Complementarity of different cosmological probes

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in colaboration with

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MATTER TO THE DEEPEST
Ustroń, Poland
1-6 September 2013

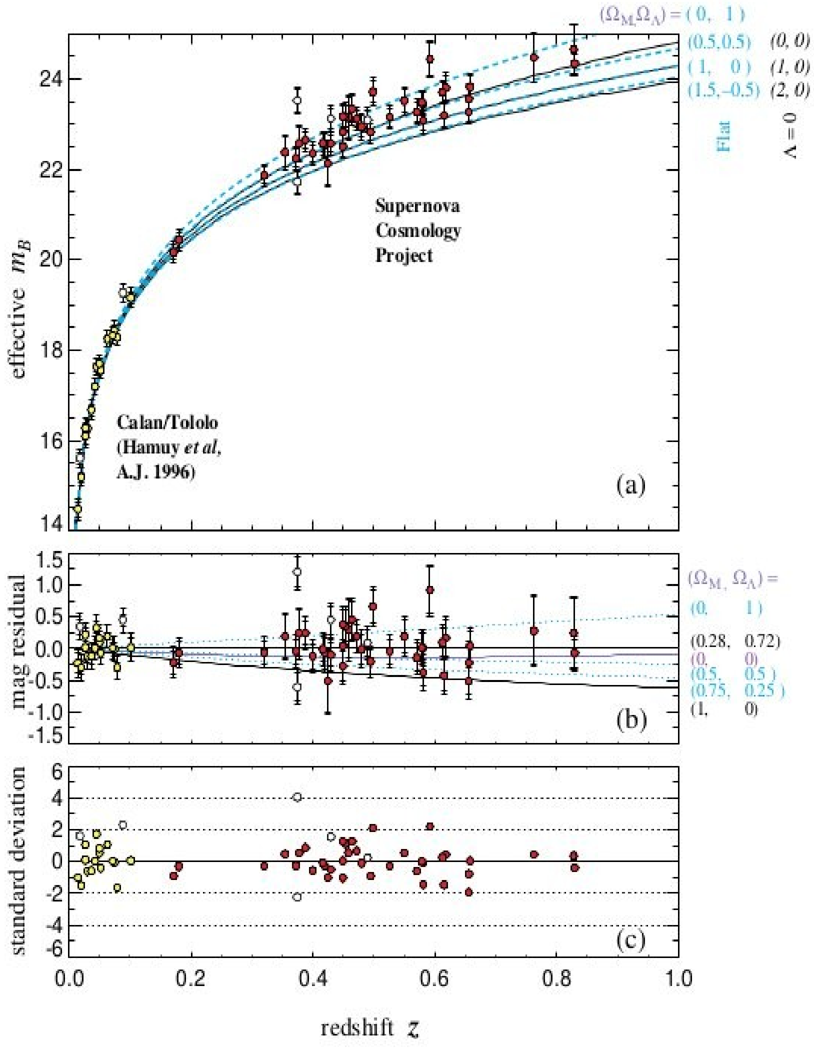
Talk outline

- Introduction – phenomenology of dark energy
- Cosmological probes – how to obtain cosmological parameters from observations?
- Strong gravitational lenses as standard(izable) rulers
- Dark Energy Complementarity – how to reach the tightest constraints on dark energy parameters from different cosmological tests
- Complementarity of strong lensing measurements to other methods
- Summary and perspectives

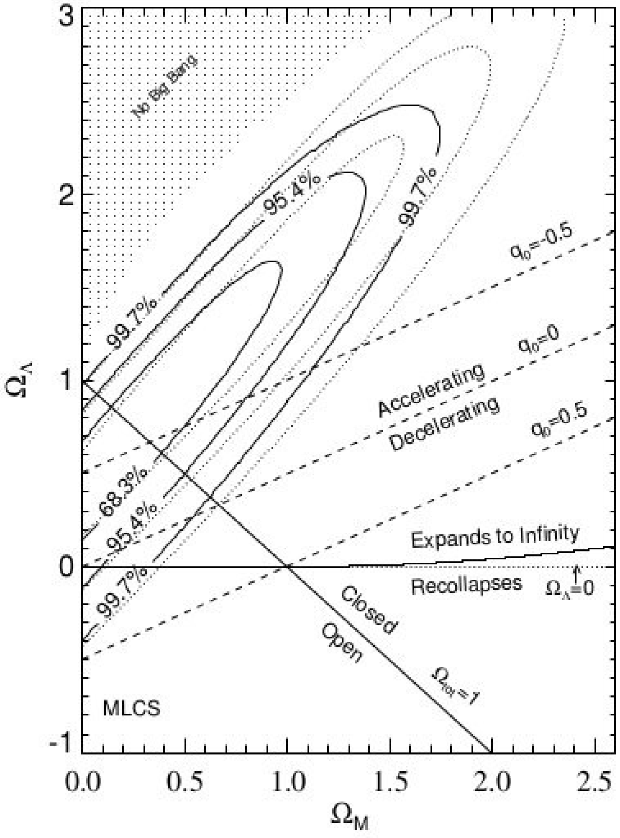
Introduction

- Observational fact: present accelerating expansion of the Universe observed in Hubble diagrams from SNIa surveys

$$\begin{aligned}\Omega_\Lambda &= 0.71 \pm 0.05 \\ \Omega_M &= 0.29 \pm 0.05\end{aligned} \quad (1\sigma)$$



Supernova Cosmology Project (Perlmutter et al.1999)



High-z Supernova Search Team (Riess et al. 1998)

Introduction

The Nobel Prize in Physics 2011
Saul Perlmutter, Brian P. Schmidt, Adam G. Riess

KUNGL.
VETENSKAPS-
AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

English
English (pdf)
Swedish
Swedish (pdf)

Press Release

4 October 2011

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2011

with one half to

Saul Perlmutter
The Supernova Cosmology Project
Lawrence Berkeley National Laboratory and University of California,
Berkeley, CA, USA

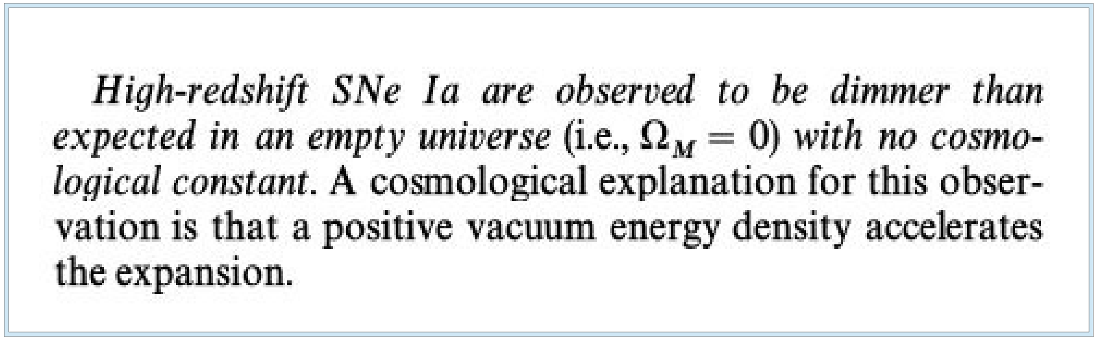
and the other half jointly to

Brian P. Schmidt
The High-z Supernova Search Team
Australian National University,
Weston Creek, Australia

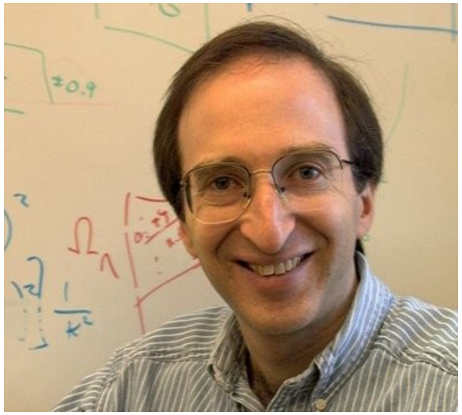
and

Adam G. Riess
The High-z Supernova Search Team
Johns Hopkins University and Space Telescope Science Institute,
Baltimore, MD, USA

"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"



High-redshift SNe Ia are observed to be dimmer than expected in an empty universe (i.e., $\Omega_M = 0$) *with no cosmological constant.* A cosmological explanation for this observation is that a positive vacuum energy density accelerates the expansion.



Introduction

- SNIa results confirmed by independent estimates of the amount of baryons and cold dark matter:

$$\Omega_k = 1 - \Omega_M - \Omega_\Lambda$$

spatially flat Universe

First BAO measurements (Spergel et al. 2003)

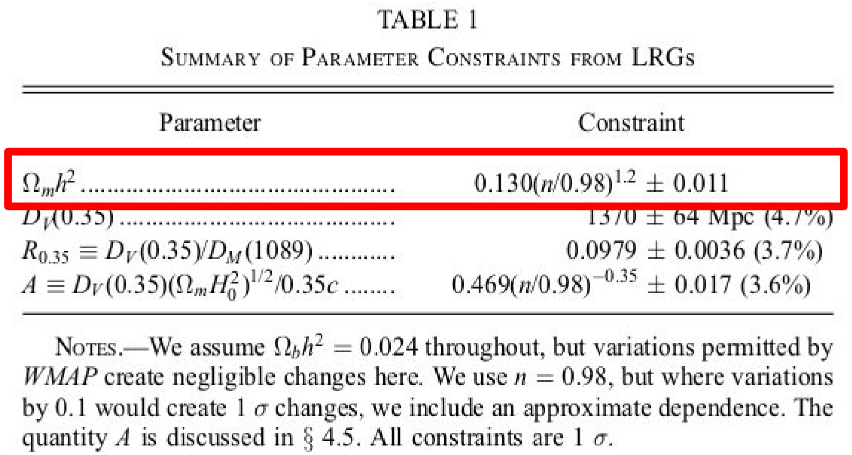


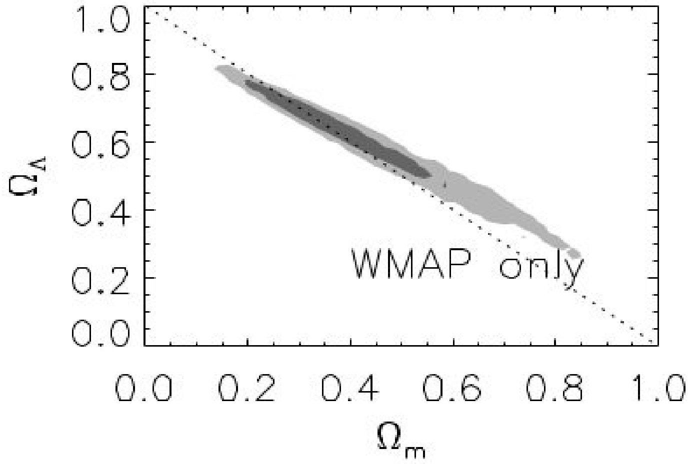
TABLE 1

Summary of Parameter Constraints from LRGs

Parameter	Constraint
$\Omega_m h^2$	$0.130(n/0.98)^{1.2} \pm 0.011$
$D_V(0.35)$	1370 ± 64 Mpc (4.7%)
$R_{0.35} \equiv D_V(0.35)/D_M(1089)$	0.0979 ± 0.0036 (3.7%)
$A \equiv D_V(0.35)(\Omega_m H_0^2)^{1/2}/0.35c$	$0.469(n/0.98)^{-0.35} \pm 0.017$ (3.6%)

Notes.—We assume $\Omega_b h^2 = 0.024$ throughout, but variations permitted by *WMAP* create negligible changes here. We use $n = 0.98$, but where variations by 0.1 would create 1 σ changes, we include an approximate dependence. The quantity A is discussed in § 4.5. All constraints are 1 σ.

