GALAXY CLUSTERS FOR COSMOLOGY

Matter To The Deepest

Chorzów

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OUTLINE

I. Clusters of galaxies – brief story and properties

II. Cosmological models

III. Cosmology and clusters

IV. Results

V. Conclusions

PLACE OF CLUSTERS OF GALAXIES IN UNIVERSE SCRUCTURE

Group of galaxies

- 3< galaxies <=50
- Galaxies are placed in the area < 1 Mpc
- Galaxies are bound together by gravity

***Local Group**

- ~ 54 galaxies
- It includes the Milky Way

Galaxy cluster

- Consist of hundreds to thousands of galaxies bound together by gravity
- Typical diameter: 1 – 10 mln ly (2 – 10 Mpc)
- Total mass: 10^{14} – 10^{15} solar masses

Galaxy supercluster

- Consist of smaller galaxy groups and galaxy clusters not strongly bound together by gravity

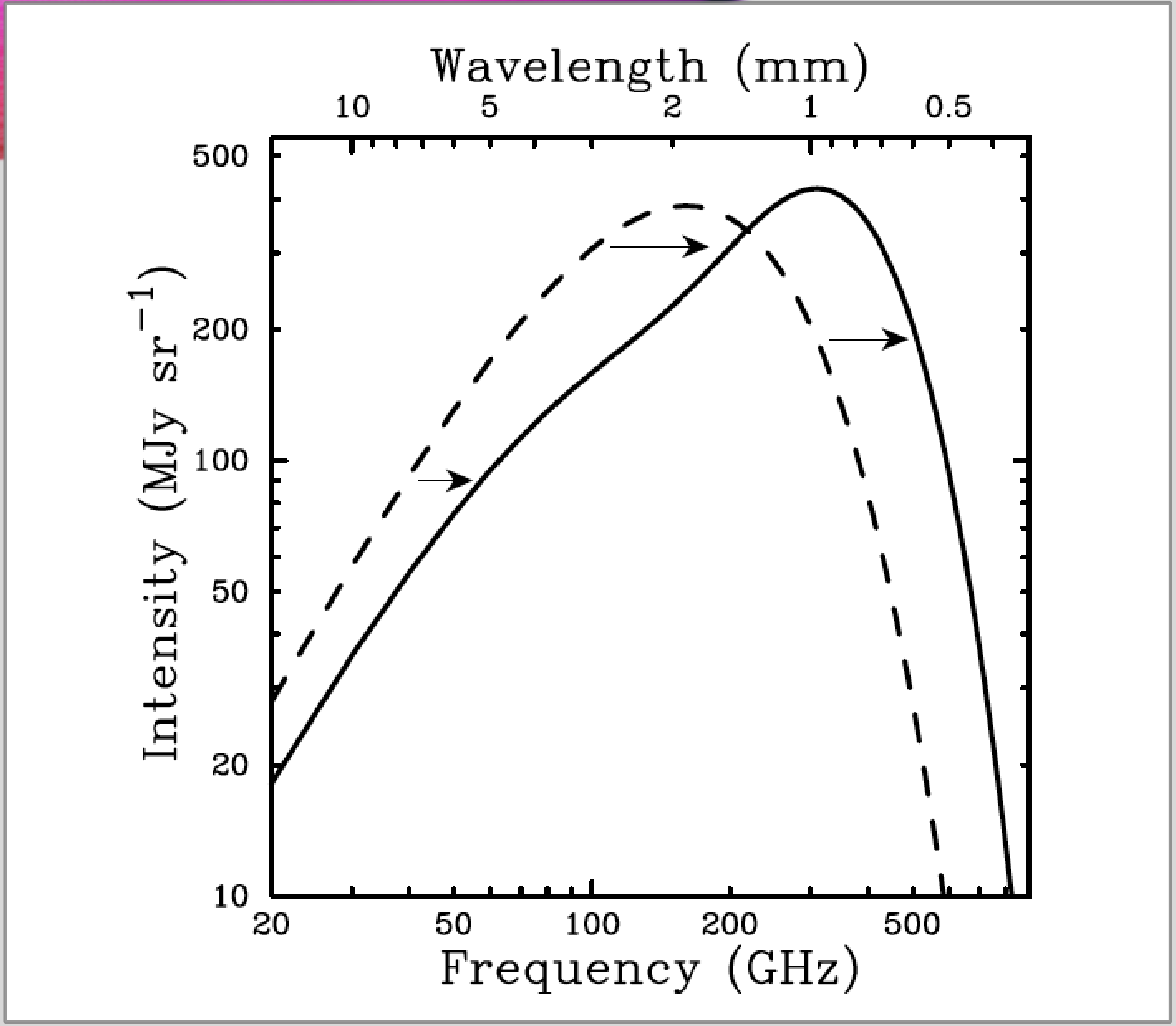
Clusters of galaxies

Arise in the early, hot phase of the Universe from density perturbations in the primordial plasma (photons + baryonic and dark matter)

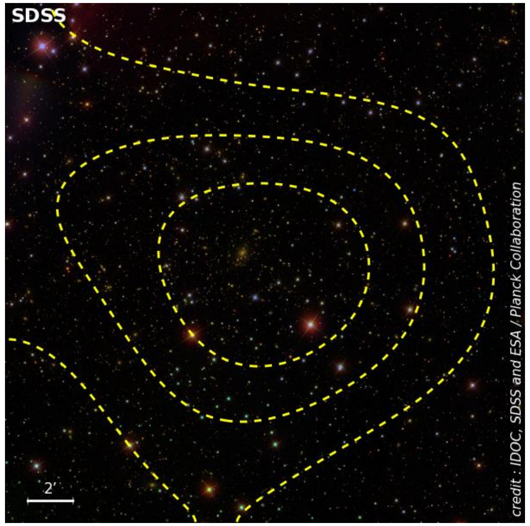
ICM (Intracluster Medium)

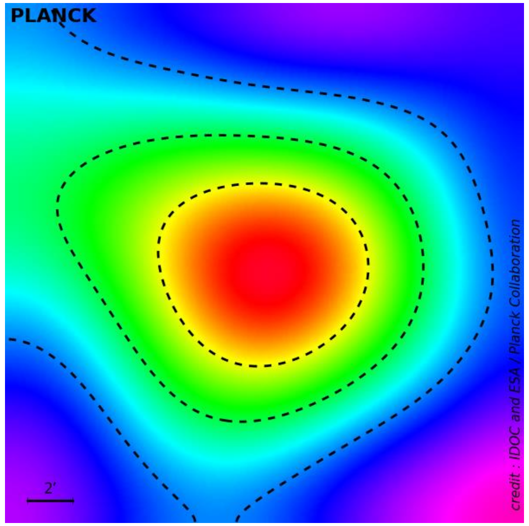
- Hot diffuse plasma that fills the intergalactic space
- Electron gas temperatures reaches10^7 K to 10^8 K
- Mostly emits X-Ray radiation through the bremsstrahlung process

Sunyaev–Zel'dovich effect – small spectral distortion of the cosmic microwave background radiation (CMB) spectrum caused by the scattering of CMB photons off a distribution of hight-energy electrons from ICM



