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Probing dark energy with strong and weak lensing by galaxy clusters

Summary

- Galaxy clusters
- Dark energy from strong lensing
- Dark energy from triplet statistics

Galaxy Clusters and Cosmology

Galaxy clusters, the largest virialized objects in the universe, provide a fair sample of the matter content of the universe

- ✓ Determination of cosmological parameters (mass to light ratios, gas mass fraction, cosmological abundances,…)

- ❖ Shape and tendency to be aligned with their first ranked galaxy and/or with their nearest neighbour
- ✓ Clues to the formation of large scale structure

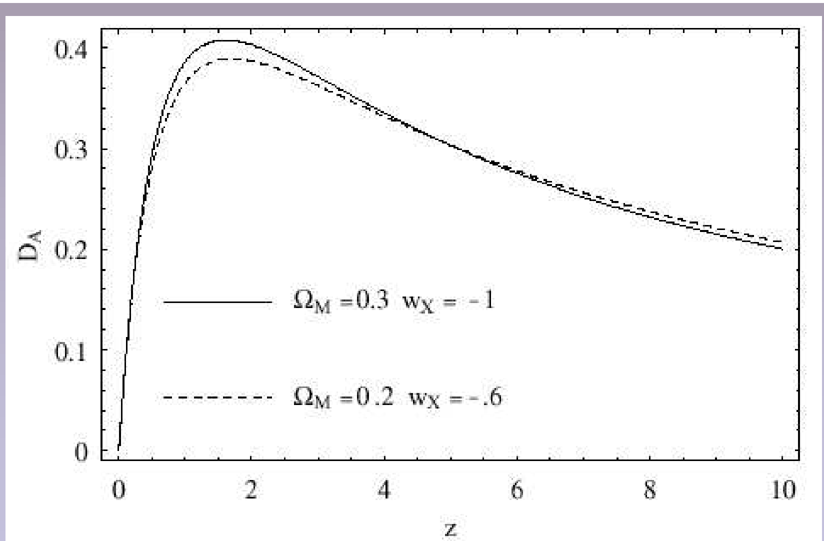
Dark Energy

Cold dark matter, Ω_{M0}, and dark energy, $p_X(z) = w_X(z)\rho_X(z)$

Angular diameter distance

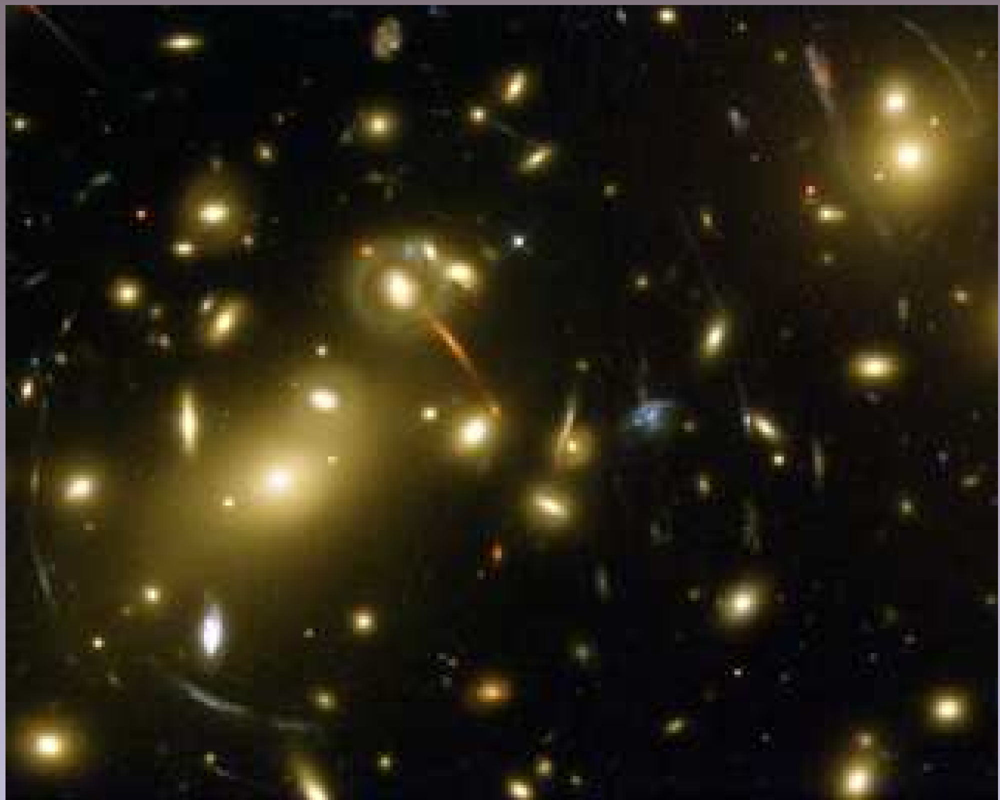
$$D_A(z_s) = \frac{c}{H_0}\frac{1}{|\Omega_{K0}|^{\frac{1}{2}}(1+z_s)}\mathrm{Sinn}\left\{|\Omega_{K0}|^{\frac{1}{2}}\int_0^{z_s}\frac{H_0}{H(z)}dz\right\}$$

