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Cosmology with Strong Lensing Systems

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&

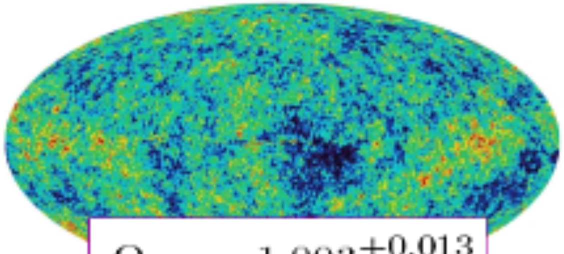
Biesiada, Cao, Covone, Gavazzi, Godlowski, Pan, Piórkowska, Sereno , Yu

Cosmology with strong lensing systems

- Cosmology from strong lensing systems
  S.Cao, M.Biesiada, R.Gavazzi, A.Piórkowska, Z-HZ 2015 ApJ 806, 185
- Testing the dark energy with gravitational lensing statistics
  S.Cao, G.Covone, Z-HZ 2012 ApJ 755, 31
- Constraints on cosmological models from lens redshift data
  S. Cao & Z-HZ 2012 A&A 538, A43
- Constraints on cosmological models from strong GL systems
  S. Cao, Y. Pan, M. Biesiada, W. Godlowski, Z-HZ 2012 JCAP 03, 016
- Testing and selecting dark energy models with lens redshift data
  S. Cao & Z-HZ 2011 PRD 84, 023005
- Combining optical and X-ray observations of galaxy clusters to constrain cosmological parameters
  H. Yu & Z-HZ 2011 RAA 84, 023001
- Testing the DGP model with gravitational lensing statistics
  Z-HZ & M. Sereno 2008 A&A 487, 831

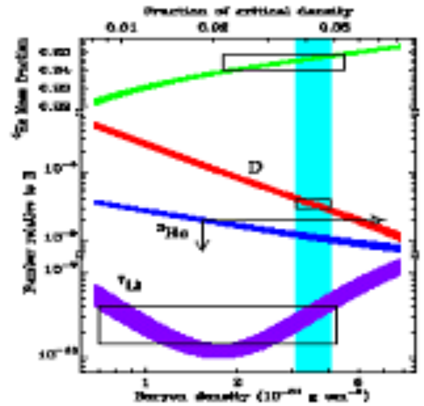
Pilars of Modern Cosmology

CMBR



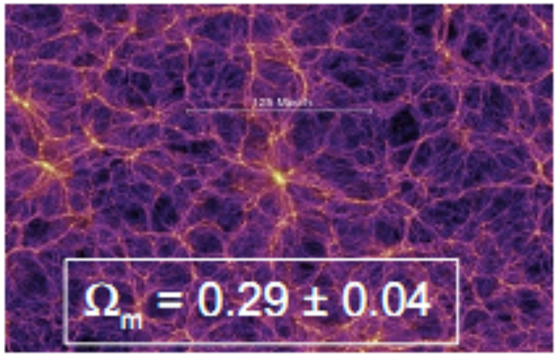
$$\Omega_{\mathrm{tot}} = 1.003^{+0.013}_{-0.017}$$

BBN



$\Omega_b = 0.042$

LSS



$\Omega_m = 0.29 \pm 0.04$

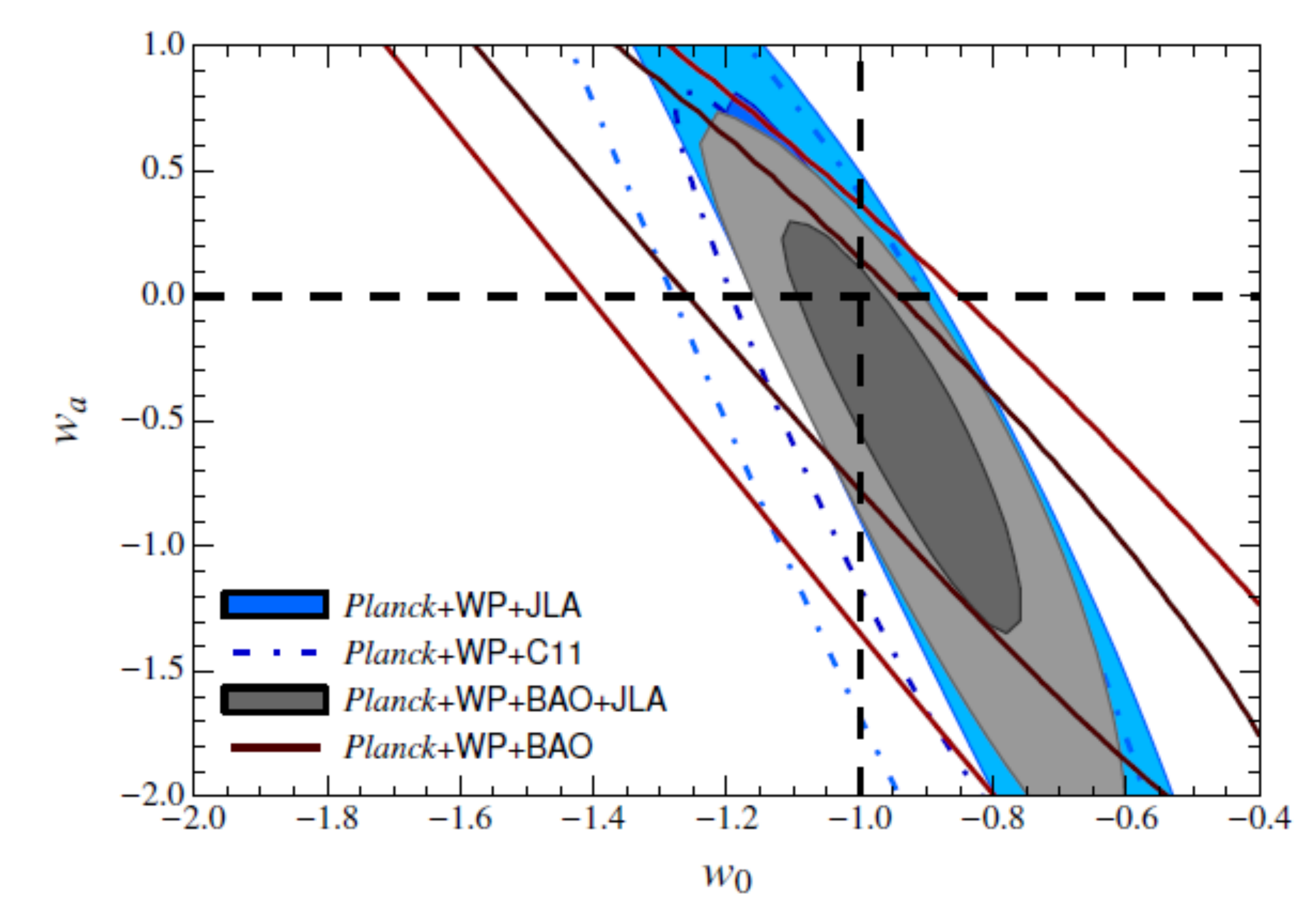
SNIa on high redshifts

Supernova 1994D and the Unexpected Universe

30.12.1998

Credit: High Z Supernova Search Team, HST, NASA

Gravitational Lensing



Betoule, et al. (2014)

Cosmology with strong lensing systems

- Cosmology from time delay
  - Strong lensing time delay challenge (TDC)

- Cosmology from standard lensing statistics
- Cosmology from lens redshift distributions
- Cosmology from D_{ds}/D_s of strong lensing systems

Basics of gravitational lensing

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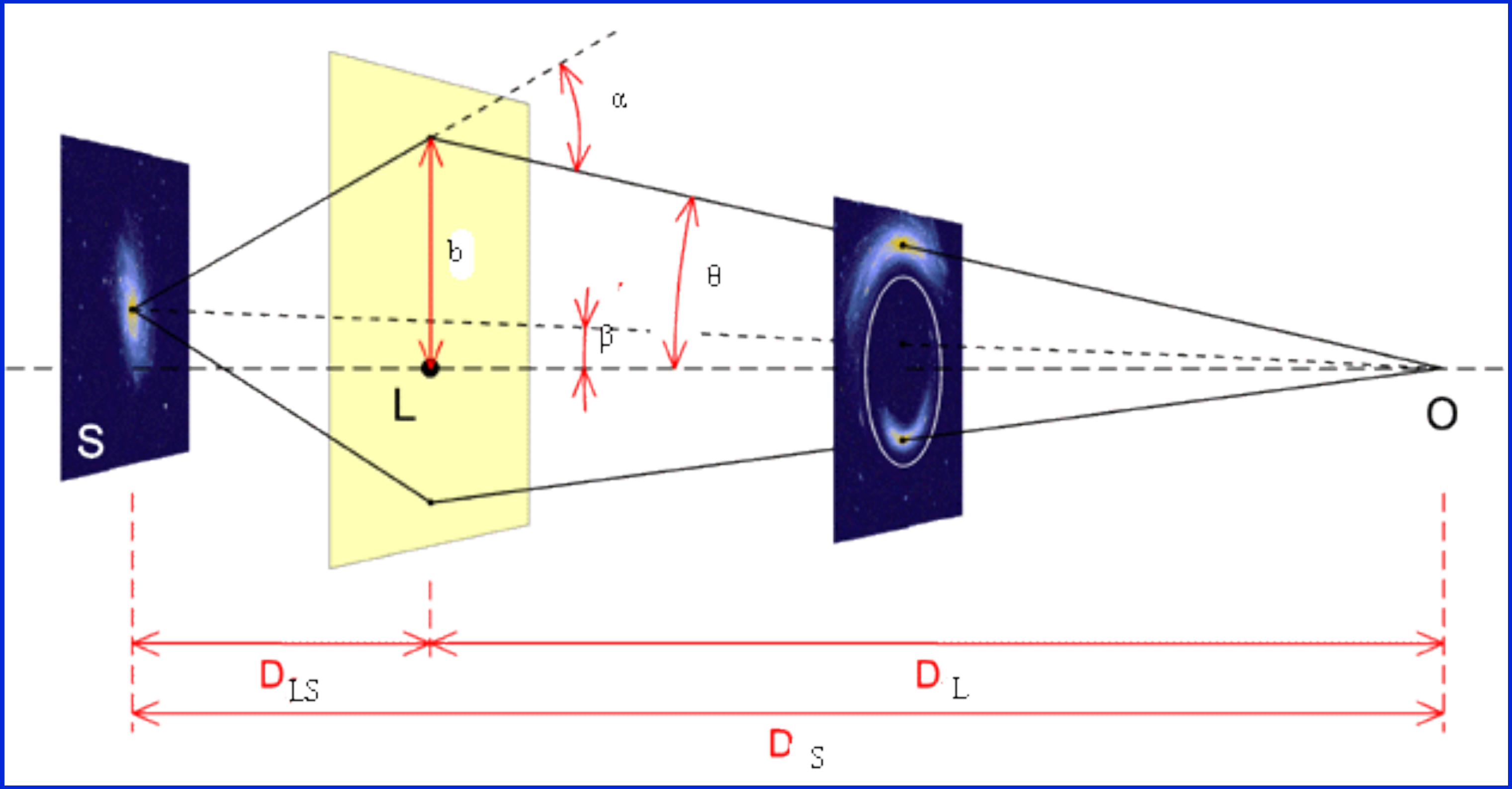
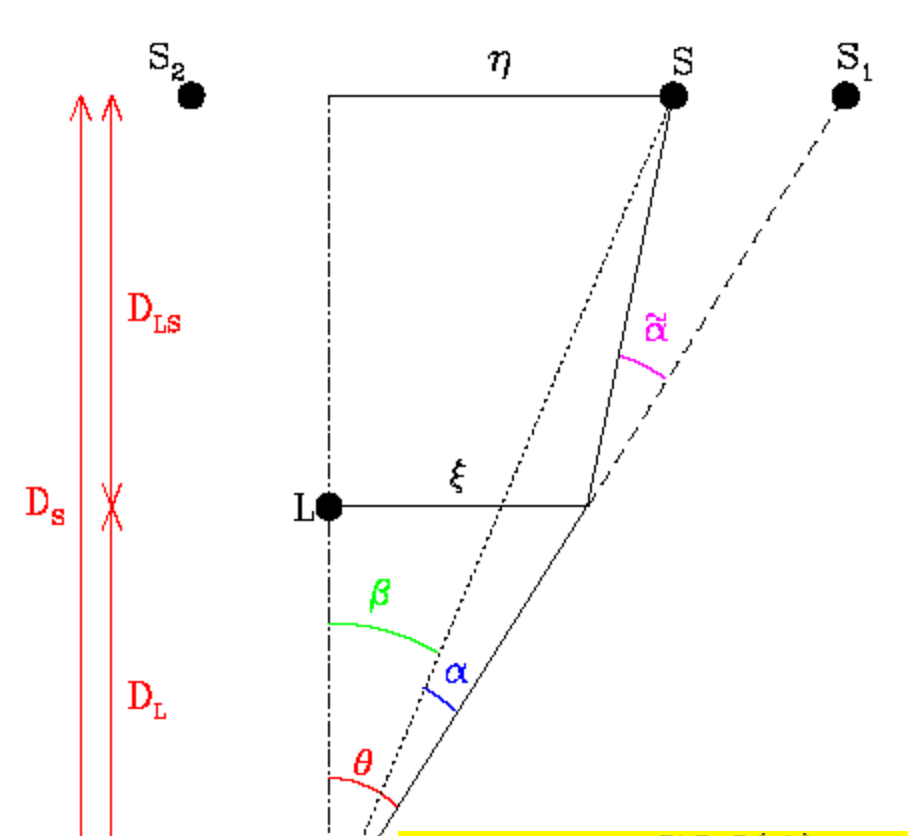
- Light rays are deflected by gravity.
  - One consequence of Einstein's General Relativity



