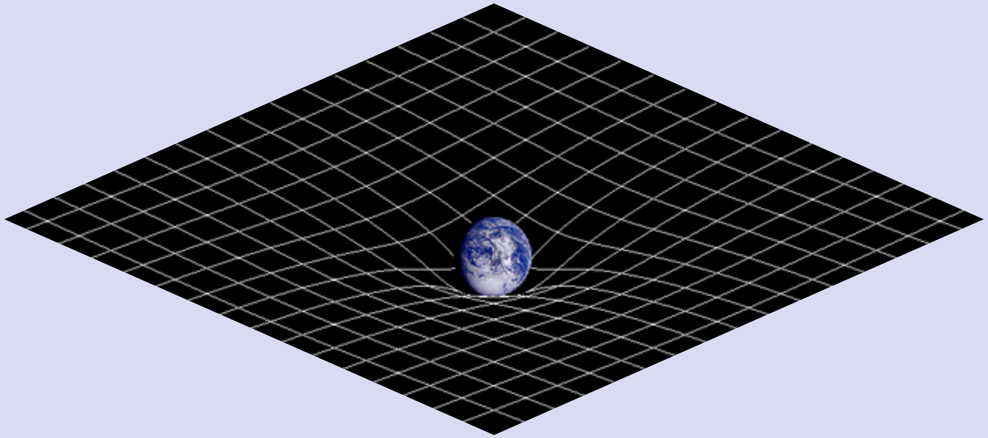
Einstein's equations

$$G^{\mu\nu} + \Lambda g^{\mu\nu} = 8\pi T^{\mu\nu}$$
$$c = G = 1$$

$$G^{\mu\nu} = R^{\mu\nu} - \frac{1}{2} R g^{\mu\nu}$$

$R^{\mu\nu}$ Ricci tensor
R Ricci scalar
$G^{\mu\nu}$ metric tensor

Interaction between gravity and energy-matter



John Wheeler: Matter tells space how to curve and space tells matter how to move

Useful reference for perturbation theory: Ma & Bertschinger 1995, ApJ, 455, 7

Cosmic energy content and expansion

Example of stress-energy tensor:

$$T^{\mu\nu} = \begin{pmatrix} \rho & 0 & 0 & 0 \\ 0 & p & 0 & 0 \\ 0 & 0 & p & 0 \\ 0 & 0 & 0 & p \end{pmatrix}$$

Fluid in a thermodynamic equilibrium

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\rho}{3} - \frac{k}{a^2} + \frac{\Lambda}{3}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) + \frac{\Lambda}{3}$$

Friedmann equations: key equations in cosmology; Einstein field equations for the FRWL metric

$$\Lambda = 8\pi G\rho_{\mathrm{VAC}} = -8\pi G p_{\mathrm{VAC}}$$

Energy density of the vacuum

Dark energy review: Frieman, Turner & Huterer 2008, ARA&A., 46, 385

Cosmic energy content and expansion

$$H^2 = \frac{8\pi G}{3}\rho - \frac{k}{a^2}$$

Friedmann equation
ρ sum of the energy densities of matter, dark energy, radiation

$$w = \frac{p_{de}}{\rho_{de}}$$

Dark energy equation of state

$$a(t) = \frac{1}{1+z}$$

a(t) scale factor
z redshift

$$E(a) = \left[\Omega_{\mathrm{m}}\, a^{-3} + \Omega_{\mathrm{de}}\, a^{-3(1+w)} + \Omega_{\mathrm{k}}\, a^{-2}\right]^{1/2}$$

$$E(z) = \sqrt{\Omega_{\mathrm{m}}(1+z)^3 + \Omega_{\mathrm{de}} f(z) + \Omega_{\mathrm{k}}(1+z)^2}$$

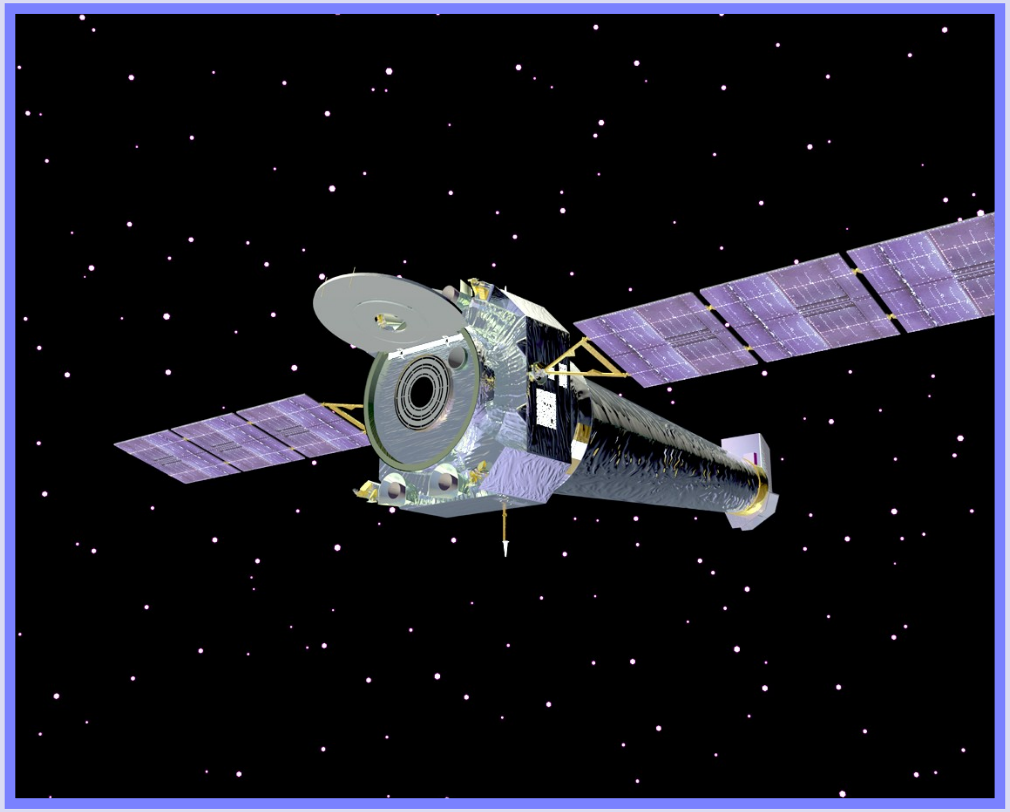
Evolution parameter
$E(a)=H(a)/H_0$

i) flat ΛCDM — w=-1, Ω_k=0
ii) flat *w*CDM — w constant, Ω_k=0
iii) non-flat ΛCDM — w=-1, Ω_k constant

The $f_{gas}(z)$ experiment

e.g. Allen et al 02, 04, 08; Ettori et al 03, 09;
Rapetti et al. 05, 07, 08; LaRoque et al 06

Chandra X-ray Observatory



Cluster cosmology revolutionized

First opportunity to carry out:

->Detailed spatially-resolved and

->X-ray spectroscopy of galaxy clusters.

Technical details for ACIS instrument (X-ray CCDs):

• Field of view 16x16 arcmin^2
• Good spectral resolution ~100eV over 0.5-8 keV range.
• Exquisite spatial resolution (0.5 arcsec FWHM).