First-Year WMAP data (Eisenstein et al. 2005)



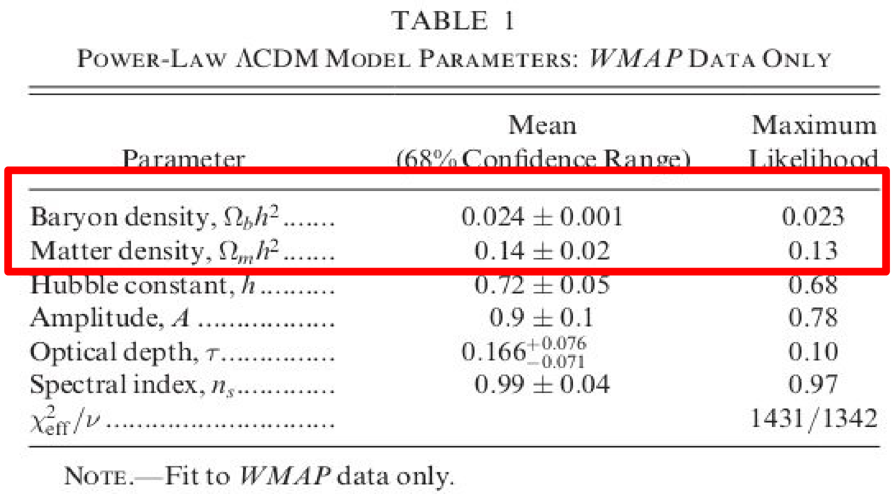


TABLE 1

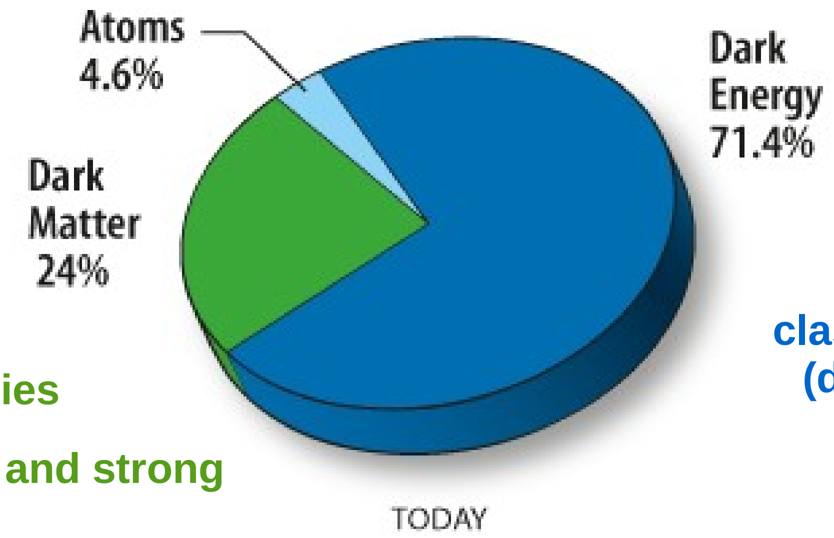
Power-Law ΛCDM Model Parameters: *WMAP* Data Only

Parameter	Mean (68% Confidence Range)	Maximum Likelihood
Baryon density, $\Omega_b h^2$	0.024 ± 0.001	0.023
Matter density, $\Omega_m h^2$	0.14 ± 0.02	0.13
Hubble constant, h	0.72 ± 0.05	0.68
Amplitude, A	0.9 ± 0.1	0.78
Optical depth, τ	$0.166^{+0.076}_{-0.071}$	0.10
Spectral index, n_s	0.99 ± 0.04	0.97
$\chi^2_{\rm eff}/\nu$		1431/1342

Note.—Fit to *WMAP* data only.

Introduction

- Cosmological consensus: most of the energy in the Universe exists in the form of the mysterious dark energy



NASA/WMAP Science Team

flat rotation curves of galaxies

gravitational lensing: weak and strong

classical cosmological tests
(distance measurements)

modification of gravity at cosmological scales

exotic material component

new physics is needed

Introduction

- ΛCDM model became a standard reference point in cosmology:
  - FRW metric (homogeneous and isotropic spacetime)

$$ds^2 = dt^2 - a(t)^2[\frac{dr^2}{1-kr^2} + r^2 d\theta^2 + r^2 \sin\theta^2 d\phi^2]$$

  - non-vanishing cosmological constant
  - pressure-less matter including dark part of it

- The expansion rate in ΛCDM model can be parametrized in a very convenient way:

$$\boxed{H^2(z) = H_0^2 \left[\Omega_{\rm m}\,(1+z)^3 + \Omega_\Lambda\right]}$$

$$\boxed{\Omega_i = \frac{\rho_i}{\rho_c}}$$

$$\boxed{\Omega_{tot} = \sum_i \left(\frac{\rho_i}{\rho_c}\right) = 1}$$

strong evidence for the spatially flatness of the Universe from observations

Introduction

- ΛCDM model even best fitted to observations suffers however from several problems of fundamental nature:

fine tuning problem

discrepancy between facts and expectations

- One can heuristically assume that dark energy is described by hydrodynamical energy-momentum tensor with (effective) cosmic EoS:

$w = 0$ dust

$w = 1/3$ radiation

$$\boxed{p = w\rho}$$

$w = -1$

cosmological constant

- Time-varying EoS as a Taylor expansion over a(t) (linear order):

$$w(z) = w_0 + w_a \frac{z}{1+z}$$

If we think that dark matter has its origins in the evolving scalar field (quintessence), it would be natural to expect that the *w* coefficient should vary in time

CPL parametrization

Chevalier&Polarski 2001, Linder 2003

Cosmological probes

- The nature of dark energy is still an open question

- We are left with the phenomenological approach based on upgrading observational fits of quatities parametrizing dark energy

density parameters or coefficients in the cosmic EoS

- The most general phenomenological form of the expansion rate is determined by a set of parameters:

$$H(t)^2 = H_0^2 \left[\Omega_m a(t)^{-3} + \Omega_r a(t)^{-4} + \Omega_X a(t)^{-3(1+w_X)} + \Omega_k a(t)^{-2} \right]$$

$$\boxed{\Omega_k = 0}$$

Technically speaking: testing cosmological models means to determine parameters from observables measured on extragalactic objects layng on cosmological distances

Cosmological probes

- One of the very direct cosmological probes could be to test the distance-redshift relation *D*(*z*) (Hubble diagram)
- In non-Euclidean geometry one distinguishes three types of distances:
  - **comoving distance**

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

not measured directly

  - **luminosity distance**

$$\boxed{D_L(z;\mathbf{p}) = (1+z)r(z;\mathbf{p})}$$

measured on objects with known luminosity
– **standard candles**

  - **angular diameter distance**

$$\boxed{D_{\mathrm{A}}(z;\mathbf{p}) = \frac{1}{1+z}r(z;\mathbf{p})}$$

measured on objects with known angular size
– **standard rulers** (statistical and individual)

linked via Etherington relation

Cosmological probes

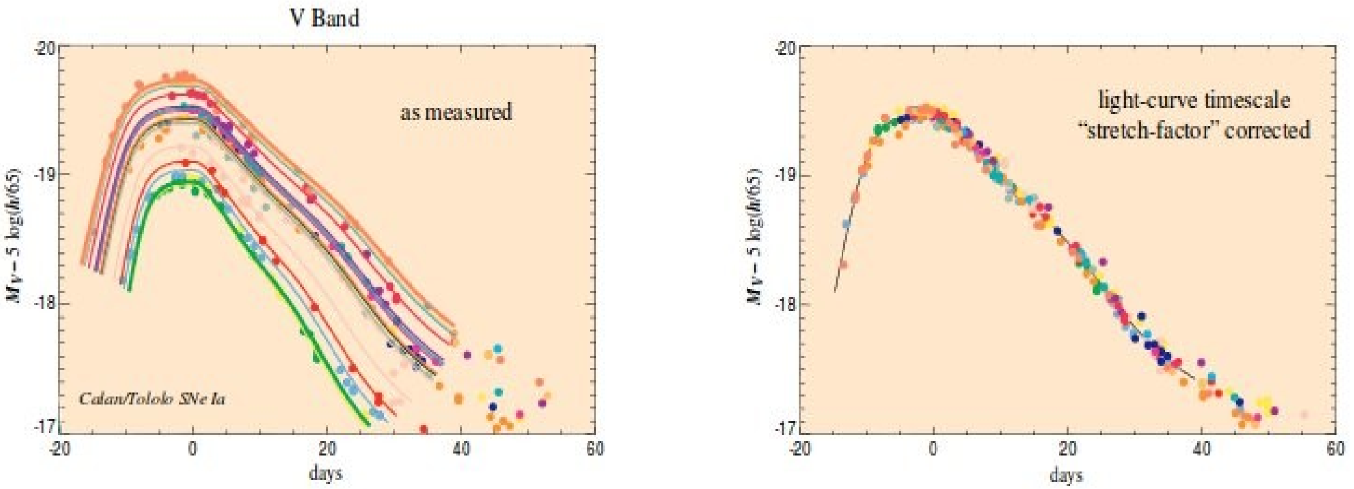
- Standard candles: **SNIa**
  - bright enough to be detected in distant galaxies (up to z ~ 1.7)
  - the most recent compilation of 557 SNIa data known as Union2

Amanullah et al. 2010, Suzuki et al. 2011

  - luminosity distance vs. redshift relation via distance modulus:

$$\boxed{\mu := m - M = 5\log_{10}(D_L(z;\mathbf{p})) + 25}$$

Standardizable – luminosity correlated with duration and spectral features of the event



Perlmutter et al. 1998

Cosmological probes

- Standard(izable) candles available in the future:

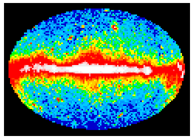
Other type of Sne (SNII-P)

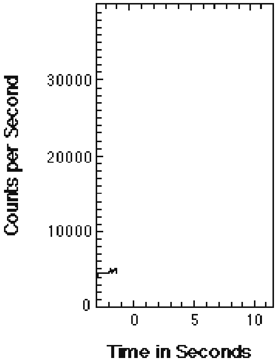
- type II SNe are not as bright as the Ia’s but they are the most common type of such a phenomenon
- correlation between expansion velocities of the ejecta and bolometric luminosities in the plateau phase

Poznanski, Nugent & Filippenko 2010

Hamuy & Pinto 2002

GRBs





- detectable up to the redshift of z ~ 8
- several suggestions to calibrate them by using correlations between various properties of the prompt emission and in some cases also the afterglow emission