Lens equation

Lens equation relates true source position ***β*** to the observed image position ***θ***



$$\tilde{\alpha}(\xi) = \frac{4GM(\xi)}{c^2}\frac{1}{\xi},$$

$$\theta D_{\rm S} = \beta D_{\rm S} + \tilde{\alpha} D_{\rm LS}$$

$$\alpha(\theta) = (D_{LS}/D_S)\tilde{\alpha}(\theta)$$

$$\beta = \theta - \alpha(\theta)$$

$$\vec{\beta} = \vec{\theta} - \vec{\alpha}(\vec{\theta})$$

Multiple images occur when lens equation has multiple solutions

Lens equation: Singular Isothermal Sphere (SIS)

$$\rho(r) = \frac{\sigma^2}{2\pi G}\frac{1}{r^2}, \tag{19}$$

where σ is the velocity dispersion and r is the distance from the galaxy centre. From the geometrical relations between the image position θ, source position β and lens, one gets the lensing equation:

$$\beta = \theta - \frac{D^{A}_{LS}}{D^{A}_{S}}\alpha. \tag{20}$$

For a SIS lens, the deflection angle is $\alpha = 4\pi(\sigma/c)^2$, which is independent of the impact parameter. The angular Einstein radius is defined as

$$\theta_E = 4\pi\left(\frac{\sigma}{c}\right)^2 \frac{D^{A}_{LS}}{D^{A}_{S}}.$$

$$D^{A}(z_1, z_2) = \frac{1}{1+z_2}\int_{z_1}^{z_2}\frac{dz}{H(z)}$$

Basics of gravitational lensing statistics

- Cosmological constraints (Ω_m, Ω_x, w_x)
- Gravitational lensing statistics
  - (e.g., Turner et al. 1984; Fukugita et al. 1992; Kochanek 1993; Chae 2007; Oguri et al. 2008; Zhu et al. 2008)

probability = distance to the source
× number density of galaxies
× multiple-imaging cross section
× magnification bias

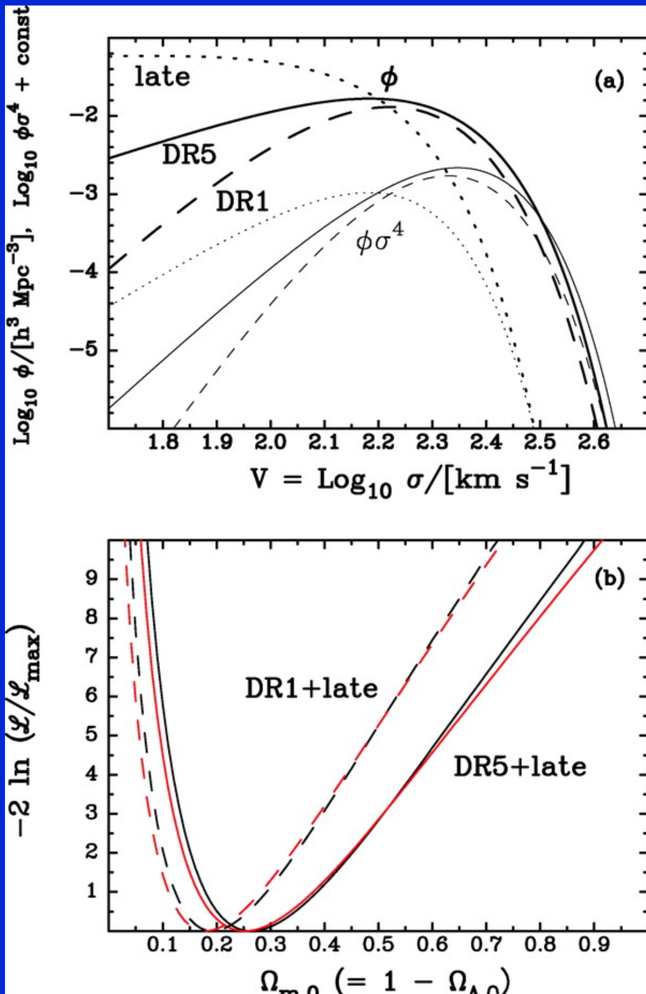
Number density of galaxies

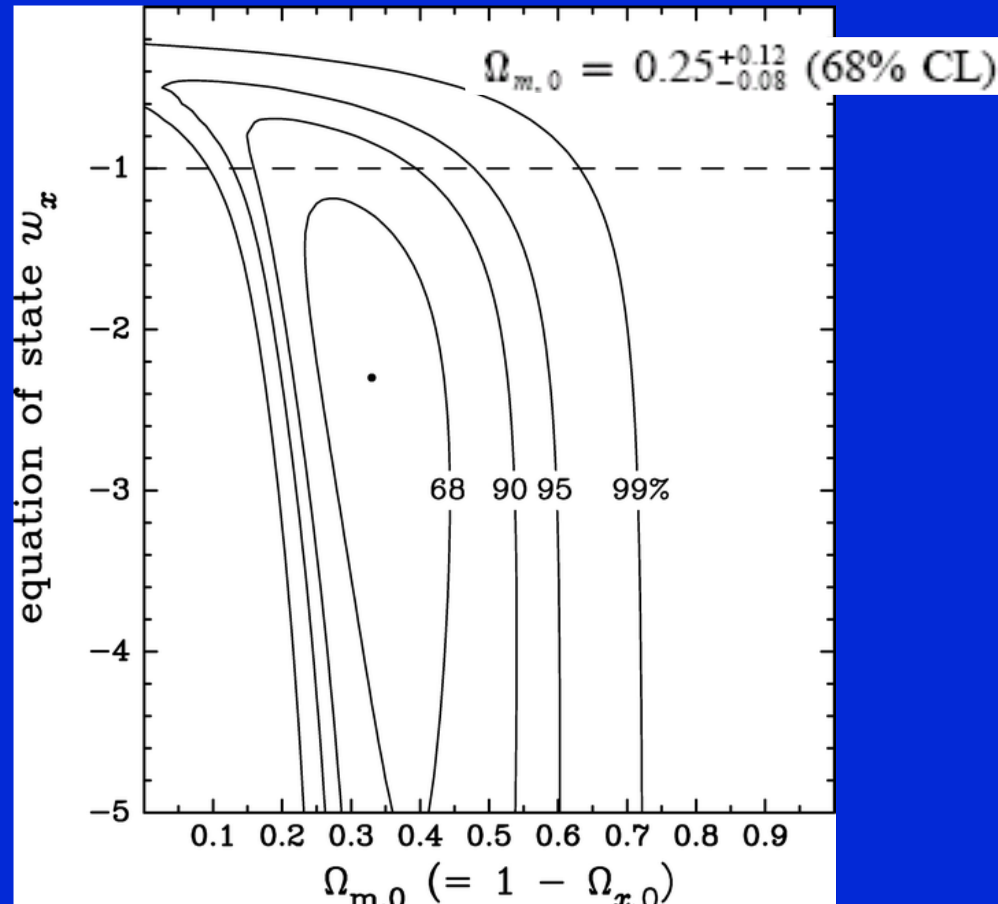
$$dn = \phi(\sigma)d\sigma = \phi_* \left(\frac{\sigma}{\sigma_*}\right)^{\alpha} \exp\left[-\left(\frac{\sigma}{\sigma_*}\right)^{\beta}\right] \frac{\beta}{\Gamma(\alpha/\beta)} \frac{d\sigma}{\sigma},$$

$$\begin{aligned}(\phi_*,\ \sigma_*,\ \alpha,\ \beta)_{\rm DR1} = {} & [(4.1 \pm 0.3) \times 10^{-3}\ h^3\ \mathrm{Mpc}^{-3},\\ & 88.8 \pm 17.7\ \ \mathrm{km\,s^{-1}},\\ & 6.5 \pm 1.0,\ \ 1.93 \pm 0.22],\end{aligned}$$

$$\begin{aligned}(\phi_*,\ \sigma_*,\ \alpha,\ \beta)_{\rm DR5} = {} & [8.0 \times 10^{-3}\ h^3\ \mathrm{Mpc}^{-3},\\ & 161 \pm 5\ \ \mathrm{km\,s^{-1}},\\ & 2.32 \pm 0.10,\ \ 2.67 \pm 0.07].\end{aligned}$$

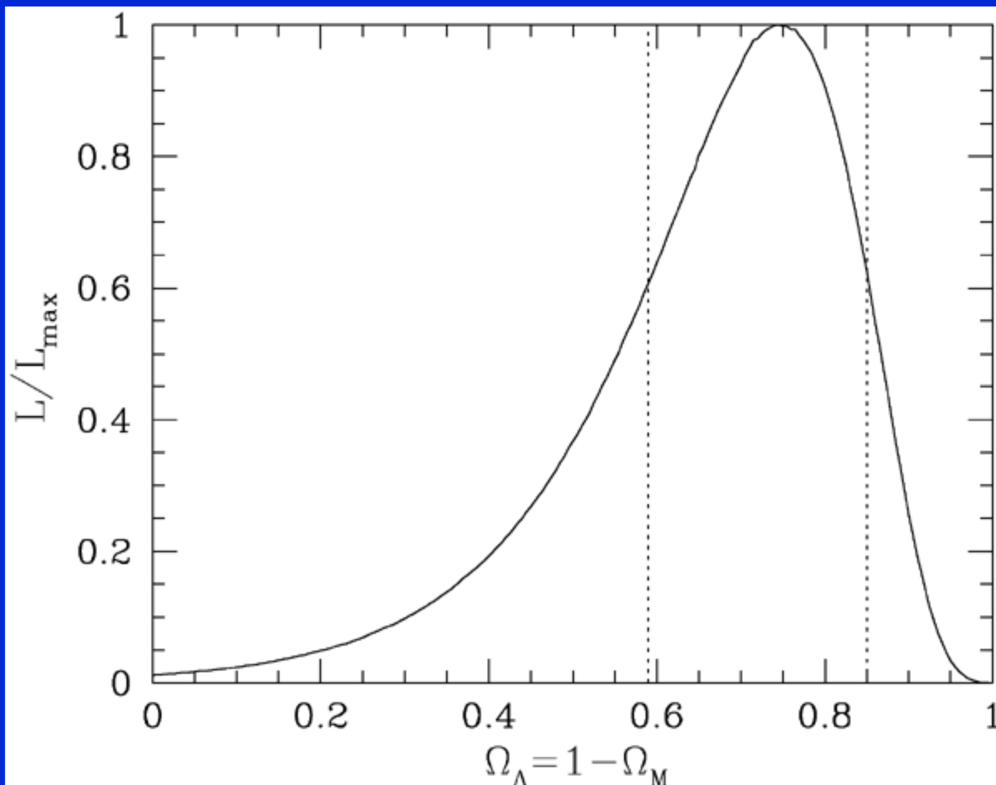
Cosmological constraints: Chae 2007

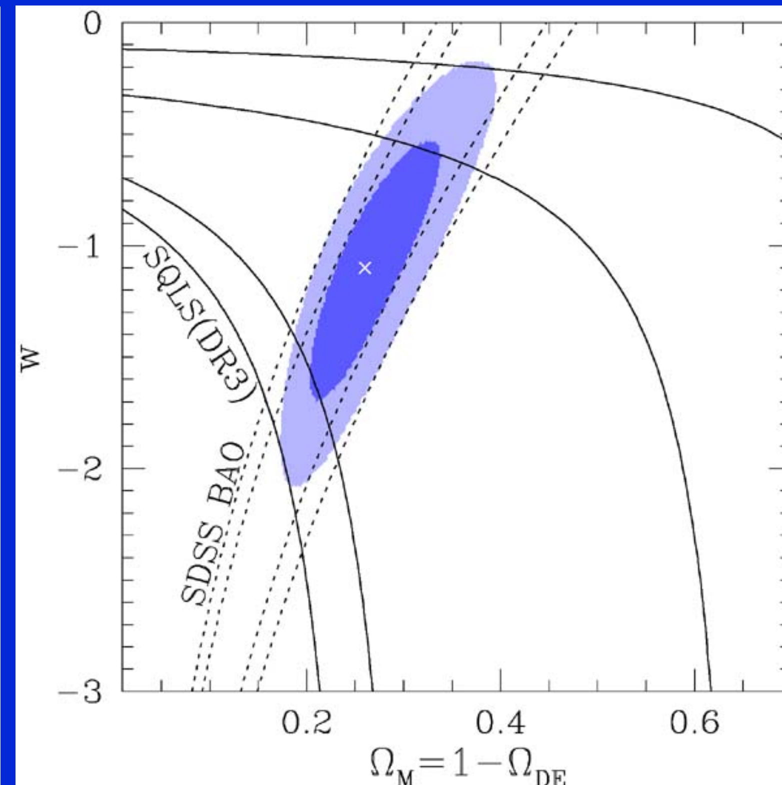




$w_x < -1.2$ ($w_x < -0.5$) at the 68% CL (95% CL)

Cosmological constraints: Oguri et al. 2008





$$\Omega_M = 0.26^{+0.07}_{-0.06}(\mathrm{stat.})^{+0.03}_{-0.05}(\mathrm{syst.}) \text{ and } w = -1.1 \pm 0.6(\mathrm{stat.})^{+0.3}_{-0.5}(\mathrm{syst.})$$

Cosmological constraints: Zhu & Sereno 2008

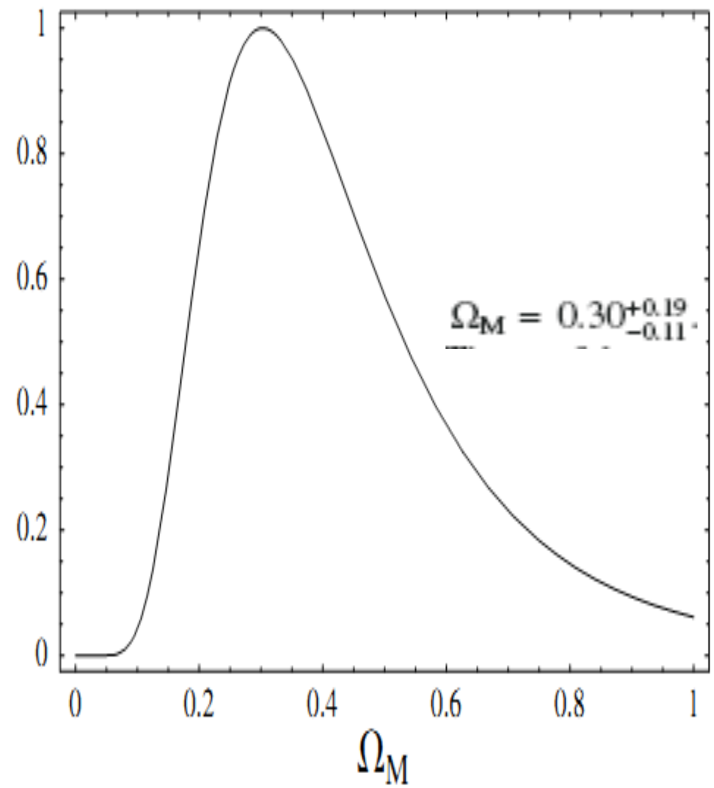


Fig. 1. Normalized likelihood, $\mathcal{L}/\mathcal{L}_{max}$, as a function of Ω_M for a flat geometry, $\Omega_K = 0$.