Measuring comic matter content using the gas mass fraction of X-ray luminous galaxy clusters

Consider a spherical region of observed angular radius θ within which the gas mass fraction is measured

$$R = \theta\, d_A$$

R physical size

$$L_x = 4\pi\, d_L^2 F_x$$

L_x X-ray Luminosity of the region
F_x detected flux

$$d_L = d_A (1+z)^2$$

d_L luminosity distance
d_A angular diameter distance

Since the X-ray emission is mainly due to collisional processes (bremsstrahlung and emission line) and is optically thin

$$L_x \propto n^2 V$$

n mean matter density of colliding gas particles
V volume of the emitting region: $V = 4\pi(\theta d_A)^3/3$

Measuring comic matter content using the gas mass fraction of X-ray luminous galaxy clusters

$$n \propto \frac{d_L}{d_A^{3/2}} \longrightarrow M_{gas} \propto nV \propto d_L d_A^{3/2}$$

M_{gas} observed gas mass within the measurement radius

$$M_{tot} \propto d_A$$

M_{tot} total mass determined by X-ray data assuming hydrostatic equilibrium (see below)

M_{gas} gas mass $\propto d_A(z)^{2.5}$ (X-ray Luminosity)

M_{tot} total cluster mass $\propto d_A(z)$ (primarily X-ray Temperature)

$$f_{gas} = \frac{M_{gas}}{M_{tot}} \propto d_L d_A^{1/2}$$

f_{gas} gas mass fraction

Measuring comic matter content using the gas mass fraction of X-ray luminous galaxy clusters

$$f_{gas} = \frac{M_{gas}}{M_{tot}} \propto d_A(z)^{1.5}$$

$$s = f_{stars} / f_{gas} = (0.16 \pm 0.05) h_{70}^{0.5}$$ Baryonic mass fraction in stars

Lin & Mohr 04, Fukugita et al 98, White et al 93

$$f_{baryon} = f_{stars} + f_{gas} = f_{gas}(1+s)$$ Baryon mass fraction

Measuring comic matter content using the gas mass fraction of X-ray luminous galaxy clusters

$$f_{baryon} = b\frac{\Omega_b}{\Omega_m}$$

The matter content of rich clusters of galaxies is expected to provide an almost fair sample of the matter content of the Universe (White & Frenk 91, White et al. 93, Eke et al. 98).

b, the bias factor accounts for the relatively small amount of gas expelled when clusters form.

$$\Omega_m = \frac{b\Omega_b}{f_{gas}(1+s)}$$

+HST+BBNS priors when clusters alone or +CMB data

Measuring cosmic acceleration using the gas mass fraction of X-ray luminous galaxy clusters

$$f_{gas}^{ref}(z) = \frac{b(z)\gamma K}{1+s(z)}\left(\frac{\Omega_b}{\Omega_m}\right)\varepsilon(\theta)\left[\frac{d_A^{ref}(z)}{d_A^{\mathrm{mod}}(z;\theta)}\right]^{3/2}$$

Apparent evolution of the gas mass fraction

$$\varepsilon(\theta) = \left[\frac{H^{\mathrm{mod}}(z;\theta)\,d_A^{\mathrm{mod}}(z;\theta)}{H^{ref}(z)\,d_A^{ref}(z)}\right]^{\eta}$$

Small angular correction

$\eta = 0.214 \pm 0.022$ Measured from the data profiles

Measuring cosmic acceleration using the gas mass fraction of X-ray luminous galaxy clusters

Small angular correction that accounts for the angle subtended at the measurement radius r_{2500} as the underlying cosmology varies

$$\varepsilon(\theta) = \left(\frac{\theta_{2500}^{ref}}{\theta_{2500}^{\mathrm{mod}}} \right)^{\eta}$$

For each cluster the measured f_{gas} value at r_{2500} corresponds to a fixed angle θ_{2500}^{ref} for the reference cosmology that is slightly different from that $\theta_{2500}^{\mathrm{mod}}$ for the test cosmology.

$$M_{2500} \propto 4\pi r_{2500}^{3} \rho_{crit} / 3$$

Mass at the measurement radius r_{2500}, for which the density is 2500 the critical density

$$\rho_{crit} = 3H(z)^2 / 8\pi G$$

ρ_{crit} critical density

Measuring cosmic acceleration using the gas mass fraction of X-ray luminous galaxy clusters

Assuming hydrostatic equilibrium (HSE) in the intracluster medium (ICM) and spherical symmetry we can calculate the mass within a given radius using the following expression (Sarasin 1988)

$$M(r) = -\frac{rkT(r)}{G\mu m_p}\left[\frac{d\ln n}{d\ln r} + \frac{d\ln T}{d\ln r}\right]$$

n(r) is the gas density
T(r) ICM temperature
k Boltzmann constant
μm_p mean molecular weight

Measuring cluster masses is one of the cornerstones of cluster cosmology. Under those assumptions we can measure the total mass from density n(r) and temperature T(r) profiles obtained from X-ray data. Note also that M(r) depends more strongly on T(r) than n(r).

Given that the temperature, and temperature and density gradients, in the region of θ_{2500} are likely to be constant, we have

$$M_{2500} \propto r_{2500}$$

Measuring cosmic acceleration using the gas mass fraction of X-ray luminous galaxy clusters

$$\left.\begin{aligned} &M_{2500} \propto r_{2500} \\ &M_{2500} \propto 4\pi r_{2500}^3 \rho_{crit} / 3 \\ &\rho_{crit} = 3H(z)^2 / 8\pi G \end{aligned}\right\} \quad r_{2500} \propto H(z)^{-1}$$

$$r_{2500} \propto H(z)^{-1} \longrightarrow \theta_{2500} = r_{2500} / d_A \propto [H(z) d_A]^{-1}$$

