Strong gravitational lensing in cosmology

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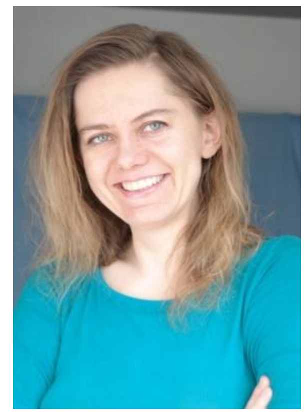

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mgr S. Miernik
(PhD student)

- Area of interest:

  - dark energy problem in the Universe
  - astrophysical limits on exotic theories (including dark matter)
  - astrophysical and cosmological gravitational wave sources

Outline

- Introduction – gravitational lensing in (real) short

- Strong gravitational lensing as a tool in cosmology:

  - dark energy problem (very briefly)

  - distance measures

  - strong lenses as standardizable rulers – our method and latest results

  - discussion

- Summary and prospects

Gravitational lensing in a pill

- Deflection of the light path near massive body can be calculated within Newtonian theory of gravity

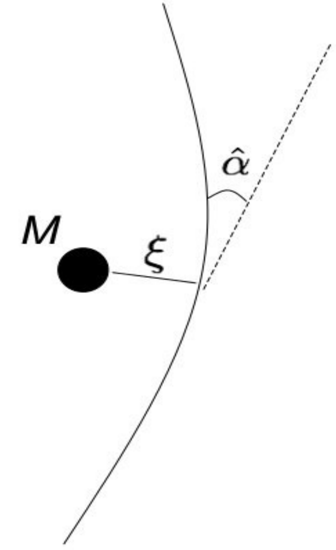
test particle with velocity v moving past an object of mass M is deflected by

$$\hat{\alpha} = 2GM/(v^2\xi)$$

if light treated as particles

$$\hat{\alpha_{\mathrm{N}}} = 2GM/(c^2\xi)$$

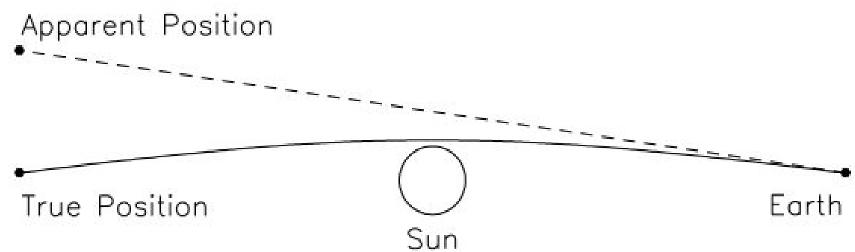
[Mitchell 1784; Soldner 1804]



after S. Suyu; lectures XXIV Canary Islands Winter School of Astrophysics 2012

- But the deflection angle drived from general theory of gravity is as twice as it:

$$\boxed{\hat{\alpha_{\mathrm{E}}} = 4GM/(c^2\xi) = 2\hat{\alpha_{\mathrm{N}}}}$$



A. Einstein (1915); proved by A. Eddington in 1919

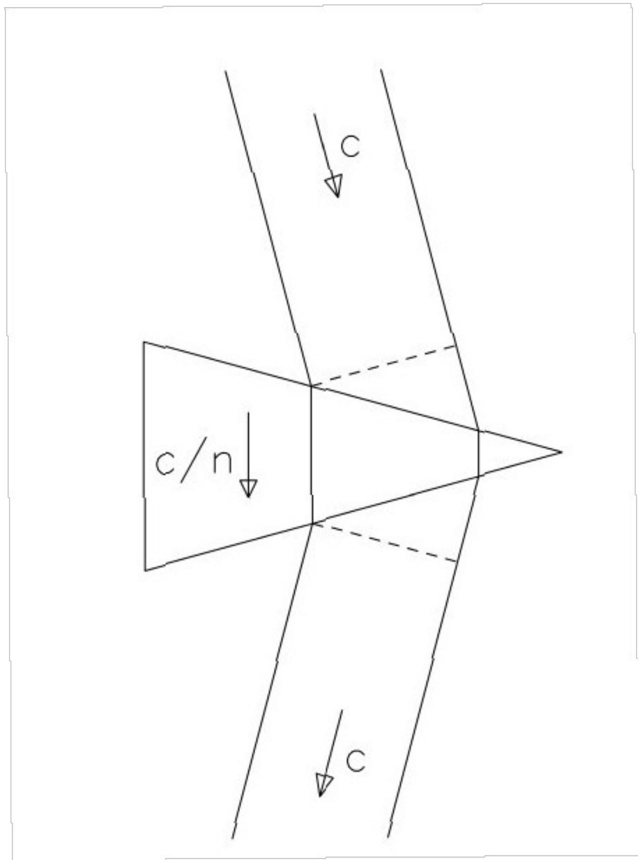
Gravitational lensing in a pill

- The effect of spacetime curvature on the light paths can be expressed in terms of an effective index of refraction n:

Schneider et al.1992

$$n = 1 - \frac{2}{c^2}\Phi = 1 + \frac{2}{c^2}|\Phi|$$

$$v = \frac{c}{n} \simeq c - \frac{2}{c}|\Phi|$$



After M. Bartelmann 1996

- Deflection is the integral along the light path of the gradient of n perpendicular to the light path:

$$\boxed{\vec{\hat{\alpha}} = -\int \vec{\nabla}_\perp n \, dl = \frac{2}{c^2}\int \vec{\nabla}_\perp \Phi \, dl}$$

Gravitational lensing in a pill

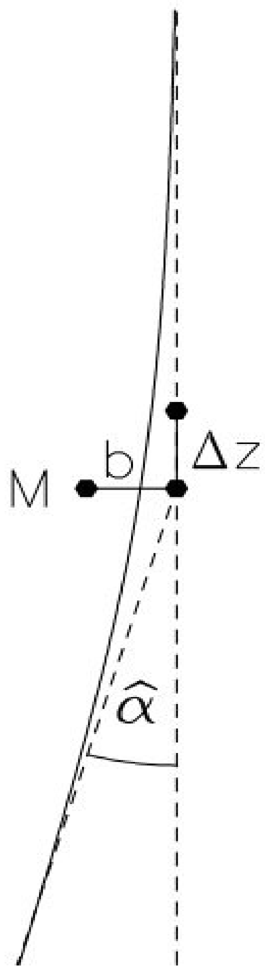
- The Newtonian potential of the point mass lens:

$$\Phi(b, z) = -\frac{GM}{(b^2 + z^2)^{1/2}}$$

- Deflection angle in this case is:

$$\boxed{\hat{\alpha} = \frac{2}{c^2} \int \vec{\nabla}_\perp \Phi \, dz = \frac{4GM}{c^2 b}}$$

twice the inverse of the impact parameter in units of the Schwarzschild radius

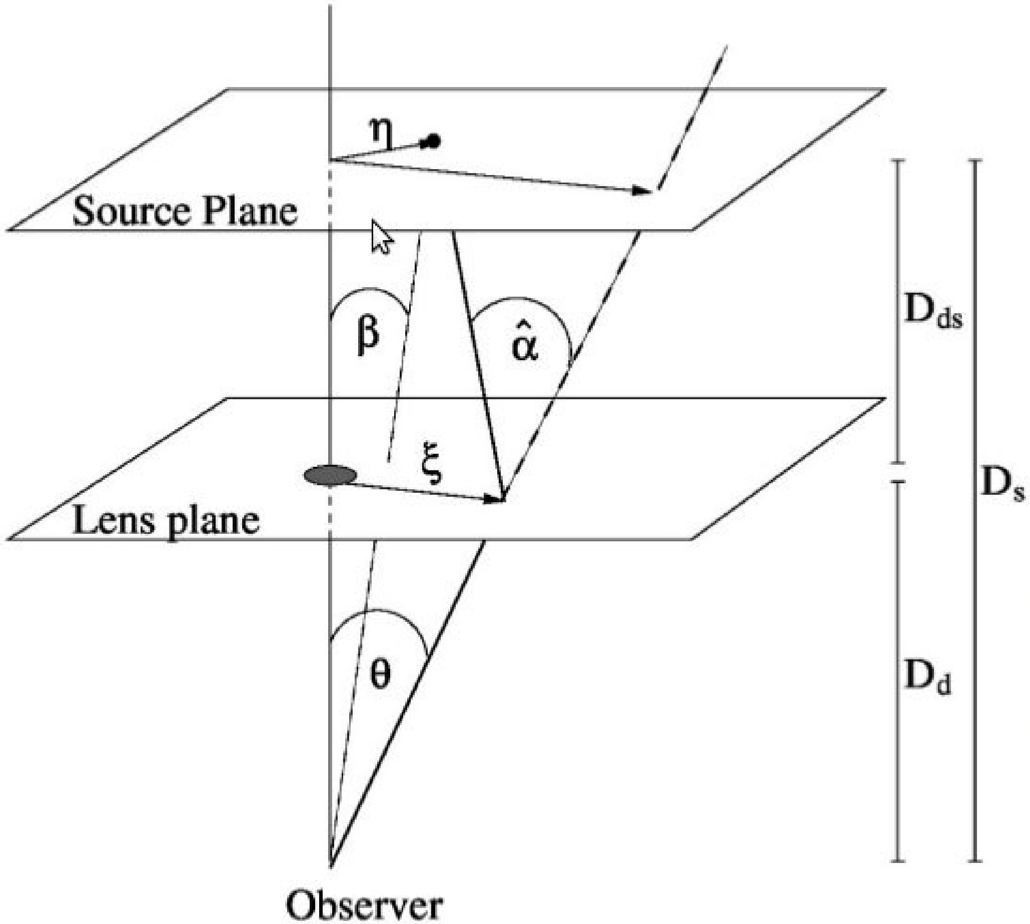


for the light ray deflected by the Sun the angle is 1."7

After M. Bartelmann 1996

Gravitational lensing in a pill

- Geometry of a typical gravitational lens system gives the so-called Lens (ray-tracing) equation:



[Schneider et al. 2006]

$$\boldsymbol{\eta} = \frac{D_s}{D_d}\boldsymbol{\xi} - D_{ds}\hat{\boldsymbol{\alpha}}(\boldsymbol{\xi})$$

In terms of angular coord.:

$$\boldsymbol{\eta} = D_s\boldsymbol{\beta}$$

$$\boldsymbol{\xi} = D_d\boldsymbol{\theta}$$

$$\boxed{\boldsymbol{\beta} = \boldsymbol{\theta} - \boldsymbol{\alpha}(\boldsymbol{\theta})}$$

where

$$\boldsymbol{\alpha}(\boldsymbol{\theta}) = \frac{D_{ds}}{D_s}\hat{\boldsymbol{\alpha}}(D_d\boldsymbol{\theta})$$

reduced deflection angle

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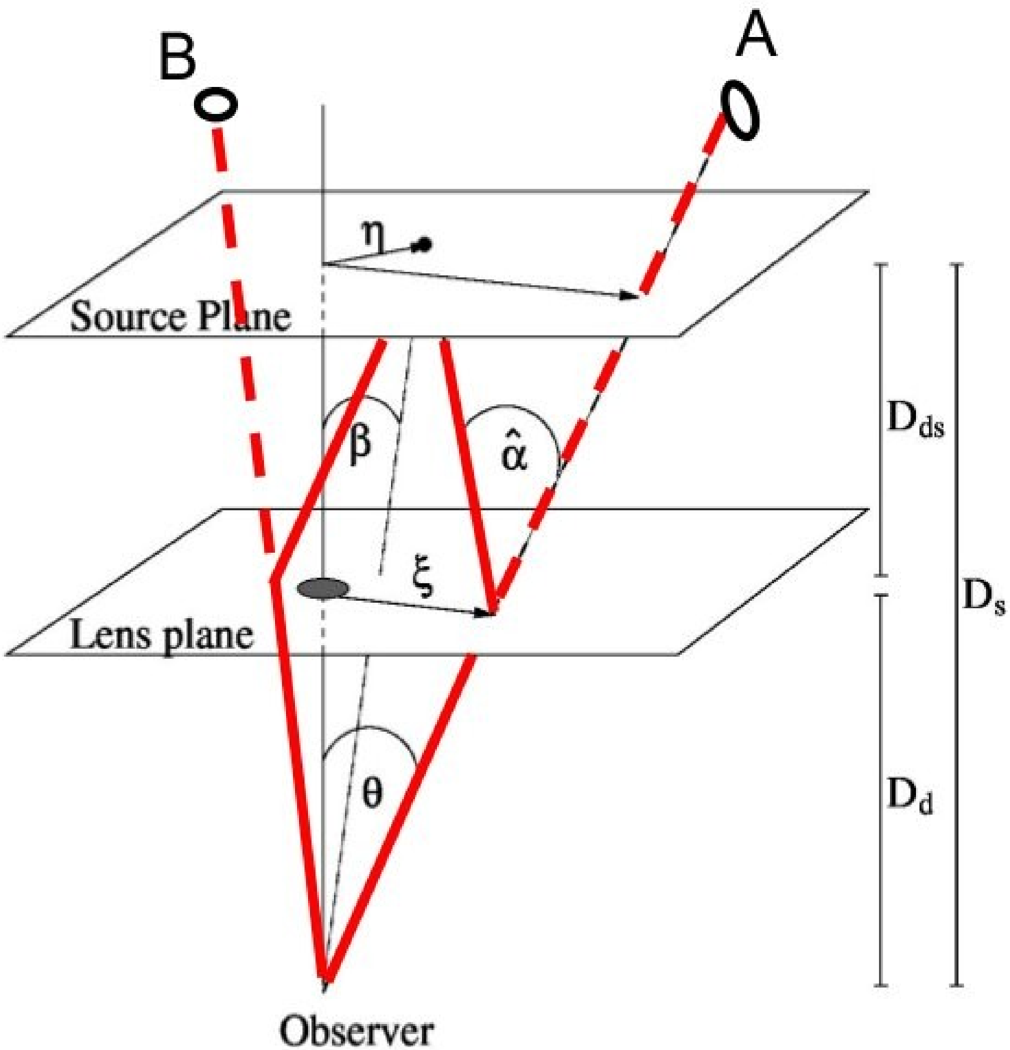
Gravitational lensing in a pill

- Gravitational lensing time delay:



[Schneider et al. 2006]

differences between travel times for light rays from different images

$$t(\vec{\theta}) \;=\; t_{\rm geom} + t_{\rm grav}$$

Shapiro time delay

$$t_{\rm grav} = \int_{\rm source}^{\rm observer} \frac{2}{c^3}\,|\Phi|\,dl$$

Gravitational lensing in a pill

- Gravitational lensing and Fermat principle:

$$(\vec{\theta} - \vec{\beta}) - \vec{\nabla}_\theta \psi = 0 \quad \Leftrightarrow \quad \vec{\nabla}_\theta \left[\underline{\frac{1}{2}(\vec{\theta} - \vec{\beta})^2 - \psi} \right] = 0$$

The so-called Fermat potential

Time delay function:

$$t(\vec{\theta}) = \frac{(1+z_\mathrm{d})}{c} \frac{D_\mathrm{d} D_\mathrm{s}}{D_\mathrm{ds}} \left[\frac{1}{2}(\vec{\theta} - \vec{\beta})^2 - \psi(\vec{\theta}) \right] = t_\mathrm{geom} + t_\mathrm{grav}$$

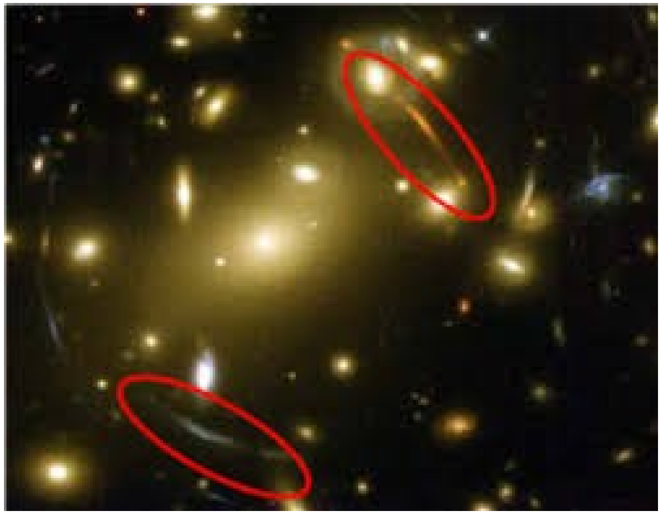
Fermat Principle for gravitational lensing

$$\boxed{\vec{\nabla}_\theta t(\vec{\theta}) = 0}$$

Images are located at points where the total time delay function is stationary

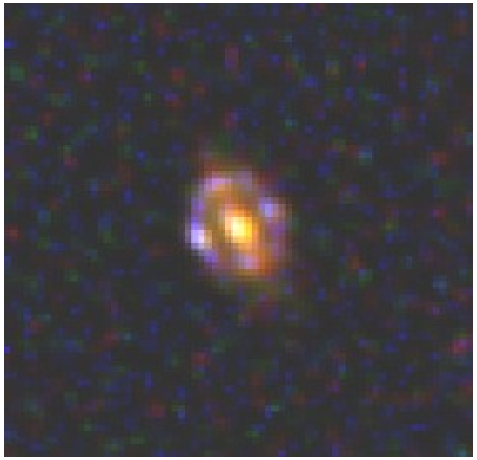
Gravitational lensing in a pill

- Source magnification and distortion: main features of gravitational lensing



Credit: HST, with red ovals added by Sarah Bridle

NASA/CXC/Univ of Michigan/R.C.Reis et al;
Optical: NASA/STScI



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Lensing conserves surface brightness

Liouville's Theorem

Flux F = surface brightness x solid angle

Magnification = $F_{observed} / F_{intrinsic} = d\Omega_{observed} / d\Omega_{intrinsic}$