Capozziello et al. 2012

Gravity-wave sources (standard sirens)

- the most promising source: inspiral and merger of a compact-object binaries consisting of neutron stars and/or black holes
- redshift and luminosity distance of the system is directly encoded in the waveform

Arabsalmani, Sahni & Saini 2013

Camera & Nishizawa 2013

Taylor & Gair 2012

Cosmological probes

- Statistical standard rulers: **CMBR and BAO**

the sound horizon
comoving distance travelled by
a sound wave in the photon-baryon
fluid by the time of decoupling (z ~ 1100)

$$r_s(z_{\rm lss}) = \int_{z_{lss}}^{\infty} \frac{c_s dz}{H(z)}$$

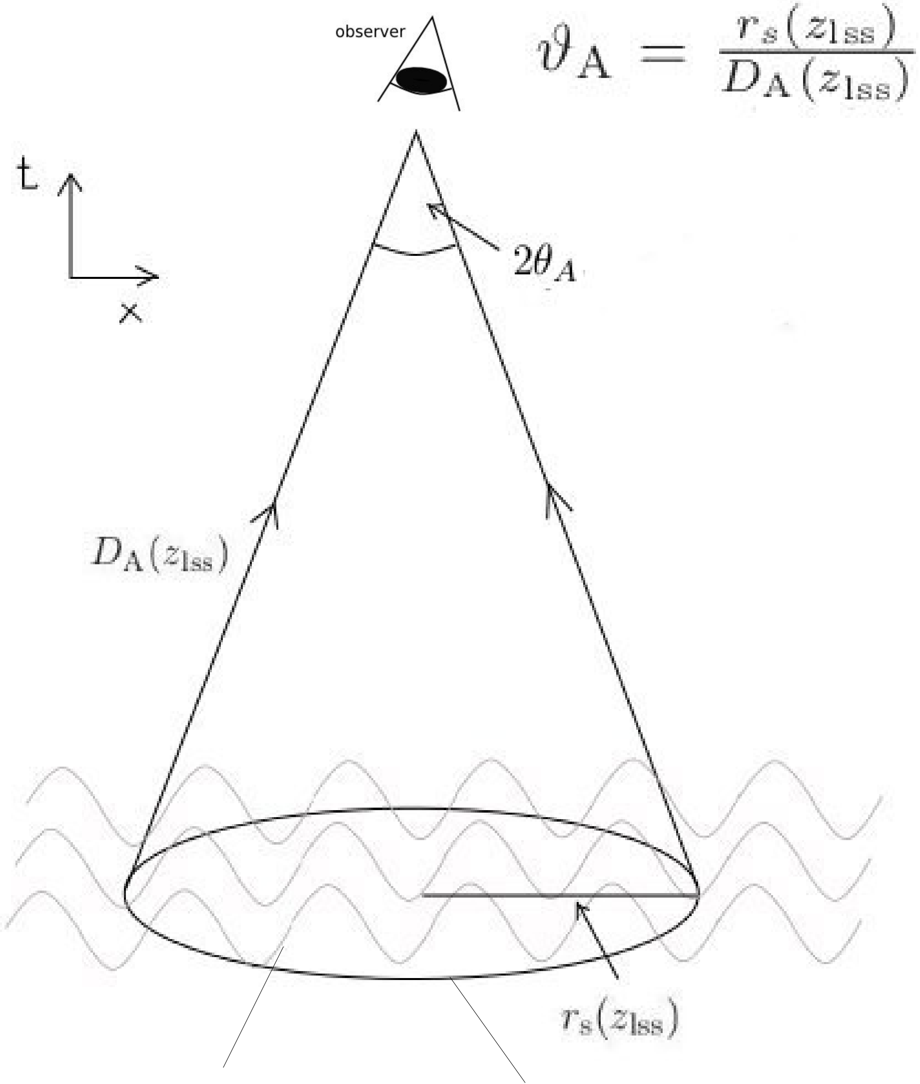
depends on baryon and
matter densities
(known from CMBR measurements)

$$r_s(z_{\rm lss}) = 146.8 \pm 1.8\text{Mpc}$$

Komatsu et al. 2008

angular size of the radius of the sound horizon size at the decoupling epoch

$$\vartheta_{\rm A} = \frac{r_s(z_{\rm lss})}{D_{\rm A}(z_{\rm lss})}$$

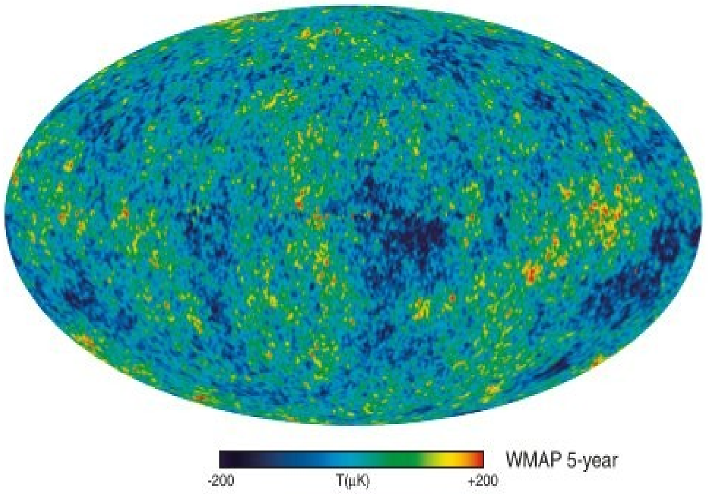


pressure waves caused by
dark matter overdensities

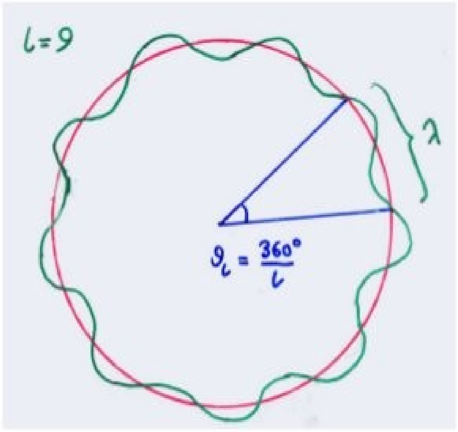
surface of last scattering

Cosmological probes

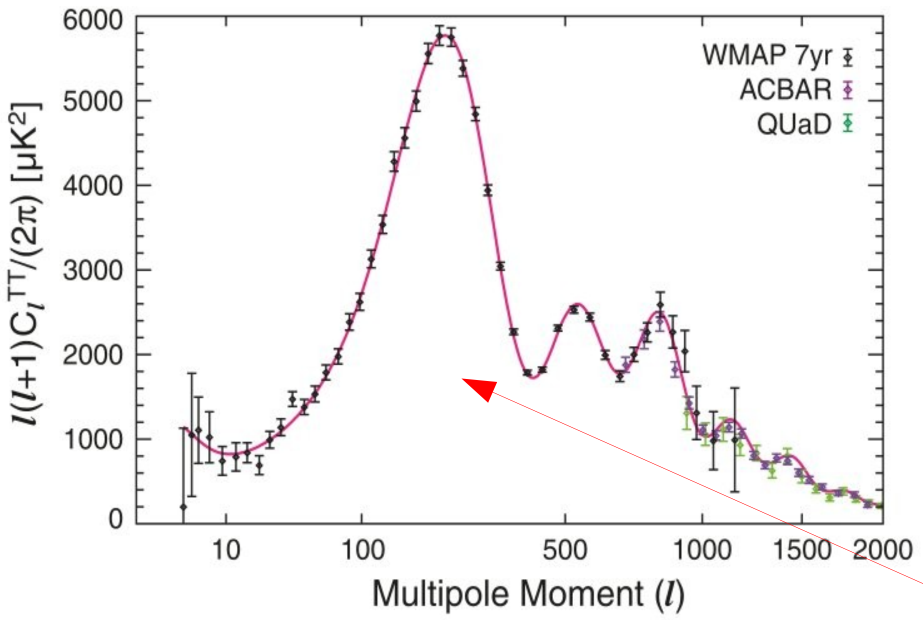
- **CMBR anisotropies** - the pattern of acoustic oscillations frozen into the CMB



the angles on the sky are related to actual physical or comoving distances via the angular diameter distance



$$\ell \propto 1/\theta$$



different multipole numbers l correspond to different angular scales:

$$\ell \approx \frac{D_A(z_{LSS})}{r_s}$$

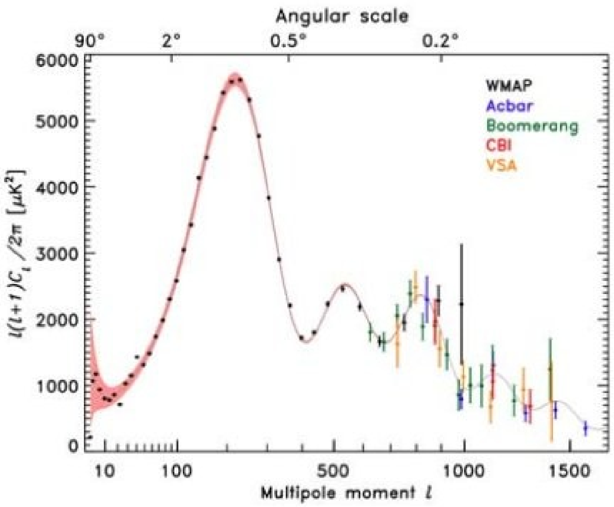
location of the first acoustic peak depends strongly on geometry and cosmology

Komatsu et al. 2010

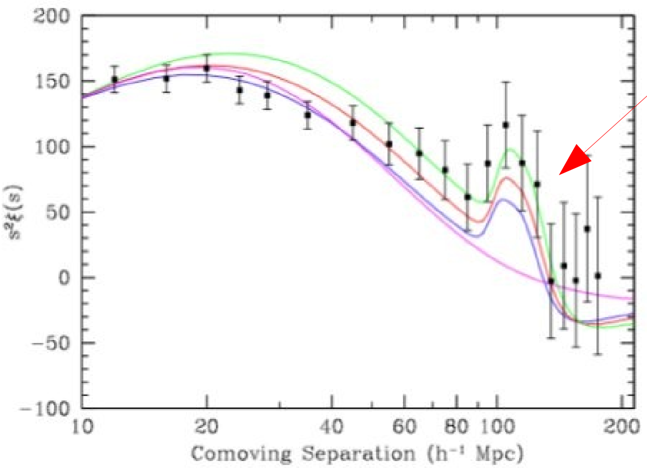
Cosmological probes

- **BAO**

Besides producing the acoustic peaks of the CMBR, pressure waves reveal themselves in clustering properties of galaxies:

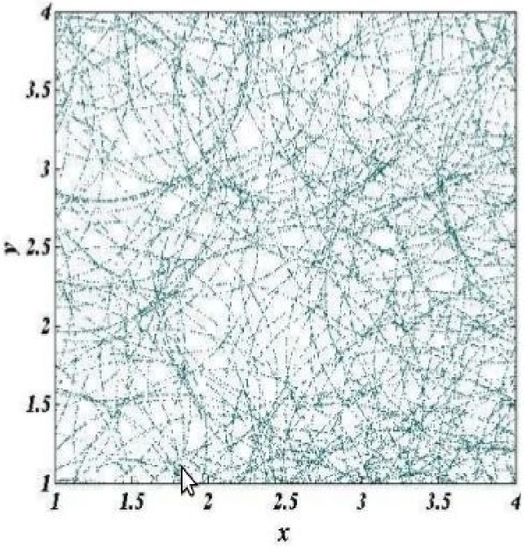


Hinshaw et al. 2003



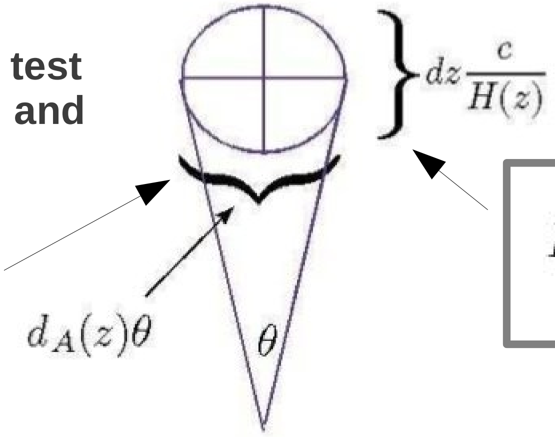
Eisenstein et al. 2005

a bump in the two-point correlation function in distribution of LRG (SDSS)



simple idea of the Alcock-Paczynski test - correlations measured in the radial and transverse direction:

$$d_A(z) = \frac{s_\perp}{\Delta\theta(1+z)}$$



$$H(z) = \frac{c\Delta z}{s_{||}(z)}$$

Bassett, Hlozek et al. 2009

Cosmological probes

- Individual standard rulers:

wide range of redshifts

Ultra compact radio sources

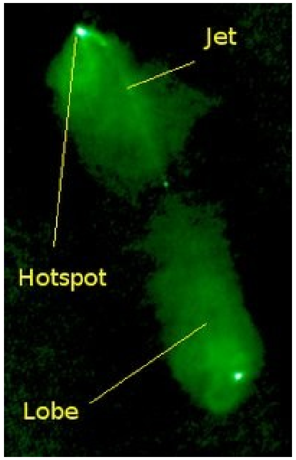
- standard ruler – size of the central region of AGNs
- evolution free sample – morphology depends only on the nature of the central engine controlled by a limited number of physical parameters: mass of the central black hole, magnetic field,
- accretion rate, angular momentum (possibly)

Gurvits, Kellermann, Frey 1998

Gurvits 1994

Double-sided radio sources (FRIIb radio galaxies)

- standard ruler – physical size of the radio bridge structure
- evolution of structure is linear with time (older are bigger)

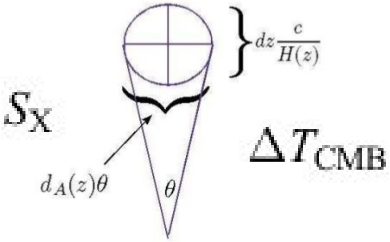


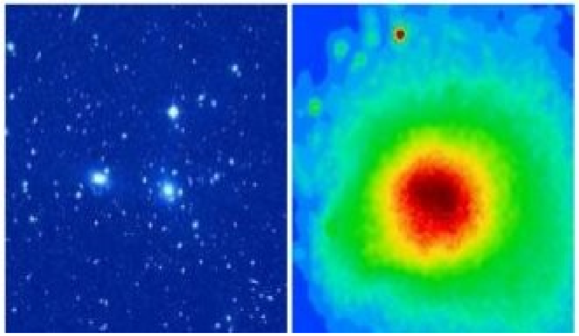
Daly 1994, 2009

Galaxy clusters

- combined X-ray+SZ data
- distance inferred from AP test (asumption: symmetrical spherical shape of the cluster)

$$D_A \equiv dl/d\theta$$

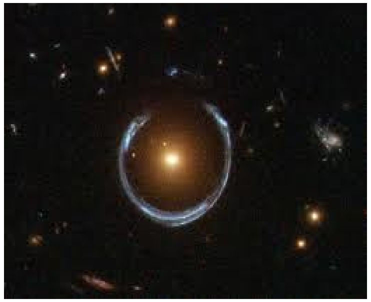




Bonamente et al. 2006

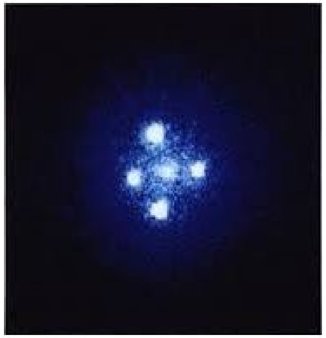
Strong lenses as standard(izable) rulers

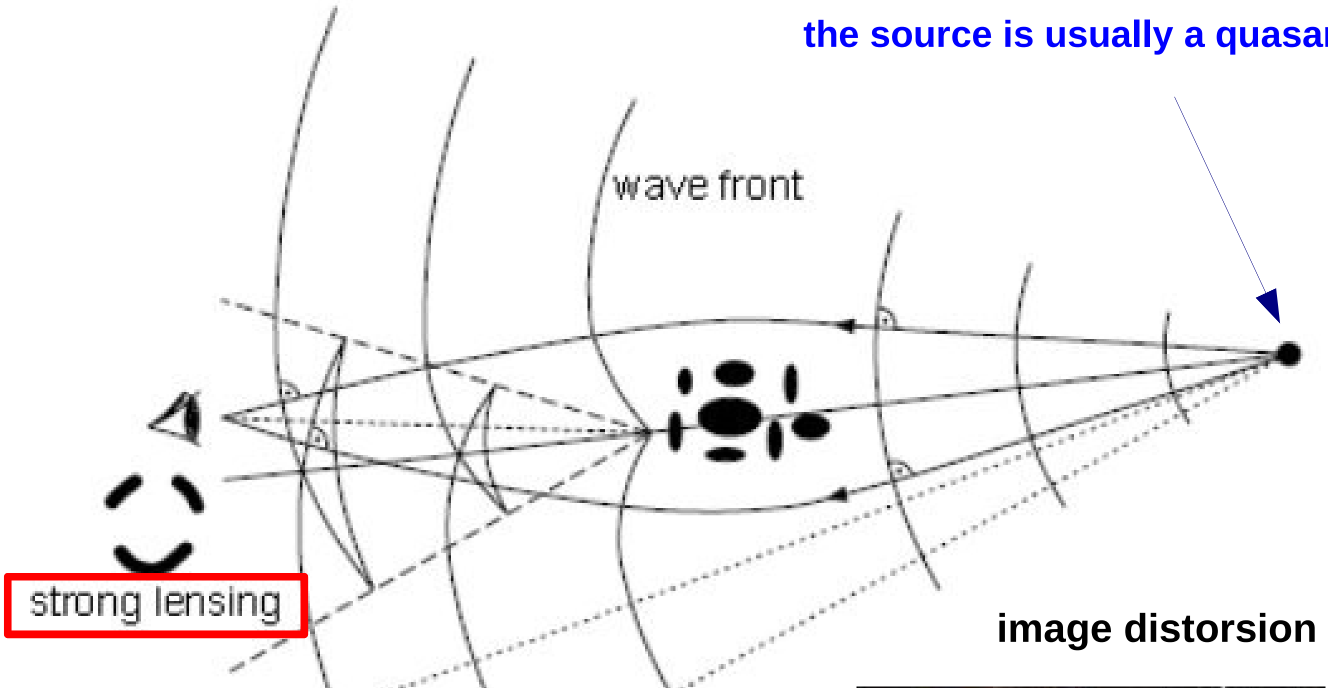
- Gravitational lensing of astrophysical objects at high redshifts by foreground galaxies is now well established and has developed into a mature branch of both theoretical and observational astrophysics



multiple images

time delays between images



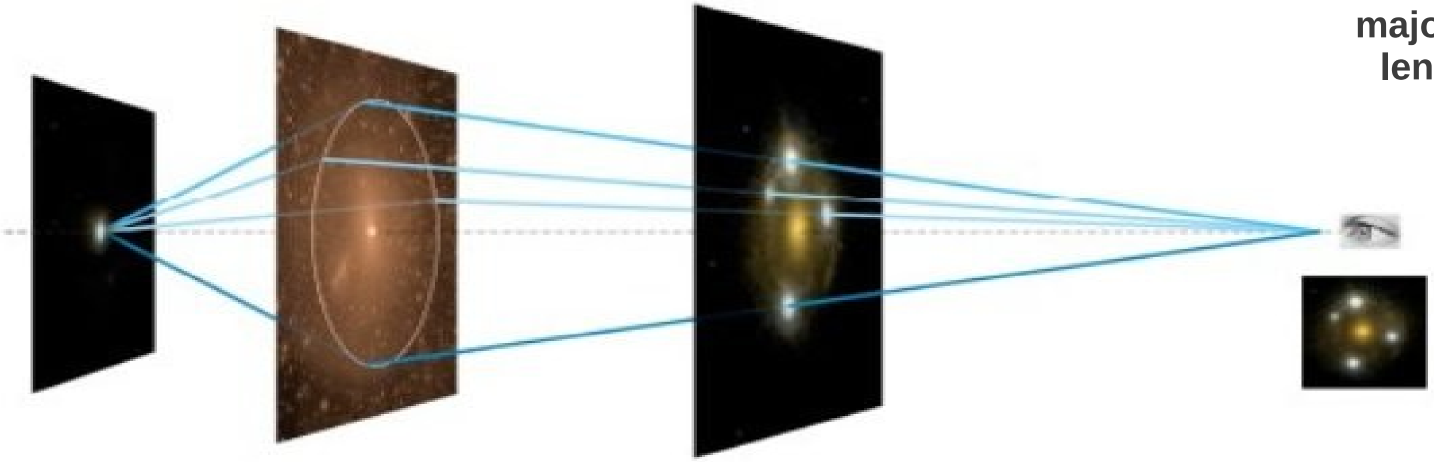


the source is usually a quasar

image distortion

Strong lenses as standard(izable) rulers

- Strong gravitational lensing occurs whenever the source, the lens and observer are so well aligned that the observer-source direction lies inside the so-called Einstein ring of the lens.



majority of cases the lens is a late-type E/SO galaxy

SIS model – the simplest realistic case

Einstein radius defines characteristic angular scale for the lens:

$$\boxed{\theta_{\rm E} = 4\pi \frac{D_{\rm ls}}{D_{\rm s}} \frac{\sigma^2_{\rm SIS}}{c^2}}$$

distance from the lens to the source

from angular image separations (astrometry)

one-dimensional velosity dispersion in lensing galaxy (spectroscopy)

distance from observer to the source

Strong lenses as standard(izable) rulers

- **The idea:** image separations in the system depend on angular diameter distances to the lens and to the source, which in turn are determined by background cosmology

$$\theta_{\mathrm{E}} = 4\pi \frac{D_{\mathrm{ls}}}{D_{\mathrm{s}}} \frac{\sigma^2_{\mathrm{SIS}}}{c^2} \qquad D_A(z;\mathbf{p}) = \frac{c}{H_0}\frac{1}{1+z}\int_0^z \frac{dz'}{h(z';\mathbf{p})}$$

this opens a possibility to constraining the cosmological model provided that we have good knowledge of the lens model (i.e. SIS model for elliptical galaxies)

growing evidence for homologous structure of early type galaxies supporting reliability of SIS assumption