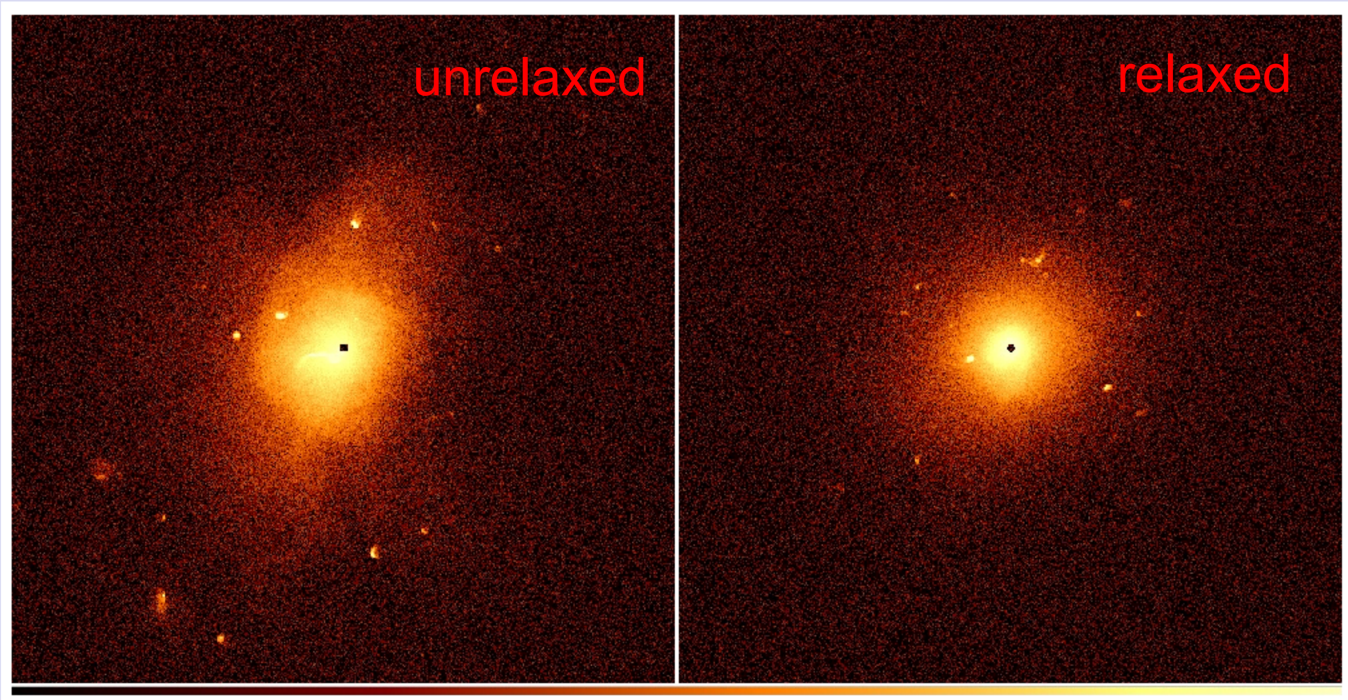
Angle spanned by r_{2500} at redshift z

$$\varepsilon(\theta) \equiv \frac{\varepsilon(\theta)^{\mathrm{mod}}}{\varepsilon(\theta)^{ref}} = \left(\frac{\theta_{2500}^{ref}}{\theta_{2500}^{\mathrm{mod}}} \right)^{\eta} \approx \left[\frac{H^{\mathrm{mod}}(z;\theta)\, d_A^{\mathrm{mod}}(z;\theta)}{H^{ref}(z)\, d_A^{ref}(z)} \right]^{\eta}$$

X-ray galaxy cluster cosmology: How well can we measure cluster mass?

Hydro dynamical simulations of X-ray galaxy clusters

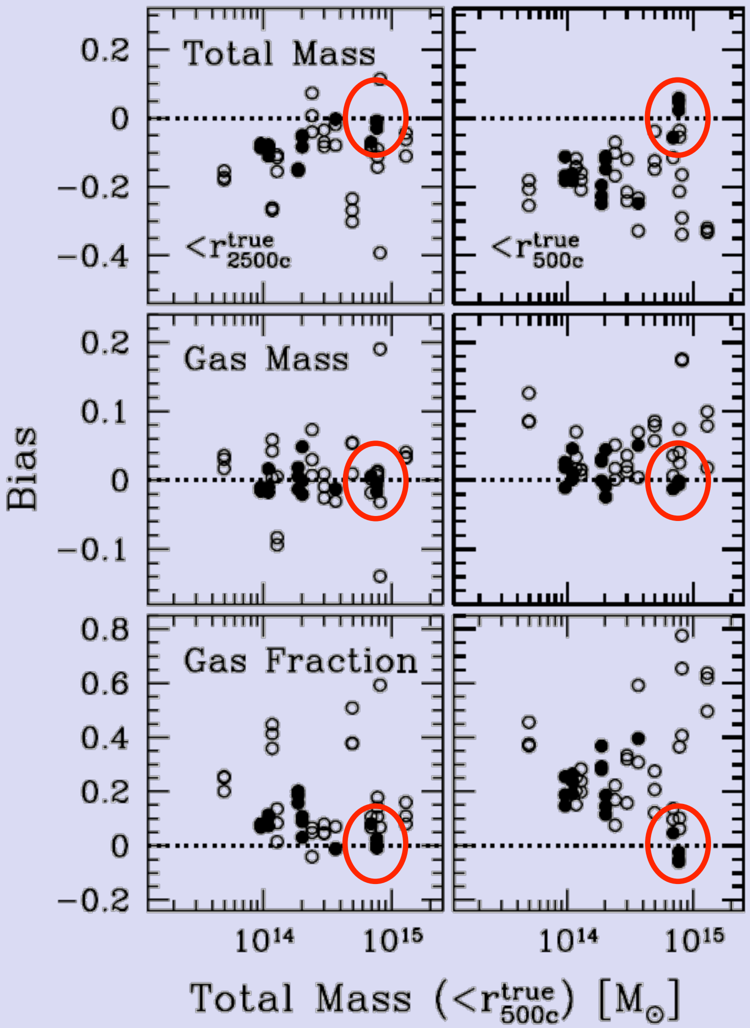
Nagai, Kravtsov, Vikhlinin 06



Very good news for X-ray galaxy cluster cosmology from the recent simulations: systematics are relatively small and can be quantified.

How accurately can we measure the mass?

Nagai, Kravtsov, Vikhlinin 06



For the largest, hottest (kT>5keV), relaxed clusters (selection based on X-ray morphology) we currently expect to measure:

a) X-ray gas mass to ~1% accuracy.

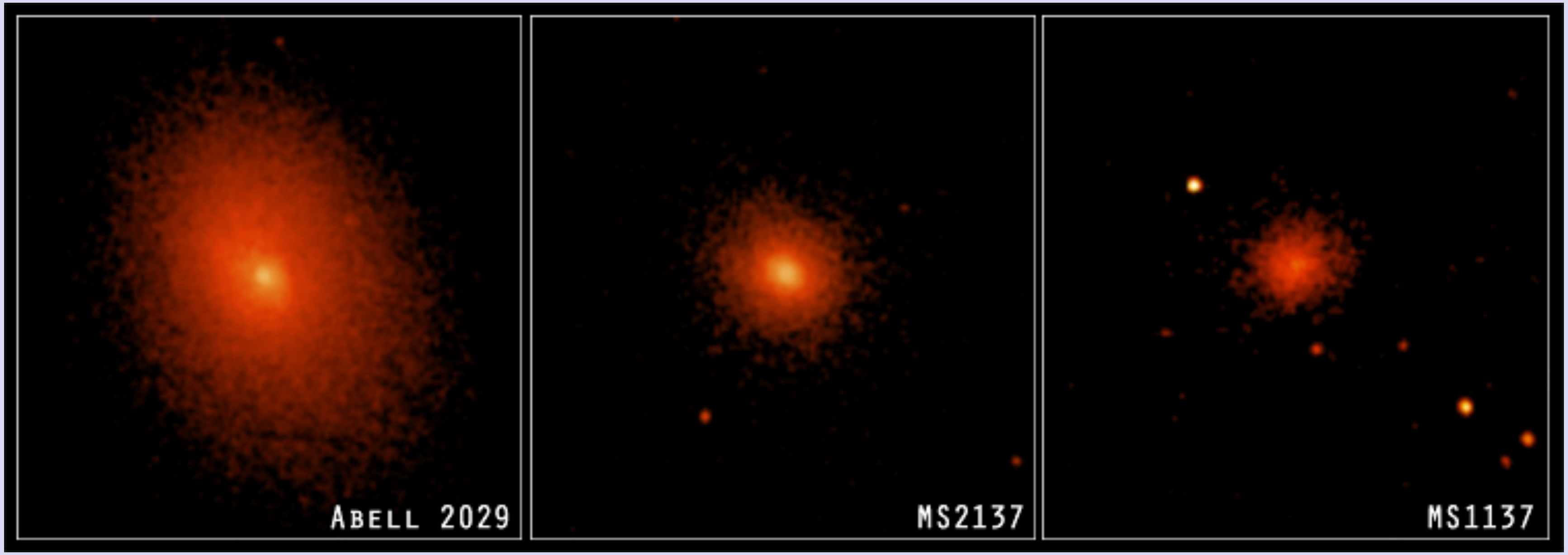
b) Total mass to few % accuracy (both bias and scatter).

Largest, relaxed clusters (filled points) inside red circles.