$$H^2 = H_0^2\left\{\Omega_{M0}(1+z)^3 + \Omega_{X0}\exp\left[3\int_1^{1+z}[1+w_X(x)]d\ln x\right] + \Omega_K(1+z)^2\right\}$$



Strong Lensing

High resolution images of central regions of strong gravitational lensing (GL) clusters directly probe the projected total mass, Σ_{TOT}.



HST optical image of A2218. Giant arcs are in the central regions. From *http://hubblesite.org*

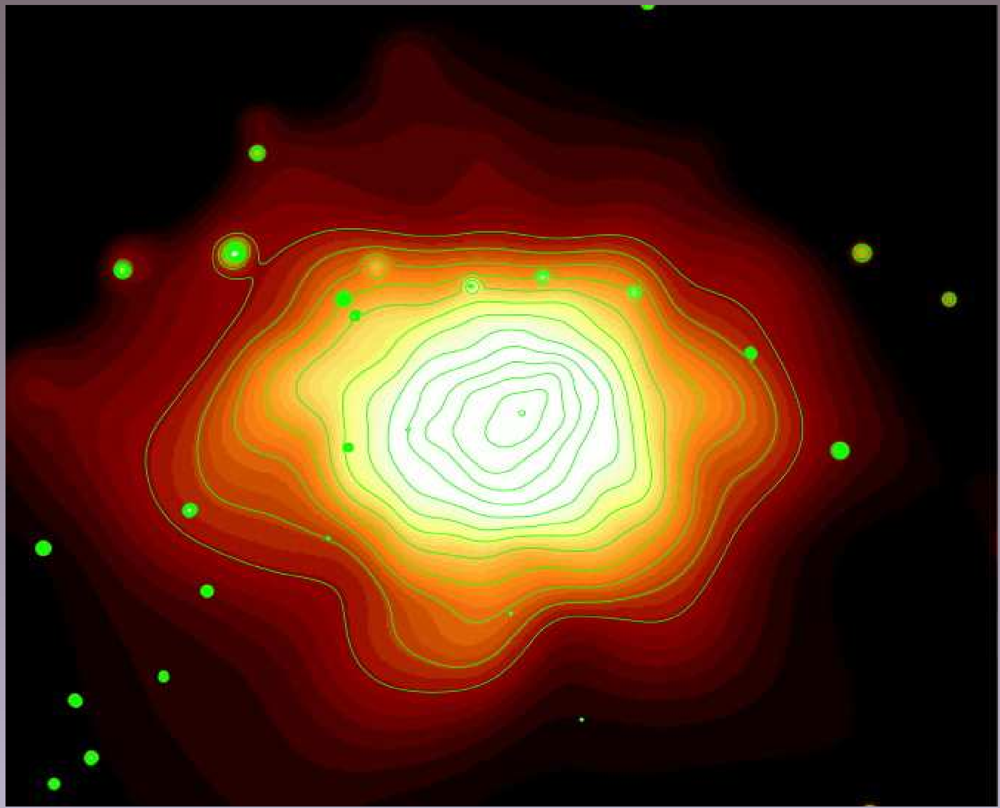
The convergence k is

$$k = \frac{\Sigma}{\Sigma_{cr}}$$

$$\Sigma_{cr} \equiv \frac{c^2}{4\pi G} \frac{D_s}{D_c D_{cs}}$$

k depends on Ω_{M0}, Ω_{X0} and w_X, but not on H_0

X-rays



A2218: adaptively smoothed, broadband Chandra image. The field is 14'.2 × 11'.87. From *Machacek et al.* (2002)

The cluster X-ray emission is due to bremsstrahlung from electron-ion collisions in the ICM. The surface brightness is:

$$S_X = \frac{1}{4\pi(1+z_c)^4} \int_{\mathrm{l.o.s.}} n_e^2 \Lambda_{eH} \, dl$$