Koopmans et al. 2006, 2009

gets canceled in the distance ratio

method is independent of the Hubble constant's value and is not affected by dust absorption or source evolutionary effects

Biesiada 2006 **Biesiada, AP, 2008** **Biesiada, AP, Malec, 2010** **Biesiada, Malec, AP, 2011**

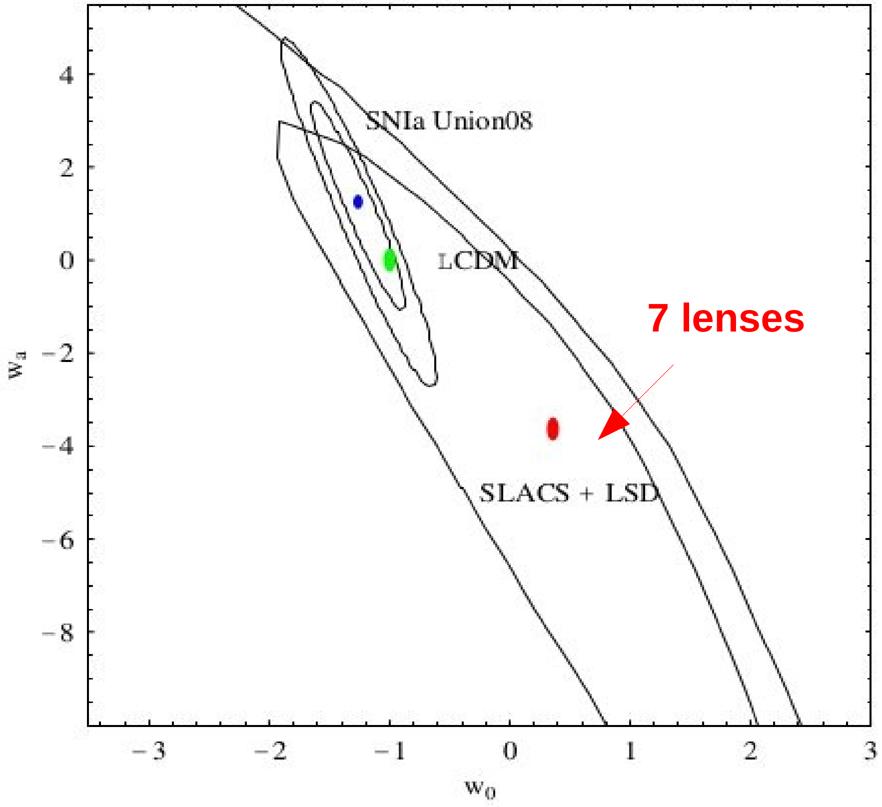
Strong lenses as standard(izable) rulers

- Cosmological model parameters (coefficients in the equation of state) are estimated by minimizing following chi-square function:

$$\boxed{\chi^2(\mathbf{p}) = \sum_i \frac{(\mathcal{D}_i^{\rm obs} - \mathcal{D}_i^{\rm th}(\mathbf{p}))^2}{\sigma^2_{\mathcal{D},i}}}$$

$$\mathcal{D}^{\rm th}(z_{\rm l}, z_{\rm s}; \boldsymbol{p}) = \frac{D_{\rm s}(\boldsymbol{p})}{D_{\rm ls}(\boldsymbol{p})} = \frac{\int\limits_0^{z_{\rm s}} \frac{dz'}{h(z';\boldsymbol{p})}}{\int\limits_{z_{\rm l}}^{z_{\rm s}} \frac{dz'}{h(z';\boldsymbol{p})}}$$

$$\mathcal{D}^{\rm obs} = \frac{4\pi\sigma_0^2}{c^2\theta_{\rm E}}$$



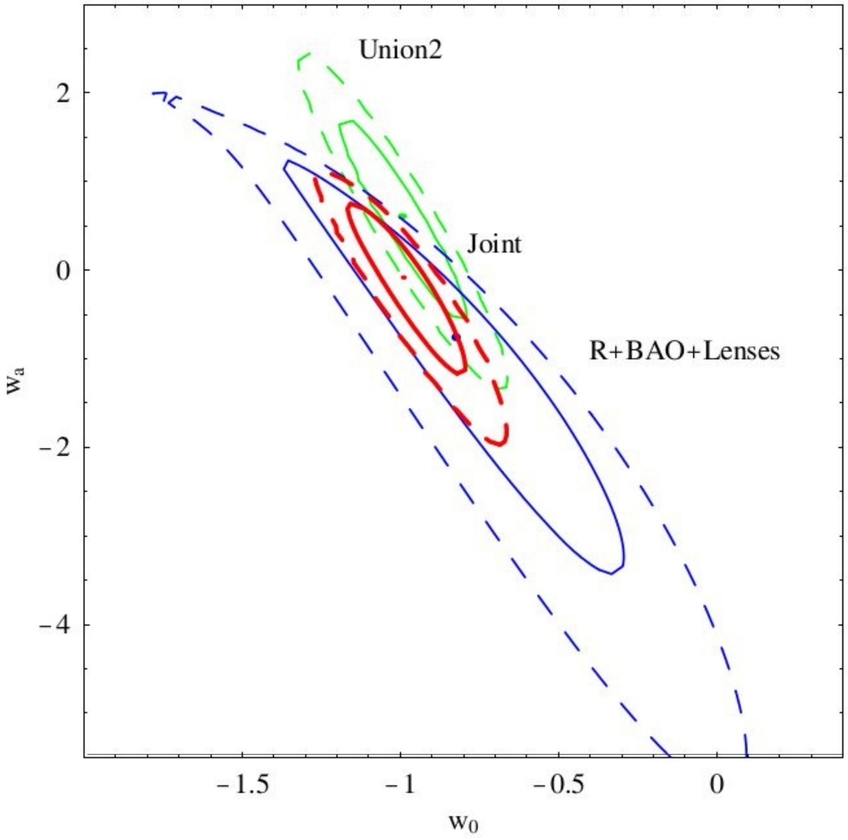
Best fits (dots) and (68%, 98%) confidence regions for CPL parameters in cosmic equation of state obtained from SLACS and SLD sample of lenses and Union08 SNIa data.

Biesiada, AP, Malec, 2010

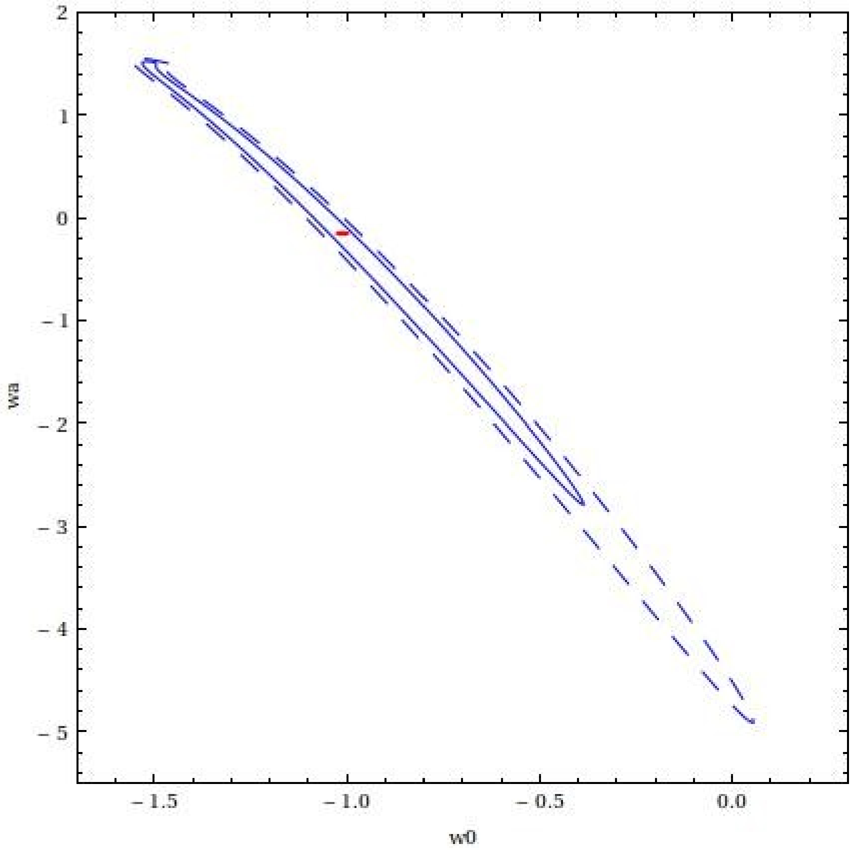
Strong lenses as standard(izable) rulers

- A joint analysis of CPL model on rulers (R+BAO+Lenses):

20 strong lensing systems with good spectroscopic measurements of central dispersions from the SLACS and LSD surveys



Biesiada, Malec, AP, 2011



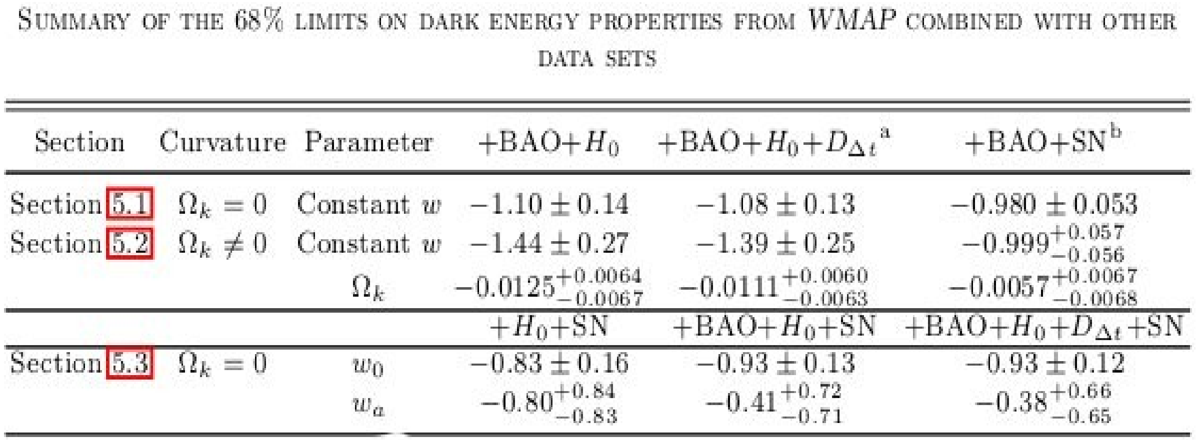
SLACS+LSD+SL2S surveys and taking into account the evolution of the total mass density slope inside the Einstein radius for each of the lens galaxy