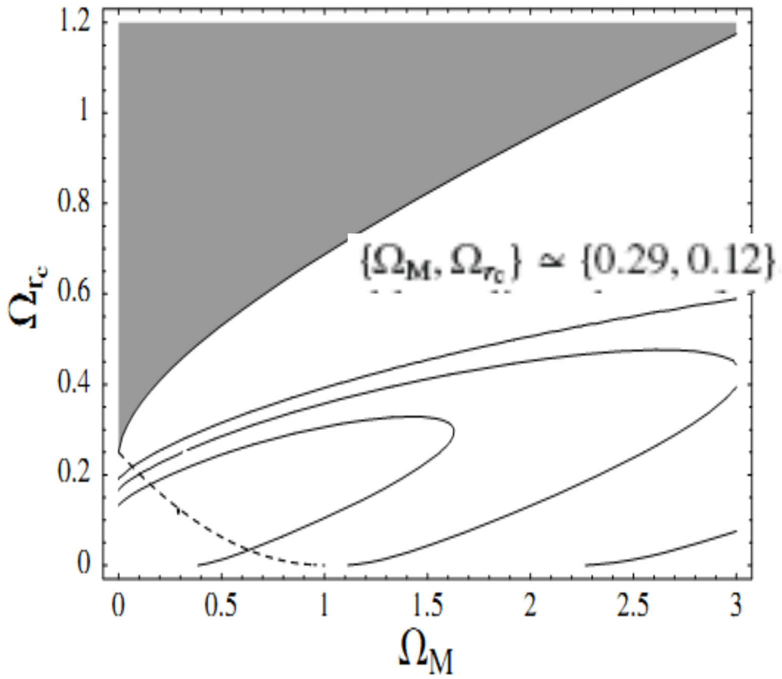


Fig. 2. Normalized likelihood, $\mathcal{L}/\mathcal{L}_{max}$, in the $\Omega_M - \Omega_{r_c}$ plane. The dot shows the best fit model and the contours denote the 68.3%, 95.4% and 99.7% confidence limits for two parameters. The dashed line represents the locus of flat models of universe ($\Omega_K = 0$); bouncing models in the upper-left shaded region do not have big bang.

Cosmology with strong lensing systems

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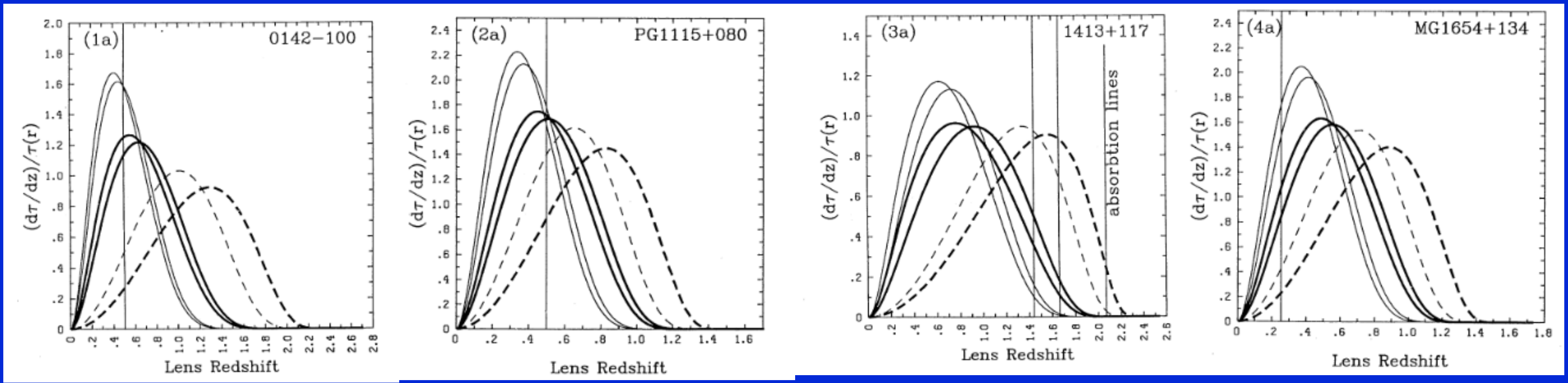
Lens redshift test: Kochanek 1992

The differential optical depth to lensing per unit redshift is

$$\frac{d\tau}{dz} = n(\theta, z)(1+z)^3 S \frac{cdt}{dz}, \qquad (1)$$

where $n(\theta, z)$ is the comoving number density of lenses that have critical angular radius for lensing θ at redshift z, S is the cross section for lensing, and cdt/dz is the proper distance interval.



Number density of galaxies

$$dn = \phi(\sigma)d\sigma = \phi_* \left(\frac{\sigma}{\sigma_*}\right)^{\alpha} \exp\left[-\left(\frac{\sigma}{\sigma_*}\right)^{\beta}\right] \frac{\beta}{\Gamma(\alpha/\beta)} \frac{d\sigma}{\sigma},$$

$$(\phi_*,\ \sigma_*,\ \alpha,\ \beta)_{\mathrm{DR1}} = [(4.1 \pm 0.3) \times 10^{-3}\ h^3\ \mathrm{Mpc}^{-3},\ 88.8 \pm 17.7\ \mathrm{km\ s}^{-1},\ 6.5 \pm 1.0,\ 1.93 \pm 0.22],$$

$$(\phi_*,\ \sigma_*,\ \alpha,\ \beta)_{\mathrm{DR5}} = [8.0 \times 10^{-3}\ h^3\ \mathrm{Mpc}^{-3},\ 161 \pm 5\ \mathrm{km\ s}^{-1},\ 2.32 \pm 0.10,\ 2.67 \pm 0.07].$$

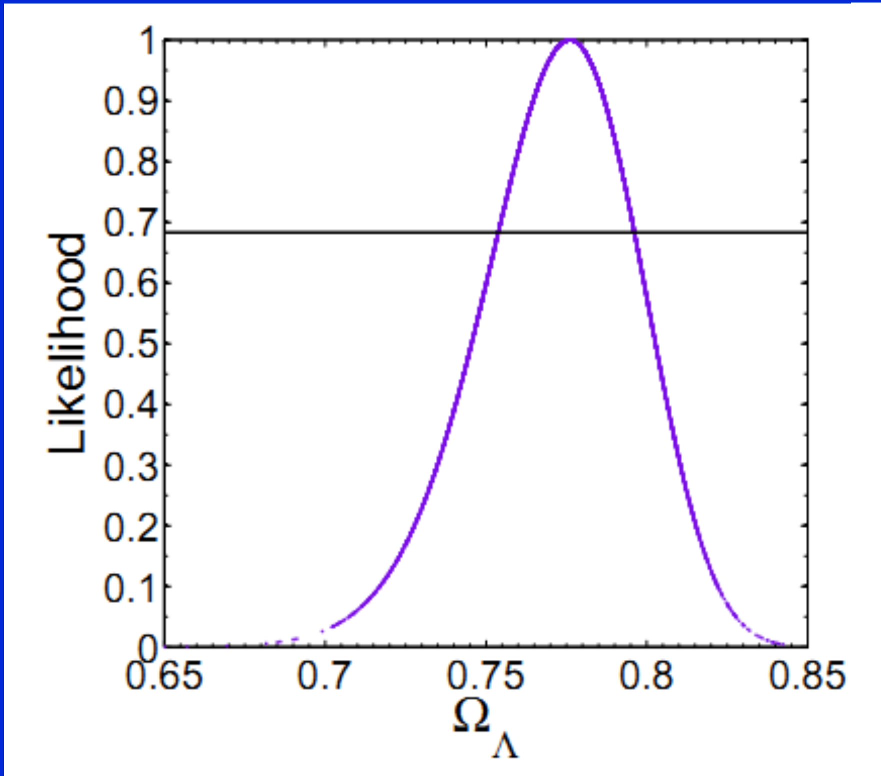
$$(\phi_*,\ \sigma_*,\ \alpha,\ \beta)_{\mathrm{late}} = [1.13 \times 10^{-1}\ h^3\ \mathrm{Mpc}^{-3},\ 133\ \mathrm{km\ s}^{-1},\ 0.3,\ 2.91], \qquad (9)$$

S. Cao & Z.-H. Zhu 2011

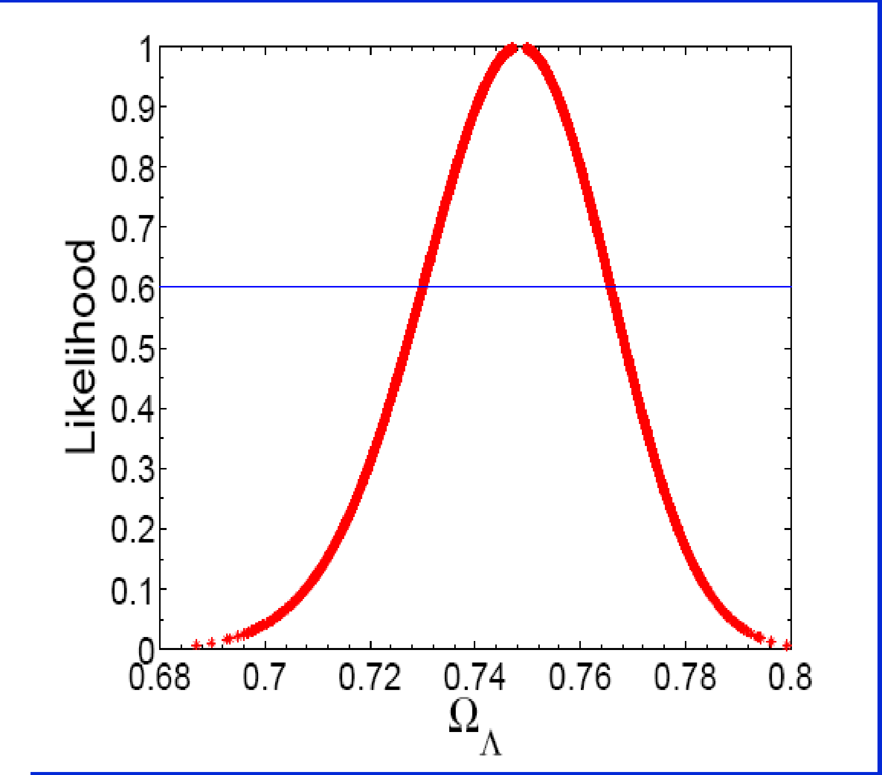
Source	Survey	Source redshift (z_s)	Lens redshift (z_l)	Maximum image separation ($''$)	Number of images	Lensing galaxy(-ies) type	Reference
B0414+054	CLASS	2.64	0.96	2.03	4	early-type	1, 2
B0712+472†	CLASS	1.34	0.41	1.27	4	early-type	1, 2
B1030+074	JVAS	1.535	0.599	1.56	2	2Gs (E+?) G2 ignored	1, 2
B1422+231†	JVAS	3.62	0.34	1.28	4	early-type	1, 2
J1632−0033	PANELS	3.42	1	1.47	2	early-type	1, 2
J1838−3427	PANELS	2.78	0.36	1.0	2	early-type	1, 2
B1933+503†	CLASS	2.62	0.755	1.17	4	[illegible]	[illegible]
Q0142-100	Snapshot	2.72	0.49	2.23	2	[illegible]	[illegible]
PG1115+080	Snapshot	1.72	0.31	2.43	4	early-type	1, 2
B1938+666	CLASS	1.8	0.88	0.91	4+2+R	early-type	1, 2, 4
J0246−0825	SDSS	1.685	0.723	1.04	2	early-type	5, 6
SBS0909+523	SDSS	1.377	0.83	1.11	2	early-type	7, 8
J0924+0219	SDSS	1.523	0.393	1.78	4	early-type	9, 10, 11
J1226−0006	SDSS	1.125	0.517	1.24	2	early-type	12, 13
J1335+0118	SDSS	1.571	0.440	1.57	2	early-type	14, 13
Q0957+561	SDSS	1.413	0.36	6.17	2	early-type	15, 16
J1332+0347	SDSS	1.438	0.191	1.14	2	early-type	17
J1524+4409	SDSS	1.210	0.310	1.67	2	early-type	18
0712+472	CLASS	1.34	0.41	1.27	4	early-type	19
B1359+154	CLASS	3.24	1	1.67	6	3Gs (E+?+?)	1, 2
B2045+265	CLASS	4.3	0.87	1.91	4	2Gs (E+?)	2, 20
B1608+656	CLASS	1.39	0.64	2.08	4	2Gs (E+L)	2, 21
B0128+437	CLASS	3.12	1.15	0.55	4	unknown	6, 14
B1152+199†	CLASS	1.019	0.439	1.56	2	2Gs [?(E)a+?] G2 ignored	1, 2
Q1208+1011	Snapshot	3.80	1.13	0.48	2	unknown	5, 7, 8
J1620+1203	SDSS	1.158	0.398	2.765	2	unknown	22
B0218+357	CLASS	0.96	0.68	0.33	2	late-type	1, 2
B1600+434	CLASS	1.59	0.41	1.38	2	late-type	1, 2
J0134.0931	PANELS	2.23	0.76	0.68	5+2	2Gs (L?+L?)	1, 2, 23