X-ray galaxy cluster data

It is crucial to use only dynamically relaxed clusters:

Regular X-ray morphology, low ellipticities, minimal centroid variation, sharp central brightness peaks centered on their dominant elliptical galaxies.



Measuring cosmic acceleration using the gas mass fraction of X-ray luminous galaxy clusters

$$F(d_A^{\mathrm{mod}}) \equiv \frac{d_A^{\mathrm{mod}}(z;\theta)^{3/2}}{\varepsilon(\theta)^{\mathrm{mod}}} = \frac{b(z)\gamma K}{1+s(z)}\left(\frac{\Omega_b}{\Omega_m}\right)\left[\frac{d_A^{ref}(z)^{3/2}}{\varepsilon(\theta)^{ref} f_{gas}^{ref}(z)}\right]$$

Angular diameter distance measurement for the fgas experiment

Compare to supernova measurements used as standard candles:

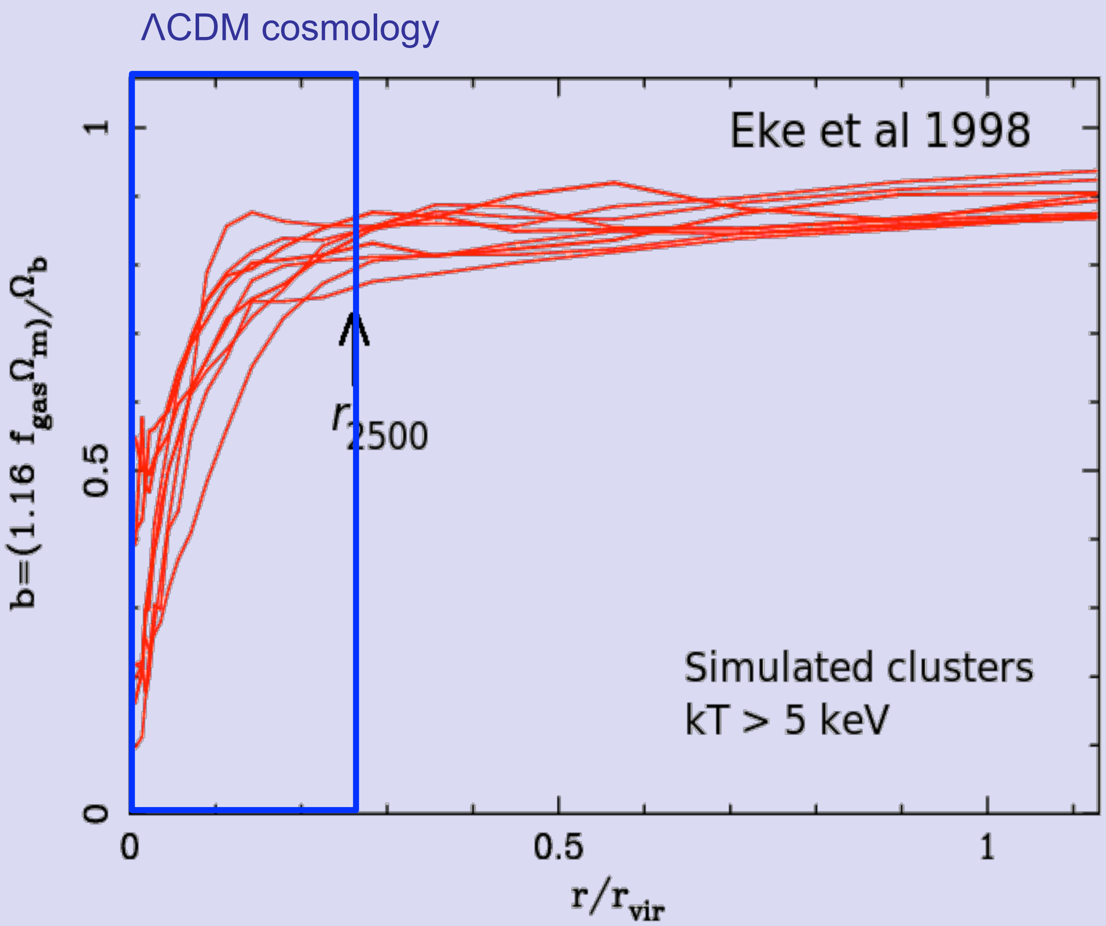
$$\mu^{th}(z) = 5\log_{10} d_L(z;\theta) + \mu_0$$

Apparent magnitude

$$d_L(z;\theta) = \frac{c(1+z)}{H_0}\int_0^z \frac{dz}{E(z;\theta)}$$

Luminosity distance

Gas mass: simulations
Low scatter total mass proxy



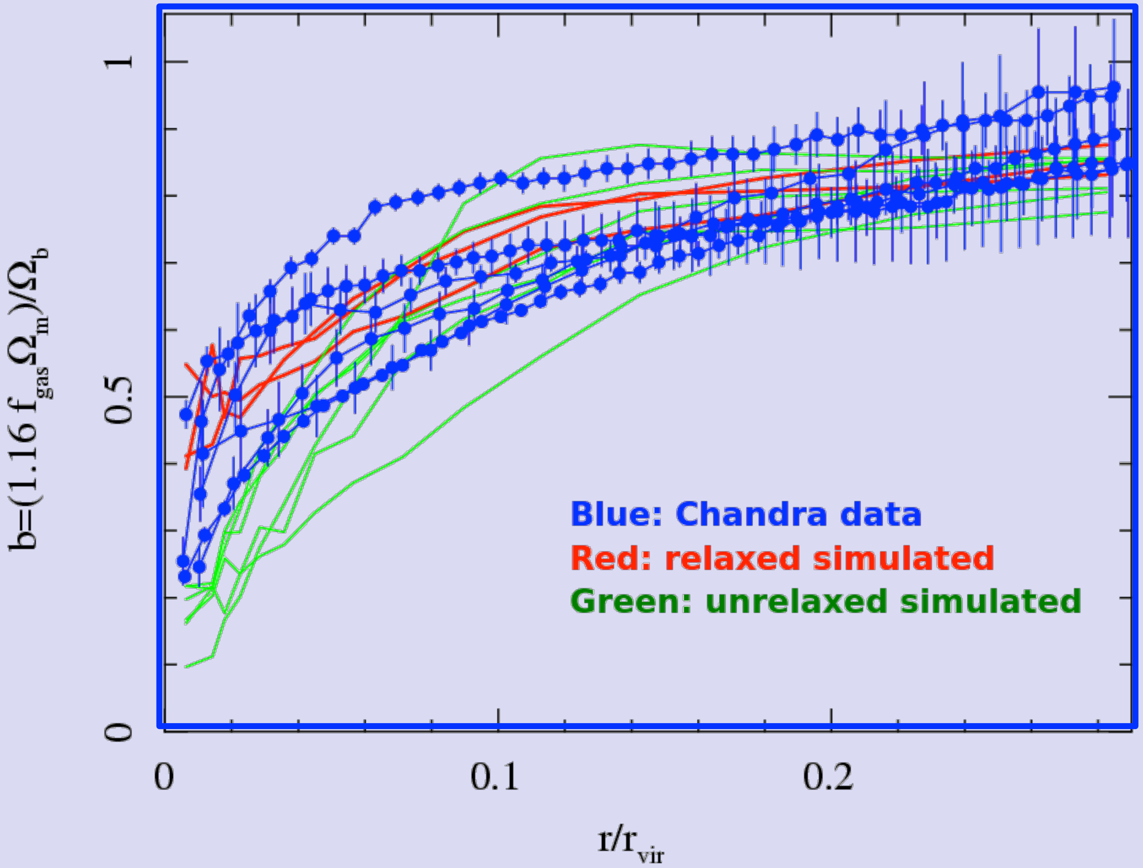
Simulations indicate low cluster-to-cluster scatter

Gas-mass low-scatter total-mass proxy through f_{gas}

Simulations indicate that the baryon mass fraction in clusters is slightly lower than the mean value for the Universe as a whole. Some gas is lifted beyond the virial radius by shocks (e.g. Evrard et al 90, Thomas & Couchman 92, Navarro & White 93; NFW 95 etc, Kay et al 04, Ettori et al 06, Crain et al 06, Nagai et al 07).