Sunyaev–Zel'dovich effect

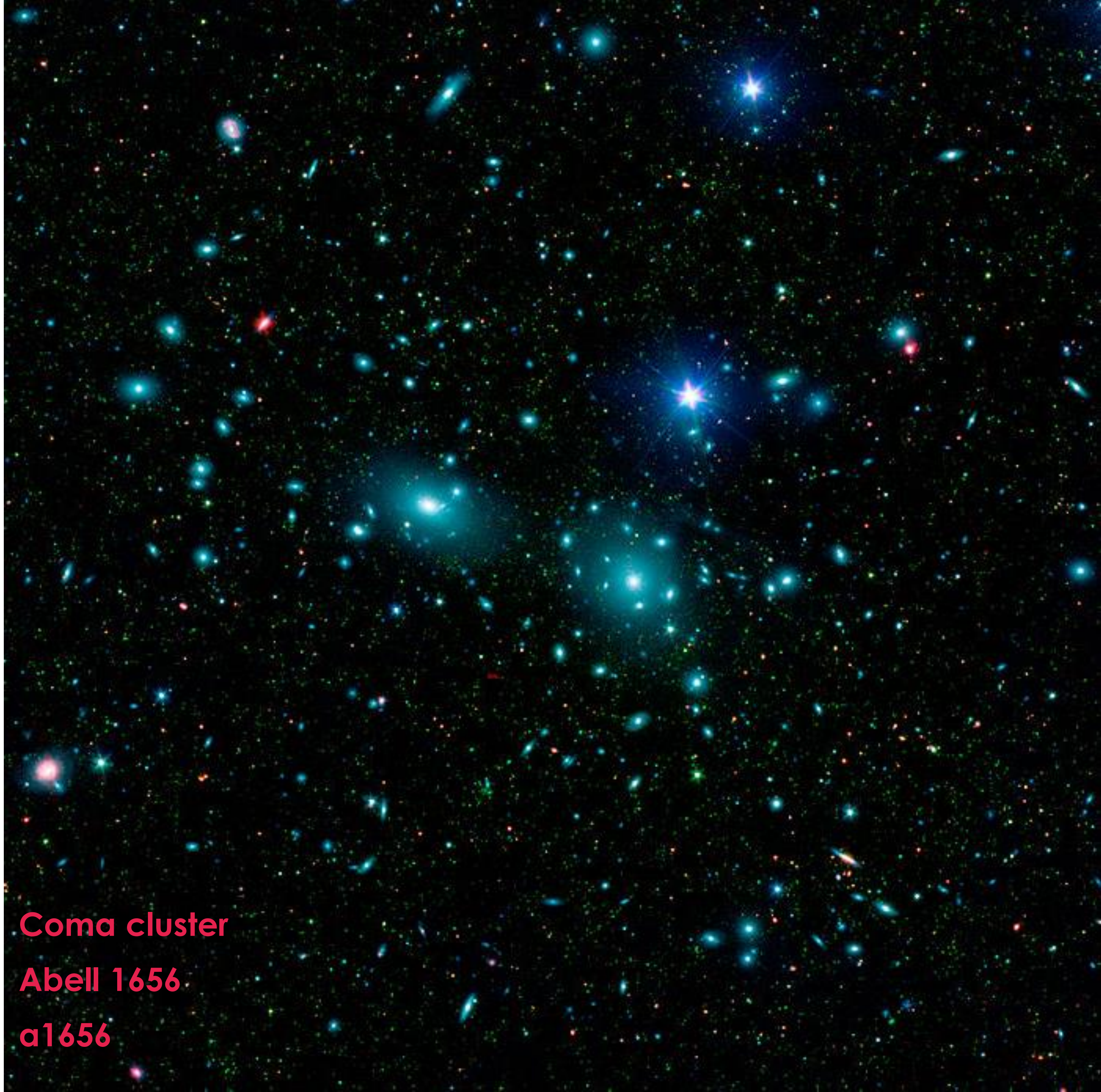




Abell 586 (RXC J0732.3+3137; ACO 586; RMJ073220.3+314120.7; PSZ1 G187.53+21.92)

BRIEF STORY ABOUT CLUSTERS

- In 1958 the American astronomer George O. Abell cataloged galaxy clusters using plates from POSS (2,712 clusters)
- Corelation between richness and frequency of occurence
    - 1224 with 50 – 70 objects
    - 383 with 80 – 129 objects
    - 68 with 130 – 199 objects
    - 6 with 200 – 299 objects
    - 1 with >300 objects



CLASSIFICATION

Regular

- Sphericaly shaped
- Rich and gigant systems
- Elliptical or irregular galaxies (increase concentration of galaxies toward the center of a cluster)
- Spiral galaxies only on their edges
- Clusters often contain a lot of hot gas
- Exaple: Coma cluster

Irregular

- No specific shape (many different shapes and densities)
- Generally poor
- Local concentration of galaxies
- Milky Way is a member of an irregular cluster, known as the Local Group

Rich

- Frequently contains 1000's of galaxy members

Poor

- Frequently contains only about 100’s members or less

BAUTZ-MORGAN CLASSIFICATION SCHEME (1970)

Clasification based on brightest galaxy in cluster:

I: Cluster has centrally located cD galaxy

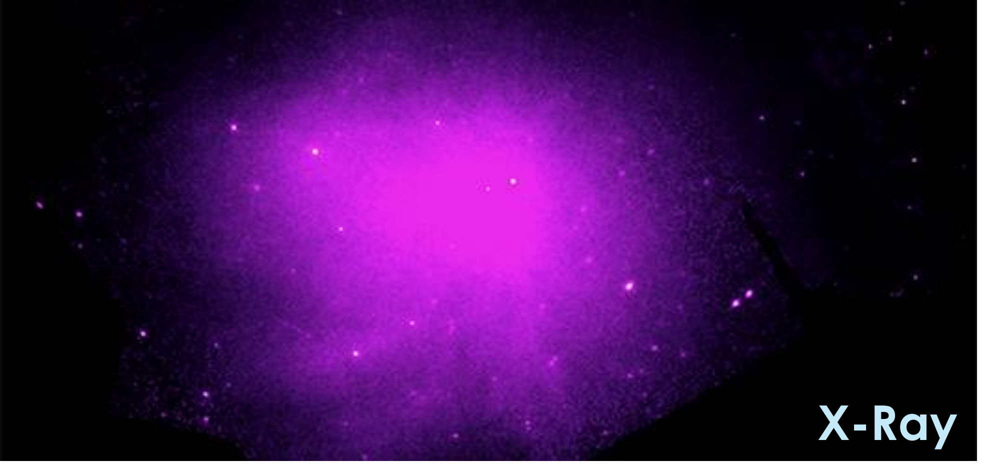
II: central galaxy is somewhere between a cD and a giant elliptical galaxy (e.g., Coma)

III: cluster has no dominant central galaxy

OEMLER (1974) CLASSIFICATION

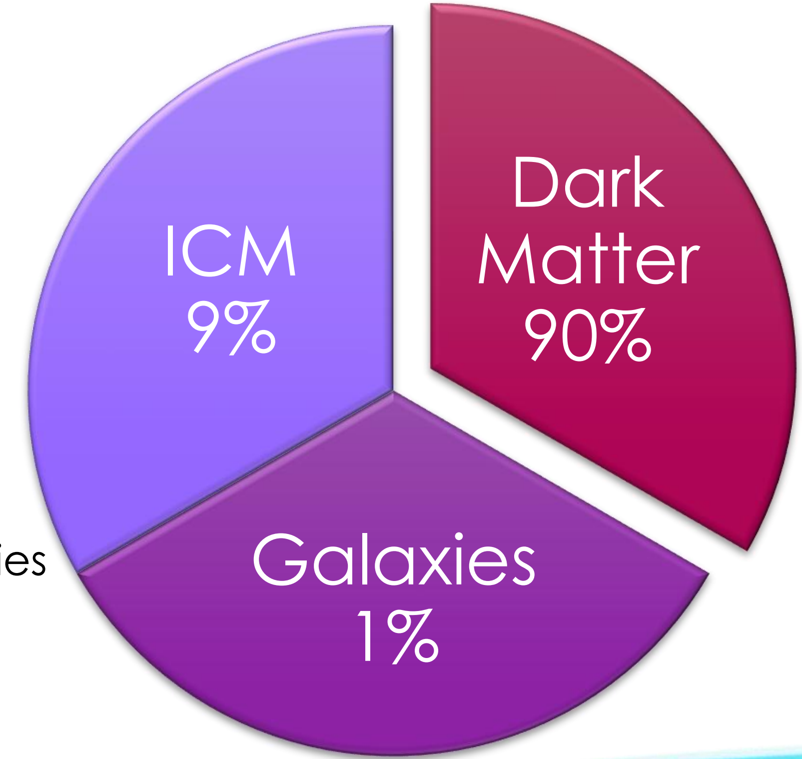
Clusters are classificatied by galaxy content:

- cD clusters: 1 or two dominant cD galaixes, E : S0 : S ~ 3 : 4 : 2
- Spiral rich: E:SO:S~1:2:3
- Spiral poor: no dominant cD, E:S0:S~1:2:1



PROPERTIES OF CLUSTERS

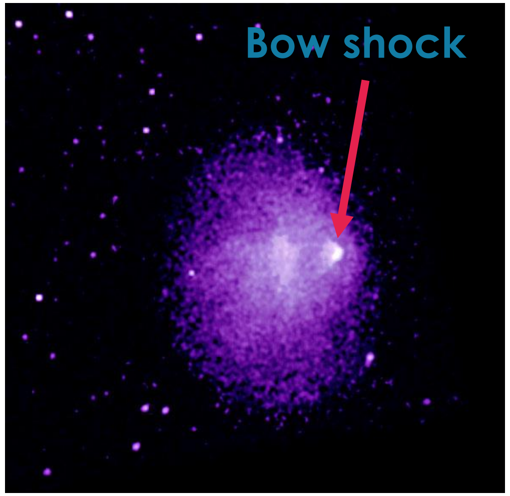
- ❑total masses of 10^{14} to 10^{15} solar masses
- ❑typically diameter 2 - 10 Mpc
- ❑T ~ 10^7 – 10^8 K
- ❑ velocities for the individual galaxies is about 800–1000 km/s.

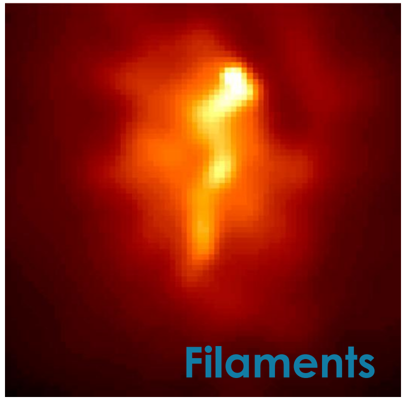


MAIN COMPONENTS OF A GALAXY CLUSTERS

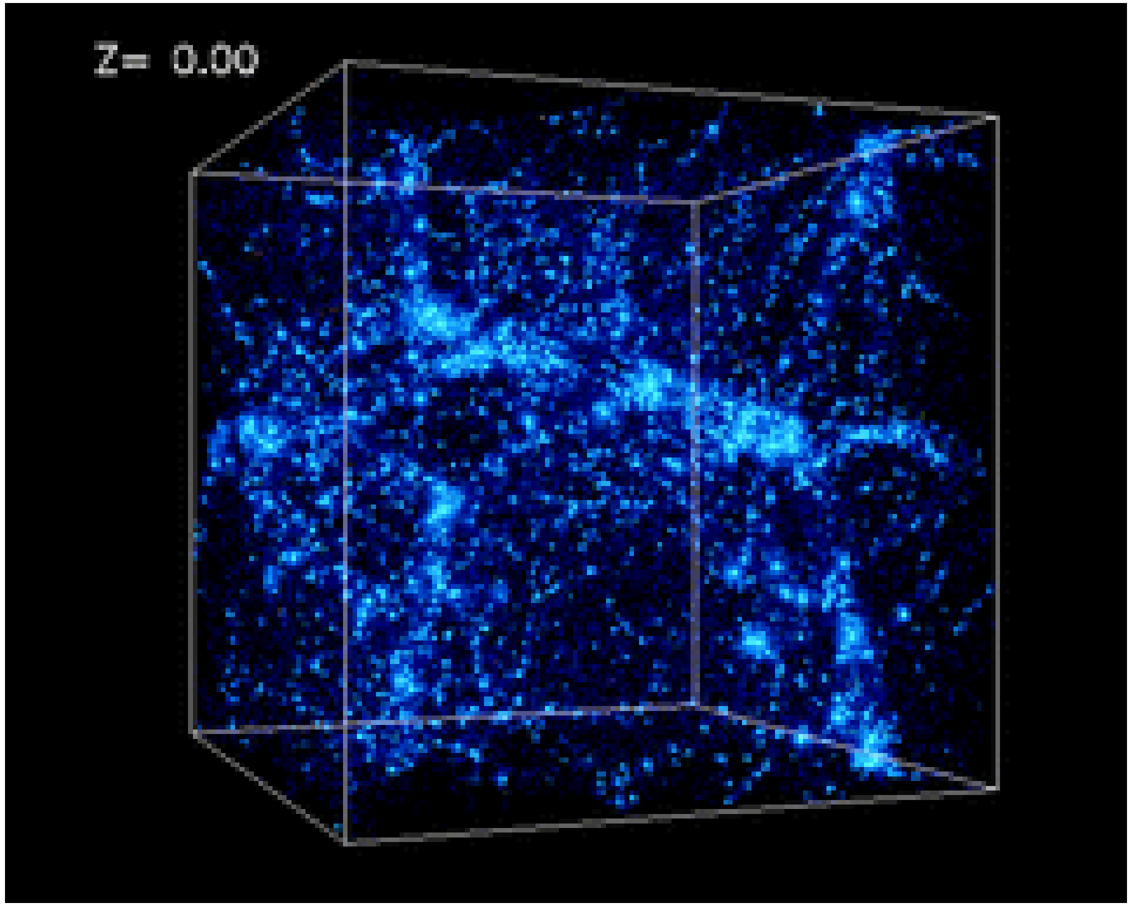
FEW IMPORTANT TRENDS

- In densest regions, gas may cool and sink toward the cluster center as a ***"cooling flow"***
- *Chandra observation* show that many clusters have substructure in the X-ray surface brightness therefore hydrodynamical equilibrium is not a great approximation. It's mean that clusters are still forming





CLUSTERS OF GALAXIES AND COSMOLOGY



Center for Cosmological Physics at the University of Chicago

COSMOLOGICAL MODELS

TESTING PROBLEM

✓Cosmological parameters are not observables

Hubble function

$$H(z, \widehat{p})$$

Cosmological models

ΛCDM
- vacuum energy is represented by cosmological constatnt Λ

Models where dark energy is represented by scalar field which is weakly conjugated with gravity (eg. Quintessence Model)

Models where dark energy is represented by scalar field which is non-weakly conjugated with gravity

Models where FRW equation is modificated (eg. Interacting Dark Energy, Cardasian Model, Bouncing Model)

...