Table 1. Summary of Strongly-lensed Sources. The properties of the strongly lensed systems from the Snapshot optical survey and the CLASS (Browne et al. 2003) and PANELS radio surveys are revised from Kochanek (1996) and Chae (2003, 2005). References are the following: 1 - the CASTLES website (http://cfa-www.harvard.edu/castles/); 2 - Chae (2003, 2005); 3 - Kochanek (1996); 4 - King et al. (1997); 5 - Inada et al. (2005) 6 - Eigenbrod et al. (2007); 7 - Oscoz et al. (1997); 8 - Lubin et al. (2000); 9 - Inada et al. (2003a); 10 - Ofek et al. (2003); 11 - Eigenbrod et al. (2006a); 12 - Inada et al. (2003b); 13 - Eigenbrod et al. (2006b); 14 - Oguri et al. (2004); 15 - Walsh et al. (1979); 16 - Young et al. (1981); 17 - Morokuma et al. (2007); 18 - Oguri et al. (2008); 19 - Fassnacht & Cohen (1998); 20 - McKean et al. (2007); 21 - Surpi & Blandford (2003); 22 - Kayo et al. (2009); 23 - Winn et al. (2001)

Combined with BAO and BAO +CMB



$\Omega_\Lambda = 0.78^{+0.02}_{-0.03}$



$\Omega_\Lambda = 0.75^{+0.02}_{-0.02}$

S. Cao & Z.-H. Zhu 2011

Testing and selecting dark energy models

Table 1: Summary of models

Model	Abbreviation	Model parameters	k
Cosmological constant	Λ	Ω_Λ	1
Constant w	w	Ω_x, w	2
Interacting dark energy ...	IDE	Ω_x, w, ξ	3
Dvali-Gabadadze-Porrati .	DGP	Ω_m	1
Generalized Chaplygin gas	GCG	A_s, γ	2
Affine equation of state ...	AEOS	Ω_x, α	2
Ricci dark energy	RDE	Ω_m, β	2

S. Cao & Z.-H. Zhu 2012

Selecting models: BIC

The BIC, also known as the Schwarz information criterion (Schwarz et al. 1978), is given by

$$BIC = -2 \ln \mathcal{L}_{max} + k \ln N, \quad (8)$$

where $\mathcal{L}_{max}$ is the maximum likelihood, k is the number of parameters, and N is the number of data points used in the fit.

A difference in BIC (ΔBIC) of 2 is considered positive evidence against the model with the higher BIC;
A ΔBIC of 6 is considered strong evidence.

Testing and selecting dark energy models

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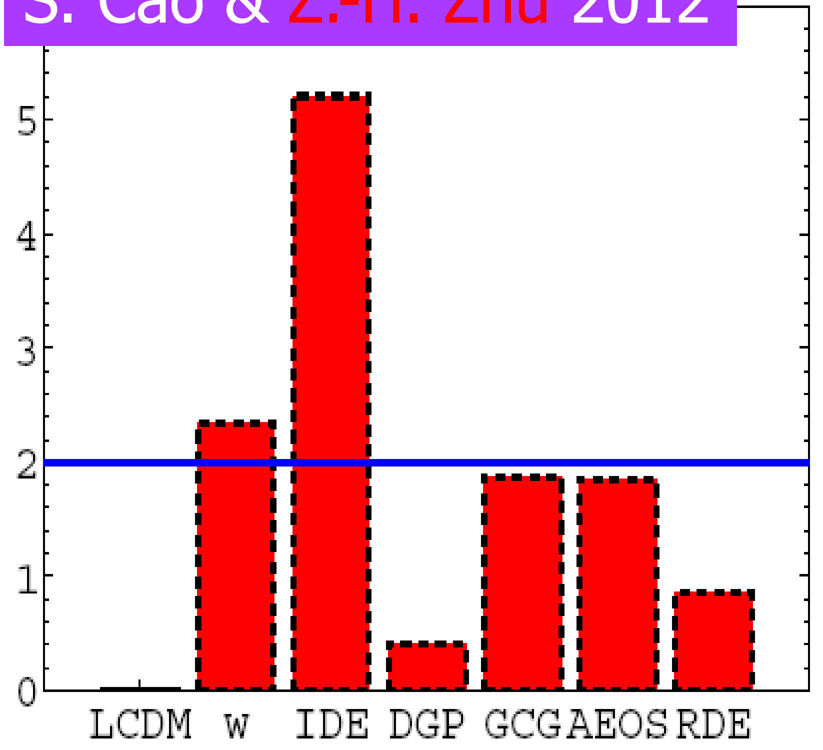

FIG. 8.— Graphical representation of the results in Table 2: the values of ΔBIC for each model. The order of models from left to right is the same as the order in Table 2.

Table 1
Summary of the Properties of the Strongly Lensed Systems, with the SLACS Lenses Written in Bold

Lens Name	z_s	z_l	$\Delta\theta('')$	Ref	Lens Name	z_s	z_l	$\Delta\theta('')$	Ref
J0029−0055	0.9313	0.227	1.92	1	J221929−001743	1.0232	0.2888	1.472	4
J0037−0942	0.6322	0.1955	2.943	1, 2	J022511−045433	1.1988	0.2380	3.54	4
J0044+0113	0.1965	0.1196	1.58	1, 3	J022610−042011	1.232	0.4943	2.306	4
J0109+1500	0.5248	0.2939	1.38	1	MG2016	3.263	1.004	3.12	5
J0216−0813	0.5235	0.3317	2.303	1, 2, 3	HST15433+5352	2.092	0.497	1.18	5, 6, 7
J0252+0039	0.9818	0.2803	2.08	1	CY2201−3201	3.900	0.320	0.830	5, 6, 7
J0330−0020	1.0709	0.3507	2.2	1, 3	CFRS03.1077	2.941	0.938	2.48	5, 6, 7
J0405−0455	0.8098	0.0753	1.6	1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
J0728+3835	0.6877	0.2058	2.5	1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
J0737+3216	0.5812	0.3223	2.065	2, 3	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
J0822+2652	0.5941	0.2414	2.34	1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
J0841+3824	0.6567	0.1159	2.82	1	MG0414+0534	2.64	0.9584	2.12	16, 17
J0912+0029	0.3239	0.1642	3.23	1, 2	HE0435−1223	1.689	0.4	2.6	18
J0935−0003	0.467	0.3475	1.74	1, 3	HE0512−3329	1.565	0.9313	0.644	19
J0936+0913	0.588	0.1897	2.18	1	B0712+472	1.339	0.406	1.28	20
J0946+1006	0.6085	0.2219	2.76	1	MG0751+2716	3.200	0.3502	0.7	17
J0955+0101	0.3159	0.1109	1.82	1	HS0818+1227	3.115	0.39	2.55	21
J0956+5100	0.4699	0.2405	2.642	1, 2	SBS0909+523	1.377	0.830	1.10	22
J0959+4416	0.5315	0.2369	1.92	1, 2	RXJ0911+0551	2.80	0.77	3.25	23
J0959+0410	0.535	0.126	1.995	1	FBQ0951+2635	1.24	0.25	1.10	25
J1016+3859	0.4394	0.1679	2.18	1	BRI0952−0115	4.50	0.41	0.99	26
J1020+1122	0.553	0.2822	2.4	1	J100424.9+122922	2.65	0.95	1.54	27
J1023+4230	0.696	0.1912	2.82	1	LBQS1009−0252	2.74	0.88	1.53	28
J1029+0420	0.6154	0.1045	2.02	1	Q1017−207	2.545	1.085	0.849	29
J1032+5322	0.329	0.1334	2.06	1	FSC10214+4724	2.286	0.914	1.59	30
J1103+5322	0.7353	0.1582	2.04	1, 3	B1030+071	1.535	0.599	1.56	20
J1106+5228	0.4069	0.0955	2.46	1, 3	HE1104−1805	2.32	0.729	3.19	31
J1112+0826	0.6295	0.273	2.98	1, 3	PG1115+080	1.72	0.311	2.42	32
J1134+6027	0.4742	0.1528	2.2	1	B1152+200	1.019	0.439	1.56	33
J1142+1001	0.5039	0.2218	1.96	1, 3	Q1208+101	3.80	1.1349	0.47	34
J1143−0144	0.4019	0.106	3.36	1	HST14113+5211	2.811	0.465	2.26	22
J1153+4612	0.8751	0.1797	2.1	1	HST14176+5226	3.40	0.81	3.25	35
J1204+0358	0.6307	0.1644	2.62	1, 3	B1422+231	3.62	0.339	1.28	32
J1205+4910	0.4808	0.215	2.44	1	SBS1520+530	1.855	0.717	1.568	8, 36
J1213+6708	0.6402	0.1229	2.84	1, 3	MG1549+3047	1.17	0.11	2.3	37
J1218+0830	0.7172	0.135	2.9	1, 3	B1600+434	1.589	0.4144	1.38	20
J1250+0523	0.7953	0.2318	2.26	1, 2	B1608+656	1.394	0.630	2.27	38
J1330−0148	0.7115	0.0808	1.706	1, 2	PMNJ1632−0033	3.424	1.0	1.47	39
J1402+6321	0.4814	0.2046	2.775	1, 2	FBQ1633+3134	1.52	0.684	0.66	40
J1403+0006	0.473	0.1888	1.66	1	MG1654+1346	1.74	0.254	2.1	41
J1416+5136	0.8111	0.2987	2.74	1, 3	PKS1830−211	2.51	0.886	0.99	42
J1420+6019	0.5351	0.0629	2.097	1, 2	PMNJ1838−3427	2.78	0.31	1.00	43
J1430+4105	0.5753	0.285	3.04	1	B1933+507	2.63	0.755	1.00	44
J1432+6317	0.6643	0.123	2.52	1, 3	B2045+265	1.28	0.8673	2.2	45
J1436−0000	0.8049	0.2852	2.24	1, 3	HE2149−2745	2.03	0.50	1.69	8, 46
J1443+0304	0.4187	0.1338	1.62	1, 3	Q2237+0305	1.695	0.0394	1.82	47
J1451−0239	0.5203	0.1254	2.08	1, 3	SDSS0246−0825	1.68	0.724	1.2	48
J1525+3327	0.7173	0.3583	2.62	1, 3	B0850+054	3.93	0.59	0.68	49
J1531−0105	0.7439	0.1596	3.42	1, 3	SDSS0903+5028	3.605	0.388	3.0	50
J1538+5817	0.5312	0.1428	2	1, 3	HE1113−0641	1.235	0.75	0.88	51
J1621+3931	0.6021	0.2449	2.58	1, 3	Q1131−1231	0.658	0.295	3.8	52
J1627−0053	0.5241	0.2076	2.42	1, 2	SDSS1138+0314	2.44	0.45	1.34	53, 54
J1630+4520	0.7933	0.2479	3.618	1, 2	SDSS1155+6346	2.89	0.176	1.96	55
J1636+4707	0.6745	0.2282	2.18	1	SDSS1226−0006	1.12	0.52	1.26	53, 54
J2238−0754	0.7126	0.1371	2.54	1, 3	WFI2033−4723	1.66	0.66	2.34	53, 55
J2300+0022	0.4635	0.2285	2.494	1, 2	HE0047−1756	1.66	0.41	1.54	56
J2303+1422	0.517	0.1553	3.278	1, 2	COSMOS5921+0638	3.15	0.551	1.6	57, 58
J2321−0939	0.5324	0.0819	3.2	1, 2	COSMOS0056+1226	0.81	0.361	2.4	57, 59
J2341+0000	0.807	0.186	2.88	1, 3	COSMOS0245+1430	0.779	0.417	3.08	57, 59
J021737−051329	1.847	0.6458	2.536	4	"Cross"	3.40	0.810	2.44	60
J141137+565119	1.420	0.3218	1.848	4	"Dewdrop"	0.982	0.580	1.52	60

S. Cao, G. Covone & Z.-H. Zhu 2012

THE ASTROPHYSICAL JOURNAL, 755:31 (13pp), 2012 August 10 doi:10.1088/0004-637X/755/1/31