Biesiada, Gavazzi & AP, in preparation **Ruff, Gavazzi et al. 2011**

Dark Energy Complementarity

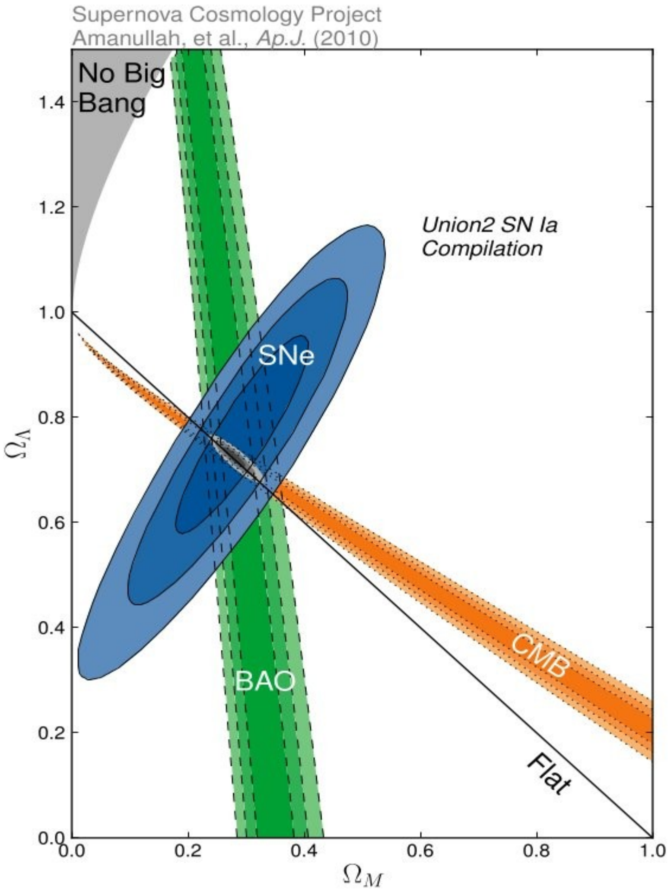
- Present status of cosmological observations:

Komatsu et al. 2010



SUMMARY OF THE 68% LIMITS ON DARK ENERGY PROPERTIES FROM *WMAP* COMBINED WITH OTHER DATA SETS

Section	Curvature	Parameter	+BAO+H_0	+BAO+H_0+$D_{\Delta t}$[a]	+BAO+SN[b]
Section 5.1	$\Omega_k = 0$	Constant w	-1.10 ± 0.14	-1.08 ± 0.13	-0.980 ± 0.053
Section 5.2	$\Omega_k \neq 0$	Constant w	-1.44 ± 0.27	-1.39 ± 0.25	$-0.999^{+0.057}_{-0.056}$
		Ω_k	$-0.0125^{+0.0064}_{-0.0067}$	$-0.0111^{+0.0060}_{-0.0063}$	$-0.0057^{+0.0067}_{-0.0068}$
			+H_0+SN	+BAO+H_0+SN	+BAO+H_0+$D_{\Delta t}$+SN
Section 5.3	$\Omega_k = 0$	w_0	-0.83 ± 0.16	-0.93 ± 0.13	-0.93 ± 0.12
		w_a	$-0.80^{+0.84}_{-0.83}$	$-0.41^{+0.72}_{-0.71}$	$-0.38^{+0.66}_{-0.65}$



Amanullah et al. 2010

we need more information about the true nature of phenomenon responsible for the accelerating universe

- The tightest constraints on the cosmic equation of state can be achieved by:

  - higher statistical precision of cosmological probes
  - robust control of systematic uncertainties of the observations

Dark Energy Complementarity

- We expect that the greatest accuracy and confidence in the measurements will come from independent crosschecks and complementarity between different methods probing the cosmology:

Albrecht et al. (DETF) 2006

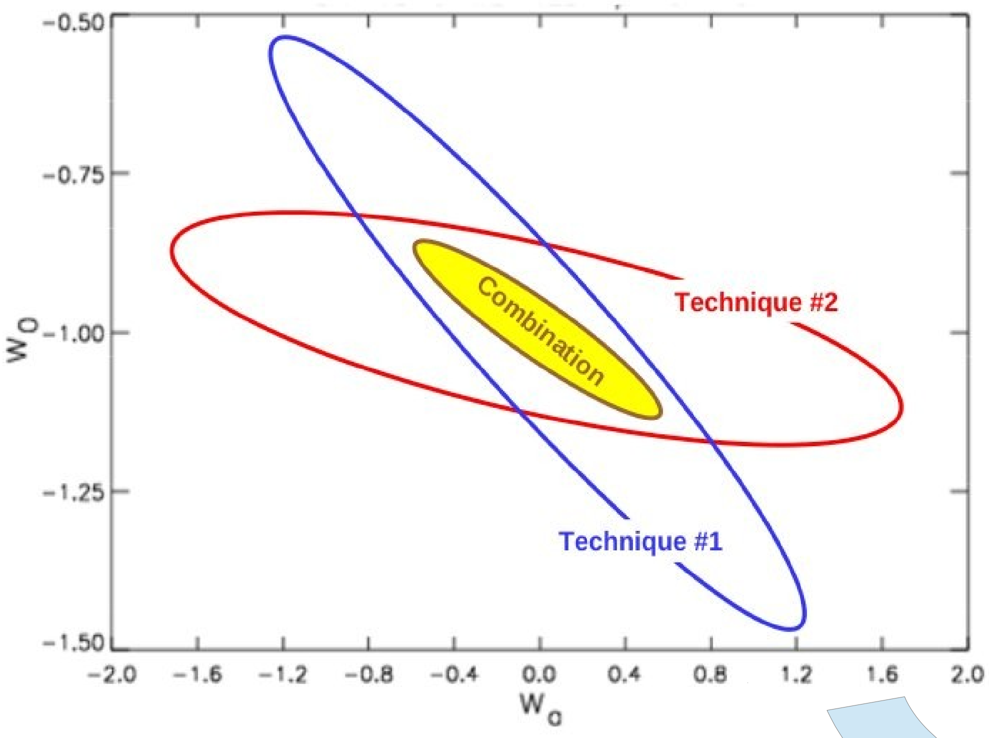
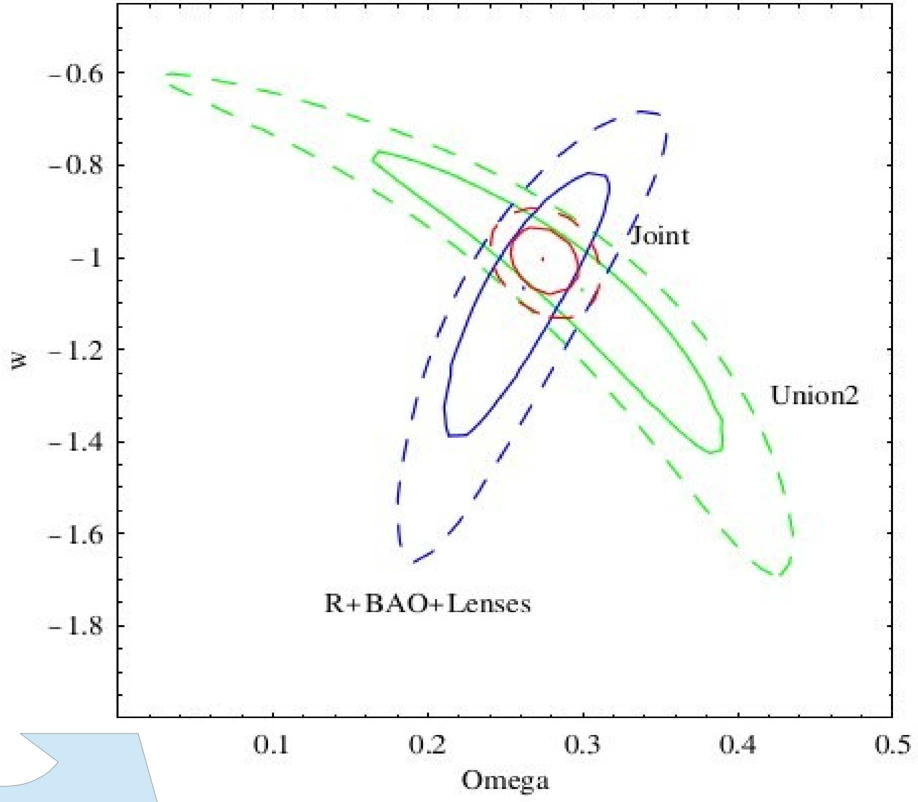


Illustration of the power of combining techniques.

Biesiada, Malec, AP, 2011

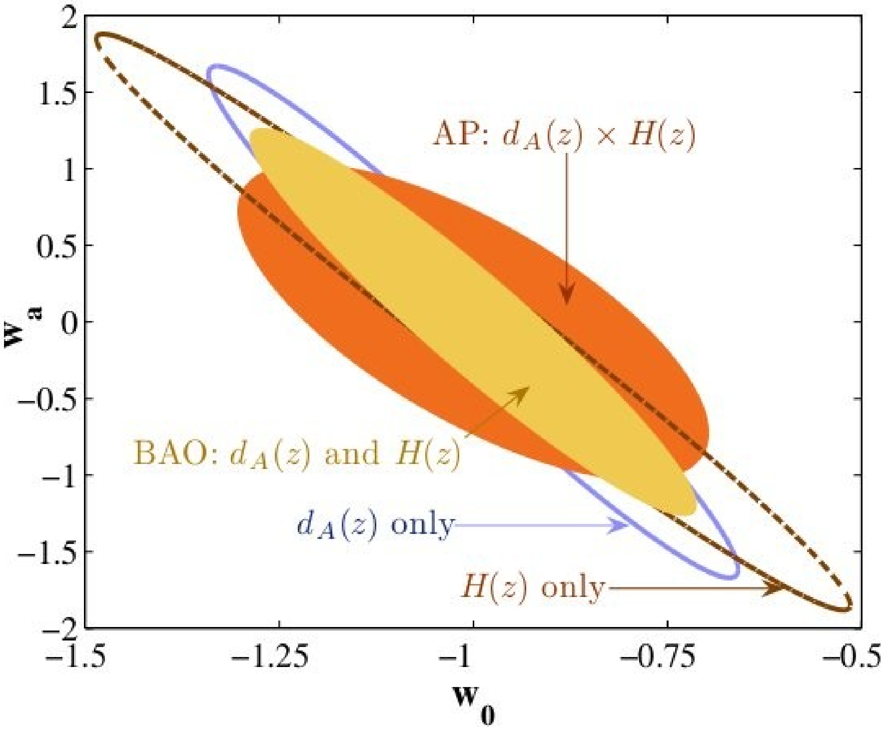


just like complementarity of standard rulers and standard candles in Omega-w parameter plane