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Gravitational lensing in a pill

- Jacobian matrix for gravitational lensing:

$$\mathcal{A}(\boldsymbol{\theta}) = \frac{\partial \boldsymbol{\beta}}{\partial \boldsymbol{\theta}} = \left(\delta_{ij} - \frac{\partial^2 \psi(\boldsymbol{\theta})}{\partial \theta_i \partial \theta_j}\right) = \begin{pmatrix} 1-\kappa-\gamma_1 & -\gamma_2 \\ -\gamma_2 & 1-\kappa+\gamma_1 \end{pmatrix}$$

where γ_1 and γ_2 are the two components of shear

$$\gamma \equiv \gamma_1 + \mathrm{i}\gamma_2 = |\gamma| \mathrm{e}^{2\mathrm{i}\varphi}$$

$$\gamma_1 = \frac{1}{2}(\psi_{,11} - \psi_{,22}) \qquad \gamma_2 = \psi_{,12}$$

Magnification in terms of κ and γ is:

$$\mu = \frac{1}{\det \mathcal{A}} = \frac{1}{(1-\kappa)^2 - |\gamma|^2}$$

where κ is the dimensionless surface mass density (a.k.a. convergence)

$$\kappa(\boldsymbol{\theta}) = \frac{\Sigma(D_\mathrm{d}\boldsymbol{\theta})}{\Sigma_\mathrm{cr}}$$

and Σ_{cr} is the critical surface mass density

$$\Sigma_\mathrm{cr} = \frac{c^2}{4\pi G} \frac{D_\mathrm{s}}{D_\mathrm{d}\, D_\mathrm{ds}}$$

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Gravitational lensing in a pill

- Source magnification:

Magnification factor is

$$\mu(\boldsymbol{\theta}) = \frac{1}{\det \mathcal{A}(\boldsymbol{\theta})}$$

- $\mu>0$: positive parity
- $\mu<0$: negative parity (mirror image of source)
- det A = 0 : critical points/curves

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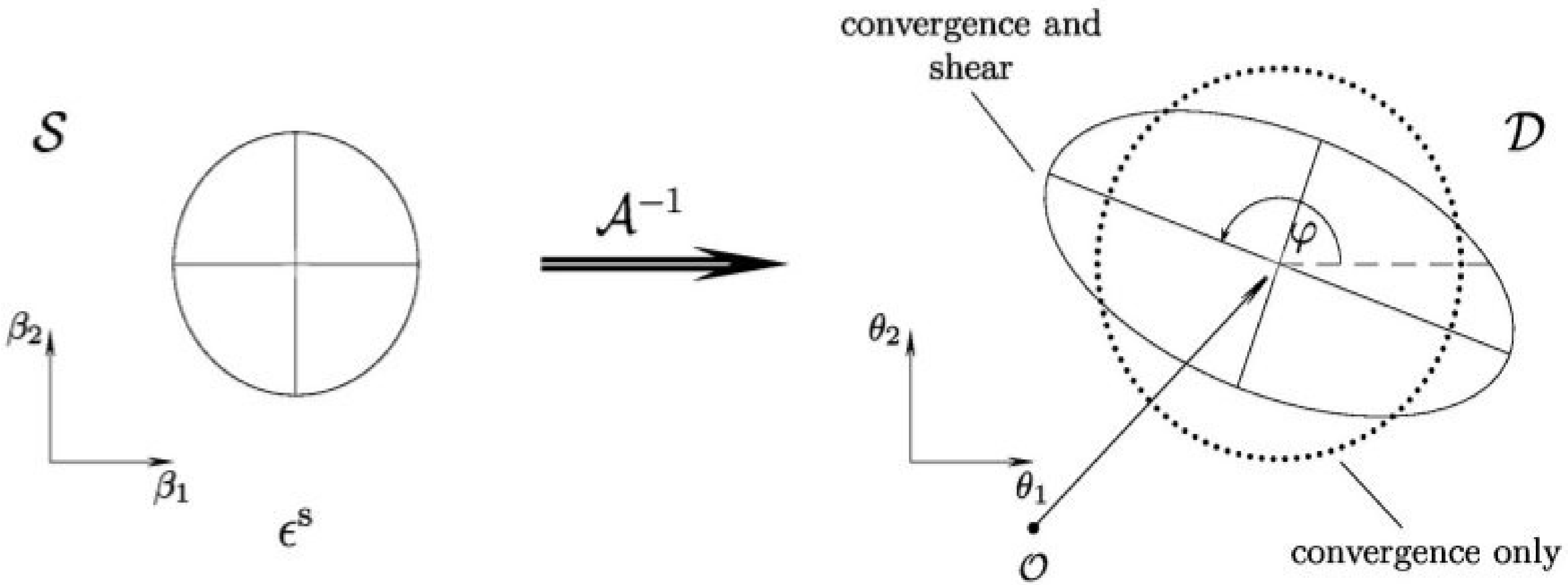
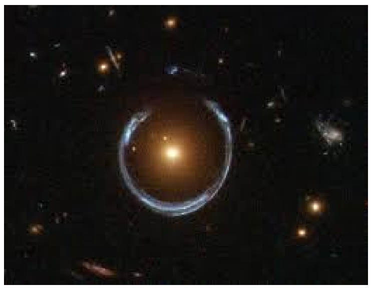
- Source distortion:

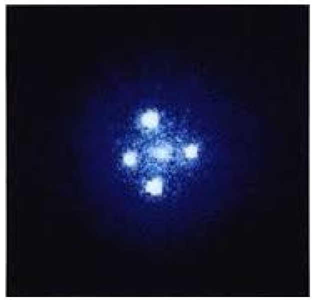


Credit: M. Bradac

Gravitational lensing in a pill

- Different regimes of gravitational lensing:

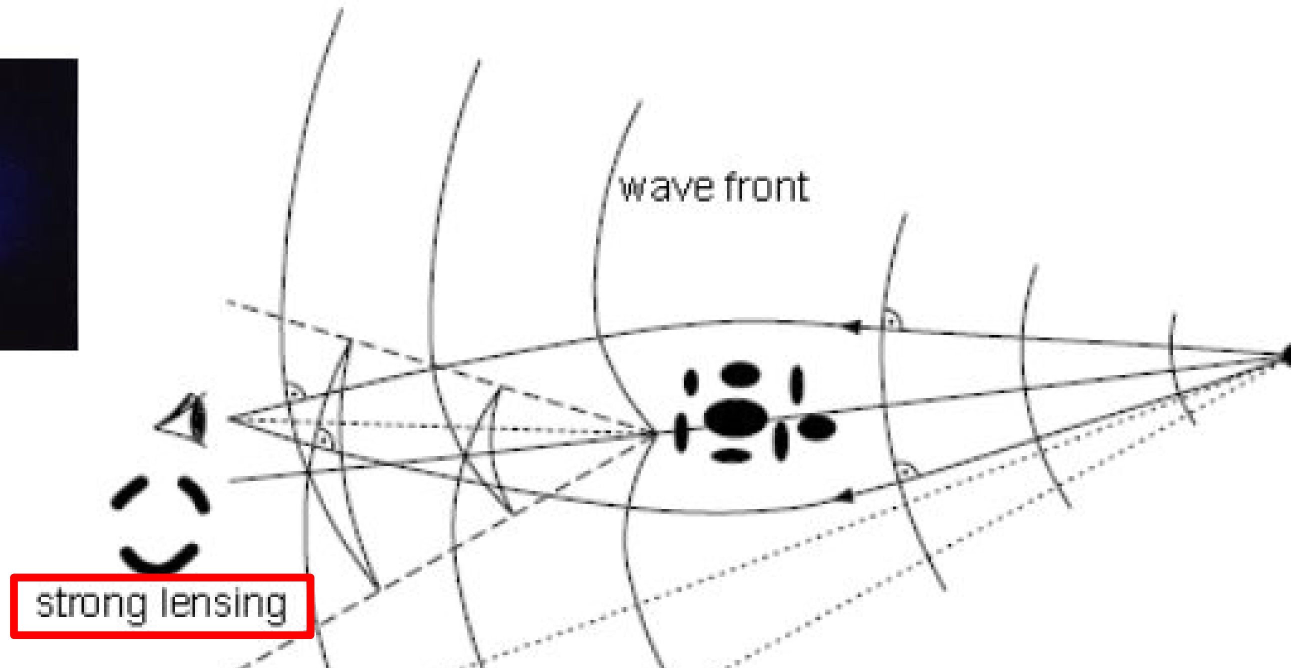


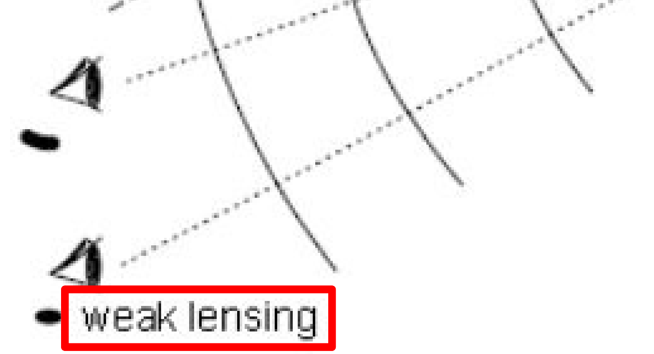


multiple images

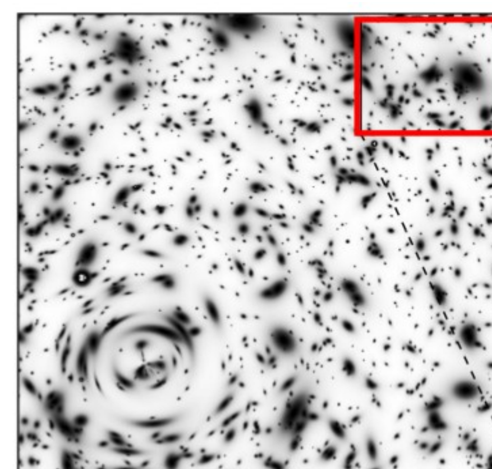
time delays between images

images distorted into rings/arcs





weak distortions of singly Imaged background sources

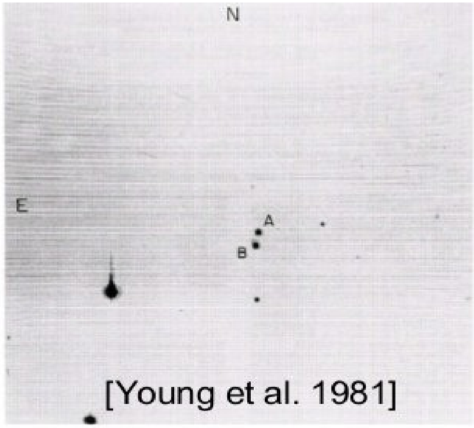


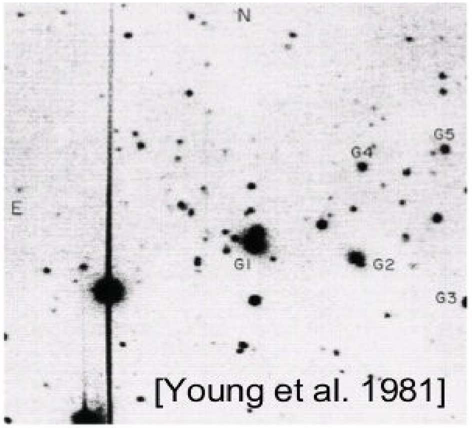
[Mellier 1999]

Gravitational lensing in a pill

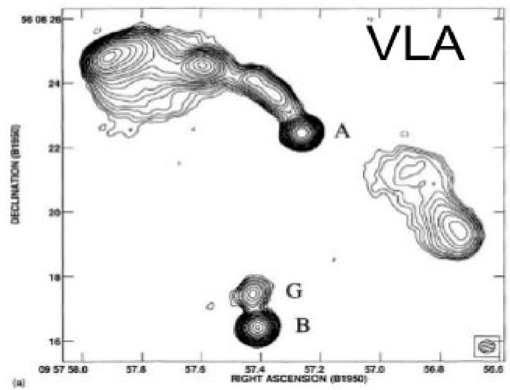
- F.Zwicky (1937): multiple images can be detected if one consider deflector as more massive than stars, e.g. galaxies

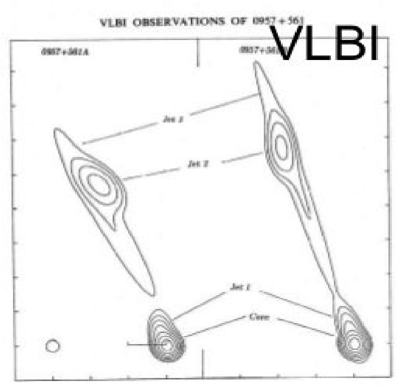
- Walsh, Carswell and Weymann (1979) – first detection of strongly lensed system: double quasar QSO 0957+561A,B

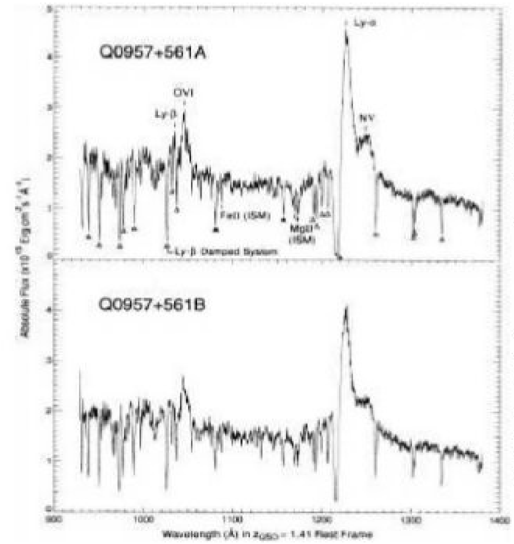




The gravitational lens 0957+561







[Michalitsianos et al. 1997]

identical spectra!

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Gravitational lensing in a pill

- Lynds and Petrosian (1986), Soucail (1987) – first detection of a giant arcs around two galaxy clusters: Abell 307

HST ACS image of Abell 370:

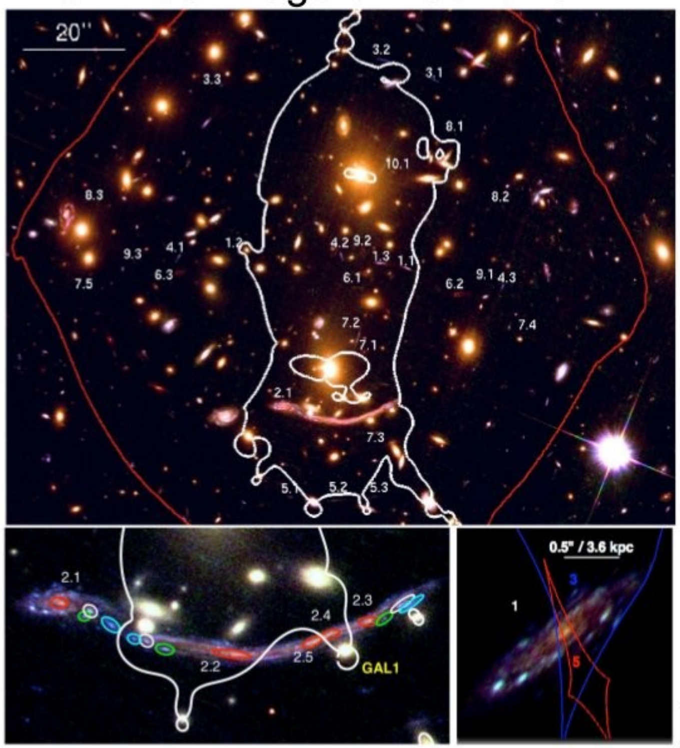
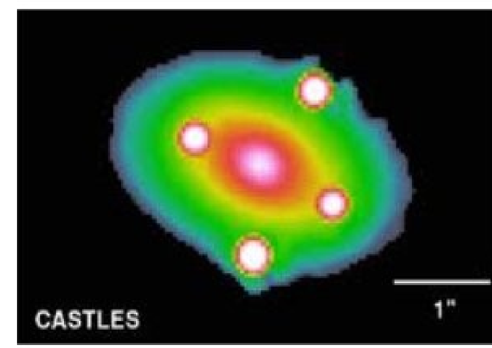


Image credit: CFHT

[Richard et al. 2010]

- Irwin et al. (1989) – first detection of microlensing effect: QSO2237+0305



- Tyson, Valdes and Wenk (1990) – first detection of a weak lensing effect

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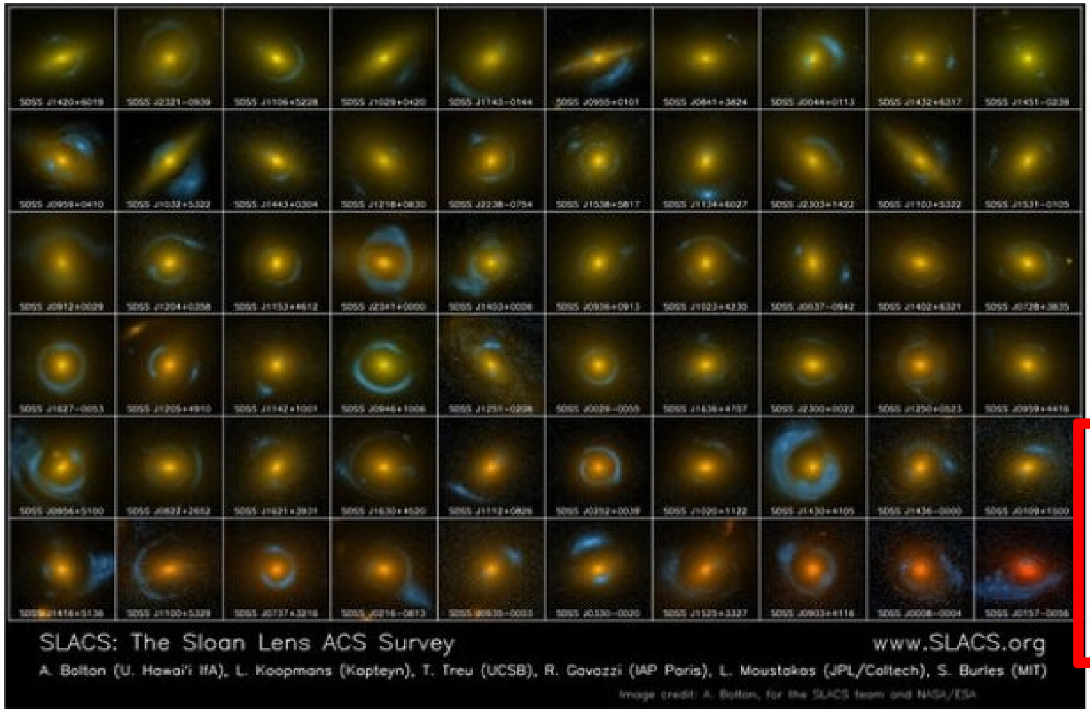
Gravitational lensing in a pill

- 1978-1992 – only 11 strong lensing systems was discovered
- Now – era of massive galactic surveys

searches concentrated on sources !