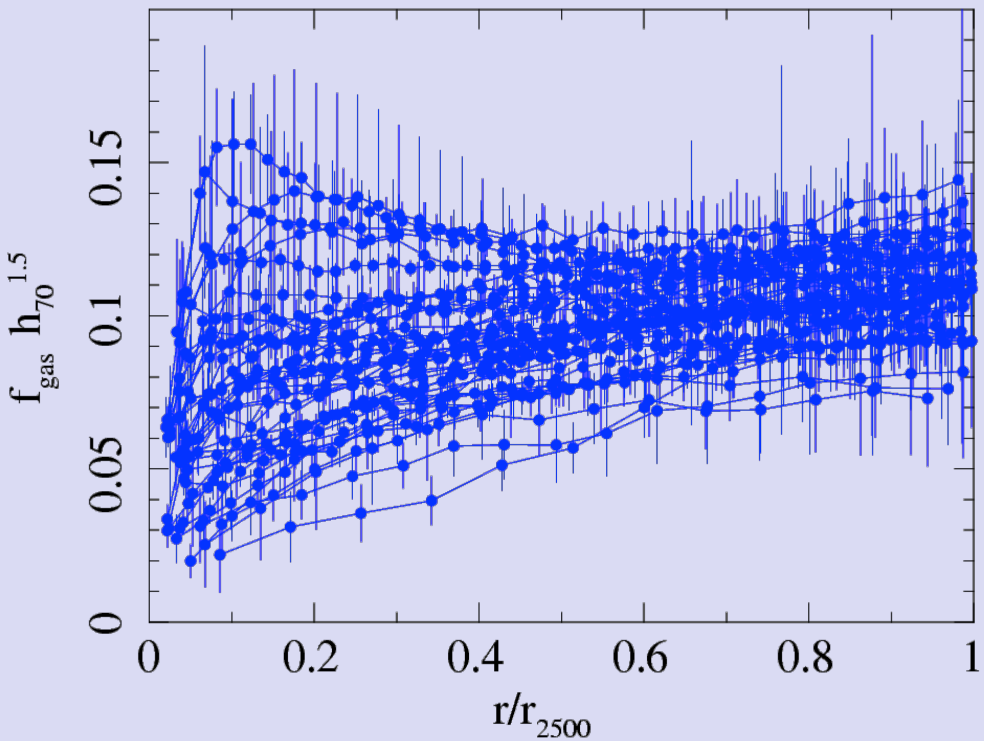
Gas mass: data
Low scatter total mass proxy

ΛCDM (Ω_m=0.3, Ω_Λ=0.7)



Undetected systematic scatter when weighted mean scatter is ~5% in distance

Chandra fgas(r) data:
42 relaxed clusters with redshifts 0.06<z<1.07



Fitting a constant value at r_{2500} :

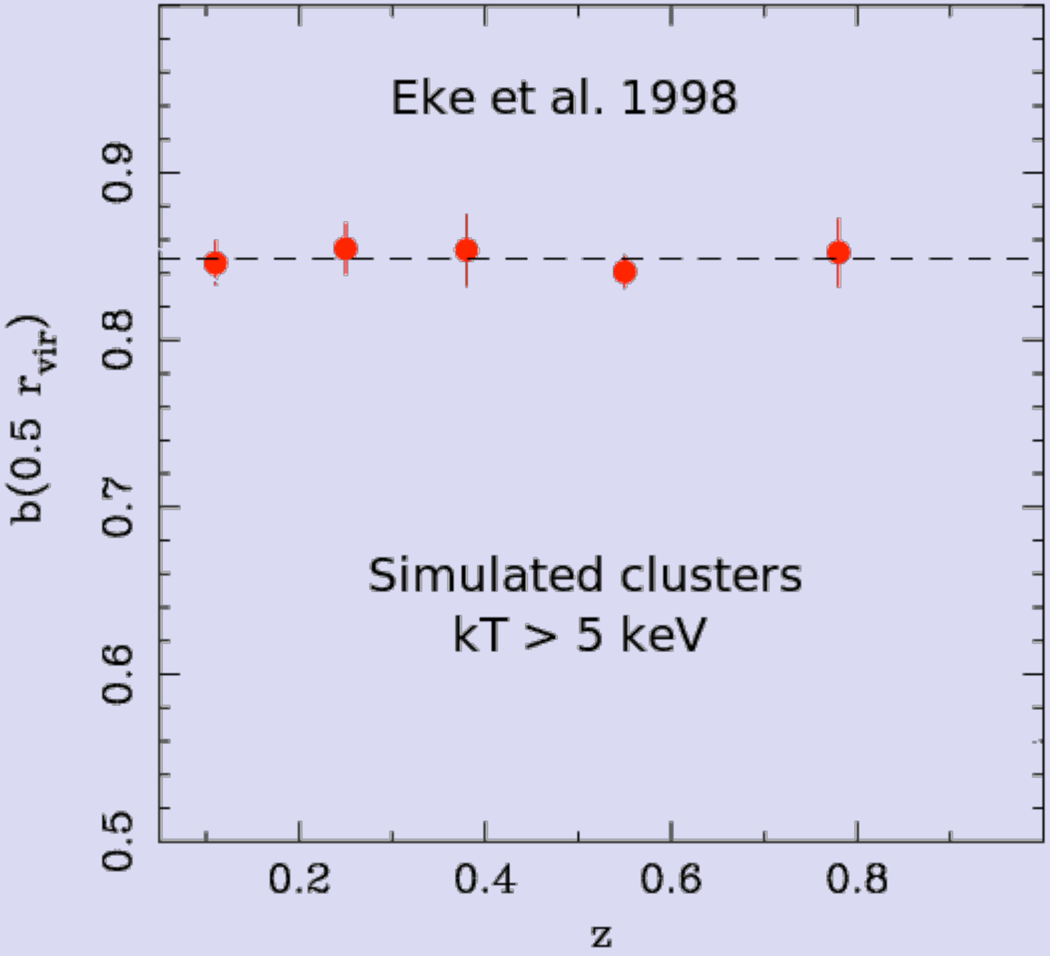
$f_{gas}(r_{2500})=(0.1104\pm0.0016)h_{70}^{-1.5}$

Fitting a power law (0.7-1.2)r_{2500} :

$f_{gas}(r_{2500})=(0.1105\pm0.0005)(r/r_{2500})^{0.214\pm0.022}$

Assuming hydrostatical equilibrium and spherical symmetry (only relaxed clusters).