Mass distribution from X-ray

Spherical, isothermal β-model (motivated by observations and numerical simulations)

ICM distribution: $$n_e = n_{e0}\left(1+\frac{r^2}{r_c^2}\right)^{-3\beta_X/2}$$

$\Longrightarrow$ X-ray surface brightness: $$S_X = S_{X0}\left(1+\frac{\theta^2}{\theta_c^2}\right)^{1/2-3\beta_X}$$

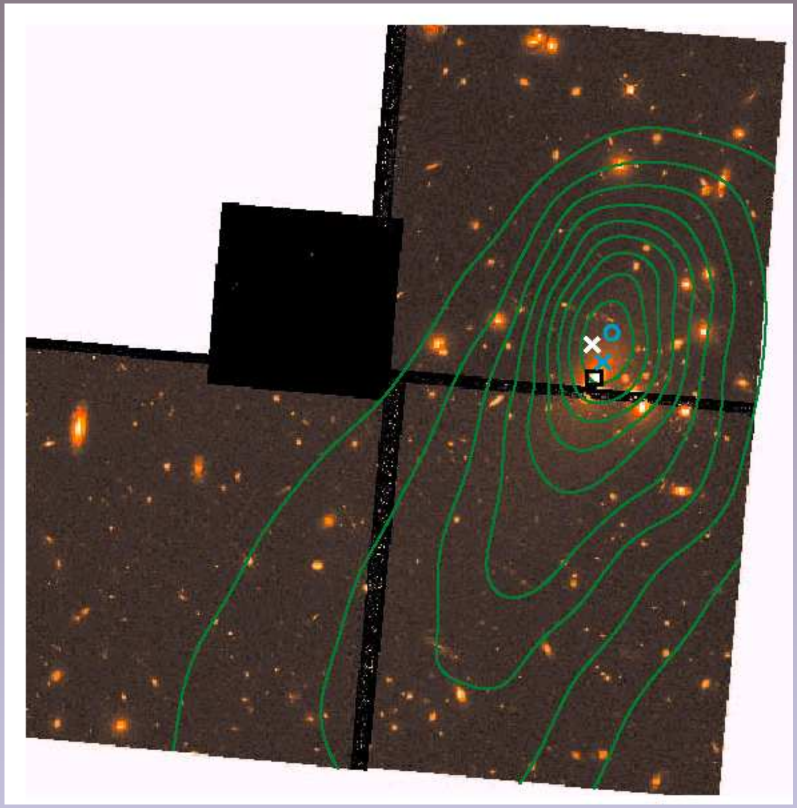
Hydrostatic equilibrium relates the total mass density, $\rho_{\rm tot}$, to n_e. If the ICM is isothermal:

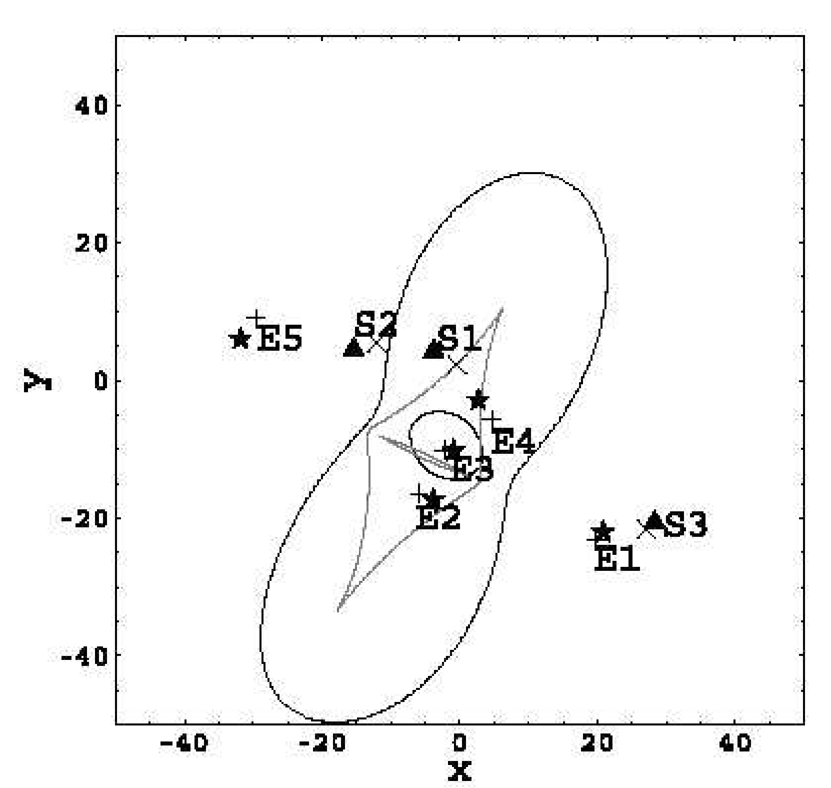
3-D density: $$\rho_{\rm tot} = -\left(\frac{k_B T_{\rm e}}{4\pi G\mu m_{\rm p}}\right)\nabla^2\left(\ln n_{\rm e}\right)$$