- Radio, optical imaging and spectroscopic surveys in recent years have led to an explosion in the discovery of lens systems
- Hundreds of strong lens systems now known

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"there is no great chance of observing this phenomenon" (Einstein 1936)

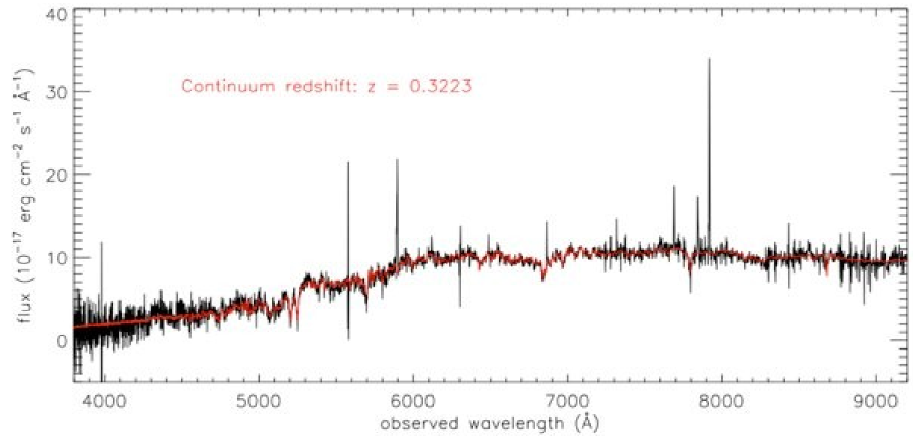
Gravitational lensing in a pill

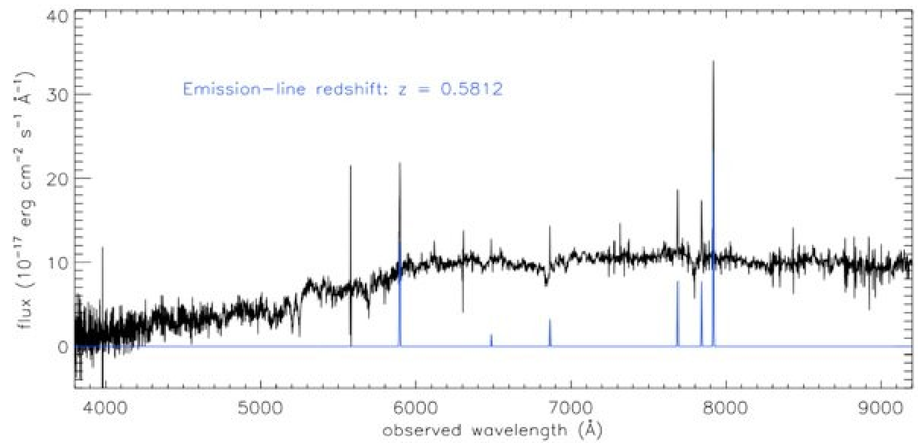
Sloan Lens ASC Survey **SLACS**

BOSS emission-line lens survey **BELLS**

spectroscopic surveys

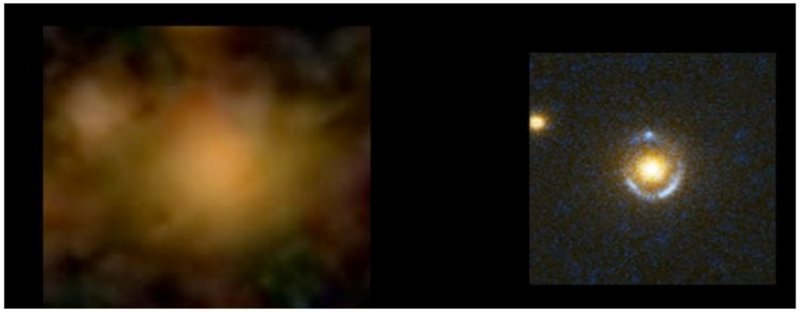
lens candidates selected
from SDSS/BOSS data





Idea:

- looking for the presence of emission lines at redshifts higher than that of the target galaxy
- + HST ACS follow-up imaging



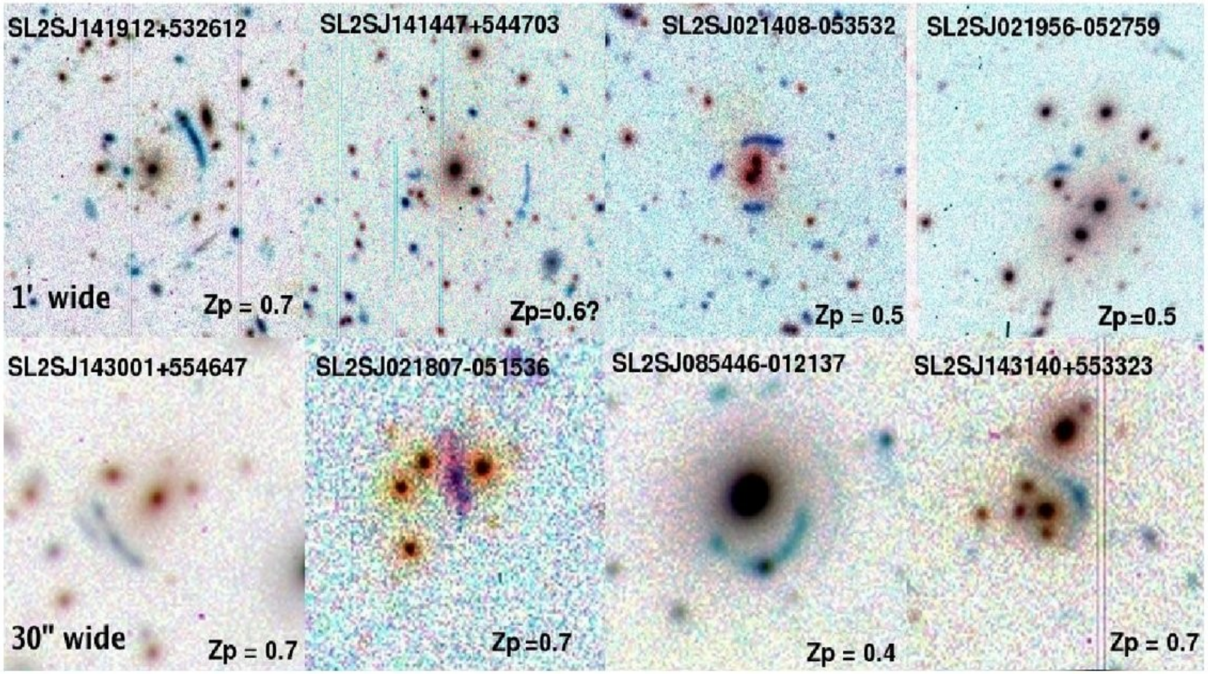
http://www.physics.utah.edu/~bolton/slacs/What_is_SLACS.html

Gravitational lensing in a pill

Strong Lensing Legacy Survey **SL2S**
from Canada France Hawaii Telescope Legacy Survey (CFHTLS)

- targets: massive red galaxies – **homogeneous sample**
- fully automated software (*RingFinder*) looking for tangentially elongated blue features around

[Gavazzi et al. 2014]



Early-type galaxies (ETGs) are more likely to serve as intervening galaxies:

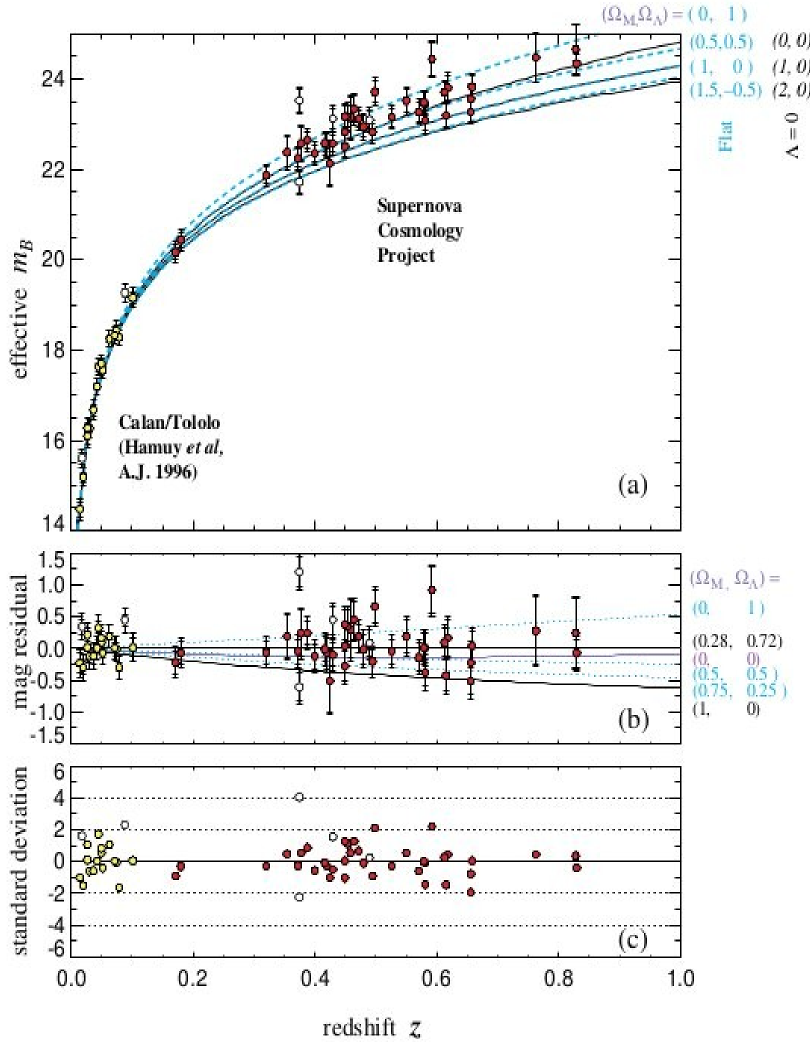
they contain most of the stellar mass of the Universe which affects statistics of gravitational lensing phenomenon

http://www-sl2s.iap.fr/

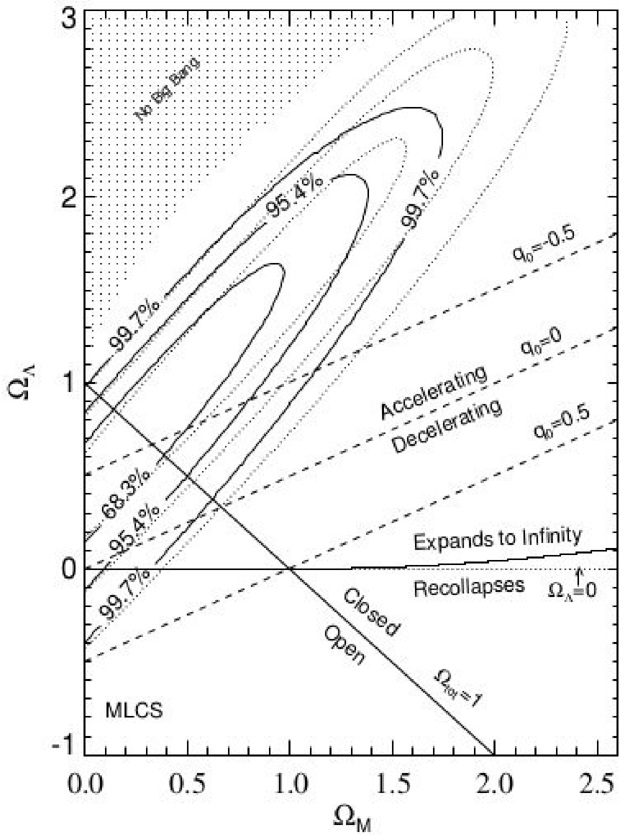
Gravitational lensing as a tool in cosmology

The nature of dark energy

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



$$\Omega_\Lambda = 0.71 \pm 0.05 \quad (1\sigma)$$
$$\Omega_M = 0.29 \pm 0.05$$



Supernova Cosmology Project (Perlmutter et al.1999) **High-z Supernova Search Team (Riess et al. 1998)**

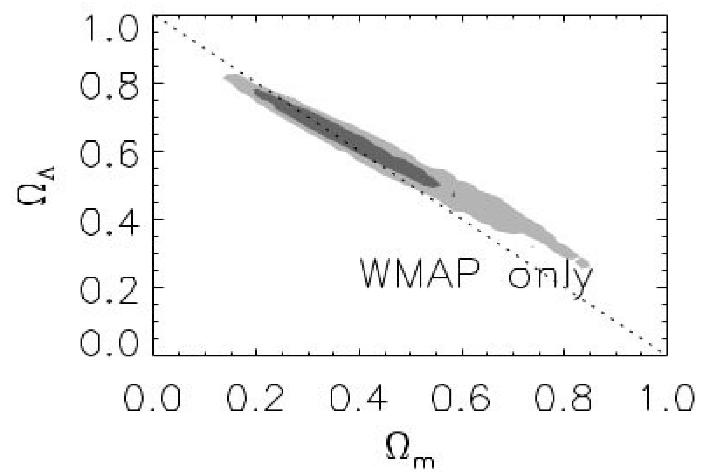
The nature of dark energy

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



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.

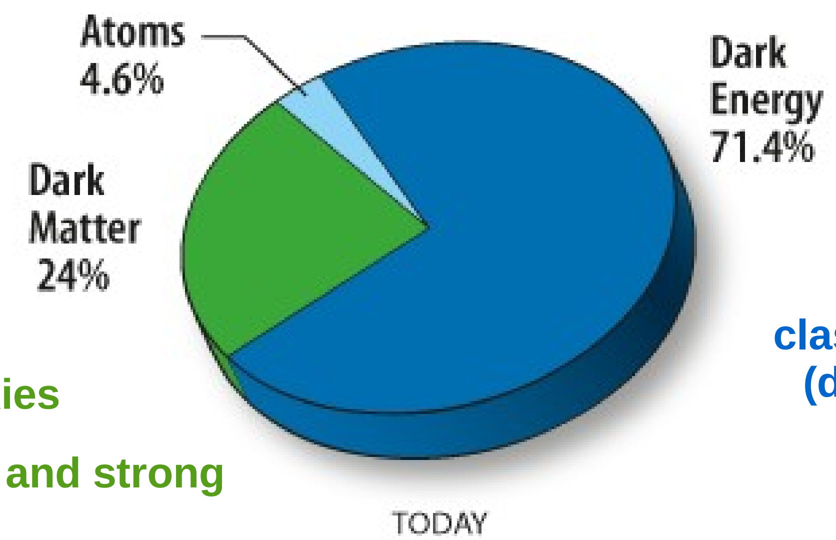
TABLE 1
Power-Law ΛCDM Model Parameters: *WMAP* Data Only

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.