Gas mass: simulations
Low scatter total mass proxy

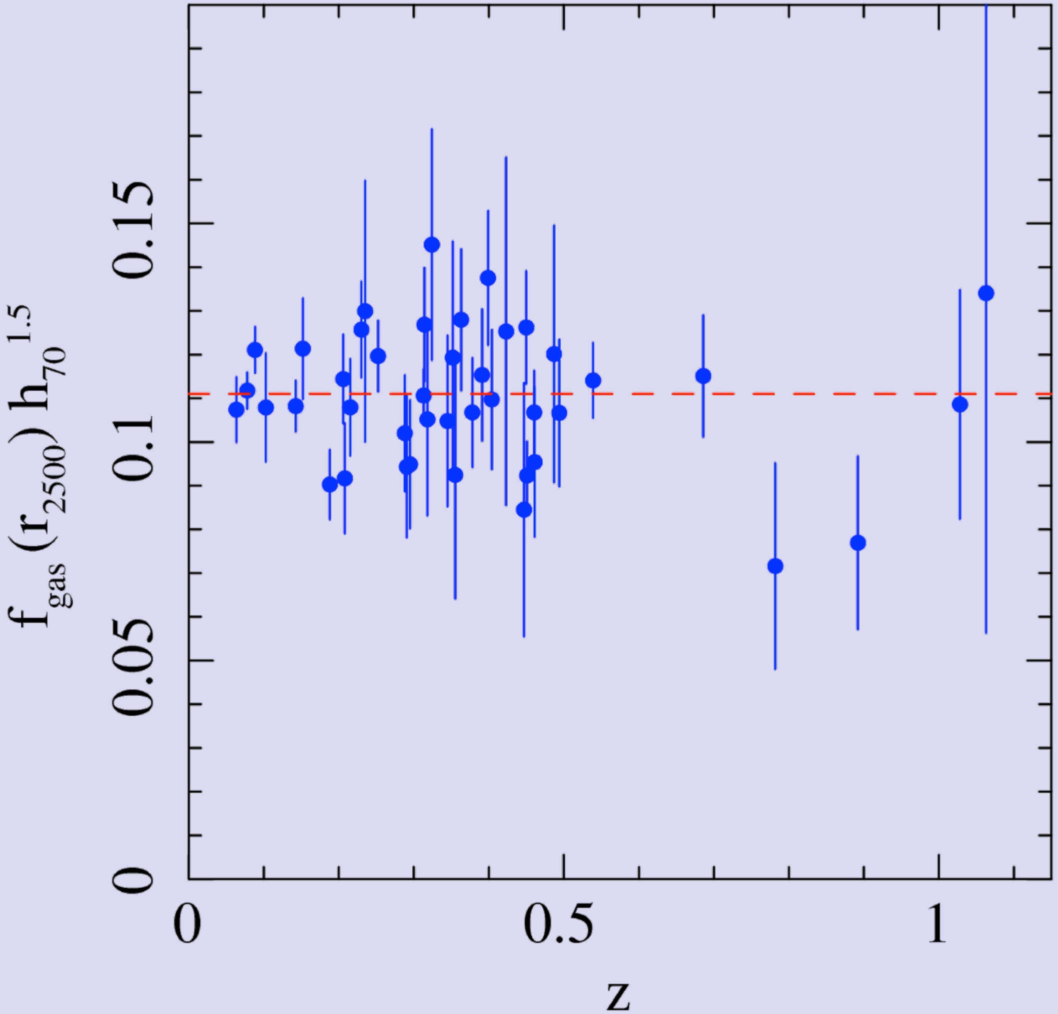


Tens of simulated clusters, $0<z<0.8$, $kT>5$keV

Minimal evolution at r_{2500}

Gas-mass low-scatter total-mass proxy through f_{gas}

Gas mass fraction: data
Low scatter total mass proxy



ΛCDM (Ω_m=0.3, Ω_Λ=0.7)

42 dynamically relax clusters

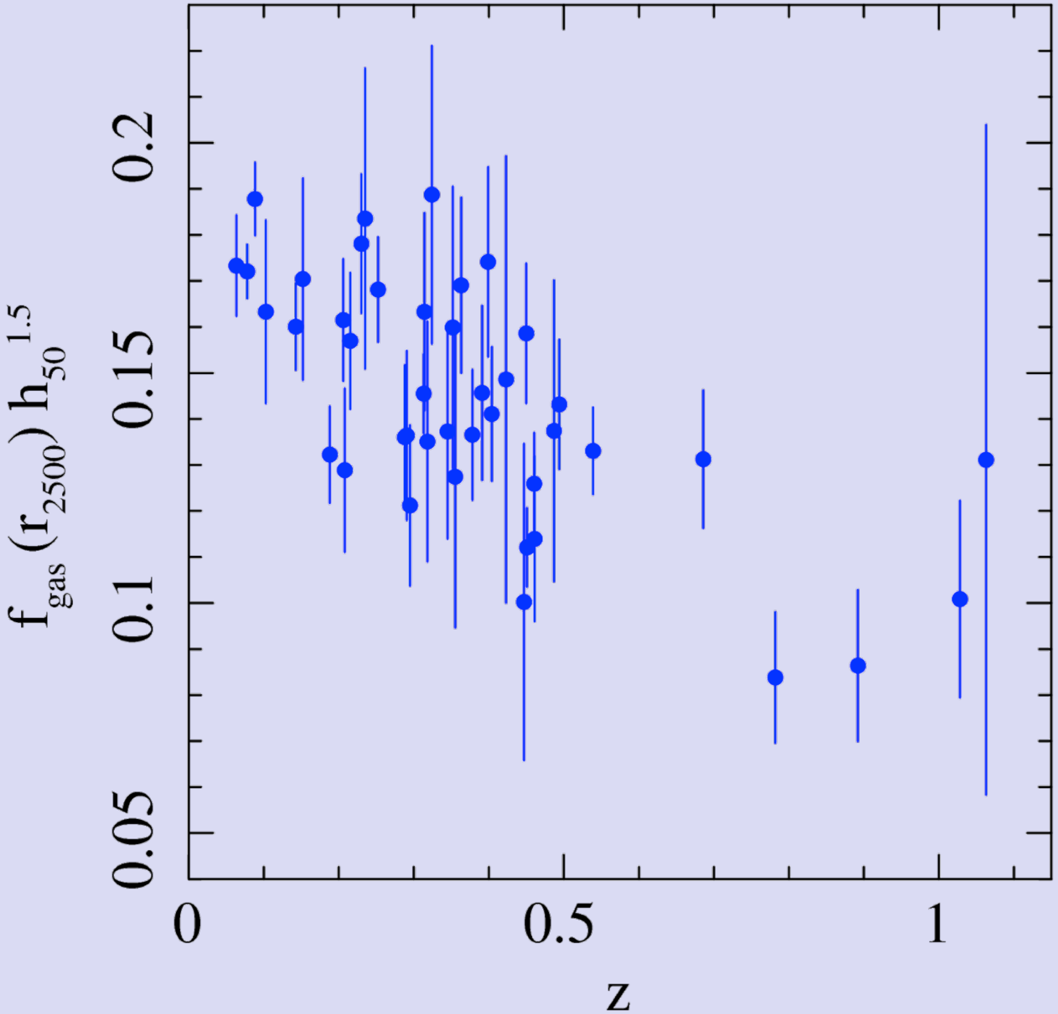
Hot kT>5keV

0.06<z<1.07

Scatter <~10% in f_{gas}

Undetected systematic scatter when weighted mean scatter is ~5% in distance

Gas mass fraction: data
Low scatter total mass proxy



SCDM (Ω_m=1.0, Ω_Λ=0.0)