QUINTESSENCE

Hypotetical cosmic fluid

=

Scalar field

=

Dark energy

$$\boxed{\boldsymbol{\omega = \frac{p_{DE}}{\varrho_{DE}}}}$$

expansion $\omega < -\frac{1}{3}$

$\omega = -1.070 \pm 0.215$*

- Homogeneous (overwhise it would be detected localy)
- Very small mass
- Weak influance on matter

$$\boxed{\boldsymbol{H^2(z,\tilde{p}) = \left[\Omega_m\,(1+z)^3 + \Omega_Q(1+z)^{3(1+w)}\right]}}$$

*M.Biesiada, B. Malec, A. Piórkowska, Res. Astron. Astrophys. , (2011)

CHEVALLIER – POLARSKI – LINDER (CPL)

One may consider $\boldsymbol{\omega}$ changing in time

$$\boldsymbol{\omega} = \boldsymbol{\omega}(\boldsymbol{t}) = \boldsymbol{\omega}(\boldsymbol{z})$$

$$\boldsymbol{\omega}(\boldsymbol{z}) = \boldsymbol{\omega}_0 + \boldsymbol{\omega}_a \frac{\boldsymbol{z}}{1+\boldsymbol{z}} = \boldsymbol{\omega}_0 + \boldsymbol{\omega}_a(1-\boldsymbol{a})$$

$\boldsymbol{\omega}_0$ - equation of state today (at z=0)
$\boldsymbol{\omega}_0$ = -0.993 ± 0.207*

$\boldsymbol{\omega}_a$ - overall evolution with time
$\boldsymbol{\omega}_a$ = 0.609 ± 1.071*

$$\boxed{\boldsymbol{H}^2(\boldsymbol{z}, \widetilde{\boldsymbol{p}}) = \left[\Omega_m\,(1+z)^3 + \Omega_Q(1+z)^{3(1+w_0+w_a)} exp\left(\frac{-3w_a z}{1+z}\right)\right]}$$

*M.Biesiada, B. Malec, A. Piórkowska, Res. Astron. Astrophys. , (2011)

COSMOLOGICAL MODELS

ΛCDM

$$H^2(z', \tilde{p}) = \left[\Omega_m \,(1+z)^3 + \Omega_\Lambda\right]$$

Quintessence

$$H^2(z', \tilde{p}) = \left[\Omega_m \,(1+z)^3 + \Omega_{\mathrm{Q}}(1+z)^{3(1+w)}\right]$$

Chevalier – Polarski – Linder

$$H^2(z', \tilde{p}) = \left[\Omega_m \,(1+z)^3 + \Omega_{\mathrm{Q}}(1+z)^{3(1+w_0+w_a)} exp\left(\frac{-3w_a z}{1+z}\right)\right]$$

Chaplygin gas

$$H^2(z', \tilde{p}) = \left[\Omega_m \,(1+z)^2 + \Omega_{\mathrm{ch}}\left[A_0 + (1-A_0)(1+z)^{3(1+\alpha)}\right]^{\frac{1}{1+\alpha}}\right]$$

Braneworld

$$H^2(z', \tilde{p}) = \left[\sqrt{\Omega_m \,(1+z)^3 + \Omega_{\mathrm{r_c}}} + \sqrt{\Omega_{\mathrm{r_c}}}\right]^2$$

COSMOLOGY FROM GASS MASS FRACTION

$$f_{gas} = \frac{M_{gas}}{M_{tot}}$$

The most common model that describes gas density profile is :

- The β model (for cool core clusters)
- Double β model (for non-cool core clusters)
- Modfication of β model

$$n_e(r) = n_{e0}\left[f\left(1+\frac{r^2}{r_{c1}^2}\right)^{-3\beta/2} + (1-f)\left(1+\frac{r^2}{r_{c2}^2}\right)^{-3\beta/2}\right]$$

The total mass of a cluster can be obtained assuming:

- Spherical symmetry of a cluster
- Isothermal gas
- Hydrostatic equilibrium of gas

$$M_{tot}(r) = -\frac{r^2}{\varrho G}\frac{dP}{dr}$$

ALLEN'S [ET AL. 2008] SAMPLE

- 42 very hot and most luminous clusters of galaxies
- z <0.05 ; 1.1 >
- Relaxed
- Doubled time of exposure

M_{tot} was obtained assuming:

- Spherical symmetry of clusters
- Hydrostatic equilibrium
- NFW model to parametrize mass density profile

$$\varrho(r) = \frac{\varrho_c(z)\delta_c}{\frac{r}{r_s}\left(1+\frac{r}{r_s}\right)^2}$$

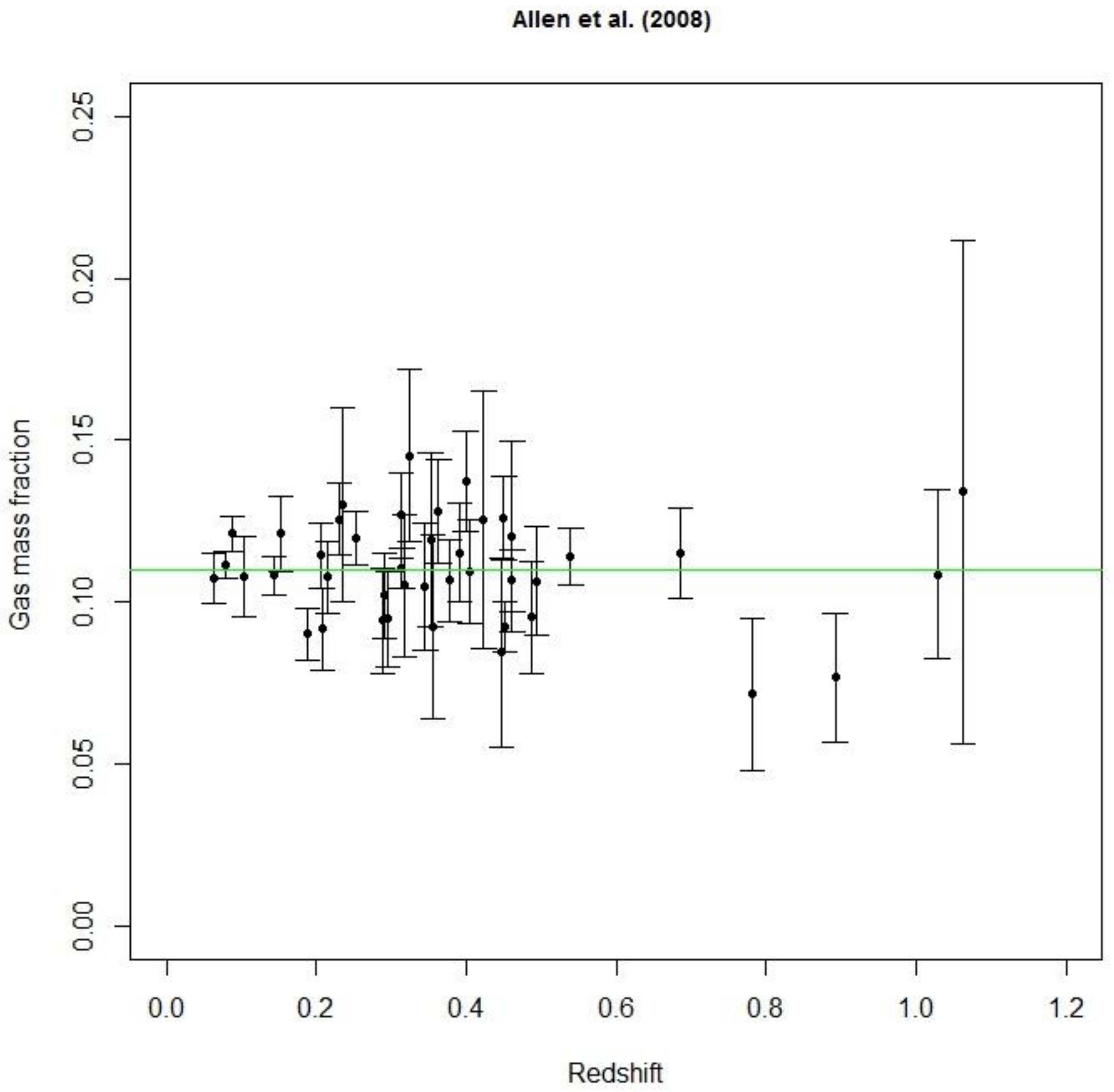
$$\delta_c = \frac{200c^2}{3\left(ln(1+c) - \frac{c}{1+c}\right)}$$

A concentration parameter

$$c = \frac{r_{200}}{r_s}$$

- Other parameters like gas mass density, pressure, mass, entropy, cooling time and f_{gas} was obtained from MC simulation and χ^2 method.