The nature of dark energy

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



flat rotation curves of galaxies

gravitational lensing: weak and strong

classical cosmological tests (distance measurements)

NASA/WMAP Science Team

modification of gravity at cosmological scales

exotic material component

new physics is needed

The nature of dark energy

- 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:

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

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

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

strong evidence for the spatially flatness of the Universe from observations

The nature of dark energy

- 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

The nature of dark energy

- The nature of dark energy is still an open question

- We are left with the phenomenological approach based on upgrading observational fits of quantities 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 laying on cosmological distances

Distance measures

- 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

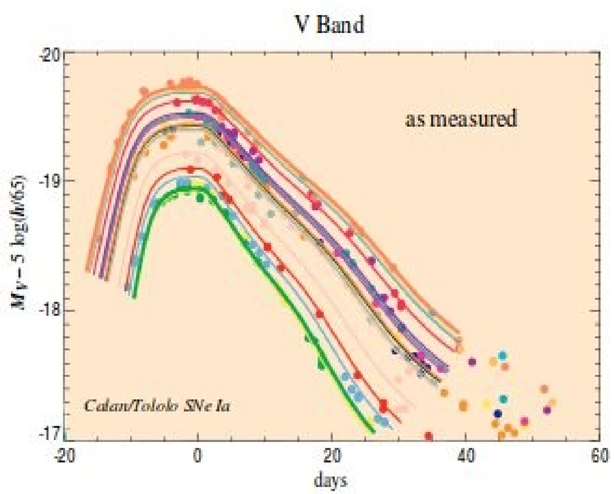
- Standard candles: **SNIa**
  - bright enough to be detected in distant galaxies (up to z ~ 1.7)
  - the most recent compilation of 557 SNIa data known as Union2

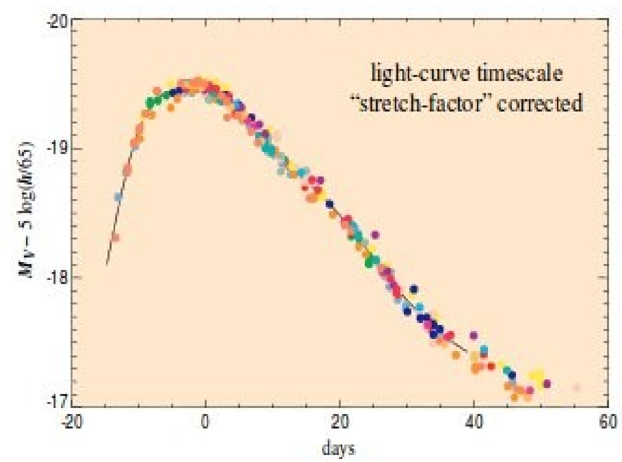
Amanullah et al. 2010, Suzuki et al. 2011

  - 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:

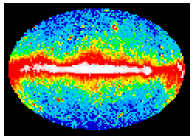
Other type of Sne (SNII-P)

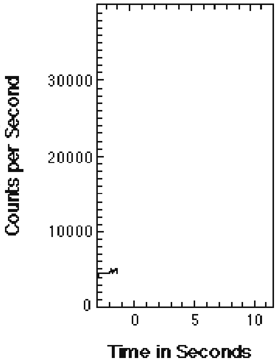
Poznanski, Nugent & Filippenko 2010

Hamuy & Pinto 2002

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

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

Gravitational-wave sources (standard sirens)

Arabsalmani, Sahni & Saini 2013

- 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

Camera & Nishizawa 2013

Taylor & Gair 2012

Cosmological probes

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

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

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

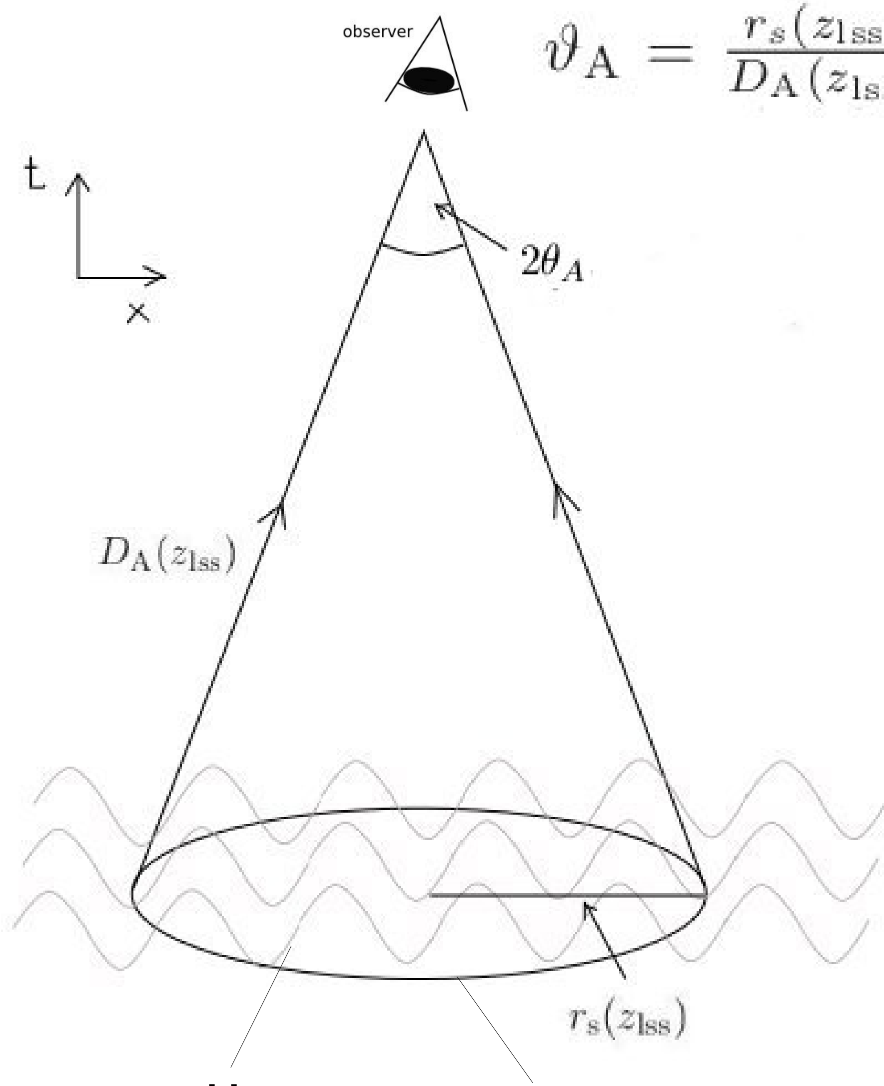
the sound horizon
comoving distance travelled by
a sound wave in the photon-baryon
fluid by the time of decoupling (z ~ 1100)

$$r_{\mathrm{s}}(z_{\mathrm{lss}}) = \int_{z_{lss}}^{\infty} \frac{c_s dz}{H(z)}$$

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

$$r_{\mathrm{s}}(z_{\mathrm{lss}}) = 146.8 \pm 1.8\mathrm{Mpc}$$

Komatsu et al. 2008

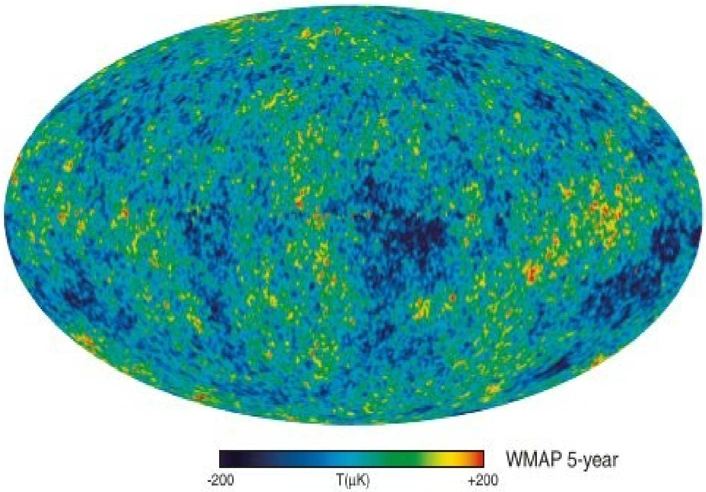


pressure waves caused by dark matter overdensities

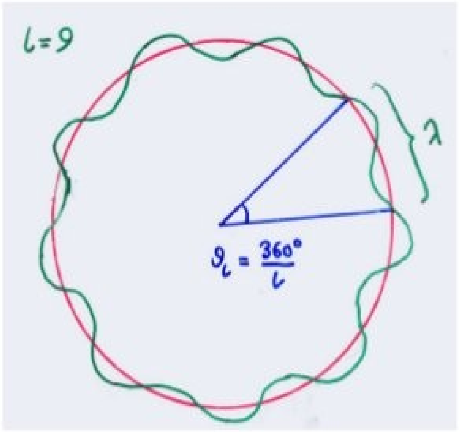
surface of last scattering

Cosmological probes

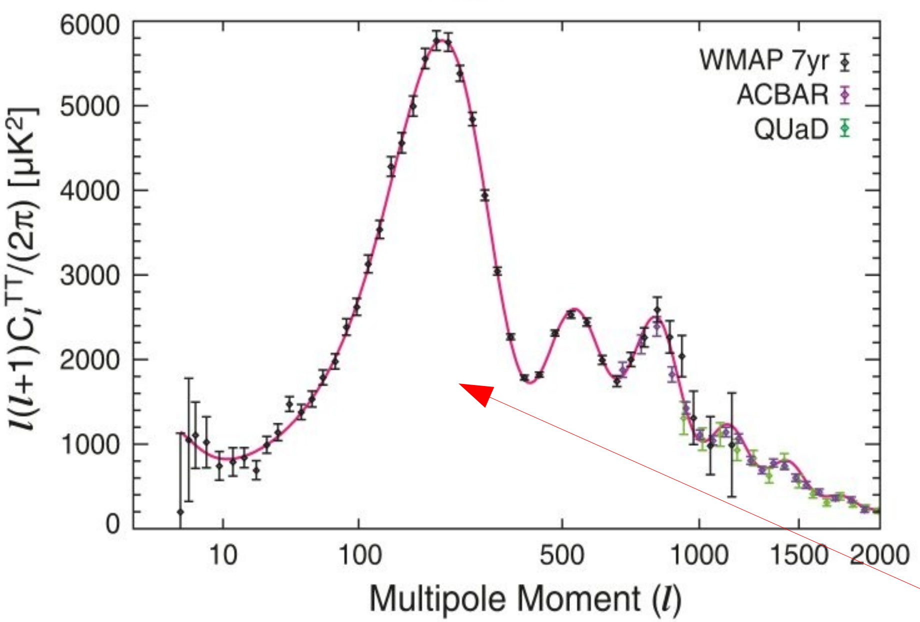
- **CMBR anisotropies** - the pattern of acoustic oscillations frozen in the CMB



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:

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

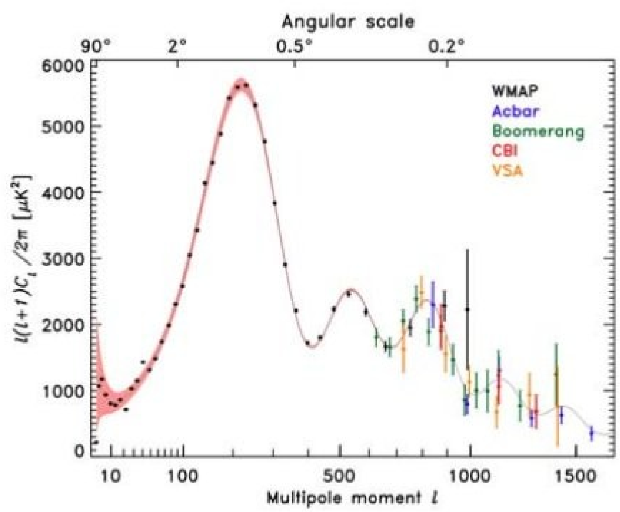
location of the first acoustic peak depends strongly on geometry and cosmology

Komatsu et al. 2010

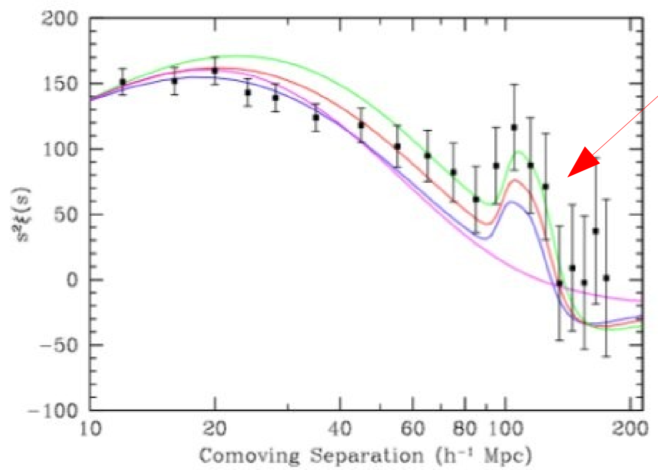
Cosmological probes

- **BAO**

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

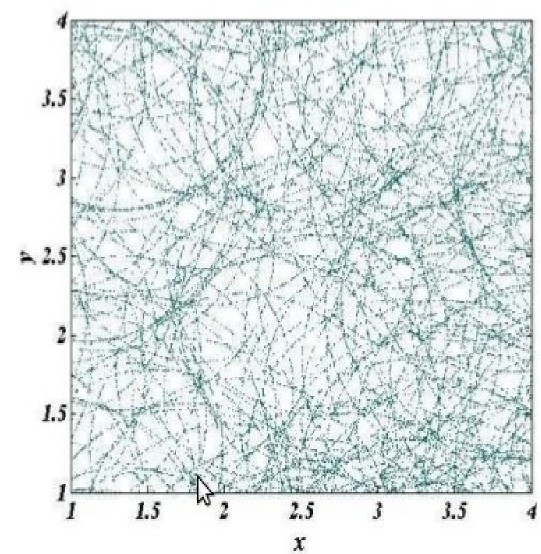


Hinshaw et al. 2003

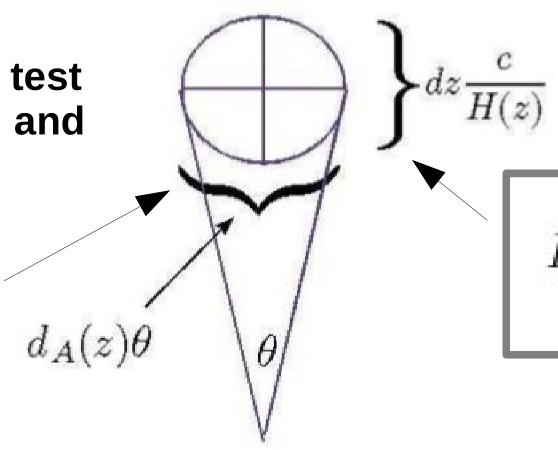


Eisenstein et al. 2005

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:



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

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

Bassett, Hlozek et al. 2009

Cosmological probes

- Individual standard rulers:

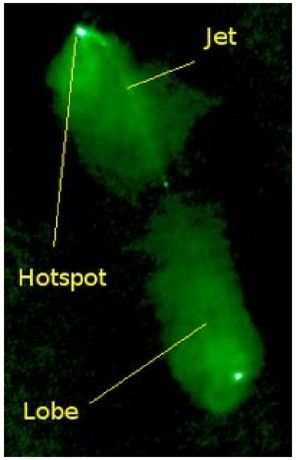
wide range of redshifts

Gurvits, Kellermann, Frey 1998

Gurvits 1994

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)



Double-sided radio sources (FRIIb radio galaxies)

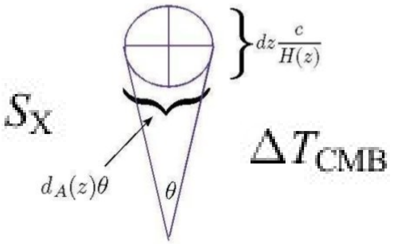
- standard ruler – physical size of the radio bridge structure
- evolution of structure is linear with time (older are bigger)

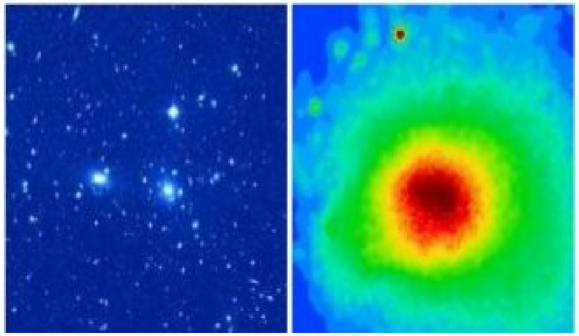
Daly 1994, 2009

Galaxy clusters

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

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

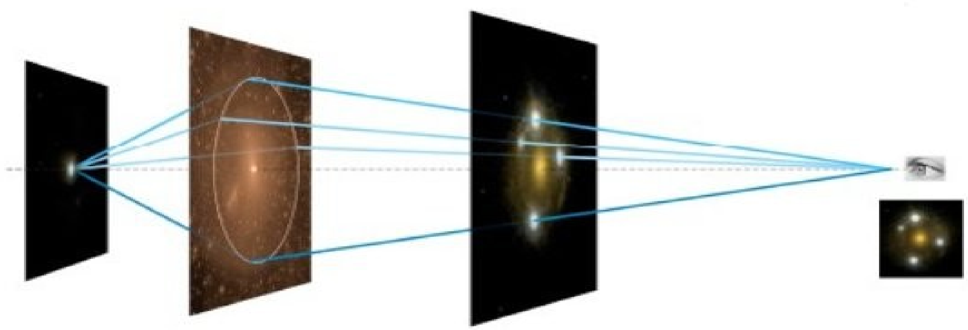




Bonamente et al. 2006

SL as standard(izable) rulers – our method

- **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



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

$$\rho(r) = \frac{\sigma_{SIS}^2}{2\pi G}\frac{1}{r^2}$$

SIS model – the simplest realistic case

Einstein radius defines characteristic angular scale for the lens:

distance from the lens to the source

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

from angular image separations (astrometry)

one-dimensional velosity dispersion in lensing galaxy (spectroscopy)

distance from observer to the source

$\sigma_{\rm SIS}$ lens velocity dispersion is well approximated by σ_{o} - central stellar velocity dispersion (see eg. Grillo et al. 2008)

Strong lenses as standard(izable) rulers

observable: **distance ratio**

$$D^{th}(z_l, z_s, p) \rightarrow \frac{D_s}{D_{ls}} = \frac{4\pi\sigma_0^2}{c^2\theta_E} \leftarrow D^{obs}$$

$$D_A(z;\mathbf{p}) = \frac{c}{H_0}\frac{1}{1+z}\int_0^z \frac{dz'}{h(z';\mathbf{p})}$$