TESTING THE DARK ENERGY WITH GRAVITATIONAL LENSING STATISTICS

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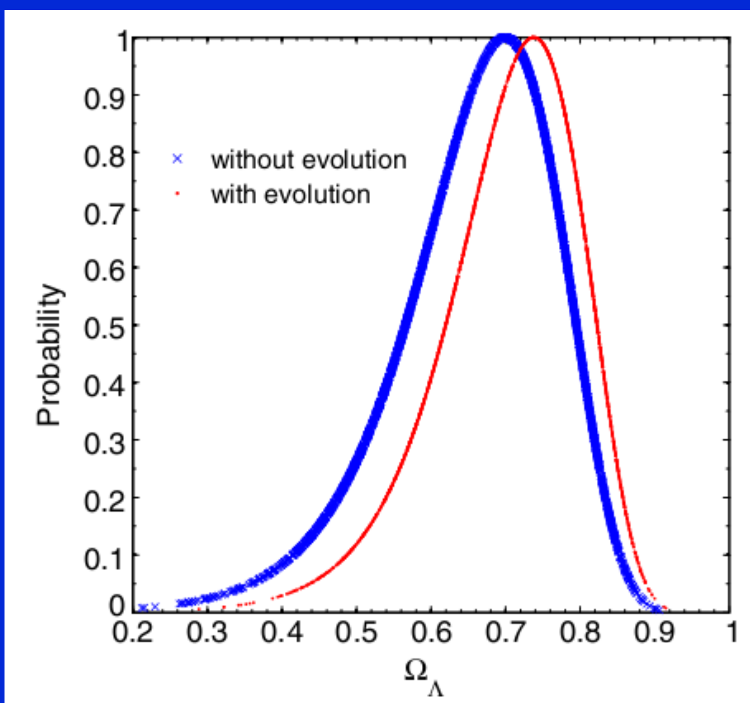
ABSTRACT

We study the redshift distribution of two samples of early-type gravitational lenses, extracted from a larger collection of 122 systems, to constrain the cosmological constant in the ΛCDM model and the parameters of a set of alternative dark energy models (XCDM, Dvali-Gabadadze-Porrati, and Ricci dark energy models), in a spatially flat universe. The likelihood is maximized for $\Omega_\Lambda = 0.70 \pm 0.09$ when considering the sample excluding the Sloan Lens ACS systems (known to be biased toward large image-separation lenses) and no-evolution, and $\Omega_\Lambda = 0.81 \pm 0.05$ when limiting to gravitational lenses with image separation $\Delta\theta > 2''$ and no-evolution. In both cases, results accounting



$$\Omega_\Lambda = 0.70 \pm 0.09$$
$$\Omega_\Lambda = 0.73 \pm 0.09$$

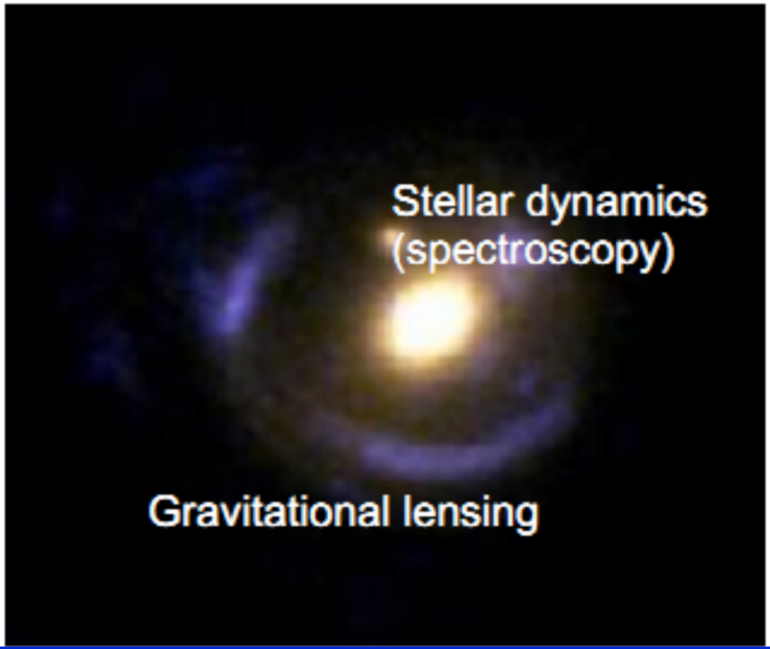
Cosmology with strong lensing systems

BEIJING NORMAL UNIVERSITY

- Cosmology from time delay
  - Strong lensing time delay challenge (TDC)

- Cosmology from standard lensing statistics
- Cosmology from lens redshift distributions
- ➡ Cosmology from D_{ds}/D_s of strong lensing systems

D_{ds}/D_s : from Einstein radius and velocity dispersion



Idea

Velocity dispersion - spectroscopy

$$\theta_E = 4\pi \left(\frac{\sigma_v}{c} \right)^2 \frac{D_{LS}}{D_S}$$

From angular separation of images

Ratio determined by cosmological models

Possible Measurement of Quintessence and Density Parameter Using Strong Gravitational Lensing Events

Toshifumi Futamase and Shijun Yoshida

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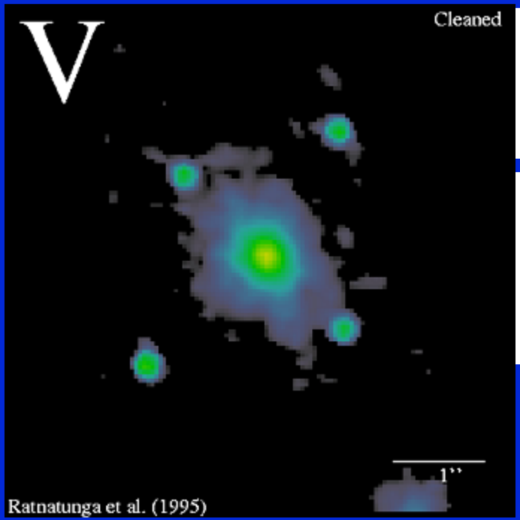
(Received December 28, 2000)

We propose a possible method of measurement of the time variability of the vacuum energy using strong gravitational lensing events. As an example we take an Einstein cross lens HST 14176+5226 and demonstrate that the measurement of the velocity dispersion with an accuracy of ± 5 km/sec may allow for the determination of the time dependence of the vacuum energy as well as the density parameter with an accuracy of order 0.1 if the lens model is fixed.



Lensing system

HST 14176+5226

z_L=0.809

z_s=3.4

ϑ_E=1.″489

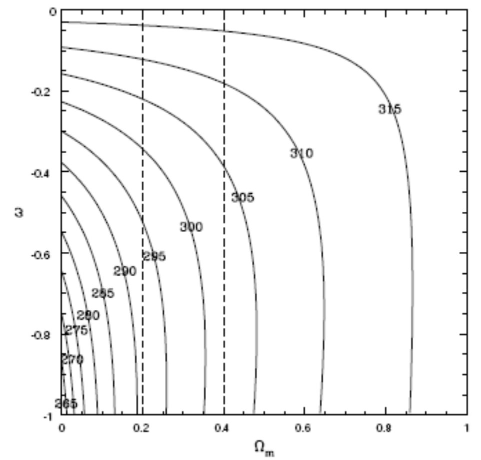


Fig. 1. Contours of constant velocity dispersion σ_v in the ω-Ω_m plane. Constant σ_v curves are drawn in steps of 5 km/sec for 265 km/sec $\le \sigma_v \le$ 315 km/sec. The dotted vertical lines correspond to $\Omega_m = 0.2$ and $\Omega_m = 0.4$.

Galaxy clusters: as cosmological probes

- Sunyaev-Zel'dovich measurements + X-ray observations
- Large sample of clusters of galaxies
- Gas mass fraction, f_{gas}
- *Lensing clusters + X-ray measurements*

Galaxy clusters: emission of X-ray

When a galaxy cluster is relaxed enough, the hydrostatic isothermal spherical symmetric β-model (Cavaliere & Fusco-Femiano, 1976) can be used to describe the intracluster medium(ICM) density profile:

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

where n_{e0} is the central electron density, β_x describes the slope, and r_c stands for the core radius.

Galaxy clusters: mass profile

Assuming all the gases are isothermal (with the temperature T_x), the gravity of relaxing cluster and its gas pressure should balance each other according to the hydrostatic equilibrium condition. With the approximation of spherical symmetry we can estimate mass distribution using gas density, which comes from x-ray luminosity fitting result.

The cluster mass profile can be given by

$$M(r) = \frac{3k_B T_X \beta_X}{G\mu m_p} \frac{r^3}{r_c^2 + r^2}, \quad (6)$$

where k_B is the Boltzmann constant, m_p is the proton mass, and $\mu = 0.6$ is the mean molecular weight (Rosati et al., 2002).

Galaxy clusters: D_{ds}/D_s

equation (6), we can derive a theoretical typical surface density, which is:

$$\Sigma_{th} = \frac{3}{2G\mu m_p}\frac{k_B T_X \beta_X}{\theta_c}\frac{1}{D_d}. \quad (7)$$

Combining the result with the critical surface mass density of lensing arcs (Schneider et al., 1992)

$$\Sigma_{ob} = \frac{c^2}{4\pi G}\frac{D_s}{D_d D_{ds}}\sqrt{\frac{\theta_t^2}{\theta_c^2}+1}. \quad (8)$$

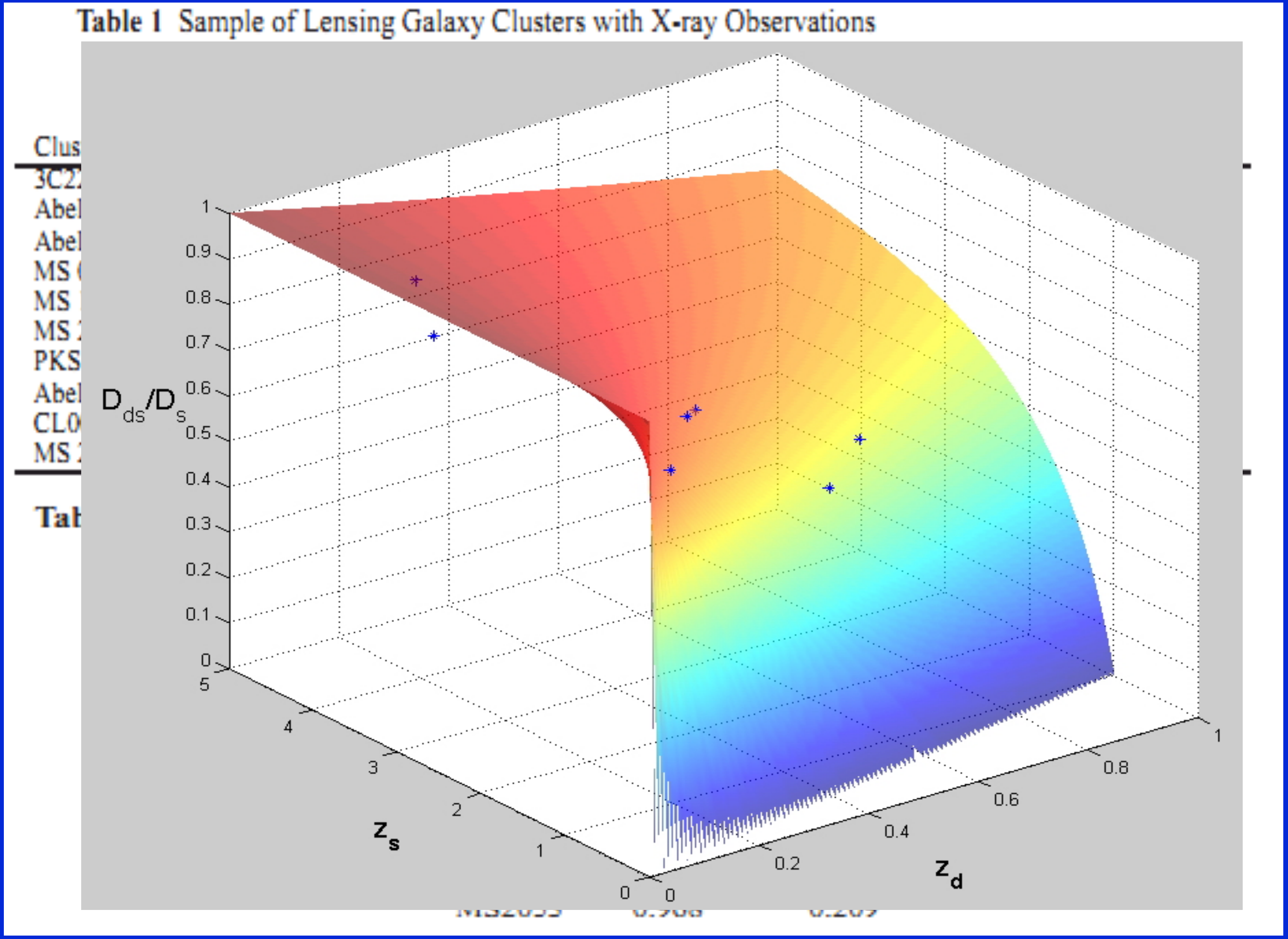
⇓

a Hubble constant independent ratio can be expressed as

$$\mathcal{D}^{obs} = \frac{D_{ds}}{D_s}\Big|_{obs} = \frac{\mu m_p c^2}{6\pi}\frac{1}{k_B T_X \beta_X}\sqrt{\theta_t^2+\theta_c^2}, \quad (9)$$

D_{ds}/D_s : data obtained

Yu & Zhu 2011



D_{ds}/D_s : more data

Bonamente et al., 2006

Table 1. Combined SLACS + LSD lens sample. The restricted sample (see text for explanation) is written in bold.