Allen's [et al. 2008] sample



The method

$$\chi^2 = \frac{\left(f_{gas}^{th}(Q, z, h, \Omega_m, \tilde{p}, \Omega_b) - f_{gas}^{obs}(Q, z, h, \Omega_m, \tilde{p}, \Omega_b)\right)^2}{\sigma^2}$$

$$f_{gas}^{th}(Q, z, h, \Omega_m, \tilde{p}, \Omega_b) \propto \left(\frac{\Omega_b}{\Omega_m}\right)\left[\frac{d_A^{\Lambda CDM}(z)}{d_A(z)}\right]^{1.5}$$

(Samushia et al. 2008)

where

d_A is an angular diameter distance

$$d_A(z;\, \tilde{p}) = \frac{1}{1+z}\frac{c}{H_0}\int_0^z \frac{dz'}{\boldsymbol{H(z';\tilde{p})}}$$

where

$\tilde{p}$ - the equation of state parameters

Fitting the density parameters $\boldsymbol{\Omega_b}$, $\boldsymbol{\Omega_m}$ to f_{gas} data of clusters of galaxies.

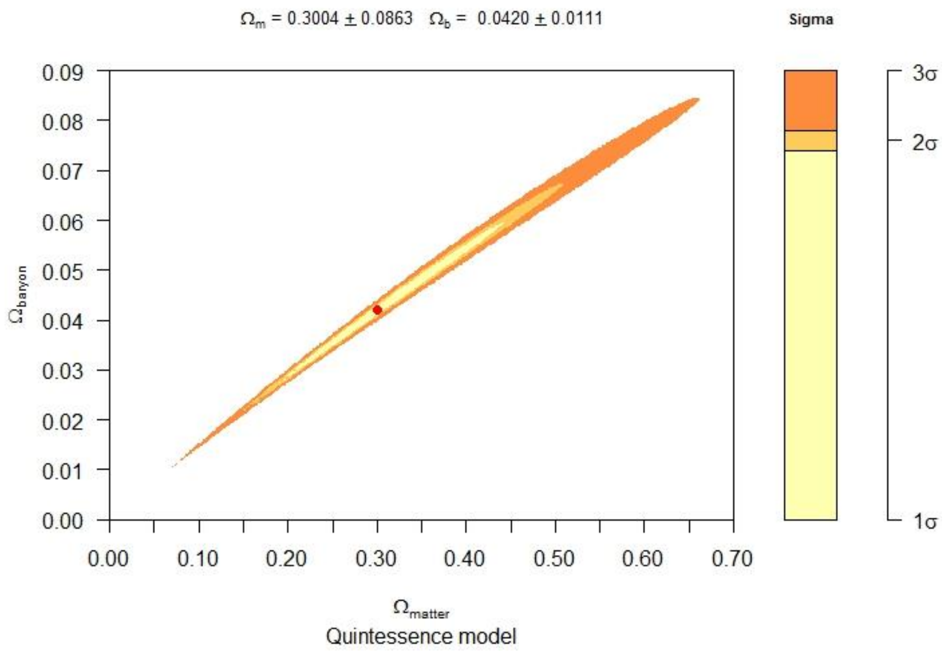
$$\boldsymbol{\Omega_b(t)} = \frac{density\ of\ baryonic\ matter\ at\ t}{critical\ density\ at\ t}$$

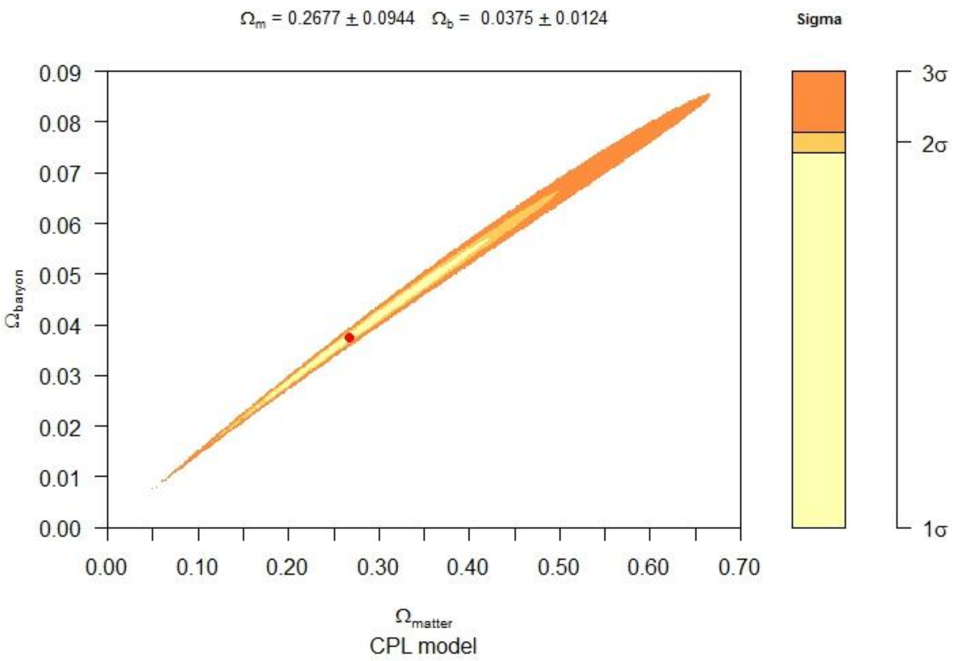
$$\boldsymbol{\Omega_m(t)} = \frac{density\ of\ \ matter\ (baronic + dark)\ at\ t}{critical\ density\ at\ t}$$

RESULTS

	Quintessece	CPL	Reference values	
Ω_m	0.3005 $\pm$ 0.0863	0.2677 $\pm$ 0.0944	0.315 $\pm$ 0.016	#from Planck (CMB)
Ω_b	0.0420 $\pm$ 0.0111	0.0375 $\pm$ 0.0124	0.0455 $\pm$ 0.00028	#from Planck (CMB)

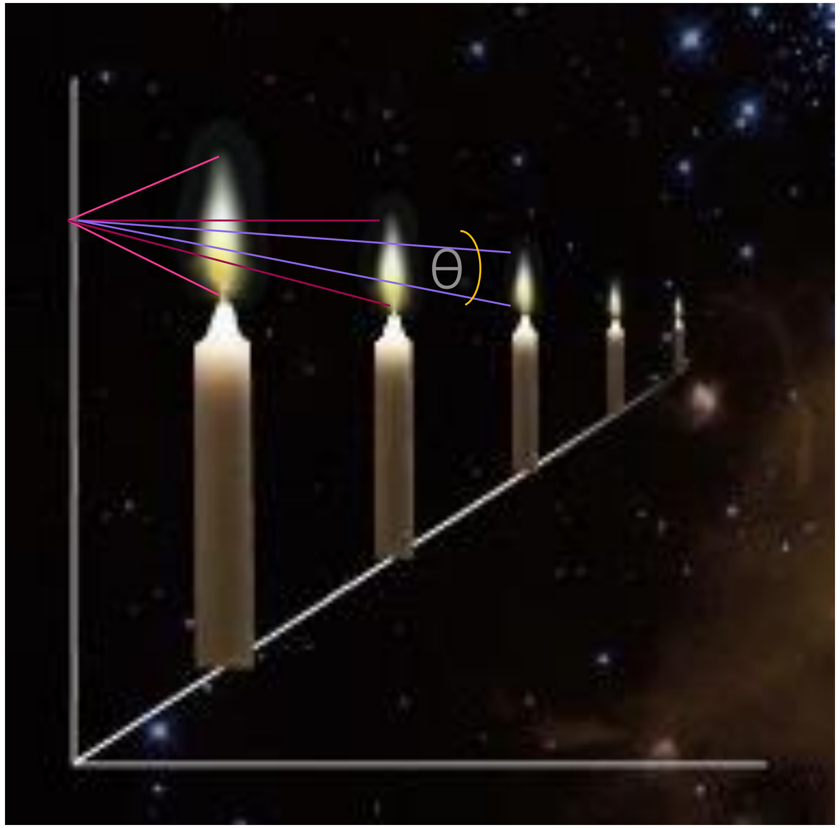
* Best fit taken from SN as a prior, w = -1.070 ; w_a = 0.609 ; w_0 = -0.993