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**

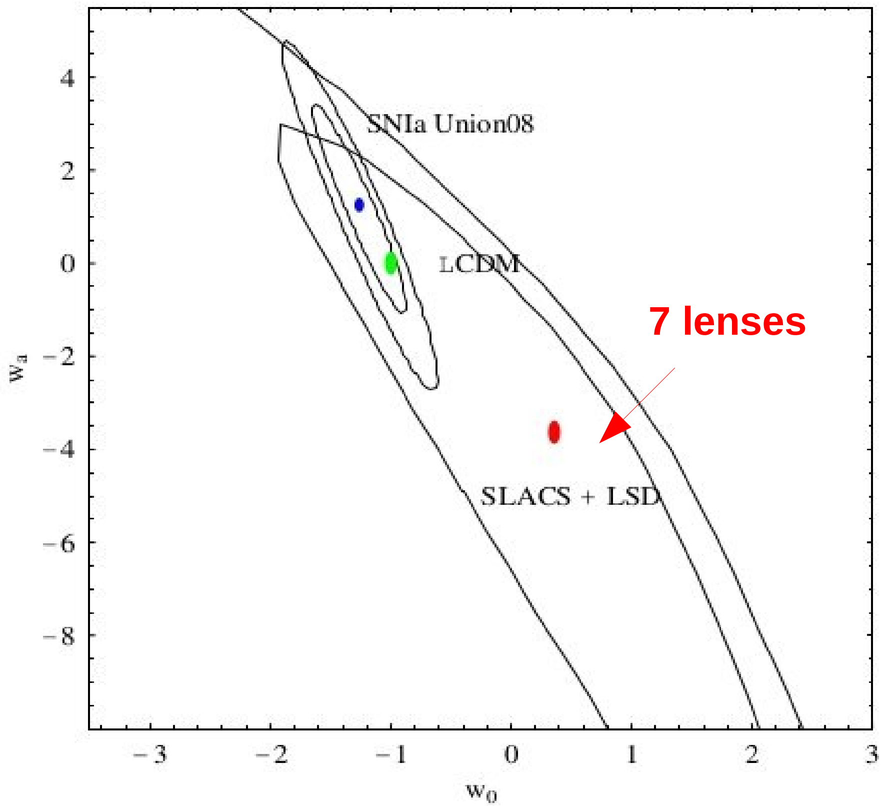
Strong lenses as standard(izable) rulers

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

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

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

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



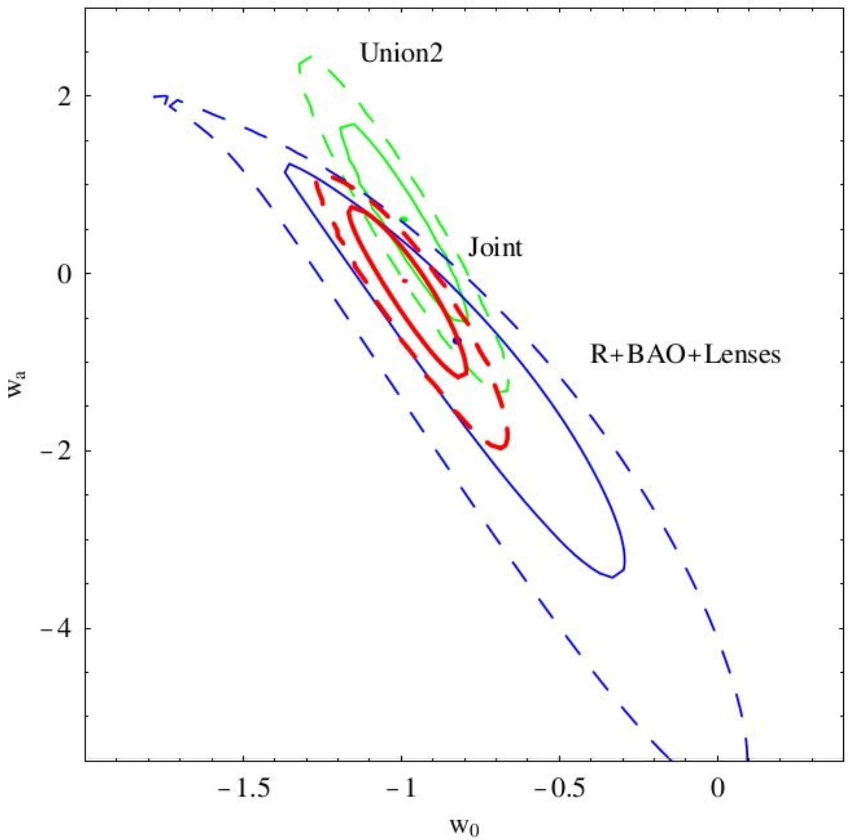
Best fits (dots) and (68%, 98%) confidence regions for CPL parameters in cosmic equation of state obtained from SLACS and SLD sample of lenses and Union08 SNIa data.

Biesiada, AP, Malec, 2010

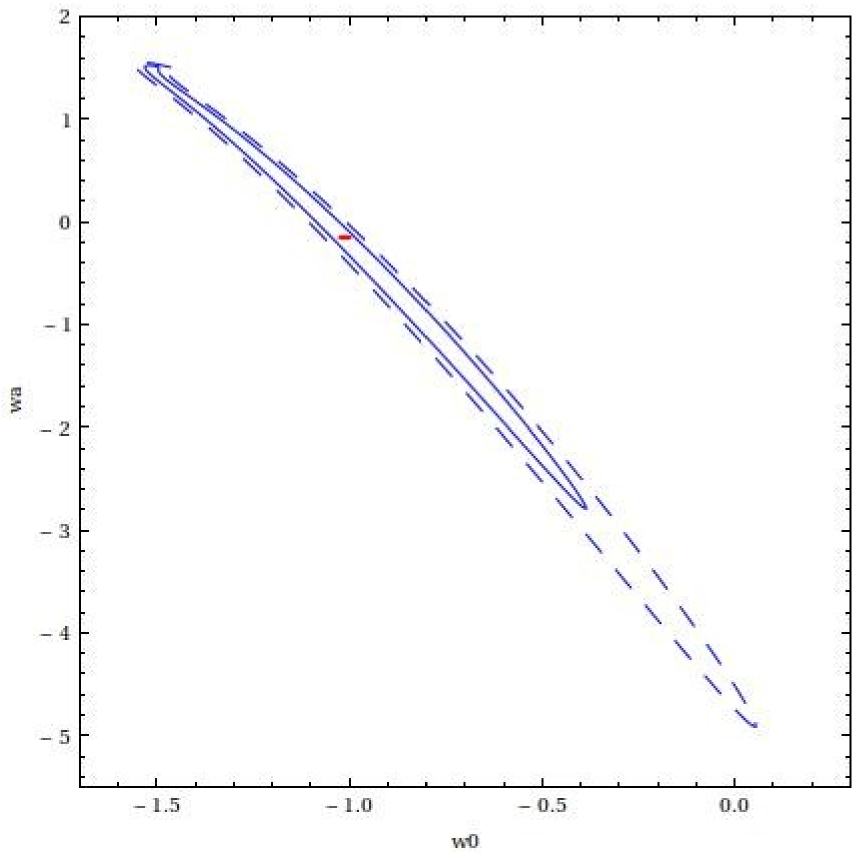
Strong lenses as standard(izable) rulers

- 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

Ruff, Gavazzi et al. 2011

Biesiada, Gavazzi & AP, COSMO Probes, Lausanne 2013

Strong lenses as standard(izable) rulers

- **First step forward:** new updated compilation of 118 lenses from SLD, SLACS, BELLS and SL2S catalogues.

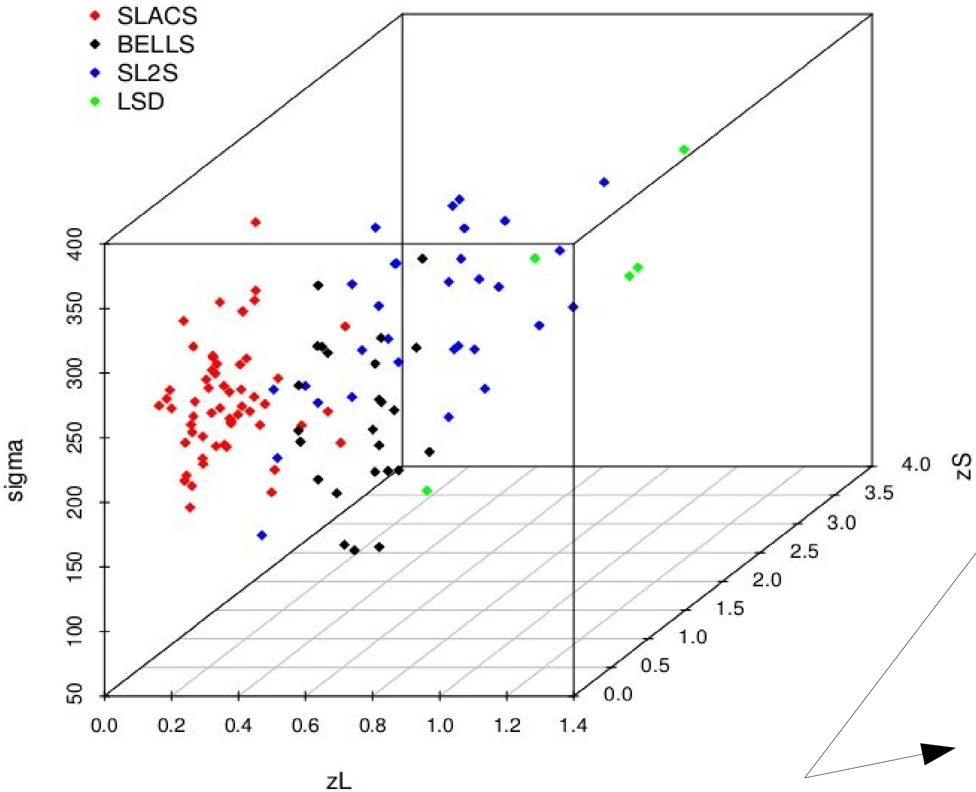
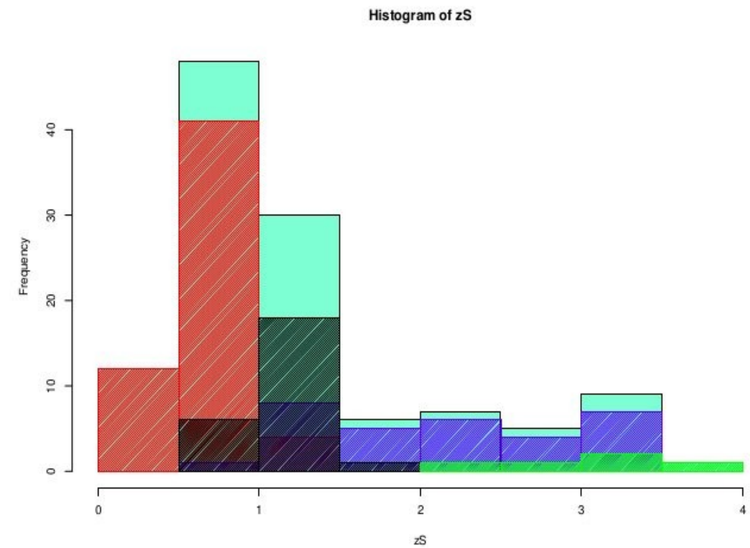
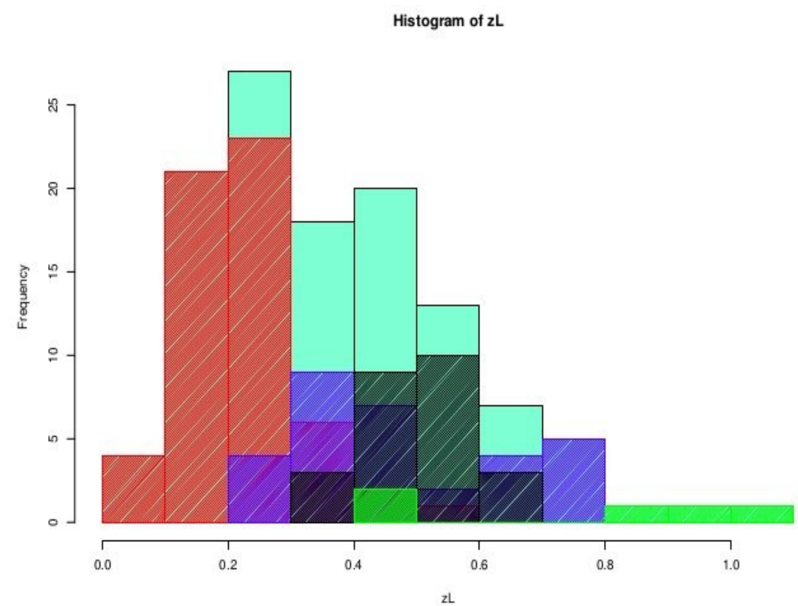


Fig. 1. Different surveys have the following median values of the lens redshifts: SLACS – $z_l = 0.215$, BELLS – $z_l = 0.517$, LSD – $z_l = 0.81$ and SL2S – $z_l = 0.456$. The above values refer to lenses used by us. SL2S survey – an ongoing one – is particularly promising for the future since it already reached the maximum lens redshift of $z_l = 0.8$.





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Strong lenses as standard(izable) rulers

- **First step forward:** new updated compilation of 118 lenses from SLD, SLACS, BELLS and SL2S catalogues:

TABLE 1
COMPILATION OF STRONG LENSING SYSTEMS

Name	z_l	z_s	σ_{ap} $[km/s]$	θ_E $['']$	survey	θ_{ap} $['']$	θ_{eff} $['']$	σ_0 $[km/s]$
J0151+0049	0.517	1.364	219±39	0.68	BELLS	1	0.89	226±40
J0747+5055	0.438	0.898	328±60	0.75	BELLS	1	1.24	334±61
J0747+4448	0.437	0.897	281±52	0.61	BELLS	1	2.87	277±51
J0801+4727	0.483	1.518	98±24	0.49	BELLS	1	0.57	103±25
J0830+5116	0.53	1.332	268±36	1.14	BELLS	1	1.1	274±37
J0944-0147	0.539	1.179	204±34	0.72	BELLS	1	1.35	207±35
J1159-0007	0.579	1.346	165±41	0.68	BELLS	1	0.99	170±42
J1215+0047	0.642	1.297	262±45	1.37	BELLS	1	1.42	266±46
J1221+3806	0.535	1.284	187±48	0.7	BELLS	1	0.93	193±49
J1234-0241	0.49	1.016	122±31	0.53	BELLS	1	1.61	123±31
J1318-0104	0.659	1.396	177±27	0.68	BELLS	1	1.06	182±28
J1337+3620	0.564	1.182	225±35	1.39	BELLS	1	1.6	227±35
J1349+3612	0.44	0.893	178±18	0.75	BELLS	1	2.03	178±18
J1352+3216	0.463	1.034	161±21	1.82	BELLS	1	1.35	164±21
J1522+2910	0.555	1.311	166±27	0.74	BELLS	1	1.08	170±28
J1541+1812	0.56	1.113	174±24	0.64	BELLS	1	0.59	183±25
J1542+1629	0.352	1.023	210±16	1.04	BELLS	1	1.45	213±16
J1545+2748	0.522	1.289	250±37	1.21	BELLS	1	2.65	247±37
J1601+2138	0.544	1.446	207±36	0.86	BELLS	1	0.63	217±38
J1611+1705	0.477	1.211	109±23	0.58	BELLS	1	1.33	111±23
J1631+1854	0.408	1.086	272±14	1.63	BELLS	1	2.07	272±14
J1637+1439	0.391	0.874	208±30	0.65	BELLS	1	0.89	215±31

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Strong lenses as standard(izable) rulers

- **Second step forward:** generalization of the SIS model to spherically symmetric power-law mass distribution.

$$\rho \sim r^{-\gamma}$$

mass inside the Einstein radius:

$$M_{lens} = \frac{c^2}{4G} \frac{D_s D_l}{D_{ls}} \theta_E^2$$

[Schneider et al.1992]

dynamical mass inside the aperture projected to lens plane:

$$\begin{aligned} M_{dyn} &= \frac{\pi}{G} \sigma_{ap}^2 R_E \left(\frac{R_E}{R_{ap}} \right)^{2-\gamma} f(\gamma) \\ &= \frac{\pi}{G} \sigma_{ap}^2 D_l \theta_E \left(\frac{\theta_E}{\theta_{ap}} \right)^{2-\gamma} f(\gamma) \end{aligned}$$

$$\begin{aligned} f(\gamma) &= -\frac{1}{\sqrt{\pi}} \frac{(5-2\gamma)(1-\gamma)}{3-\gamma} \frac{\Gamma(\gamma-1)}{\Gamma(\gamma-3/2)} \\ &\times \left[\frac{\Gamma(\gamma/2-1/2)}{\Gamma(\gamma/2)} \right]^2 \end{aligned}$$

[Koopmans et al. 2005]

formula for the einstein radius in general spherically symmetric power-law lens mass distribution

$$\theta_E = 4\pi \frac{\sigma_{ap}^2}{c^2} \frac{D_{ls}}{D_s} \left(\frac{\theta_E}{\theta_{ap}} \right)^{2-\gamma} f(\gamma)$$

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Strong lenses as standard(izable) rulers

- Making our sample more uniform – correction of the velosity dispersion.

$$\theta_E = 4\pi \frac{\sigma_{ap}^2}{c^2} \frac{D_{ls}}{D_s} \left(\frac{\theta_E}{\theta_{ap}} \right)^{2-\gamma} f(\gamma)$$

new observable

$$\boxed{\mathcal{D}^{obs} = \frac{c^2 \theta_E}{4\pi \sigma_{ap}^2} \left(\frac{\theta_{ap}}{\theta_E} \right)^{2-\gamma} f^{-1}(\gamma)}$$

we need to transform all velosity dispertions measured within an aperture to those, measured within circular aperture of radius *Reff / 2*

$$\sigma_0 = \sigma_{ap} (\theta_{eff}/(2\theta_{ap}))^{-0.04}$$

uncertainties of the effective radius contribute less than 1% to the uncertainty of *σ 0*

[Jorgensen et al.1995]

this operation makes our observable more homogeneous for the sample of lenses located at different redshifts

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Strong lenses as standard(izable) rulers

- Monte Carlo (CosmoMC package) simulations of the posterior likelihood

$$\mathcal{L} \sim \exp(-\chi^2/2)$$

$$\boxed{\chi^2 = \sum_{i=1}^{118} \left(\frac{\mathcal{D}^{th}(z_{l,i}, z_{s,i}; \mathbf{p}, \gamma) - \mathcal{D}^{obs}(\sigma_{0,i}, \theta_{E,i})}{\Delta \mathcal{D}_i^{obs}} \right)^2}$$

γ taken as a free parameter !