$\Longrightarrow$ 2-D density: $$\Sigma(\theta) = \Sigma_0\frac{1+(1/2)\left(\theta/\theta_{\rm c}\right)^2}{\left[1+\left(\theta/\theta_{\rm c}\right)^2\right]^{3/2}} \qquad \Sigma_0 = \frac{3}{2}\frac{k_{\rm B}}{G\mu m_{\rm p}}\frac{T_{\rm X}\beta_{\rm X}}{\theta_{\rm c}}\frac{1}{D_{\rm d}}$$

Cluster mass distribution

X-ray determined potential wells provide good fits to strong lensing systems.



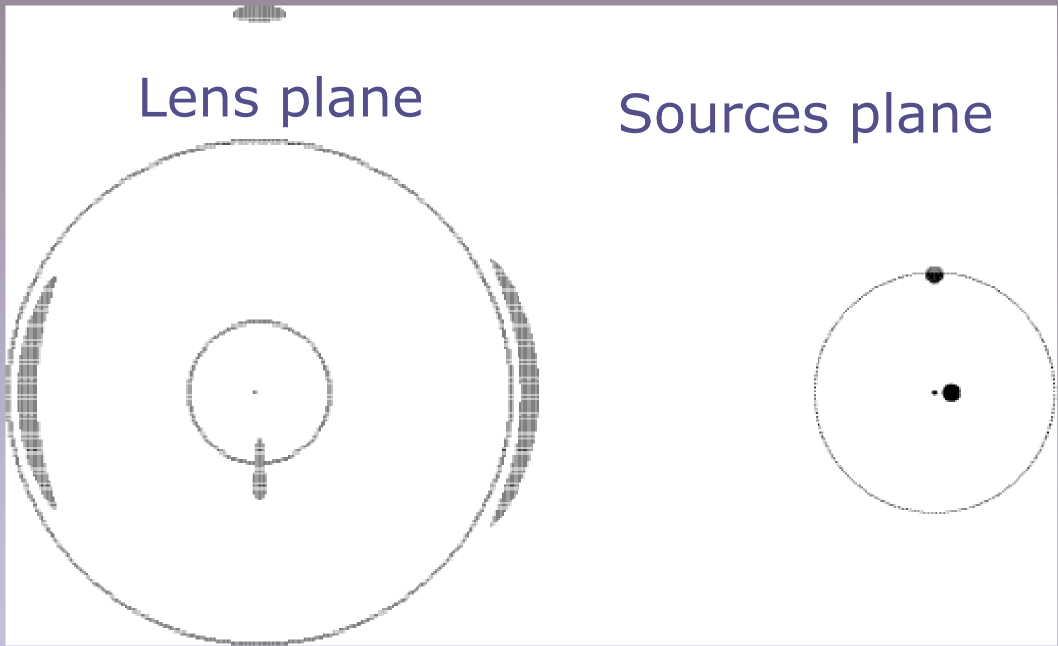


AC114 from De Filippis, Sereno, Bautz, Longo (2005) ApJ, 625, 108

Giant Arcs and Cosmology

Giant luminous arcs form near *critical lines*, locus of formally infinite magnification