Lens ID	z_l	z_s	θ_E (arcsec)	σ_0 (km s^{-1})
SDSS J0037−0942	0.1955	0.6322	1.47	282 ± 11
SDSS J0216−0813	0.3317	0.5235	1.15	349 ± 24
SDSS J0737+3216	0.3223	0.5812	1.03	326 ± 16
SDSS J0912+0029	0.1642	0.3240	1.61	325 ± 12
SDSS J0956+5100	0.2405	0.4700	1.32	318 ± 17
SDSS J0959+0410	0.1260	0.5349	1.00	229 ± 13
SDSS J1250+0523	0.2318	0.7950	1.15	274 ± 15
SDSS J1330−0148	0.0808	0.7115	0.85	195 ± 10
SDSS J1402+6321	0.2046	0.4814	1.39	290 ± 16
SDSS J1420+6019	0.0629	0.5352	1.04	206 ± 5
SDSS J1627−0053	0.2076	0.5241	1.21	295 ± 13
SDSS J1630+4520	0.2479	0.7933	1.81	279 ± 17
SDSS J2300+0022	0.2285	0.4635	1.25	305 ± 19
SDSS J2303+1422	0.1553	0.5170	1.64	271 ± 16
SDSS J2321−0939	0.0819	0.5324	1.57	245 ± 7
Q0047-2808	0.485	3.595	1.34	229 ± 15
CFRS03.1077	0.938	2.941	1.24	251 ± 19
HST 14176	0.810	3.399	1.41	224 ± 15
HST 15433	0.497	2.092	0.36	116 ± 10
MG 2016	1.004	3.263	1.56	328 ± 32

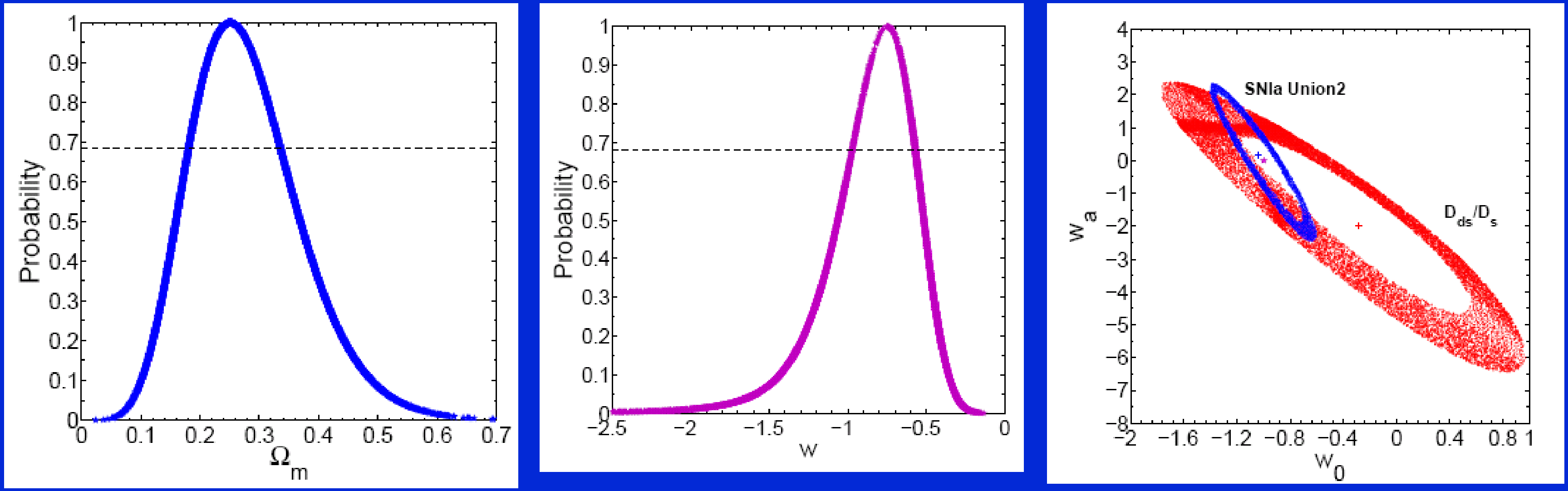
D_{ds}/D_s : more data

Kubo et al., 2010

Table 1. Parameters for Each Strong Lens System

System	R.A. (deg)	Decl. (deg)	z_l	z_s	θ_E[d] ($''$)	σ_v (km s^{-1})
SDSS J0952 + 3434	148.16760	34.57947	0.3491 ± 0.0001[b]	2.1896 ± 0.0001[f]	6.9	566 ± 12
SDSS J0957 + 0509	149.41330	5.15887	0.4469 ± 0.0002[b]	1.8230 ± 0.0003[b]	8.0	651 ± 12
SDSS J1207 + 5254	181.89964	52.91645	0.2717 ± 0.0002[b]	1.9257 ± 0.0002[b]	9.4	644 ± 10
SDSS J1318 + 3942	199.54796	39.70749	0.4751 ± 0.0002[a]	2.9437 ± 0.0003[b]	8.5	642 ± 11
SDSS J1450 + 3908	222.62770	39.13865	0.2893 ± 0.0002[a]	0.8613 ± 0.0003[b]	4.4	501 ± 17
SDSS J1537 + 6556	234.30500	65.93910	0.2595 ± 0.0001[b]	0.6596 ± 0.0001[b]	8.1	707 ± 13
SDSS J1723 + 3411	260.90067	34.19946	0.4435 ± 0.0002[b]	1.3294 ± 0.0002[b]	4.7	530 ± 17

Cosmological constraints from D_{ds}/D_s



Cosmological model	Best-fitting parameters	χ^2/dof
ΛCDM	$\Omega_m = 0.251^{+0.095}_{-0.080}$	1.514
wCDM	$w = -0.750^{+0.202}_{-0.255}$	1.489
CPL	$w_0 = -0.287 \pm 0.887$	1.457
	$w_a = -1.994 \pm 2.720$	

S. Cao, Y. Pan, M. Biesiada, W. Godlowski, Z-HZ 2011

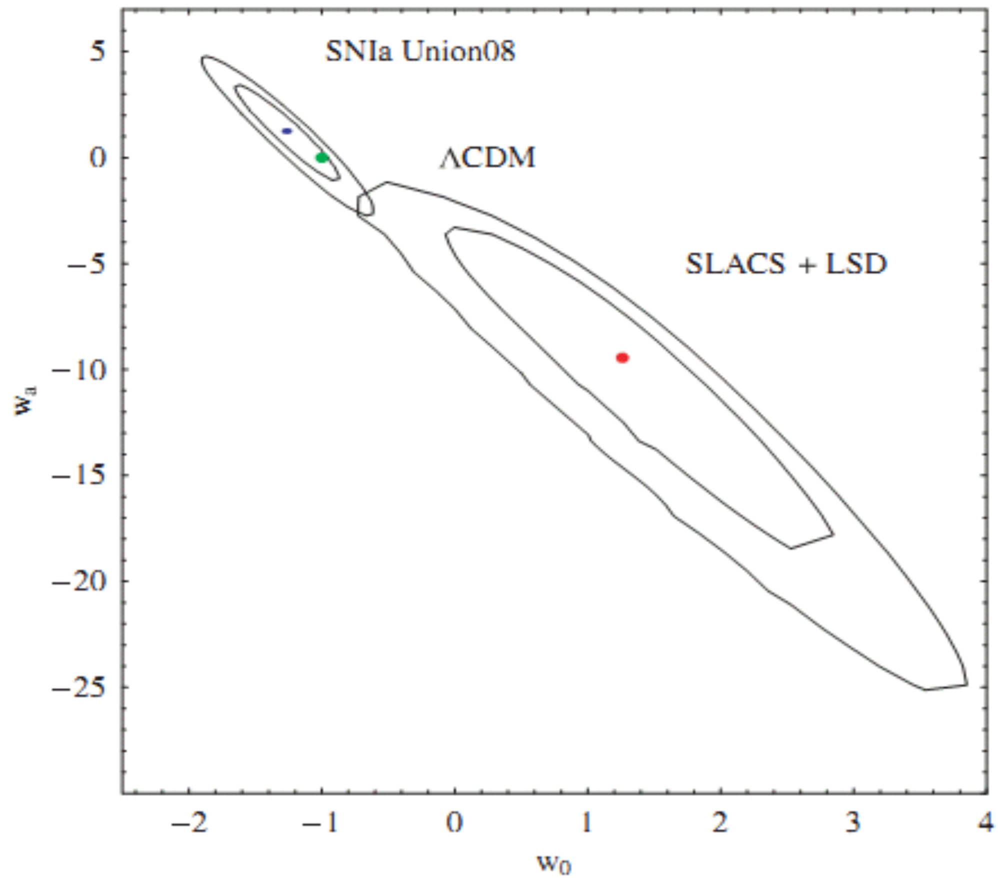


Figure 1. Best fits (dots) and (68 and 95 per cent) confidence regions for Chevalier–Linder–Polarski parameters in the cosmic equation of state obtained from the full SLACS + LSD sample of lenses and Union08 SNIa data. A dot corresponding to the ΛCDM model is added for reference.

Biesiada et al., 2010

New ideas for this method:

- **Work on larger well-defined samples!**
- **Consider the evolution of lens mass density profile!**

The Astrophysical Journal, 806:185 (12pp), 2015 June 20 doi:10.1088/0004-637X/806/2/185

COSMOLOGY WITH STRONG-LENSING SYSTEMS

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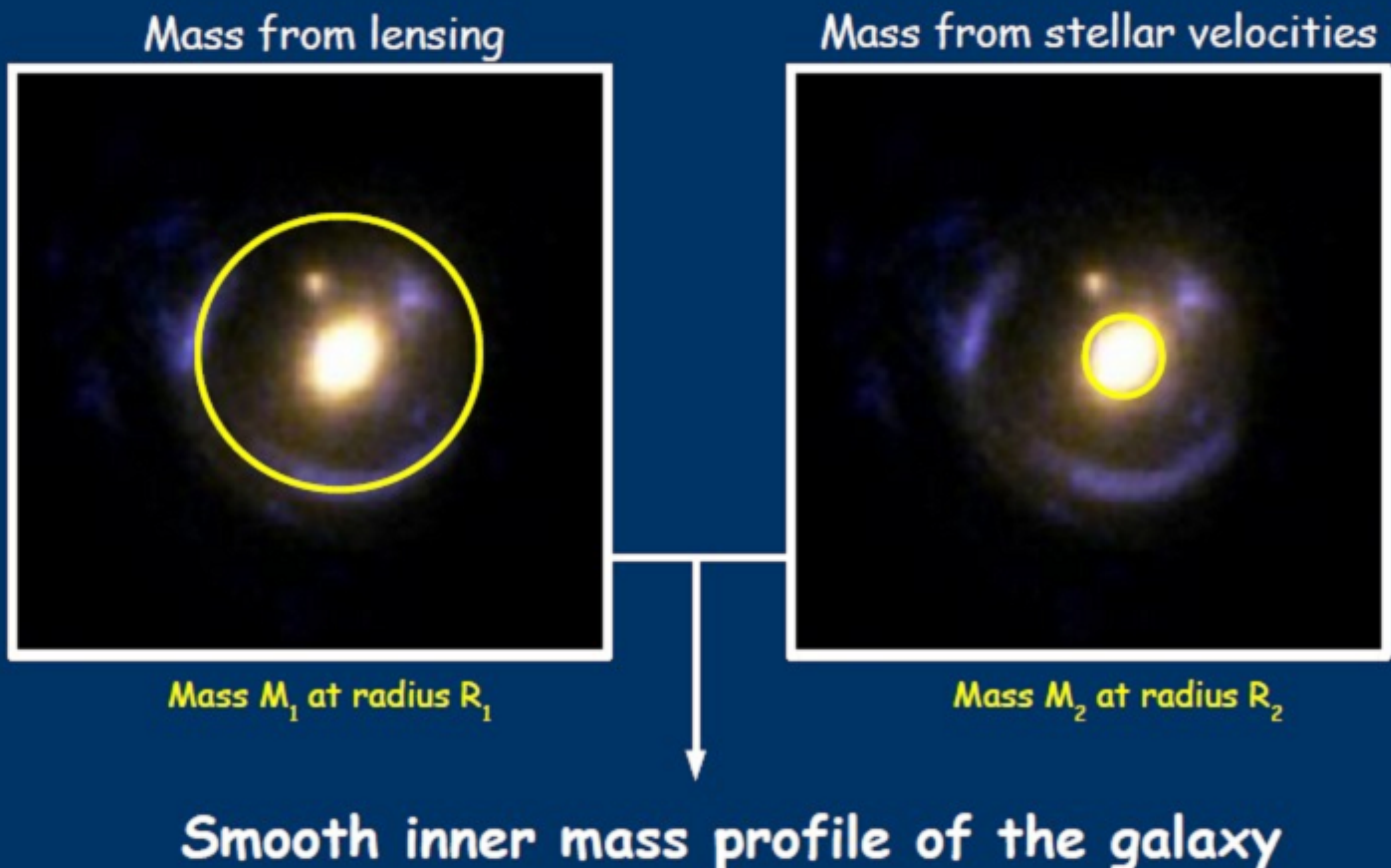
ABSTRACT

In this paper, we assemble a catalog of 118 strong gravitational lensing systems from the Sloan Lens ACS Survey, BOSS emission-line lens survey, Lens Structure and Dynamics, and Strong Lensing Legacy Survey and use them to constrain the cosmic equation of state. In particular, we consider two cases of dark energy phenomenology: the XCDM model, where dark energy is modeled by a fluid with constant w equation-of-state parameter, and in the Chevalier–Polarski–Linder (CPL) parameterization, where w is allowed to evolve with redshift, $w(z) = w_0 + w_1 \frac{z}{1+z}$. We assume spherically symmetric mass distribution in lensing galaxies, but we relax the rigid assumption of the SIS model in favor of a more general power-law index γ, also allowing it to evolve with redshifts $\gamma(z)$. Our results for the XCDM cosmology show agreement with values (concerning both w and γ parameters) obtained by other authors. We go further and constrain the CPL parameters jointly with $\gamma(z)$. The resulting confidence regions for the parameters are much better than those obtained with a similar method in the past. They are also showing a trend of being complementary to the Type Ia supernova data. Our analysis demonstrates that strong gravitational lensing systems can be used to probe cosmological parameters like the cosmic equation of state for dark energy. Moreover, they have a potential to judge whether the cosmic equation of state evolved with time or not.