COSMOLOGY FROM DUALITY RELATION

LUMINOSITY DISTANCE AND ANGULAR DIAMETER DISTANCE



Comoving distance

$$r(z;p) = c\int_0^z \frac{dz'}{H(z';p)} = \frac{c}{H_0}\bar{r}\,(z';p)$$

Luminosity distance

$$D_L(z;p) = r(z;p)(1+z)$$

Angular diameter distance

$$D_A(z;p) = \frac{1}{1+z}\,r(z;p)$$

THE ETHERINGTON DUALITY RELATION

$$\boxed{D_L = D_A(1+z)^2}$$

$$\eta(z) \stackrel{\text{def}}{=} \frac{D_A}{D_L}(1+z)^2$$

$$\boxed{\eta(z) = \sqrt{\frac{D_A^{th}(z)}{D_A^{obs}(z)}}}$$

Assumptions:

- ✓ no absorption of photons from the beam coming from the source to the observer
- ✓ light moves along null geodesis

DATA

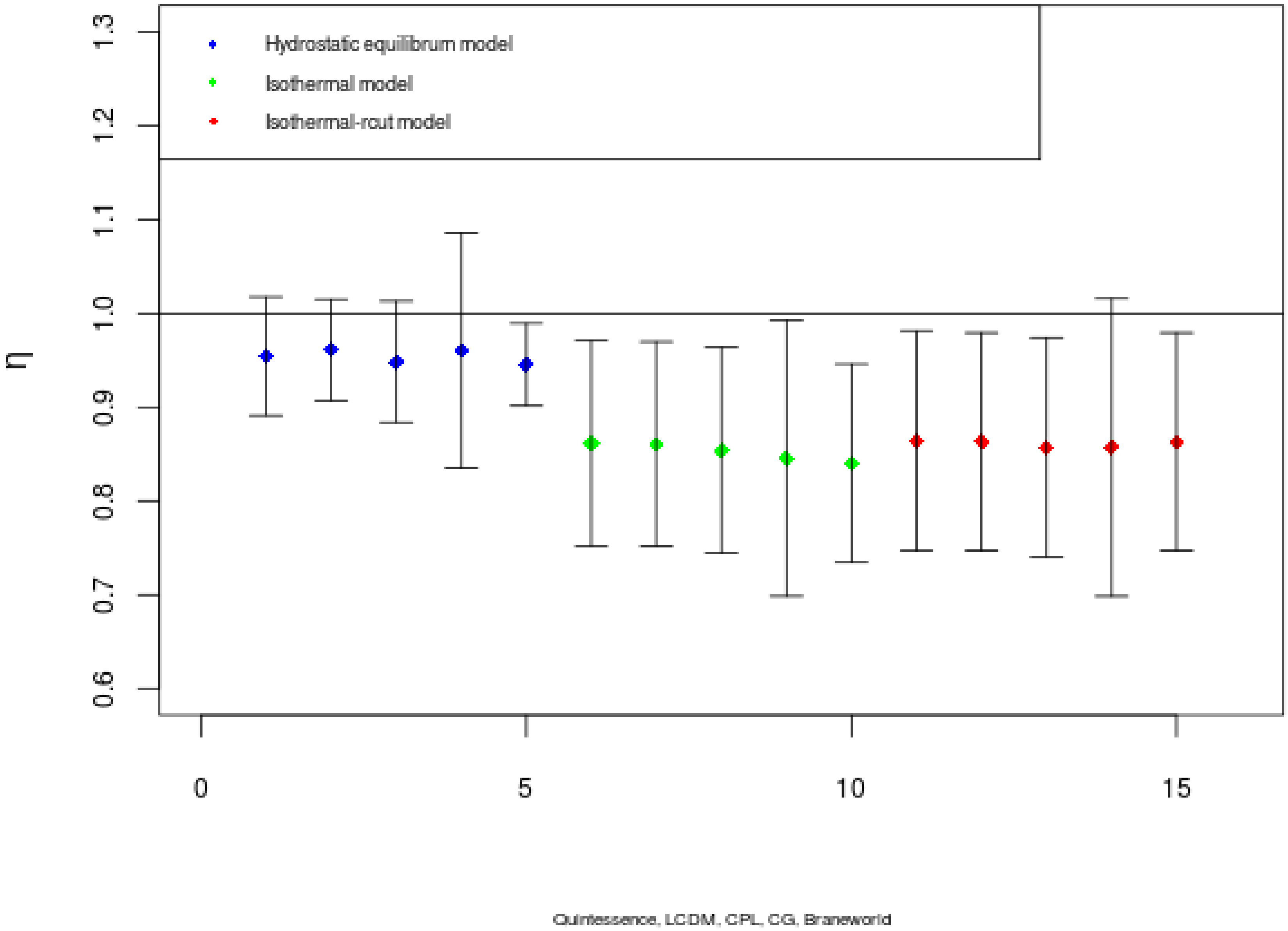
- **38** clusters of galaxies (Bonamente et al. [2006])
- Joint anlysis of interferometric SZE observations and Chandra X-Ray imaging spectroscopy observations
- Redshift: $0.14 \leq \mathbf{z} \leq 0.89$

RESULTS

Cosmological model	Parameters
ΛCDM	$\Omega m = 0.275 \pm 0.020$
Quintessnce	$\Omega m = 0.299 \pm 0.075$
	$w = -1.070 \pm 0.215$
Chevalier-Polarski-Linder	$\Omega m = 0.228 \pm 0.156$
	$w0 = -0.993 \pm 0.207$
	$wa = 0.609 \pm 1.071$
Chaplygin Gas	$\Omega m = 0.275 \pm 0.020$
	$A = 0.999 \pm 0.004$
	$alpha = 0.006 \pm 0.372$
Braneworld	$\Omega m = 0.177 \pm 0.015$

M.Biesiada et al.., Res. Astron. Astrophys. , (2011)

RESULTS



Hydrostatic equilibrum model
Isothermal model
Isothermal-rcut model
η
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0
5
10
15
Quintessence, LCDM, CPL, CG, Braneworld

THE GAS DEPLETION FACTOR IN GALAXY CLUSTERS

Gas depletion factor $\gamma(z)$

Corresponds to the ratio by which f_{gas} is depleted with respect to the universal baryonic mean

The goal of our work was to invesitgate the posible redshift evoluiton of $\gamma(z)$

- Hydrodynamical simulations suggest constant depletion factor
- Our results reveal the tend of $\gamma(z)$ **decreasing** with redshift

The method

Based on non-parametric reconstruction using the measurements of Hubble parameters from cosmic chronometers