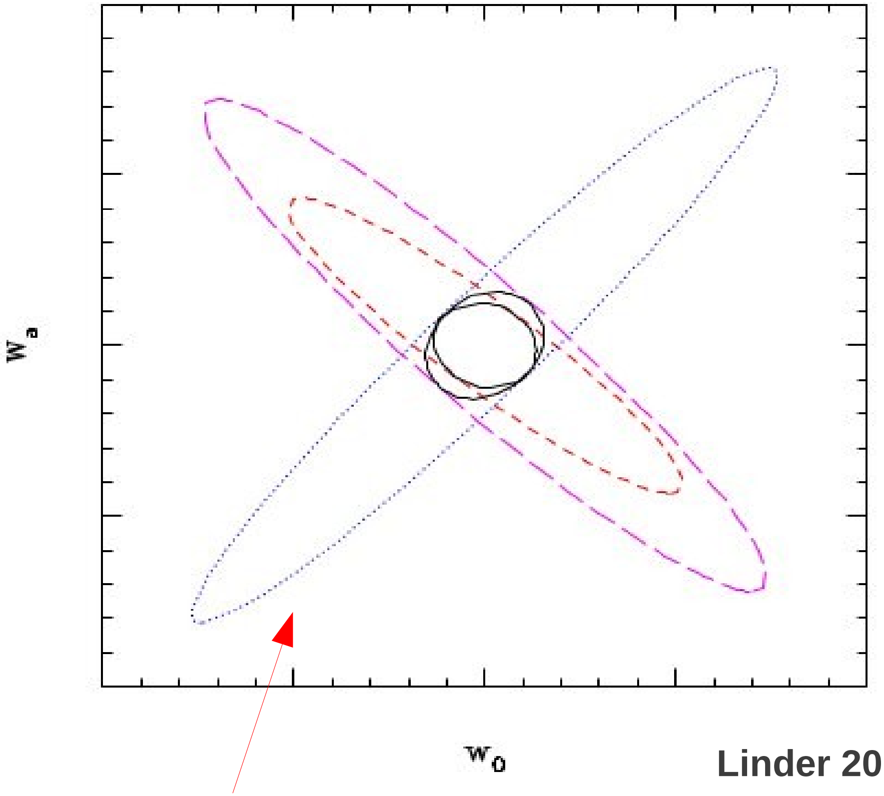
Dark Energy Complementarity

- Problem: all the known methods of distance measurements possess a similar fundamental dependence on the cosmic equation of state through the Hubble parameter, or expansion rate.

Complementarity between methods can only be partial in w0-wa parameter plane !



Bassett, Hlozek et al. 2009



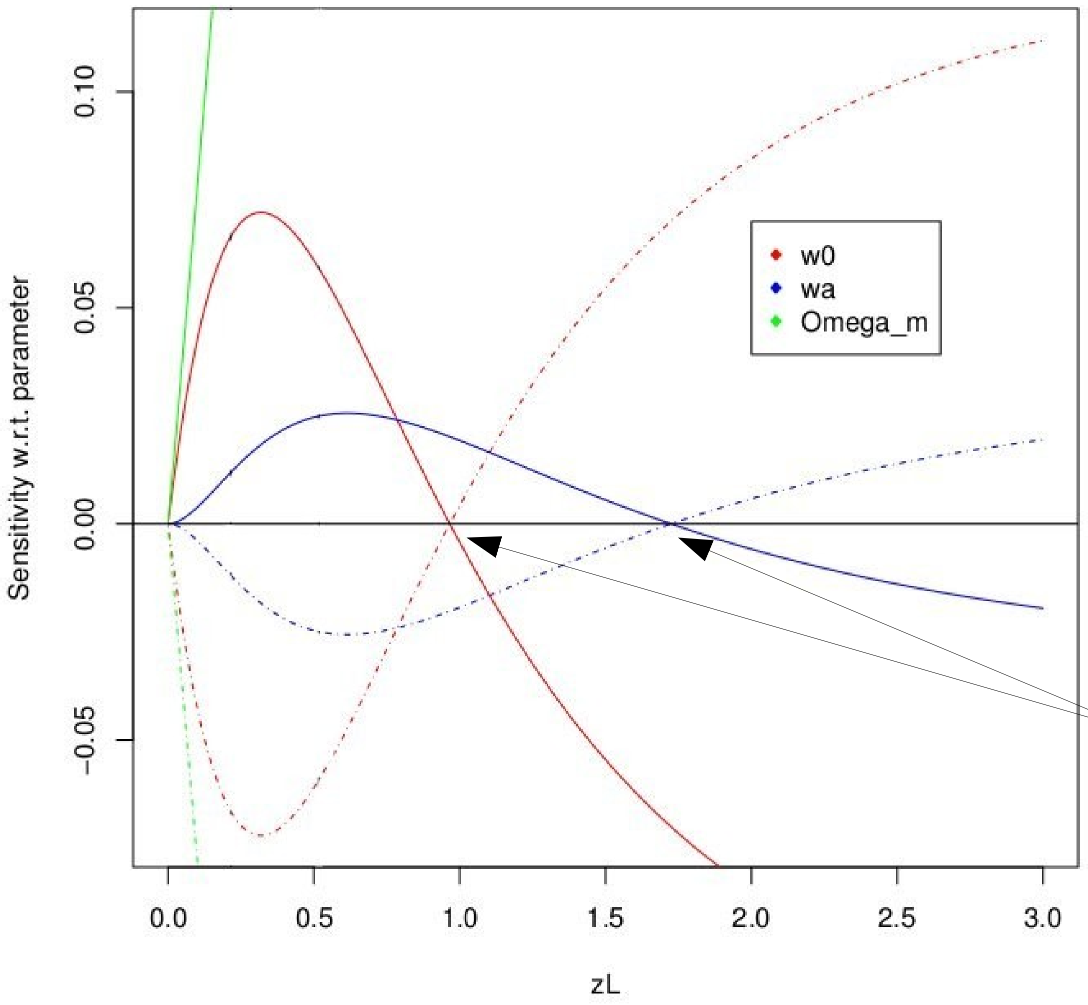
Linder 2004

Breaking degeneracy: construction of a cosmological probe whose sensitivity lies orthogonally in the w0-w1 parameter plane

Complementarity of strong lensing measurements

- For a certain redshift range competition between two ingredients in the distance ratios in stron gravitational lensing measurements may cause a positive correlation between w0 and wa:

$$\mathcal{D}^{\rm th}(z_{\rm l}, z_{\rm s}; \boldsymbol{p}) = \frac{D_{\rm s}(\boldsymbol{p})}{D_{\rm ls}(\boldsymbol{p})} = \frac{\int_0^{z_{\rm s}} \frac{dz'}{h(z';\boldsymbol{p})}}{\int_{z_{\rm l}}^{z_{\rm s}} \frac{dz'}{h(z';\boldsymbol{p})}}$$

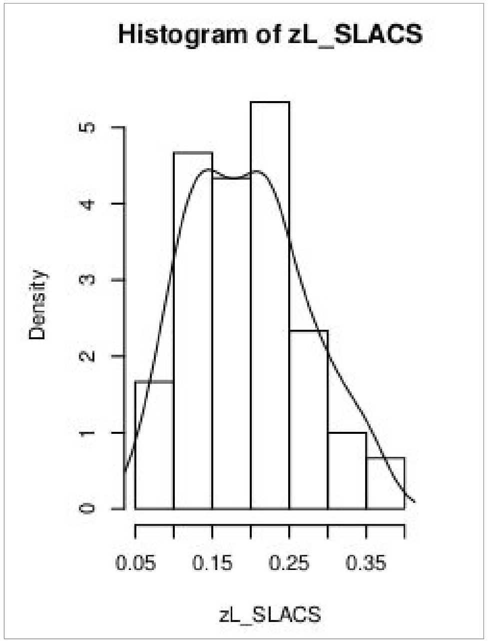


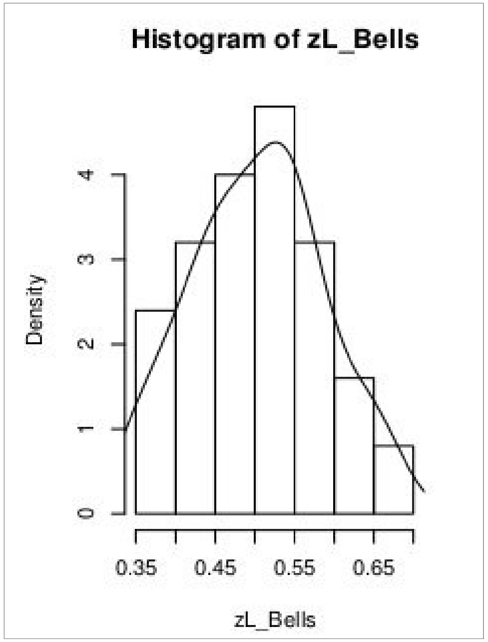
we expect that the correlation between w0 and wa should shift from negative to positive depending on the redshift

the crossings from negative to positive sensitivity occur at different redshifts

We consider here only: $z_s = 2z_l$

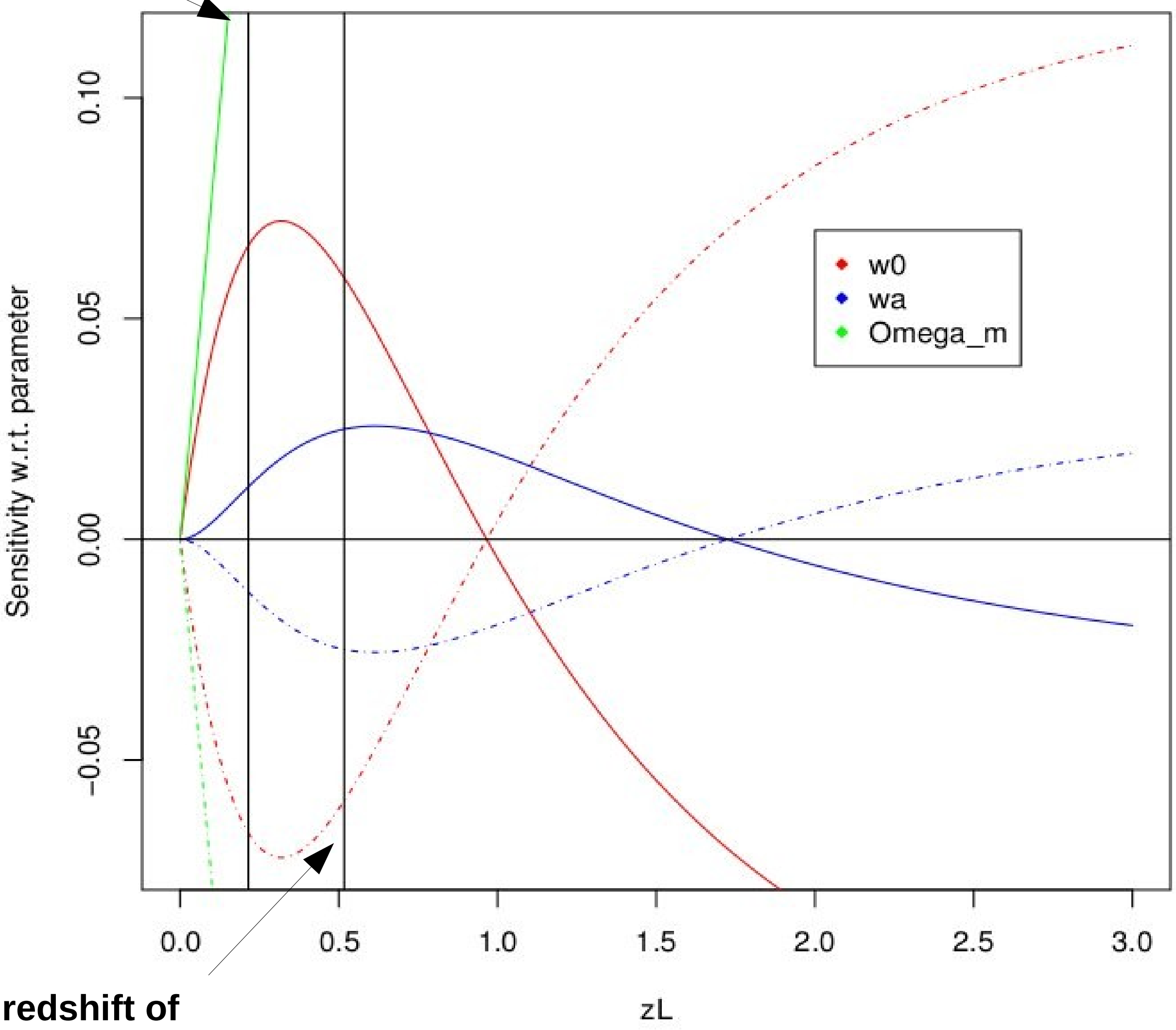
Complementarity of strong lensing measurements