Imaging of an extended source by a spherical lens

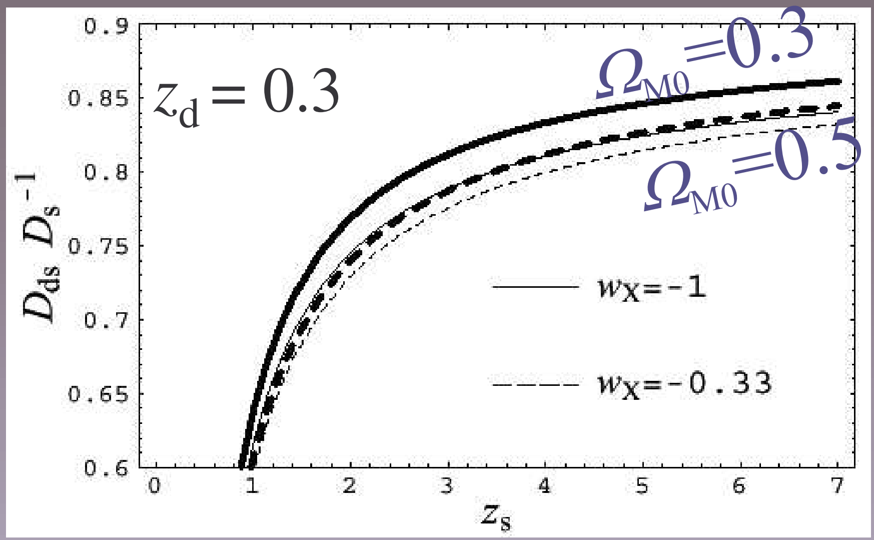


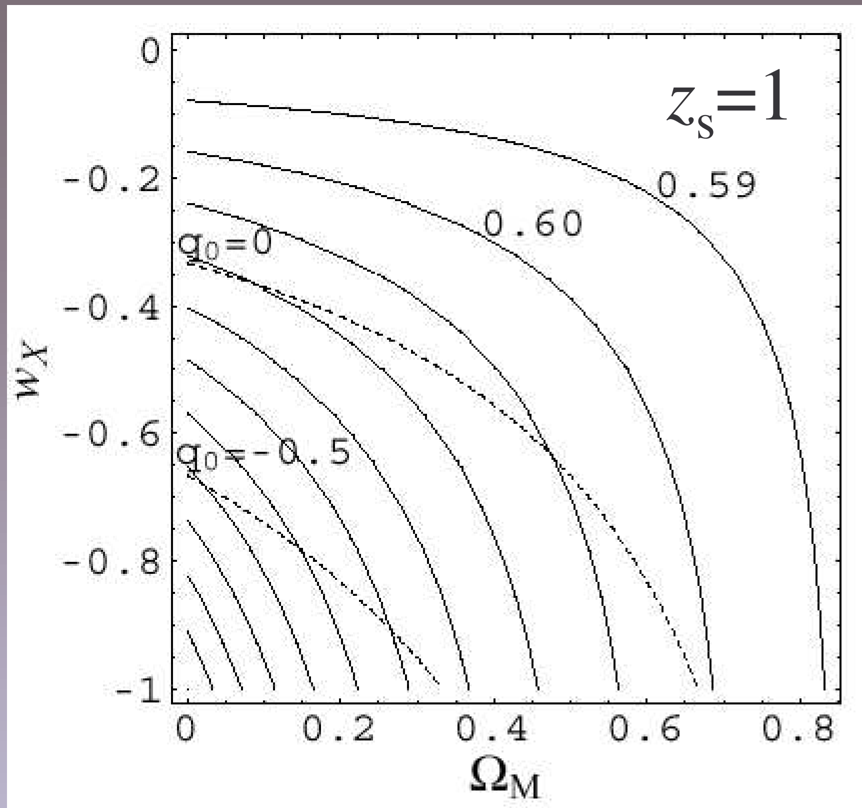
✓ Their angular radius depends on cosmology through the ratio D_{ds}/D_s

$$\theta_t = \sqrt{\left(\frac{6\pi\beta \; T_e D_{ds}}{\mu m_p c^2 \; D_s}\right)^2 - \theta_c^2}$$

Distance Ratio and Cosmology

(Sereno, 2002, A&A, 393, 757)





- Nearly flat for $z_s \gtrsim 2.5$
- Dependence on Ω_{M0} and w_X of the same order

o Sensitivity on w_X is maximum for intermediate w_X

o Accelerating and decelerating models can be distinguished

Determining cosmological parameters

…with giant arcs in a sample of rich X-ray galaxy clusters

(Sereno & Longo (2004) MNRAS, 354, 1255)

Mass profiles (β_X and θ_c) and normalizations (T_X) are determined from detailed *X-rays* observations.