Sample

182 galaxy clusters detected by the Atacama Cosmology Telscope(ACT) Polarization experiment
Redshift $0.1 < z < 1.4$

91 SZ clusters reported earlier in ACT compilation (parametric model fit)
Redshift $0.1 < z < 1.0$

Gas depletion factor for R500

Gas depletion factor and gas mass fraction

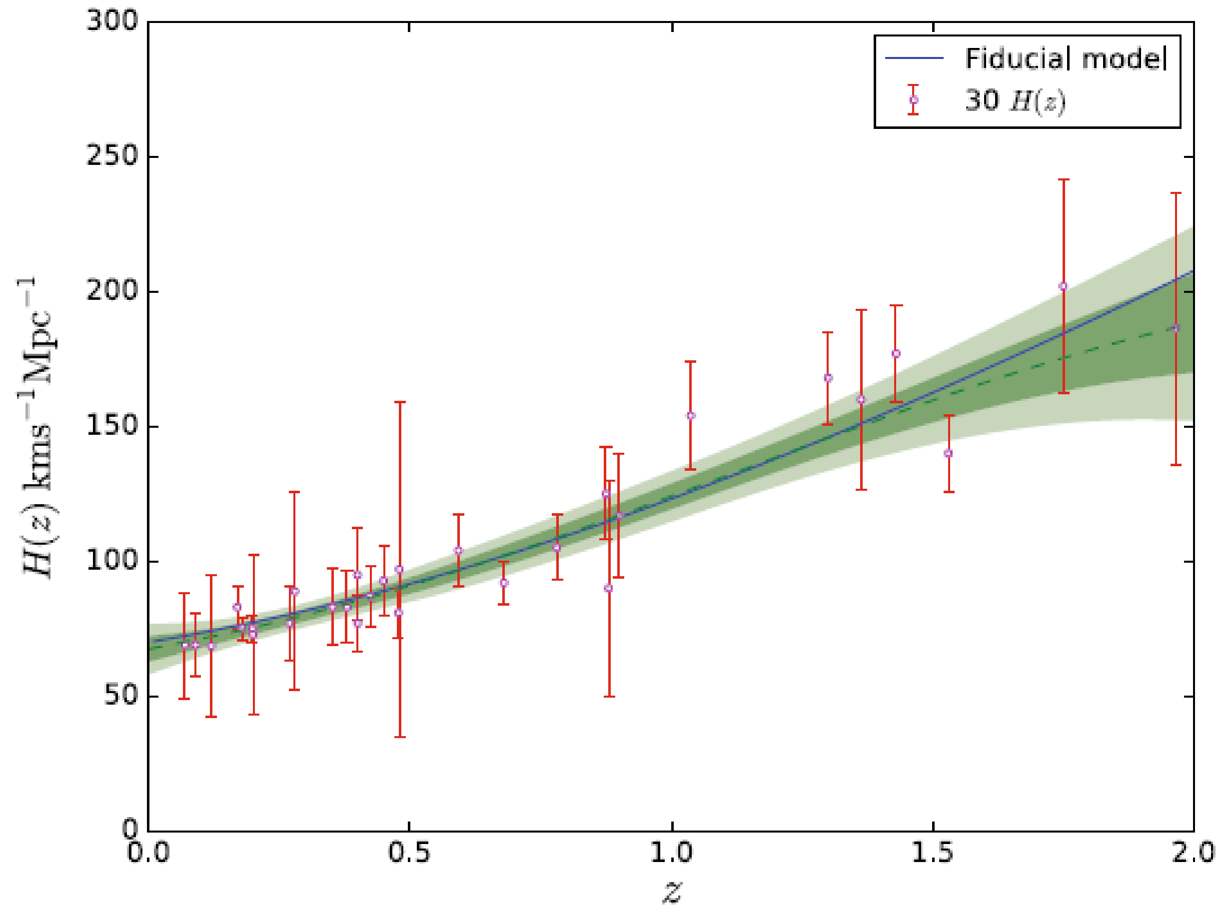
$$f_{gass}^{ref} = K(z) A\, \gamma(z) \left(\frac{\Omega_b}{\Omega_m}\right) \left[\frac{D_A^{ref}(z)}{D_A(z)}\right]^{1.5}$$

K(z) – the calibration constant
A – quantifies the change in the angle subtended as the cosmology is varied

$$\gamma(z) = \frac{f_{gass}^{ref}}{K(z)} \left(\frac{\Omega_b}{\Omega_m}\right)^{-1} \left[\frac{D_A^{ref}(z)}{D_A(z)}\right]^{-1.5}$$

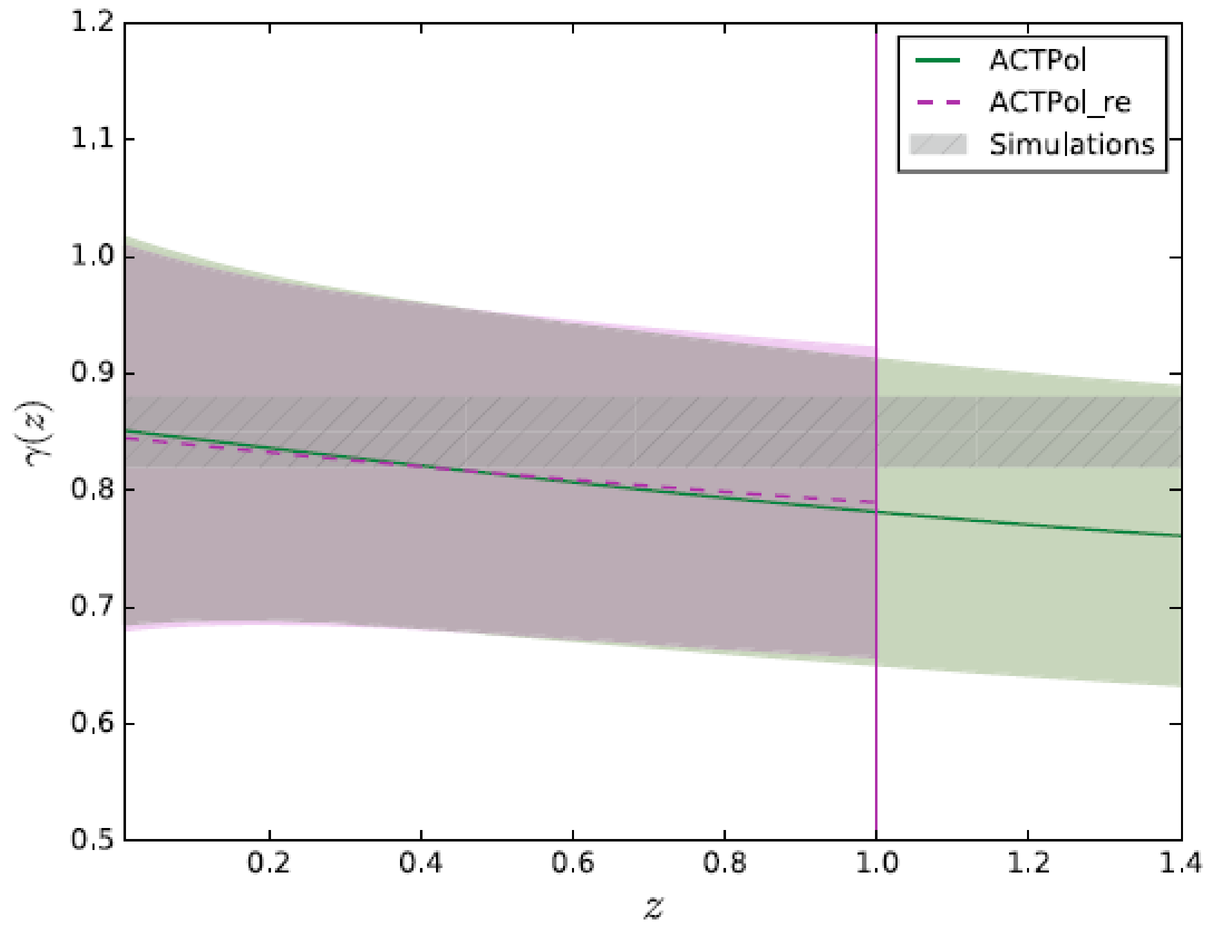
We drived true D_A directly from cosmic chronometers H(z) measurements using Gaussian Process in Python