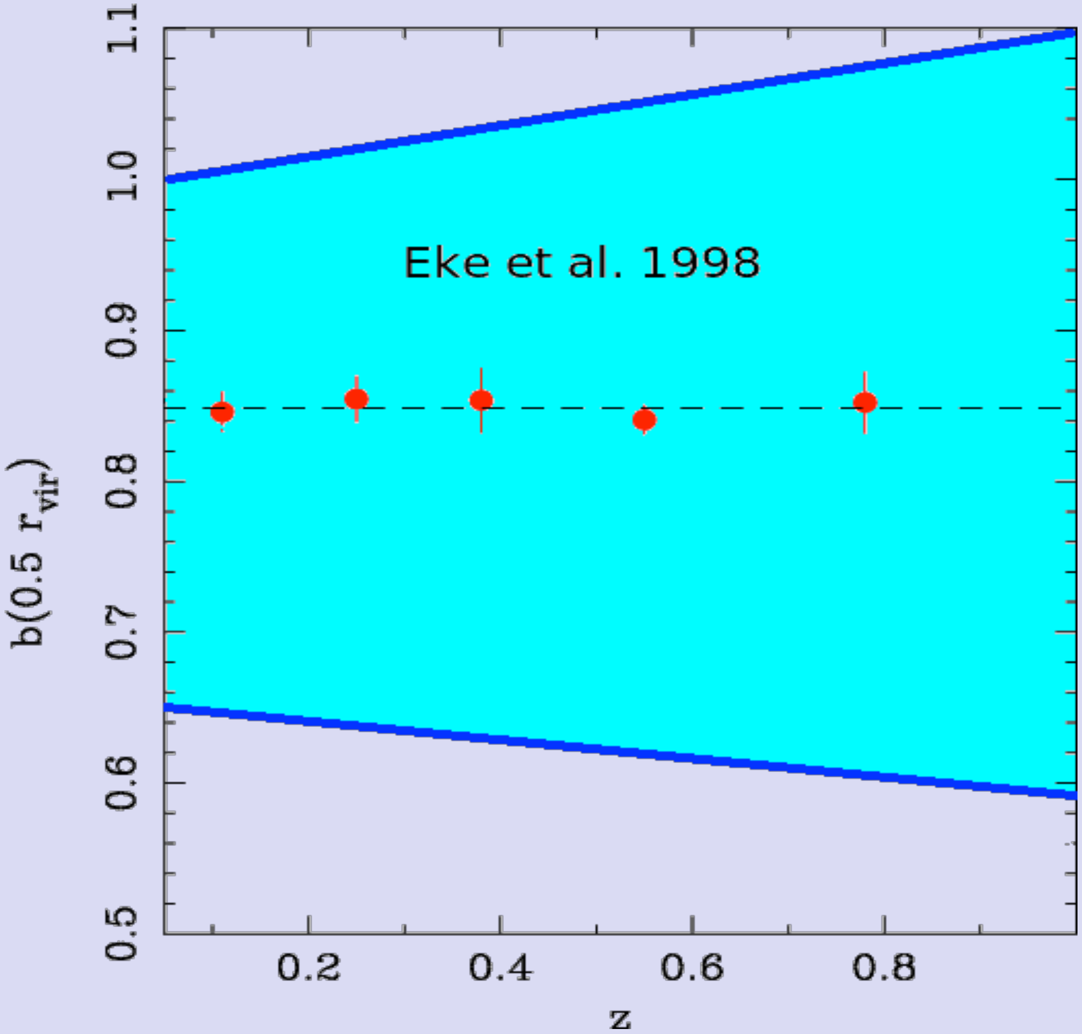
42 dynamically relax clusters

Hot kT>5keV

0.06<z<1.07

Scatter <~10% in f_{gas}

Allowances for systematic uncertainties



1) Gas depletion (simulation physics)

$b(z)=b_0(1+\alpha_b z)$

normalization:
20% uniform prior
$0.65 < b_0 < 1.0$

evolution:
10% at z=1 uniform prior
$-0.1 < \alpha_b < 0.1$

Allowances for systematic uncertainties

2) Instrument calibration and modelling (gas clumping, etc.)

1.0±0.1, 10% Gaussian prior on K

3) Baryonic mass in stars

$s(z)=s_0(1+\alpha_s z)$

normalization s_0: 30% Gaussian uncertainty (observational)

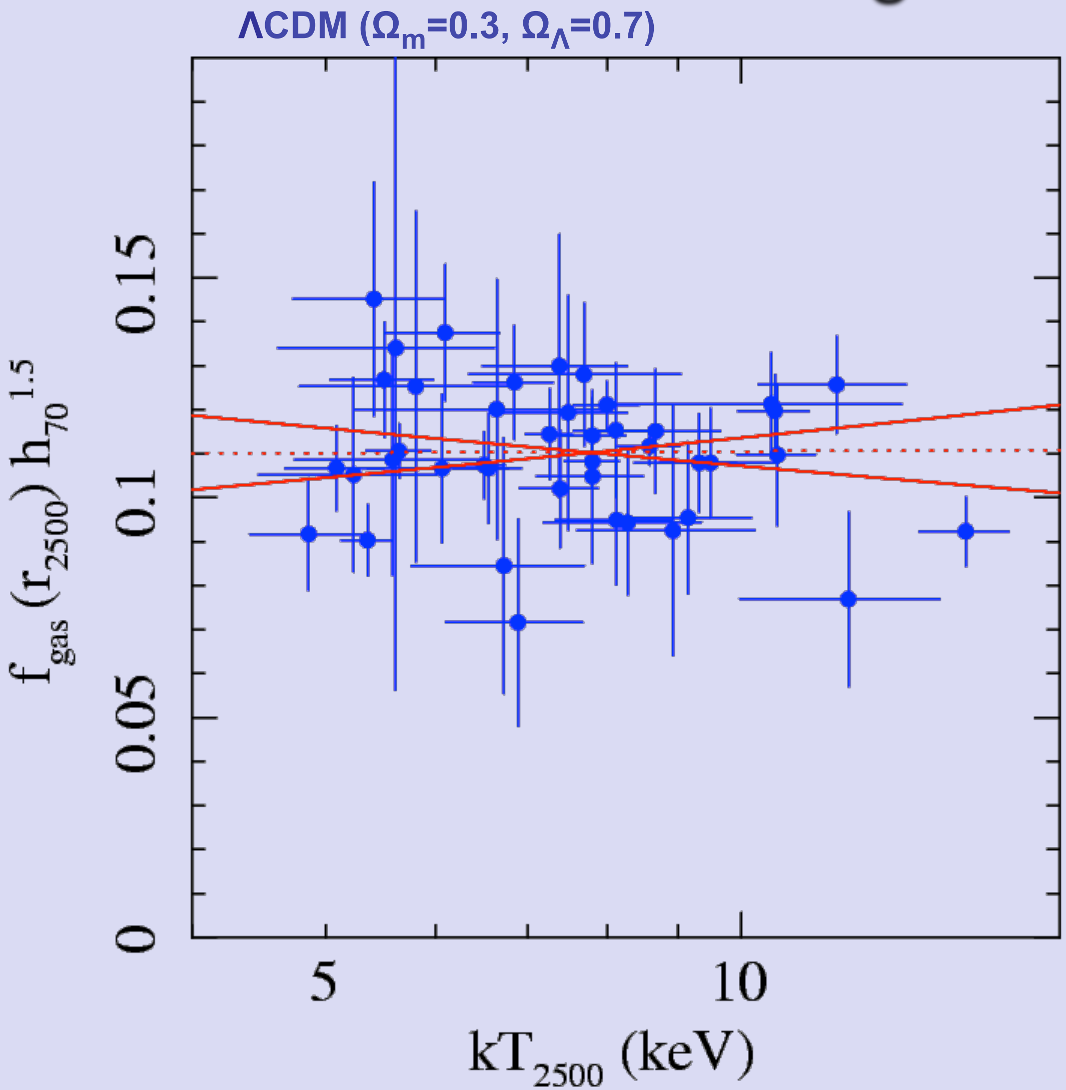
evolution $-0.2 < \alpha_s < 0.2$: 20% at z=1 uniform prior (observational)