Key words: dark energy – galaxies: fundamental parameters – gravitational lensing: strong

Methodology: Lensing & Dynamics



GRAVITATIONAL LENSING & STELLAR DYNAMICS

Mass Profiles and Shapes of Cosmological Structures
G. Mamon, F. Combes, C. Deffayet, B. Fort (eds)
EAS Publications Series, Vol. ?, 2005

Koopmans, L.V.E.[1]

2.1 Combining Lensing Mass and Stellar Velocity Dispersions

Let us suppose the following spherical scale-free model for the lens galaxy:

$$\begin{cases} \nu_l(r) &= \nu_{l,0} r^{-\delta} \\ \nu_\rho(r) &= \nu_{\rho,0} r^{-\gamma'} \\ \beta(r) &= 1 - \langle\sigma_\theta^2\rangle / \langle\sigma_r^2\rangle \end{cases} , \quad (2.1)$$

where $\nu_l(r)$ is the luminosity density of stars – a trace component – embedded in a total (i.e. luminous plus dark-matter) mass distribution with a density $\nu_\rho(r)$. The anisotropy of the stellar velocity ellipsoid is β, constant with radius. For a lens galaxy with a projected mass $M_{\rm E}$ inside the Einstein radius $R_{\rm E}$, the luminosity weighted average line-of-sight velocity dispersion inside an aperture $R_{\rm A}$ is given, after solving the spherical Jeans equations, by

$$\langle\sigma_{||}^2\rangle(\leq R_{\rm A}) = \frac{1}{\pi}\left[\frac{GM_{\rm E}}{R_{\rm E}}\right] f(\gamma', \delta, \beta) \times \left(\frac{R_{\rm A}}{R_{\rm E}}\right)^{2-\gamma'} , \quad (2.2)$$

where

$$f(\gamma', \delta, \beta) = 2\sqrt{\pi}\left(\frac{\delta-3}{(\xi-3)(\xi-2\beta)}\right) \times \left\{\frac{\Gamma[(\xi-1)/2]}{\Gamma[\xi/2]} - \beta\frac{\Gamma[(\xi+1)/2]}{\Gamma[(\xi+2)/2]}\right\} \times \left\{\frac{\Gamma[\delta/2]\Gamma[\gamma'/2]}{\Gamma[(\delta-1)/2]\Gamma[(\gamma'-1)/2)]}\right\} \quad (2.3)$$

with $\xi = \gamma' + \delta - 2$. Similarly,

$$\sigma_{||}^2(R) = \frac{1}{\pi}\left[\frac{GM_E}{R_E}\right]\left(\frac{\xi-3}{\delta-3}\right) f(\gamma', \delta, \beta) \times \left(\frac{R}{R_E}\right)^{2-\gamma'}. \tag{2.4}$$

In the simple case of a SIS with $\gamma' = \delta = \xi = 2$ and $\beta = 0$, we recover the well-known result

$$\sigma_{||}^2(R) = \frac{1}{\pi}\left[\frac{GM_E}{R_E}\right] \quad \text{(SIS)}, \tag{2.5}$$

Now, the idea is that

mass inside Enstein radius calculated from lensing

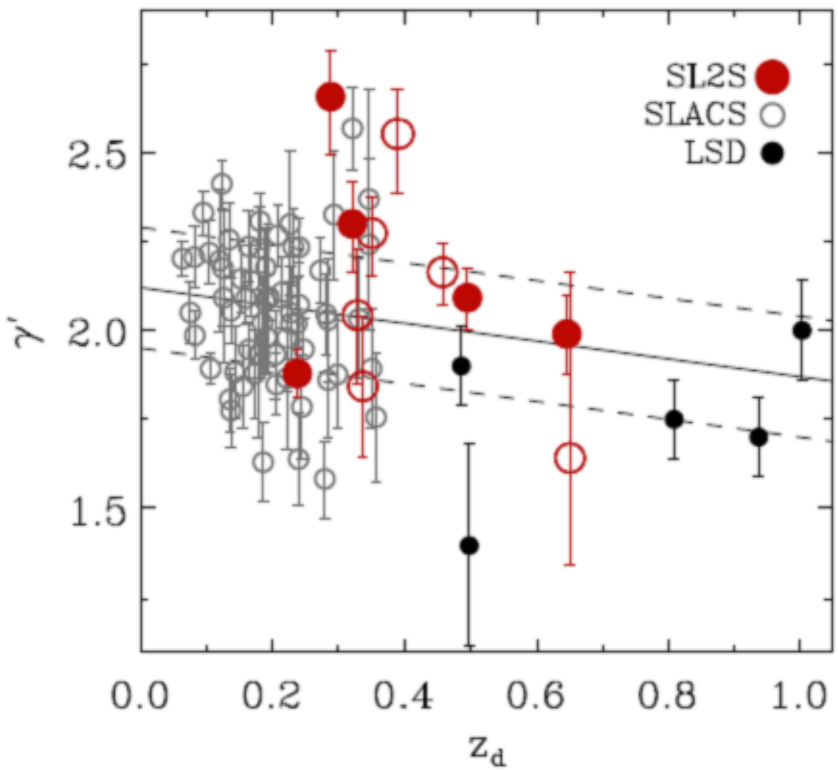
$$M_l = \frac{c^2}{4G}\frac{D_l D_s}{D_{ls}}\theta_E^{\ 2}$$

should be equal to mass inside Einstein radius calculated from dynamics

$$M_d = \frac{\pi}{G}\sigma_0^{\ 2} R_E \left(\frac{R_E}{R_{ap}}\right)^{2-\gamma} f(\gamma, \delta, \beta)$$

THE SL2S GALAXY-SCALE LENS SAMPLE. II. COSMIC EVOLUTION OF DARK AND LUMINOUS MASS IN EARLY-TYPE GALAXIES

Andrea J. Ruff[1,2*], Raphaël Gavazzi[3], Philip J. Marshall[1,4], Tommaso Treu[1†], Matthew W. Auger[1], and Florence Brault[3]



$$\langle\gamma'\rangle(z_{\rm d}) = \langle\gamma'_0\rangle + \frac{\partial\langle\gamma'\rangle}{\partial z_{\rm d}} z_{\rm d} \pm S_{\gamma'}.$$

For the SL2S data alone, we find $\langle\gamma'_0\rangle = 2.22^{+0.17}_{-0.21}$, $\partial\langle\gamma'\rangle/\partial z_{\rm d} = -0.16^{+0.48}_{-0.51}$ for the gradient and, in this evolving γ' case, the scatter is $S_{\gamma'} = 0.23^{+0.09}_{-0.06}$. When we include the SLACS and LSD data points, we find $\langle\gamma'_0\rangle = 2.12^{+0.03}_{-0.04}$, $\partial\langle\gamma'\rangle/\partial z_{\rm d} = -0.25^{+0.10}_{-0.12}$, and $S_{\gamma'} = 0.17^{+0.02}_{-0.02}$.

Lensing Sample

SLACS	57 lenses
BELLS	25 lenses
SL2S	31 lenses
LSD	5 lenses
Total	**118 lenses**

the Sloan Lens ACS Survey, BOSS emission-line lens survey, Lens Structure and Dynamics, and Strong Lensing Legacy Survey

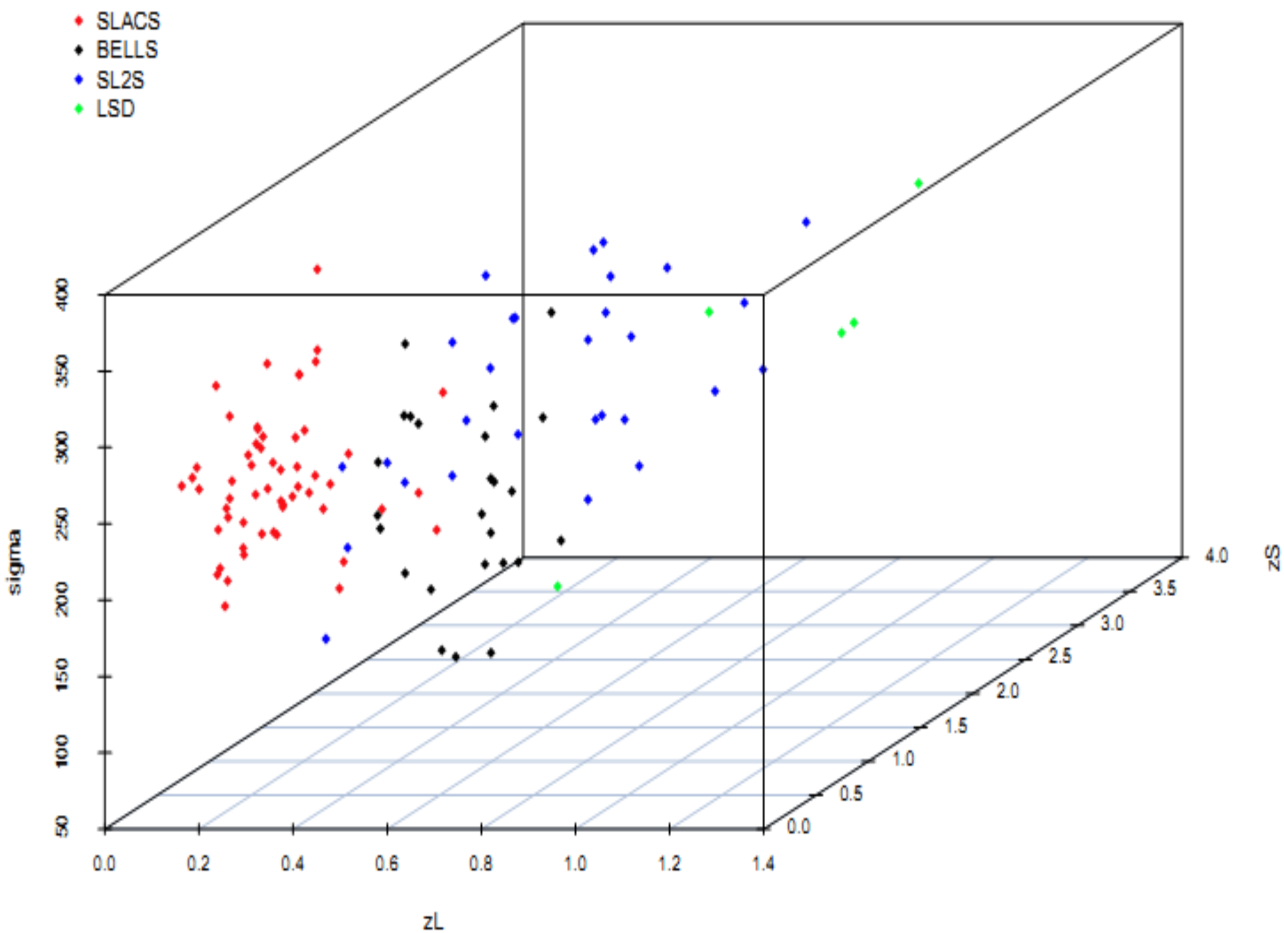


Fig. 1.— Scatter plot of our sample of 118 strong lensing systems. One can see a fair coverage of redshifts in the combined sample.

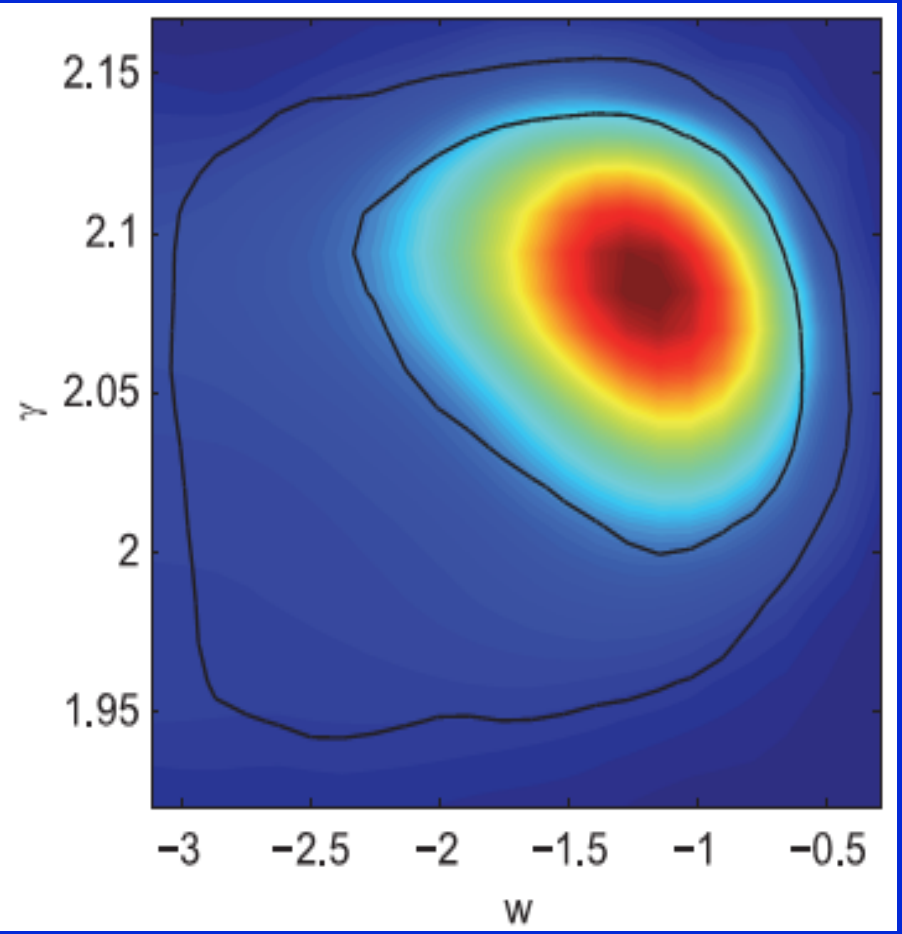
Cao et al. (2015)