Assumptions:

- Hydrostatic equilibrium
- Isothermality
- Spherical symmetry

$$\left.\frac{D_{ds}}{D_s}\right|_{obs} = \frac{\mu m_p c^2}{6\pi} \frac{1}{\beta_X T_X} \sqrt{\theta_t^2 + \theta_c^2}$$

χ^2-statistics

$$\chi^2 = \sum_{\text{systems}} \left\{ \left[\left.\frac{D_{\text{ds}}}{D_{\text{s}}}\right|^{i}_{\text{obs}} - \frac{D_{\text{ds}}}{D_{\text{s}}}\left(z^i_{\text{d}}, z^i_{\text{s}}; \Omega_{\text{M0}}, \Omega_{\text{X0}}, w_{\text{X}}\right) \right] \Big/ \sigma_i \right\}^2$$

Statistical errors from

- model parameters (β_X and θ_c)
- temperature (T_X) and metallicity (μ)
- arc position ($\theta_t = \varepsilon\, \theta_{arc}$)

Systematics

- choice of model (central cusp,…)
- temperature (polytropic profile, off-set,…)
- ellipticity and sub-structures

Galaxy Cluster Selection

A careful selection of the sample requires:

1. Arcs with known spectroscopic redshift
2. Agreement of X-ray with optical and/or lensing mass
3. Regular X-ray morphology
4. *T*, from *Chandra* or *XMM*, agrees with *ROSAT* or *ASCA*

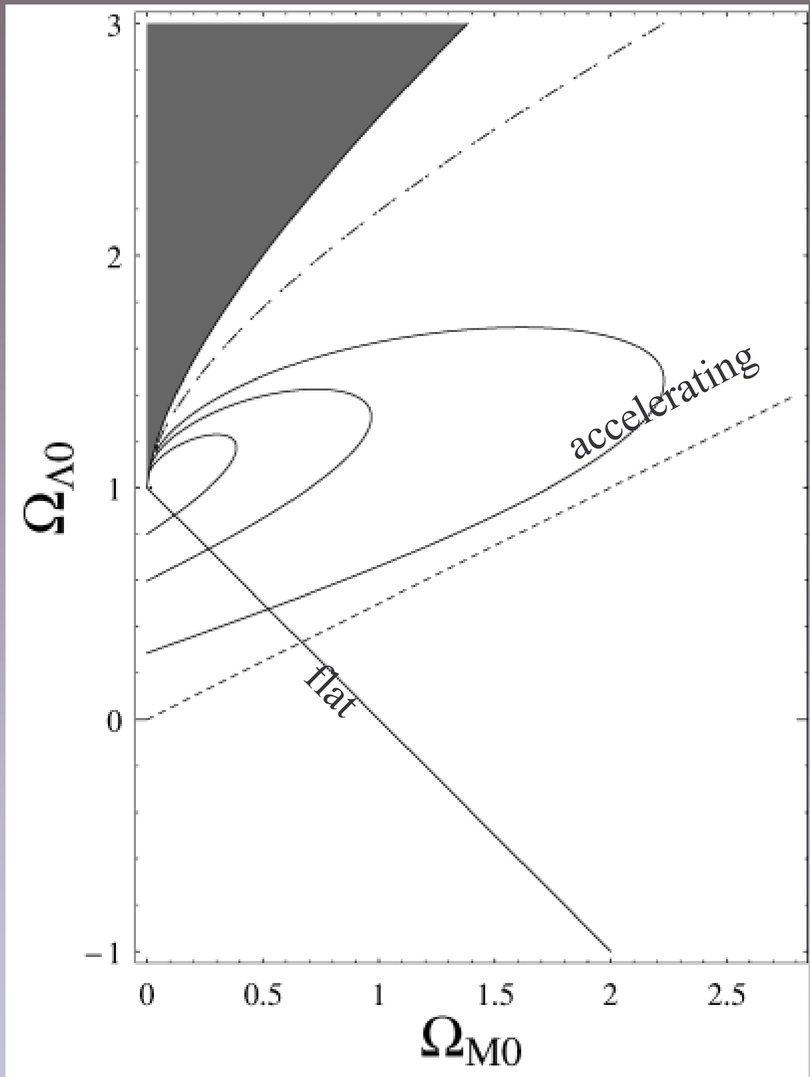
A final sample of 6 relatively relaxed, luminous clusters (*A2390*, *MS0451*, *MS1358*, *MS2137*, *PKS0745*, *RXJ1347*).