mean redshift of SLACS sample

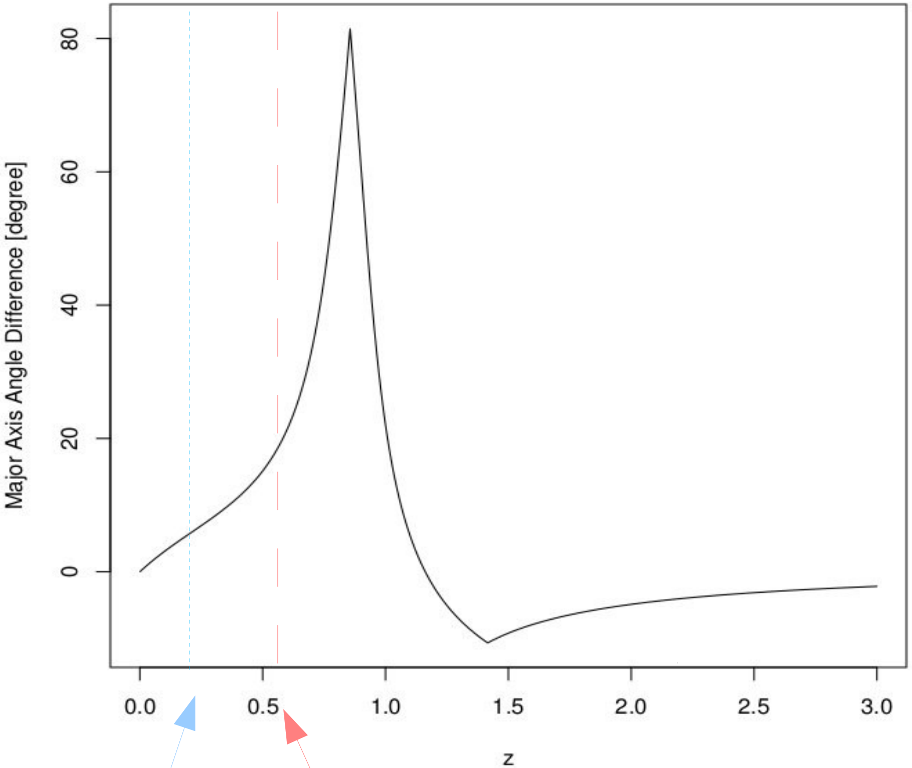
Different samples of lenses at different redshifts give opportunity to test cosmology in a complementary way:



mean redshift of BELLS sample

Complementarity of strong lensing measurements

- Strong lensing measurements are not perfect orthogonal to other distance measurement methods in the w0-wa plane but to a certain extent they can be considered as complementary:

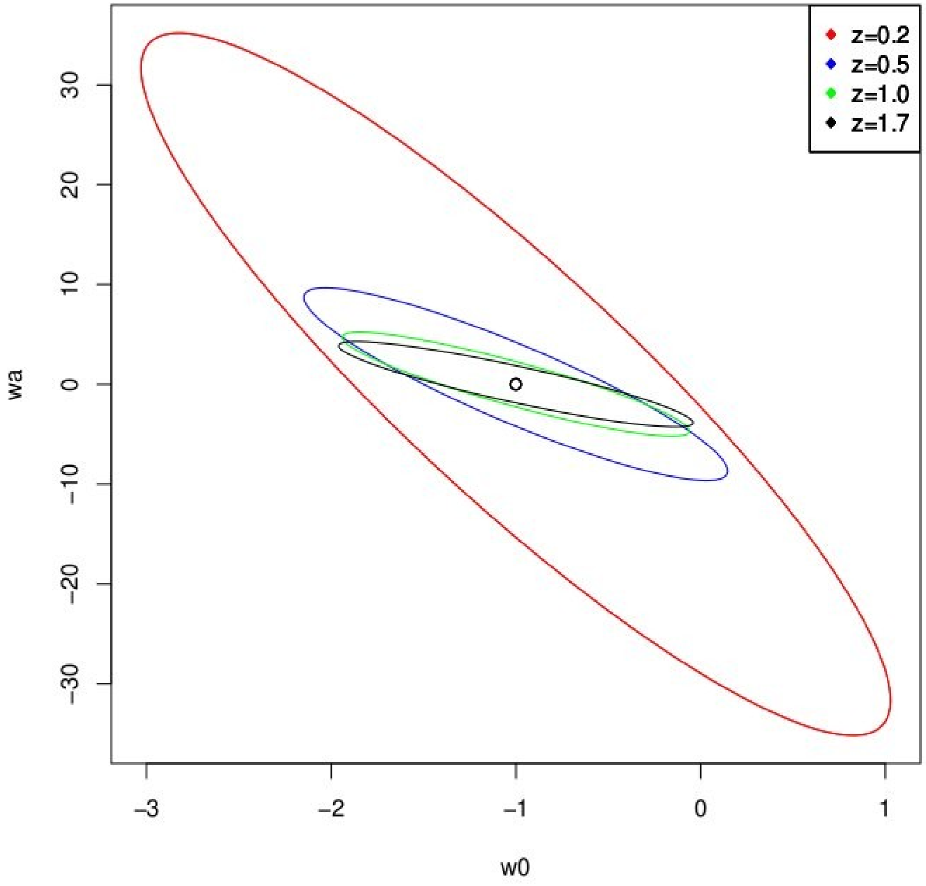


SLACS sample

BELLS sample

major axis angle of confidence contour for an idealized experiment as a function of redshift:

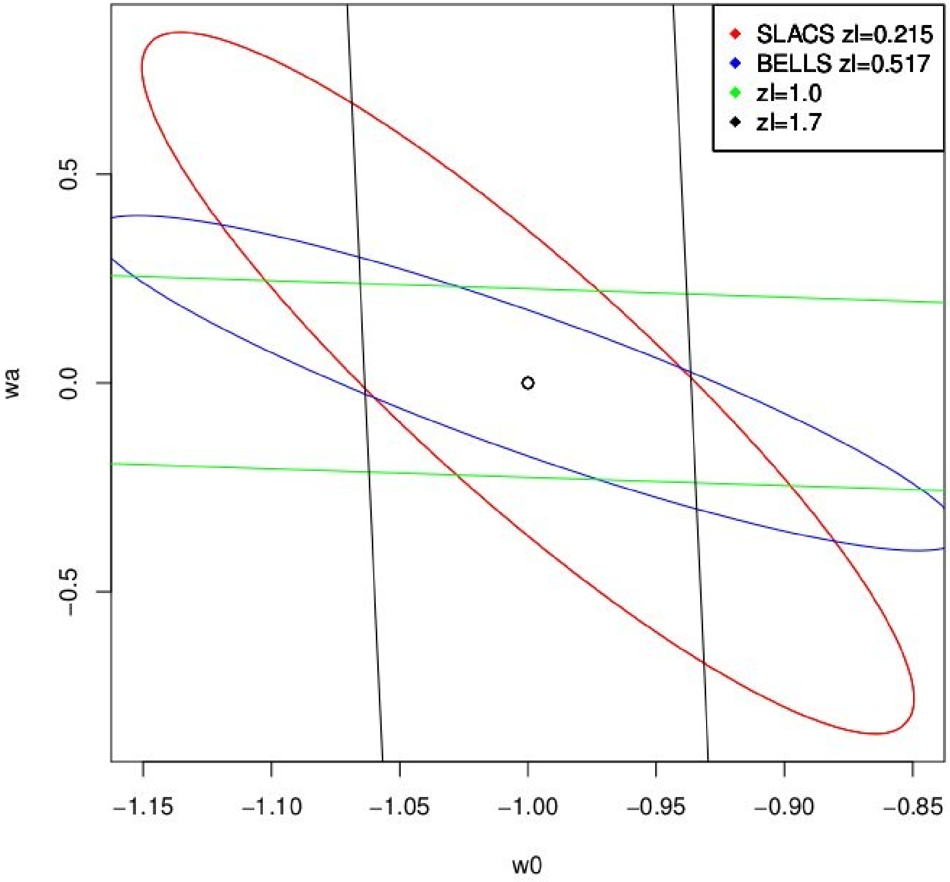
confidence contours for an idealized experiment measuring the distance ratio for several samples with different redshifts:



Complementarity of strong lensing measurements

- How to get more information about the nature of dark energy from strong lensing measurements – future prospects:

confidence contours for an idealized experiment measuring the distance ratio for several samples with different redshifts:



- complete data with time delays between images (distances not just ratios)
- new large catalogs of strong lensing surveys (photo-z method)
- increasing number of strong lenses discovered by searches such as:

  CLASS , SLACS, SL2S, SQLS,
  HAGGLeS, AEGIS, COSMOS,
  CASSOWARY

- new projects:

  Pan-STARRS1, LSST2,
  JDEM / IDECS3, SKA4

Summary:

- The present acceleration of the cosmic expansion is a fundamental challenge to standard models of both particle physics and cosmology

- Many various experiments (devided into two classes: standard candles and standard rulers) has been developed to put some constraints On dark energy parameters.

- Strongly lensed systems with known central velocity dispersions are a new class of "standard rulers" (Einstein radius being standardized by stellar kinematics)

a technique competitive with other methods

- The greatest accuracy and confidence in the measurements of dark energy parameters can be achieved by independent crosschecks and complementarity between different observations

orthogonality in w0-wa parameters plane

- Strong lensing measurements may help to break w0-wa degeneracy - the angle of the major axis of the confidence contour depends od the redshift of the sample

offer some complementarity in w0-wa parameters plane

Thank you for your attention

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