Table 1
Compilation of Strong-lensing Systems

Name	z_l	z_s	σ_{ap} (km s^{-1})	θ_E ($''$)	Survey	θ_{ap} ($''$)	θ_{eff} ($''$)	σ_0 (km s^{-1})
J1402+6321	0.205	0.481	267 ± 17	1.35	SLACS	1.5	2.7	268 ± 17
J1403+0006	0.189	0.473	213 ± 17	0.83	SLACS	1.5	1.46	219 ± 17
J1416+5136	0.299	0.811	240 ± 25	1.37	SLACS	1.5	1.43	247 ± 26
J1430+4105	0.285	0.575	322 ± 32	1.52	SLACS	1.5	2.55	324 ± 32
J1436–0000	0.285	0.805	224 ± 17	1.12	SLACS	1.5	2.24	227 ± 17
J1451–0239	0.125	0.52	223 ± 14	1.04	SLACS	1.5	2.48	225 ± 14
J1525+3327	0.358	0.717	264 ± 26	1.31	SLACS	1.5	2.9	264 ± 26
J1531–0105	0.16	0.744	279 ± 14	1.71	SLACS	1.5	2.5	281 ± 14
J1538+5817	0.143	0.531	189 ± 12	1	SLACS	1.5	1.58	194 ± 12
J1621+3931	0.245	0.602	236 ± 20	1.29	SLACS	1.5	2.14	239 ± 20
J1627–0053	0.208	0.524	290 ± 14	1.23	SLACS	1.5	1.98	295 ± 14
J1630+4520	0.248	0.793	276 ± 16	1.78	SLACS	1.5	1.96	281 ± 16
J1636+4707	0.228	0.674	231 ± 15	1.09	SLACS	1.5	1.68	236 ± 15
J2238–0754	0.137	0.713	198 ± 11	1.27	SLACS	1.5	2.33	200 ± 11
J2300+0022	0.228	0.464	279 ± 17	1.24	SLACS	1.5	1.83	285 ± 17
J2303+1422	0.155	0.517	255 ± 16	1.62	SLACS	1.5	3.28	254 ± 16
J2321–0939	0.082	0.532	249 ± 8	1.6	SLACS	1.5	4.11	246 ± 8
J2341+0000	0.186	0.807	207 ± 13	1.44	SLACS	1.5	3.15	207 ± 13
Q0047–2808	0.485	3.595	229 ± 15	1.34	LSD	1.25	0.82	239 ± 16
CFRS03–1077	0.938	2.941	251 ± 19	1.24	LSD	1.25	1.6	256 ± 19
HST 14176	0.81	3.399	224 ± 15	1.41	LSD	1.25	1.06	232 ± 16
HST 15433	0.497	2.092	116 ± 10	0.36	LSD	1.25	0.41	125 ± 11
MG 2016	1.004	3.263	328 ± 32	1.56	LSD	0.65	0.31	347 ± 34
J0212–0555	0.75	2.74	273 ± 22	1.27	SL2S	0.9	1.22	277 ± 22
J0213–0743	0.717	3.48	293 ± 34	2.39	SL2S	1	1.97	293 ± 34
J0214–0405	0.609	1.88	287 ± 47	1.41	SL2S	1	1.21	293 ± 48
J0217–0513	0.646	1.847	239 ± 27	1.27	SL2S	1.5	0.73	253 ± 29
J0219–0829	0.389	2.15	289 ± 23	1.3	SL2S	1	0.95	298 ± 24

Cao et al. (2015)

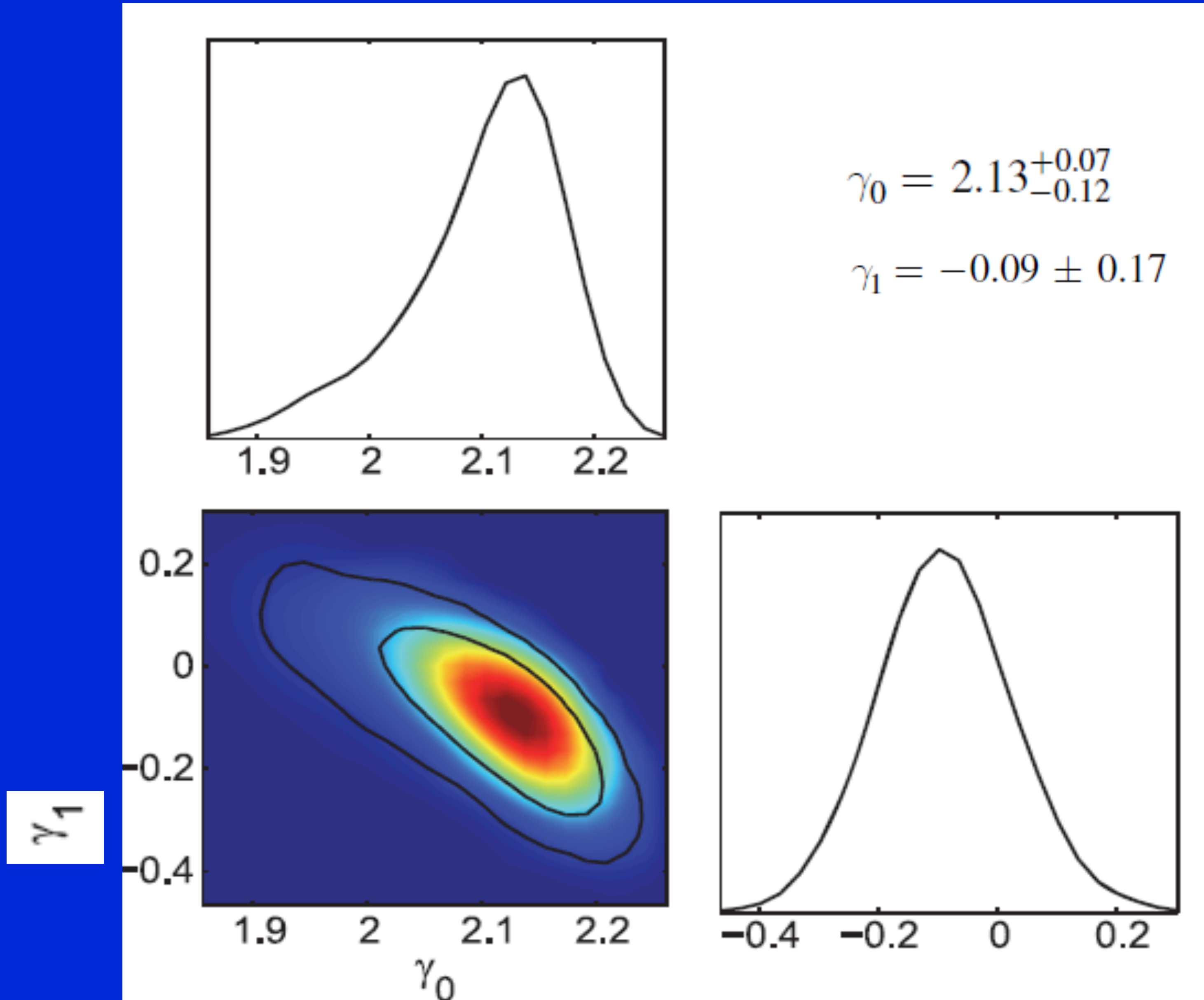
$$\rho \sim r^{-\gamma}$$



$$w_0 = -1.15^{+0.56}_{-1.20}$$

$$\gamma_0 = 2.07 \pm 0.07$$

Cao et al. (2015)



Cao et al. (2015)

$$w(z) = w_0 + w_1 \frac{z}{1 + z}$$

$$w_0 = -1.05^{+1.43}_{-1.77}$$

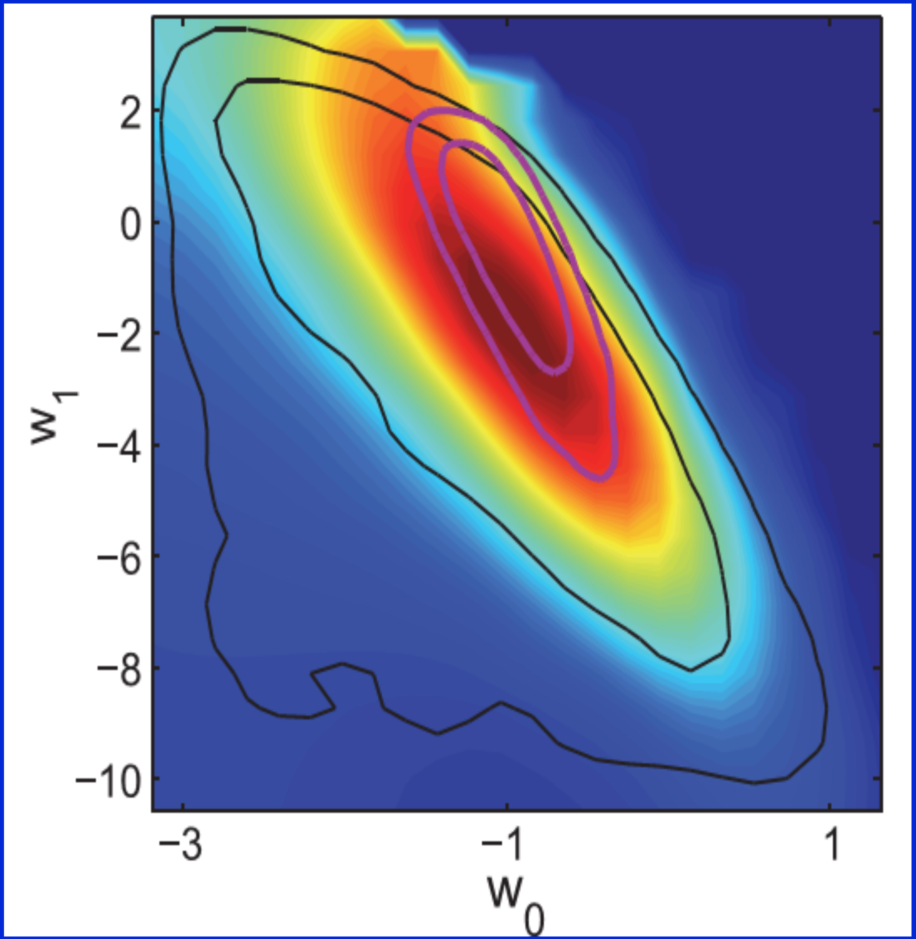
$$w_1 = -1.65^{+4.25}_{-6.35}$$

From strong lensing

$$w_0 = -1.00 \pm 0.40$$

$$w_1 = -0.12^{+1.58}_{-2.78}$$

From SN Union2.1



Cao et al. (2015)

Conclusion & perspectives

- Strong lensing systems with known central velocity dispersions are a new class of "standard rulers‟ (Einstein radius being standardized by stellar kinematics)
- Measurements of time delays between images – will provide distances not just distance ratios!
- Strong lens redshift test, which is independent of magnification bias, can be a complementarity to other cosmological probes.
- Strong lensing systems will be abundant because of existing surveys such as CLASS, SLACS, SL2S, SQLS, AEGIS, COSMOS, CASSOWARY, BELLS, and new projects such as Pan-STARRS, LSST, JDEM / IDECS3, SKA4.

Thanks for your attention !

Beijing Normal University: main building

Beijing Normal University: astronomy department

- Founded in 1960

  — the second Department of Astronomy (DA) at Universities in China
- Staff: 25+4

  — a modern Astrophysics Lab

  — an Astronomy Detection Technology Lab

  — an Accurate Satellite Orbit Determination Lab

  — an Astronomical Observations Lab

Beijing Normal University: astronomy department

— Undergraduate student: ~25 /year;
Graduate student: ~20 /year;
In total: ~160 students in astronomy.

— Master's degree in 3 areas:
Astrophysics,
Astrometry and Celestial Mechanics,
Optics.

— Ph.D. degree:
Astrophysics.

—Equipments:

two 40-cm telescopes on the campus;

one radio telescope on the campus;

¼ time of a 85-cm telescope at XL;

A computer room for students.

Beijing Normal University: astronomy department

- Research funding:

  ～50,000 ＄/person/year

- Funding sources:

  National Natural Science Foundation
  Ministry of Science and Technology
  Ministry of Education
  Beijing Local Government
  Chinese Academy of Sciences
  Beijing Normal University
  etc.

Beijing Normal University: astronomy department

- Research fields:
  - Cosmology
  - Stellar physics
    variable stars, massive stars, stellar evolution.
  - Quasar & Galaxy
  - High energy astrophysics
  - Laboratory astrophysics

My group

- Staff:
  —Prof.M Biesiada & Dr.S Cao,Z Li: Cosmology
  —Prof.P Tozzi & Dr.H Yu: X-ray clusters
  —Prof.M Hendry, H Siong & Dr. F Zhang: GWs, NR

- Students:
  —PhD student: 8
  —MSc Graduate student: 7
  —Undergraduate student: 3

- Research fields
  —Cosmology: DE , Lensing, X-ray clusters
  —Gravitational waves