5%

SLACS Team

$$\delta\mathcal{D} = \frac{\Delta\mathcal{D}}{\mathcal{D}} = \sqrt{4(\delta\sigma_{ap})^2 + (1-\gamma)^2(\delta\theta_E)^2}$$

TABLE 2

DARK ENERGY ($XCDM$ MODEL AND CPL PARAMETRIZATION) CONSTRAINTS OBTAINED ON THE FULL 118 STRONG LENSING (SL) SAMPLE.

Cosmology (Sample)	w_0	w_1	γ_0	γ_1
XCDM1 (SL; σ_{ap})	$w_0 = -1.45^{+0.54}_{-0.95}$	$w_1 = 0$	$\gamma_0 = 2.03 \pm 0.06$	$\gamma_1 = 0$
XCDM1 (SL; σ_0)	$w_0 = -1.15^{+0.56}_{-1.20}$	$w_1 = 0$	$\gamma_0 = 2.07 \pm 0.07$	$\gamma_1 = 0$
XCDM2 (SL; σ_{ap})	$w_0 = -1.48^{+[illegible]}_{-0.94}$	$w_1 = 0$	$\gamma_0 = 2.06 \pm 0.09$	$\gamma_1 = -0.09 \pm 0.16$
XCDM2 (SL; σ_0)	$w_0 = -1.35^{+0.67}_{-[illegible]}$	$w_1 = 0$	$\gamma_0 = 2.13^{+0.07}_{-0.12}$	$\gamma_1 = -0.09 \pm 0.17$
CPL1 (SL; σ_{ap})	$w_0 = -0.15^{+1.27}_{-1.60}$	$w_1 = -6.95^{+7.25}_{-3.05}$	$\gamma_0 = 2.08 \pm 0.09$	$\gamma_1 = -0.09 \pm 0.17$
CPL1 (SL; σ_0)	$w_0 = -1.00^{+1.54}_{-1.95}$	$w_1 = -1.85^{+4.85}_{-6.75}$	$\gamma_0 = 2.14^{+0.07}_{-0.10}$	$\gamma_1 = -0.10 \pm 0.18$
CPL2 (SL; σ_{ap})	$w_0 = -0.16^{+1.21}_{-1.48}$	$w_1 = -6.25^{+6.25}_{-3.75}$	$\gamma_0 = 2.08$	$\gamma_1 = -0.09$
CPL2 (SL; σ_0)	$w_0 = -1.05^{+1.43}_{-1.77}$	$w_1 = -1.65^{+4.25}_{-6.35}$	$\gamma_0 = 2.14$	$\gamma_1 = -0.10$
CPL2 (SN)	$w_0 = -1.00 \pm 0.40$	$w_1 = -0.12^{+1.58}_{-2.78}$	$\square$	$\square$

[a]In our fits we separately considered observed velocity dispersions σ_{ap} and corrected velocity dispersions σ_0, $XCDM1$ corresponds to assumption of non-evolving power-law index γ, while $XCDM2$ assumes its evolution $\gamma(z) = \gamma_0 + \gamma_1 z_l$. Fixed prior of $\Omega_m = 0.315$ was assumed according to the Planck data. While fitting CPL parameters we assumed evolving lens mass density with γ_0 and γ_1 as free parameters (CPL1) and then fixed them at best-fit values (CPL2). For comparison fits of CPL parameters using Union2.1 supernovae data (SN) is shown.

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Strong lenses as standard(izable) rulers

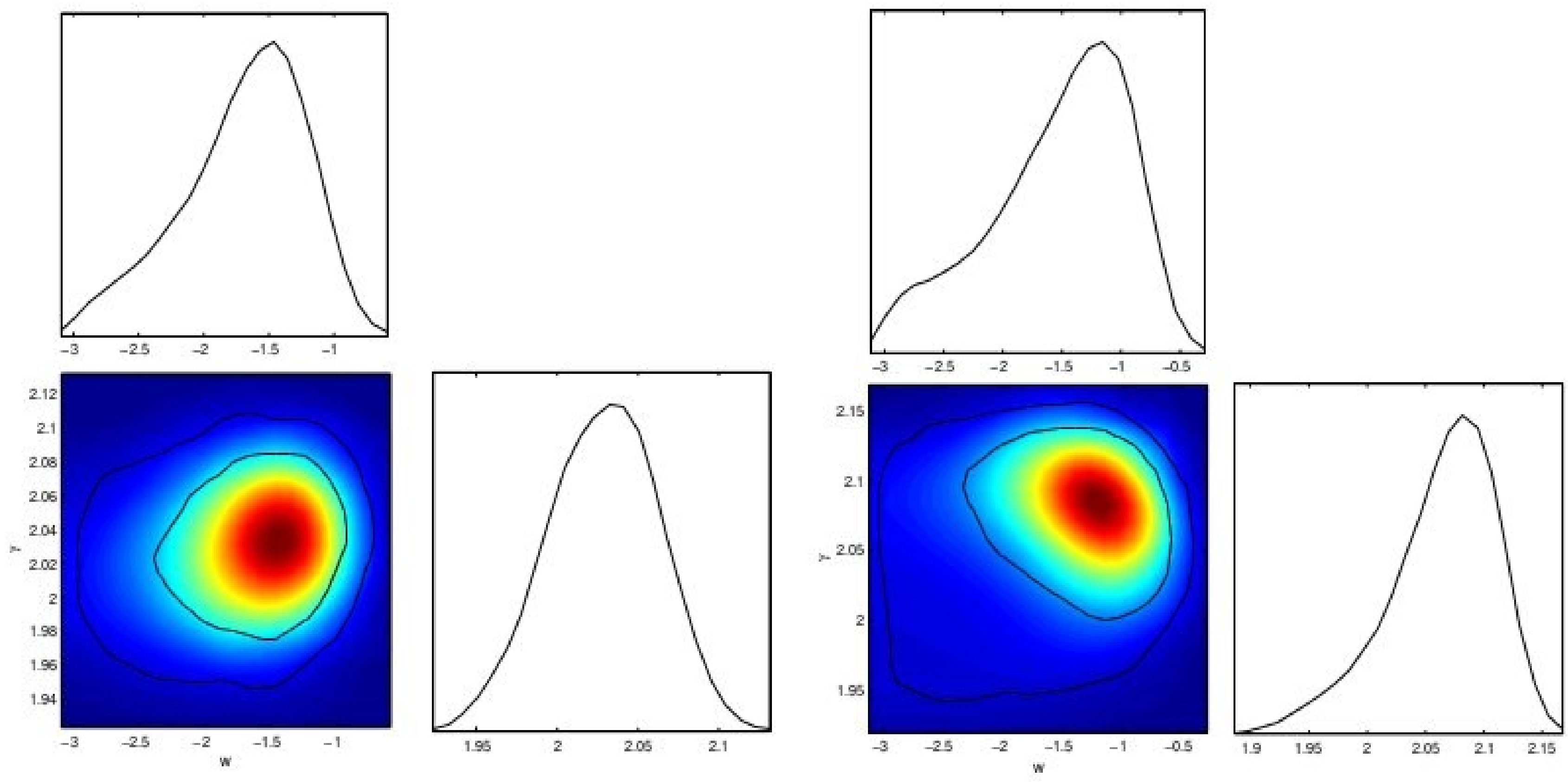

Fig. 3.— Joint fits of mass density slope γ and w coefficient in the XCDM model. Left panel shows the results obtained with velocity dispersion within the aperture σ_{ap} while on the right panel corrected velocity dispersion σ_0 was used. $\Omega_m = 0.315$ is assumed based on the Planck observations (Ade et al. 2014). Marginalized probability density functions for γ and w are also shown.

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Strong lenses as standard(izable) rulers

- **Third step forward:** taking into account possible evolution of the power-law Index γ with redshift – $\gamma(z)$

mass density power-law index γ of massive ETG evolves with redshift !

[Ruff et al. 2011]
[Brownstein et al. 2012]
[Sonnenfeld et al. 2013]

$$\gamma(z_l) = 2.12^{+0.03}_{-0.04} - 0.25^{+0.10}_{-0.12} \times z_l + \ 0.17^{+0.02}_{-0.02}(scatter)$$

therefore we also performed fit assuming linear relation:

$$\boxed{\gamma(z_l) = \gamma_0 + \gamma_1 z_l}$$

TABLE 2

DARK ENERGY ($XCDM$ MODEL AND CPL PARAMETRIZATION) CONSTRAINTS OBTAINED ON THE FULL 118 STRONG LENSING (SL) SAMPLE.

Cosmology (Sample)	w_0	w_1	γ_0	γ_1
XCDM1 (SL; σ_{ap})	$w_0 = -1.45^{+0.54}_{-0.95}$	$w_1 = 0$	$\gamma_0 = 2.03 \pm 0.06$	$\gamma_1 = 0$
XCDM1 (SL; σ_0)	$w_0 = -1.15^{+0.56}_{-1.20}$	$w_1 = 0$	$\gamma_0 = 2.07 \pm 0.07$	$\gamma_1 = 0$
XCDM2 (SL; σ_{ap})	$w_0 = -1.48^{+0.54}_{-0.94}$	$w_1 = 0$	$\gamma_0 = 2.06 \pm 0.09$	$\gamma_1 = -0.09 \pm 0.16$
XCDM2 (SL; σ_0)	$w_0 = -1.35^{+0.67}_{-1.50}$	$w_1 = 0$	$\gamma_0 = 2.13^{+0.07}_{-0.12}$	$\gamma_1 = -0.09 \pm 0.17$
CPL1 (SL; σ_{ap})	$w_0 = -0.15^{+1.27}_{-1.60}$	$w_1 = -6.95^{+7.25}_{-3.05}$	$\gamma_0 = 2.08 \pm 0.09$	$\gamma_1 = -0.09 \pm 0.17$
CPL1 (SL; σ_0)	$w_0 = -1.00^{+1.54}_{-1.95}$	$w_1 = -1.85^{+4.85}_{-6.75}$	$\gamma_0 = 2.14^{+0.07}_{-0.10}$	$\gamma_1 = -0.10 \pm 0.18$
CPL2 (SL; σ_{ap})	$w_0 = -0.16^{+1.21}_{-1.48}$	$w_1 = -6.25^{+6.25}_{-3.75}$	$\gamma_0 = 2.08$	$\gamma_1 = -0.09$
CPL2 (SL; σ_0)	$w_0 = -1.05^{+1.43}_{-1.77}$	$w_1 = -1.65^{+4.25}_{-6.35}$	$\gamma_0 = 2.14$	$\gamma_1 = -0.10$
CPL2 (SN)	$w_0 = -1.00 \pm 0.40$	$w_1 = -0.12^{+1.58}_{-2.78}$	□	□

[a] In our fits we separately considered observed velocity dispersions σ_{ap} and corrected velocity dispersions σ_0, $XCDM1$ corresponds to assumption of non-evolving power-law index γ, while $XCDM2$ assumes its evolution $\gamma(z) = \gamma_0 + \gamma_1 \ z_l$. Fixed prior of $\Omega_m = 0.315$ was assumed according to the Planck data. While fitting CPL parameters we assumed evolving lens mass density with γ_0 and γ_1 as free parameters (CPL1) and then fixed them at best-fit values (CPL2). For comparison fits of CPL parameters using Union2.1 supernovae data (SN) is shown.

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Strong lenses as standard(izable) rulers

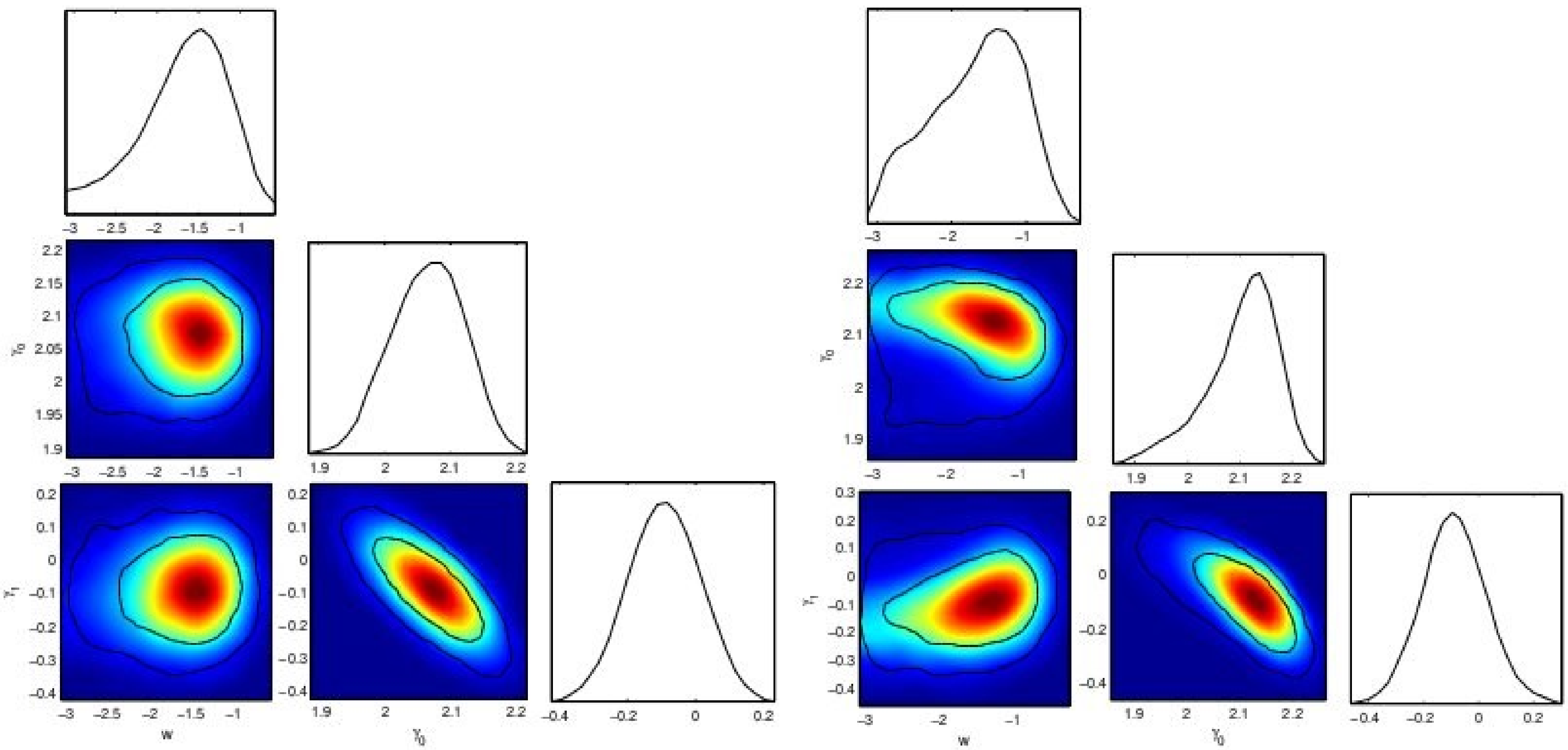

Fig. 4.— Joint fits of w coefficient in the XCDM model and mass density slope parameters (γ_0, γ_1) in evolving slope scenario $\gamma(z) = \gamma_0 + \gamma_1 z_l$. Left and right panels display the results obtained by using σ_{ap} and σ_0 respectively.