✓ Near coincidence of X-ray peak with CD galaxy

✓ Massive cooling flow clusters (apart MS0451)

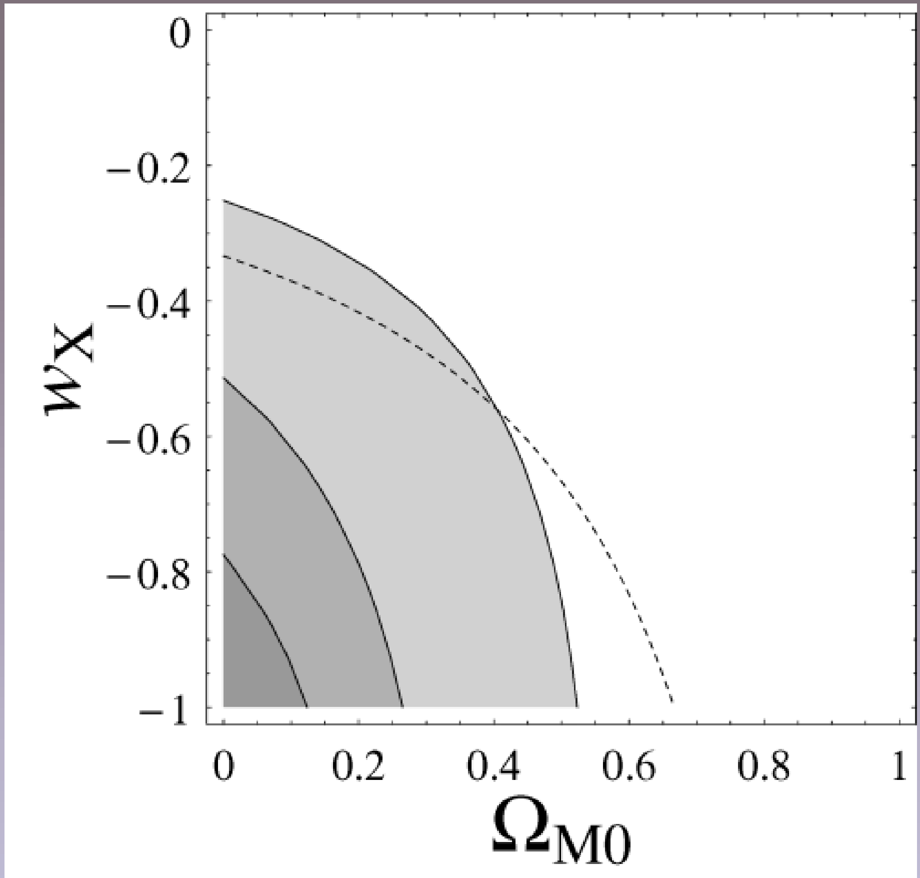
✓ Luminous (T >5 KeV)

The cosmological constant



- At 3-σ C.L, the Einstein-de Sitter model is exluded and accelerating modeles are preferred.
- data are compatible with spatial flatness
- Whichever the bayesian prior, cosmological constant dominates ($\Omega_{\Lambda 0} \approx 1.07 \pm 0.20$)

Dark energy



Priors: flat universe and $w_X \geq -1$:

- ❖ Dark energy, with strongly negative pressure, dominates
- ❖ Parameter estimates
- o $w_X \approx -0.84 \pm 0.14$
- o $\Omega_{M0} \approx 0.10 \pm 0.10$

Relaxing lower limit on w_X:

- ❖ NEC is verified at 3-σ C.L.
- ❖ Λ is still compatible.

Weak lensing

The observed ellipticity of a background galaxy depends on the reduced shear ***g***

$$\boldsymbol{\epsilon}_i = \bar{\boldsymbol{\epsilon}}_{S,i} + \boldsymbol{g}_i^o \quad \text{with} \quad \boldsymbol{g}_i^o = \frac{\omega_i^o \boldsymbol{\gamma}_\infty}{1 - \omega_i^o \kappa_\infty}$$

Lensing parameters can be related to the value they would have at infinite redsfift

$$\kappa = \omega(z)\kappa_\infty \; ; \; \boldsymbol{\gamma} = \omega(z)\boldsymbol{\gamma}_\infty$$

$$\omega_a(z) = \frac{D_{LS}}{D_{OS}} \qquad \omega(z) = \frac{\omega_a(z)}{\omega_a(\infty)}$$

Triplet statistics

3 background galaxies at (nearly) the same angular position probe the same local mass distibution (2 parameters, k_∞ and γ_∞). If at different redshifts, they can constrain cosmology, i.e. $\omega(z)$ (Gautret et al. (2000), A&A, 353, 10).

The geometrical complex operator G, built from the measured ϵ_i and z_i of the three galaxies, depends only on cosmology, not on mass distribution

$$G_{ijk}(\Omega, \lambda) = \begin{vmatrix} 1 & \omega_i & \omega_i \epsilon_j \epsilon_k^* \\ 1 & \omega_j & \omega_j \epsilon_k \epsilon_i^* \\ 1 & \omega_k & \omega_k \epsilon_i \epsilon_j^* \end{vmatrix}$$

G = 0 when the cosmological parameters are equal to the actual ones (apart from noise!)