Hubble parameter measurements from cosmic chronometers (red points) and the reconstruction of *H(z)* function (green envelope). Blue line corresponds to the fiducial cosmological model



Reconstructed gas depletion factor γ *(z)* for the full (green solid line) and reduced (magenta dashed line) ACTPol cluster sample, with the shadow regions showing the 1σ region calculated with the error propagation. The gray dashed region corresponds to the hydrodynamical simulation results

One can see that central values of our reconstructed γ *(z)* are consistent with hydrodynamical simulations up to the redshift z = 0.4, afterwards the reconstructed γ *(z)* continues decreasing.



- One can see that the difference between the full and reduced ACTPol samples is negligible. This means that the evolutionary trend $\partial\gamma / \partial z < 0$ of the depletion factor cannot be simply attributed to the leverage of galaxy clusters located at $z > 1$.

- Therefore, the trend of $\gamma(z)$ decreasing with redshift revealed in our study could reflect real evolutionary processes of intracluster medium within $R500$

In the second step, we investigated the issue of γ *(z)* evolution using a parametric approach

$$\gamma(z) = \gamma_0(1 + \gamma_1 z)$$

where
γ_0 denotes the depletion factor normalization
γ_1 quantifies possible evolution with redshift

$$\chi^2 = \sum_{i=1}^{n} \frac{(\gamma_{th}(z_i) - \gamma_{obs}(z_i))^2}{\sigma_{i,obs}^2}.$$

Confidence contours for the γ *(z)* parameters in γ *(z)* = γ0*(*1+γ1z*)*.

Green solid lines and magenta dashed lines correspond to the fits obtained on the the full and reduced ACTPol cluster sample

For the full ACTPol sample

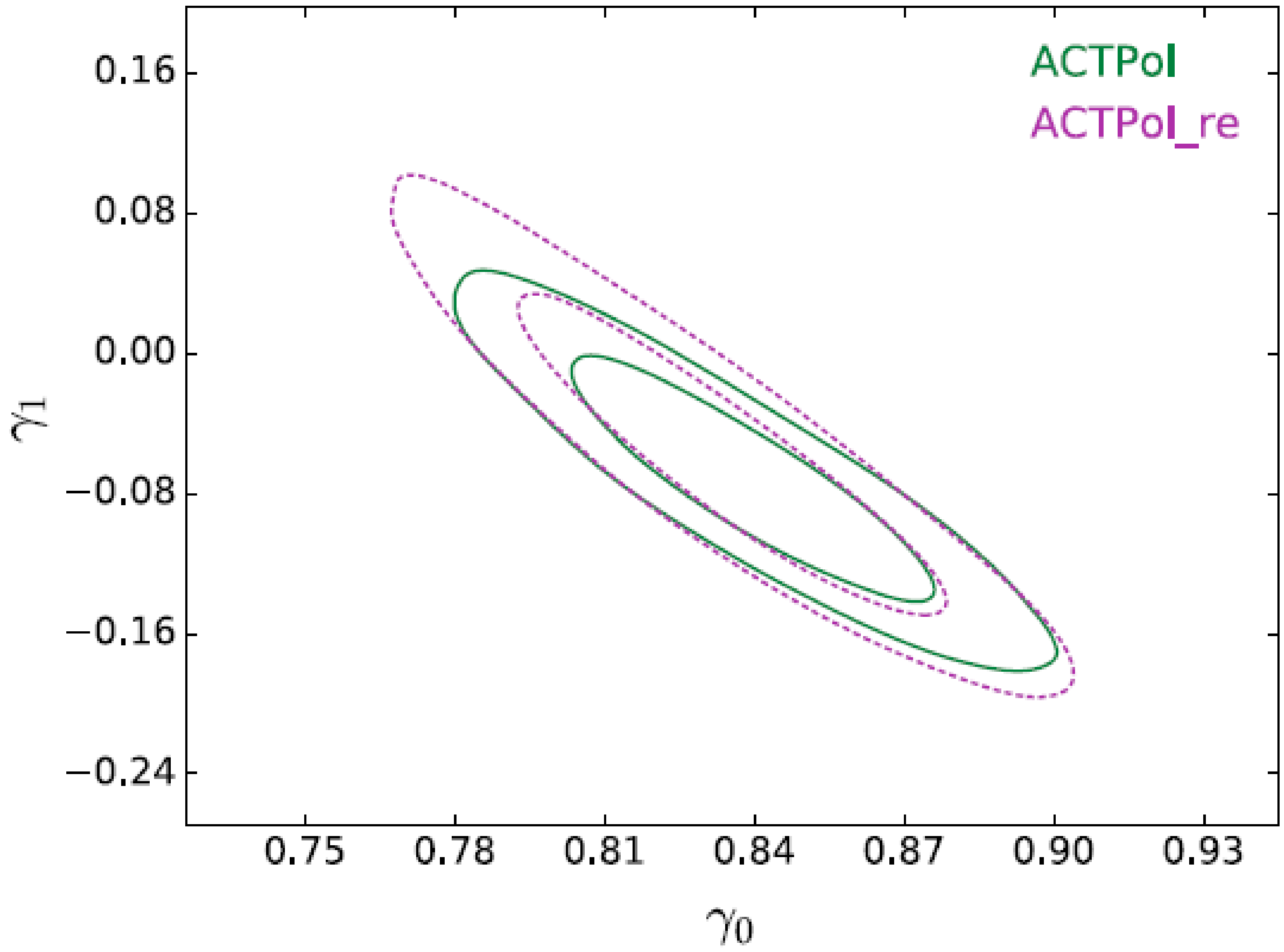
$$\gamma_0 = 0.840^{+0.025}_{-0.025}(1\sigma)^{+0.048}_{-0.048}(2\sigma),$$

$$\gamma_1 = -0.072^{+0.044}_{-0.049}(1\sigma)^{+0.095}_{-0.086}(2\sigma)$$

For the ACTPol-re sample

$$\gamma_0 = 0.835^{+0.028}_{-0.028}(1\sigma)^{+0.056}_{-0.056}(2\sigma),$$

$$\gamma_1 = -0.060^{+0.056}_{-0.063}(1\sigma)^{+0.120}_{-0.110}(2\sigma)$$



CONCLUSIONS

- Clusters of galaxies are a good tool for testing cosmology;
- The density parameters $\boldsymbol{\Omega_b}$, $\boldsymbol{\Omega_m}$ obtained from GC are in a very good agreement with Planck's results;
- The energy parameters obtained from GC are in a very good agreement with SNIa results;
- The Etherington duality relations shows that parameter η wealky depends on the cosmological model but strongly depends on the gas distribution in the cluster. Furthermore the parameter η is systematically less then 1.
- The results of deplation parametr could pave the way to explore the hot gas fraction within large radii of galaxy clusters as well as its possible evolution with redshift, which should be studied further on larger galaxy cluster samples
- When one uses f_{gas} observations as a cosmological tool the derived f_{gas} values should be calibrated with the baryon depletion factor γ

THANK YOU!