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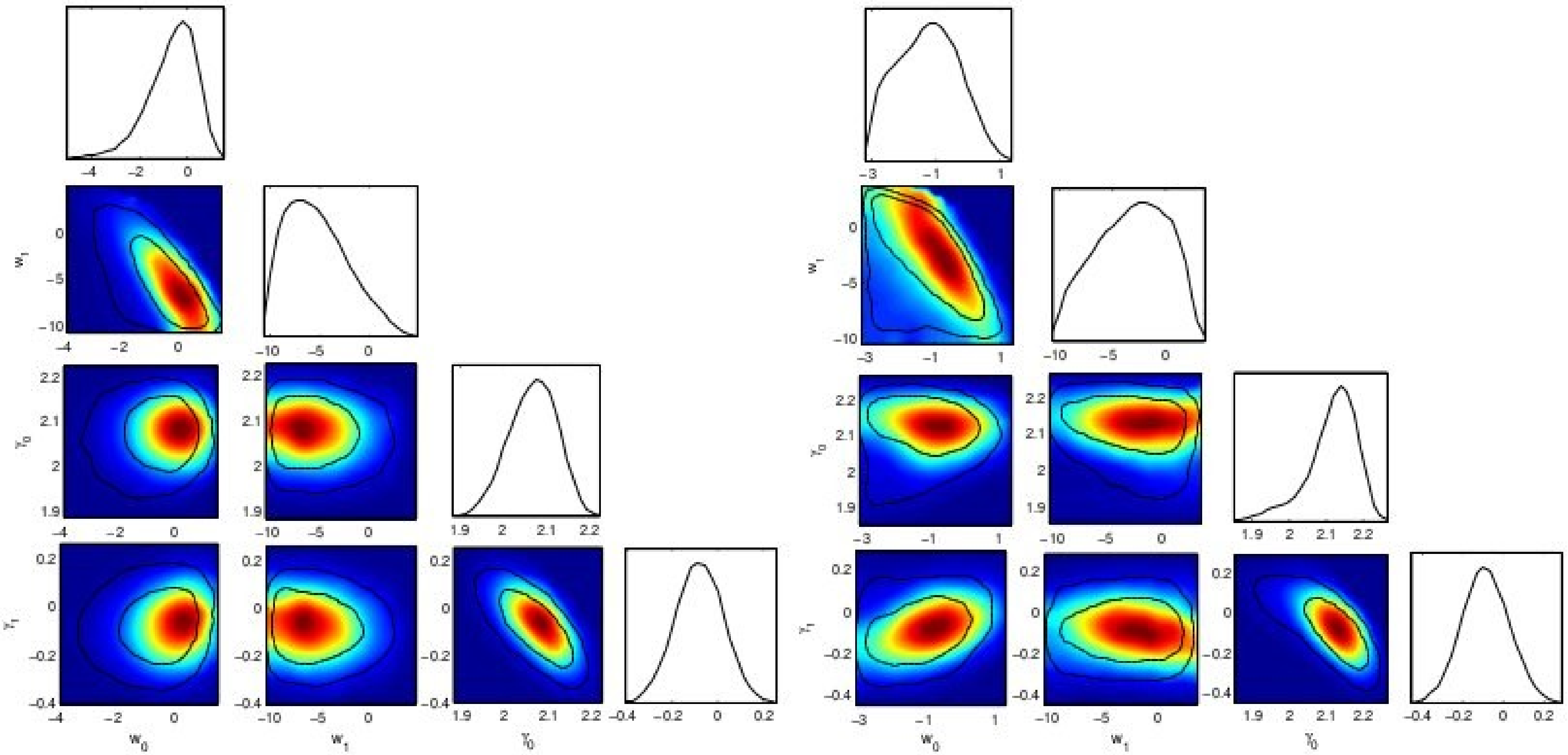

Fig. 5.— Joint fits of (w_0, w_1) evolving cosmic equation of state coefficients in the CPL parametrization. Lensing galaxies were assumed to have evolving mass density slope $\gamma(z) = \gamma_0 + \gamma_1 z_l$ and (γ_0, γ_1) parameters. Left and right panels display the results obtained by using σ_{ap} and σ_0 respectively.

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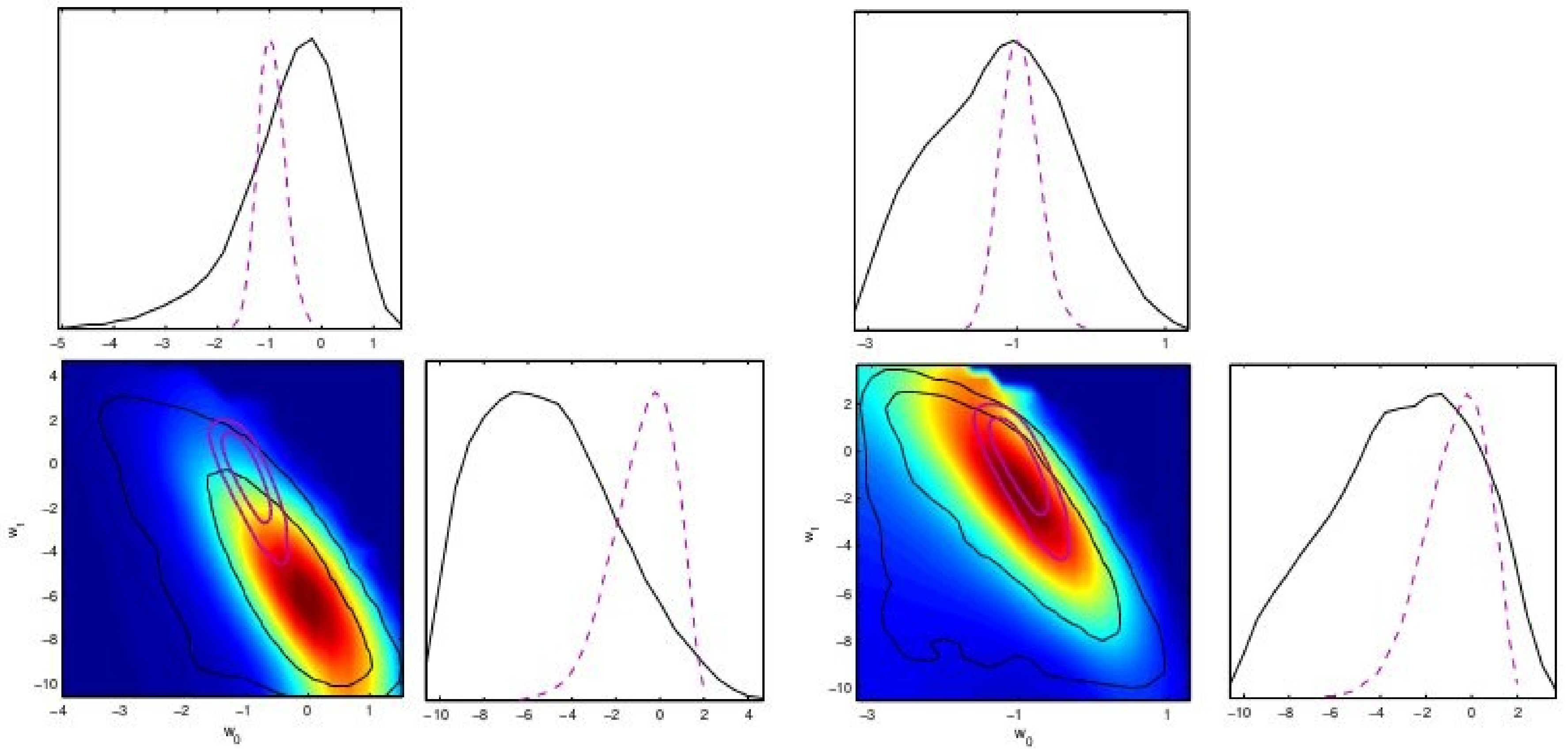

Fig. 6.— Joint fits of (w_0, w_1) evolving cosmic equation of state coefficients in the CPL parametrization. Lensing galaxies were assumed to have evolving mass density slope $\gamma(z) = \gamma_0 + \gamma_1 z_l$ and (γ_0, γ_1) parameters were fixed at our best-fit values in $XCDM$ model. Left and right panels display the results obtained by using σ_{ap} and σ_0 respectively.

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Strong lenses as standard(izable) rulers

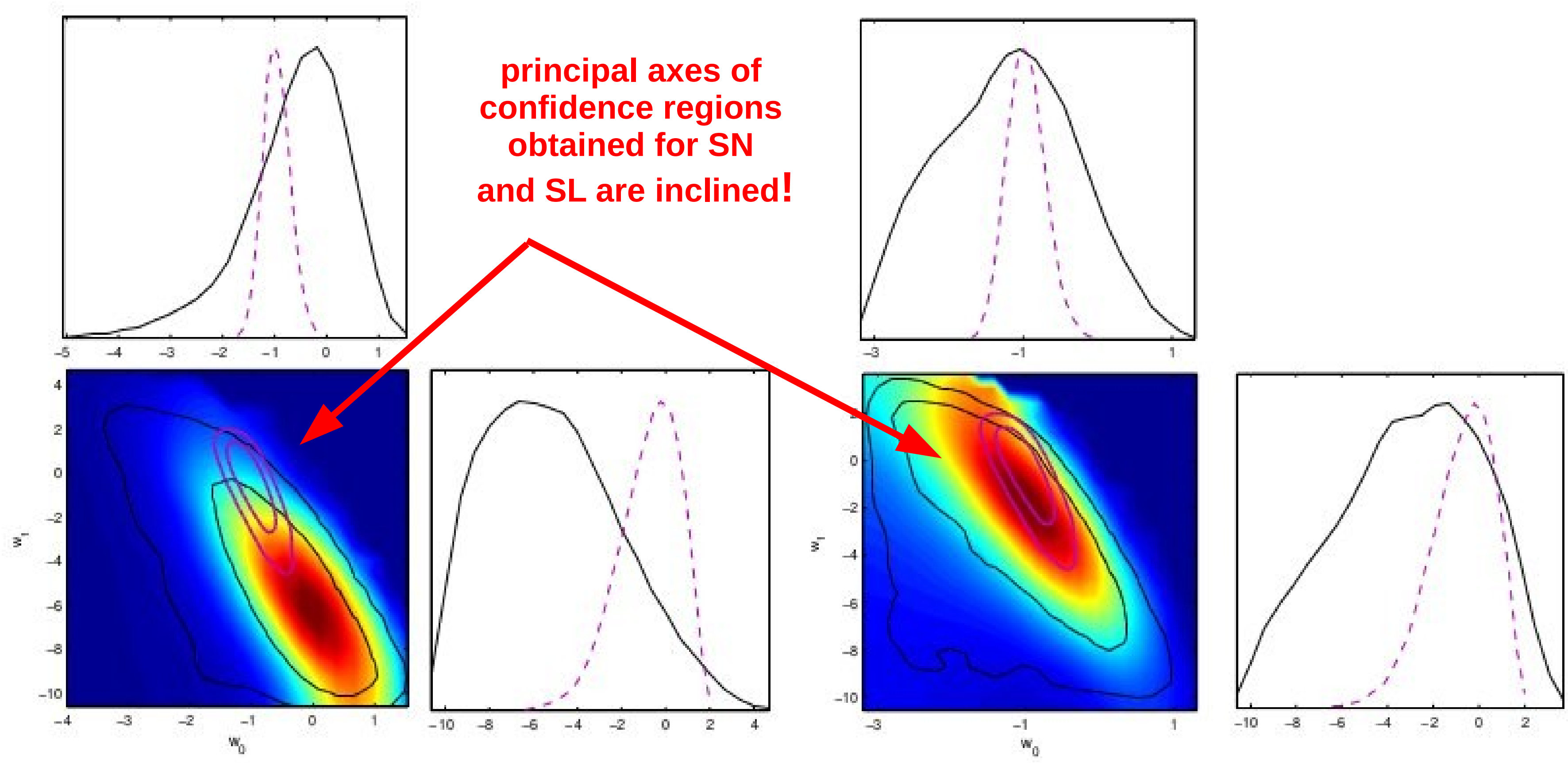


Fig. 6.— Joint fits of (w_0, w_1) evolving cosmic equation of state coefficients in the CPL parametrization. Lensing galaxies were assumed to have evolving mass density slope $\gamma(z) = \gamma_0 + \gamma_1 z_l$ and (γ_0, γ_1) parameters were fixed at our best-fit values in $XCDM$ model. Left and right panels display the results obtained by using σ_{ap} and σ_0 respectively.

this inclination is higher than in previous studies

[Biesiada, AP & Malec, 2010] **[Biesiada, Malec & AP, 2011]**

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

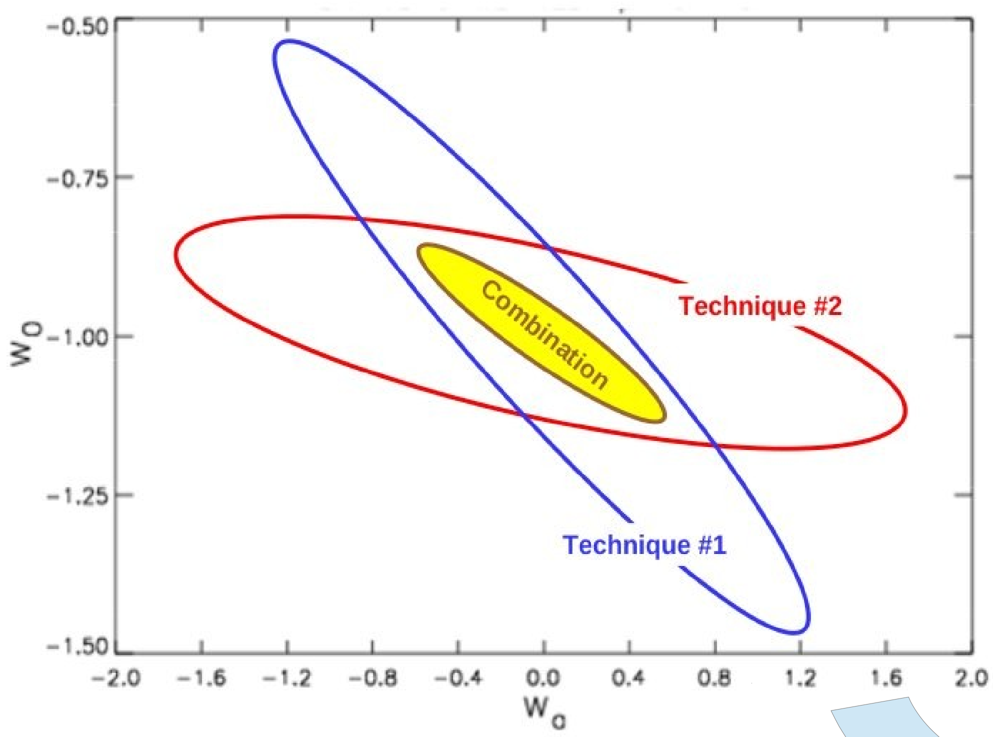
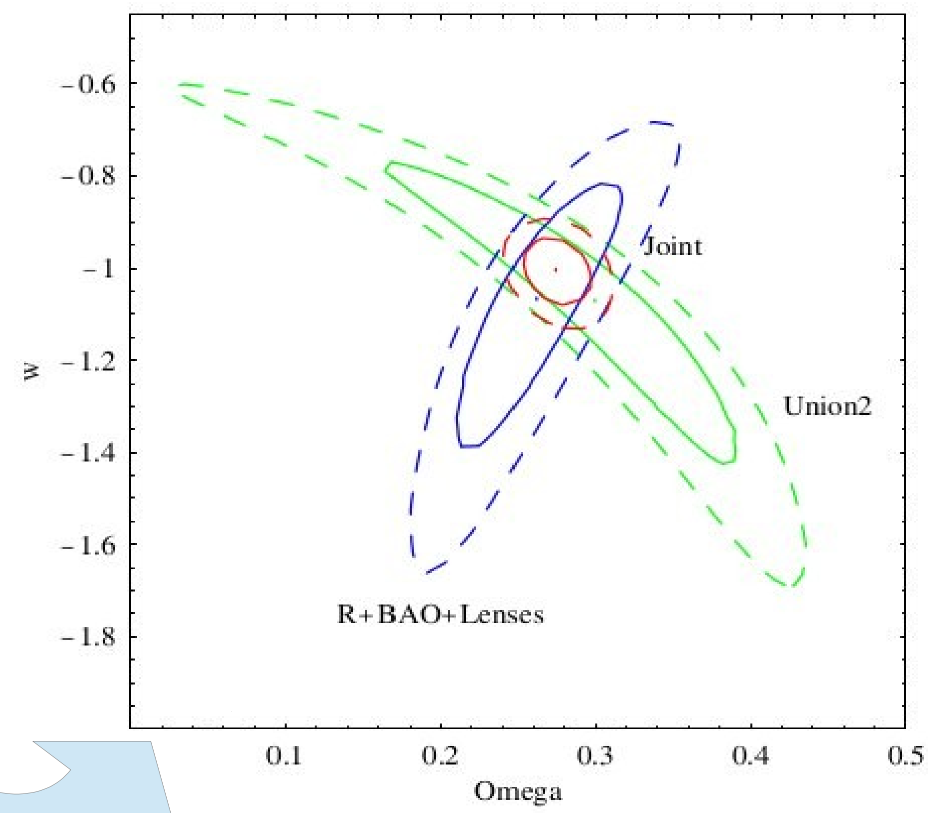


Illustration of the power of combining techniques.