Noise on *G*

Sources of noise

- intrinsic source ellipticities
- errors on measured ellipticities
- sources do not experience exactly the same potential
- errors on measured (photometric) redshifts

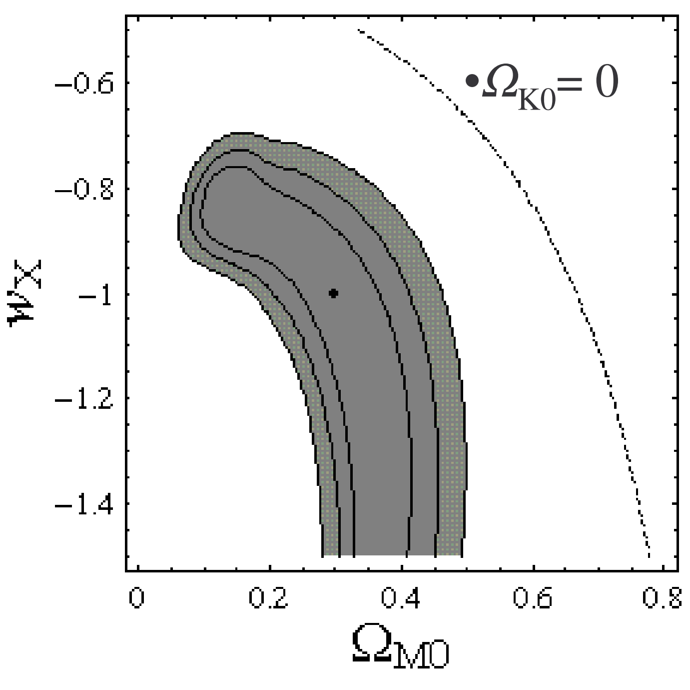
Systematics

- asymmetry of photometric $\Delta\omega$
- contamination by background structure (galaxy-galaxy lensing or large scale structures)

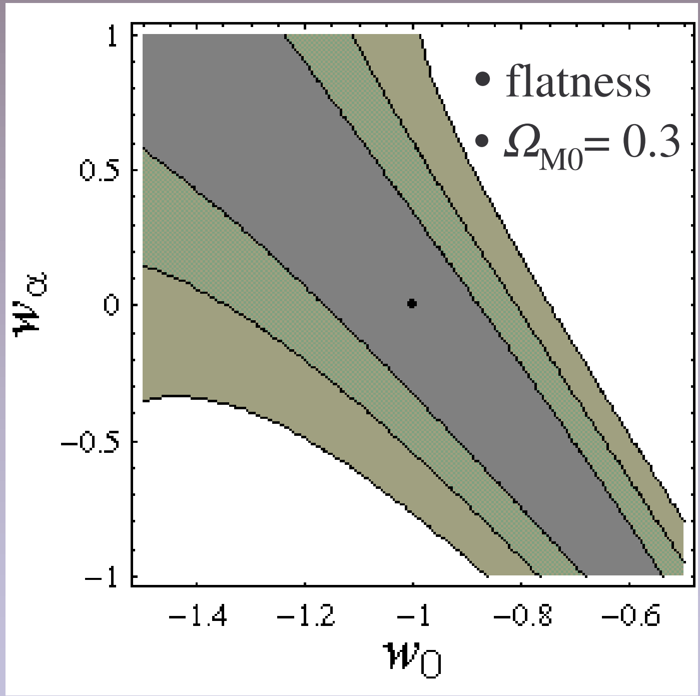
Future surveys

LSST-like cosmic shear surveys (~15,000 deg^2, 30-60 gal/arcmin, $\sigma_\epsilon \approx 0.2$-$0.3$, $z_{med} \sim 0.9$) will detect more than 10^5 massive clusters at intermediate z (Wang et al. (2004) PRD 70, 123008; Huterer et al. astro-ph/0506030)

No evolution: $w_X = cost$



Evolution: $w_X(z) = w_0 + w_\alpha\, z/(1+z)$



Conclusions

- Galaxy clusters are very well known

- ✓ Giants arcs in *X*-ray clusters seem to support dominating dark energy with a strongly negative pressure, in agreement with CMB, LSS and SNe (Λ is still the best one)

- ❖ Triplet statistics offers good prospects in weak-lensing regime
  - o Purely geometric, differently from standard shear power spectra
  - o Different weak-lensing regime with respect to cross-correlation tomography (g instead of γ)