4) Non-thermal pressure support in gas: (primarily due to bulk motions)

$\gamma = M_{true}/M_{X\text{-}ray}$

$1 < \gamma < 1.1$
10% uniform (Nagai et al 07, Werner et al 09, Sanders et al 09)

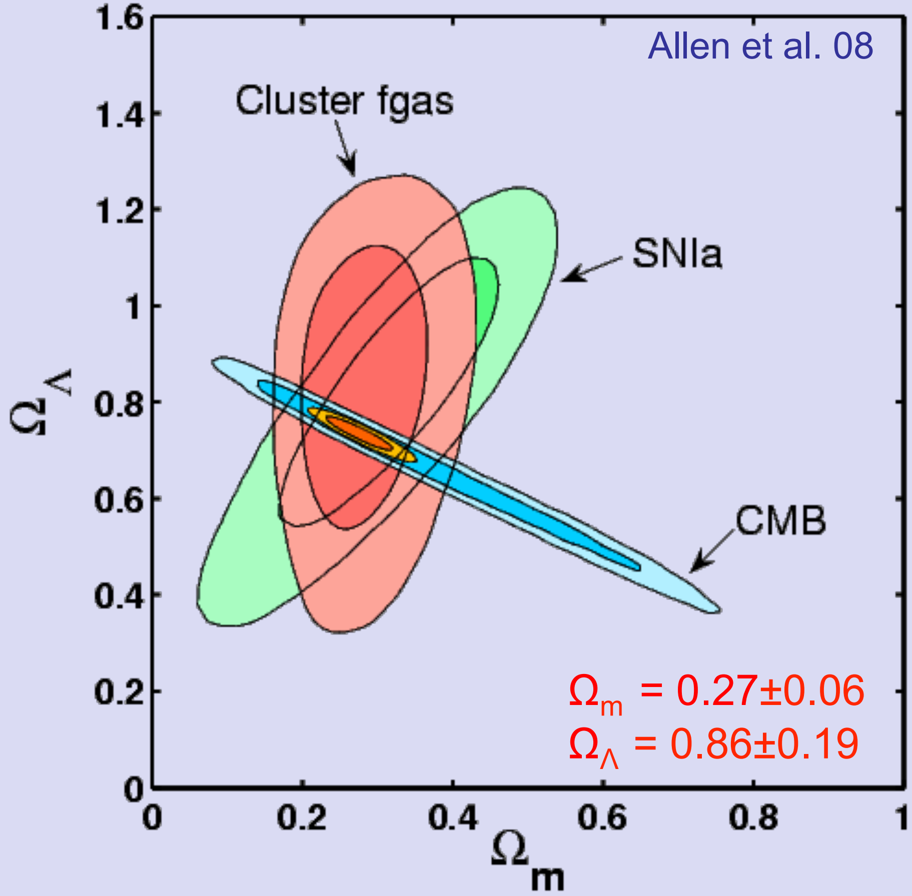
Chandra f_{gas}(kT) data



Best fitting power law:
α=0.005±0.058 (solid lines 2σ limits).

f_{gas} essentially independent of temperature for the massive, dynamically relaxed clusters in the analysis.

Constraints on ΛCDM from three independent experiments



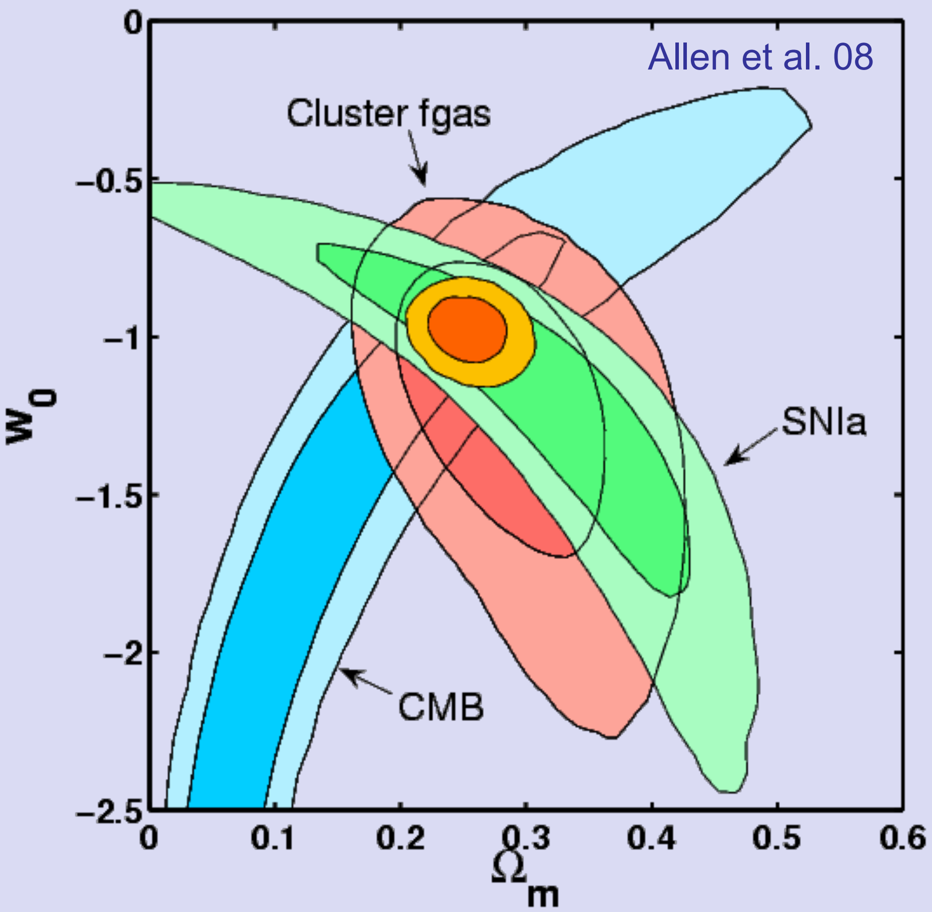
42 f_{gas} clusters (Allen et al 08) including standard BBNS+HST priors and full systematic allowances.

192 SNe Ia [Davis et al 07: Riess et al 07 (Gold sample), Wood-Vasey et al 07 (ESSENCE), Astier et al 06 (1rst year SNLS].

CMB data from WMAP3, CBI, Boomerang, ACBAR (prior $0.2<h<2.0$).

Combined constraints
$\Omega_m = 0.275 \pm 0.033$
$\Omega_\Lambda = 0.735 \pm 0.023$

Constraints on wCDM from three independent experiments



42 f_{gas} clusters (Allen et al 08) including standard BBNS+HST priors and full systematic allowances.

192 SNe Ia [Davis et al 07: Riess et al 07 (Gold sample), Wood-Vasey et al 07 (ESSENCE), Astier et al 06 (1rst year SNLS].

CMB data from WMAP3, CBI, Boomerang, ACBAR (prior 0.2<h<2.0).

Combined constraints
$\Omega_m = 0.253 \pm 0.021$
$w_0 = -0.98 \pm 0.07$