Biesiada, Malec, AP, 2011

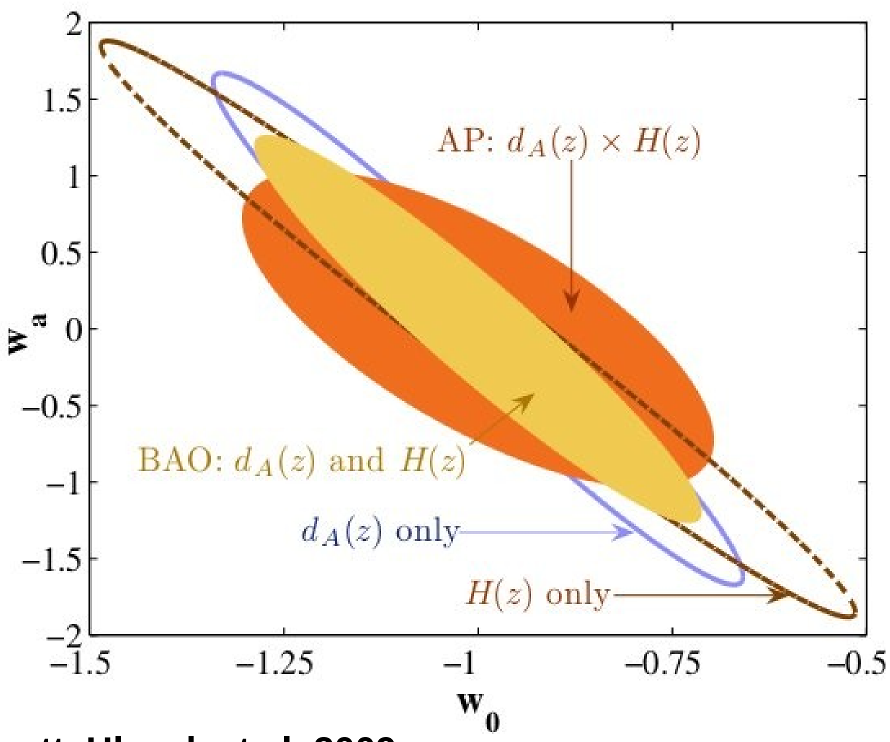


just like complementarity of standard rulers and standard candles in Omega-w parameter plane

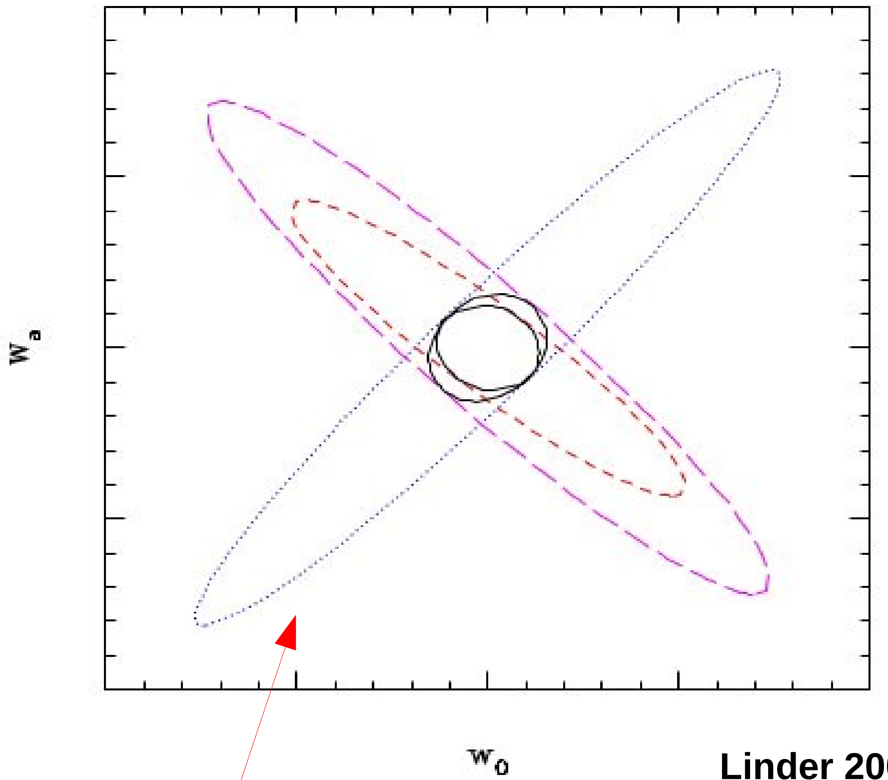
Dark Energy Complementarity

- 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

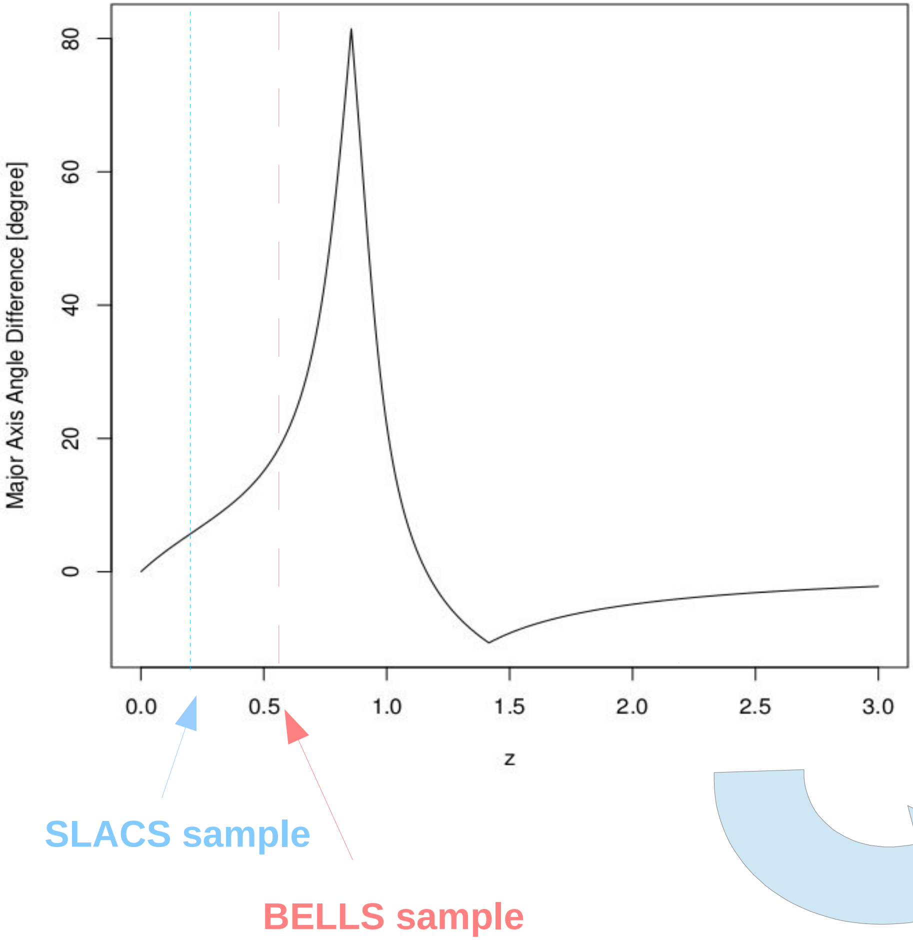


Linder 2004

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

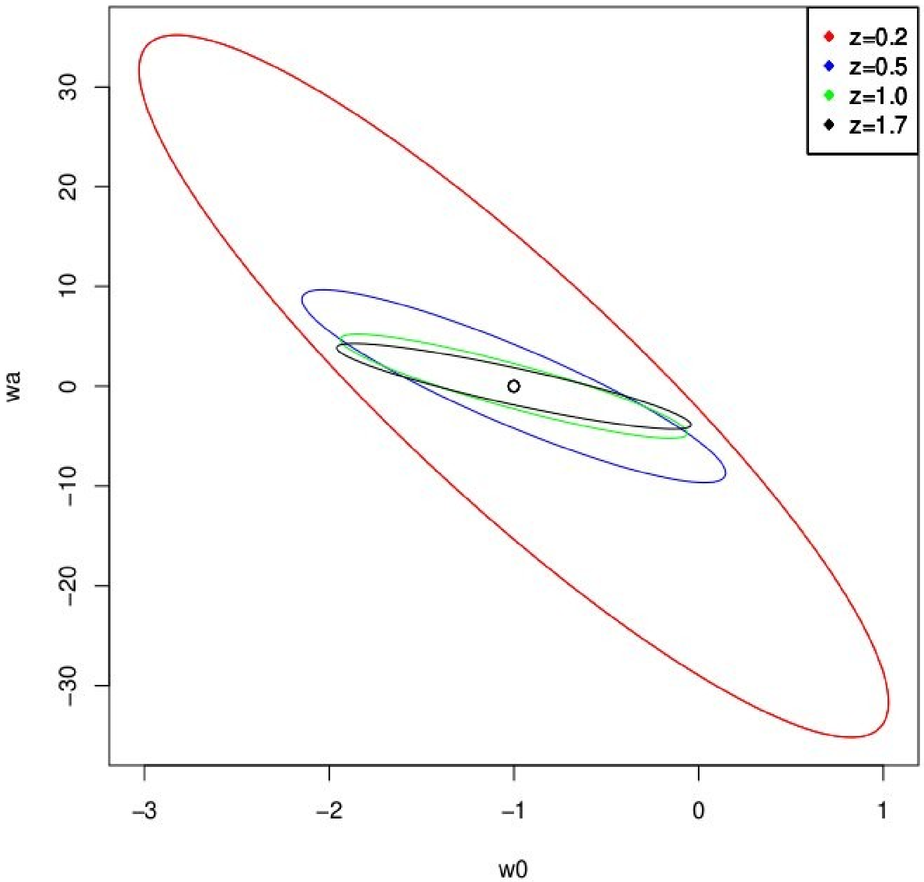
Complementarity of strong lensing measurements

- 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:



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:



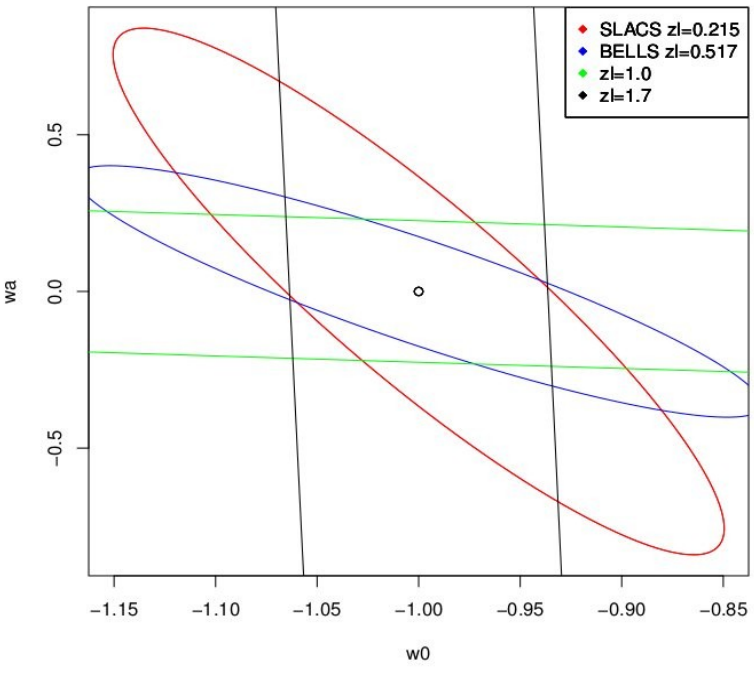
AP, Biesiada & Gavazzi, 2013

Complementarity of strong lensing measurements

Fisher matrix analysis:

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

- 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

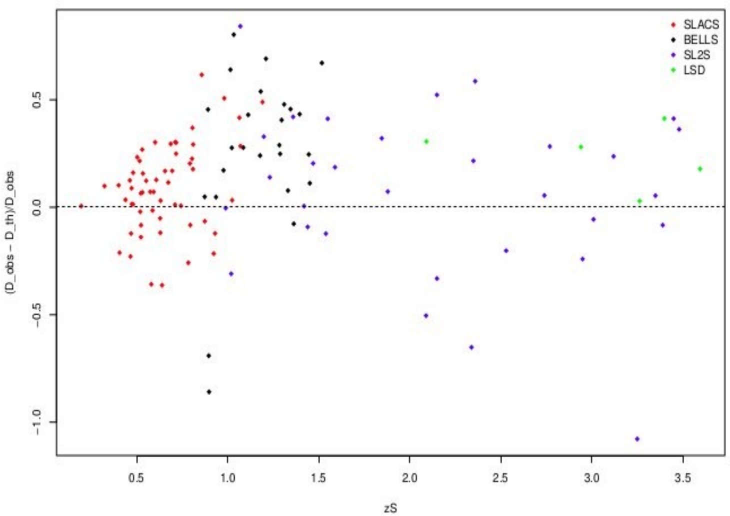
confidence contours for an idealized experiment measuring the distance ratio for several samples with different redshifts:

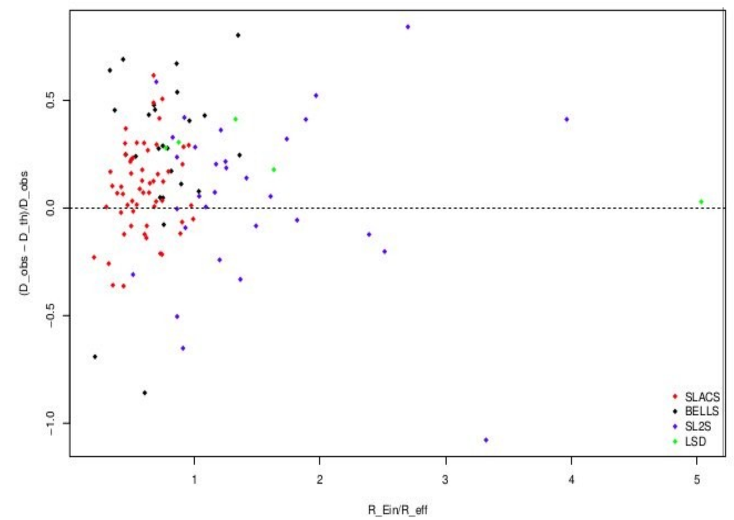
AP, Biesiada & Gavazzi, 2013

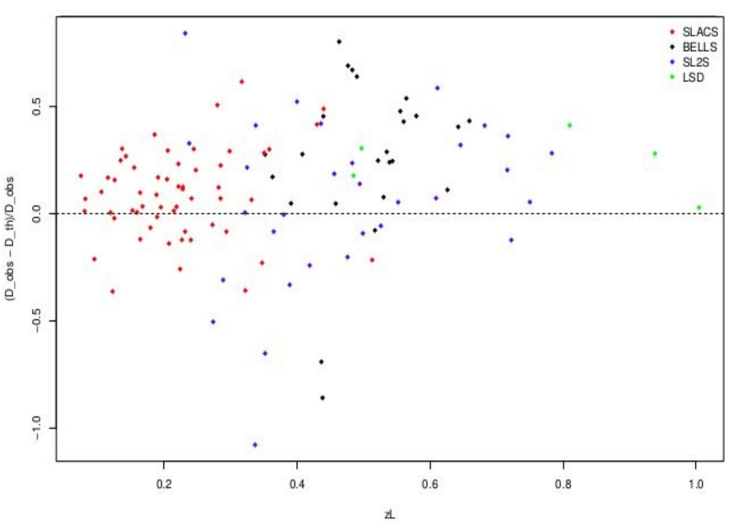
Strong lenses as standard(izable) rulers

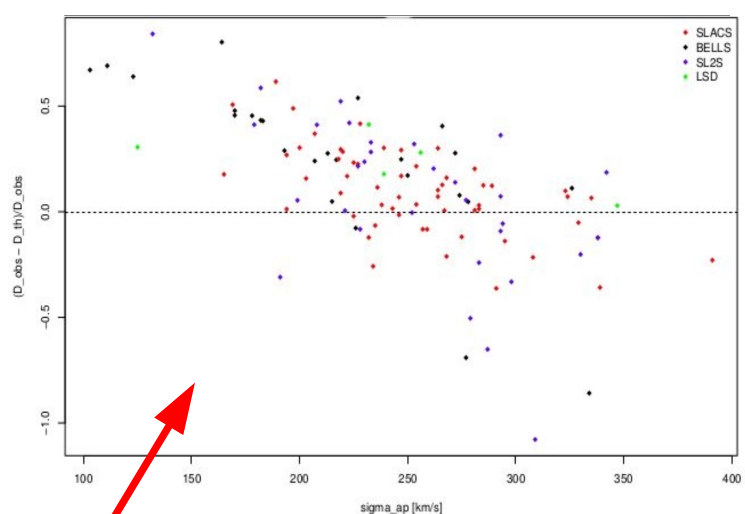
- Fourth step forward: study of systematics
  – diagnostics of residuals

$$(\mathcal{D}^{obs} - \mathcal{D}^{th})/\mathcal{D}^{obs}$$









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noticeable anti-correlation (correlation coeff. ca. -0.6)

Strong lenses as standard(izable) rulers

- Fourth step forward: study of systematics – further discussion.

(correlation coeff. ca. -0.6)

  - Noticeable anti-correlation visible in residuals as a function of the velocity dispersion is especially pronounced for lenses with σ0 < 230 km/s.
    If one excluded small velocity dispersion lenses the result would be comparable to other diagnostics discussed.

elliptical galaxies with smaller observed velocity dispersions are more centrally concentrated

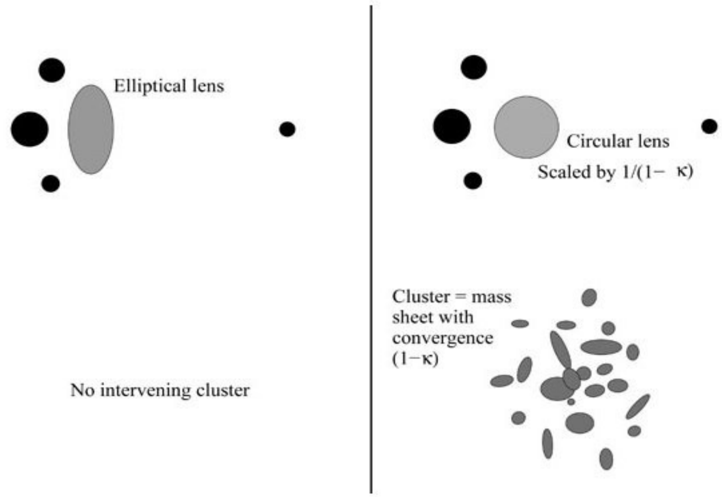
[Shu et al. 2014]

(scatter at the level of +/-50%)

  - Individual properties of lenses (environment, deviation from spherical symmetry) are crutial for our method (not considered here)

  - „mass-sheet degeneracy” problem

contamination of secondary lenses – clumps of matter along or near the line of sight



[Falco, Gornstein,Shapiro, 1985]

[Schneider&Sluse, 2013]

after Courbin
[http://ned.ipac.caltech.edu/level5/March03/Courbin/]

Conclusions and prospects:

- Our analysis demonstrates that strong gravitationally lensed systems can already now be used to probe cosmological parameters, especially the cosmic equation of state for dark energy.

- Further developments of this idea needed

sources of systematics: **[Koopmans et al. 2005, 2006]**

- in our analisys power-law index γ should be understood as an effective descriptor capturing both the density profile and anisotropy parameter of velocity dispertions (β)

[Barnabe, Spiniello & Koopmans, 2014]

- three-dimensional shape of galaxies (prolatness/oblatness) **[Chae et al. 2003]**

- influence of the line-of-sight contamination

- Careful choice of the sample in terms of lens and source redshifts will allow for cosmological analysis in a complementary way

breaking degeneracy between dark energy parameters

[Piórkowska et al. 2011]

Thank you for your attention

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